Magnetism and Spintronics III

12/01/2005

Magnetoresistance effects:

Magnetoresistance (MR) = R(B)-R(0)

- Anisotropic magnetoresistance (AMR)
- Giant magnetoresistance (GMR)
- Tunneling magnetoresistance (TMR)
- Colossal magnetoresistance (CMR)

Spin torques: (the opposite effect of MR)
polarized carrier spin rotates magnetization of nanomagnets

Magnetic devices:

- Hard drives
- MRAMs

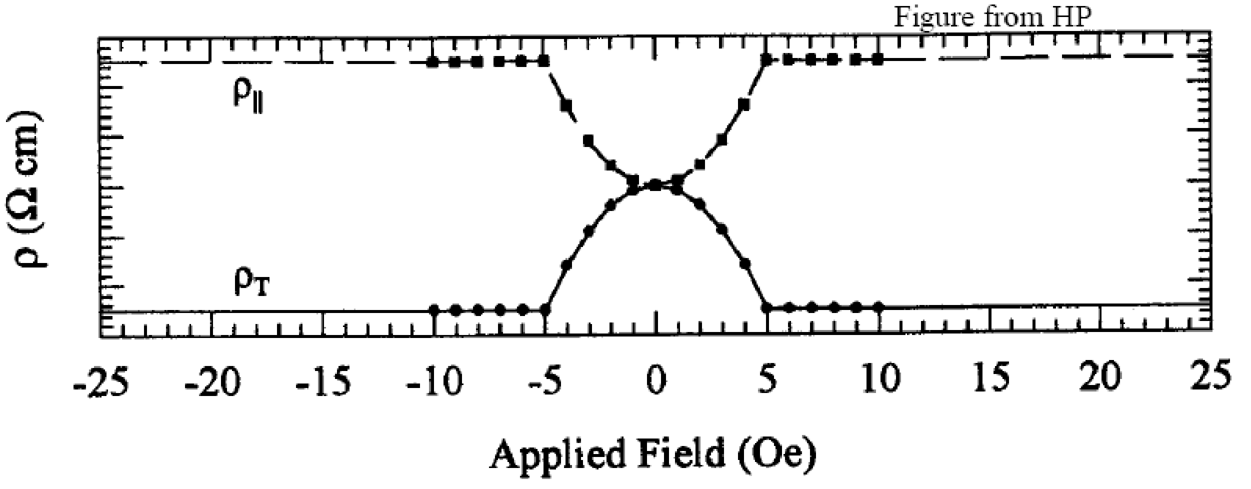
Spin based electronics (Spintronics)

- Spin injection
- Spin field effect transistors

Waser, Ch 4, 23, 24

Anisotropic magnetoresistance (AMR)

In a FM material, measured resistance depends on relative directions of ***M*** and ***J***.



Data from bulk permalloy (80% Ni, 20% Fe).

- Resistance *lower* if ***M*** perpendicular to ***J***.
- Resistance *higher* if ***M*** parallel to ***J***.

Anisotropic magnetoresistance (AMR)

Origin: 3d orbitals affected by M, resulting in a larger scattering cross-section (higher resistance) for electrons moving *parallel* to ***M***.

Typical size of effect: ~ 1%. Used in read heads before the discovery of GMR

Typical field scale: determined by physics of reorienting ***M***.

- In bulk permalloy, 5 - 10 Oe.
- In wires with large aspect ratios, ~ 1 T.

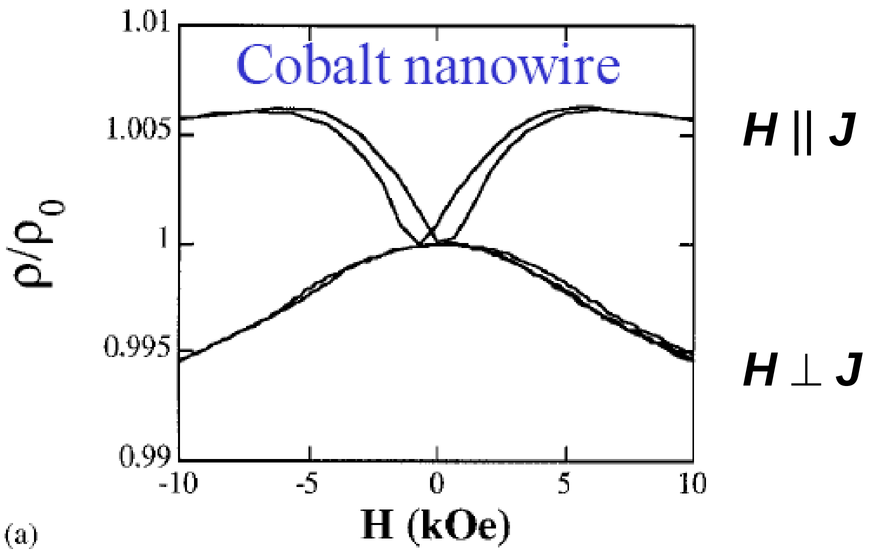


Figure from Fert *et al.*, JMMM **200**, 338 (1999).

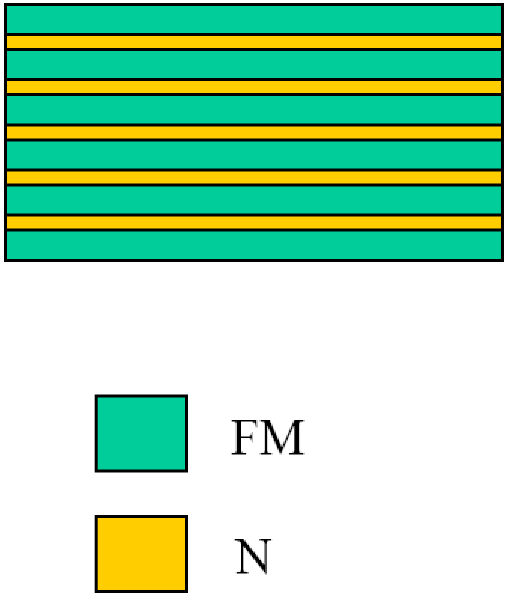
Giant magnetoresistance (GMR)

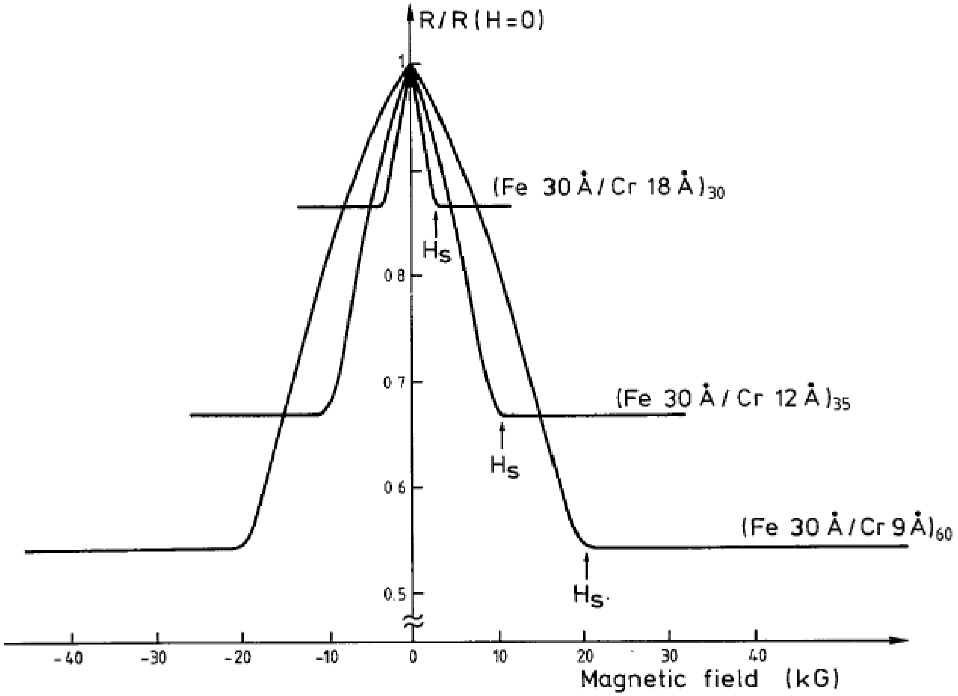
Figure from Baibich *et al.*, PRL **61**, 2472 (1988).

- Discovered in laboratory *c*. 1988.
- Not a trait of pure FM materials! Requires *nanostructured composites* of FM and nonmagnetic metals.
- *Superlattice* of thin alternating layers of FM and normal (N) metals.
- MR ratio ~10-40%

Magnetoresistance ratio $\frac{\Delta R}{R_P} = \frac{R_{AP} - R_P}{R_P}$

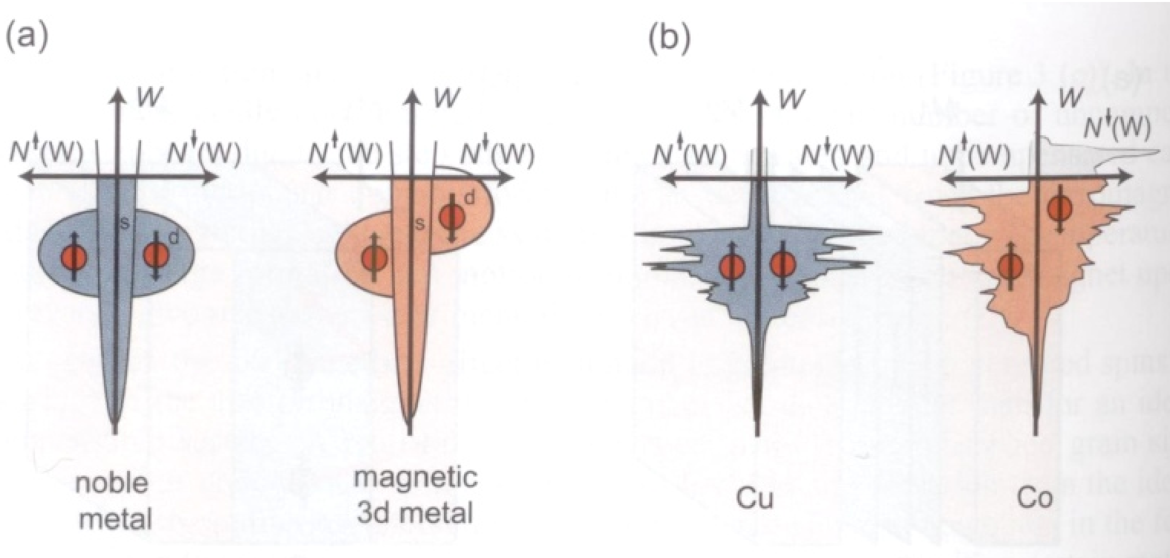
Layered structure

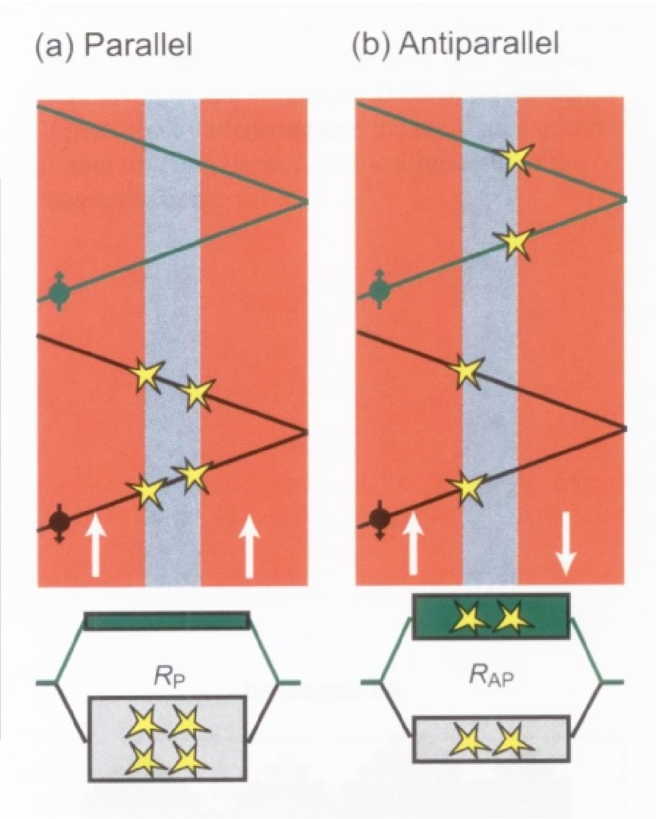




Giant magnetoresistance (GMR)

