MICROELECTRONICS in the 1970's

Rockwell International

MICROELECTRONICS IN THE 1970'S

by
Martha Smith Parks

Author of "Story of Microelectronics . . .
First, Second and Future Generations"

FOREWORD

As one of the world's acknowledged electronics industry leaders for over two decades, Rockwell International presents this account of the increasingly important role played by microelectronics in the 1970's.

Rockwell International has pioneered in the evolution of microelectronics almost since this technology's beginning in the late 1940's. Today, the company's microelectronic products range from tiny solid-state microcircuit devices to complete microelectronic systems for defense, space, commerce, industry, and private consumer.

The role of microelectronics in the 1970's is important for many reasons. First of all, it makes things easier for us—in providing us, for example, with such conveniences as handheld calculators, digital clocks and wristwatches, and truly portable personal radios and TV sets. Also, it saves us money—by increasing reliability, lengthening equipment lifetimes, and lowering costs to produce, operate, and maintain a broad variety of products. With microelectronics, furthermore, it has become feasible to accomplish for the first time many system chores impossible with any previous approach—such as, for instance, almost literally two-dimensional imaging displays . . . functionally huge but physically small electronic communications systems . . . adaptive, self-testing data processors and computers.

Perhaps of greatest significance today, however, is microelectronics' notable ability to operate on mere microwatts of power. With modern man's ever-increasing energy requirements, coupled with the progressive depletion of the world's energy resources, this can prove to be microelectronics' most meaningful characteristic of all.

Acknowledgements

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Credits

about the author . . .

Martha Smith Parks was graduated from Stephens College and the University of Mississippi with majors in English and journalism. She studied electronics at the American Defense School, Memphis, Tennessee; the University of Cincinnati; and the Aircraft Radio Engineering School, Dayton, Ohio. Following graduation from the latter, she was retained by that Signal Corps-sponsored institution as an instructor in theory, operation, and maintenance of airborne radio and radar, and was subsequently made head instructor of the school's training program for radio engineering aides. During this same period, she was chief editor of the airborne radio maintenance manual prescribed for use in Federal depots throughout the United States. Upon completion of her assignment as head instructor at the Aircraft Radio Engineering School, she worked as a radio engineer, engaged in airborne electronics development at Wright Field, Ohio; as a nuclear research instrument design engineer at Oak Ridge National Laboratories, Oak Ridge, Tennessee; and as a missile test equipment development engineer at Capehart-Farnsworth, Ft. Wayne, Indiana. In 1955, she was brought to California by Hughes Aircraft Company to assist in development of test specifications for electronic components. Joining Rockwell International's Autonetics Division in 1956, she has been able to combine journalism training with electronics engineering experience, as writer and writing supervisor for this technological organization. She is a member of Delta Rho Alpha, Delta Delta Delta, Eta Sigma Phi, and Chi Delta Phi. She is also a member of American Women in Radio and Television, the American Society for Psychical Research, the Southern California Society for Psychical Research, the Audubon Society, the American Wildlife Federation, and the National Federation of Press Women, and is President of the Los Angeles District, California Press Women. She is a member of Mensa, international organization whose membership is limited to those with measured IQ's in the upper 2% of the general population, and she is listed in Who's Who of American Women, Volume 8, 1974-75.

CONTENTS

ILLUSTRATIONS

SIDEBARS

TABLES

I. INTRODUCTION

On December 23, 1972, the science of microelectronics celebrated its 25th birthday. Exactly 25 years before that date, this astonishing technology's "time had come"—with the invention of the transistor by John Bardeen, Walter Brattain, and William Shockley.

Since its birth in 1947, microelectronics has proved itself "astonishing" from a multitude of aspects—first of all, because of its ubiquitous penetration into almost every phase of man's life . . . including medical diagnosis, crime prevention and police administration, traffic control on earth and in the sky, education, entertainment, hospital management and patient monitoring, space exploration and communication, and national defense.

Microelectronics is "astonishing," too, for its uniquely interdisciplinary nature. Unlike any other technology, the design, development, and production of microelectronic devices demand a closely interworking team of chemists, physicists, metallurgists, circuit and system design engineers, photographic experts, semiconductor device production specialists, applications engineers, and operations analysts. Increasing need is felt, also, as the elements of microelectronics become ever smaller and more densely packed within each device, for computer experts to program and operate the computer aids that are so essential in the design, layout, and generation of the masks used to produce microelectronics' highly integrated circuit devices.

Finally, microelectronics is "astonishing" for its accelerating rate of growth. One microelectronics development builds upon another, to produce a veritable microelectronics explosion of constant advancement and breakthrough.

Extrapolation of microelectronics into the future, at its present growth rate, points to a tomorrow that even a modern Jules Verne would hesitate to predict. In fewer years from now than conceivably seems possible, microelectronics will be literally everywhere. The small size and high-function capability of ultra-dense microelectronics circuitry already permits the fabrication of entire systems on tiny, single chips. This capability, combined with the digitization of traditionally analog systems, and the conversion to electronics of present mechanical approaches, is going to make it possible for microelectronics to virtually wave a magic wand over our daily lives.

To make just a few reasonable predictions, based on today's trends and development, microelectronics should in the not too distant future be able to . . .

. . . Produce pre-programmable autopilots for our private automobiles, that will give us the choice either of dialing a new destination by inputting coordinates from our "dial-a-route" directory, or of inserting a cassette from a glove compartment library of our most often-traveled itineraries.

. . . Enable us to operate our own home computer terminals, communicating with a computer "central" the way we now communicate with a telephone central—to automatically perform our banking, our shopping, our bill-paying, our income tax computations—to serve, in other words, as our own captive, low-cost family accountants.

. . . Locate for us in any library on earth, and present to us on the screen of our home TV set the automatically turned pages of any book ever published—only seconds after we have punched the button to request it.

. . . Give us the power not only to predict, but to *make*, the "weather" within a licensed radius around our home. Microelectronic environmental control units will monitor and manage our domestic ecologies just as efficiently as present-day systems monitor and manage the ecology aboard a spaceship to the moon.

. . . Permit some of today's most desperately ill terminal and near-terminal cases to become tomorrow's out-patients, living normal, active lives, through the boon of microelectronic implants that will take over the monitoring and direction of bodily functions, such as today are only partially performable even by unwieldy external heart pacers and power supplies, and bulky banks of dialysis equipment.

The few predictions given here barely tap microelectronics' potential for bringing to reality the wonders of tomorrow. As a pioneering designer, producer, and systems user of microelectronics almost since its beginning 25 years ago, Rockwell International has prepared this book to describe microelectronics' great potential . . . and to show how it is being developed and applied today to hasten the arrival of tomorrow's wonders. In straightforward, nonmathematical language, the book is designed to present a broad overview of microelectronics state-of-the-art in the 1970's . . . of the steps through which it progressed to this state . . . and of the directions it seems to be taking for the future.

Following this brief introduction in Chapter I, the reader is given, in Chapter II, a quick synopsis of first- and second-generation microelectronics, and is told in simple terms how microelectronics "works" and how microelectronic devices of the '70's are typically fabricated.

In Chapter III, one of the '70's most marked microelectronics trends—large-scale-integration or "LSI"—is discussed in the detail which its importance merits. LSI is first defined, and its effects are then described on the system designer and user, on reliability, and on costs. The necessity for computer aids in design and production of LSI circuitry is also described, and examples of earlier and present-day microelectronic circuitry are compared to illustrate this necessity. LSI special intra- and interconnection methods are discussed in detail.

In Chapter IV, the new *materials* of microelectronics are covered—including silicon-on-sapphire, gallium arsenide and beryllia, luminescent and light-sensitive materials, and that wondrously versatile family known as the "ferrites." Also covered are some of the devices made possible by the development of these materials . . . such as lasers, microacoustic components, bubble memories, and liquid crystal displays.

Chapter V discusses the growing applicability of microelectronics to radar and other formerly analog, high-frequency, and high-power circuitry, via the new materials and through new approaches such as electronic scanning and digitization.

Chapter VI extrapolates from today's microelectronics state-of-the-art to give readers a brief but thought-provoking look into the future. After reading Chapter VI, we believe you will be tempted to do some crystal-gazing of your own. And . . . if we may make one final forecast . . . we predict that time will prove both our imaginings to be exceedingly "tame" beside what actually comes to pass.

Chapter VII presents a brief recap of the foregoing sections.

II. EVOLUTION, REVOLUTION... WHAT MICROELECTRONICS IS AND HOW IT CAME TO BE

HOW IT ALL BEGAN

The evolution of microelectronics is inextricably intertwined with the development of the class of materials known as "semiconductors." The name "semiconductor" applies to materials that have an ability to conduct electrical current somewhere between the *high* conductivity of *conductors* such as copper, silver, and aluminum, and the *low* conductivity of *insulators* such as rubber, wood, and certain plastics.

Thus, the saga of microelectronics begins with one of the earliest uses of a semiconductor, as a crystal detector for the first crude home radio receivers in the 1920's. The "crystal" in the detector was actually a hunk of semiconductor material—generally, either carborundum or galena. The operator of the radio receiver turned a knob to move a thin wire—appropriately called a "cat's whisker"—over the surface of the crystal, until he found a spot where the semiconductor's characteristic ability to conduct current better in one direction than in the other (i.e., ability to "rectify") was particularly pronounced. At this spot, the radio signal was effectively "demodulated" through rectification, and the operator could hear the music or speech being broadcast from the station he had "tuned in."

Throughout the '20's and '30's, the semiconductor's ability to rectify was exploited in such devices as copper oxide and selenium rectifiers for conversion of large amounts of a-c voltage or current to dc in power supplies. Not until the 1940's, however, were processes perfected for producing semiconductors of the necessarily high purity to serve as *precision circuit components*, that could be relied upon to behave in accordance with predictions, and to do so every time they were used. In the late '40's, such components became practical for everyday use in circuitry, with the introduction of silicon and germanium *diodes*. Then, in the early '50's, semiconductor devices with the ability to *amplify* became generally available—these were the "*transistors*" first successfully devised and applied by Schockley, Brattain, and Bardeen in 1947.

The microelectronic diode and transistor substitutes for vacuum tubes offered many advantages over their bulky predecessors. In the first place, the semiconductor devices could operate with much lower supply voltages—as much as ten times lower—than those required for vacuum tubes. No voltage at all was required for filaments, because, unlike vacuum tubes, the new devices had no filaments. All this added up to power supplies that could be significantly smaller and lighter—as could everything else be, in any electronic system made up of the new components.

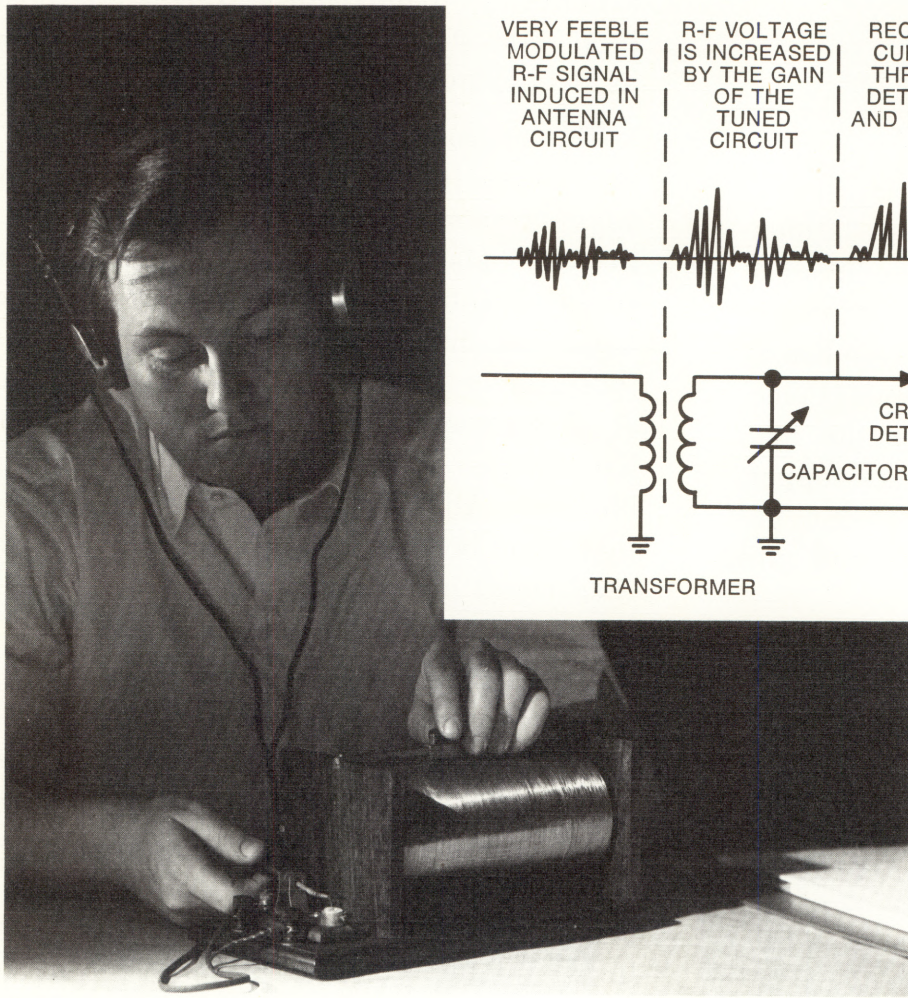
SOME OF THE REASONS

The impressive *smallness* of microelectronics was, in the late '40's, its greatest drawing card. The systems required to guide and control missiles and aircraft were more intricate than any electronic systems ever devised prior to World War II. The increasing functional complexity of the systems meant that the circuitry to perform the functions had to be increasingly complex, and this meant a constant increase in number of components per system with each functional advance. To keep system weight down, and range and payload up, electronic components and the systems containing them simply *had* to decrease in size and weight.

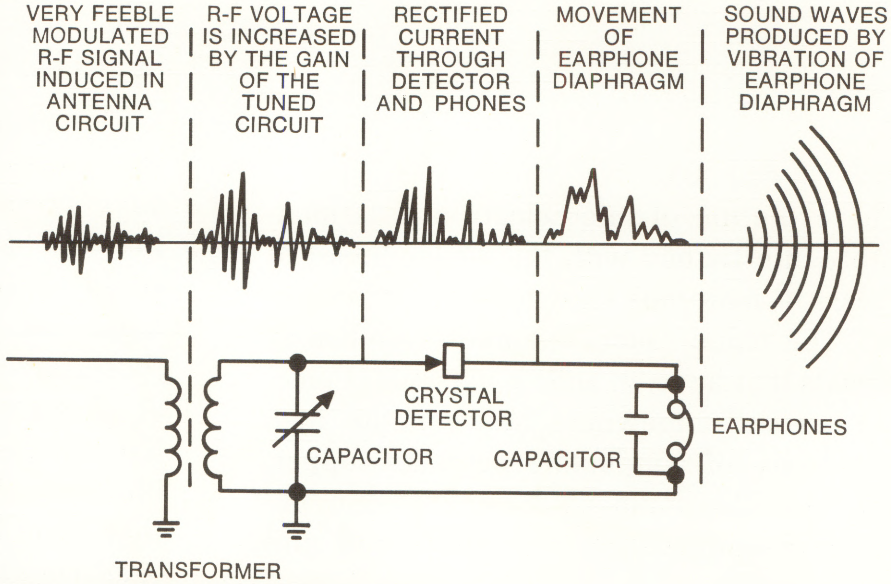
There was another problem, too, that stemmed from increasing system complexity. This problem had to do with the important consideration of reliability.

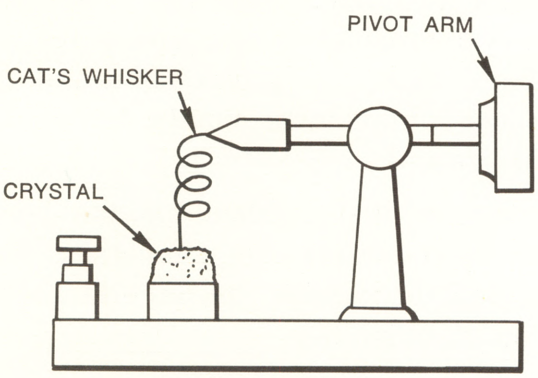
Unfortunately, as parts per electronic system go up, the system's overall reliability goes down—for a straightforward mathematical reason: The reliability of a system is equal to the *product* of all the individual reliabilities of all the system's separate components. To illustrate, in a system made up of just *two* components, each having a reliability of

MICROELECTRONICS AND SEMICONDUCTORS SHARED A COMMON CRADLE...

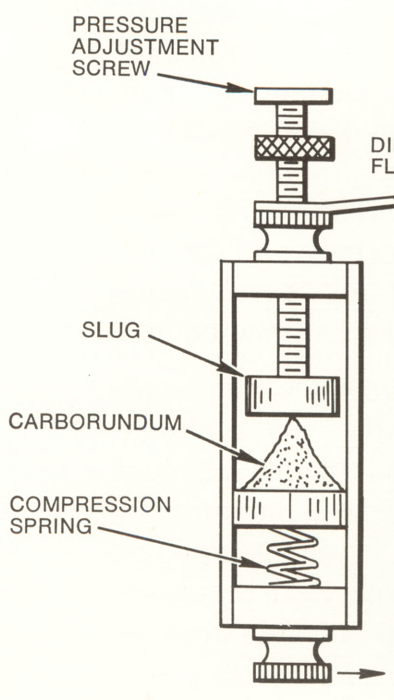


How an Early Crystal-Detector Radio Receiver Worked





One of the Earliest Crystal Detectors. All of this early detector was out in the open, completely exposed to view. The light "cat's whisker" can be seen resting against a galena crystal.



A Later, "More Sophisticated" Crystal Detector. A form of carborundum crystal detector (vintage circa 1932) is cut open to reveal its parts. The carborundum crystal was held in contact with a metal slug under about 5 pounds pressure, exerted by a spring. Screw adjustment of the spring tension was made for best contact. The combination's efficiency as a rectifier arose from low resistance to current flow from slug to crystal, but high resistance from crystal to slug.

The Semiconductor Family Tree

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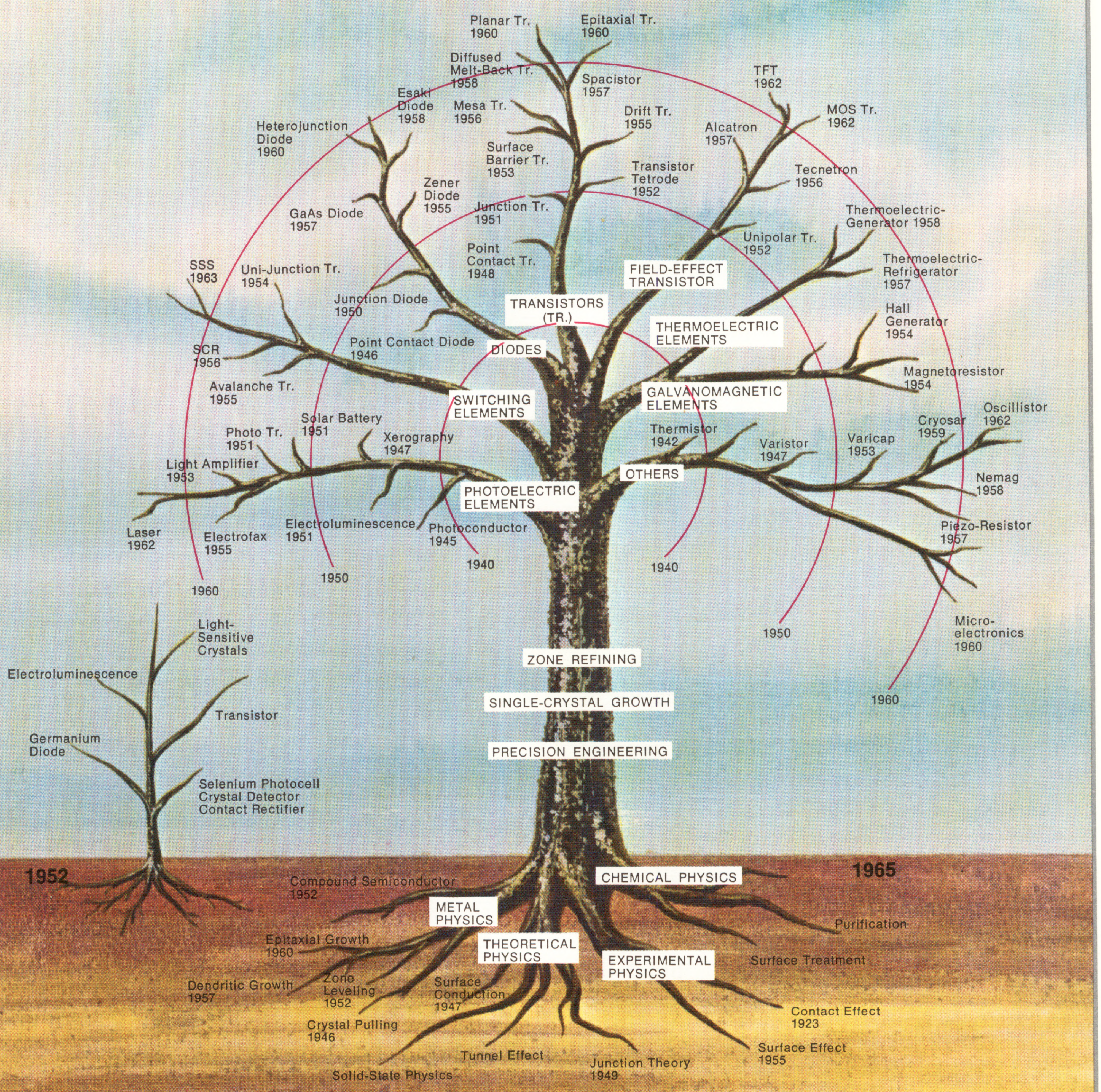


In February 1965, the above illustrations were published in **Electronic Industries** magazine, along with an article by Masamitsu Kawakami and Kiyoshi Takahashi, Professor and Asst. Professor, respectively, Tokyo University of Technology, Tokyo, Japan. The article went on to say that, since the little sapling, at left above, reached the height shown by W. C. White in an earlier article in **Electronics** magazine, September 1952, the semiconductor technology had branched outward and upward to form, in 1965, the mighty tree* at right. In 1965, one would surely have believed that microelectronics must have reached full growth—but, in the intervening years since, the lone tree has grown into a veritable forest! Some offspring have evolved predictably. Others can be nothing else than revolutionary mutants!

*Roots of the large tree in illustration represent basic research from which semiconductor technology has sprung. Large main divisions of the trunk indicate functional classification, while individual branches denote devices. Where possible, Kawakami and Takahashi included dates indicating years when devices first became available commercially; otherwise, dates indicate years of publication of first reports on devices.

99%*, the system reliability would be the product of 99% x 99%—that is, it would be 98.01%. In a system containing *four* 99%-reliability components, system reliability would be the product of 99% multiplied by itself *four* times—(0.99-to-the-*fourth*-power)%, or 96.05%. In a system of *seven* 99%-reliability components, system reliability would be only $(0.99)^7$%, or 91.34%! And so on . . .

In an intricate electronic system such as the one that guided and controlled the Air Force's intercontinental ballistic missile, Minuteman I, for instance, the components numbered in the thousands—and, at the same time, the system's reliability was required to be extremely high. That is why a special first-of-its-kind reliability-improvement program was undertaken in 1960 to ensure that Minuteman I electronic components were of the necessary unprecedented reliability. The program was highly successful and led to component reliability breakthroughs that were of benefit to the entire electronics industry.

For sophisticated Minuteman II, however, even the ultra-high-reliability components achieved for Minuteman I were not reliable enough. The more advanced guidance and control system for the later missile had many more tasks to perform than its forebear, and this meant that many more components were required. This, as we have just seen, meant that *each component* must be many times more reliable, in order just to maintain the overall *system* reliability of the earlier, less complex system.

The answer was microelectronics—not only microelectronics, but an entirely new breed of microelectronics. A microelectronics that was not only inherently more reliable than the earlier diodes and transistors—but one that permitted *many more functions* to be performed *with fewer components*!

The new kind of microelectronics was called "integrated circuitry." In this new kind of microelectronics, a single block of semiconductor material was processed to contain within itself the functional equivalent of a number of separate or "discrete" transistors, diodes, resistors, and capacitors, as well as the interconnections to tie elements into what was called an "integrated circuit," or "IC." A single monolithic IC—no bigger and no heavier than a discrete transistor—could perform, depending on the details of its design, as a complete amplifier, multivibrator, or flip-flop!

It is easy to see what the revolutionary new IC concept did for reliability. First of all, since fewer components were required for "mechanizing" more complex functions, higher reliability was inherent in use of the new components. Besides, structurally and physically, each of the monolithic devices—with no separable, movable parts other than its leads to the outside world—was actually more rugged and thus more reliable than any older discrete components. IC's were, furthermore, less subject than discrete components to the unreliability that comes with human handling, for in both actual manufacture and in assembly into systems IC's required fewer steps to be made by human operators.

Minuteman II was the first major weapon system to be mechanized throughout with microelectronics. In addition to IC's, it employed a second type of "first-generation" microelectronics—the ceramic printed circuit (CPC) or "thick-film" device.

An example of what this "technological update" meant to the Minuteman system was Minuteman II's D37 microelectronic guidance-and-control computer—which was only one-fourth as large as its predecessor, the D17 in Minuteman I; had only half the weight and power requirements of the D17; yet had a memory capacity two-and-one-half times as great as that of the D17.

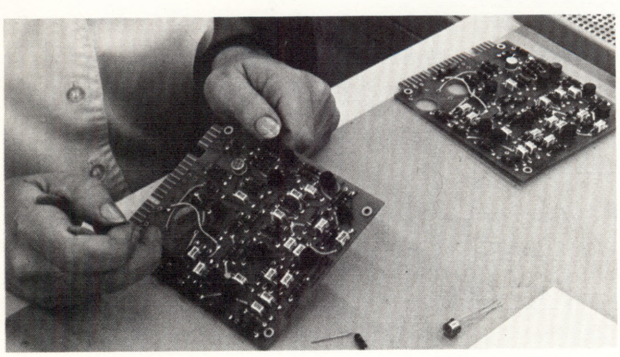
Applied microelectronics was pushed even further on the Minuteman III's D37D computer, increasing computer capacity and capability manifold, with a less than four-pound increase in computer weight.

**When a system has a predictable reliability of 99%, it is predictable that it will perform reliably 99 times out of 100.*

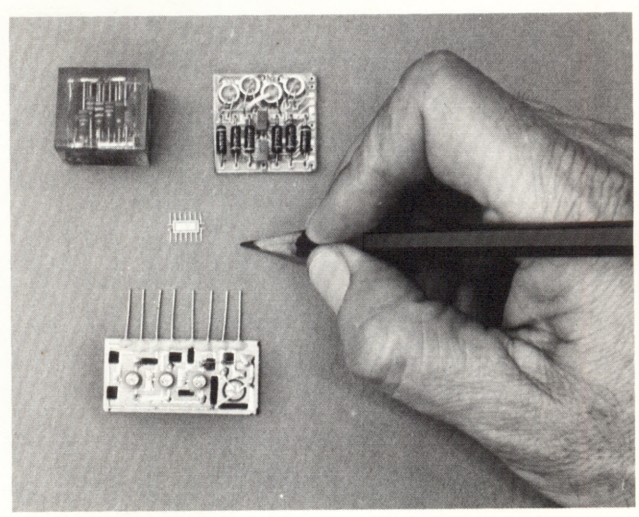
FIRST-GENERATION APPROACHES TO MICROELECTRONICS

Evolution from vacuum tubes to modern microelectronics has covered a span of two decades and has advanced through a series of approaches. First, the large vacuum tubes evolved into smaller "peanut" and "acorn" versions—then these were replaced by solid-state semiconductor diodes and transistors. Bulky discrete capacitors and resistors, and even the discrete solid-state diodes and transistors, next gave way to monolithic semiconductor integrated circuits (IC's) and to thin- and thick-film (or ceramic printed) circuit devices. Today, these first-generation microelectronics approaches are being improved upon by a still-advancing technology.

A vacuum tube looms giant-like over a transistor. Both are from yesterday's generations, and in many applications, have been succeeded today by smaller, but more capable and more reliable, approaches to electronics.

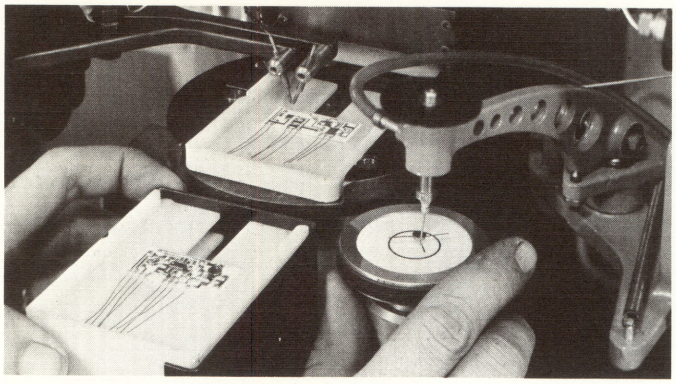


Before the conception of "integrated" microelectronics approaches, individual microminiature transistors, capacitors, resistors, and diodes were attached to single-layer circuit boards. Assembly of each board with its components involved many separate hand-soldering and wiring operations.



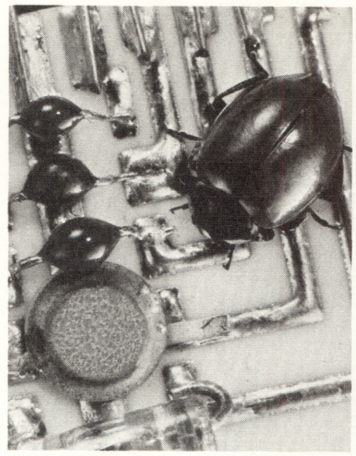
Four first-generation approaches to microminiaturizing a flip-flop circuit are grouped to give a comparison of relative sizes. At upper left is a plastic-encapsulated package of discrete components, while at upper right is a thin-film device. The ceramic printed circuit version of the flip-flop is at bottom of the picture, and the integrated circuit is at center. All four approaches perform the identical flip-flop function.

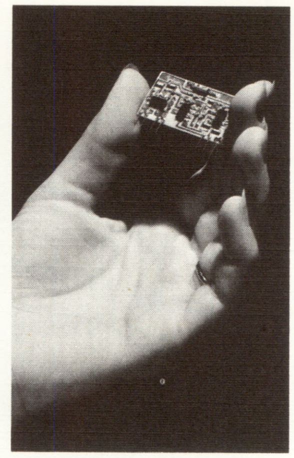
CERAMIC PRINTED (THICK-FILM) CIRCUITS



Discrete components are resistance-soldered to screened resistor-conductor networks on ceramic substrates to form ceramic printed circuits.

One of the earliest forms of microelectronics was the screened or ceramic printed circuit (CPC) process. CPC's are still of great use for many high-temperature, high-power applications. They are made by a technique adapted from silk screening. First, the circuit pattern is printed on a high-resolution metal screen. Then, in separate operations, the conductor and resistor materials are pressed through the screen onto a tiny (as small as ¼-inch square), wafer-thin substrate of alumina or other ceramic.

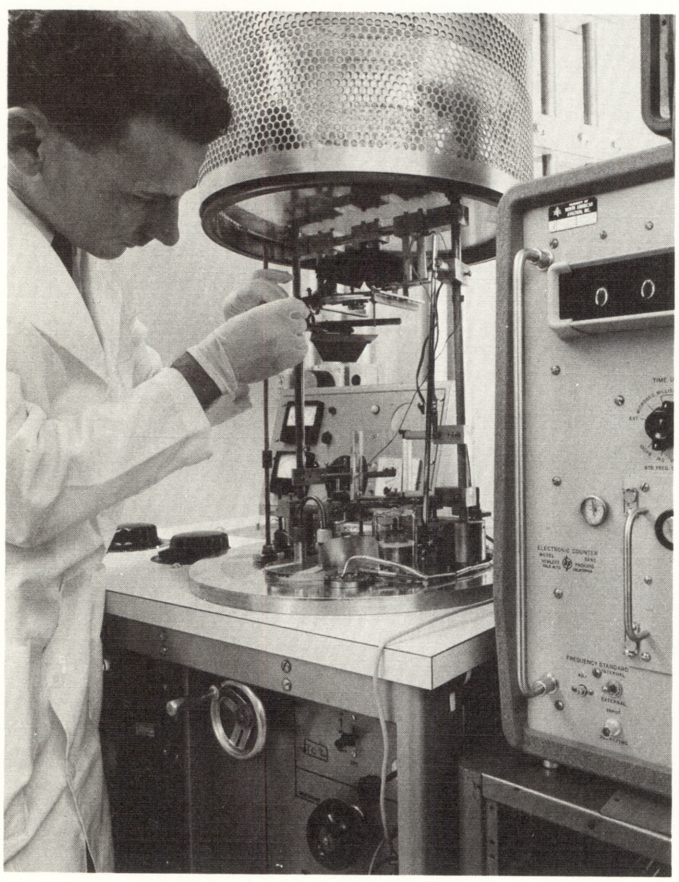




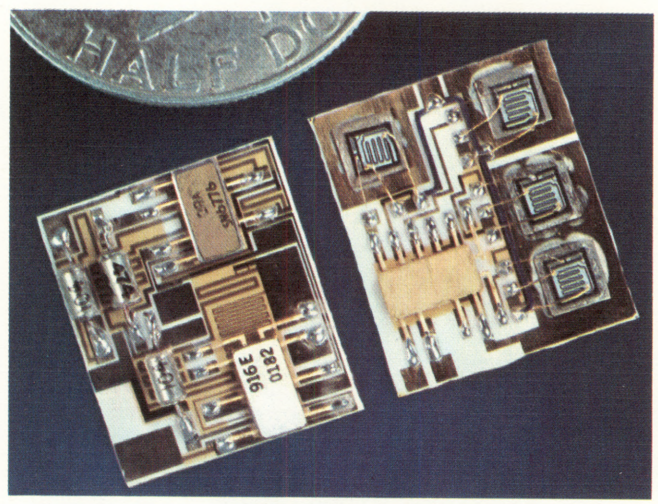
Here's how the CPC and its attached components look close up. (Ladybug gives idea of size.)

When both conductor and resistor patterns have been printed, the wafer is placed, first, in a low-temperature oven which dries the pattern, and, then, in a high-temperature furnace which fires the resistor and conductor patterns in place on the substrate. Next, the conductors are dip-soldered, and additional components, such as transistors, diodes, and capacitors, are soldered, welded, or bonded to the substrate. In a final step, the substrate is placed in a special jig and encapsulated.

THIN-FILM CIRCUITS



Hood of vacuum chamber raised, engineer puts masked thin-film substrate into place. Monitoring equipment (right) gives vacuum, temperature, and deposition data, as vapor from heated metals rises to form circuit.



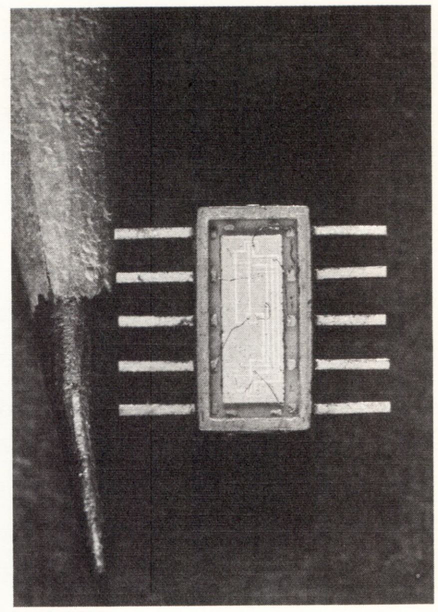
Films of inactive material are deposited on glass to make up a thin-film circuit's conductors, resistors, and capacitors. Separate "discrete" transistors, diodes, and even whole uncased IC's are bonded to the deposited network.

Another first-generation microelectronics approach (still of great utility for microwave applications in particular) is the "thin-film" technique. With the "vacuum deposition" thin-film process, resistive and conductive materials are vaporized in a vacuum, then deposited on the substrate through a mask. The resulting pattern forms the conductors and passive components in the circuit. In subsequent operations, insulating layers are deposited on the substrate and covered by additional film to form an interconnected resistor-capacitor network. Individual components are then bonded to the network to complete the circuitry.

INTEGRATED CIRCUITS

"Boat-load" of silicon wafers is readied for diffusion furnace.

"Glass jungle"—valves, metering devices, heating elements—for mixing and distributing furnace and dopant gases.



IC general-purpose amplifier.

A common method for fabricating semiconductor IC's is "planar diffusion." As the name indicates, it involves diffusion of various "foreign" or "impurity" atoms into the upper surface of a wafer or slice of silicon. Depending upon the valency of the injected atoms, the pure silicon is converted into either n-type semiconductor with an excess of negative-charge carriers (electrons), or p-type semiconductor with an excess of positive-charge carriers (holes).

To make sure that the diffusion occurs only in the wanted pattern for the circuitry involved, the silicon wafer or slice to be diffused is first covered with a protective coating of silicon dioxide into which "windows" are cut by photoetching. Then, when diffusion takes place, the impurity atoms are injected into the wafer only at those locations where there are windows; everywhere else the wafer remains unaffected by the diffusion.

During the diffusion process, temperature, pressure, humidity and materials must all be precisely controlled, or the diffusion will not be predictable in type, depth, intensity, or homogeneity.

More than one diffusion is required to make an IC. A single device must undergo separate diffusions to provide n, n+, p, and/or p+ regions. Even the simplest p-n junction diode represents a combination of n and p diffusions.

Since each diffusion for an IC requires a separate mask, one IC device requires a whole set of masks. The masks are originally drawn very precisely by skilled draftsmen. They are then reduced several hundreds of times photographically. A step-and-repeat photolithographic process prints the reduced mask pattern over and over, like the individual stamps in a sheet of postage stamps, to form an "array" of masks on a wafer measuring only a few centimeters across.

When all the above fabrication steps have been accomplished—i.e., masks have been made and imprinted on the wafers, and the wafers have been photoetched and diffused as many times as necessary for the particular circuits they are to contain—and when, in addition, any required intraconnections have been formed by metal deposition between circuit elements, the hundreds of separate circuits within the array must be scribed apart like the squares in a Hershey bar. Each of the individual "dice" thus created contains a single circuit. It is mounted in an appropriate package (either as a complete unit within itself or as part of a thin-film hybrid assembly), bonded to the package's leads that go to the outside world, and sealed.

The urgency of the Minuteman program, and the pioneering work in microelectronics necessitated by that urgency, are generally considered throughout industry to have had the effect of propelling microelectronics technology forward by at least *two decades*, within an actual interval of only *two years.*

STEPS TOWARD INTEGRATING MICROELECTRONICS

In all, first-generation microelectronics included—in addition to *discrete* transistors, diodes, and passive components—three different *compound* types of microelectronics. These were the IC, CPC (or thick-film device), and the "thin-film" circuit.

Whereas the IC was monolithic and completely self-contained, both the CPC and the thin-film were actually hybrid devices, consisting of networks of conductors and passive components deposited on insulating substrates. CPC printed components included only resistors, and discrete capacitors had to be added later; with the thin-film approach, both resistors and capacitors could be formed right on the substrate along with the conductors. In either approach, active devices—diodes, transistors, even entire IC's—and high-powered or high-valued passives were attached to the networks in the form of discrete components.

Each of the first-generation approaches to microelectronics offered particular advantages, depending upon the application involved. Semiconductor IC's, with their high-element-density per given area of substrate, were ideal for the digital circuitry of computers and other data processors, which is generally characterized by high repetitiveness and low power.

For the analog circuitry of radio and radar, IC's did not provide the necessary high capacitances and inductances. For this type of circuitry, the "high-resolution" conductor networks possible with thin-film hybrids proved best, with capacitances and inductances added as discrete components in any values necessary.

For linear applications—where microelectronics had to interface with servomechanisms and electromechanical transducers—neither IC's nor thin-film hybrids would do. For these applications, CPC's proved preferable—their ceramic substrates and the discrete components attached thereto were well able to dissipate the higher power required in linear applications. Moreover, capacitances of any value could be affixed to the CPC's for operating at the low frequencies necessary in linear applications.

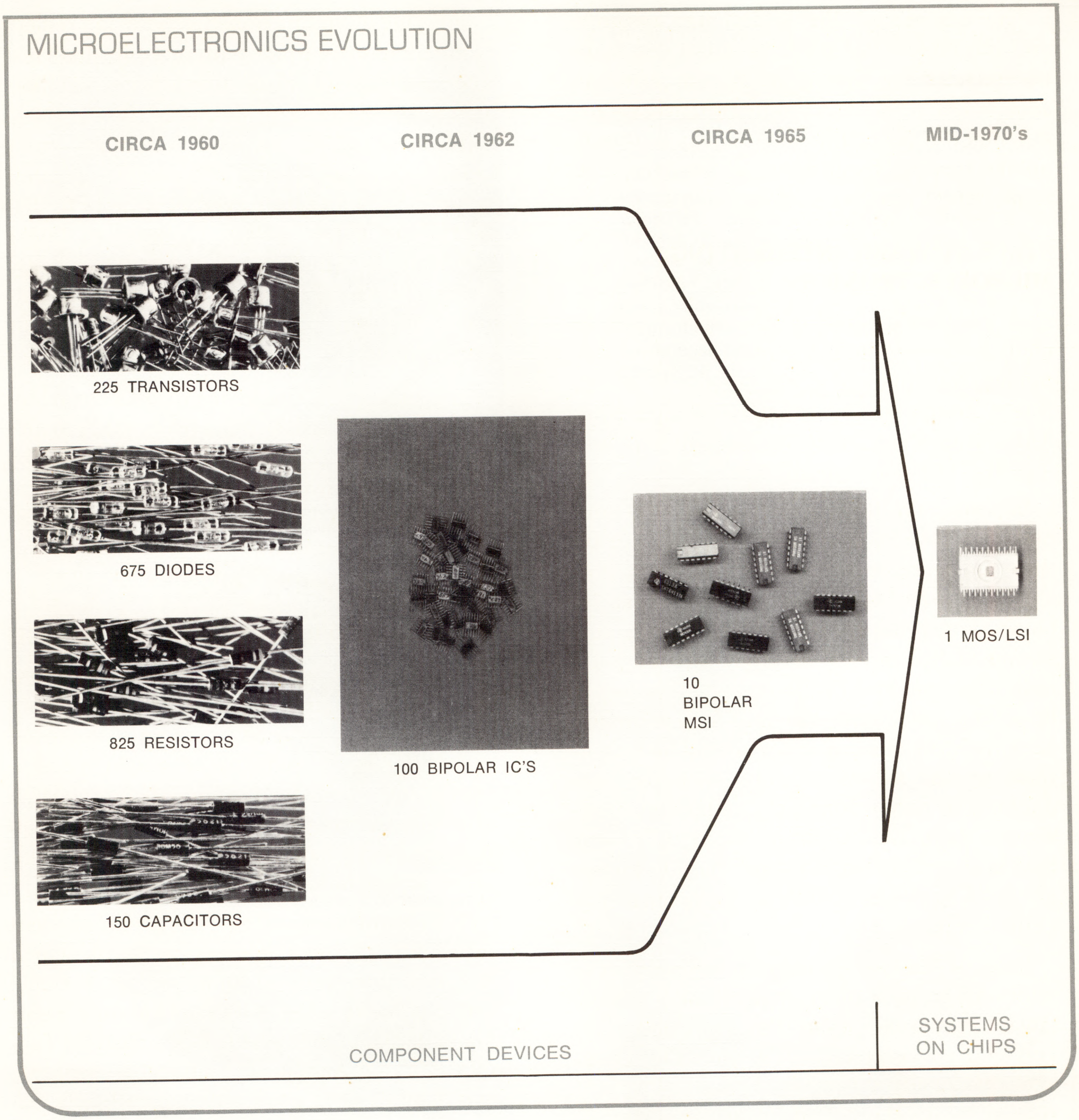
All types of first-generation microelectronics are still used, and each is still considered "best" for certain applications. Since the mid-1960's, however, one "second-generation" approach—"MOS" (metal oxide semiconductor) technology—has played an increasingly prominent role.

SECOND-GENERATION BREAKTHROUGH

Around 1965, when MOS devices were first being given practical application, a single chip was able to contain as many as a thousand different circuit elements in a quarter-of-a-square-inch area. In the mid-'70's, one MOS unit, measuring typically around a sixth of an inch on a side, can include up to 15,000 field-effect transistors.

Because of its amazing ability to implement extremely complex designs, each of which includes thousands of functions on a single semiconductor chip, MOS technology helps alleviate the urgent problem of reliability fall-off with the increased number of separate components that once automatically accompanied increased system complexity. MOS also enhances reliability by lowering the amount of inter-component wiring required, and by lessening the human-operator handling involved in wiring and assembling separate components.

Another MOS advantage is its relatively low power consumption. A typical power of less than 100 microwatts per MOS memory cell makes it possible to construct a 1024-bit memory with a total power consumption of only one-fourth of a watt—or about one-fifth as much as has to be dissipated by a memory



that is built from first-generation integrated circuitry.*

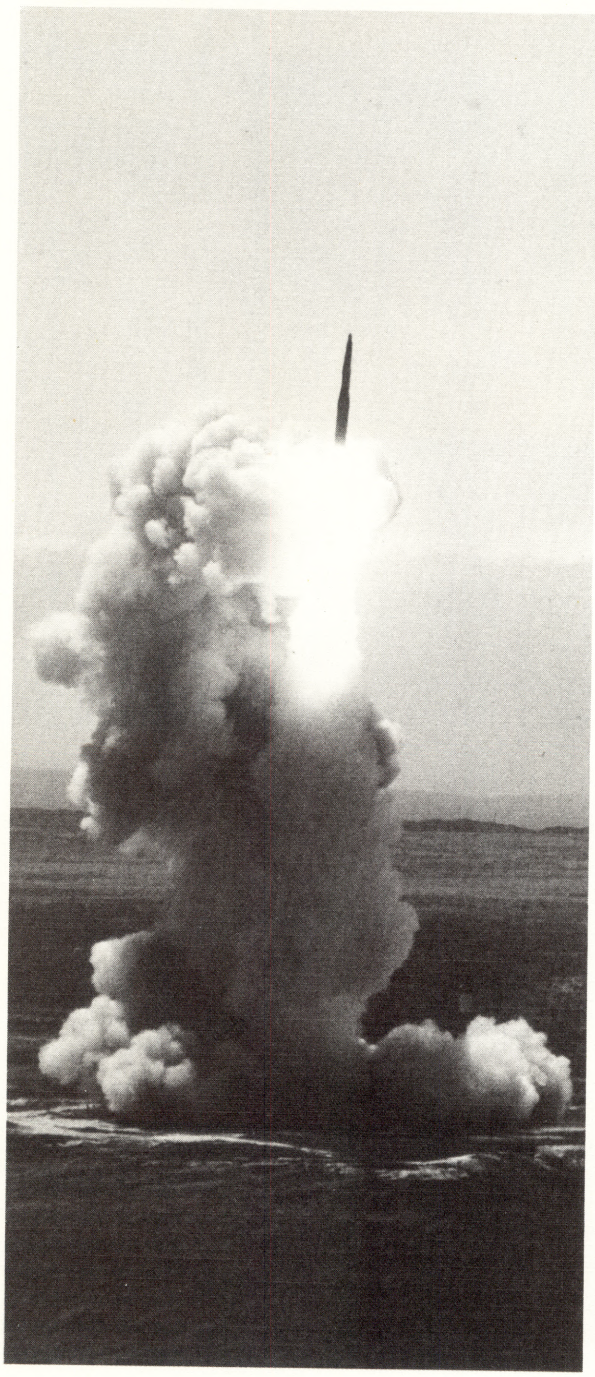
Because MOS devices operate from power supply voltages that are comparable with those of computer peripheral circuits, they reduce energy losses at interfaces and make for more efficient computers generally.

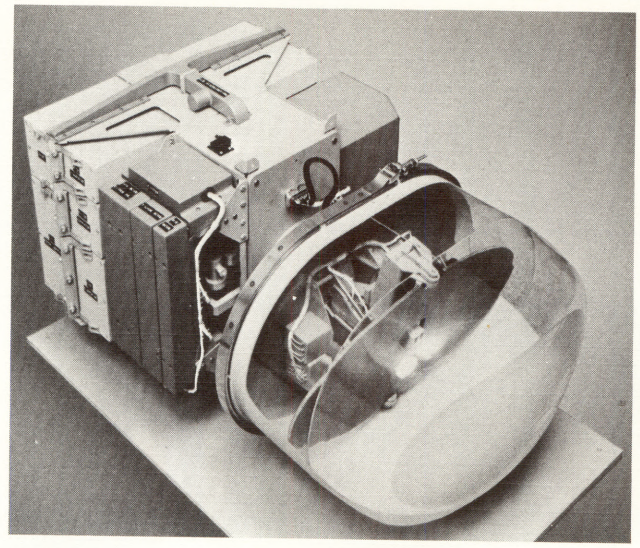
**The march of science and the reduction in computer power requirements are especially dramatic when we contrast the low power demands of a MOS memory with those of the year-1844-model computer of Charles Babbage in the account of computer history, included at the end of Chapter III. The ancient Babbage machine used heavy cast-iron counting drums and consumed the full 60 horsepower of a large steam engine to perform the simplest decade calculation.*

ONE COMPANY'S COMMITMENT . . .

BACKGROUND

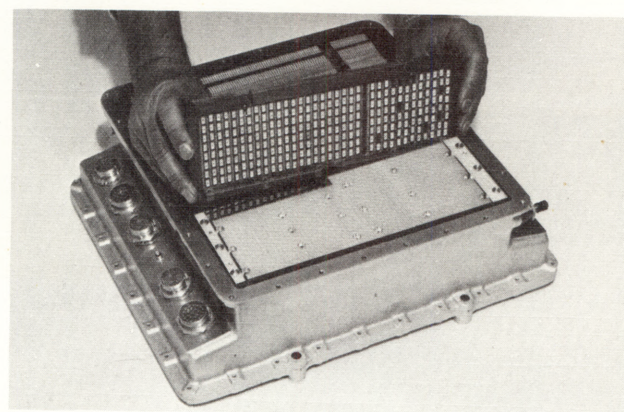
Microelectronics and Rockwell International have been teammates almost since the inception of this technology. Rockwell designed and produced the first all-transistorized computer and the first solid-state multimode radar. The first major weapon system to be implemented throughout with microelectronics was the U.S. Air Force's Minuteman II intercontinental ballistic missile—for which Rockwell provided guidance and control plus supporting ground equipment, with all equipment mechanized by means of "first-generation" semiconductor integrated circuits (IC's) and ceramic printed-circuits devices.





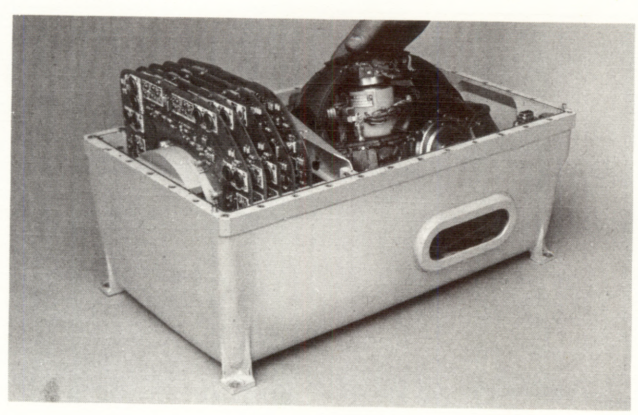
RADAR

Rockwell R45 radar was nation's first multimode airborne radar to use microelectronics.



COMPUTERS

IC's comprised 95% of electronics in early microelectronic computer — Rockwell D26C.



NAVIGATORS

Microelectronics reduced size and weight of Rockwell N16 by factors of approximately 10 and 6 and power consumption by around 4 times, and improved reliability 10-fold over non-microelectronic predecessors.

40,000-Square Foot MOS Circuit Device Production Facility

NEW DIVISION ESTABLISHED IN 1969

To meet the exacting demands of next-generation microelectronics, Rockwell International established, in 1969, an entire organizational structure within the corporation. To house the new Microelectronics Division's production operations, the company built a multimillion-dollar facility, equipped with a uniquely complete assemblage of the most advanced MOS (metal-oxide-semiconductor) device processing equipment.

IN THE 1970's . . .

Rockwell International continues to apply microelectronics to promote product reliability and performance.

The original Microelectronics Division established in 1969 has evolved into the corporate Microelectronics Group. Not only this Group, but other Rockwell Groups responsible for the company's automotive, government, industrial, and aerospace products, exploit microelectronics to company and customer advantage. Microelectronic products of the corporation range from digital wristwatches to sophisticated radars and inertial navigation systems . . . from automated knitting machines to low-cost calculators . . . and from computerized typesetters and bindery paper cutters to bubble domain memories and liquid-crystal displays.

The many other very basic advantages of MOS technology include self-isolation between circuit elements; ease of making diffused cross-unders with the MOS process (in contrast to bipolar IC's); amenability of the MOS approach for high-complexity circuitry, due to high inter-element impedance; and, quite important for schedule and budget, high yield of MOS processes for producing complex circuitry arrays.

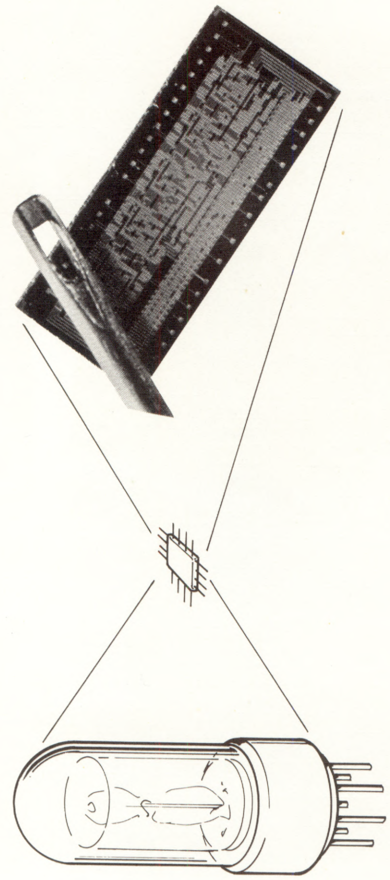
It is true that the higher the degree of integration, the greater the design restriction, and the less universal in application is any microelectronics approach to a given "function." However, once designed and developed, the highly integrated, batch-produced MOS system is highly cost-effective.

The dense MOS circuitry not only contains many times more circuit elements in a given area than a bipolar IC, but this advantage is multiplied by the semiconductor industry's abiilty to fabricate chips with large overall dimensions. The big, high-density MOS chips give the user *more functions per chip.* Furthermore, since the system can be built with fewer chips, more functions are achieved per equipment weight and volume, *and per system purchase price dollar.*

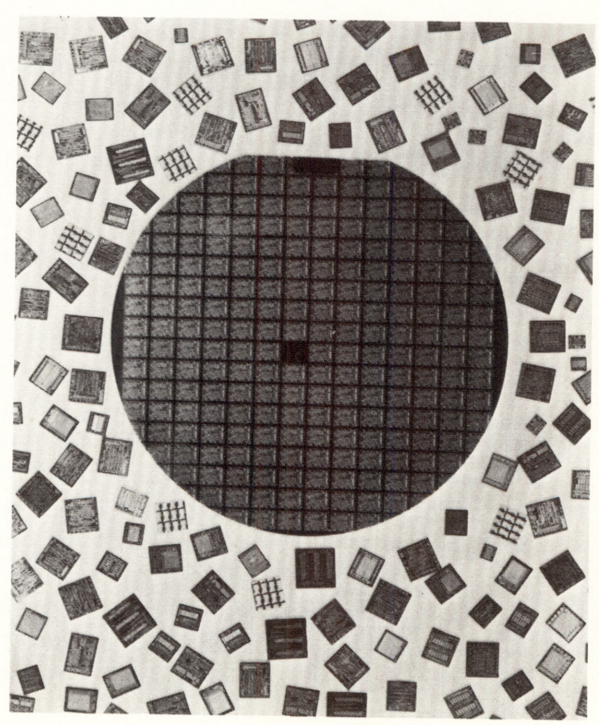
The simplicity of MOS fabrication is a basic contributor to MOS economy. MOS devices and bipolar IC's are fabricated with similar —in many cases, identical—techniques, but MOS circuitry can be produced in slightly more than half as many steps as an IC. Significant differences are that—in contrast to bipolar IC's—MOS circuitry does not require an epitaxial crystal layer, does not require a diffused buried layer, and, for the entire fabrication processing, requires only a single diffusion ("CMOS," discussed subsequently, is an exception to this last requirement).

The user's production dollar also means more with MOS, because of the already mentioned significantly decreased necessity of MOS for interfunction wiring, and for manual assembly and test, compared with bipolar IC's.

WITH MOS, ENTIRE SYSTEMS CAN PASS THROUGH THE EYE OF A NEEDLE



VARIETY — *Photograph below is representative of proficiency Rockwell International has achieved in designing and producing ultra-dense circuits with the MOS process. In the '60's and '70's the corporation has designed hundreds of MOS circuits and marketed millions of MOS devices.*



Finally, the user benefits financially from the almost automatic logistics savings possible with MOS, due to smaller number of total quantities as well as number of types of spares that must be stocked, the higher replacement level, and the reduced requirements for maintenance time and skill.

Since MOS emergence from the laboratory into the realms of the practical, around 1965, the cost-of-ownership of this type of circuitry has dropped manifold. This fact, of course, makes the MOS approach highly appealing for a broad variety of users—in commercial, industrial, and consumer products, as well as the "older" applications of defense and space.

In the mid-'70's, MOS technology is making it possible to produce calculators no bigger than a man's hand, costing only a fraction as much as their electromechanical predecessors with equal functional capability, and containing all required calculating circuitry on a single chip . . . solid-state devices that prevent skidding of huge trucking "trailers" on rain-slick highways . . . controls for printing presses and automobile ignition systems . . . capture combination and frequency synthesizer systems for electronic musical organs . . . multiplex systems that eliminate literally miles of wiring in jumbo jet aircraft . . . solid-state point-of-purchase credit-card readers . . . avionic systems with complete built-in self-test capability, and with reliability measuring orders-of-magnitude times that which was achievable before the Microelectronics Age.*

THE TERMS AND TECHNICALITIES OF SOLID-STATE MICROELECTRONICS

It would seem wise at this point to digress from the history of microelectronics and, before going further, to define terms. What, for instance, *is* a "semiconductor"? What are "diodes" and "transistors"? Just what do we mean when we speak of "bipolar" IC's and "unipolar," "field-effect" MOS?

Semiconductors

The electrons in a "conductor" such as ordinary copper wire are free to move from atom to atom and form an electrical current. A "semiconductor" material, on the other hand, at room temperature normally has only a small number of free electrons, but, if slight amounts of certain other materials are intermixed with the semiconductor, the atoms of these "impurities" or "dopants" can provide the free (mobile) current *carriers* to make the semiconductors act like a conductor.

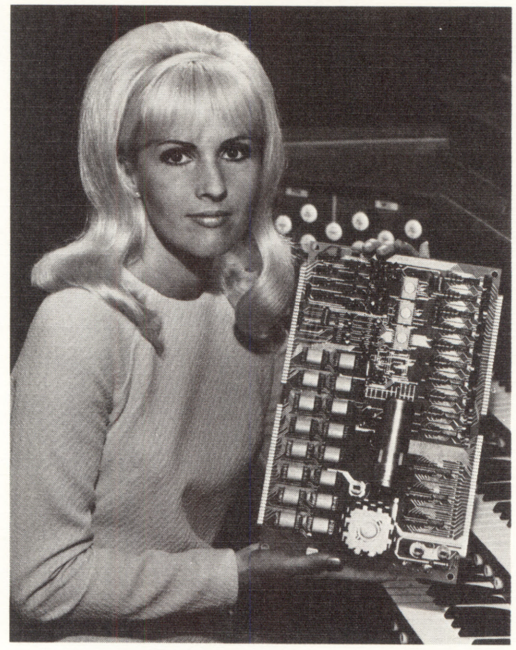
Impurities which *contribute* free electrons to semiconductors are called "n-type" impurities ("n" for the "negative" charge of the electron), and semiconductors doped with such electron *donors* are called "n-type" semiconductors. Operation of the other category of semiconductor—the "p-type"—depends on the addition of materials whose atoms *accept* electrons from the semiconductor atoms, resulting in the *absence* of electrons (the absence is called a "hole") from the semiconductor atoms. Each hole can be considered as having a charge opposite in sign to that of the missing electron or, in other words, positive—and the "p" in "p-type" stands for "positive." Holes can flow from atom to atom in a block of p-type semiconductor, just as electrons do in a block of n-type semiconductor, and moving holes can also be said to constitute a current, but of opposite direction from the flow of an electron current.

In order for a semiconductor to be usable in a device for an electronic circuit, its electrical characteristics must be predictable; thus, the amounts and types of impurities with which it is doped must be precisely controlled.

Common n-type impurities are phosphorus, antimony, and arsenic. Common p-type impurities are boron, aluminum, and gallium.

**All examples cited here are actual Rockwell International products.*

MOS TECHNOLOGY GIVES MICROELECTRONICS ENTREE INTO TRANSPORTATION . . . ENTERTAINMENT . . . CONSUMER PRODUCTS FOR HOME AND OFFICE

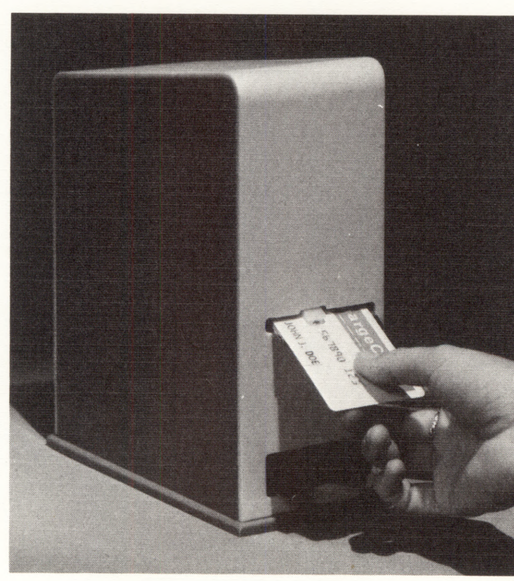


Musical Beauty for Electronic Organs

Organists will be able to play with expanded tone variety, and organ music writers will be able to create more exciting compositions with this Rockwell-developed system for controlling the instrument's voices. The complete plug-in MOS system occupies only about 1/100 the space required for conventional systems.

Dialing Convenience and Reliability

The tiny MOS circuit shown at right in the photo was developed by Rockwell International to replace the conventional telephone dialing circuitry (center). The MOS circuit is compatible with existing telephone equipment and operates on only 4 volts.

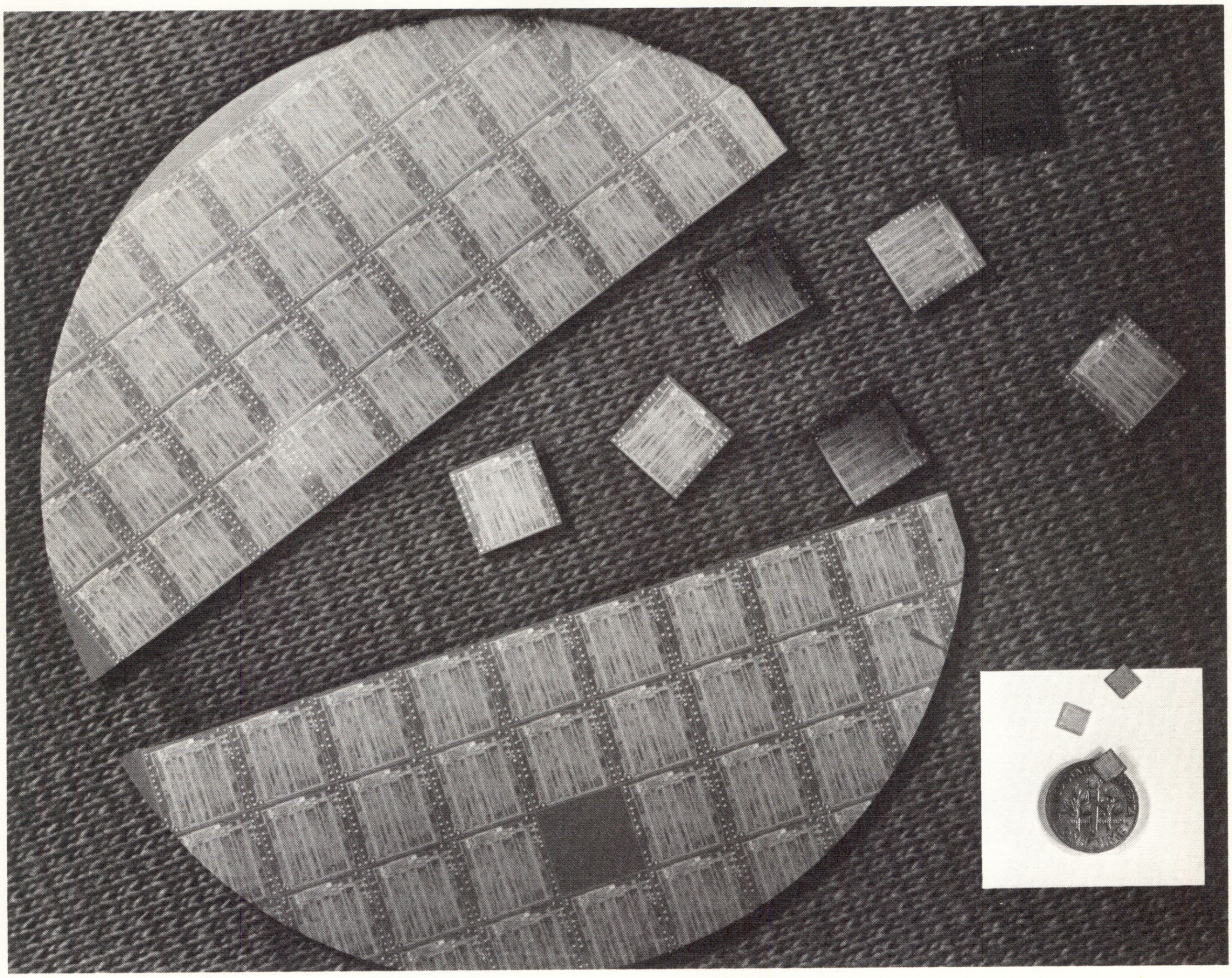


Point-of-Purchase Credit Checker

An embossed credit card reader is an integral part of a Rockwell computer-controlled service station credit check and billing system. The reader employs MOS circuitry and pattern recognition techniques to read the numbers on a customer's card, and to convert the reading to digital signals that can be transmitted to the credit card center. Credit authorization and billing information can be transmitted to and from stations — located anywhere in the United States — in seconds.

Safe Braking on Rainswept and Ice-Slick Highways

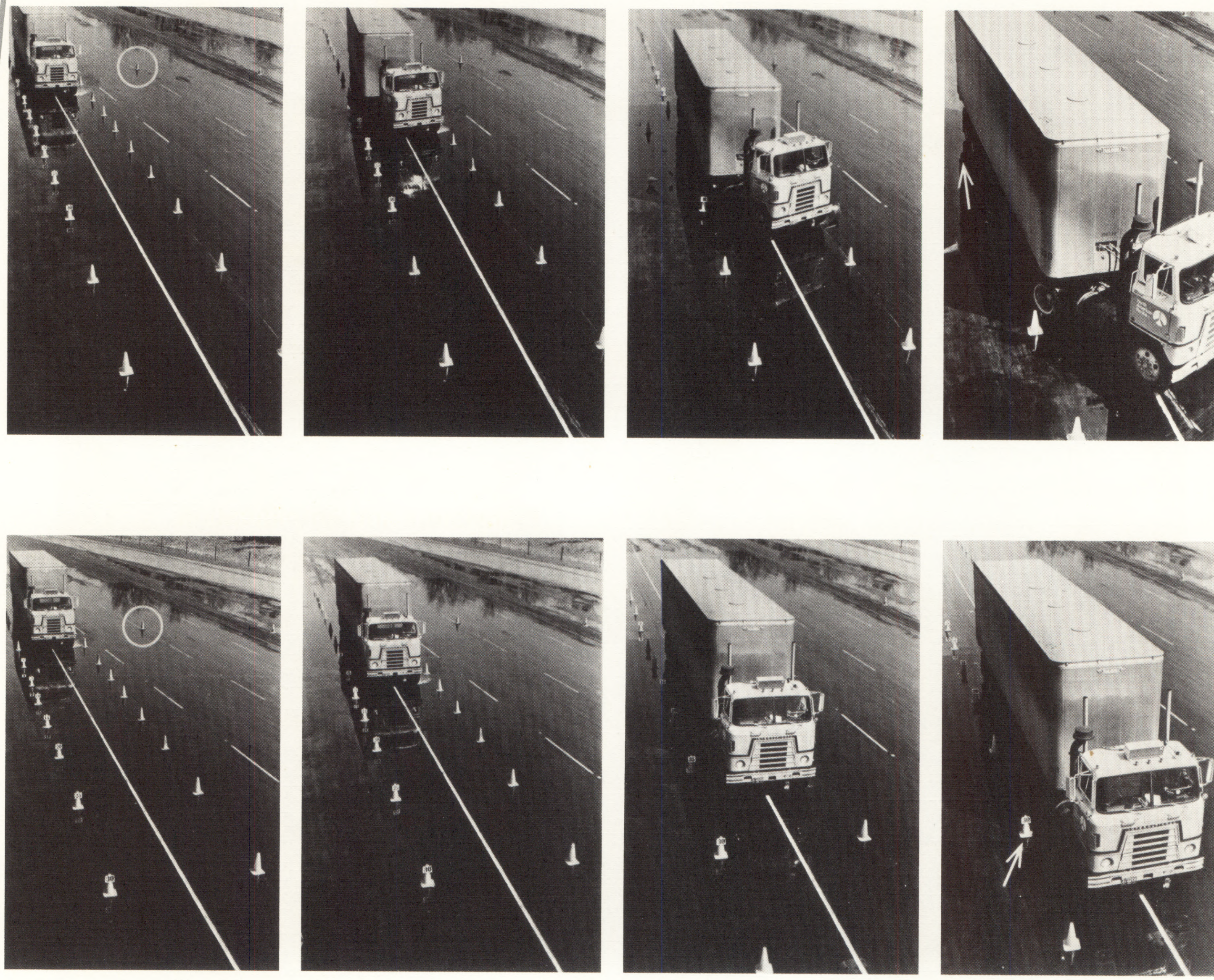
Rockwell automotive and electronics engineers got together to figure out a way to bring tractor-trailers to safe, controlled stops. In May 1973, the result was formally unveiled at a national press conference near San Diego, California. It's called the "Skid-Trol"* anti-wheel lock system, and it can help bring a truck to a safe, sure, in-lane stop on any road surface and in any weather imaginable.



Heart of Skid Trol *is its digital "computer" with 2,000 MOS transistors on a single "chip" of silicon about the size of a match head. The computer is encased in the Skid-Trol pneumatic valve. One valve is used on each axle of the truck, tractor, or trailer. A sensor within each wheel reads the wheel speed and gives this information to the computer. When the brakes are applied, the computer makes as many as 500 decisions 50 times per second to regulate the air pressure on each wheel. (See three actual-size "computer" chips alongside a dime, and magnified view of an array of chips above.)*

Truck Lab — *Skid-Trol undergoes rigorous test in a Rockwell simulation laboratory. By means of simulation techniques, hundreds of thousands of test miles have been "driven" with Skid-Trol at varying speeds on combinations of icy, wet, and dry pavements. Every conceivable road condition and load factor can be simulated.*

*Trademark registered



Dramatic Demonstration — *The two series of photos contrast what happens in two similar emergency stops. The tractor-trailer rig in the top series operates without benefit of Skid-Trol. The brakes are applied, the rig starts to skid, it scatters the pylons marking a 12-foot-wide lane, and the rig ends up as shown. In the bottom series, Skid-Trol helps the driver keep his vehicle in lane and make a safe stop. The circled pylons in the two photos at left mark the point where brakes are applied. The arrow in the bottom right photo marks the point where the vehicle in the "system-on" demonstration came to a stop. In the top right photo, the arrow marks the spot where the same pylon was in the "system-off" stop before being knocked out by the skidding trailer, indicating a longer stopping distance.*

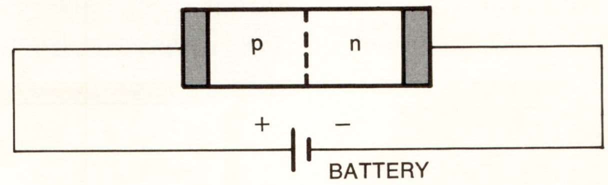
JUNCTION DEVICES

P- and n-type sections of semiconductor materials are combined to form active electronic circuit components—diodes and transistors. Operation of these components depends upon the behavior of holes and electrons about and across the p-n junction, and the diodes are thus called "p-n junction" diodes, while the transistors are called "p-n-p" or "n-p-n," depending on the physical arrangements of the materials of which the devices are fabricated. The active functional elements of bipolar IC's are junction diodes and transistors.

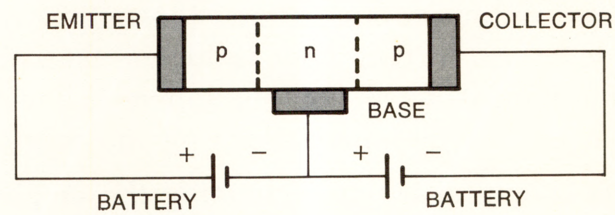
Diodes and Rectification To help us understand the operation of such devices, we can consider the accompanying diagram of a p-n-junction diode.

The diode shown here is made from a slab of n silicon, one-half of which has been diffused with p-type impurities. When a battery is connected to the diode in such a way that the p portion of the semiconductor is biased positively, and the n portion is biased negatively, then the p-type attracts electrons from the n-type, and the n-type attracts holes from the p-type—and the resulting movements of holes and electrons make up flow of current. If the battery is connected so that the diode is biased in the other direction, essentially no current will flow. Now, if instead of alternately connecting a battery first one way and then the other, we apply an alternating voltage to the device, it will first conduct current, and then not conduct current, as the polarity of the applied signal changes with each half cycle. In other words, the semiconductor combination acts as a "rectifier"—a one-way valve for current flow.

Performance of semiconductor devices as "amplifiers" is somewhat more complicated.



P-n junction diode



P-n-p junction transistor

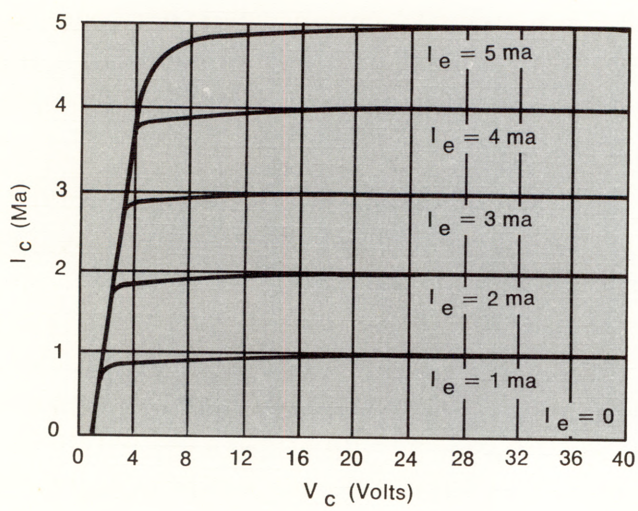
Transistors and Amplification Take, for purposes of explanation, the p-n-p transistor diagrammed above. With the two batteries connected as indicated, the left-hand p section is biased positively with respect to the central n section, and the right-hand p section is biased negatively with respect to the central n section. Both hole and electron currents are encouraged to flow between the left and central sections, but between the right and central sections the effective impedance to any current flow is extremely high.

