GMR Read head

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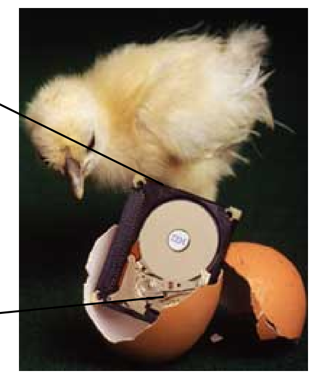
ECE, CMRR

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

Product scaling

100 Gbyte
mobile drive

8 Gbyte

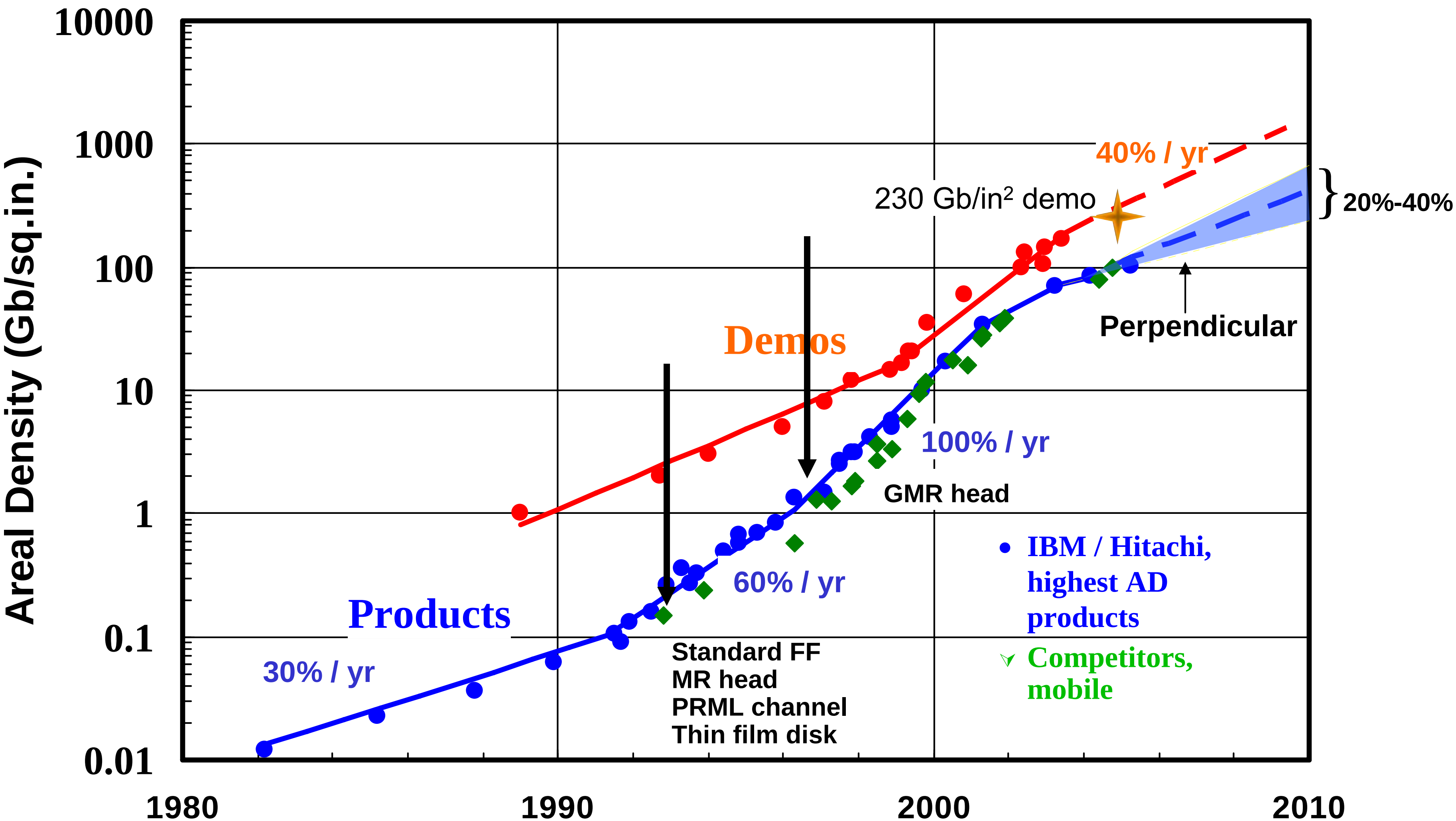


2 kbits/in^2
70 kbits/s
50x 24 in dia disks
$10,000/Mbyte

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

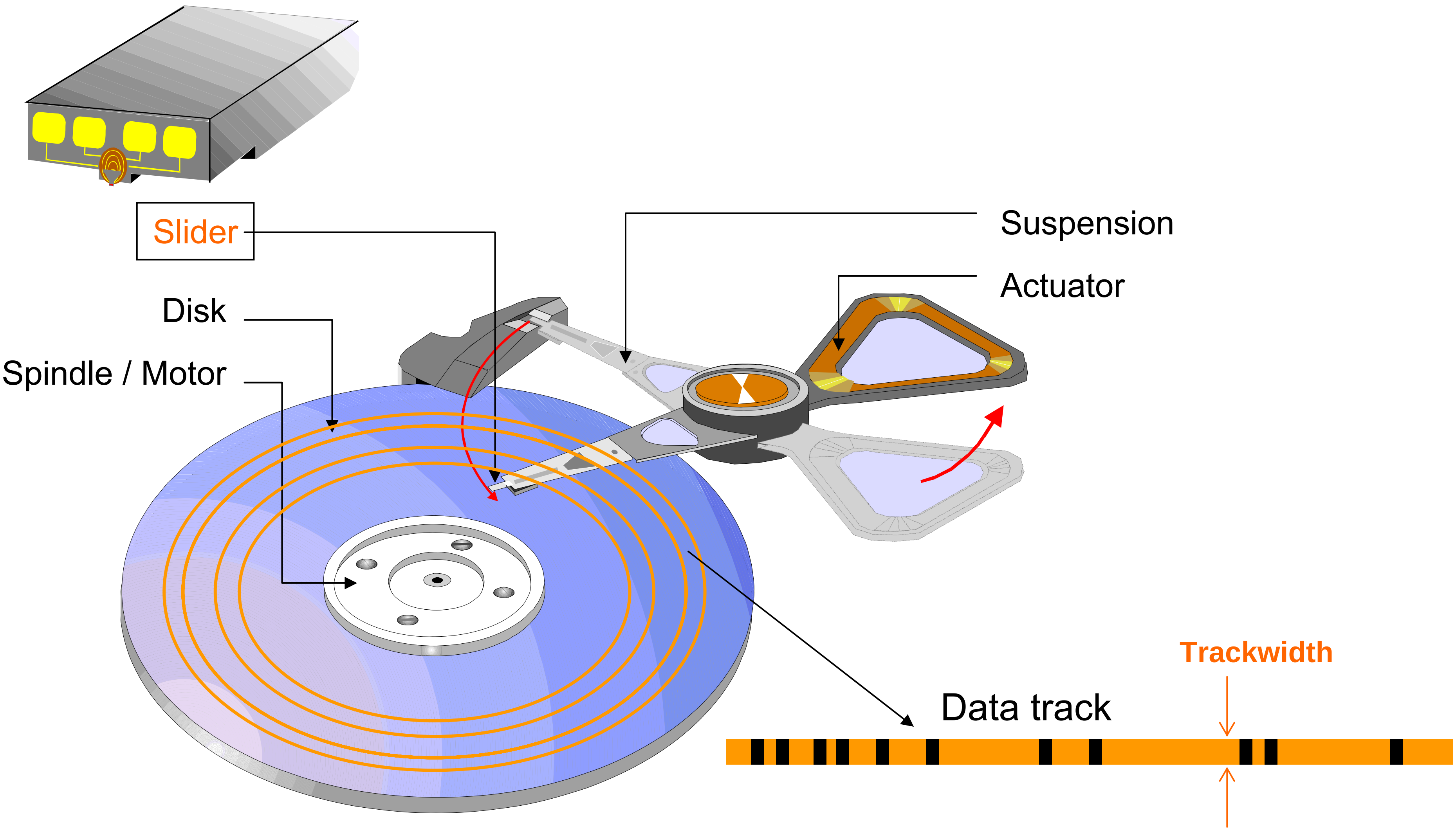
Microdrive
78 Gbits/in^2
1 x 1” dia disk

