THE PHYSICS & DESIGN OF MAGNETORESISTIVE HEADS

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"Recording Head Technology & Applications"

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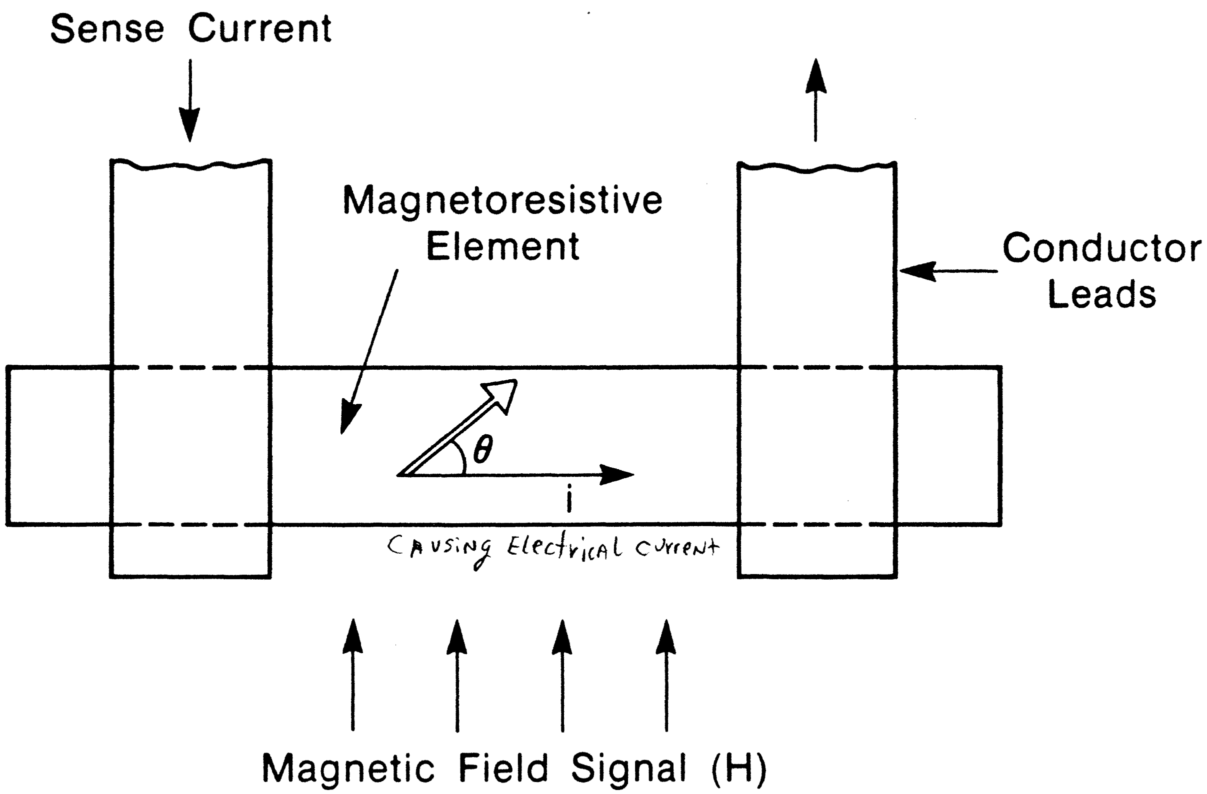
Magnetoresistive Sensors

Outline

1. Introduction
2. Recording Environments & Common Configurations
3. Basic Performance
    - Amplitude
    - Linear-density Resolution
    - Track-density Resolution
4. Basic Issues
    - Linearization of MR Response — Transverse Biasing Techniques
    - The Barkhausen Noise Problem — Longitudinal Biasing Techniques
    - Example



I. Introduction

- Basic Magnetoresistive Effect

$$R(\theta) = R_0 + \Delta R \sin^2\theta$$

- Common Magnetoresistive Material —

Nickel Iron

Permalloy ($Ni_{81}Fe_{19}$)

High magnetic moment ($4\pi M_s \simeq 10^4$ g.)
High permeability ($\mu \simeq 2000$
$H_K \simeq 4$ Oe)
Low Magnetostriction
High MR Coefficient ($\Delta\rho/\rho \simeq 2.5\%$)

Magnetoresistive Elements as Read Heads in Magnetic Recording

Advantages

- Large signal output compared to inductive read elements
- Velocity independent signal amplitude
  flux-sensor instead of $d\Phi/dt$ sensor
  useful for low-velocity small disk systems
  tape recording systems.
- Good linear-density resolution with the shielded MR sensor

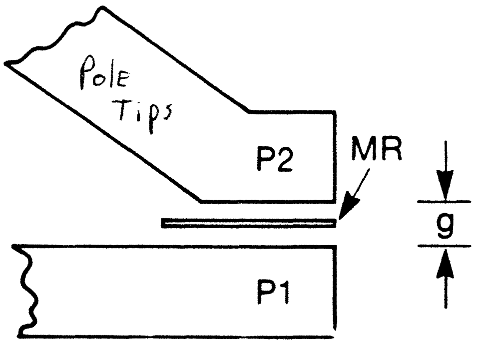
Issues

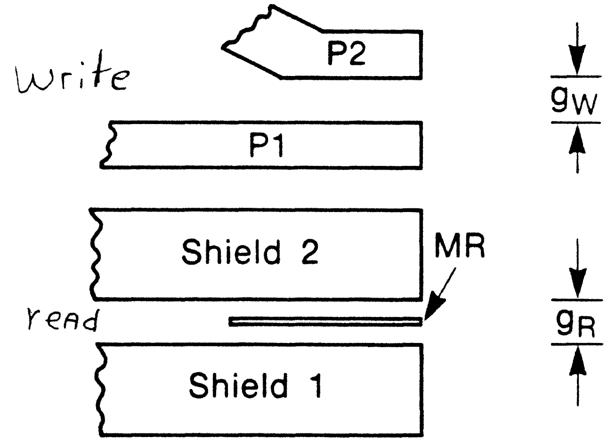
- Linearization of MR responses
- Suppression of Barkhausen noise
- Sensitivity to thermal noise from medium asperities
- Vulnerability to wear & corrosion at the open surface facing the medium

II. Recording Environments & Common MR Configurations

MR Sensor Designs are Constrained by Various Recording Performance Requirements:

1. Linear Resolution
    - Presence of soft-magnetic shields around the sensor
      may significantly impact 1) transverse biasing
      2) signal flux conduction &
      3) domain properties of sensor.
2. Write Capabilities
    - Presence of inductive write element in the vicinity
    - Two primary approaches:



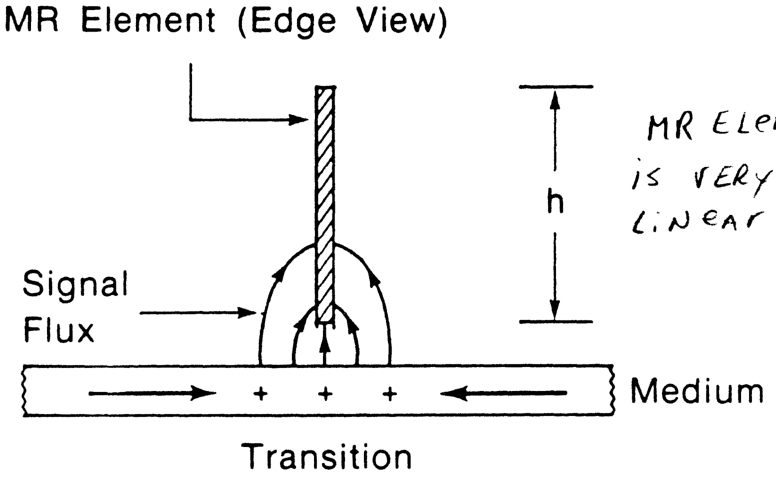


Integrated Approach	Piggyback Approach
— Simpler fabrication	— More fabrication steps
— Easier R/W track alignment	— Harder R/W track alignment
— Common R/W gap	— Separate R & W gaps
— Significant MR sensor perturbation during write	— Less MR sensor perturbation during write

3. Track Resolution
    - Certain geometries & dimensions may be preferrable.

Common MR Read Head Configurations:

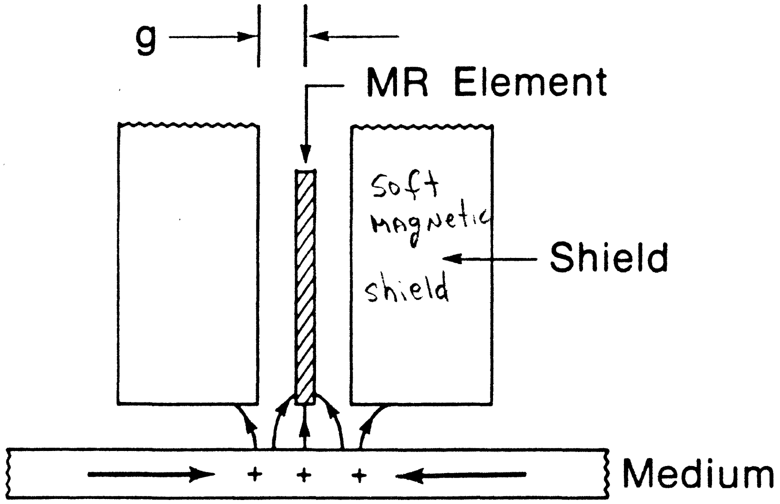
Class A: Unrecessed MR Sensors



MR Element Height is very important in linear density resolution

(a) The Unshielded MR Sensor

- Simplest in operation & fabrication
- High efficiency: Signal flux enters & leaves along entire height of sensor
- Poor linear-density resolution: Limited by height of sensor
- Novel modifications: Saturate most of the sensor except the ends by magnetic bias
- May be useful in low linear-resolution applications or equalization-intensive environments



