GMR Read head

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Introduction to recording
Basic GMR sensor
Next generation heads TMR, CPP-GMR
Challenges
Product scaling

RAMAC 1956

- 2 kbits/in²
- 70 kbits/s
- 50x 24 in dia disks
- $10,000/Mbyte

100 Gbyte mobile drive

- 130 Gbits/in²
- 630 Mb/s
- 2 x 2.5” glass disks
- <$0.01/Mbyte

Microdrive

- 78 Gbits/in²
- 1 x 1” dia disk
- 8 Gbyte
Areal density trends

![Graph showing areal density trends with various labels and data points.]

- **Products**
  - IBM / Hitachi, highest AD products
  - Competitors, mobile

- **Demos**
  - 60% / yr
  - 100% / yr

- **Areal Density (Gb/sq.in.)**

- **Year Range**
  - 1980 to 2010

- **Density Values**
  - 0.01
  - 0.1
  - 1
  - 10
  - 100
  - 1000
  - 10000

- **Growth Rates**
  - 30% / yr
  - 40% / yr
  - 20% - 40%
Recording basics

- Suspension
- Disk Actuator
- Spindle / Motor
- Slider
- Data track
- Trackwidth
- Actuator
Magnetic recording components

\[ B = 25 \text{ nm} \ (\sigma < 3 \text{ nm}), \]
\[ W = 140 \text{ nm}, \ t = 14 \text{ nm} \]
\[ \sim \text{GHz data rates / 10 year retention} \]
Magnetic recording components
Magnetic recording components

B = 25 nm (σ<3 nm),
W=150 nm, t = 14 nm
data rate ~ GHz

“Compass” that responds to local magnetic field and varies the resistance
Recording basics

![Diagram showing recording basics with signal and time axes.]
Recording basics

Signal

Time [ns]
Magnetic resolution

\[ \text{PW}_{50} / T = 3 \]
Anisotropic Magneto-resistance (AMR)

Bulk property of magnetic materials

- High resistance
- Low resistance

1-2% effects

Angle between I and M

Resistance

0 90 180 270 360
AMR Sensor

- Hard Bias
- Contact
- NiFe
- Insulating Spacer
- NiFeX
- MR Layer
- Soft Adj. Layer

I
Giant Magneto-resistance (GMR)

Interface property of magnetic materials

- High resistance
- Low resistance

10-20% effects

GMR sensor

- Hard Bias
- Contact
- Antiferromagnetic Exchange Film
- Pinned Layer
- Free Layer
- NiFe
- Cu Conducting Spacer
- M
- I
GMR sensors and scaling

Spin dependent scattering in a single alloy
GMR sensors

Track of data

Pinned layer
Spacer layer
Free layer
GMR sensors

Fringe field from bits rotates free layer magnetization

Track width

\( \Delta R \)

\( H_{\text{applied}} \)
GMR sensors

The reference ferromagnetic layer magnetization is pinned by an antiferromagnetic layer and does not rotate in small magnetic fields.
Pinned layer is AP pinned to obtain flux closure to minimize magneto-static coupling to free layer

Utilize AP coupling property of Ru, Ir…

![Diagram of GMR sensors with arrows indicating magnetic fields and a graph showing J (arb. units) vs. thickness (Ru)](image)
GMR sensors

External hard magnet bias

$H_{\text{applied}}$

reference
GMR sensors

1) Produce undercut resist structure
   (193nm photolithography)

2) Ion Mill, then IBD HB/leads

3) Lift-off Resist
GMR sensors and scaling

Total gap

Current-in-plane (CIP)

downtrack direction
GMR sensors

State-of-the-art magnetic hard disk drives
GMR sensors

- The **height** of the sensor is controlled by lapping (polishing) *not* by lithography.
- → The smallest feature in a thin film head is determined **mechanically**
GMR read head

Works great, what’s the problem

$\Delta R$ not increasing
R increasing
Shorting to the shields
Edge damage for small features

New sensor geometry

**CPP-Tunnel Magnetoresistance (high R)**
(Current-perpendicular-to-plane)

**CPP-GMR (low R)**
(Current-perpendicular-to-plane)

**CIP-GMR**
(Current-in-plane)

**GMR spin-valve**

**Magnetic tunnel-valve**

**Tunnel-valve head**

57.8 nm

500 Å

150 nm
CPP sensor

Sensor deposition

Photo/Ion mill

Insulator/hard bias deposition/Insulator deposition

Top lead and shield

Current
TMR sensor

Juliere (1975)

\[ MR = \frac{R_{dP} - R_p}{R_p} = \frac{2P_1P_2}{1 - P_1P_2} \]

with \( P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \)
TMR sensor

1) Barrier + magnetic electrode interfaces determine maximum TMR
   AIOx 70%TMR and MgO >500% TMR