Areal density trends

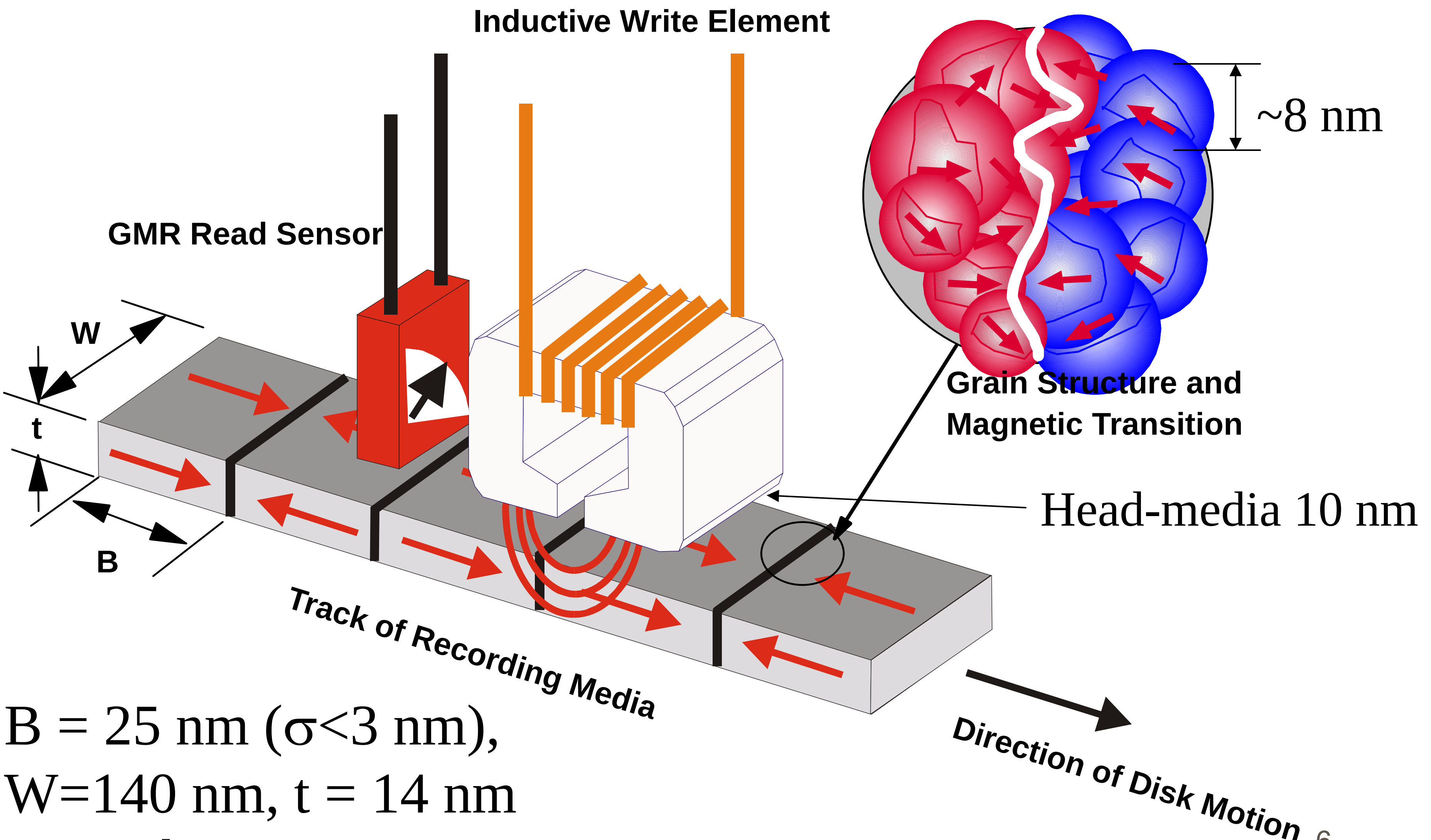


1975

Recording basics



Magnetic recording components

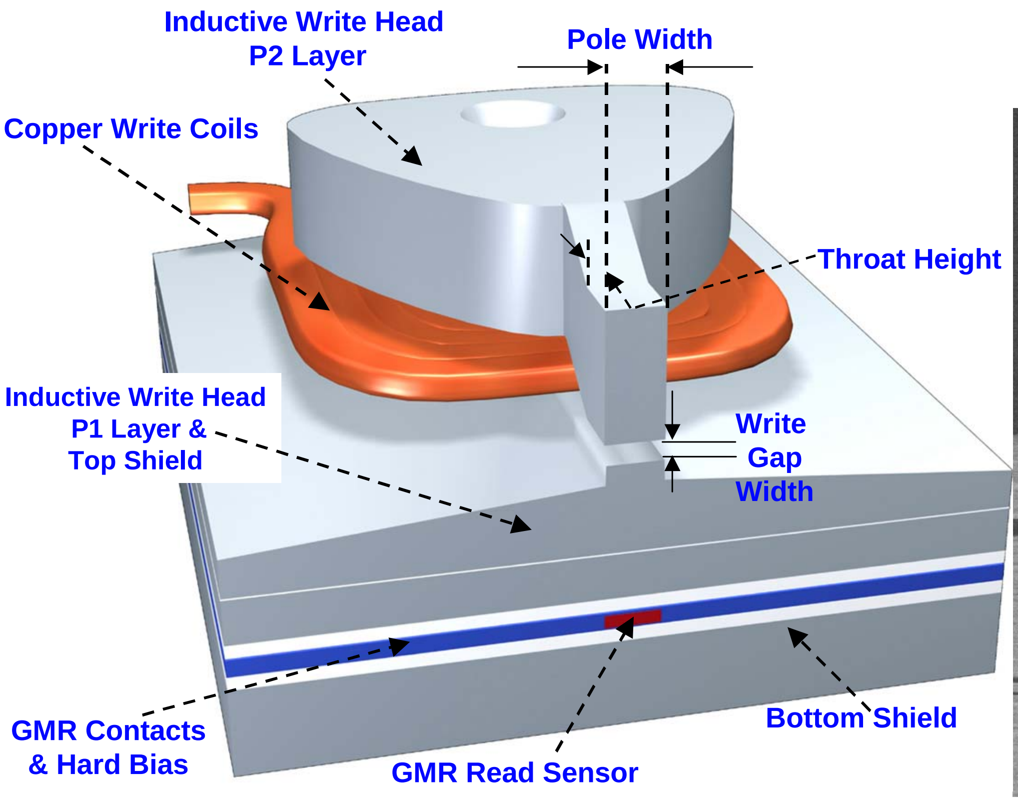


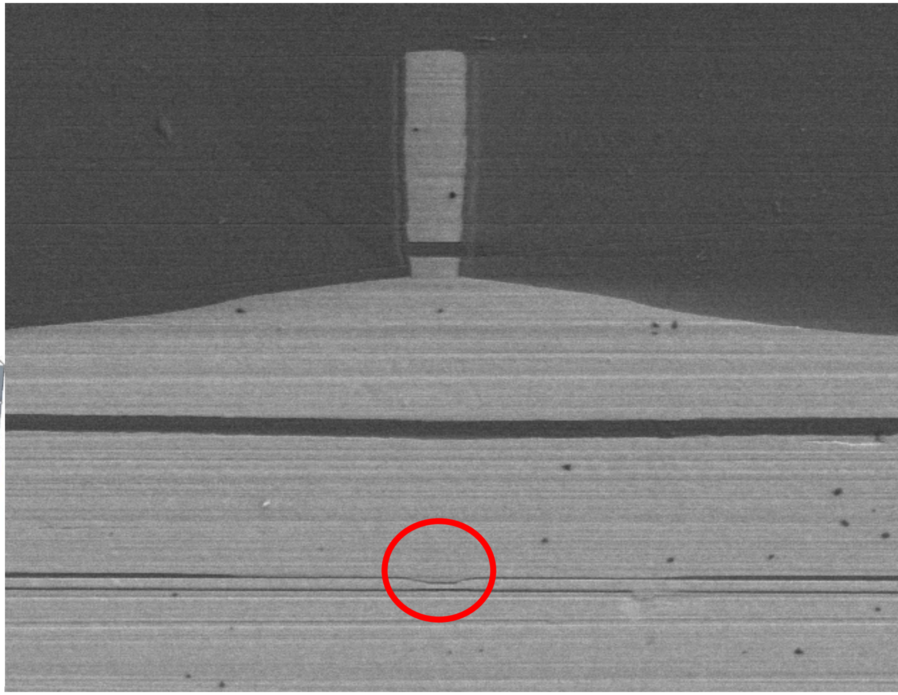
B = 25 nm (σ<3 nm),

W=140 nm, t = 14 nm

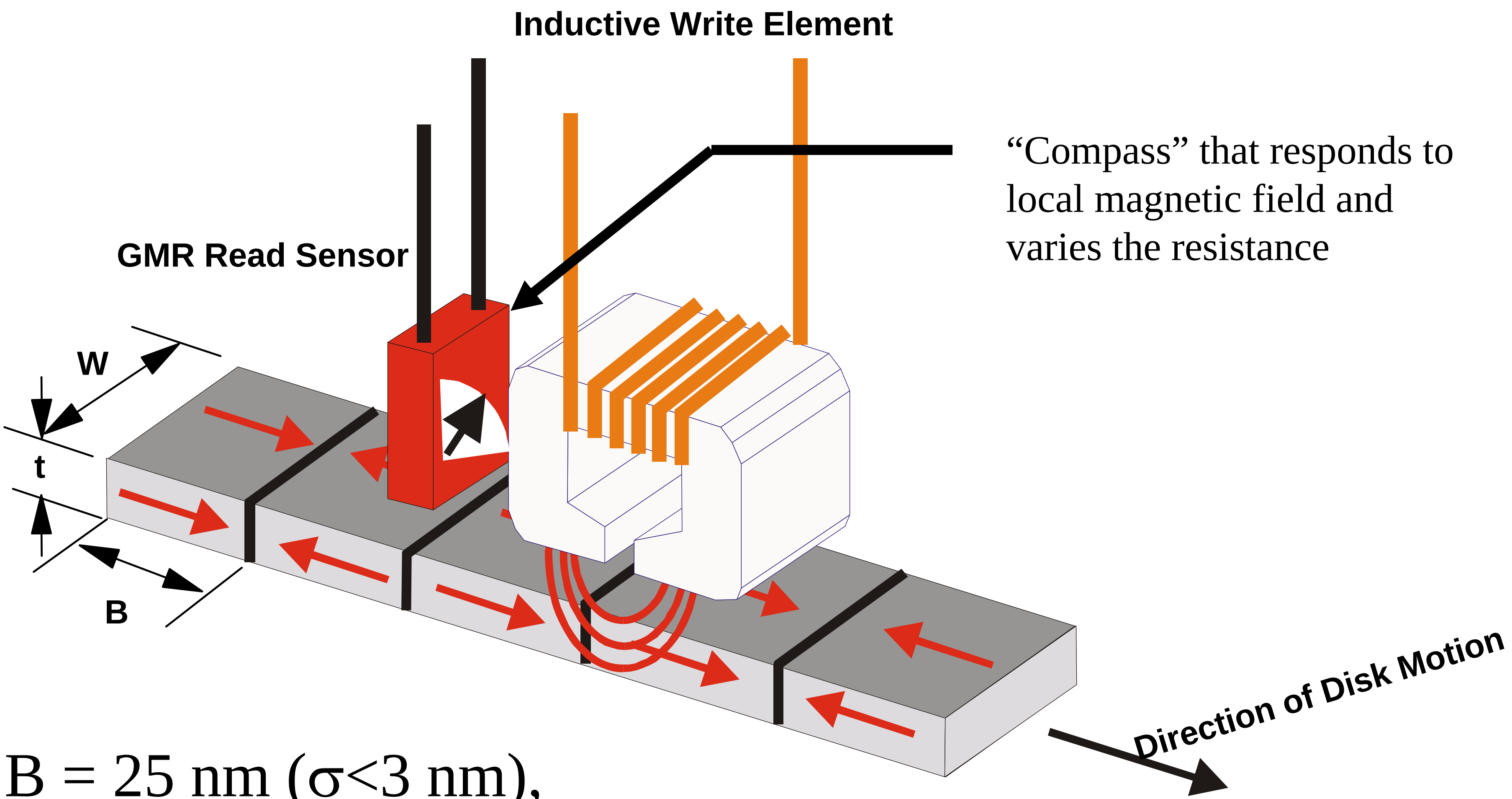
~ GHz data rates / 10 year retention

Magnetic recording components





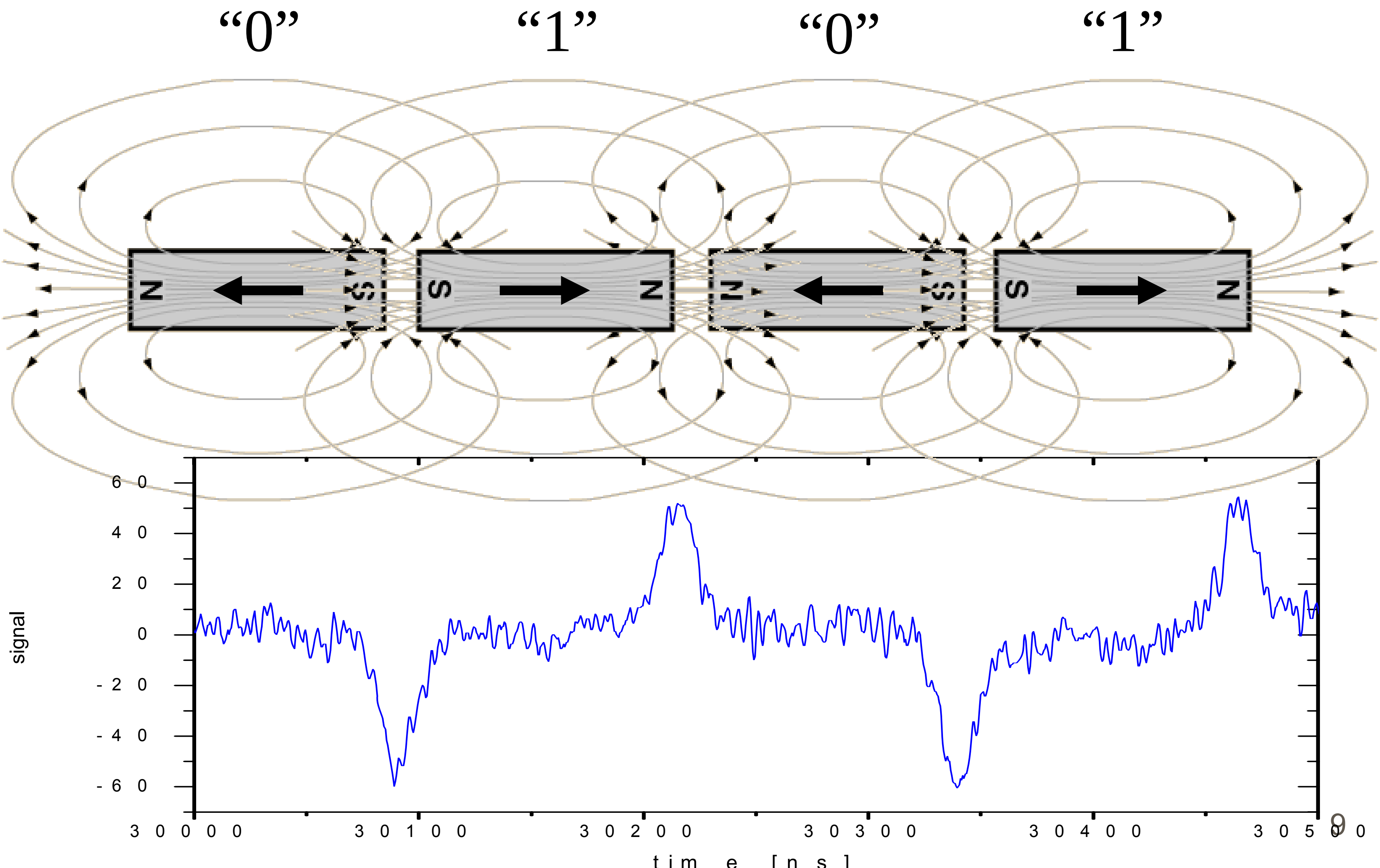
Magnetic recording components



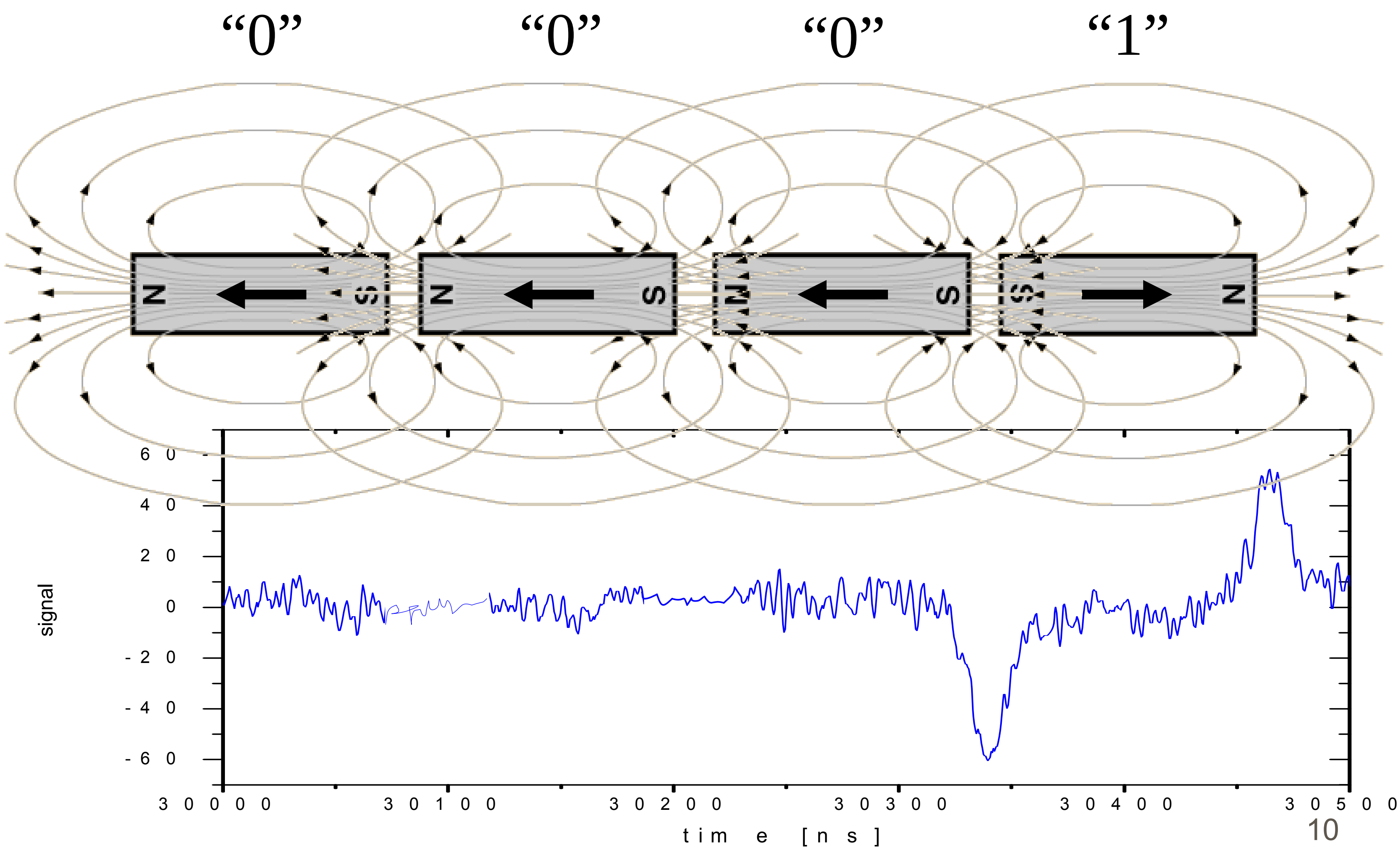
"Compass" that responds to local magnetic field and varies the resistance

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

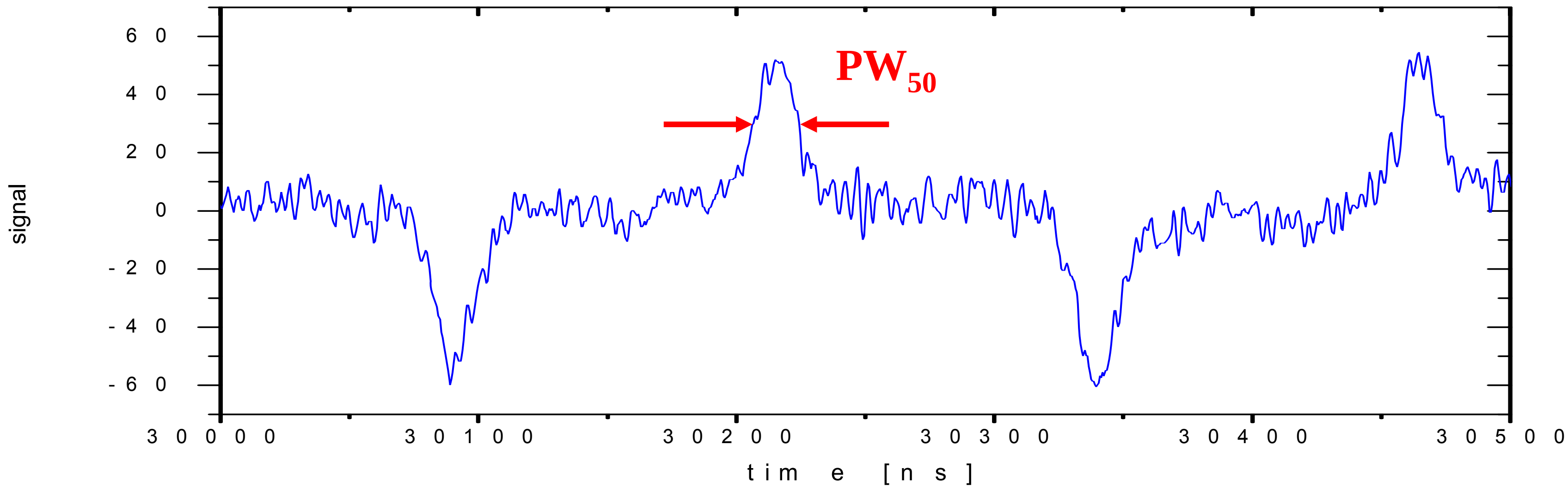
Recording basics

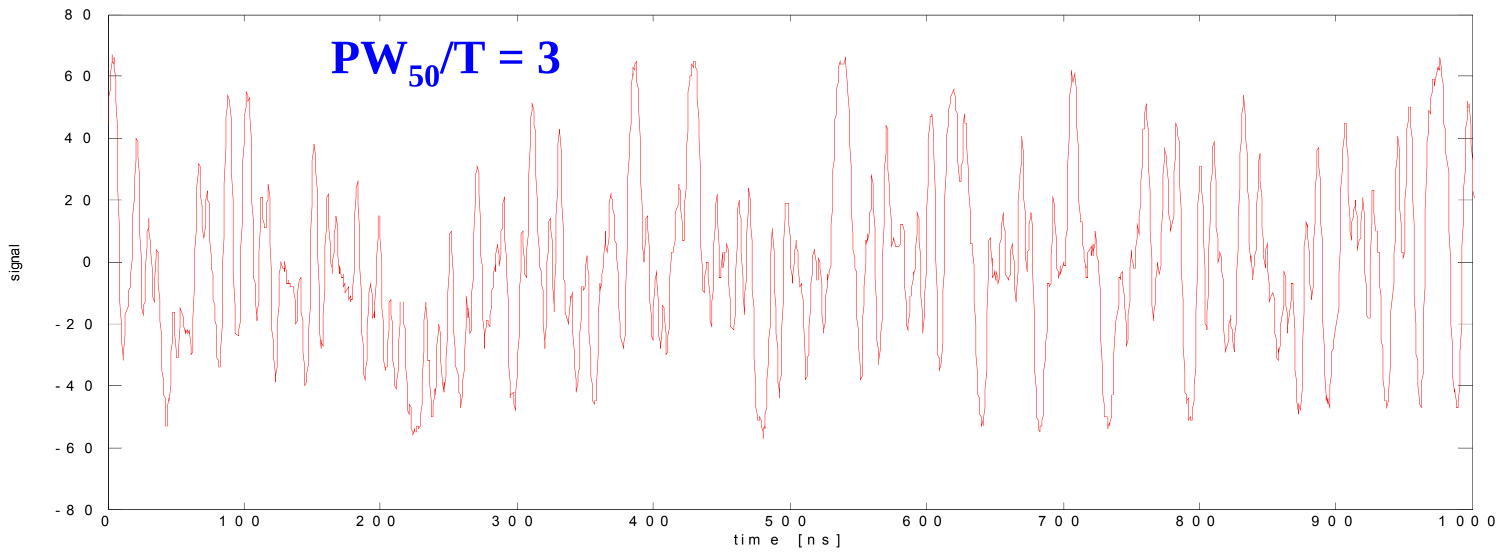


Recording basics



Magnetic resolution

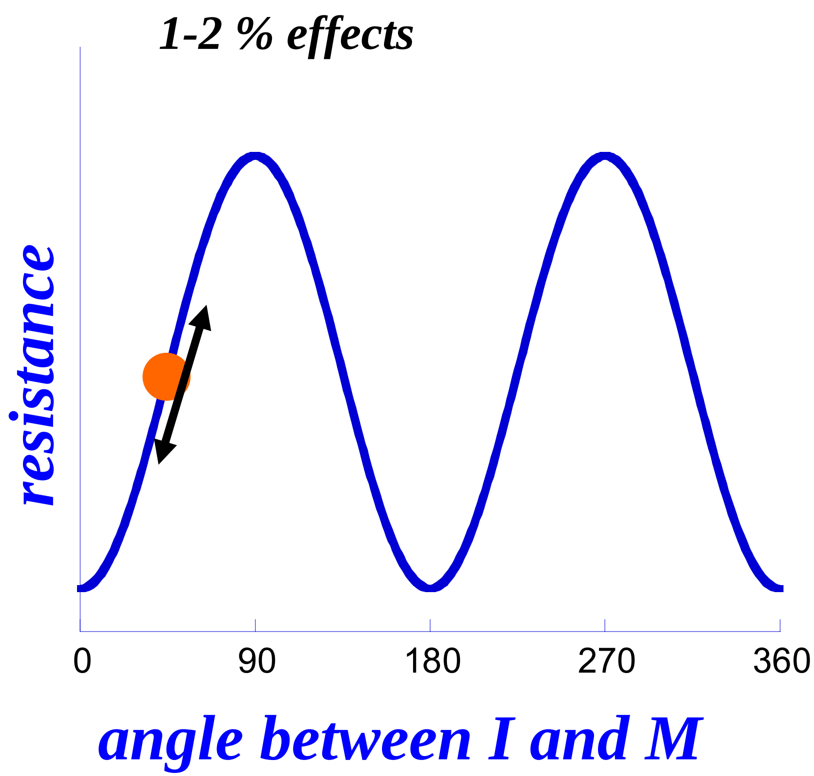




Anisotropic Magneto-resistance (AMR)