For ease of discussion, let us now refer to the various sections of the transistor as they are labeled in the diagram—emitter, base, and collector.

When the p-n-p transistor is biased as shown here, the emitter is said to be biased in the "forward" direction with respect to the base, and the collector is said to be biased in the "reverse" direction with respect to the base. Unless so biased, this transistor will not operate efficiently as an amplifier. With no voltage applied to any of the transistor elements, no current—either hole or electron—flows. With the emitter biased as shown, however, holes move into the base region as they do in the simple p-n-junction diode, and these "injected" holes tend to progress further into the base region as a result of mutual repulsion (diffusion forces). If the base region is thin enough, the holes reach the collector junction, from which they are then attracted into the negatively biased collector.

If an alternating signal is superimposed on the emitter bias, the flow of holes through the transistor is modulated, and a load resistor can be connected between collector and base for development of a similarly modulated output voltage. Since the output impedance to current flow is higher than the input impedance, the output voltage is a magnification of the input signal on the emitter.

It is helpful in understanding the amplification action of a transistor to examine a set of transistor collector characteristic curves. In the next diagram, the collector current I_c of an actual transistor is plotted for a number of values of collector bias voltage V_c, for the particular form of connection shown in the previous diagram of a junction transistor—the common-base connection.



Common-base transistor collector characteristic. Collector current I_c is plotted vs collector voltage V_c for various values of emitter current I_e.

Collector output impedance can be defined as the change in collector voltage due to a change in collector current with the emitter current constant. Similarly, the emitter (input) impedance is defined as the change in emitter voltage due to a change in emitter current, with collector current constant. Emitter impedance is very low for the transistor considered here—only about 100 ohms—because the emitter is biased in a forward direction, and large emitter current changes thus result from small signal voltage changes.

Since voltage amplification is equal to the ratio of output impedance to input impedance, the voltage amplification factor of the transistor used in this way is very high.

The transistor which we have discussed here is termed a "p-n-p junction" transistor, because it is composed of alternate p-,n-, and p-type materials, and because its functioning depends on the application of bias voltages across junctions between these materials. "N-p-n junction" transistors consist of an n-type emitter, a p-type base, and an n-type collector, with bias polarities or directions just opposite to those for the p-n-p device. Instead of hole emission, electron emission from the n-type emitter is of importance; otherwise, the principles of the two transistors are the same.

FIELD-EFFECT DEVICES

General Use. For low-power, repetitive, digital circuitry of the type prevalent in digital computers and other digitized systems, the most economical approach is, generally, not bipolar IC but the high-density MOS. In place of the junction devices which characterize bipolar technology, MOS depends for its operation on "field-effect" transistors (FET's). Each MOS system can contain, within a single chip measuring typically only 1/36 of a square inch, as many as 15,000 FET's.

Field-effect transistors are often spoken of as being "unipolar"* in contrast to the "bipolar" character of point-contact units and junction devices such as semiconductor IC's.

This terminology was proposed by W. Shockley in his article, "A Unipolar 'Field-Effect' Transistor," Proc. IRE, November 1952, pp 1365-1366.

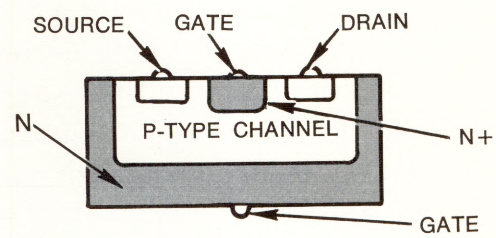
This is due to the fact that, in the point-contact units and junction devices, minority carriers* are injected into heavily doped regions. Since carriers of *both* types—holes and electrons—are involved in the process of maintaining space-charge neutrality in the injection region, the devices are said to be "*bi*polar." In FET's, however, current flow between input and output consists of *one* type of carrier only—*either* holes *or* electrons—and the size of the current (and thus the amplification) is controlled by changing the number of carriers of this one type. For this reason, FET's are said to be "*uni*polar."

Operation and Types There are two basic classes of FET's—each class being defined by its mode of operation; these two classes are "depletion FET's" and "enhancement FET's." Both function by controlling an electric field or "space charge" within the host semiconductor.

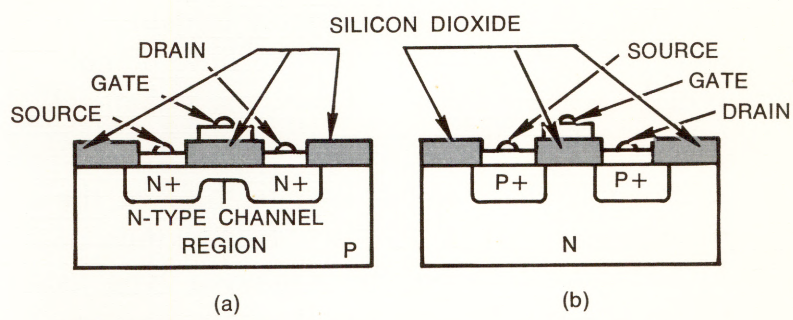
In the depletion FET, control is effected by means of a metal element called a "gate," deposited on the semiconductor surface. With appropriate voltages applied to the device's other two surface electrodes—a "source" and a "drain" that correspond, respectively, to the "cathode" and "anode" or "plate" of a vacuum tube—signal voltages on the gate cause the depth of the space-charge field within the semiconductor to vary in step with them. As the field depth shrinks and expands, it leaves more or less room for source-to-drain current to flow through a narrow "channel" in the semiconductor. Thus, an input signal voltage on the gate can be used to modulate the depletion FET's source-to-drain current and, as with the junction transistor discussed above, can cause an amplified signal voltage to appear across a load resistor connected in the output.

*"Minority carriers" is the name given to the current-carrying media (holes and electrons) in a semiconductor material when the carriers have the opposite type of conductivity (p or n) to that of the "host" material, e.g., p-type carriers (holes) in an n-type semiconductor. So-called "majority carriers," on the other hand, have the same kind of conductivity as the region through which they flow, e.g., n-type carriers (free electrons) in an n-type semiconductor region.

For the space-charge field in a depletion FET to exist in the first place, the FET's gate must be reverse-biased to inhibit current flow between drain and source. The greater the bias, the further into the semiconductor the space charge penetrates, the narrower the conducting channel between drain and source, and the smaller the amount of current flow in the absence of signal.



Junction FET



MOS FET's: *(a) depletion or normally "on"; (b) enhancement or normally "off"*

Just as there are two kinds of FET—depletion and enhancement—there are two kinds of *depletion* FET. In one of these—the "junction depletion FET"—a p-n junction serves as the gate to control the space charge. In the other—the metal-oxide-semiconductor (MOS) depletion FET—the gate consists of a metal electrode that is separated from the semiconductor by insulating oxide. Both types deplete the internal channel of carriers when appropriate gate voltages are applied—thus the name, "depletion FET."

Junction FET's cannot operate in the enhancement mode. This mode is open only to the MOS FET. To understand the enhancement mode, let us consider the performance of a "p-channel" MOS device in that mode.

A p-channel enhancement MOS FET consists of a block of n-type semiconductor into which there have been diffused two heavily p-doped islands. The source and drain of this transistor are actually two separate diodes with the gate spanning the region between them. When a negative bias is applied to the gate, electrons are repelled from, and holes are attracted to, this region; if the bias is large enough, the material in this region will actually convert to p-type, and the source and drain will be separated only by a very low-impedance path. A heavy hole current then flows between the drain and the source and, if a load resistor is connected between these two elements, a voltage proportional to the gate voltage will appear across it. If an alternating voltage is applied to the gate, an amplified version will appear across the load resistor. This type of transistor is called an *enhancement* FET, because the flow of current between source and drain is *enhanced* by the gate voltage.

Probably the simplest way to think of the difference between the two basic kinds of FET's is to consider the depletion type as being a normally "on" unit, while the enhancement type is normally "off" to current flow. (For logical operation, MOS FET's function quite similarly to relays, with their essentially two-state, on-off operation.)

Complementary MOS Both n-p-n and p-n-p types of MOS transistors can be attained by making the proper diffusions into the correct substrate. Not until the late 1960's was a practical process achieved for making both types on a commonly shared substrate. The resulting technique is termed "CMOS," for "complementary MOS."

With CMOS, pairs of n-p-n and p-n-p transistors are fabricated on a single substrate, with the two devices in each pair being identical except that one transistor of each pair is an n-p-n device, while the other is p-n-p.

The opposite polarities of the two transistors in each CMOS pair permits them to be "packed" in much greater proximity to each other, and to other pairs, than active elements can be located in "ordinary" MOS. For many systems, CMOS can thus permit overall elemental density to be greater, signal paths shorter, operating power smaller, and functional speeds faster. Complementary MOS is accordingly being found useful for a variety of high-speed, low power digital circuits as well as for very low-power analog systems.

Low power requirements are making CMOS pretty much standard for watch circuits and battery-operated communications systems, and its high noise immunity renders it particularly useful for automobile control and many military applications. Moreover, CMOS offers military applications an additional advantage in that it lends itself to radiation hardening.

Radiation-Hardened MOS In 1971, Rockwell International successfully demonstrated a dramatic microelectronics breakthrough—the fabrication of MOS circuits "hardened" to both the permanent and the transient effects of nuclear radiation. For the first time, MOS' many benefits became available for the radiation-environment applications of defense and Space.

To achieve the hardened devices, a special oxide-growth procedure was combined with chromium doping of the gate oxide, to limit permanent ionizing-radiation damage to the p-channel MOS structures produced by the novel process. Transient radiation responses were reduced by means of silicon-on-sapphire (SOS)* dielectric isolation.

An example of a hardened MOS system is shown on page 25 in an enlarged microphotograph of a Rockwell high-density dynamic shift register. The system dissipates one-half milliwatt per stage at 2 MHz with a 20-volt clock amplitude. Maximum and minimum operating frequencies for the circuit are 10 MHz and 1 kHz, respectively. Radiation tests demonstrate that its hardness levels far exceed those required for advanced ballistic system and computer applications. Specific radiation test results for the dynamic shift register system pictured are classified, but typically demonstrated radiation effects on hardened MOS/SOS circuitry are indicated on pages 24 and 25.

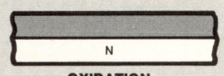
*SOS and its remarkably beneficial properties are described

COMPARISON OF TYPICAL PRODUCTION PROCESSES FOR A MOS DEVICE AND A BIPOLAR IC

MOS Device | **Processing Step** | **Bipolar IC**

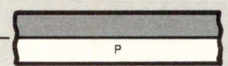
1

MOS Device: Silicon dioxide is grown over the entire surface of a semiconductor wafer.



OXIDATION

Bipolar IC:

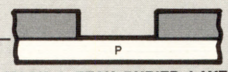


OXIDATION

Silicon dioxide is grown over the entire surface of a semiconductor wafer.

2

Bipolar IC:

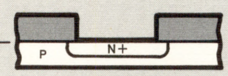


MASK & ETCH BURIED LAYER

Photoresist material is applied over the oxide and ultraviolet light is then used to form a pattern in the latter. The oxide is then etched away in accordance with the pattern. (All masking and etching operations are performed in an essentially similar manner throughout the processing.)

3

Bipolar IC:

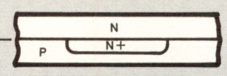


DIFFUSION

N+ material is diffused into the p-type substrate to form a buried n+ layer.

4

Bipolar IC:

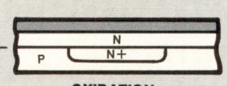


EPITAXIAL GROWTH

The wafer surface is stripped of oxide and is then covered with an epitaxial growth of n-type material.

5

Bipolar IC:

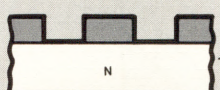


OXIDATION

Silicon dioxide is grown over the entire surface of the wafer.

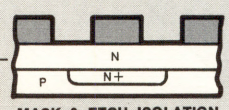
6

MOS Device: Next, the n-type wafer that is used as a substrate is coated with a photoresist material. A "p mask" is used with ultraviolet light to form a "window" pattern in the silicon dioxide. An etching process removes the silicon dioxide from the windows.



MASK & ETCH-P REGIONS

Bipolar IC:

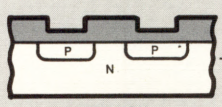


MASK & ETCH-ISOLATION

The silicon dioxide is masked and etched to form windows for the isolation diffusion.

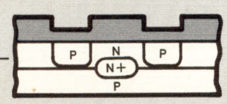
7

MOS Device: In a high-temperature oven containing gaseous boron, p-type impurities are deposited through the windows onto the n-type substrate and are diffused. Silicon dioxide is then grown over the device.



DIFFUSION

Bipolar IC:

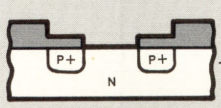


DIFFUSION

P material is deposited through the windows and diffused. Silicon dioxide is grown on the surface.

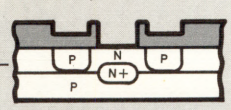
8

MOS Device: As before, the silicon dioxide is coated with photoresist material, after which an appropriate pattern is etched to form the gate region.



MASK & ETCH-GATE

Bipolar IC:

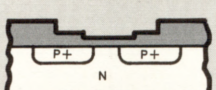


MASK & ETCH-BASE

The silicon dioxide is masked and etched to form the base window.

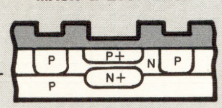
9

MOS Device: For a third time, silicon dioxide is grown over the surface of the wafer. The oxide thickness is controlled by the length of time the material is permitted to grow, and can be made to meet precise design specifications.



GATE OXIDE GROWTH

Bipolar IC:

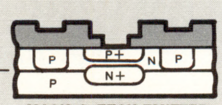


DIFFUSION

P+ impurities are diffused into the base window. Silicon dioxide is grown over the entire surface.

10

Bipolar IC:

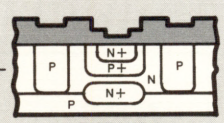


MASK & ETCH-EMITTER

An emitter window is masked and etched in the silicon dioxide.

11

Bipolar IC:

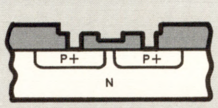


DIFFUSION

N+ impurities are diffused through the emitter window. Silicon dioxide is grown over the surface.

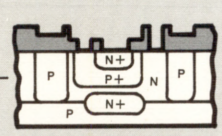
12

MOS Device: The contact pattern for the MOS circuitry is etched to form holes in the silicon dioxide for use as contacts to the device.



MASK & ETCH-CONTACTS

Bipolar IC:

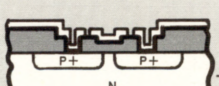


MASK & ETCH-CONTACTS

Contacts to the emitter, base, and collector are masked and etched through the silicon dioxide.

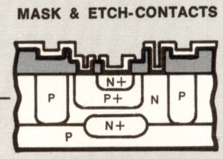
13

MOS Device: Aluminum is evaporated over the entire surface. The aluminum is then etched to form interconnections for the device. (The source and drain are in contact with the aluminum.)



METALLIZE MASK & ETCH

Bipolar IC:

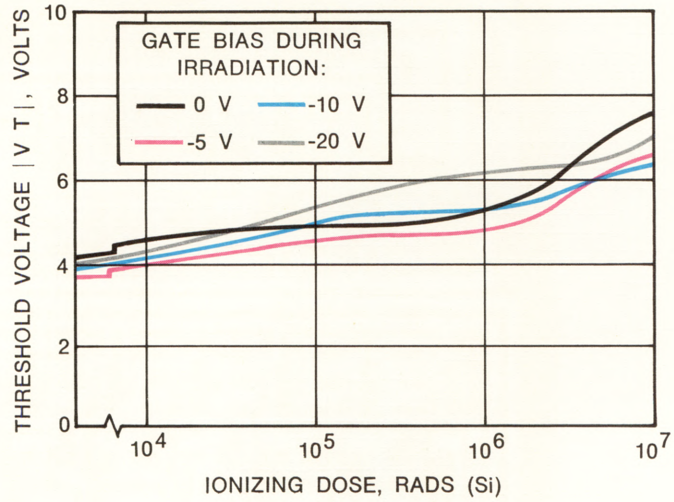


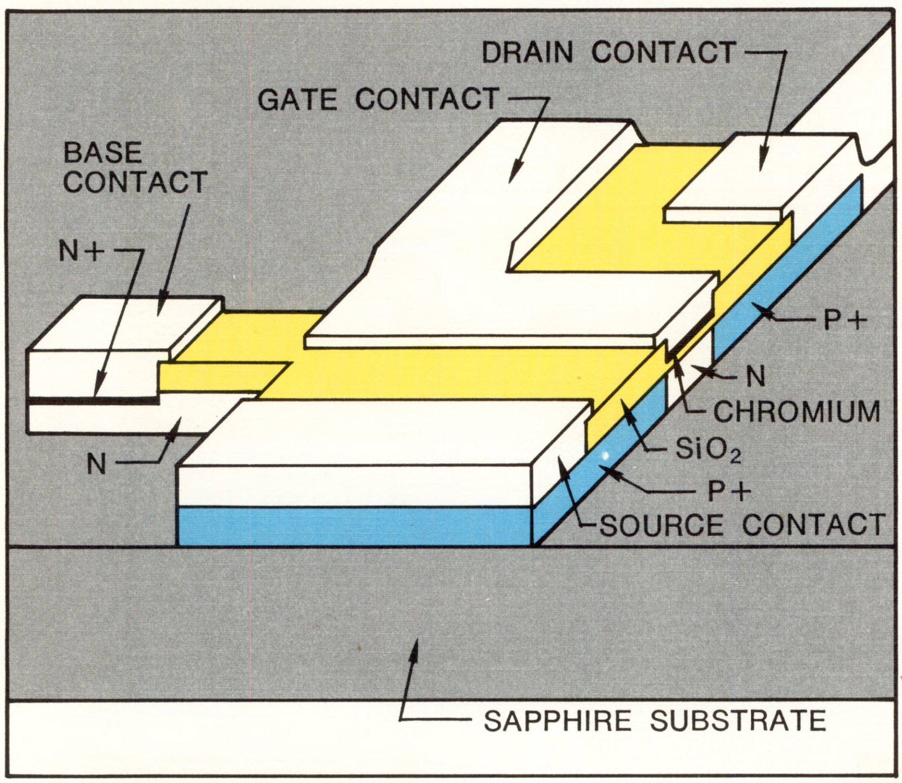
METALLIZE MASK & ETCH

Metal is deposited over the entire surface. The metal is masked and etched to form interconnections to the emitter, base, and collector.

RADIATION-HARDENED MOS/SOS CIRCUITRY

Hardened MOS/SOS Transistor Threshold Voltage Change With Ionizing Dose



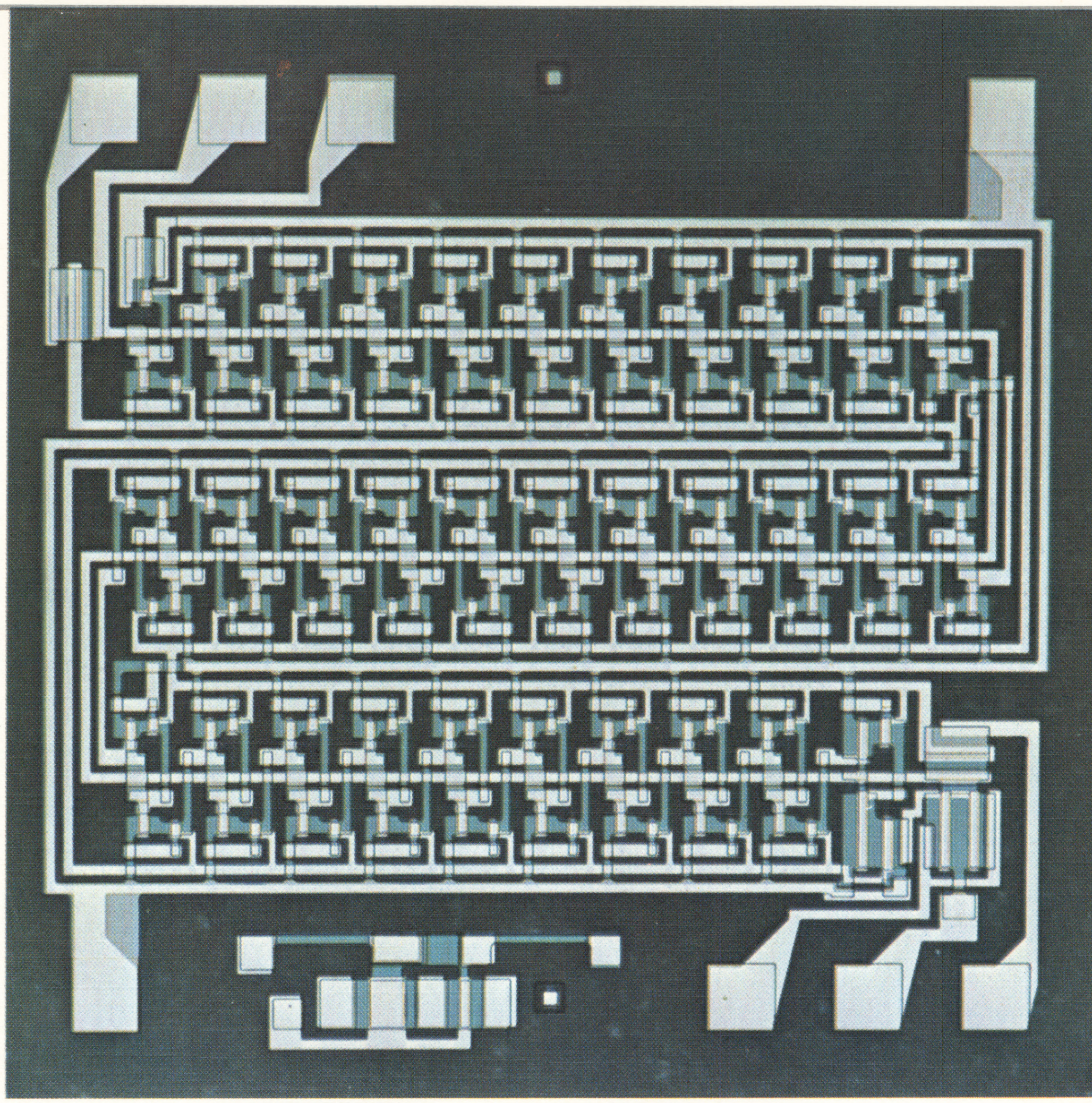


Hardened MOS/SOS Structure

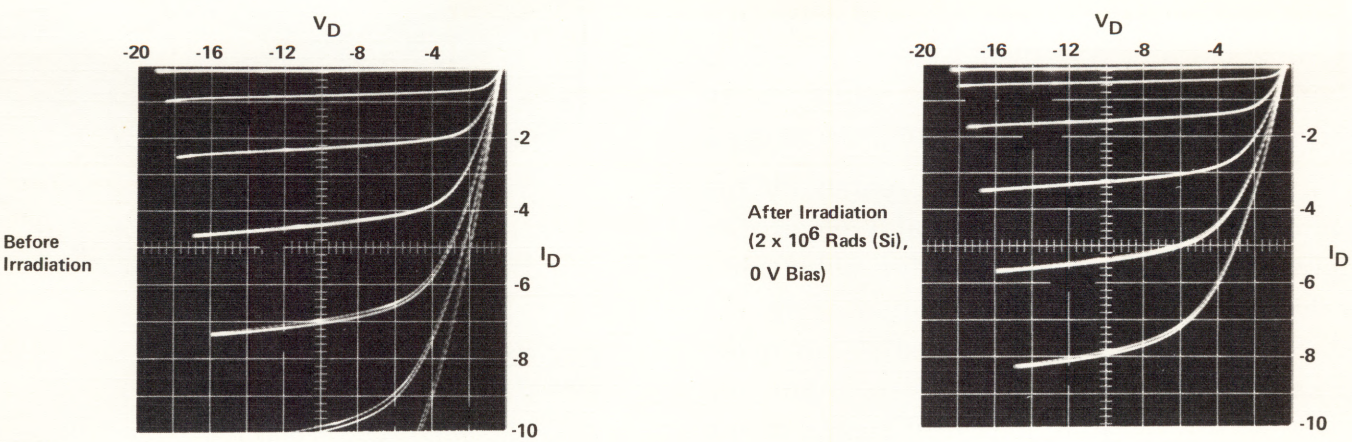
Parameter	Symbol	Measurement Conditions	Nominal Values: Before Irradiation	Nominal Values: After Irradiation*
Drain junction breakdown voltage	BV_{DSS}	$V_G = V_S = V_B = 0$ V; $I_D = 1\mu a$	-25 V	-25 V
Gate dielectric breakdown voltage	BV_{GS}	$V_S = V_D = V_B = 0$ V	±100 V	±100 V
Gate threshold voltage	V_{GT}	$V_S = V_B = 0$ V; $V_D = -10$ V; $I_D = 10\ \mu a$	-4 V	-6 V
Transconductance	g_m	$V_S = V_B = 0$ V; $V_D = -10$ V; $I_D = 5$ ma	1200 μmho	1200 μmho
Drain junction leakage current	I_{DO}	$V_G = V_S = V_B = 0$ V; $V_D = -15$ V	$<$20 na	$<$20 na

Hardened P-Channel MOS/SOS Transistor Performance Characteristics

*2 x 10^6 rads (Si), 0 V bias.



Radiation-Hardened 32-Bit, P-Channel MOS/SOS Dynamic Shift Register



Hardened MOS/SOS Transistor Drain Voltage vs Drain Current Before and After Irradiation

Under one of the earliest contracts in the nation for MOS hardening, Rockwell research scientists in 1973 began a program to design, fabricate, and test-verify hardened CMOS circuits for the U.S. Air Force. Two circuits resulted from this program—a 256-bit random-access memory and an 8-bit digital multiplexer—both built on sapphire substrates, and data and techniques were developed for minimizing radiation-induced transients in Air Force electronic equipment.

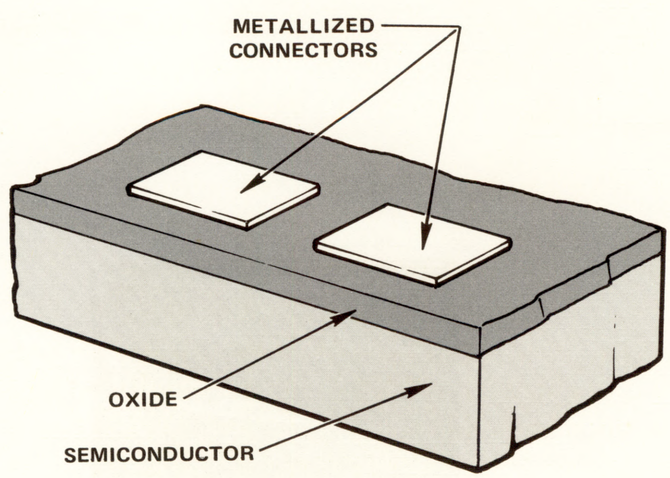
MOS-CLASS "CCD'S" CARRY A CHARGE FOR ALMOST EVERYBODY

A technique,* by means of which devices are fabricated in the form of MOS-type "sandwiches" of metal-oxide-semiconductor but require *no* diffusions promises to yield memory cell densities approaching 5×10^9 per square inch.** Vastly cheaper to produce because of their simple construction, arrays of the "charge-coupled devices" (CCD's) made by the technique also offer a remarkable versatility—having the ability to serve not only as high-density analog memories, but also as high-speed digital shift registers, variable delay lines, and highly efficient imaging devices.

CCD's function through the creation and storage of minority carriers in "potential wells"—i.e., localized, defined spaces within the semiconductor substrate, in which the material's n or p polarity is "inverted" or "depleted" to acquire the opposite polarity. In a p-type substrate, the "well" space would, in other words, become n-type, while in an n-type substrate it would change to p-type.

The depletion "wells" are created by the application of voltages to metal electrodes deposited on the semiconductor substrate's oxide-coated surface and connected to the individual three or four elements that make up each "cell" of the CCD array. Input and output to the CCD are made by means of p-n junction diodes which can be fabricated on the same monolithic chip as the CCD array itself. Charges are shifted along the row or chain of devices by applying successively higher potentials to the cell elements.

Stated most simply, the CCD operates as an array of MOS capacitors that pass an injected charge from one capacitor to another. A d-c biasing voltage, V_1, applied to the electrode connected to the first element of a given cell causes a depletion layer to form at the semiconductor-insulator interface at that point. A voltage, V_2, greater than V_1 and also of the proper polarity to cause depletion, creates an even "deeper" well beneath the next element's electrode and the minority carriers (electrons in a p substrate, holes in n material) are attracted from the first well to the second, deeper one. Then, by applying a still larger, similarly polarized voltage, V_3, to electrode three, the charge is transferred to that electrode. In this manner, charges are moved along from one element to another within cells, and from cell to cell, until they have traversed the entire CCD "chain." This kind of action is obviously ideally suited for digital shift register and variable analog delay line applications.



CCD Fabrication Is Low in Cost, Simple

CCD's are fabricated in only two or three simple steps. First, the surface of a semiconductor wafer is oxidized to form a thin insulator. Second, a metal pattern of conductors and electrodes is deposited on the oxide. (Third step might be required to form a thicker oxide beneath the conductors to prevent unwanted depletion layers from forming underneath the latter.) No diffusions are necessary.

*Announced by Bell Laboratories, Electronics, May 11, 1970, page 112.

**"Designer's Guide to Charge-Coupled Devices," Dr. Barry T. French, Electronic Design News, pp 34-38, January 20, 1973.

Two-dimensional arrays of CCD's are at least as valuable for the creation of non-volatile, "permanent" (up to a year) storage, read/write memories. Such charge-coupled memory systems (CCM's) combine the characteristics of the CCD with MNOS (metal-nitride-oxide-silicon) FET technology to provide the storage capabilities. * Simply stated, charge is inserted into a CCM and transported to its storage site as in a CCD, and is permanently stored at that site in accordance with MNOS principles. Replicating the stored pattern and shifting this information out in a CCD fashion provides readout.

Probably one of the most exciting uses of CCD's, to laymen as well as to scientists, is their service as high-resolution imagers.

A basic TV camera requirement, to cite one application for such an imager, is for parallel-to-serial conversion. This characteristic is inherent in two-dimensional CCD arrays. For such an application, here's how the array works: Light from the object or scene to be "picked up" falls upon all of the array's cells in parallel (that is, simultaneously) through transparent conducting electrodes, and then passes through the insulating oxide layer (also transparent) and into the semiconductor substrate. In the substrate the photons interact with the silicon, with each photon generating a charge proportional to the intensity of the light sensed at that point.

The charges are read out serially, cell-by cell, in typical CCD fashion. Appropriately sequenced and synchronized readout scan of the rows of the array ensure that the "picture" built up by the resulting output will be an accurate replica of the originally viewed object or scene.

With their simple, economical fabrication . . . remarkable versatility . . . ultra-high elemental density and resolution . . . power dissipation as low as 1 to 5 microwatts per bit . . . and the demonstrated ability to operate at frequencies above 10 MHz—CCD's and CCM's are a real challenge to other types of microelectronic memories, and show promise of taking over the all-solid-state imaging field.

**In a MNOS FET the gate insulator consists of a double layer. Closest to the semiconductor is a thin (about 20 Å) layer of silicon oxide. This layer is covered by another insulator, typically silicon nitride, which is around 500 Å thick. "Tunnelling" of charge through the thin oxide layer provides memory, which is sensed by the effect of this transfer on the threshold of the transistor.*

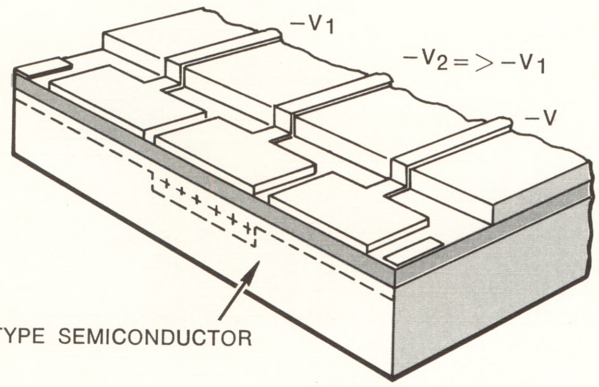
AN APPROACH THAT LITERALLY HAS EVERYTHING—FILM HYBRIDS

An approach that combines all microelectronics approaches into one is the film hybrid technology. In this approach, *uncased* (and thus, much diminished in overall dimensions) bipolar IC's, MOS subsystems, discrete transistors, and other microminiature components are bonded to a network of deposited metallic film conductors and deposited resistors on an insulating substrate. The entire assemblage is then enclosed in a single, sealed unit.

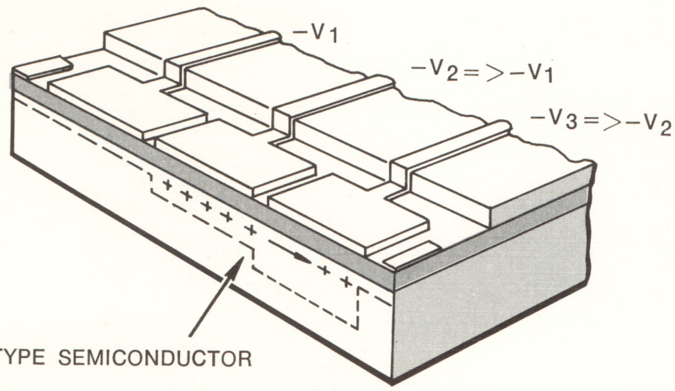
The film hybrid approach has the obvious benefits of: (1) eliminating essentially all intrasystem and device *wiring* . . . and, through bonding of the uncased devices, reducing wiring requirements to only those leads that are needed to go from the hybrid to the "outside world; and (2), (3), and (4) because of the drastic reduction of wiring and the use of bonding, an enhanced amenability to automated production . . . a significantly heightened reliability . . . and lower system lifetime cost-of-ownership.

Hybrid microelectronic systems comprise both "thin-film" and "thick-film" types. The two types are of equal benefit in many respects, but each has certain relative advantages and disadvantages in comparison with the other. Cost, yield, and fabrication techniques are basically the same for the two approaches. The major physical difference lies in the resistivity of thick-film resistors, which is from five to 100 times that of thin-film resistors. Thin-film resistor tolerance, stability, and temperature coefficient, however, are from two to 20 times better than for thick-film circuits. Thin-film circuits also have better resolution and narrower bandwidths than are possible in thick-film circuitry, with a consequent higher density for a given resistivity. Both thin- and thick-film hybrids find broad application in the 1970's.

CCD'S AND CCM'S ARE CHARGING AHEAD IN MEMORY AND IMAGING FIELDS...



STORAGE MODE



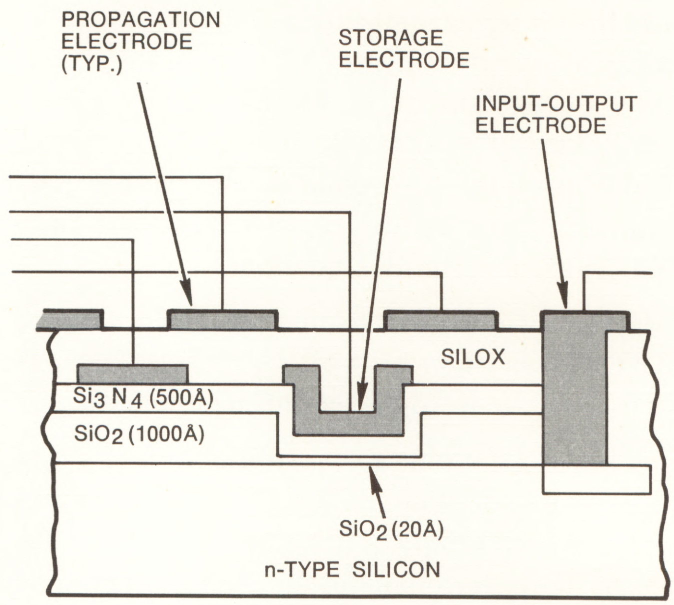
TRANSFER MODE

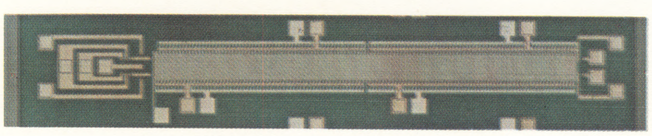
BASIC CCD OPERATION

Successively larger electrode voltages "pull" minority carriers from one propagation or transfer electrode to the next in a CCD "chain."

CCM STRUCTURE

Basic CCM structure resembles that of a standard CCD. The oxide layer, however is very thin in the storage regions and an additional layer of silicon nitride is added before the first-layer gates are deposited.





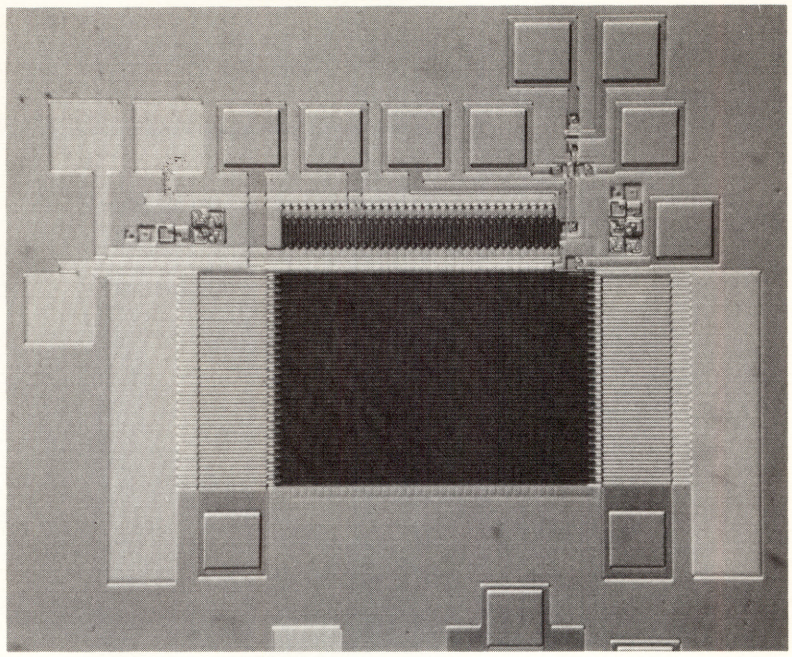
CCD DUAL 128-CELL ANALOG DELAY LINE

This Rockwell structure can also serve as a digital shift register. It works well at input frequencies up to 10 MHz and at temperatures ranging from −240 C to +125 C.

Rockwell scientists investigate properties of a charge-coupled memory.

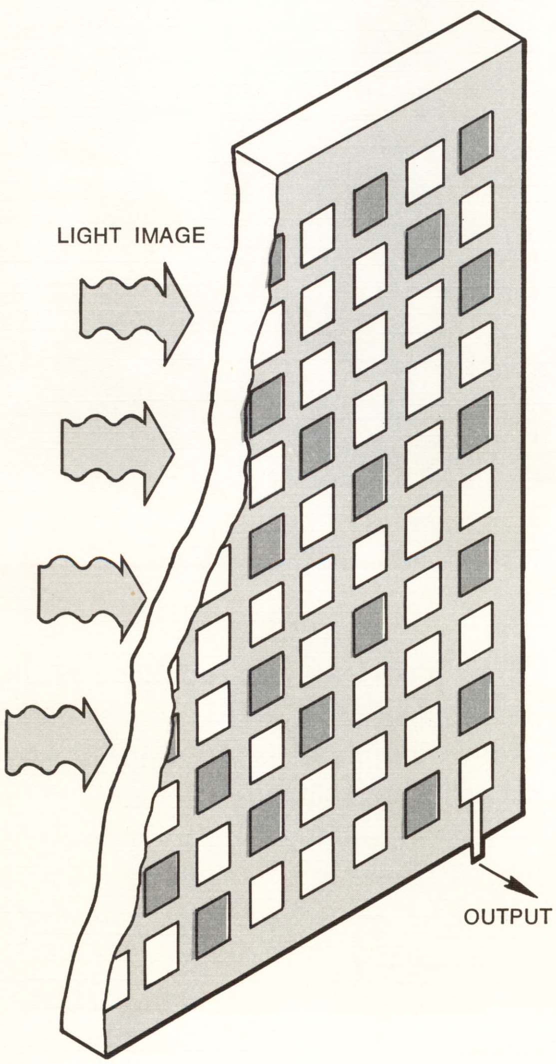
CCD IMAGER

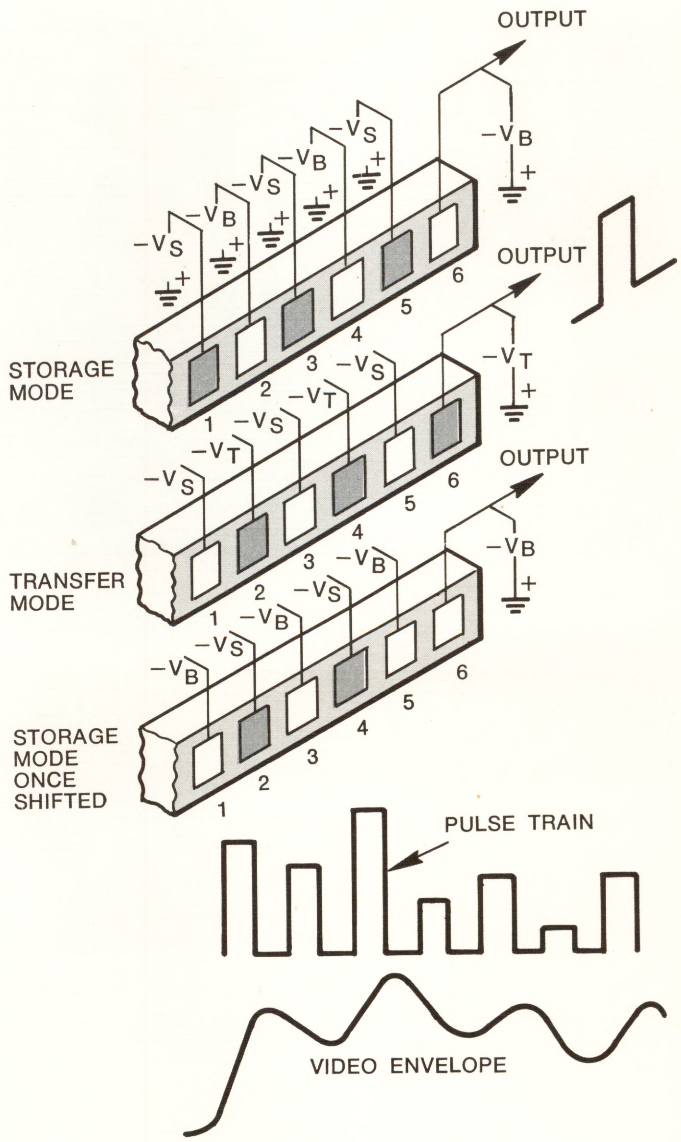
The CCD array is the large dark rectangle at center of the photograph. The smaller dark rectangle is the output multiplexer.



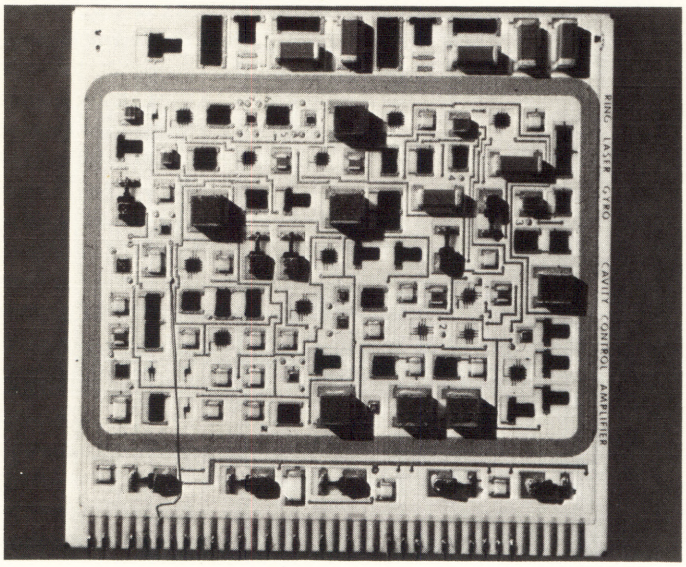
HOW A CCD IMAGER WORKS

In a two-dimensional CCD imaging array, the quantity of charge at each storage electrode corresponds to the intensity of the image incident on the substrate. The storage voltage, V_S, greater than bias voltage, V_B, forms the potential wells that trap the charge. In the transfer mode, a transfer voltage, V_T, greater than V_S, shifts the charge one space, resulting in a pulse at the output whose amplitude corresponds to the quantity of the charge. Thus, the output is a series of pulses whose envelope is the video analog of the image. Of course, the drawings presented here are greatly simplified. Actually, outputs would be multiplexed by a second on-chip, high-speed CCD in addition to the imager.



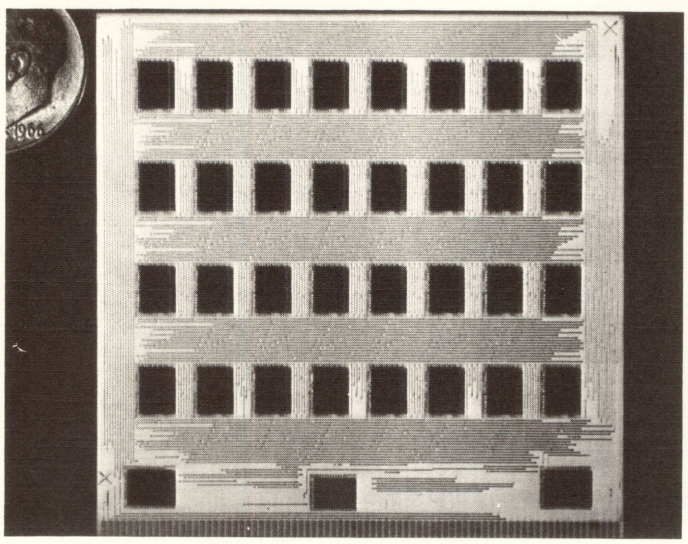


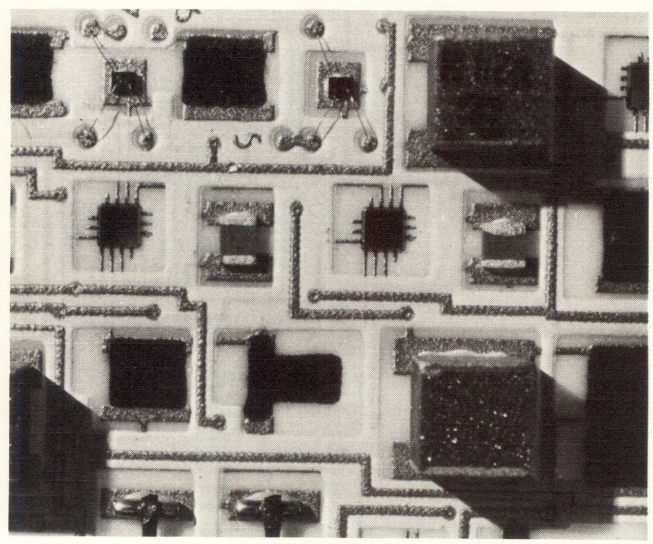
MORE THAN 1½ MILLION ROCKWELL THICK-FILM HYBRIDS ARE ACTIVE IN MINUTEMAN II AND III



Rockwell International produces thick-film hybrids in a 13,000-sq. ft., air-conditioned, dust-controlled area within the company's Anaheim, California complex. Facilities and personnel are provided for producing screens, adjusting screened resistors, attaching discrete components, and functionally testing the circuits. Tight process control is assured for the thick-film circuits by means of intensive chemical analysis, test pattern measurement, equipment qualification, and rigid materials and packaging inspection procedures.

The extensive facilities at Anaheim are backed up by thick-film circuitry production at Rockwell's West Virginia Plant, where more than a million high-reliability circuit devices have been produced and delivered for systems to support defense and space programs.





THICK-FILM HYBRIDS

In thick-film hybrid systems, the uncased microelectronic devices are bonded to a network of noble metal conductors and cermet resistors on a fired ceramic substrate. The thick-film type of hybrid is ideal for high-power, low-frequency, linear applications, and is extensively applied in ballistic missile and aircraft guidance and navigation systems.

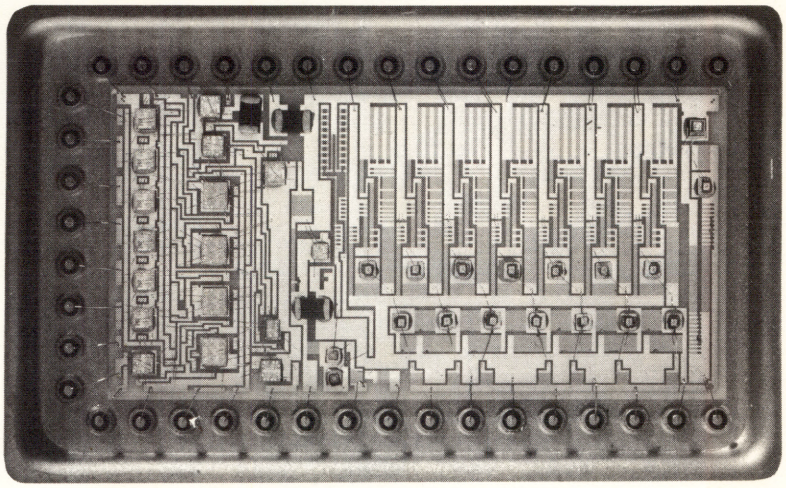
THIN-FILM HYBRIDS

The most extensively applied microelectronics in electromagnetic, communications, and radar equipment is the thin-film hybrid. The versatile approach offers significant benefits for digital, analog, and microwave applications. To illustrate its capability—a single 1- or 2-sq in. sealed package can contain a complete microwave receiver "front end" (mixer, circulators, filters, etc); a master frequency generator; or a receiver/duplexer.

THIN-FILM HYBRIDS OFFER A VERSATILE APPROACH TO MICROELECTRONIC SYSTEMS

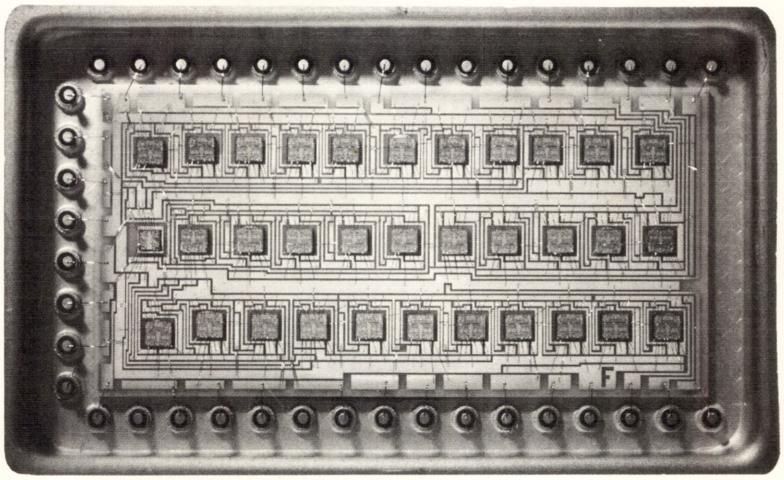
ANALOG

Rockwell's analog circuits span the frequency and power spectrum from DC to 200 MHz, and from a few milliwatts to 22 watts, respectively. A typical circuit contains from 60 to 80 active and passive elements. The active elements (transistors, diodes, and IC and MOS units) are uncased devices, interconnected to thin-flim NiCr resistors and chip capacitors with a thin-film gold conductor network. Proven assembly techniques are used such as ultrasonic and thermocompression wire bonding, and silver-loaded epoxy for device attachment.



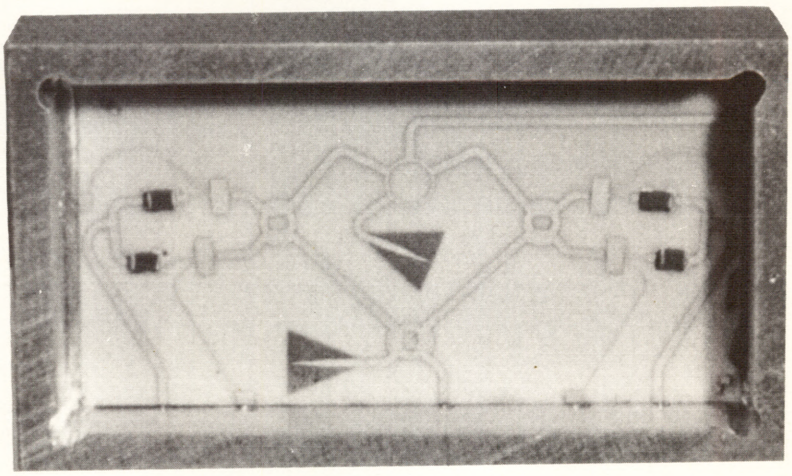
DIGITAL

A number of digital functions (shift registers, counters, special gating logic) have been designed and fabricated using uncased DTL and TTL MOS logic devices. A typical circuit has 25 active devices equalling as many as 75 to 100 individual logic functions. The same assembly techniques employed to fabricate linear circuits are used to interconnect the uncased IC's to a thin-film gold conductor network.



MICROWAVE

Rockwell has utilized microstrip technology to construct radar, communication, and electronic warfare subsystems—including L-band and Ku-band transceivers, master frequency generators, and L-band through Ku-band microwave receivers. Several orders-of-magnitude decrease in cost, size, and weight can be achieved by using microstrip techniques rather than conventional microwave designs.*



**Extremely narrow deposited metal "stripline" conductors, especially useful in microwave applications, where the relationship of physical dimensions of circuitry vs wavelength becomes meaningful to circuit performance.*

Thin-Film Hybrid Microcircuits Produced by Rockwell International as "Off-the-Shelf Standards"

ANALOG AND ANALOG/DIGITAL MICROCIRCUITS

7-BIT ADC
- 40-pin package
- Reference supply included
- Clock rate: 5MHz
- Input voltage range: 0 to 2.56 volts
- Full-scale error at 25°C: ±0.25%

100-MHz, 3-BIT ADC
- 30-pin package
- Input-voltage range: 0 to 2.56 volts
- Power dissipation: 2.5 W

HIGH-SPEED, 8-BIT DAC
- 30-pin package
- Full-scale output voltage: 2.789 volts
- Bit switching relay: 20 nsec
- Bit switching time: 20 nsec

MOS 4-PHASE CLOCK DRIVER
- 14-pin package
- Converts TTL logic to MOS logic
- Drive capability: 1000 pf/ϕ; R_t and F_t: 50 to 125 nsec; clock rate: 10 KHz to 1 MHz

RECEIVER CIRCUIT
- 30-pin package
- Converts logic levels within the range of ±10V dc to standard DTL or TTL logic levels
- Remotely programmable

DC VIDEO AMPLIFIER
- 14-pin package
- Maximum bandwidth: 15 MHz
- Gain accuracy ±20 mV
- Input impedance: 300 KΩ minimum
- Output impedance 50Ω or 90Ω

HIGH-FREQUENCY CRYSTAL OSCILLATOR
- 14-pin package
- Drives DTL and TTL logic
- Output pulse: 0 to 5V square wave; frequency dependent on external crystal
- Frequency range: 2 to 25 MHz

60-MHz IF LOG AMPLIFIER
- 14-pin package
- Voltage gain: 4 (for signals $<$250 mV) 1 (for signals $>$250 mV)
- Input impedance: 2KΩ
- Output impedance: 200Ω

LOGIC DRIVER
- 14-pin package
- Single package contains three identical digital pulse mode circuits
- Output R_t and F_t $<$20 nsec; load: 25 ft of terminated RG188 coaxial cable

DIGITAL MICROCIRCUITS

COUNTERS	
5-bit synchronous	6-bit up-down
6-bit synchronous	10-bit up-down
6-bit ripple	14-bit up-down
7-bit ripple	
8-bit ripple	
9-bit ripple	
12-bit ripple	
14-bit ripple	

SHIFT REGISTERS					
Length	Inputs	Outputs	Length	Inputs	Outputs
3-bit	Serial	Parallel	13-bit	Serial	Parallel
3-bit	Serial	Serial	14-bit	Serial direct	Parallel
4-bit	Serial	Serial	14-bit	Parallel sets	Serial
6-bit	Serial	Decoded	14-bit	Serial	Serial
6-bit	Serial	Parallel	14-bit	Serial	Parallel
7-bit	Serial	Parallel			
13-bit	Serial	Serial			
13-bit	Parallel sets	Serial			

MICROWAVE INTEGRATED CIRCUITS

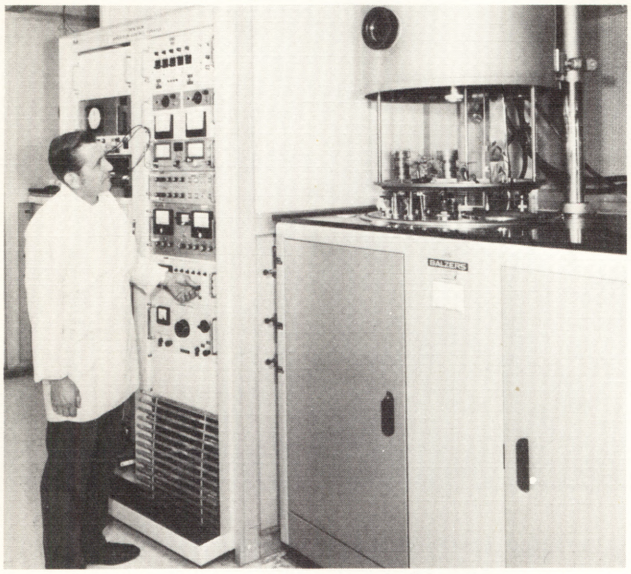
TRANSCEIVERS (L- THROUGH KU-BAND)
- Mixers
- Circulators
- Voltage Variable Attenuators
- Modulators
- Filters
- Power Amplifiers
- Low-Noise Amplifiers

MASTER FREQUENCY GENERATORS (L- THROUGH Ku-BAND)
- Fundamental Oscillators with or without Multipliers
- Couplers for Injection Locking
- Single-Sideband Modulators
- Power Amplifiers
- Local Oscillator/Transmitter Time-Share Switches

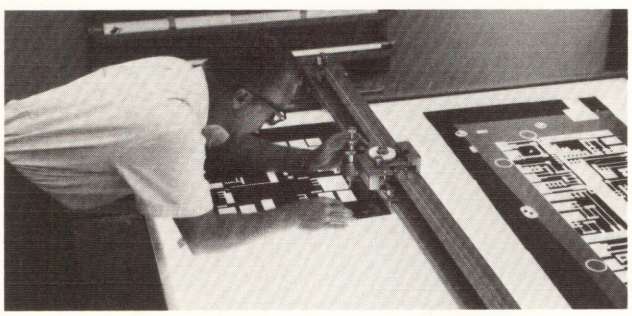
MICROWAVE RECEIVERS (L- THROUGH Ka- BAND)
- Local Oscillator Frequency Generators
- Preselector Filters
- Balanced or Image-Rejection Mixers
- Diode Limiters
- Diode Switches (Monopulse Difference Channel Time-Share Switches)

Rockwell Has a Product Line of More than 1,000 Different Types of Thin-Film Hybrid Microcircuits

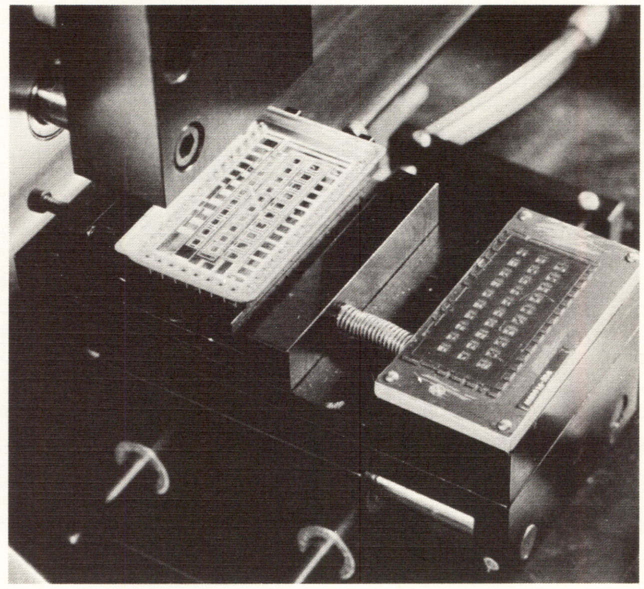
The microcircuits are manufactured in Rockwell's 18,000 sq. ft. of thin-film hybrid production facilities, capable of producing more than 10,000 digital and analog thin-film microcircuits per month.



Production Vacuum-Deposition



X-RAY Machine Photomicrograph Station



Semi-Automatic Die Placement Machine For Digital Microcircuits

Product Inspection

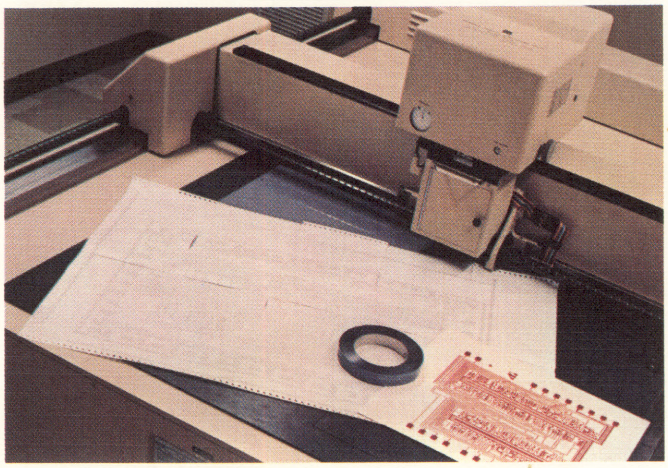
PRESENT TRENDS AND FUTURE DIRECTIONS

To recap our discussion to this point—all types of microelectronics approach, including those applied in the '50's and '60's as first-generation techniques, are still being used. For some applications, only discretes offer sufficient power-generating and heat-dissipating capabilities. For others, bipolar IC's perform adequately and, at the same time, are the most economical.

The star that continues to rise, however, is the MOS technology, with its special sub-categories such as CMOS, MNOS, and radiation-hardened MOS/SOS devices. "Third-generation" MOS-type CCD and CCM devices are increasingly important parts of the 1970's' microelectronics picture. Hybrid film systems combine all the diverse types of microelectronics and their benefits into single, sealed, high-reliability packages.

In Chapter III, we shall see how the extremely high elemental density that can be achieved with the 1970's microelectronics is making possible new ways of performing old systems tasks, and are, furthermore, enabling systems to be configured in new ways, to perform new tasks never before feasible by *any* approach.

GENERALIZED DESCRIPTION OF HOW MOS DEVICES ARE TYPICALLY PRODUCED...

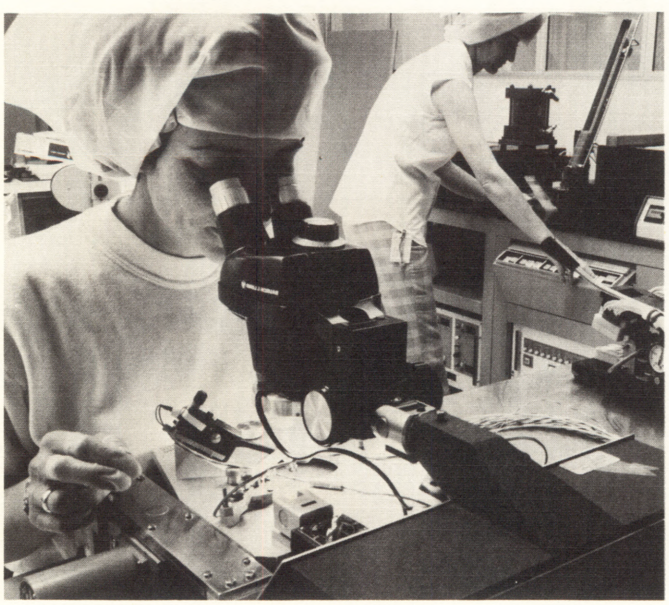


PROCESS:

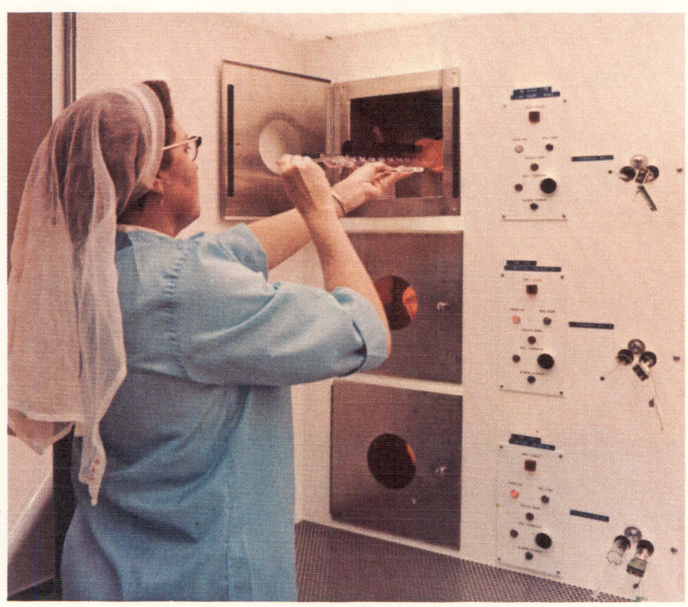
ENGINEERING CIRCUIT CONCEPT → 7094 COMPUTER → AUTOMATIC PLOTTER → 120 MASK SET

A computer generates a paper checkprint and a punched tape describing the MOS circuit layout in terms of plot points. The computer-generated tape is used to drive an X-Y plotter, which delivers "film positive" overlays to serve, after photoreduction, as diffusion masks. For each MOS device, a mask set of five masks is made.

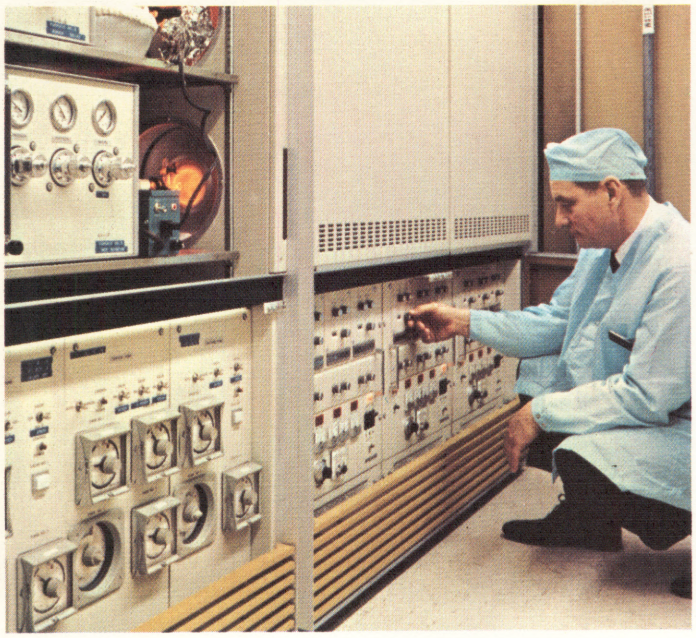
The many-times-ultimate-device-size masks made by the plotter are photographically reduced to form a 1-times-size production mask set. Each mask in the set typically contains hundreds of identical circuit patterns. MOS design engineering delivers to a MOS production facility: release drawings, mask sets and process specifications.



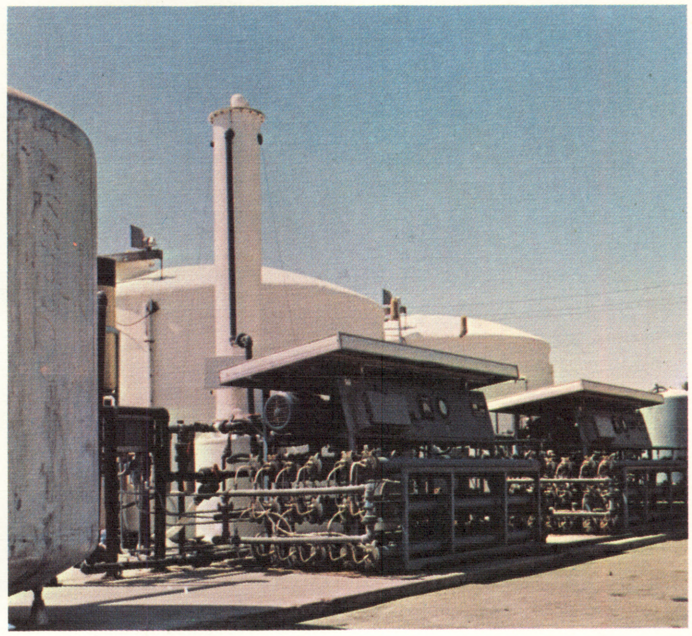
Before production gets under way, the "raw" wafers must be inspected for flatness, and for crystal dislocations and resistance in ohms per square centimeter.



Wafers are inserted into diffusion furnaces for growth of oxides to serve as device gate and insulation, and for diffusion of source and drain.



Manufacturing engineer adjusts power levels for diffusion furnaces. Other adjustments set furnace temperature, pressure, and gaseous flow-rates.



Processing gases, electrical power, and ultra-pure water are all demanded by the oxidation processes required for MOS production. The distilled water used must be purified until it has a specific resistance of many megohms and contains much fewer than 10 parts per million of solid impurities and of dissolved carbon dioxide. Some of the special water-purifying equipment is pictured above.

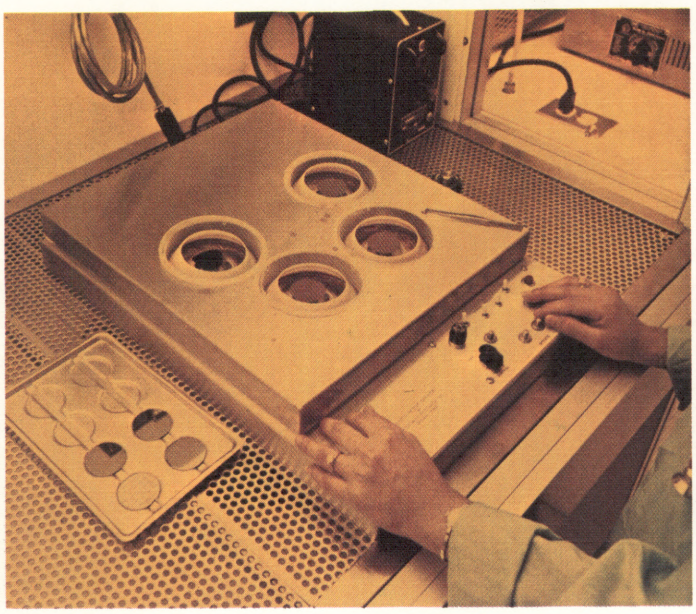
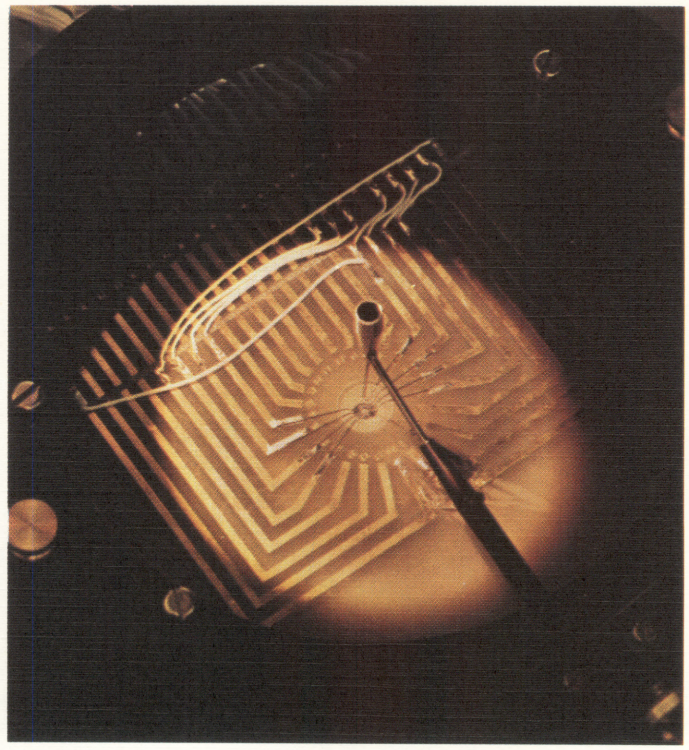


Photo resist is applied evenly over the surface of rotating wafers.

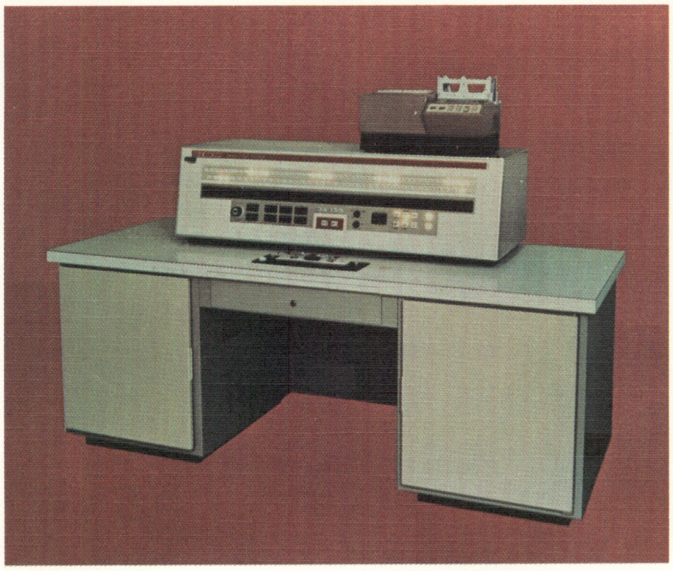
Oxide is selectively removed for each diffusion by exposing the photo-resist-coated slice to ultraviolet light through the appropriate mask from the device mask set, desealing the unpolymerized photo-resist, and selectively etching the oxide exposed by the "windows" thus opened. Position of each mask is precisely aligned relative to others in the set by means of a microscope and electromechanical alignment system.

Circuit intraconnections can be made by depositing aluminum on the MOS slices, followed by selective etching to leave only the desired intraconnection pattern.



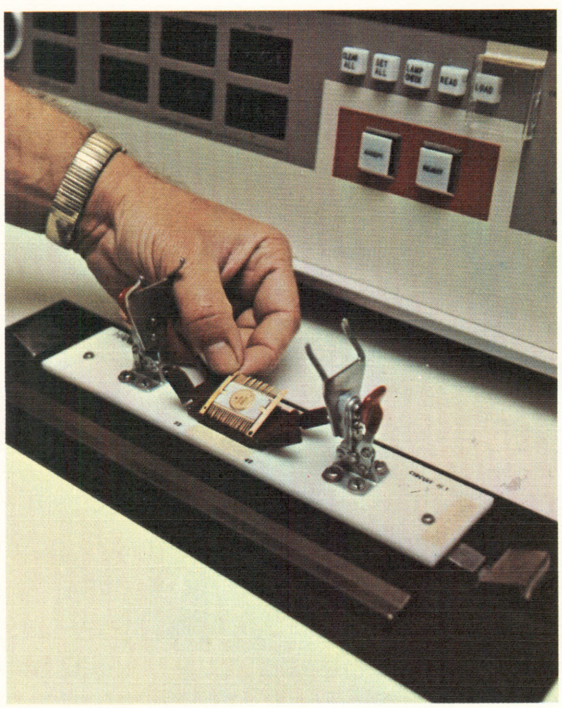
Production test probe checks every circuit on each MOS/LSI wafer and feeds signals into a computer which compares them with those for a "perfect" circuit. (Only those arrays whose circuits check "100% perfect" when tested in this way are accepted by Rockwell's Microelectronic Device Division.)