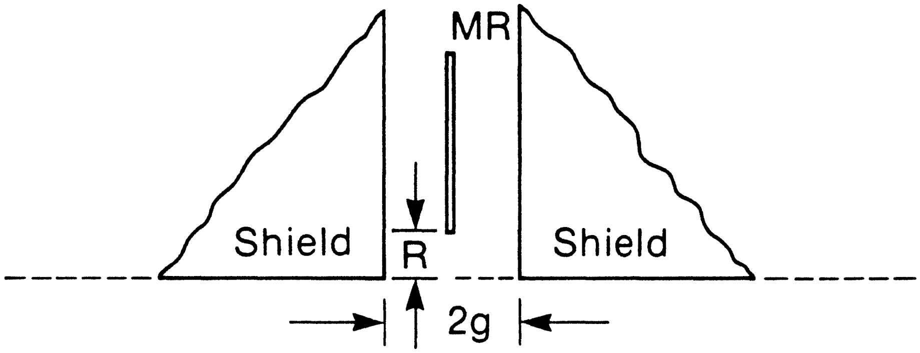
(b) The Shielded MR Sensor

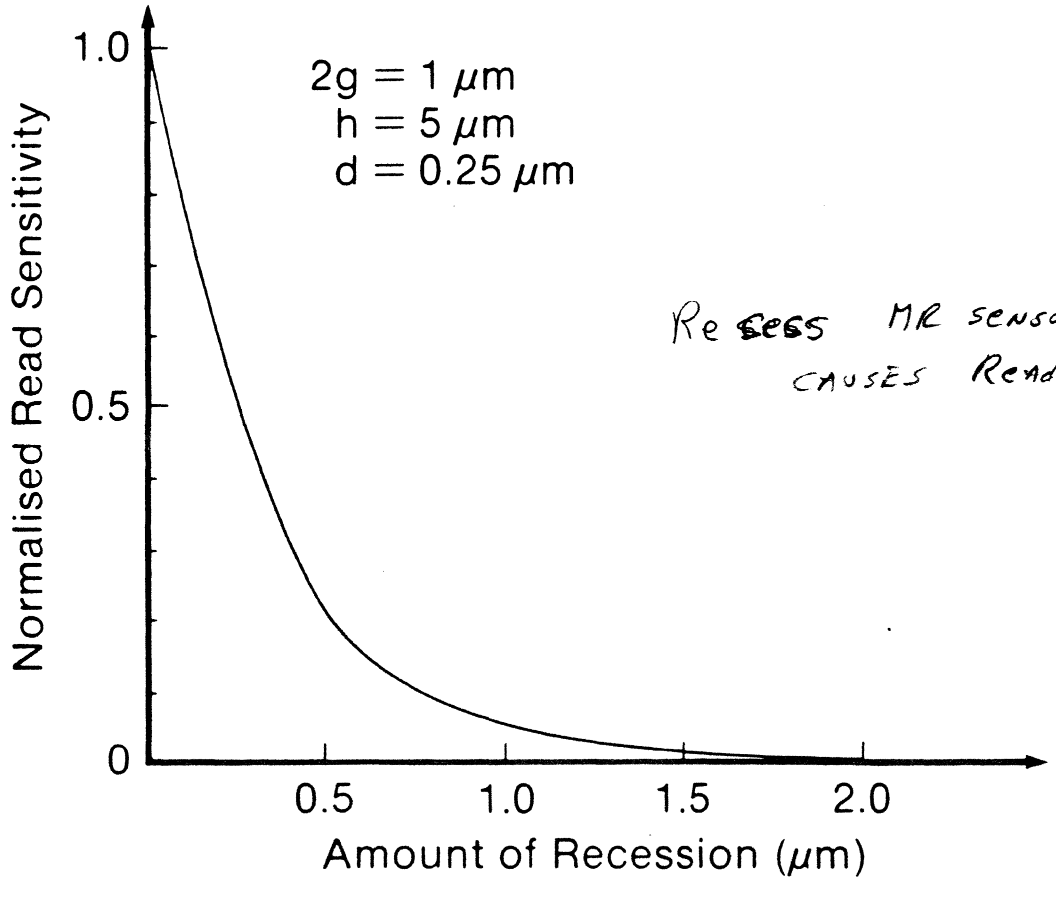
- Popular configuration
- Achieves linear-density resolution by use of soft-magnetic shields on each side of MR sensor
- Presence of shield may impact transverse & longitudinal biasing schemes — Image charge
  Image current effects
- Presence of shield creates highly non-uniform signal flux profile along height of MR sensor
  - Profile relaxing from lower to upper end of sensor due to flux leakage from sensor to shield
  - Most signal detection activity occurs at lower end of the sensor
  - For good linearization, transverse bias profile must also be adequate at lower end of sensor.

Class B: Recessed MR Sensors

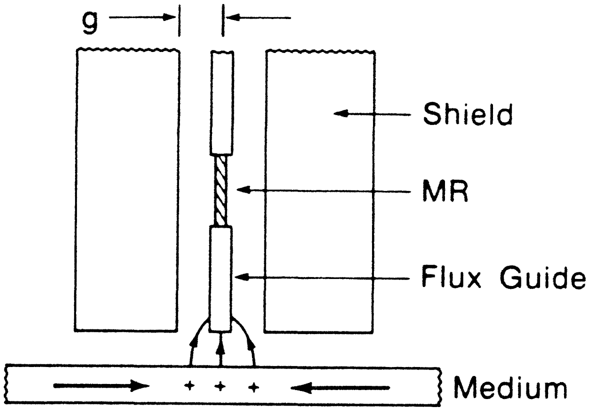
- Advantage: Protection of MR sensors from wear & corrosion at the open surface
- Disadvantage: A recessed MR element has very low read efficiency

  Flux-guidance structures are necessary.





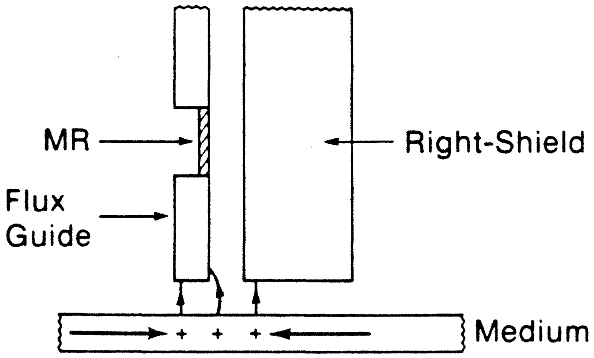
Recess MR sensor
causes Read Sensitivity



soft magnetic material

(c) Flux-Guided & Symmetrically Shielded Sensor

- Relatively low read efficiency.
- Flux-guides may have their own Barkhausen Noise problems.
- Sophisticated biasing & feedback schemes may be implemented through the flux-guide circuit to improve performance.
- Narrow track applications with wide-track MR sensors by using flared flux-guides.

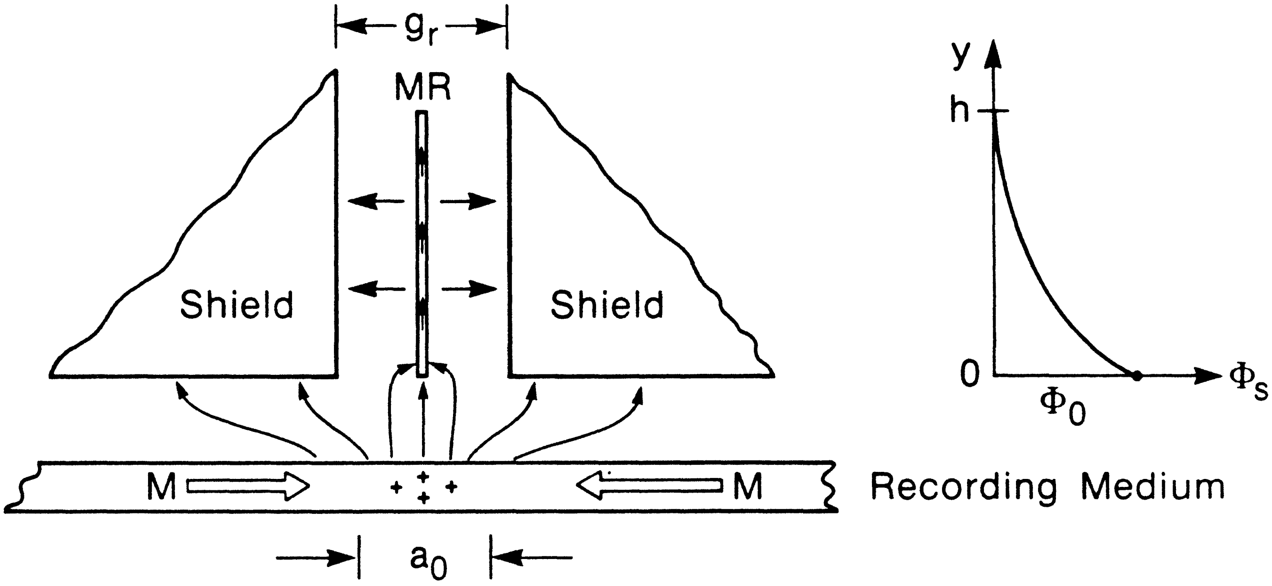


(d) Flux-Guided & Asymmetrically Shielded Sensor

- Readback waveform character similar to an inductive head.
- Half-shielded MR sensor may produce leading-edge trailing-edge waveform asymmetries.

III. Basic Performance of the MR Sensor

A. Readback Amplitude



Methodology:

1. Compute incident signal flux (Φ_0) on lower tip of MR from transition in medium ——

   Reciprocity Theorem

2. Compute signal flux propagation profile ($\Phi(y)$) along height of MR sensor ——

   Transmission Line Model

3. Compute bias profile & combine with signal profile to get total magnetic response profile along height of MR sensor

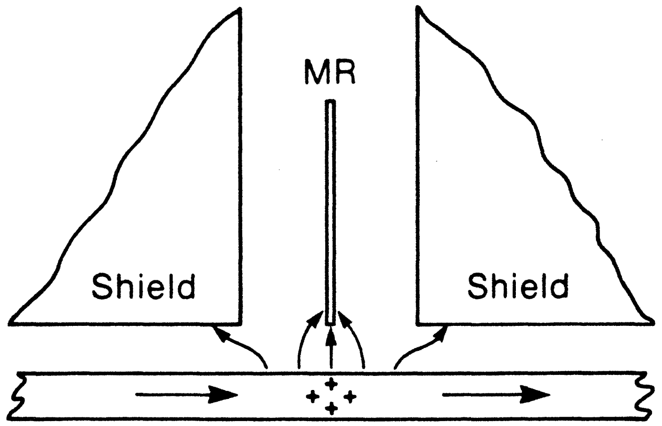
4. Compute corresponding MR effect response:

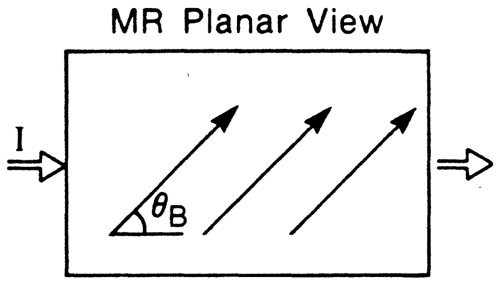
$$\Delta R = R\left(\frac{\Delta\rho}{\rho}\right)\int_0^h \frac{m_y^2(y)}{M_s^2}\,dy$$

