THE EUROPEAN SCHOOL ON MAGNETISM 2015

FROM BASIC MAGNETIC CONCEPTS TO SPIN CURRENTS

Aug 24 - Sep 4 [2015]
Cluj-Napoca
Romania

Common magnetoresistance measurements: AMR, GMR, AHE/SHE, TMR

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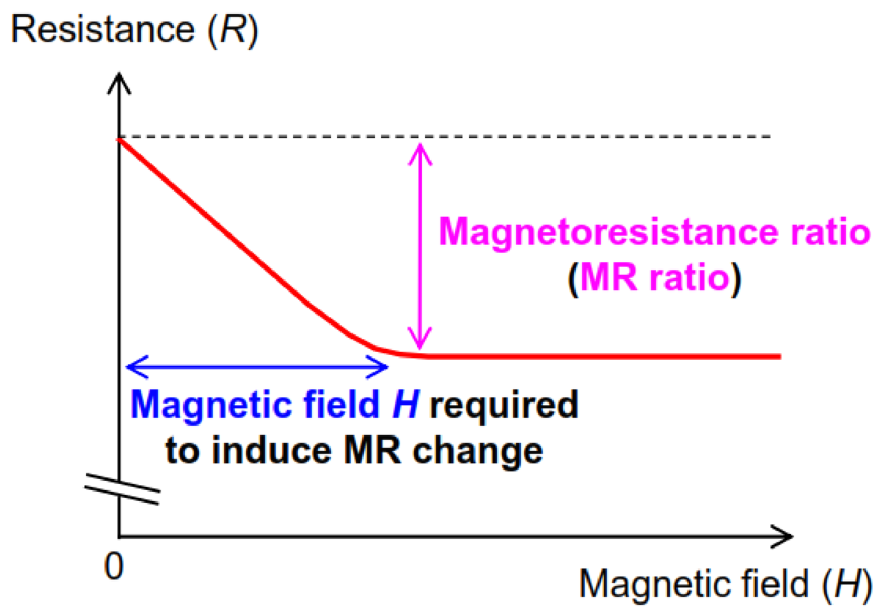
Question:

What is "*magnetoresistance*" ?

A change in resistance by an application of *H*.

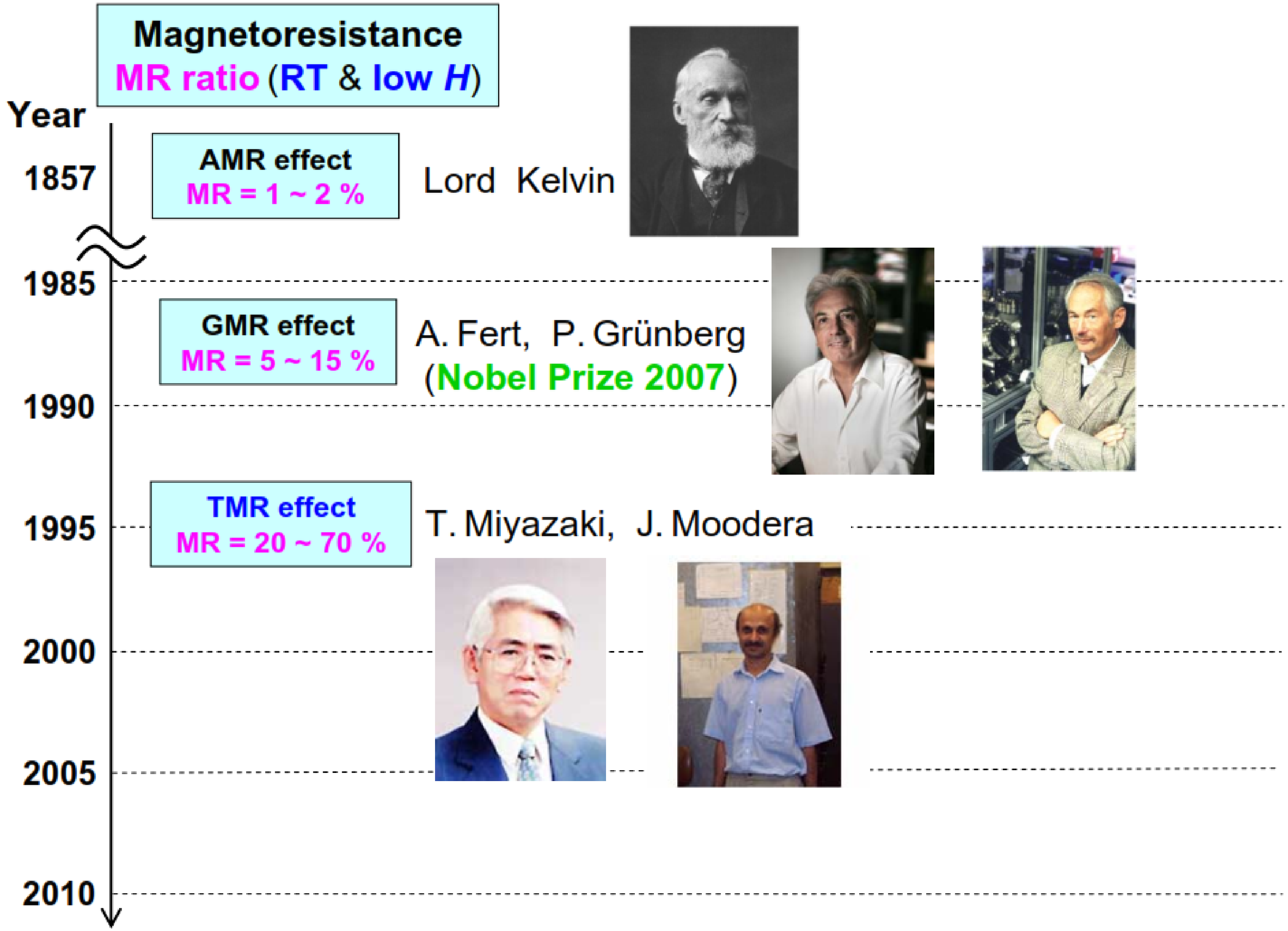
Magneto-Resistance ; **MR**



MR ratio at RT & a low *H* (~1 mT) is important for practical applications.

From S. Yuasa

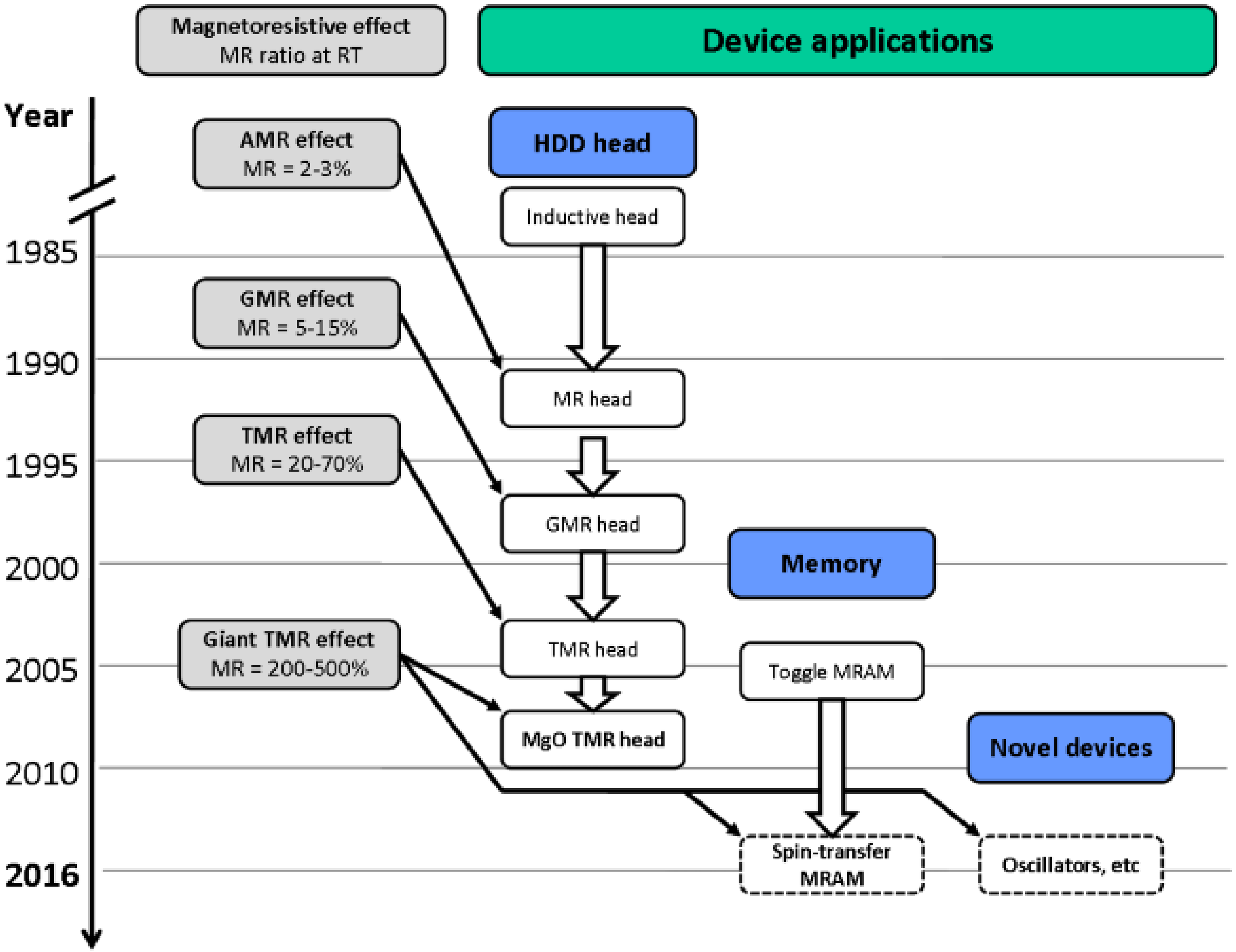
MR an old story…



From S. Yuasa

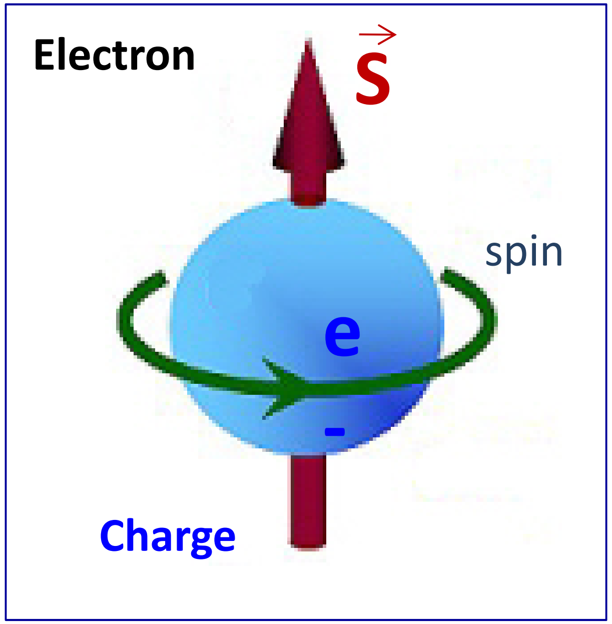
MR: significant impact in data storage technologies

Magnetic recording technology evolution



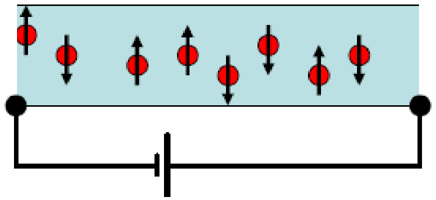
S. Yuasa and D. D. Djayaprawira, " Journal of Physics D: Applied Physics, vol. 40, no. 21, p. R337, 2007.

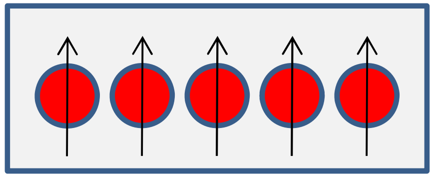
MR: Physical basis of SPINTRONICS

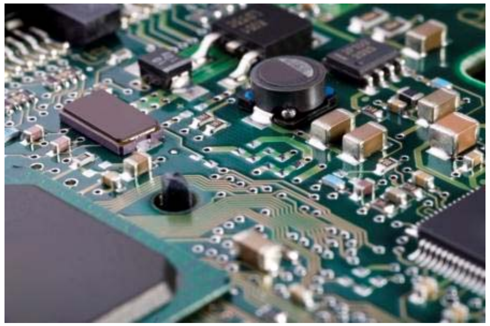


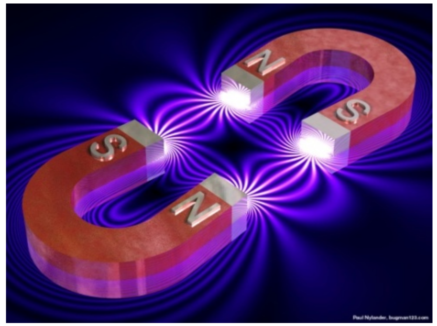
Electron = charge + spin

electronics **magnetism**









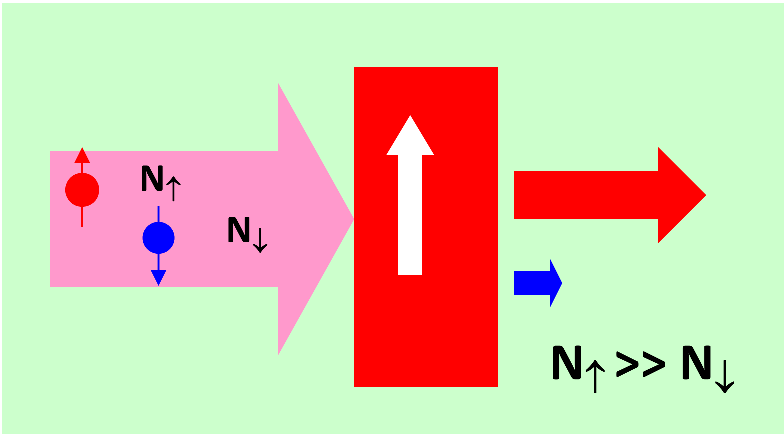
Purpose of spin-electronics:
combine electronics and magnetism in order to make new devices
in which both the charge and the spin of the electron play an active role

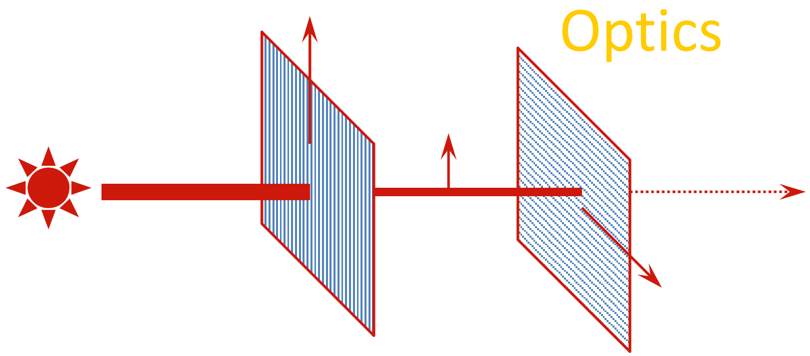
``Teaching electrons new tricks´´ by manipulating the electron spin in solid state electronic devices…

MR: Physical basis of SPINTRONICS

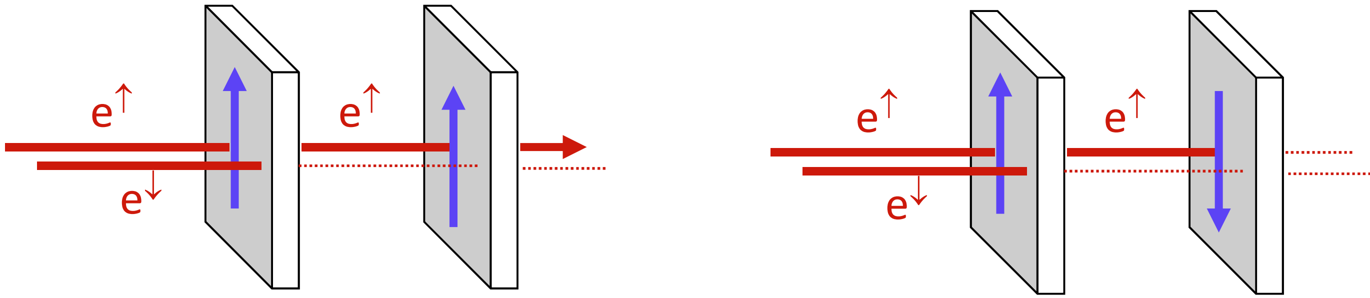
Take advantage of the electron spin as a new degree of freedom
to generate new functionalities and devices

Basic (1st) ideea: Magnetic materials can be used as **Polarizer** and **Analyzer** of electrons (spin filters)





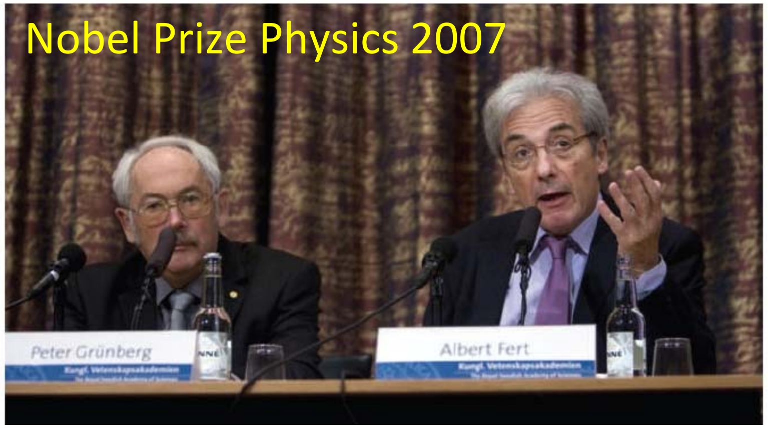
Spin filters



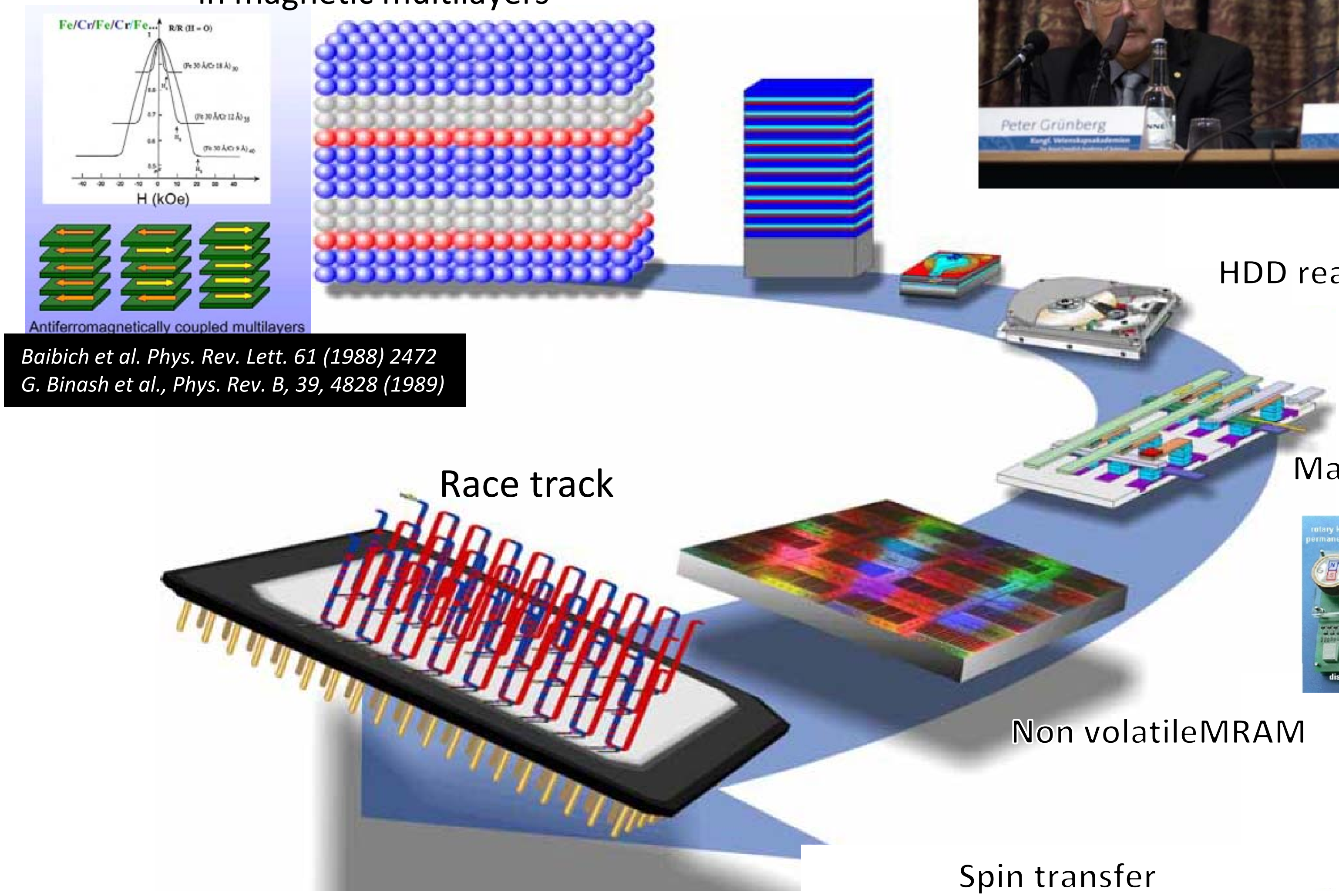
$$\sigma_{\uparrow\uparrow} > \sigma_{\downarrow\uparrow} \Rightarrow R_{\uparrow\uparrow} < R_{\downarrow\uparrow}$$

However, spin currents can be generated otherwise (spin-orbitronics, spin caloritronics…)…

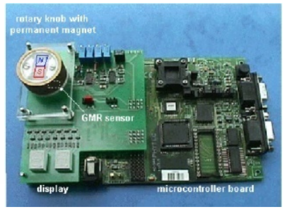
SPINTRONICS: excellence research area



1988: The giant magnetorezistance (GMR) in magnetic multilayers



Baibich et al. Phys. Rev. Lett. 61 (1988) 2472
G. Binash et al., Phys. Rev. B, 39, 4828 (1989)



Microwave generation,
High frequency oscillators

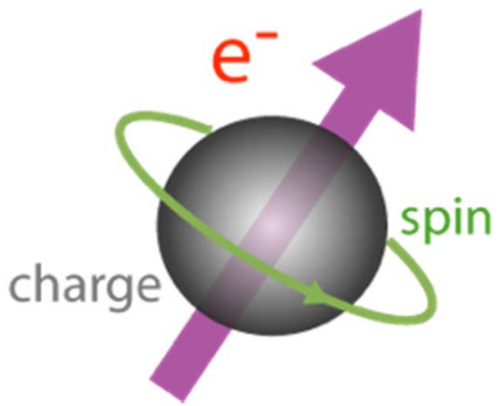
Outline

- **Origin of the spin-dependent transport**

- **Main magnetorezistive and spin dependent transport effects:**
  Physical basis, examples, applications.

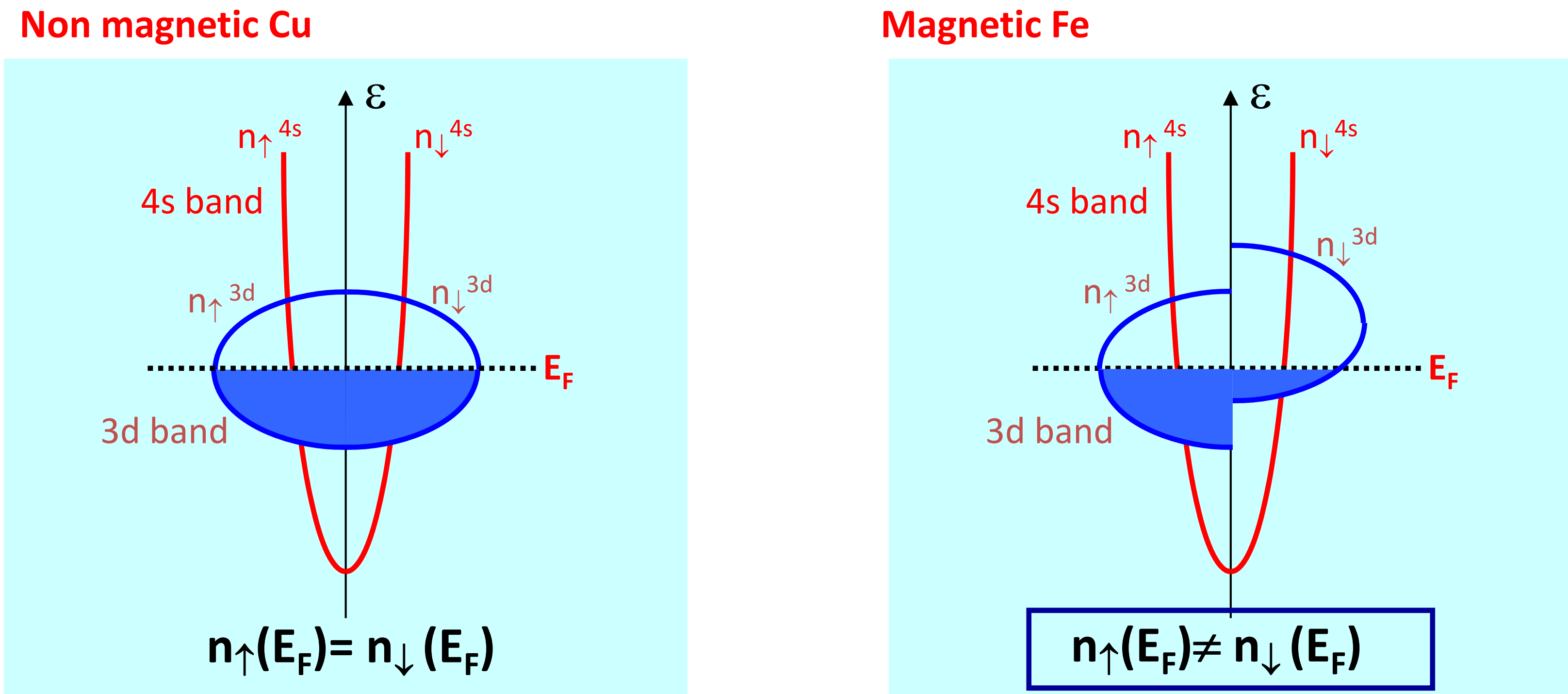
  - AMR: Anizotropic magnetorezistance
  - GMR: Giant Magnetorezistance
  - Anomalous Hall effect, Spin Hall effect (SHE, ISHE)
  - TMR: Tunnel Magnetorezistance (TMR, TAMR)

Origin of the spin-dependent transport.
Basic energies in magnetism.



Origin of spin dependent transport

Band structure of nonmagnetic and magnetic materials



Most of transport properties are determined by DOS at Fermi energy

➡ Spin-dependent density of state at Fermi energy

➡ Different spin population : polarized current

Origin of spin dependent transport

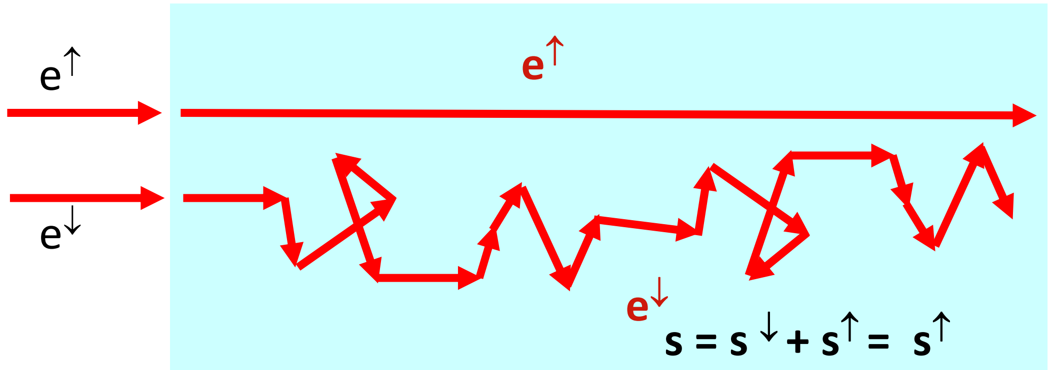
m*(d) >> m*(s) ⟹ J mostly carried by **s** electrons in transition metals

Scattering of electrons determined by DOS at E_F :

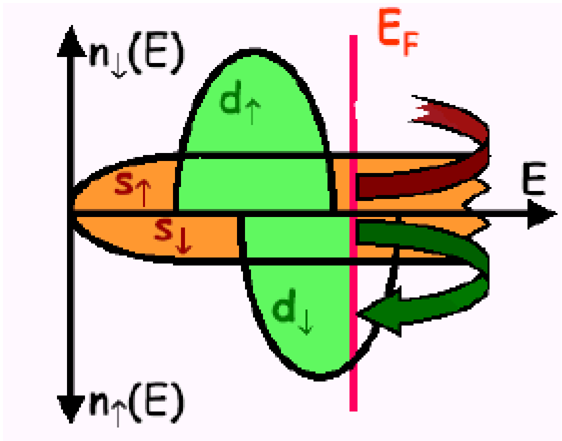
Fermi Golden rule :

$$P^{i\to f} \propto \left|\langle i|W|f\rangle\right|^2 n(E_F)$$

⟹ **Spin-dependent scattering rates**



Ni or **Co**



Example: $\lambda_\uparrow^{Co}$ =10nm $\lambda_\downarrow^{Co}$=2nm

⟹ **Spin-dependent carrier densities** and **scattering rates** both contribute to spin **dependent transport in magnetic multilayers**

Basic energies in magnetism

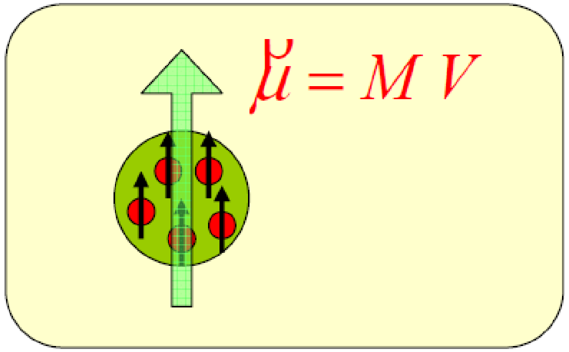
Recall…

Exchange interaction

quantum effect

tends to keep the spins parallel

"magnetization" *M* in ferromagnets
= *magnetic moment per unit volume*

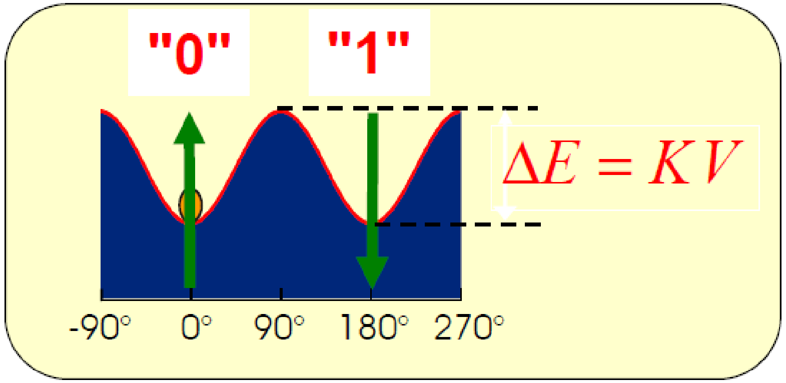


Magnetic anisotropy energy

quantum relativistic effect

total energy changes with the orientation of *M*

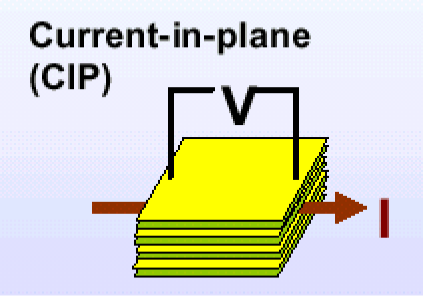
magnetic storage of binary information



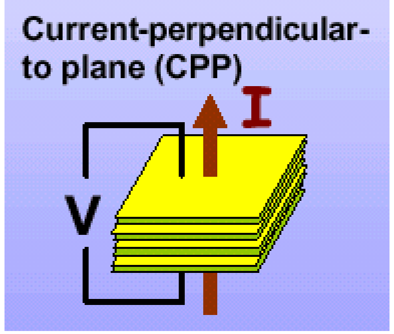
Main magnetorezistive and spin dependent transport effects

- ❑ **AMR:** Anizotropic magnetorezistance
- ❑ **GMR:** Giant Magnetorezistance
- ❑ **AHE:** Anomalous Hall effect
- ❑ **TMR:** Tunnel Magnetorezistance (TMR, TAMR, …)

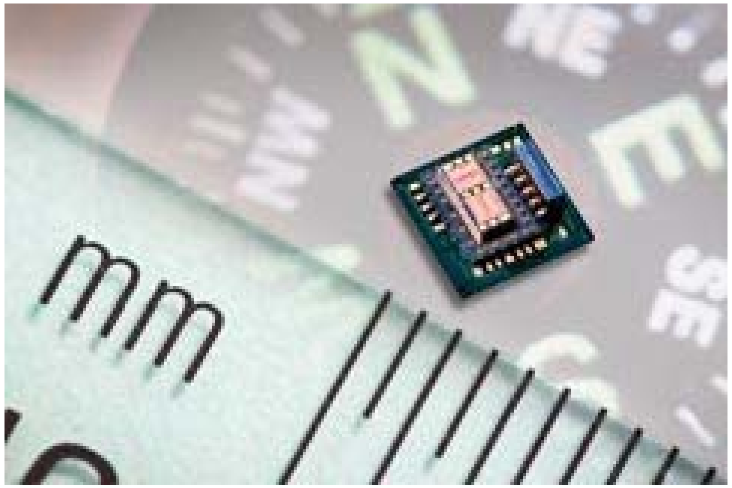
Device geometry (GMR, TMR)**:**



- ❑ Current-in-plane **(CIP)**
- ❑ Current-perpendicular-to-plane **(CPP)**



Anisotropic Magnetorezistance (AMR)



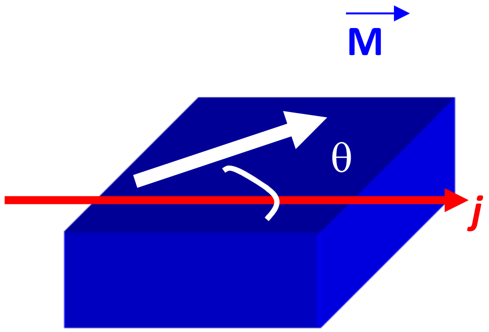
MEMSIC *three-axis anisotropic magnetoresistance (AMR) magnetometer, the MMC3316xMT*

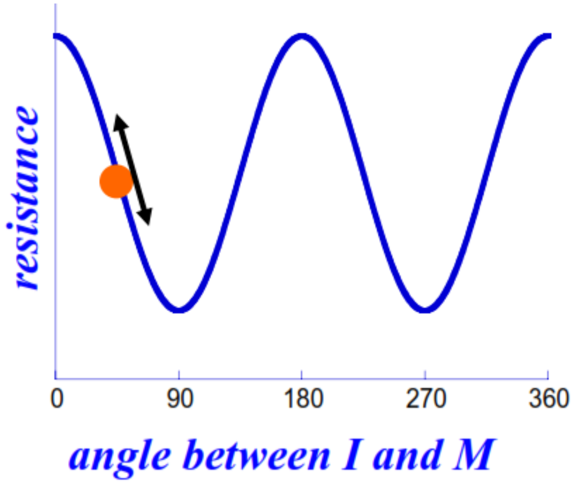
Prior to the discovery of giant magnetoresistance, the main MR effect known in magnetic transition metals (Fe, Ni, Co and many of their alloys) at room temperature was the "**Anisotropic magnetoresistance**" (AMR).