A very important parameter of MOS circuitry is gate oxide thickness, because it determines the device's speed of operation.

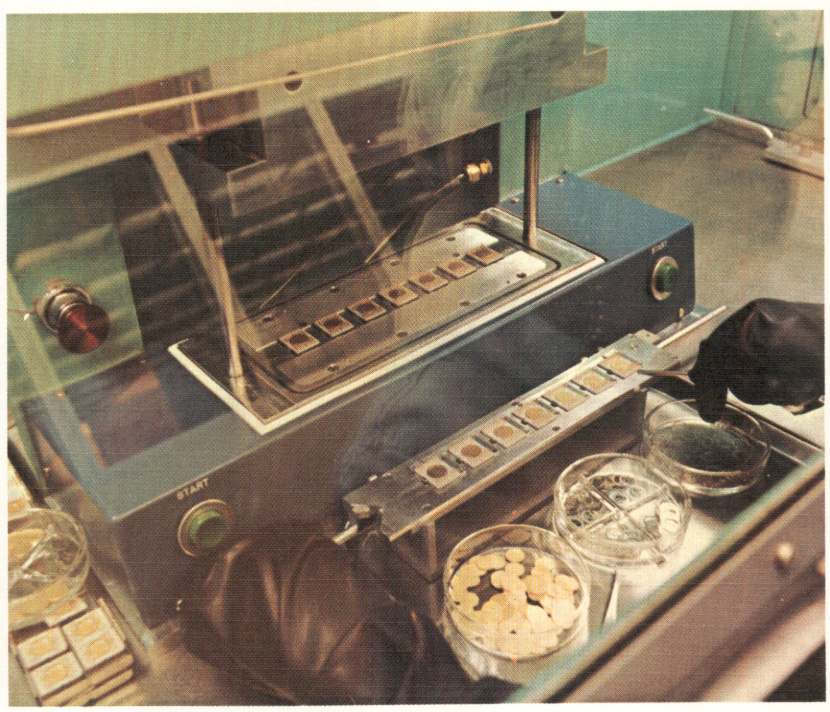


Each device produced must undergo quality control testing and inspection. Randomly selected areas on each slice are checked at each step in the production process, to determine that the step is acceptable. At each step, the product is either accepted, sent back for rework, or permanently discarded, depending on the flaw detected.

Completed MOS devices experience a multi-cycle ordeal of temperature extremes.



To test strength of completed-device outgoing leads, the devices are placed, with leads outward, around the periphery of a high-speed centrifuge. At full speed of the system, the leads are subjected to a centrifugal pull of thousands of g's.



For those which require hermetic seals completed MOS devices are given a helium leak test under high-vacuum conditions.

III. EVER SMALLER, EVER DENSER, EVER MORE RESPONSIBLE: LSI

Looked at in wide perspective, microelectronics in the 1970's continues to pursue one very marked and significant trend, already discussed to some degree. This is the constant progression toward ever greater elemental density, culminating in the circuit/system design approach termed "LSI" (large-scale-integration).

WHAT LSI IS

Just what is LSI? Its most obvious characteristic is the ability to pack literally thousands of microelectronic active elements into microscopic areas—the ability to get an entire functioning electronic system onto a single quarter-inch-square or smaller semiconductor chip. It is the natural outgrowth of microelectronics' continuing race toward smallness as described in Chapter II.

The remarkableness of LSI is not, however, its ability to pack an astounding number of active elements into a small space. The real significance of this approach lies in the new flexibility which LSI gives to systems designers, and in the new schemes it enables them to apply in mechanizing and configuring traditionally electromechanical as well as electronic systems.

LSI IMPETUS GIVERS

It is difficult to determine precisely whether LSI has played more the role of *cause* or *effect* in the development of today's monolithic microelectronics state-of-the-art. It is certainly the motivating force as well as unique tool for new system organizations and new concepts to ensure and improve reliability. And, from these considerations, LSI can justifiably be thought of as a *cause*.

At the same time, LSI is undeniably the *effect* of certain accomplishments in the development of new exotic materials for the fabrication of microelectronic devices. (These materials are discussed in Chapter IV.)

Certain trends in users' requirements have almost dictated the development of LSI. The increasing functional complexity required of electronic systems has indeed generated an urgent need for a way to use fewer components to perform more tasks, and to perform them with greater reliability and at lower costs. LSI, permitting the containment of an entire system on a single chip, offers solutions to these requirements.

LSI'S CONNECTIONS—WITHIN ITS OWN CHIP COMMUNITY AND WITH THE OUTSIDE WORLD

One of LSI's persistent problems has been that of connections—both "inter" and "intra." Density limits, as well as constraints on speed and power, ultimately depend on how an LSI system's elements are connected with each other. Just as important is the manner in which the system makes contact with other entities outside the home chip.

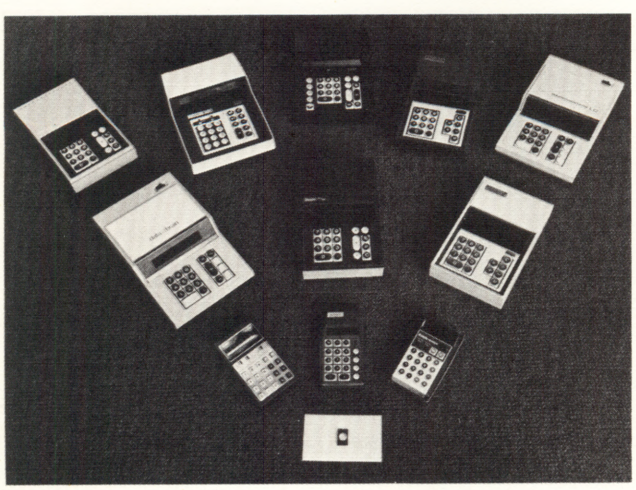
Wire bonds are both costly and unreliable if not properly controlled. Closely paralleling the constant trend toward higher and higher density has been a search for a method of LSI connection that is fast to perform, lends itself to automation, and stands up well against all sorts of operational and environmental onslaughts.

Two connection methods—"beam-lead" and "flip-chip" bonding—have shared the spotlight. Flip-chip bonding has been applied successfully to both MOS arrays and bipolar IC devices. Beam-lead bonding is used for interconnection between MOS systems and the outside world, but has not yet been perfected for intraconnection within MOS circuitry due to its destructive effect on the critical surface conditions upon which MOS device performance depends.

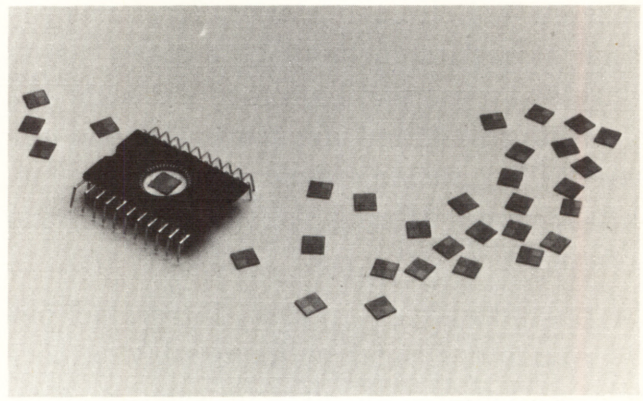
THE KEYS HAVE TO BE BIG ENOUGH FOR FINGERS...

...That's about all that limits the "smallness" of calculators that use the MOS/LSI microelectronics of the 1970's. In 1972, prices of handheld, "mini-calculators" went below $100 for the first time... brought high-quality calculators within the financial reach of the average businessman and housewife.

One of Microelectronics' Earliest Invasions of Commercial Products was represented by Rockwell International's original $30 million contract from Sharp Electronics in 1968 to provide custom MOS circuits for a pioneering 3-lb MOS desk calculator.



Typical Calculators Based on Rockwell's One-Chip MOS/LSI Calculator Circuits. In addition to supplying circuits to calculator manufacturers around the world, Rockwell produces complete machines for mass merchandisers on a custom, contract basis.



Rockwell International Has Designed Basic One-Chip Calculator Circuits which it "micro-programs" to produce varieties of unique machines. Millions of these circuits, which include "electronic sliderule" versions, have been delivered.

In This Magnified Photograph of a MOS/LSI Array of Single-Chip Calculator Circuits each chip contains more than 14,000 transistors. Functional areas on a single chip are indicated by callouts on the photo, and include a RAM (random-access memory), ROM (read-only memory), registers, and logic circuitry. The tiny squares—each actually about the thickness of a human hair—around the edges of each chip are "pads" or connection points to connect the chip to the "outside world," once it is cut from the array and packaged into a finished device.

A considerable amount of both time and money has been spent throughout industry to perfect practical MOS beam-lead methodology and to apply flip-chip bonding to MOS circuitry. Each technique has its vociferous advocates and its equally vociferous detractors.

The beam-lead, sealed junction process was pioneered by Bell Laboratories. Since its origination, it has found favor with many manufacturers and users of both medium-scale and large-scale integrated devices, who find the technique promising from angles of production cost, product ruggedness, and electrical characteristics.

In the beam-lead process, integrated circuits and other semiconductor devices are batch-fabricated with electroformed electrodes cantilevered beyond the edge of the wafer. The gold leads are built up to the desired thickness (around 12 microns), and the underlying material is then etched away to leave the beam leads extending beyond the periphery of the device. To communicate with other chips and power supplies, the projecting beams are bonded to circuit-board pads.

The beam-lead technique can be used to provide rugged little bridges between the elements *within* element circuitry. Trenches etched beneath the leads furnish perfect air isolation between the elements and, in some cases, can replace isolation diffusions or solid-dielectric isolation. Parasitic capacitance (less than 0.05 picofarad per lead) is no higher than with wire-bonded and brazed-chip assembly. The low capacitance means that the beam-leaded circuitry can be "fast," and switching speeds with it are comparable to the speeds available with chip-and-wire circuitry. (Flip-chip-bonded circuitry is also "fast," however.) Width of beam leads does not have to be constant, and the leads can be shaped to match the impedance of stripline (deposited metal interconnections on the substrate) with which they may connect, or can be widened to provide better heat conduction.

A significant advantage of beam leads is that, once the leads have been fabricated, the devices containing them can be completely sealed with an insulating layer which eliminates the need for the costly enclosures that unprotected dice require.

One of the greatest contributions of the beam-lead process is to reliability. First of all, the gold-to-gold bonding is inherently more reliable than the bonding of dissimilar metals in other approaches. Also, the beam leads are relatively stout (they successfully pass test forces of well over 100,000 g's).

Flip-chip bonding has been in use since the early 1960's. Process details of the firms applying it vary, but the essence of all procedures is the use of balls or bumps of metal on the device pad sites. The chip is flipped (thus the term "flip chip") so that its bumps line up with pads on the mating surface. Bonding is then accomplished in a one-shot ultrasonic, thermocompression, or reflow solder operation.

Flip-chip bonding has about as many enthusiastic supporters as beam-lead. The supporters point out that flip chips are easier to fabricate, and that they are accordingly more practical for high-volume production. Moreover, flip-chip processing is compatible with existing IC production lines.

In a given area of chip, a flip-bonded device can have many more elements than is possible with beam leads. Similarly, a greater number of flip-bonded chips can be packed into a given area of hybrid device substrate, because the flip-bonded chips have no beam leads to extend over the edge of the chip and take up valuable substrate "real estate."

Flip chips have the *disadvantage* that extreme precision is required to match the mating bumps on a chip and its receiving surface, and once the chip has been flipped these bumps cannot be seen, either during or after the mating, unless the substrate is transparent. With beam leads, bonds are visible after formation, and a number of different attachment methods can be used—soldering, spot welding, and ultrasonic or thermocompression bonding. During beam-lead bonding, heat and pressure go mostly to the leads—little reaches the active semiconductor area; this is not true with flip-chip bonding.

The future no doubt holds the final solution to the problem of LSI connections. Optical connections—with light serving as actual link between elements and circuits—are being worked on today. SOS, for one, will be quick to exploit this approach, once perfected. The transparency of sapphire makes optical connections particularly attractive. Other new material combinations hold even greater promise than SOS for this approach, due to their photoemissive and photosensitive properties.

One thing is certain. Those techniques that are most readily automated—and that thus offer highest reliability and greatest production economies—will prove to be eventual LSI connection winners.

THE PROFOUND EFFECTS OF LSI

The advent of LSI has had profound effects on the very basics of such things as systems reliability, organization, and costs.

ON RELIABILITY

Because LSI permits an entire system to be contained on just one tiny microelectronic chip, redundancy for the sake of reliability can be economically carried out all the way to the system level. This possibility is of especial significance for those applications in which size and weight are at a real premium, as, for example, in an aircraft or a space vehicle. On a lower level, within each system, subsystems and circuits can be repeatedly duplicated on each chip—compounding reliability by compounding redundancy.

Through functional redundancy possible to a significant extent for the first time with LSI, defect-tolerant systems can be designed, capable of continuing to operate adequately with as high as 90 percent of system components having failed! This can be an extremely reassuring advantage of LSI, as viewed by an astronaut 200,000 miles from Earth and depending on his electronics to get him safely back to his home planet.

ON SYSTEM ORGANIZATION

With LSI, system mechanization and organization techniques heretofore considered completely unfeasible may prove to be the most economical and reliable form.

Analog approaches formerly used exclusively for certain functions can be discarded for digital approaches using LSI. Cumbersome tuned inductance-capacitance combinations are supplanted by digital filters that need be no larger to handle frequencies as low as 10 hertz than to handle those measuring in the gigahertz range.

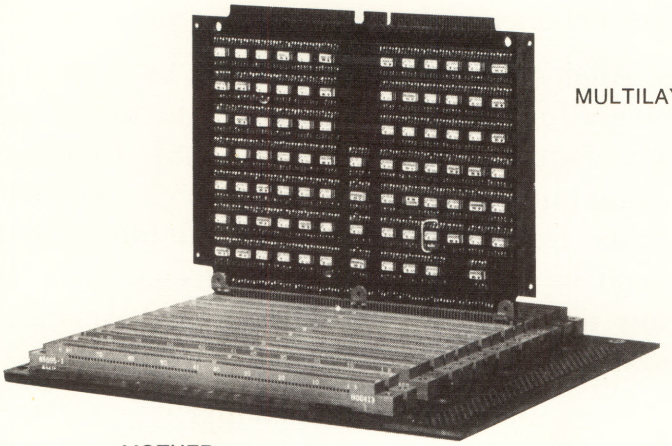
Computers can be divided (partitioned) into functional LSI chip computing "cells," and the latter can be distributed throughout an installation at the most strategic operating points. Each functional cell can be made several times redundant to ensure a fail-safe system.

With vacuum tubes or first-generation microelectronics, hardware to implement the innovating reliability and digitization schemes would be prohibitively large and heavy. But, with LSI, one needs a microscope merely to see the circuits!

To illustrate the potentially dramatic impact of LSI on system organization, let's take a look at a subsystem to which the new approach offers readily apparent benefits. This is the real-time data processing and handling subsystem of a guidance and control (G&C) system for a missile, airplane, or spaceship. One of the most vital parts of the G&C system, this subsystem must tie together the various functions of all the other G&C subsystems, coordinate them, and direct them. Failure of the data processing and handling subsystem would be truly catastrophic to the total system's performance. LSI microelectronics makes possible a number of otherwise unfeasible approaches to the data handling and processing function.

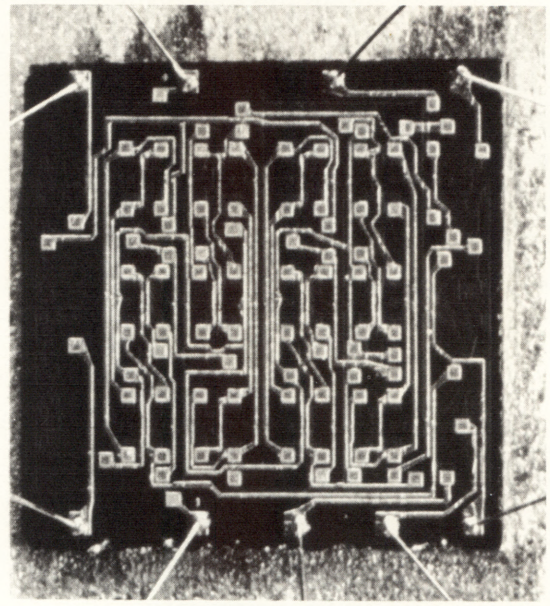
YOU'VE GOT TO HAVE CONNECTIONS

FIRST-GENERATION MICROELECTRONICS . . .

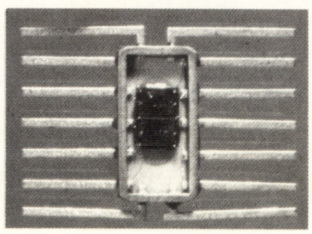


MULTILAYER BOARD

MOTHER
INTERCONNECTION
BOARD

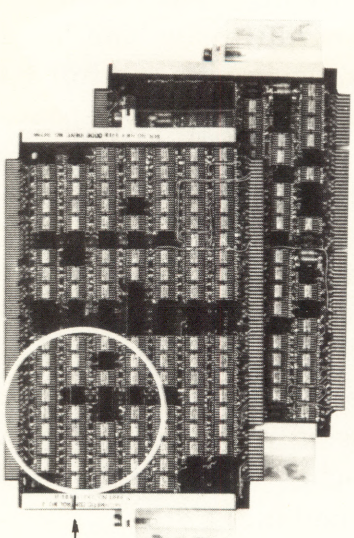


IC CHIP

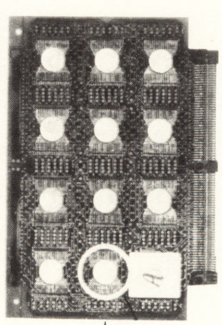


FLAT—PACK
SIC

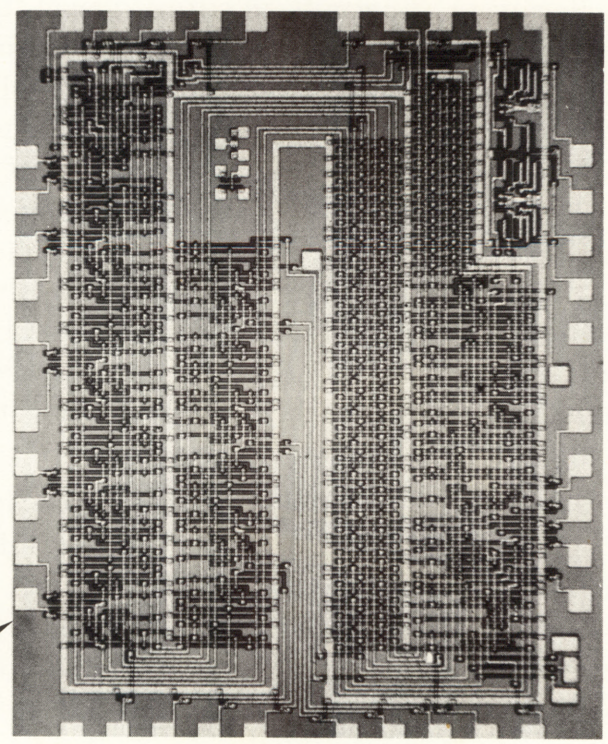
ADVANCED-GENERATION LSI . . .



MANY
BIPOLAR
1ST-GENERATION IC's =

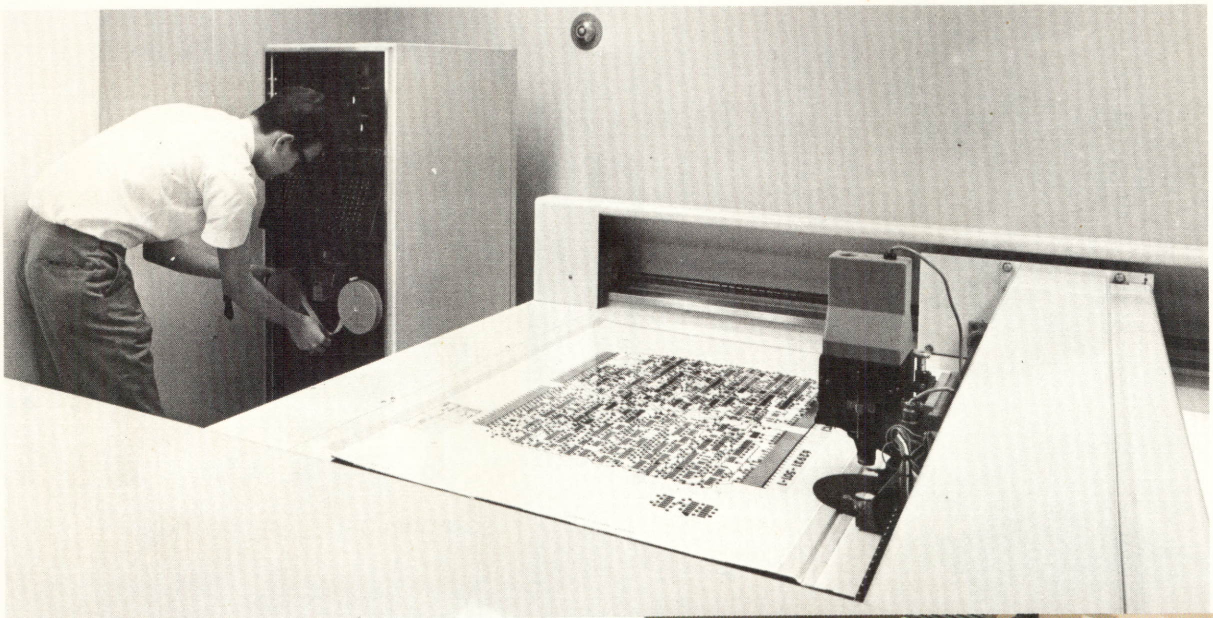


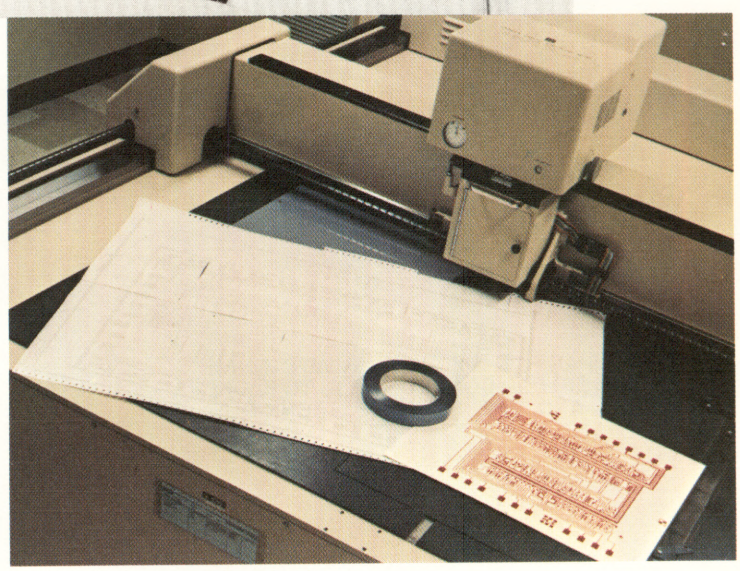
JUST 1
MOS LSI DEVICE



MOS LSI CHIP

MAKING THE RIGHT CONNECTIONS MEANS A LOT





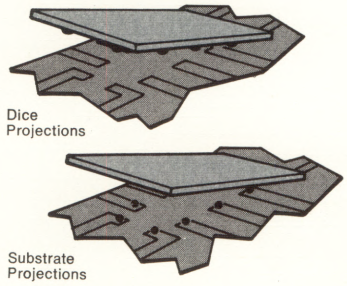
WITHIN THE LSI CIRCUITRY ITSELF

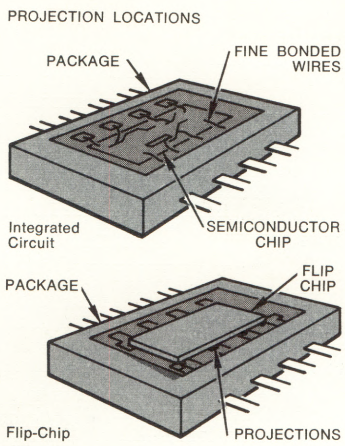
The high density and extreme complexity of LSI circuitry demand computer aid in designing, checking, and fabricating the oversize masks from which final production masks are made. The metal films that form the intraconnections within the circuitry are deposited in a vacuum evaporator. Many wafers, each containing hundreds of circuits are "metallized" in a single operation.

. . . AND FROM THE LSI TO THE "OUTSIDE WORLD"

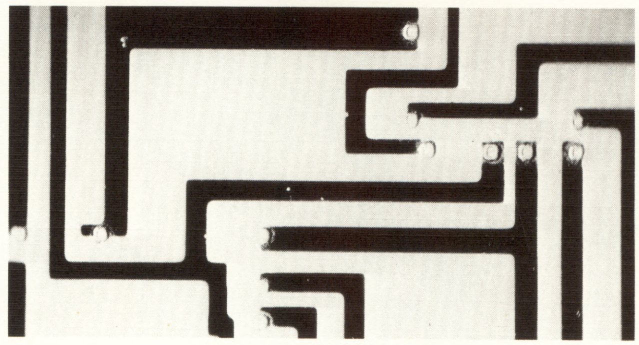
Two starring contenders for the lead role are flip-chip and beam-lead bonding.

FLIP-CHIP BONDING

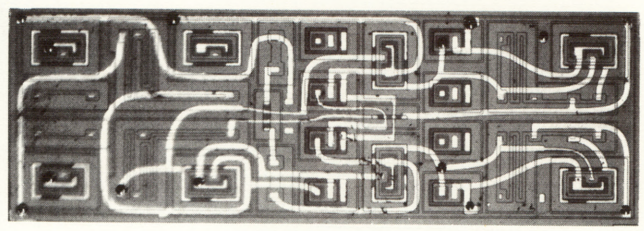




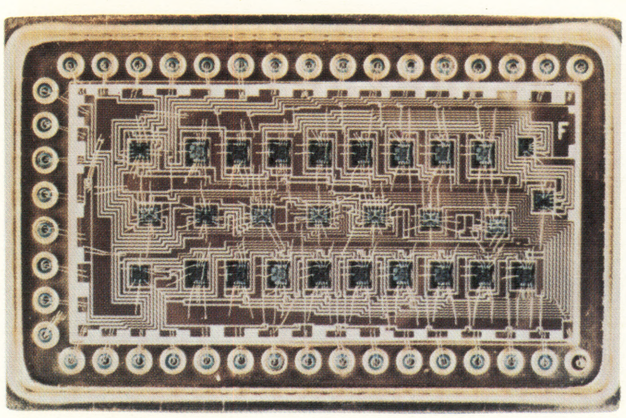
COMPARISON OF THE CONVENTIONAL METHOD FOR CONNECTING IC TO PACKAGE AND THE FLIP-CHIP TECHNIQUE



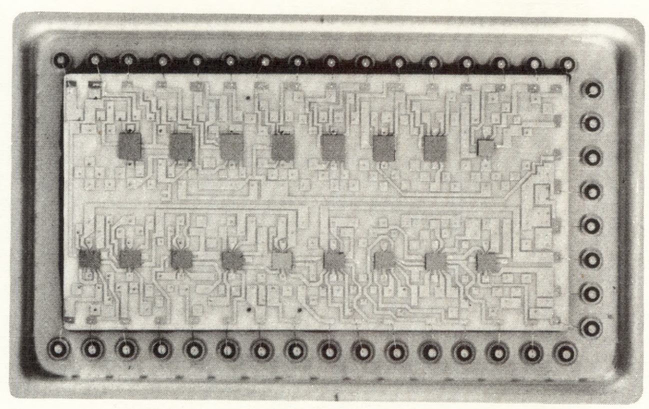
ELECTRODEPOSITED PROJECTIONS



CONICAL COLD PROJECTIONS FLIP-CHIP BONDED BY THERMOCOMPRESSION TO GOLD THIN-FILM-IC INTRACONNECTS



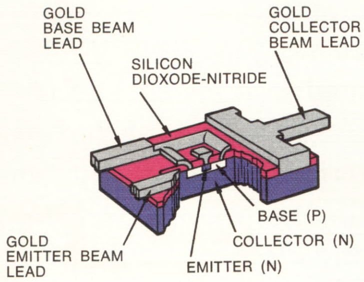
A 28-device hybrid circuit with over 700 "flying lead" (wire) bonds

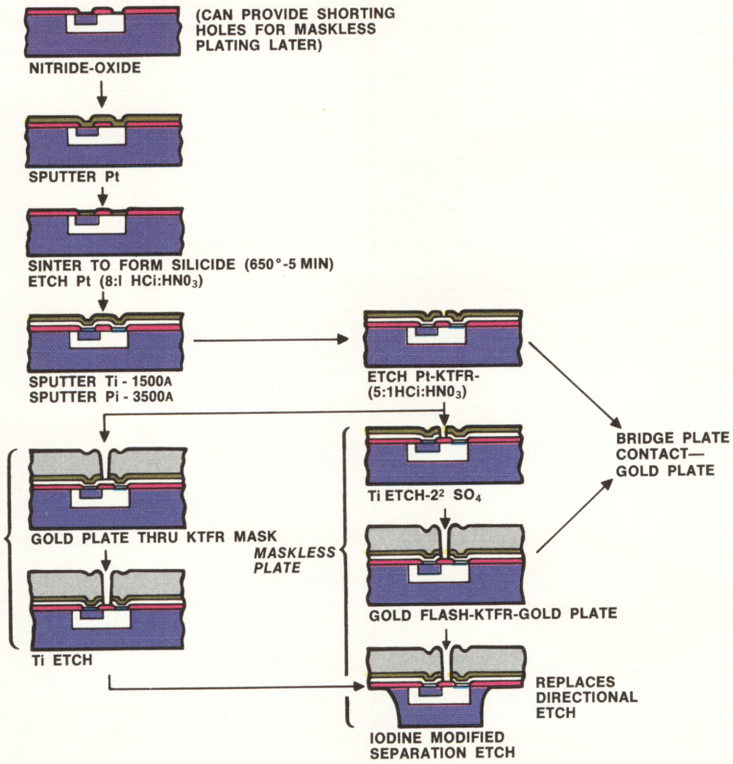


Functional hybrid circuit with 17 flip-chip bonded devices

BEAM-LEADING BIPOLAR CIRCUITRY

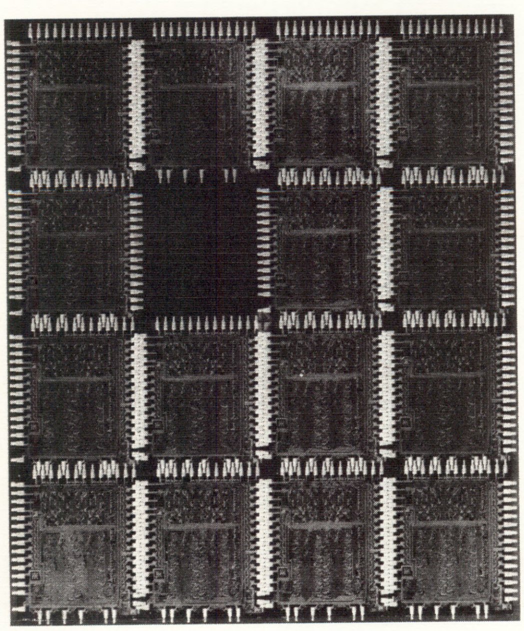
Some of the methods for achieving beam leads for bipolar circuitry are shown at left.



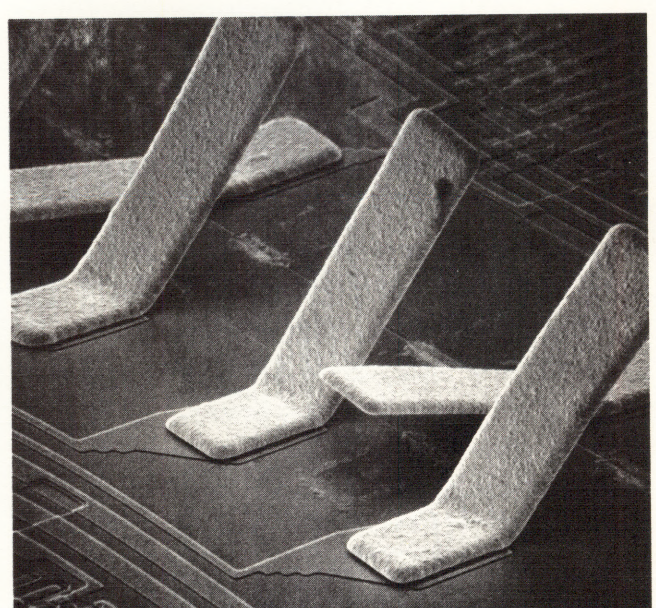


BEAM-LEADING MOS CIRCUITRY

MOS circuitry is very sensitive to surface conditions of the wafer, and the beam-leading process that is used successfully with bipolar devices includes a surface-disturbing technique of "sputtering" metal onto the wafer. To be practical for MOS, the beam-leading process must be able to deposit metal without simultaneously depositing a permanent electrical charge that changes the circuitry's function characteristics. Only a few MOS device producers have developed such a process. Rockwell International has developed a gold beam-lead process for use with MOS/LSI, and is in advanced development of an aluminum beam-lead process.



Beam-Leaded MOS/LSI Circuits in Pilot Production by Rockwell



Enlargement of a Scanning Electron Micrograph of Rockwell Gold Beam Leads Applied to MOS Circuitry

DISTRIBUTED LOGIC

One concept made feasible by LSI is the "distributed logic" scheme mentioned briefly above. This scheme permits a high degree of operational flexibility and reliability. Instead of being performed by a single centralized integrated computer, the computing functions are distributed among individual, physically separated "computing cells"—with each cell being capable of performing a complete significant "subtask." Several cells hooked in parallel form a "computing group"; a number of interconnected groups form the complete computer. If any computing group should cease to function, the computer is so arranged that any other computing group can perform its "task." In fact, the computer might conceivably be so designed that the guidance and control (or other) system which it coordinates continues to operate at least adequately enough to complete its main "mission"—for a spaceship, perhaps, the mission of safely reaching a destination literally millions of miles away—with only a single computing group left operating.

Without LSI microelectronics, the distributed logic computing scheme would obviously be impractical. Just imagine the size and weight of such a subsystem, put together with old-style vacuum tubes and discrete passive components. Even with transistors—or, for that matter, with first-generation semiconductor IC's and early MOS devices—such a scheme would be prohibitively bulky on the long voyages of interplanetary spaceships, where every pound of cargo has literally vital significance to human crews. With today's CCM, MOS, SOS, CCD and other upcoming LSI microelectronics developments, distributed logic organization is feasible, practical, and economical.

AUTOMATICALLY ADAPTIVE SYSTEMS

Another data-processing approach made reasonable for the first time by LSI microelectronics is the self-organizing, self-adaptive system concept, in which a system is able not only to perform its own organization—but even to restructure itself over a period of time, as might be necessary in order for it to continue to be the best scheme under changing operational or environmental conditions.

As one example of how a self-organizing, self-adaptive scheme could be used to advantage, just imagine the flight control system for a high-performance aircraft capable of flying at altitudes ranging from ground-hugging to the literal edge of space, and at velocities going from helicopter-type hovering to well past the thermal barrier. With an LSI-mechanized, self-organizing, self-adaptive control system, the aircraft would be able to *automatically* reorganize, compensate for, and direct the vehicle's controlling mechanisms *to keep its operating parameters optimum,* continuously and smoothly, over the whole diverse span of environments and flight envelope that the craft was required to experience. Without LSI, a scheme of such complexity would be—virtually impossible.

MICROPROGRAMMING

What LSI has to offer in the way of new approaches to *hardware* is obvious. But the story doesn't end there. With LSI, both hardware and software are finding their tasks shared and lightened by a new alternative—"firmware."

Formerly, when a computer was instructed by an operator to carry out a sequence of operations, it was requested to do so entirely by means of the programs known as "software." The software programs accomplished the required operations by activating a string of hard-wire-connected "hardware" units inside the computer. Performance of each and every step, even the smallest operation, in the complex sequence, required action by a combination of the hardware units. The greater the number of different instructions, or the more complicated the instructions which a computer had to carry out, the more hardware was required and the more complex the interwiring had to be. When it was necessary for the computer's special purpose to be altered or increased in scope, hardware replacement and addition could be extremely costly.

For reasons of economy, convenience, and other significant benefits, computer designers are turning increasingly to the "firmware" (or, as it is often termed, "microprogramming") alternative to the strictly hardware/software approach.

Like hardware, firmware is an integral part of the computer. Unlike hardware, however, firmware is not made up of units of equipment. It consists, rather, of the "characterization" of hardware (i.e., small "control memories"), accomplished by programming or encoding into them certain basic elemental operations, often-used and repetitive instructions, and special-purpose functions peculiar to the computer's "mission."

Like software, firmware consists of instructions which cause the computer to perform certain functions. In a microprogrammed computer, however, the software has only to issue "higher-level" instructions which then, in turn, initiate the *firmware* microinstructions to carry them out in functional detail.

Less hardware *and* software are needed in a microprogrammed system than in strictly hardware/software machines, and to increase the computer's capability or to change its mission, the small microprogrammed control memories can be readily and economically exchanged for larger-capacity or differently coded ones. Customization, growth, versatility—all are made easier by microprogramming. In addition, the functional reliability of a microprogrammed computer is enhanced by the general use in such systems of read-only memories (ROM's). Once encoded, a ROM's contents are physically impossible to alter and thus cannot be compromised or lost through improper computer use by operators.

To attain the greatest functional capacity in the smallest volume and at the lowest cost, control ROM's for microprogrammed computers are usually formed from MOS and SOS large-scale-integrated arrays.

When used as a microprogrammed control ROM, the LSI array may be considered as a matrix of "rows" and "columns" of diodes or transistors, depending upon whether it is formed from SOS or MOS elements, respectively. In either case, the matrix contains a vertical "column" of elements for each control gate and a set of horizontal elementary "rows," each of which has access to all of the gates. Each microinstruction then consists of a sequence of horizontal lines, each connected to the combination of gates necessary to create the desired data path. Each horizontal row corresponds to a micro-operation, and each sequence can be considered a microprogram.

ON COSTS

The attributes which characterize LSI all add up to reduced costs. Repeatability of LSI circuitry invites high-volume production and automation—and both of these are reflected in lower cost to manufacture.

Multiplying all of the density advantages of earlier integrated microelectronics, LSI of the '70's is not only cheaper to produce—but cheaper to use and maintain throughout the lifetime of the products that are implemented by this approach.

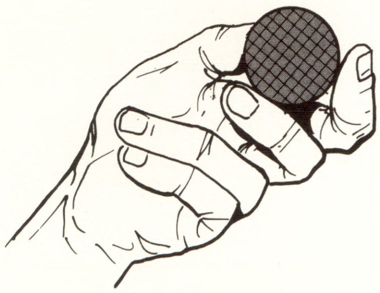
AND . . . ON THE DESIGNER HIMSELF

One of the most remarkable by-products of LSI has been the diminishing of the separation between the former "types" of electronics engineer. When complete subsystems are too small to view with the naked eye, definitions tend to overlap, and terms like "component" and "circuit" become meaningless.

Where once the logic expert, the circuit man, the device designer, and the system engineer each had his own clearly defined and separate arena for activity, there is now a melding of functions and responsibilities. The logic expert is, for instance, involved in the design of the hardware, and the circuit man is virtually synonomous with the system engineer.

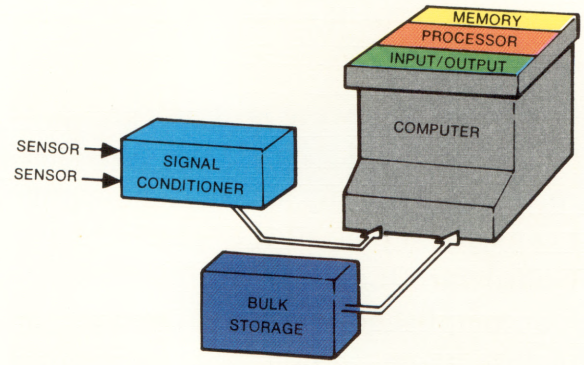
With LSI, the designer must be, to an increasing extent, a disciplinary generalist—possessing broad practical knowledge, training, and skills in a multitude of interworking but diverse disciplines, in addition to the intensified knowledge, training, and expertise which he must have in his own specialty.

LSI...
THE PERFECT GIFT FOR AN ORGANIZATION MAN



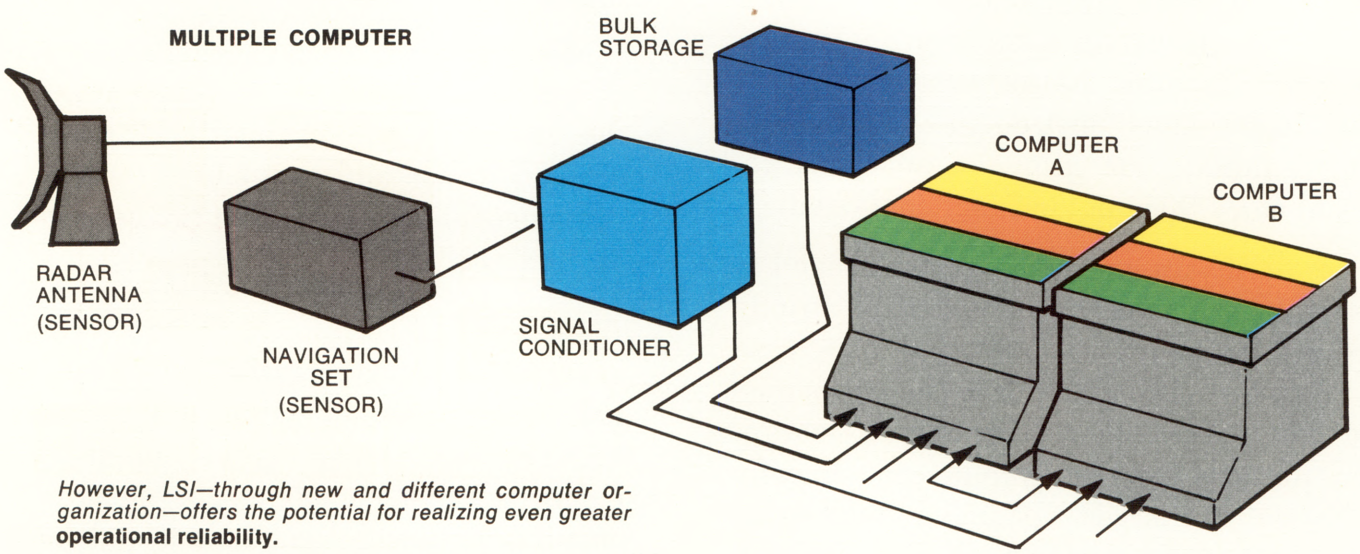
With LSI, each microelectronic device can provide many circuit functions per unit volume, yet require less power. Thus, new concepts of systems organization—never before feasible—become practical and economical for the first time. The systems designer can select, from a number of different organizational alternatives, the scheme that best suits his requirements.

SINGLE COMPUTER



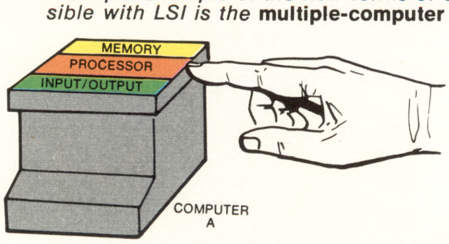
For example, he may choose a single computer for the system and, simply by using microelectronics throughout, he can achieve high reliability.

MULTIPLE COMPUTER



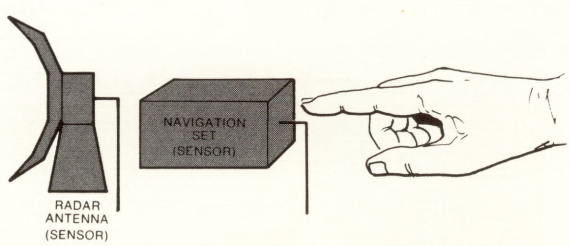
However, LSI—through new and different computer organization—offers the potential for realizing even greater ***operational reliability.***

A simple example of the new forms of organization possible with LSI is the ***multiple-computer*** *scheme.*

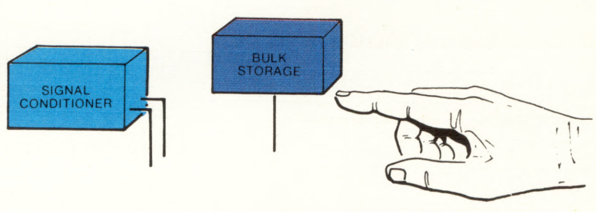


In the multiple-computer scheme, two computers, A and B, have separate memory, processor, and input/output sections.

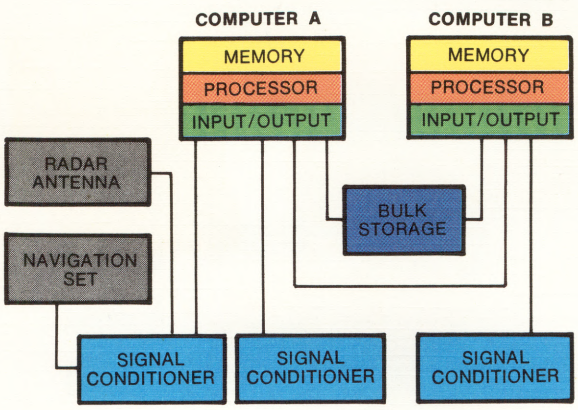
The computers can be configured to suit a variety of tasks and to maintain effective operational reliability.



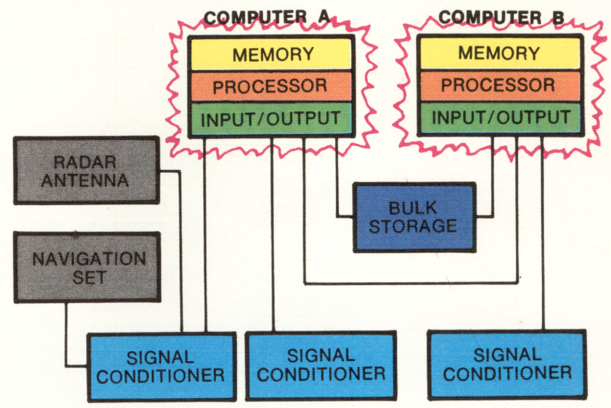
In the example given here, signals from a radar antenna and a navigation set . . .



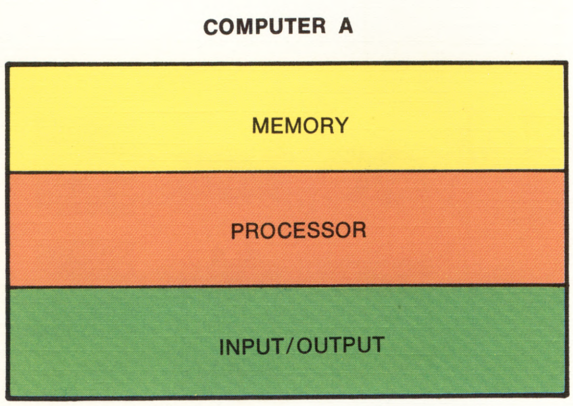
. . . are fed to the computer through signal conditioners. A bulk storage unit, such as a solid-state LSI array memory, completes this hypothetical system.



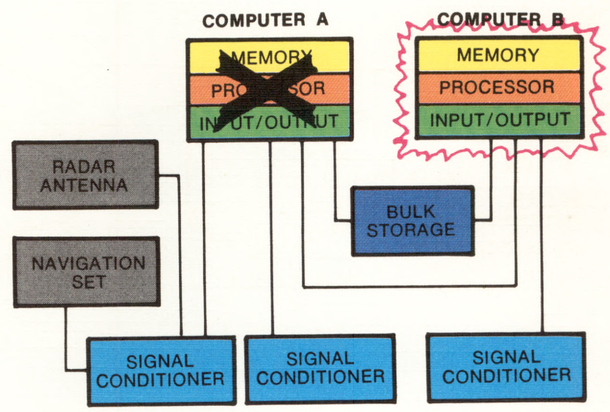
Such a system can be practically implemented with LSI microelectronics, because high device densities permit more extensive application of computers in a way heretofore considered impractical from standpoints of size, weight, and cost.



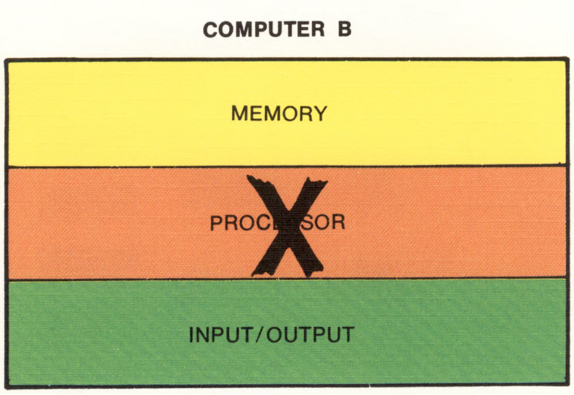
If any computing group should cease to function, any other computing group can perform its tasks.



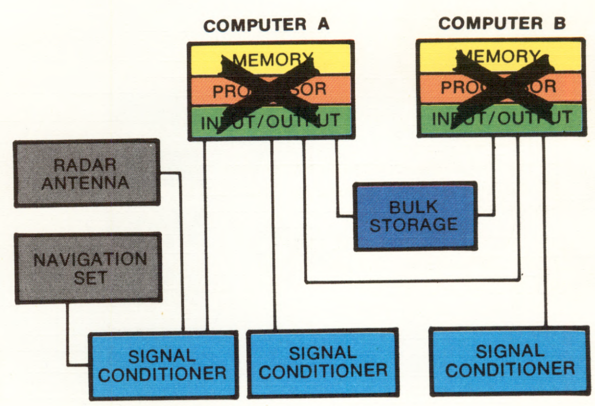
Then suppose the memory of Computer A should cease operating.



The system still continues to operate, but in a degraded mode. Further degradation of the system can occur with the mission objectives still being accomplished as long as Computer B continues to operate.

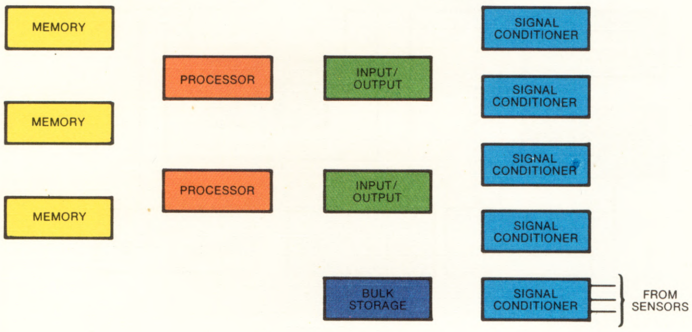


But if, say, the processor in Computer B should cease operating . . .

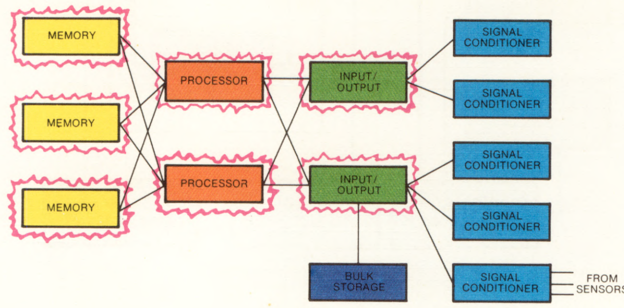


. . . then the entire system becomes inoperable.

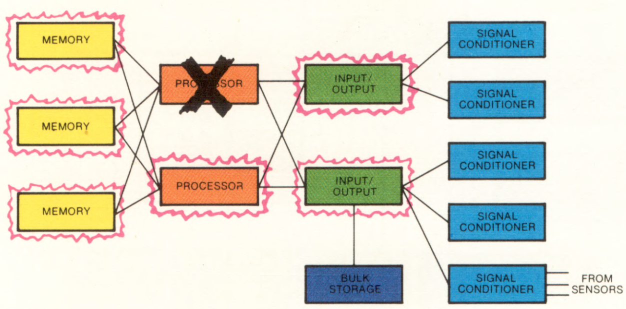
MULTIPROCESSOR SCHEME



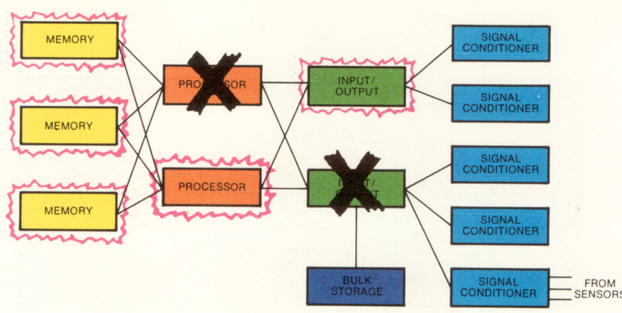
A further refinement of the multiple-computer concept is the ***multiprocessor****.*



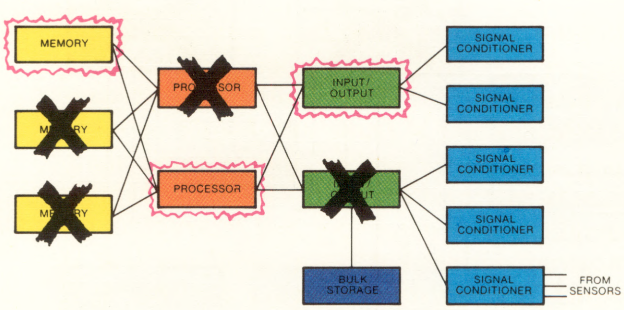
In the multiprocessor scheme, the memory units, processors, and input/output sections of the computers are all interconnected.



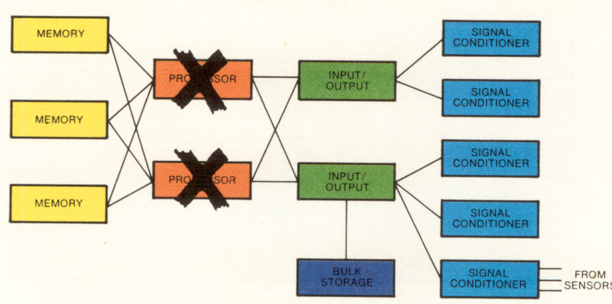
If a processor should cease operating, a new path is selected, and the system continues to perform its tasks.



If an input/output section ceases to function, again the system is reconfigured.

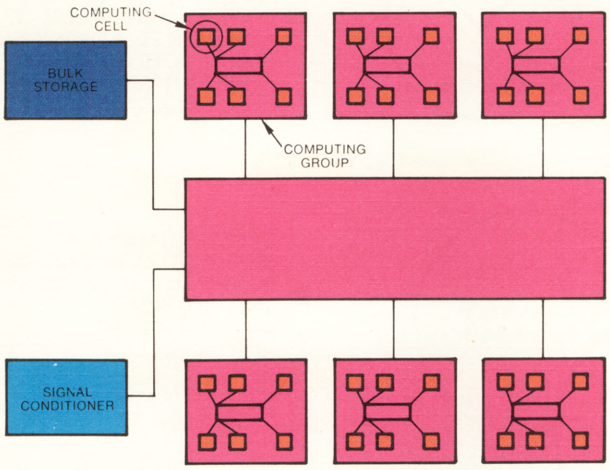


The multiprocessor system could lose many more sections than the multiple-computer scheme and still meet its mission objectives.

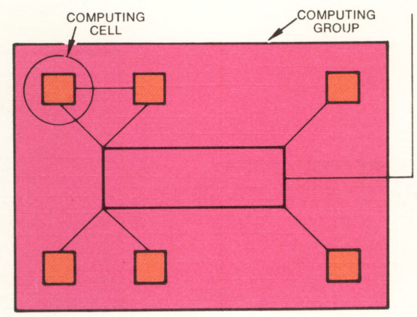


However, in this example, if any ***function*** *is* ***totally*** *lost, the system becomes inoperable.*

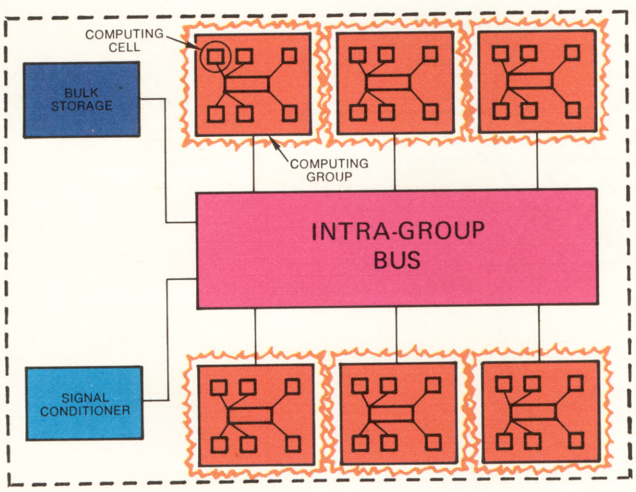
DISTRIBUTED PROCESSOR SCHEME



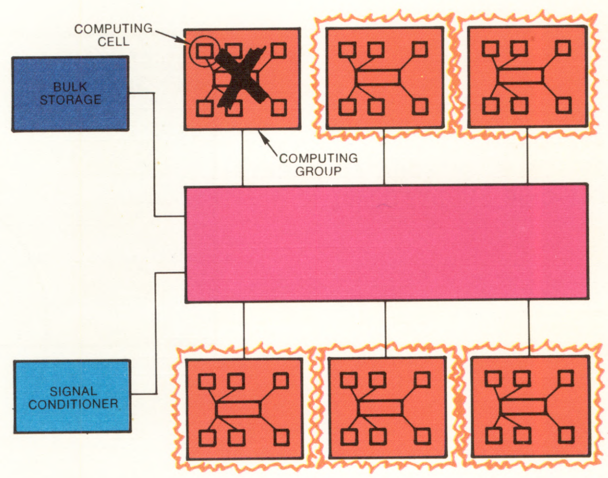
A concept with an even greater defect-tolerant capability than the multiprocessor is the **distributed processor** *scheme. While such a system may involve additional cost, it offers many levels of reconfiguration to attain even greater operational reliability.*



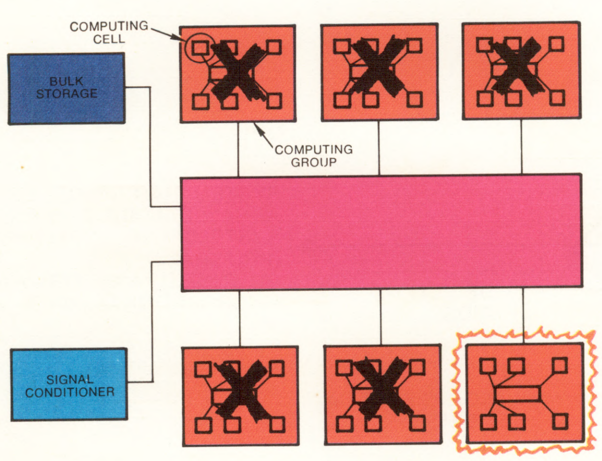
In the distributed processor scheme, one chip or computing cell performs a significant and complete subtask. Several of these cells are hooked in parallel to form a computing group.



The computing groups are, in turn, connected through a "bus" to form the complete computer.



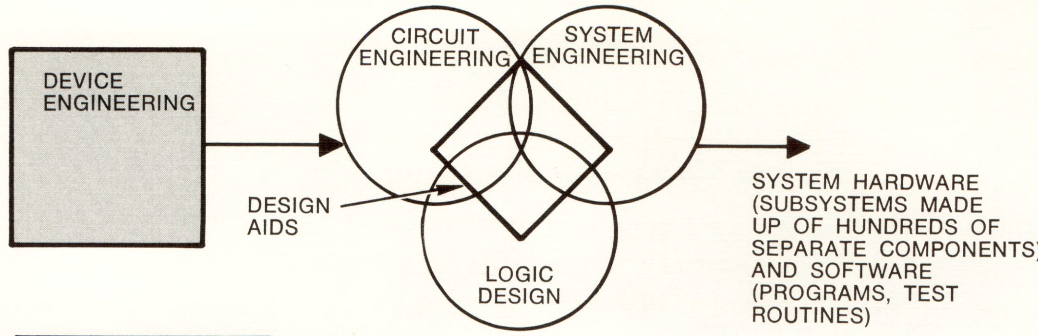
If any computing group should cease to function, any other computing group can perform its tasks.



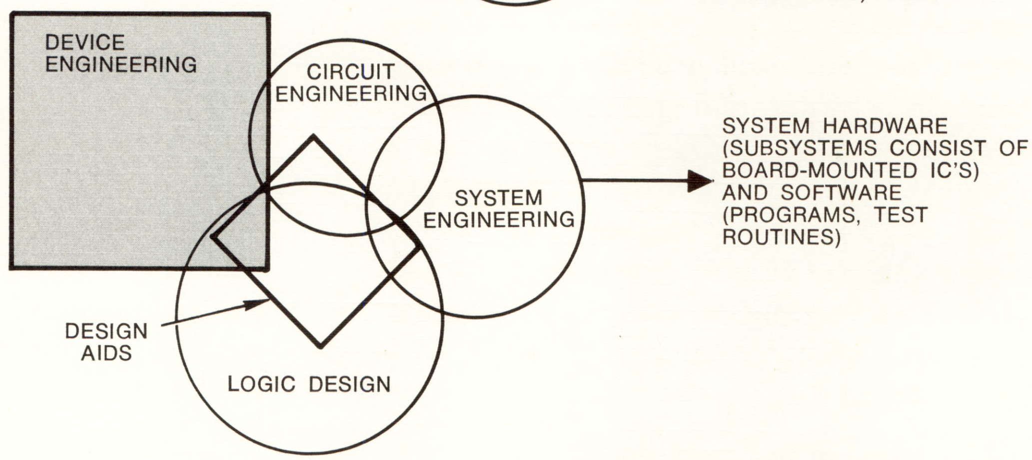
The distributed processor computer systems could be designed in such a way that, with only one computing group left operating, the system could still meet its mission objectives, although in a degraded mode.

With the schemes illustrated, plus many other choices that have become both practical and economical with LSI, systems can be organized to achieve virtually any height of reliability and performance. At the same time, there is now available with LSI, the capability for automatic detection and correction of impaired performance — a capability that is basic to the realization of self-organizing, self-adaptive systems.

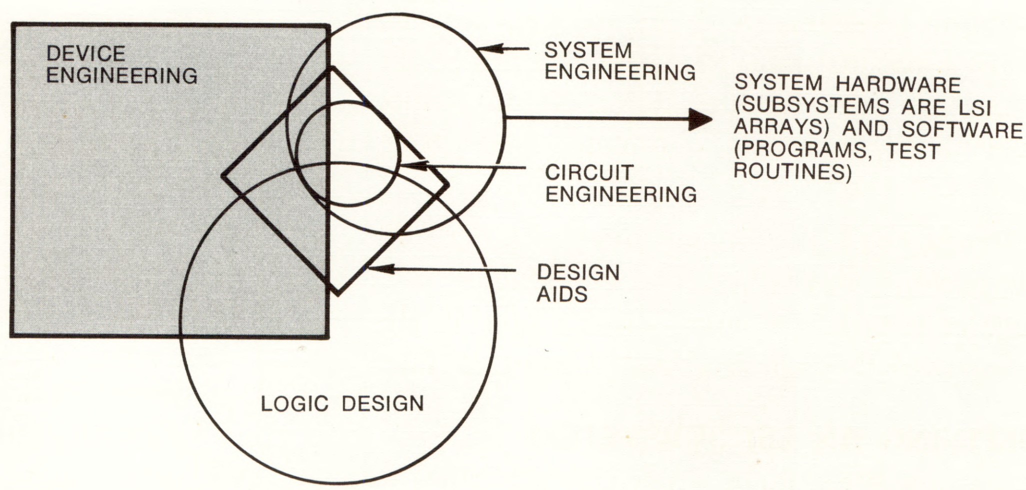
YESTERDAY AND THE DAY BEFORE: DISCRETE COMPONENTS



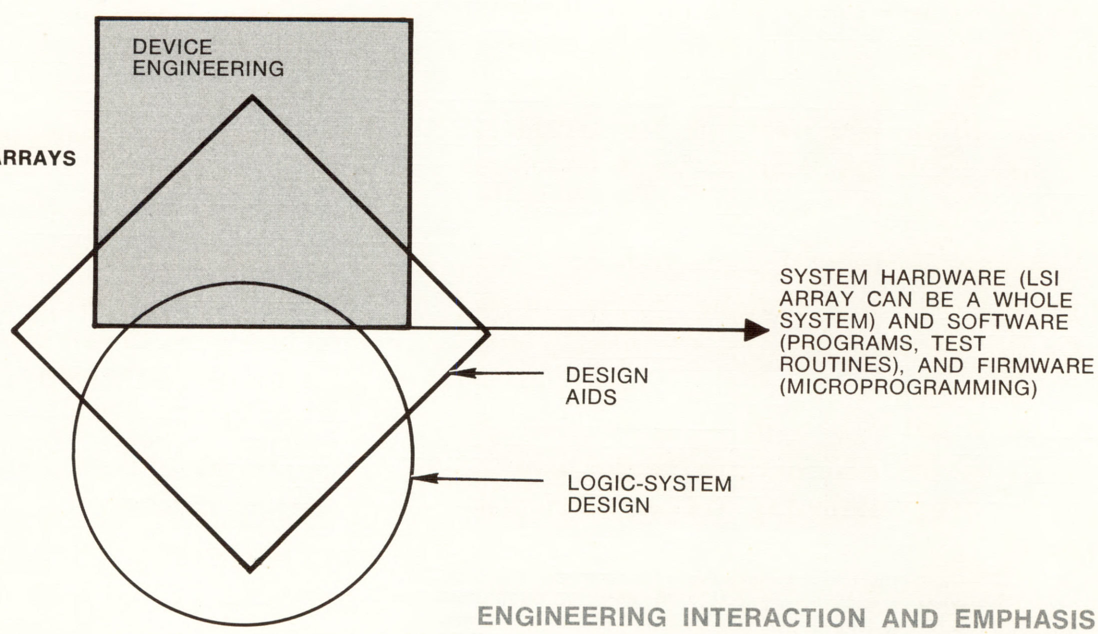
YESTERDAY AND TODAY: INTEGRATED CIRCUITS (IC's)



TODAY: LARGE-SCALE—INTEGRATED ARRAYS (SINGLE-CHIP SUBSYSTEMS)



FUTURE: LARGE-SCALE—INTEGRATED ARRAYS (SINGLE-CHIP SYSTEMS)



ENGINEERING INTERACTION AND EMPHASIS

They have changed drastically (and the changing is far from finished) with the development of LSI microelectronics.

For, throughout its history, microelectronics has become constantly more multidisciplinary. Now—just to achieve the materials necessary for accomplishing LSI requires a whole gamut of disciplines, including the ability to grow crystals, to achieve the growth of one crystalline material upon another, and to perform the controlled diffusion of impurities into semiconductors—as well as a whole series of technological specialists in materials, chemistry, physics, and electronics. Then, in order for useful devices to be fabricated to exploit the special properties of the new materials, other troops of technologists must be brought into the picture—vacuum specialists, production engineers, computer programmers, and photolithographic experts form only a partial list.

Only when armed with the necessary combination of special and general abilities and know-how, can the LSI designer work in the necessary close cooperation with the other specialists-generalists who make up the complete LSI team.

Truly, the LSI designer must be a man for all seasons, throughout the challenging passage of microelectronics—from materials development through final device manufacture.

DEFINING AN LSI SUBSYSTEM

Certain basic tasks must be performed to get an LSI system ready to be produced. Most basic of all, each *subsystem** must be defined. What is the overall job each is required to perform? From what sort of input must it undertake to do this job? In what form and how quickly must the output be delivered?

Also very importantly, in what sort of environment will the system be required to perform? With what other systems must it interface? What power is available to it? How big and heavy can it be? (In sufficient number, even fly-weight LSI devices could conceivably be over-ponderous for a deep-space probe!)

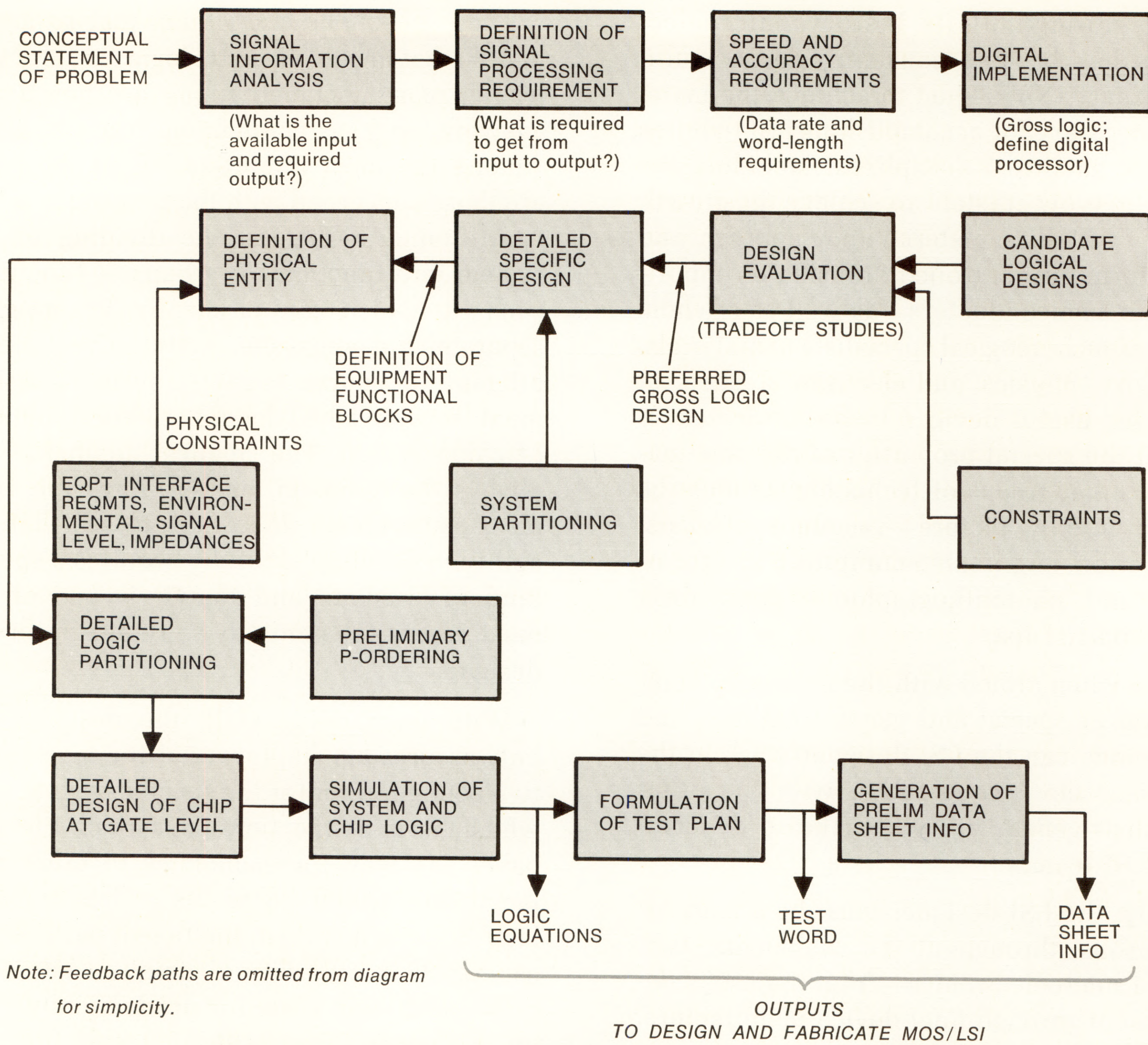
**A "subsystem" as used here would be a full arithmetic unit, for example, while "system" would denote an entire computer made up of a number of subsystems.*

These questions and others just as meaningful—having to do with logic, accuracy, a testing plan, documentation—are posed and answered in a system-defining series of steps. Among the most important of all the steps are those concerned with the procedure called "partitioning"—that is, the dividing of the system into functions or groups of functions, each of which can efficiently be assigned separate-chip, subsystem status. The designer attempts, of course, to get the system's assignment accomplished by the smallest number of chips he can. The smallest number is not always the optimum number, however, from all considerations. It is easy to see that the ability to partition skillfully requires a special kind of wisdom, and that it is one of the most essential talents to be found in an LSI designer.

With partitioning skill, the designer not only assures his employers of the most effective configuration for the specific system with which he is at the time concerned. He also paves the way for economies in other systems with which he or his colleagues may later become involved. Inefficient partitioning can result in a variety of unique custom arrays—with high costs for production, servicing, spares stocking, and documentation. Efficient partitioning can result in a dependable stock of standard arrays, economically applicable for broad systems usage.

In addition to partitioning to minimize the total *number* of separate chips that make up his system, the designer must meet two other prime objectives: to minimize the different *types* of chips employed, and to minimize the *interconnections* between chips. The second of these two requirements is to some degree the corollary of the requirement to minimize the total number of chips. The fewer the chips, the fewer, of course, will be the total number of between-chips interconnections.

Minimizing the *types* of chips calls for the basic circuitry on each chip to be highly versatile, so that with the least or no adaptation the chip can be applied with high repeatability in a variety of functions throughout the system of which it is to be a part. High



SOME OF THE STEPS TYPICALLY REQUIRED TO ACHIEVE A MOS/LSI SYSTEM

repeatability obviously dictates high quantities of each type and lends itself to automated production, reduced storage and logistics requirements, and simpler testing procedures.

COMPUTER AIDS TO DESIGN

Without the digital computer as a willing and capable assistant, LSI would still be science fiction.

To make certain that any system is partitioned with the highest possible circuit-to-pin ratio, most of the interconnections have to be made internally on the chips. For highly complex systems (and only such systems would ever be given the LSI treatment in the first place), literally thousands of interconnections are involved. The most skillful of human partitioners would find it virtually impossible, unassisted, to determine the truly optimum division of the system into chip-status subsystems, and to plot, then, the intricate connections within chips and between chips for minimization of the latter. However, by complementing the engineer's problem-detection capability with the precision of a computer, the most complex partitioning and planning of connections become practical. Fed the logic equations for the system by the designer, the computer unerringly designs a minimum-chip, minimum-interconnections system—and takes an economically brief time to do it.

But partitioning is only one LSI area in which computer aid is indispensable. It is just as essential in logic design, physical layout, and the performance of device and system testing.

Since, with LSI, one semiconductor wafer can hold a subsystem or even an entire system, the function and cost of this one "component" represent a much higher percentage of total system performance and cost than they have for any previous electronic component—even for a second-generation bipolar IC. If for example, a single-chip MOS digital differential analyzer (DDA), carrying a thousand transistors goes bad, a much bigger "hole" is left in the digital computer of which it is part, than was left in older systems with the failure of a single vacuum tube, a single transistor, or a single IC flip-flop. Similarly, slippage of LSI device production schedules due to design errors, poor production processing, or inadequate testing is much more costly—in direct proportion to the larger role the device is designed to play in the destined application.