Origin, spin dependent scattering





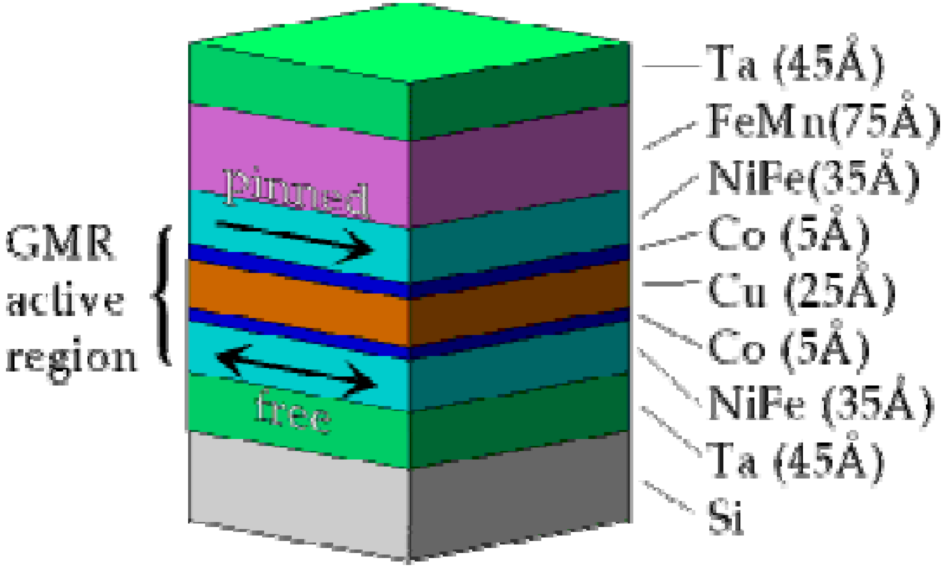
- Spin up (majority) 3d electrons have good match of density of states at same E and k, between FM and N, less scattering.
- Spin down (minority) electrons suffers more scattering at the interface.
- Two current model: current carried by spin-up channel and spin-down channel. Total conductance is the sum of the two.

Giant magnetoresistance (GMR)

- Original device was current-in-plane (CIP).

- GMR effects also observed in current-perpendicular-to-plane (CPP) devices with higher MR ratio.

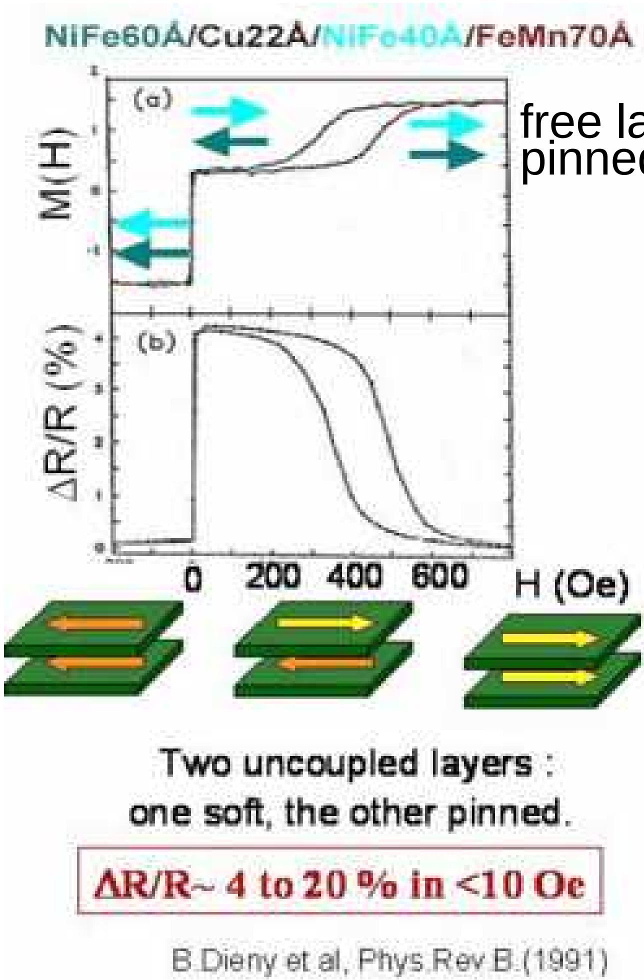
A spin valve based on GMR



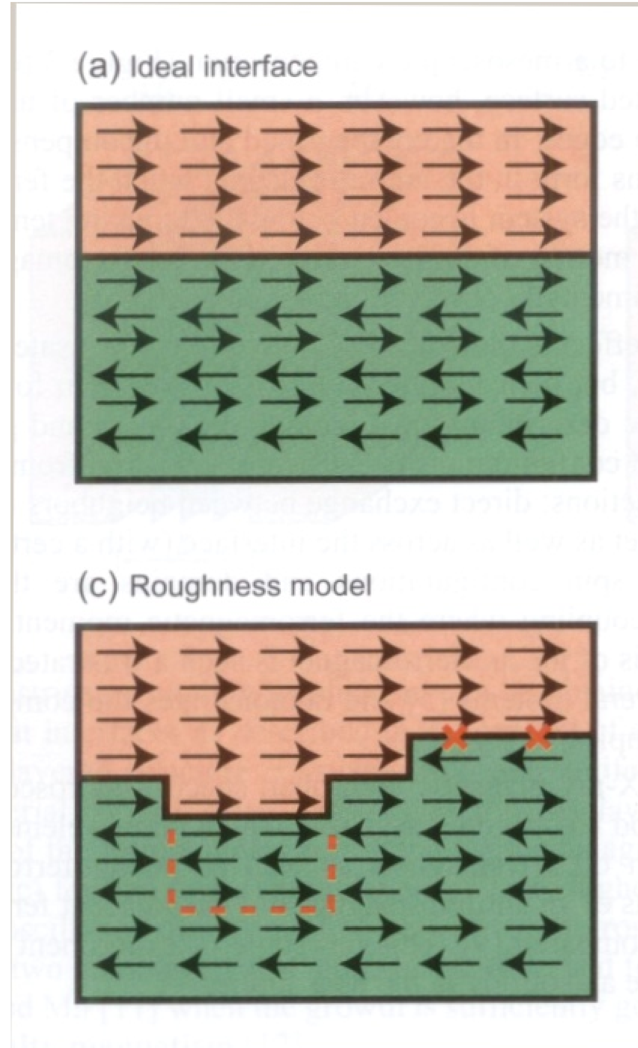
Use antiferrromagnetic "pinning layer" to lock magnetization of one FM layer.

The 2nd FM layer is magnetically soft - ***M*** easily realigns in small fields.

Spin valve - exchange anisotropy



free layer
pinned layer



FM layer
“pinned”

AF layer

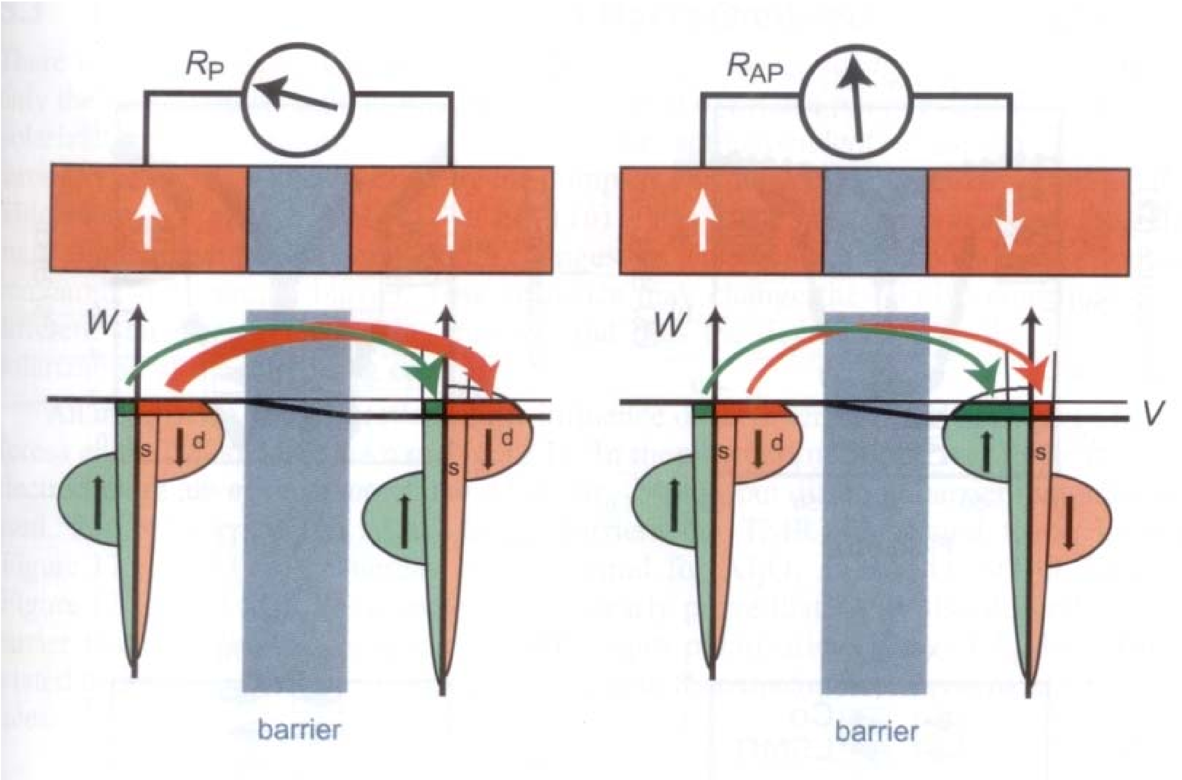
Pinning of the “fixed” layer due to exchange coupling with the AF layer

Tunneling magnetoresistance (TMR)

Always CPP

Two current model:

Tunneling conductance depends strongly on relative densities of states of spin species.



*N*s are proportional to the relevant densities of states at the Fermi level.

$$G_{\uparrow\uparrow} \sim (N_\uparrow)^2 + (N_\downarrow)^2 \qquad G_{\uparrow\downarrow} \sim 2N_\uparrow N_\downarrow$$

Tunneling magnetoresistance

Define spin polarization $P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$

Model of Julliere (1975):

$$G_{\uparrow\uparrow} \sim (N_\uparrow)^2 + (N_\downarrow)^2 \qquad G_{\uparrow\downarrow} \sim 2N_\uparrow N_\downarrow$$

Assume that tunneling preserves spin (clean interfaces, thin barrier so that spin is not flipped, etc)

$$\frac{\Delta R}{R_{\uparrow\uparrow}} = \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}} = \frac{2P^2}{1-P^2}$$

Polarization P in some common metals:
Ni: 23% Fe: 40% Co: 35% NiFe: 32%

Meservey *et al.*, Phys. Rep. **238**, 173 (1994)

Tunneling magnetoresistance

• Typical size of effect: ~ 100%.
As in GMR. depends on percentage of spin polarized carriers at Fermi level.

• Note that relative directions of ***M*** and ***J*** not directly relevant.

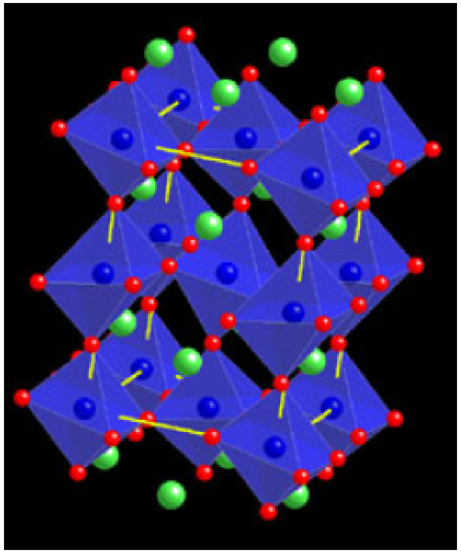
• Typical field scale: determined by physics of reorienting *relative* directions of adjacent FM layer magnetizations.
Usually arranged to be low.