- **AMR**= dependence of the electrical resistivity on the relative angle between the direction of the sense current and the local magnetization.

$$\boxed{\rho(\theta) = \rho_{\perp} + (\rho_{\parallel} - \rho_{\perp})\cos^2\theta}$$

W. Thomson, Proc. Roy. Soc. 8, 546 (1857)





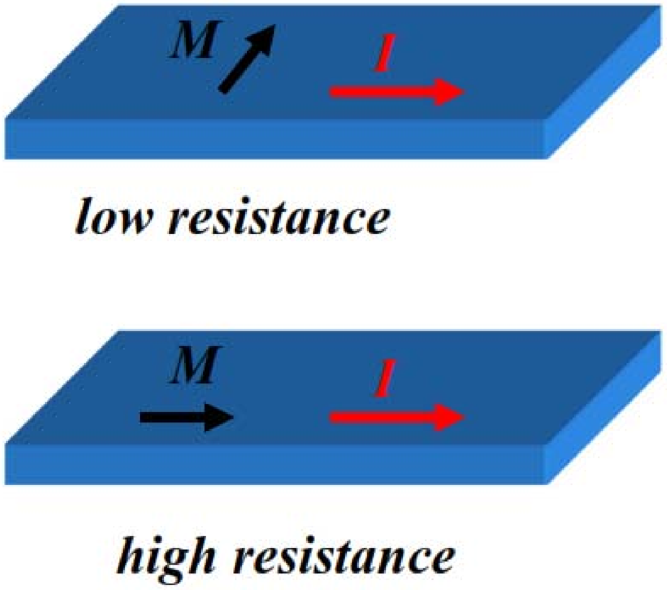
1857: W. Thomson (lord Kelvin) demonstrates AMR in FM materials

1975: Mc Guire@Poter, AMR reviewed, detailed study

Mc Guire, IEEE Trans.Magn.,MAG-11, 4 (1975) 1018

- AMR: bulk property of magnetic materials

Resistivity ρ⊥ lower than ρ||



$$\rho(\theta) = \rho_{\perp} + (\rho_{\parallel} - \rho_{\perp})\cos^2\theta$$

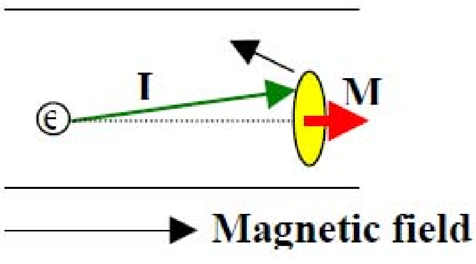
- ❑ **Δρ/ρ= 3 to 5%** in bulk NiFe and CoFe alloys at RT
- ❑ AMR decrease with reduction of the film thickness and patterning due to additional scattering (grain boundaries, film interfaces)

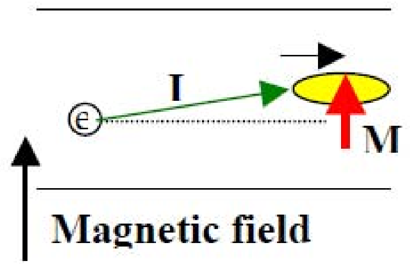
❑ AMR: consequence of an anisotropic mixing of spin-up and spin-down conduction bands induced by the spin-orbit interaction

Campbell et al, Phys.Rev.Lett.24, (1970) 269

❑ **AMR**: used as main MR effect in early generations of read heads, before using the GMR
Recent developements in mobile phones magnetometer

❑ AMR phenomenological





I parallel to M

⇩

Electronic orbits perpendicular to current

⇩

Increased cross section for scatetring

⇩

High resistance

I perpendicular to M

⇩

Electronic orbits parallel to current

⇩

Reduced cross section for scatetring

⇩

Low resistance

⇨ **Resistivity ρ⊥ lower than ρ||**

❑ AMR Quantum mechanics

Mechanism of AMR: **spin-orbit interaction**

mixes up and down states

s states scatter on d states

Hamiltonian

$$\boxed{\hat{H} = \lambda \vec{L} \cdot \vec{S}}$$

The operator of SO interaction can be written as:

$$\mathbf{LS} = L_x S_x + L_y S_y + L_z S_z = L_z S_z + (L^+ S^- + L^- S^+)/2,$$

Rising and lowering operators

$$\hat{L}_+|\ell, m\rangle = \sqrt{\ell(\ell+1) - m(m+1)}\hbar|l, m+1\rangle$$

$$\hat{L}_-|\ell, m\rangle = \sqrt{\ell(\ell+1) - m(m-1)}\hbar|l, m-1\rangle$$

$$S_+|s\ m_s\rangle = \hbar|s\ m_s + 1\rangle$$
$$S_-|s\ m_s\rangle = \hbar|s\ m_s - 1\rangle$$

➡ $3d\uparrow(m_l) \rightarrow 3d\downarrow(m_l+1)$

➡ $3d\downarrow(m_l) \rightarrow 3d\uparrow(m_l-1)$

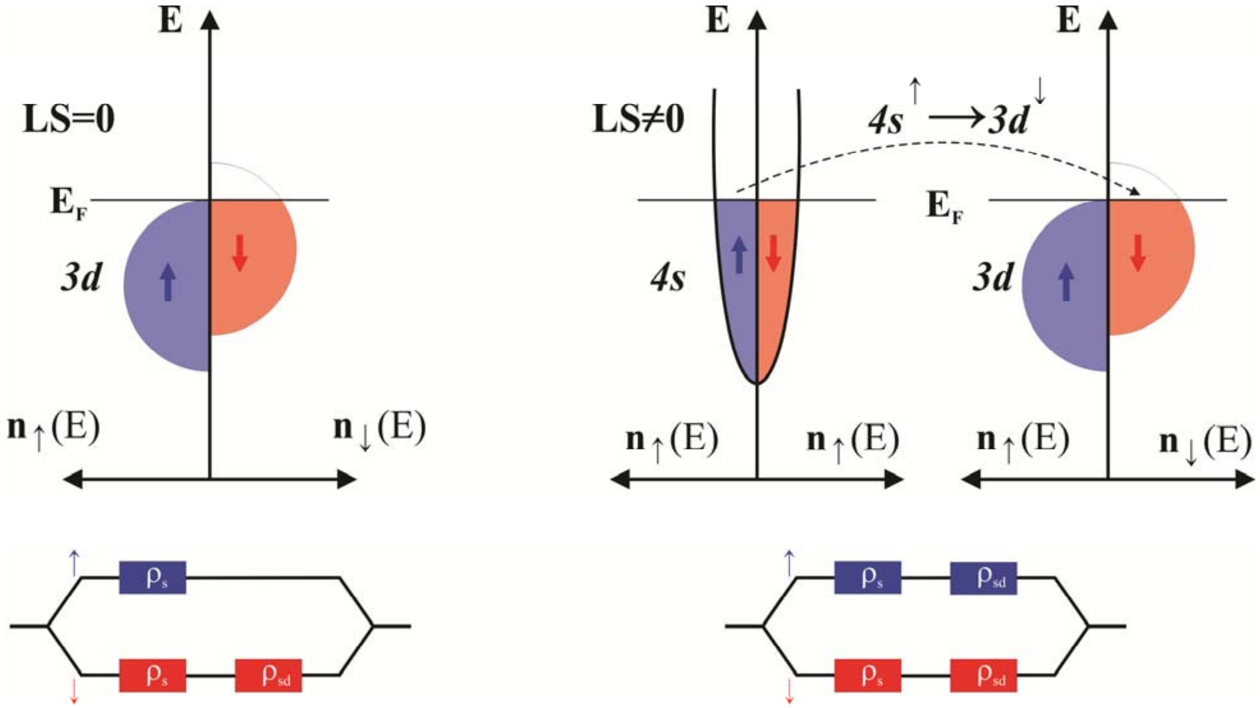
Mixing of up and down states

See also Practicals on Rashba

Simplified case: Strong ferromagnet no 3d↑ states

LS=0 => only s-d scattering in down channel allowed , no s↑→ d↑ scattering

LS≠0 => Inclusion of spin-orbit coupling opens up the possibility of spin-flip transitions in the s-d channels. As a consequence, also the spin-up channel will now contribute to the conductivity.
4s↑→ 3d↓ scattering => **increase of rezistivity**



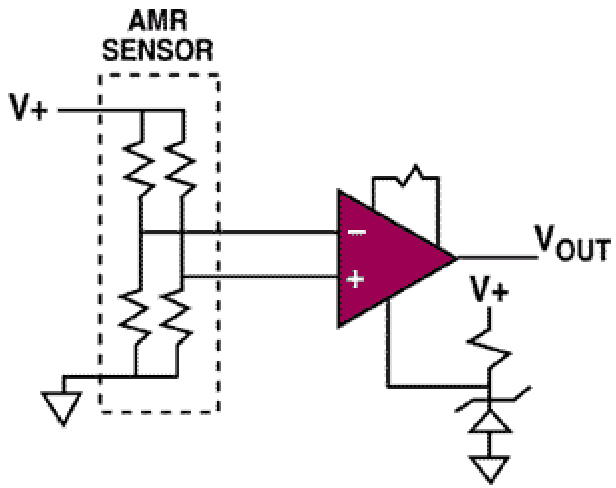
Exercise (practicals)

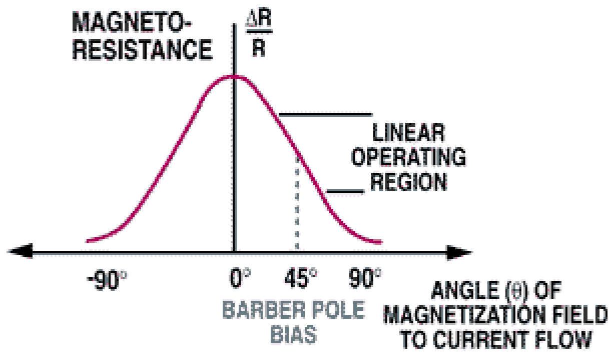
s↑→ d↓ scattering rate depends on the direction of momentum of **s** electron $\hbar\vec{k}$
relative to clasical orbit of unocupied orbital **d**

Clasical orbit: momentum **L** parallel to **M => scattering rate depends on angle between** $\hbar\vec{k}$ and **M**

❑ AMR Sensor circuit. Applications

➡ Wheatstone bridge configuration is used to ensure high sensitivity and good repeatability



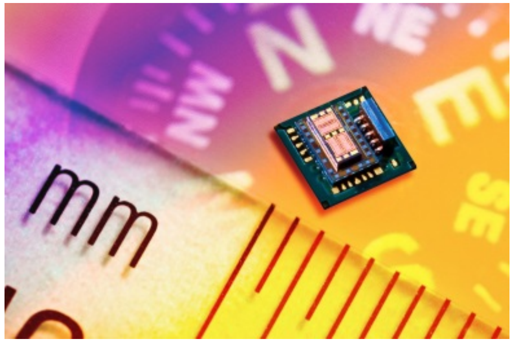


AMR thin films were used in magnetoresistive heads from 1992 to 1998

The introduction of AMR films in magnetic recording technology in 1992 major breakthrough which led to a doubling in the rate of increase of storage areal density per year (from 30%/year to 60%/year).

AMR: Magnetometer basics for mobile phone applications

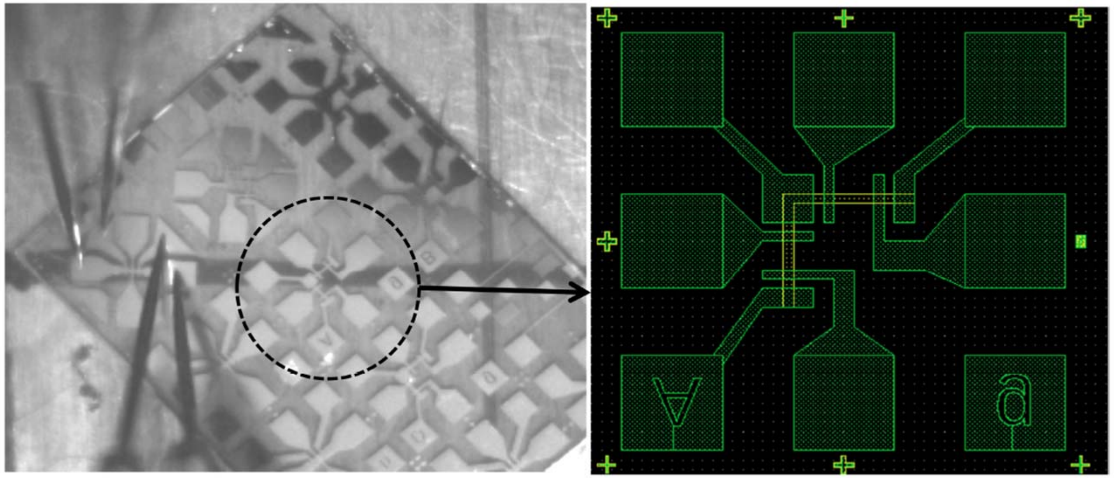
MEMSIC Powerful Sensing Solutions

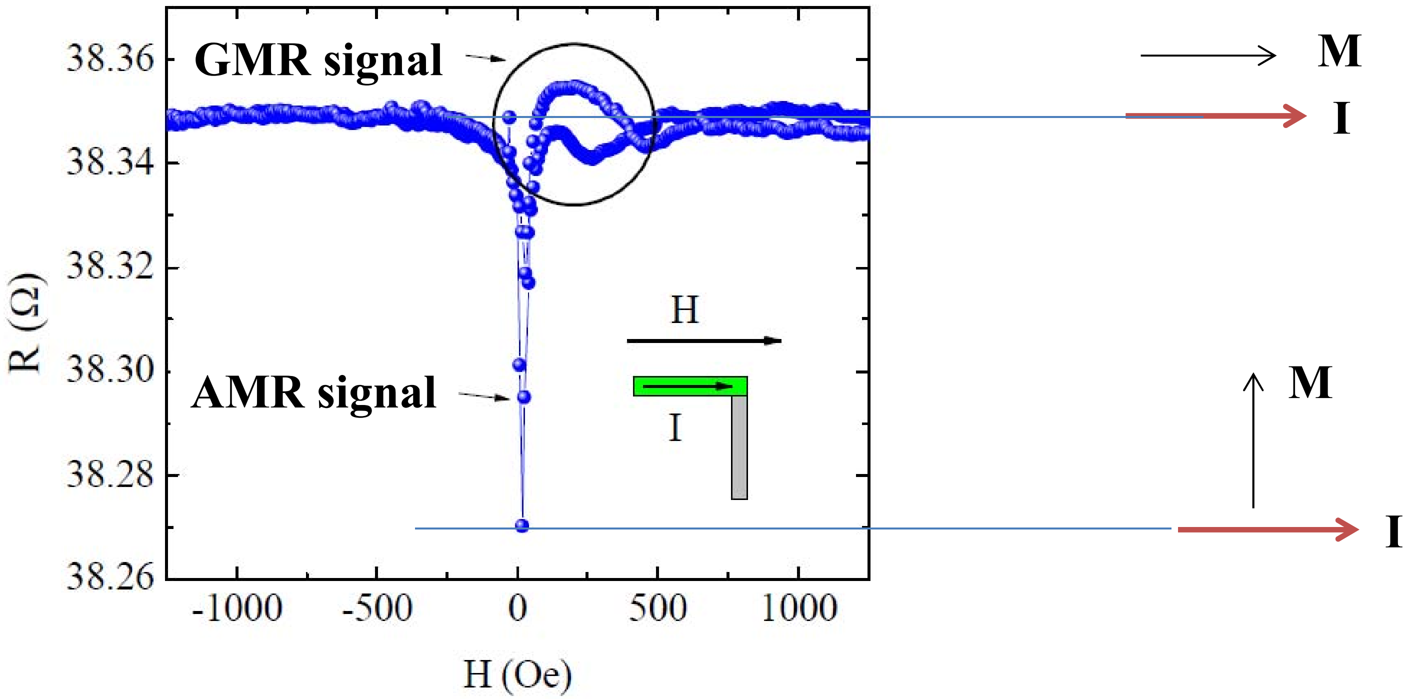


Although the AMR principle supplies a lower output signal level than other competitive approaches, the level is more than enough for consumer mobile phones. Recent developments in AMR technology have made AMR even more competitive with the Hall effect. AMR also has better sensitivity than other methods and reasonably good temperature stability. (*three-axis AMR magnetometer, the MMC3316xMT*)

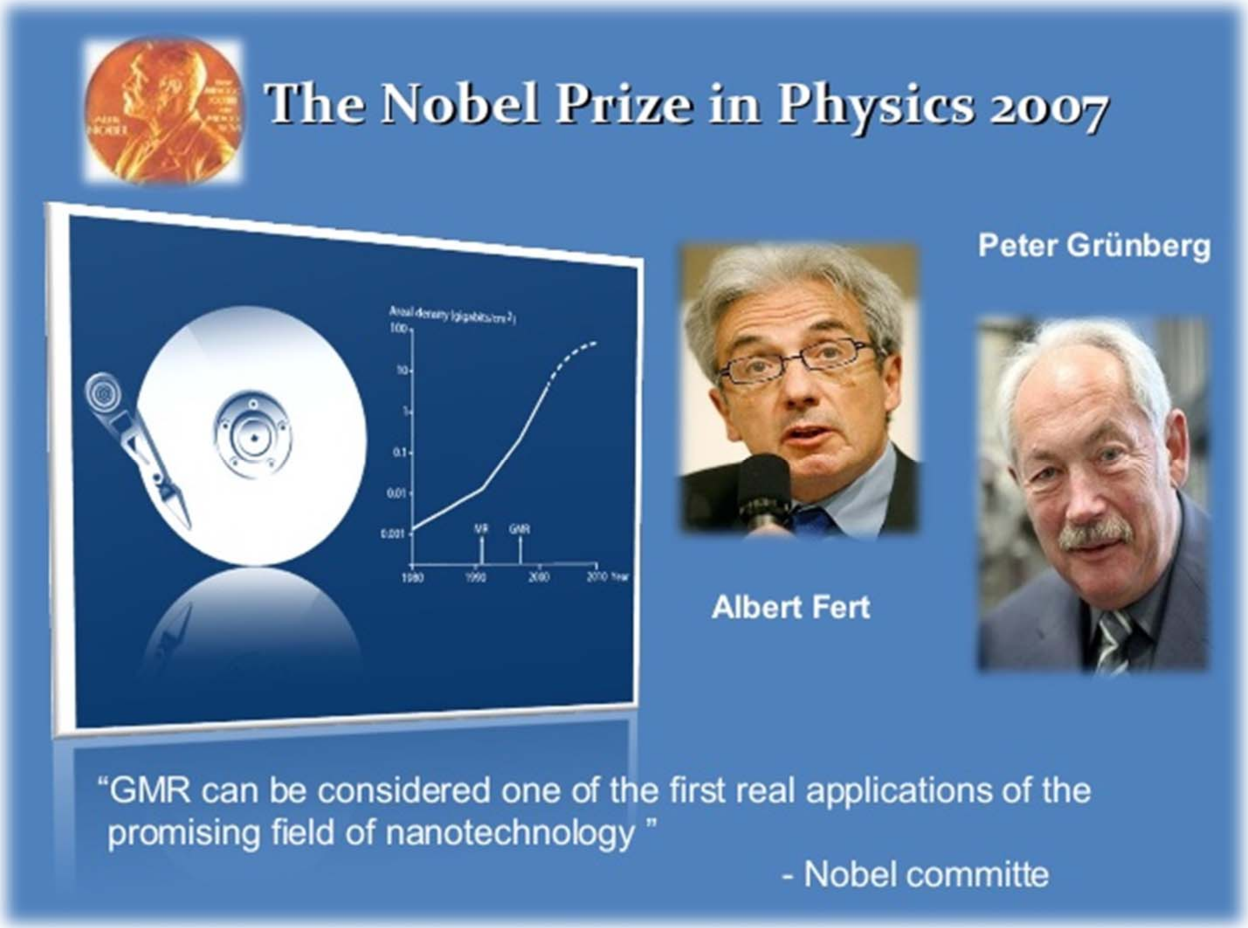
Sometimes AMR signal has to be removed (compensated geometry -litho)

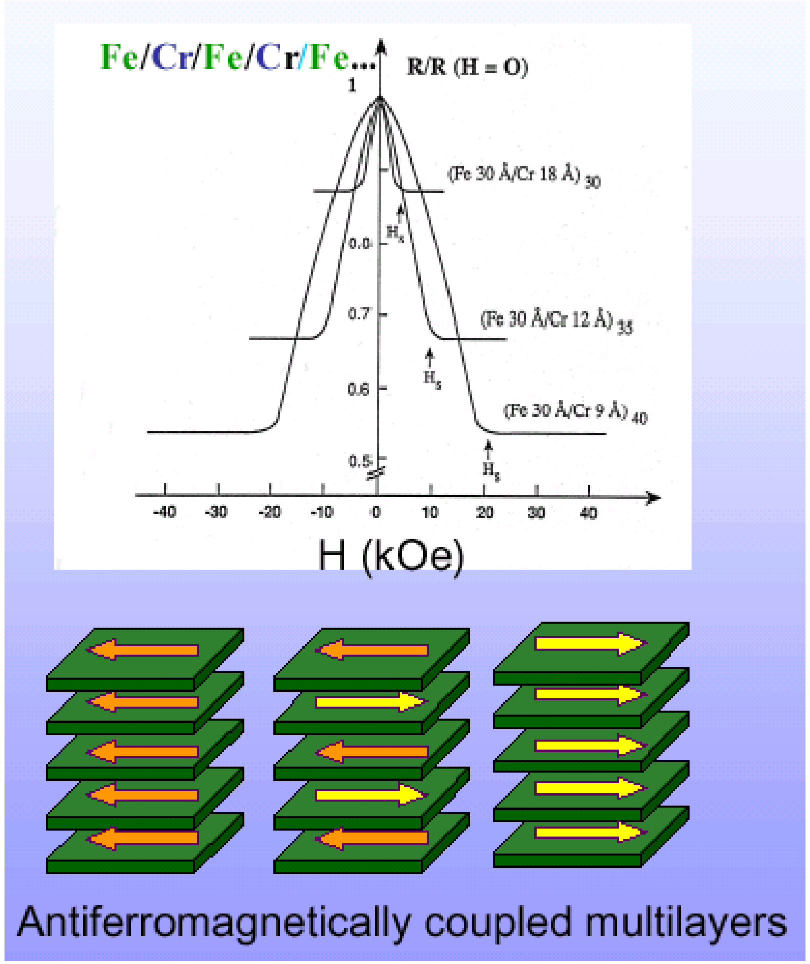
C4S/TUCN





Giant Magnetorezistance (GMR)





The birth of spin electronics:

1988 discovery of Giant Magnetoresistance

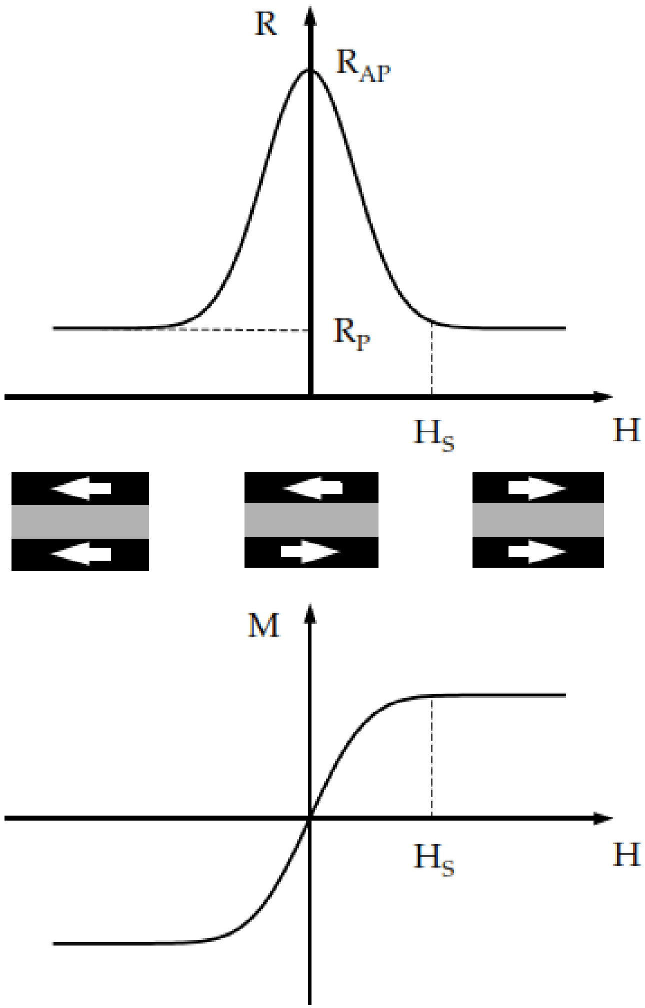
A.Fert et al (Orsay), P. Grunberg (Julich)

2007 Nobel prize for Physics

Baibich et al. Phys. Rev. Lett. 61 (1988) 2472
G. Binash et al., Phys. Rev. B, 39, 4828 (1989)

Peter Grünberg (left) and Albert Fert discuss their Nobel-Prize-winning discovery of giant magnetoresistance with the press in 2007.

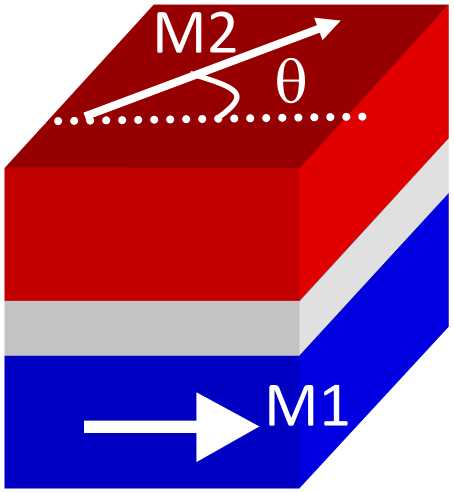
GMR: Giant Magnetorezistance effect



$$GMR=(R_{AP}-R_P)/R_P$$

Schematic representation of the GMR effect

❑ **GMR -** From antiferromagnetically coupled multilayers to "**spin-valves**"



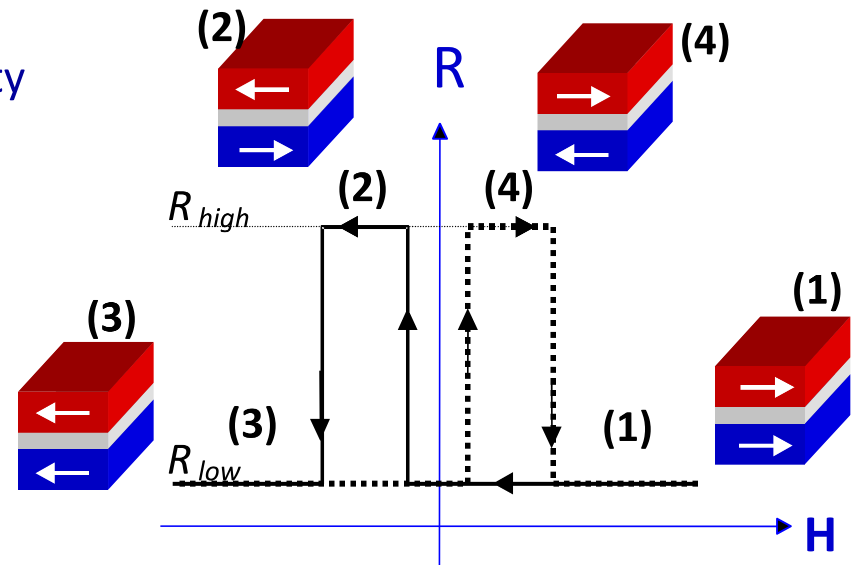
$$R = \frac{R_p + R_{ap}}{2} + \frac{R_p - R_{ap}}{2}\cos(\theta),$$
$$\theta = (\vec{M}_1, \vec{M}_2)$$

Spin valve effect

- Multilayers with double coercivity

- **Hard-soft architecture**

  control independently the two magnetizations



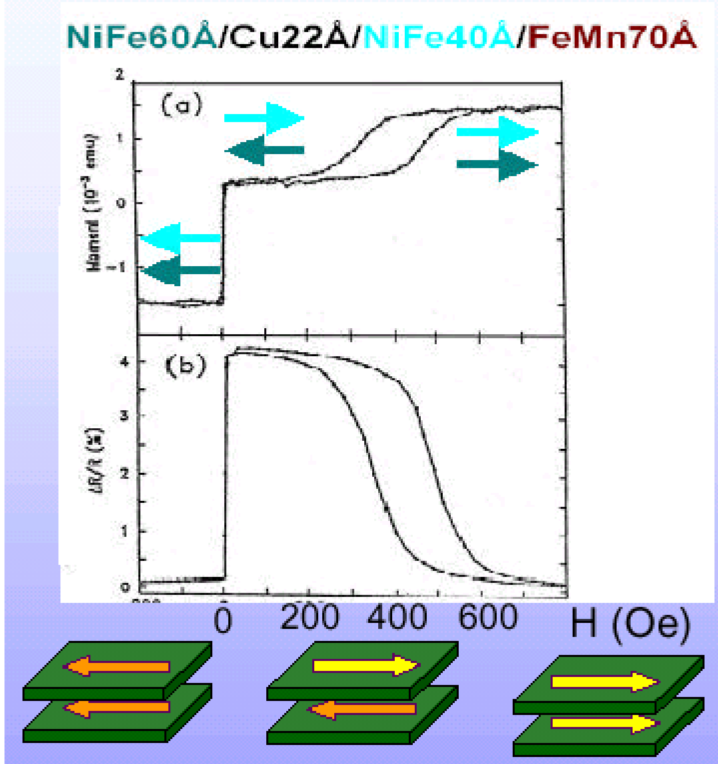
❑ **GMR -** From antiferromagnetically coupled multilayers to “**spin-valves**”

A significant step towards applications of GMR in devices was achieved by ***Parkin et al***:
GMR in sputtered multilayers.

Phys.Rev.Lett.,64 (1990) 2304.

Spin-valves were discovered in 1990.

Dieny et al:
Journ.Appl.Phys.69, (1991) 4774-9
J. Magn. Magn. Mat. 93 (1991),101-4.
Phys. Rev.B. 43 (1991), 1297-300.



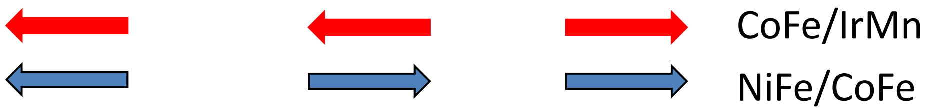
Two uncoupled layers :
one soft, the other pinned.

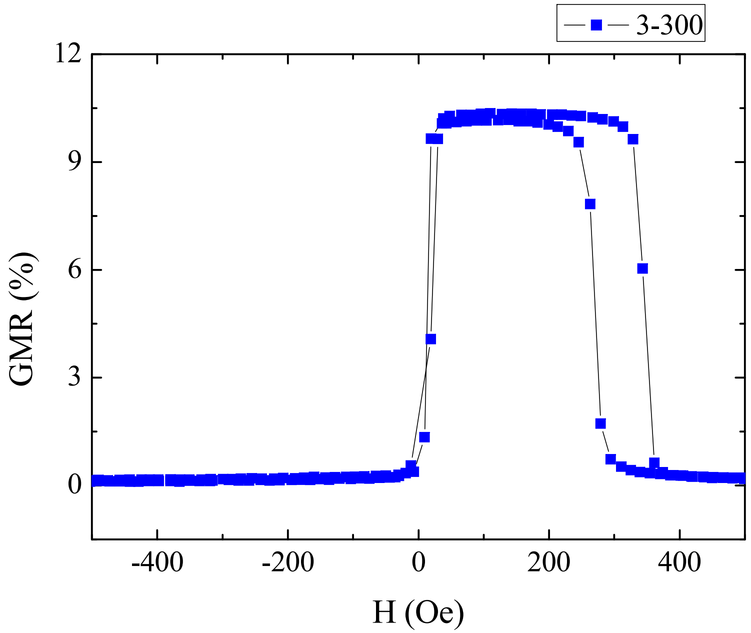
$\Delta R/R<20\%$

B.Dieny et al, Phys.Rev.B.(1991)

❑ **GMR -** From antiferromagnetically coupled multilayers to “**spin-valves**”

C4S/TUCN





Si/SiO2//Ta(3nm)/
NiFe(4nm)/CoFe(2nm)/Cu(2.16nm)/CoFe(4nm)/IrMn(10nm)/Ta(3nm)

State of the art specular SVs reach MR values ~20%.
(with use of Nano-Oxide layers at interfaces)

J. Hong et al, in Magnetics Conference, 2002. INTERMAG Europe 2002. Digest of Technical Papers. 2002 IEEE International, pp. CA3(2002).