Because of its greater importance to the mother system, any LSI device calls for the utmost certainty all the way through its career that its design is correct and reliable, and that the finished product will perform within specifications. The device must be checked, rechecked, and re-rechecked throughout its design and production—but the checking is far beyond the capacity of man alone. This becomes readily evident when one compares the early MOS circuitry at left in the next illustration, with the intricate LSI single-chip calculator at right in that illustration. Laying out and checking the set of masks to produce the early MOS system was, with care, not too formidable a task for a human performer. With the most exhaustive scrutiny, human error might have been held to around 10% for an eyeball examination of such a unit. For the 14,200-transistor single-chip calculator, however, not even Superman could make an acceptable score, either in laying out the masks or in checking mask registry—*without computer assistance.*

The extreme concern for accuracy required by LSI begins with the device design. Two engineering design aids typifying those which are used in the design of MOS/LSI circuitry are the "P-ORDER" and "M-ORDER" programs described in some detail below.

The logic equations describing the function to be implemented on the LSI chip are encoded and are then used as inputs for the P-ORDER program. Directed by the latter, a digital computer produces an ordered list of logic equations to indicate the interconnections that will require the minimum length of metal to make them, and a minimum number of crossovers.

Although the P-ORDER program minimizes the total length of interconnections and the number of crossovers, it gives no "thought," whatsoever, to the pattern in which the interconnections should be laid down to make the most efficient use of available chip area. The P-ORDER program, in other words, has a one-track mind, and the track it chooses for the interconnections is simply the minimum-length, fewest-crossovers one—this could be a circle, a spiral, a single long line, or what-have-you. The P-ORDER program doesn't care—but the M-ORDER program does.

Taking as input the list or ordered equations produced with the P-ORDER program, the M-ORDER program uses the same digital computer to determine the best configuration for the interconnections indicated by the P-ORDER program, and "squares up" the array, filling in empty spaces, and reducing the overall chip area required for the device.

After fifty or more iterative runs have been made with the P- and M-ORDER programs, an engineer manually makes any rearrangements of logic terms or their positions on the chip that appear to be necessary, and the layout is then considered to be acceptable—for the next step in the careful, computer-aided processing leading to a reliable, high-performance device.

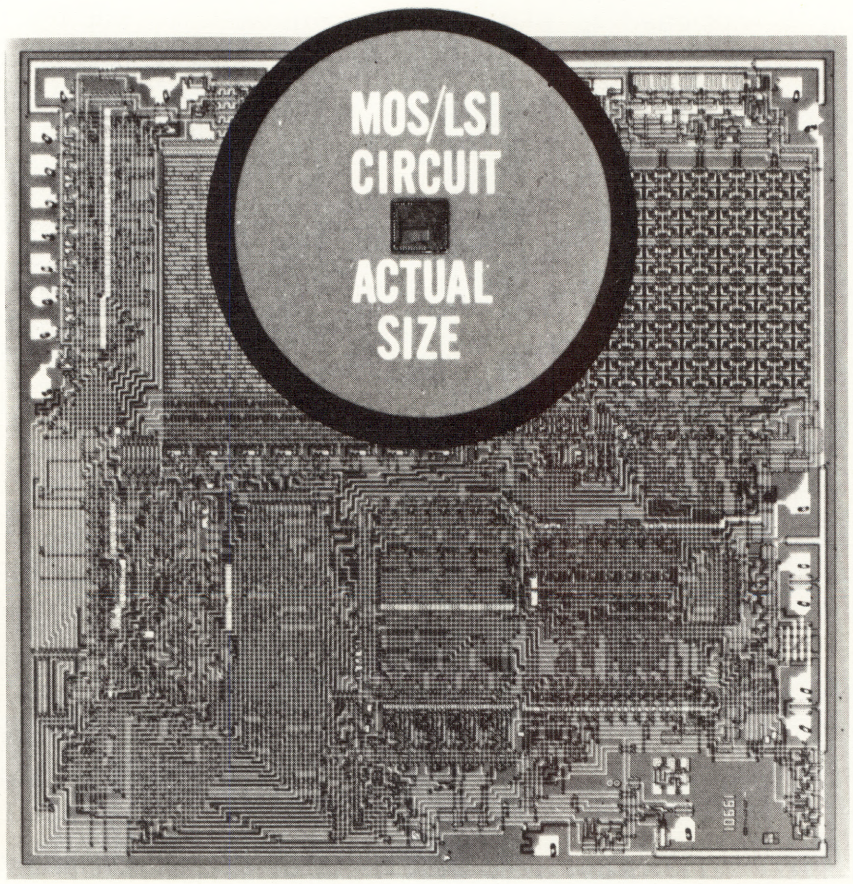
Much time and money, that would otherwise be spent for design and design-proofing, are saved through the use of computer programs to place and interconnect standard LSI functions—or "catalog cells," as they are termed—within custom device layouts. The units are called "catalog cells" because they can be selected and ordered out of the computer data bank as readily as one can select and order items from a mail-order catalog. Most of their detailed layout has already been completed and is available in the bank; only their placement and their interconnections within the custom device remain to be carried out.

The circuitry on each LSI chip is laid out through a set of masks—one for each diffusion, one for each layer of interconnection metal, etc. With circuit dimensions themselves measuring in just a few mils, even the tiniest of deviations in mask layout is vital—as is, also, the precise registry of each mask with others in the set. To eliminate any possibility that human errors might affect the accuracy of the masks, they must be drawn by an automatic X-Y plotter under tape control. Procedures for generating and using control tapes are always models of rigorous caution and precaution. In general, they include such steps as the following:

1. A composite drawing (that is, a superimposed combination of all the masks in the device mask set) is hand-made of the circuitry.

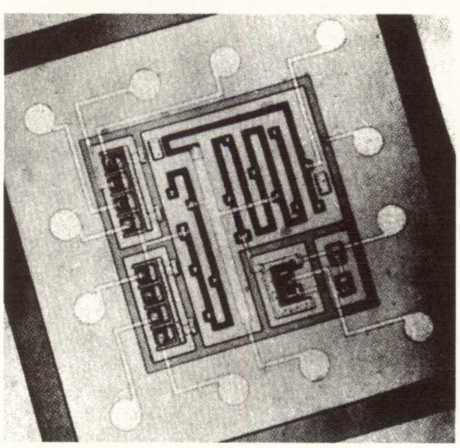
WHAT A DIFFERENCE A DECADE MAKES

MOS/LSI Circuitry of the 1970's



Complete Calculator on a Chip was first volume-produced and marketed by Rockwell in 1973.

Early MOS Circuitry



Around 50 Mils

Comparison of the complexities of earlier and present-day MOS circuitry reveals the growing necessity for man to be assisted by computers in designing, laying out, checking, and testing microelectronics.

2. With end-point encoding as input, a specially designed computer program produces incremental encoding to define the P and M (p-type semiconductor and metallization) regions of the device.
3. The listing produced in Step 2 goes through a "MOS-INPUT" program to serve as input for a "MOS MASK" program. The output of the computer thus programmed is a tape that specifies the reticle for each X-Y coordinate of the masks.
4. Under the direction of the tape generated in Step 3, the automatic plotter drafts masks which are many times the size of the final device circuitry.
5. Exhaustive checks are made, both manually and by computer, to ensure freedom from inaccuracies.
6. If results of the checks made in Step 5 are satisfactory, standard procedures are initiated to generate the mask set.

One might think that, after the routine of carefully designed operations, precautions, and checks described above, the next step after mask set generation would surely be to go into device production. Before actually making this serious commitment, however, it is not enough for the engineer to know that his device is logically correct and efficiently laid out. Just as importantly, he must know that the device will perform without errors under its normal range of operating conditions, as well as under any abnormal overstress conditions that it may conceivably have even the remotest possibility of experiencing.

COMPUTER-ASSISTED DESIGN

Rockwell International makes use of the company's vast computer facilities for designing highly dense and complex LSI circuits. In the course of designing hundreds of different circuits, unique resources have been accumulated, including computer-aided-design (CAD) programs and skilled design personnel. In addition to using "standard cell" techniques, the firm's designers have developed a custom layout method by which the electronic functional capabilities and efficiencies of circuits are increased. In the latter technique, logic layouts are devised directly from equations. Shown above is typical activity in the computer terminal facility.

One of the first practical, large-scale, computer-aided systems for testing microelectronic circuit performance prior to production is the "SCAN-TRAC" system developed by the Autonetics Group of Rockwell. SCAN-TRAC performs circuit analysis by means of two digital computer codes—SCAN (*S*ystem of *C*odes for *AN*alysis of circuit and systems) and TRAC (*T*ransient *R*adiation *A*nalyses by *C*omputer). The SCAN-TRAC system delivers data in, at most, only around a tenth of the time it generally takes to make evaluations.

SCAN-TRAC is capable of evaluating microelectronic circuitry performance all the way from the steady-state condition of a single semiconductor IC, to the behavior of an entire system subjected to transient phenomena. To obtain an evaluation, actual performance data are fed into a computer, where they are compared with an ideal circuit-performance model stored in the computer's memory. Both linear and nonlinear circuit models can be accommodated.

Problem solutions are delivered from SCAN-TRAC to the concerned engineer in the form of a computer printout and a graphic representation on a cathode ray tube. The engineer feeds his problems to the computer at the end of the workday and, next morning, obtains the solutions the computer has worked out for him during the night. Normally, the computer batch-processes all the problems handed it. If the problem is urgent enough, however, the engineer can enter his data directly, and in a relatively short time can obtain a display of the results of the conditions he's introduced.

With SCAN-TRAC, MOS P-ORDER and M-ORDER programs, and a variety of other computer aids for design and production, producers are able to achieve the design "sureness" that is so necessary for LSI. The computer systems keep important tests and checks from being either too little or too late, and keep LSI device production on schedule and within budget.

As present trends continue, and LSI density becomes greater and greater in the future, the role played by digital computers in circuit design and device production will become more and more inclusive. Even some of the decisions that, today, are still made by the human engineer will eventually have to be delegated to his electronic teammates. The ability to theorize, to form new design concepts, and to visualize ingenious new schemes and methodology for implementing the concepts, however, will probably remain solely man's for some time to come.

The question comes naturally to mind: Is there any limit to microelectronic element density, and, if there is, what will it be? Right now, LSI circuitry is implemented by means of photolithography, and the ultimate limit on element resolution is determined by the wavelengths of photolithography's tool—light. But other media are foreseeable beyond light. Electron wavelengths are much shorter than those of light, and *electron-lithography* will predictably extend the limits now imposed on element density by *photolithography*, just as the *electron* microscope has already extended the ability of the scientist to see far beyond the limits imposed by the *light* microscope.

And, of course . . . we can go on even beyond electron-lithography to envision such outré approaches as "molecular electronics." In the dim and distant future in which this long-predicted technology may at last be achieved, huge macro-molecules, each electrochemically performing a vital subsystemic function, may cause the terms "element" and "element density" to become without meaning.

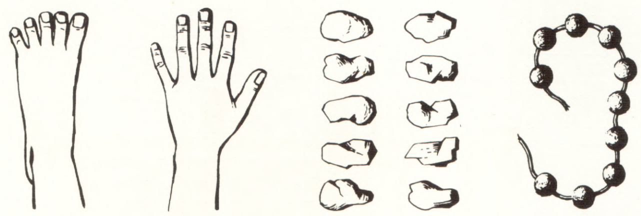
COMPUTERS ARE DESIGNERS' GIRL FRIDAYS

Computerized Circuit Analysis is Made Before Commitment to Hardware
Schedule delays and budget overruns are avoided by computer checks of preliminary specifications and design approaches. The early checks eliminate almost all necessity, once production is under way, to backtrack and to repeat expensive time-consuming processes, in order to undo design errors.

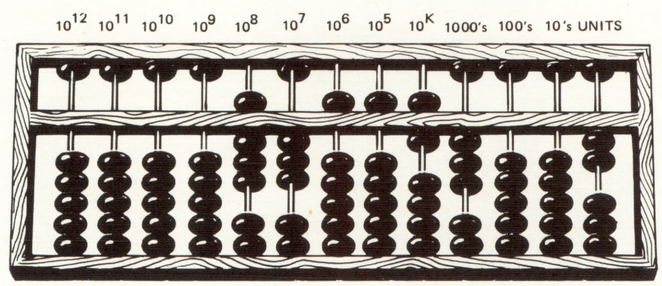
With a Computer's Help, the Designer Can See at Once What Happens When He Changes Things
A system made up of a cathode ray tube connected to a digital computer lets a circuit designer verify circuit performance quickly and improve his design on the spot. With a "pen light," the designer makes tentative changes to the circuit drawn by an electron beam on the face of the tube. The computer immediately analyzes the changes and delivers a printout of how they would affect circuit performance.

Computers "Talk Back" to Questioning Engineers
A Rockwell engineer uses a SCAN-TRAC "conversational" computer terminal for high-speed remote entry of his circuit design problems. If he's not in a hurry, the engineer can input his problem at the end of the work day and pick up the answer next morning. For urgent situations, access via the terminal to the central computer, as well as the computer's response, can be immediate. SCAN-TRAC terminals are located throughout principal design areas.

THE SYNERGISTIC SAGA OF TWO SYMBIOTIC SCIENCES… COMPUTERY AND MICROELECTRONICS



TOES AND FINGERS   STONES   BEADS



ABACUS

PRIMITIVE MEANS OF MANIPULATING QUANTITIES

Ever since man first grasped the concept of "quantity," he has sought devices to aid him in handling numbers. First of all, he availed himself of his own built-in devices —and counted on his fingers and toes.

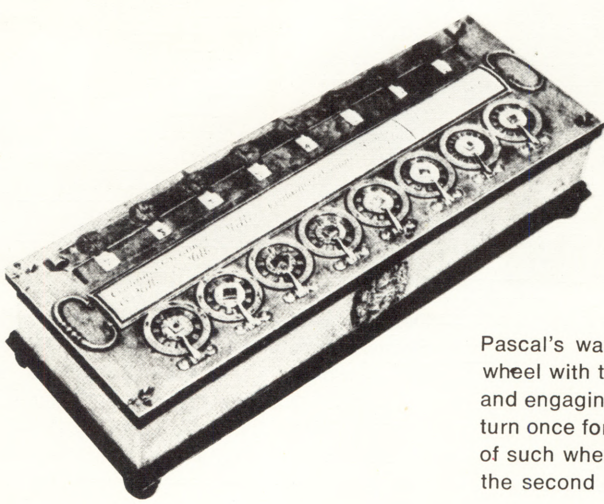
Next, he expanded his calculating system into the outside world and began lining up sticks and stones as symbols for his number-juggling. He did not forget his original aids, however, and honored them by naming the numerical signs he finally devised "digits" after them.

The abacus was first devised around 4000 B.C. in the Orient. Both the Chinese and the Japanese have a word for it. To the Chinese originators, the abacus is the "suan pan." The Japanese call their modified version "soroban."

Reading from right to left in oriental fashion, the vertical lines in the abacus represent units, tens, hundreds, etc. Each bead below the horizontal divider is moved up by the operator to indicate "one." Each bead above the divider is moved down to indicate "five." The value of the setting shown here is 835,563,002.

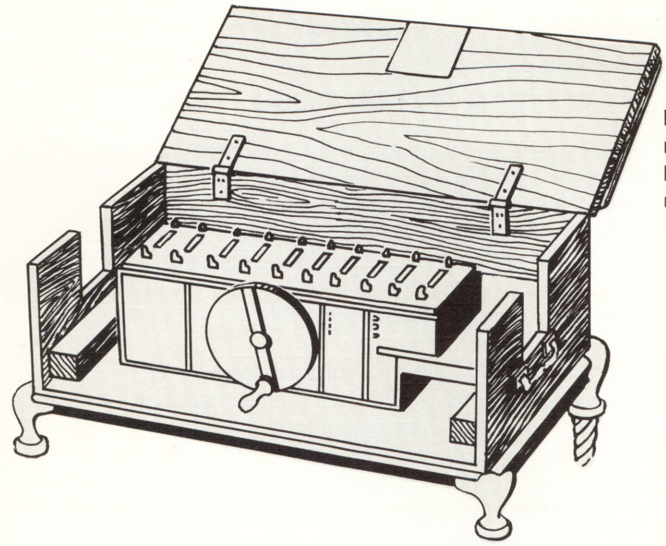
EARLY MECHANICAL CALCULATORS

The evolution of modern calculators from our ancestors' humble pebble counting is readily apparent to the linguist. The modern words "calculate" and "calculator" are directly derived from the Romans' word for small stone—"calculus."



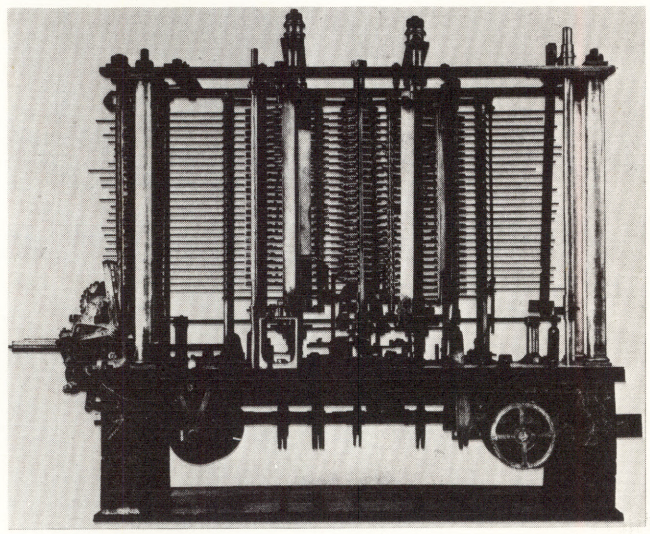
Calculator — Blaise Pascal (1642)

Pascal's was the first machine to make use of a gear wheel with ten teeth, the tenth being larger than the rest and engaging a second wheel. which was thus caused to turn once for every ten turns of the first wheel. In a series of such wheels, the first wheel accordingly toted up 1's, the second 10's the third 100's, etc.



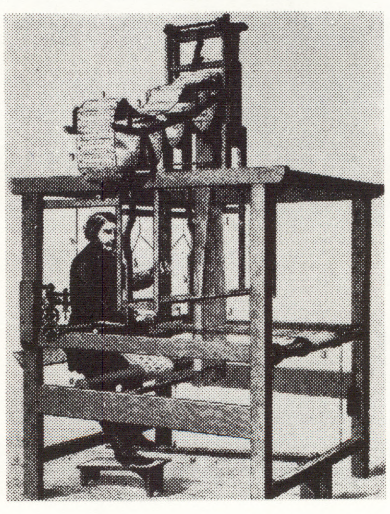
Reckoning Machine —
Baron von Leibnitz (1672)

Baron Gottfried von Leibnitz, German philosopher and mathematician, developed an advanced version of Pascal's machine which could also (although somewhat unreliably) perform multiplication and division.



"Babbage's Folly" —
Charles Babbage (Nineteenth Century)

The concepts of Charles Babbage—although he was concerned only with mechanical systems—included most of the basic "black box" functions of modern electronic digital computers, such as input-output capabilities and internal storage of data and the program for manipulating the data.



A Weaver at a Jacquard Loom (1804)

Hollerith Tabulating Machine (1890)

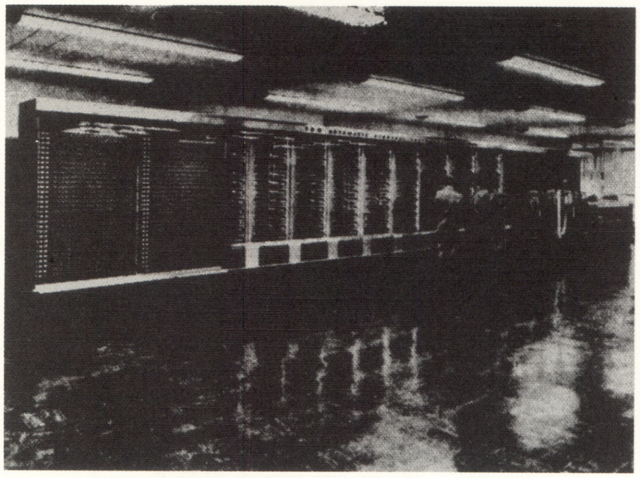
ADVENT OF THE PUNCHED CARD

In 1804 a major conceptual advance was made by a French mechanician, J. M. Jacquard, who introduced a punched-card program to direct the operations of a textile-weaving loom.

About 75 years after Jacquard used punched cards to control a loom, a noted statistician, Dr. Herman Hollerith, was engaged by the U. S. government to tabulate the 1880 census. Having studied such equipment as Jacquard's loom, and realizing that the amount of time and work required to complete the census would render his figures obsolete before he could finish processing them by manual or available mechanical means, Dr. Hollerith devised a punched-card calculating system. In this system, punched holes made use of electromagnetic principles to automatically actuate statistical recording machinery.

The Hollerith system reduced the time for recording the 1880 census data by two-thirds, and decreased the data processing time by a factor of eight over manual methods.

Dr. Hollerith left the government service to form the Computer Tabulating-Recording Company, which later became the International Business Machine Company. The card system which he developed became the well known IBM punched-card system.

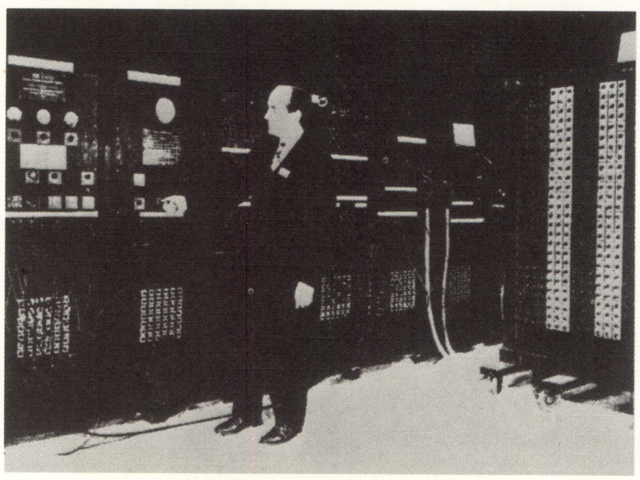


Mark I (1944)

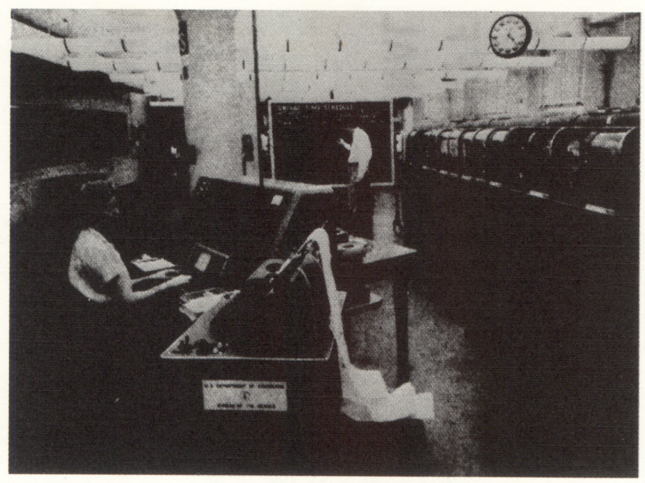
STEPPING STONES ALONG THE WAY

Development of computers resumed during the depression years, making use of the readily available pool of skilled tool-makers at that time. In 1934, to solve ballistic problems for artillery weapons, a mechanical differential analyzer was undertaken—based, interestingly enough, on principles developed by Charles Babbage in the nineteenth century.

In 1939, Howard Aiken of Harvard University began work on the ASCC (Automatic Sequential Controlled Calculator) better known as Mark I. Built with IBM assistance, Mark I was completed in 1944. It had punched-card input and output, and calculations were performed by relays and mechanical devices.



ENIAC (1946)



UNIVAC (1951)

ELECTRONIC PIONEERS

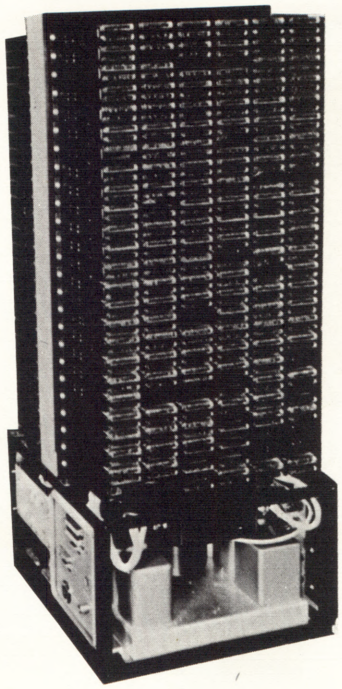
ENIAC (Electronic Numerical Integrating Automatic Computer) was the world's first electronic digital computer. Under government sponsorship it was developed as an answer to World War II's crying need for extensive ballistic tables.

ENIAC was designed by J. P. Eckert (in picture above with ENIAC) and J. W. Mancheley. It was constructed at the Moore School of Electrical Engineering, University of Pennsylvania, later was moved to Aberdeen, Md., Ballistic Research Laboratory.

Completed in 1946, ENIAC contained more than 19,000 vacuum tubes, weighed almost 30 tons, and occupied more than 15,000 feet of floor space.

UNIVAC I, Serial No. 1, the world's first commercial electronic computer, was installed at the U. S. Census Bureau in 1951. It is now retired in the Smithsonian Institution.

MOBILE COMPUTERS



NADAN (1950)

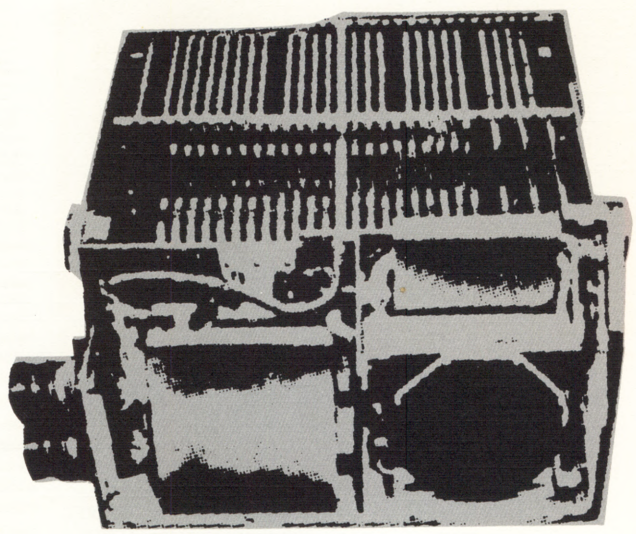
5.9 CU FT 315 LB 1.6KW
1740 RPM ROTATING DISK
MEMORY
93 INTEGRATIONS
29 BINARY DIGITS/NO.
350 TUBES
3500 CRYSTAL DIODES

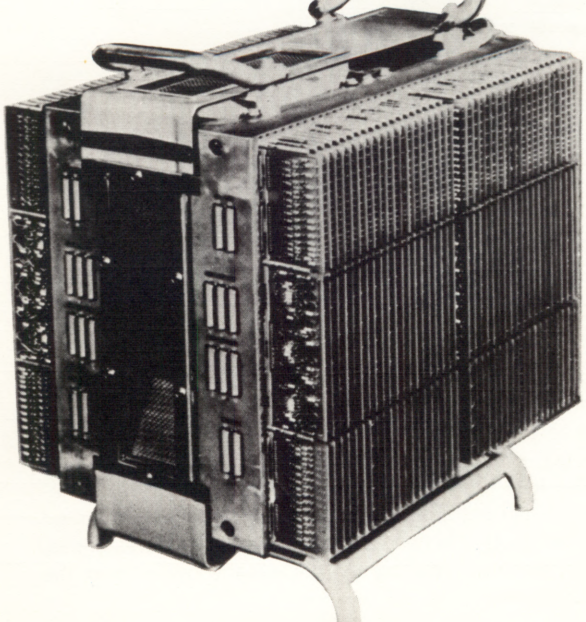
Three years after World War II, Rockwell International (then North American Aviation) designed and produced its first computer—the NADAN (North American Differential Analyzer). Like other electronic computers of its day, it was powered by vacuum tubes, but in other ways it was far superior. Its tubes were surrounded by water cooling jackets to reduce heat and increase life. Crystal diodes, sealed to reduce power leakage, replaced less reliable tube diodes.

NATDAN (1952-57)

2.9 CU FT 140 LB 100W
1000 RPM ROTATING DISK
MEMORY
93 INTEGRATIONS
29 BINARY DIGITS/NO.
904 TRANSISTORS
3200 CRYSTAL DIODES

The nation's first digital airborne computer was North American's NATDAN (North American Transistorized Differential Analyzer), a transistorized version of the NADAN, designed to serve as navigation computer for the X-10 Navaho missile.





RECOMP I (1954-57)

5.7 CU FT 216 LB 600W
INCLUDING REFRIGERATOR
1740 RPM ROTATING DISK
MEMORY
2048 WORDS
39 BINARY DIGITS/NO.
1500 TRANSISTORS
4000 LOGICAL DIODES

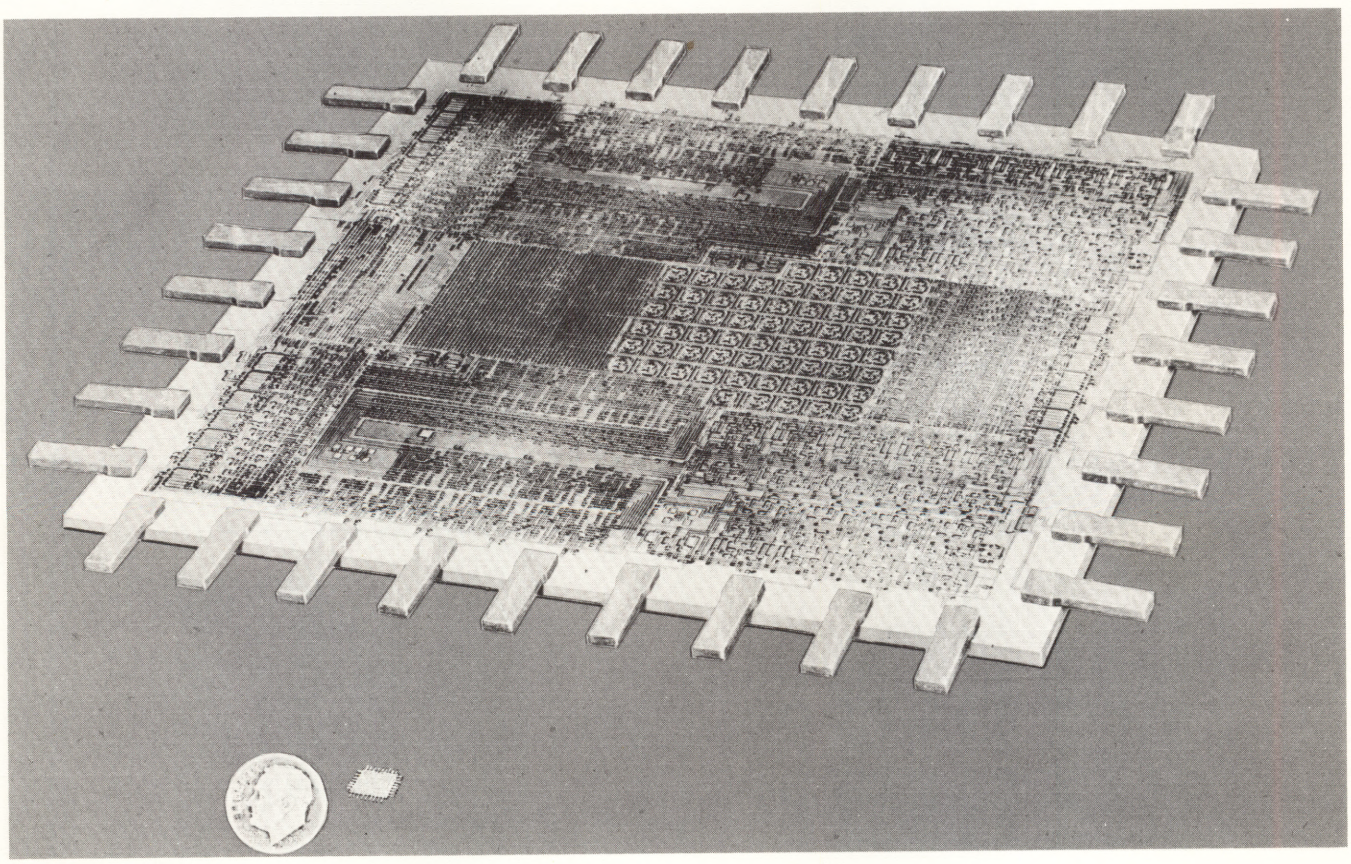
The first all-transistorized ground-vehicular digital computer was North American's RECOMP I (RELiable COMPuter I)—designed and developed while installed in a truck. It contained 1500 transistors and 4000 diodes.

A PIONEERING APPLICATION OF MONOLITHIC MICROELECTRONICS

The computer for Minuteman I—the D17—symbolized the ultimate in a discrete component computer. Through close control of component quality, the D17's reliability was 100 times that of available computers at the time of its development in the early '60's. To achieve even higher reliability, with no greater weight, Rockwell's Autonetics Division built the D37 computer for Minuteman II—the first major weapon system to make use of monolithic microelectronics throughout for guidance and control (G&C). The microelectronics employed by Minuteman II consisted of bipolar integrated circuits and ceramic printed circuits devices. Their use reduced the D37's electronic component count from 14,472 to 6,434—less than half the D17's. They gave the Minuteman II new accuracy and longer range and permitted the new system to have additional functional capabilities, while actually reducing overall weight and size of the G&C system.

WORLD'S FIRST MOS/LSI COMPUTER (AUTONETICS' D200-1)

In 1967, Rockwell International introduced the world's first MOS/LSI computer—the D200-1. By the 1970's, the D200-1 archtype was developed into an entire family of high-performance MOS/LSI systems.



TODAY . . . Rockwell International leads the way in achievement of the first complete-calculator-on-a-chip.

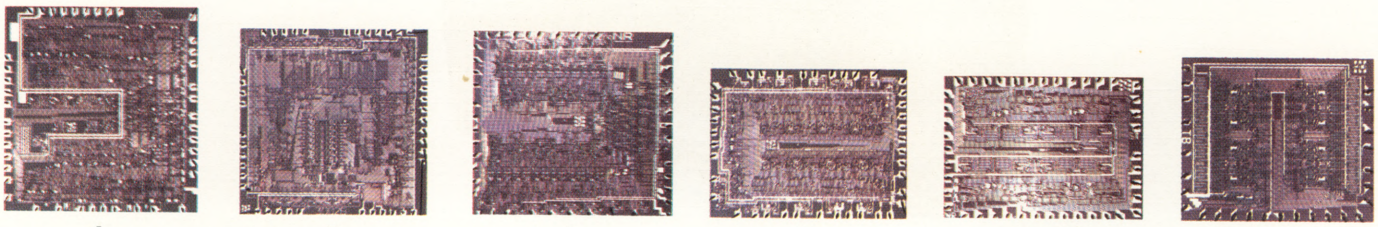
TOMORROW . . . Complete-computer-on-a-chip? Extrapolation of continuing microelectronics progress makes this ambitious dream possible.

MOS/LSI COMPUTERS TODAY

The nation's first MOS/LSI computer—the patriarchal D200-1 can, in the 1970's, take pride in a versatile family of descendants.

Each member of the family is configured from a set of basic MOS/LSI logic circuits, a set of MOS/LSI central processing units offering various wordlengths, a choice of input/output and power supply options, and a selection of three different memory types—plated-wire, magnetic core, and solid-state semiconductor.

D200-series computers are being produced by Rockwell's Autonetics Group for both aircraft and space applications.



A
8-BIT ADDER

B
BUFFER REGISTERS AND LOGIC

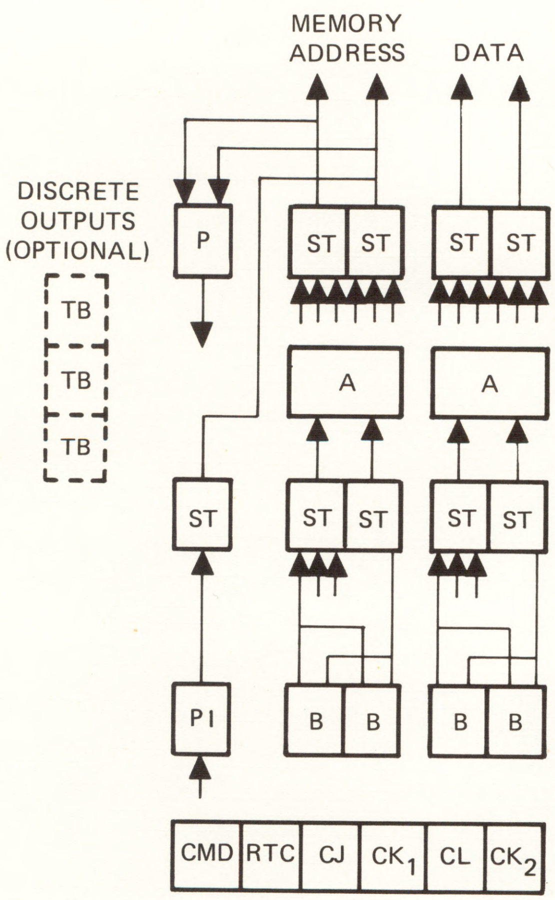
P
16-BIT COUNTER

P1
8-CHANNEL INTERRUPT

ST
3-WAY, 8-BIT MULTIPLEXER

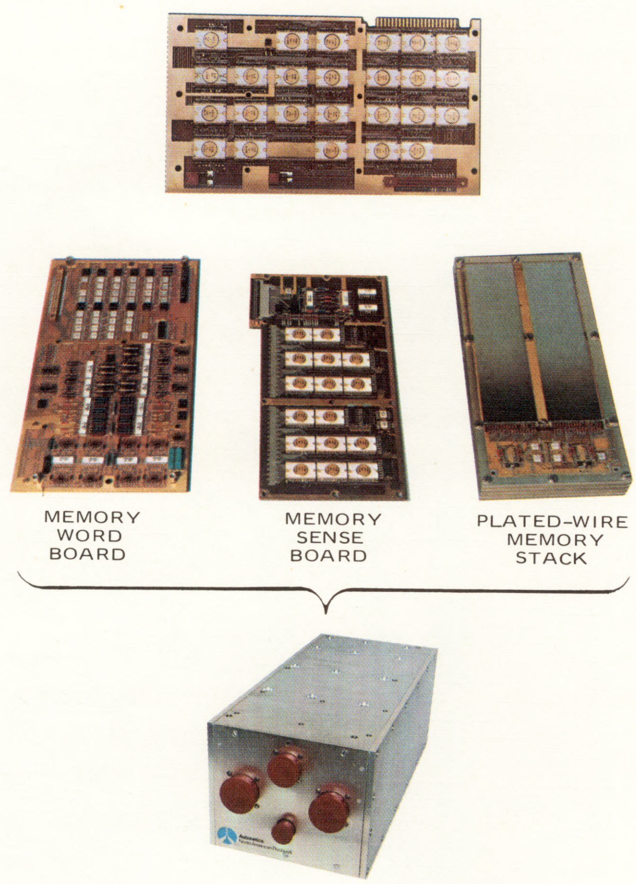
TB
8-BIT TIME BUFFER, I/O

Tyical D200 MOS/LSI Building Blocks



16-Bit Wordlength Central Processor Unit (CPU)

CPU's of different wordlengths are obtained by combining different types and quantities of MOS/LSI building blocks.



D216 Computer

All MOS/LSI circuits for D200-series computers are manufactured by Rockwell International.

IV. NEW MATERIALS, NEW DEVICES

Without the new materials of microelectronics, LSI would be impossible. To realize the impact of this statement, just try to picture a 2000-vacuum-tube diode matrix memory for an airborne computer...or an 800-vacuum-triode-plus-4000-discrete-passive-component digital differential analyzer for a spacecraft!

Other new developments and trends in microelectronics would also be impossible or completely impractical without certain of the new materials. The advances and breakthroughs in microwave microelectronics would be, for example, still far in the misty future if it were not for the availability of materials like gallium arsenide, single-crystal beryllium oxide, silicon-on-sapphire, and the highly versatile magnetic materials.

WHAT MAKES THE MATERIALS POSSIBLE

All of the new materials result from new abilities to design, control, and repeat processes for consistently, uniformly, and predictably producing usable quantities of the materials with the necessary physical and electronic properties.

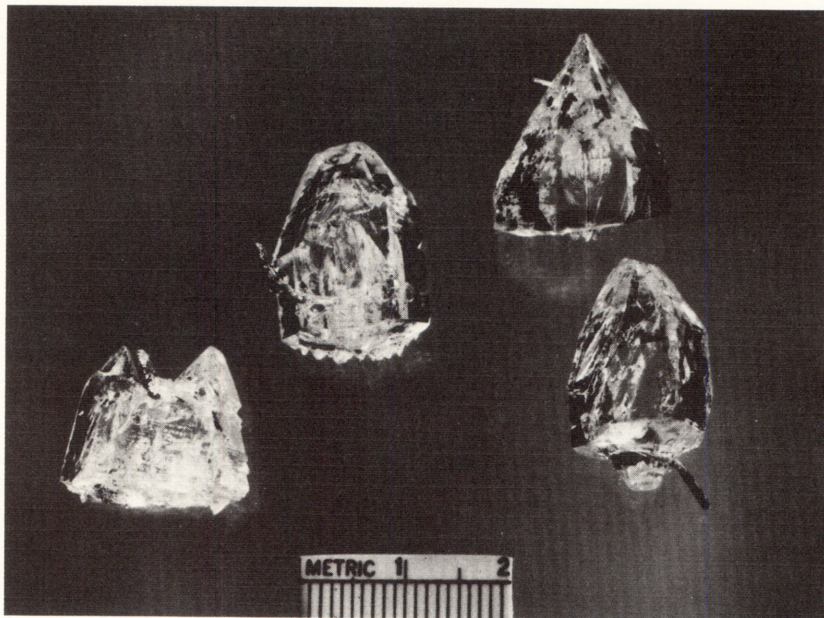
Many of the materials are born of the new abilities to grow highly pure crystals and, most especially, to grow them on other highly pure crystals. This latter process is called "epitaxy." A significant contributor to microelectronics is 'heteroepitaxy," in which the underlying crystal or "substrate," and the crystal grown upon it, are two different chemical materials.

Heteroepitaxy makes use of such high-sounding growth techniques as chemical vapor deposition, vapor transport, and liquid-phase epitaxy to grow thin (only microns thick!) films on insulating substrates. The newly perfected processes—with their precisely controlled conditions of temperature, pressure, and timing—permit crystals, of which both the films and the substrates are composed, to be grown with the heretofore unachievable purity demanded by microelectronics.

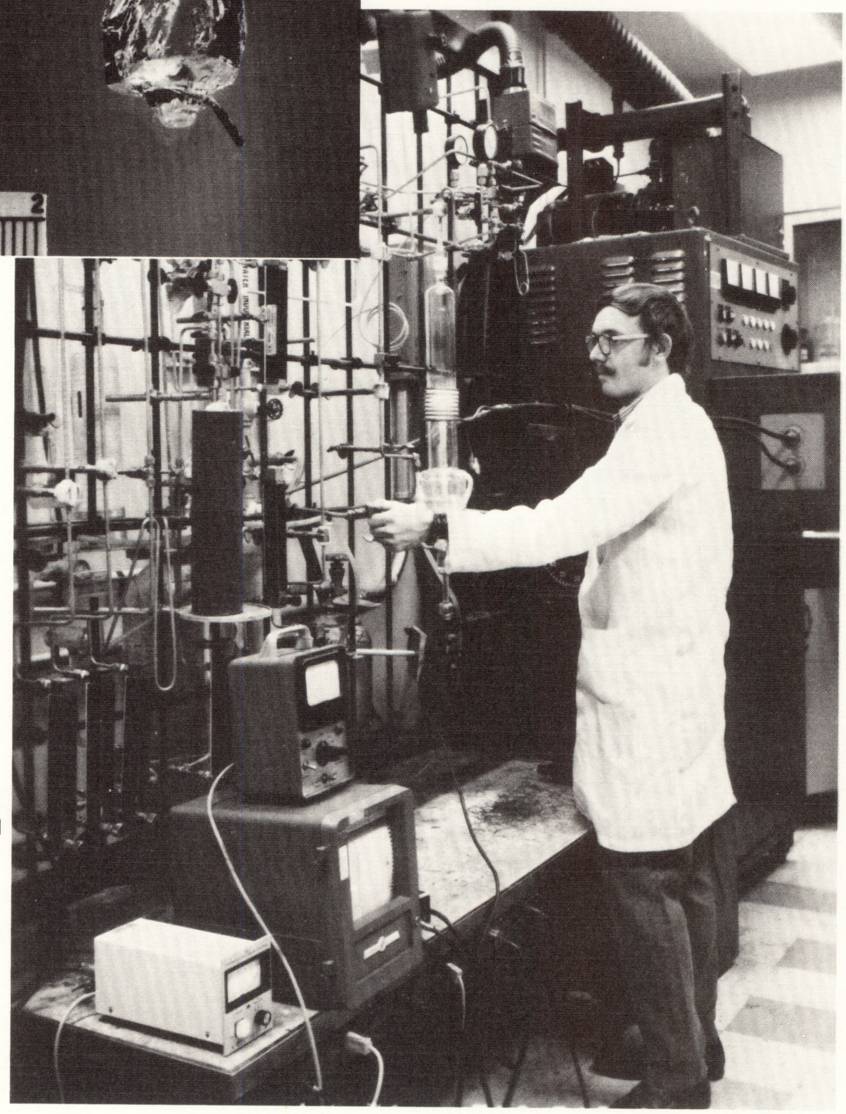
Microelectronics not only demands ultrapurity of the crystalline semiconductor and insulating materials that go to make up integrated circuits, solid-state microwave generators, and MOS devices; it even specifies how the materials' atoms must be arranged. The lattice-like pattern must be what is called a "single-crystal" one—in other words, a material's atoms must be three-dimensionally positioned within the crystal in a repetitive pattern based on a single motif; there can be only this one repeated motif, or the material is not eligible for single-crystal status. Only with *pure* (free of other materials) single-crystal materials can devices be fabricated to have predictable, reproducible, uniform characteristics, and to perform accordingly when used in electronic systems.

In addition to pure single-crystalline materials, a number of other remarkable substances are helping to determine the future directions of microelectronics. These substances include those with special exploitable properties—materials that generate electricity when exposed to light, and materials that emit light when exposed to electricity . . . materials that are valued for their ability to conduct sound waves . . . materials that exhibit one set of characteristics to a signal sent through them in one direction, and entirely different characteristics when the direction of the signal's travel is reversed . . . materials capable of storing as many as a billion bits of digital data in a 1-sq in. area . . . and materials that become transparent or opaque depending upon whether or not they are subjected to an electric field.

To transform the exotic materials of microelectronics, once achieved, into devices that can take advantage of their remarkable properties, a whole phalanx of special skills and processes have had to be devised, developed, and invented. Among these are the photolithographic, diffusion, deposition, and bond-



BERYLLIUM OXIDE CRYSTALS



BERYLLIUM OXIDE
CRYSTAL GROWTH SYSTEM

MATERIALS AND DEVICE RESEARCH AND DEVELOPMENT

Beryllium oxide is one of many exotic materials being studied by Rockwell International in continuing programs of materials and device research and development.

MATERIALS RESEARCH

Electronic, magnetic, acoustical, mechanical, and optical properties of various materials are studied with a view toward solid-state device application. Among the materials studied are semiconductors, laser hosts, ferroelectrics and ferromagnetics, and piezoelectrics—in the form of thin films or bulk single crystals, depending upon the intended application.

DEVICE RESEARCH

Device research is directed toward development of solid-state devices which exploit the special electronic, magnetic, acoustical, mechanical, and optical properties determined during materials research. Among the devices studied are transistors for integrated-circuit microwave applications . . . photodetectors for both visible and invisible wavelengths . . . varactor diodes covering microwave and millimeter wave frequencies . . . surface acoustic wave (SAW) devices such as programmable tapped delay lines and tapped delay line correlators . . . and microwave generators employing such phenomena as the Gunn and "avalanche" effects.

ing skills already discussed. Others—such as the process for fabricating silicon-on-sapphire circuitry, the ability to adjust compound ratios to obtain desired propertes in luminescent materials, and methodology for formation of certain types of "microacoustical" circuit components—are discussed in the present chapter.

In combination—the innovating skills and processes, the sophisticated equipment to apply them effectively, and the material media with which they work, yield the devices and approaches for the new microelectronics of today and tomorrow.

HETEROEPITAXIAL ARISTOCRAT—SILICON-ON-SAPPHIRE

The first material to qualify as a semiconductor "host" for integrated circuits was silicon, and a material combination that has been almost synonomous with early LSI is silicon-on-sapphire (SOS). The interelement isolation provided by sapphire's extremely high resistance permits extremely high element density, and the SOS approach to LSI has proven to be a particular boon in computer and other data-processing systems organization, and in filling requirements for radiation-hardened systems as explained in Chapter II.

The first successful heteroepitaxial growth of single-crystal silicon on an insulating sapphire substrate was reported by a Rockwell International scientist in 1963—in a paper presented to the American Physical Society meeting in Edmonton, Canada. The story of silicon-on-sapphire (SOS), one of the major breakthroughs of second-generation microelectronics, is now a familiar one. An entire technology has grown from this breakthrough alone.

One of the first requirements of a substrate for successful single-crystal growth is that the substrate itself be single-crystalline. The substrate then serves as a sort of "template" to the material growing upon it, so that the latter turns out to be single-crystalline, too. Since "sapphire" is simply another name for single-crystal alumina, it obviously satisfies this first heteroepitaxial requirement.

The controlled growth of a single-crystal film of one material upon another depends not only on the compatibility of the overlaid and underlying crystal patterns, but also upon the physical condition of the substrate. Surface scratches, impurities, and other defects can completely sidetrack the substrate's ability to guide the growing film material in its achievement of single-crystalline structure. Thus, in SOS technology, the sapphire substrate must undergo multiple lapping, polishing, ultrasonic cleaning, and, finally, gas-phase etching in a chemical reactor at an extremely high temperature, before it is suitable to serve as a base for growing single-crystal silicon.

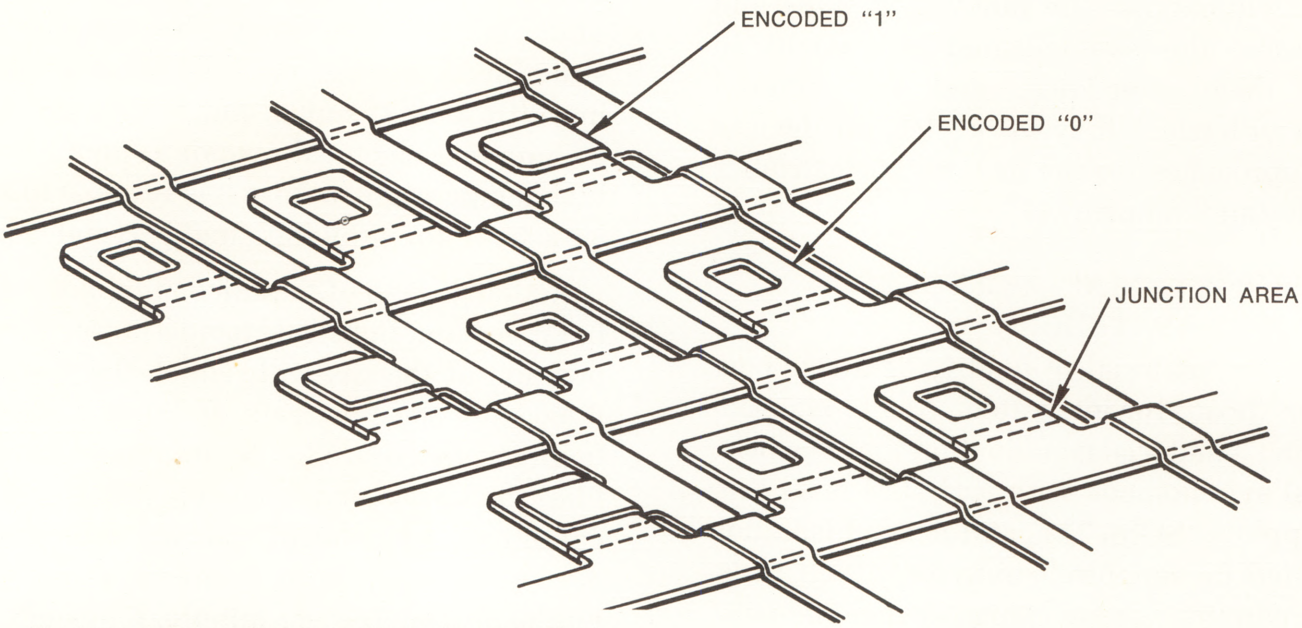
Actual growth of the silicon film takes place in the reactor. Substrate temperature, the composition of the gas with which the reactor is filled, and the flow rate of the gas must all be precisely controlled to obtain the requisite film thickness and quality. With optimum conditions of control, silicon film can be grown on sapphire at a rate of about three-tenths of a micron per minute. Films destined for device fabrication are usually from one to ten microns thick and are grown on sapphire wafers as large as one-and-a-quarter inches in diameter. For research purposes, single-crystal silicon-film sheets have been grown many hundreds of microns thick.

To produce SOS devices, the silicon film is etched down to the substrate to form tiny, electrically isolated "islands." Circuit elements are diffused into these thin-film islands to make devices, just as circuits are diffused into bulk silicon to make devices. The isolation between islands is practically "total"; the resistivity of sapphire at room temperature is approximately 10^{12} (ten thousand billion) ohms per centimeter!

Formation of the basic islands and the circuits they contain involves a whole sequence of photolithographic, oxidation, and diffusion processes. Interconnections, crossovers, and certain passive components are added directly onto the insulating substrate by vacuum-deposition.

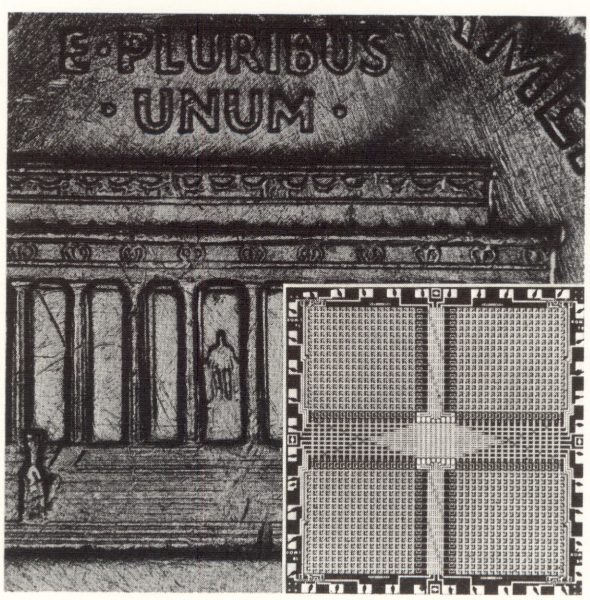
THE VERSATILE SOS DIODE ARRAY

One of the most versatile of SOS/LSI arrays is a diode array. The thousands of diodes which make it up are formed by diffusion in the epitaxial layer of silicon. Laid out in a grid of uniform horizontal rows and vertical columns, the diodes can be individually connected or not, to adapt the array for performing a variety of functions, such as logic matrices . . . read-only memories and microfiles . . . code converters . . . selectors and decoders . . . and tables of fixed commands, characters, diagnostic checks, trigonometric functions, multiplication, and addition. Entire systems can be formed on a single substrate by combining the SOS diode array with other electronic elements on the substrate.

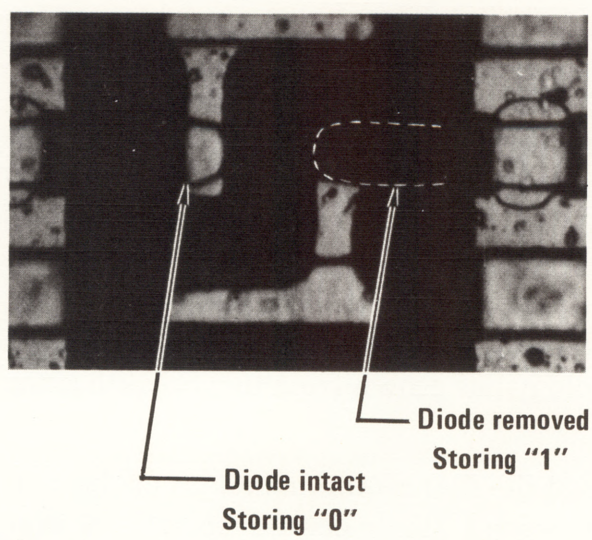


The lower set of conductors is silicon, the upper aluminum. Tabs in silicon contain diodes; contact is made through similar tabs on the aluminum layer.

SKETCH OF PORTION OF SOS DIODE MATRIX
SHOWING CONNECTIONS FOR READ-ONLY MEMORY APPLICATION



SOS Diode Array
(Shown with U.S. Penny to Indicate Size)



Enlargement Showing
Diode-Array Programming

ACTUAL PHOTOGRAPHS OF AN SOS DIODE ARRAY

To program SOS diode-array memories, Rockwell uses a laser "micromachine tool" that burns away or leaves intact individual tiny diodes. The presence or absence of a diode then represents either a stored "0" or a stored "1" for binary coding to correspond with the desired programming.

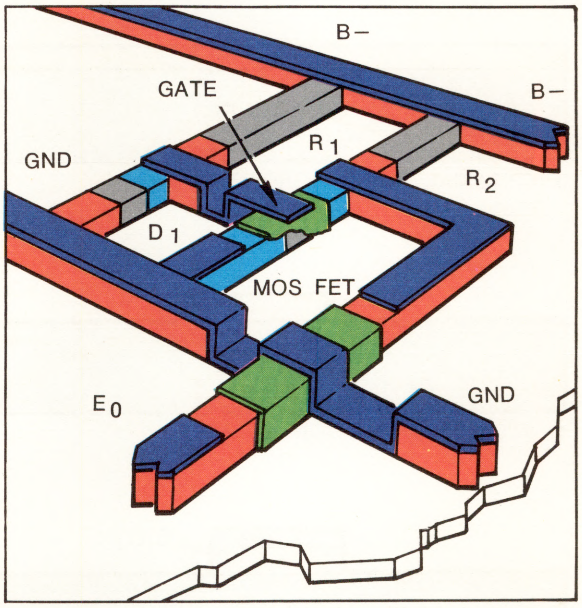
SOS technology permits a new degree of freedom in the design of complex, multifunctional devices. At the same time, the high element density and diversity of SOS offer an unrivalled potential both for reliability enhancement through redundancy, and for cutting production costs through batch fabrication. Many types of circuits and circuit elements—including diodes, resistors, capacitors, bipolar integrated circuits, and MOS FET's—can be fabricated simultaneously on a single sapphire substrate. Making a conservative estimate by present-day photolithographic standards of 10,000 interconnected thin-film devices per square inch on a 10-mil substrate, it can readily be calculated that a SOS 30-bit, 8,000-word memory—approximately 250,000 bits—with accompanying electronics, would occupy less than two cubic inches in volume.

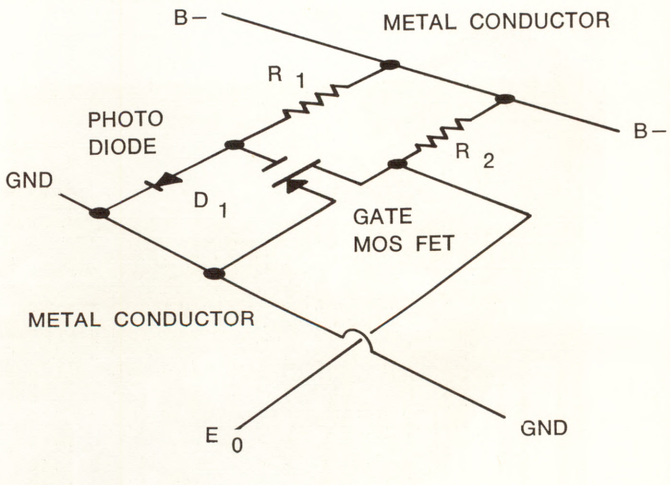
Looking into the future, transparency of sapphire points to its suitability for short, direct, through-the-substrate optical coupling of circuits, and for literally speed-of-light transmission of data. Of particular significance in this age of space exploration and nuclear science is the exceedingly high radiation resistance of SOS—which renders SOS circuitry well able to cope with whatever the 1970's may have to offer in both manned and unmanned radiation environments.

GLAMOROUS WORKHORSE— GALLIUM ARSENIDE

Since the announcement of SOS in 1963, many other exotic materials and heteroepitaxial combinations with impressive capabilities and potentials have been developed; many others are being explored.

One of the most versatile "contenders" is gallium arsenide (GaAs). This many-talented substance threatens to usurp the white-haired-boy-of-microelectronics position held for so long by silicon. In addition to being able to do anything silicon can do (and often do it better), gallium arsenide has certain unique properties above and beyond the capabilities of silicon.

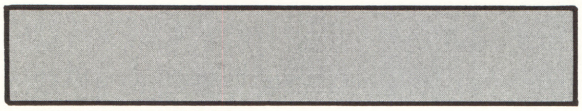




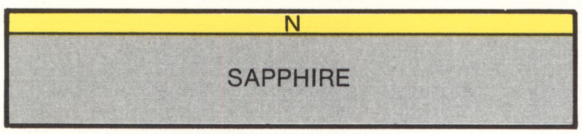
SIMPLE CIRCUIT DEMONSTRATING ATTRIBUTES OF SILICON-ON-SAPPHIRE (SOS) TECHNOLOGY

SOS DIODE FABRICATION REQUIRES SPECIAL SKILLS AND FACILITIES

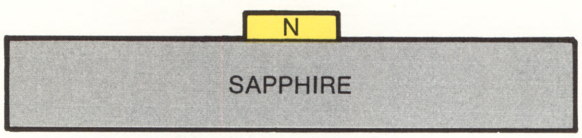
TYPICAL FABRICATION STEPS



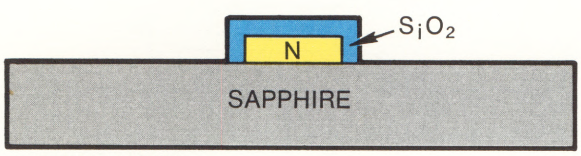
a. SAPPHIRE WAFER



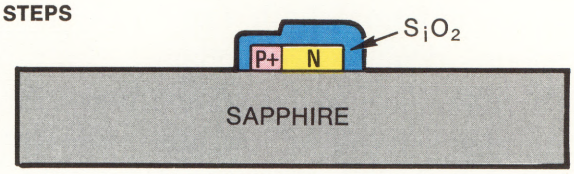
b. EPITAXIAL SILICON GROWTH



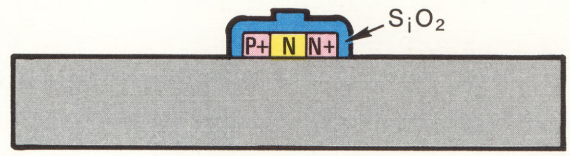
c. ETCHING OF SILICON ISLANDS



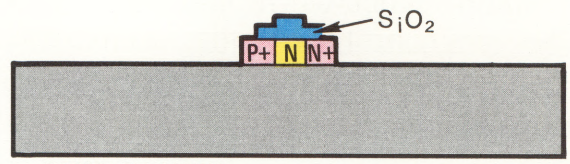
d. OXIDIZATION



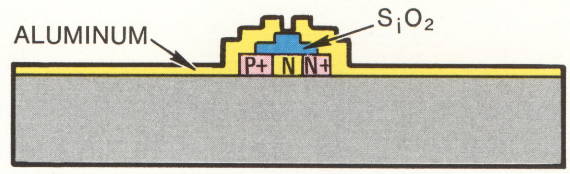
e. P MASK AND DIFFUSION, AND REOXIDIZATION



f. N MASK AND DIFFUSION, AND RE-OXIDIZATION



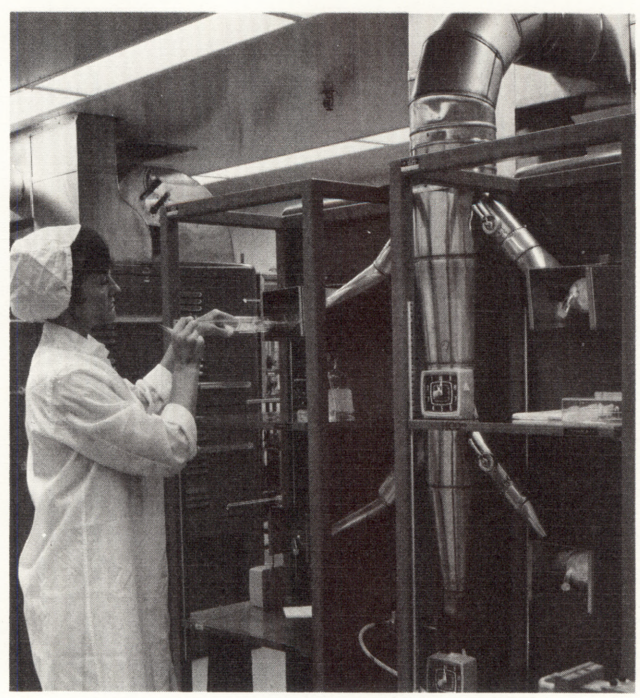
g. CONTACT MASK



h. METALLIZATION AND ALLOY

SOS MASK ALIGNMENT

Laboratory assistant uses microscope to align diode mask on a silicon-on-sapphire wafer. Unmasked area is then photo-etched, and diodes are diffused into the openings.



DIODE DIFFUSION

Dopants are diffused into silicon-on-sapphire wafer to form a diode memory array. The laboratory assistant uses quartz rod to place wafer in diffusion furnace.

Gallium arsenide heteroepitaxy provides the basis for an entire new technology, analogous to the technology of silicon-on-sapphire but with the capability to perform at much higher power and at much higher frequencies. Bulk GaAs offers what is now a veritably unequalled medium for *solid-state microwave generation.* And, as if this were not enough to assure GaAs of winning the pennant, the new material has certain remarkable *acoustical* and *luminescent* properties—discussed at length later in this book—that make it usable for many applications completely outside the ballpark for silicon.

In the branch of GaAs technology analogous to the technology of SOS, beryllium oxide (beryllia) most often plays the important supporting role played by sapphire as an insulating substrate for silicon circuitry. GaAs-on-beryllia is a breakthrough of at least SOS stature—for achievement of high-power, high-frequency, solid-state oscillators (see pages 113 through 119). Heat dissipation has always been one of the insurmountable problems in developing such oscillators. Because beryllia is one of the most efficient heat conductors known (equivalent to brass and almost as good as copper in this respect), its use as a substrate for high-power oscillators is a natural.

GaAs FET's are capable of out-performing conventional silicon MOS devices with respect to both maximum frequency and maximum temperature. Gallium arsenide was originally given particular attention for transistor development because of a characteristically high electron mobility that offers good high-frequency response, and a wide energy band gap that allows good performance at high temperatures.

NEW LIGHT ON THE SUBJECT: LUMINESCENCE AND LIGHT SENSITIVITY

HISTORY AND BACKGROUND

Gallium arsenide is just one of a number of compounds being exploited in the 1970's for applications requiring luminescence. The elements from which these compounds are formed all come from the same four groups in the periodic table of elements. Later, we shall see why this is true. For now, it will be helpful to review briefly the history of luminescence research.

Luminescent light is *cold* light. It is not, like incandescent illumination, accompanied by heat. Luminescence is found throughout nature. It creates the flashing signal sent by the firefly to attract a mate. It "powers" the fleshy "headlights" given by nature to deep-sea denizens to light their way about an ocean floor, at depths where the sunlight has been unable to penetrate since life began.

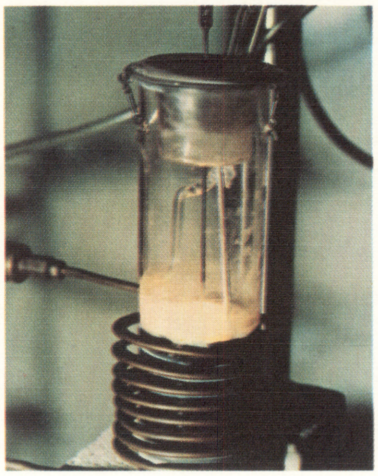
For over a decade-and-a-half, scientists at Oak Ridge, Tennessee, paid children in that community a generous bounty per head of fireflies collected and turned over to the laboratory men for study. But even before the Oak Ridge efforts first got under way, luminescence had long been a challenging subject for researchers.

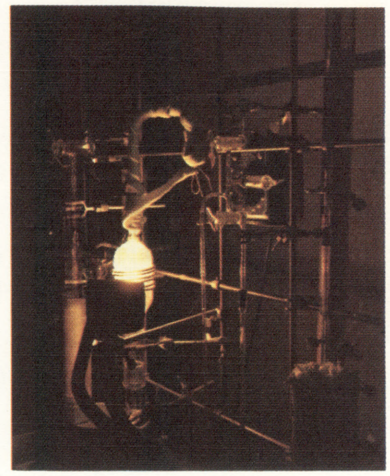
More than 35 years ago—in 1936—French physicist Georges Destriau found that certain materials could be made to glow when submitted to a high a-c voltage. His discovery was exploited by coating two capacitor-like metal plates with any one of certain phosphorescent powders, and then applying voltage between the plates. The so-called "Destriau effect" was at first thought to have great promise for practical applications, but both the voltages and the frequencies required to generate light bright enough to be useful were too high—and the promise was never borne out.

After Destriau, solid-state luminescence research was mainly centered on the study of single crystals of various semiconducting compounds. In 1962, a very important breakthrough occurred when MIT's Lincoln Laboratory, GE, and IBM made almost simultaneous announcements of the attainment of laser action with GaAs diodes.

What is there about GaAs and certain other semiconductor compounds that singles them out for starring roles in the exciting arena of luminescence?

MATERIALS—THEY SET THE COURSE FOR MICROELECTRONICS...



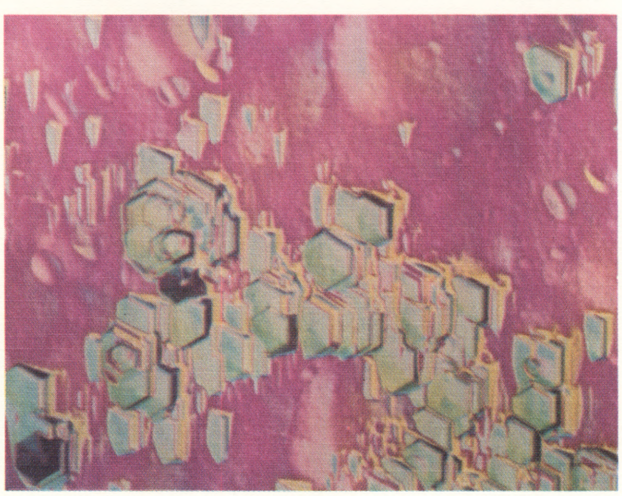


CRYSTAL GROWTH

A wide range of crystals is grown from many different materials in a variety of forms. Growth techniques include hydrothermal, Czochralski, Bridgman, chemical vapor deposition, Verneuil, and flux methods. Each technique is selected for compatibility with the melting temperature of material being processed and for the crystal structure which it produces—thin-film, long-rod, bulk, or large-crystal.

SINGLE-CRYSTAL MAGNETIC MATERIALS

Rockwell's interest in computer application of magnetic effects goes back to 1960. Both metallic and oxide thin-film studies have been performed. Also demonstrated: feasibility of growing epitaxial single-crystal films of magnetic oxides which are particularly suited for memory elements; and elementary bit capability of epitaxial ferrites on magnesium oxide. Strong emphasis is being given microwave and ultrasonic device development. The achievement of epitaxial yttrium iron garnet (YIG) on yttrium aluminum garnet (YAG) has constituted a major breakthrough for transducers, delay lines, tunable filters, and surface wave devices. Illustrated above is ferrite epitaxy.

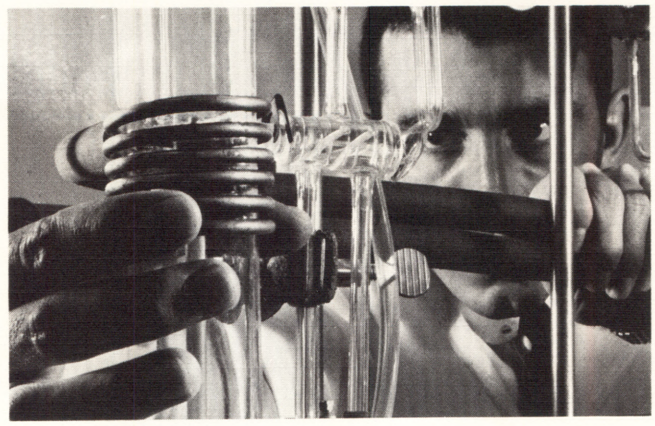


MICROCOSMIC METROPOLIS

This is not a rooftop view of some other-world city that would greet an alien astronaut upon his return to his home planet. It is, rather, a photomicrograph showing the crystallinity of a cadmium sulfide film. The film, only a few microns thick, is grown in single-crystal form on a foreign (in this case, germanium) surface. Hexagons all point in same direction, indicating that a single crystal has been formed. The work is part of Rockwell's continuing research and development of epitaxial films for microcircuit applications.

FLYING SAUCERS

And these are not the alien voyager's spacecraft. These "unidentified flying objects" are from a Rockwell metallographic laboratory, not outer space. They are defects on sapphire crystal which have been identified through a microphotograph enlarged 300 times. Analysis of minute defects is vital to performance evaluation of the materials of third-generation microelectronics.

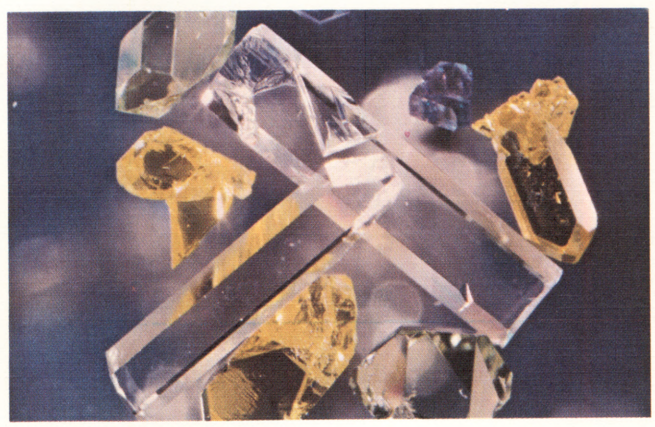


DEPOSITION BREAKTHROUGH

Rockwell scientists achieved first reported deposition of single-crystal silicon upon an insulating substrate (sapphire). From this breakthrough has come the whole important SOS technology—with its revolutionary new approaches to computer organization and large-scale-integrated microelectronics circuitry.

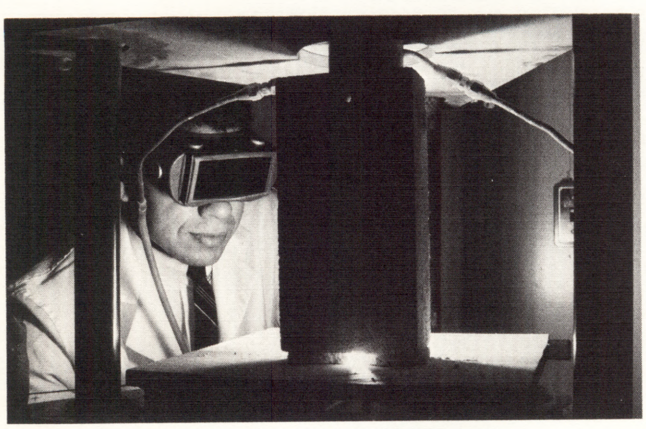
A WHOLE NEW TECHNOLOGY

Gallium arsenide heteroepitaxy provides the basis for a new technology analogous to the technology of silicon on sapphire—but with promise of much higher frequency application and even greater versatility. This is a reactor used for heteroepitaxial growth of gallium arsenide on sapphire.