5. Compute voltage response

$$\Delta V = I\Delta R$$

Example:

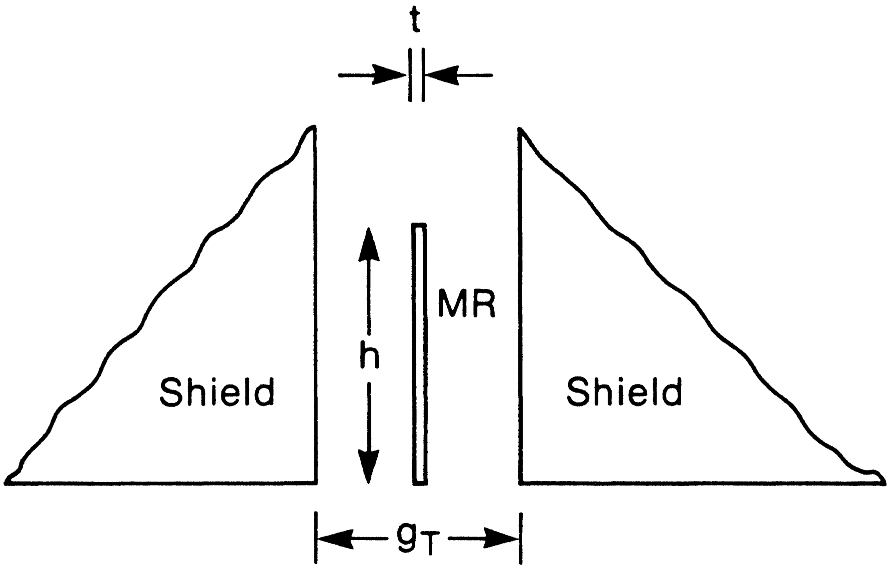




MR Sensor:	Permalloy $Ni_{81}Fe_{19}$	
	Thickness	400Å
	Height	7.5 μM
	Bias Angle	45°
	Resistivity	25 $\mu\Omega$-cm
	MR Coefficient	2%
Recording Medium:	Moment ($M_r\delta$)	2×10^{-3} emu/cm^2
	Transition Width (a_0)	0.3 μm
Operation:	Total head-medium separation:	0.25 μm
	MR Current:	10 mA

Performance:

- About 24% of flux from transition is incident on lower end of MR sensor.
- Maximum magnetic response occurs at lowest end of sensor, roughly equal to ±15° rotation of $\vec{M}$.
- Signal flux decreases exponentially up the height of sensor with a characteristic length of 4.7 μm.
- Total MR response available is 165 μV/μm.
- Signal MR response is 55 μV/μm.



General Dependence of MR Output Amplitude on Head Parameters:

1. Primary dependence on MR current.
   Maximum current usually limited by thermal and/or electromigration considerations.

2. Roughly linear dependence on total gap (g_T).
   Reduction of g_T for better linear resolution will degrade output amplitude.

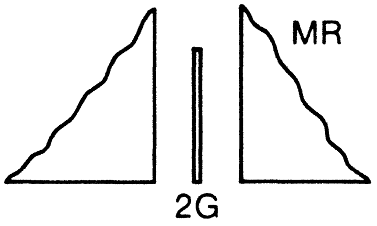
3. Significant dependence on thickness of MR sensor.
   Thinner sensor exhibits higher magnetic response & larger MR effects.
   Minimum sensor thickness usually determined by film properties control considerations.

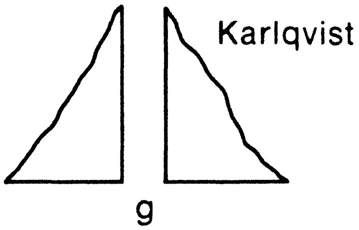
4. Sensor output also increases as height is reduced, due to resistance increase & better magnetic signal profile along height of sensor.

B. Linear-Density Resolution

(1). Rough Description:

Shielded MR head with total gap 2G has similar resolution as
Ferrite (Karlqvist) head with gap G. (R. Potter)





(2). Methodology:

Use Reciprocity Theorem:

$$\Delta V(x) \propto \int_{-\infty}^{\infty} dx \int_{d}^{d+\delta} dy\ \vec{M}(x-\bar{x},y) \cdot \vec{H}_f(x,y)$$

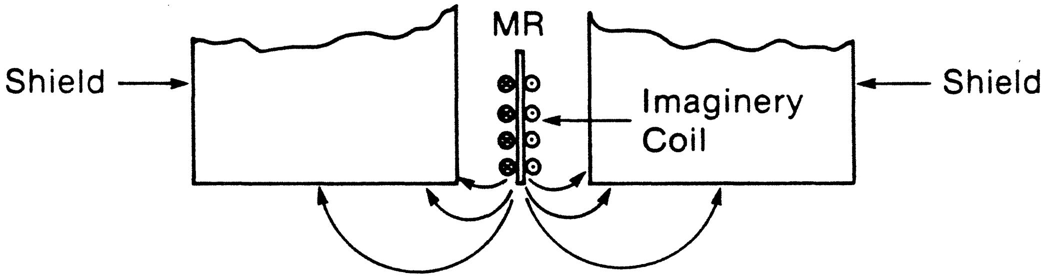
Readback voltage

Integration along track

Integration along medium thickness

Transition magnetic profile in medium

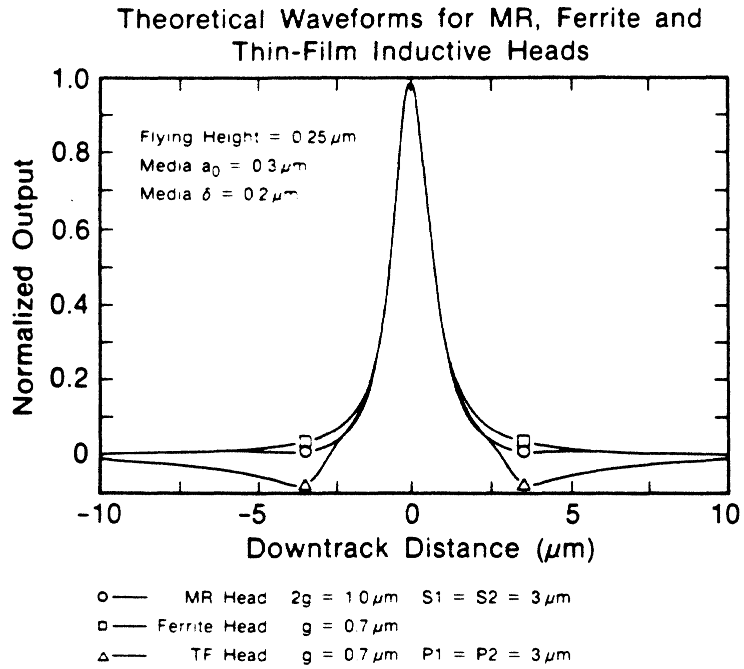
MR head 'fringe-field' by imaginery excitation of MR elements



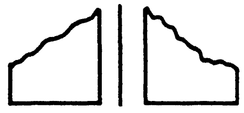
Computation of MR head fringe-fields:

1. Karlqvist Approximation (analytical)
2. Numerical modeling
3. Conformal mapping (D. Heim)

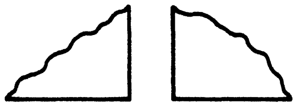
Example:



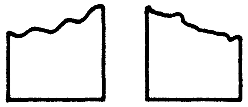
MR

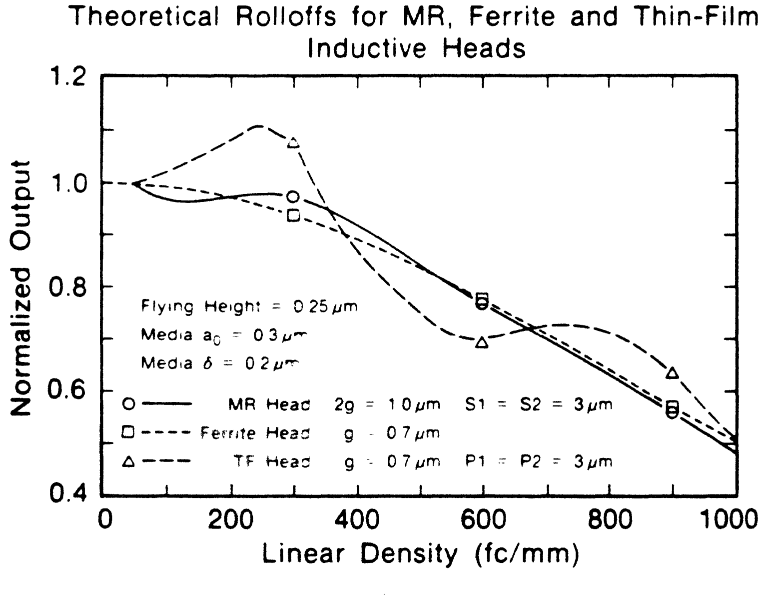


Ferrite



Thin-Film





(i) Linear-density resolution of a shielded MR head (total gap g_T) is similar to a ferrite head with a smaller gap (~0.7 g_T)

(ii) Finite shield thickness causes modulations in the rolloff. This effect is much smaller than those in thin-film inductive heads.

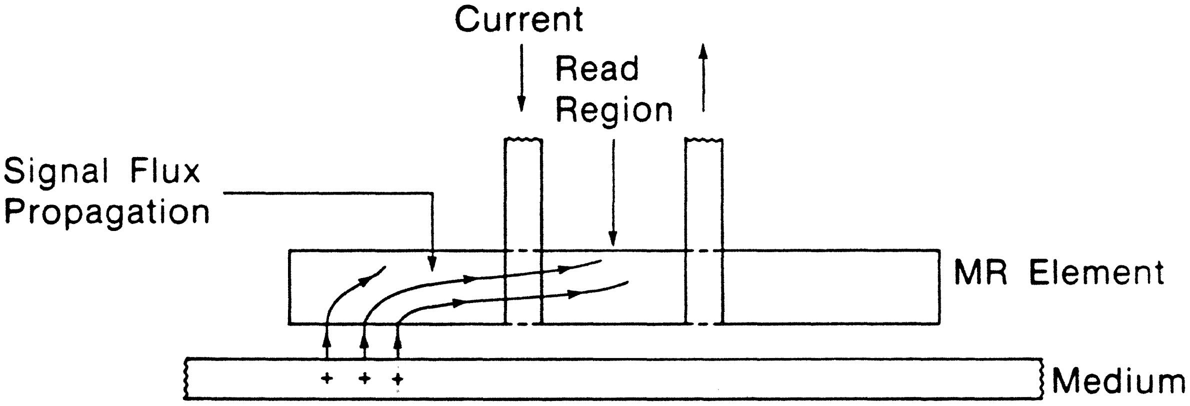
C. Track-Density Resolution

Consider a long & shielded MR sensor

(1). Track resolution is limited by two side-reading mechanisms:

a. Injection of sidetrack signal into sensor end regions and propagation of flux into middle active region.

b. To a lesser extent, direct injection of sidetrack flux into the middle active region.