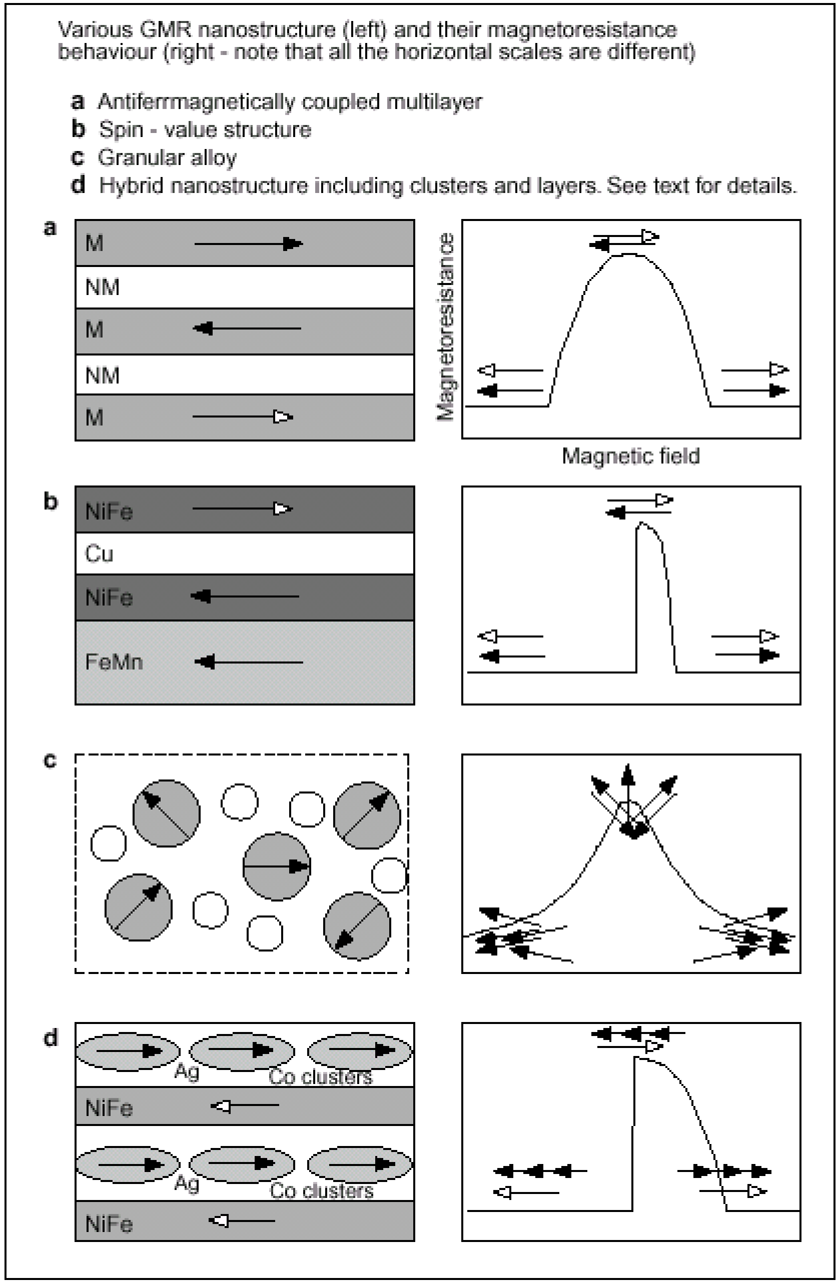
❑ GMR - Structures

Antiferromagnetically coupled multilayers

Spin valve structure

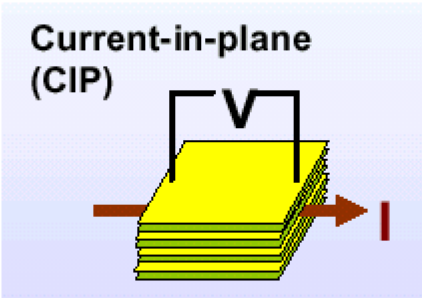
Granular material

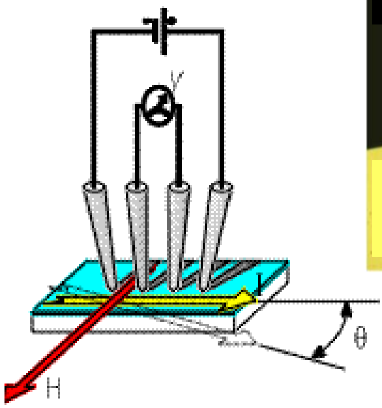
Hybrid cluster/layer

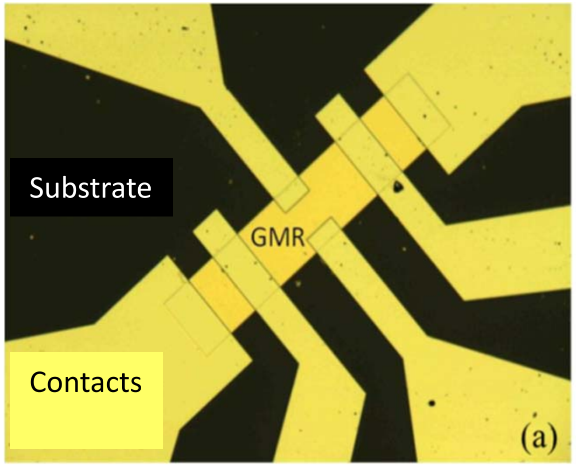


GMR: Giant Magnetorezistance effect

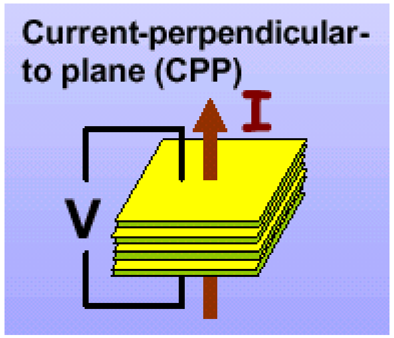
Experimental measurement geometry

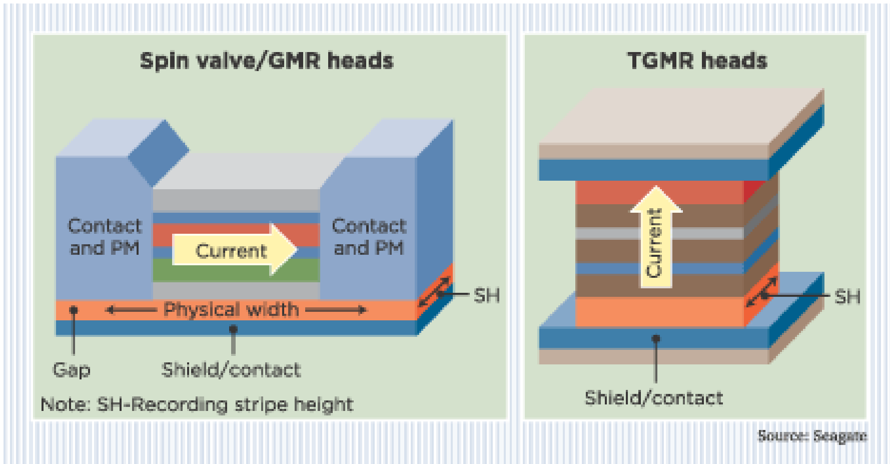






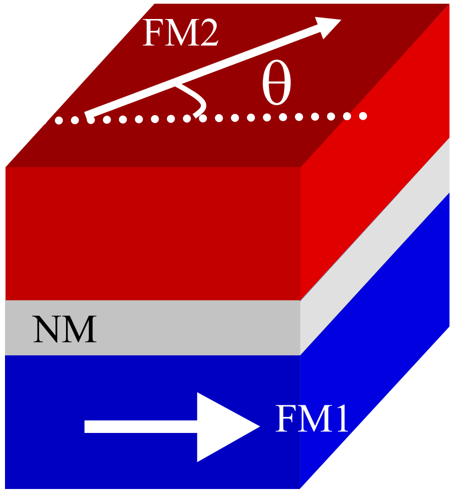
CIP-GMR device patterned at TUCN

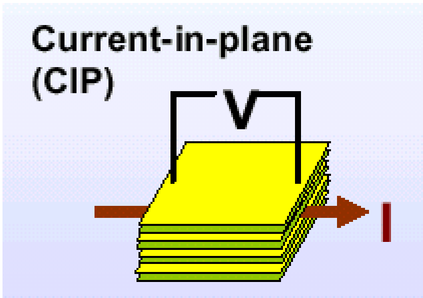




$$GMR=(R_{AP}-R_P)/R_P$$

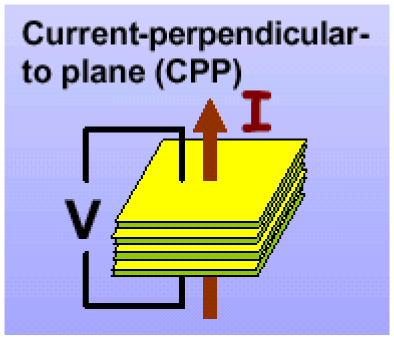
GMR – Main length scales





CIP-GMR

mean free paths (λ) for electrons scattering in FM-metal ($\lambda_{FM}^{\uparrow}$ and $\lambda_{FM}^{\downarrow}$) and the NM metal ($\lambda_{NM}$)



CPP-GMR

spin diffusion lengths in FM (l^{sf}_{FM}) and NM (l^{sf}_{NM})

Two current model of a ferromagnet

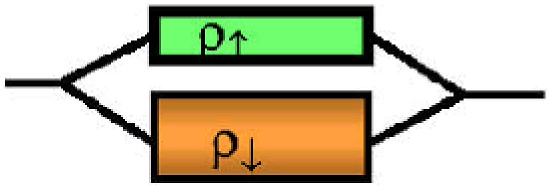
If spin flip scattering is negligible ⇒ Two conduction channels in parallel *(Mott - 1930)*

Electronic transport: two type of carriers : $e^{\uparrow}$ et $e^{\downarrow}$

Characteristic lengths $\lambda_{\uparrow} \neq \lambda_{\downarrow}$

$n^{\uparrow} \neq n^{\downarrow}$

$\Rightarrow \sigma^{\uparrow} \neq \sigma^{\downarrow}$



$$\sigma = \sigma^{\downarrow} + \sigma^{\uparrow}$$

$$\rho = \frac{\rho^{\downarrow}\rho^{\uparrow}}{\rho^{\downarrow} + \rho^{\uparrow}}$$

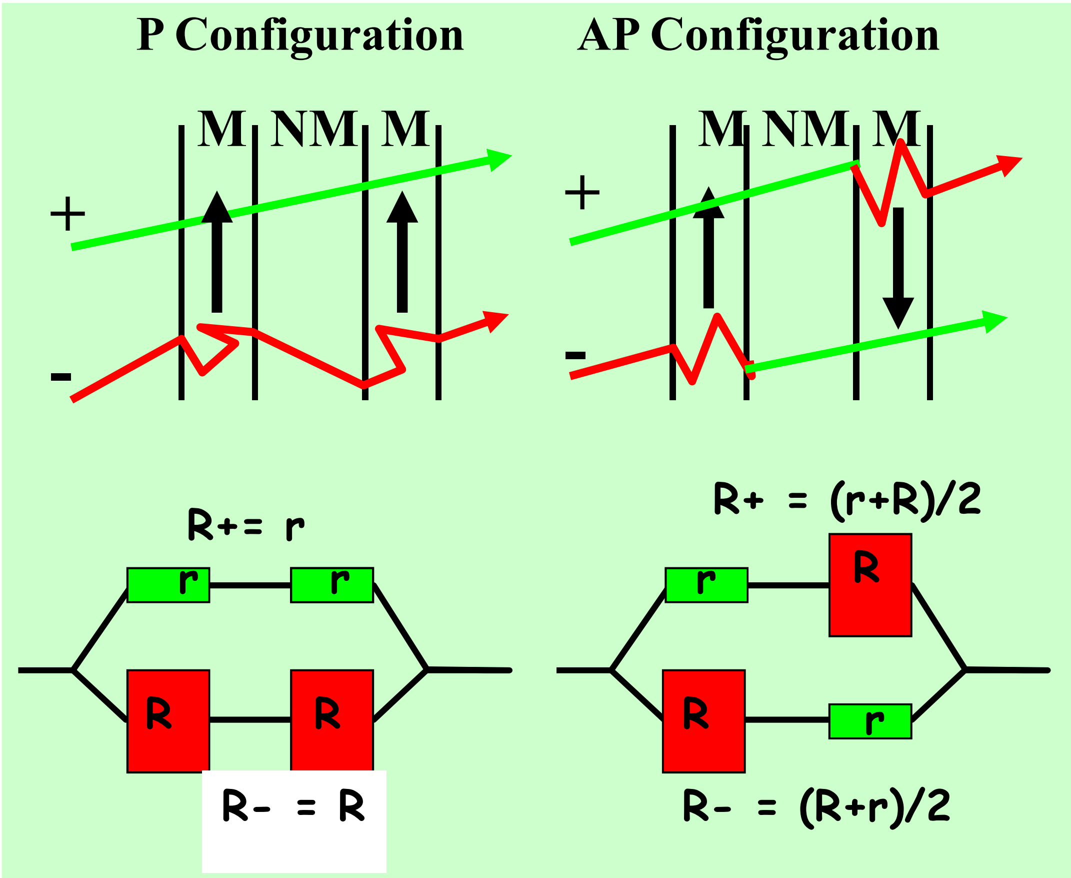
Spin asymmetry coefficient

$$\alpha = \frac{\rho\downarrow}{\rho\uparrow}$$

❑ GMR Mechanism: Resistor model

Validity:

CIP: mean-free paths of the electrons >> thickness of the various layers
CPP: thickness << spin diffusion (flip) length



$$R_P = \frac{Rr}{R+r} \approx r < R_{AP} = \frac{R+r}{4}$$

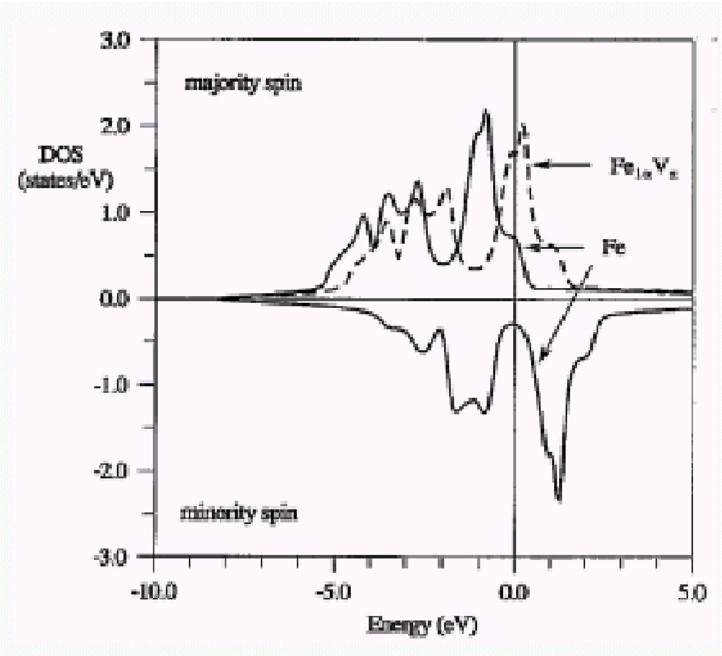
$$\frac{\Delta R}{R_{AP}} = \left(\frac{R-r}{R+r}\right)^2$$

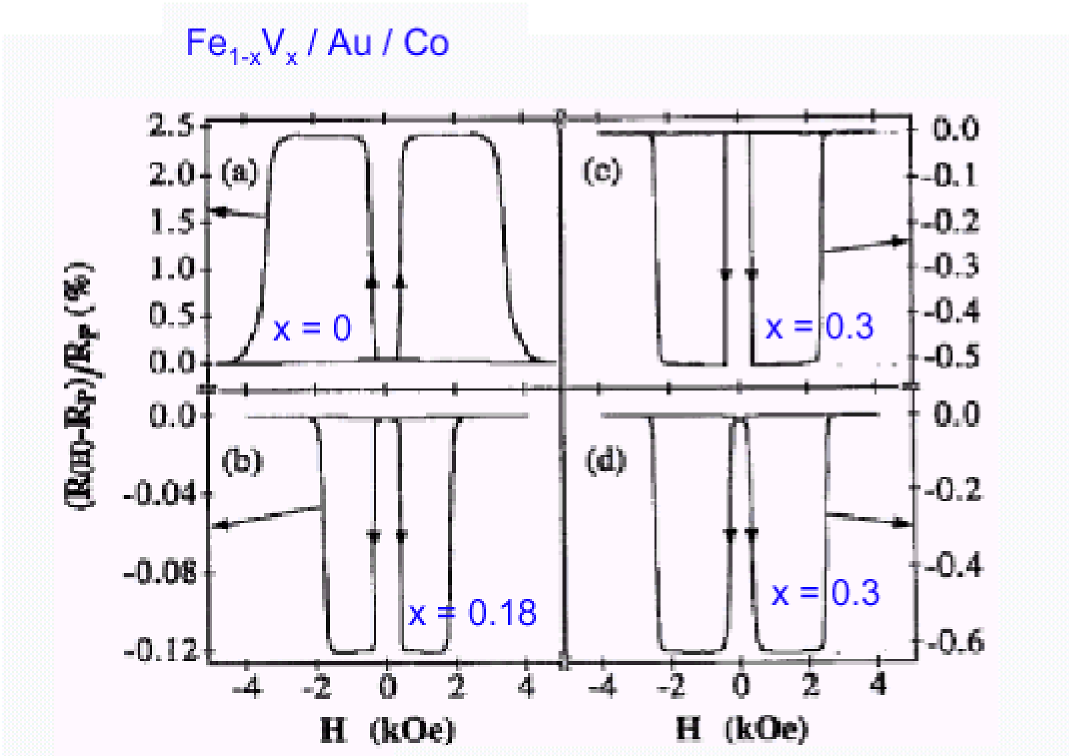
$$\frac{\Delta\rho}{\rho_P} = \frac{(1-\alpha)^2}{4\alpha}$$

! key role of spin scattering asymmetry in the origin of the GMR

Key role of spin scattering asymmetry in the origin of the GMR

Dependent on DOS(E_F)





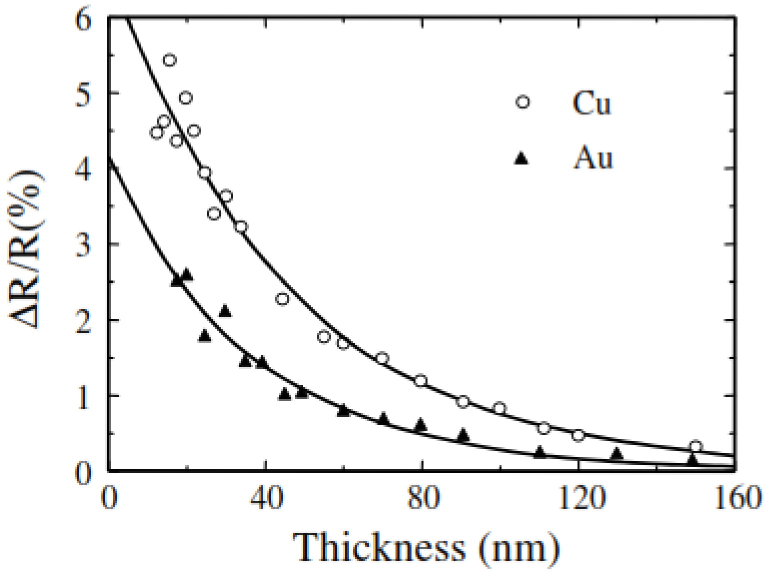
Renard *et al.*, PRB **51**, 12821 (1995)

GMR: More accurate approach: remember G. Bauer (1)

spin dependent interface transmission probabilities, k resolved transmissions

GMR Mechanism

Nonmagnetic layer thickness dependence



$$\frac{\Delta R}{R} = \left(\frac{\Delta R}{R}\right)_0 \frac{\exp(-d_{NM}/l_{NM})}{(1+d_{NM}/d_0)}$$

B . Dieny et al, J. Appl.Phys. 69, 4774, (1991)

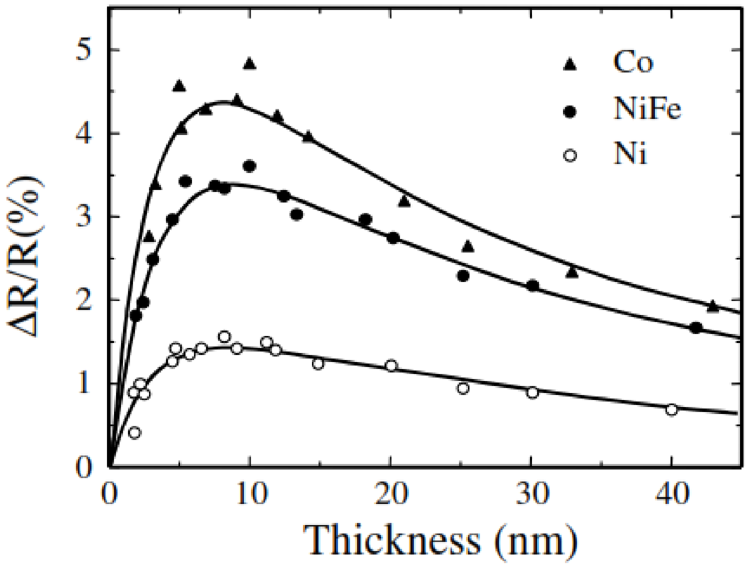
Phenomenological expression containing significant part of involved physics

Si/Co(7nm)/NM(d_{NM})/$Ni_{80}Fe_{20}$(5nm)/$Fe_{50}Mn_{50}$(8nm), NM=Cu, Au
where $l_{NM}=\lambda_{NM}/2$, d_0 –effective thickness
λ =mean free paths for electrons scattering

Fitting experimental data one can determine decay lengths
e.g. l_{Cu}=6nm and l_{Au}=5nm
determined by scattering in the spacer (phonons, grain boudaries, deffects) correlated with λ_{NM}

❑ GMR Mechanism

Magnetic layer thickness dependence



$$\frac{\Delta R}{R} = \left(\frac{\Delta R}{R}\right)_0 \frac{1-\exp(-d_{FM}/l_{FM})}{(1+d_{FM}/d_0)}.$$

B.Dieny et al, Phys.Rev. B ***45,*** *806 (1992).*

Phenomenological expression containing significant part of involved physics

➡ Fitting experimental data one can determine decay lengths

FM(d_{FM})/Cu(2.2nm)/$Ni_{80}Fe_{20}$(5nm)/$Fe_{50}Mn_{50}$(8nm)/Cu(1.5nm), FM=Co, NiFe, Ni
where $l_{FM}=\lambda_{FM}/2$, d_0 –effective thickness

Roughness dependence

interfacial roughness drastically influence GMR due to the influence on the spin-dependent scattering (*recall G. Bauer 1/1 –spin dependent interfacial transmission*)

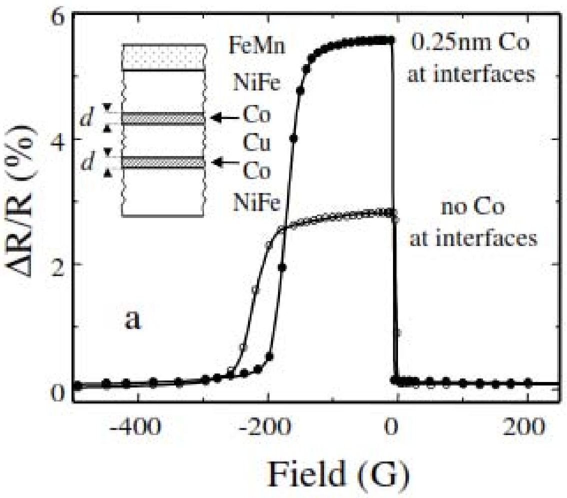
Impurity dependence

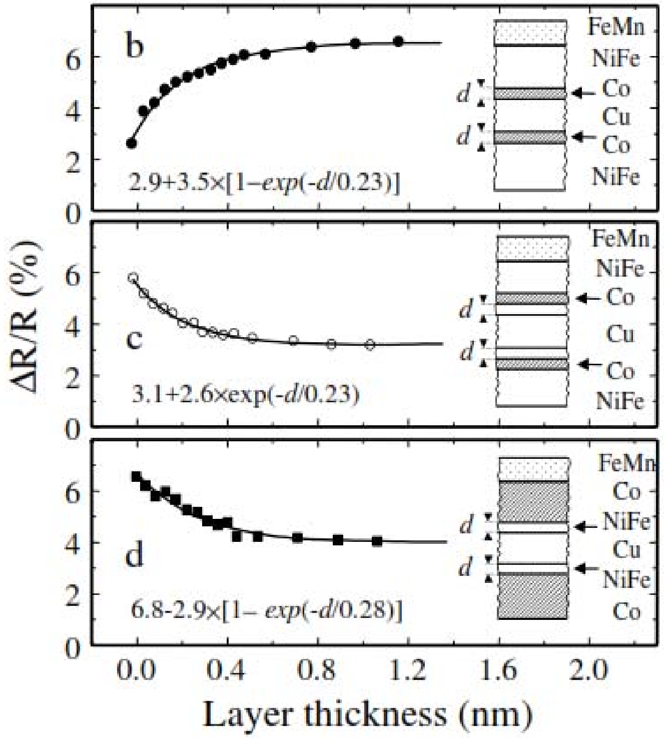
tunning asymmetry of scattering rates in the up/dn conduction channels by introducing impurities both in bulk of FM or at interfaces

Effect of a thin layer inserted at the interfaces in spin valves

- Non-magnetic layers at interface are source of strong spin-independent scattering and can drastically reduce GMR
- Dead-layers same.
- Placing thin FM layers (Co) at interface enhances GMR

  enhance spin polarization and magnetic properties (reduced Ni moments and noncolinear Fe moments at inter-diffused NiFe/Cu interfaces reduce GMR).





S.S.P. Parkin, Phys. Rev. Lett. ***71****, 1641 (1993).*

Si/NiFe(5. 3nm) /Cu (3. 2nm) /
NiFe(2. 2nm) /FeMn (9nm) /Cu (1nm)

Nano-oxide layers at interfaces enhance GMR

Complex Physics intrinsic (band structure) and extrinsic (diffusion, scale lengths) aspects

Temperature dependence

! Important for potential applications

Many experiments found GMR decreasing with increasing T

$GMR_{4.2K}/GMR_{RT}$~ 2 – 3 (Fe/Cr -> 3.1 Co/Cu -> 1.8)

*F. Petroff, A .Barthelemy, A. Fert et al, J. Magn. Magn. Mat . **93**, 95 (1991).*
S. S. P. Parkin , et al, Appl.Phys. Lett. 58, 2710 (1991).

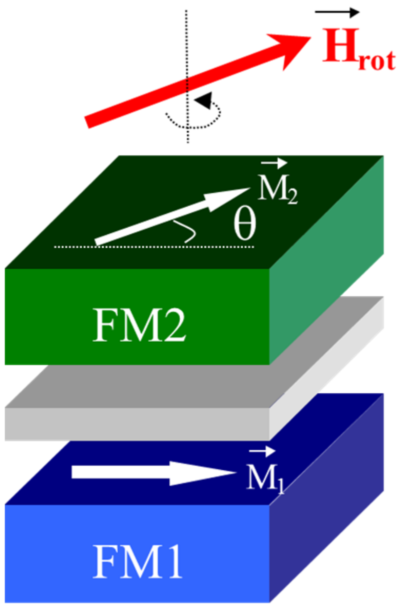
Major factors (detrimental for GMR in T):

- ✓ inelastic scattering by phonons in NM (spin conserving) but
  enhancing saturation resistivity of multilayers
  shortening mean-free path in NM spacer layer

- ✓ inelastic scattering by phonons in FM (spin dependent)

- ✓ electron-magnon scattering (=>spin-flip) reduces GMR at high T
  (less sigificant at RT for FM with high T_{Curie})
  temperature dependent spin flips on ”loose” spins (presence of roughness/interdiffusion at interfaces reducs moment s and magnetic nearest neighbours)

Angular dependence



- HDD read heads
- Non-volatile storage elements
- HF oscillators
- Logical gates…

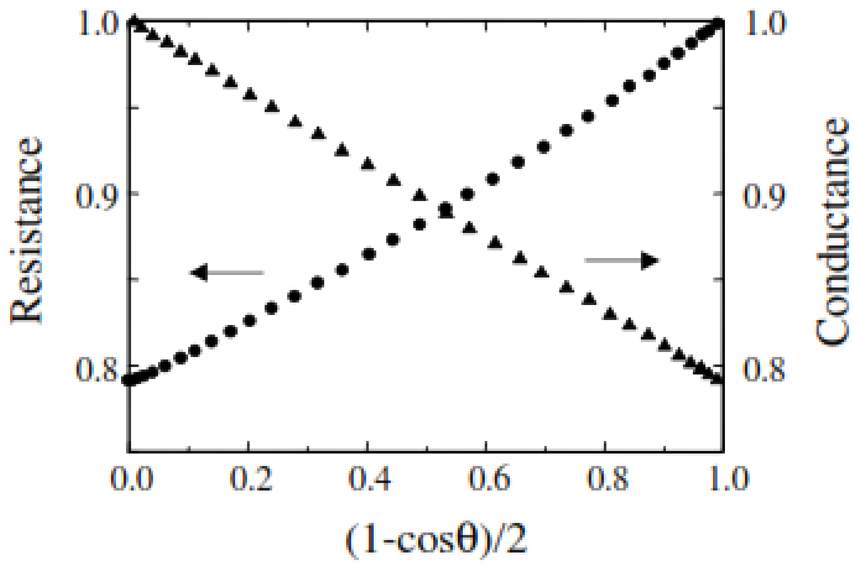
Automotive sensors (ABS) (SIEMENS)

Phenomenologically

$$R(\theta) = R_P + \left(R_{AP} - R_P\right)\frac{1-\cos(\theta)}{2}, \qquad \theta = (\vec{M}_1, \vec{M}_2)$$

Dieny et al, Phys. Rev. B 43, 1297 (1991)

and theoretical QM approach (fee-electrons, ab-initio…)
roughly valid for both CIP and CPP GMR geometries

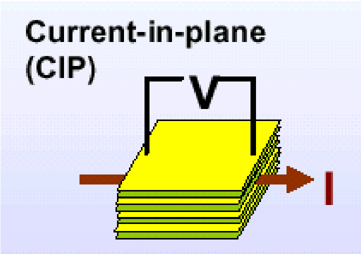


[Co(0.4nm)/A g(4nm)/N iFe(4nm)/A g(4nm)]$_{15}$ multilayer

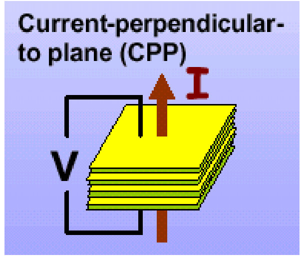
L . B.Steren et al, J.Magn. Magn. Mat. ***140-144****, 495 (1995); Phys.Rev. B* ***51****, 292 (1995).*

Comparing CIP-GMR and CPP GMR

Length scales and spin polarized transport mechanisms are different



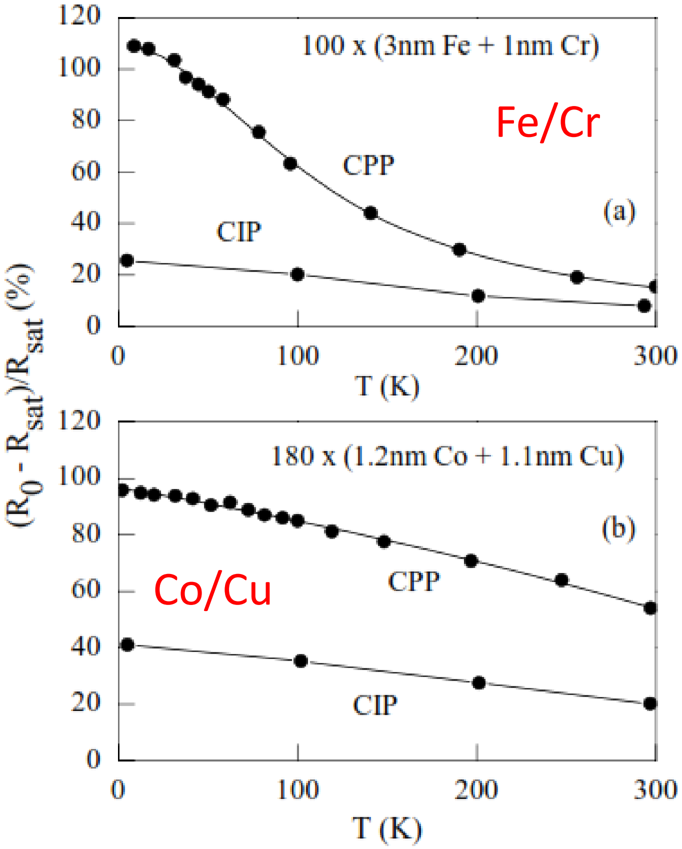
CIP-GMR
mean free paths (λ)
for electrons scattering
in FM-metal ($\lambda_{FM}^{\uparrow}$ and $\lambda_{FM}^{\downarrow}$)
and the NM metal (λ_{NM})



CPP-GMR
spin diffusion lengths
in FM (l^{sf}_{FM})
and NM (l^{sf}_{NM})

Relative weightning of bulk and
Interface scattering contribution
Differ from CIP to CPP-GMR

➡ *no direct correlation,*
for same multilayer
structure different effects



$\Delta R/R_P$ vs temperature T,
for nanopillar multilayers of :
(a) FeCr, and (b) Co/Cu

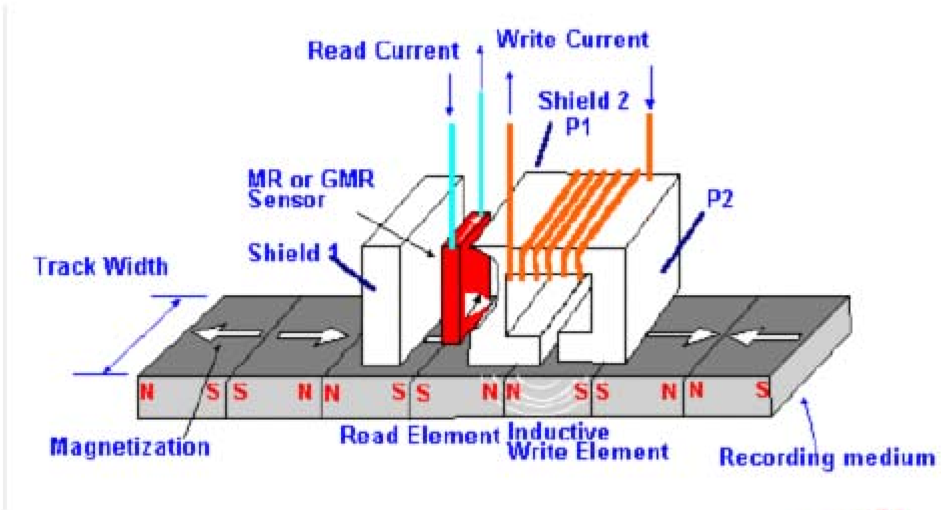
M. A. M. Gijs et al,
Phys. Rev. Lett. 70 , 3343 (1993);
J. Appl. Phys. 75, 6709 (1994)

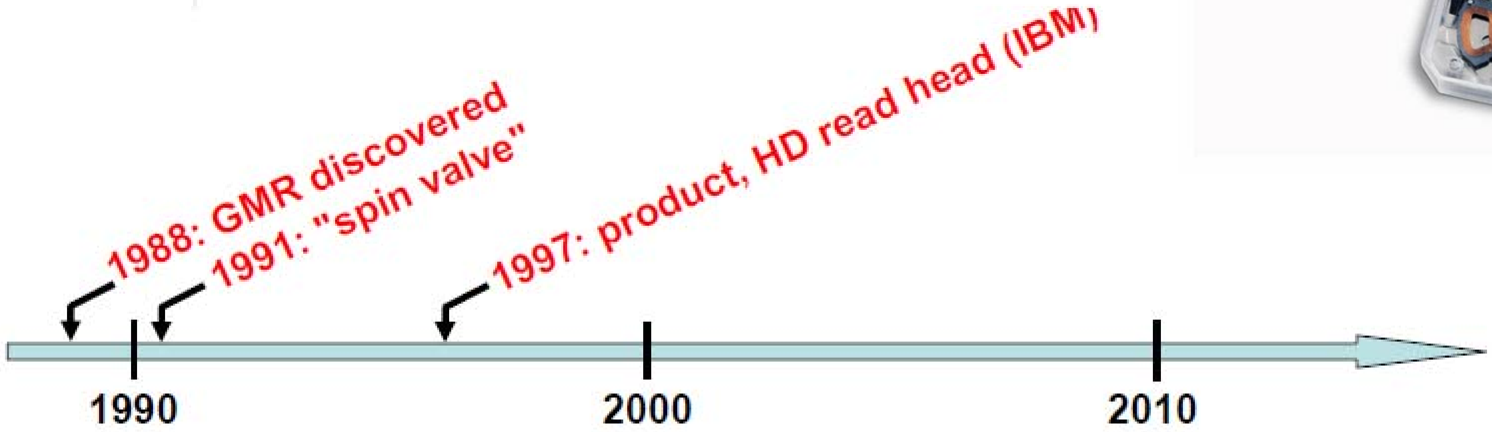
J. Bass et al,
J Magn. Magn. Mater. 200, 2
74 (1999).