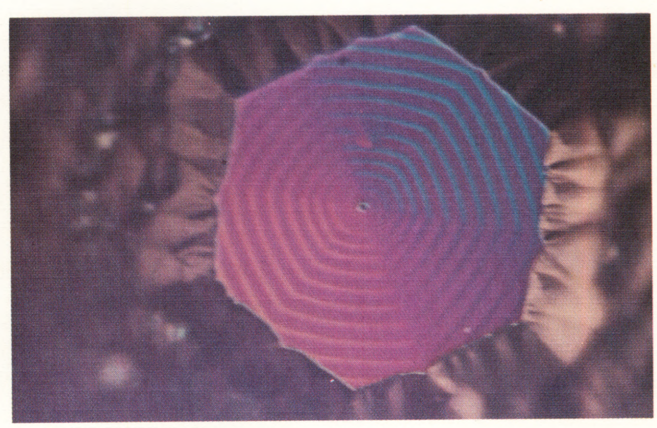
"JEWELS" WITH A FUTURE

In the technology of gallium arsenide heteroepitaxy, beryllium oxide plays the important role of substrate, comparable to the role played by sapphire in SOS technology. Above are beryllium oxide crystals grown by the Electronics Research Division.



IN CRYSTALS AS ELSEWHERE, YOU HAVE TO HAVE PULL

Rare earth crystals are grown in unique crystal puller while technician monitors the equipment. Crystals are grown inside block kiln which helps control, dissipate heat.



SURREALISTIC PENTAGON

Beryllium oxide crystal magnified approximately 100 times by microscope exhibits unreal coloring, shape.

THE PHYSICS OF LUMINESCENCE

Earlier in this chapter, we devoted a considerable amount of attention to material inner structure. We talked about the three-dimensional patterns called "lattices," in which a crystal's atoms are arranged. We defined "single crystal" as crystalline material in which one repeated lattice pattern appears, in contrast to amorphous crystalline material in which the lattice pattern varies among a number of configurations. But—to this point, we have said not one word about what the mysterious *forces* are, that hold the material's atoms in these patterns.

To understand exactly what luminescence is, and why GaAs and certain other semiconductor compounds have the ability to luminesce, we must return our attention to crystal structure, and this time we must take particular notice of the binding forces that hold together any material's atoms.

The forces that bind a solid's atoms into three-dimensional lattices are of two kinds. One kind—"covalent"—has to do with *elementary* solids, the other—"ionic"—with *compound* solids.

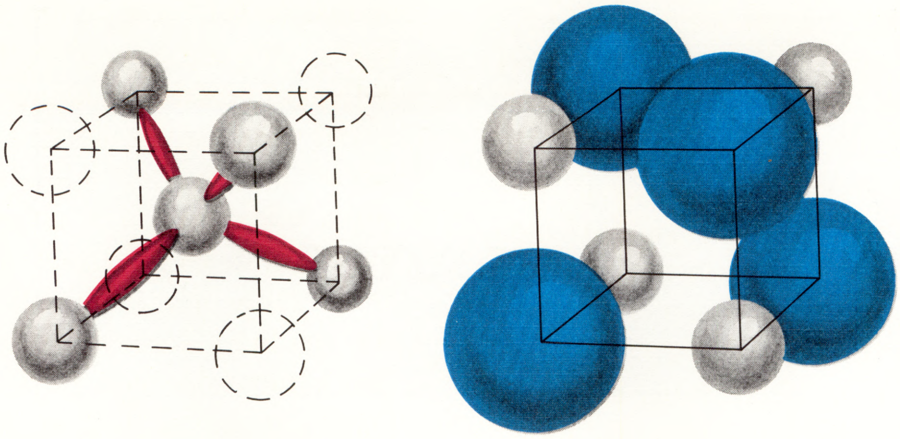
In an elementary solid, the electrons responsible for interatomic binding form negatively charged "clouds" (fields) around and between positively charged "cores" of the atoms. The strong electrostatic attraction between the negative clouds and the positive cores holds the atoms in fixed positions and at fixed distances from one another—somewhat as the force of gravity holds the sun and planets in the three-dimensional configuration that is our solar system. The resulting atomic matrix is the solid's structural lattice. The binding attraction that maintains it is called a "covalent" bond.

The energy levels of the binding electrons throughout a solid cover an almost continuous spectrum of different energy-level bands. At low temperatures, any band is either completely filled, half-filled, or completely empty. If the highest-energy band of those that are occupied is only half-filled, or if it overlaps in energy the next highest allowed* band, elec-

**Energy levels can exist only in discrete energy-value bands corresponding to the orbital radii of the orbital electrons. The greater the radius, the less energy is required for an electron to escape its orbit and go traveling.*

THE "ESSENCE" OF IT ALL...

INCANDESCENCE	Broad-band radiation emitted by matter as a consequence of the thermal motion of its constituent atoms. (To obtain incandescence, energy is introduced into a piece of material and is converted into thermal motion, measurable as a rise in the material's temperature. The higher the temperature, the greater the number of high-energy photons or light quanta that are released.)
LUMINESCENCE	Narrow-band radiation emitted by matter as a result of a change in energy states (usually of electrons) when the sample is excited by an external source of energy that does not significantly change the temperature of the sample.
ELECTROLUMINESCENCE	Electrically induced luminescence (e.g.,Destriau effect).
PHOSPHORESCENCE	Luminescence caused by absorption of radiation, such as X rays or ultraviolet light, and continuing for a noticeable time after the radiation causing the luminescence has stopped.
FLUORESCENCE	Property of emitting radiation as the result of, and only during, the absorption of radiation from some other source; also the emitted radiation.



ELECTRONS INVOLVED *in luminescence in most semiconducting solids are the binding electrons that hold the crystal lattice together. In a solid with covalent bonds, typified here by germanium* (left), *these binding electrons form negatively charged clouds* (color), *between the positively charged cores of the atoms* (black). *In a solid with ionic bonds, typified here by sodium chloride* (right), *the binding electrons are outermost electrons of both the positively charged sodium ions* (black) *and the negatively charged chlorine ions* (color).

trons can move about inside the solid under the influence of an externally applied electric field. A material with electron mobility of this sort is a "metal."

There can be no change in the net charge of either a completely filled band or an empty one. Thus, if the highest-energy occupied band in an elementary solid is completely filled and the next highest-energy one is empty, and if the two bands are separated by an "energy gap" of finite "width," then the solid is an "insulator" at low temperatures—and there can be no transfer of charge (current flow) through it, unless sufficient energy is provided to overcome the gap.

When two elements combine to form a compound, the atomic cores of one have either a positive or a negative charge with respect to the atomic cores of the other. The difference in charge creates the electrostatic attraction between cores that is called an "ionic" bond.

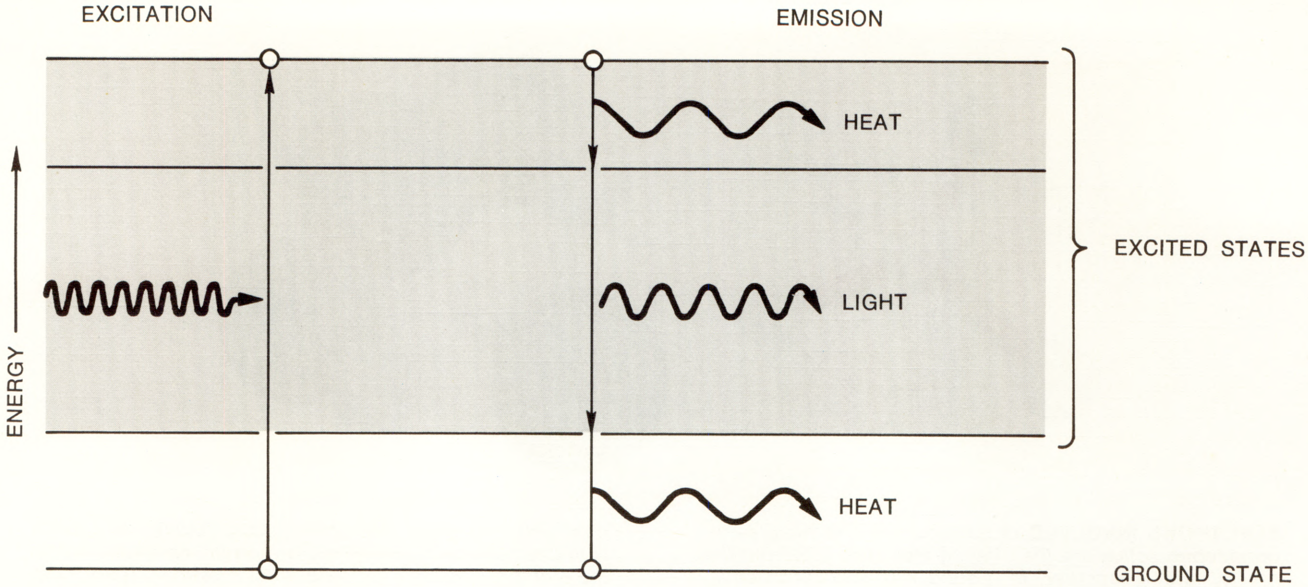
All compound solids utilize both kinds of bonding—covalent and ionic—to some extent, but the proportion of each varies widely—from almost totally ionic for a compound made up of elements from Groups I and VII of the periodic table, to almost completely covalent for a compound of two elements from Group IV.

Pure "semiconductors" are actually insulators with very narrow inter-band energy gaps. At room temperature their binding electrons can acquire energy from heat to become mobile enough to jump from the highest normally filled band (the "valence" band) into the normally empty band (the "conduction" band). Not only can the conduction-band *electrons* thus carry a current through the solid, but, as mentioned in Chapter II,* the *holes* left in the valence band can also constitute a current—of opposite charge and direction to the electrons.

The addition of impurities ("doping") to a semiconductor can be performed to supply it with either extra electrons or extra holes—to act as charge "carriers," to increase the ability of the semiconductor to conduct current, and to convert it from what is effectively an insulator into a real semiconductor.

Of the two basic kind of dopants that can be injected into semiconductor materials—"donors" and "acceptors"—donor substances have an abundance of free electrons to donate to the semiconductor host. The energy state of these electrons is close to the conduction-band energy level of the host and, under proper conditions of temperature and applied electrical voltage, they will readily enter the host's conduction band to combine with holes

**The following discussion repeats to some extent the explanation of semiconductor impurity injection presented in Chapter II. It is expanded upon here as required in the context of "luminescence."*



ENERGY-LEVEL DIAGRAM *of an electron in an isolated atom (for example, in a gas) illustrates the general mechanism of luminescence. An external excitation, which can be a high-energy photon, or light quantum (left), promotes the electron from its ground state to a higher energy state. When the excited electron returns spontaneously to a lower energy state (right), the energy difference between the two states can be carried away in the form of another photon. Relaxation processes following both excitation and emission produce heat, so that the energy of exciting photon is always greater than that of emitted photon.*

there. Injection of electron-rich impurities is called "n-type" doping ("n" for negative, because of the electron's negative charge).

Acceptor materials have *fewer* free electrons than the host. The host's electrons readily combine with the injected acceptor atoms, thus generating a quantity of holes to sustain a hole current under proper conditions of temperature and applied electrical voltage. Injection of acceptor impurities is called "p-type" doping ("p" for positive, because of a hole's positive charge).

When a hole and an electron recombine within a semiconductor—whether directly across the gap or at a donor or acceptor impurity site—the surplus energy from the no longer "excited" electron can be dispensed with, either as a phonon (a vibrational quantum) or as a photon (a light quantum). In the latter case, the energy lost by the excited electron when it fills the hole is transmitted to the photon, and the semiconductor *emits light*.

When the application of an electrical voltage to a semiconductor sample directly results in electron-hole recombinations that cause the emission of light, the semiconductor material is said to be "luminescent."

Certain compounds of elements from Group III and Group V in the periodic table of elements are particularly efficient in converting electricity to photons rather than phonons. Gallium arsenide, for example, which is being given so much attention today in luminescent research and device development, is a combination of gallium from Group III and arsenic from Group V.

The efficiency with which heavily "doped" p-n junctions in GaAs and other Group III and Group V semiconductors perform direct-gap conversion of injected carriers into photons is almost 100 percent at high currents.

In order to be useful in luminescent devices, the light generated by carrier-into-photon conversion must be able to escape from the block of semiconductor. But escape can be denied in a number of ways. Much of the light may be absorbed by inactive parts of the device. Another significant amount is lost by reflection back into the semiconductor from the flat interface of the semiconductor crystal with the air. (The light is radiated outside the semiconductor only when the photon strikes the interface perpendicularly, or at some angle differing from ninety degrees by no more than

I	II	III	IV	V	VI	VII
3 LITHIUM (Li)	4 BERYLLIUM (Be)	5 BORON (B)	6 CARBON (C)	7 NITROGEN (N)	8 OXYGEN (O)	9 FLUORINE (F)
11 SODIUM (Na)	12 MAGNESIUM (Mg)	13 ALUMINUM (Al)	14 SILICON (Si)	15 PHOSPHORUS (P)	16 SULFUR (S)	17 CHLORINE (Cl)
29 COPPER (Cu)	30 ZINC (Zn)	31 GALLIUM (Ga)	32 GERMANIUM (Ge)	33 ARSENIC (As)	34 SELENIUM (Se)	35 BROMINE (Br)
47 SILVER (Ag)	48 CADMIUM (Cd)	49 INDIUM (In)	50 TIN (Sn)	51 ANTIMONY (Sb)	52 TELLURIUM (Te)	53 IODINE (I)
79 GOLD (Au)	80 MERCURY (Hg)	81 THALLIUM (Ti)	82 LEAD (Pb)	83 BISMUTH (Bi)	84 POLONIUM (Po)	85 ASTATINE (At)

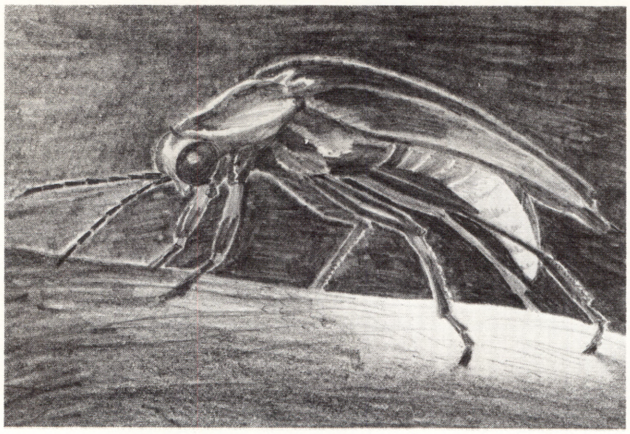
SHORT FORM of the periodic table contains all the elements that combine in pairs to form semiconducting binary compounds suitable for use as light sources. The elements that so combine are in identically "shaded" columns. The best light-emitters are compounds from Group II and Group VI (sometimes called II-VI compounds) and those from Group III and Group V (III-V compounds). Each element is accompanied by its atomic number: the number of protons in its nucleus or the number of electrons bound by them.

WAVELENGTH (ANGSTROM UNITS)	SEMICONDUCTING COMPOUND	SYMBOL	TYPE	METHOD OF EXCITATION	EFFICIENCY (PERCENT)
3,300	ZINC SULFIDE	Zn S	II–VI	ELECTRON BEAM	6
4,900	CADMIUM SULFIDE	Cd S	II–VI	ELECTRON BEAM	25
3,800	ZINC OXIDE	Zn O	II–VI	ELECTRON BEAM	?
4,900 - 6,800	CADMIUM SULFIDE-SELENIDE	Zn Te	II–VI	ELECTRON BEAM	6
5,400	ZINC TELLURIDE	Cd $S_x Se_{1-x}$	II–VI	AVALANCHE	1
5,500 , 7,000	GALLIUM PHOSPHIDE	Ga P	III–V	*p-n* JUNCTION	0.01 , 1.0
6,200	ZINC SELENIDE-TELLURIDE	Zn $Se_x Te_{1-x}$	II–VI	PHOTO-*p-n* JUNCTION	18
6,300 - 8,500	GALLIUM ARSENIDE-PHOSPHIDE	Ga $As_x P_{1-x}$	III–V	*p-n* JUNCTION	20
7,000 - 8,500	ZINC-CADMIUM TELLURIDE	$Zn_x Cd_{1-x}$ Te	II–VI	*p-n* JUNCTION	6
7,800	CADMIUM SELENIDE	Cd Se	II–VI	ELECTRON BEAM	6
8,500	CADMIUM TELLURIDE	Cd Te	II–VI	*p-n* JUNCTION ELECTRON BEAM	12
8,500	GALLIUM ARSENIDE	Ga As	III–V	*p-n* JUNCTION ELECTRON BEAM AVALANCHE LASER BEAM	80
15,000	GALLIUM ANTIMONIDE	Ga Sb	III–V	*p-n* JUNCTION ELECTRON BEAM	?
31,000	INDIUM ARSENIDE	In As	III–V	*p-n* JUNCTION ELECTRON BEAM LASER BEAM	?
41,000	MERCURY-CADMIUM TELLURIDE	$Hg_x Cd_{1-x}$ Te	II–VI	LASER BEAM	?
54,000	INDIUM ANTIMONIDE	In Sb	III–V	*p-n* JUNCTION ELECTRON BEAM	?
65,000 - 165,000	LEAD-TIN TELLURIDE	$Pb_x Sn_{1-x}$ Te	IV–VI		?
65,000 - 165,000	LEAD-TIN SELENIDE	$Pb_x Sn_{1-x}$ Se	IV–VI	LASER BEAM *p-n* JUNCTION	?

MOST EFFICIENT light-emitting semiconductors are listed in this table, along with the characteristic wavelength at which they radiate, the groups they represent and the methods used to promote their electrons to excited states. The efficiency of each source is equal to the ratio of the energy of the light emission (output) to the energy of excitation (input). All the emissions listed were obtained at 77 degrees Kelvin (degrees centigrade above absolute zero) except the red band of gallium phosphide at 7,000 angstrom units, which was obtained at room temperature (300 degrees K.). The emissions that are suitable for use in lasers are "shaded" in the table.

BIOLUMINESCENCE

is the ability of certain living things to give off light. It is the result of chemical processes that go on in the tissues of animals or plants. Although living things may give off light, they do so without producing any appreciable heat. Most luminescent animals are found in the ocean. For example, many squids are luminescent. The firefly is a familiar land example. In the plant kingdom, certain bacteria and fungi are luminescent. Bioluminescence is studied by scientists who are conducting research to discover a means of producing light chemically, without heat.

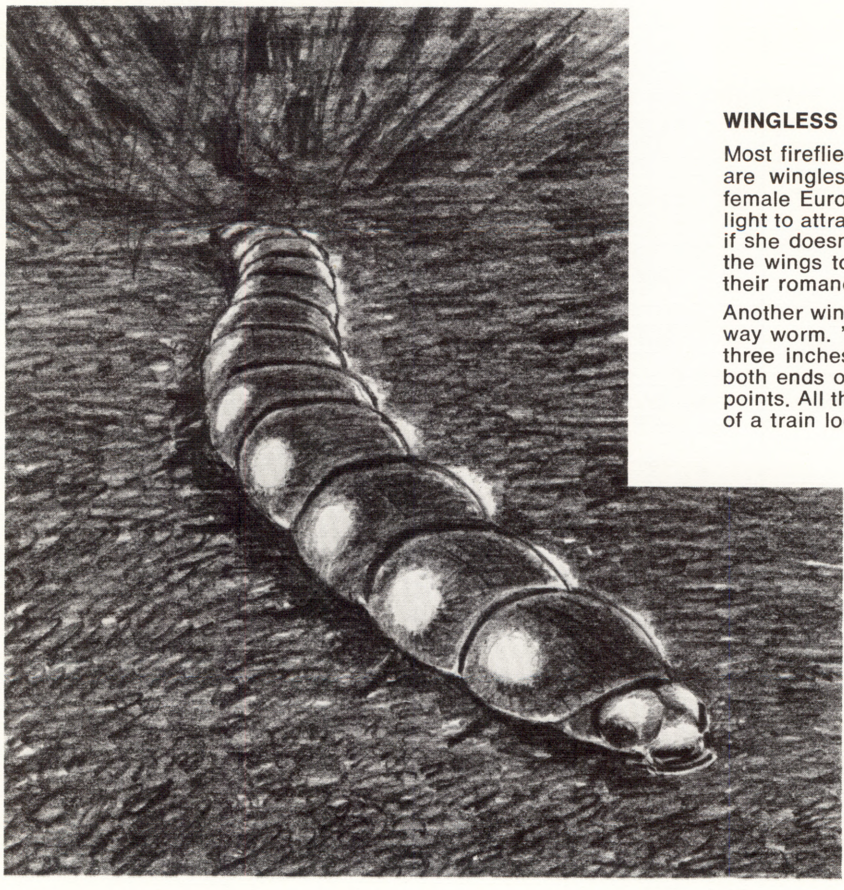


De Geer's Firefly

The lovesong of the firefly is sung, not in sonic trills, but in optic flashes. Electrochemically generated "cold light"—luminescence—leads the little insect to the warm embrace of love.

FIREFLIES OR "LIGHTNING BUGS"

Several different kinds of beetles are called "fireflies," "fire beetles," or, in the South where most of them in the United States are found, just plain "lightning bugs." The most common U. S. variety is about half an inch long, predominantly black with reddish-brown "trimming." The romantically alluring flashes are produced by reactions of five chemicals in the firefly's abdomen—adenosine triphosphate, luciferin, oxygen, magnesium, and luciferease—bound together by a chemical controller. The flash is initiated when nerve stimulations release another chemical—inorganic pyrophosphate—which breaks the bond; it goes out when another chemical destroys the pyrophosphate.

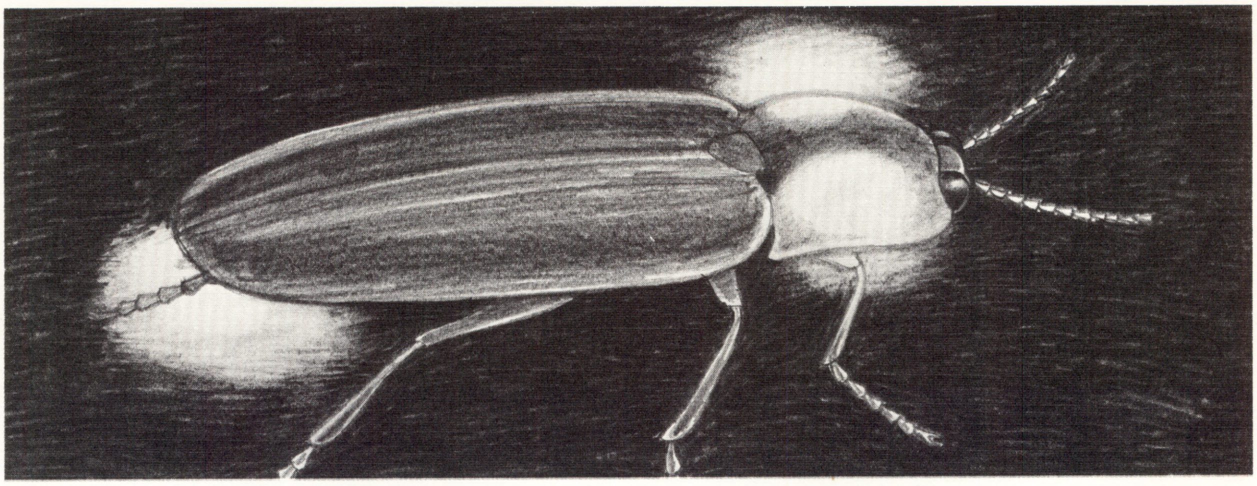


WINGLESS FIREFLIES

Most fireflies have wings, but there are some types that are wingless. An insect in the latter category is the female European glowworm. She has the power to emit light to attract a mate, but no wings to fly away from him if she doesn't like his looks once he gets there. He has the wings to reach her, but he flashes no light to spoil their romance.

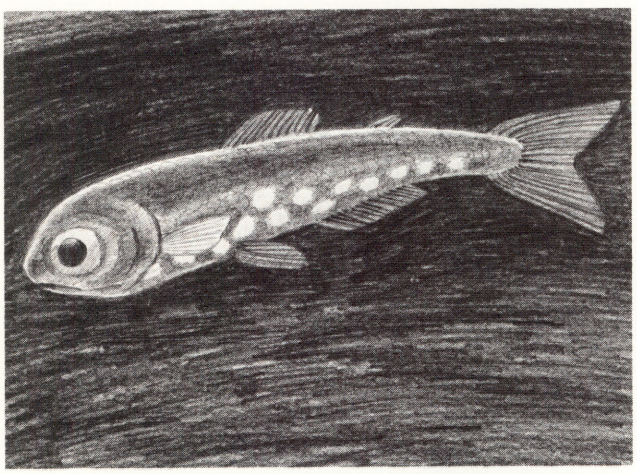
Another wingless firefly is Paraguay's aptly named "railway worm. " This remarkable-looking creature is about three inches long and sends out strong red light from both ends of its body, as well as green light from other points. All this fancy illumination gives it the appearance of a train locomotive sending out railway signals.

Railway Worm

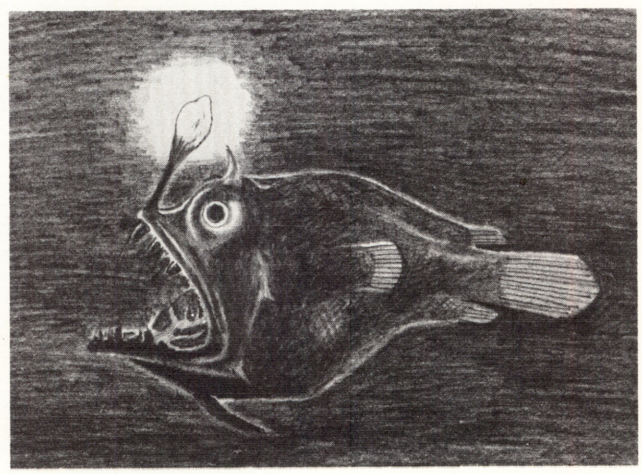


FIRE BEETLES OR CUCUYOS

The fire beetles or "cucuyos" of South America and the West Indies are both utilitarian and ornamental. Measuring more than an inch long, they are much brighter than North American fireflies. On each side of the body, near the head, two large spots emit a bright greenish light; another spot, at the end of the abdomen, sends out a reddish light. Sometimes a large number of cucuyos are imprisoned in a bottle and used as a lantern. They give their light in flashes, but with enough of them in the bottle, some are lighting constantly and together they give a continuous though wavering light, bright enough to read by. In Cuba and Puerto Rico, people sometimes tie cucuyos to their feet to illuminate their way through tropical forests and along mountain trails. Imitating the female insect's successful tactics, human Cuban females sometimes attempt to lure the opposite sex by pinning the glowing cucuyos to their clothes or wearing them attached to golden chains about their necks.



Lantern Fish



Deep-Sea Angler

Built-in headlights not only help denizens of the deep seek out lady loves—they also help the denizens in the avoidance of collision and in location of food. Metabolically created luminescence is as natural to these creatures as taste buds are to man.

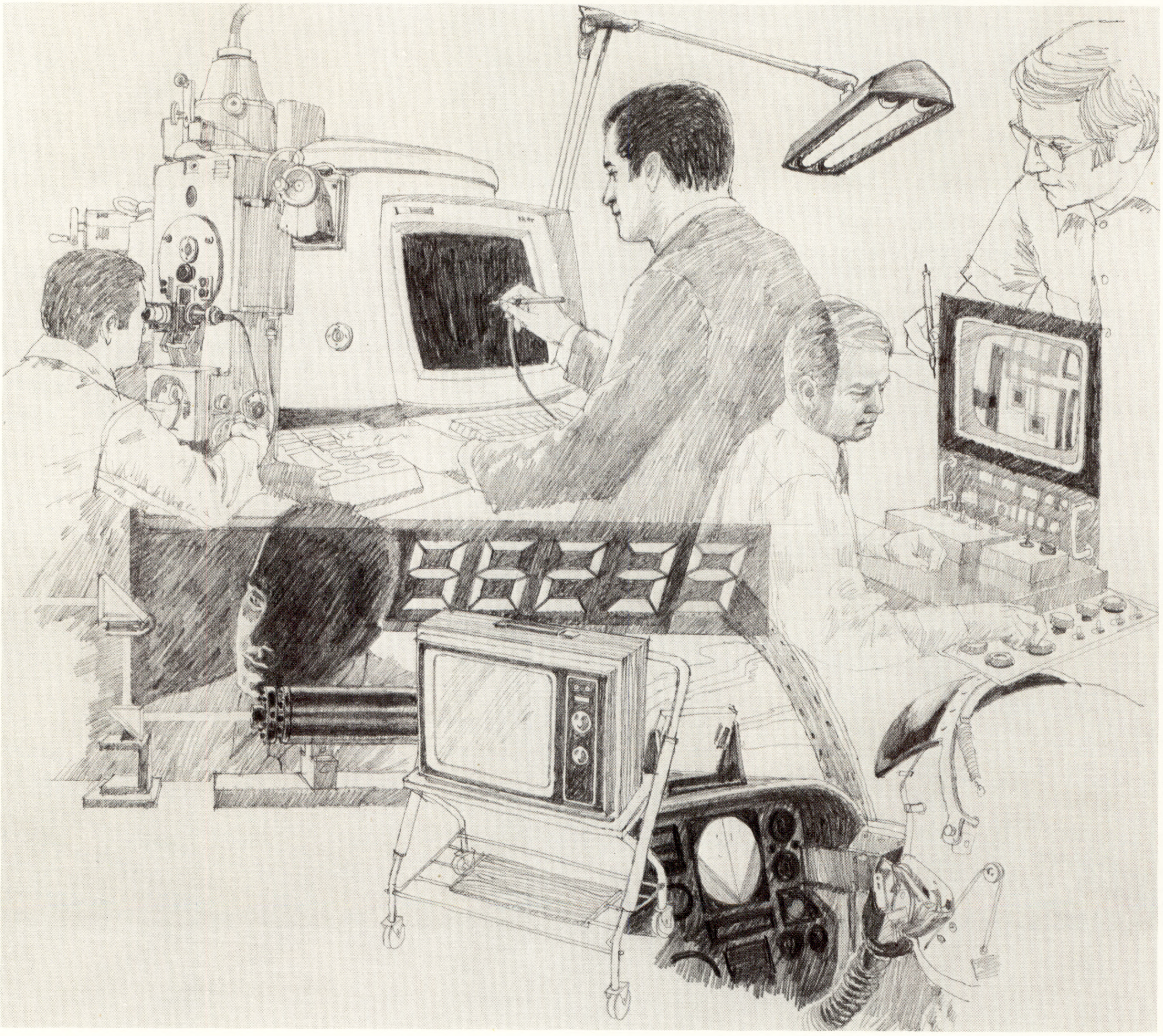
LANTERN FISH

Lantern fish live deep in the sea and would have a hard time romantically if it were not for their special light-emitting equipment. Several series of little pearl-sized, pearl-shaped organs on the sides of their heads and bodies help them keep their amorous trysts, as well as find their daily food on the dark ocean bottom.

ANGLERS

The deep-sea "angler" is very well named. Its light-emitting gland is at the tip of a stalk that rises from the end of its snout. The lighted stalk serves as a lure to other smaller fish that are the angler's favorite food. When the little fish, drawn by the light, approach near enough, they are gulped into the angler's huge, teeth-lined mouth and are swallowed.

With no inherent need for luminescence in order to feed, travel, or romanticize, man did not evolve this capability. Now, though, with lasers, microelectronic displays, and other advanced devices, he is learning to exploit luminescence to satisfy his newly risen needs in a technological era.



MICROELECTRONICS, LUMINESCENCE, AND MAN

Before microelectronics, man's uses of luminescence outside the laboratory were confined to cathode ray tubes, television tubes, electron microscopes, and fluorescent lamps. Cathode ray tubes, television tubes, and electron microscopes all employ fluorescent screens that glow when struck by streams of electrons from a cathode. Fluorescent lamps consist of tubes, filled with argon gas and mercury vapor, with electrodes at both ends. When a high enough voltage is applied between the electrodes, electrons are impelled through the gas and vapor from one electrode to the other. As they travel, these electrons dislodge other, "secondary," electrons from the mercury atoms, and the atoms emit ultraviolet light. The ultraviolet light strikes a phosphor lining inside the tube and causes it to glow visibly, with a color depending on the particular phosphor.

a maximum amount determined by the index of refraction between the crystal and the air.) Losses can be greatly reduced by careful choice of shape for the active material, and by encapsulating the semiconductor p-n-junction diode in a transparent material that comes nearer matching the index of refraction of the semiconductor in air.

LASERS

If a large enough number of electrons in a luminescent material are given sufficient energy by an externally applied source, the photons thus produced will impart exciting energy to other electrons, which will in turn produce other photons, and so on. When this artifically "pumped" process becomes a sustained one, the system is said to "lasing" or operating as a "laser" (*l*ight *a*mplification by *s*timulated *e*mission of *r*adiation).

The light *emitted* by a laser will all be of the same frequency and thus will be monochromatic (single-colored). It will also be emitted in a narrow, coherent (all-in-step) beam.

The specific frequency of laser light is determined by the material used. The frequency is proportional to the difference in energy between the upper and lower energy states of the material and this, in turn, depends on the width of the gap between the states, which is different for different materials.

Laser action is the most efficient way to collect the light generated by luminescence, and gallium arsenide is one of the most efficient photon generators among luminescent laser materials.

The 1.4-electron volt band gap of GaAs at 300 degrees Kelvin (degrees centigrade above absolute zero) dictates that the light emitted from this compound must lie in the infrared region of the spectrum—at a wavelength of approximately 9,000 angstroms at room temperature, and of about 8,400 angstroms at 77 degrees Kelvin, the temperature of liquid nitrogen.

Gallium phosphide (GaP), another Group III-Group V compound, has an "indirect gap" of 2.3 electron volts and emits at a wavelength of about 5,400 angstroms. (In "indirect materials" like GaP, photon-producing electron-hole recombinations take place by indirect routes through the host compound's energy spectrum, rather than directly across the gap between highest and lowest energy levels.) By appropriate-doping, GaP can be made to emit either green or red light, depending upon the temperature of its environment.

The diverse routing of the photons within an "indirect" material obviously means that such a material cannot be used to produce a coherent-light output. Coherent emission *can* be obtained, however, from certain *combinations* of indirect and direct compounds. GaAs and GaP can be combined, for example, to yield coherent stimulated emission. However, injection laser* action has been achieved for the combination—$GaAs_xP_{1-x}$—only with an x greater than 0.5. In compounds thus proportioned, the band-to-band transition is *direct* as in GaAs, but with x less than 0.5, the transition is *indirect* as in GaP. Wavelengths of the light emitted by the Ga(As,P) alloy lasers are greater than 6,300 angstroms at low temperatures, near the lower limit of attainable p-n-junction laser wavelengths.

**Injection lasers are so called because their performance depends on the injection of carriers under a field across a p-n junction. Electrons are driven into the region populated by holes. The recombination of electrons with holes is accompanied by the emission of light.*

BRIGHT FUTURE FOR LUMINESCENT AND LIGHT-SENSITIVE MATERIALS

The "reciprocal" abilities of luminescent and light-sensitive materials to *emit* light when stimulated, and to *detect* light of appropriate frequencies, make them almost ubiquitously useful.

These capabilities render the materials ideal for service in optical interconnection of circuits where speed is of the essence. Location of devices formed of luminescent and light-sensitive materials on opposite sides of a transparent substrate such as sapphire, for example, yields the ultimate in rapid linking of computer and other data-processing circuitry.

Electrical compatibility with semiconductor integrated circuits, bulk microwave devices, and stripline and microstrip gives luminescent and light-sensitive devices practically a *carte blanche* for incorporation into all-on-one-substrate solid-state systems.

A luminescent material application that is being given serious attention by both developers and producers is the solid-state, flat-screen display. Tiny, individual, thin-film, electroluminescent cells, deposited on a common substrate, offer the prospect of almost limitless resolution for radar, television, and fine-detail presentation of digital information. In contrast to light-emitting diodes, the density of such cells is not restrained by interwiring considerations. Also, unlike diodes, which fail individually, suddenly, and sometimes catastrophically, the electroluminescent cells fail gradually—simply dimming in light output as they deteriorate.

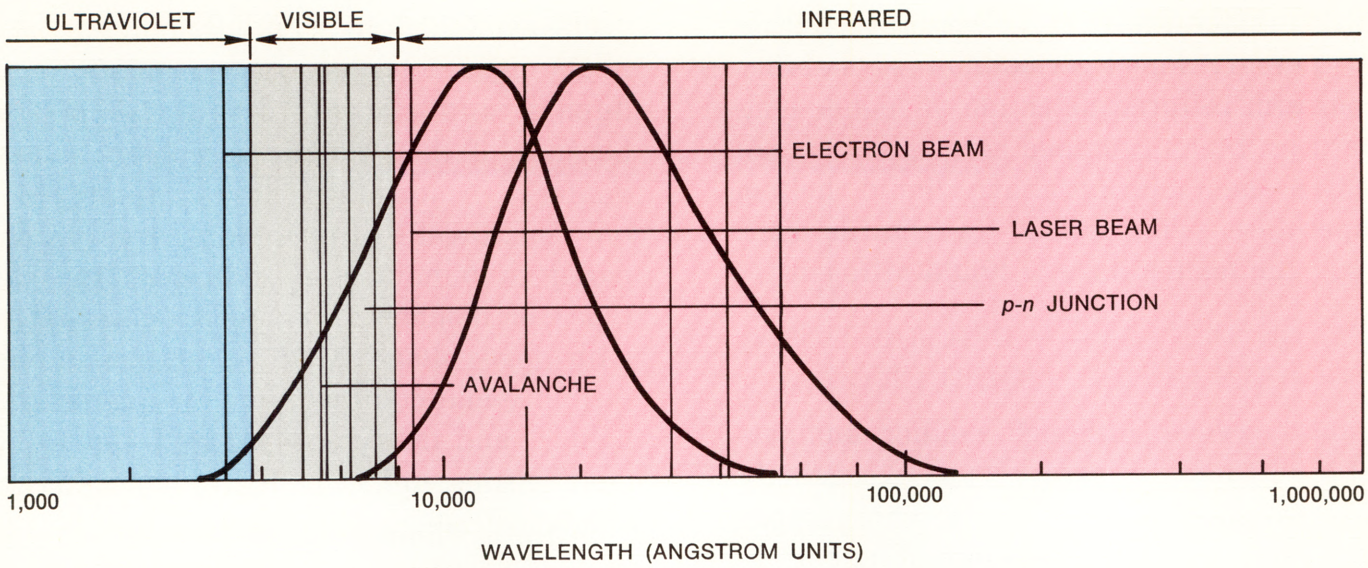
Where small display size is of particular advantage, luminescent materials are particularly attractive. Solid-state displays might be installed, for instance, right where the action is—in head-mounted systems, manual instruments, etc.—to keep important data in the field-of-vision of the operator, whether he is working in a photographic darkroom or a uranium mine on Earth . . . unfreezing a stuck solar battery array in space . . . or exploring the surface of a distant planet.

Of course, to be useful, displays must be *visible*. Right now, the only solid-state, *visible* light source that is available for practical application is an alloy of gallium arsenide and gallium phosphide. In the formula for the alloy—$GaAs_{1-x}P_x$—the parameter x can have any value from 0 to 1. For pure GaAs, x is 1, and conduction-band electrons are highly mobile; for pure GaP, x is 1, and conduction-band electrons are not quite so mobile. Experimenters have found that the highest luminous efficiency at room temperature is obtained from an alloy composition that has most of its conduction electrons in the band that is characteristic of GaAs. Output of injection diodes fabricated from the alloy is visible red light—bright enough for practical display service.

All the materials with wide-enough gaps to permit visible light emission are compounded from elements in Groups II and VI of the periodic table. However, cadmium telluride (CdTe) is the only *compound* (as opposed to *alloy*) from these groups at present that can be doped for both n- and p-type conductivity; it is thus the only one suitable for application in an injection laser.

Considerable research and development attention has been given to CdTe and, also, to various alloys of zinc selenide with zinc telluride ($ZnSe_xTe_{1-x}$). Zinc telluride can be doped with p-type impurities for high hole-conduction, and zinc selenide with n-type impurities for high electron-conduction. Over some range of values of x, combinations of the two compounds are sought in which both types of conduction are possible, and from which p-n-junction injection lasers can be fabricated.

Injection lasers are, in fact, one of the most intriguing of the many applications for luminescent materials. Such lasers have particular importance in communications. The coherent output of p-n-junction injection lasers, covers a tremendously broad band of frequencies at infrared wavelengths—in the neighborhood of 400 gigacycles. Outputs of the lasers are highly efficient, coherent, and directional. With GaAs injection lasers, communications



WAVELENGTHS SPANNED *by currently available semiconductor light sources are indicated by color in this schematic representation of a portion of the electromagnetic spectrum. The broad-band emission spectra for two incandescent lamps (gray curves) are shown for comparison; the maximum filament temperatures of the lamps are 3,100 degrees centigrade (left) and 1,400 degrees C. (right). The black horizontal lines show the ranges covered by four different methods used to excite luminescence in semiconducting crystals.*

have been achieved over a distance of several miles.

In any total communications system, there must be a detector, as well as an emitter, of signals. Here, *light-sensitive* materials play a brilliant role.

The most sensitive and most used material for detecting infrared has generally been mercury-doped germanium, but a variety of combinations promises to replace mercury-doped germanium for applications not requiring that material's extreme sensitivity to light. Detection of infrared has, of course, many potential uses—both military and peaceful, including, for example, the conduct of satellite surveys of earth resources, detection of missile warheads from space, and measurement of enemy troop and equipment concentrations on the ground.

Lead-tin-telluride seems particularly promising for infrared detection. The factor that makes mercury-doped germanium sensitive to infrared (that is, the element which acts as the infrared light absorber) is the mercury. The germanium is capable of "holding" only a little mercury, and it takes a thick piece of germanium to contain enough mercury to absorb all the light that can be expected to enter the device in actual operation.

Although lead-tin-telluride is not so sensitive as mercury-doped germanium, the entire lead-tin-telluride crystal is the light absorber. Thus, very thin films of this substance can, with a given infrared input, yield as high an output as a massively thick chunk of doped germanium.

Ability to use lead-tin-telluride in thin-film form obviously means smaller-size, lighter-weight devices. It also means that the luminescent detectors can be built on the same substrate with other microelectronic communications system components. And it means the advantage offered by almost all types of solid-state microelectronics—an inherent amenability to batch fabrication and automated production and, thus, lower fabrication costs and higher device reliability.

Accuracy of any light-sensitive detector, and its ability to distinguish between a multitude of competing signals including background noise, rise with the number of cells into which it is divided. For the thick, mercury-doped germanium, each individual cell "cube" would have to be cut and literally pasted into place. With a thin film of lead-tin-telluride, thousands of separate little cells could be made photolithographically with truly microscopic individual dimensions and extremely high density.

Still another advantage of lead-tin-telluride over mercury-doped germanium is its ability to perform infrared detection at higher temperatures. Mercury-doped germanium cannot operate satisfactorily above liquid helium temperature, whereas lead-tin-telluride operates at the temperature of liquid nitrogen.*

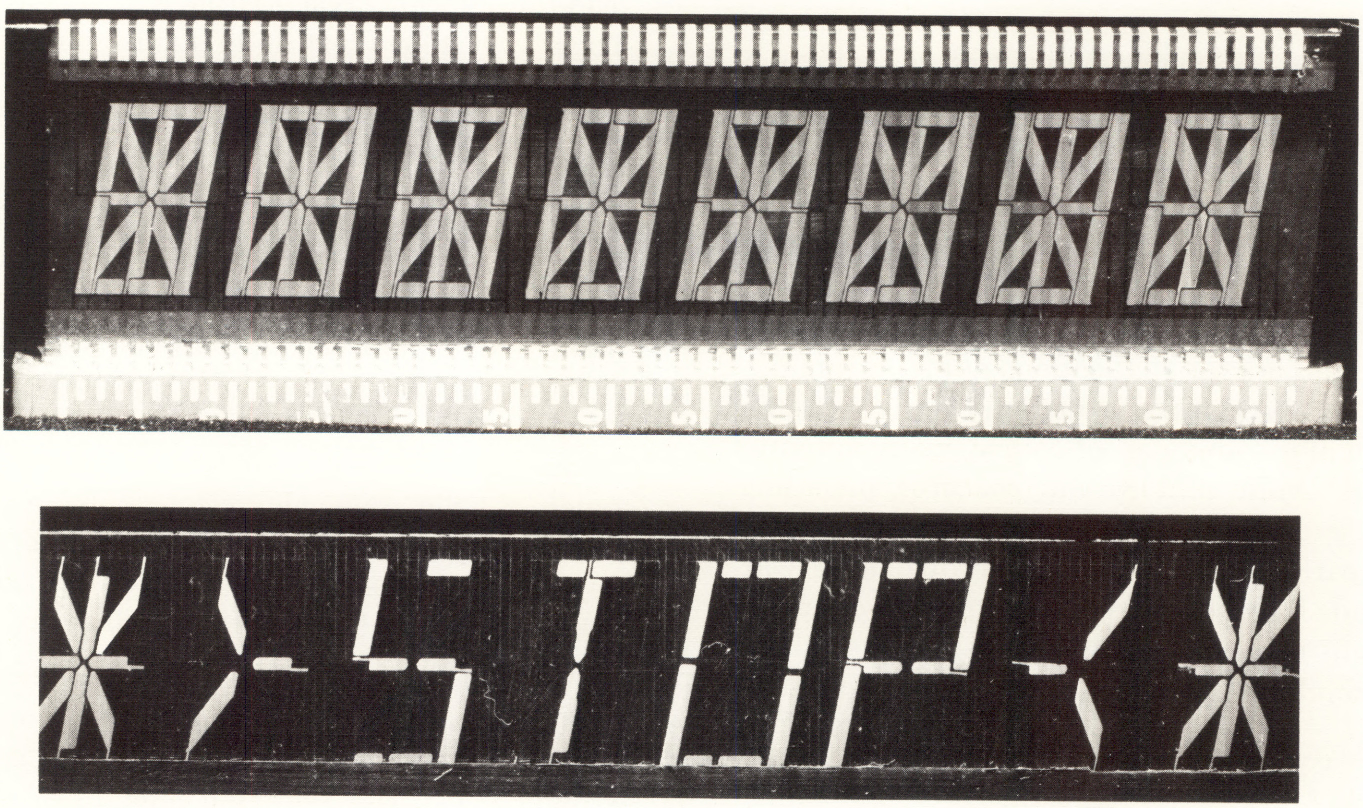
NOW ON DISPLAY—A BRILLIANT NEW MATERIALS GROUP: LIQUID CRYSTAL

Liquid crystal, although neither luminescent nor light-sensitive, forms an exceedingly important class of materials in whose application light is an important operating parameter.

Liquid-crystal displays (LCD's) are being given delighted acceptance by all sorts of users—watch designers, automotive component manufacturers, instrumentation producers, and aircraft display planners—because of their unique combination of advantages. Among these are a requirement for only microwatts of operating power, as compared to hundreds of milliwatts for other types of displays . . . complete compatibility with low-voltage MOS electronics . . . high visibility and contrast even in brightest daylight . . . and the typically only $^1/_8$-inch-thick, "flat" display units which they make possible.

In truth, "liquid crystal" is neither crystal nor liquid. Liquid crystal materials partake, however, of the characteristics of both of these states of matter—hence the poetically pleasing name.

WITH BASIC "STARBURST" ELEMENT, ALL NUMBERS, LETTERS, AND SYMBOLS ARE POSSIBLE



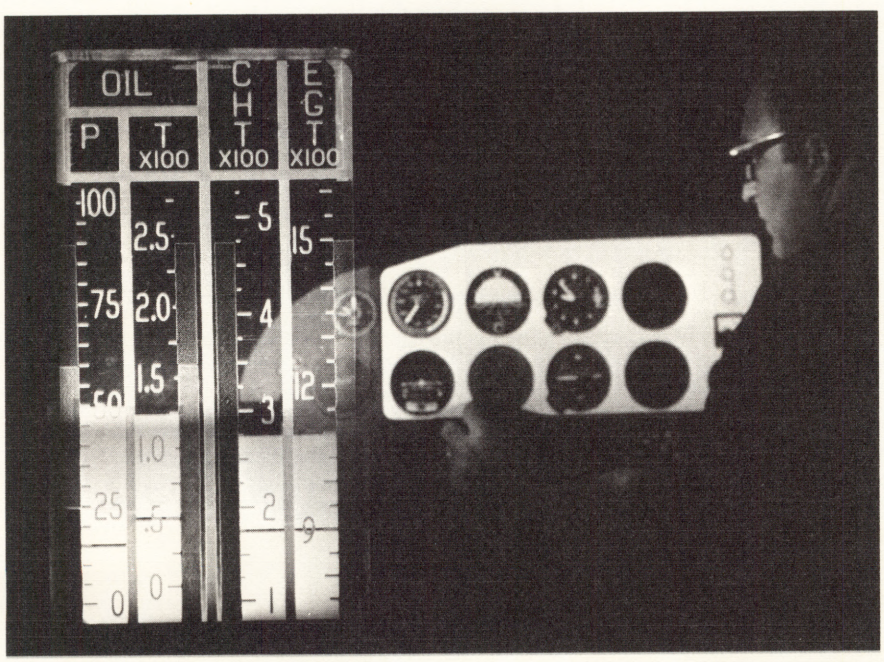
Mixed-compound semiconductors such as lead-tin-telluride are not only useful for detection of heat and infrared light. They are also proving their worth as high-performance detectors in Rockwell International's unique carbon dioxide laser radar system. This radar system is the only known operating laser radar system in the world, and Rockwell's achievement of, and ability to repeat, lead-tin-telluride thin-film deposition on insulating substrates are both unique breakthroughs of this company's laboratories. The compounds of the lead-tin-telluride are formed while the constituents are in the gaseous state. The ratio of the constituents while in the gaseous state are not exactly the same as their ratio in the produced compound, but the differences are known and the product can be uniformly and predictably reproduced.

Webster's defines liquid crystal as "A mesomorphic substance having observable optical anisotropy like a crystal as evidenced by double-diffraction polarization, but having such low viscosity as to behave mechanically like a liquid." What this boils down to is that the organic chemicals termed "liquid crystal" are liquids in that they flow and conform to the shapes of their containers, but their molecules are arranged uniformly as though they were crystals. It is exactly these two properties that make liquid crystal the particularly appropriate display medium that it is proving to be.

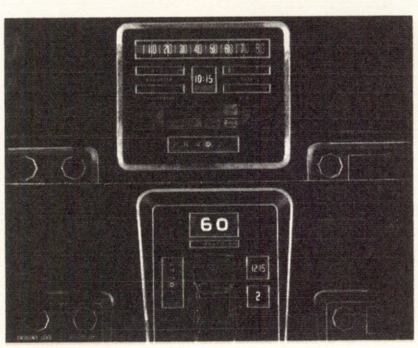
When exposed to light, liquid-crystal materials either scatter the light, or let it pass through undisturbed, depending upon whether or not, the materials are, at the same time, subjected to an electrical field. This strange behavior was discovered away back in 1888, but the phenomenon was regarded merely as a laboratory curiosity until late in the 1950's, when investigations of practical use began. Now, in the 1970's, LCD's are being volume-produced for a variety of applications.

Working well at the typical 25-volt levels of MOS logic circuitry, LCD's provide compact, high-efficiency, low-powered monitoring/status displays to go along with LSI microelectronics to form complete, reliable, low-cost, small-size systems. Liquid crystal characters can be manufactured small enough for use in a digital wristwatch. They can, on the other hand, be made about twice as large as the lowest-cost conventional displays (i.e., fluorescent and neon-type tubes) at about half the cost.

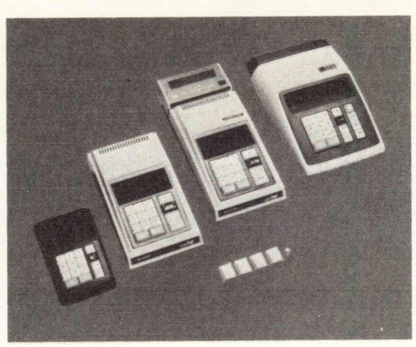
LIQUID-CRYSTAL HAS MANY APPLICATIONS...



Aircraft Engine Instrument Display



Automotive Displays

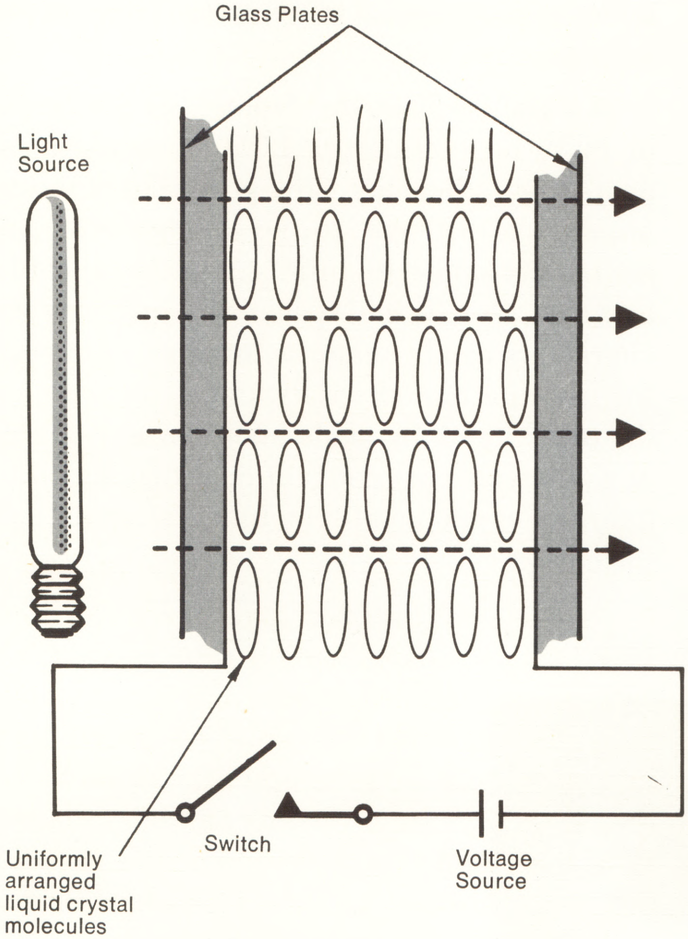


Rockwell MOS/LSI Calculators Feature Liquid-Crystal Displays

Multimeters

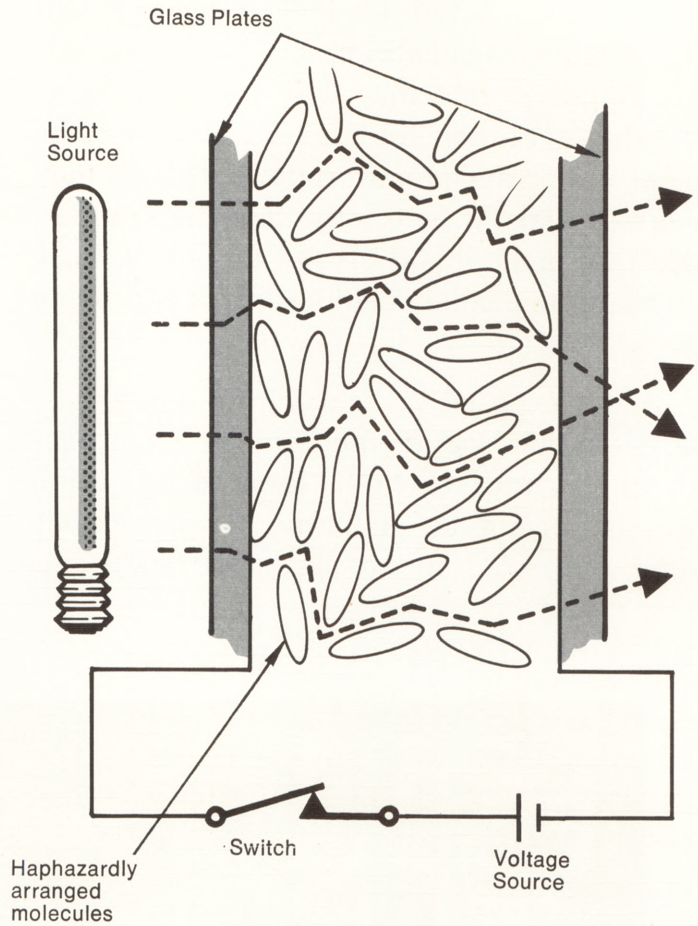
LIQUID-CRYSTAL DISPLAYS LIGHTEN CALCULATOR TASKS

NO EXCITATION, NO GLOW



In absence of electrical excitation, liquid crystal is transparent, and incipient light rays pass through "undisturbed."

EXCITATION PRODUCES BRIGHT GLOW



With electrical excitation, the liquid crystal molecules are "upset" so that they scatter light rays and the area appears to glow.

In LCD's being mass-produced by Rockwell International for MOS/LSI calculators, 7-segment digits are used. Each digit is ½-inch high and is formed by applying tin oxide—a transparent electrical conductor—on the insides of two glass plates. The two plates are separated by a space of only around one-third the thickness of a human hair (about 1/1000 inch), and this space is filled with liquid crystal.

HOW DIFFERENT NUMBERS ARE FORMED

Each digit has 7 segments, and each segment has its own separate, transparent lead.

Different numbers are formed by electrically exciting different combinations of segments and the segments' associated liquid crystal.

Each digit in the display is a figure "8" composed of seven separate segments, with tin oxide leads connected to each segment. When a segment is electrically excited, the liquid crystal associated with the segment appears to glow. If all the segments of a digit are energized, an "8" appears; six segments produce a zero, "0"; five, a "5"; two, a "1"; and so on. Eight independent decimal points, a minus sign, and two dots to signal that the display's capacity has been exceeded complete the LCD.

ANOTHER VERSATILE MATERIALS FAMILY—THE FERRITES

The future of "light" generating, sensitive, and reactive materials is certainly, in more ways than one, a glowing one. But there is another family of materials that is strongly vieing for the spotlight. These materials are the ferrites.

Ferrite circulators and isolators replace yesterday's unreliable T-R (transmit-receive) tubes to keep transmitter signals out of a system's receiver, and vice versa. They act as one-way streets for guiding microwave signals, and can function as microwave switches, duplexers, and buffers. Fabricated from high-resolution microstrip* deposited on ferrite substrates, such devices have just about revolutionized high-frequency microelectronics over the past decade (see page 119).

What are the properties of ferrites that have propelled these materials into positions of such prominence and importance? The properties are three, all equally unique: Ferrites have an insulator's high resistivity, the ability to be magnetized, and functional nonreciprocity—that is, they perform one way in one direction, and an entirely different way in the opposite direction.

How can any single material act like both an insulator and a metal? As with luminescent materials, the "strange" behavior of ferrites derives from the basic crystalline structure of the substances involved, and the binding forces of their atoms.

There are three basic groups of ferrites—spinel, garnet, and magnetoplumbite. Each is characterized by a differently patterned crystal lattice, but all three are made up of atoms of oxygen, metals, and rare earths. Spinel crystals are tiny cubes, garnet crystals are microscopic dodecahedrons, and, as one would imagine, hexagonal magnetoplumbite ferrite crystals are diminutive six-sided solids. Because the bonds between the atoms of all three kinds of ferrite crystals are ionic, their lattice-atom electrons are very tightly bound. The dearth of free electrons to move about and carry current is what makes a ferrite behave like a very high-resistance insulator. Typical resistivities range from 10^7 to 10^{10} ohms per square centimeter.

The second valuable property of ferrites is their un-insulator-like ability to be magnetized. Here, some definitions are called for, in order to avoid the understandably common confusion over the difference between "ferromagnetism" and "ferrimagnetism."

Any *ferromagnetic* material (for example, iron) contains a number of different areas called "domains." Within each domain, all the atoms' magnetic moments line up and point in the same direction. From one domain to another, moments gradually shift direction, in parallel, until they assume the new direction of the second domain. In an "antiferromagnetic" material, the individual atomic magnetic moments are equal in magnitude, but every other one is opposite in direction and thus they cancel out one another's effects, with the result that a sample of the material has no *net* magnetism. In a *ferrimagnetic* material, adjacent moments are also oppositely directed, but are unequal in magnitude; consequently, the material has a net magnetism. Ferrites, compounded of rare earths and metallic oxides, are ferrimagnetic.

The third ferrite property—behavioral nonreciprocity—is both the most interesting and the most complex.

In truly passive electronic circuitry, performance is reciprocal. You can, for example, label the two ends of a wire A and B, and it doesn't make any difference whether you connect A to the positive terminal of a battery and B to the negative, or B to the positive and A to the negative. The same amount of current will flow through the wire in either event. It doesn't matter whether the end of the resistor that has the color-code bands on it faces north, south, east, west, up, or down—the resistance in ohms that the resistor presents to current flow will always be the same.

Extremely narrow deposited metal "stripline" conductors, especially useful in microwave applications, where the relationship of physical dimensions of circuitry vs wavelength becomes meaningful to circuit performance.

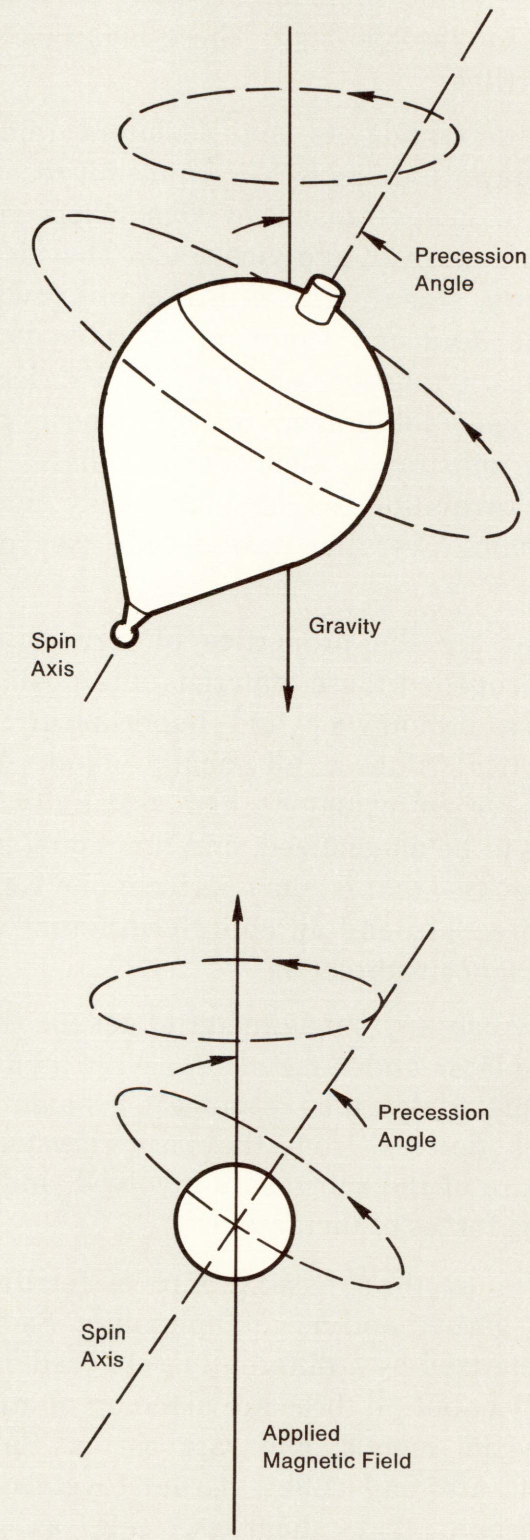
But ferrimagnetic materials do not consistently act in this reciprocal manner. Sometimes they do, sometimes they don't. It all depends.

It depends, first, on what electromagnetic region a ferrite is operating in. If it is the region of microwaves, then its performance becomes nonreciprocal. Other determining factors in ferrite reciprocity vs nonreciprocity are: just how the ferrite is positioned in the applied microwave magnetic field, how the microwave field is polarized, and how strongly the ferrite is biased with a d-c magnetic field.

The two important effects that can be either reciprocal or nonreciprocal in ferrites are phase shift and attenuation. Placed in a linearly polarized microwave magnetic field and properly d-c field-biased, a rod of ferrite will conduct electromagnetic energy equally well in either direction, and the amount of phase shift for a given length will be equal in both directions along the rod. If, however, the ferrite is positioned at certain critical points in a circularly polarized microwave magnetic field, and is biased into the region of "gyromagnetic resonance," both phase shift and attenuation will differ with direction of propagation down the rod.

Now—just what do we mean when we speak of "proper d-c field-biasing" and "gyromagnetic resonance"?

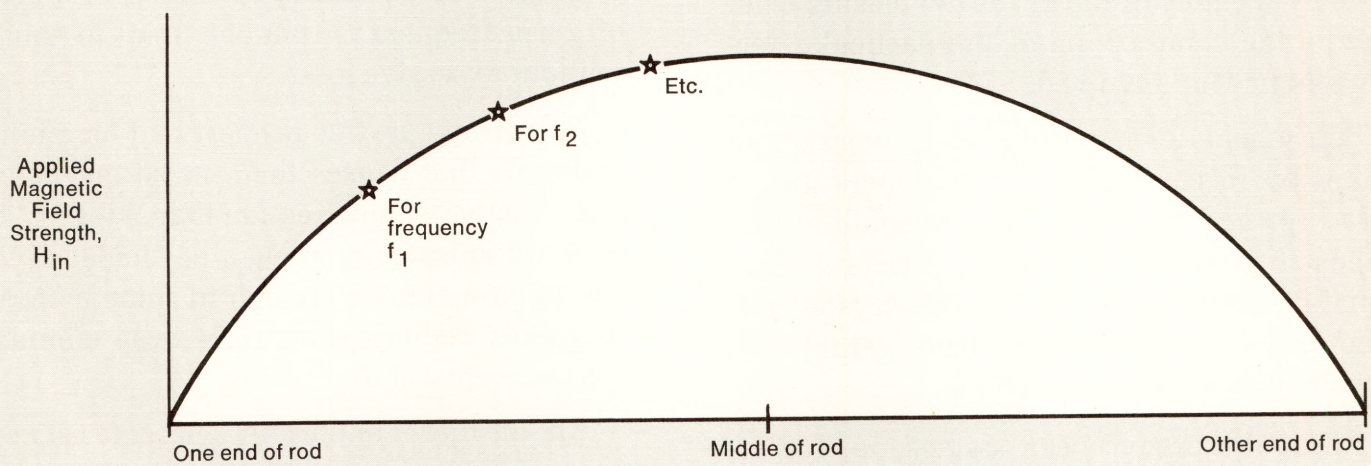
You have probably noticed how a spinning top seems to sort of nod back and forth as it rotates. What is actually happening is that the tip of its spin axis is *precessing*—that is, it is describing a little circle—about the direction of the force of gravity (see diagram). This is because the spinning top has two forces on it, each attempting to control the top's position and attitude. First is the spin force itself—this force acts circularly in a plane that is more or less horizontal to the earth surface; thus, the axis of the spin is more or less "off" precise vertical. The second force is gravity—which does, of course, act vertically. The two competing forces cause the top to precess, in its attempts to reconcile them.



TOY TOP VS SPINNING ELECTRON

A spinning orbital electron subjected to an external magnetic field is like a spinning top subjected to gravity. In an attempt to line up with the direction of the applied magnetic field, all the ferrite electrons' spin axes precess about the latter. If there were no resistance to this precessional motion, the spin axes would continue to precess about the applied field axis at a characteristic (natural) frequency called the "Larmor frequency." Because of energy dissipation processes in the material, the precession angle will slowly decrease until the spin axes are lined up with the applied field direction. If, however, the ferrite is placed in an alternating electromagnetic field that is perpendicular to the d-c biasing field and has the Larmor frequency, the energy lost in the material during each cycle can be absorbed from the a-c field. The spin axes will then continue to precess about the d-c field axes with a constant precession angle, continually absorbing power from the a-c field. This is the condition called "gyromagnetic resonance." (When related to ferro- or ferrimagnetic materials, the resonance condition is commonly referred to as "ferro- or ferrimagnetic resonance.")

The repeated interaction between orbiting electrons and an applied electromagnetic field, as described above, is the process responsible for phase shift and attenuation effects in ferrites.



SYMMETRICAL MAGNETIC FIELD DISTRIBUTION IN A FERRITE ROD AND FERRIMAGNETIC RESONANCE

When an r-f magnetic field is applied to a ferrite rod, the electromagnetic energy seems to travel down the rod, to be reflected from the far end of the rod, and to reappear unchanged at the input end after a delay equal to the time to make the trip. Actually, during its round-trip through the rod, the r-f energy has been converted into mechanical (elastic) energy and back to r-f energy again. The "ferrimagnetic resonance" point ☆ along the rod's length at which this occurs is different for each different frequency. In research jargon it is called the "turning point." This frequency-discriminating behavior is termed "dispersiveness"; it is of extreme importance for many filter and delay line applications.

The magnetic field inside a sample of ferrite varies with the sample's shape. In a sphere, the internal magnetic field is about equal to the applied field, and its resonant frequency varies linearly with the applied field's strength. If the external field is doubled, the resonant frequency doubles, for example. The stronger the external field, the higher the frequency.

The internal magnetic field inside a rod of ferrite is distributed symmetrically along its length, approximately as shown in the diagram at the bottom of page 91. The resonant frequency has one value at one point along the length of the rod, and other values at other points. Although the specific resonant frequency differs with specific location along the rod, resonant frequencies at all points increase with a stronger external magnetic field.

Frequencies depend not only on shape of the piece of ferrite and magnitude of the applied alternating field. They are determined, also, by the magnitude of the d-c biasing field, and by the composition of the particular ferrimagnetic field involved.

Ferrimagnetic materials being worked on today by researchers and developers are of three principal kinds: polycrystalline (as opposed to single-crystalline) ferrites, hexagonal-crystal ferrites, and single-crystal garnets (such as gadolinium iron garnet and yttrium iron garnets, or "YIG").

All of these have been singled out for attention because of their special attributes. Among the attributes of interest are what the scientists term saturation magnetization, Curie temperature, linewidth, and anisotropy.

Saturation magnetization is the point beyond which increase of applied field strength causes no increase in a sample's net internal magnetization. It is important because the lowest operating frequency in megahertz for most ferrites is approximately equal to the saturation magnetization in gauss. Thus, the lower the saturation magnetization, the lower the frequency at which the ferrite can operate.

Curie temperature is the temperature at which net magnetization drops to zero. Curie temperature is important because of its relationship with saturation magnetization. The latter decreases with temperature rise until the Curie temperature is reached, beyond which point it is completely unaffected by increase in temperature.

Linewidth is inversely proportional to a ferrimagnetic material's ability to carry a signal from one point to another without "insertion loss" or, in other words, attenuation of the signal by absorption as it travels through the material. Linewidth is a measure of the difference (expressed in uints termed "oersteds") between the low and high values of applied biasing magnetic field strengths at which the power absorbed by the material from the alternating field is equal to half the maximum absorbed by that material at any field strength. Linewidth is important because it is a measure of a material's "Q"* and, thus, a measure of its ability to transport a signal of given frequency from one point to another without excessive loss.

Anisotropy is the property of crystalline materials that causes them to be magnetized more easily in one direction than another. The effect of anisotropy along a particular crystal can be pronounced enough in some materials to greatly reduce, sometimes even eliminate, the necessity for d-c biasing.

All of these important characteristics of ferrimagnetic materials can be altered by ploys that smack of alchemy . . . in which some of the materials' iron atoms are replaced with atoms of other materials. The ability to change characteristics in this manner permits ferrite compounds to be precisely tailor-made for special performance requirements.

**The "Q" of an a-c circuit is the ratio of its reactance to its resistance. The voltage developed across the reactance is usable signal, but the voltage developed across its resistance subtracts from the signal. Thus, a high Q indicates an efficient, low-loss a-c circuit.*

The exotic behavior of ferrites seem almost heaven-made for some applications. Probably the most widespread use at present is in microwave signal "isolators" and "circulators." Both types of device take advantage of the non-reciprocal attenuation property of ferrites, to keep signals out of places they should not enter and to transmit them without loss to the destinations for which they are intended. A most common use of these devices, already mentioned, is to isolate a receiver from a transmitter sharing a single antenna. Ferrite isolators and circulators also serve as buffers between amplifier and frequency multiplier stages, and as protective receiver-input limiters. Ferrite microwave filters have been fabricated with high Q's over enormous tuning ranges. Phase shift of from 0° to 360° has been attained with ferrite units for electronically-scanned, solid-state radar antennas. Frequency filters have been made in ferrite which "sort out" microwave signals into their frequency components—a vital function for spectrum surveillance. New epitaxial materials now available allow whole filter banks to be made on small "chips" of crystal of the garnet class. (Functioning of ferrite devices as components of systems and subsystems is discussed in greater detail in Chapter V, "The Expanding Invasion of the Microwaves.")

ON THE SURFACE, VERY PROMISING—MICROACOUSTICS

Already, ferrites have revolutionized microelectronics. Where their prospects are most exciting, however, lies in a most basically different, yet very closely related, technology—"microacoustics."

The devices of the related technology are, like their electronic cousins, solid-state and monolithic. In addition to ferrites, they employ such of our old electronic-world friends as semiconductors, single-crystal substrates, heteroepitaxy, and microstrip. But—instead of depending primarily on current flow or the movement of an electric field, the newer devices depend on the motion of a sound wave through or along the surface of a solid. The "surface-wave mode" is the approach offering most to microcircuitry.

A clever name was originally proposed for the new science: "praetersonics." "Praeter" is Latin for "beyond, beyond the range of, surpassing"—and "praetersonics" was just a fancy way to say "ultra-ultra-ultra-sound." The term has long since been discarded, however, as being too *ultra fancy*—and the name that has stuck and is used today is "microacoustics."

No matter what you call it—microacoustics, microsound, microsonics, or praetersonics (all of which have found some favor at some time or another during the last few years), the new technology yields a family of components that operate well over 10 gigahertz, with bandwidths of more than 1 gigahertz.

HOW MICROACOUSTICS CAN BE APPLIED

The microacoustics technology was born of the urgent need in the 1960's and '70's for faster, simpler, *communications.* In defense, space exploration, commerce, and industry—ever burgeoning amounts of information require processing and transmittal.

First of all, in the complex command/control system for our Army, Air Force, and Navy, a multitude of signals from sensitive radars and various other sensors—infrared, laser, and television—must be digitized, routed, integrated, and otherwise processed to monitor tactical situations, to guide and control vehicles, to inform and instruct personnel, and to detect, track, and destroy enemy threats.

In the exploration of Space, also, huge amounts of data must be processed to keep ground stations telemetrically informed of astronauts' physical conditions and of spaceship location and progress, to handle communications between Earth and space crew, and to direct the actual guidance and control of the spacecraft itself.

In commercial, industrial, and scientific areas, needs for rapid processing of voluminous amounts of data are just as formidable. Marketing reports, criminal identification and tracking, banking transactions, medical research, abstracting and dissemination of scientific reports, public carrier reservations control—these are but a few of the myriad applications.

All of the many demands for high-speed, high-volume data and signal processing reduce to a few basic and common needs—for efficient storage of masses of information in as small a space as possible, for processing of each set of data as fast as possible to allow time for all of the data to be handled, and for as wide a bandwidth as possible in order to take care of the many different frequencies with which the data or signals may arrive for processing.