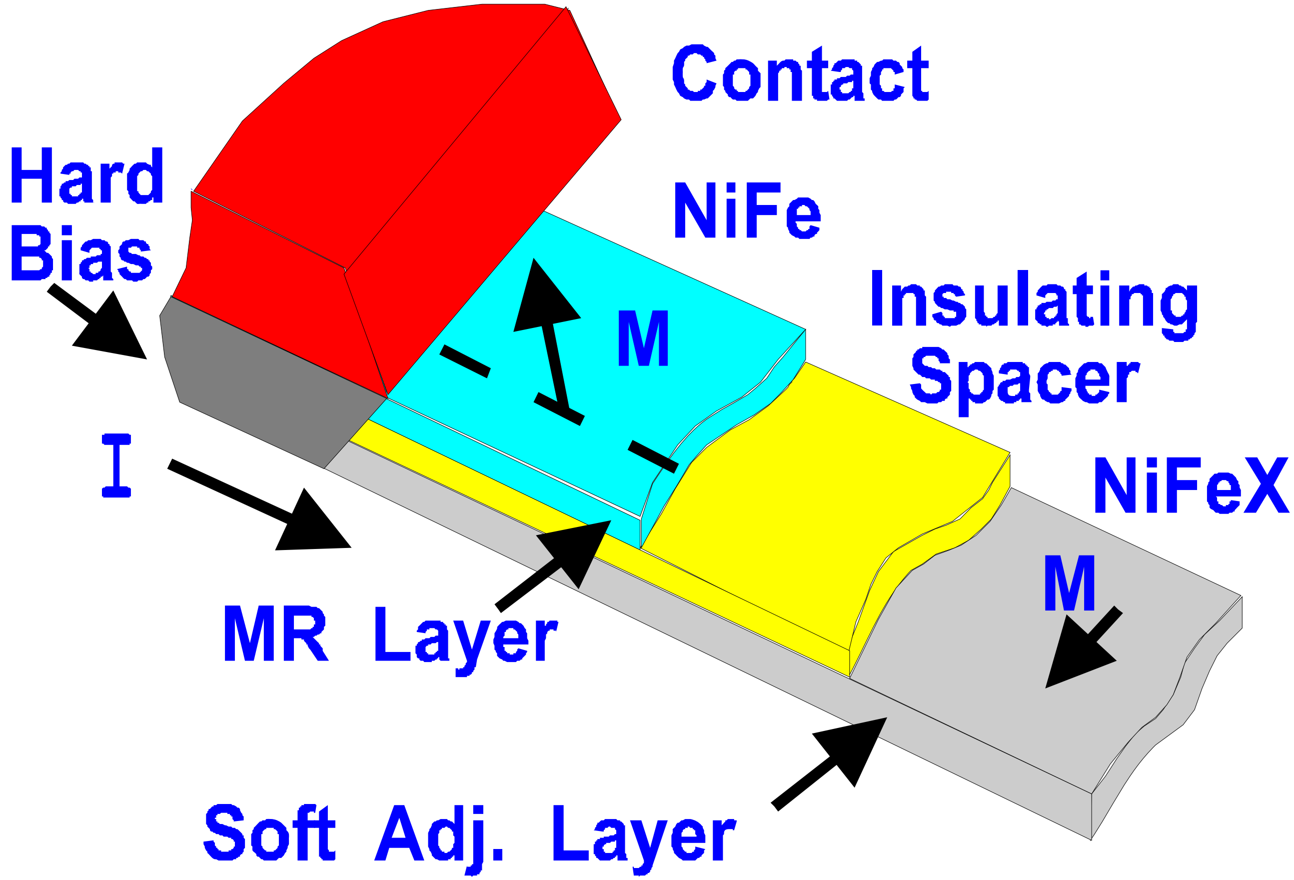
high resistance

low resistance

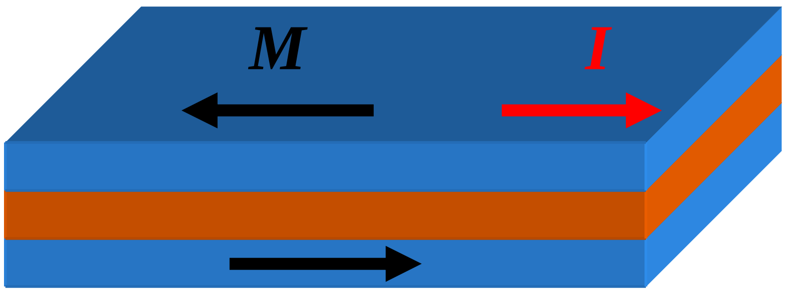


Bulk property of magnetic materials

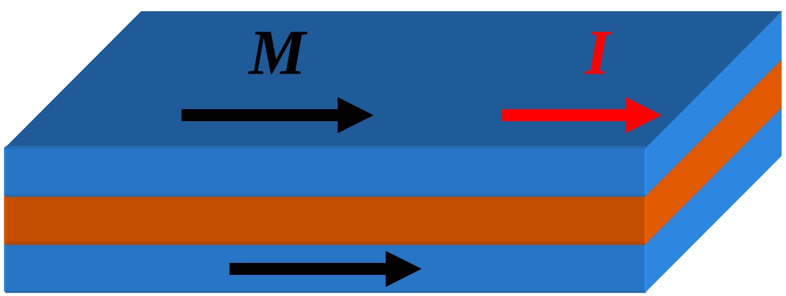
AMR Sensor


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

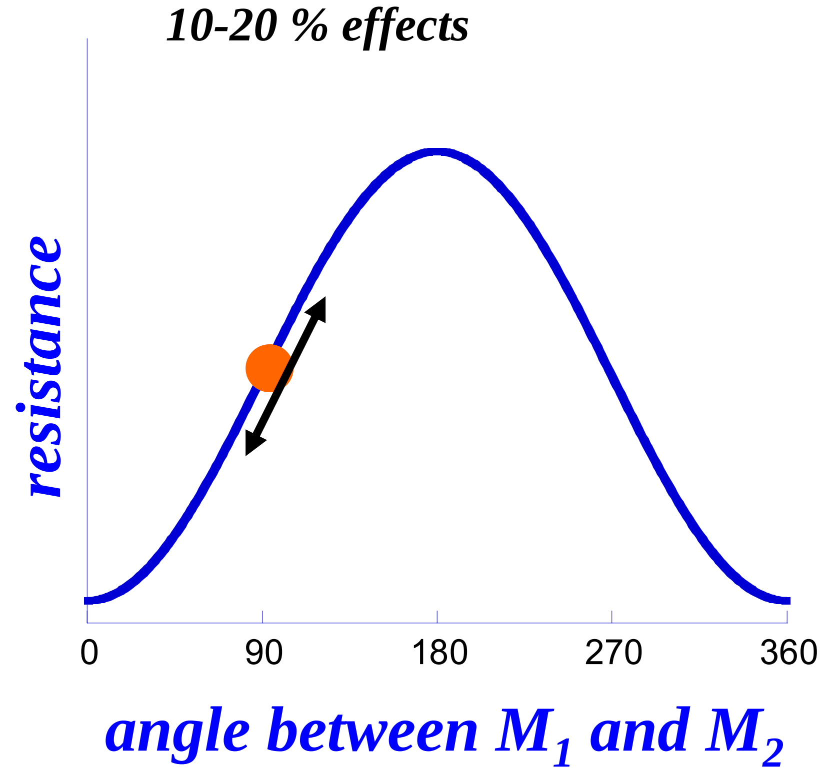
Giant Magneto-resistance (GMR)



high resistance



low resistance

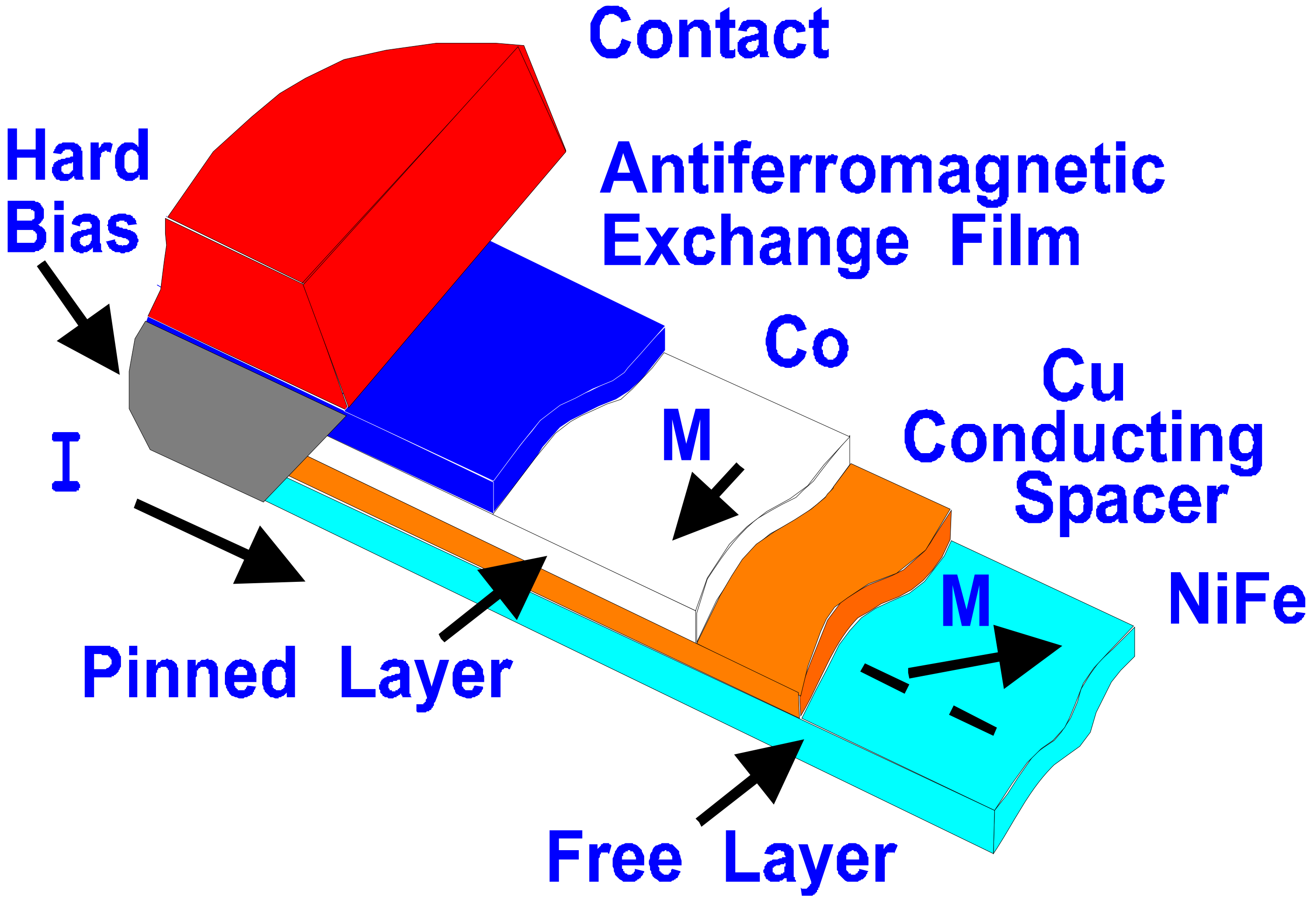


Interface property of magnetic materials

Baibich et al. Phys. Rev. Lett. ***61*** *2472 (1988)*

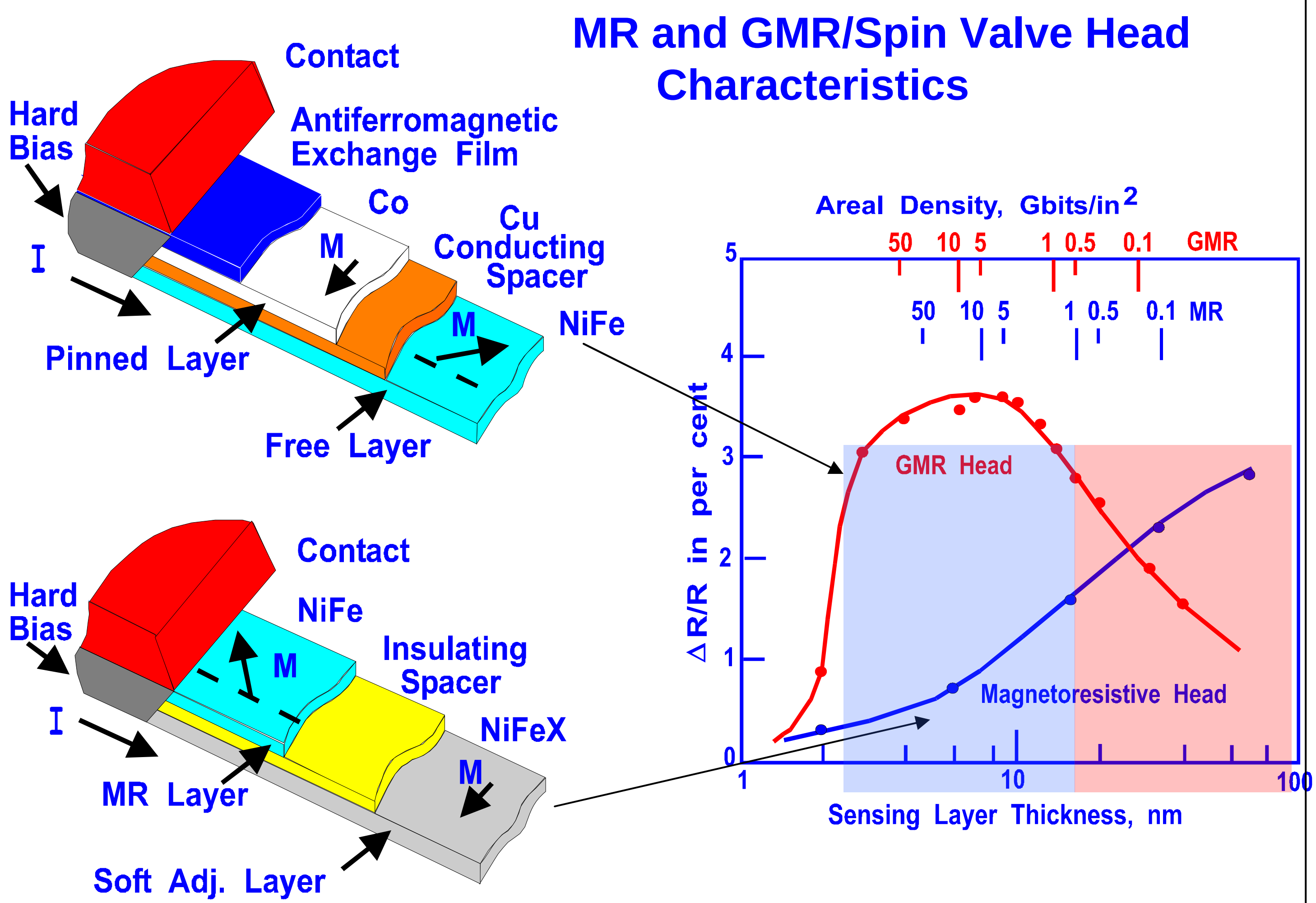
Binasch et al. Phys. Rev. B ***39****, 4828 (1989); P. Grunberg, U.S. patent # 4,949,039*