Heusler based GMR-SV: large CPP-GMR vs small CIP-GMR (RT)

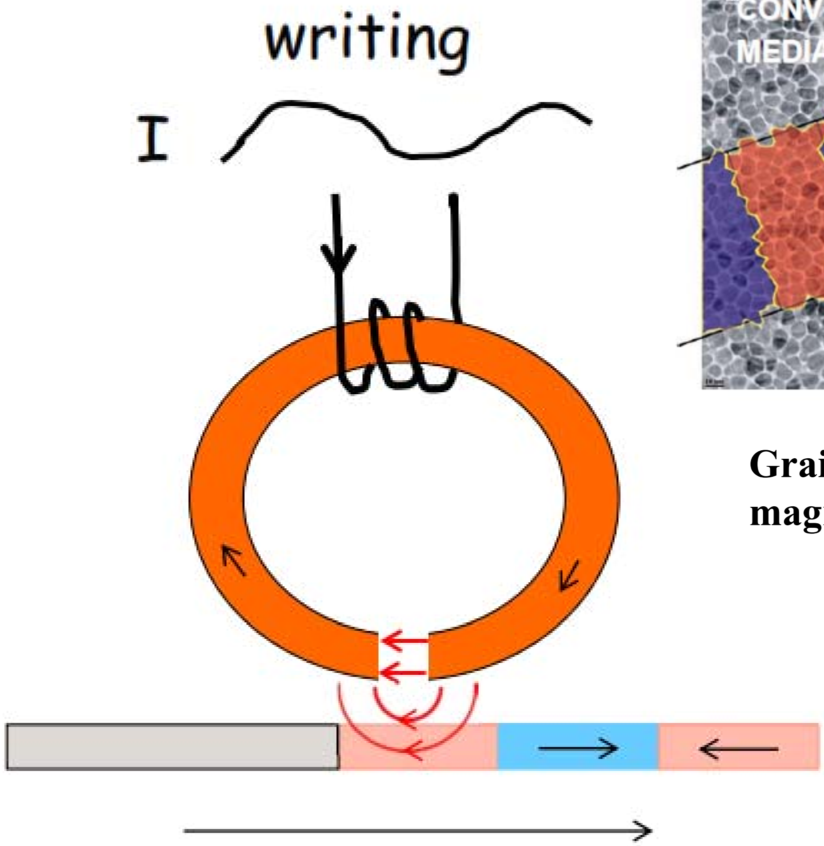
❑ GMR – Applications - READ HEADS/HDD

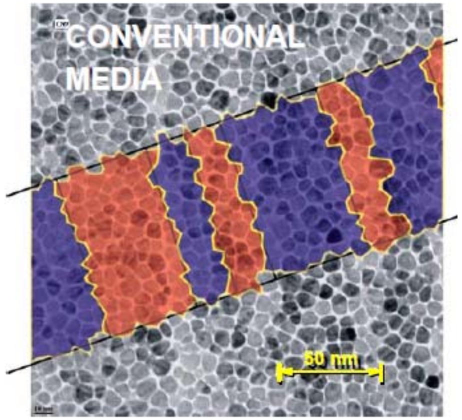
The first "Spin Electronics" product: the "spin valve" read head in hard disk



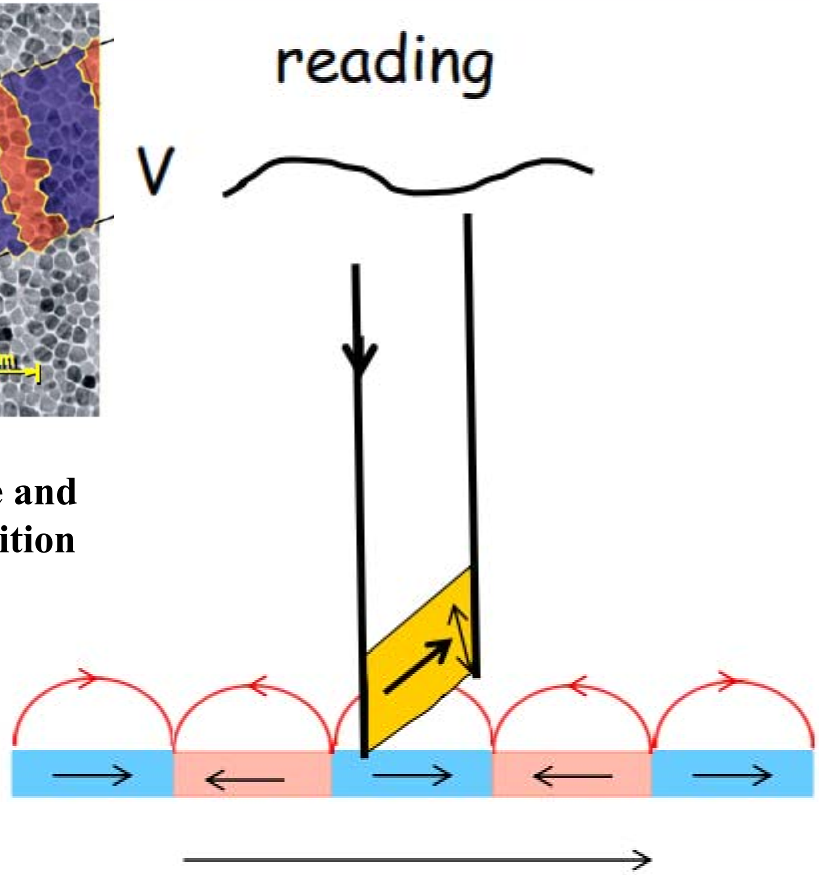


Magnetic recording

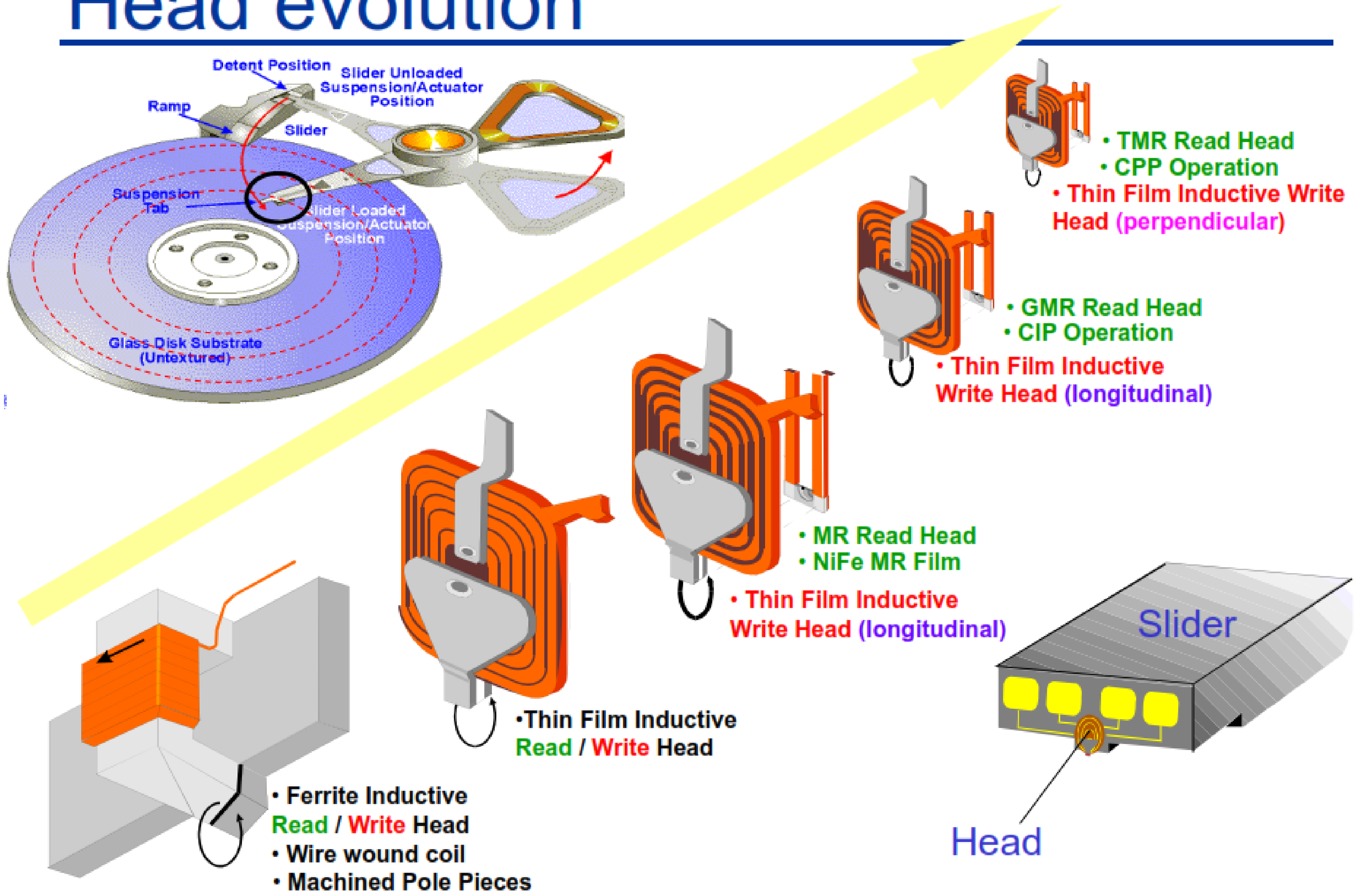


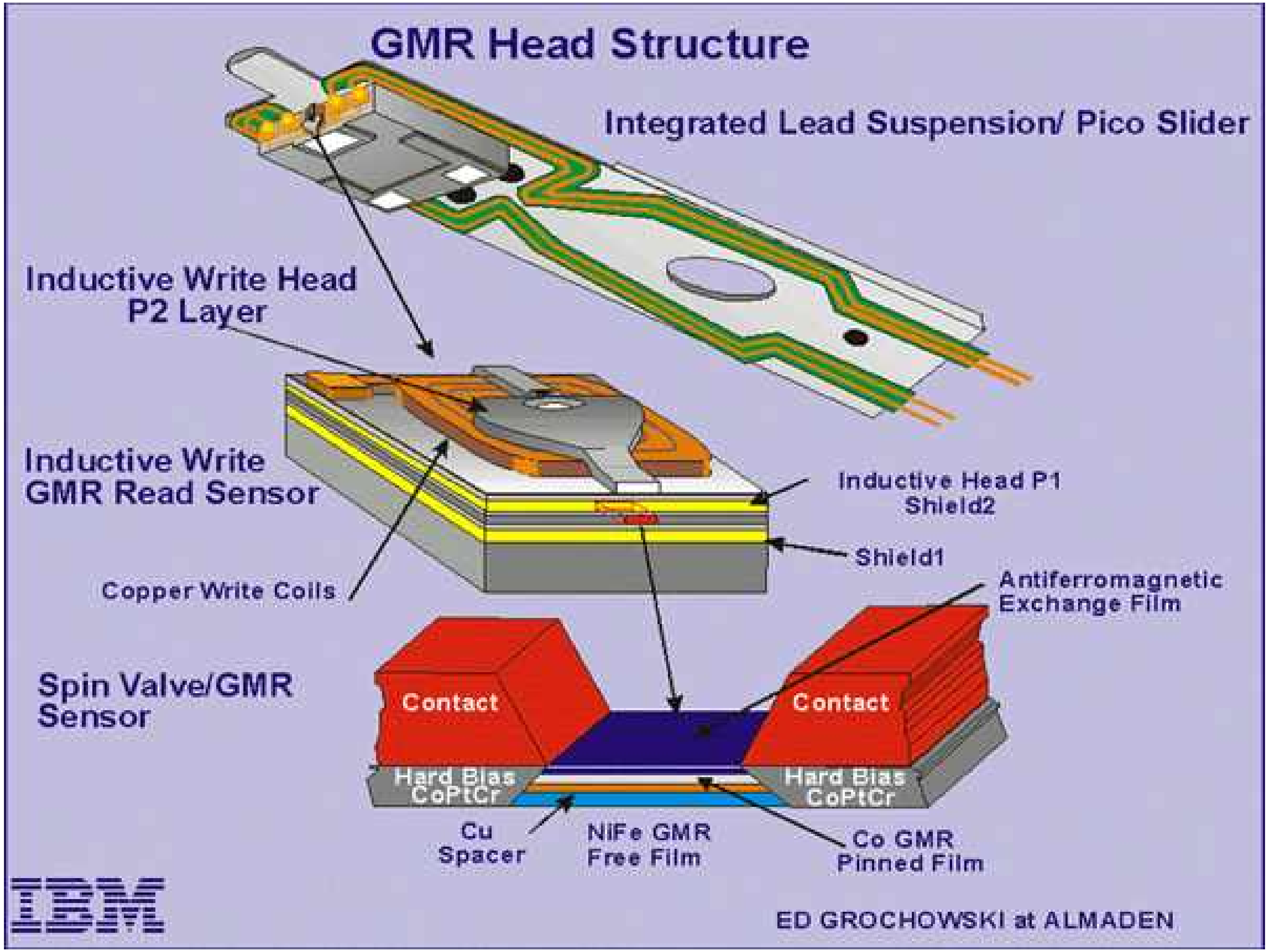


Grain structure and magnetic transition



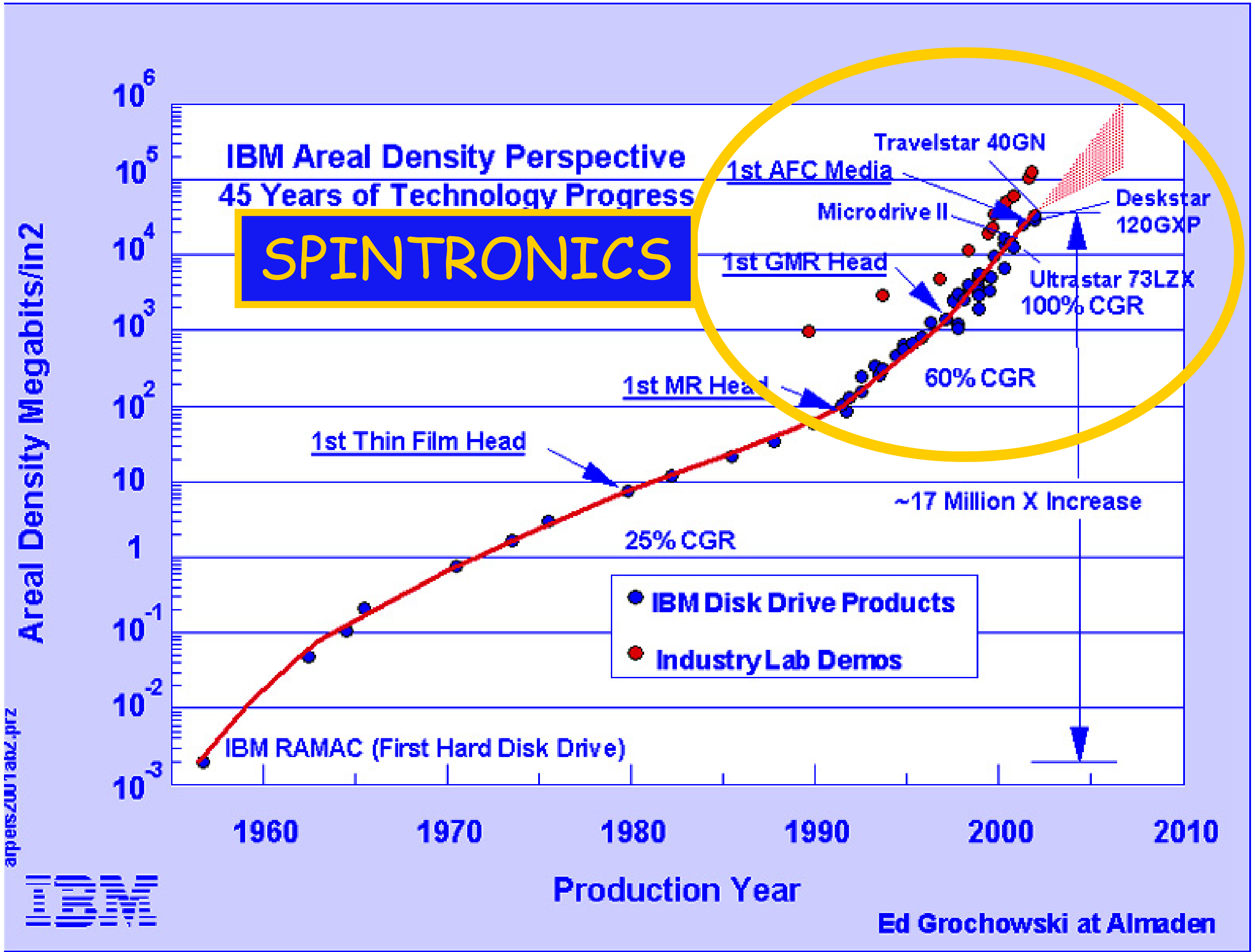
Head evolution



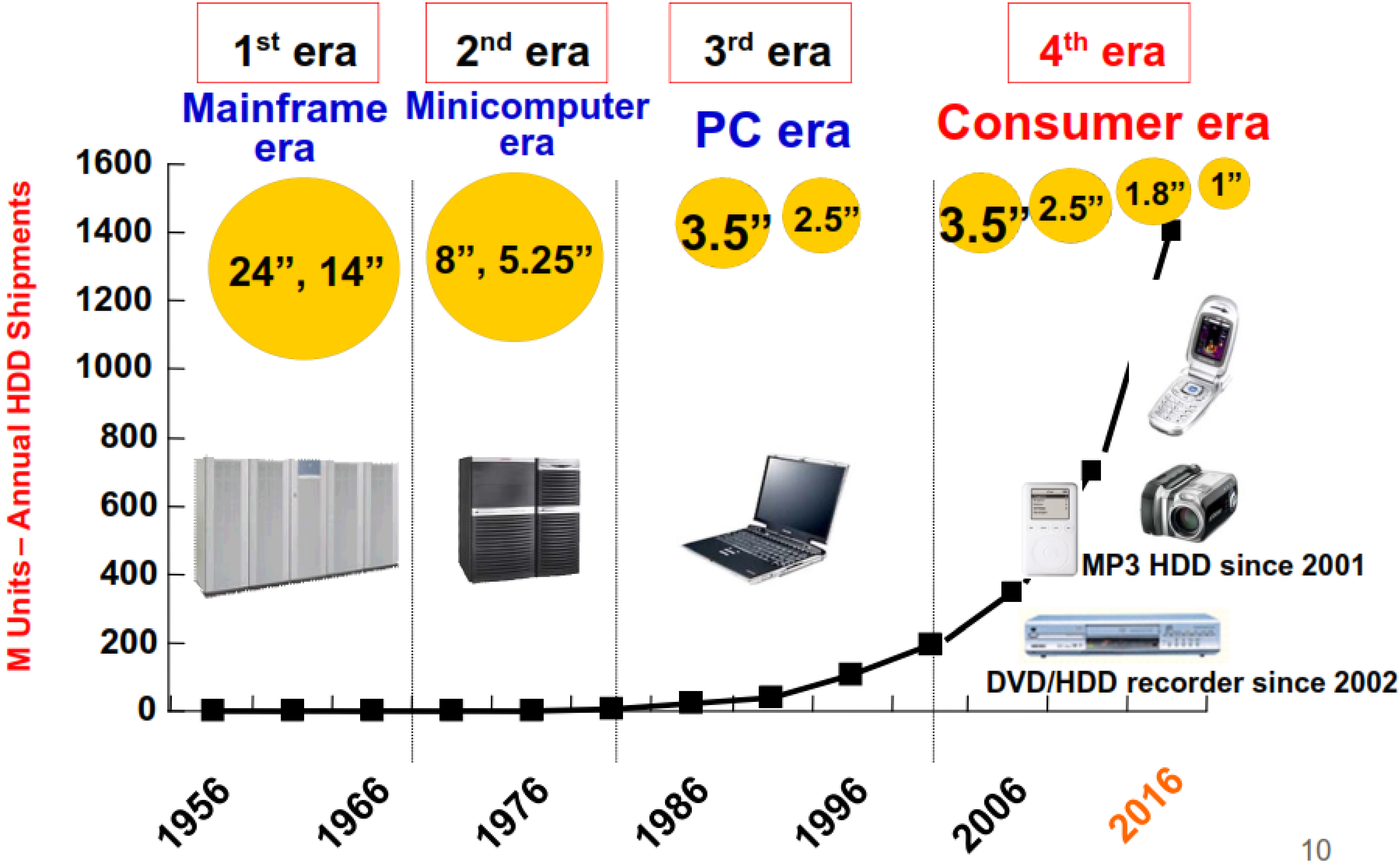

GMR Head Structure
Integrated Lead Suspension/ Pico Slider
Inductive Write Head
P2 Layer
Inductive Write
GMR Read Sensor
Inductive Head P1
Shield2
Shield1
Copper Write Coils
Antiferromagnetic
Exchange Film
Spin Valve/GMR
Sensor
Contact
Contact
Hard Bias
CoPtCr
Hard Bias
CoPtCr
Cu
Spacer
NiFe GMR
Free Film
Co GMR
Pinned Film
IBM
ED GROCHOWSKI at ALMADEN

Impact of GMR read-heads in storage areal density increase

Moore law

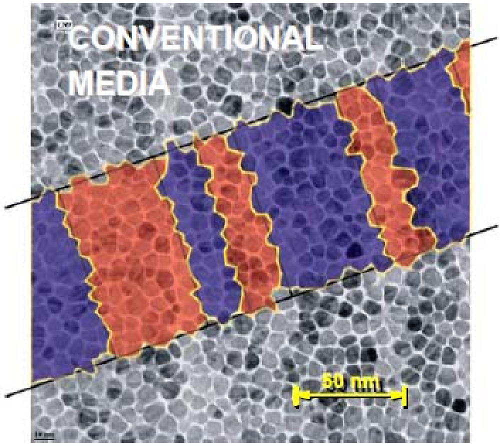


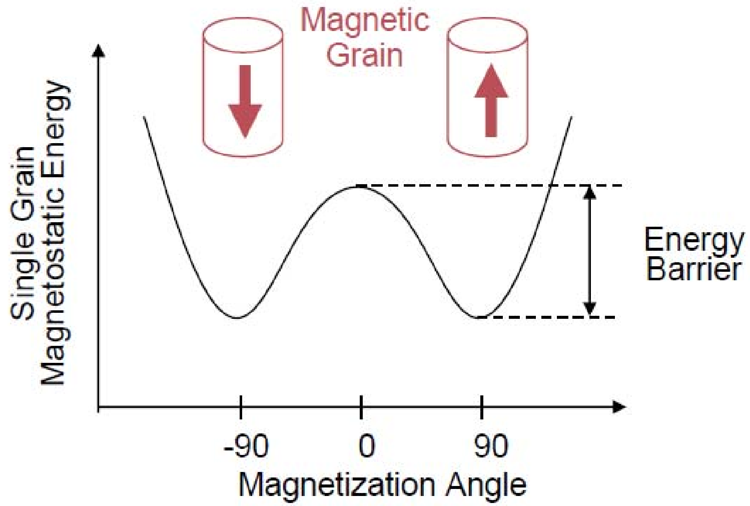
Drive applications



Writeability, Thermal Stability, and SNR

HITACHI
Inspire the Next





Magnetic Stability:

$$\frac{\text{energy barrier}}{\text{thermal energy}} \propto \frac{\text{anisotropy x volume}}{k_B \text{ x temperature}} = \frac{K_u V}{k_B T}$$

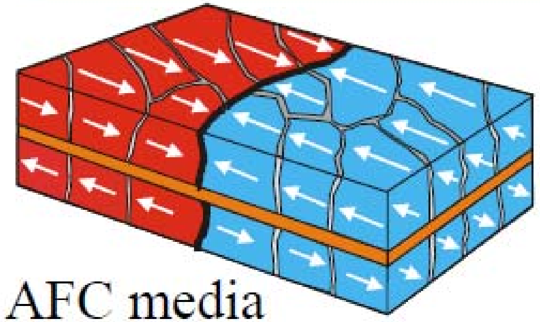
Problem:

- To increase SNR, need small grains.
- Smaller grains are thermally unstable.
- To avoid thermal instability, increase grain anisotropy Ku.
- This increases the medium coercivity and makes the medium difficult to write.

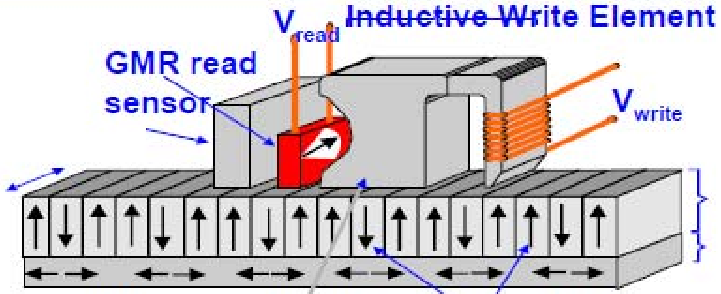
Solutions:

- Capped and exchange spring media.
- Work with larger 'grains': patterned media.
- Work with higher anisotropy: thermally assisted recording (TAR).

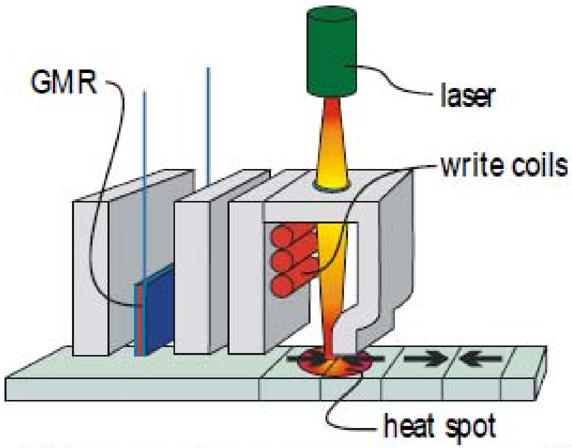
Advanced media and systems



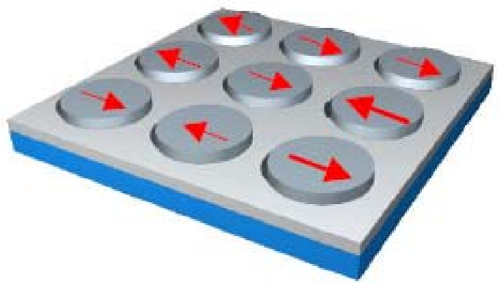
AFC media



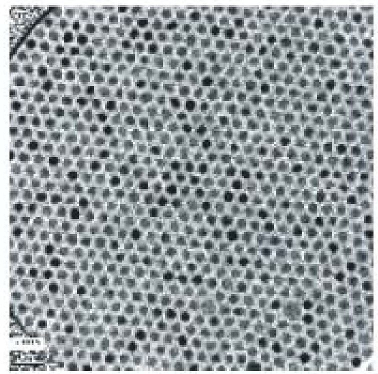
Perpendicular recording



Thermal assisted recording

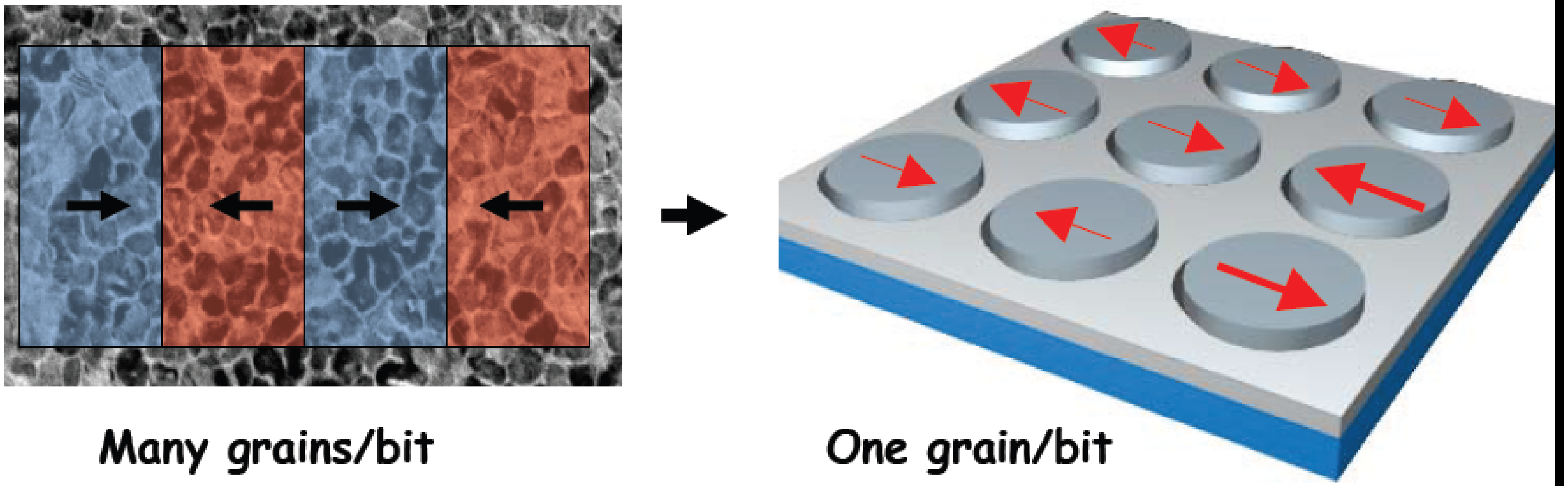


patterned media



self-organized media

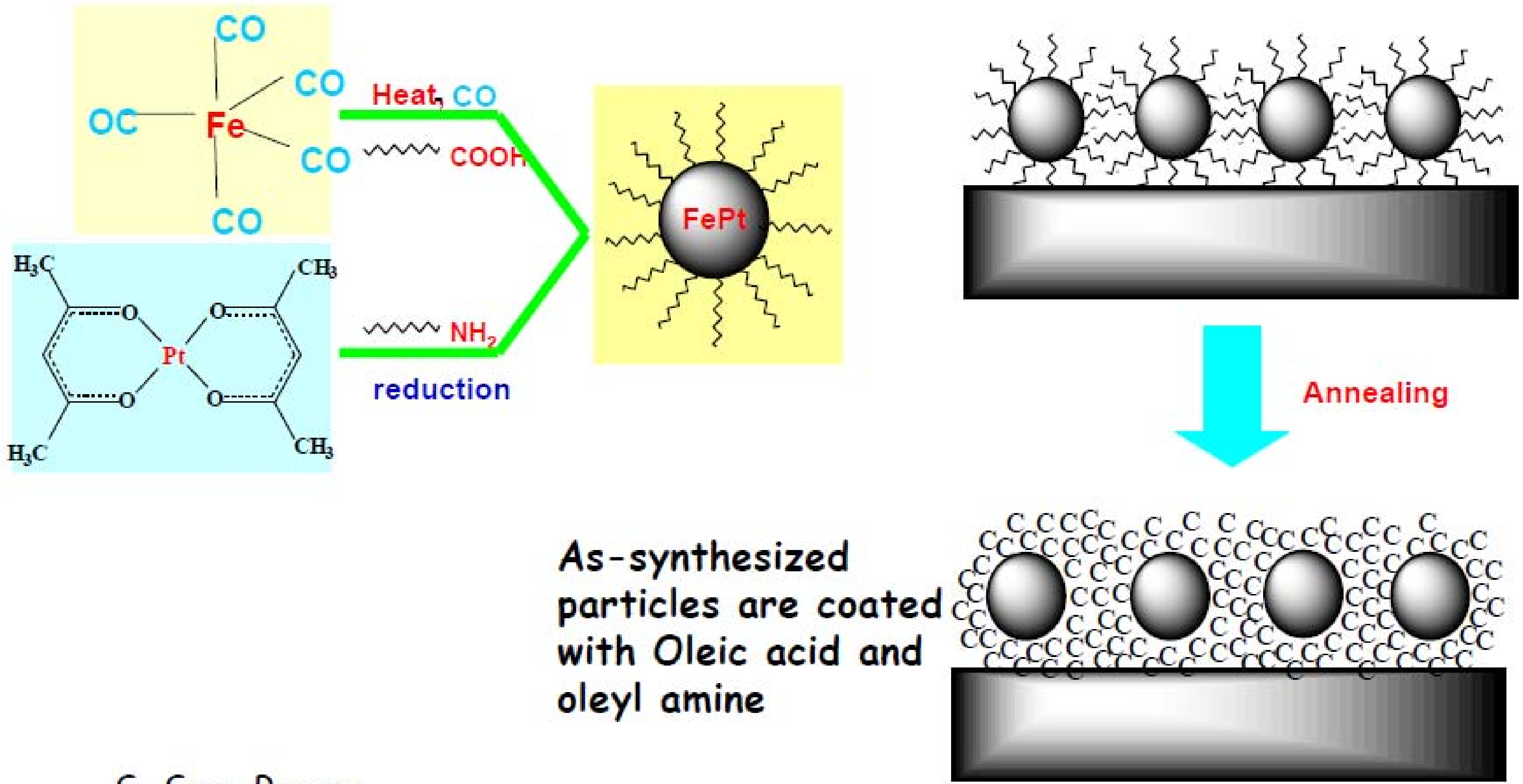
Patterned media



Many grains/bit   One grain/bit

- Bit Pattern Defined By Lithography
- Ultimate Structure – 1 Grain of Magnetic Alloy/Bit

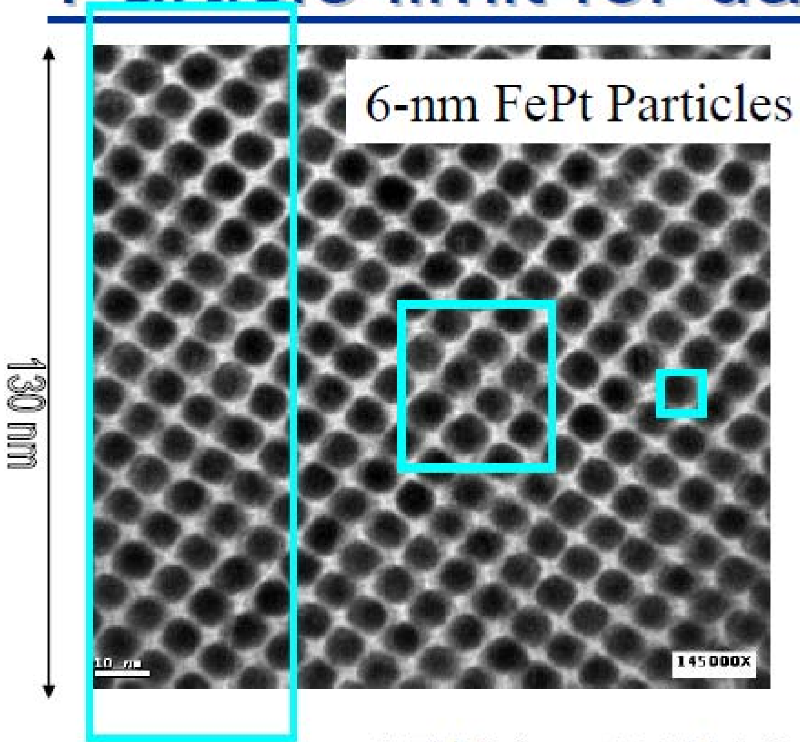
Self-assembly + annealing



As-synthesized particles are coated with Oleic acid and oleyl amine

S. Sun, Brown

Particle limit for data storage



100 Gbit/in^2 bit cell ~130 particles 4:1

1 Tbit/in^2 bit cell ~13 particles 1:1

13 Tbit/in^2 bit cell ~1 particle 1:1

Assume 6 nm Particles in 7x7nm square array

density > 10 Tbit/in^2 possible

- **room temperature**
- **t^{max}~10 years**
- **K^{max}~2 10^8 erg/cc**

~2nm particles on 3x3nm : 50-70 Tbit/in^2

CPP-GMR sensor (e.g. HDD read-heads)

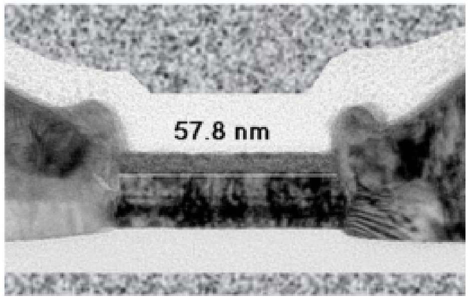
Highest GMR~65%(RT) CPP-GMR *SSP. Parkin et al, Applied Physics Letters, 58 (23), 2710, (1991).*

- ❑ However, **because the active length of these structures is the multilayer thickness**, usually much smaller than the typical device lateral dimensions, these structures exhibit very small resistances that would require either sub-micron fabrication or extremely sensitive electrical measurements and thus are not normally used as sensing devices.