As just one example of what is already involved today: A typical missile radar can be required to handle, in just a few minutes, hundreds of thousands of separate reflected microwave returns, over bandwidths of several hundreds of megahertz. Tomorrow's "all-purpose" space electronics system—for guidance and navigation, rendezvous and tracking, telemetry, and communication—will be required to handle as many as a billion bits of information in a single second, and bandwidths will be measured in hundreds of megahertz. With microacoustics, this becomes a feasible capability.

Take the first need—for small-space storage of data. In a one-*centimeter*-long length of solid-state, microacoustical delay line, it is possible to store a signal that would require a one-*kilometer*-long length of air-filled transmission line!

This attribute of microacoustical devices—physical smallness—is perhaps the hardest one of all for the uninitiated to swallow. The first thought that strikes almost any layman's mind when he first hears about acoustic microcircuitry is, "But sound waves are so *big!*"

We think that, because sound waves are slow-moving, they must be lumbering, gross. We think of electrical current and electric fields as flashing along at the speed of light, vibrating at ultra-high frequencies, with wavelengths measured in microns. Few of us stop to apply the simple, basic formulas that give a valid comparison and a true picture of the differences between acoustical and electronic "dimensions."

It is true that sound moves very, very slowly compared to electrons or an electric field—100,000 times as slowly, in fact. It is for just this reason, however, that the sonic wavelength is much *shorter* than the electromagnetic wavelength at the same frequency.

Let's take an example.

Suppose we have two signals—an acoustical one, and an electromagnetic—both at a frequency of 1000 megahertz (which is one gigahertz or 10^9 hertz). At this frequency, the wavelength, λ_{em}, of the electromagnetic signal, travelling at the speed of light, is 30 centimeters or 300,000 microns. (One micron is equal to 10^{-6} meters or 10^{-4} centimeters.) To find wavelength, velocity is divided by frequency. Thus,

$$\begin{aligned} \lambda_{em} &= \frac{V_{em}}{10^9} = \frac{300 \times 10^6 \text{ meters/second}}{10^9} \\ &= 300 \times 10^6 \times 10^{-9} \\ &= 300 \times 10^{-3} \\ &= 0.3 \text{ meter} \\ &= 30 \text{ centimeters or } 300{,}000 \text{ microns} \end{aligned}$$

Because sound, however, travels only one-hundred-thousandth (10^{-5}) as fast as an electromagnetic signal, at the same 10^9-hertz frequency, the wavelength, λ_{ac}, of the acoustical signal would be just 3 microns! To see how this is so, we use the same equations as before, thus,

$$\begin{aligned} \lambda_{ac} &= \frac{V_{em} \times 10^{-5}}{10^9} \\ &= \frac{300 \times 10^6 \times 10^{-5} \text{ meters/second}}{10^9} \\ &= 300 \times 10^1 \times 10^{-9} \\ &= 300 \times 10^{-8} \\ &= 0.000003 \text{ meter} \\ &= 0.0003 \text{ centimeter or 3 microns} \end{aligned}$$

These figures do not lie. They are based on accepted laws of physics, and they offer a convincing argument for the emphasis being placed on attainment of acoustical microcircuitry: For a given frequency, acoustical wavelengths are only a fraction of the size of electromagnetic wavelengths. It follows, then, that acoustical devices need be only a fraction of the size of the electronic ones. Storage devices and delay lines, for instance, can be much smaller with acoustics than with electronics. Many applications that have long existed in concept, but have been impossible because of the space it would take to implement them with electronics, now become feasible with acoustics, for the first time.

Microacoustics' basic advantage of smaller size is offset at some frequencies, however, by the disadvantage of higher attenuation.

With the microacoustic approach, attenuation is proportional to the square of signal frequency, but with the electromagnetic approach attenuation is proportional only to frequency raised to the "$^1/_2$" power. Thus, when the frequency of an acoustical signal is quadrupled, the attenuation through a given medium becomes sixteen times as great—but when the frequency of an electromagnetic signal is quadrupled, attenuation is only doubled. There is obviously some crossover point at which attenuation with acoustics equals attenuation with electromagnetics for the same frequency. This point, in fact, happens to be around 2 gigahertz. At and beyond this point, there would be no advantage—insofar as attenuation is concerned—in using acoustics rather than electronics, but below 2 gigahertz we still have quite a big field to play in and acoustics has many other offerings such as size advantage to offset this questionable "weakness" at higher frequencies.

Will microacoustics ever replace microelectronics?

Actually, micro-*electronics* and micro-*acoustics* are as compatible as that trite but ever-loving pair—ham and eggs. Mixing metaphors a bit, they are really two faces of the same key, and complement rather than compete in unlocking the door to the world of the micro- and millimeter waves.

MICROACOUSTIC COMPONENTS

The three basic surface acoustic wave (SAW) components with which microacoustics technology performs its wonders are the transducer, the transmission line, and the amplifier. These primary elements, combined into various end-product devices, are being fabricated and marketed to fill a variety of applications.

TRANSDUCERS

Microacoustic transducers are used to transform an electrical signal into sound waves and to introduce the latter to the surface of a sound-propagating solid. They take a number of forms. One type sends the sound down a shallow wedge onto the surface. This type is useful to some degree at low frequencies, but it is not very efficient, because most of the energy is lost through reflection at the interface between the wedge and the solid, with only a small portion being usefully transmitted along the solid's surface.

Better than the wedge is a comb-shaped transducer, with "teeth" separated by spaces of one acoustical wavelength. This, too, is "lossy," however. Also, at high frequencies its dimensions become so small that it is difficult to fabricate and mount in the necessary "on-edge" position—although a modified version of the comb transducer can be directly deposited on a substrate for use up to about 3 gigahertz.

Most practical, so far, is the interdigital transducer, in which the teeth or fingers (depending on how you personally view the "anatomy" of a comb!) of *two* combs interlock, with a half-wavelength spacing between each two fingers. This type of transducer lies flat on the surface of a piezoelectric* material and can be photolithographically formed. Researchers have achieved gigahertz operation and broad bandwidths with interdigital transducers.

**A piezoelectric material is one which responds to mechanical strain with an electrical voltage, and to an electrical voltage with a mechanical strain. In the latter case, if the applied electrical voltage is alternating, the mechanical strain, or pressure, progresses as a sound wave through the material.*

TRANSMISSION LINES

A microacoustic transmission line is made up of two transducers (one at each end of the line to form input and output) and a length of acoustically propagating material in-between. The acoustical medium consists of a thin, acoustically propagating film overlaid epitaxially onto a suitable substrate.

Delay Lines When a microacoustic transmission line is used as a delay line, the signal travels to the "far-end" transducer, where it appears as a delayed pulse of voltage. The time of travel from input to output constitutes the delay.

Acoustical waves travel with different velocities through different materials, and the amount of delay obtained with a given line depends on line material and length.

Waveguides If one wishes a Rayleigh* wave to travel in any direction other than a straight line, there are various ways of getting it to do so. One way is to send it through grooves cut into the surface of the acoustically propagating material. Another way is to beam it through a strip of "acoustically slow" material overlaid onto a "faster" acoustic substrate. With some loss, the acoustic energy will follow the "slow" material around gradual bends. Like a fast-moving automobile, though, the wave won't make the curves if they're too sharp! A solution to this difficulty is to overlay a "fast" material with a "slow" one, and to then cut a groove in the overlay for the surface wave to travel along.

A "fallout" benefit from overlay transmission line techniques is that loose coupling can be obtained between closely adjacent lines. Thus, formation of directional couplers with this approach is possible.

AMPLIFIERS

In any microacoustic amplifier, the principle involved is that when a sound wave is passed through a piezoelectric material, an electrical field is generated which travels along with the acoustical signal, and the electrical signal thus produced is capable of amplification.

There are two basic types of surface-wave amplifier. In one (the combined-medium amplifier or "CMA"), different materials with different properties to satisfy the different requirements are epitaxially layered to form an open-face sandwich type of structure; the substrate material is the piezoelectric acoustic propagator, and the overlay is the interacting semiconductor for amplification. In the other surface-wave amplifier type (the separated-medium amplifier or "SMA"), the various material layers are actually spatially separated by an air gap.

MICROACOUSTIC MATERIALS

As with virtually all the other microcircuit and microdevice achievements discussed in this book, the achievements of microacoustics are made feasible through advances in the materials sciences. And it is directly due to the properties of certain materials that microacoustic devices can and do behave in the extremely useful ways they do.

Surface acoustic wave (SAW) devices demand a variety of materials having a variety of properties. Piezoelectric or ferrimagnetic materials are needed for transducers, low-loss materials are required for transmission lines, and semiconductor materials are necessary for amplifiers.

Around 1963, new materials with the requisite properties for SAW applications began to be investigated. Among the most prominent of the materials studied during the last decade or so have been cadmium sulfide, zinc oxide, lithium niobate, magnesium oxide, yttrium aluminum garnet or "YAG," and the ever more famous in ferrimagnetic circles—yttrium iron garnet or "YIG." The properties of these and other materials valuable for microacoustics are indicated in the accompanying table.

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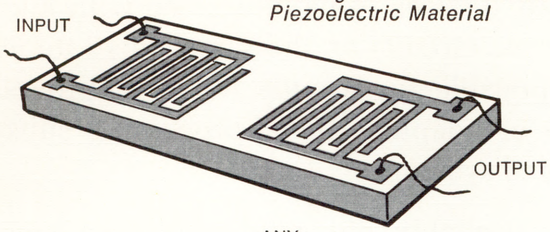
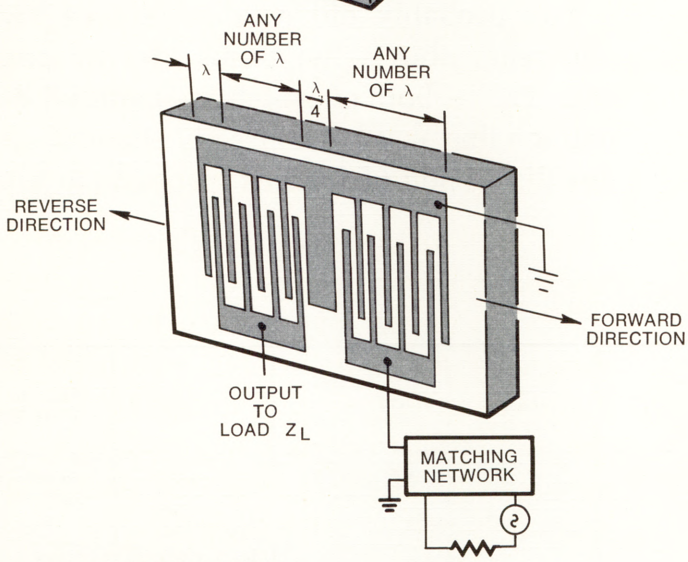
* *Lord Rayleigh first derived the equations governing the propagation of surface elastic plane waves along the stress-free boundary of a semi-finite, isotropic, and perfectly elastic solid. The particle motion at the surface is retrograde elliptical, and the velocity v_S is slightly less than the bulk transverse wave velocity v_T. Rayleigh formally set down his equations in a report published in November 1885, in the Proceedings of the London Mathematical Society, Vol. 17, pages 4-11.*

SURFACE ACOUSTIC-WAVE COMPONENTS

TRANSDUCERS

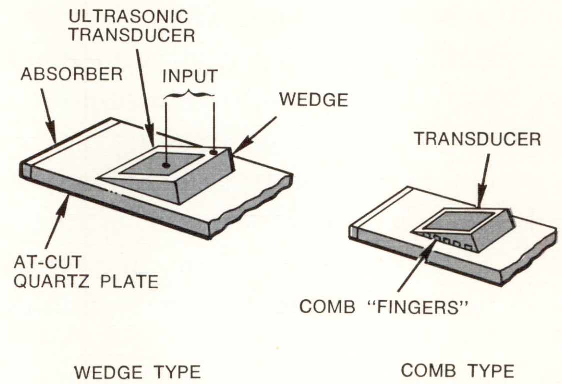
Interdigital Transducers on Piezoelectric Material



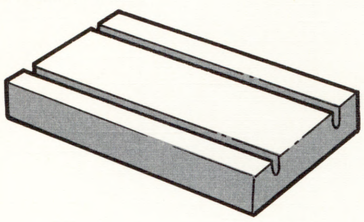


Directional Transducer

This directional transducer uses a resonated array as an acoustic reflector spaced a quarter wavelength (λ/4) from the driven array.

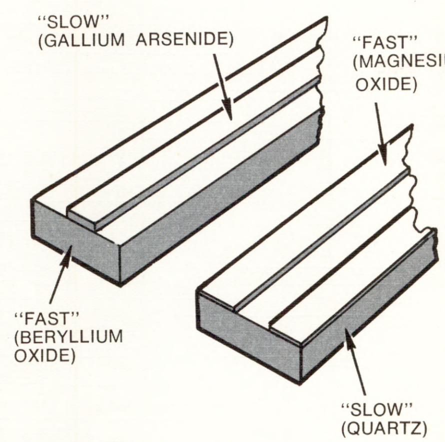


TRANSMISSION LINES



Slot-type Waveguides

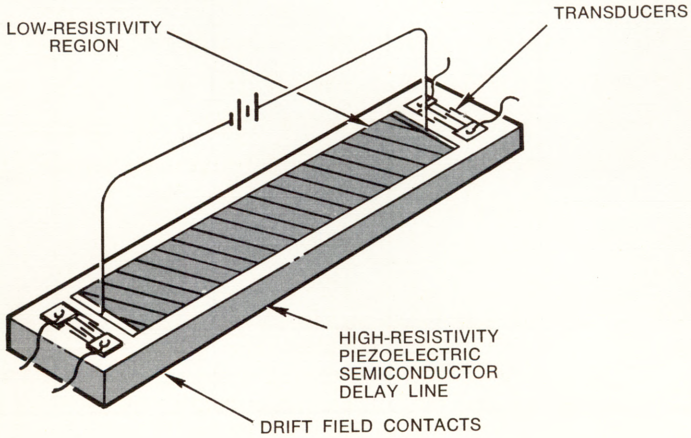
Insertion loss (that is, the loss in input signal strength during signal conversion from an electrical to an acoustical wave) between widely separated wedge transducers decreases sharply when slot waveguides are deeper than an acoustical wavelength.



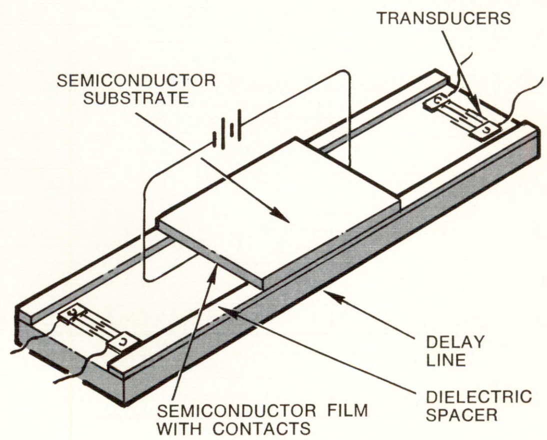
Overlay Transmission Lines

On the device at left above, the acoustic wave travels along the surface of the overlay. On the device at right, the wave travels through the slot between strips of overlay.

AMPLIFIERS



Combined Medium Amplifier



Separated Medium Amplifier

Because surface acoustical waves, by definition, travel only along the surface, only thin films of the propagating materials are required. These semiconductor films are applied by heteroepitaxial techniques on substrates of "good," low-loss acoustical materials. The semiconducting layers then serve for amplification as discussed above. They also can be combined with other types of circuit elements to form complete single-substrate subsystems and systems—thanks to an exciting new material combination consisting of thin epitaxial films of piezoelectric aluminum nitride on sapphire. This recent achievement promises to revolutionize microacoustic technology, since it permits microelectronic-device-quality silicon to be grown on the sapphire substrate adjacent to the aluminum nitride. This technological breakthrough, permitting microacoustic devices to be integrated with microelectronic circuits on the same substrate, will be applicable for a wide range of programmable or adaptive signal-processing subsystems and systems.

You probably did a "double take" when you read, above, the terms "ferrimagnetic" and 'YIG"—both of which are material designations that you have already encountered in our discussion of ferrites (pages 89 to 93).

EPITAXIAL FILM AND SUBSTRATE PROPERTIES

Material	Velocity Shear Wave (Cm/Sec)	Acoustic Impedance (Gm/Cm²/Sec × 10⁵)	Density (Gm/Cc)	Acoustic Attenuation (At 1 GHz)	Surface Wave Velocity (Cm/Sec)	Crystal Class and Space Group	Coupling Coefficient	Material Classification
CdS	c-axis 1.768×10^5 a-axis 1.768×10^5 1.840×10^5	8.51 8.51 8.86	4.82	8.0 db/cm	1.46×10^5 basal plane	Hex. — 6 mm	$k_{33} = .262$ $k_{51} = .119$ $k_{15} = .188$ $k_t = .154$	Piezoelectric Semiconductor
ZnO	a-axis ⊥ c 2.70×10^5 a-axis ll c 2.73×10^5	15.82 15.50	5.67	6.0 db/cm	2.62×10^5 basal plane	Hex. — 6 mm	$k_t = .282$ $k_{15} = .316$ $k_{31} = .189$ $k_{33} = .403$	Piezoelectric Semiconductor
$LiNbO_3$	010 3.995×10^5 010 4.458×10^5	18.77 20.943	4.70	2.6 db/cm	Y-cut Z-oriented 3.40×10^5	Trigonal 3m	$k_{15} = .61$ $k_{33} = .17$	Insulator Piezoelectric Piezoelectric
YIG $Y_3Fe_5O_{12}$	⟨100⟩ — ⟨010⟩ 3.84×10^5 ⟨110⟩ — ⟨110⟩ 3.90×10^5	19.87 20.18	5.17	0.25 db/μsec		Body center cubic	Non-Piezoelectric	Ferromagnetic Insulator
YAG $Y_3Al_5O_{12}$	⟨100⟩ — ⟨010⟩ 5.03×10^5 ⟨110⟩ — ⟨001⟩ 5.027×10^5 ⟨110⟩ — ⟨110⟩ 4.94×10^5	22.87 22.87 22.50	4.55	1.0 db/μsec		Body center cubic		Insulator
MgO	⟨100⟩ — ⟨001⟩ 6.37×10^5 ⟨110⟩ — ⟨110⟩ 5.22×10^5	23.24 19.06	3.65			Cubic m3m		Insulator
BeO	c-axis 7.005×10^5 a-axis 7.026×10^5	21.0 21.2	3.01			Hex. — 6 mm	$k_p = .017$ $k_{31} = .010$	Piezoelectric Insulator
Al_2O_3	c-axis shear 6.04×10^5	24.0	3.986	2.5 db/μsec		Trigonel 3m		Insulator
Si	⟨100⟩ — ⟨001⟩ 5.84×10^5 ⟨100⟩ — ⟨110⟩ 4.69×10^5	13.61 10.90	2.332	5.0 db/μsec		Cubic m3m		Semiconductor
Ge	100 3.55×10^5 110 2.76×10^5	18.9 14.7	5.32	10.0 db/μsec		Cubic m3m		Semiconductor
GaAs	100 3.35×10^5 110 2.475×10^5	17.75 13.12	5.307			Cubic 43m	$k_{14} = .065$	Piezoelectric Semiconductor
AlN	---	---	---	---	6.12×10^5	Hex. — 6 mm	k = .1	Piezoelectric

The microacoustic application of ferrites should not come as too much of a surprise, when we remember how the energy from an electromagnetic input is transferred to the spin energy of a ferrite's electrons. This energy, as it travels down a ferrite by altering the magnetic dipoles' precession angles is accompanied by a coherent acoustical wave; its mode of travel is called "magnetoelastic." Bond lengths of the acoustically propagating material's lattice atoms alternately stretch and shrink to launch and transmit the acoustic wave along the material.

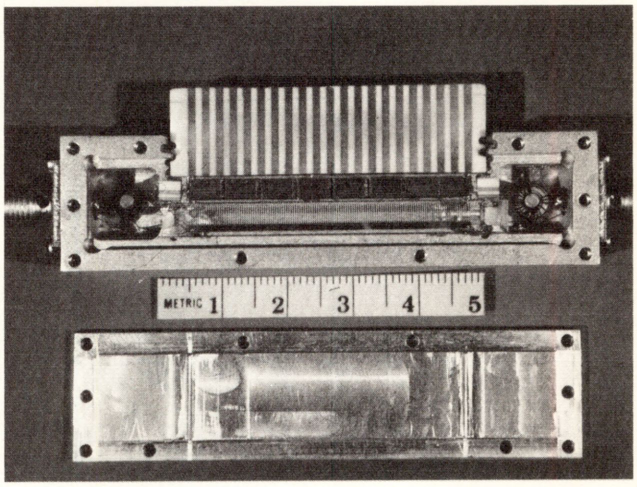
It is interesting to examine just how certain material properties generate certain behavioral properties in acoustical devices. Let us take YIG, for example, to see why a delay line fabricated of a ferrite can exhibit the valuable property of "dispersiveness"—or, in other words, why a ferrite delays different frequencies by different amounts as they travel through it or along its surface.

The magnetic field within any sample of YIG—whether it be rod, bar, or film—is distributed symmetrically along the YIG's length (see diagram, page 91). The field is minimum at each end of the sample, maximum in the center, and decreases with distance in either direction from the center. Ferrimagnetic resonance occurs for different frequencies at different points along the length of the sample. For any given frequency, this "turning point," at which electromagnetic energy is turned into acoustical energy, exists where the prodnct of gyromagnetic ratio, γ,* times the magnetic field strength, H_{in}, is equal to twice the frequency, f—or, precisely, where $\omega = \gamma H_{in}$, with ω being equal to $2\pi f$.

Each frequency reaches its turning point after travelling a specific distance along the YIG, and this distance is different from the distance to the turning point for any other frequency. Velocity of an acoustical wave in a given material medium is different for every frequency; thus, the *time* it takes each frequency to travel to turning point is different

**Gyromagnetic ratio, γ, is a constant whose value depends on the material's composition. For YIG, γ is 2.8 megahertz per oersted of magnetic field strength.*

A HINT OF THINGS TO COME IN MICROACOUSTICS...



The above photograph offers a hint of things to come in microacoustics. The unit pictured is a programmable tapped delay line developed by the Electronics Research Division of Rockwell International for use as at matched filter in new coded-waveform spread spectrum communication systems. This device takes an incoming waveform which is coded in some way, decodes it, and sends the uncoded information on into the receiver. Combined in the package are one microacoustic tapped delay line and eight SOS integrated circuits which control the acoustic device. Digital programming of the device can rapidly set it to match a large number of different incoming waveforms.

Devices like the one shown here will soon be made on the same substrate with epitaxial material combinations, in much the same manner as MOS/LSI chips used in inexpensive microelectronic calculators now on sale in retail stores.

Dreaming a bit further into the future . . . imagine how marvelous it might be if sapphire or some other transparent layer were interposed between the acoustical substrate and the semiconductor overlay to provide optical interconnection between devices. Such an approach would eliminate many of the requirements for external linkages, and would afford an opportunity for three-dimensional LSI!

from the *time* it takes for any other frequency to travel to turning point (time equals distance divided by velocity) in that medium. Since time is finite, the duration of travel constitutes a delay between input and output, and this delay is unique for every frequency.

It should have become pretty obvious by now what we are leading up to: a ferrite like YIG can be used to obtain delay that varies with frequency. And this is how one defines a "dispersive delay line": a transmission line that delays different input frequencies by different amounts of time.

As with microacoustics, exciting new material combinations are being developed in the 1970's in *micromagnetic* technology. This technology employs magnetostatic surface waves—similar to acoustic surface waves in that they travel close to the surface of the magnetic material—but with greater than 10 times the velocity of acoustic surface waves. This means that magnetostatic devices can operate at more than 10 times the frequency of acoustic devices—well up into the microwave region.

Once again, in *micromagnetic* technology, epitaxial material combinations are being used—in this case, thin magnetic YIG films on gadolinium garnet substrates. Devices with good electrical properties have been operated at frequencies above 9,000 megahertz!

"So *what*?" you may now be asking.

So *everything*, for today's and tomorrow's data processors—which will need ever smaller and more capable devices to handle ever increasing amounts of data. So *everything*, too, for systems to exploit the *microwaves*, as we shall see in Chapter V.

First, though—before entering the realm of the microwaves—we have yet another new and provocative materials/device development with which to become acquainted —bubble memories.

BILLION-BIT MEMORIES FROM FAST-MOVING BUBBLES

A NOVEL APPROACH TO MASS MEMORY STORAGE

Attacking the 1970's problems of "too much data," "too little time to handle it," and "too little space to store it" are the group of scientists who are involved with the new (since 1971) phenomenon of "bubble memories."

Bubble memory technology promises storage density of up to a billion bits per square inch, and access time 10 times shorter than can be attained with the fastest of other sequential memory systems, such as drum, disk, and tape types.

From what wondrous materials are bubble memories formed? Hold your breath—for, again, it is that marvelously ubiquitous ferrite family—to be specific, the special group of synthetic garnets with the general formula $A_3B_5O_{12}$, where A can be yttrium, any of the rare earths, or certain other special materials, and B can be iron in combination with other elements such as gallium and aluminum.

BASIC PRINCIPLES OF BUBBLE MEMORIES

With the bubble memory approach, data are stored within magnetic domains* that are contained in thin films of single-crystal garnet materials epitaxially grown on a nonmagnetic, single-crystal garnet substrate.** The irregular, whorl-shaped domains represent an energy balance between the tendency to minimize the flux line closure, and the energy required to make the 180-degree magnetic transition across the domain wall. When the epitaxial garnet film is subjected to an appropriately strong and directed external magnetic field (generally introduced by permanent magnets), the irregular domains shrink into neat, uniformly shaped cylinders—or "bubbles." The presence or absence, then, of a "bubble" at any of certain magnetically defined loca-

The domains or "bubbles" are actually regions within the parent film material that have a magnetic character different from that of the surrounding film. They can actually be seen with a polarizing microscope.

***Research is being pursued to enable bubble memories to be formed with polycrystalline materials.*

tions in the film represents a binary "0" or "1" bit of stored digital data.

Bubble memories are both analogous to, and different from, older types of magnetic memories. In both kinds of memory, data are stored as states of magnetization. In bubble memories, however, it is the stored data (or bubbles) which move through the storage medium (the film), in contrast to the older types in which the storage medium itself (disk, drum, or tape) moves, and the data remain stationary. This basic difference gives rise to one of the bubble memory's most meaningful advantages after size, speed, and density—namely, high reliability due to the absence of moving mechanical parts.

HOW BUBBLE MEMORIES FUNCTION

A typical bubble memory system includes all the features of more conventional systems—storage elements, a method for controlling storage and circulation of data, and provisions for data detection and nondestructive readout (NDRO).

STORAGE

Bubble memory storage of data is, as stated earlier, in the form of shrunken magnetic domains or "bubbles." Bubbles are generated when the internal magnetic fields at a designated site within certain kinds of film materials are subjected to a pulsed external magnetic field of the proper intensity, directed perpendicularly to the localized internal field. The on-off conditions controlling the pulsing of the external field provide for the two-stage storage of digital information.

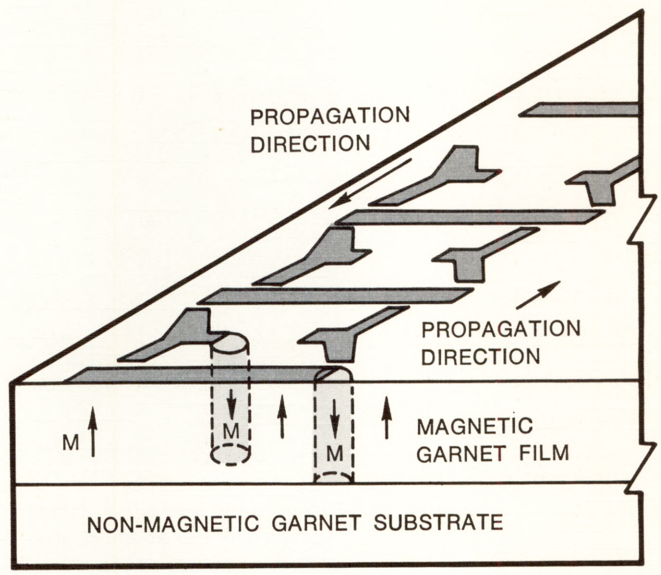
CONTROL

Circulation of bubbles for storage and access (analogous to the rotation of a magnetic disk, drum, or tape) can be accomplished in a variety of ways, all of which have in common the technique of exposing the stored bubbles to a moving magnetic field that causes the bubbles to progress along specifically defined "tracks" in the garnet storage medium. The tracks are typically defined by thin-film Permalloy* structures laid down on the film.

*An easily magnetized and demagnetized alloy composed of about 80% nickel and 20% iron.

DETECTION

To extract information from the memory, bubble absence or presence can be detected by several methods. The technique most generally used is based on the "magnetoresistance effect." With this approach, the bubble detector or output sensor consists of a Permalloy resistive element, which forms part of a bridge circuit located in the memory track. When a bubble passes this element, it causes its resistance to change. This unbalances the bridge and, as a result, a detectible signal appears at the memory's output.

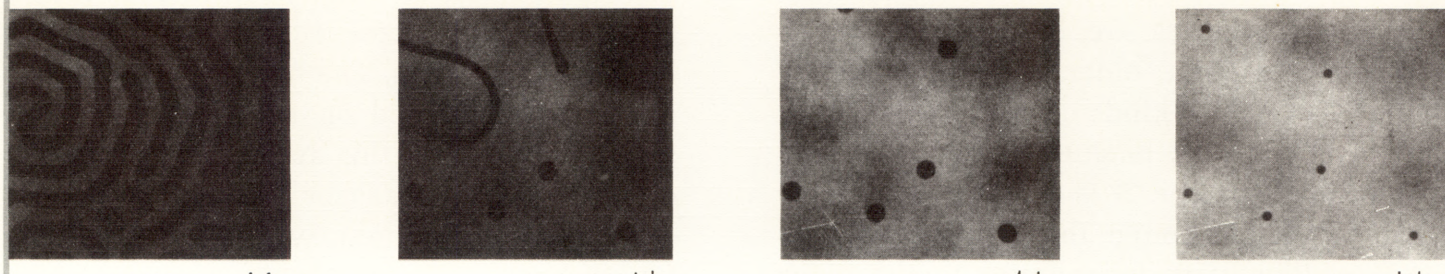


With the bubble memory approach, data are stored within magnetic domains contained in thin films of single-crystal garnet materials epitaxially grown on a nonmagnetic, single-crystal garnet substrate.

NONDESTRUCTIVE READOUT

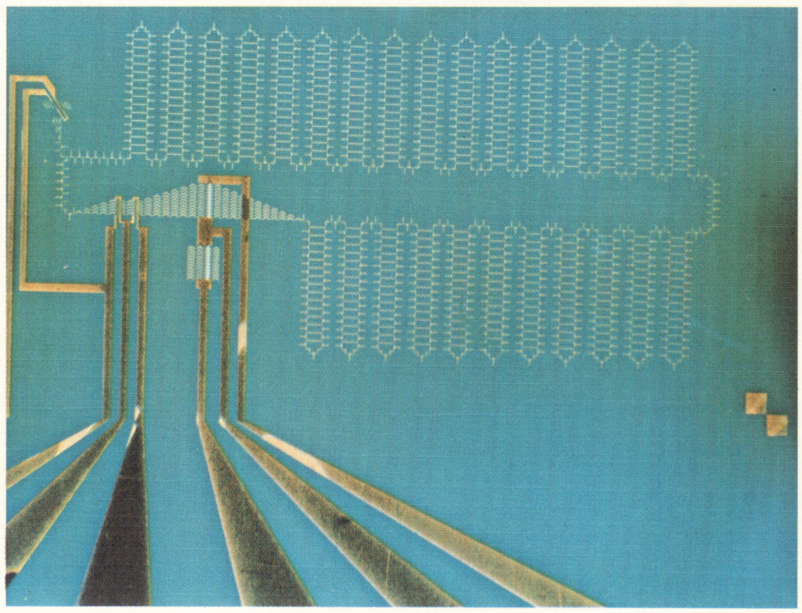
NDRO is the ability for data to be withdrawn from a computer memory without being destroyed—it is a desirable or essential feature in many computer applications. One way of achieving NDRO with bubble memories is to employ "replication" or division of each bubble into a pair of two bubbles. Thus, whenever a computer user reads out a bit of data and, accordingly, destroys one bubble, the destroyed bubble's "mate" remains in storage to represent that particular bit of information for the next user.

BUSY BUBBLES . . .



10 μm | 10 μm | 10 μm | 10 μm

0.0 0e | 21.0 0e | 21.7 0e | 28.2 0e



Through and around a system of Permalloy "tracks," deposited on an epitaxial layer of single-crystal garnet, magnetic bubbles speed along like microscopic express trains!

APPLICATIONS FOR BUBBLE MEMORIES—TODAY AND TOMORROW

The capacity per given volume of bubble domain memories, their ability to be batch-fabricated, and their potentially high reliability make this type of memory a strong rival to even such advanced approaches as charge-coupled device technology. Ultimately, bubble memories should find application in commercial, industrial, and consumer products because of the economies they offer. Their most immediate value, however, is for avionic and space electronic systems, where their absence of moving parts should increase system reliability significantly over that achievable with presently used disk and tape types of storage and recording hardware.

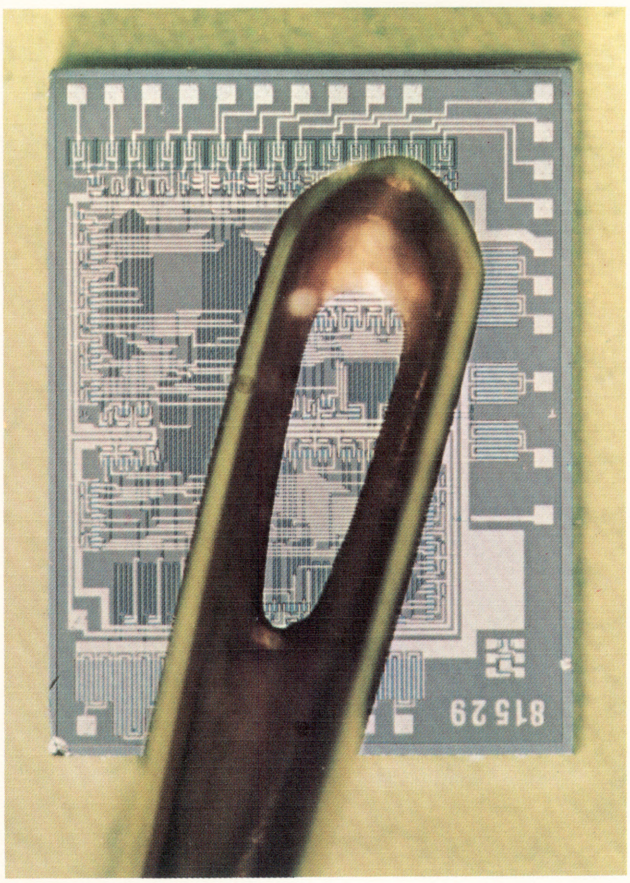
AN ACKNOWLEDGED DEBT TO MATERIALS RESEARCHERS

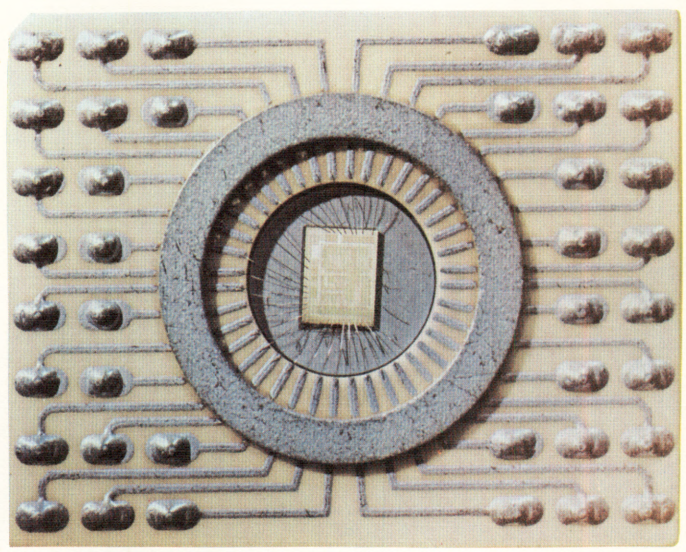
We believe that, after reading this chapter, you will agree that microelectronics could certainly not have progressed to its present advanced state of evolution without the contributions of the materials and device researchers. Through their developments and technological breakthroughs, microelectronics has been able to penetrate almost every area of application. In Chapter V, we shall see how the persistence of these scientists has teamed with the creativity of systems experts, to open to microelectronics the last, most obstinate defender—the microwaves.

V. THE EXPANDING INVASION OF THE MICROWAVES

When microelectronics first began to be touted for weight reduction, reliability improvement, and cost cutting, one segment of users remained futilely beating at the door. They were the radar systems users, and they had good reason to "want in out of the cold."

The circuitry of radar was, to a great extent, analog as opposed to digital,* and for analog circuitry there were simply no microelectronics answers. The obvious move was to digitize, and this was done to as great an extent as possible.





DIGITIZATION OF ANALOG FUNCTIONS WITH LSI MICROELECTRONICS

This MOS/LSI subsystem was one of the first applications of high-density microelectronics to digitize traditionally analog functions. Designed and produced by Rockwell for a King Radio Company navigation set, the device contained over 100 logic gates. In the King equipment, it implemented a decoder which converted standard VHF control panel channel and frequency positions into digital data. A single one of the LSI devices replaced 20 separate bipolar IC's.

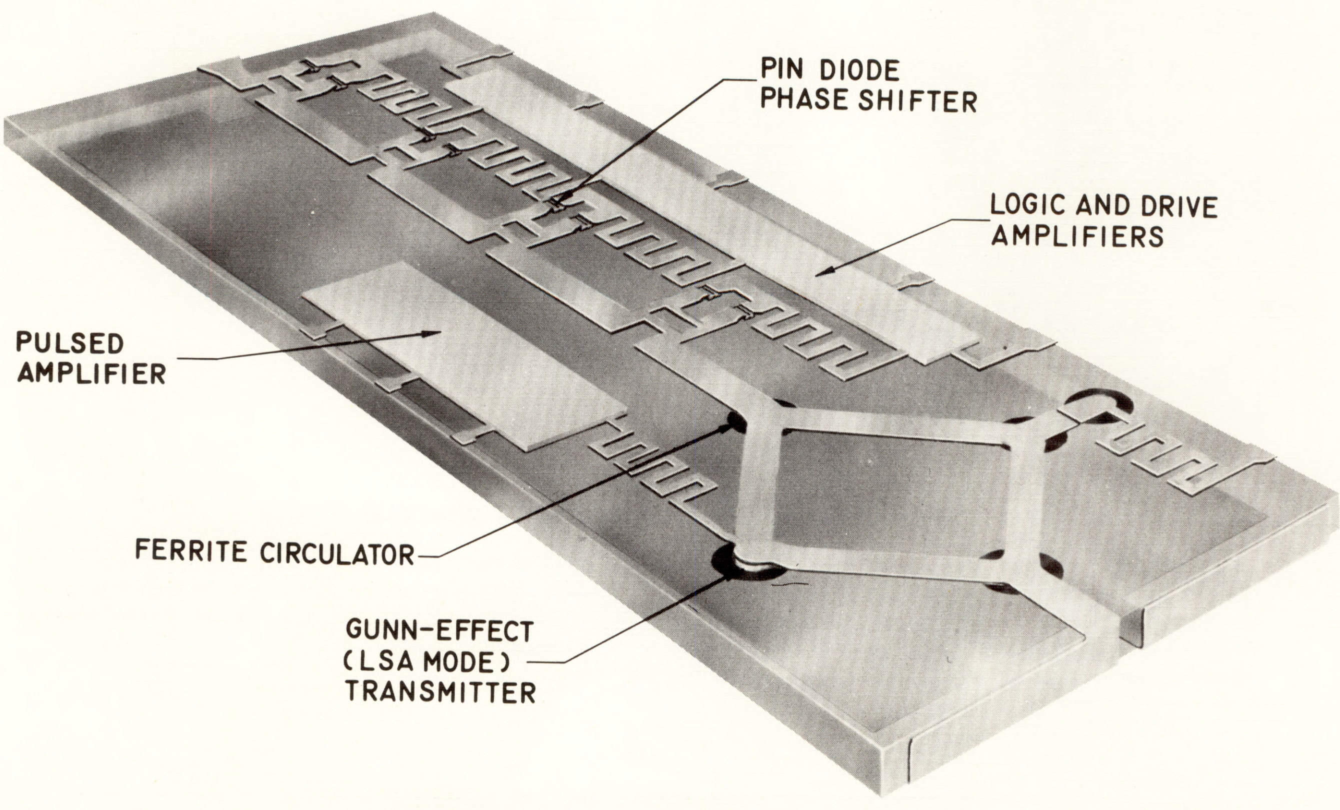
**Analog* circuitry deals with *continuously changing* voltages and currents. *Digital* circuitry deals with *pulses* of voltage and current. Digital circuitry *counts*, while analog circuitry *measures*. Most computer circuitry is digital. Much of the circuitry of radar—filters, delay lines, signal generators—has always been analog. With LSI microelectronics, it has become feasible for the first time to replace some radar analog circuitry with digital circuitry that can perform the same functions, in less space, with less weight, and requiring less power.

Some radar functions could not be digitized, however—some 50 percent of them, in fact, that came from only around one percent of the radar components, including magnetrons, klystrons, motors, synchros, mixer diodes, TR tubes, rotary joints, and driven potentiometers.

Toward the end of the second decade of microelectronics' remarkable career, a "crack" finally began to appear in the doorway leading to the elimination of such gremlins. All of them—even the unwieldy, motor-driven, mechanical antenna, and the big, heavy magnetron and klystron signal generators—were challenged by solid-state contenders. Some of the new approaches have proved practical, while others are still in the development phase in the mid-1970's.

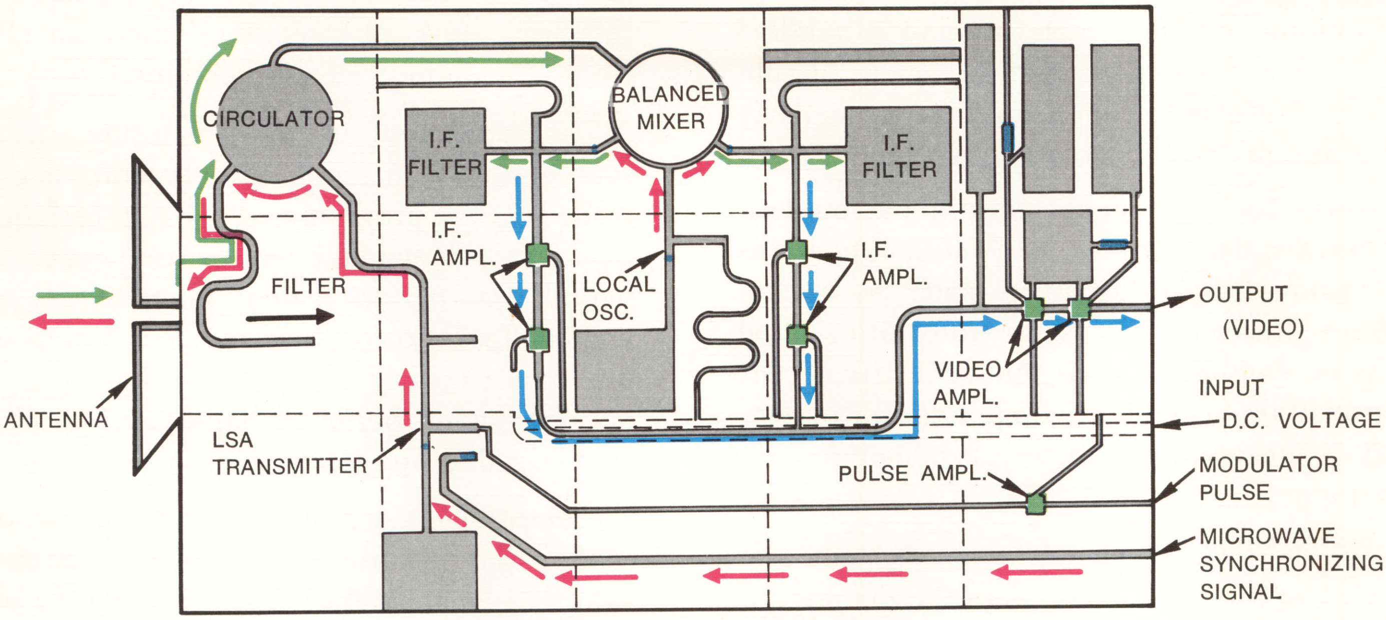
VARIOUS GENERAL APPROACHES TO SOLID-STATE RADAR

A number of advanced approaches to solid-state radar are being pursued. One concept takes advantage of a whole set of new microelectronics advances—including silicon-on-sapphire, microstrip interconnections, ferrite lumped constants, and solid-state oscillators. An entire antenna/receiver/transmitter is contained by each module in this approach. The components of each module are laid out on a common sapphire substrate (see illustration), and the dipole antenna is deposited along one edge of the substrate and is interconnected via microstrip to a set of ferrite circulators. From there it goes to a stripline and PIN diode phase-shift circuit. In the transmit mode, the signal is appropriately shifted in phase and then fed to a Gunn effect oscillator, where it is amplified and sent on to the antenna. For a 1-watt, 10-gigahertz module, modular dimensions are only about $^1/_2$ inch wide by $1^1/_2$ inches long.

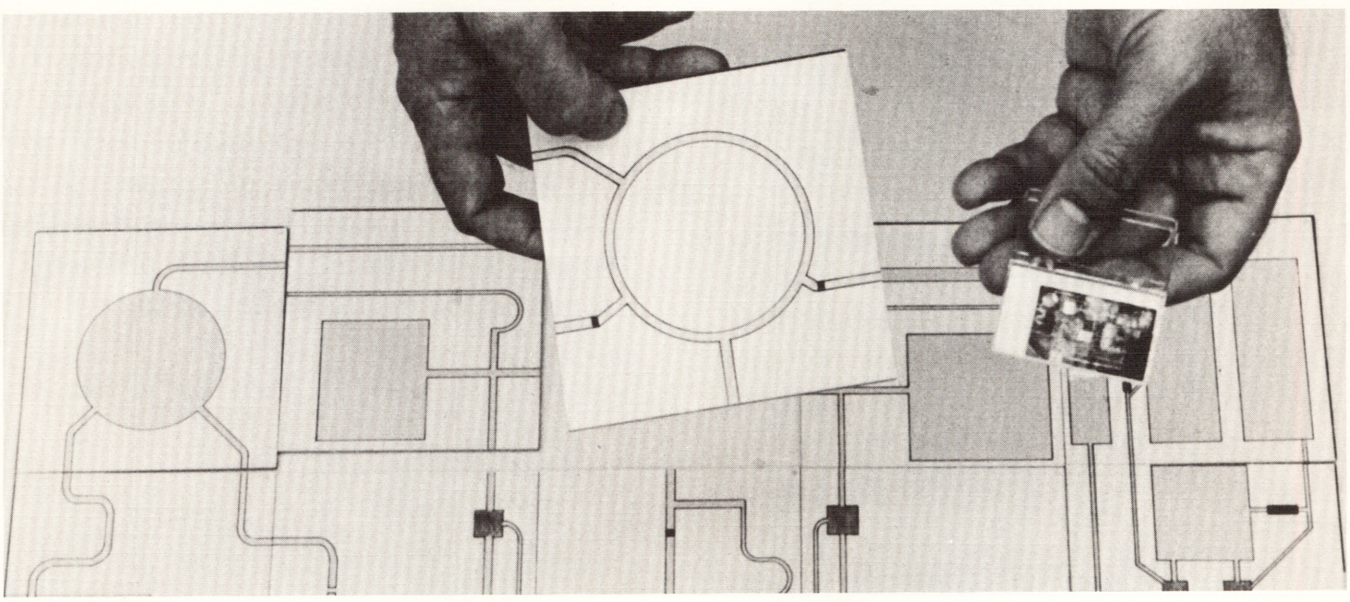


CONCEPT FOR A SINGLE-SUBSTRATE (SAPPHIRE) SOLID-STATE RADAR MODULE

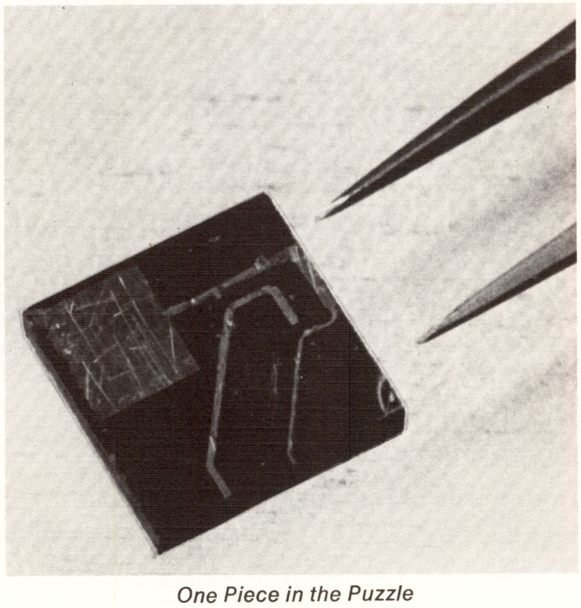
JIGSAW PUZZLE RADAR



COMPLETE SUBSYSTEM



This Rockwell approach to solid-state radar takes maximum advantage of the special properties of various substrate materials to optimize operating parameters for each function. Functions are handled by separate squares, and squares are microstrip-connected to form radar module (above). Typical functional square is high-power oscillator (right) on single-crystal beryllium oxide substrate. Materials for other functions include hetero-epitaxial combinations of silicon or gallium arsenide on sapphire, and ferrimagnetic YIG on YAG.



One Piece in the Puzzle

Another provocative solid-state radar concept employs an ingenious 'jig-saw puzzle'' technique, in which each function is handled by the circuitry on a separate square of substrate, fabricated from a material particularly appropriate for the function involved.

The ''jigsaw'' concept permits custom-tailoring of radar modules. Each square contains a basic unit of circuitry—such as mixer, phase shifter, or oscillator-transmitter—that can be combined to fit the application. The parameters of individual squares can be varied as necessary to meet specifications for frequency.

ELECTRONIC SCANNING

One of the most intriguing solid-state radar developments has been the concept of ''electronic scanning,'' in which mechanical nutation of the radar antenna is replaced by dividing the system output into small ''power packets,'' and then releasing these in a controlled sequence of transmission.

Two general approaches have been taken to electronic scanning. One approach replaces only the cranky, gimballed antenna with solid-state devices, while the rest of the radar remains conventional. The second approach replaces the entire kit-and-caboodle—antenna, receiver, and transmitter—with solid-state equipment.

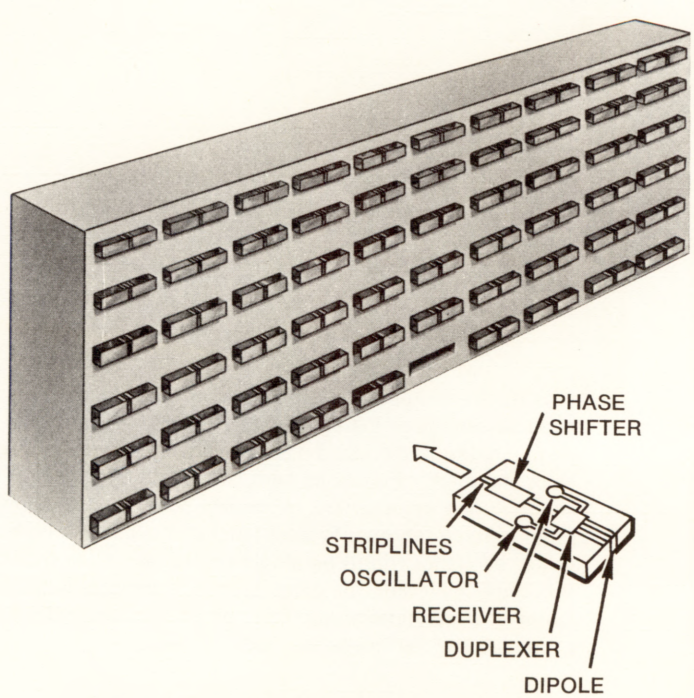
Both electronic scanning approaches make use of an array of solid-state devices. In the antenna-replacement-only scheme, the gimballed dish is supplanted by an array of tiny, separate but identical, radiating elements. In the complete-solid-state-system approach, the entire radar, except for power supply, controls, and displays, is implemented by an array in which each element contains not only a tiny electromagnetic radiator, but receiving and microwave power-generating circuitry as well.

PHASED-ARRAY ANTENNAS

There are two basic modes of operation for phased-array antennas. One mode assigns a slightly different frequency to each of tiny, separate but identical radiating elements. The other 'tunes'' all the elements to one common frequency, but shifts the phase of each module with respect to all the other modules. In this way, over an interval of time, an electronic ''scanning'' effect is obtained.

The movement of the electronic array's scan pattern in azimuth and elevation is controlled by the programmed shifting of individual array elements' phase or frequency. The overall scan pattern is determined by the size and configuration of the array. Resolution and pointing accuracy are governed by the number of elements per given ''aperture'' (total effective radiating surface area) of the antenna.

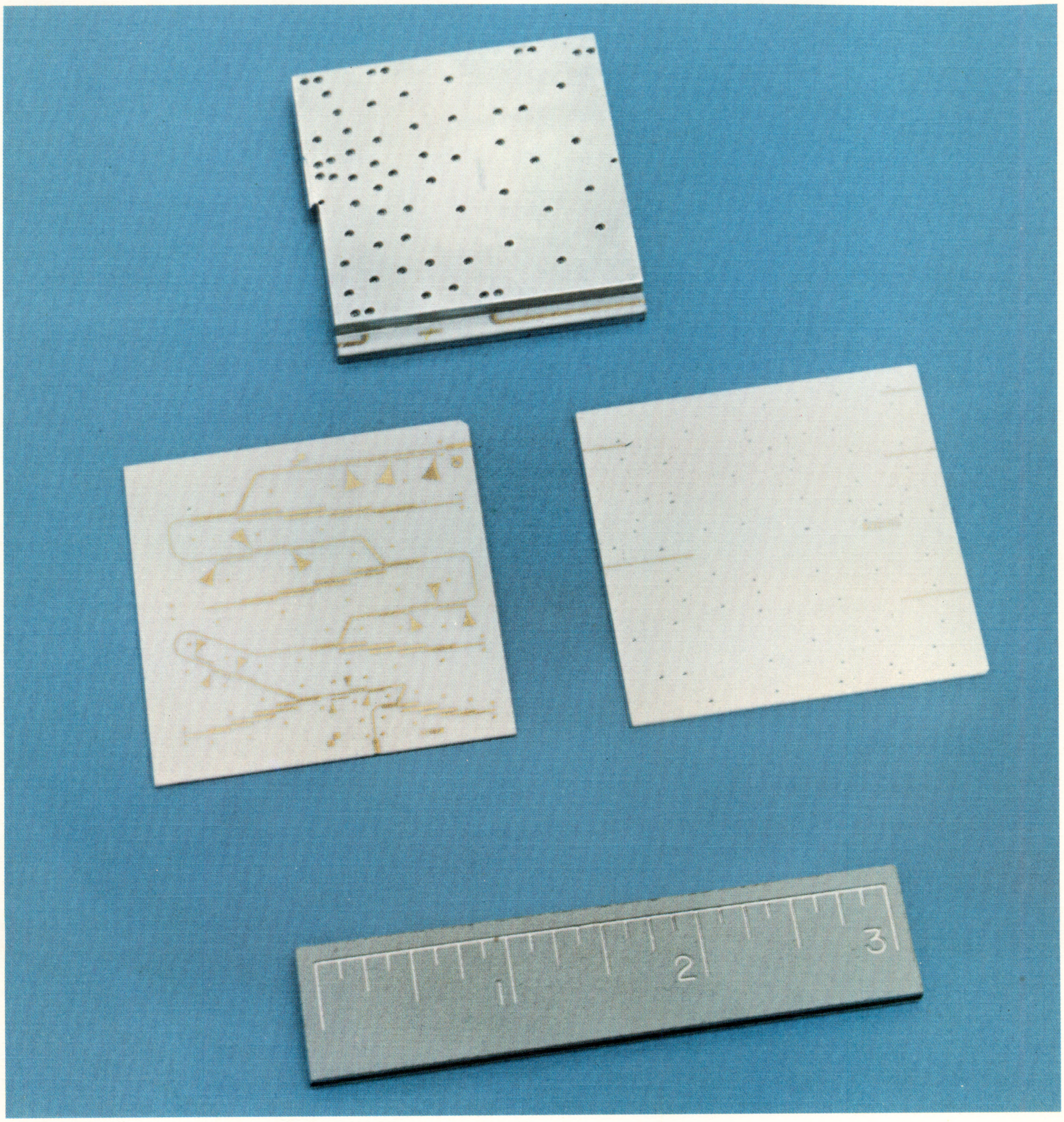
Electronically scanned antennas are in operation and performing well today as parts of avionic systems, where their modularity permits their elements to be laid out in a flat, planar configuration, or to be separated and distributed ''conformally''—to follow, for instance, the leading edge of an airplane wing, or to fit with areodynamic compatibility around the tapered nose of a missile. A hypersonic missile or aircraft thus equipped can be freed entirely from the heat problems that pester mechanical antenna radomes.



ONE CONCEPT OF A SOLID-STATE, PHASED-ARRAY, MULTIPURPOSE RADAR

HYBRID THIN-FILM MICROCIRCUITS FOR THE MICROWAVES

Four separate Rockwell microcircuits such as those pictured below formed a vital part of the Apollo spacecraft's high-gain antenna system.

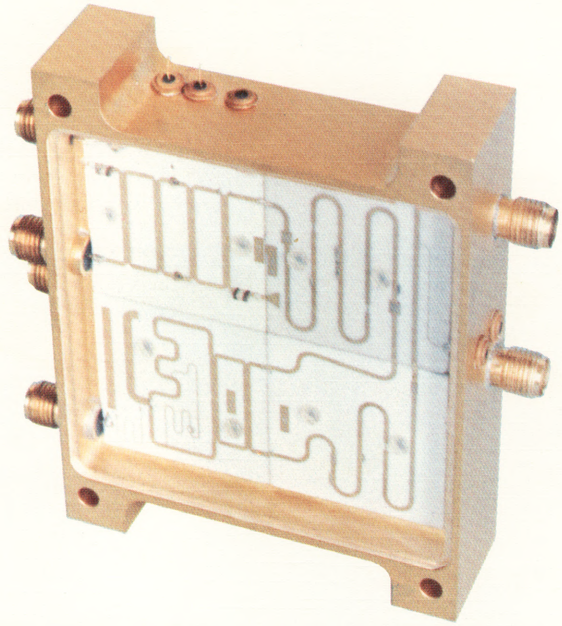


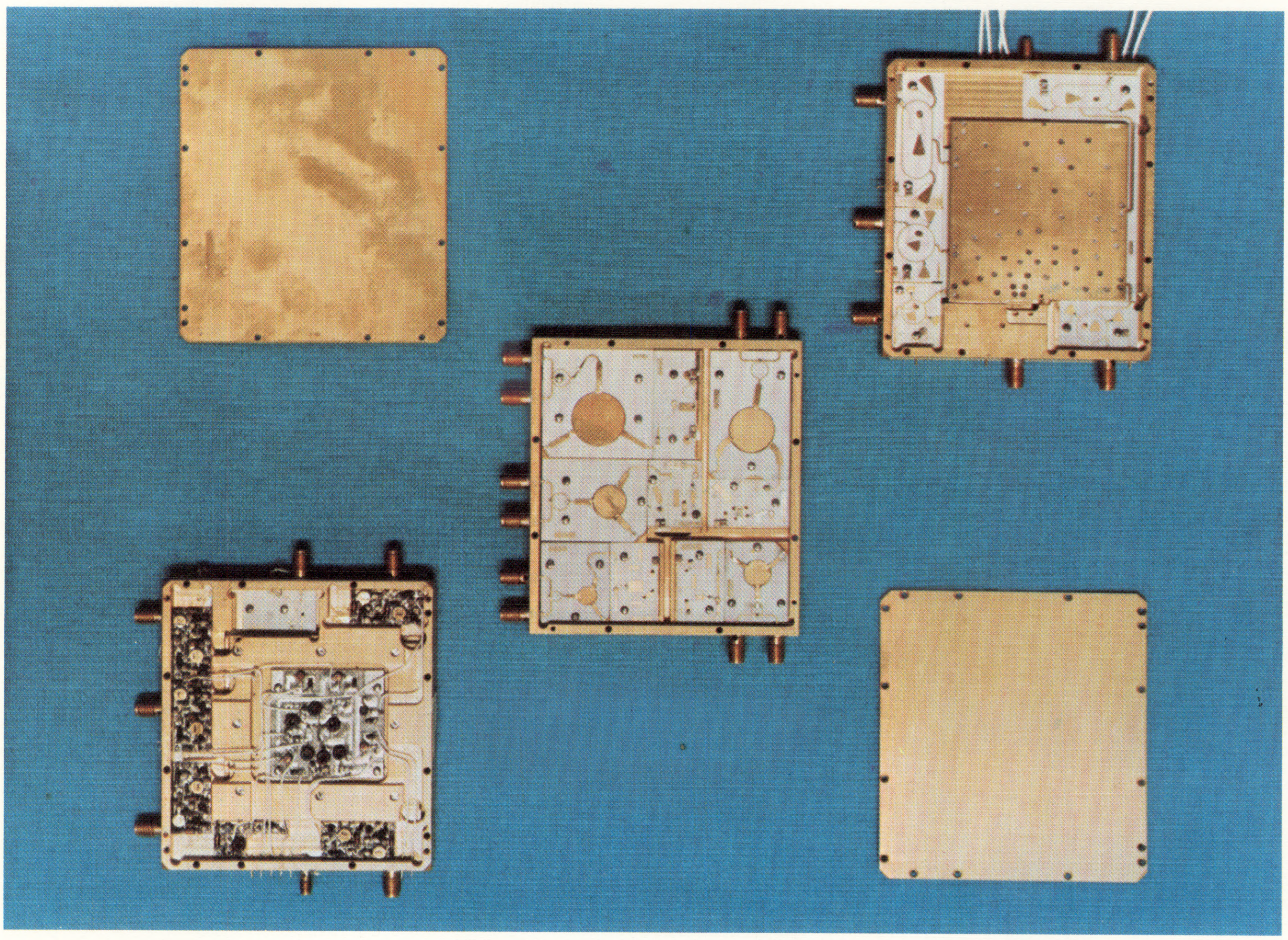
FREQUENCY MULTIPLEXER

This five-channel multiplexer is a cascade of complementary bandpass and bandstop filters. It divides the 2 GHz-to-10 GHz frequency band into five parts. Two alumina substrates are sandwiched together to form the high dielectric tri-plate configuration.

L-BAND TRANSCEIVER

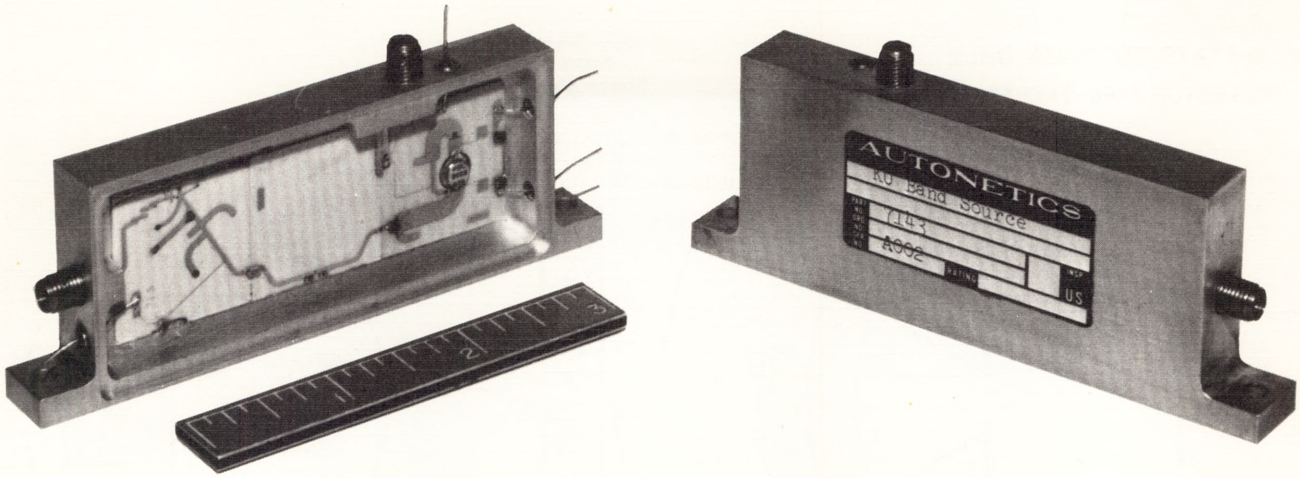
This two-level package contains a complete L-band transceiver which performs all of the functions described here with self-contained elements. On "transmit," the pump frequency (1.68 GHz) is coupled through a band-pass filter to a balanced modulator. The signal from the modulator is filtered, and the 1.56-GHz signal then goes through a variable attenuator to the antenna. Upon "receive," the pump frequency goes to a mixer. The received signal is filtered to remove the image frequency and then combined with the pump frequency in the mixer to produce the intermediate frequency (IF). Another version of this system includes a 20-watt, five-stage transmit amplifier; a 2.5-db noise figure, two-stage receive amplifier; and a transmit-receive (TR) switch.





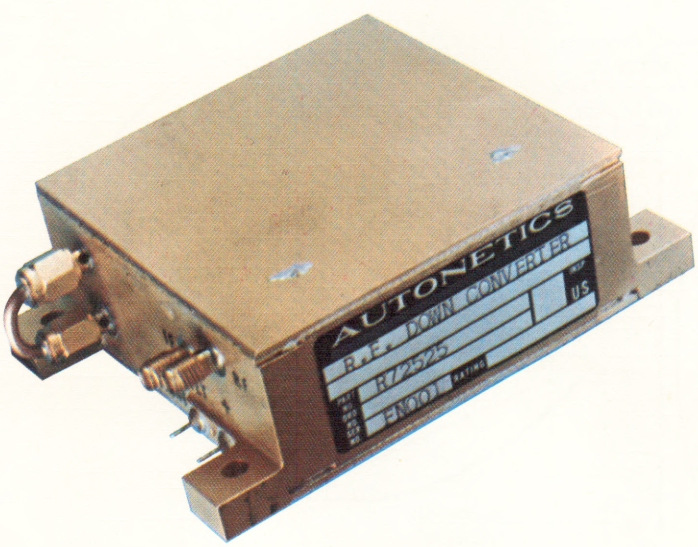
WIDEBAND MICROWAVE RECEIVER

The three layers of this wideband receiver are shown. The middle layer is comprised of five fundamental oscillators covering S-band through X-band. The generated signals from all five oscillators pass through an isolator and a power divider to the upper and lower packages which are identical to each other, and each of which contains five mixers, a multiplexing filter, a variable attenuator, five IF preamplifiers, and an IF multiplexer.



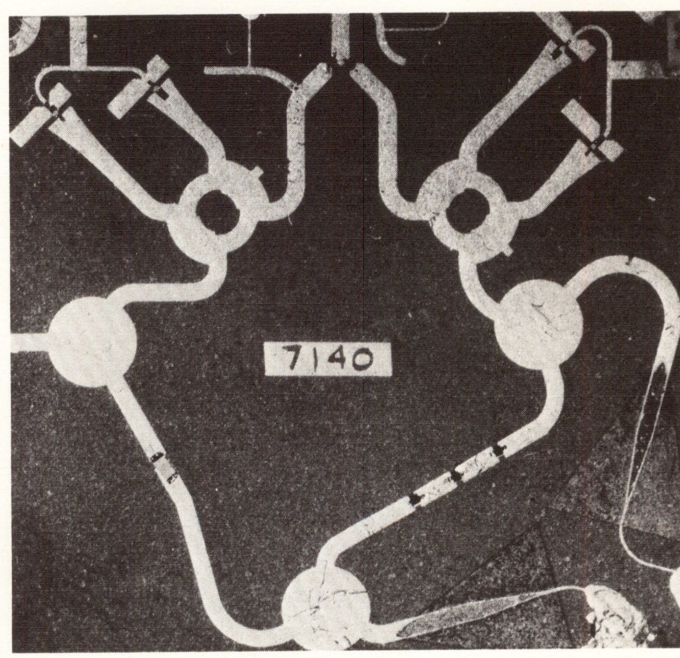
KU-BAND SOURCE

This Ku-band source is comprised of an S-band oscillator, a 6-db pad, and a "times eight (X8)" multiplier. Two of these systems, together with four image-rejector receivers, were flight-tested for 2,000 hours with no failures. The output frequency for this oscillator is tunable from 16 to 17 GHz. Output power is 10 milliwatts.



RF DOWN CONVERTER

The RF down converter contains both a local oscillator and an image rejection mixer. The local oscillator is a transistor type and is varactor-tuned over a 15-percent bandwidth with ±1-percent linearity. The signal is multiplied to X-band with a "times four (X4)" multiplier. The image rejection of the mixer is 20 db, and the typical noise figure is 9 db.



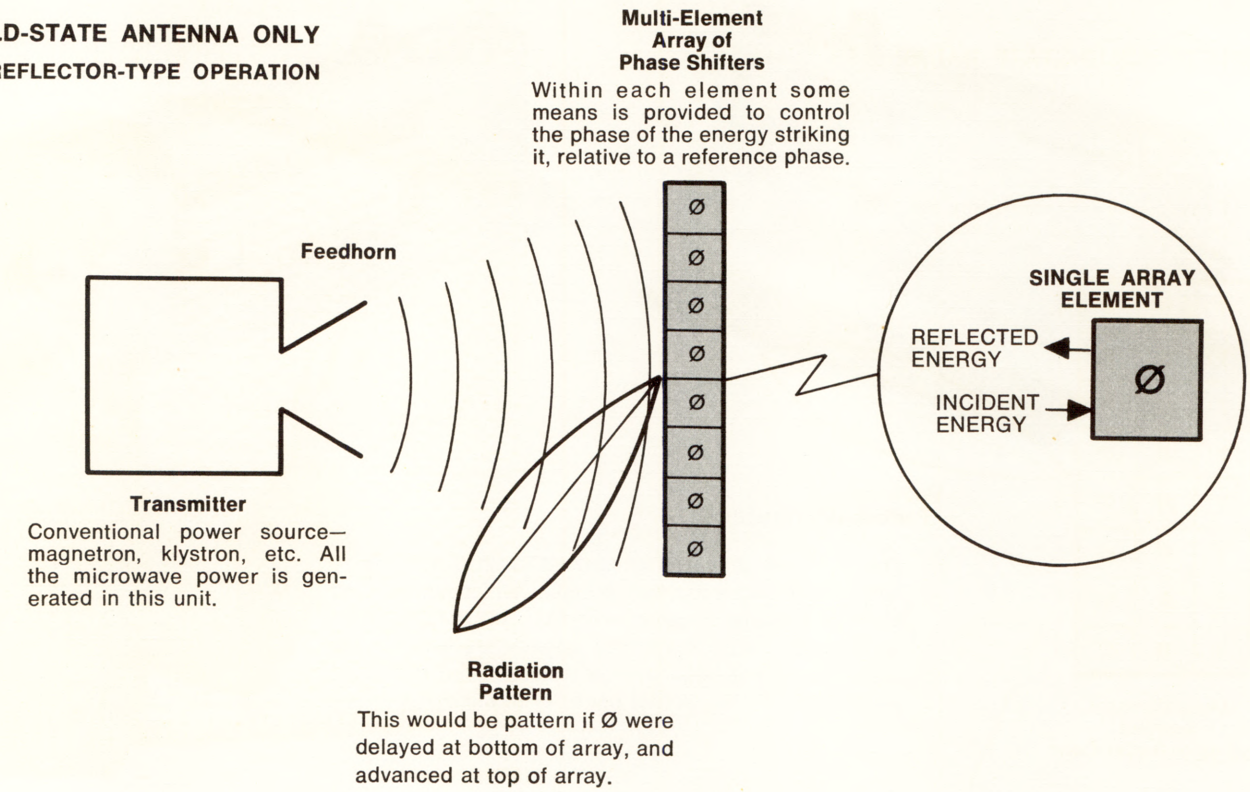
KU-BAND TRANSCEIVER

This Ku-band transceiver is fabricated on a ferrite substrate with a chrome-gold metallization. The pump frequency is directed toward a biphase modulator or the balanced mixer. A variable attenuator is included in the transmit arm. A four-port duplexer connects the transmitter and the receiver to the antenna.

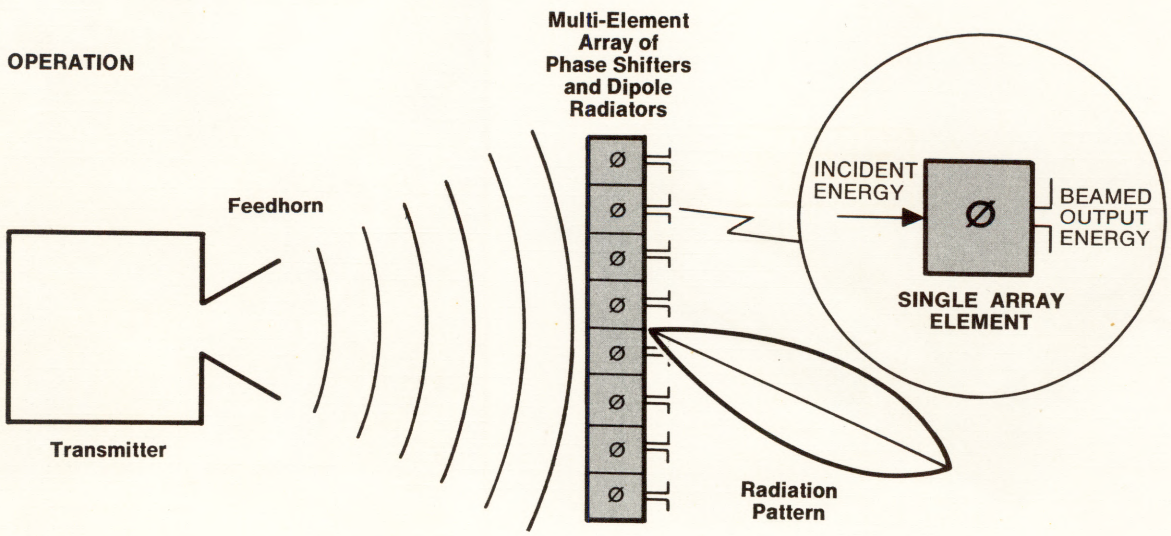
ELECTRONIC SCANNING TECHNIQUES

SOILD-STATE ANTENNA ONLY

REFLECTOR-TYPE OPERATION

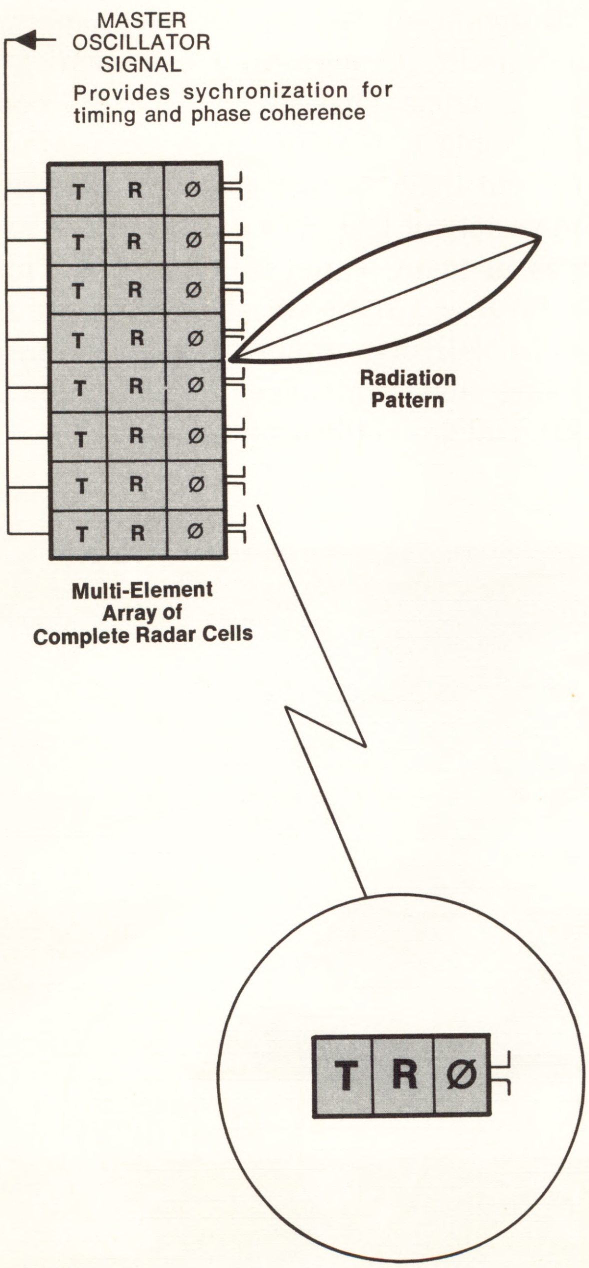


LENS-TYPE OPERATION



Lens-type operation has advantage in that the transmitter does not shadow or block the antenna array, and the entire surface of the array is available for radiating the beam.