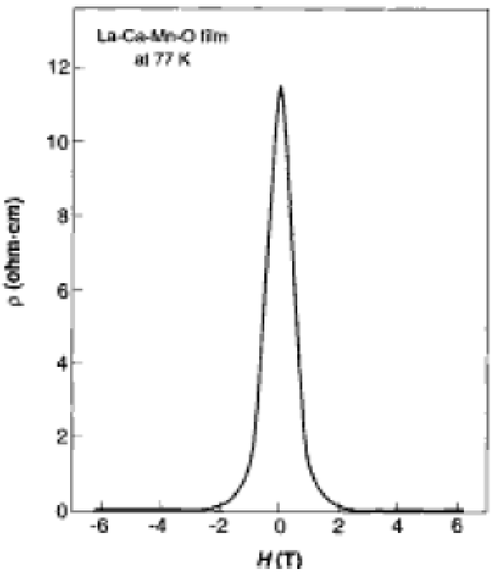
• Interface quality is again crucial - growing good tunnel barriers is very tough without doing odd things to the magnetic properties at the interface.

GMR and TMR, workhorse of modern magnetic storage industry soon after their discoveries.

Colossal magnetoresistance (CMR)

- Discovered in 1993.
- Size of effect: ~ 100000% (!)
- Takes place in specific family of compounds, perovskites of the form $A_{1-x}B_xMnO_3$, where A = (La, Pr, Nd, Sm), B = (Ca, Sr, Ba).
- Physical mechanism is completely different than any described so far.





Colossal magnetoresistance

- Mechanism: *phase transition* between conductive FM ordering of Mn ions and insulating AFM ordering of Mn ions.

Replacing rare earths with light metals changes some of the Mn from Mn^{3+} to Mn^{4+}. Charge can hop from Mn to Mn via the oxygen anions. Strong FM exchange favors hopping of aligned spins (high conductance).

- Still not well understood!

- Extremely temperature and doping dependent - challenging to get useful, reproducible behavior at room temperature.

- Of much interest because of large effects and very high spin polarization of carriers.

Spin currents and magnetization – spin torques

We've been talking about how ***M*** affects ***J***, ability to transport charge, as manifested through magnetoresistive effects.

One can also consider the converse: can a current ***J*** of carriers with a net spin polarization affect ***M***?

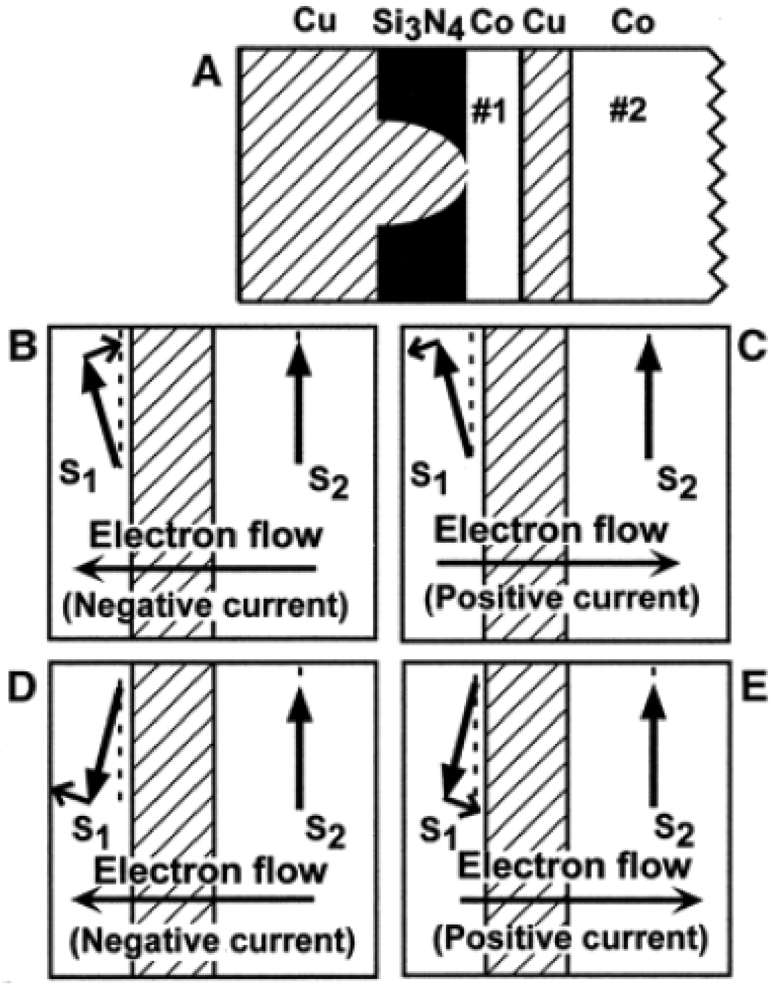
Yes!

• A current with a net spin polarization means a flow of *angular momentum* from one region to another.

• This results in a net *torque* on the spins in those regions, and for high enough torques, it can be energetically favorable for domains to rearrange themselves.

Spin currents and magnetization

Myers *et al.*, Science **285**, 867 (1999)



•Based on CPP GMR structure

•Magnetization in S_2 is fixed

•Spin polarized electron current rotates magnetizaiton in S_1

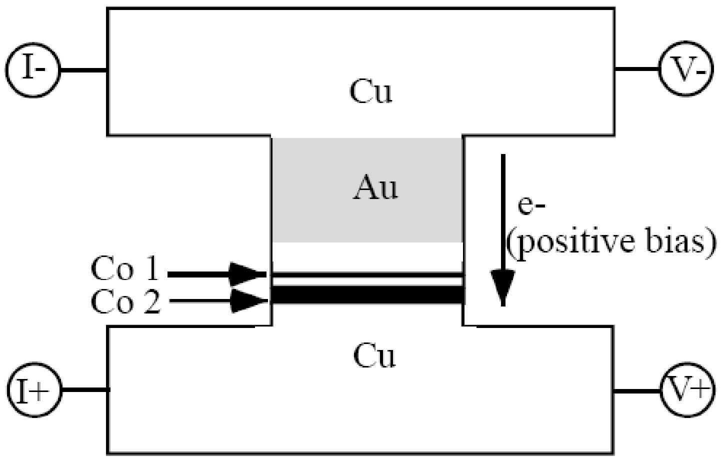
•Negative current results in parallel configuration

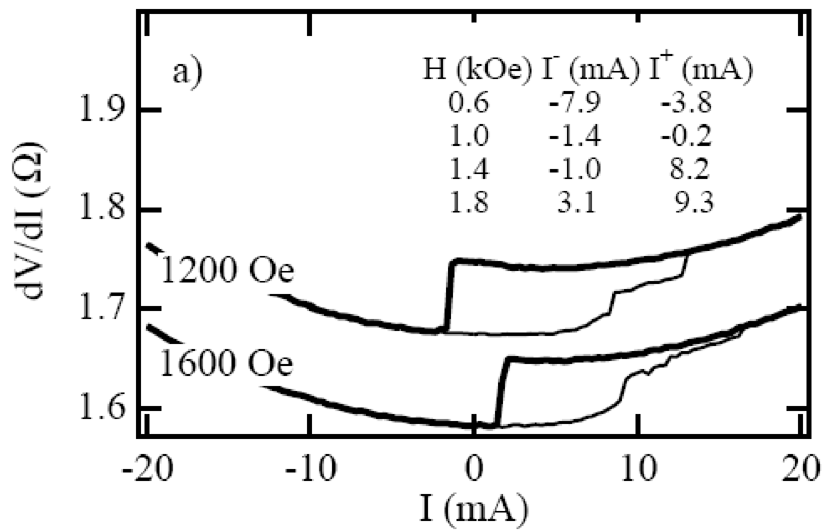
•Positive current results in antiparallel configuration (due to backscattering of spin down electrons)

•Polarization read out with the GMR effect

Spin currents and magnetization

Katine *et al.*, PRL **84**, 3149 (2000)



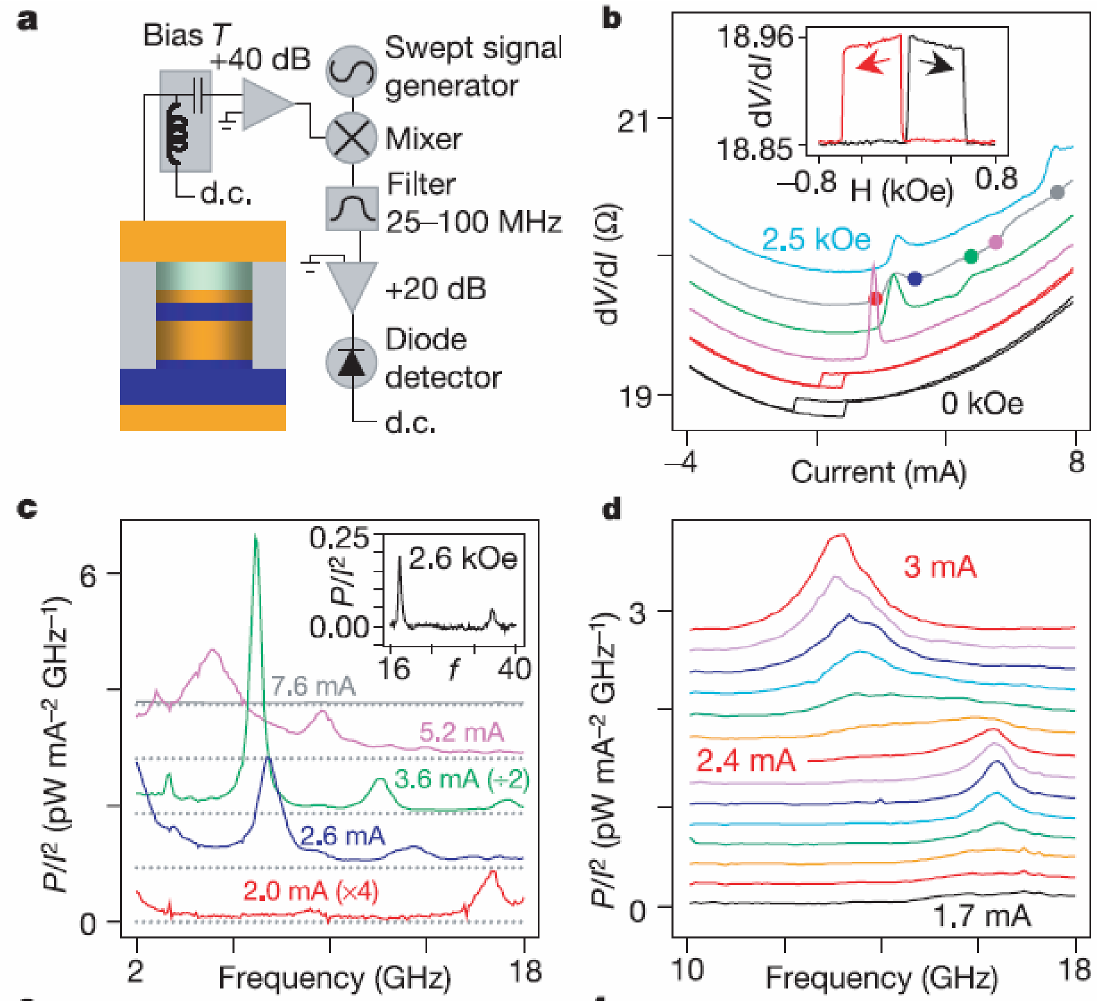


Clear demonstration of current-induced magnetization reversal.

Ability to manipulate ***M*** without applying external fields. Potentially very attractive technologically.