2) Thickness of given barrier material
   Determines RA= Resistance x Area

3) TMR is independent of specific materials in sensor stack
   → Sensor design is highly flexible

Key goals:  
- Smooth substrate+underlayers
- continuous ultrathin barrier growth
- Stable chemistry @ barrier interfaces
- No shunting of barrier during lithography
TMR sensor

The resistance of the device depends on RA product

R (per unit area) depends exponentially on the barrier thickness

A is set by size of the bits (decreases with time).

To keep the resistance of the device constant you need to thin the barrier over time (or find lower R barrier materials).
TMR sensor

ΔR/R (%)

RA (Ω-μm²)

Low RA (high current):
+ Amplifier noise
+ Ampere curling field
+ Thermal/electromigration
[+spin-torque]

High RA (low current):
+ Shot noise
+ Voltage bias limit
+ RC time constant

300 Gb/in²
65 MB/s

150 Gb/in²
50 MB/s

70 Gb/in²
40 MB/s

35 Gb/in²
31 MB/s

26.5 dB head S/N
15% utilization
Vop = 180 mV

CPP Spin-valves
CPP Tunnel valves

35 Gb/in²
31 MB/s

300 Gb/in²
65 MB/s

150 Gb/in²
50 MB/s

70 Gb/in²
40 MB/s
TMR sensor

CoFeB/MgO/CoFeB

Y. Nagamine et al. (Anelva corp.)
Intermag ‘06
CPP GMR Sensor

In absence of low RA tunnel barrier move to metal devices.

CIP-GMR Shunting effect limits maximum signal
CPP GMR Sensor

Free layer (M=30-50A NiFe)

AP-pinned layers (∆M = 0)

Antiferromagnet (J_{ex} > 0.3 erg.cm²)

CoFe/Cu interfaces

Spin mixing layers

Total gap < 500A

J.Y. Gu et al., JAP 87, 4831 (2000)
CPP GMR Sensor

Want high resistance high spin polarized materials

Heusler alloys

Maat et al., JAP


e.g. NiMnSb, CrFeAl, ...
CPP GMR Sensor

Compared to TMR, CPP GMR has lower $R$, $\Delta R$ & $\Delta R/R$

So how to get a signal?

Current: $>10^8$ A/cm$^2$

Heating
Electromigration
Spin - transfer torques
Spin transport

$R \sim R_0 + \Delta R \,(1-\cos(\theta))$

GMR metallic
TMR insulator

$I_{\text{bias}}$

$F_1$  NM  $F_2$
Spin transfer effect

- Current polarized by F1
- Transfer of spin angular momentum to $M$
- $J \sim 10^7$ A/cm$^2$

$\vec{T}_I = \frac{\omega_t}{M_0} \vec{M} \times (\vec{p} \times \vec{M})$
Magnetization dynamics

\[
\frac{d\mathbf{m}}{dt} = \gamma_0 \mathbf{H} \times \mathbf{m} + \alpha \left( \mathbf{m} \times \frac{d\mathbf{m}}{dt} \right)
\]

Field torque (precession)

Damping torque (dissipation)

Spin torque (negative friction)
Magnetization dynamics


\[ I_C^{P-AP} \approx \frac{A \alpha M_S V}{g(0)p} \left( H + H_{dip} + H_{K/} + 2\pi M_S \right) \]
GMR sensor

Thermal fluctuations
fluctuation-dissipation theorem

\[ S \sim \frac{k_B T}{M} V_{\text{free}} \]

Smith and Arnett, APL 78, 1448 (2001).
Sensors need a lot of properties not just $\Delta R/R$

Opportunities for new materials and new phenomena
Non-magnetic magnetic sensors

Metal dot embedded in high mobility low carrier density semiconductor (i.e. InSb).

At low field $E$ is $\parallel$ to metal/SC boundary and $j$ follows $E \rightarrow$ low $R$.

At high fields because of the Lorentz force the angle between $j$ and $E$ can approach 90 degrees with little current flowing through metal $\rightarrow$ high $R$.

- Attractive because immune from magnoise, spin-torque
- However geometry is challenging for a slider-type sensor

Solin, APL 80, 4012 (2001)