COMPLETE SOLID-STATE RADAR

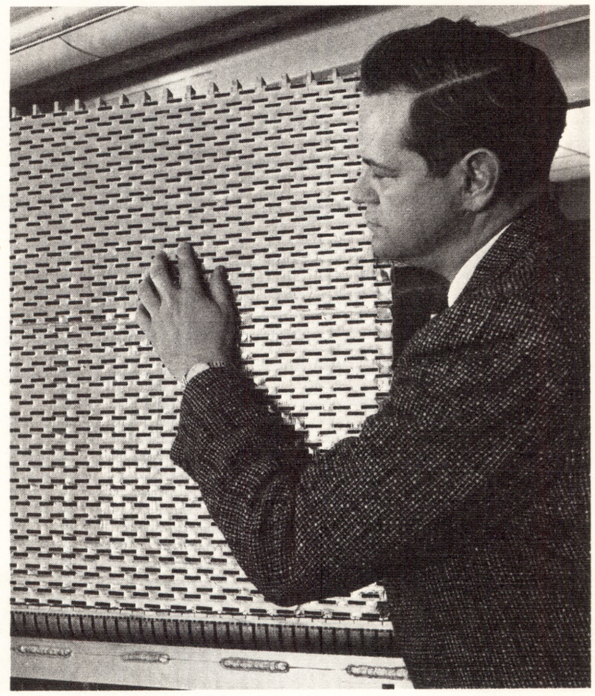


SINGLE ARRAY ELEMENT

Each element contains complete transmitter, receiver, and phase-shifter/radiator. Sync signal from master oscillator keeps T and R signals separated.

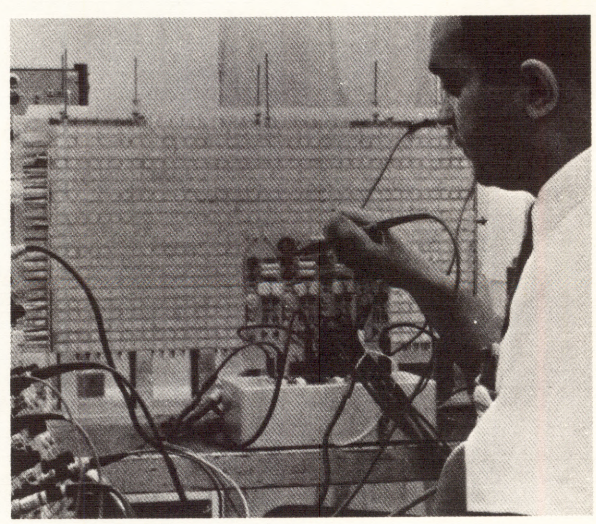
***Various Means of Microwave Power Generation and Element Mechanization** are employed by different designers. One version has a frequency multiplier on each cell and uses discrete components; another has a tiny bulk solid-state oscillator on each cell. Both versions have a master oscillator for timing and synchronization.*

TWO KINDS OF ELECTRONICALLY SCANNED ANTENNAS



VOLFRE

The Volfre (volumetric frequency-scanned) antenna is capable of highly versatile beam-positioning at extremely rapid scan rates by means of frequency variation alone. Rockwell has fabricated, assembled, and successfully demonstrated operation of the Volfre system, including necessary control and r-f circuitry for driving the antenna.



VOLPHASE

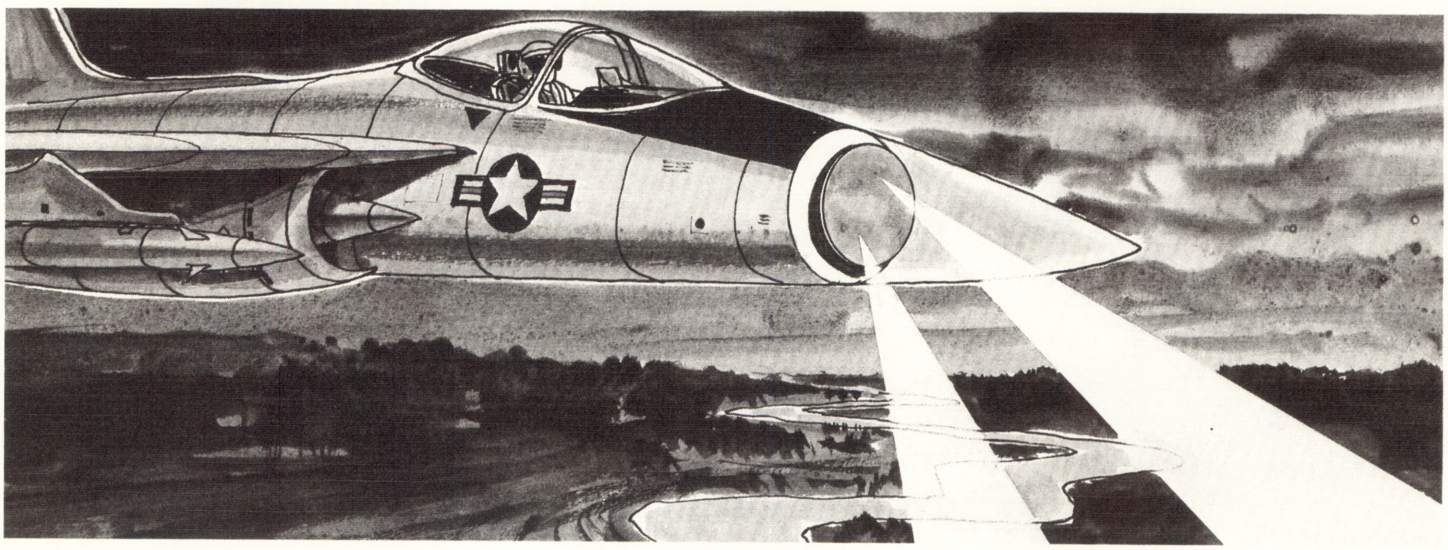
This Volphase (volumetric phase-scanned) radar antenna concept consists of an array of 1600 individual phase-shift elements. Rockwell's development of the low-cost, light-weight elements and a unique r-f feed system have been major technological breakthroughs toward accomplishment of a complete engineering prototype system.

Because electronic scanning is entirely without inertia, the direction toward which it "points the antenna" can be changed virtually instantly. Thus, scanning rates can be fantastically high—well up into the megahertz! Inertialess phased arrays offer particular advantage for spacecraft and satellites, in that such vehicles, equipped with the arrays, would not have to compensate for the motion reaction caused by moving mechanical dishes.

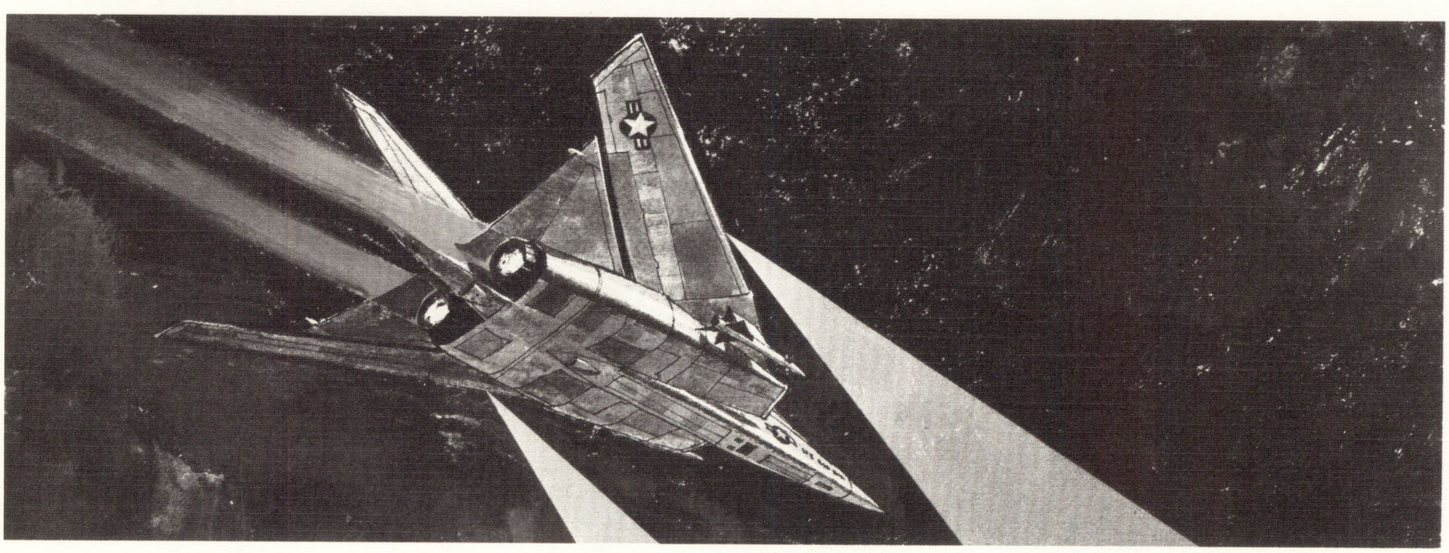
SCANNED "COMPLETE RADARS"

Still in the developmental phase in the 1970's, scanned complete radar systems have one major disadvantage: single array elements do not produce enough power, and too many elements are, accordingly, required per array in order to attain the total required radiated microwave output.

The benefits that could be obtained with scanned complete systems are many, and they are all significant. Among the most important is their ability to perform a combination of tasks. A single phased-array system could readily replace two or more conventional radars and their dish antennas, to perform a broad variety of tasks in a variety of modes—such as air-to-air search with tracking of multiple targets, air-to-air and air-to-ground weapons delivery, ground mapping, terrain following and avoidance, identification of threats, and ground-beacon tracking.



NOSE INSTALLATION



WING-EDGE INSTALLATION

Electronically scanned antenna array is inherently capable of almost any configuration and installation.

An interesting possibility offered by scanned complete systems is the development of *adaptive* radars, capable of adapting to changes in mission conditions. Signal characteristics—such as pulse width, compression ratio, or power level—could be electronically varied—*automatically*—by the systems to match threats posed by the enemy. Furthermore, once energy had been detected from an enemy radar, it could be countered immediately, and again automatically, with a volley of jamming radar energy beamed from the electronically scanning antenna.

GENERATING MICROWAVE POWER

For many years, the only means available for generating microwaves were magnetron and klystron vacuum tubes—large, bulky, heat-productive, and unreliable. The only *microelectronic* devices capable of generating the high *frequencies* could not generate the high *power* required by sophisticated microwave radar and communications systems. Nor would they have been able to get rid of all the heat that goes with high power if they *had* been able to generate it.

Next to mechanical antennas, microwave generators are the components with which radar systems people long felt the need for microelectronics most keenly. Along with antennas, they have been the very greatest contributors to microwave systems unreliability. But now, again, materials science has come to the rescue, and materials advances have made it possible for microwave system design engineers to penetrate this last bastion against microelectronics.

Entree has been gained through "hot-electron" or "high-field" devices. Without these devices, the "complete solid-state radar" would be an impossible achievement.

Of course, microwave discrete transistors were under development long before hot-electron devices. Their power-generating ability and their efficiency still compare favorably with, even surpass, solid-state oscillator performance in some instances. However, the upper frequency limits for transistors are far below those for hot-electron devices—with transistors operating best below, and hot-electron devices operating best above, about 10 gigahertz. The range of greatest utility for both present and future microwave systems lies far beyond this—with millimeter-wave systems operating at 30 GHz and above.

The terms "hot-electron" and "high-field" are intriguing ones, as applied to the generation of microwave signals. Just what do they imply in this context?

A "hot-electron" or "high-field" device is one in which a very large electric field interacts with the material's band structure in any number of ways, to produce properties not present in the material at low fields. In particular, high electric fields cause carrier density instabilities which lead to microwave oscillations capable of significant power generation.

Three kinds of solid-state oscillators have "created the most waves" among designers—these are the Gunn effect, LSA (Limited Space Accumulation), and avalanche or Impatt (Impulse Avalanche Transit Time) types. The three differ functionally in how each uses an electric field within a semiconductor; they differ operationally in their output frequencies and power limits. Thus, these characteristics determine choice of which oscillator type to use for a given application.

The functioning of all semiconductor oscillators depends on the peculiar electrical properties of certain classes of semiconductors, including gallium arsenide, cadmium telluride, and indium phosphide, and probably other as yet untried Group III-V and II-VI semiconductors. (Yes, you are right—these are the same talented friends we met back in our discussion of luminescence. Gallium arsenide is the only one of these compounds to be produced so far with the required purity to be practically useful for all semiconductor oscillators. Versatile creature, gallium arsenide!)

The property of GaAs which so well suits it for bulk oscillation is the negative resistance it shows at electric fields greater than about 3,000 volts per centimeter. Below that magnitude, increase of a voltage applied between a

GaAs diode's cathode and anode causes the current flow between those two elements to increase proportionately. But, at the critical 3,000 volts per centimeter, current strangely starts to drop with voltage increase.

This peculiar behavior results from gallium arsenide's being—in common with the other materials that have bulk-oscillation talents—a "two-valley" semiconductor, with two different electron-conduction band valleys at two different energy levels. One band—the one operating below the 3,000-volt state—is termed "low-energy" because the electrons it contains require little additional energy to leave that band and move into the second, or "high-energy" band. The high-energy band is normally empty.

Somewhat simplified, what happens is this: When a power-supply potential of, say, 6 volts is first applied across a block of GaAs, the latter behaves as a quite ordinary "ohmic"* material, with current increasing or decreasing in step with the applied voltage. As the latter is raised, though, the space charge within the GaAs builds up, and some of the higher-energy electrons in the low-energy band are excited into the high-energy one. Finally, at around 3,000-volts-per-centimeter field strength, enough of the higher-energy electrons have moved into the upper band to make the less mobile electrons dominant there. At this point in time, current through the block of GaAs decreases, and so, effectively, the resistivity of the GaAs reverses and becomes "negative."

Although electric field intensity measures in the thousands of volts in a GaAs bulk oscillator, the voltage applied between the cathode and anode of the device is only from around 6 to 28 volts for a piece of material from 10 to 50 microns thick.

GUNN EFFECT OSCILLATION

In normal ohmic material, space charge *decays* exponentially according to a time constant set by the material dielectric constant and conductivity. When the resistivity becomes negative, however, as it does at the 3,000-volts-per-centimeter space charge point in GaAs, space charge *grows* exponentially with time and produces a circumscribed high-potential field—or "domain"—within the bulk of the semiconductor. The narrower the inter-valley energy gap and the lower the temperature, the more marked is this phenomenon.

Inside the high-field domain, conductivity remains negative, but outside the domain and across the diode's output terminals conductivity is positive. With time, the high-field domain drifts across the diode. When it reaches the anode, it is dissipated, and if the supply voltage has not changed, an identical high-field domain will then appear at the cathode and travel across the diode as the first one did. The repetition of this behavior continues as long as the applied voltage remains unaltered, and the cyclic reversals of conductivity at the anode constitute the oscillator's "Gunn effect" output—so-named for the effect's discoverer, J. B. Gunn.

The Gunn effect diode is a transit-time device, and its output frequency is equal to the speed with which the high-level domain drifts across the diode—about 10^7 centimeters per second in GaAs—divided by the length of the diode's active semiconductor material. Thus, for an active region of around 10 microns thickness, output frequency for a Gunn diode would be about 10 GHz.

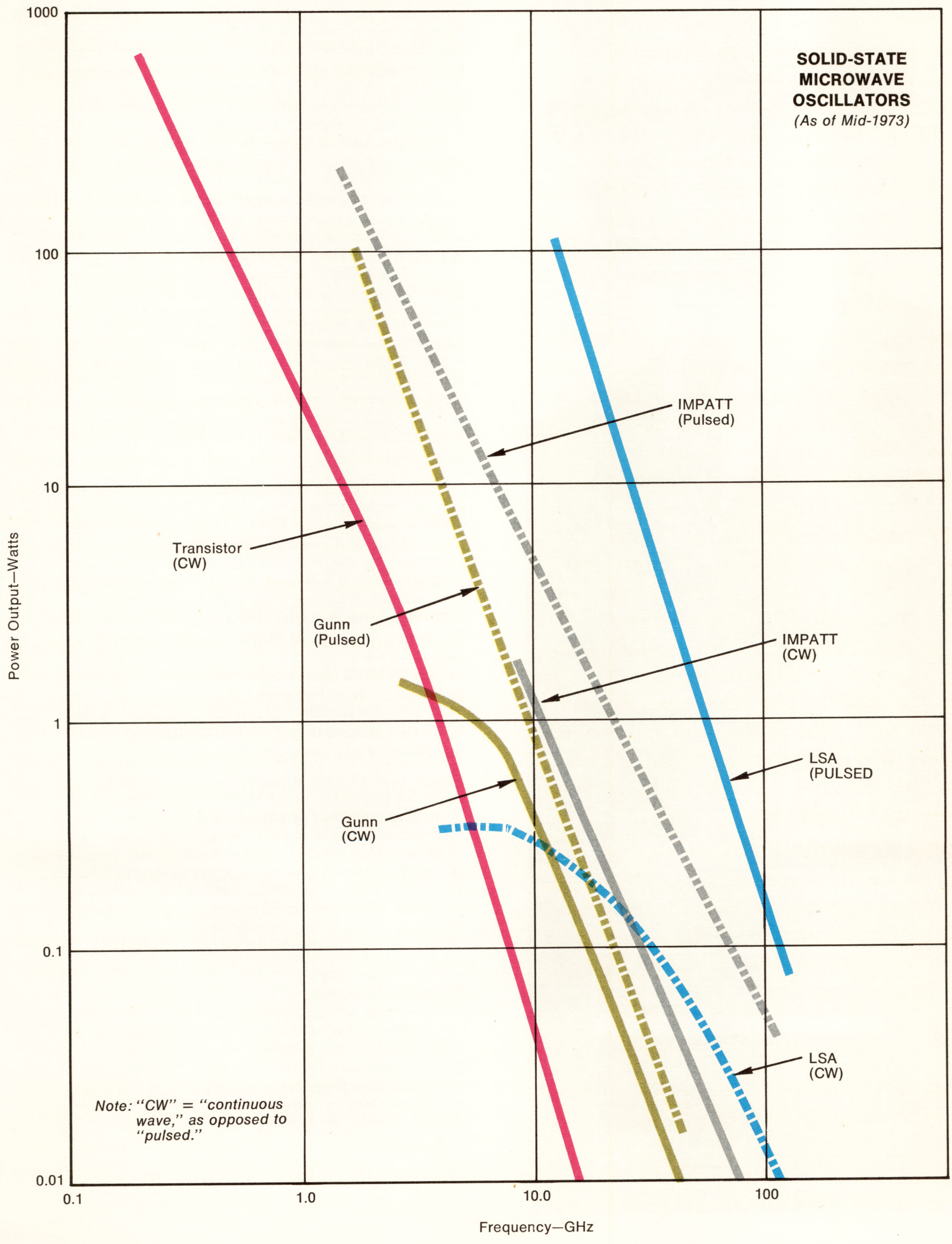
Since the Gunn effect oscillator is a transit-time device, a Gunn diode must be short to operate in the millimeter range (above 30 GHz). Its short length limits the active volume and, accordingly, limits the *power* available from the device.

LSA OSCILLATION

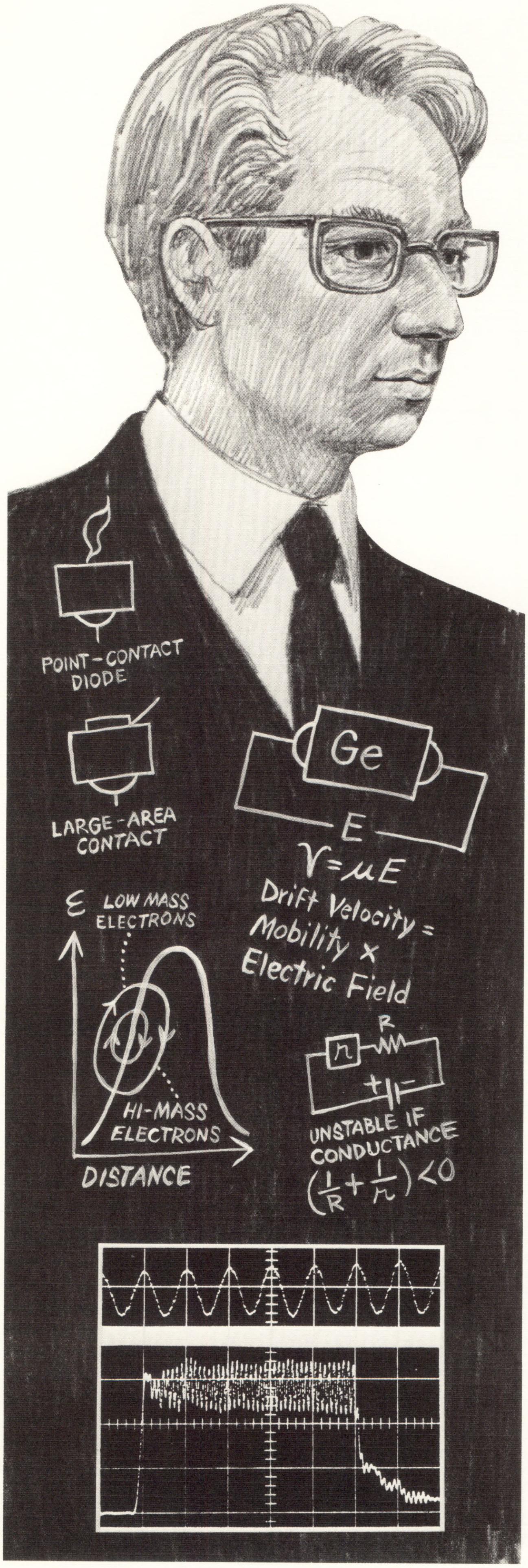
As with the Gunn effect oscillator, LSA mode requires high-quality gallium arsenide, cadmium telluride, or indium phosphide. Also like the Gunn effect oscillator, an LSA device makes use of the semiconductor material's

**An ohmic material is one which follows Ohm's law: current equals voltage divided by resistance.*

reversal of conductivity with the attainment of critical space charge. Unlike the Gunn device, however, the LSA oscillator suppresses the space charge buildup and thus permits a negative resistivity to appear across its output terminals.



A MODERN BEN FRANKLIN AND HIS "KEY" TO THE MICROWAVES



The phenomenon of microwave oscillation (known as the "Gunn effect") in a bulk specimen of semiconductor was first reported by J. B. Gunn, Thomas J. Watson Research Center, IBM Corp., Yorktown Heights, N.Y. in 1963.

Quoting from Mr. Gunn's report: "There has been a number of previously reported observations of the generation of electrical oscillations when a current is passed through a homogeneous semiconductor. However, in most of those cases both holes and electrons were present, and in addition a magnetic field, a very low temperature, special doping, or a special geometry of specimen was necessary to elicit the effect. In this letter we give a brief preliminary account of a new phenomenon, in which the application of a high electric field to a homogeneous body of a III-V semiconductor gives rise to strong oscillations of current, with frequency in the microwave range. Under the conditions of the experiment (room temperature, zero magnetic field), only electrons are believed to be present."[1]

Gunn made the momentous discovery, disclosed in the mild understatement quoted above, while experimenting with so-called "hot electrons" (electrons with average energy higher than that of the lattice) in an attempt to explain observed negative resistance phenomena in semiconductors. His discovery and his modest revelation of it ushered in a veritable new era for microelectronics applications.

Later (1965), in published recollections[2] of the early days of his experimentation, Gunn allowed himself to become slightly more lyrical. He reminisced thus: ". . . the hope of a new negative-resistance device was not in fact realized, but something much more interesting was—namely a coherent oscillator capable of delivering a substantial fraction of an ampere at frequencies of 1000 megacycles and over. The reason this was so interesting, not only to us but to the semiconductor industry generally, was that it was impossible in those days to generate appreciable amounts of power with transistors at these frequencies. You needed one of the many different vacuum tubes which suffered from the well-known disadvantage of being breakable and requiring relatively bulky power supplies.

"There were all sorts of questions that needed to be answered before we could know whether this was a really useful device. For example, it's one thing to see oscillations at 1000 megacycles and it's another to know you have a device with a bandwidth of 1000 megacycles. Bandwidth is a measure of the amount of information that can be transmitted, and the usefulness of a device for information-handling purposes often depends very much on how large this bandwidth is.

"In this respect the device looked hopeful because the current usually started to vary within one cycle of turning on the driving voltage. The fact that the amplitude builds up almost instantaneously did suggest that the bandwidth was of the same order of frequency as the oscillation. This is very unusual and it made one think that whatever the basis for this curious phenomenon, it was something that could be put to use, perhaps for communication applications like microwave telephone links or in phased-array radars.

"First, however we had to determine whether the device could be made to run continuously, or what in the jargon is called c-w for continuous-wave—a hangover from radio telegraphy. All the experiments so far on hot electrons had been done in a pulse mode where you kept the electrical field on only long enough to make the measurement—a microsecond or less. Otherwise you would be heating the lattice as well as the electrons, and the specimen would just blow up. If we could achieve c-w operation then the thing would be much more useful than if it was forever doomed to run in a pulse mode.

"To do this required that we find a way to cut down the electron density in the gallium arsenide. In principle this is easy—you merely ask your friendly crystal grower for a purer crystal. But in fact this turned out to be impossible because at that time we were already working at the limits of the crystal growing technology. So then my colleague Norm Braslau, John Staples [Gunn's technician], and I tried something else—we made the slab [the GaAs specimen] shorter so the heat would have less distance to go before being removed at the contacts. For the kind of gallium arsenide that was available we had to make it so thin that it really was unmanageable. But we did make one batch which for some reason had a lower electron density than we expected. I think what happened was that some contamination occurred and the impurity atoms cancelled some of the free electrons normally present. This, combined with the fact that we were already making the device as thin as we could, allowed it to run continuously. In fact, we actually ran one for a week just to show that the oscillations could be sustained that long. We reported this in November 1964, and c-w operation was reported nearly simultaneously by people at Bell Laboratories and MIT Lincoln Laboratory. Thus, one of the big question marks was removed. Since then, crystal perfection techniques have improved and I think the c-w problem is essentially solved."

Even Gunn himself did not at first understand just exactly what went on in the phenomenon he had discovered. After a goodly amount of experimentation, observation, and cogitation, he worked out his theory for "... the way [the] disturbance [propagates] along the length of the crystal. It moves without changing its amplitude and at a constant velocity which turns out to have the magical value of 10^7 cm/sec we computed a long time ago by multiplying the frequency of the oscillation by the length of the specimen. From the data we got about the rate of change of potential with this technique we were able to deduce that the potential itself was moving in the following way. When the applied voltage is first raised above the threshold value needed to make the current go unstable, the electric field is distributed uniformly along the length of the sample. Very soon afterwards the instability appears in the form of a high-field region at the cathode.... As time goes on, this high-field region moves away from the cathode toward the anode. When it reaches the anode it disappears and the electric field reverts momentarily to its initial uniform distribution. As soon as that happens the conditions that gave rise to the appearance of the high-field region at the cathode are reproduced and a new high-field region appears there and moves through the crystal following this same sequence. This process repeats itself cyclically."

He went on to say: "Briefly the picture is this: When the electric field gets high enough, electrons begin to transfer from the lower valley to the upper one. Once even a few electrons have transferred, the conductivity decreases because the electron mobility in the upper valley is less. This causes the electric field in that region to increase further, which in turn causes more electrons to transfer. In this way the rate of transfer increases and the field builds up almost explosively. We have made movies of the actual potential distribution in gallium arsenide and find out that this is indeed what happens—once it takes off it goes very quickly. As soon as the shock wave appears, the field and the current are reduced proportionately and the wave starts to travel.

"... All these things involve the transfer of electrons between states of different mobility."

But, in 1965, when Gunn was setting down the above remarks, there were still tough, unsolved problems. As he put it, "Before we can use the gallium arsenide device as a microwave oscillator, there are several loose ends that need tying down. For instance, you're dealing with an awful lot of power per unit volume—something on the order of 10 milliwatts per cubic centimeter—and we need better structures for dissipating this heat."

Today, heteroepitaxy provides the very thin gallium arsenide that Gunn needed, but that he and his colleagues could not produce, back in 1964. And as a substrate for the thin GaAs film there is beryllium oxide—with a heat-dissipating capability equal to that of brass and rivalling copper's.

References

1. J. B. Gunn, "Microwave Oscillations of Current in III-V Semiconductors," *Solid State Communications,* Vol. 1, pp. 88-91, 1963. Pergamon Press, Inc.
2. J. B. Gunn, "The Gunn Effect," *International Science and Technology,* pp. 43-56, October 1965.

The LSA oscillator is a development of Bell Telephone Laboratories. The phenomenon basic to its operation is sometimes referred to as the "Copeland effect" after John A. Copeland, the scientist who discovered it.

The LSA oscillator is not a transit-time device, and the growth and decay rates for the space charge are functions of the semiconductor's doping or carrier density. For the same millimeter-wave output frequency, the LSA diode can be much larger than the Gunn effect diode and can deliver much higher power.

Supplied with low d-c voltages, present LSA oscillators indicate that before too long such devices should be furnishing c-w (continuous wave as opposed to pulse), millimeter (30 to 300 GHz) output, with around 20% efficiency, and hundreds of kilowatts of pulsed microwave power. No other approach —including Gunn effect diodes—can point to the possibility of performance to compare with this.

IMPATT (OR AVALANCHE) OSCILLATION

The name "IMPATT" was coined at Bell Laboratories, where avalanche oscillators were predicted by W. T. Read in 1957. IMPATT is an acronym formed from *IMP*act *A*valanche *T*ransit *T*ime. IMPATT devices, first operated in 1964, are the furthest along in both development and performance among the high-field devices. Units have been operated both as oscillators and as amplifiers over a range of from 0.4 to 100 GHz, with power output ranging from milliwatts up to more than 100 watts. Devices with power output of up to 0.5 watt cw (continuous wave, i.e., unpulsed) at 10 GHz are readily available commercially.

IMPATT's exhibit a frequency-dependent negative resistance which gives rise to their interesting microwave device properties. This negative resistance is obtained when the diode is back-biased into its high reverse-current or avalanche mode. The negative resistance occurs specifically because the diode current and voltage are almost 180 degrees out of phase—due to the combined effects of the avalanche-generation ionization phenomenon, and the transit time delay of carriers thus generated passing through the device under the influence of the high electric field impressed upon the device.

Operation of an IMPATT is governed by the dimensions of its transit region, its doping level, and the density of the current flowing through it, as well as the microwave circuit background in which it is mounted. The IMPATT is easy to fabricate—in either silicon or gallium arsenide, by epitaxial or hetero-epitaxial techniques—and is capable of a wide range of operation and application.

COMPARISON OF SOLID-STATE OSCILLATOR TYPES

It is a wise man, indeed, who refrains from reining in his thoughts of what tomorrow may bring in the fast-moving world of microelectronic millimeter device development.

For now, it would seem that any one of the three solid-state contenders—Gunn effect, LSA, and IMPATT—can offer reliable power generation up to 10 watts, at from 5 to 100 GHz, with the LSA diode promising even beyond these limits.

The LSA and Gunn diodes display lower noise characteristics than comparable IMPATT devices. Power requirements for the LSA are versatile—devices can be designed to operate at anywhere from 25 to more than 500 volts. Least versatile in this respect is the Gunn diode—its requirement being 100 volts divided by the output frequency in gigahertz.

SUMMING UP THE GENERATION OF MICROWAVES

No *single device*—whether it be transistor, Gunn-effect, LSA, or IMPATT—is capable of generating sufficient power for a modern sophisticated radar system. The devices have to be "ganged"—operated in parallel, with their individual outputs summed to provide the required total.

In a phased array, complete-solid-state radar, a tiny generator is provided on each antenna element. In other solid-state microwave systems, many separate generators can be "locked" together electronically to provide the high summed output.

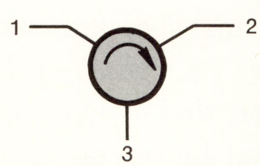
Sold-state devices can be combined to provide as high as 50 to 100 watts peak power per square wavelength of radar aperture—a figure that is at least competitive with non-solid-state approaches.

OTHER MICROWAVE COMPONENTS

Along with the microwave generator, there are many other circuit components that go to make up a complete solid-state system. Amplifiers, switches, limiters, waveguides and transmission lines, delay lines, isolators, protectors, filters, mixers—all are required for forming the total microwave radar transmitter/receiver complex.

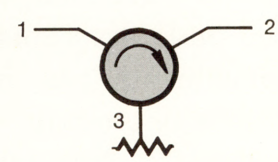
Advances and breakthroughs in materials, heteroepitaxy, microphotolithography, and diffusion and deposition processes are giving birth to a complete assortment of the required solid-state components and are, in fact, in many cases even giving the designer a choice among several alternates.

FERRITE COMPONENTS



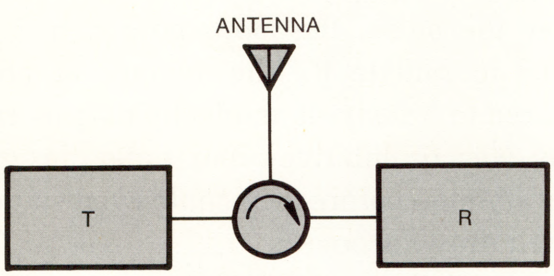
3-PORT CIRCULATOR

In this circulator, which would be formed of microstrip on a ferrite substrate, energy can circulate in only one direction, as indicated by the arrow. Energy entering port 1 or 2 circulates, clockwise, to next port unattenuated, with practically none passing to the remaining port.



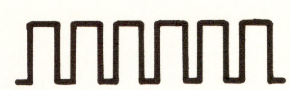
ISOLATOR

Termination of the middle port of a 3-port circulator with the proper impedance effectively closes that port and permits energy to pass only from port 1 to port 2—not vice versa.



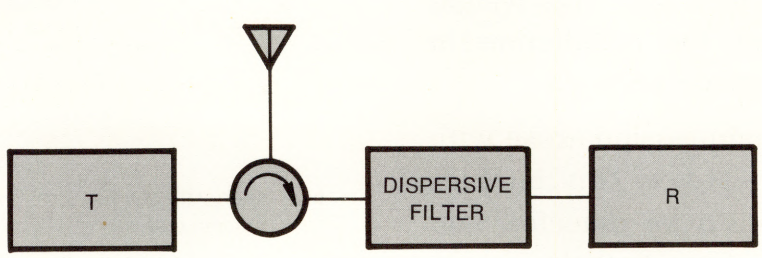
DUPLEXER

A circulator can act as a traffic cop to separate a receiver (R) and a transmitter (T) using a common antenna.



PHASE SHIFTER

Ferrite phase shifters are available in waveguide, coaxial, stripline, and microstrip types. The microstrip units can be reciprocal or nonreciprocal. For a phased-array antenna, reciprocal type can handle both transmitter (T) and receiver (R) functions without switching.



FILTERS

A ferrite (particularly YIG) delay line serves as a compact, efficient dispersive filter for a radar transmitter/receiver pulse-compression system (see diagram above). Ferrite filters—both dispersive and nondispersive—have many other applications. Frequency-selective filters can suppress frequencies only a few megahertz away from a desired frequency; they are thus useful in protecting receivers from large, unwanted signals. YIG filters are excellent for tuning oscillators.

Some pages back, we discussed ferrites and microacoustics. As you will remember, ferrites and other acoustical materials have unique properties that particularly fit them for microwave applications. Ferrites offer nonreciprocal attenuation and high Q, and these valuable characteristics are now being exploited in such microwave components as isolators, circulators, filters, and phase shifters. Microacoustics is being applied to form a versatile variety of both reciprocal and nonreciprocal microwave components—including waveguides, amplifiers, delay lines, and dispersive filters—all with the very big advantage of being many times smaller than their microelectronic counterparts designed to operate at the same frequencies.

In addition to the ferrite and acoustical circuit elements, a wide assortment of passive microwave components can be fabricated from stripline and microstrip, deposited on insulating substrates such as sapphire.

And, finally, to round out the capable and talented family of microwave microelectronic components, there are active devices such as varactors, PIN diodes, and Schottky-barrier diodes.

PULSE COMPRESSION

An especially significant breakthrough in the invasion of the microwaves has been the development of "pulse compression"—a sophisticated technique for increasing radar resolution and effective power. Ferrites and microacoustics combine to enable the dispersive filters, required for implementing pulse compression, to be small and lightweight enough to be practical for installation in advanced aircraft and space vehicles.

The need for pulse compression arose with World War II, when relatively tiny missiles returning to earth had to be detected and identified against an extremely noisy background of chaff, aircraft, antiaircraft projectiles, and other missiles.

Long before pulse compression was successfully implemented, theoreticians had predicted its feasibility as a means of gaining the increased resolution obtainable with a *narrow* radar pulse, without paying the price of the *increased power* demanded by a narrow pulse.

To detect and identify the sought-for missile echoes amongst all the noise, every attempt was made by radar system designers to achieve narrow pulsewidth.

The wider the pulse, the greater the number of spurious echoes that could fall within its bounds to add to the confusion of finding and recognizing it. The designers' problem was compounded, also, by the requirements of a narrow pulse system for higher power.

In order for a radar to achieve *range*—just as important as *resolution* in some applications—there must be sufficient energy expended to carry its signals to the target. And, the energy expended in any radar pulse transmission is equal to the "area" of the pulse—which is, like any other area, the product of width times height.

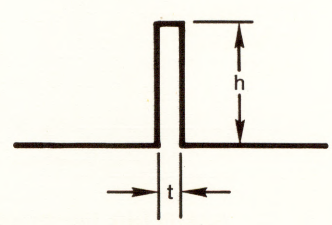
With a radar pulse, width is, of course, pulsewidth, t, and height, h, is power. The next diagram graphically shows that, the narrower the pulse, the more power, h, is required to radiate it. The amount of power required to broadcast an ideally narrow radar pulse was prohibitive—and radar designers were stymied before they could even sit down to their drawing boards.

But there were still other problems. Bandwidth, β, is equal to the reciprocal of t. That is,

$$\beta = \frac{1}{t}$$

ht = energy that can be put into pulse

(h = power,
t = time or pulsewidth)



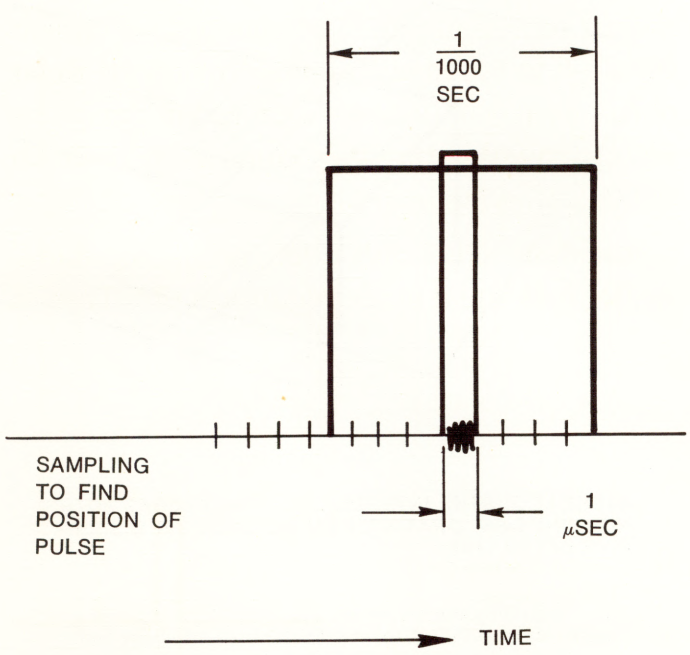
THE ENERGY IN A PULSE IS EQUAL TO ITS AREA.

And, the smaller t is (that is, the narrower the radar pulse is), the greater is the bandwidth required to transmit it.

The theoreticians looked at this simple mathematics and scratched their heads and thought very hard. It became obvious to them that, at least mathematically, *if one could inject a wide bandwidth into space, it would effectively be just the same as projecting a narrow pulse into space.**

Why is a wide bandwidth equivalent to a narrow pulse? Stated very simply, it's because the narrower the transmitted pulse, the less certainty there is where, in time, the pulse is, and the more "samples" must be taken to discover its location within a given interval.

For a pulse one-thousandth of a second wide, it could be necessary to take samples 1000 times in a second to "find" it. For a pulse a microsecond wide, however, one might be required to sample a million times within a second in order to locate the pulse's position in time. Thus, the narrower the pulse, the higher frequency of sampling required—or, in other words, the wider must be the bandwidth, β, required to cover the frequency.



SAMPLING FREQUENCY MUST INCREASE WITH DECREASE IN PULSEWIDTH.

By "space" here, we mean "etheric" space, not necessarily "outer."

What this all adds up to is that, ideally, it is most "desirable" to a radar receiver to "see" a very *narrow, high-powered* pulse—narrow enough to pinpoint a target, high enough in power to stand out above a noisy background. But to the transmitter, for reasons of size, weight, and economy of operation, it is desirable to be able to transmit a *wide* pulse, with relatively *low power.* Since the pulse received by the receiver is the pulse transmitted by the transmitter, this presents a problem.

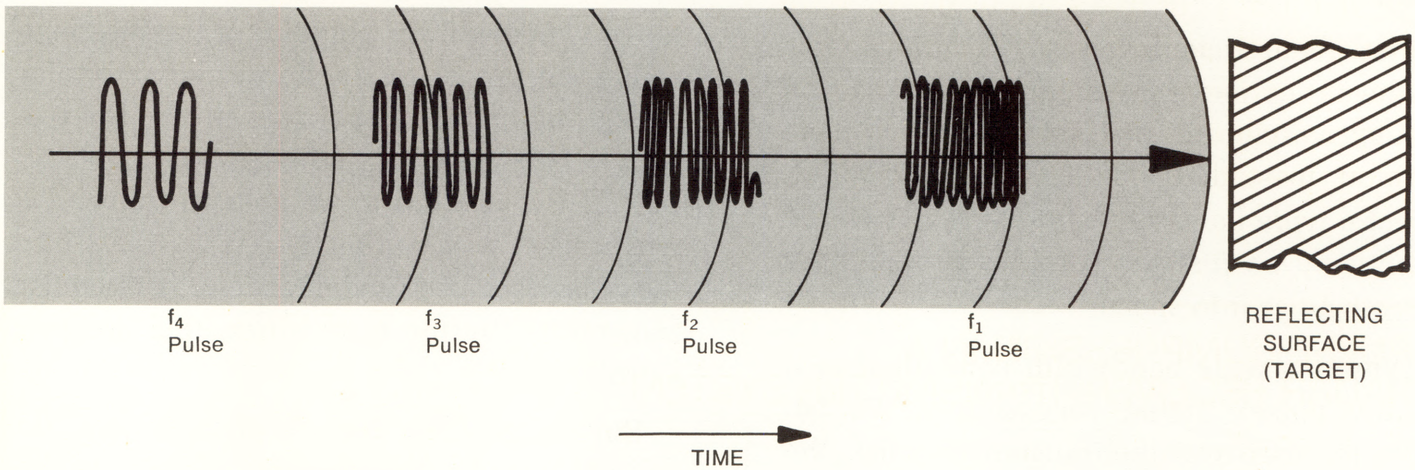
But the problem has an answer—and the answer is *pulse compression*. There are different ways to accomplish pulse compression, physically and electronically. One of the most satisfactory is the dispersive delay line.

You will remember that a "dispersive" delay line is one which delays signals of different frequencies by different amounts (see page 100). This peculiar property permits us to transmit the kind of pulse that the radar transmitter wants to transmit, and to receive the kind of pulse that the radar receiver wants to receive. In so doing, it gives us high resolution and effective high-power output, with actual low-power expenditure.

To understand how this is accomplished, suppose we transmit, sequentially in time, four (it could as easily be three or a hundred) pulses, each of a different frequency, and each of equal duration in time (pulsewidth). Suppose that at a certain instant, t_1, we send out the pulse with frequency f_1, at t_2 we send out frequency f_2, at t_3 we send out frequency f_3, and at t_4 we send out frequency f_4. All of these pulses are fairly narrow, but all are of relatively low amplitude and thus place no stringent demands for power on the transmitter.

Following reflection from the target, the four pulses come back to the receiving antenna just as they were sent out from the transmitter—in sequence. With pulse compression, however, these reflected, sequential pulses are not allowed to enter *the receiver proper* immediately upon their return to the antenna.

A PULSE-COMPRESSION RADAR SENDS OUT PULSES OF DIFFERENT MICROWAVE FREQUENCIES AT DIFFERENT TIMES.



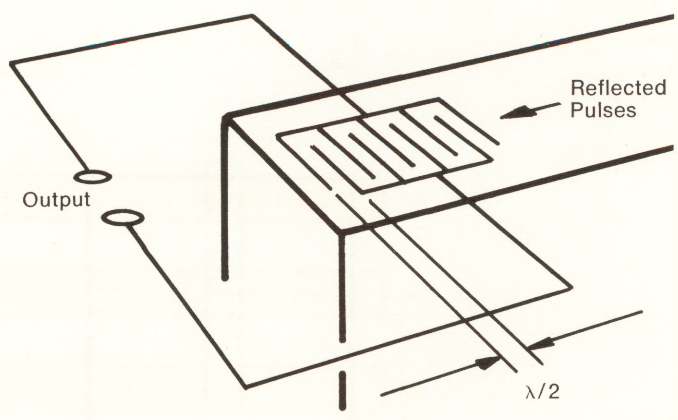
The first pulse sent out and returned (the f_1 pulse) is taken from the antenna to a delay line. After, and only after, being delayed a certain amount by the delay line, the f_1 pulse is permitted to enter the receiver proper.

By this time, the f_2 pulse should have returned from the target, and this pulse, too, is now inserted into a delay line. This second line is slightly shorter than the f_1 delay line, however—just enough shorter to make f_2 take exactly as long to reach the receiver proper after being transmitted, as it takes f_1 to reach the receiver proper after being transmitted, returning to the receiving antenna, and travelling through the first delay line—even though f_1 was transmitted earlier in time than f_2.

The other two pulses, the one with frequency f_3 and the one with frequency f_4, that were sent out third and fourth, respectively, in the series of pulses, are treated similarly. The later in time that each pulse was transmitted, the shorter the delay line that it is made to pass through to enter the receiver. The delay line lengths are precisely designed so that all four pulses arrive at the receiver simultaneously.

Because the pulses arrive simultaneously, their amplitudes add at the receiver input, and what the receiver sees is a single, tall, narrow pulse—although we have broadcast a series of different-frequency pulses of low amplitude over a considerable period of time. In other words, we have achieved the theoreticians' long-sought goal of pulse compression.

The assemblage of delay lines required to perform the above operations and shown in the next illustration is called a pulse-compression filter or a dispersive filter.



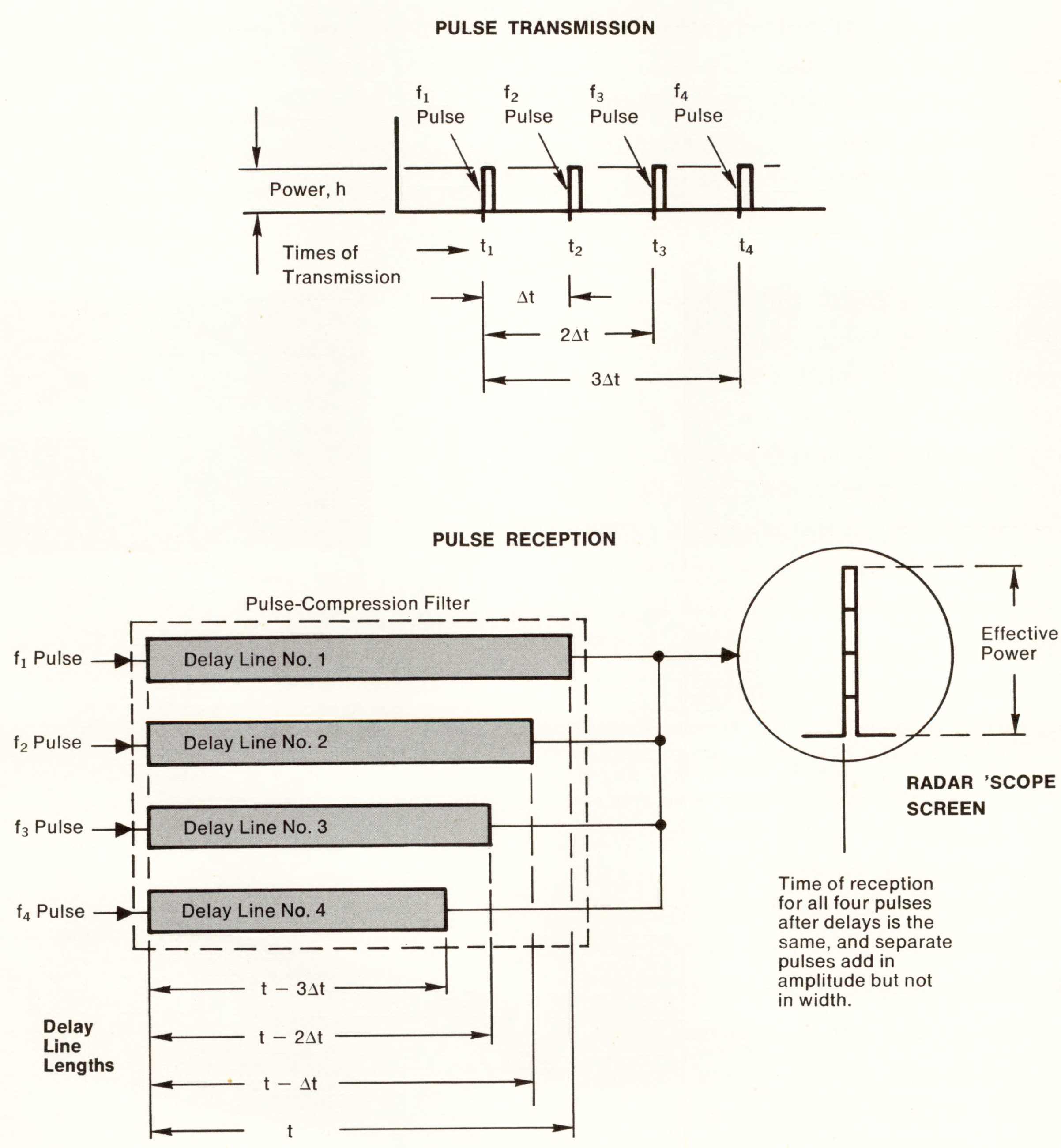
MICROACOUSTIC, INTERDIGITAL STRUCTURES WITH NON-UNIFORM GRATING CAN BE USED AS DISPERSIVE DELAY LINES.

First frequency out would be the one whose half wavelength corresponded to the spacing of the first interdigital pair accosted by the reflected acoustical wave. Second frequency out would be the one whose half wavelength matched the spacing of the next interdigital pair accosted by the reflected wave . . . etc. The spacing would not have to be varied in any particular sequence—thus, the variations could be used to set up pulse coding patterns.

Pulse compression filters formed of discrete components would be prohibitively large and heavy for many applications. With a microacoustic surface-wave dispersive filter, however, performance requirements can be met by a single unit—measuring in cubic centimeters instead of cubic feet, and weighing ounces instead of pounds.

Earthbound radars are not the only systems benefitting from microacoustics in this way. Pulse compression has vital meaning for outer space, where telemetry and voice communications, as well as high-powered, high-resolution radar signals for tracking space-

PULSE COMPRESSION IN A RADAR RECEIVER-TRANSMITTER SYSTEM

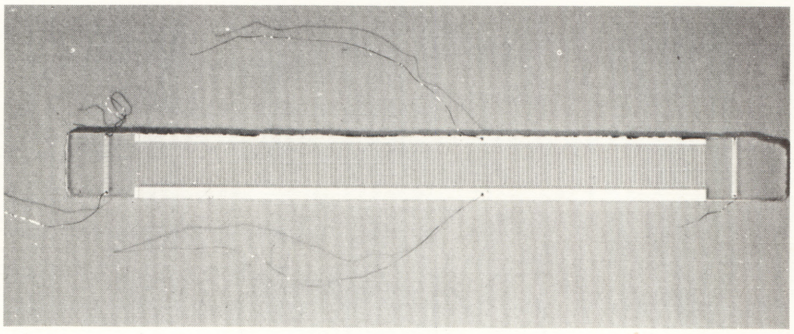


THE WAVE OF THE FUTURE...

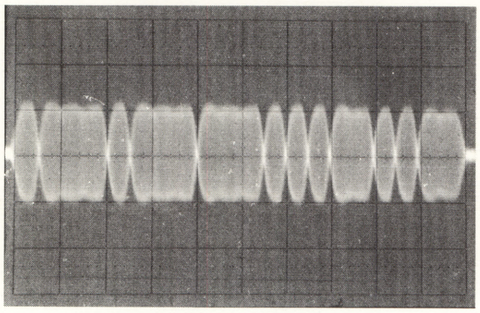
Surface acoustic wave (SAW) components have been developed by Rockwell's Electronics Research Division for application in microwave communications and radar equipment. The SAW units serve as tapped delay lines, dispersive delay lines, and filters.

Rockwell SAW tapped delay lines form a unique class of matched filters for phase-coded waveforms in the 10- to 1000-MHz frequency range. They find many applications in radar, spread-spectrum communications, and telemetry transmission systems. The dispersive delay lines are used in pulse-compression radars. The bandpass filters are designed for specific applications in the 10- to 1000-MHz range.

An example of system usage of SAW devices is a Rockwell navigation/data link modem that enables precision time-of-arrival measurements to be obtained between UHF transceivers. The modem features a SAW analog matched filter (AMF) for processing a 5-megabit/second PN-coded waveform. The AMF is only 50 "chips" in length, and is capable of providing timing accuracies of approximately 20 nanoseconds. In addition to the time-of-arrival capability, the modem can be used to transmit and process digital data.



1



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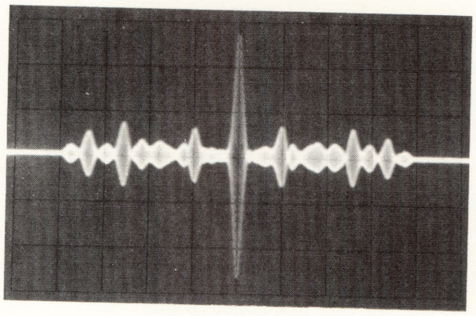


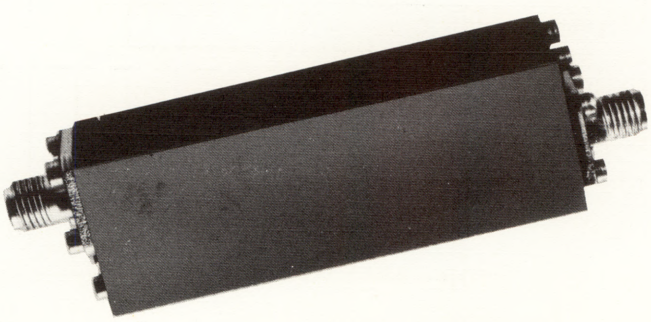
3

MICROACOUSTIC TAPPED DELAY LINE

The 127-tap delay line in "1" above, designed for 120-MHz center frequency and 10-MHz chip rate (100-nsec time delay between taps), is fabricated on a 2-in. x 0.18-in. x 0.050-in. quartz bar. Coded waveforms can be both generated and correlated with the microacoustic lines. For example, the 20-chip, biphase-coded waveform generated by impulsing one tapped delay line (photo "2" above) can be correlated with a reciprocal (time-reversed) tapped delay line (photo "3").

MICROACOUSTIC DISPERSIVE LINE

This dispersive delay line for a pulse-compression radar is only about 6 cm long.



craft, must be beamed over hundreds of thousands and eventually millions of miles, against the background of an entire galaxy—and where equipment size and weight are at a particularly high premium.

SWITCHING AND CONTROL

Transistor techniques, materials, and design knowledge first began to be applied to improve microwave switching and control components—semiconductor diodes—in the 1950's. During the intervening years, semiconductor diodes have been developed that can control hundreds of kilowatts of microwave power, even megawatts under pulse conditions. The versatile devices are capable of serving as duplexers, protectors, power switches, mixers, and—of great importance for phased-array radars—phase shifters. By variation of certain design parameters, the devices can be optimized for high-power or for high-speed and broad-band applications.

Two of the most eminent members of the family of semiconductor diodes for microwave application were introduced to the technological public in June 1958 by A. Uhlir, in what is now a classic scientific paper—"The Potential of Semiconductor Diodes in High Frequency Communications." These two members were the diffused-junction p-n varactor and the PIN, or plasma, diode.

Three basic types of diode are available today for microwave applications: the p-n-junction diode, the PIN diode, and the Schottky-barrier diode. Characteristics of these three basic types can be design-modified for a broad variety of functions. Among the devices thus obtained are variable-resistance diodes—"varistors"—useful as mixers, clippers, and fast rectifiers; variable-reactance diodes—"varactors"—useful as mixers and low-noise amplifiers; and variable-impedance diodes, useful as limiters, protectors, and switches.

P-n junction diodes are familiar devices by this time. The main improvements achieved for them lie in greater power capabilities. The larger the diode, of course, the more power it can handle (even the largest are barely visible to the naked eye). The power-handling capabilities of available devices in the 1970's are many times those of their ancestors in the 1950's.

PIN DIODES

The PIN, or plasma, diode is a highly efficient microwave switch. It has the ability to handle much higher power, with much less loss, in this application than the Schottky barrier type discussed subsequently.

Structurally, a PIN diode is similar to the p-n junction diode. It differs from the latter by the addition of a *relatively* undoped* layer of semiconductor that is sandwiched between p- and n-type layers, both of which are very highly doped. It is the undoped layer that gives the PIN diode its name—"P," of course, for p layer; "N" for n layer; and "I" for "insulator."

The switching action of a PIN diode comes from the high ratio of its impedance with forward bias (p layer positive) to its impedance with reverse bias (p layer negative).

With reverse bias, the center layer of the PIN diode—without a surplus of either holes or electrons—plays an insulator's role. With forward bias, however, the other two layers inject both holes and electrons into the center layer, to form a highly conducting "plasma."

With forward bias, the impedance of the PIN diode may drop to less than one ohm. With reverse bias, on the other hand, it may rise to more than 10^9 ohms at dc, and to more than 10^5 at microwave frequencies. The off-on impedance ratio of a PIN diode is not quite so high as the similar ratio of an open and shut mechanical switch, which could be infinite, of course. It is sufficiently great, though, to make this little device a wonderful and welcome tool for microwave switching and control.

**This layer is only "relatively" undoped in that it is infused with both p and n dopants to the extent necessary to make the material act like an insulator to both the n and the p layers.*

SCHOTTKY BARRIER DIODES

A Schottky barrier diode essentially consists of a layer of n semiconductor, sandwiched between a highly doped layer of the same injection type, and a metal.

When they are used as switches, Schottky barrier diodes do not exhibit the *positive action* of PIN diodes, because they do not have the PIN's dramatically high off-on impedance ratio. They *do* have the ability ordinarily to switch *faster* than the PIN, however, because they are majority carrier devices. Since only one type of doping and one type of carrier (electrons) are involved, there is no storage of minority carriers, and the device has very low capacitance. In a switching circuit, low capacitance is synonymous with speed.*

Schottky barrier diodes are extremely useful as power rectifiers at lower frequencies, and for such functions as detection, fast clipping, and high-speed logic.

COMPARISON OF DIODE TYPES

In the role of switch, a PIN diode is, as mentioned above, considerably slower than a Schottky barrier diode, but switching times have been attained as short as 1 nanosecond with PIN's. If PIN's are made thin enough, they can perform their switching much faster than otherwise. Of course, however, the thinner the diode, the less its ability to handle high power. The tradeoff between speed and power must be optimized for each application.

There are two common types of varactor—depletion-layer and charge-storage.

In a depletion-layer varactor, varying reactance is derived from the varying thickness of the space charge field within a reverse-biased diode, when the applied voltage is varied. The precise pattern of the reactance variation depends on the diode material's "doping profile."

Both PIN diodes and Schottky barrier diodes can perform as depletion-layer varactors, but only a PIN diode can perform as a charge-storage varactor.

In the charge-storage varactor, the varying reactance derives from minority-carrier storage. Since Schottky barrier diodes *have no minority carriers*, they are incapable of performing as charge-storage varactors.

Varactors are useful as up-converters (mixers for converting from low to high frequencies), in which application they offer amplification as well as conversion. They are also useful for high-efficiency harmonic generation and electronic tuning of oscillators.

As varistors, Schottky diodes are preferable, because their impedance, being essentially free of capacitance, is almost purely resistive.

WHAT THE INNOVATING MICROWAVE COMPONENTS CAN MEAN

Impressive dividends will come from the newly available solid-state microwave components.

Samples of these dividends can include such first-time-practical achievements as an adaptive radar system with automatically selectable operational modes of cw, long pulse with pulse compression, and short pulse; an efficient, adaptive, all-inertialess-scan radar with built-in RF source redundancy for reliability enhancement and/or high-power, high-resolution capability; a low-peak, high-average-power radar; and modular microwave systems.

Along with system organization and capability innovations will come further benefits in the form of major reductions in overall system weights and sizes; orders-of-magnitude increases in reliability; and, for small, less sophisticated radars, complete-system-throwaway maintenance concepts.

**In electronics, capacitance has the same "dragging" or slowing-down effect as inertia does in mechanics.*

VI. A LOOK INTO THE CRYSTAL BALL

MICROELECTRONICS IS ALMOST EVERYWHERE

Physical smallness, dependability, and a steadily decreasing price tag are letting microelectronics perform more and more tasks in more and more diverse phases of our lives.

The marvels that are now being accomplished with microelectronics may lead one to wonder what is left for tomorrow. Extension of current trends, however, points undeniably to even greater ubiquity for its applications in years to come, and to its penetration of truly every aspect of man's social, sociological, industrial, and scientific affairs.

In this chapter, we propose to take a look into the crystal ball (a *single*-crystal one, of course!)—to view both today's varied spectrum of microelectronics applications and their foreseeable future extensions.

Our predictions, based on already accomplished applications and readily observable *evolutionary* trends, should be reasonable ones. The actual future, it would seem, is bound to be even more remarkable than the predictions—which do not take into account the *revolutionary* breakthroughs and discoveries that will undoubtedly continue to enliven microelectronics' career.

FOR EVERYBODY AND EVERYTHING: A MASS OF DATA

By far the greater proportion of present and projected applications of microelectronics have one common denominator: the processing of information. Every day, as pointed out in Chapter IV, there is more and more information to process . . . for individuals, for businesses, for government, for science.

"Information," as we use it here, is an extremely broad term, and the information to be processed is of many, many kinds.

There is, for instance, the kind of information that is processed in *communications*—voice messages, telemetry data, weather data, entertainment programs, etc. There is the kind of information that is processed in *medicine*—symptoms for diagnoses, prescriptions, patients' progress charts, pulse rates, blood pressure, EEG's and EKG's, progressive symptomic changes versus specific treatments, etc. There is the kind of information that is processed in *crime prevention* and *law enforcement*—police force deployment, fingerprint files, "most-wanted" lists, facsimile photographs of criminals, "modi operandi" files, etc.

There are, also, volumes of information to be processed in government administration, in banking, education, resources management, law, earthly transportation, and outer space exploration. Panel guessing-games on TV, telemetered heartbeats of moon-bound astronauts, stock inventory for a huge mail-order concern—all share the burgeoning need common to every aspect of society, for processing an ever greater amount of information.

Even you are part of the pattern. There is for you, as for every other individual, a set of uniquely descriptive data. There are, first of all, your name, your birth date, your race, your height, your hair and eye color, and your weight. There are your home address, your business address, your home and office telephone number. If you have insurance policies, these, too, add identifying numbers to your "data signature." Credit cards and charge accounts add further code numbers and letters. Clubs and other affiliations add yet more. And so on, almost literally ad infinitum.

Although there is more and more information to process, there are still the same unchanging numbers of minutes in an hour, hours in a day, days in a week. Since the total available time does not change, but the required information processing within that time *does*, the information must be processed *faster*. And this is where microelectronics comes in—for microelectronics cannot only handle more information in less space . . . it can also handle it at greater speeds and in larger simultaneous quantities than any other approach. It is only with microelectronics that we are able to process today's data. Certainly, it is only with microelectronics that we will be able to handle the burgeoning data problems of the future.

CAPTAIN OF THE RANKS—THE MICROELECTRONIC COMPUTER

Acknowledged leader of microelectronics' onslaught on information processing is and will continue to be the digital electronic computer.

Until the past few years, computers were used almost exclusively to juggle vast masses of facts and figures—to perform intricate calculations that would take man long periods (sometimes as much as years, even centuries) to perform unassisted. Today, however, computers have expanded beyond their original role of programmed calculator. With microelectronics, their capabilities have been multiplied manifold, while their physical size has been many times reduced. Thus, computers of reasonable size have taken on new functions—to analyze and to discriminate, to make choices and decisions, and to adapt automatically to changing conditions.

Today, computers are already keeping track of our bank and charge accounts, checking up for the Government on our income tax returns, and calculating our take-home pay from our jobs. They figure our house payments for the loan companies, compute our use of telephone and utilities, and bill us accordingly.

Yes, computer participation in our lives is already extensive, but it's still all done behind the scene, or as computer people say, "off-line." The information is processed "somewhere," in "some" vaguely remote office or other official facility, and the first thing we know about the processing is when the output reaches us in the form of punched cards or printed statements in our mailboxes. As individual citizens, taxpayers, and human beings, you and I do not yet operate computers ourselves, either at home or in the office.

Tomorrow, microelectronic *home* and *small-business* computer remote input/output terminals may predictably be as common as residential and office telephones are today. A single giant *computer central* will be able to take care of the general computational needs of thousands of using subscribers—just as one *telephone central* now services thousands of telephone subscribers. The technique of "time sharing" will let the computer central sample the various problems put to it by the subscribers—each during a, say, nanosecond pulse interval—so that it is able to work on and solve a multitude of problems with lightning rapidity and with seeming simultaneity.

AT HOME WITH MICROELECTRONICS

The availability of microelectronic computers for the home will have profound effects on life as it is lived day-by-day in the average household.

At least as many households as can today afford a color television set, will tomorrow feature a prominent piece of living-room "furniture"—the "home electronic-center console" (or, as it might affectionately be called, "HECC"—pronounced "heck").

In a single HECC—no bigger overall than a modern spinet piano—will be located, in addition to a central coordinating microelectronic intermediate processing unit, the microelectronic circuitry and the power* for controlling every electrical appliance** in the house . . . for communications throughout the house and between the household members and the outside world . . . for home entertain-

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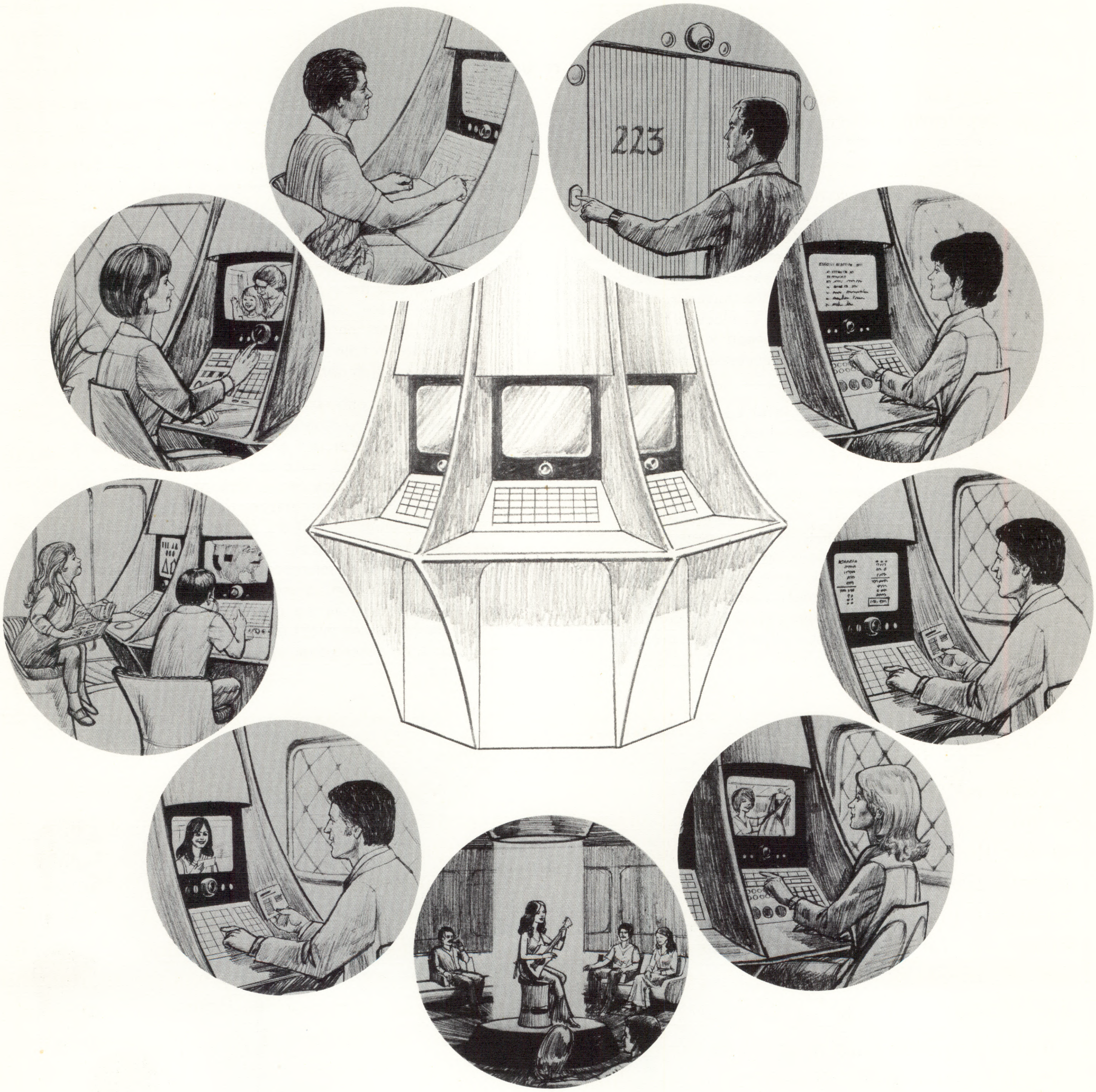
**Solid-state microelectronic switching devices of the future make it feasible to generate alternating electrical power at frequencies of more than 1 kilohertz, as compared to the 60 hertz we use today. The higher-frequency power means that generating equipment can be smaller and less expensive to operate, and that power can be distributed at lower rates to users. Solid-state microelectronic devices also help in the distribution. Used to convert dc to ac and vice versa, they make it economical to transmit d-c power over short distances. This is very important economically, since d-c line loss is lower than a-c line loss, especially at high voltages.*

***All the appliances are themselves implemented with microelectronic circuitry for economical, low-powered, maintenance-free operation.*

THE HOME ELECTRONIC-CENTER CONSOLE...

Just About Everything You'll Want—By HECC!



ment of almost every description . . . and for carrying out many other functions and providing many services not now available to the average citizen within his or her own home.

Into the home electronic-center console are routed the automatic ironer, dishwasher, vacuum-cleaning installation, and microwave cooker. The housewife's proper pushing of buttons on the console will program HECC's self-contained minicomputer to direct all these machines to carry out all her housework, while she, from a favorite couch, watches her favorite TV serial by pushing another button. Into the HECC console, also, she inserts her shopping lists for automatic and instantaneous transmission to retail stores.

ENTERTAINMENTS OF THE FUTURE: HOLOGRAPHIC MOVIES AND TV THEATER-IN-THE ROUND

HOW IT WORKS

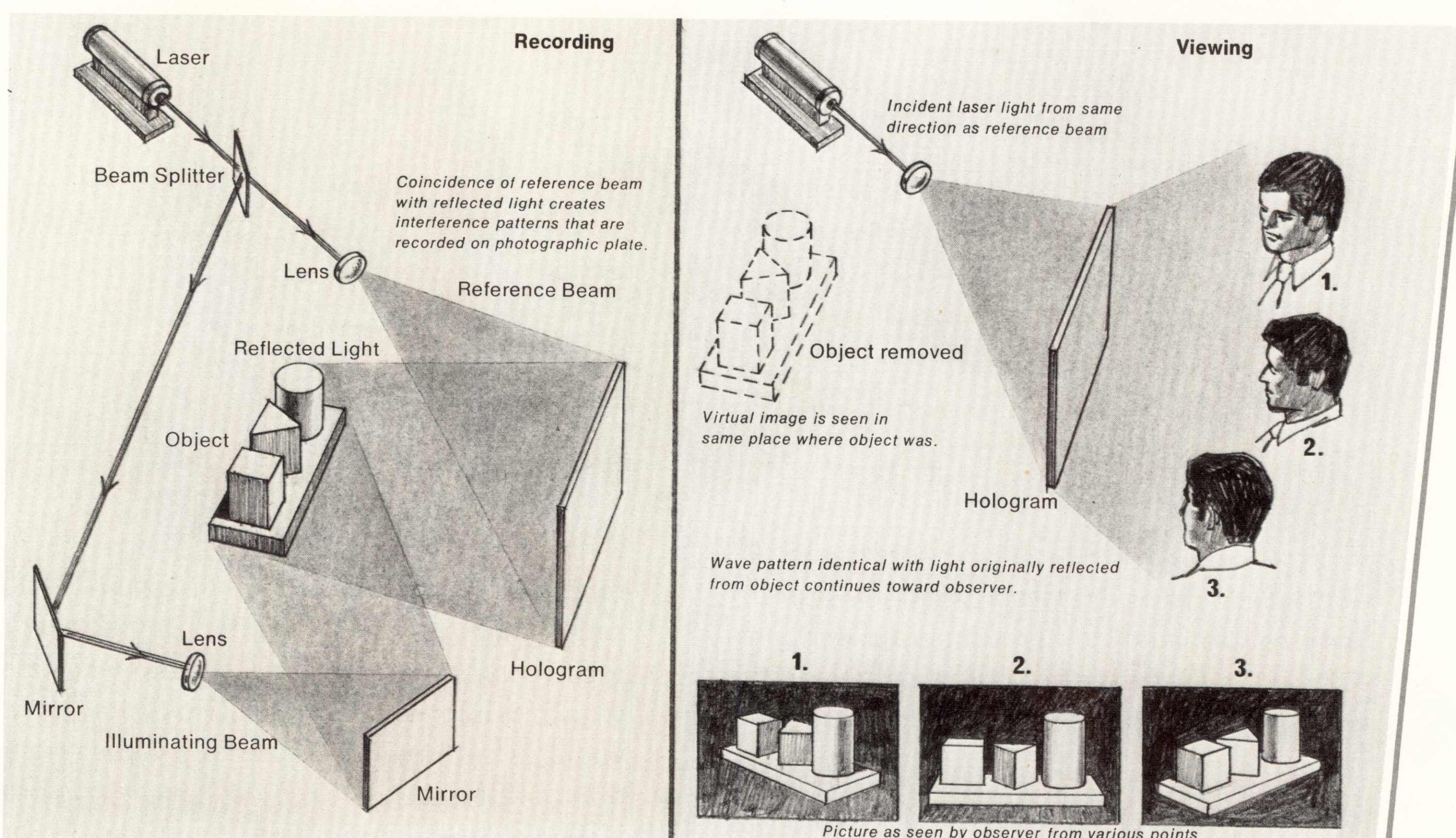
Holography is a lensless form of three-dimensional photography. Instead of ordinary light, it uses the strong monochromatic light from a laser to illuminate the object to be photographed.