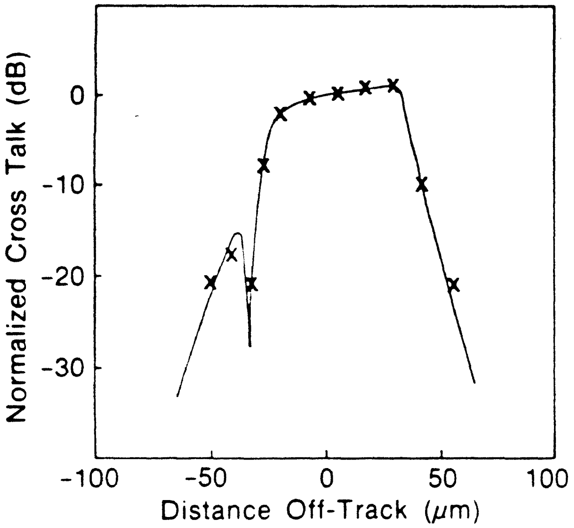
(2). Methodology:

- 2-dimensional analytical transmission-line model. (N. Yeh)
- Finite-element numerical models.

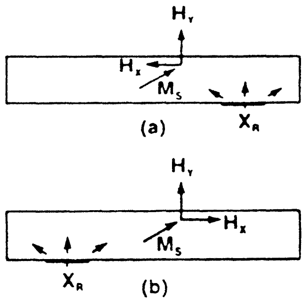
(3). General features of MR track-profile:

a. Left-Right Profile Asymmetry —
due to Anisotropic signal flux propagation
Different interactions with the bias profile.

b. Possible existence of compensation point.



Comparison of crosstalks from calculation and experiment.



Addition (a) and subtraction (b) of the H_x and H_y crosstalk.

(N. Yeh, IEEE Mag Tran, MAG-18, No. 6, 1982)

c. Insensitivity of side-reading profile towards linear density

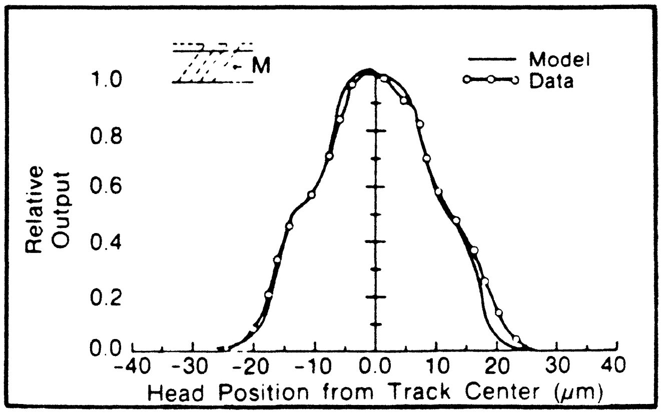
Distinct contrast to inductive-head side-reading behavior, where side-reading is most serious at lowest densities.

d. Dependence of trackprofile on MR sensor bias angle.

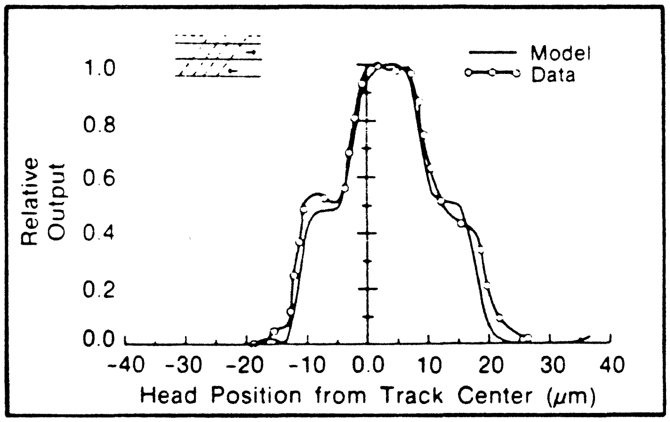
e. Dependence of trackprofile on MR sensor domain states.

Example

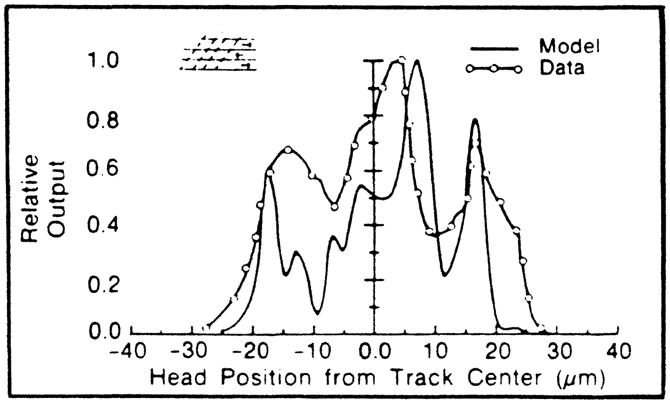
(B. Davidson, R. Simons & M. Corault
IEEE Mag. Tans. MAG-20, No-5, 1984)



Displacement Curve — Single Domain



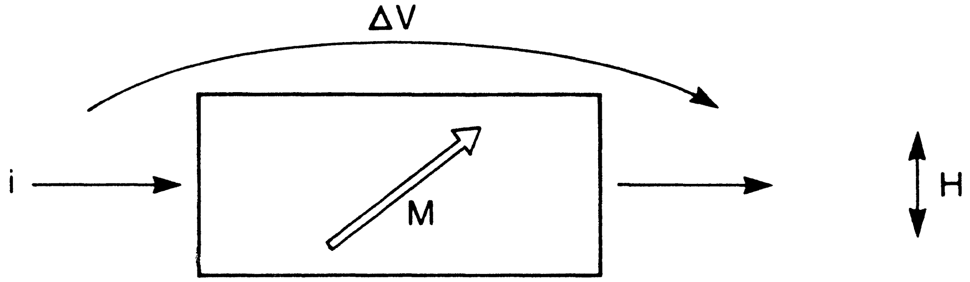
Displacement Curve — Two Domains

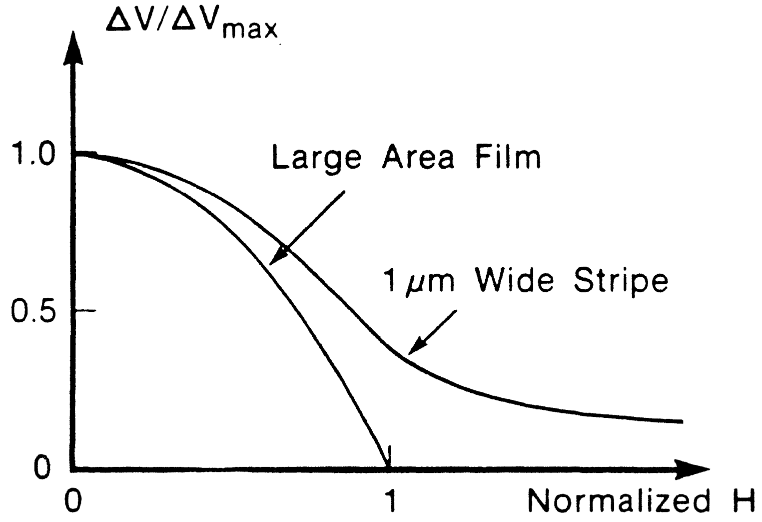


Displacement Curve — Three Domains

IV. Basic Issues

A. Linearization of MR Response — Transverse Biasing





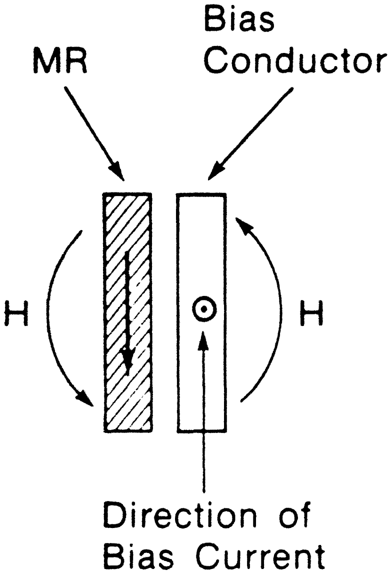
- Basic Response: Non-Linear
  MR element as a square-law sensor

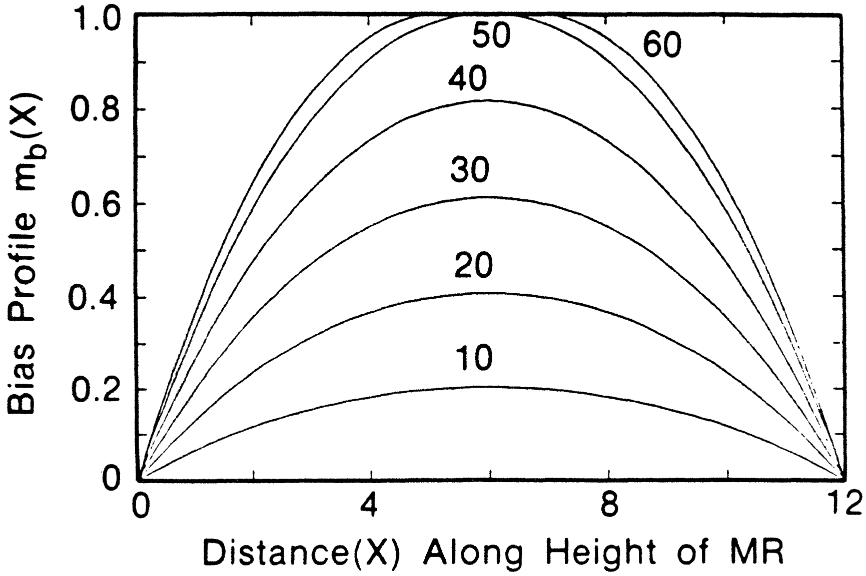
- Two Approaches to Transverse Biasing
  - a. Canting the quiescent magnetization with a bias field (H_{BT})
  - b. Canting the current path with special conductor patterns