GMR sensor



Contact
Hard
Bias
Antiferromagnetic
Exchange Film
Co
Cu
Conducting
Spacer
M
I
M
NiFe
Pinned Layer
Free Layer

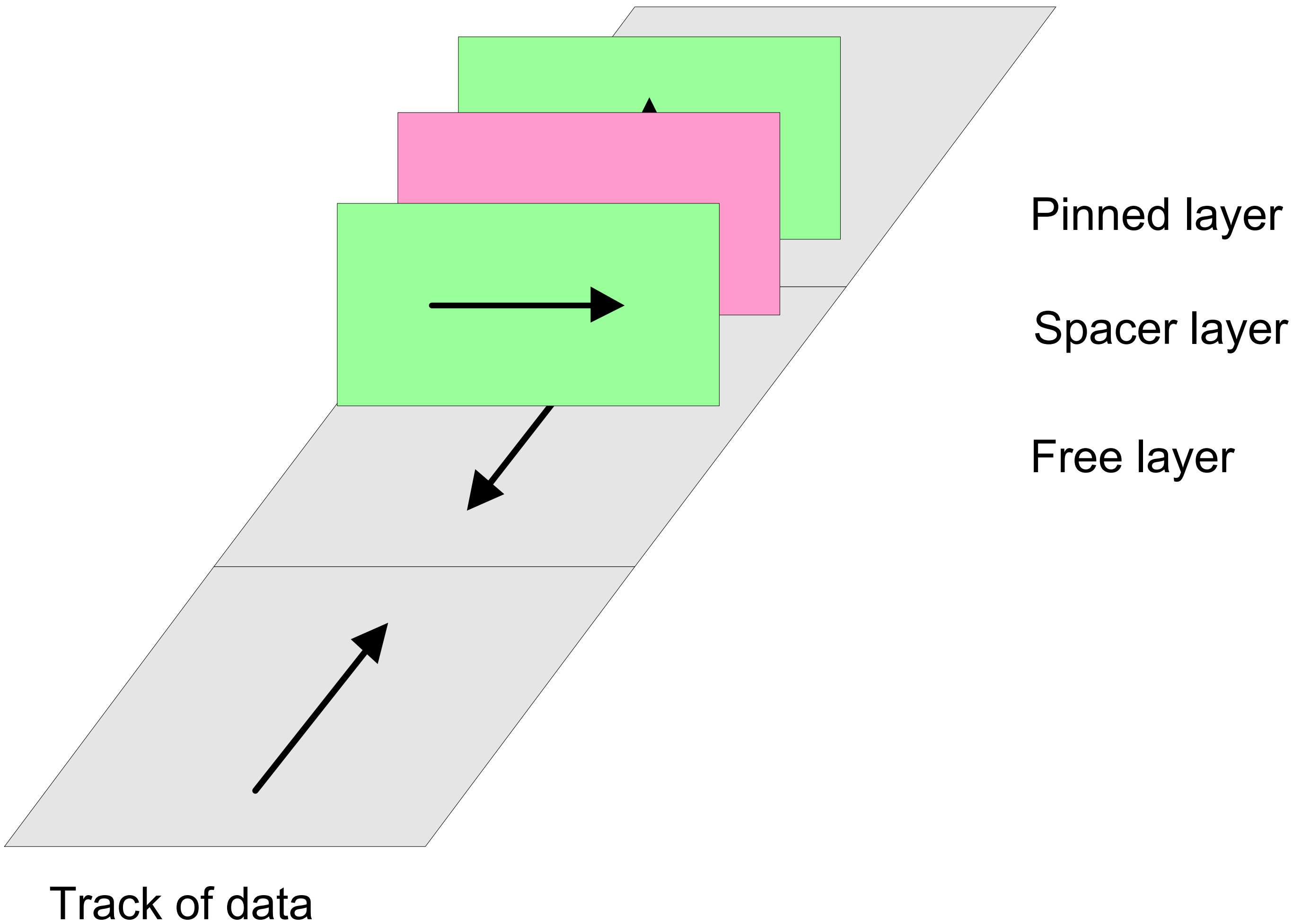
GMR sensors and scaling



Spin dependent scattering in a single alloy

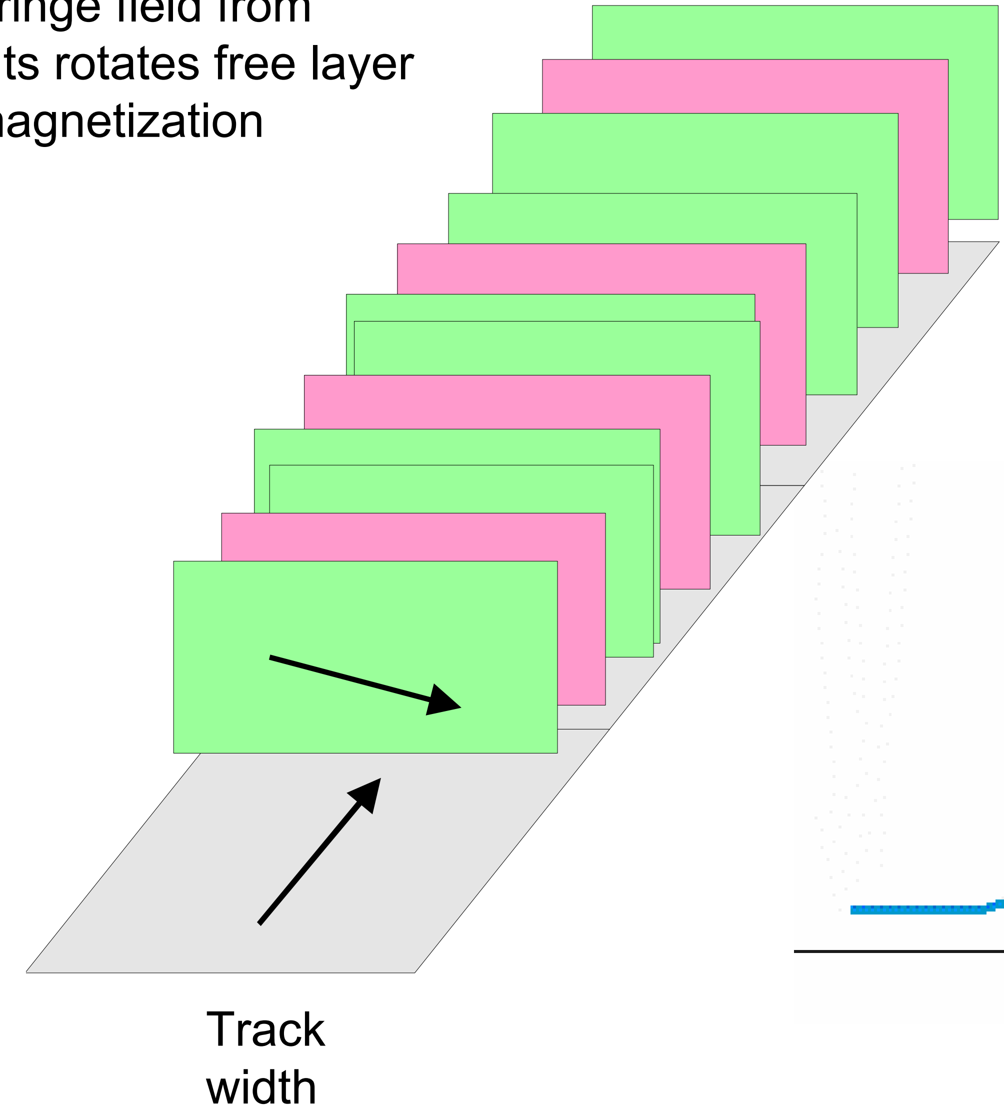
Grochowski/Gurney

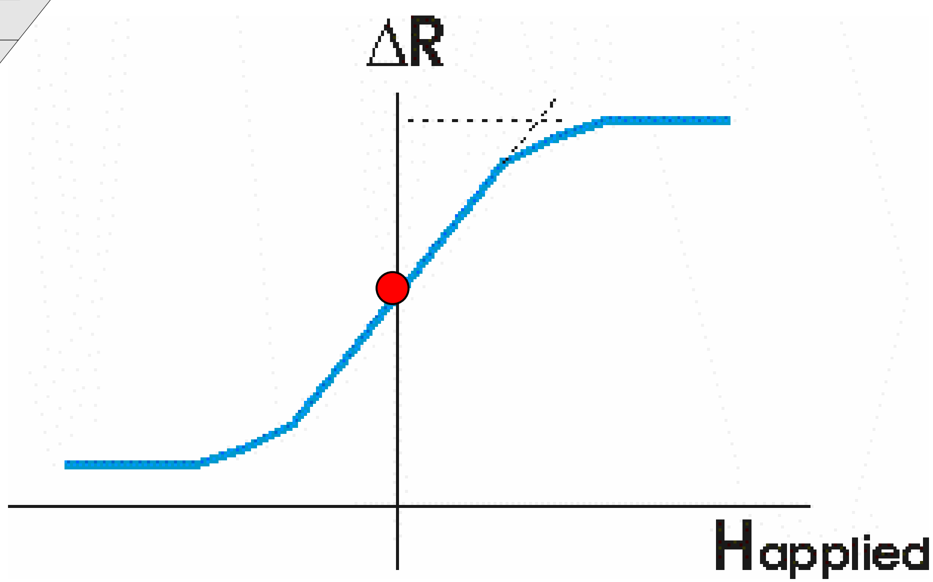
GMR sensors



GMR sensors

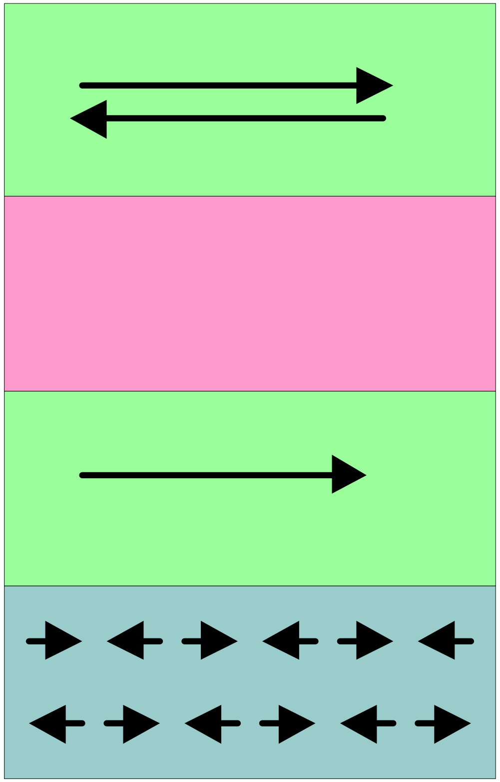
Fringe field from bits rotates free layer magnetization

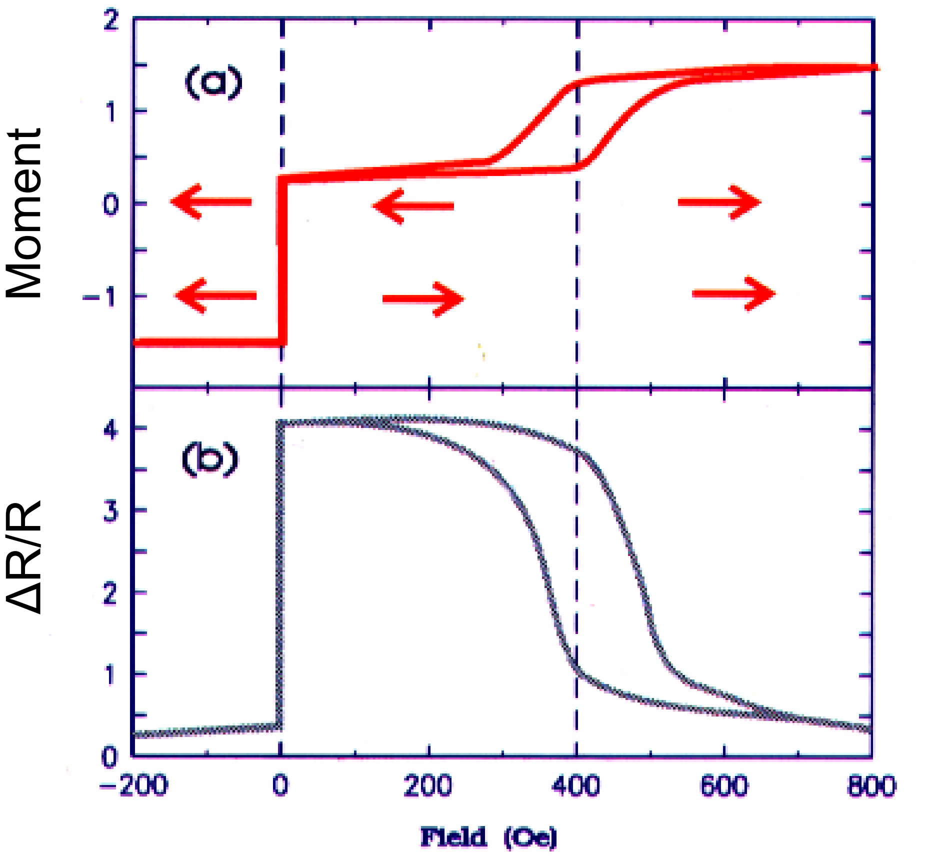




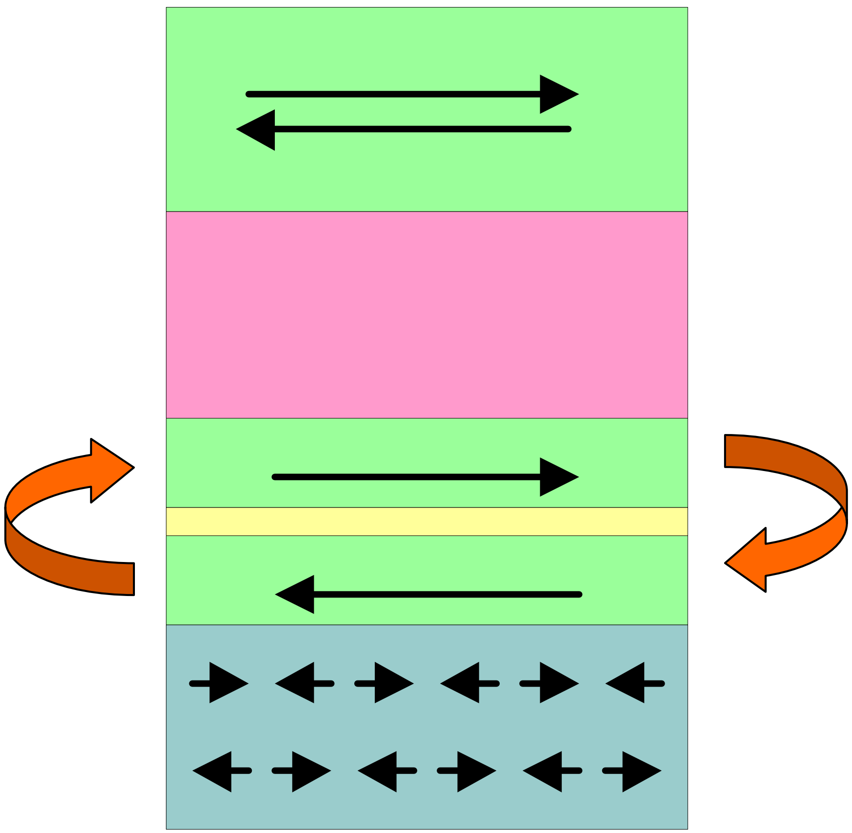
GMR sensors

- The reference ferromagnetic layer magnetization is pinned by an antiferromagnetic layer and does not rotate in small magnetic fields