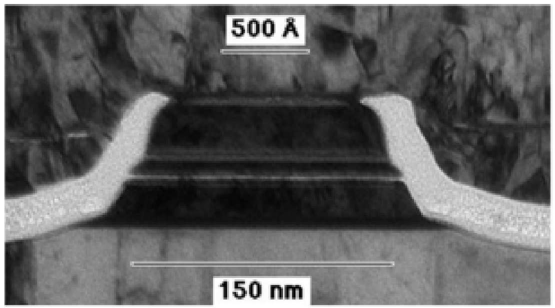
- ❑ **New regain in interest** for next generation HDD-read heads because extreme miniaturization requires MTJ with small RxA and large TMR, difficult to obtain…

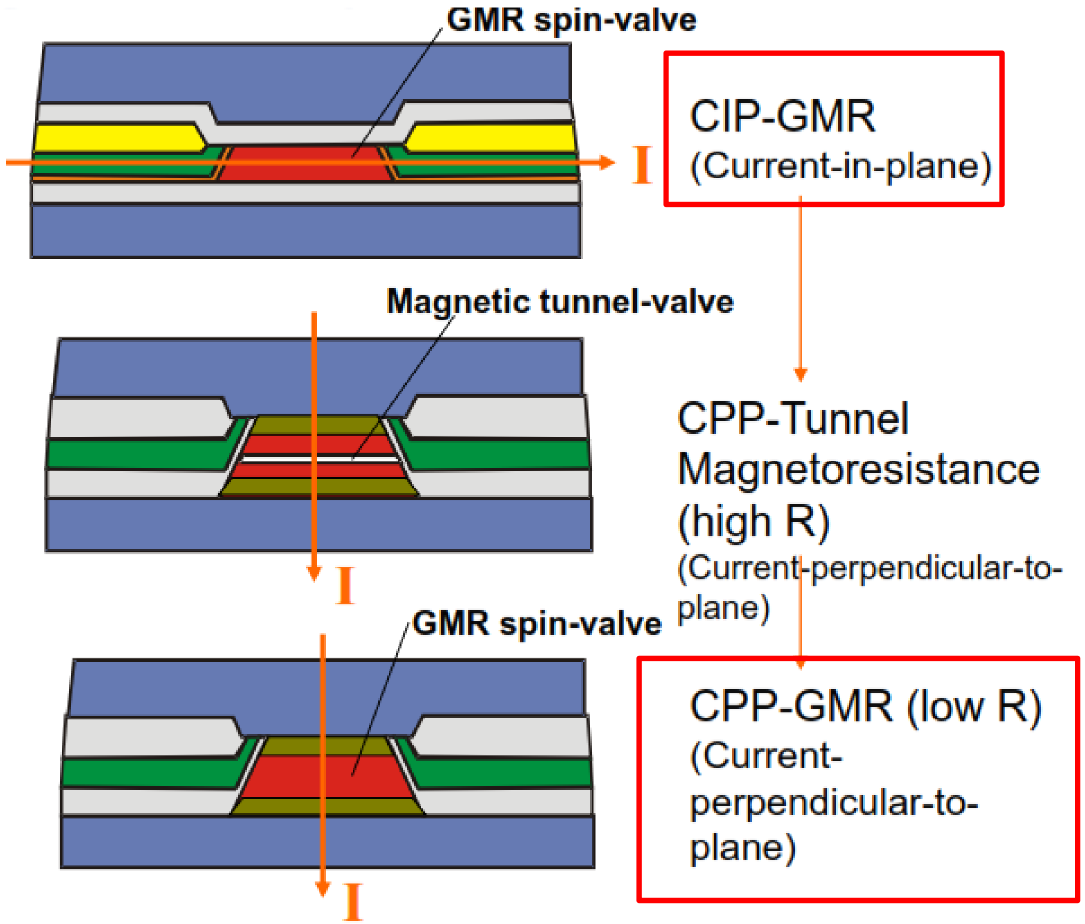
CPP-GMR sensor (e.g. HDD read-heads)

In absence of low RA tunnel barriers one moves back towards metal devices



Tunnel-valve head





Read Head Sensor Technologies

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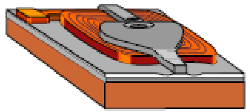
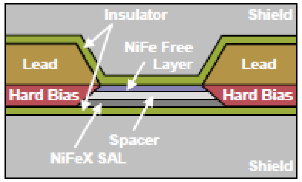
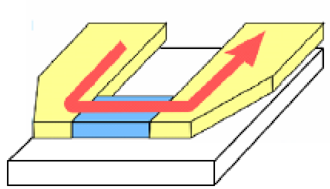
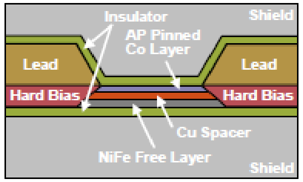
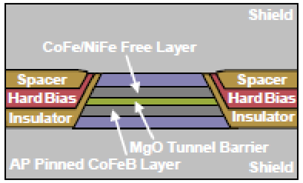
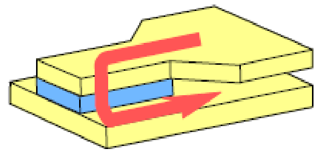
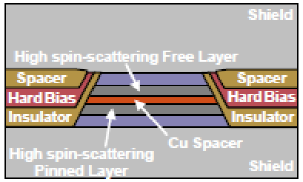
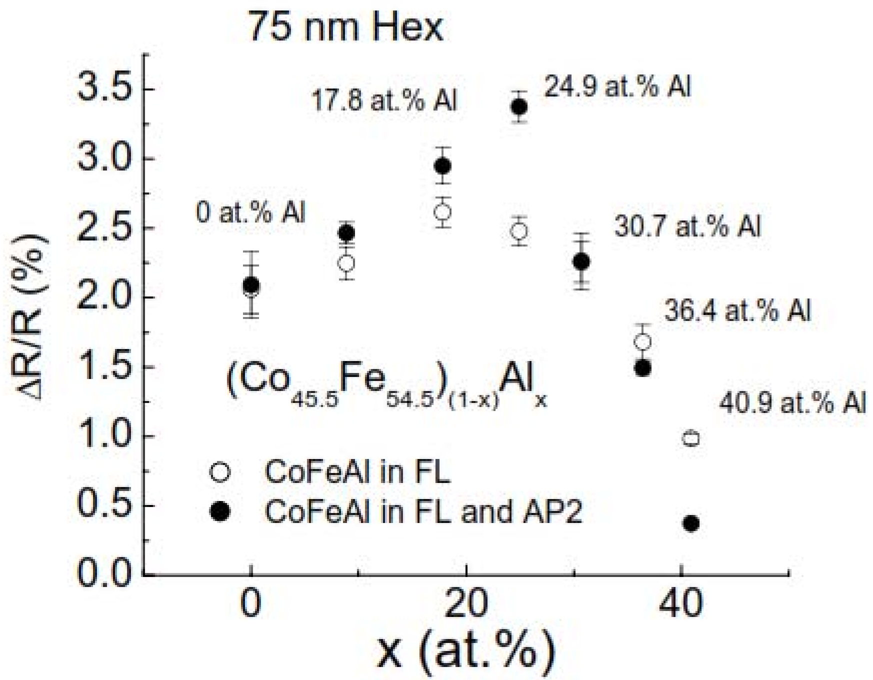
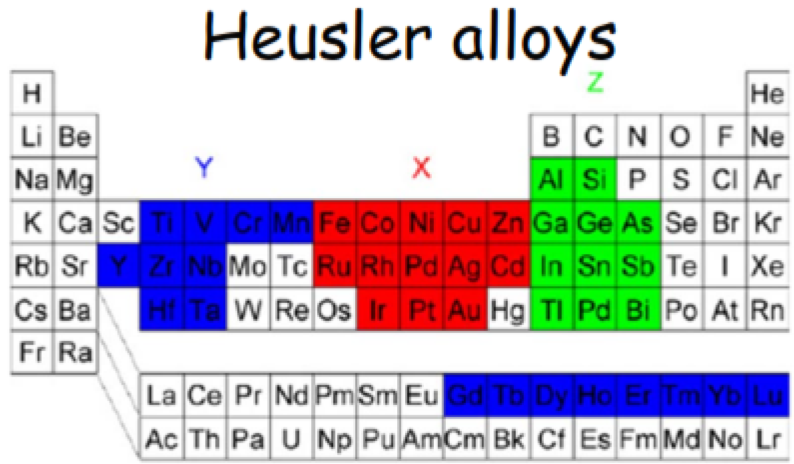
Year	Areal Density	Sensor Technology	Structure	MR Effect	Current Geometry	Major Noise Sources
1979	10 Mb/in^2 (LMR)	Thin-film Inductive		N/A	N/A	Barkhausen Johnson
1991	100 Mb/in^2 (LMR)	MR Sensor		Anisotropic MR	CIP (Current In Plane) Lead Lead  Bottom Shield	Johnson
1997	2 Gb/in^2 (LMR)	Spin Valve		Giant MR		Johnson
2006	100 Gb/in^2 (PMR)	Tunnel Valve		Tunneling MR	CPP (Current Perpendicular to the Plane) Shield  Shield	Johnson Shot Noise Mag Noise
2011	1 Tb/in^2 (PMR)	CPP GMR		Giant MR		Johnson Mag Noise Spin Torque

CPP-GMR sensor (e.g. HDD read-heads)

requires high resistance high spin-polarized FM materials





e.g. NiMnSb, CrFeAl, …

S. Maat et al, J. Appl. Phys.

Good candidates: large spin polarization
but low Gilbert damping => major magnoise
=> Damping artificial tuning, compromise GMR ratio/damping

Very active research field

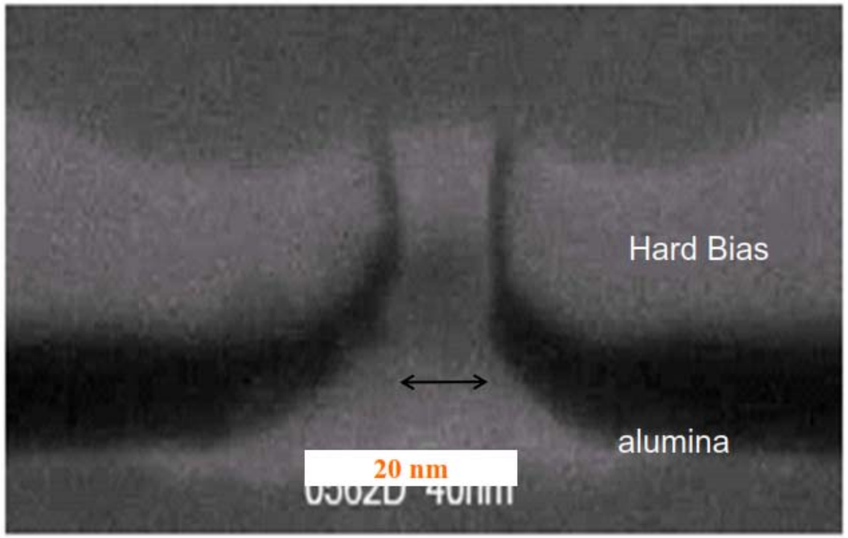
Advanced head?

- 1 Tbit/in^2 sensor design?

- cube of material roughly 30 nm per side
- generate a sufficient signal voltage (1mV)
- thermally stable
- current densities low enough so that spin-torque-driven excitations do not degrade the signal-to-noise ratio.

Katine and Fullerton, JMMM **320**, 1217 (2008).

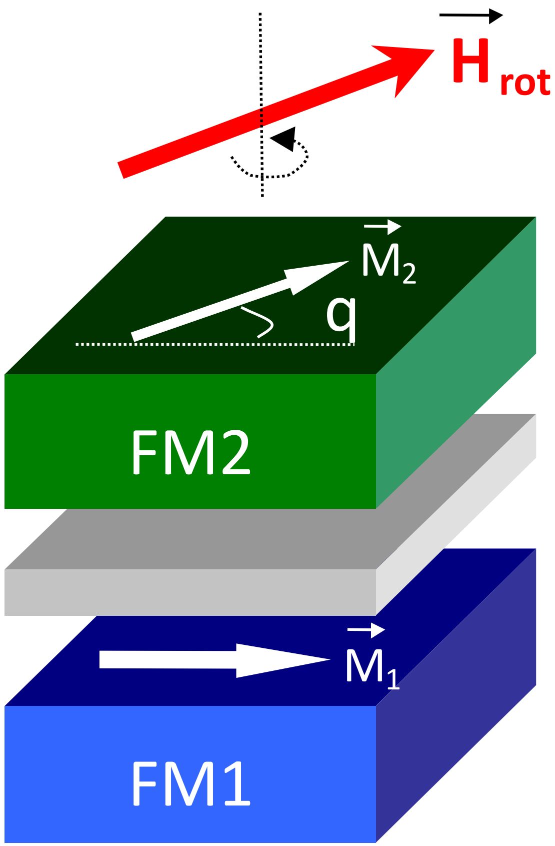
From E. Fullerton, *http://www.ijl.nancy-universite.fr/documents/colloques/14jan2011/documents/FullertonNancy2011.pdf*



CPP-GMR sensors with the resolution required for 1 Tb/in^2 recording have been built and tested.

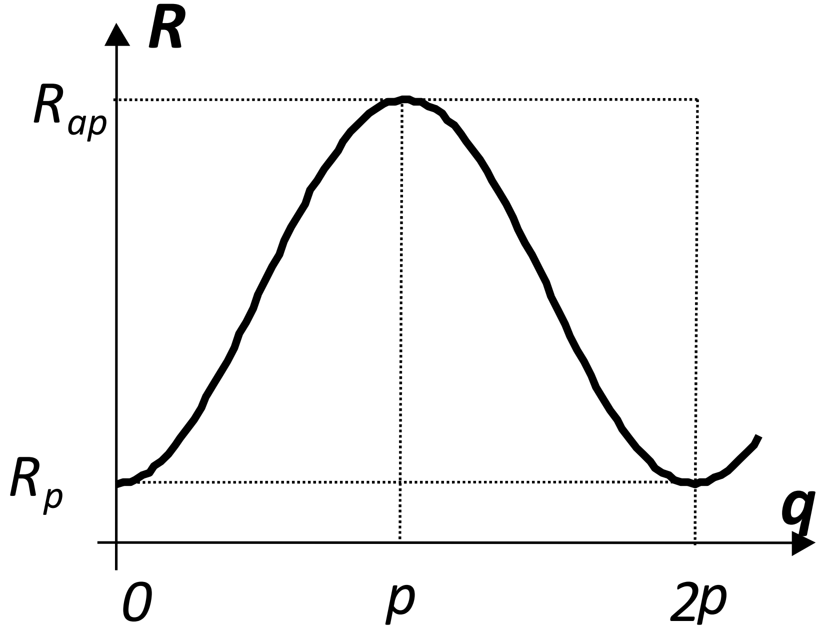
J. Katine, Hitachi

Application of spin-valves: GMR angular sensor

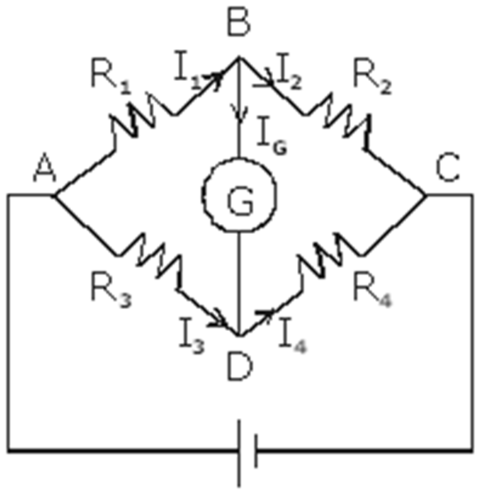


$$R = \frac{R_p + R_{ap}}{2} + \frac{R_p - R_{ap}}{2}\cos(\theta),$$

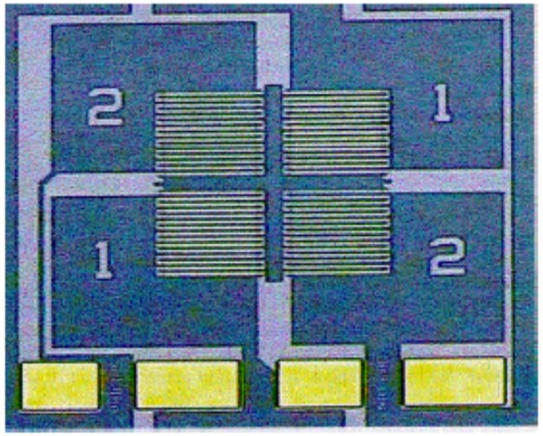
$$\theta = (\vec{M}_1, \vec{M}_2)$$

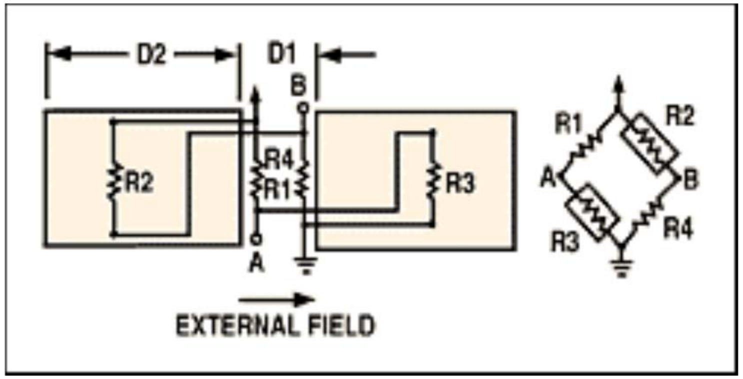


GMR circuit technique



Due to their outstanding sensitivity, Wheatstone Bridge Circuits are very advantageous for the measurement of resistance, inductance, and capacitance.



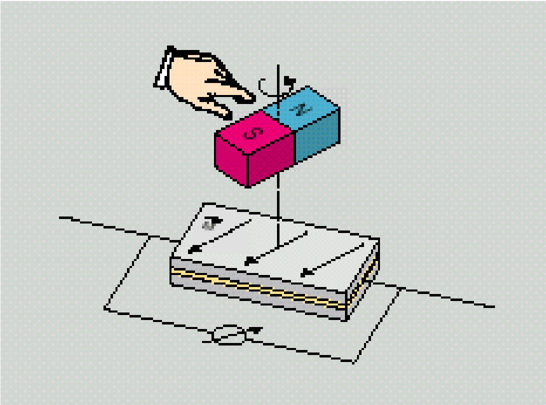


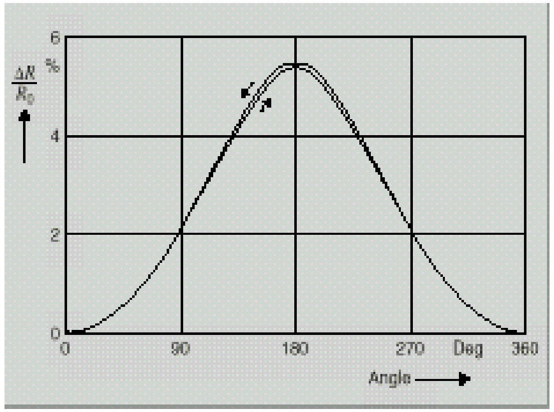
GMR resistors can be configured as a Wheatstone bridge sensor. Two of which are active. Resistor is 2 μm wide, which makes the resistors sensitive only to the field along their long dimension.

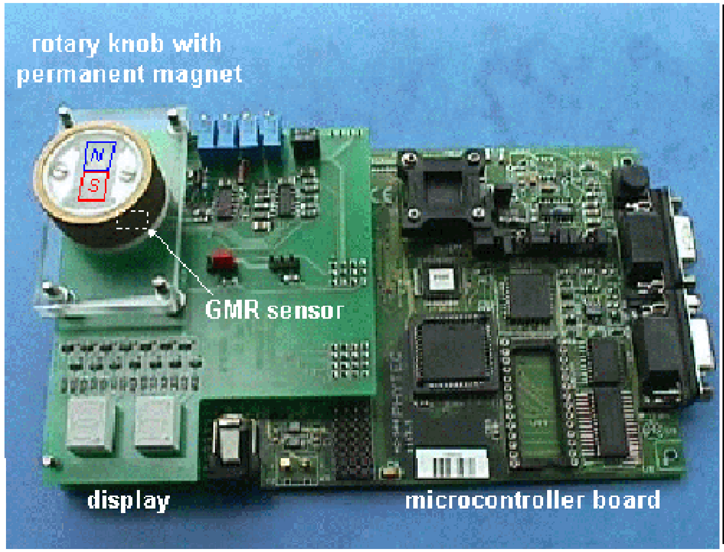
Application of spin-valves: GMR angular sensor

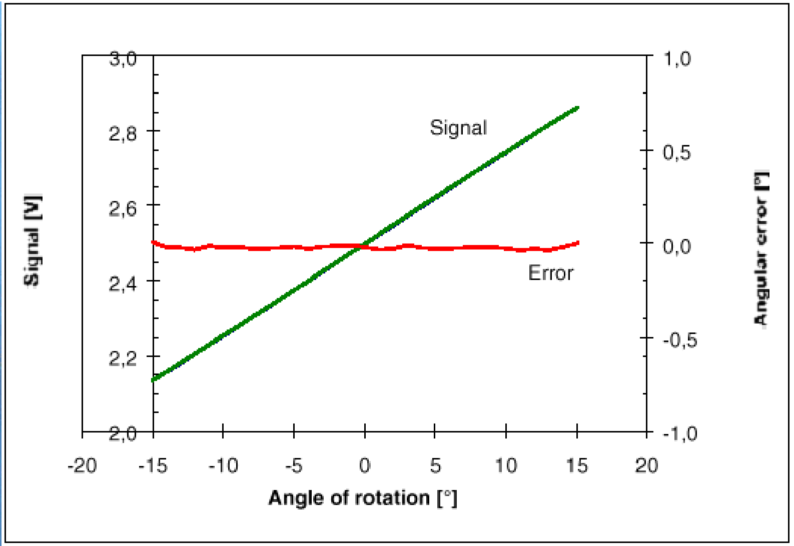
GMR angle detector: (spin valve)

H.A.M. van den Berg et al JMMM 165, 524, (1997)



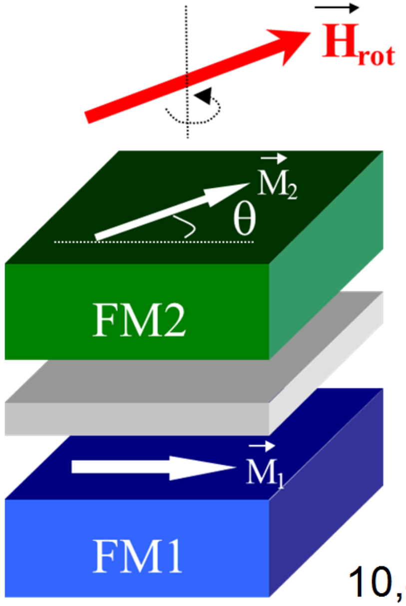




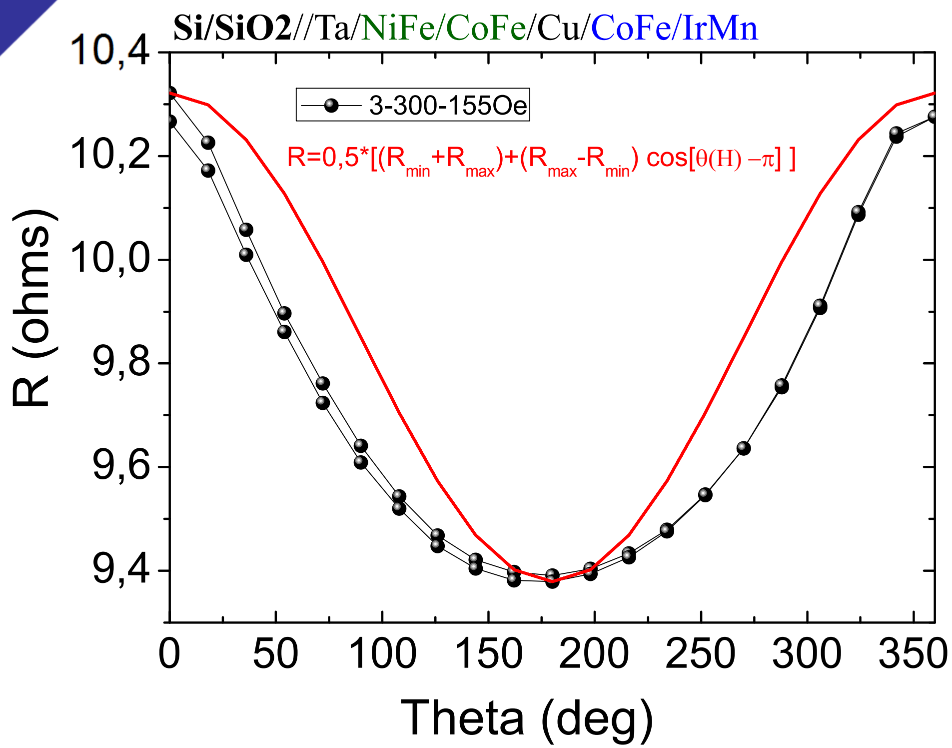


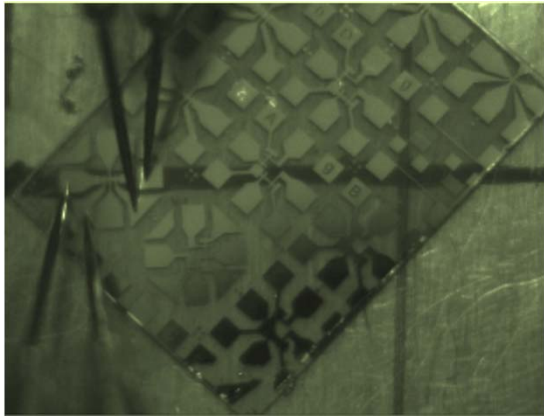
Siemens Aktiengesellschaft

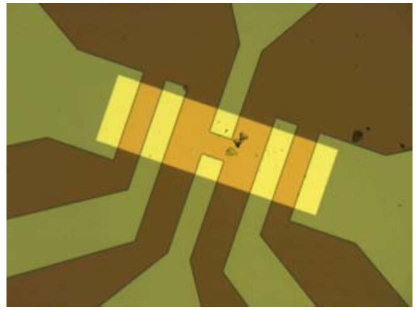
Angular dependence in spin-valves



$$R(\theta) = R_P + \left(R_{AP} - R_P\right)\frac{1-\cos(\theta)}{2},$$
$$\theta = (\vec{M}_1, \vec{M}_2)$$







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Cod SMIS-CSNR: 12467

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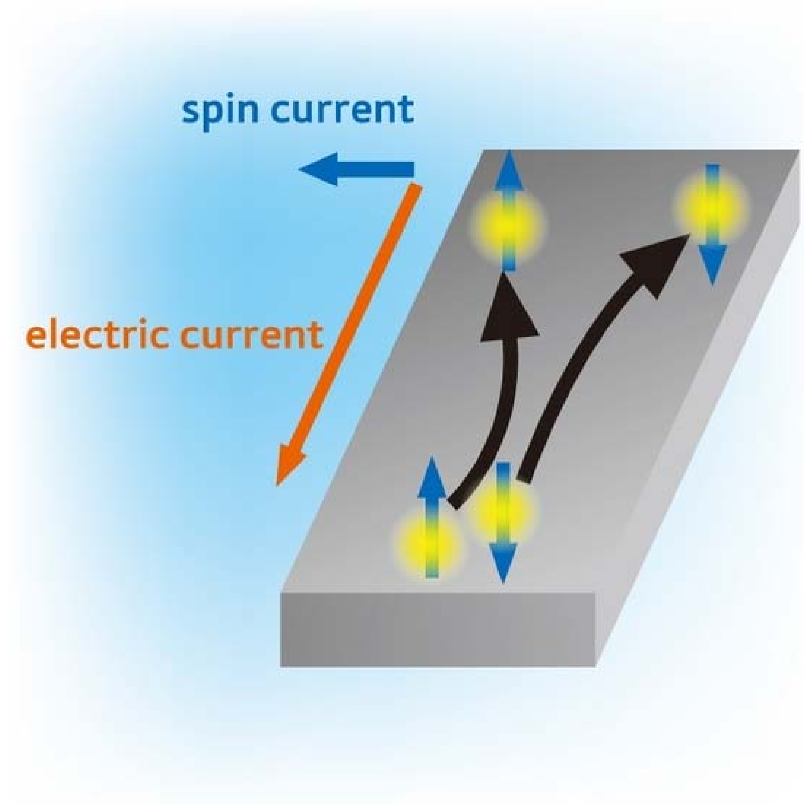
Instrumente Structurale 2007-2013

Anomalous Hall effect (AHE) and Spin Hall Effect (SHE)

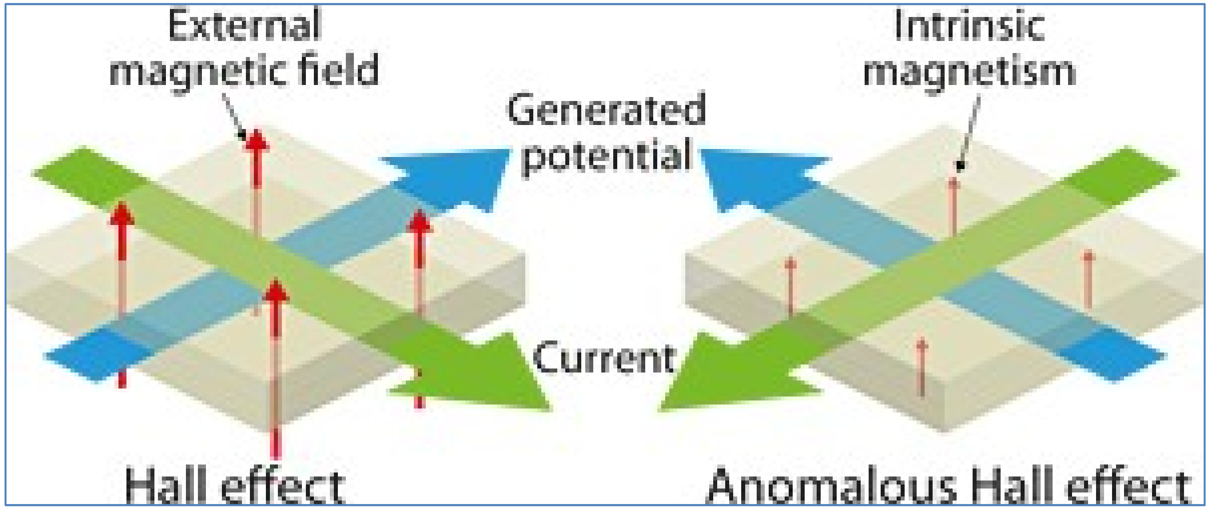


(3) AHE: Anomalous Hall effect

Review paper
Anomalous Hall effect
Naoto Nagaosa et al,
Rev. Mod. Phys. **82**, 1539 (2010)

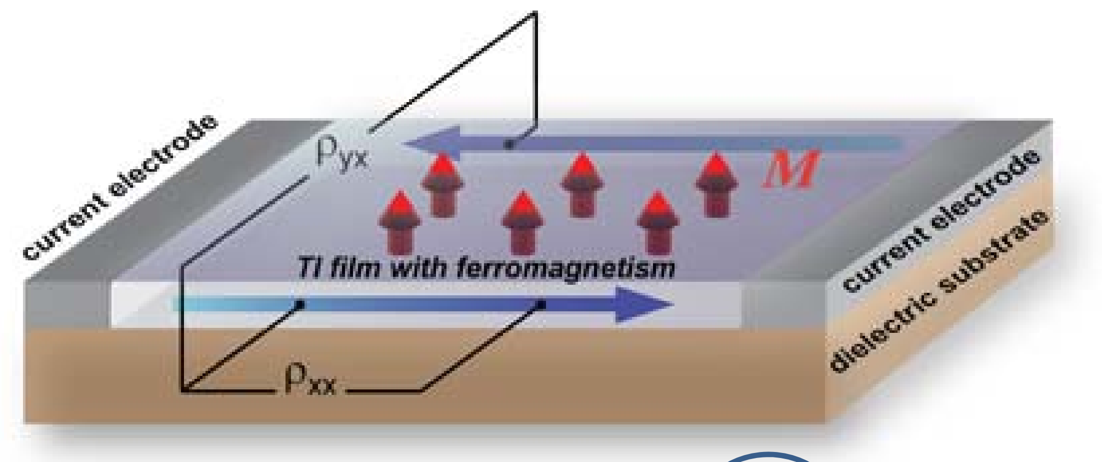
When a conductor is placed in a magnetic field, the Lorenz force pushes the electrons against one side of a conductor, defining the so-called **Hall Effect (OHE=Ordinary Hall effect)**.

discovered by Edwin H. Hall during his PhD-work and was published in 1879



In ferromagnetic metals the effect is order of magnitude higher than in non-magnetic systems => **Anomalous Hall Effect (AHE)**.