Microwave spin torques

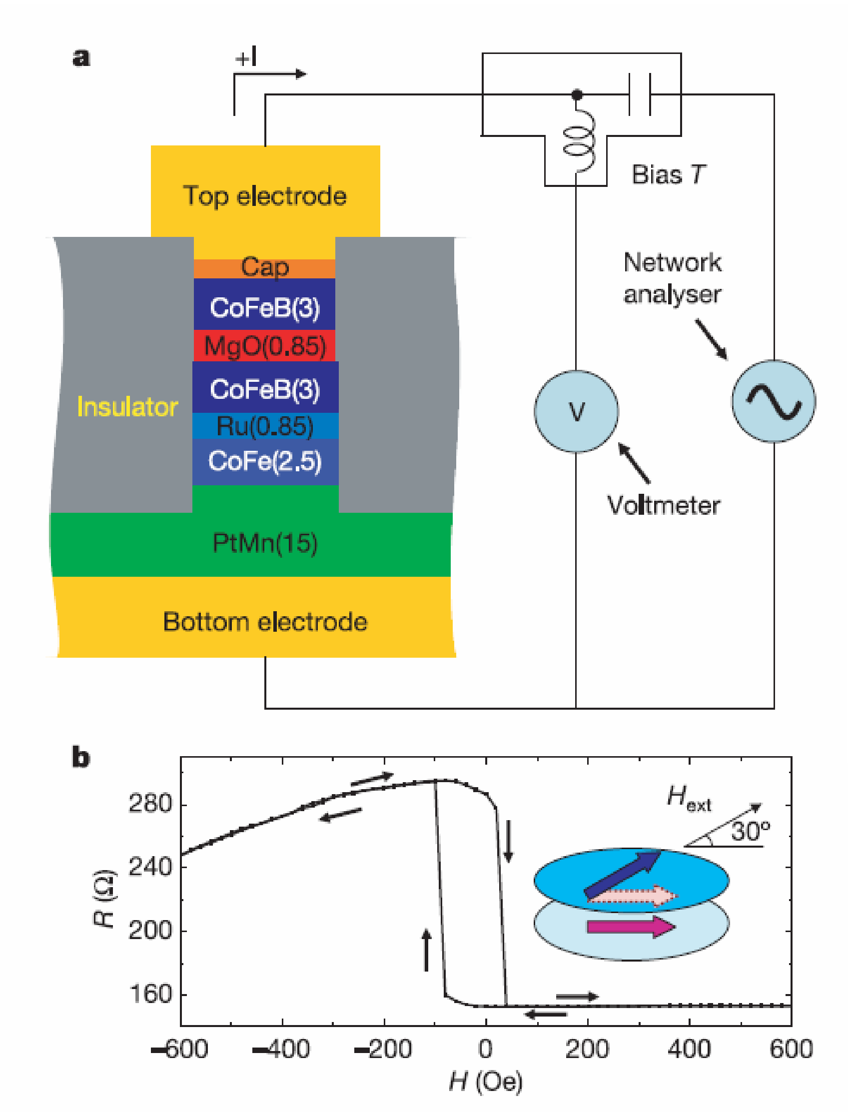
Kiselev, *Nature*, **425**, 380 (2003)

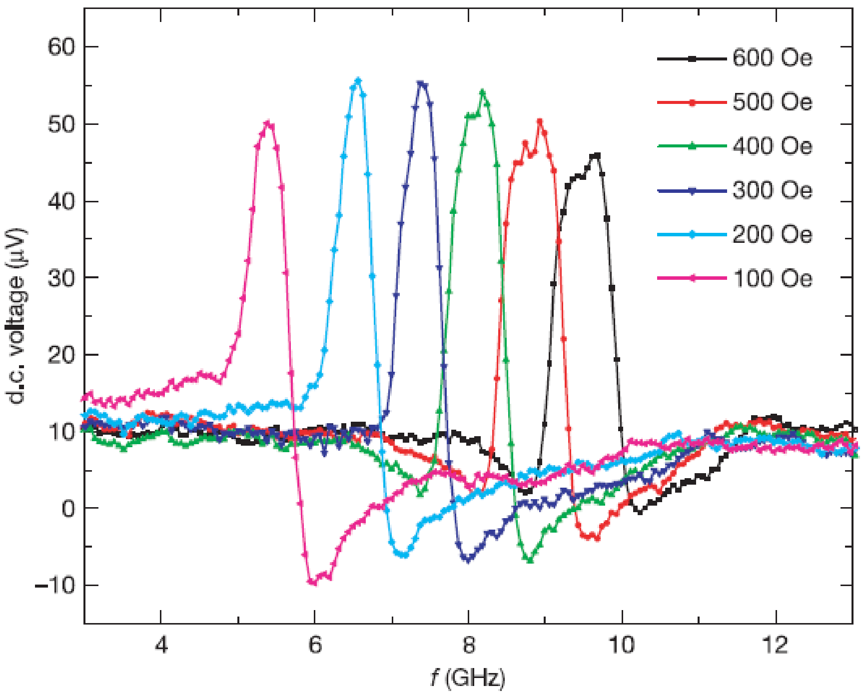


Microwave oscillations of the nanomagnet driven by the spin polarized current were recently detected directly

Microwave spin torques

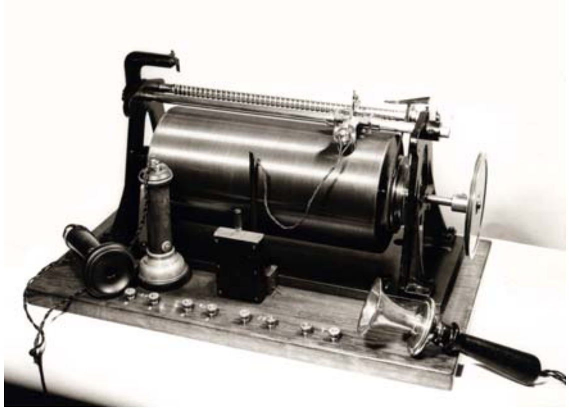
Tulapurkar, *Nature*, **438**, 339 (2005)





a.c current rotates magnetization in the free layer, resulting in a measurable d.c current at resonance.

Magnetic data storage, where it all began



1878 Oberlin Smith invents magnetic recording – patterns of domains in steel wire.

1898 Valdemar Poulsen invents reel-to-reel metal tape recording, and the telephone answering machine.

1948 Sony introduces reel-to-reel recorder using coated tape.

1958 RCA introduces *stereo* tape - cartridge needs special player.

1962 Phillips introduces cassettes.

1965 Motorola, RCA introduce 8-tracks.

1984 Cassette outsell LP records.

Magnetic data storage, where it all began

RAMAC (1956)

- First hard disk drive
- 50 24” disks
- Stored a total of 5 MB of information.
- Areal density = 2kb/in^2
- Data rate = 70 kb/sec.

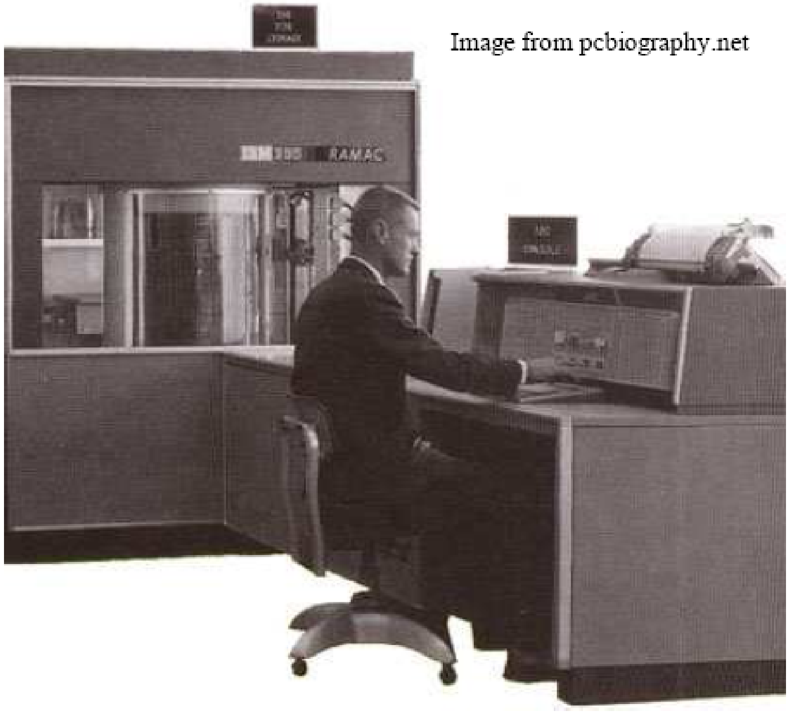
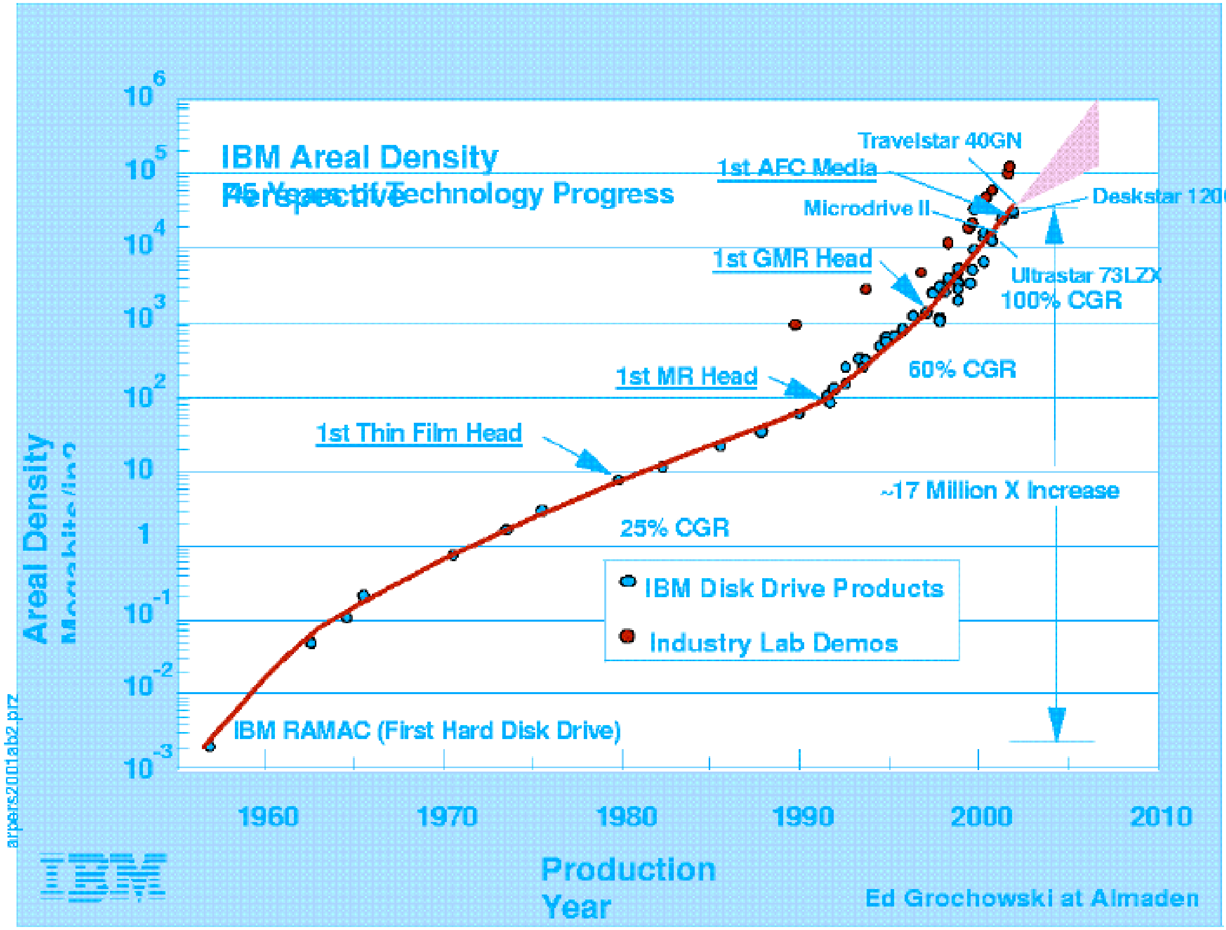