α. Principle Techniques for Generating Transverse Bias Field

Electrical

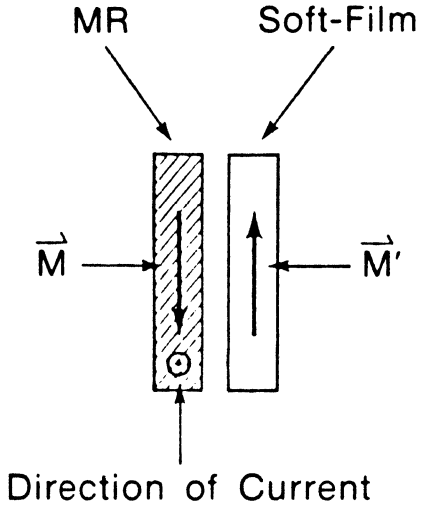
(i) Shunt Biasing



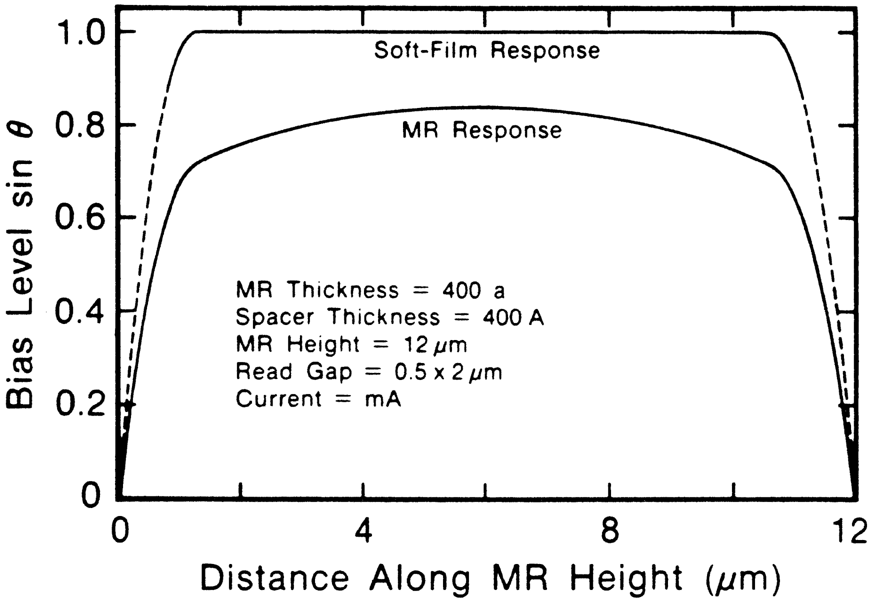


- Simplest biasing technique
  uses magnetic field from a current carrying conductor.
- Weak effects: Conductor needs substantial current.
- Electrical shunting between MR & conductor reduces signal significantly.
- Non-uniform bias profile
- Enhancements: Non-symmetrical placement of sensor between the shields.

(ii) Soft-Film Biasing



Bias Profile of a Soft-Film Biased MR Sensor



- Combining bias effect of current & flux-closure.

  Two films rotate in opposite directions in response to applied current.

- Strong effects.

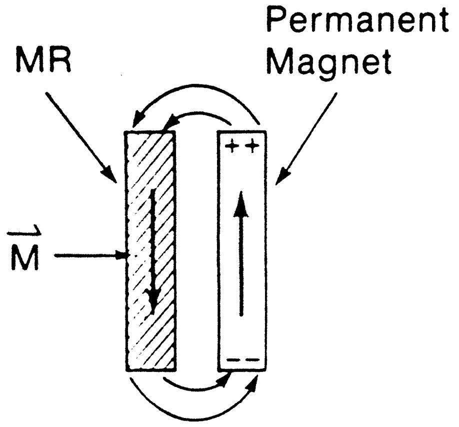
  Permeability limited.

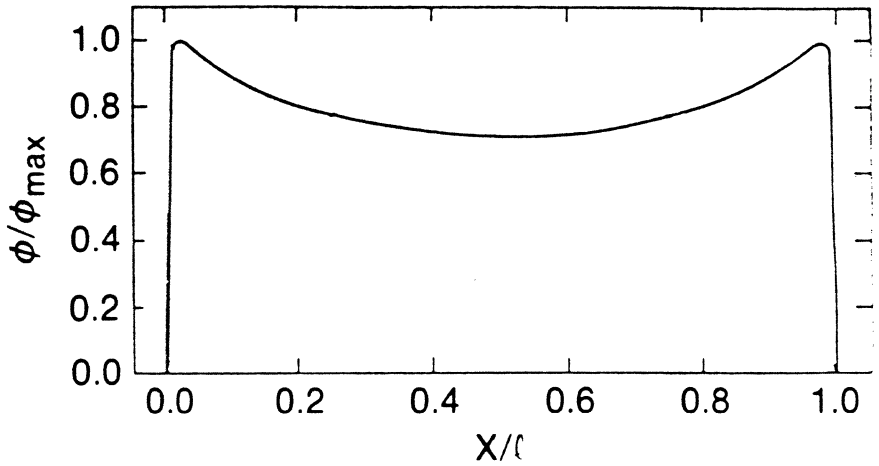
- Thin spacer for uniform bias profile.

- Selection of soft-film material important:
  high permeability
  high resistivitity
  low MR coefficient . . . etc.

- Saturated soft-film operations.

(iii) Permanent Magnet Biasing

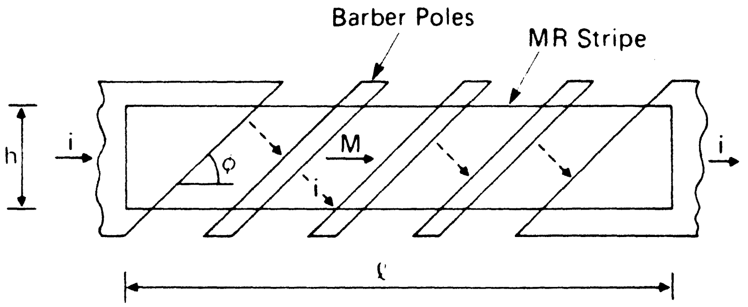


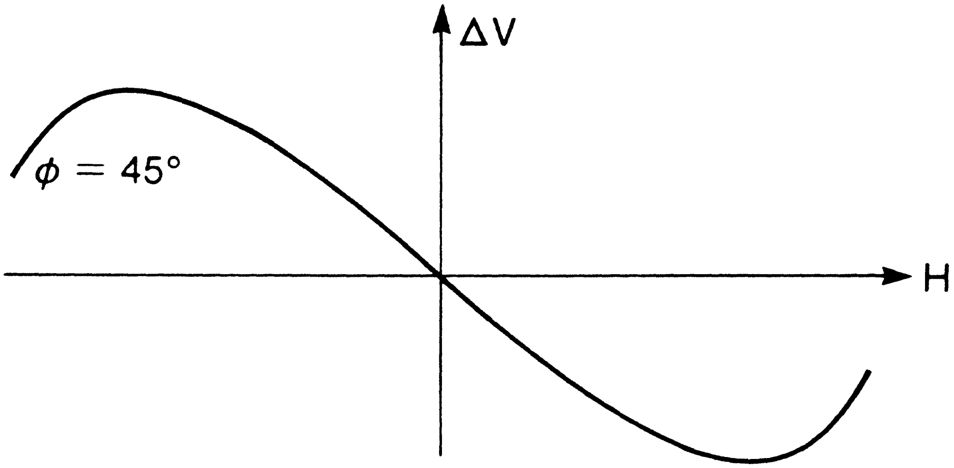


(D. Thompson, MMM Proceedings, 1974)

- Simple technique:
  Uses field from a permanent magnet.
- Good Bias Profile: Strong biasing effects at the ends.
- Selection of permanent magnet film important.
- Some separation between MR & permanent magnet necessary to avoid MR magnetic softness degradation.