The origin of AHE is complex, often controversial, and involves **intrinsic** and **extrinsic mechanisms**



Review paper
Anomalous Hall effect
Naoto Nagaosa et al,
Rev. Mod. Phys. **82**, 1539 (2010)

$$\boxed{\rho_{xy} = R_0 H_z + R_s M_z}$$

(AHE)
Hall effect contribution due to spontaneous magnetization

(OHE)
R_0 depends on the carrier density

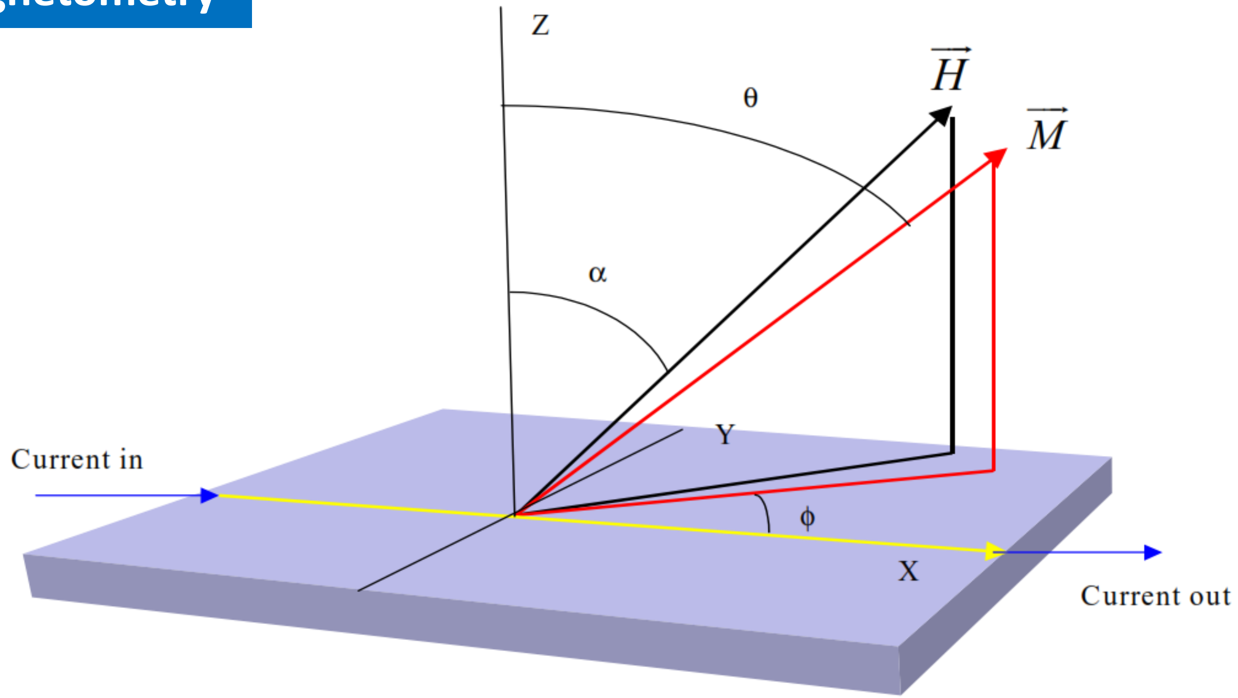
Depends on variety of material parameters and on ρ_{xx}

Analyzing the scaling law gives insight on different AHE mechanisms

Outline (we limit our overview to):

- **AHE magnetometry**
- SHE, IHE mechanisms. Spin current generation

(a) AHE magnetometry



t= film thickness

$$V_H = \boxed{(R_H I/t) B\cos(\alpha)} + \boxed{(\mu_0 R_s I/t) M\cos(\theta)} + \boxed{(kI/t) M^2 \sin^2(\theta)\sin(2\varphi)}$$

OHE depends on B_z

AHE depends on M_z

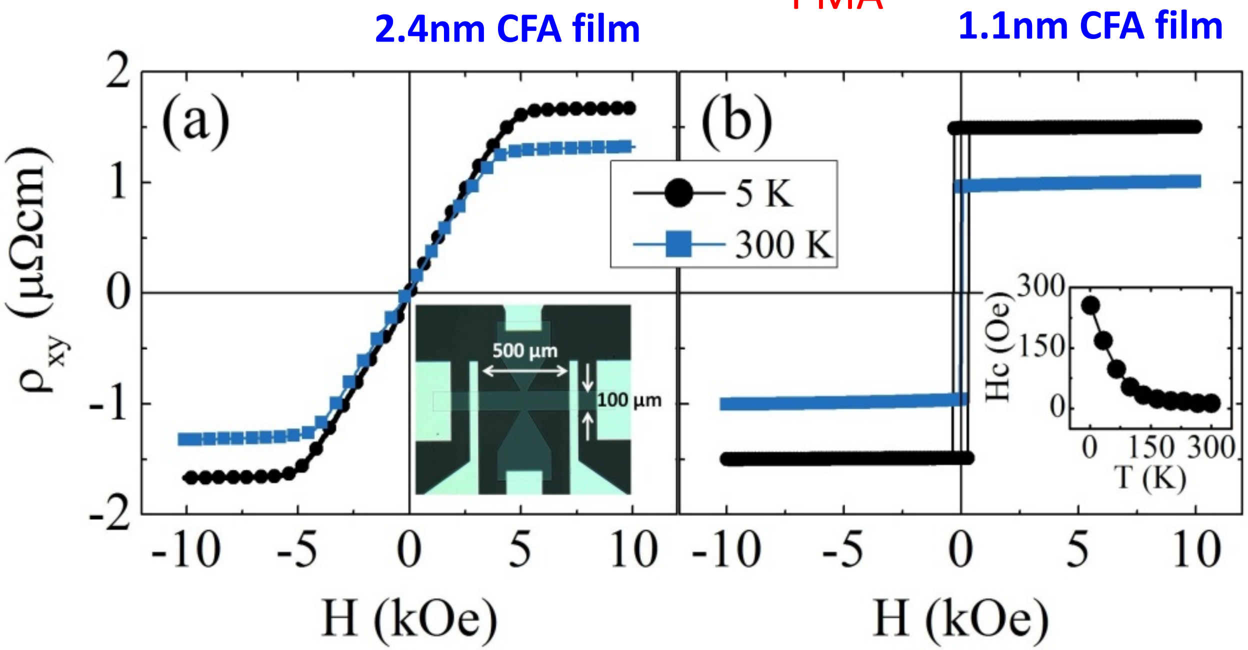
PHE (planar Hall effect) or AMR depends on M^2

- Signal ~ 1/t (opposite to standard magnetometry where signal~ t
- AHE megnetometry ideal for ultrathin magnetic film characterization
- + cryostate facilities => M(T) , faster and versatile SQUID alternative

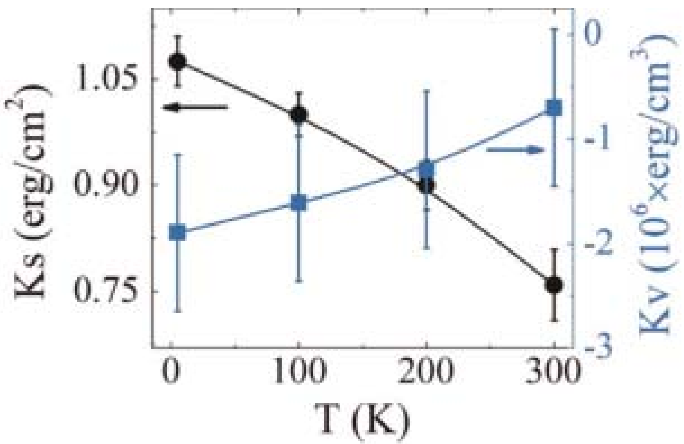
AHE magnetometry

M.S. Gabor et al, J. Magn. Magn. Mat. 392 (2015) 79–82

PMA



+ micromagnetic models (S-W) ➡ Anisotropy temperature dependence, etc…



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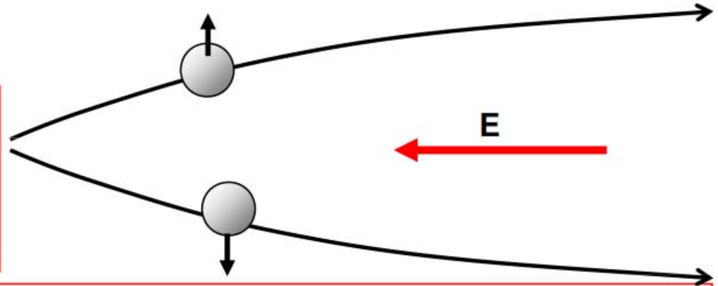
AHE mechanisms

Review paper
Anomalous Hall effect
Naoto Nagaosa et al,
Rev. Mod. Phys. **82**, 1539 (2010)

See Jungwirth, Valenzuela

a) Intrinsic deflection

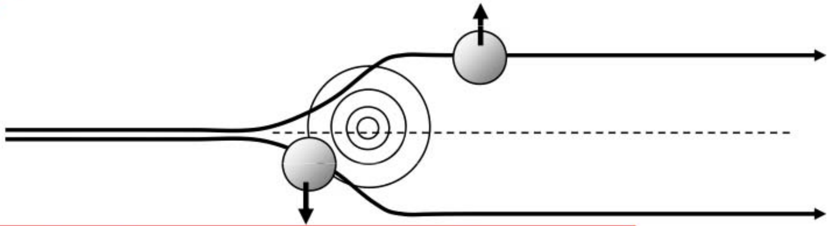


Interband coherence induced by an external electric field gives rise to a velocity contribution perpendicular to the field direction. These currents do not sum to zero in ferromagnets.

$$\frac{d\langle\vec{r}\rangle}{dt} = \frac{\partial E}{\hbar \partial \vec{k}} + \frac{e}{\hbar} E \times b_n$$

Electrons have an anomalous velocity perpendicular to the electric field related to their Berry's phase curvature

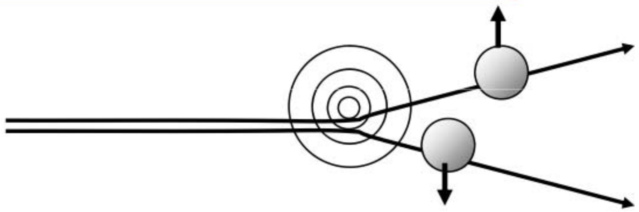
b) Side jump



The electron velocity is deflected in opposite directions by the opposite electric fields experienced upon approaching and leaving an impurity. The time-integrated velocity deflection is the side jump.

c) Skew scattering

Asymmetric scattering due to the effective spin-orbit coupling of the electron or the impurity.



$$\boxed{\sigma_{xy}^{AH} = \sigma_{xy}^{AH-int} + \sigma_{xy}^{AH-skew} + \sigma_{xy}^{AH-sj}}$$

In any real material all of these mechanisms act to influence electron motion

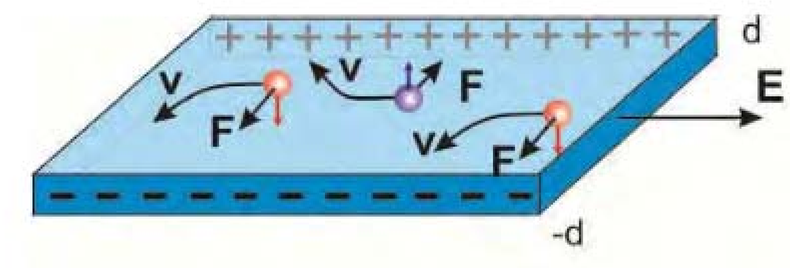
Spin Hall effect (SHE)

From AHE to Spin Hall effect (SHE)

FM material

➡ **Anomalous Hall effect (1881)**

E.H. Hall, Phil . Mag. 12, 157 (1881)



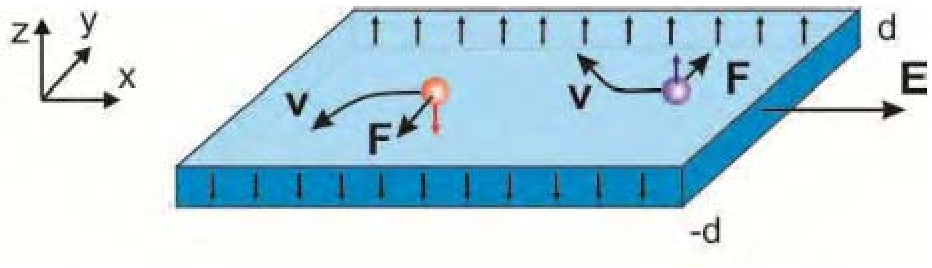
FM material: n$^{\uparrow}$(E)≠ n$^{\downarrow}$ (E)) => **V$_H$**

(Hall voltage appear and can be measured)

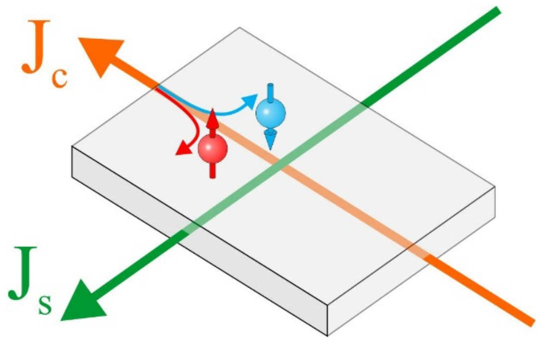
NM material with SOI

➡ **Spin Hall effect**

M.I. Dyakonov & V.I. Perel, JETP Lett. 13, 467 (1971); J.E. Hirsch, PRL 83, 1834 (1999)



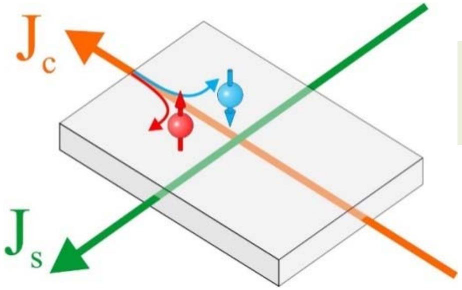
Scattering of electrons by an unpolarized target results in spatial separation of electrons with different spins due to **spin-orbit interaction**



$$J_s = J^{\uparrow} - J^{\downarrow}$$

Conversion of a charge current into a spin current by asymmetric deflection of the spin-up and spin-down e$^-$.

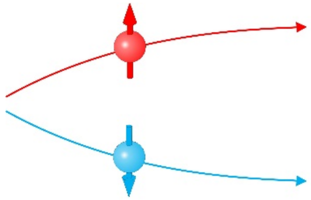
SHE mechanisms



$$J_s = J^{\uparrow} - J^{\downarrow}$$

NO Hall voltage
Because in NM material
$n^{\uparrow}(E) = n^{\downarrow}(E)$)

INTRINSIC



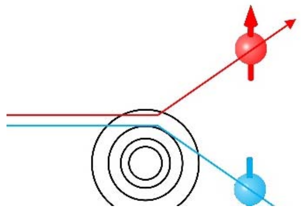
Band structure

S. Zhang, PRL 85, 393 (2000);
S. Murakami et al, Science 301, 1348 (2003);
J. Sinova, et al., PRL 92, 126603 (2004).

$$\mathbf{v}_{\mathrm{k},\uparrow(\downarrow)} = \frac{1}{\hbar}\frac{\partial E_{\mathbf{k}}}{\partial \mathbf{k}} + e\mathbf{E}\times\boldsymbol{\Omega}_{\mathbf{k}}$$

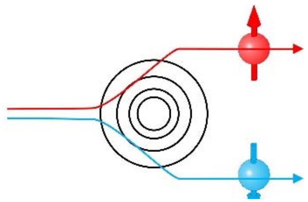
anomalous velocity related to the Berry phase in the presence of SOI. (Pt, Pd etc.)

EXTRINSIC



skew scattering

Smit, Physica 24, 39 (1958)



side jump

Berger, PRB 2, 4559 (1970)

asymteric scattering due to SOI terms of impurity scattering potentials. (e.g. $Cu_{1-x}Ir_x$ *)

Y. Niimi, et al,P. R. L. **106, 126601, 2011*

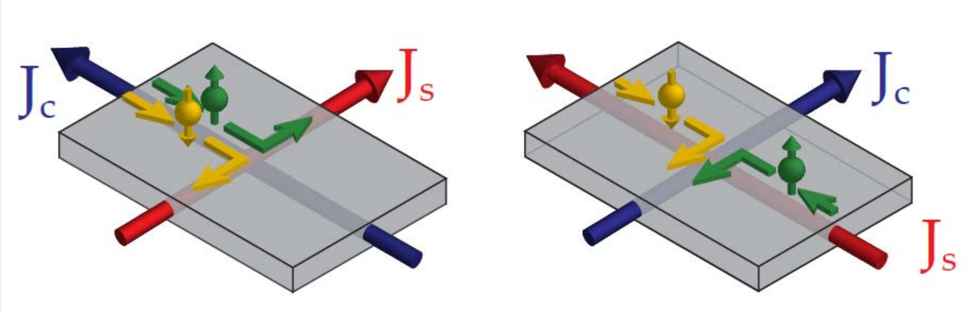
SOI the key for spin current generation => necessity of materials with enhanced SOI

SPIN-ORBITRONICS

Spin Hall effect (SHE)

Inverse spin Hall effect (ISHE)

$$J_s = -\frac{h}{2e}\left(J_{\uparrow} - J_{\downarrow}\right)$$



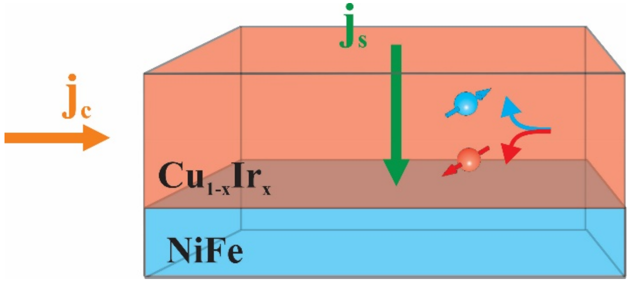
Nonmagnetic materials with SOI

Generate spin currents using charge currents
(B=0, M=0)

Generate charge currents from spin currents
Conversion spin current/electric field)

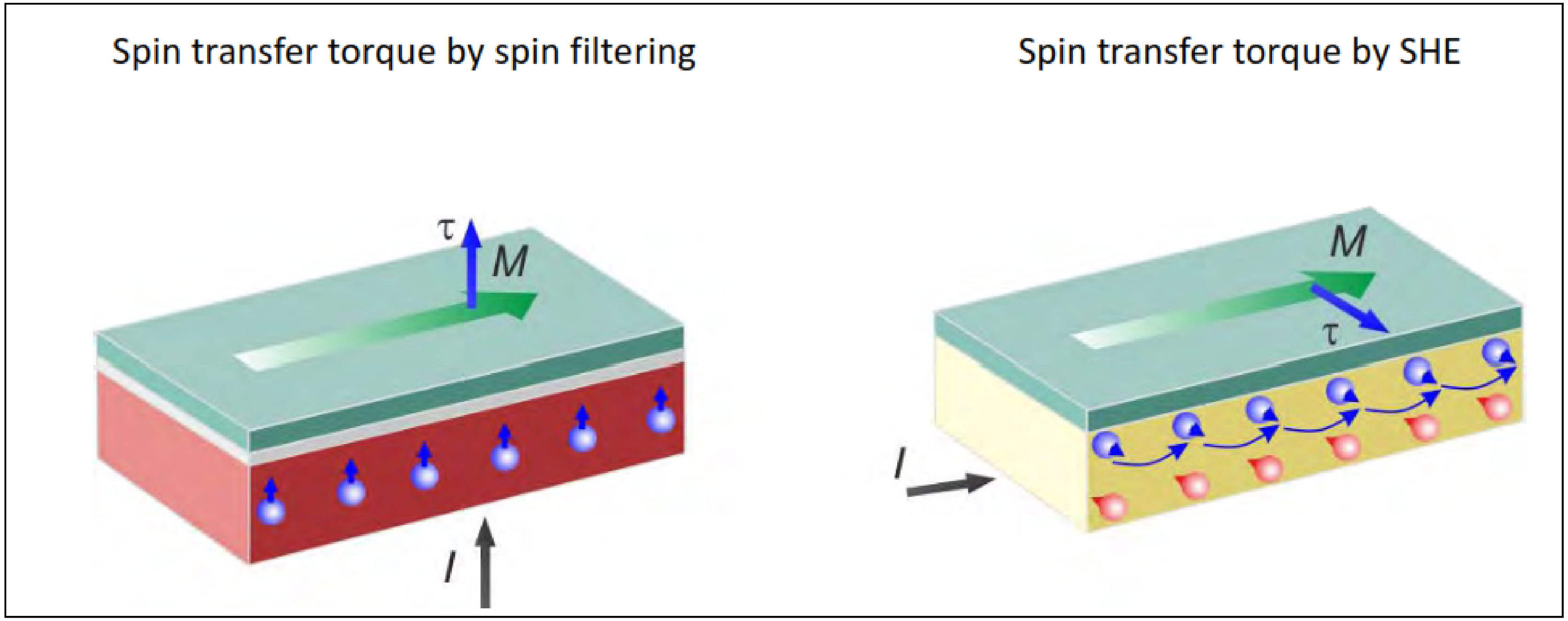
Concept

- (1) Generate spin currents by SHE in NM materials with enhanced SOI
- (2) **BILAYERS NM/FM :** Manipulate the magnetization of adjacent FM layers by STT effects



New generation of spintronic devices GMR, MTJ,...

(1) Generate spin currents by SHE in NM materials with enhanced SOI



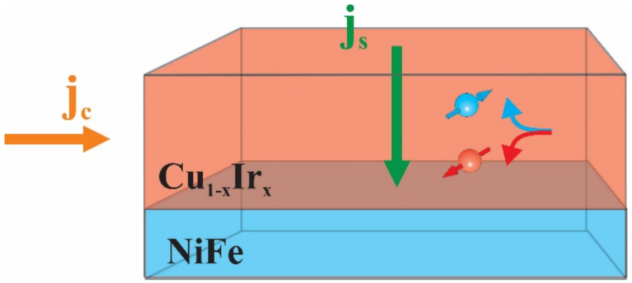
Torque ~ $J_s = J$ *Polarization

J = I / Transverse Area

Torque ~ $J_s = J * \Theta_{SH}$

J = I / Longitudinal Area

(2) BILAYERS NM/FM : Manipulate the magnetization of adjacent FM layers by STT effects



Magnetization dynamics governed by LLG equation

$$\frac{\partial \boldsymbol{m}}{\partial t} = -\gamma \boldsymbol{m} \times \boldsymbol{H}_{eff} + \alpha \boldsymbol{m} \times \frac{\partial \boldsymbol{m}}{\partial t} - b\boldsymbol{m} \times (\boldsymbol{m} \times \boldsymbol{\sigma}) - a(\boldsymbol{m} \times \boldsymbol{\sigma})$$

Zhang et al., PRL, 88, 236601, (2002)

Js produces two types of torques on the magnetization (**m**)

- damping-like term: $\beta \boldsymbol{m} \times (\boldsymbol{\sigma} \times \boldsymbol{m})$
- filed-like term: $\boldsymbol{\alpha}(\boldsymbol{m} \times \boldsymbol{\sigma})$

M switching if $J_s > J_c$

Manipulate domain walls

Dynamical effects on M
(e.g. modulate Gilbert damping)

Spin Hall: ***Spin torque is in fixed direction, can*** result in antidamping

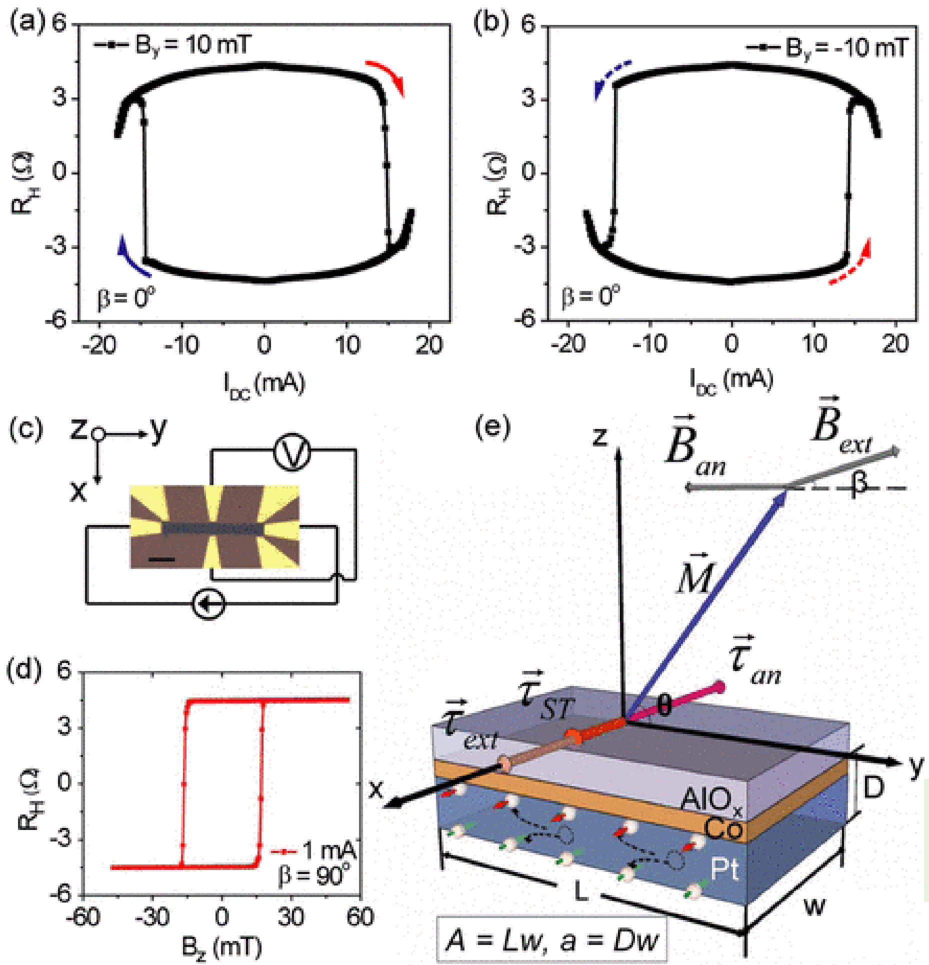
To manipulate the magnetization spin Hall torque only requires that the torque compensates the damping

Ex. 1 Magnetic switching by spin torque from the spin Hall effect

BYLAYERS

L. Liu et al, Phys. Rev. Lett. 109, 096602 (2012)

In Pt/Co bilayer the spin-Hall effect (SHE) in Pt can produce a spin torque strong enough to efficiently rotate and switch the Co magnetization.



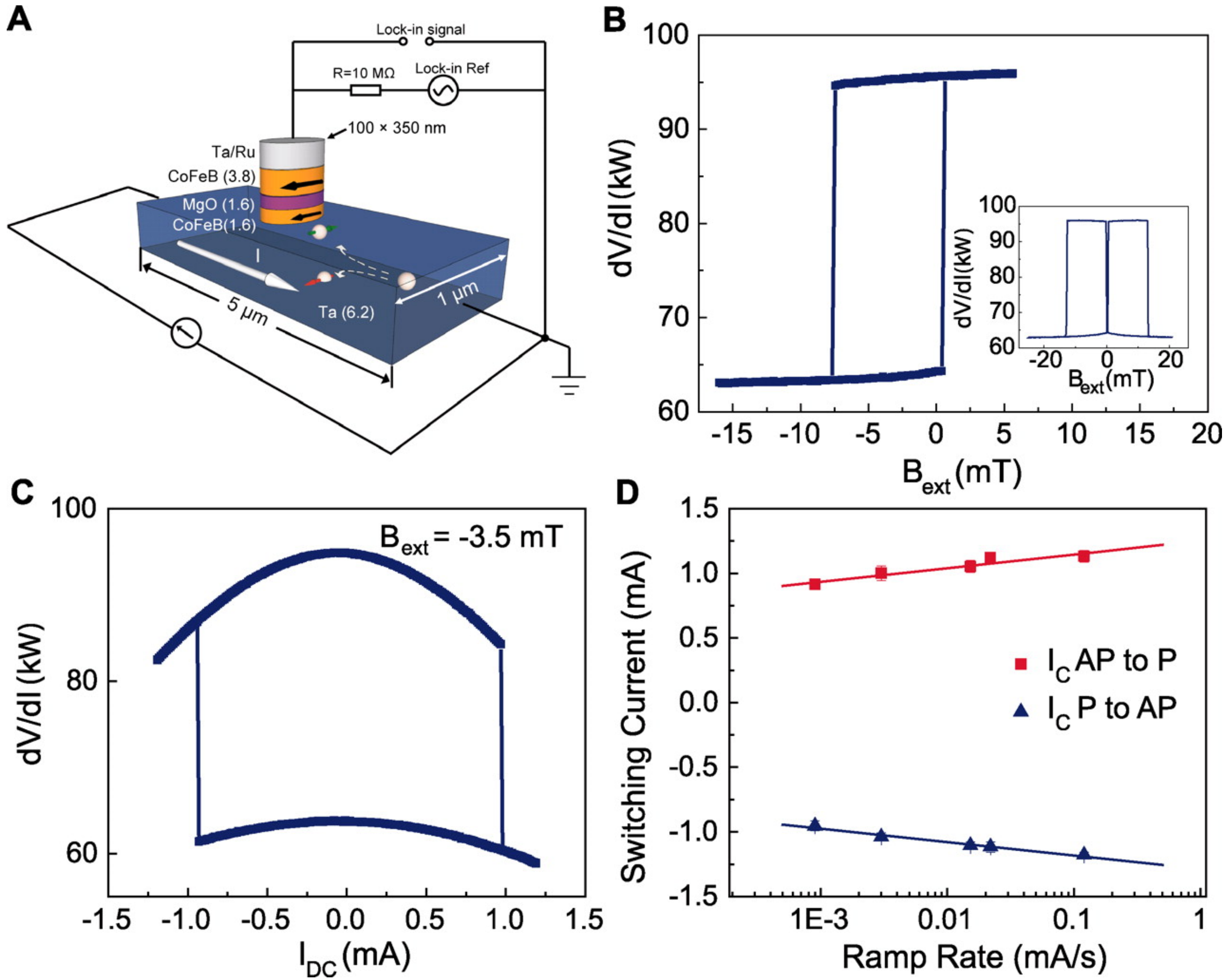
(a), (b) Current-induced switching in a **Pt/Co/AlOx** sample (RT) in the presence of a small, fixed in-plane magnetic field By with (a) By=10 mT and (b) By=−10 mT.
(c) Top view of the sample (50 µm scale bar).
(d) R_H as a function of B_{ext} perpendicular to the sample plane. (e) Illustration of the torques exerted by the external field $\vec{B}_{ext}$, the anisotropy field $\vec{B}_{an}$, and the SHE torque $\vec{\tau}_{ST}$ for positive current, when $\vec{B}_{ext}$ and M are in the yz plane. The dashed arrows show the direction of electron flow for positive current.

Buhrman and Ralph groups, Cornell Univ. Work performed at Cornell NanoScale Facility

Ex. 2 **Spin-Torque Switching with the Giant Spin Hall Effect of Tantalum**

MTJ devices

L. Liu et al, Science 336 , 555, (2012) - **Cornell**



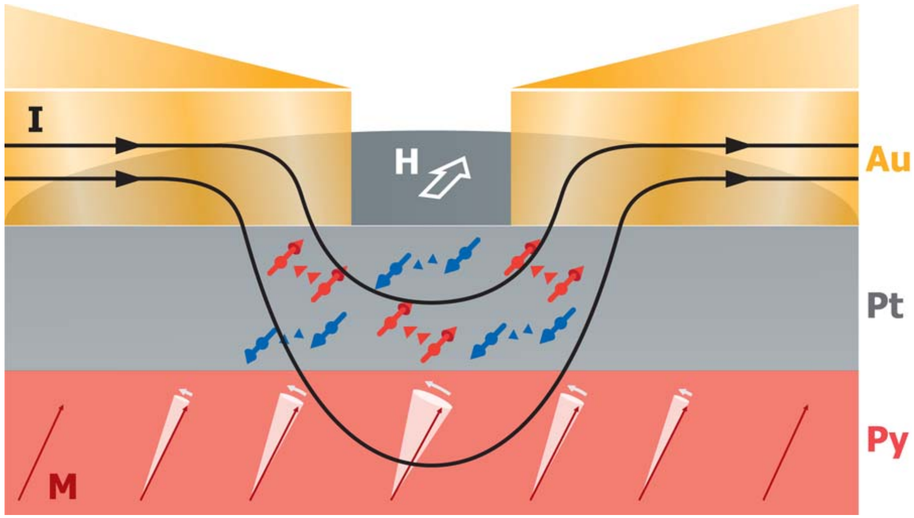
Buhrman and Ralph groups, Cornell Univ. Work performed at Cornell NanoScale Facility

Ex. 3 Magnetization dynamics detected by electrical transport measurements with devices containing just one single ferromagnetic component

R. H. Liu et al, Phys. Rev. Lett. 110, 147601 (2013)

FMR likewise dynamic analysis

Microwave Emission by the Spin Hall Nano-Oscillator



Credit: APS/A. Hoffmann

- **H** defines the stable equilibrium position of the magnetization **M** FM (Py)
- Au contacts enable a high charge-current density ***I*** in a small area of the Pt/Py bilayer

→ Experimental versatility

Spin current generated in Pt

↓

Torque =negative damping in Py

↓

spontaneous excitation of magnetization precession (wider cones).