Image from pcbiography.net

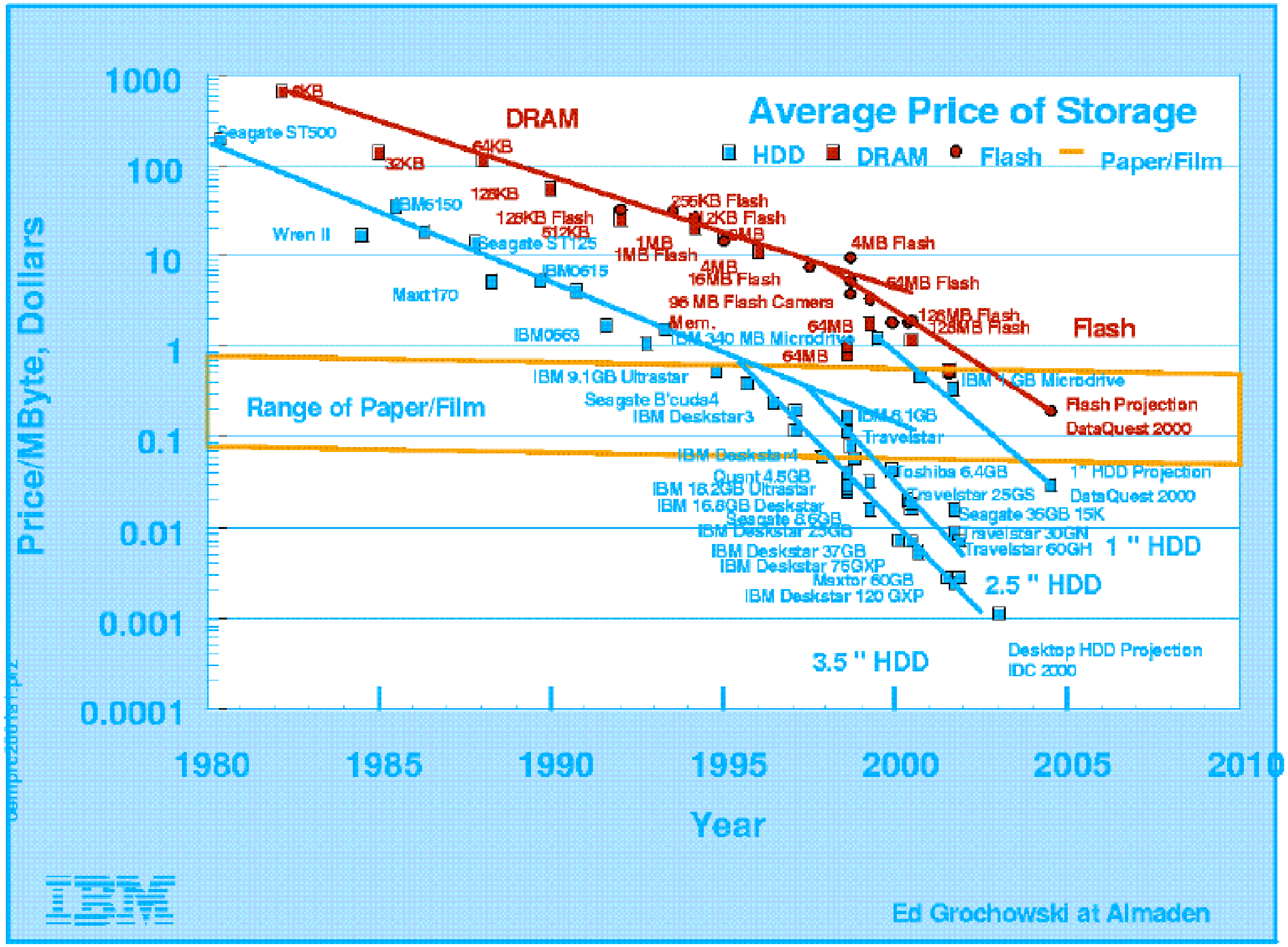
Historical trends

Image from IBM presentation



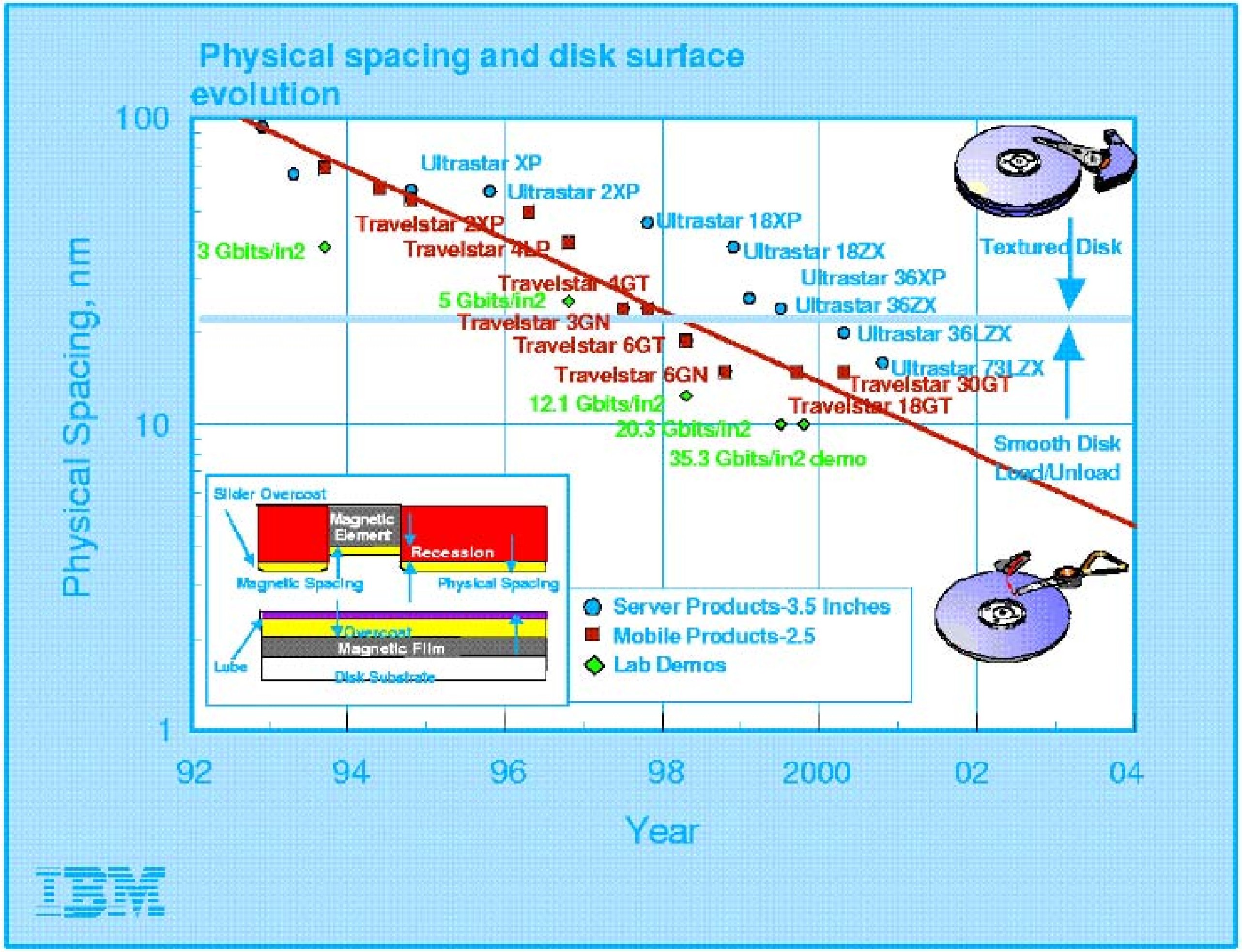
Historical trends

Image from IBM presentation



Historical trends

Image from IBM presentation



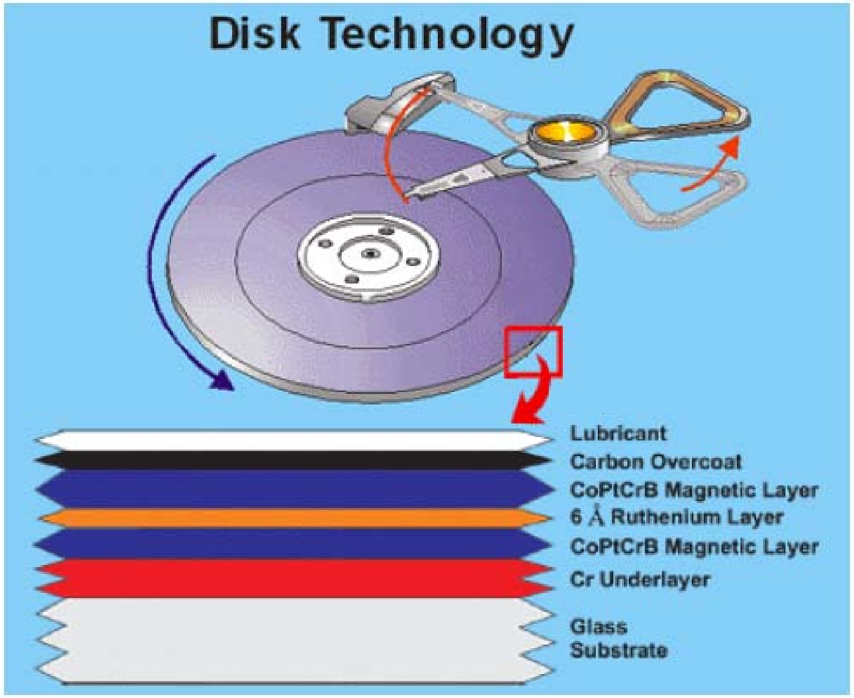
Magnetic storage: hard drives

Image from IBM website

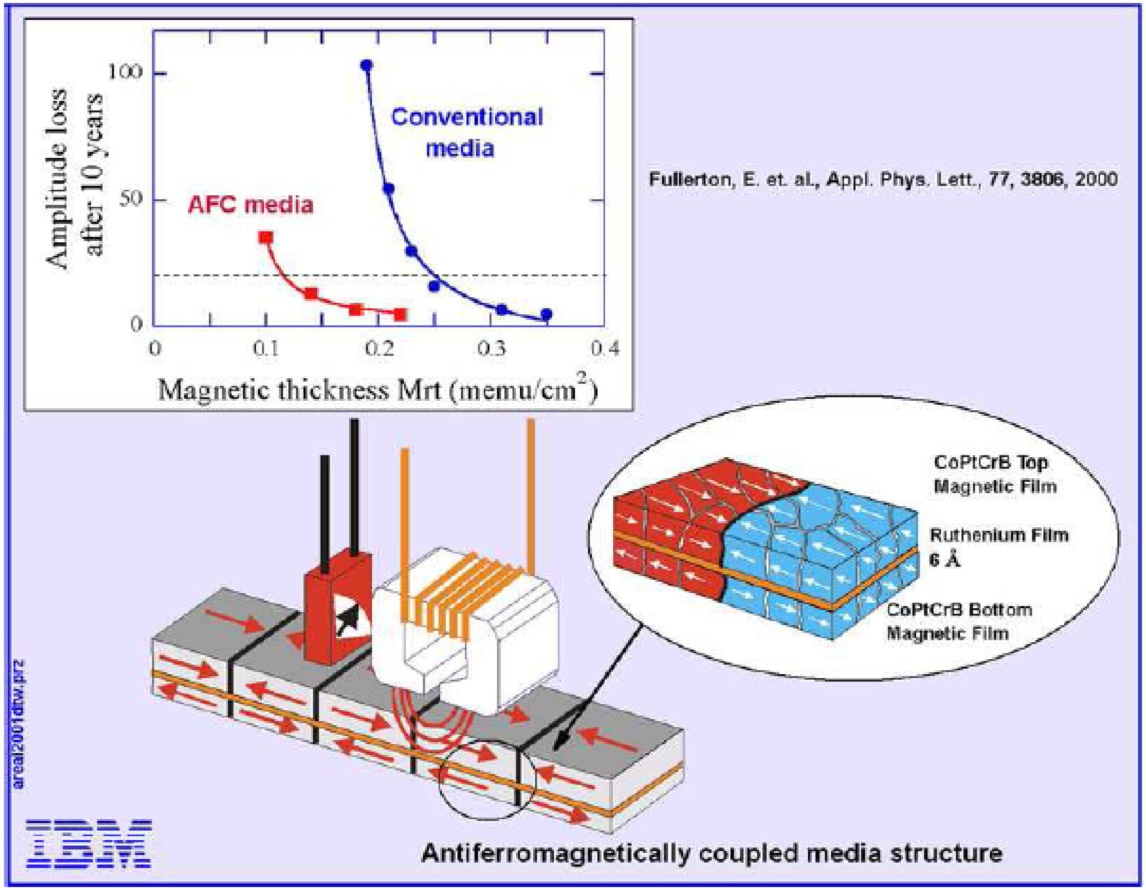
Disk medium:

• 2.5” diameter, 34 Gb/in^2 (typical size ~ 140 nm)
• CoPtCr alloy (M_{sat} = 4 x 10^5 A/m, H_c = 2.7 x 10^5 A/m, K = 1.5 x 10^5 J/m^3)

• storage medium, layered structure, including special AFM layer:



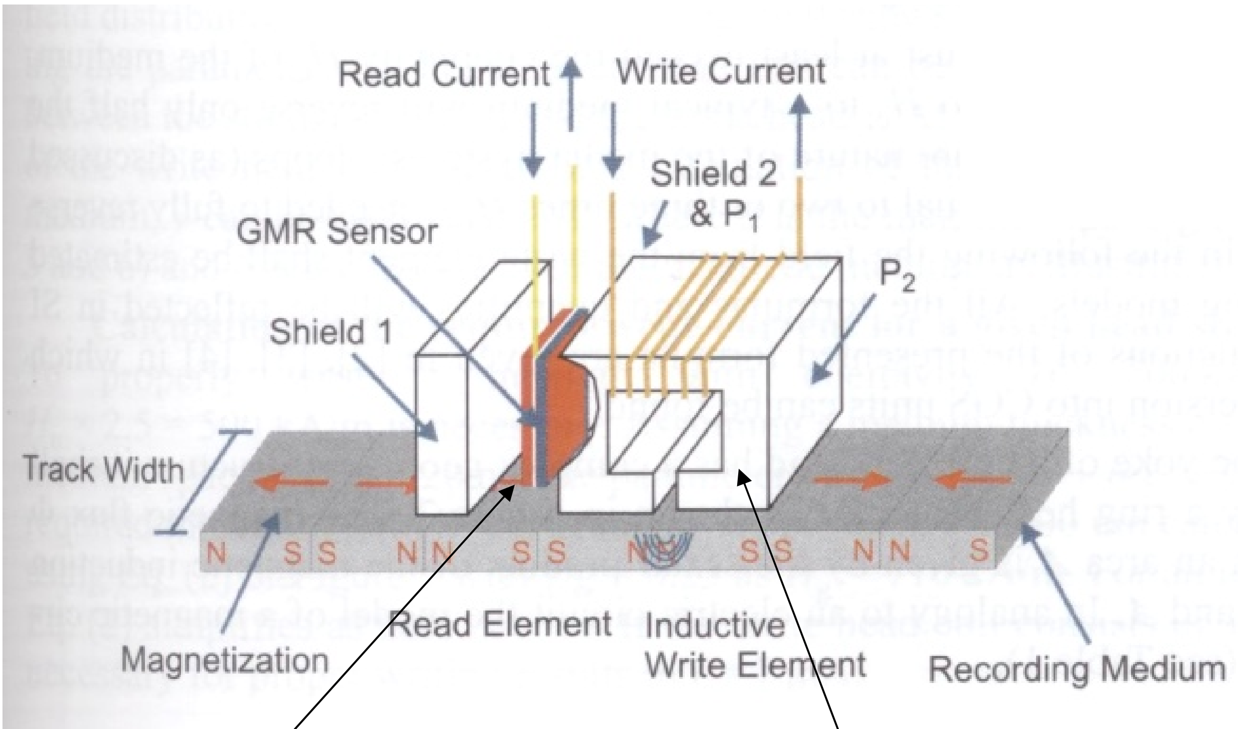
Magnetic storage: hard drives



Individual grain in a bit ~ 10 nm on a side.
Antiferromagnetic “pixie dust” layer “stiffens” disk medium without strongly altering its coercivity (write-ability).

Magnetic storage: hard drives

Head structure



GMR read head

Inductive writing

Increasing hard drive density - Vertical media

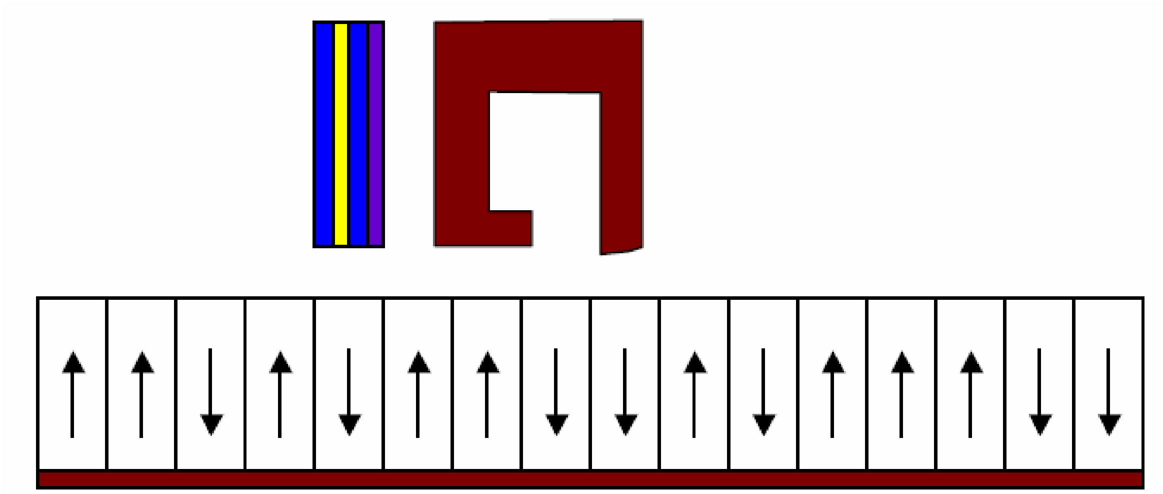
Potential advantages:

• Can get better thermal stability by larger bit volumes without sacrificing bit area density.

• Better signal to noise under some circumstances because fringing fields over larger area tend to influence read head.

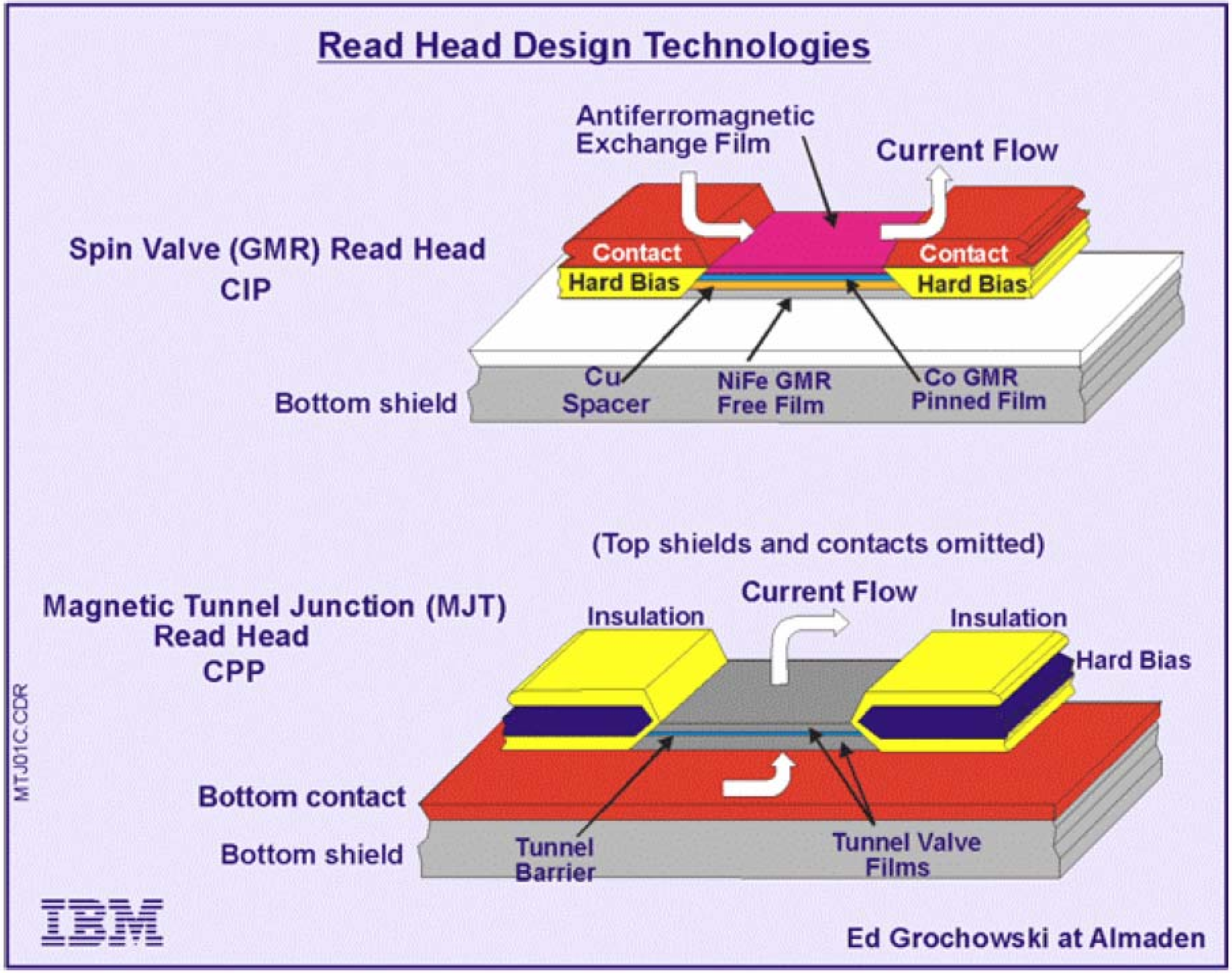
Disadvantages:

• Textured growth of medium on substrate can be quite tricky.



Increasing hard drive density - Using TMR read heads instead

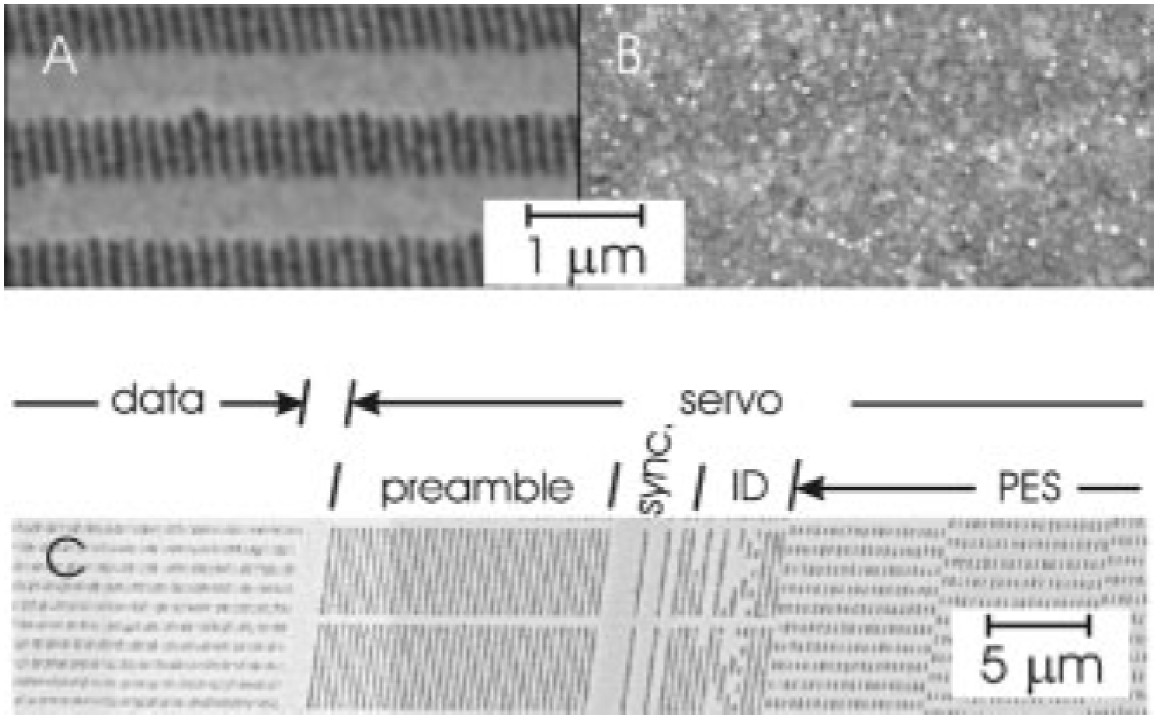
Larger resistance ratio ~ 40%



Patterned media

Dietzel, Adv, Mater, **15**, 1152, (2003)

Don't rely just on film growth: make nanostructured media with prearranged bit locations - single domain particles.