β. Barberpole Biasing Technique

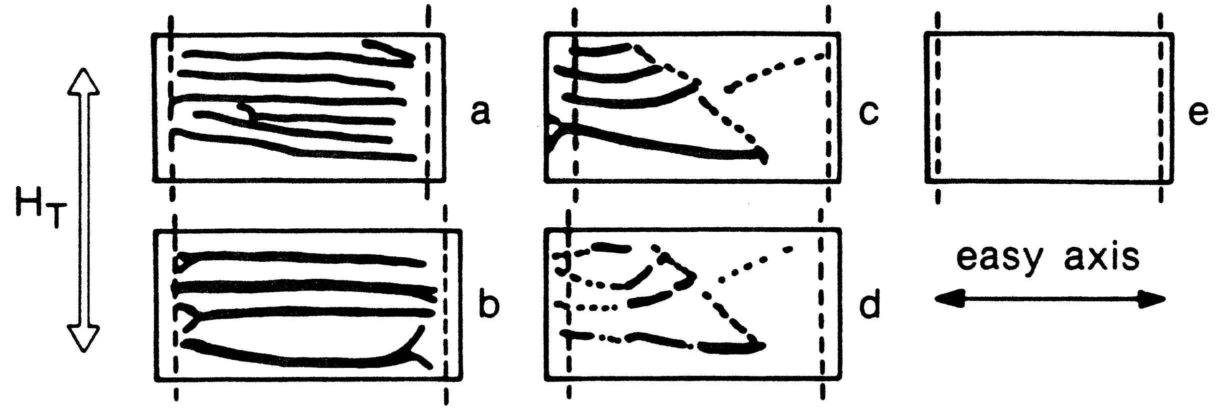


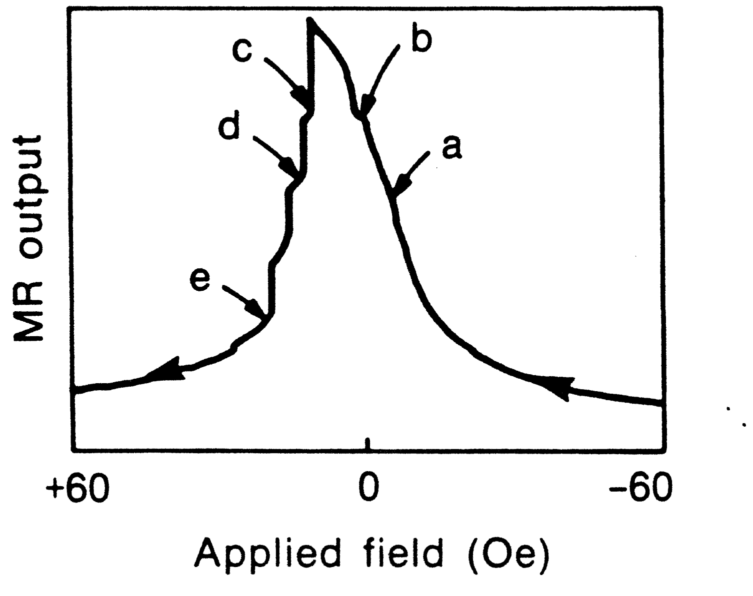


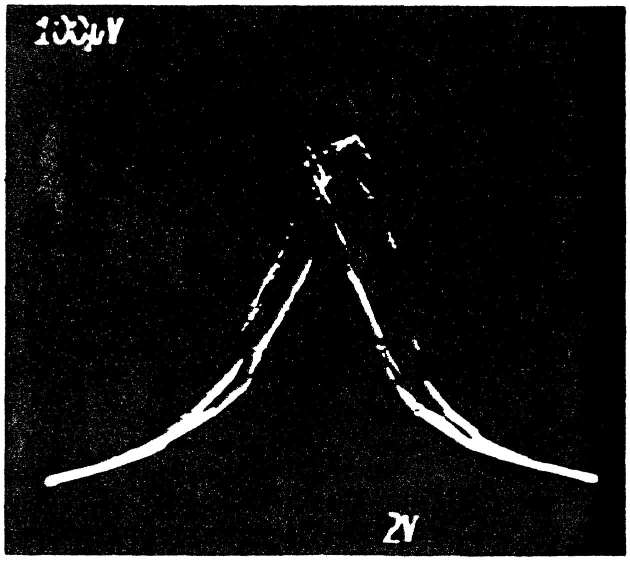
- Canted current path from Barberpole conductor patterns.
- Optimum bias state yields no even harmonics —
  superior linearity characteristics.
- Smaller signal amplitudes —
  basic operating principle areal
  penalty from conductor stripes.
- Lithographic definition and alignment important.
- Effects of non-uniform current distribution.
- Slanted contacts may affect read trackwidth profiles.
- Significant impact of multidomain activities.

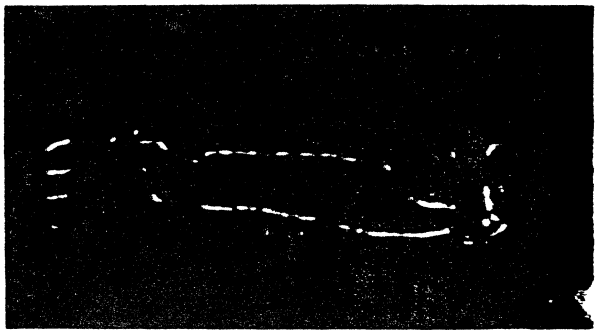
Relations Between Domain Activities & Barkhausen Noise

- Simultaneous measurement of MR response
  & domain pattern
  (bitter pattern technique).
- Wall-state transitions are significant contributors to Barkhausen Noise.









B. The Barkhausen Noise Problem:

- Noisy MR response from small MR elements.
- Barkhausen Noise — from multidomain behavior.
- Nature of domain activities.
- Relations between various domain activities & noise.
- Origin of domains in small MR sensors.
- Strategies for domain suppression.

Relations Between Domain Activities & Barkhausen Noise

- Simultaneous measurement of MR response
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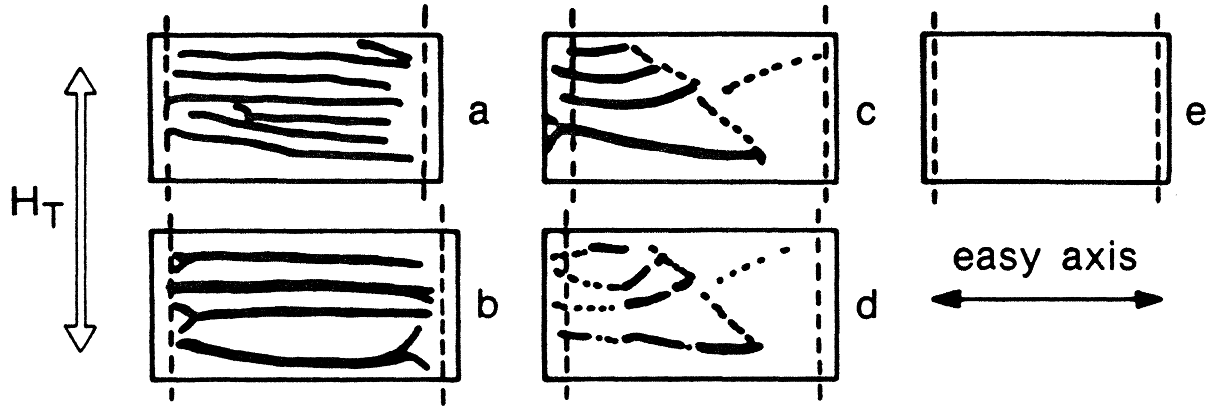
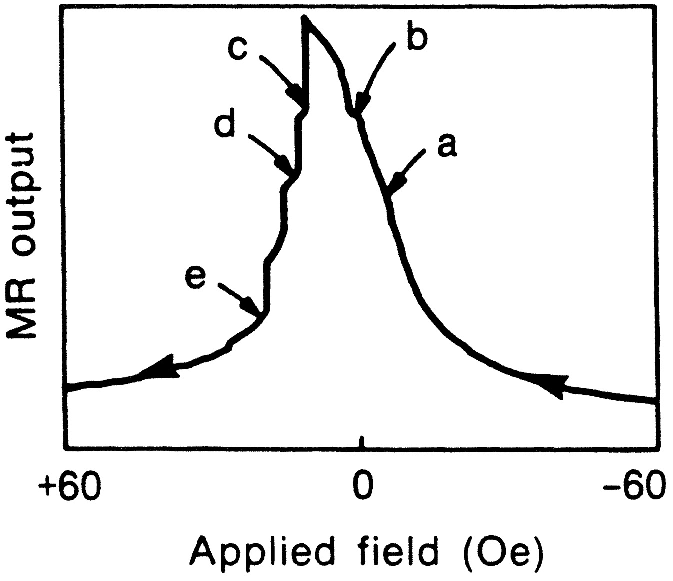
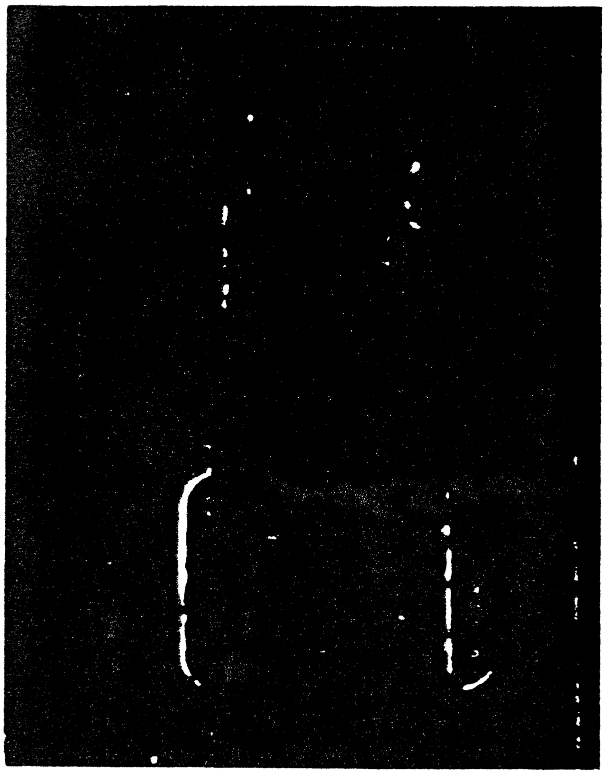
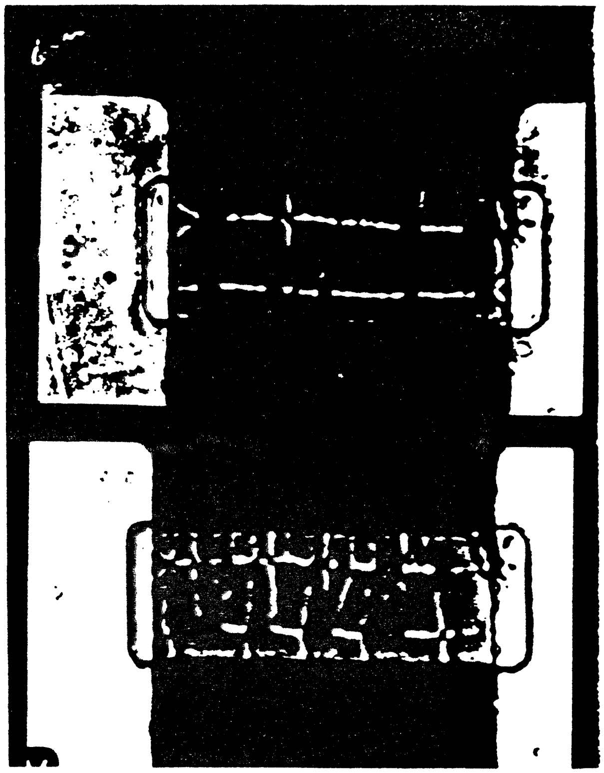
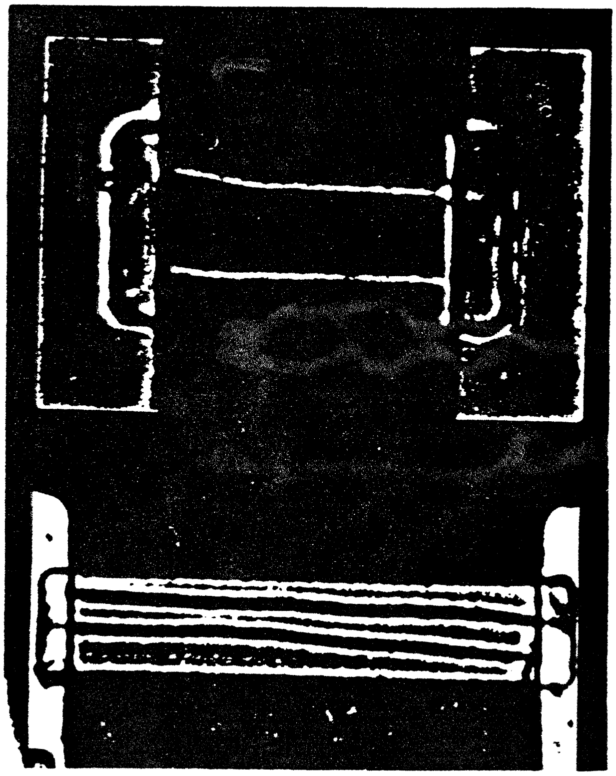
- Wall-state transitions are significant contributors to Barkhausen Noise.