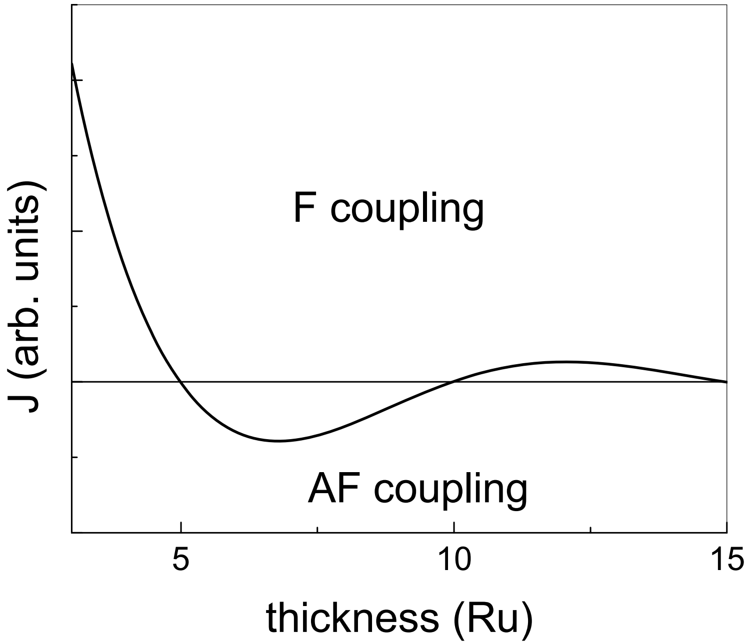


GMR sensors

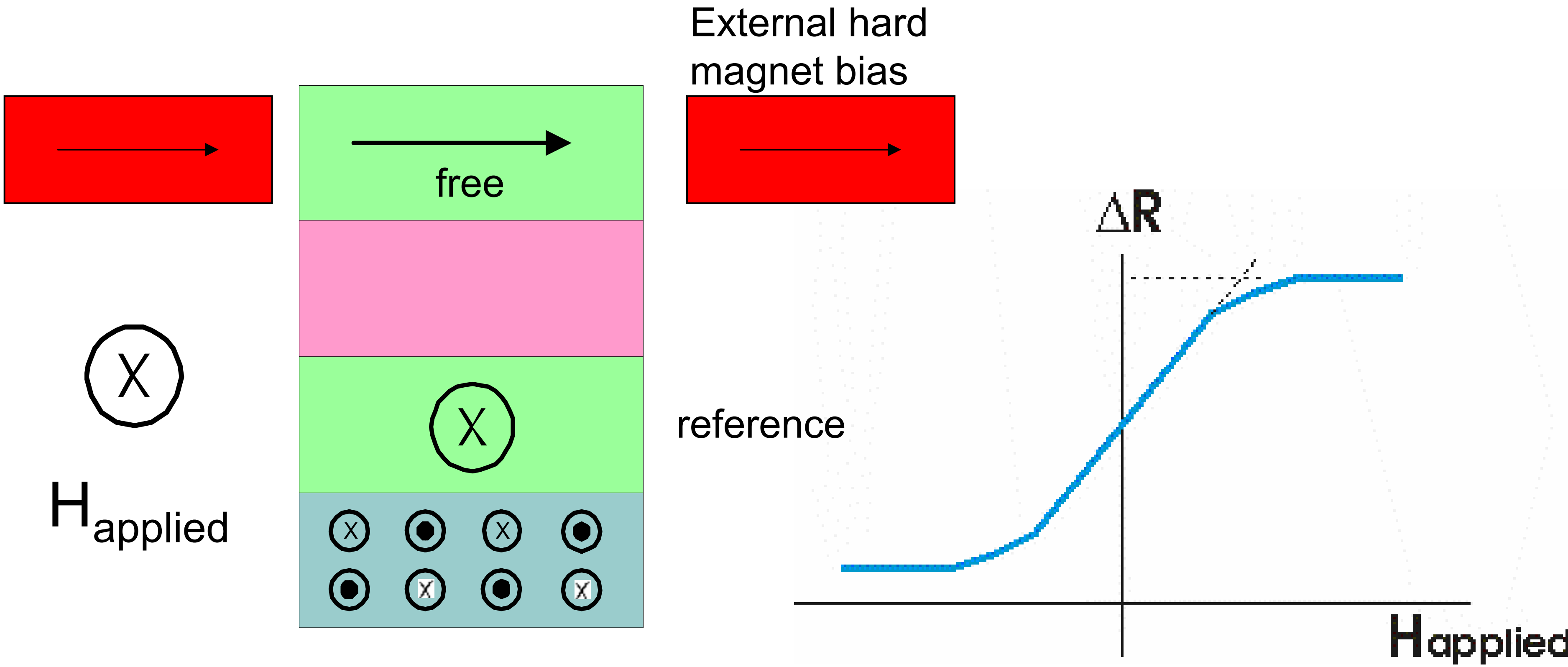


Pinned layer is AP pinned to obtain flux closure to minimize magneto-static coupling to free layer

Utilize AP coupling property of Ru, Ir…

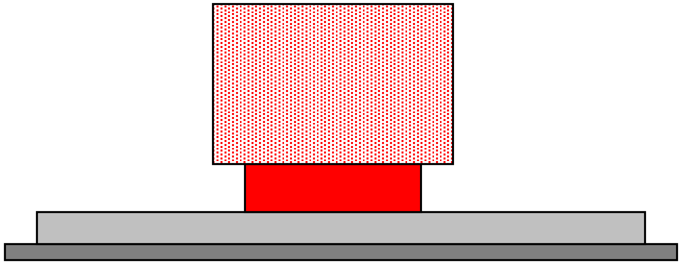


GMR sensors

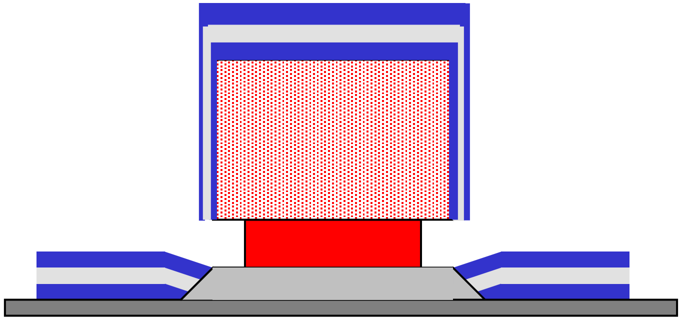

External hard
magnet bias
free
reference
X
X
$H_{applied}$
ΔR
$H_{applied}$

GMR sensors

1) Produce undercut resist structure (193nm photolithography)