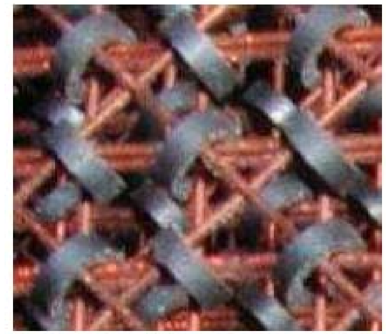


Several different approaches:

- E-beam lithography (far too slow)
- Resistless ion projection direct structuring (IPDS)
- Nanoimprint lithography
- Electrochemistry through porous mask
- Self-organization / self-assembly

Magnetic memory, where it all began

- Core memory – use magnetization of ferrite “cores” as computer memory in the 1960s.
- $6000 per 1kb



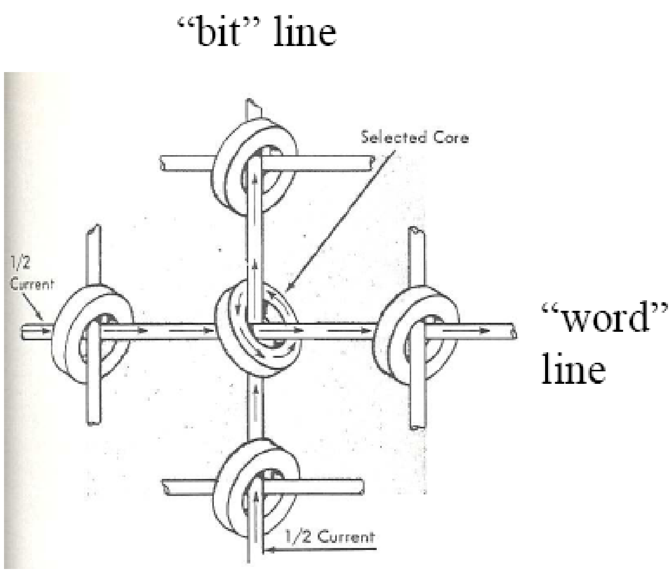


Image from Columbia Univ. ACIS

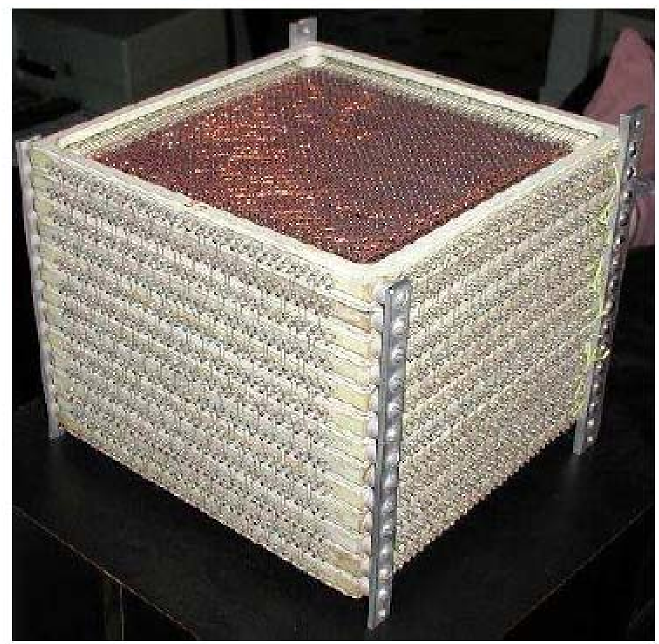
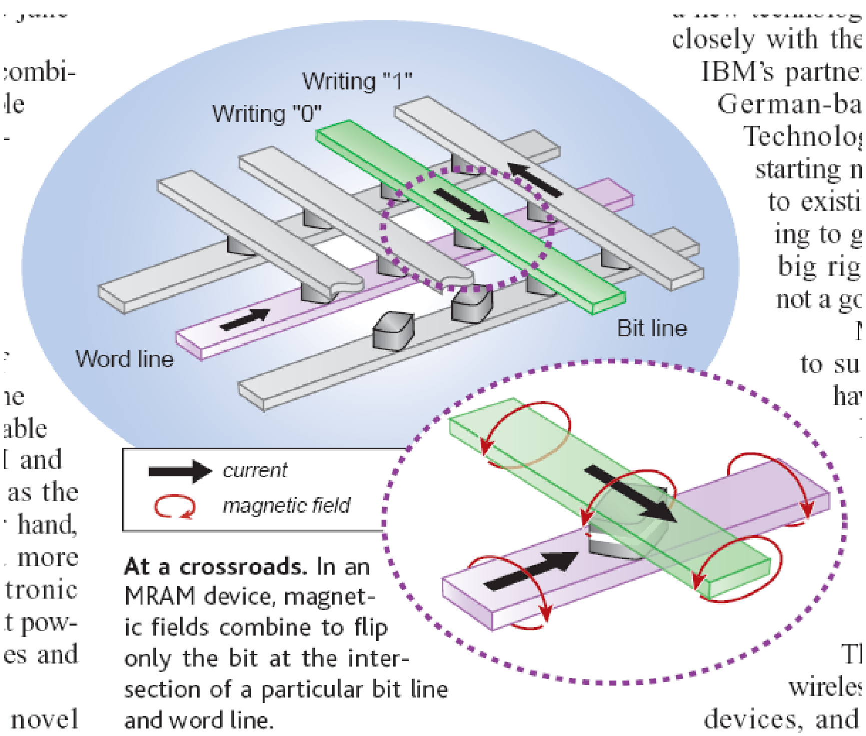
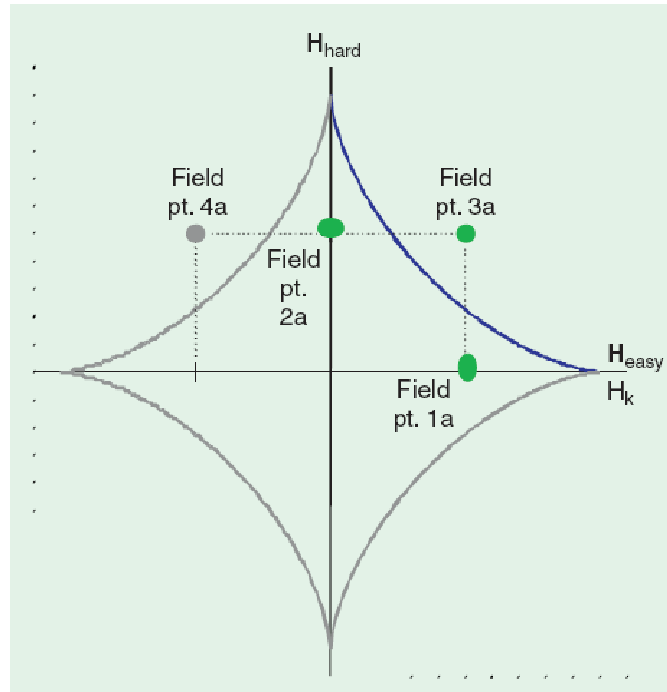


Image from pcbiography.net

MRAM, crossbar structure



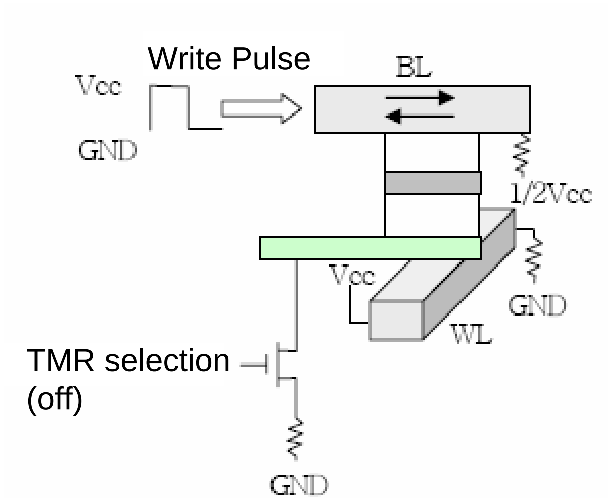
switching astroid.

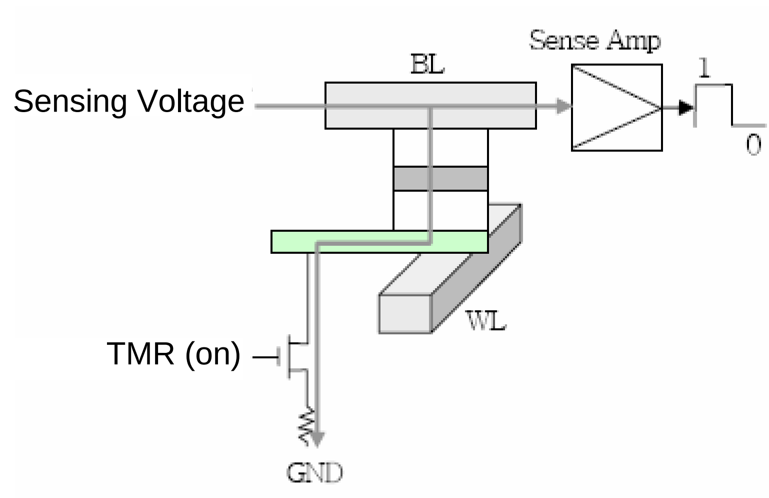


Bit is written when both the “easy axis” and “hard axis” lines (bit line and word line) are selected.

MRAM

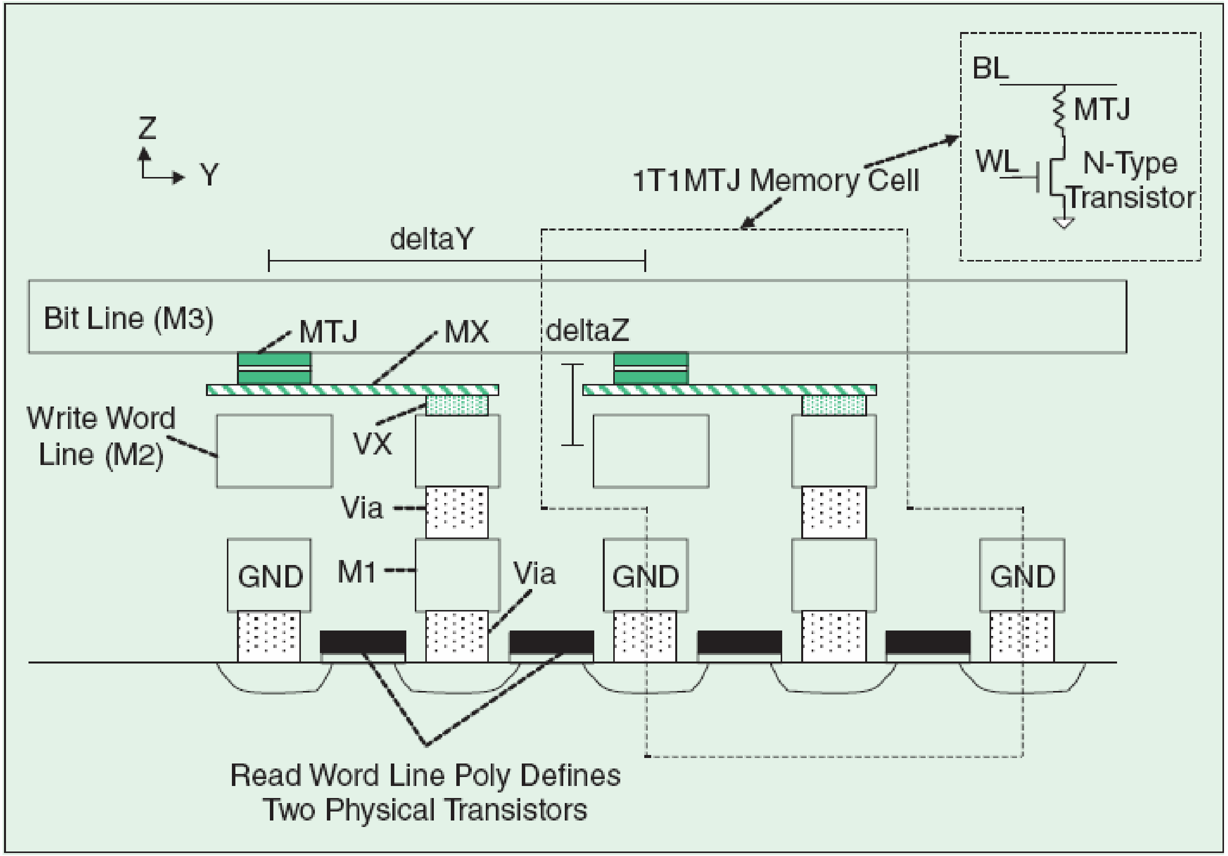
Read-out with TMR effects





Utilization of CMOS controls

Integrated MRAM/CMOS structure



Spintronics

Basic idea: use spin as well as charge of electron for information processing / useful devices.