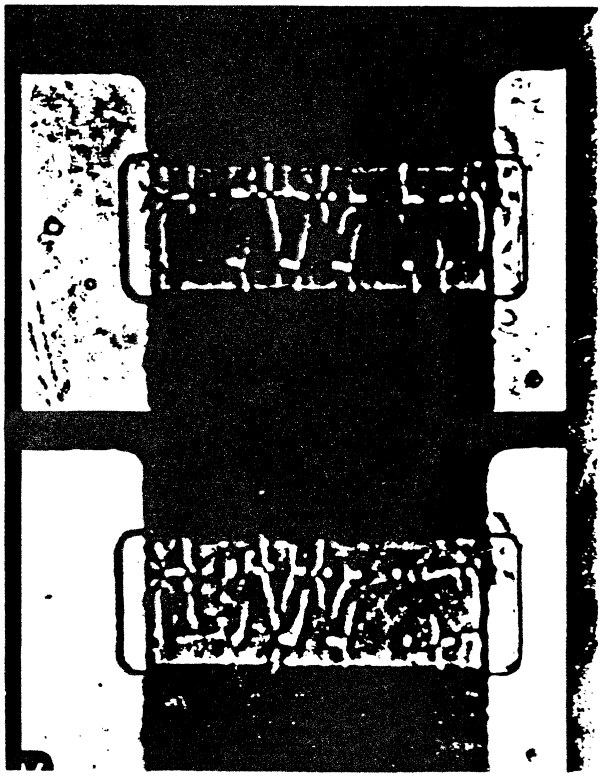






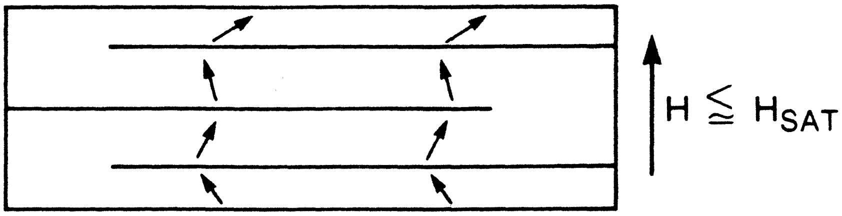




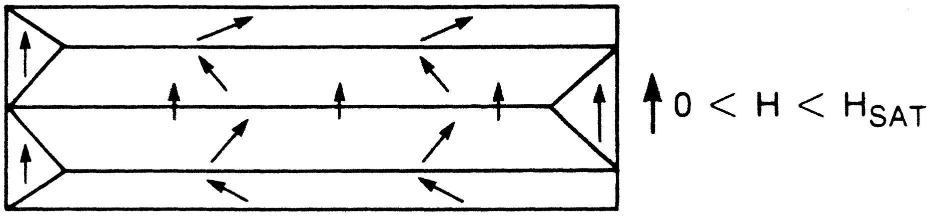


Transverse Magnetic Response of a Small MR Element

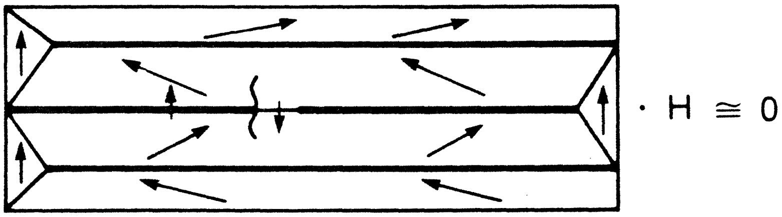
(1) Ripples



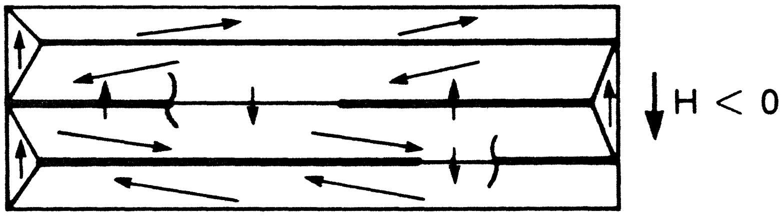
(2) Buckling Domain Pattern



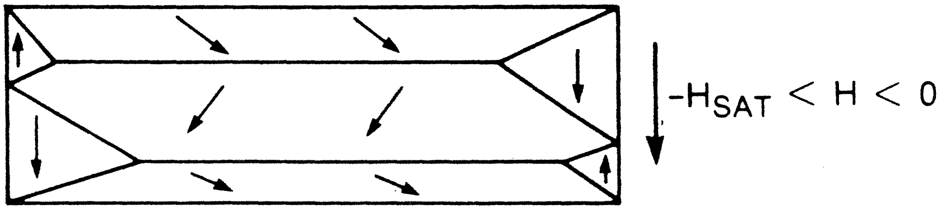
(3) Formation of a N^- segment



(4) Expansion & formation of more N^- segments

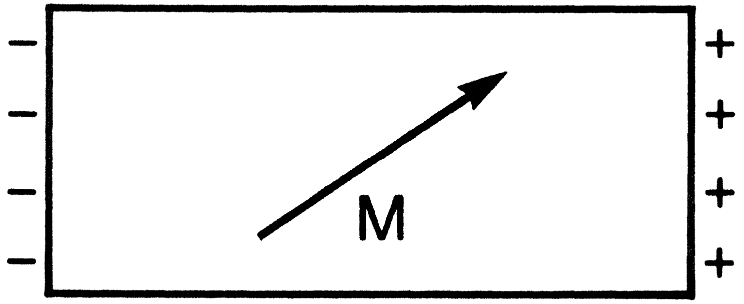


(5) After complete transition to N^- walls

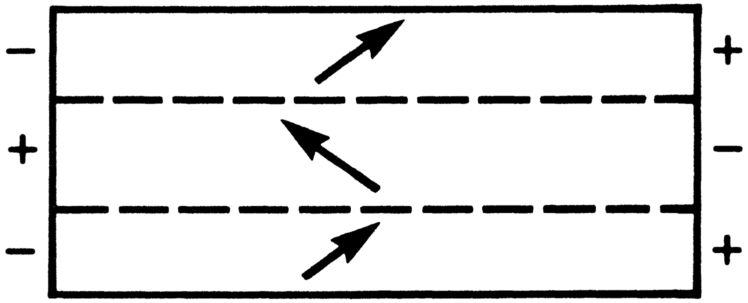


Two Possible Causes for Domain Formation:

- Dispersion of the Anisotropy Easy-Axis
- Longitudinal Demagnetization Effect



High E_{DL}

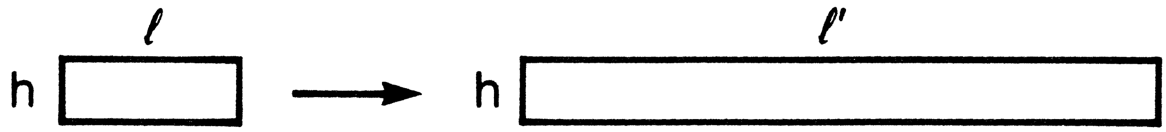


Low E_{DL}

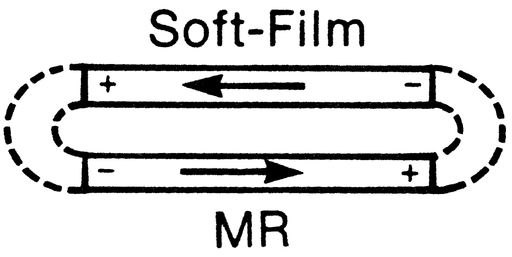
Suppression of Domain Activities

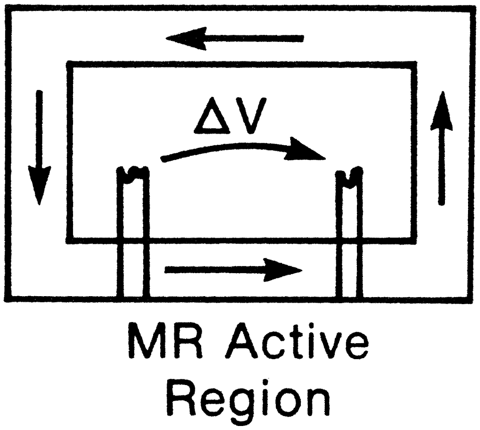
(a) Reduce Longitudinal Demagnetization Effect

- Geometrically: Increase aspect ratio (ℓ/h)