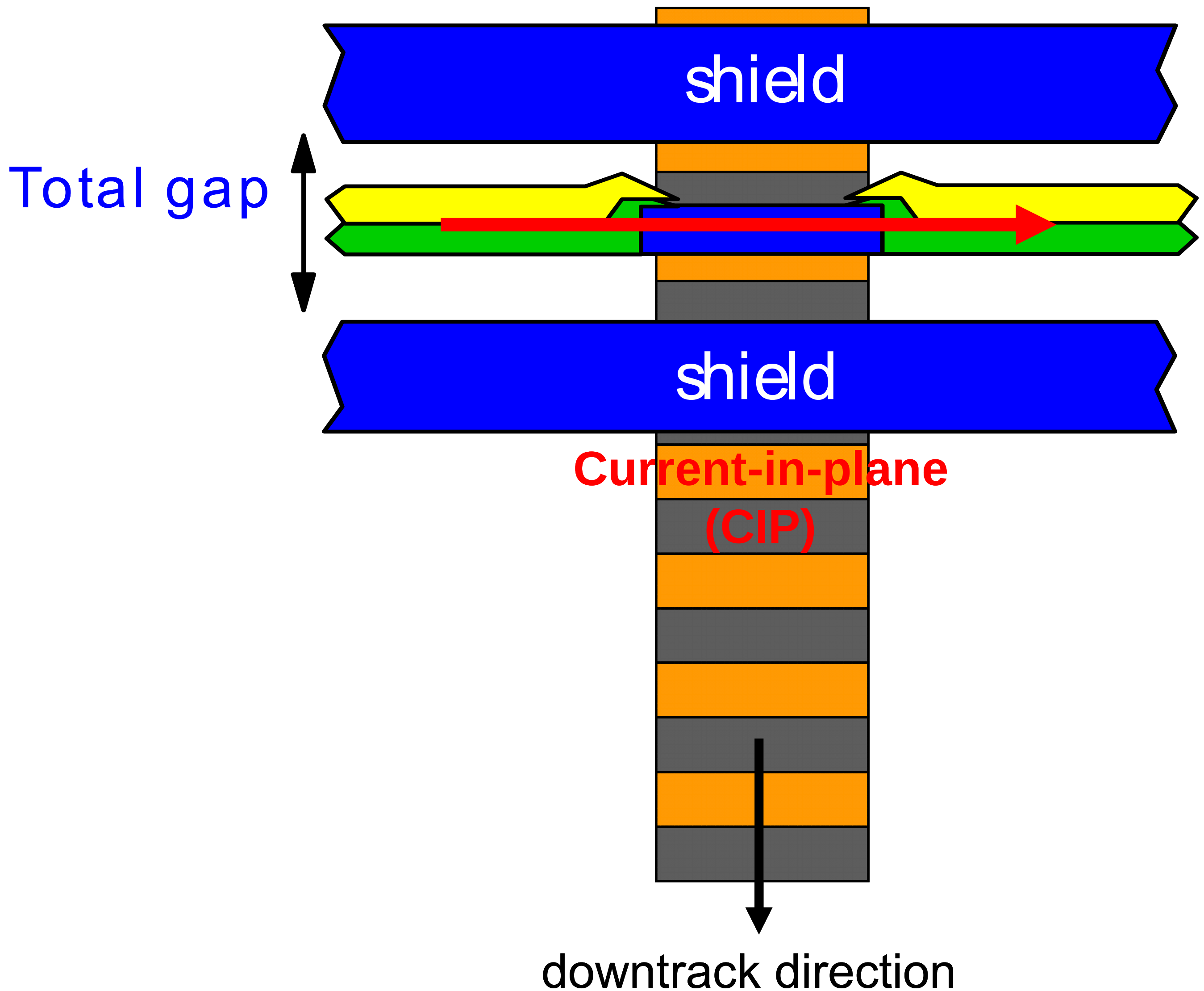


2) Ion Mill, then IBD HB/leads

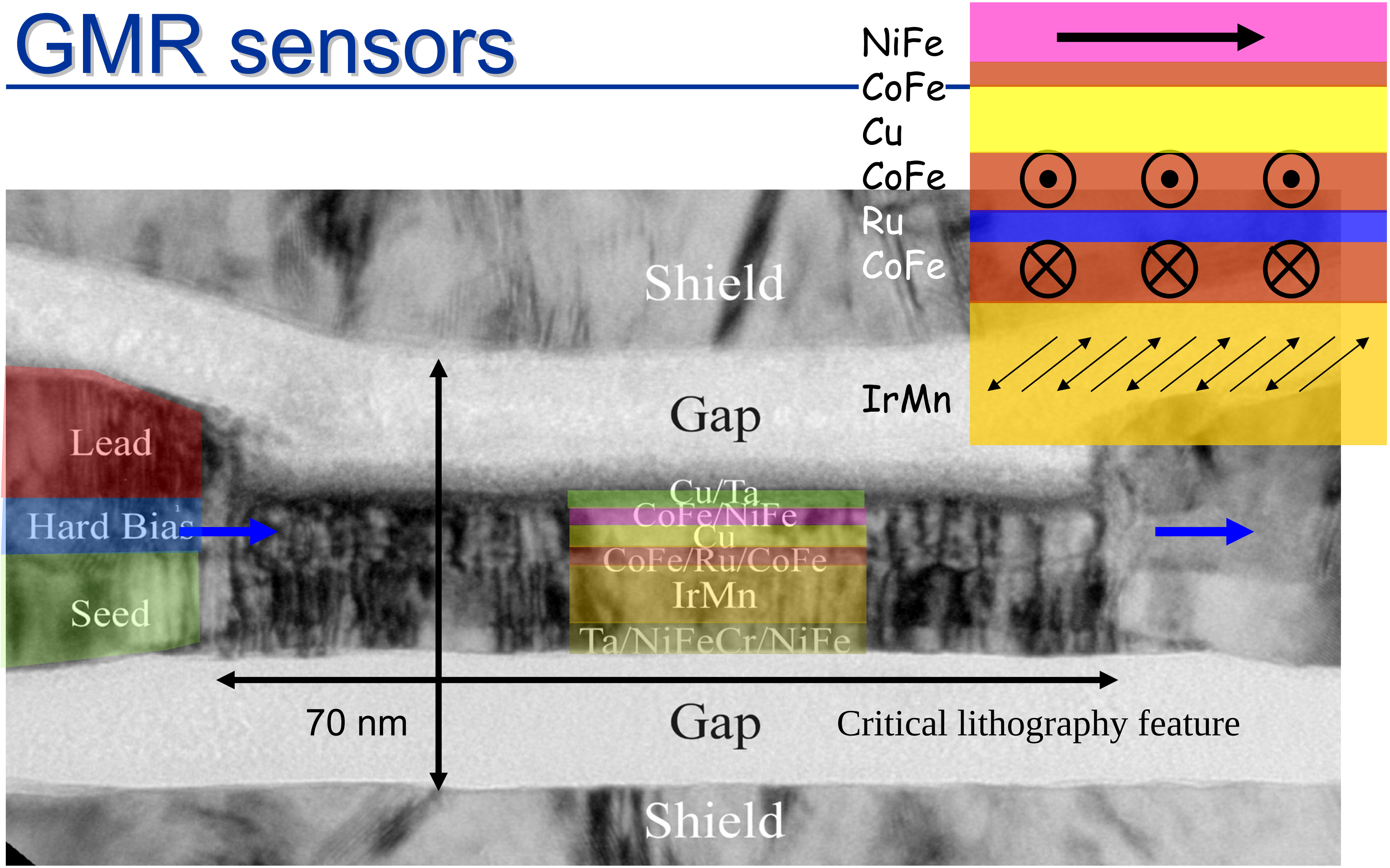


3) Lift-off Resist

GMR sensors and scaling



GMR sensors

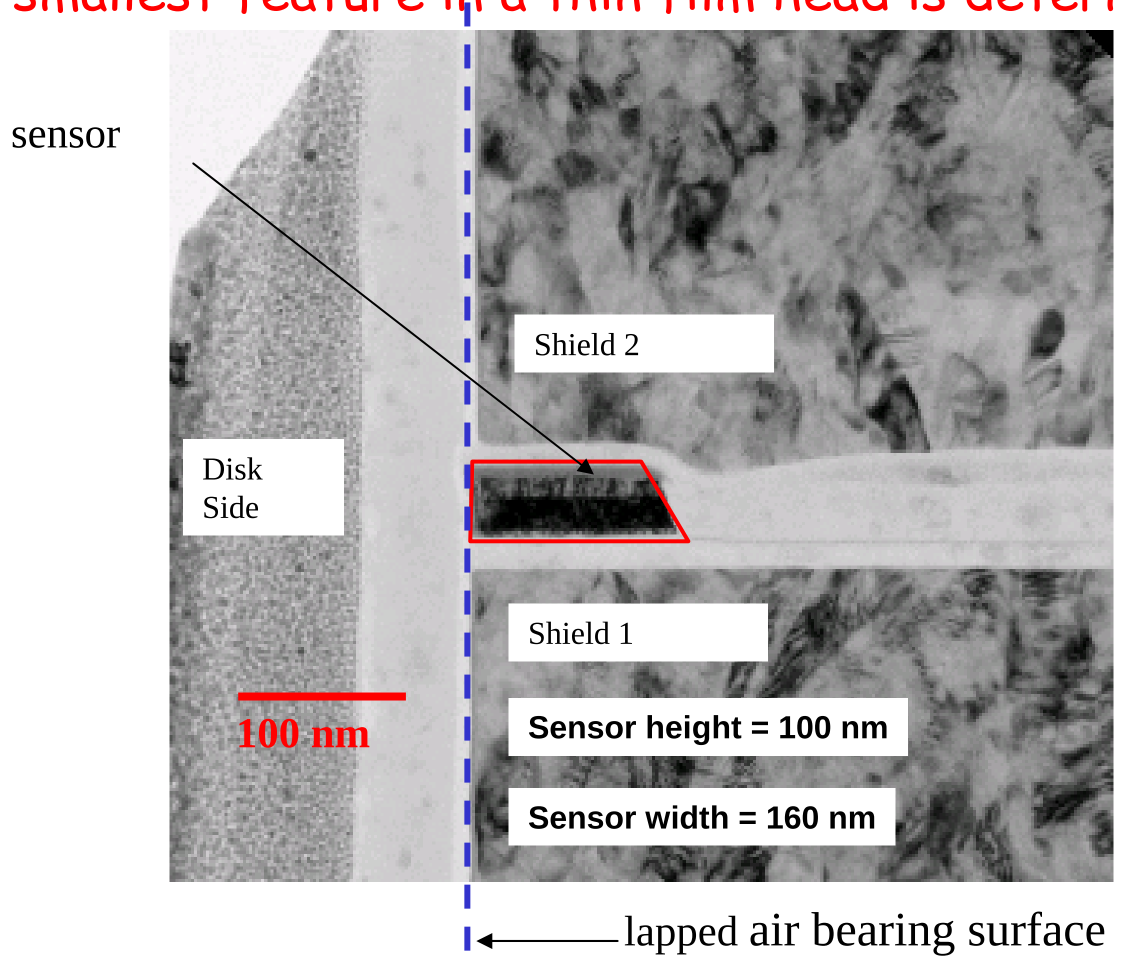


State-of-the-art magnetic hard disk drives

I. R. McFadyen, E. E. Fullerton and M. J. Carey, MRS Bulletin **31**, 379 (2006).

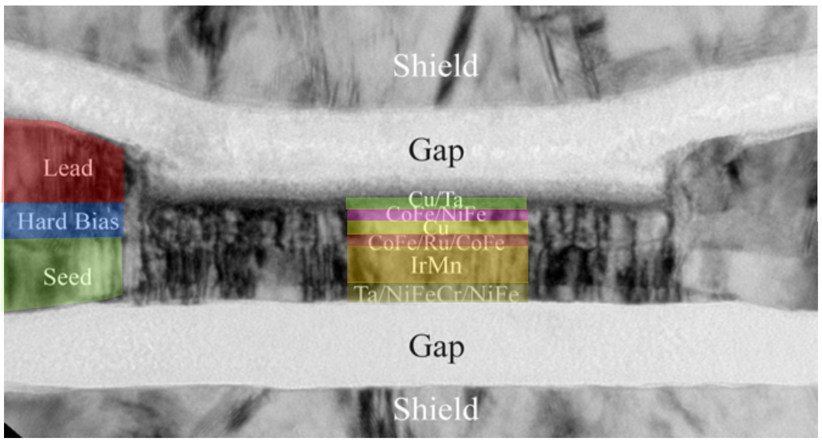
GMR sensors

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

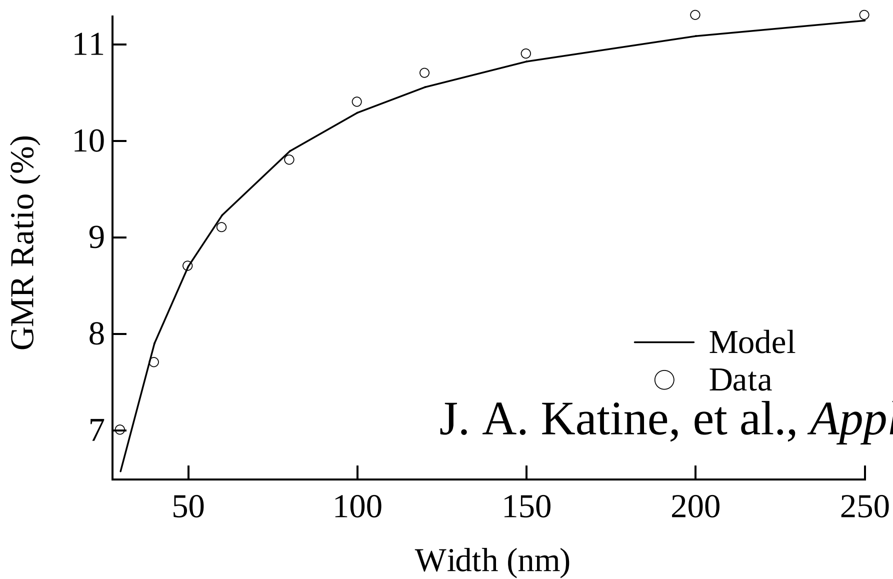


GMR read head

Works great, what's the problem

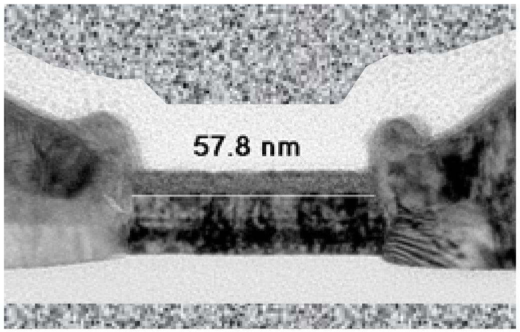


ΔR not increasing
R increasing
Shorting to the shields
Edge damage for small features

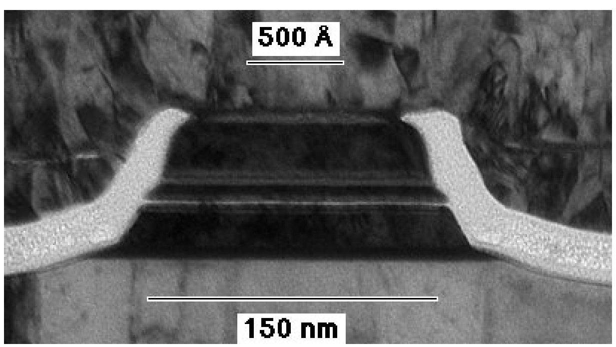


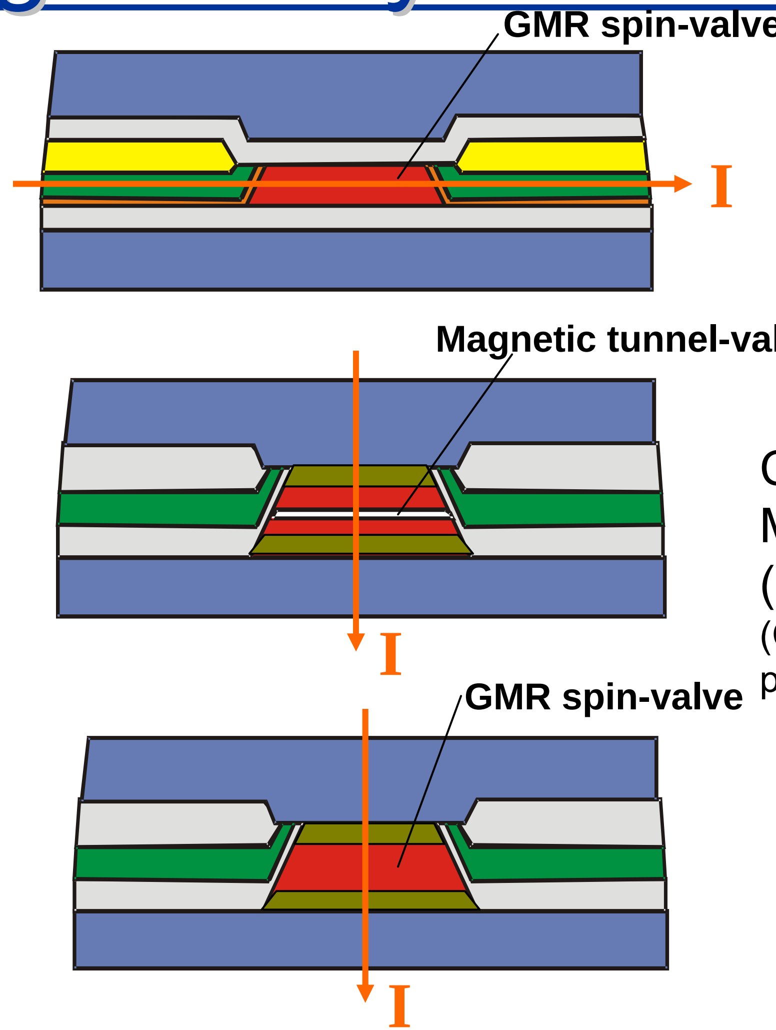
J. A. Katine, et al., *Appl. Phys. Lett.*, **83**, 401 (2003).

New sensor geometry



Tunnel-valve head





CIP-GMR
(Current-in-plane)

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

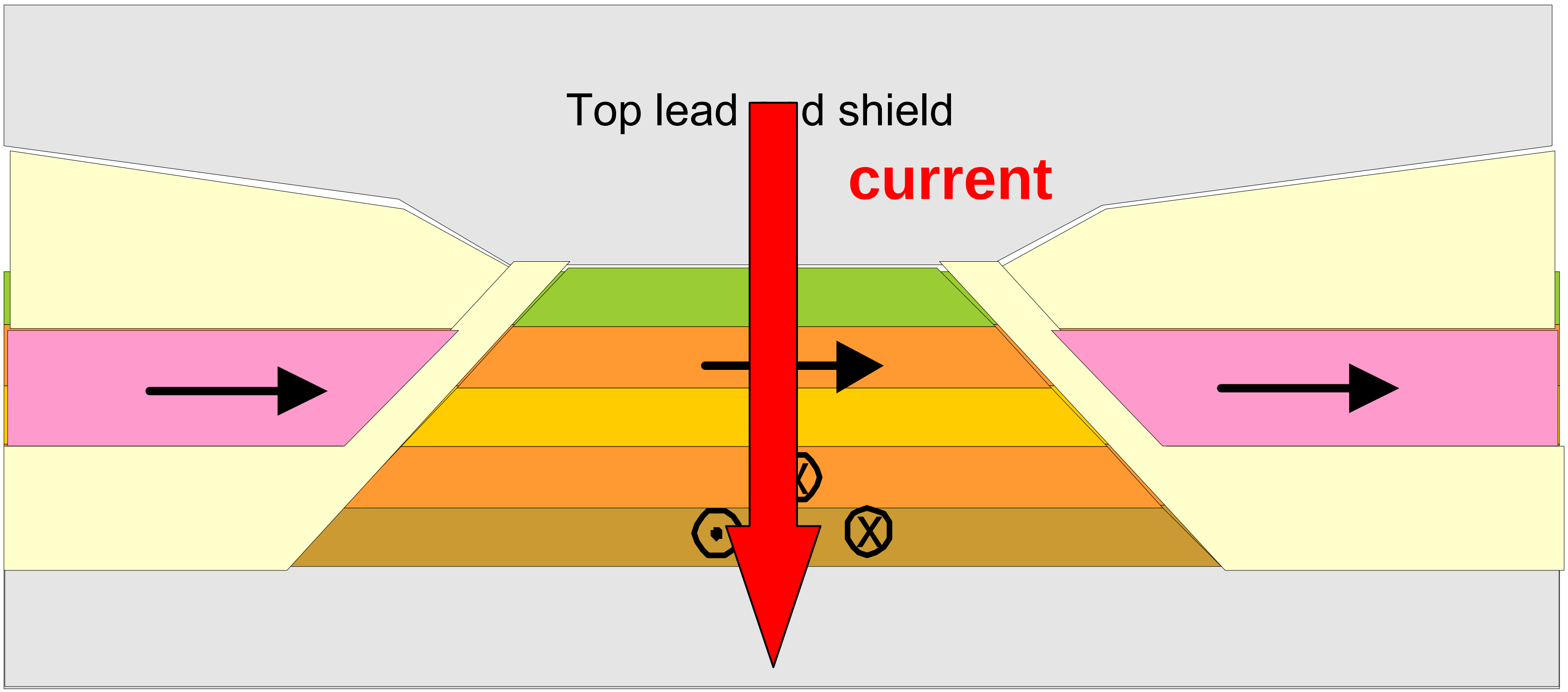
CPP-GMR (low R)
(Current-perpendicular-to-plane)

CPP sensor

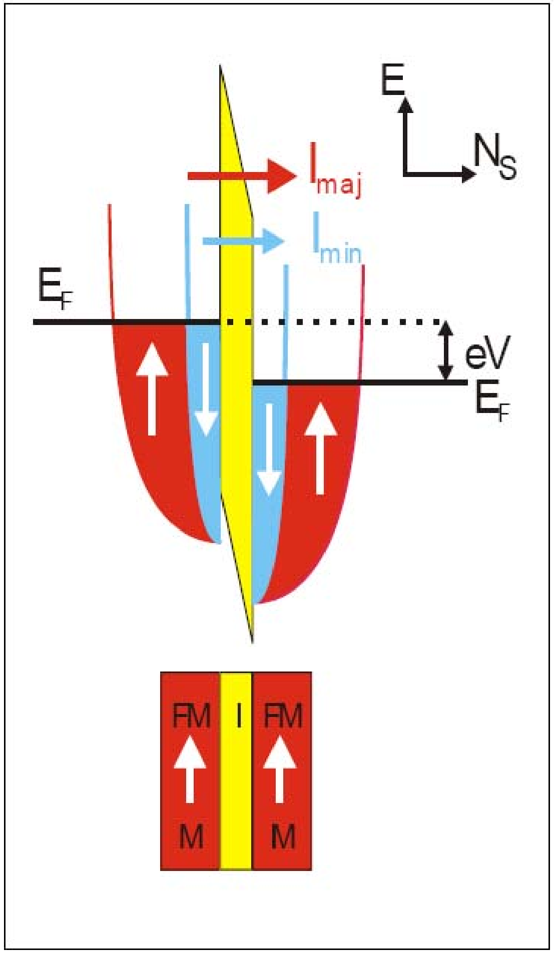
Sensor deposition

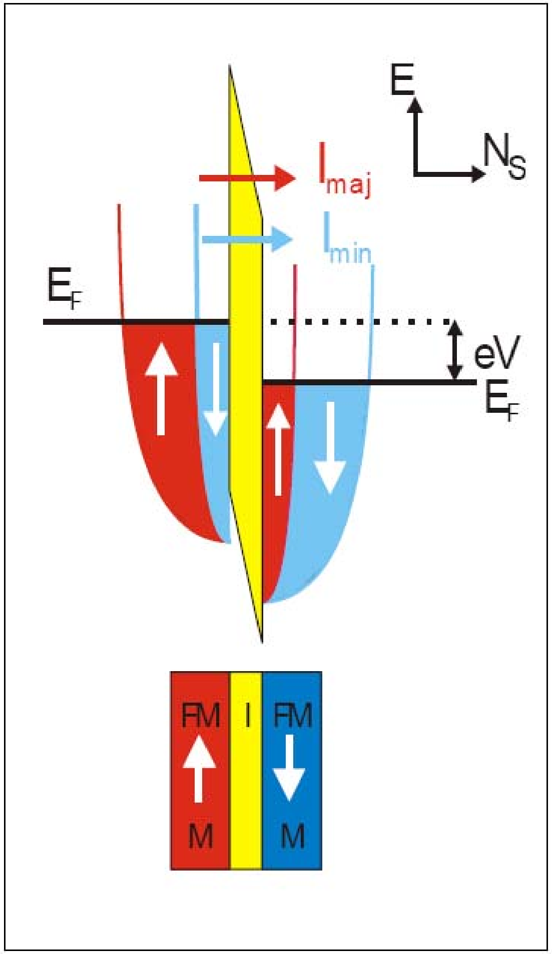
Photo/Ion mill

Insulator/hard bias deposition/Insulator deposition



TMR sensor



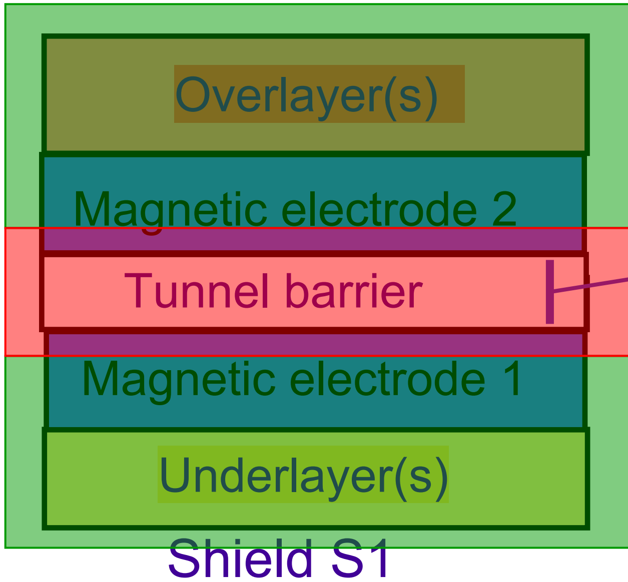


Juliere (1975)

$$MR = \frac{R_{AP} - R_P}{R_P} = \frac{2P_1P_2}{1 - P_1P_2}$$

$$\text{with } P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

TMR sensor



1) Barrier + magnetic electrode interfaces determine maximum TMR AlOx 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

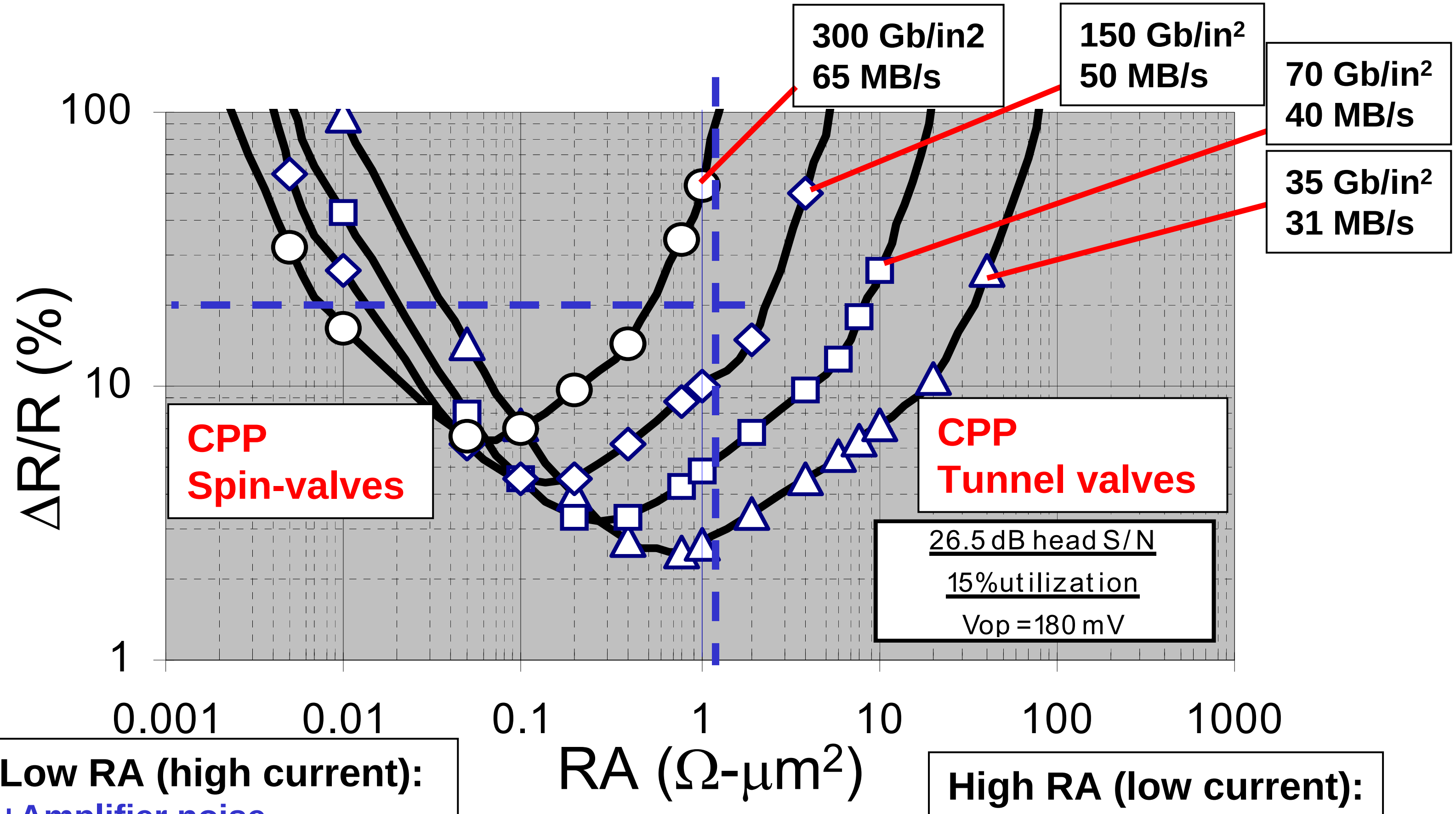
The resistance of the device depends on RA product