↓

Resistivity changes associated with the time varying magnetization

↓

voltage changes and concomitant microwave generation at the **rf** frequencies characteristic of magnetization precession

Buhrman and Ralph groups, Cornell Univ.
Work performed at Cornell NanoScale Facility

Ex. 4 **Spin Hall effect tunnelling spectroscopy**

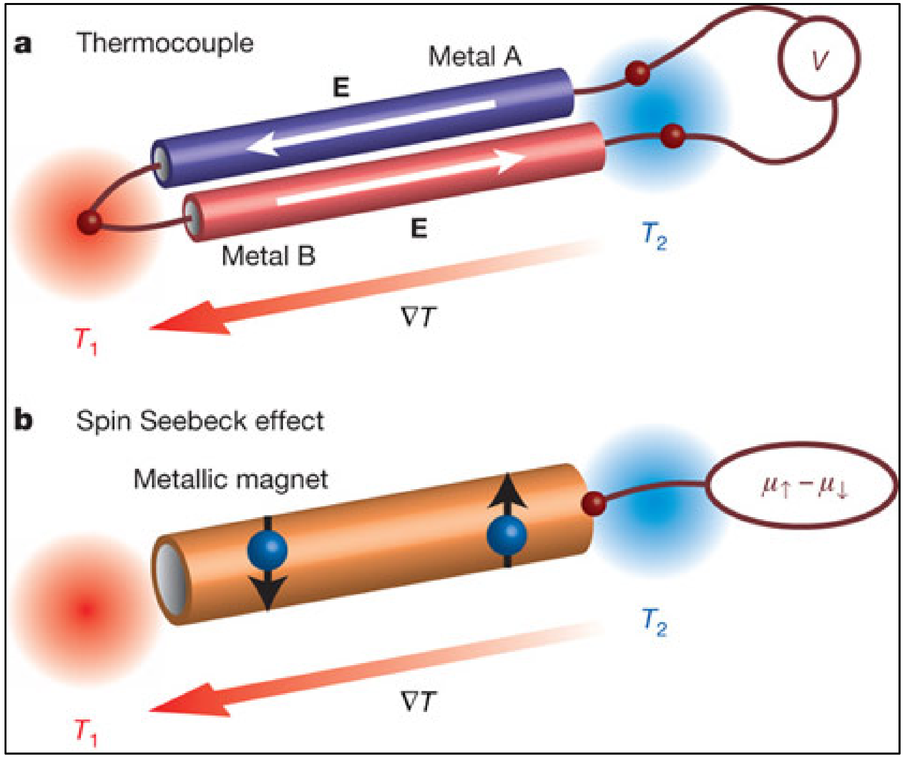
Deeper and deeper analysis…

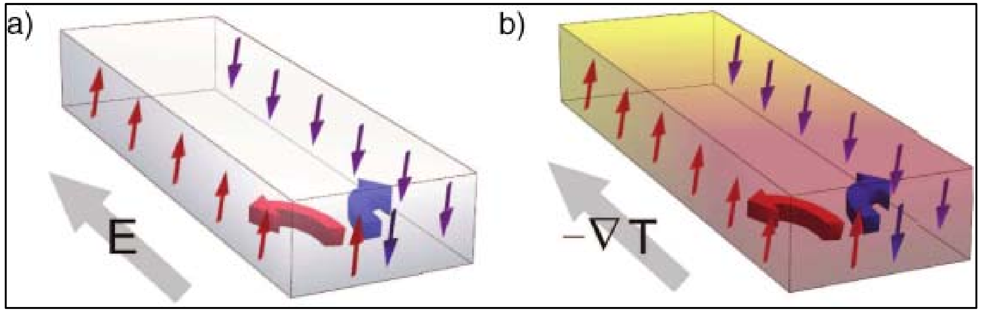
L. Liu et al, Nature Physics 10, 561–566 (2014) doi:10.1038/nphys3004

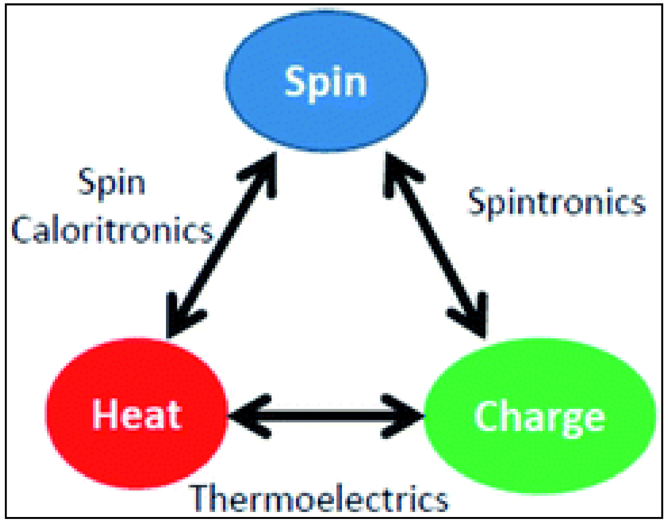
- The spin Hall effect (SHE) and ISHE have been widely used to generate and detect spin currents
- SHE, which originates from the spin–orbit interaction, is expected to be energy dependent
- **By tunnelling spectroscopy technique** developed to measure the SHE under finite bias voltages.
- The SHE has been studied for typical 5*d*transition metals. At zero d.c. bias, the obtained spin Hall angles confirm the results from spin-torque experiments.
- At high bias, the transverse spin Hall signals of these materials exhibit very different voltage dependences. The SHE tunnelling spectra have important implications in pinpointing the mechanisms of the SHE and provide guidelines for engineering high-SHE materials. Moreover, SHE tunnelling spectroscopy can be directly applied to two-dimensional surface states with strong spin–orbit coupling, such as Dirac electrons in topological insulators.

NEXT …

Spin currents can be generated electrically, thermically …







Convergence areas

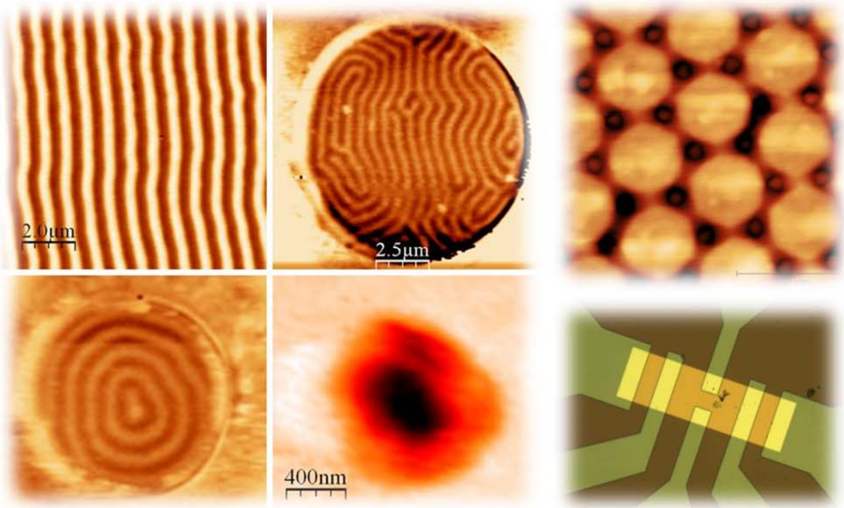
More details, see courses:

- Transport of heat, charge and spin: **Gerrit Bauer**, *Sendai, Japan*
- Spin caloritronics: **Gerrit Bauer**, *Sendai, Japan*
- & Sources of spin currents: **Sergio Valenzuela**, *Barcelona, Spain*

Tailoring of MR devices with optimal functional magneto-transport properties

Real fundamental and experimental/technological issue

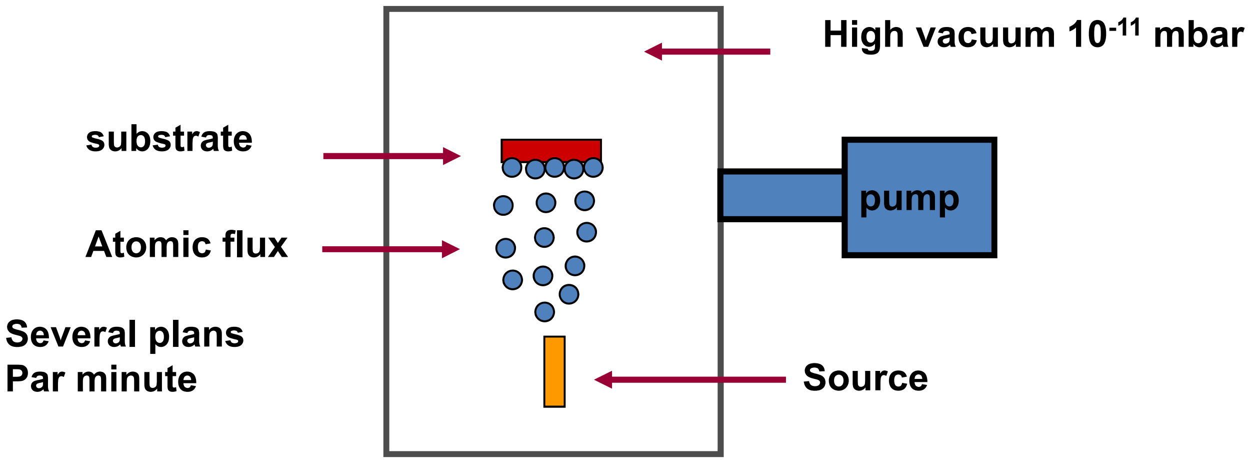
Growth, characterization (structural, magnetic, electric,…) in-situ/ex-situ, patterning (UV, e-beam, clean room facilities…).



Optimal properties requires extreme control of growth

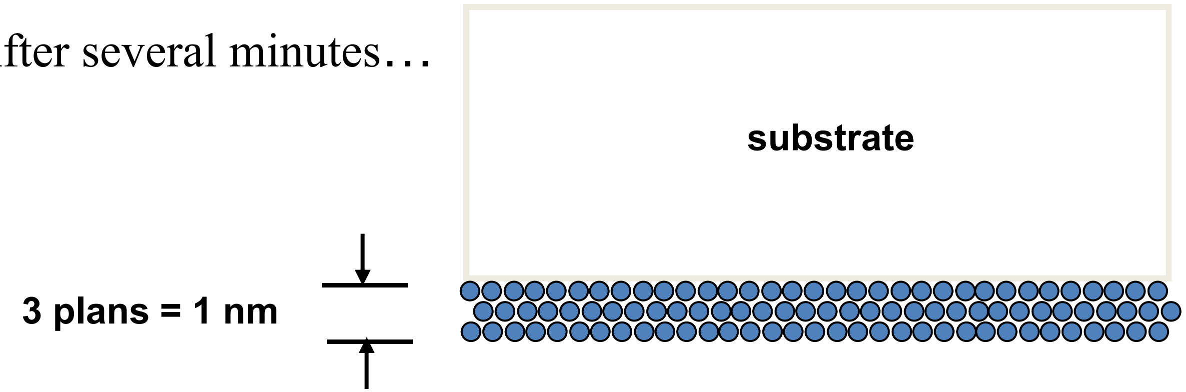
Magnetic/transport properties correlated/tuned to structural, morphological…

Growth of thin films : e = several nm



Techniques: MBE, sputtering, laser ablation, CVD, etc….

After several minutes…

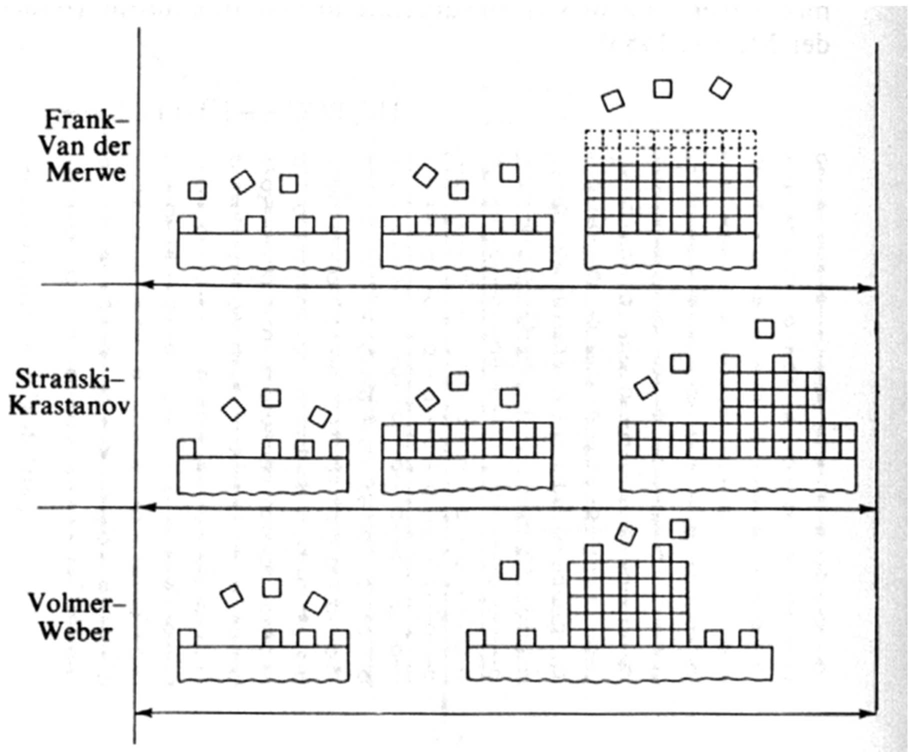


Even at equillibrium (e.g. MBE), controlling growth is a challanging task

Growth kinetics

- Extremely complex thermodynamic statistical aspects
- Substrate temperature, deposition rate, vacuum, wetting (surface energies)

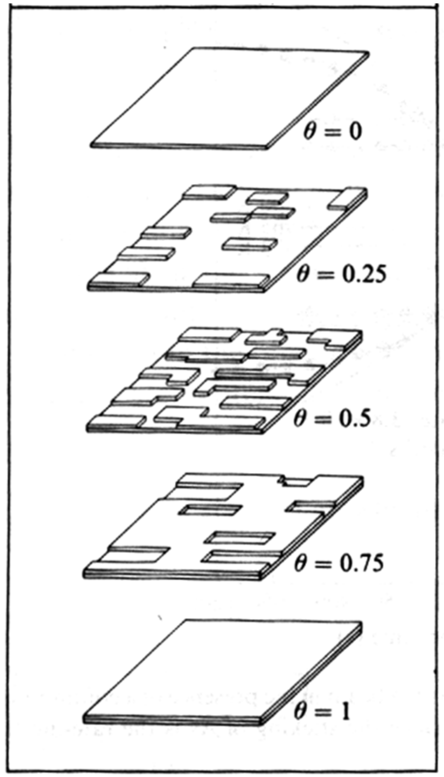
Growth modes



2D growth
Layer by layer

Mixt growth

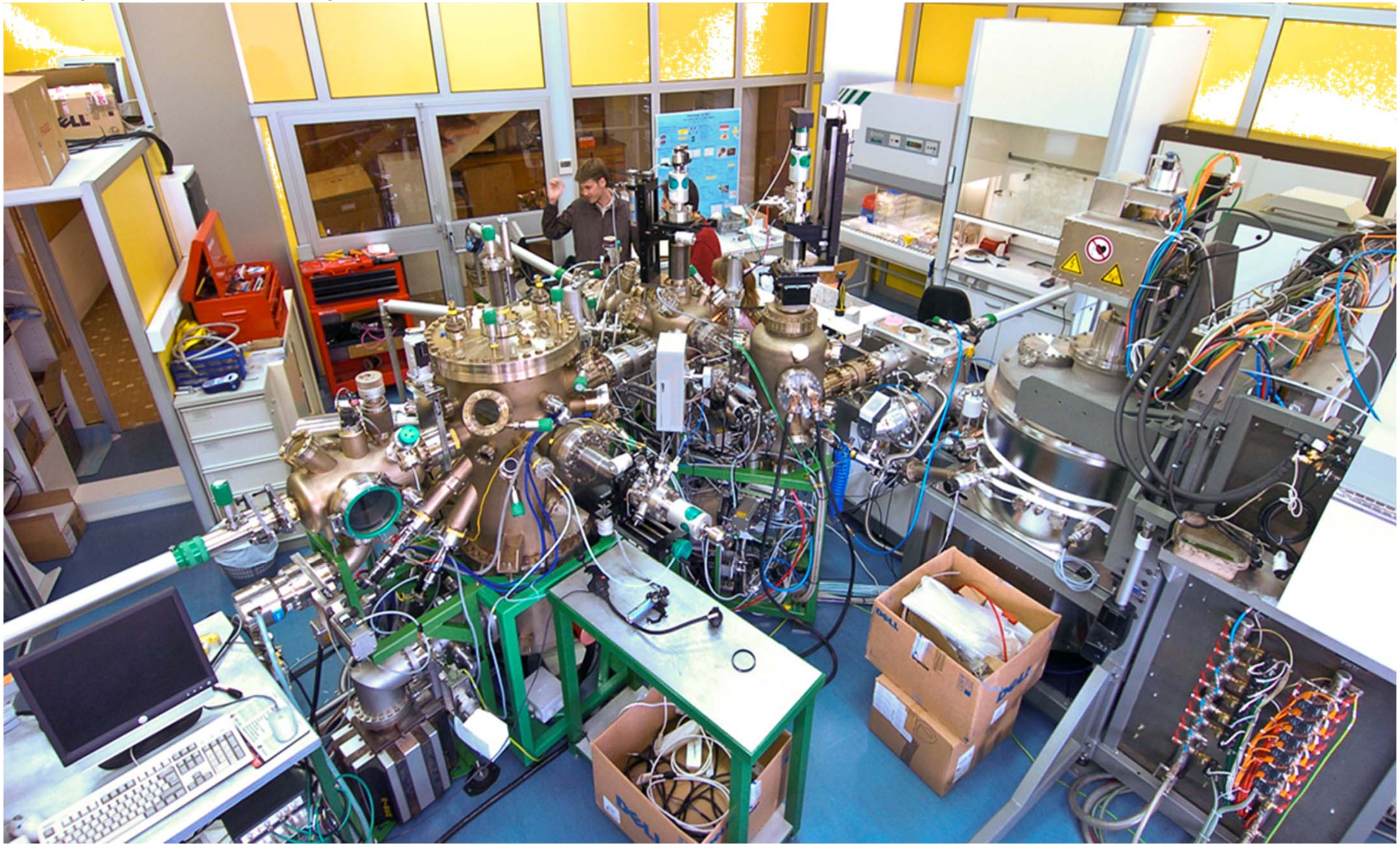
3D (island)
growth



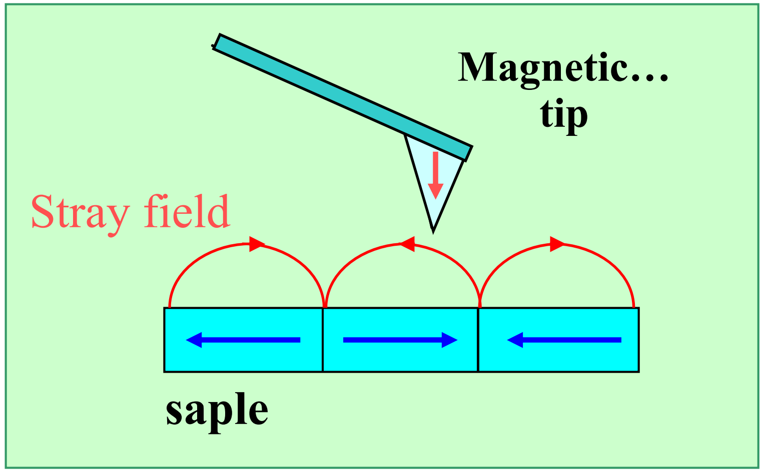
- **Often in industry sputtering prefered, aut of equillibtium, trial and error optimization method used**
- **Ultimate target: high reproducibility of functional properties of films and stacks**

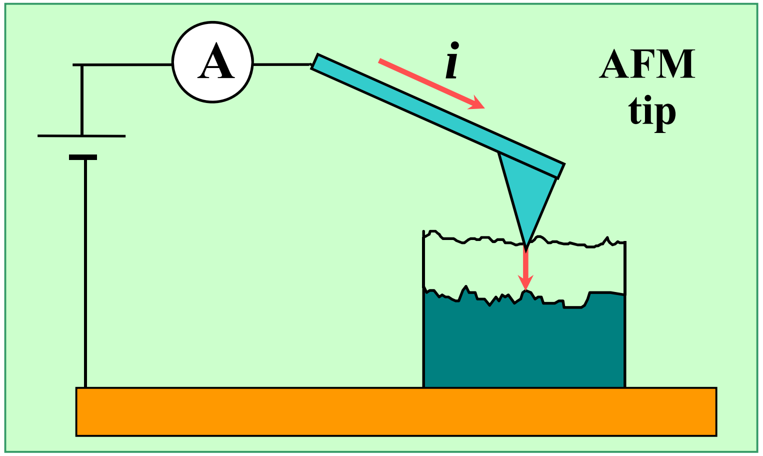
MML samples elaboration requires UHV thin film elaboration facilities
often coupled multiple facilities (Sputtering, MBE (model systems), …)

Complex MPGA Nancy

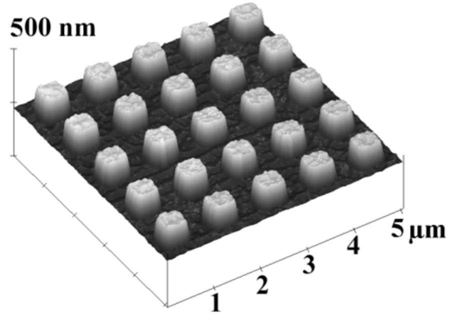


Morphology and micromagnetism optimization monitored by Atomic/Magnetic force microscopy

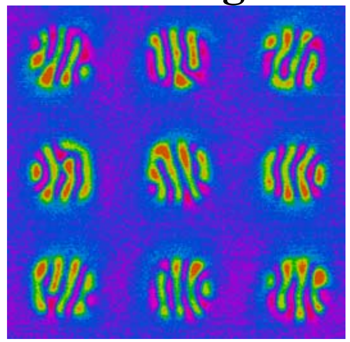




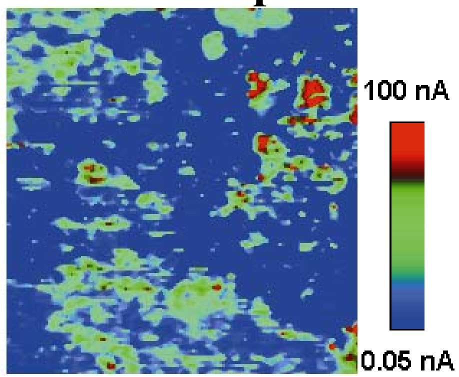
Topography



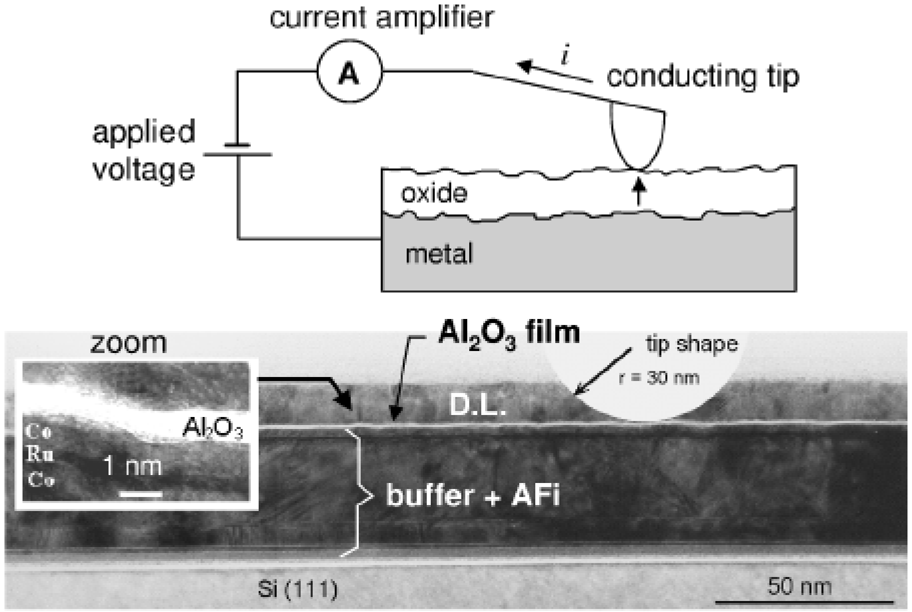
Micro- magnetism

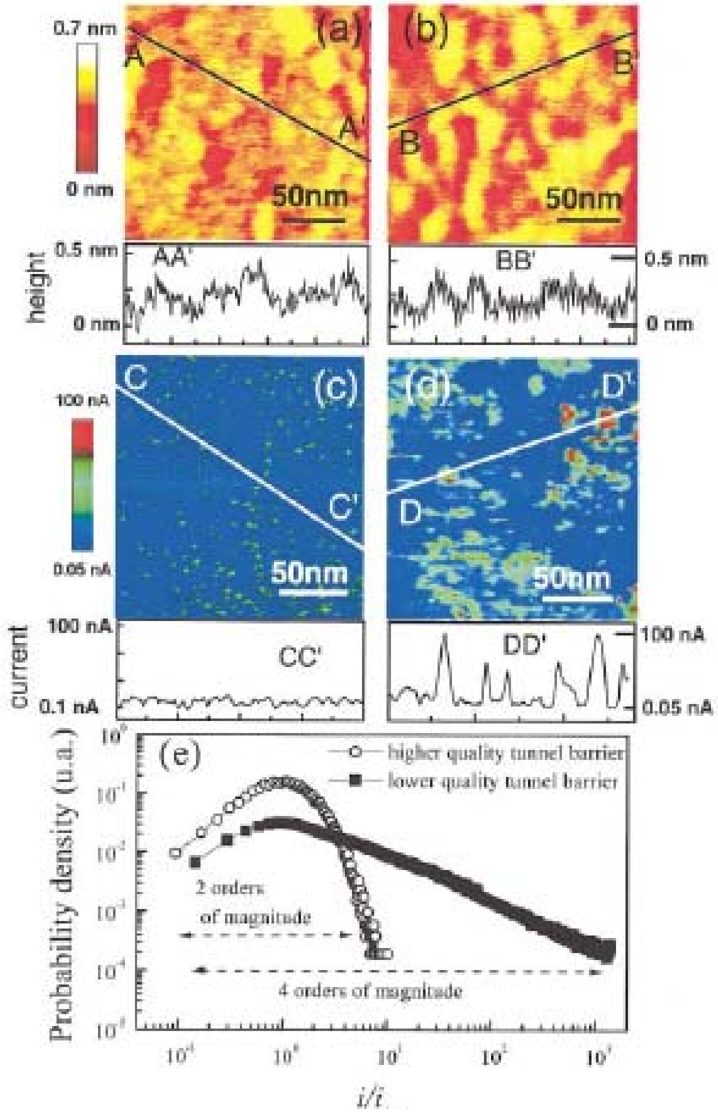


Current map



V. Da Costa, C. Tiusan, T. Dimopoulos, K. Ounadjela
Tunneling phenomena as a probe to investigate atomic scale fluctuations in metal/oxide/metal magnetic tunnel junctions.
Physical Review Letters 85, (4), 876,(2000).



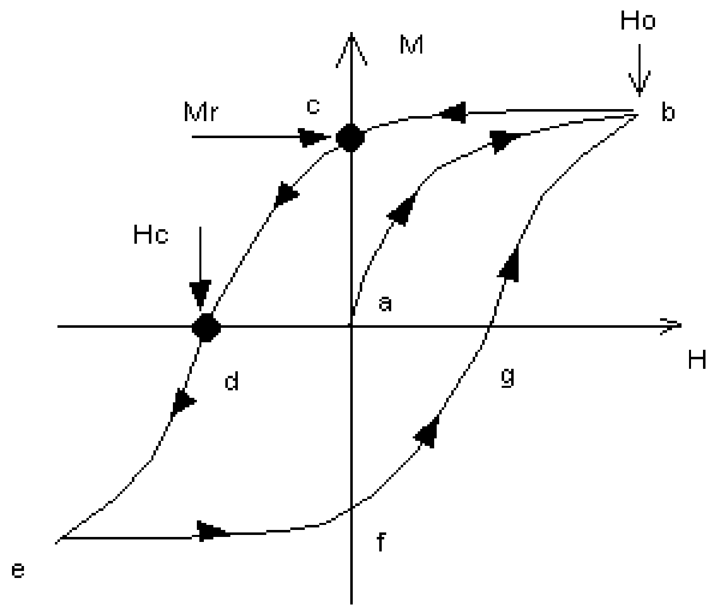


VOLUME 85, NUMBER 4 PHYSICAL REVIEW LETTERS 24 JULY 2000

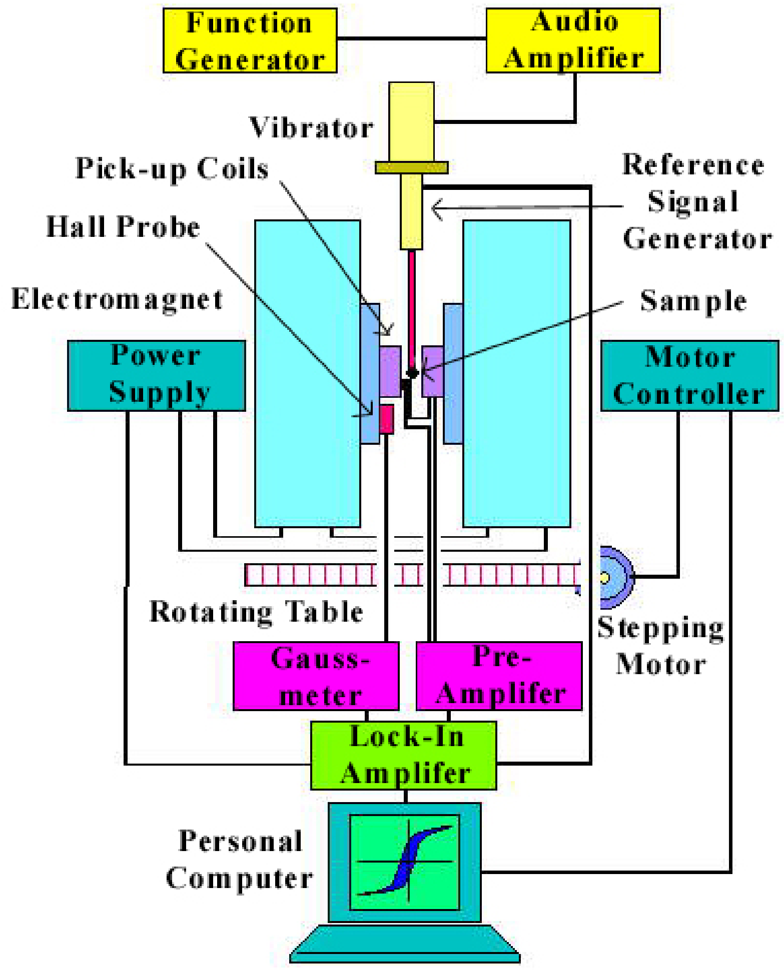
Tunneling Phenomena as a Probe to Investigate Atomic Scale Fluctuations in Metal/Oxide/Metal Magnetic Tunnel Junctions

Magnetic characterization

Vibrating Sample Magnetometer (VSM)



10^{-6} emu sensitivity (10^{-7} emu by using DC power supply)

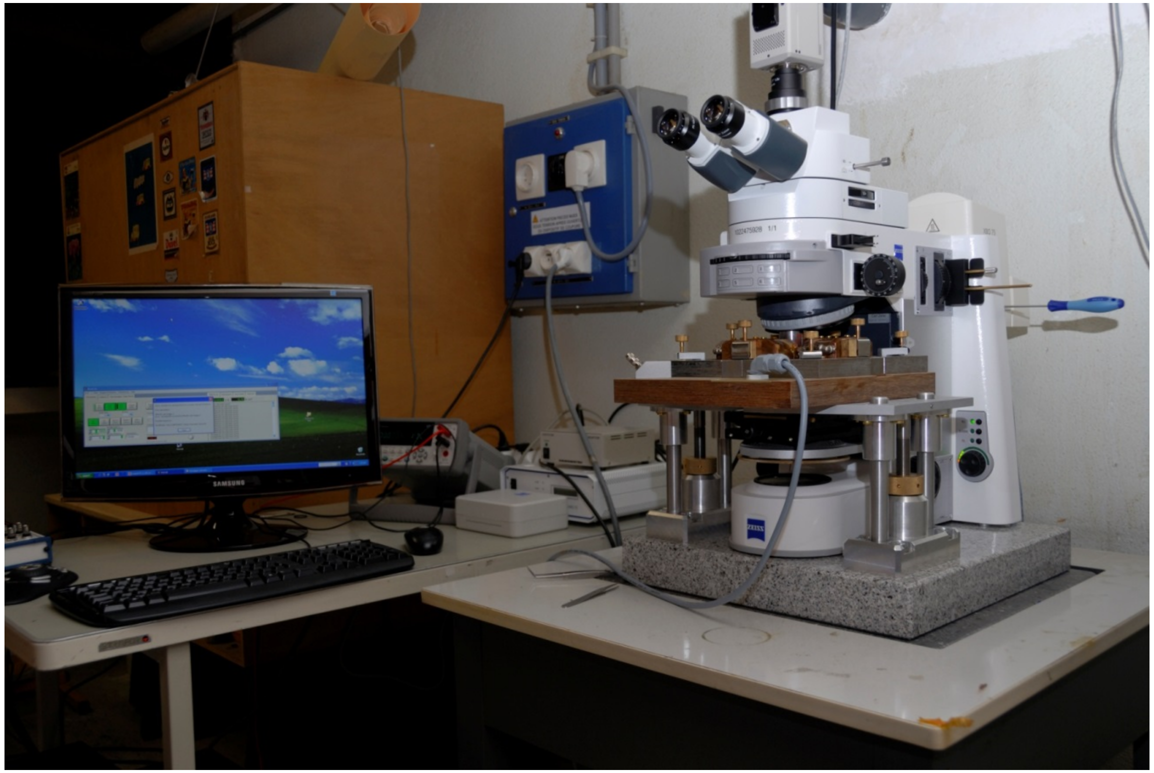


System diagram of Vibrating Sample Magnetometer

- measures the magnetic properties of materials.
-the material is placed within a uniform magnetic field is and made to undergo sinusoidal motion (i.e. mechanically vibrated) => **magnetic flux change.**
This induces a voltage in the pick-up coils, which is proportional to the magnetic moment of the sample.