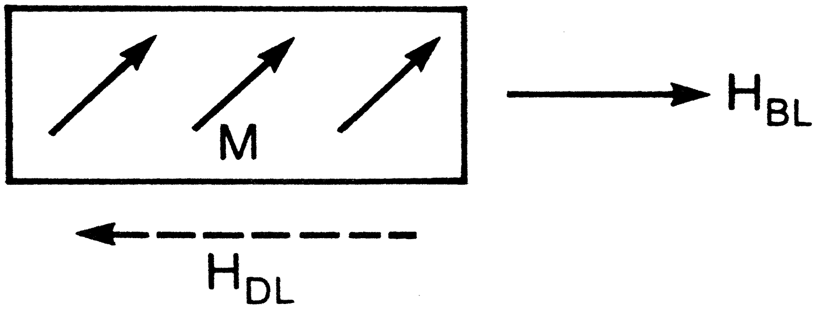


- Magnetically: Flux-closure environments



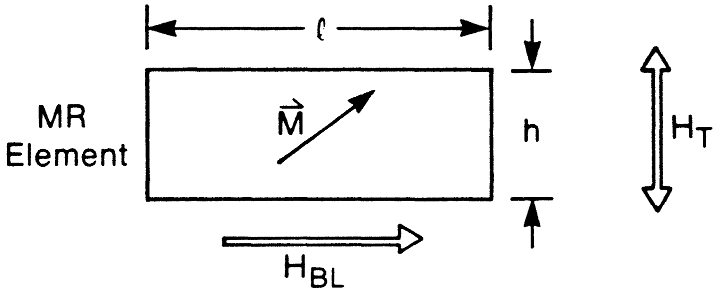


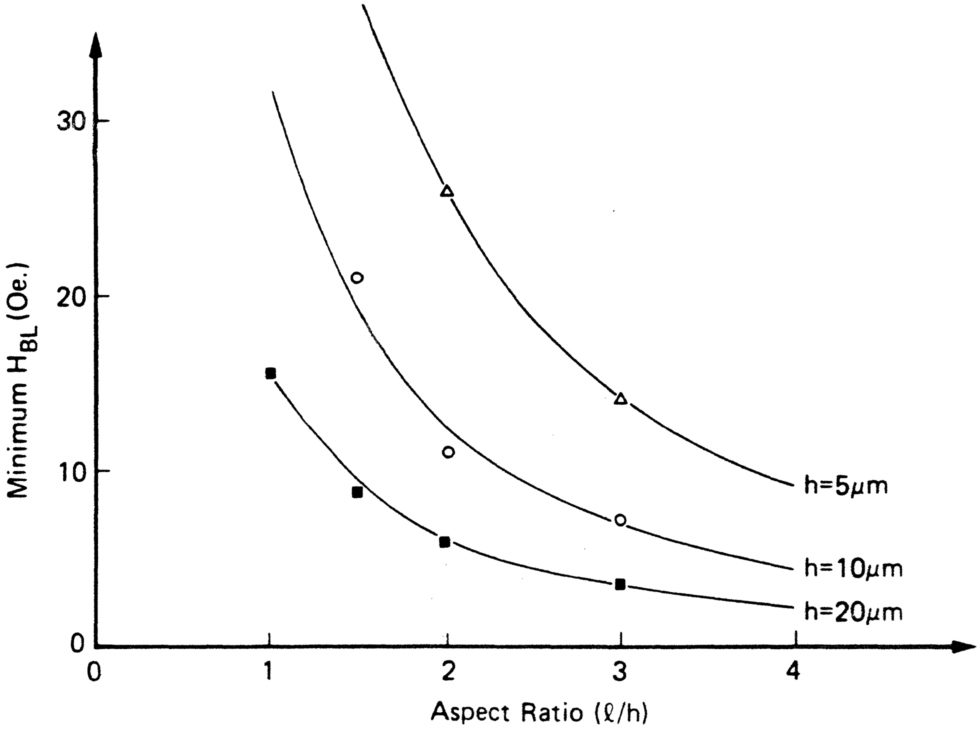
(b) Stabilization of Single Domain State by a Longitudinal Bias Field



Minimum Longitudinal Bias for Barkhausen Noise Suppression

- Rectangular MR elements
- Transverse field excitation
- Minimum H_{BL} measured for quiet MR response
- Symbols: Data
  Lines: Longitudinal demagnetization field calculated by ellipsoidal approximation.
- Longitudinal demagnetization as primary cause of Barkhausen Noise



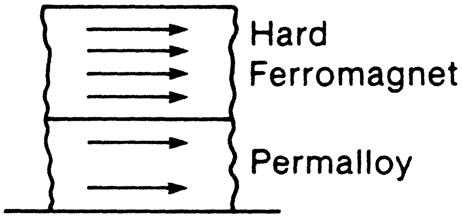


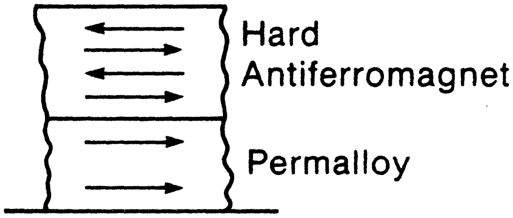
Techniques for Generating Longitudinal Bias (H_{BL}):

A. Exchange Biased Film Structures:

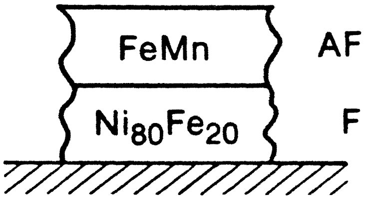
- MR sensor layer (permalloy: soft ferromagnet) in interfacial atomic contact with
  hard magnetic layer (ferromagnet, ferrimagnet, antiferromagnet)

- Hard magnetic layer as an 'anchor', produces an effective bias field to MR layer through interfacial exchange coupling

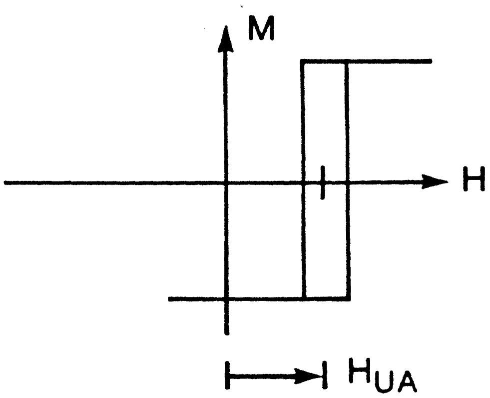




- Examples:
  (i) NiFe/FeMn (antiferromagnet)

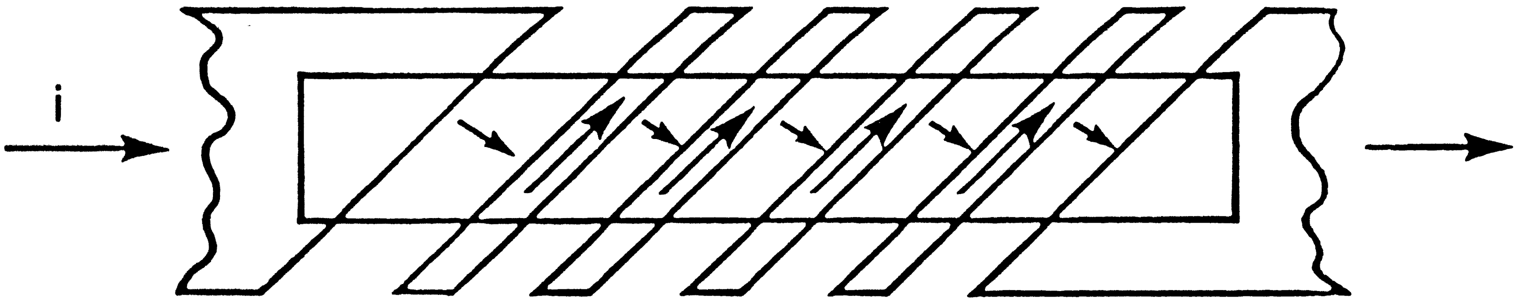


$H_{UA} = 20 \sim 50$ Oe.



  (ii) NiFe/TbCo (ferrimagnet)
  $H_{UA} \simeq 100$ Oe. (400 Å NiFe)

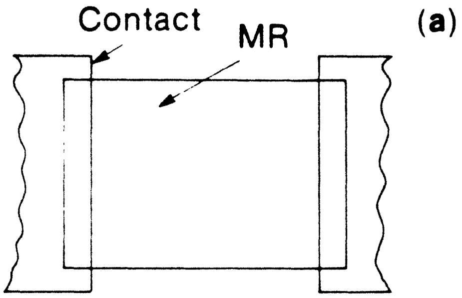
B. Barberpole Biasing

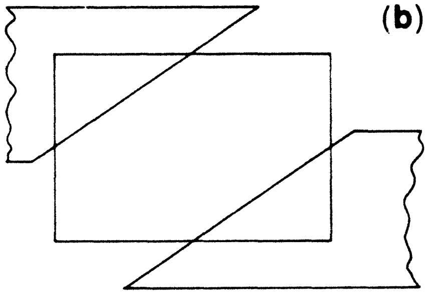


- Small longitudinal bias field (H_{BL}) generated by current along conductor stripes.
- Pulses of large H_{BL} may be applied by current pulses to initialize sensor before reading.

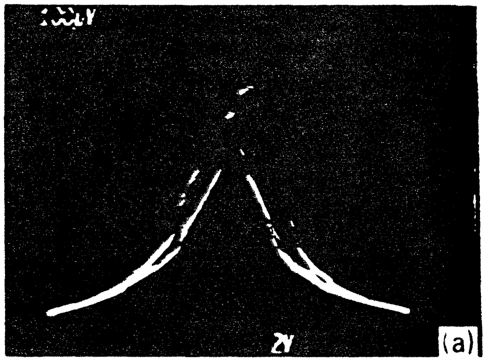
Transverse & Longitudinally Biased MR Sensors

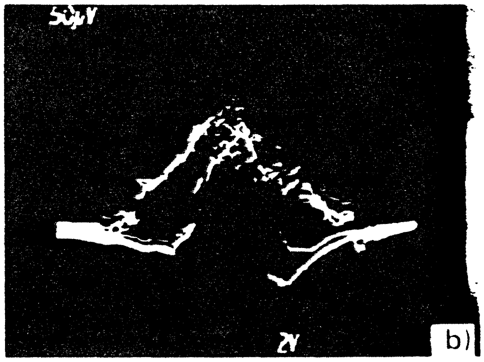
- Small, Unshielded MR Sensors (10 μm x 15 μm)
- Normal & 'Barberpole' Conductor Patterns
- With & Without Longitudinal Exchange Bias from
  NiFe/FeMn : 25 Oe for 400Å NiFe



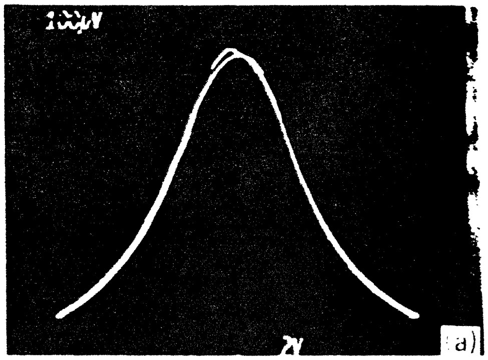


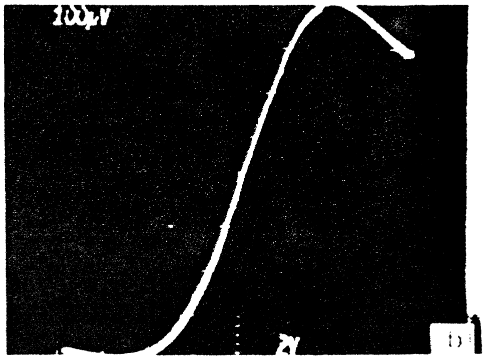
No H_{BL}





With H_{BL}





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