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

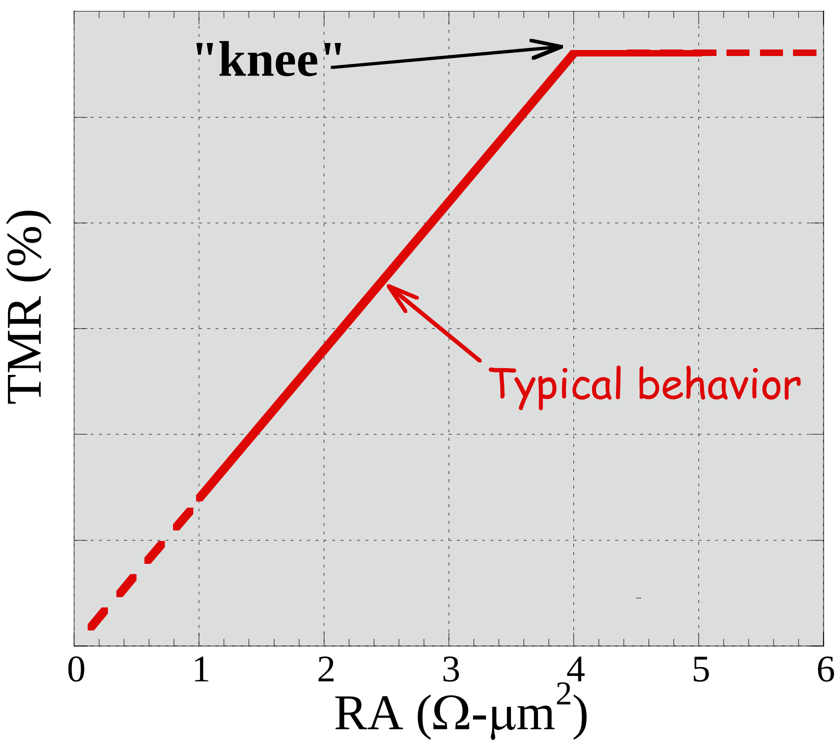


Low RA (high current):
+Amplifier noise
+Ampere curling field
+ Thermal/electromigration
[+spin-torque]

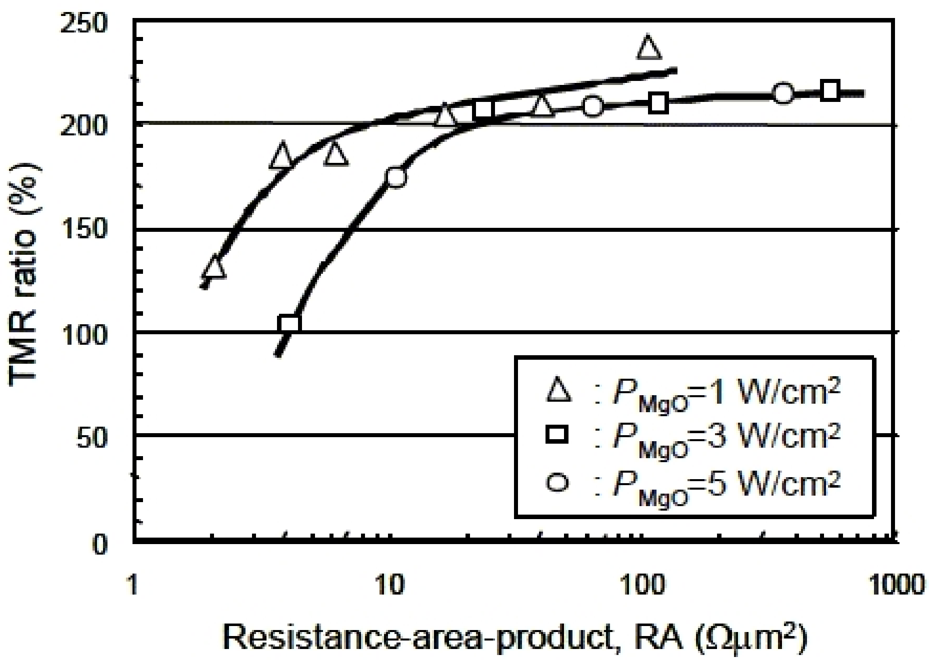
Johnson noise

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

TMR sensor



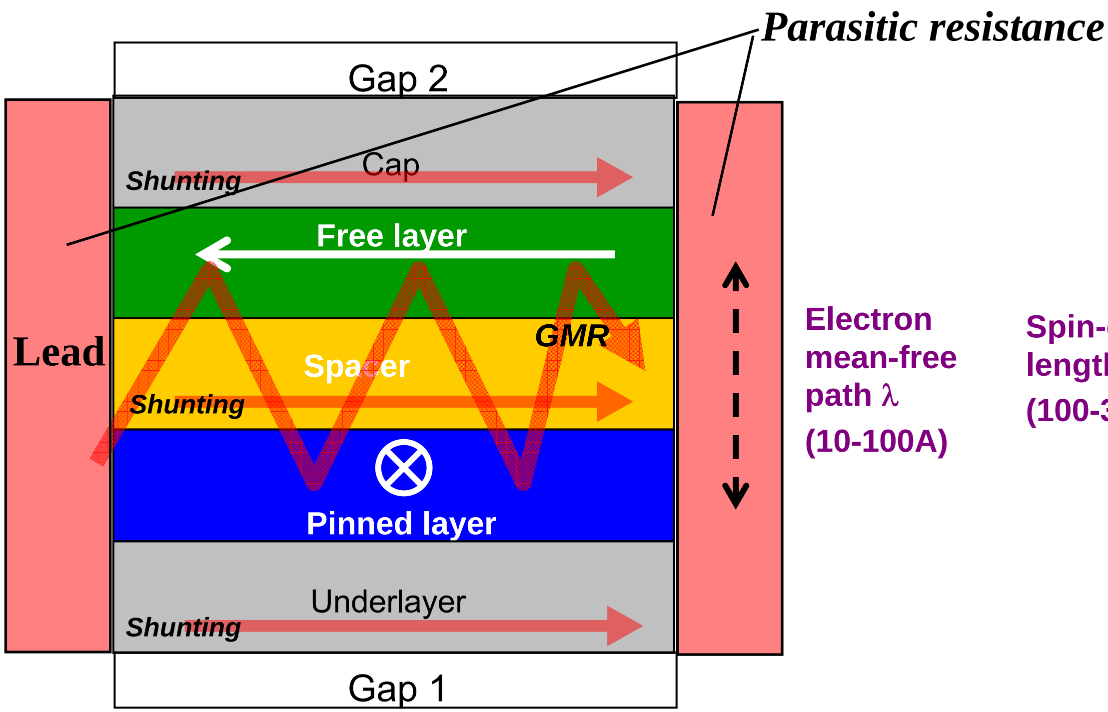
CoFeB/MgO/CoFeB



Y. Nagamine et al. (Anelva corp.)
Intermag '06

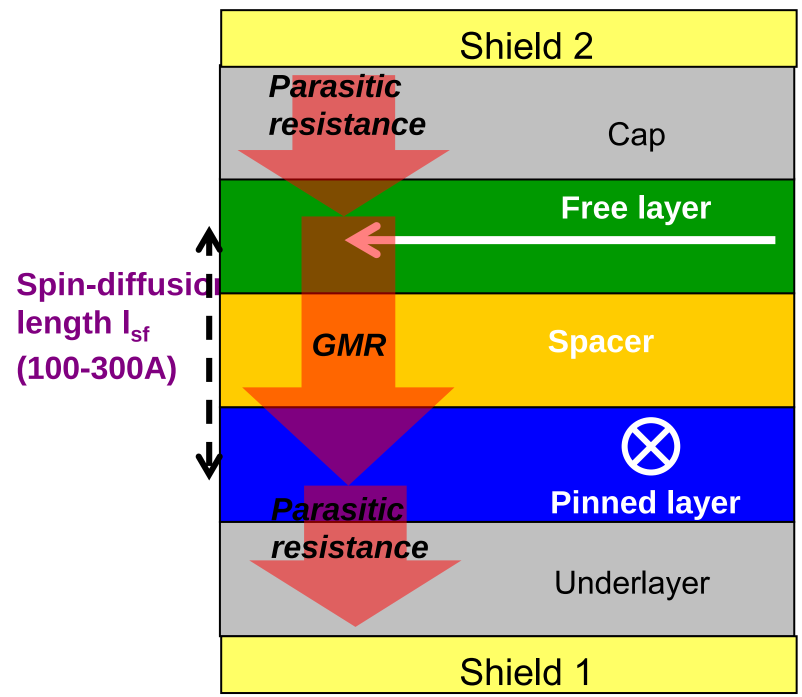
CPP GMR Sensor

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

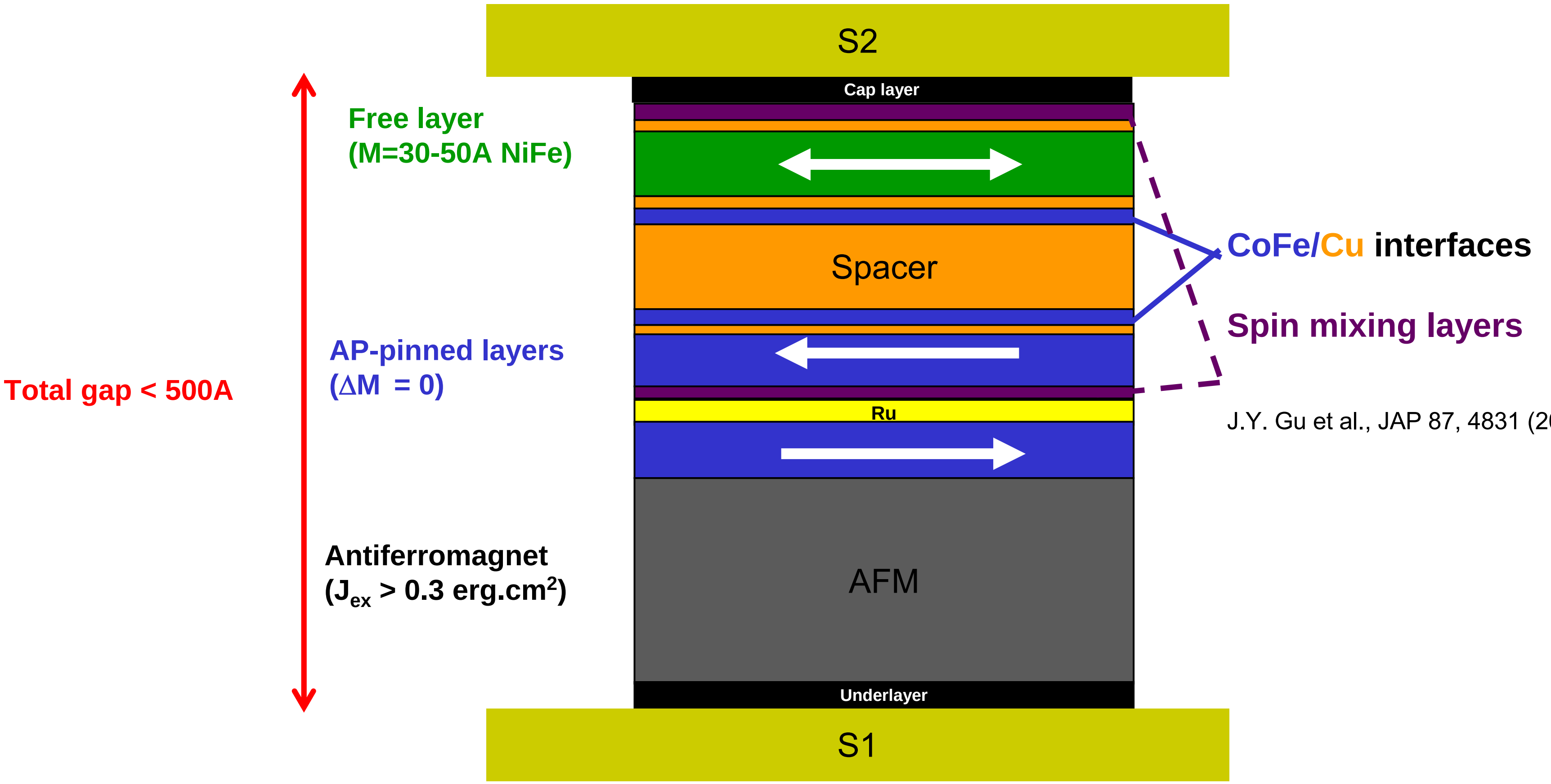


CIP-GMR Shunting effect limits maximum signal

CPP-GMR



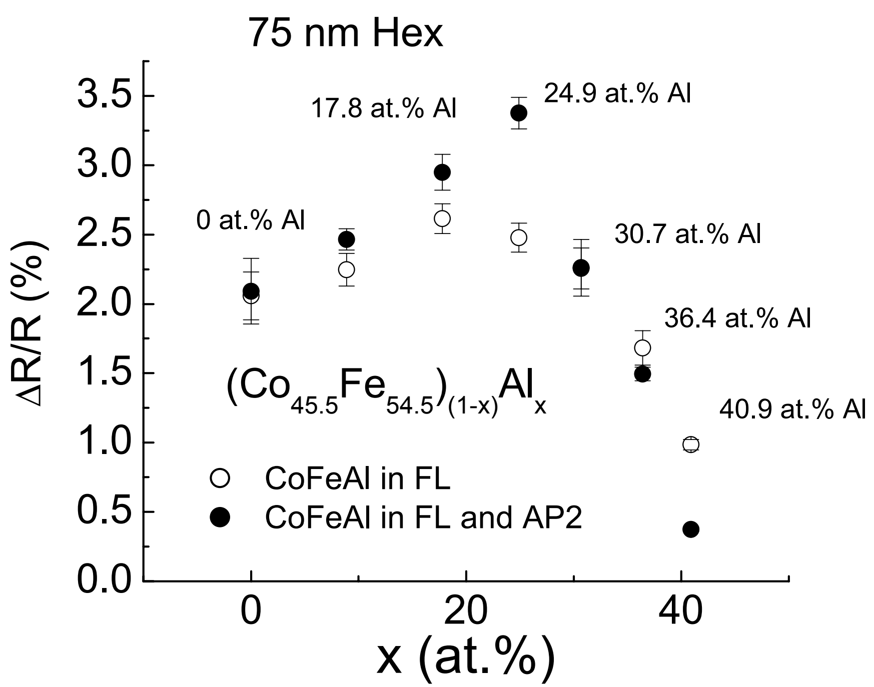
CPP GMR Sensor



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

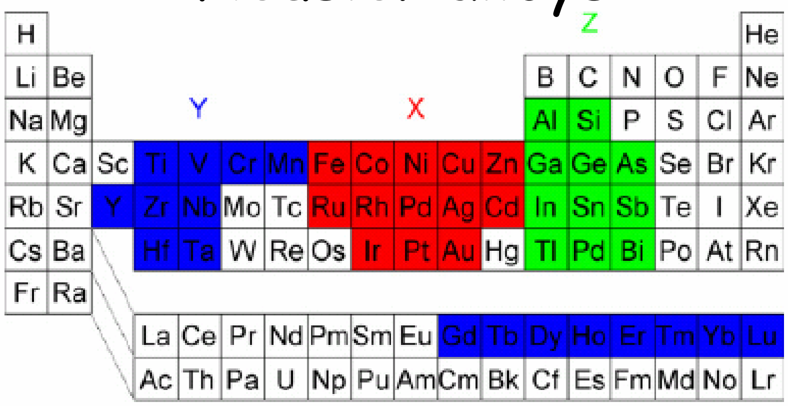
CPP GMR Sensor

Want high resistance high spin polarized materials



Maat et al., JAP

Heusler alloys



e.g. NiMnSb, CrFeAl, …

Hirohata et al.,
Current Opinion in Solid State and Mat. Sci. **10**, 93 (2006).