Problems:

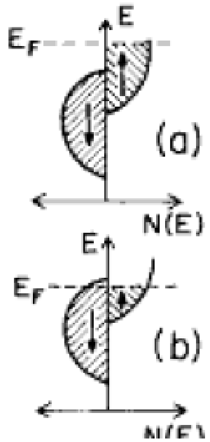
- Need to get spin-polarized electrons - would like to do so without enormous magnetic fields.

- Would like to manipulate spin degree of freedom, again without big magnets if possible.

- Want to read out spin information somehow.

Sources of spin polarized carriers

Two main ways of getting carriers with net spin polarization:



• Ferromagnetic contacts
Recall our numbers for polarization in some common ferromagnets: (from Meservey *et al.*, Phys. Rep. **238**, 173 (1994)
Ni: 23% Fe: 40% Co: 35% NiFe: 32%

• Optical pumping with circularly polarized light

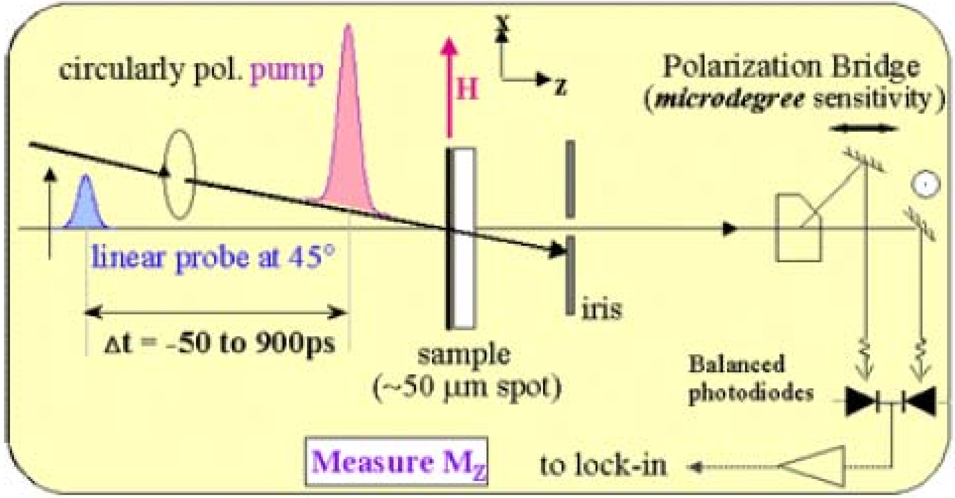
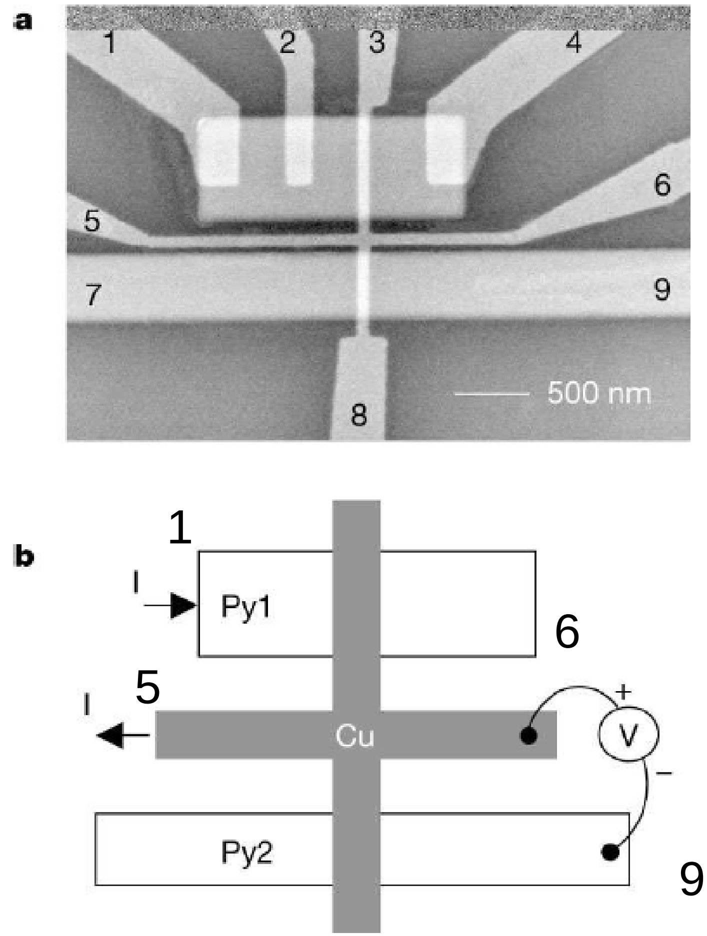


Image from Awschalom group, UCSB

Spin injection in an all-metal structure

Jedema *et al.*, Nature **410**, 345 (2001)



Py pieces small enough to be single domain.

Py pieces have differing geometric anisotropies: magnetization can be controllably flipped one at a Time.

The non-local voltage is non-zero only when non-equilibrium spins injected from 1 accumulate at 6 due to diffusion

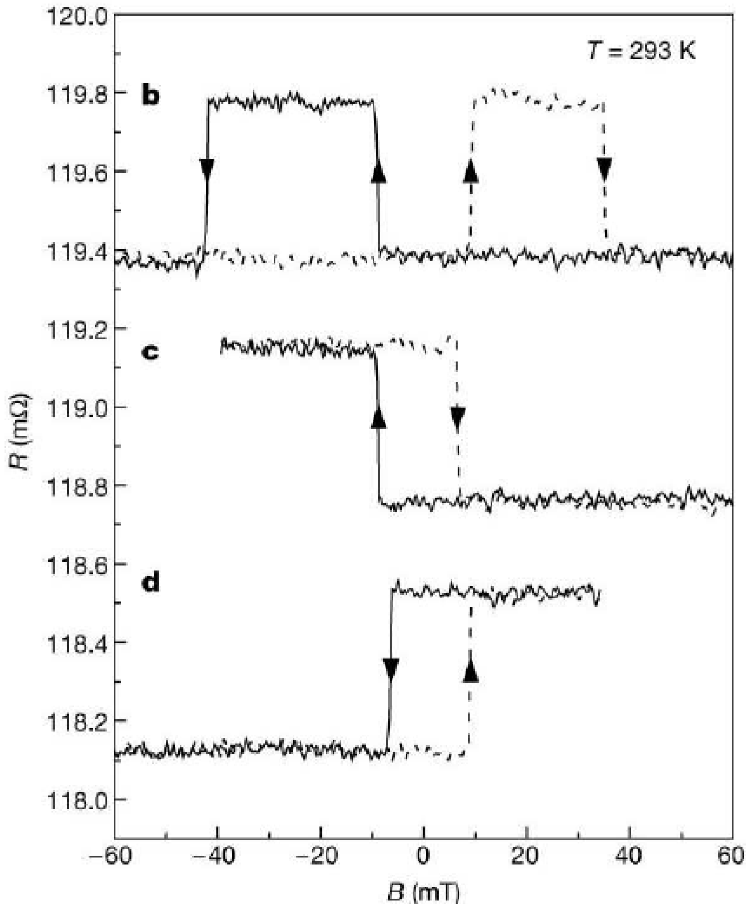
Nonlocal spin valve effect

Jedema *et al.*, Nature **410**, 345 (2001)

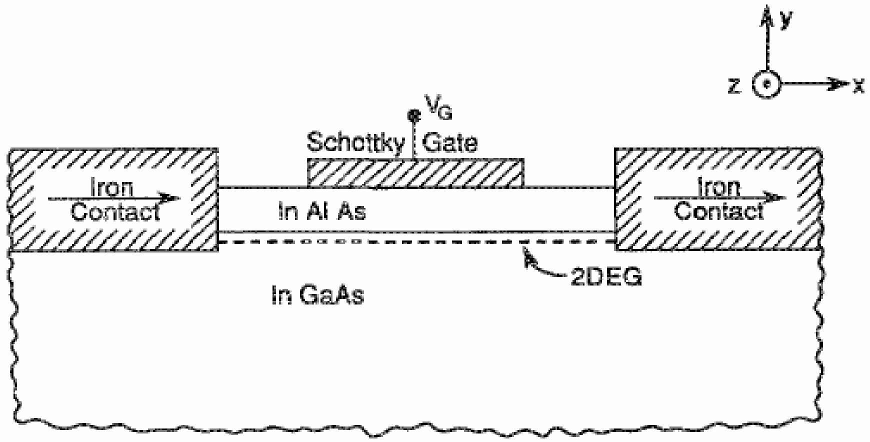
When sweeping in-plane field, shorter Py piece flips first.

As predicted, higher voltages measured when Py magnetizations are antialigned.

this works even at room temperature!



Datta-Das spin transistor



Datta and Das, Appl. Phys. Lett. **56**, 665 (1990)

Working principle: spin-orbit coupling

•Because of relativistic effects, electric fields look, to the moving electrons, like they have a small magnetic field component.

•Electron spin can thus be rotated by controlling the electric field, using a gate. (avoiding external magnetic fields completely)

•This is enhanced in materials with strong spin-orbit scattering (no
•inversion symmetry = III-V) - the Rashba Effect.

Spin injection from metals into semiconductors

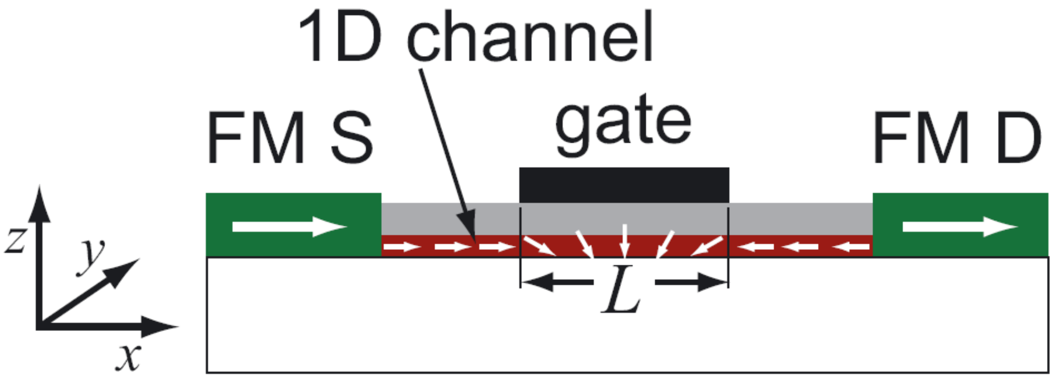
$$P_{SC} = P \cdot \left(\frac{R_{FM}}{R_{SC}}\right)\left(\frac{2}{2(R_{FM}/R_{SC}) + (1-P^2)}\right)$$

- So, while spin polarization of current in semiconductor is proportional to that in FM, it's reduced by a factor of (R_{FM}/R_{SC}), which can be ~ 10^{-4} !

- Conductance mismatch between materials will cause big suppressions of spintronic effects.

- Make *tunnel junctions* rather than direct Ohmic contacts to improve injection efficiency
- Dilute magnetic semiconductors

Datta-Das spin transistor



Issues:

- Ballistic device preferred: spin relaxation smears signal
- Efficient spin rotation with electric field through spin/orbit coupling (material, structure)
- Single 1D channel required: spin/orbit coupling different in different 1D channels
- Local Hall effects caused by FM electrodes

A successful SFET has not been realized yet!