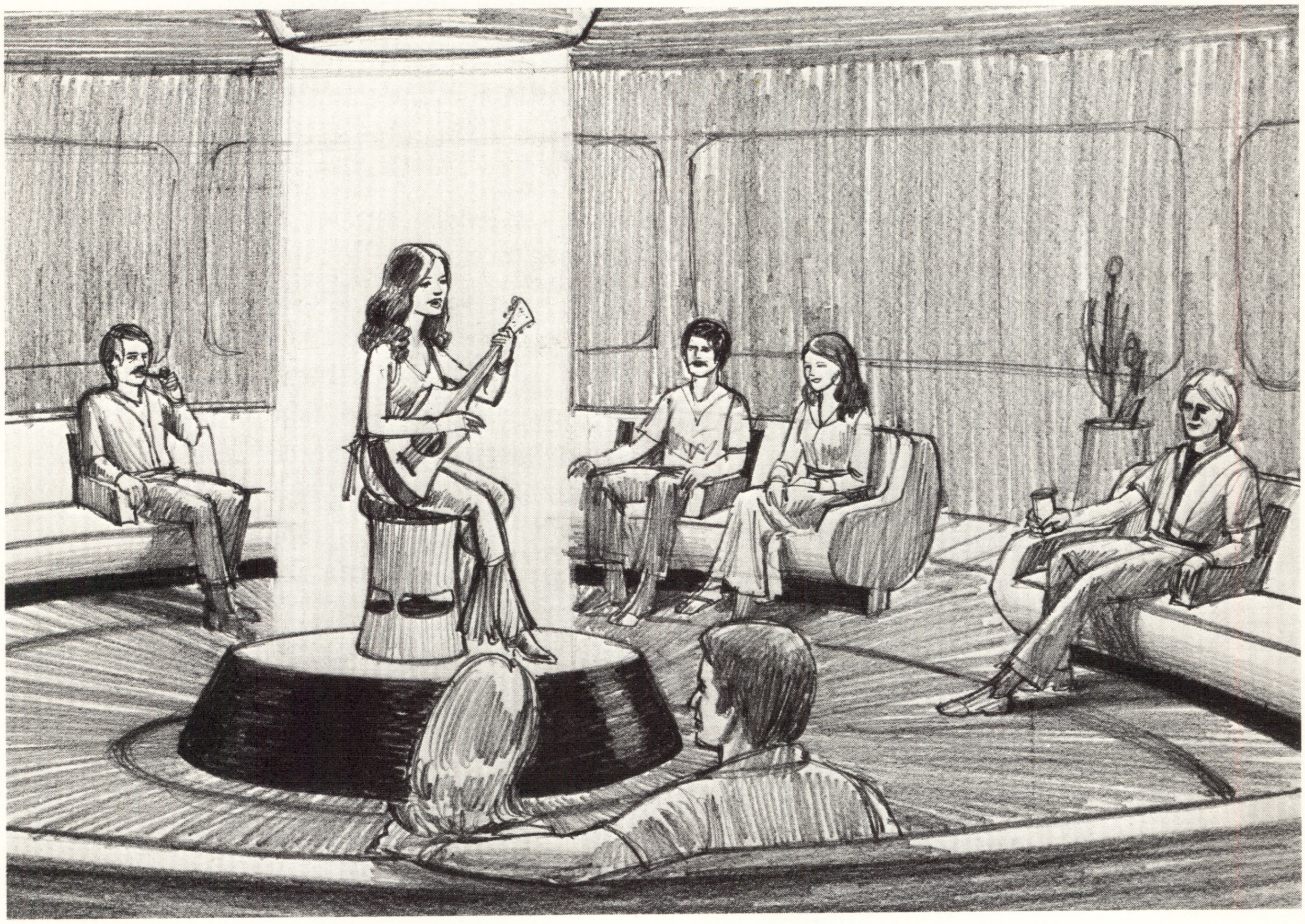
Holography was discovered in the late 1940's by a British scientist named Dennis Gabor. Until the laser was developed, however, Gabor's discovery had to remain just an interesting phenomenon. After the laser came along, it was a different story, and in 1962, Emmet N. Leith and Juris Upatnieks of the University of Michigan used a double laser beam to produce a three-dimensional image that could be viewed in the round, from different angles, without stereoscopes, colored glasses, or other special apparatus.

To make a "holograph," a laser beam is split into two beams—a reference beam which throws light directly onto a photographic plate, and a second beam whose light is guided by mirrors to illuminate the object to be photographed. The light reflected from the object mixes with the "unmodulated" reference light to form an interference matrix on the plate. When the plate is developed, it shows a whorled pattern that is completely unrecognizable by the human observer as a photograph of the object. However, the unrecognizable pattern has stored within its whorls all the data necessary to create a three-dimensional image of the object, when properly processed.

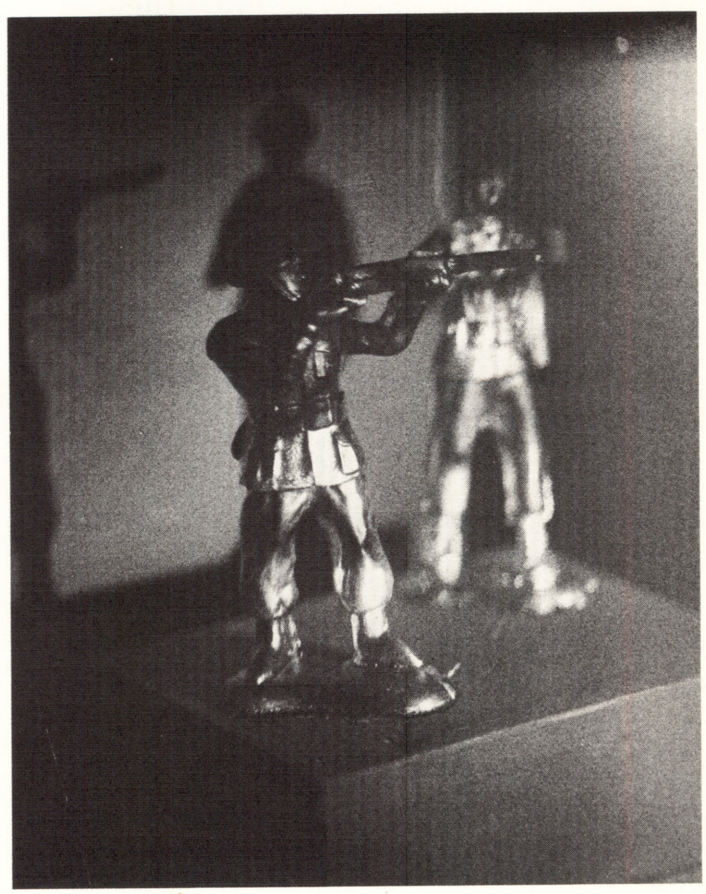
The light is reflected from any "holographed" object in an overall three-dimensional matrix that is unique for each object. Added to the reference light and applied to the photographic plate, the unique pattern is stored in the plate's emulsion until a laser beam exactly like the original reference one is again played upon the plate. This beam "subtracts" from the recorded pattern somewhat as the local oscillator frequency subtracts from the audio-modulated carrier frequency in a radio receiver. As a result, only the replica of the reflected light is left to form an image, and a dazzling, three-dimensional "duplicate" of the photographed object appears before the observer—so faithfully true to the original that it is hard to believe it is *not* the original that one is viewing.

Holography not only permits making and observing three-dimensional photographs. It also permits photographic data to be stored with a density never before possible. Every microscopic spot on a hologram contains a complete replica of the total photograph, each being a view of the photographed object as seen from a slightly different angle from all the rest. Also, thick emulsions can serve as a storage medium for "stacking" a fantastic number of microscopically thin photographic replicas, each, again, presenting a slightly different viewing angle from all the rest. It is easy to visualize how these principles might be developed and exploited to yield three-dimensional movies and TV theater-in-the-round.





A PLEASANT EVENING AT HOME VIEWING HOLOGRAPHIC TV



THE LITTLE MAN THAT ISN'T THERE

Laser holography by Rockwell's Electronics Research Division produces a three-dimensional picture that lets you see behind the toy soldier, foreground. Holographic pictures appear so real, observers are inclined to reach out for the figures, only to get a handful of air.

The console computer searches out appropriate stores for availability of the goods she requests and locates the best price for each item. The order is filled, and mechanical means are directed to make delivery. The bill is totaled, then subtracted from the housewife's bank account. All of this is done automatically, under computer control, simply by the housewife's pressing of the correct buttons on HECC or its remote control keyboard. For frequently used routines, she doesn't even have to press buttons—instead, she simply inserts into HECC a pre-programmed cassette for each routine involved.

The same electronic-center console that sees to the housewife's shopping, entertainment, and housecleaning also serves as communications center for the household—whether it be for a call to the next-door neighbor or for a radio visit with Aunt Maude on Mars. All personal communications go through the computer, with calls listed and messages recorded during the absence of the householders. At such times, of course, each caller is informed of the householders' absence, and probable time of return. (There is no need to fear that burglars will take advantage of such information, thanks to still another dependable function of the HECC. Its monolithic microelectronic circuitry makes its watchdogging of the home at least 99.9999999% reliable. Immediate "macing" of intruders by a computer-directed mace-sprinkling system, and automatic provision of the police with facsimile photographs of the criminals in action at the scene of the crime, are assured.)

A facsimile reproduction of any daily newspaper is available from the console; nine times out of ten, news is still happening while the subscriber reads it. Direct connections through the microelectronic computer with every library in the country give each subscriber the choice of real-time, TV-screen, page-by-page presentation of any book or periodical in print, for instant reading; or a facsimile printed copy of any book or periodical for permanent retention; or *both* TV presentation *and* permanent copy.

When vacation time rolls around, the family punches the appropriate HECC button for direct connection with a travel agency. In response, the TV screen shows them scenes at various spas, quotes prices, and lets them view pictures of available diversions and accommodations at each resort. Once the decision on the preferred destination has been made, the head-of-the-house or his helpmate steps over to the computer keyboard and punches out the choice. If the set is an extremely up-to-date, expensive one, however, the operator can remain comfortably ensconced on the sofa and direct the computer simply by means of voiced commands. The requested reservations are automatically recorded and confirmed by facsimile message. At the end of the month, the householder is billed through central computer-controlled withdrawal of funds from his bank account, and his name is entered into the central computer memory as a holder of reservations for the given room number, at the given hotel, at the given spa, on the given dates.

Other future everyday chores for the household microelectronic computer undoubtedly include the husband's storage of his tax data in the remote computer central, the children's storage of homework problems, and the wife's request for a computerized search to be made of department store inventories for the particular pair of shoes that she "must" have for the vacation. Solutions come back automatically and almost instantaneously (except for the tax returns which are kept in data bank storage until tax year's end, of course). They are delivered in the householders' own living room in the most appropriate forms—neatly typed tax accounts, accurately completed homework, or list of stores that stock the goods the housewife is seeking.

At night, when Dad is through consulting HECC for latest stock market forecasts, and the children no longer need its assistance in doing their homework, the whole family settle down to enjoy any one of a broad variety of pushbutton-selected electronic entertainments—including three-dimensional, holographic, colored TV "in the round,"* stereophonic radio and recorded music, and their choice of reading (facsimile and TV screen) or being read to (pattern-recognition and audio playback)—both of which are performed under the direction of the electronic-center console's microelectronic computer.

MICROELECTRONICS AND THE COMMUTER

Before Dad (or Mom either, for that matter) leaves home in the morning for work, he enjoys a HECC-directed, high-frequency-cooked breakfast, then has his erstwhile electronic "chef" don "another hat" to present him with accurate weather forecasts transmitted via satellite. This is particularly important if he *flies* to work—whether in a driverless, pre-programmed, computer-controlled fly-bus, or in his own casette-programmed private plane. In his casette-controlled, ground-effect hover car, weather conditions are not quite so limiting, of course.

On the way to work, Dad (or Mom) consults a wrist TV-radio to check on possible changes in the weather forecasts heard at home, on stock reports, and on traffic conditions and news reports. On the fly-bus, a self-adaptive control computer automatically and optimally reroutes the vehicle as required by weather, traffic, or mechanical malfunction of the vehicle itself. In a private conveyance, the passenger (there *is* no pilot) continues to listen to his wrist TV-radio throughout the ride, in order to be alerted to insert a different pre-programmed casette into his vehicle's self-contained control computer when an alternate route must be taken.

Of course, there are some who predict that commuting is itself going to be eliminated eventually through microelectronics. Why commute miles to an office or other place of business, when you can relax in the comfort of your own home, with everything needed to conduct business—conferees, facts and figures, instantaneous communications, files, and documentation—literally at your fingertips through the computer-controlled electronic center console?

If, however, you're a hydroponics farmer in a glassite bubble on the moon, a liquid-metals miner on the planet Venus, or the operator of a precision factory aboard a satellite circling Earth, you are *obliged* to commute. Even so, you find microelectronics to be a helpful fellow-traveler. Its small bulk and ultra reliability combine into the ideal medium for space guidance, control, and communications. Many-times redundant, self-adaptive, self-"healing" microelectronic systems for data telemetry, voice conversations, navigation information from Earth, and automatic spacecraft piloting make your trip a safe one, and allow your wife to relax in confidence that you'll eventually reach home again—although, depending on your itinerary, you may have to travel anywhere from miles to light-years (in cryogenically suspended animation) to get there.

MICROELECTRONICS HELPS US MAKE A LIVING

Once safely arrived at the office or other place of business, the man or woman of tomorrow finds microelectronic computers to be ever-present, essential VIP's.

Lawyers use microelectronic minicomputers to perform research, to write briefs, and to file records and documentation. Small-business operators use such computers to do their bookkeeping and routine planning. Computers figure customers' bills, send out statements, conduct inventories, and reorder short-supply items.

Big-business management is freed by computers from routine decision-making. Executive time and effort are reserved for policy-

Since holographic images are truly three-dimensional, future TV viewers can be seated all the way around the viewing area—which in actuality is just that—a clear space in the room, not a fixed, two-dimensional, physical screen, as is required by today's television.

making and for the exercise of judgments still exclusively the province of the human brain.

Bankers continue the computer-application trail-blazing role that characterizes them to-day. The whole banking and credit system has evolved into a single, computerized, time-shared central exchange. A push of a button on any depositer's HECC keyboard calls forth a bank statement at any instant. Bills are paid and purchases are made by the depression of other buttons to transfer funds from the buyer's account to the creditor's, with immediate, automatic adjustment of bank balances and issuance of new statements—all under computer control. Central storage of credit rating data for the entire nation's population enables loans to be granted—or refused—in literally microseconds.

HELPS EDUCATE US . . .

Teachers find their loads lightened by computer-directed teaching machines, working through home electronic centers as well as in classrooms. For the home student, the whole Library of Congress is available by computer-controlled retrieval, to serve as source material for the term paper. Computerized teaching centers grade both oral and written work by students via television, radio, and facsimile. Experts from all over the world—in art, science, literature, philosophy, and engineering—are available via home electronic center and satellite relay to serve as instructors in their specialties.

HELPS GUARD OUR SAFETY . . .

Crime preventers and law enforcers make Dick Tracy look as old-fashioned as a Keystone Kop. It goes without saying that every man in the Police Department wears a wrist TV-radio similar to those worn by commuters—except that the police units are supplied with all the bands and both AM and FM, and can both send and receive, of course. A special vest-pocket, microelectronic facsimile receiver/transmitter permits the officers to transmit back to headquarters photographs taken at the crime scene, to serve as evidence later and to permit immediate computerized file-search and identification of the criminal. Also sent back by facsimile are any fingerprints the criminal has inadvertently left behind. In FBI files in Washington, D.C., billions of fingerprints from all over the world are stored by means of microelectronic memory matrices, in the amount of space formerly required by a single print. Microelectronic pattern-recognition machines review the billions of prints in microseconds and, for any print that has a counterpart in the files, flash its identification to the querying police department anywhere on the globe.

The amazingly dominant role played by the computer in our daily lives today and increasingly in the future can largely be credited to high-density microelectronics. Consider just one area, for instance—that of the home computer. A machine capable of performing all the home computer functions we have predicted would, without LSI microelectronics, require an installation space almost as big as man's entire house—it certainly would not fit into a console in his living room!

Similarly, if computers could not be built with low-power MOS and other LSI devices, the electric bill would send the average home owner to the poorhouse within a single day's use of home electronic center. About the only person, in fact, who would be on easy street under these circumstances would be the electronics repairman.

However, with small, compact, low-powered, economical-to-operate monolithic microelectronics, all our predictions for the inroads of the computer into our everyday lives become reasonable. Repairmen may find it "tough going," as computers and other complex electronic systems do their own repairing. Just wait and see—at microelectronics' amazing pace, you'll no doubt still be around to observe in person.

AND . . . MICROELECTRONICS HELPS KEEP US WELL

One of the most fertile fields for compact microelectronic computers is medicine. With their twin abilities to store huge masses of data and to calculate at lightning speed, microelectronic computers are able to show up, in reasonable lengths of time, otherwise unobservable interrelationships between diseases and their causes, and between treatments and their effects on such dreadful killers as cancer. Stocked with sufficient data relating to disease-identifying syndromes, computers can be used to diagnose. Their suitability is obvious for the routine but complex side of medicine involved in hospital management and administration, blood bank inventorying and management, and drug and medical stock monitoring and upkeep. However, while the computer is an undoubted leader in microelectronics' blitzkrieg assault on medicine, it is not the only general in the army. Dramatic inroads into the medical field are also being made by microelectronics unaccompanied by computer—in prosthesis and in monitoring (even controlling) vital human body functions. Microelectronics quite literally is keeping some of us alive!

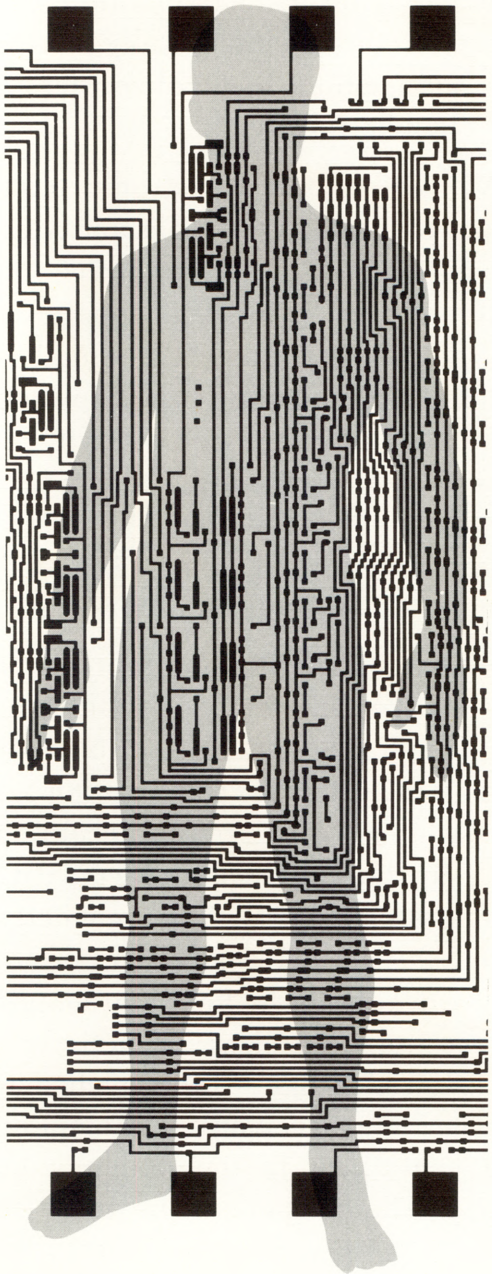
In the 1960's, microelectronics permitted patients to wear strapped to their bodies, or to carry in their pockets, units to continuously monitor their vital signs and to pace essential processes such as heartbeat. Today, microelectronics goes even further and allows the patients to carry pacers inside their bodies. Tomorrow, not only the heart-stimulating pacer circuitry will be implanted, but the telemetry to broadcast conditions to remotely located attending physicians, as well. Telemetric delivery of data to a central diagnostic center will keep the center informed of any patient malfunction, so that the center can then immediately transmit back to the patient strong corrective signals to remedy the malfunction.

Circuitry implanted inside the body cannot be accidentally dislodged, and electrodes remain in constant contact with the muscle or organ of concern. Any adverse reactions of the body tissue to the circuitry as a foreign intruder can be prevented by encapsulating it in epoxy resin covered with an outer layer of silicon rubber, and by using electrodes and lead wires made of platinum. Both silicon and platinum are biologically inert, and, since the body cannot metabolize them, they cannot react harmfully.

Monolithic microelectronic circuits, such as are found in bipolar IC's and MOS devices, are particularly suited for both implanted and externally worn medical apparatus, because of their characteristically small size, light weight, high reliability, and low power consumption. MOS, of course, will play an increasingly important role, due to its capability for high elemental density and the consequent potential it offers for multichannel monitoring and control of vital functions.

As early as 1969, the Brain Research Institute of the University of California devised and applied a microelectronic telephone-telemetry system for transmitting brain waves of patients from remote locations directly back to the University's Medical Center for computer analysis. The telemetry pack—about the size of a small transistor radio—was worn by the patient and amplified brain waves and other electrical activity picked up by electrodes that were attached to him. A special radio received these amplified signals and sent them to the patient's home telephone. The telephone line then transmitted them to a University laboratory, where they were recorded by a conventional EEG (electroencephalograph) machine and subjected to computer analysis. Records could be made at any time, day or night, by simply dialing a special number and leaving the phone off the hook for a specified period. The patient was free to move about the house or yard during the entire recording. Most of the monitored patients had had epilepsy or other neurological disorders. Divers with the bends were monitored with the remote telemetry system while in a distant decompression chamber.

MICROELECTRONICS WILL ADD MANY MORE ALPHABETICAL COMBO'S TO THE NOW-FAMILIAR EEG, EKG, EMG...



Many, if not all, biological functions are accompanied by generation of electric potentials. For this reason most machines for recording the functions are electrical. Examples are the electroencephalograph (EEG), electrocardiograph (ECG or EKG), and electromyograph (EMG) systems which record the tiny voltages and currents that accompany brain, heart, and muscle action, respectively.

Generation of electricity by the nervous system has been recognized for well over a hundred years, but not until this century has the knowledge been put to practical use.

Pioneer among medical recorders was the EKG, developed by William Einthoven, 1924 Nobel Prize winner in medicine and physiology. His recording oscillograph was very sensitive and fast of response for his time.

Today, its descendants are among the physician's and medical researcher's most important tools. In 1929, Hans Berger developed a method of recording electric potentials from the brain through the scalp. From this development grew the EEG.

In the future, transducers for measuring, monitoring, recording, and even controlling bodily functions will not be limited to just the three locales of brain, heart, and muscles. They will be literally *plastered* all over the place.

If all the locales that future microelectronics will be capable of monitoring on the human body were monitored at the same time, the patient would look like a walking circuit board! Pasted-on or painted-on electrodes would interconnect some units; wireless interconnections would be made by telemetry. Many functions would be monitored by microelectronic implants which could not be accidentally dislocated or dislodged, and which would safeguard the patient's well-being every minute, day and night.

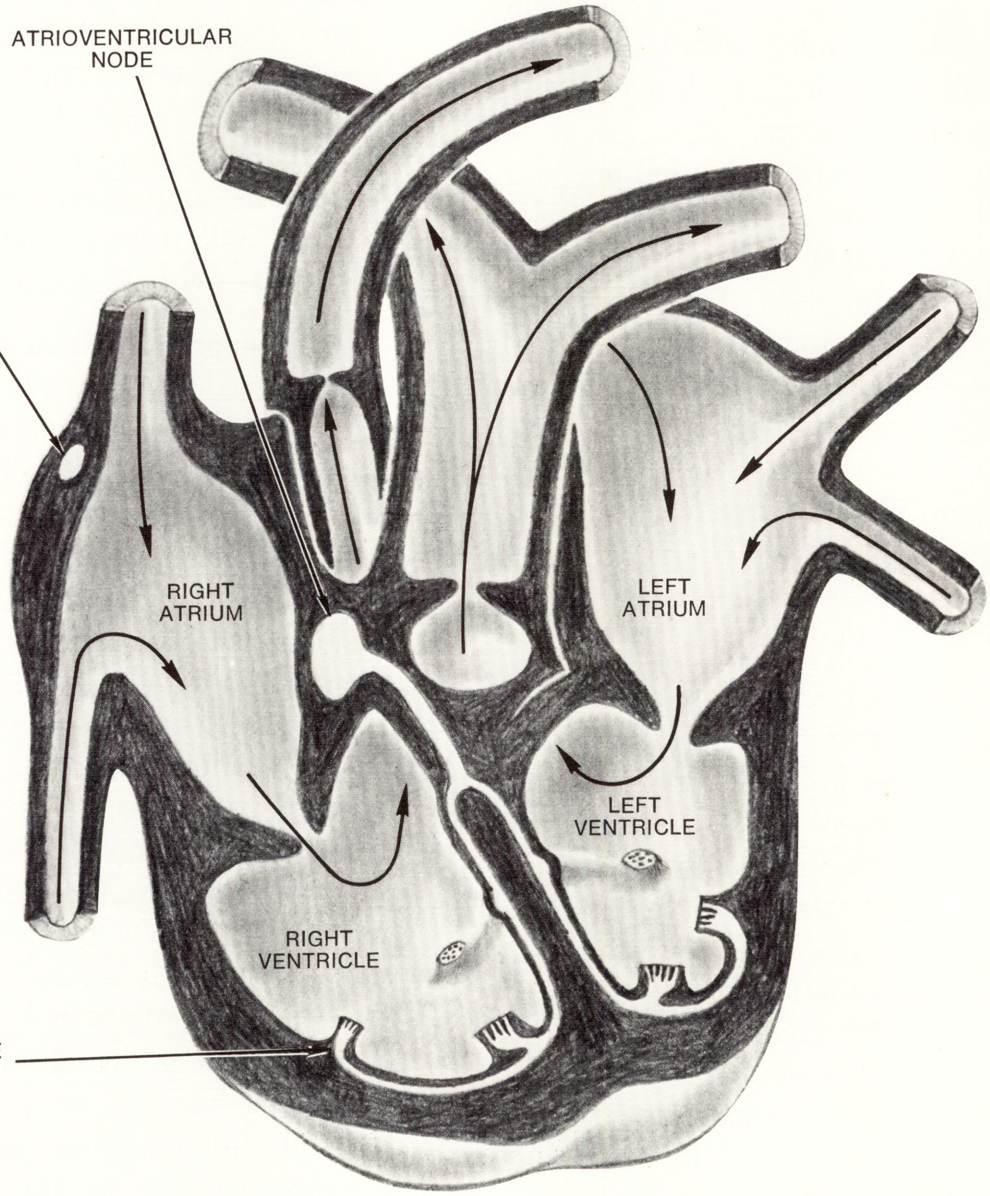
Just as today the aeronautical or automotive engineer locates transducers at many points over and throughout the vehicle and its engine, to measure vibration, shock, heat, noise, etc. in the system, so the future medical doctor will place transducers at many points over and throughout the human body to measure, diagnose, monitor, and control. As many as 20 or 30 different body functional parameters will be measured simultaneously and recorded graphically.

Not all these operations will be performable or practical in the laboratory. As just one example from a myriad, cardiac activity of heart patients going about their normal daily routine will have to be measured to determine whether any part of the routine should be curtailed or eliminated. For this sort of application, microelectronic units will be used. Some will be worn externally by the patient, while others will be implants. Outputs to recorders and to human observers, and inputs for damping, synchronizing, or reprogramming, will be conveyed by means of telemetry.

These same technologies—telemetry and microelectronics—are teamed today for space communications and for monitoring of astronaut physical well-being by observers back on Earth. In fact, many of the electronics requirements for space—small size, low weight, ultra reliability—are identical with those for medicine. And many of the electronics developments for space—sensitive electro-sensors, transducers, and amplifiers; the technique of painting metal electrodes directly on the human body; special techniques for microwave generation and modulation; and digitization and telemetric transmission of data—are directly applicable to medical needs.

Problems induced by the movements of "electronics-wearers" will be avoided by the widespread use of microelectronic implants—which do not have trailing wires to interfere with action, and which can be relied upon to stay in place and in contact to make their important measurements and to perform their important assigned tasks of monitoring and control.

NATURE'S OWN PACEMAKER...AND ITS MICROELECTRONIC REPLACEMENTS



What we call our "heart beat" is actually the rhythmic contraction-and-relaxation of the heart under the control of a tiny clump of specialized muscle cells—the "sinoatrial" (SA) node. It is nature's own pacemaker, assigned prime responsibility for regulating the pumping action of our heart.

To start the pumping cycle, the SA node contracts and, as it does so, it sends out electrical signals to a second clump of specialized cells—the "atrioventricular" (AV) node. From the latter, electrical impulses travel through still other specialized cells, called "Purkinje fibers," which branch out from the AV node through the ventricular walls of the heart. This procedure forms a complete cycle.

The consistent repetition of the cycle is characteristic of a healthy, normal heart. Sometimes, however, nature's own pacemaking "circuitry" gets out of order and the heart skips beats, or contracts at an irregular, erratic rate. If this goes on too long or too often, the *natural* SA node "pacemaker" has to be given assistance by artifical means. One way of doing this is to use electronic circuits to apply shocks of electricity at the right times and in the right amounts. These shocks pace the heart just as the SA node would do in a healthy organ.

Yesterday's pacers were worn outside the body—some of today's are worn inside as microelectronic implants. Tomorrow, a single tiny, multichannel package will be able not only to pace the heart, but, simultaneously, to monitor blood flow rate, blood pressure, and several other vital body processes.

Although the 1969 unit was not suitable for implant, its modern microelectronic descendants will certainly be.

Microelectronics not only permits circuitry to be small enough for implanting. As already mentioned, high-intensity microelectronics also allows more channels of information to be handled simultaneously than ever before. An example of this ability, although not an implant, is a Swedish four-channel telemetry system used to monitor and forewarn of epileptic seizure bursts, by transmitting electroencephalographic data from disturbed children at play. With the microelectronic telemeter mounted on his head, a disturbed child fitted with the system is free to play without the restriction of interconnecting wires. This unit is constructed entirely from flat-pack IC's. If implemented with MOS/LSI, it could be even smaller and more comfortable and less restrictive to wear.

As denser, smaller, cheaper microelectronics becomes available, medical applications are going to become more and more comprehensive. Microelectronic pacer implants will be able to go far beyond today's relatively simple units, and will be able to monitor and control blood pressure and flow rate simultaneously with the monitoring and control of the heart itself. Microelectronic controls, furthermore, will not be limited to the heart—units will be implanted even within the human brain, to pace glandular functions throughout the entire body; to correct pathological personalities by injecting electrical fields to cancel out "sick" ones; to forestall epileptic seizures; and to compensate for deficiencies in visual, auditory, or motor nerve system functions.

Future microelectronics will even provide extensions and replacements for human physical powers. In a Mexican system termed the "anauroscope," microelectronics teams with actual human nerve centers to permit the blind to literally "see" again. Users of the anauroscope wear special goggles which pick up luminous images in photoelectric cells and transmit the electric impulses to electrodes placed on the nerve just above each eye, and the stimulation then goes to visual receptor centers in the brain. Blind people equipped with anauroscopes are said to be able to walk around obstacles and no longer require a cane for general "navigation." It requires only a normal amount of imagination to extend the anauroscope's ability to achieve an even more marvelous system which, with continuing advances in microelectronics and implant expertise, will restore truly natural vision to the blind—without goggles!

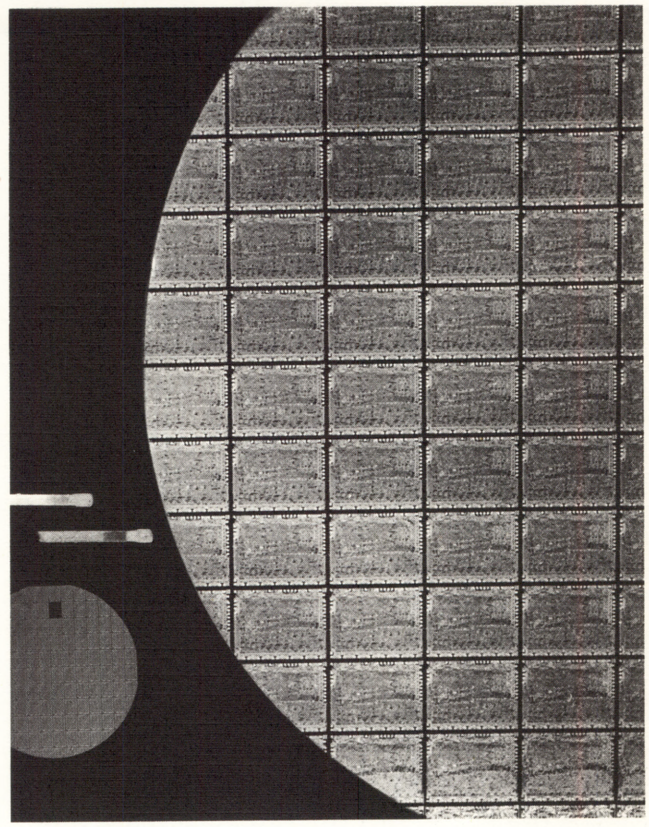
Another area in which microelectronics can restore and/or enhance human physical powers is that of prosthetics. Where amputees once had nothing more cheering to look forward to than the attachment of a cosmetic but essentially non-functional, artificial hand or other limb, microelectronics can allow artificial appurtenances to be manipulated by the amputee's own nerves, almost as naturally as the original fleshly ones. A provocative prosthetic example, already achieved and reported by medical researchers in Stockholm, is a microelectronic electromyographic amplifier, designed to pick up the electromyographic potentials from the residual digital flexor muscles in a hand-amputee. The muscle-action potentials thus detected and amplified are used to switch an electric motor on and off to actuate an artificial hand. Some day, multiple amputees will be able, through microelectronics, to enjoy almost as great motional freedom, variety, and force with artificial limbs as with natural ones.

At UCLA (University of California at Los Angeles), a small group of professors in the College of Engineering and School of Medicine established in the 1960's a new science of great import for medical microelectronics—"biocybernetics." Since expanded, courses set up in the new science were designed to link the engineer's research in computer, communication, and control theory, with the biological knowledge of the physiologist, biochemist, and endocrinologist.

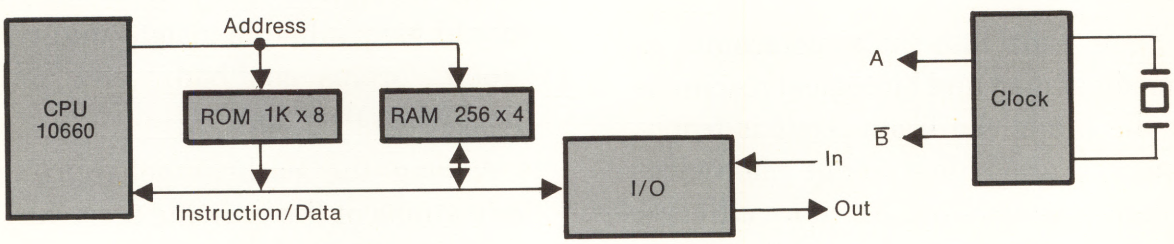
NO ARTIFICIAL BRAIN YET...BUT WE'RE GETTING THERE!

Using the brain's *parallel processing* approach to carry out its data-handling machinations is a Rockwell MOS/LSI system introduced in early 1973. The Parallel Processing System (PPS) is capable of cutting costs of microelectronic equipment substantially, while reducing model-change leadtime to weeks instead of months.

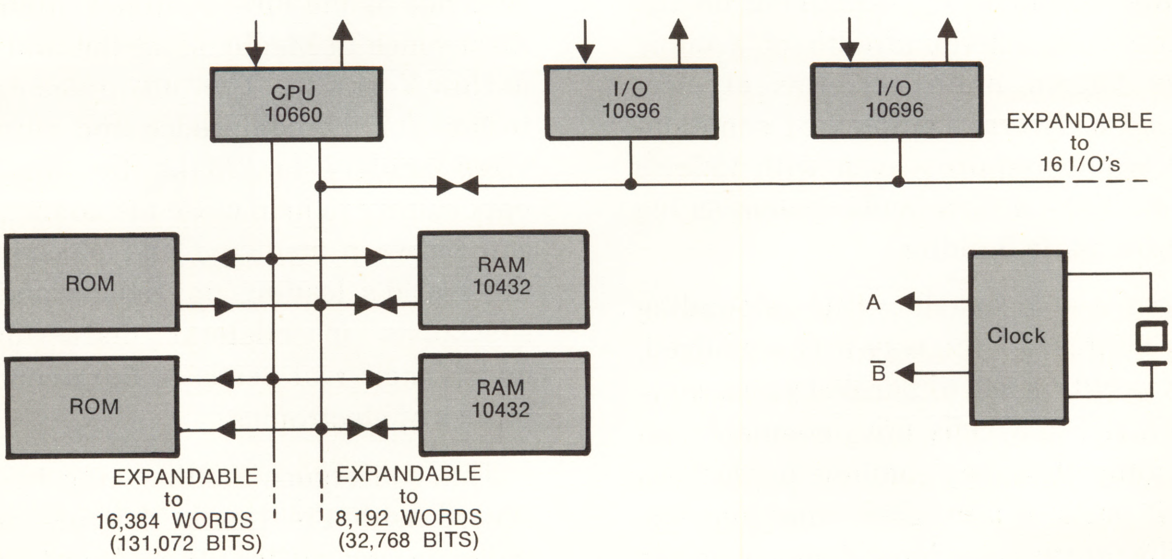
Implemented with five MOS/LSI "chips"—each containing a complete subsystem—the PPS is about twice as fast and typically costs about a third less than other MOS/LSI processors. It performs the arithmetic and logic functions of a four-bit parallel microprocessor. Its operation is based on a powerful one-chip MOS/LSI central processing unit (CPU) controlled by ROM microprogramming and possessing its own input/output (I/O) capabilities.



Magnified view of MOS/LSI array central processing unit (CPU) circuits. One of these CPU's serves as key subsystem in the PPS. Matches indicate actual size of the CPU.



Basic PPS Configuration



PPS Expansion Capabilities

Biocyberneticists are concerned with such practices and procedures as the use of computer monitoring and control in hospital intensive care units. Visualized by the researchers is a hospital computer, programmed with the patient's disease state and general data on physiology and blood chemistry. Thus programmed, the computer would analyze the patient's condition on a 24-hour basis. Eventually, it should be able to help the physician in prescribing proper medication and even in administering certain medicines automatically.

Other biocybernetics research is aimed at determining the brain wave patterns which activate specific muscles in the body. The ultimate objective of this project is to develop a "by-pass" system, channeled through a telemetering device and computer, which could be used, for instance, to transmit the brain's instructions for "clinch the fist" to the appropriate muscles if the connecting nerves between the brain and the muscles were damaged beyond repair.

At the same time that microelectronics is teaching medical men and biological researchers about the brain, the brain itself is teaching designers a great deal about microelectronic system organization. No more efficient nor more microminiaturized machine exists than this fluid-cooled, hermetically sealed information-processing system. Within the confines of the human skull, occupying on the average less than one-hundredth of a cubic meter, the human brain performs at electronic speed a diverse complex of computations that would require—even with today's microelectronics—a man-made system as big as the Empire State Building.

The brain is able to achieve its astounding efficiency because of the way it is organized, and by its resulting use of *parallel* processing. Its individual brain cells are undeniably erratic, but altogether they combine to work on the several parts of a problem *simultaneously*, and the answer—achieved much faster than is possible with the largest computers—is essentially the *consensus* of the results of processing by individual cells. This technique, applied in the organization and functioning of microelectronic arrays, is being used by scientists and engineers in the 1970's to design highly efficient artificial neuron networks for pattern recognition, automatic reading and learning machines, and adaptive computers for the most complex control operations. Systems implemented with the arrays are, to yesterday's systems, like virtual Einsteins and make the older machines seem almost imbecilic in their limited capabilities. Furthermore, the combination of high-density microelectronics technology with system organization modeled after the human brain permits even the "smartest" of the new-generation processors to be of reasonable size for practical use.

In developing "high-IQ," self-adaptive computers modeled after our own brains, we no doubt will learn much about what makes the latter work well or not. Brain-emulating computers should be able not only to teach us about the well-functioning, healthy brain, but should give valuable insight into what makes "good" brains go "bad," and how to cure them when they do.

Among the earliest generally publicized indications of the growing teamwork between medical men and electronics engineers was found in the 1969 announcement, in *Medical World News* magazine, of the imminent occurrence of the First National Conference on Electronics in Medicine, at the Statler Hilton in New York City. The "ad" urged early registration for the conference and earnestly advised readers to "Make the most of this opportunity to help close the communications gap between medicine and electronics. Join the world's leading physicians and medical specialists in bilateral discussions. Help match their real needs to the dynamic capabilities of electronics."

The conference outline was in complete accord with the trends that are continuing today in the 1970's. It included five major headings: "Computers in Medicine," "Demonstrations," "Medical-Engineering Relationships," "Systems Engineering," and "Instrumentation in Medicine." Under "Computers in Medicine," topics to be discussed included: "Computers Join the Medical Team," "What Are Computers Doing in Medicine?," "Diagnosis by Computer," "Data Processing in the Doctor's Office," "How To Communicate with the Computer," and "Small Computers —New Para-Medical Aids." Under "Demonstrations" were such provocative items as patient-monitoring and computer-aided diagnosis systems, and a pulmonary function analyzer. Speakers on "Instrumentation in Medicine" were concerned with the proper design and use of medical instrumentation, and with standards and Government regulation of standards for instrument safety. "Medical-Engineering Relationships" and "Systems Engineering" sessions, as their names implied, sought to discover better ways to doctor-engineer communication and of applying systems engineering methodology used so successfully by the aerospace industry, to the problems of hospital administration, health care, and medicine in general.

In the May 1973 issue of Institute of Electrical and Electronic Engineers *Transactions of Biomedical Engineering*, we are presented with a number of dramatic illustrations of how far we have come in medical electronics since the 1969 announcement, in *Medical World News*, of the First National Conference on Electronics in Medicine. In the cited *Transactions*, on pages 189 through 193, we are shown four NASA scientists'* chest X-rays of a dog with implanted multichannel telemetry units. In the same article, we are also told of a helmet for astronauts, already developed, that contains all of the electronics needed for telemetering of as many as eight simultaneously functioning channels. Most startling revelation in the cited article, however, is an account of a swallowable capsule for human ingestion.

In the 1970's, doctors and engineers have quite definitely "gotten together," and are teamed to apply electronics—and in medicine, particularly, this must mean *microelectronics* —to the fulfillment of medical needs.

A FINAL PREDICTION

And thus it seems that microelectronics is going to have a profound impact on every facet of our lives—housework, entertainment, transportation, communication, business and commerce, education, law and crime, and medicine and health. You name it—microelectronics will be there helping us to do it faster, more reliably, and more economically.

It is trite but certainly true that what the mind of man can conceive, sooner or later he can and almost always does bring to reality. Microelectronics is no exception. This writer's imaginings may, in some instances, seem startling, but they probably represent only a small and timid sampling of what will actually come to pass with the microelectronics of tomorrow.

**Harold Sandler, Thomas B. Fryer, Salvador A. Rositano, and Robert D. Lee, Biomedical Research Division, NASA, Ames Research Center, Moffett Field, Calif.*

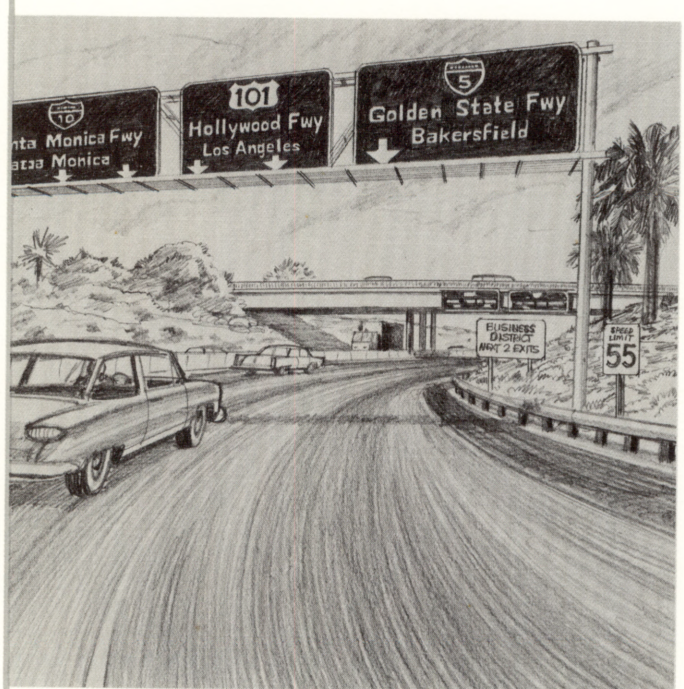
JUST A FEW OF THE INTRIGUING POSSIBILITIES WITH TOMORROW'S MICROELECTRONICS

TODAY . . .

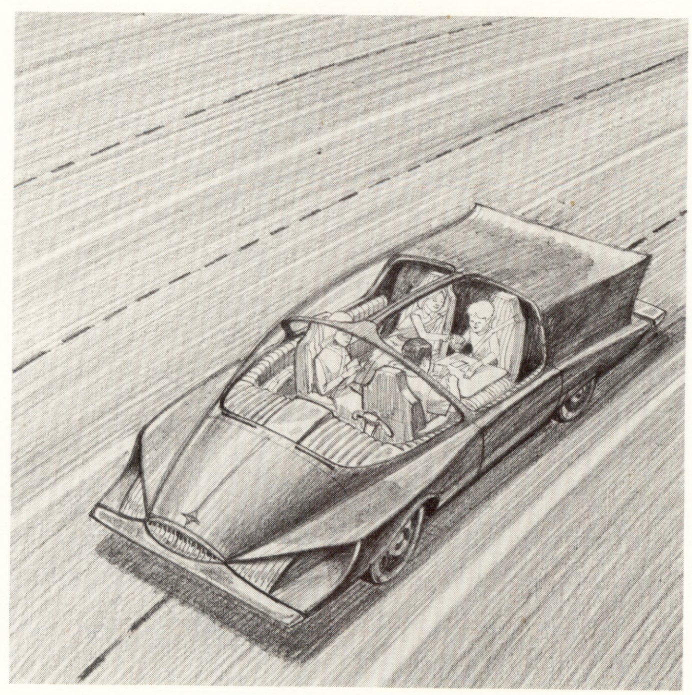
Telephone centrals handle millions of subscribers because almost everybody has a telephone. Without telephones, business, commerce, and social intercourse would come to a standstill.

TOMORROW . . .

Computer centrals handle millions of subscribers because almost everyone has a Home Electronic Center directly connected to a central municipal computer. Without Home Electronic Centers, a great part of business, commerce and social intercourse would come to a standstill.



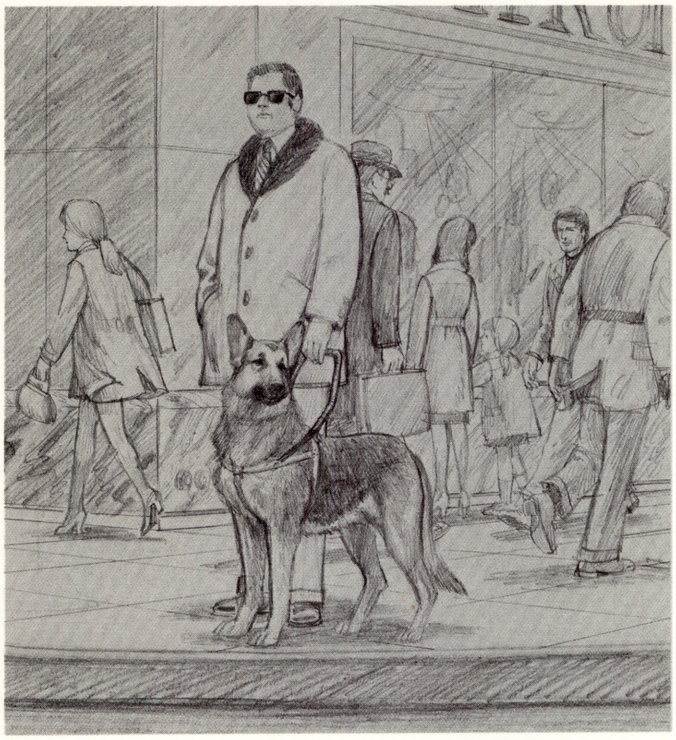
Drivers watch for confusing, ambiguous, hard-to-see freeway signs to direct them.



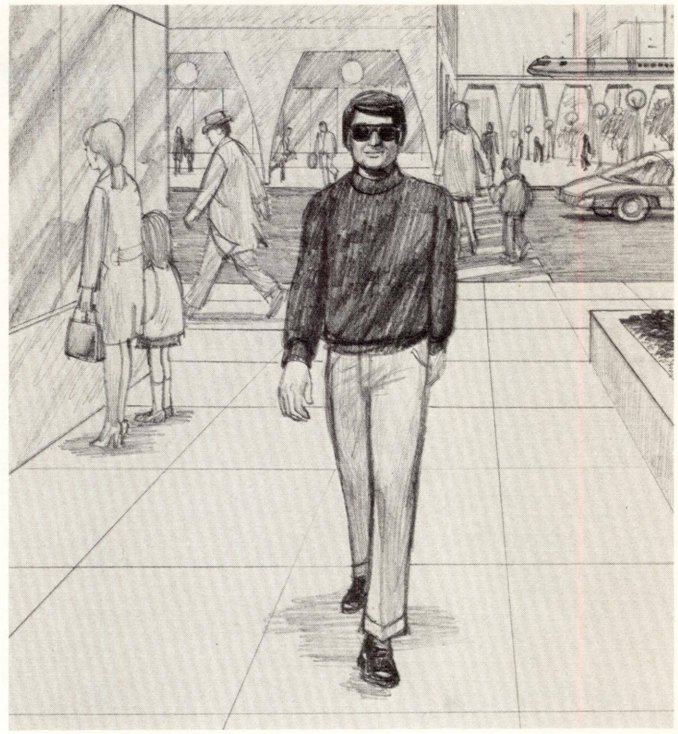
Preprogrammed-route cassettes instruct computers and guidance/control systems controlled by the latter to guide the private cars, in which they are installed, to their destination—completely without "driver" participation.

TODAY . . .

TOMORROW . . .

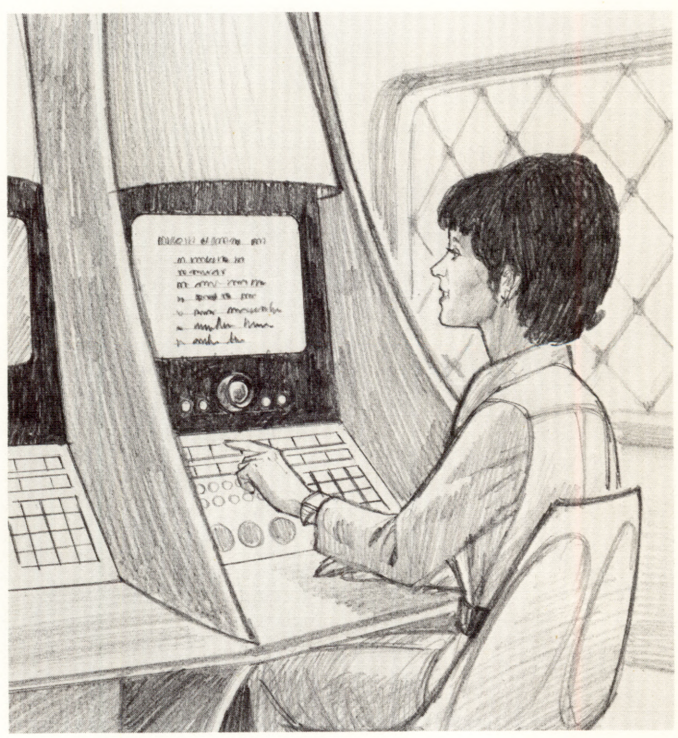


Totally blind man dares not venture out into the busy world, unless accompanied by his faithful "seeing-eye" dog.



Blind man, equipped with his own personal, *brain-implanted,* microelectric "radar," walks confidently, safely, *alone,* down busy city street.

Lady of the house spends many hard-working hours at such household chores as dusting.



Household chores are accomplished under the automatic direction of the Home Electronic Console. Environmental control with a precision found today only in certain laboratories keeps homes constantly dust-free.

TODAY . . .

Ambulance service flashes electrocardiograms ahead to hospital while patient is still travelling in ambulance toward hospital.

Children must leave home for remote classrooms.

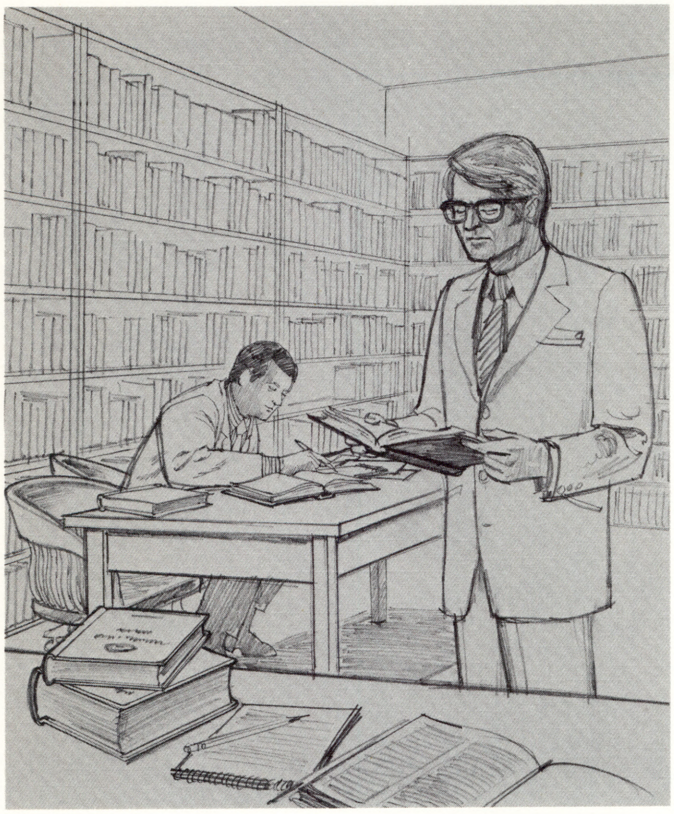
TOMORROW . . .

Implant sends personally-coded trigger signal to heart center in case of trouble. Electrocardiographic data are then automatically transmitted to center for diagnosis and, if necessary, for transmittal back to patient of heart-pacing electrical impulses—all of this by microelectronic implanted transmitter and control circuitry in the patient, working in conjunction with the remote center in the hospital.

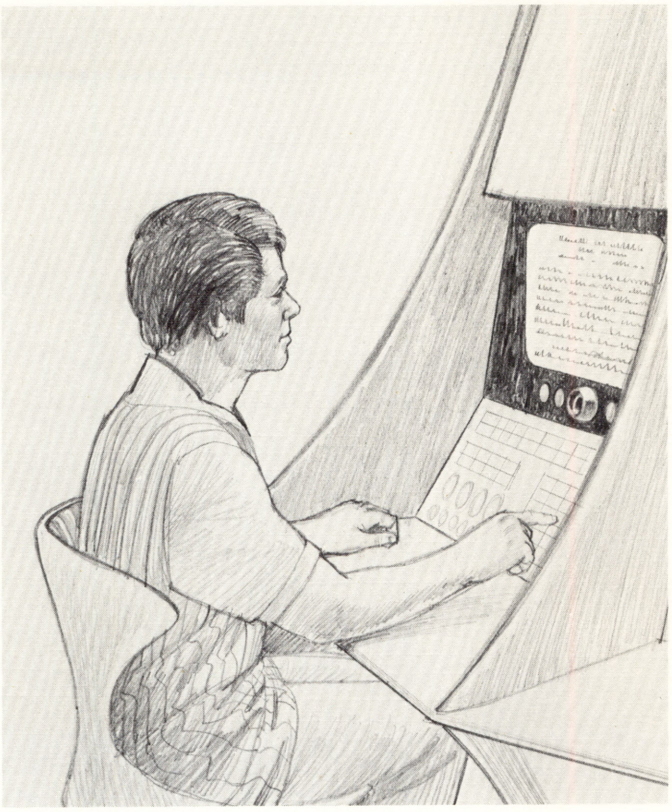
Children are taught, graded, and corrected—*at home,* via the Home Electronics Console. All the libraries in the world are available to them as reference for term papers and study in general.

TODAY . . .

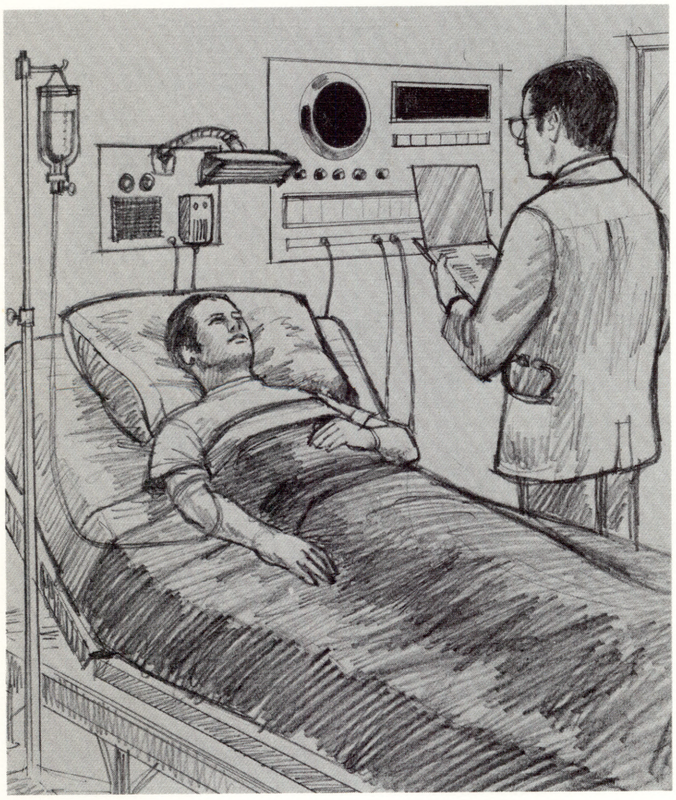
TOMORROW . . .



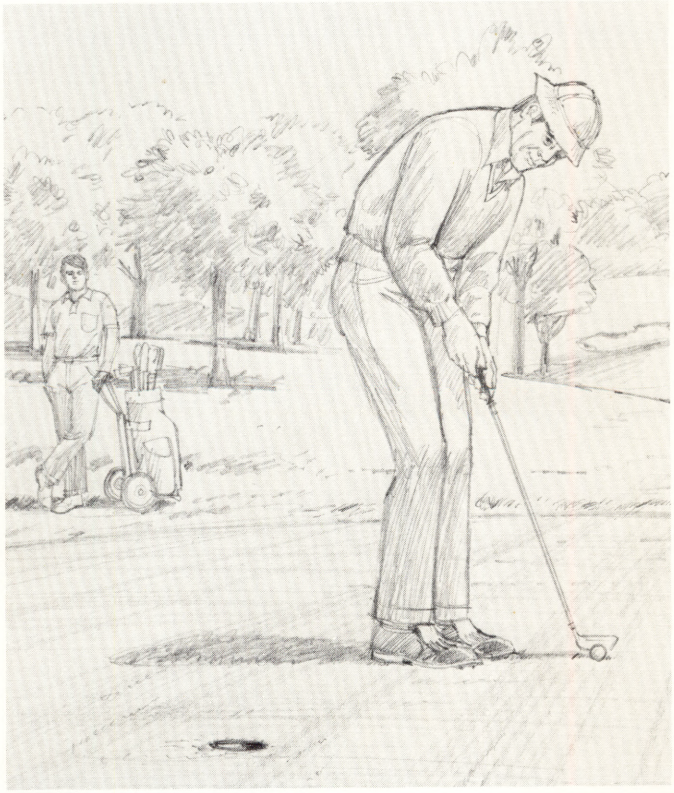
Researchers must make many trips to many libraries—spend hours, weeks, months at exhaustive physical searches of stacks.



Computerized searches compile bibliographies. Any book in the world is available for TV screen reading via the Home Electronic Console.



Complicated external interconnections for monitoring patients are expensive, clumsy, immobile—can even be dangerous due to faulty grounding.

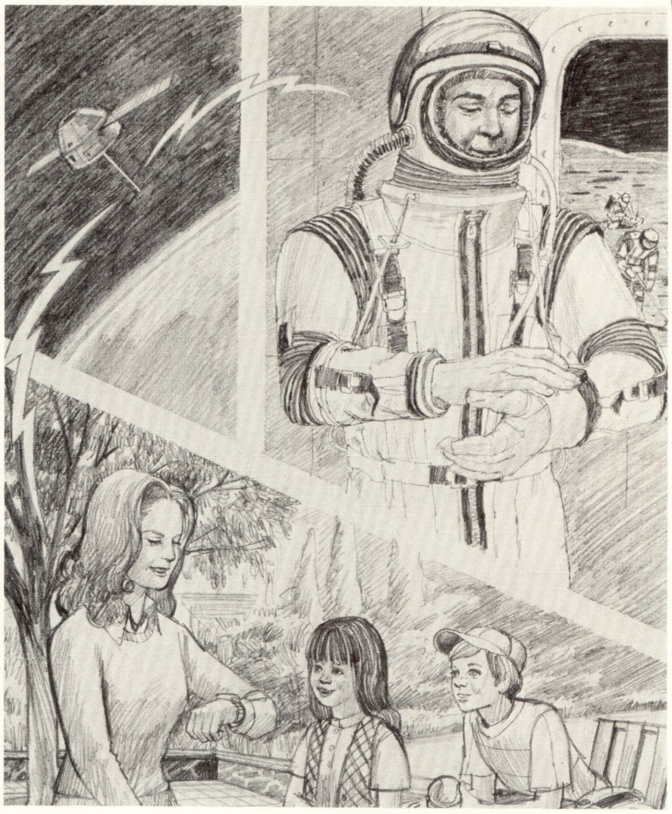


Implanted monitor constantly broadcasts mobile patient's condition to remote diagnostic center. No external wiring interferes with the patient's continuance of normal activities.

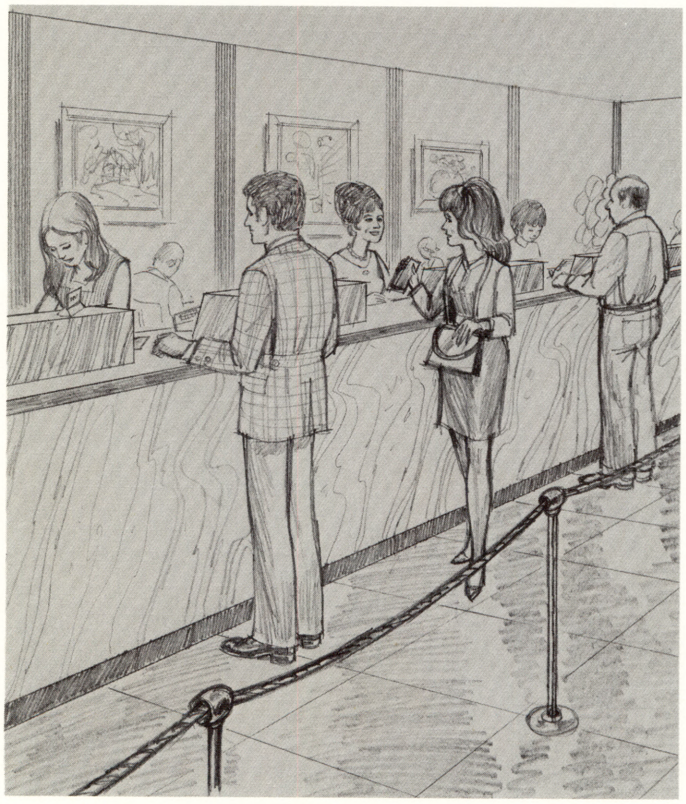
TODAY . . .

"Manned" paging systems—or, at best, loud-speaker intercoms—are effective only in immediate areas.

TOMORROW . . .



Around-the-globe—even interplanetary—paging systems will permit coded calls to contact only the wanted person through a wrist-worn "paging receiver."

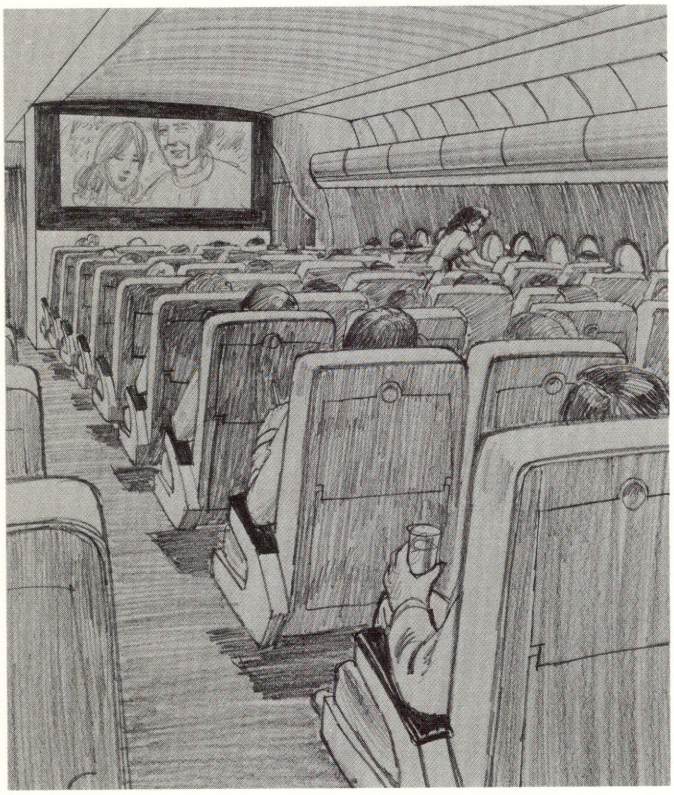


Banking is conducted in person or by mail.

Banking is conducted entirely remotely—by computers. All business transactions can be completely "electronic" ones. No actual money needs ever to change hands.

TODAY . . .

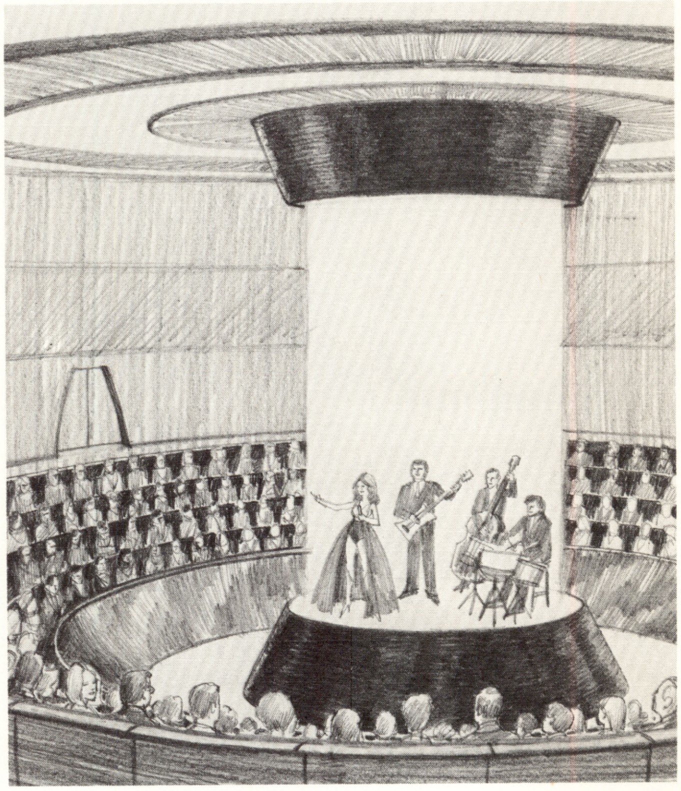
Every police patrol car and helicopter is equipped with two-way radio.



Two-dimensional movies and stereo music use MOS/LSI microelectronic multiplexing systems to eliminate literally miles of "hard-wire" interconnections aboard super-jet commercial aircraft.

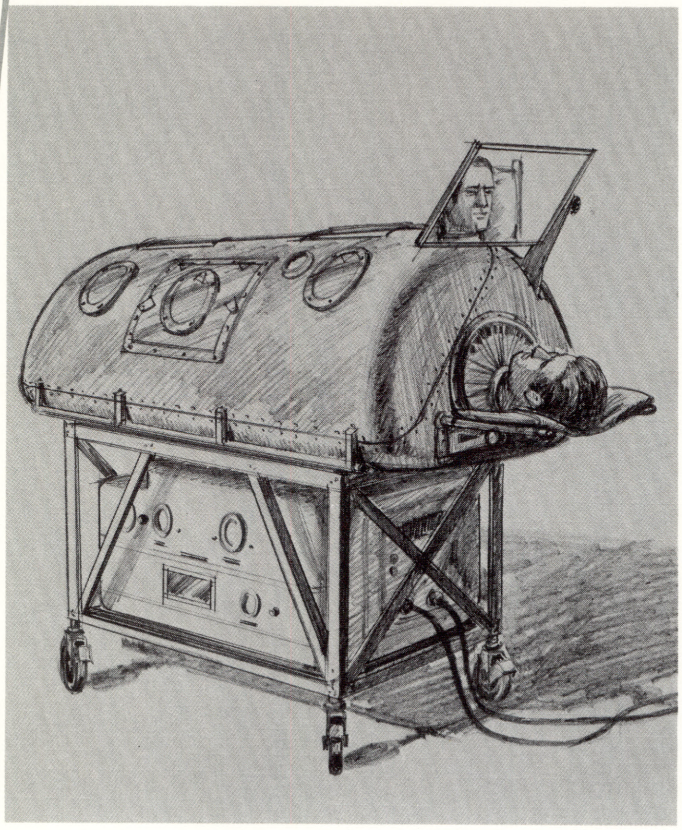
TOMORROW . . .

Wrist TV-radios and vest pocket facsimile systems will be general issue equipment for every patrolman.



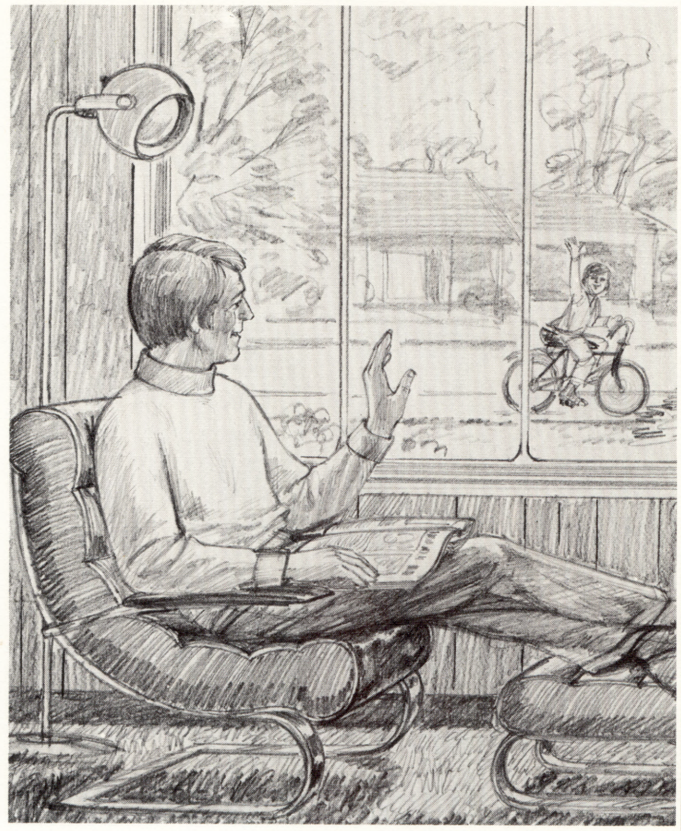
Three-dimensional, holographic TV and movies will be the entertainment fare—whether passengers are aboard an atmospheric jetter, rocketship shuttle to some satellite spa, or a space-cruiser to a distant planet.

TODAY . . .



This man is completely paralyzed. Day after day, he lies in an iron lung—unable to turn the pages of a book to read, unable to turn his head to look out the window at his playing child, unable to turn the dials of a TV set to see and hear news of what's going on in the world that's closed to him.

TOMORROW . . .



Believe it or not, this man is also "completely paralyzed" —but, thanks to microelectronic implants, he can bypass paralyzed nerves, can send impulses directly from brain to muscles, and can thus control his hands to turn the pages of a book or adjust the dials of a TV set . . . can turn his head to smile through the window at his playing child.

VII. THERE IS NO END TO OUR STORY

In this book, we have followed microelectronics through its career—from early discrete components back in the late 1940's, through first-generation integrated devices of the 1950's and 1960's, to present-day large-scale-integrated devices capable of performing in a quarter-of-an-inch area, functions that used to require tens and hundreds of cubic feet.

We have taken a look together at the startling developments in materials and in processes that make today's hardware/software accomplishments possible. We have extrapolated from these accomplishments to make predictions of microelectronics' exciting future. And . . . in making our survey of today and our predictions of tomorrow, it is almost impossible not to conclude that microelectronics either has, or is going to have, something important to do with every phase of man's life in this world.

But the story of microelectronics doesn't end *in this world.*

Man is just now on the very threshold of learning to know firsthand a little of the vast Universe of which *this* world is actually an infinitesimally small part.

Out of this world, microelectronics will be important, too. It's going to be one of man's vital tools to enable him to get out . . . and out . . . and out . . . to other planets . . . other stars.

Microelectronics is—like man himself—a tiny entity in the vast cosmos of time and space. But—again like man—microelectronics will have a significant and unending role to play. The fascinating drama of man and of his brain-born partner, microelectronics, will never cease to unfold. Each act will, no doubt, be more intriguing than the one before.

This writer is gratified to have been in on at least the opening scenes. Aren't you?

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