CPP GMR Sensor

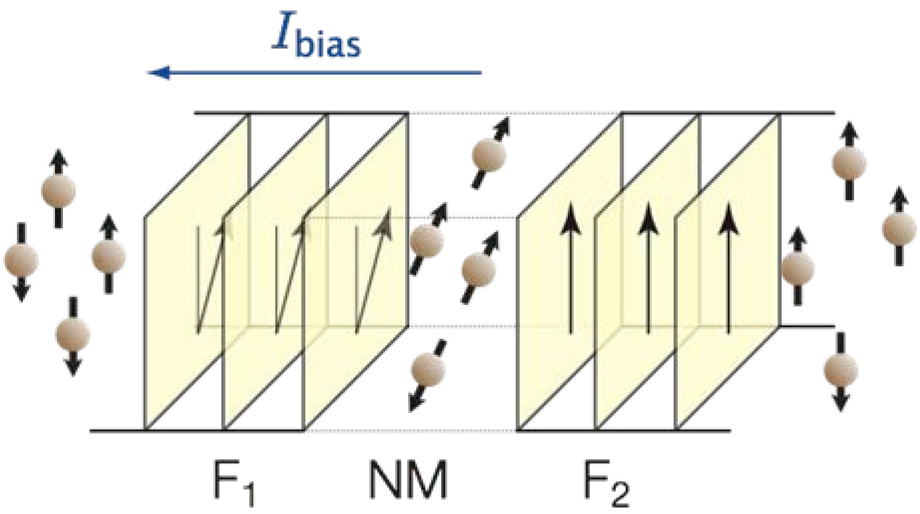
Compared to TMR, CPP GMR has lower R, ΔR & $\Delta R/R$

So how to get a signal?

Current: > 10^8 A/cm^2

Heating
Electromigration
Spin – transfer torques

Spin transport



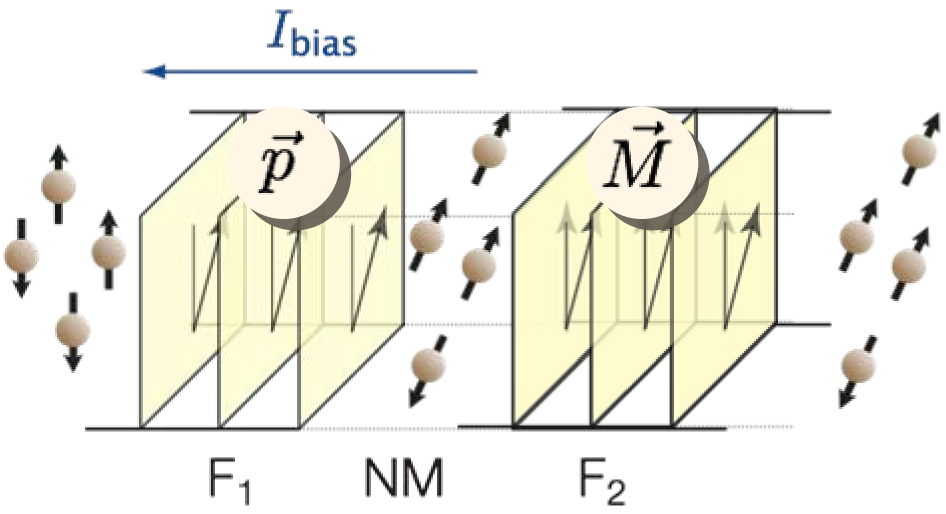
$R \sim R_0 + \Delta R\,(1-\cos(\theta))$

GMR metallic

TMR insulator

Spin transfer effect

J. Slonczewski, J. Magn. Magn. Mater. 159, L1 (1996)
L. Berger, Phys. Rev. B 54, 9353 (1996)



- 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

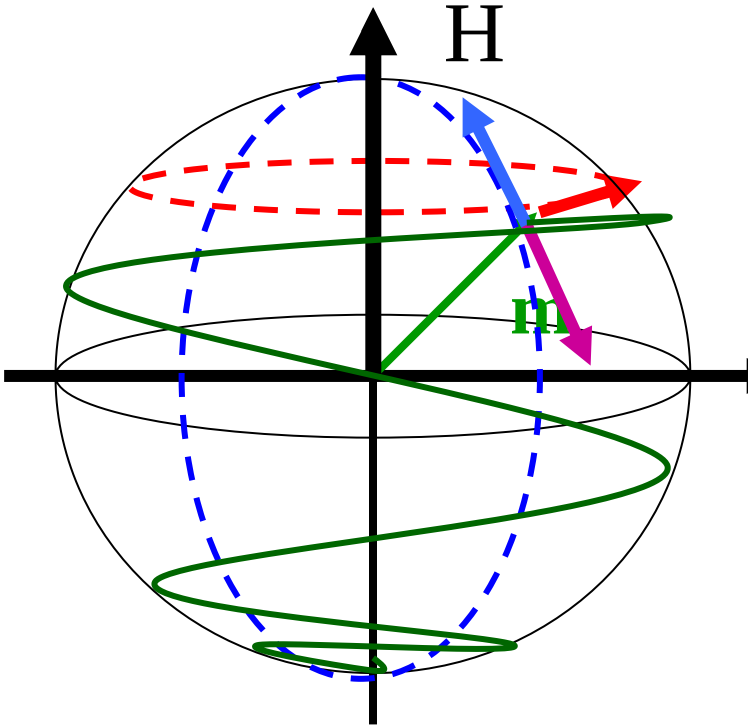
$$\frac{d\mathbf{m}}{dt} = \gamma_0 \mathbf{H} \times \mathbf{m} + \alpha\left(\mathbf{m} \times \frac{d\mathbf{m}}{dt}\right)$$

Field torque (precession)

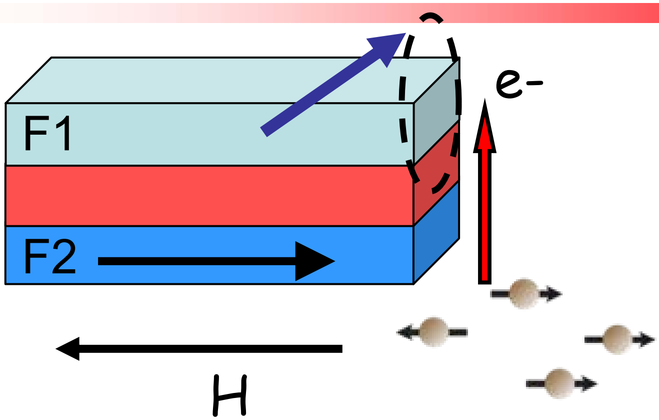
Damping torque (dissipation)

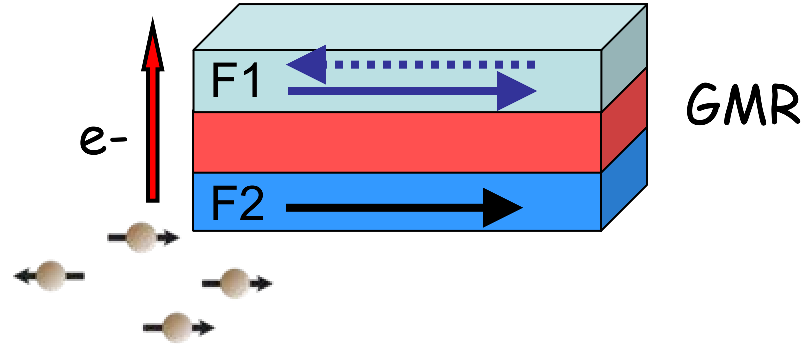
$$-\frac{IP_i g\mu_B}{eM_s t}\left(\mathbf{m} \times \left(\mathbf{m} \times \mathbf{p}\right)\right)$$

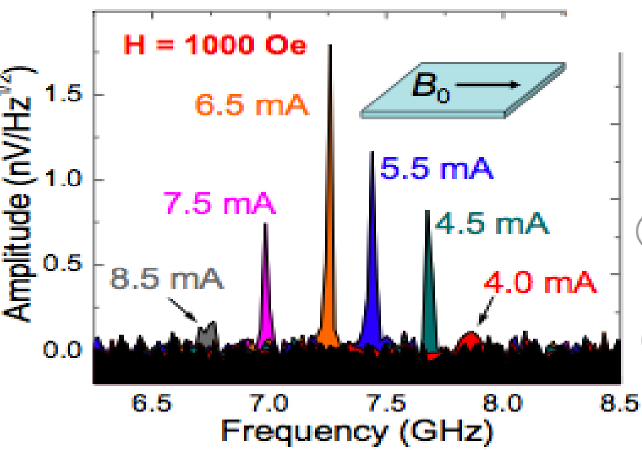
Spin torque (negative friction)



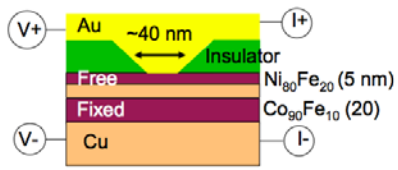
Magnetization dynamics

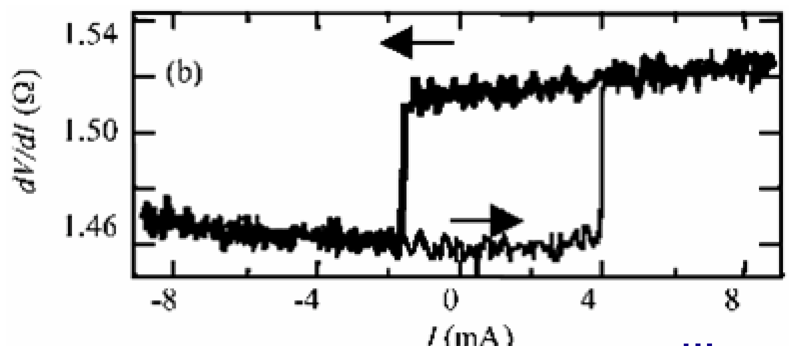






Nano contact





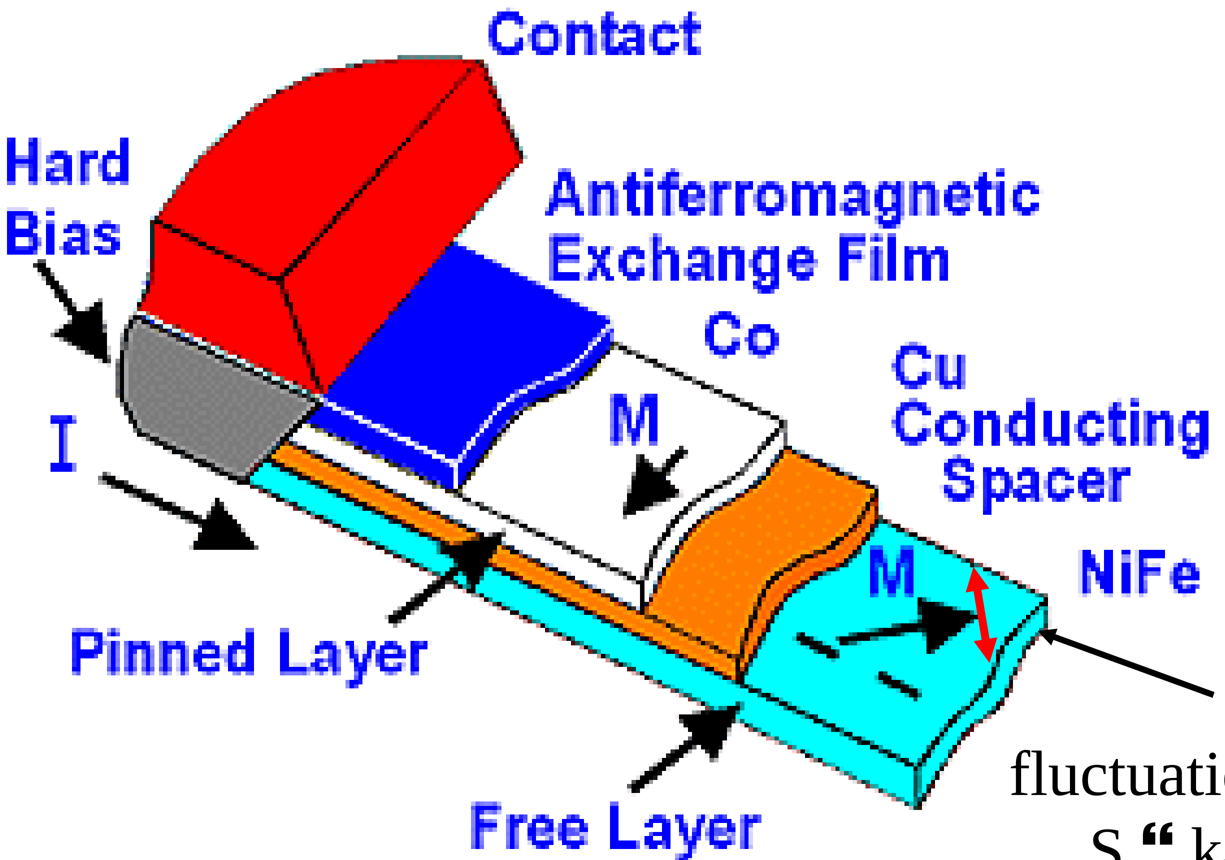
nano-pillar

M. Tsoi et al., Phys. Rev. Lett. **80**, 4281-4284 (1998)
W. H. Rippard et al., Phys. Rev. Lett. **92**, 027201 (2004)

J.A. Katine et al., Phys. Rev. Lett. **84**, 3149 (2000)

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

GMR sensor



Thermal fluctuations

fluctuation-dissipation theorem

$S \propto k_B T / M V_{free}$

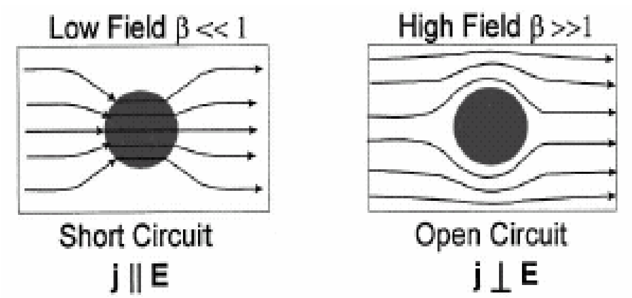
Smith and Arnett, APL **78**, 1448 (2001).

Sensors

Sensors need a lot of properties not just $\Delta R/R$

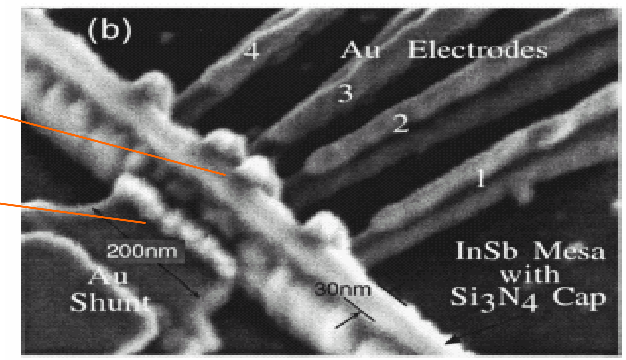
Opportunities for new materials and new phenomena

Non-magnetic magnetic sensors

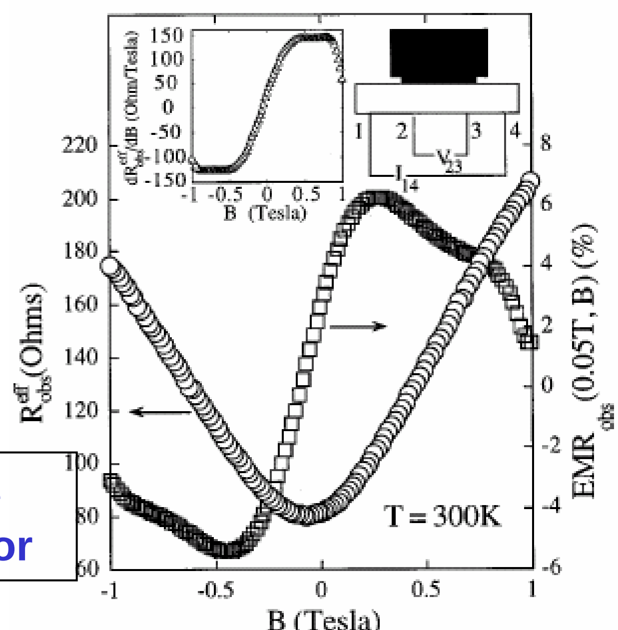


High-mobility SC

Metal shunt



Solin, APL 80, 4012 (2001)



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

At low field E is _|_ to metal/SC boundary and j follows E → 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 → high R.

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