Magnetic characterization

MOKE microscope



MPMS SQUID/VSM system
Quantum Design

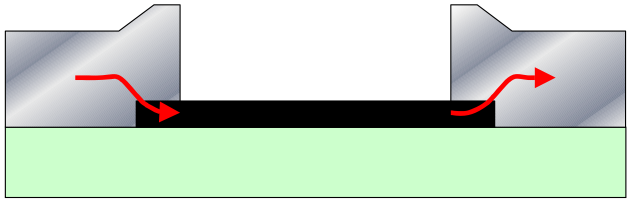
Sensitivity <10-8emu
Temperature range: 1.8-1000K

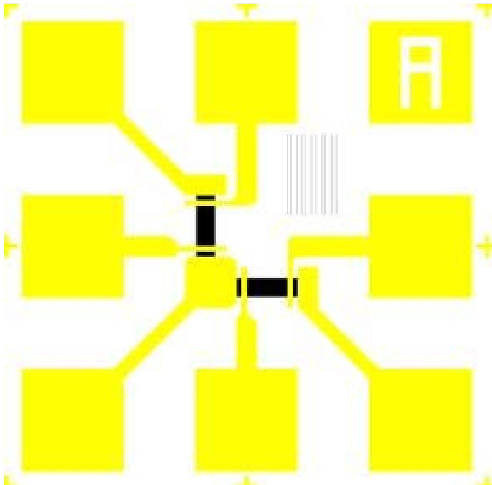
+ dynamic characterization (FMR)…

Magneto-transport experiments require device patterning

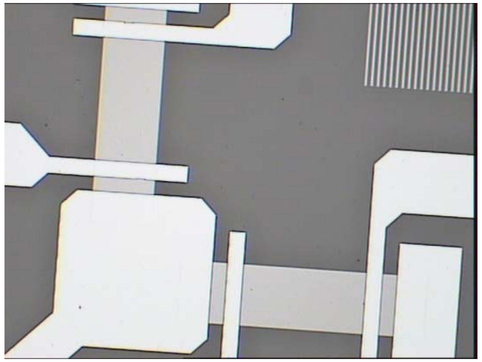
Micrometric size => UV litho
Sub-micrometric=> e-beam, other alternatives

Magneto- transport measurements in a specific configuration/ geometry



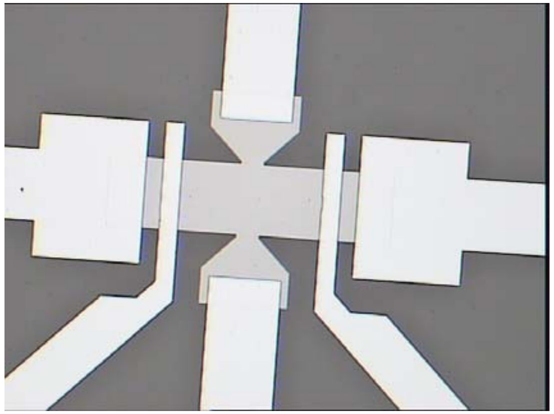


AMR

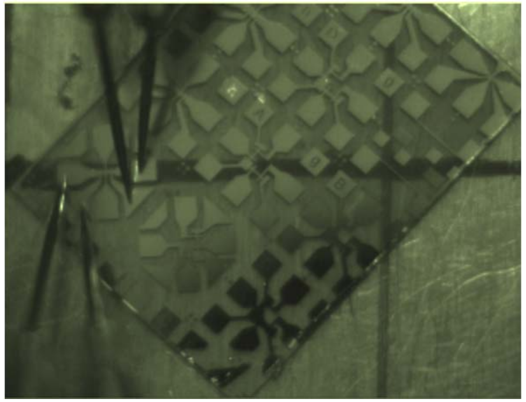


$$R = R_0 + \tfrac{1}{2}\Delta R \cos 2\theta$$

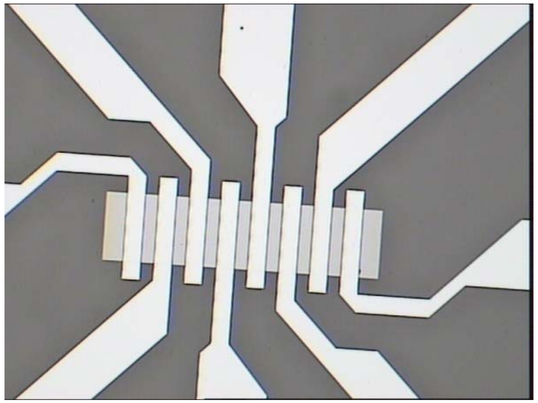
Effet Hall



$$R = \tfrac{1}{2}\Delta R \sin 2\theta$$



Etc…



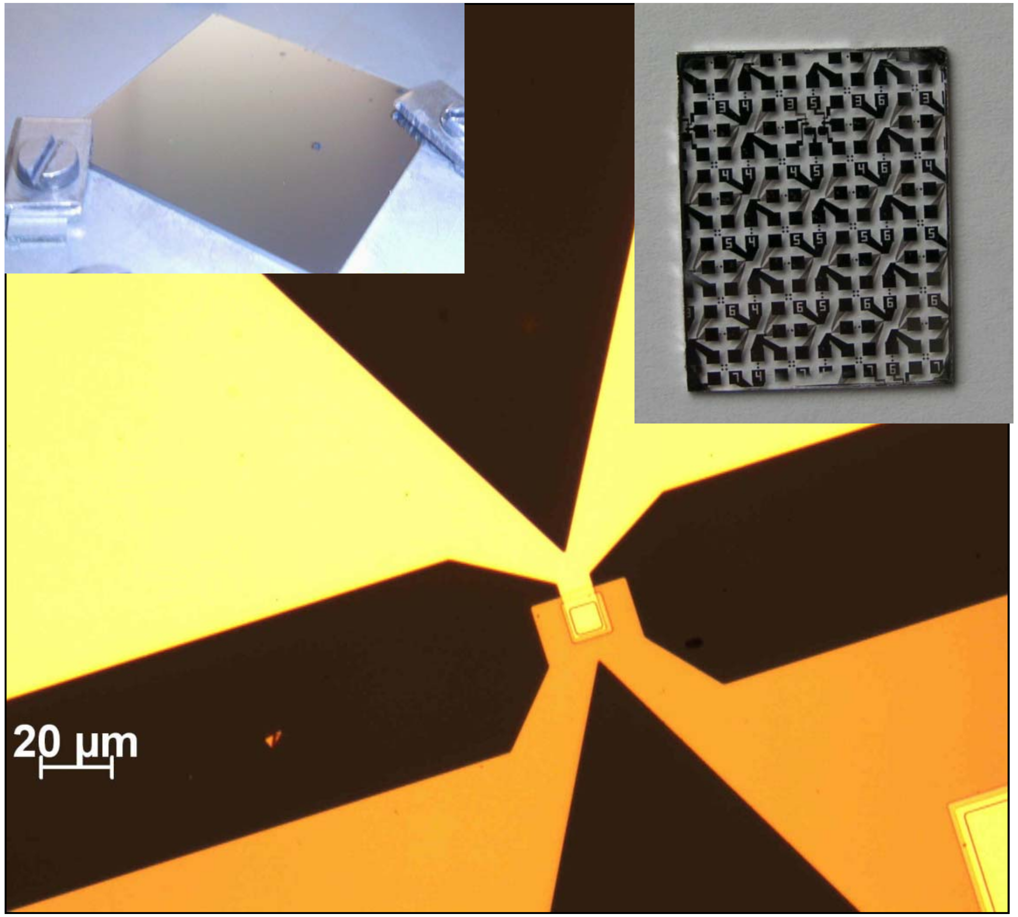
Complex pattering for CPP devices

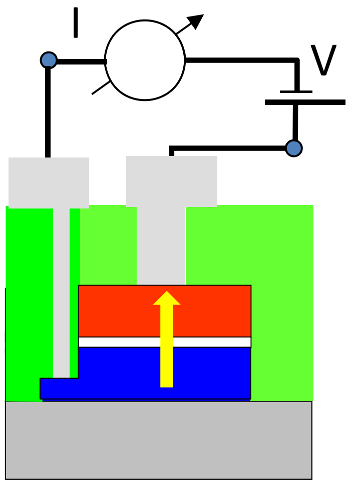
Micrometric size => UV litho
Sub-micrometric=> e-beam, other alternatives

Thin film
Multilayer stack

LITHOGRAPHY

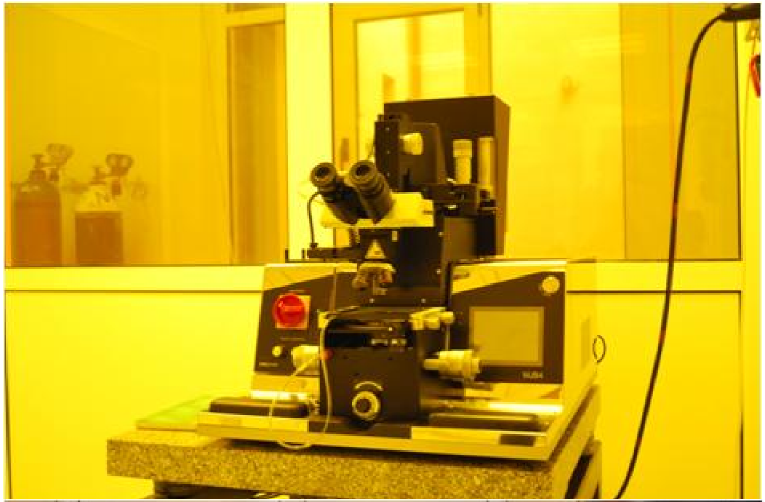
Spintronic CPP device

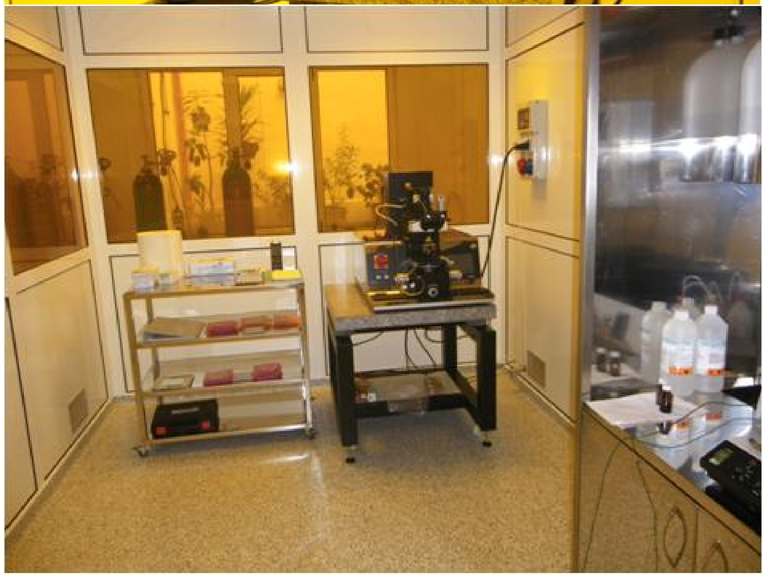


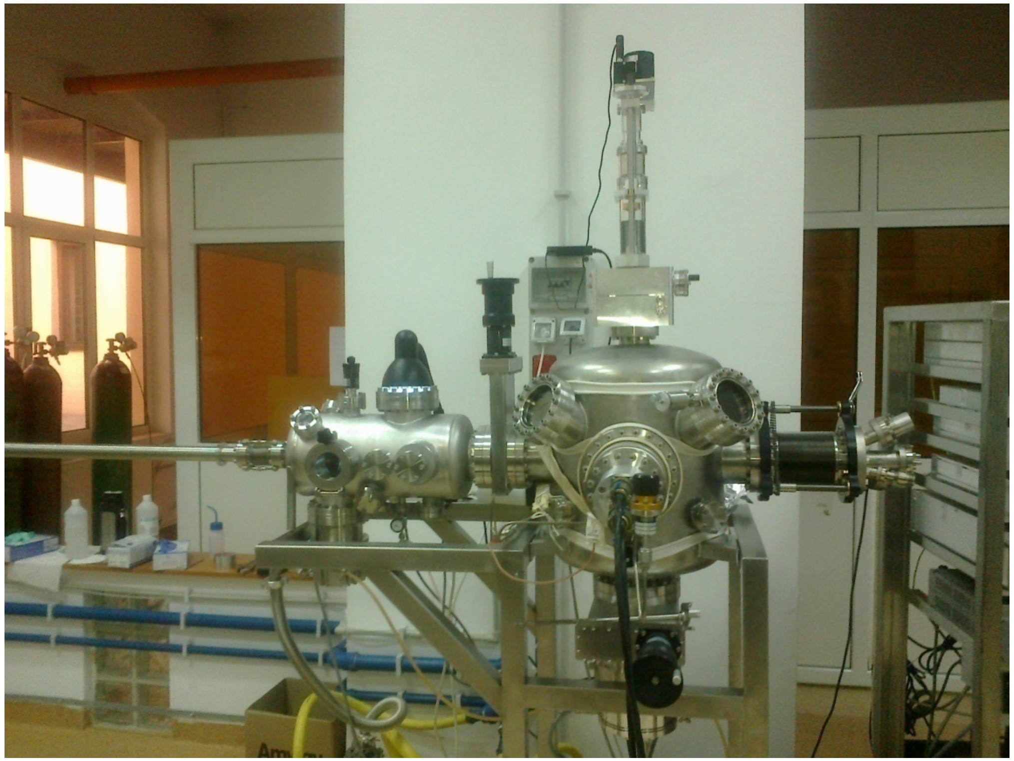


Clean room facilities

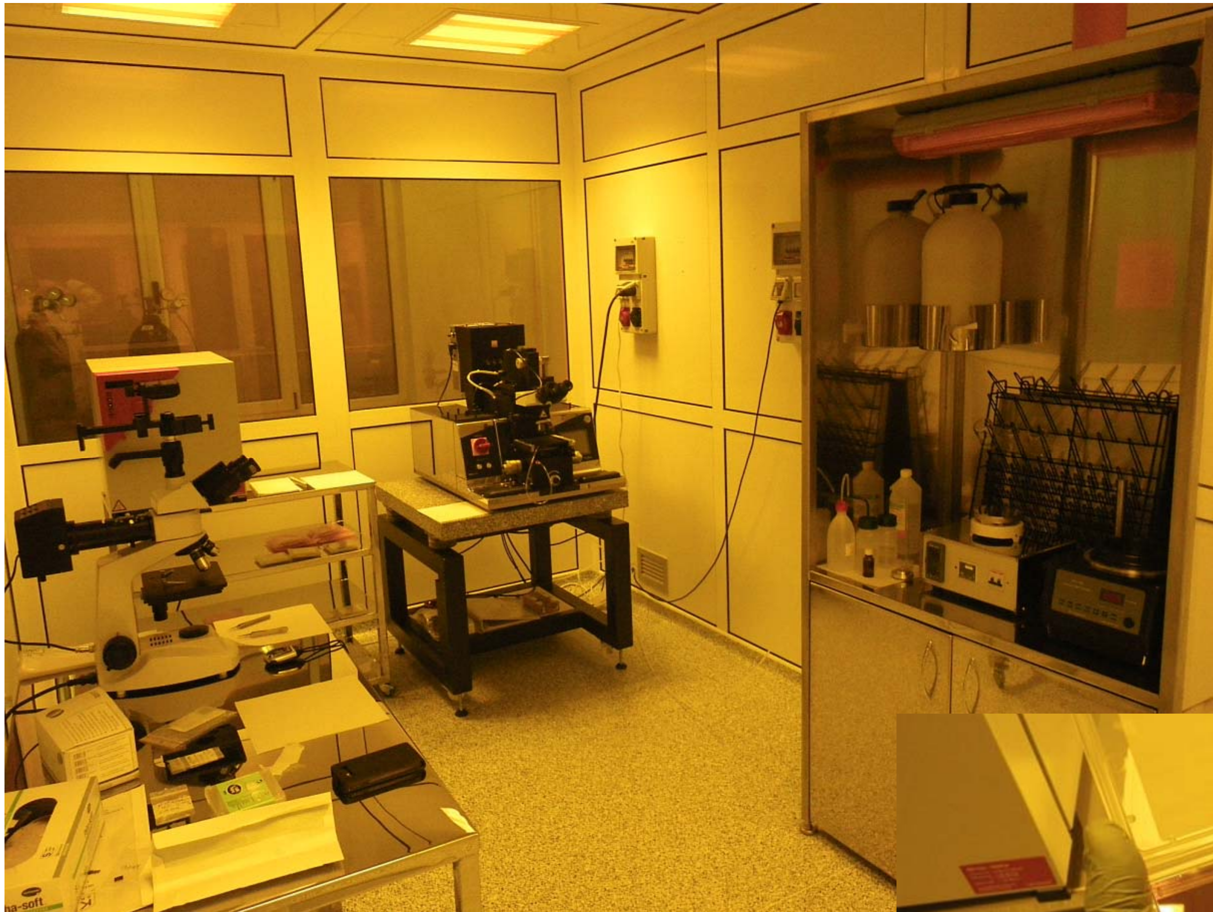
-Optical lithography (MBJ4 SUSS mask aligner);
-Ion Beam etching assisted by Auger Spectroscopy
-Chemistry laboratory facilities for nanolithography





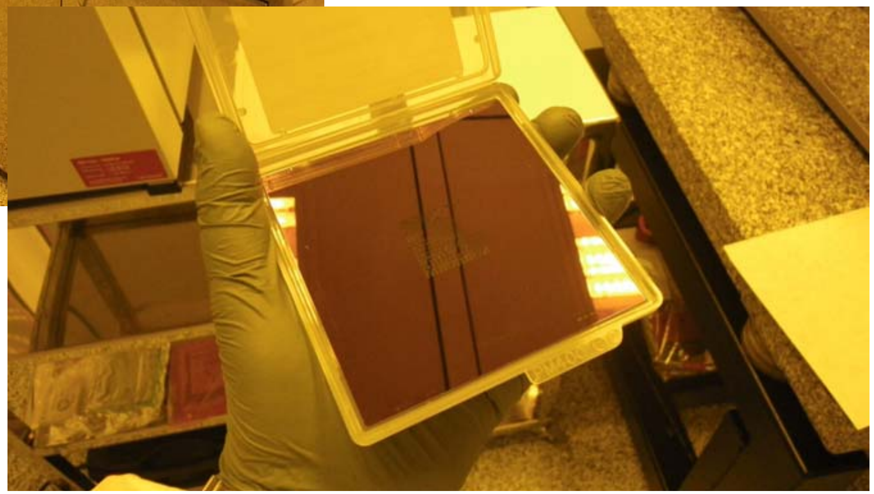


Clean room utilities



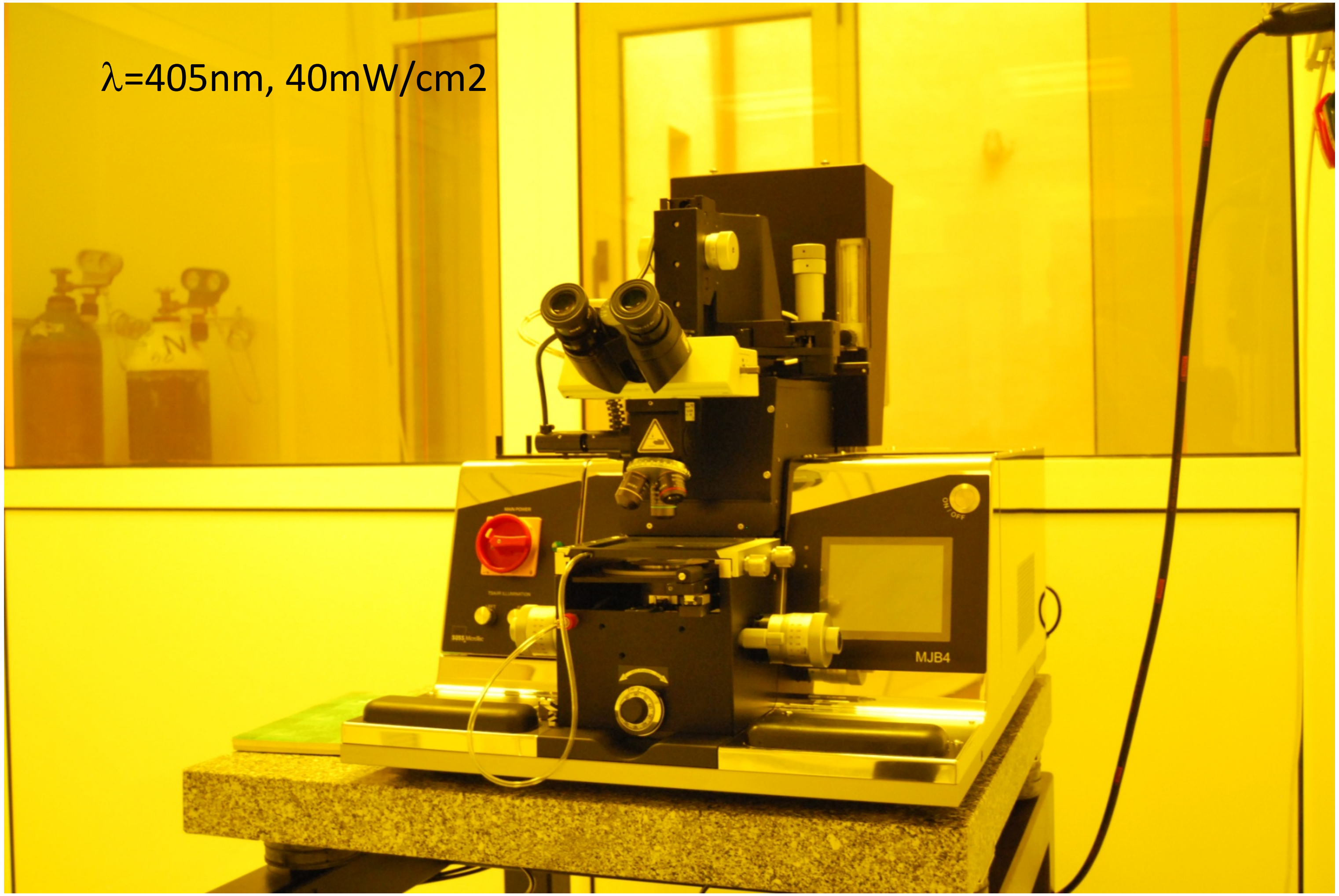
Clean room

Mask



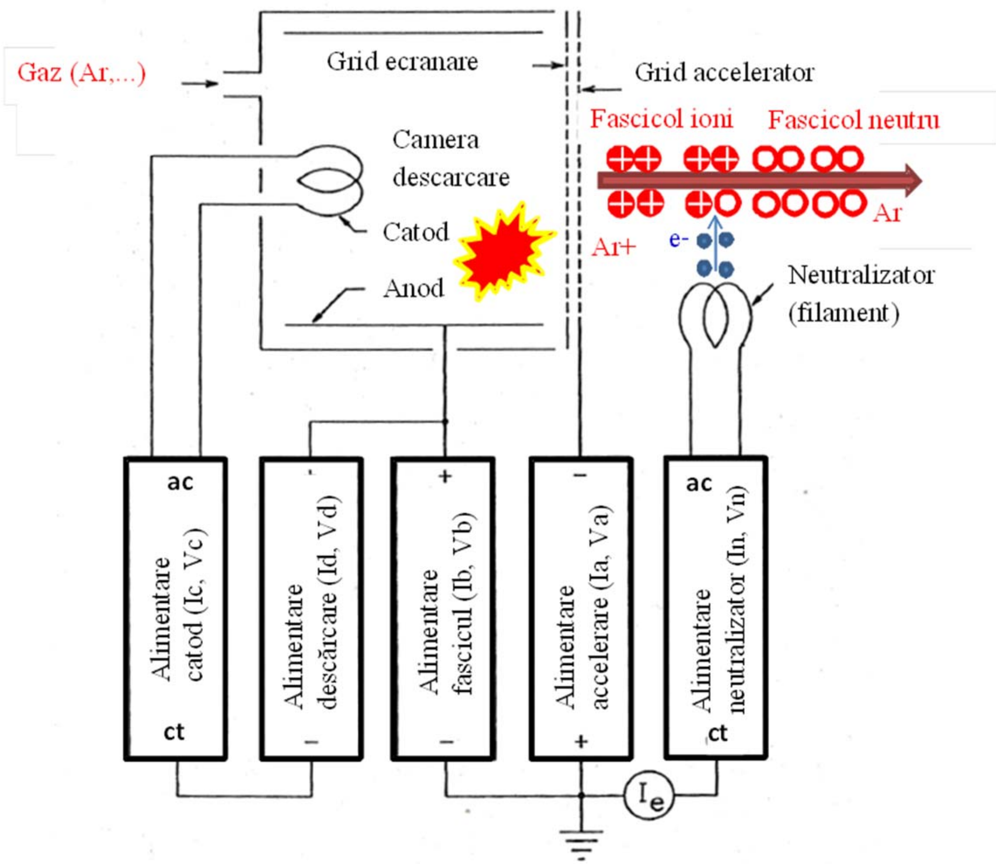
Clean room utilities

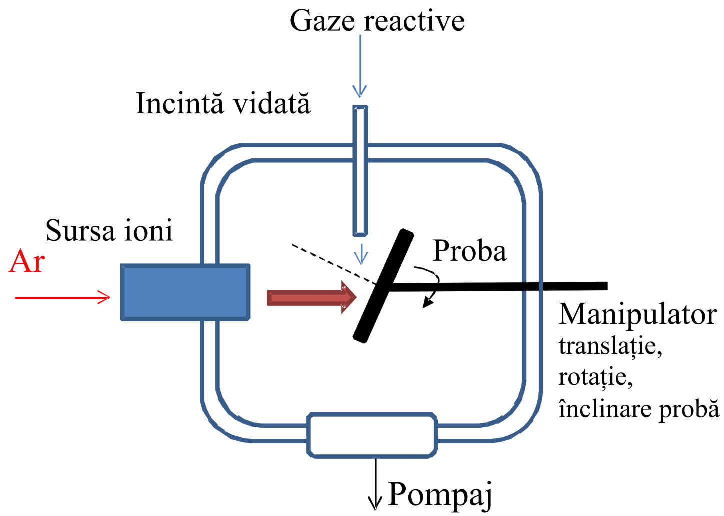
Mask aligner

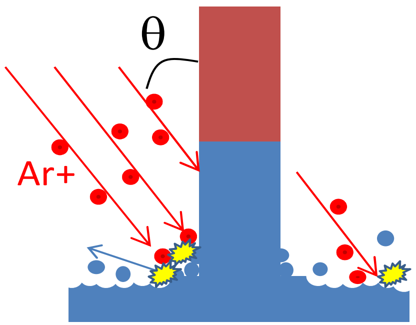


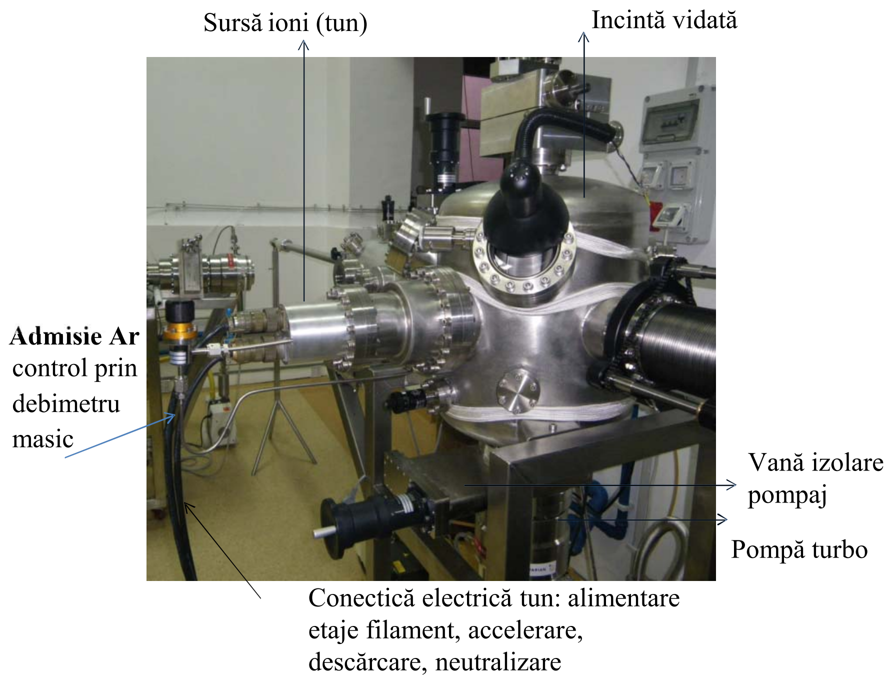
C4S-UTCN

The ion beam etching plant









Other clean room utilities

- Optical microscope
- Profilometer

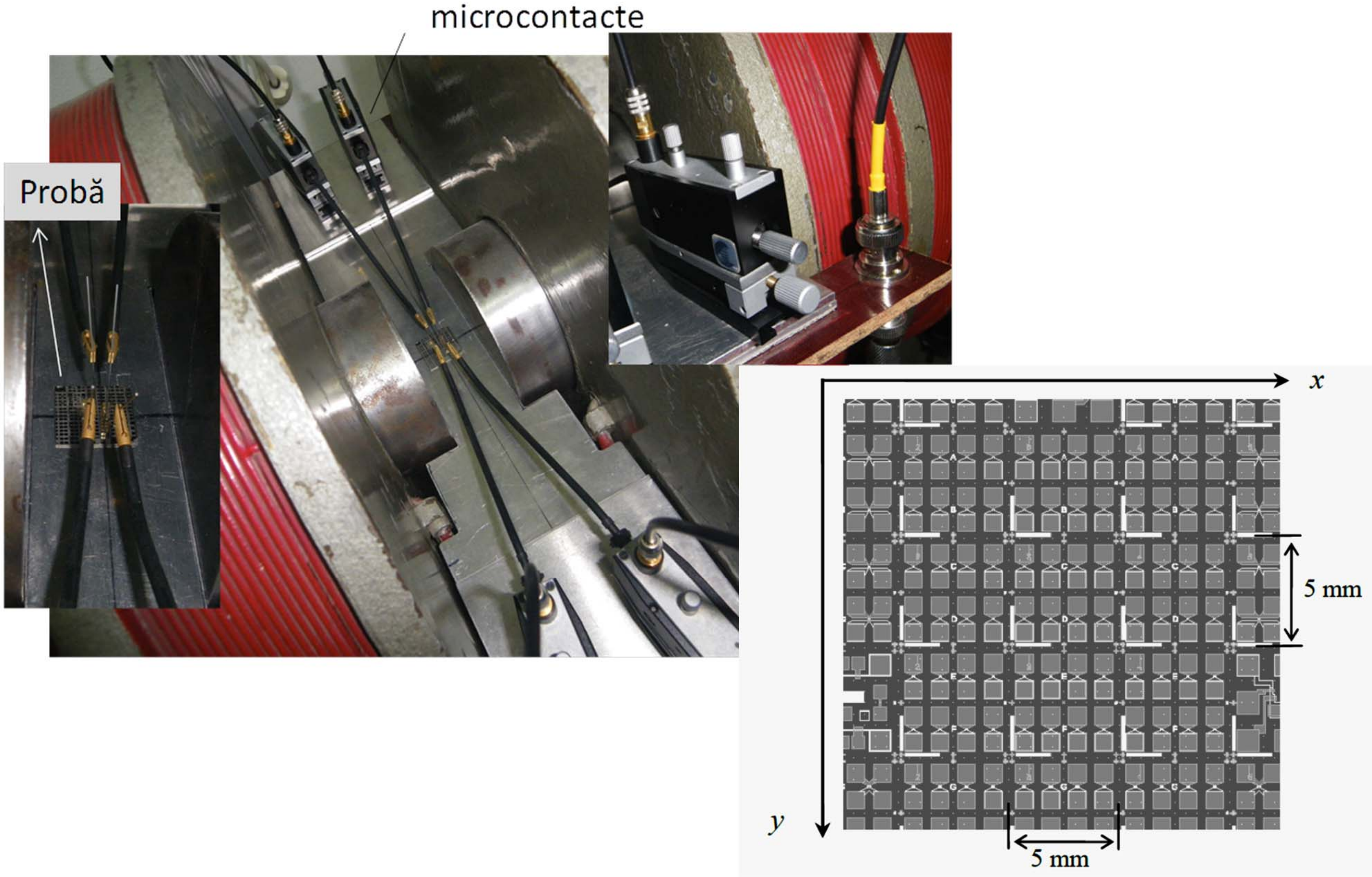
- CIP "Bonding"

Optical microscope
C4S UTCN up to 100x

- Point testers
  - Karl Suss DC et RF tester

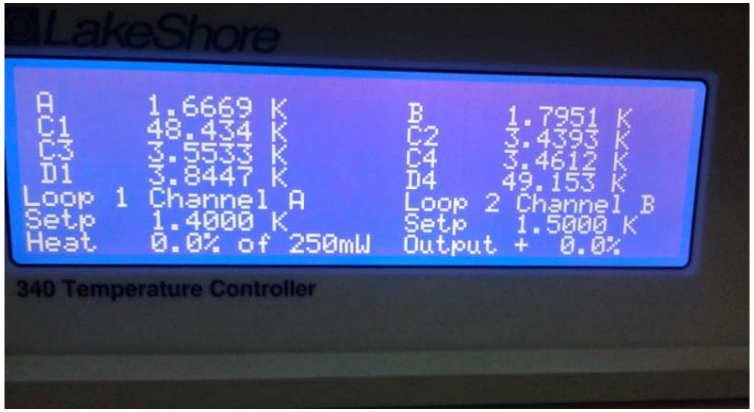
DC measures under field

Room temperature characterization facilities



Low temperature characterization facilities

Cryogen- free system with cryostat and VTI 1.8-300K and up to 7T magnetic field, sample rotation option



Magneto-electric characterization in variable field and temperature

Thanks!

Tomorrow morning: TMR