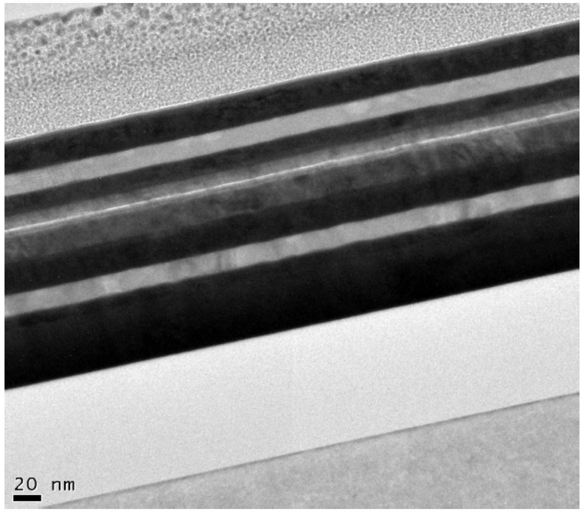
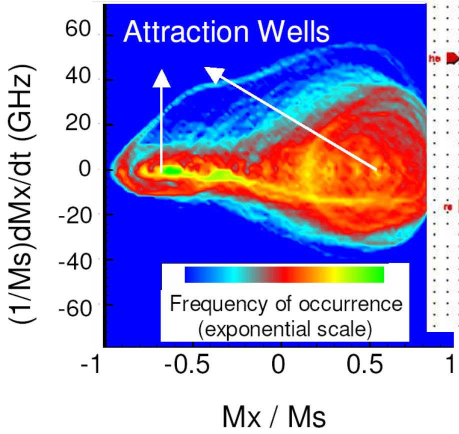
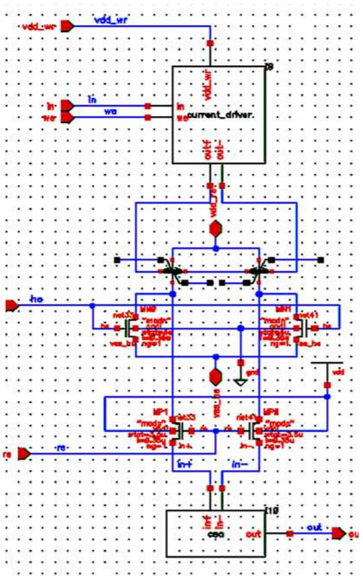
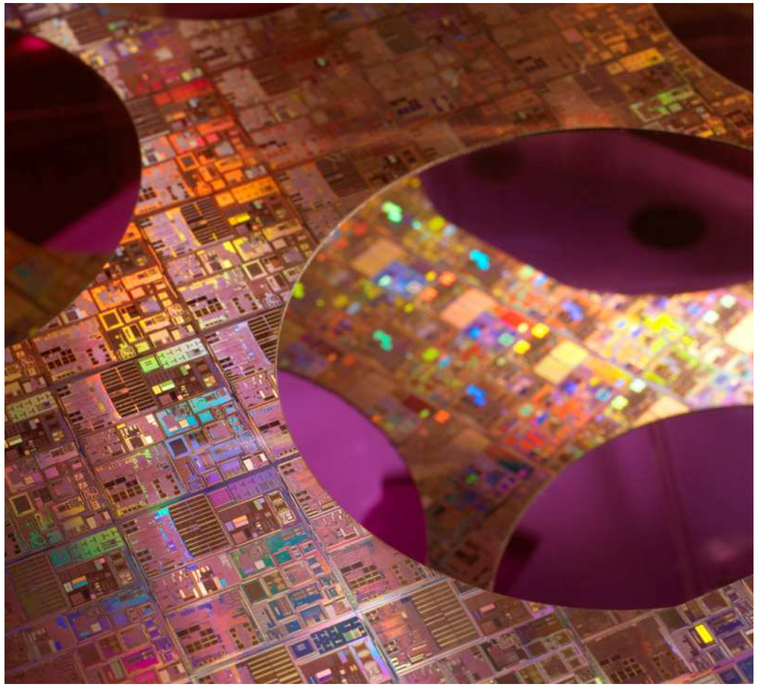
Spinelectronics:
From Basic Phenomena to Applications



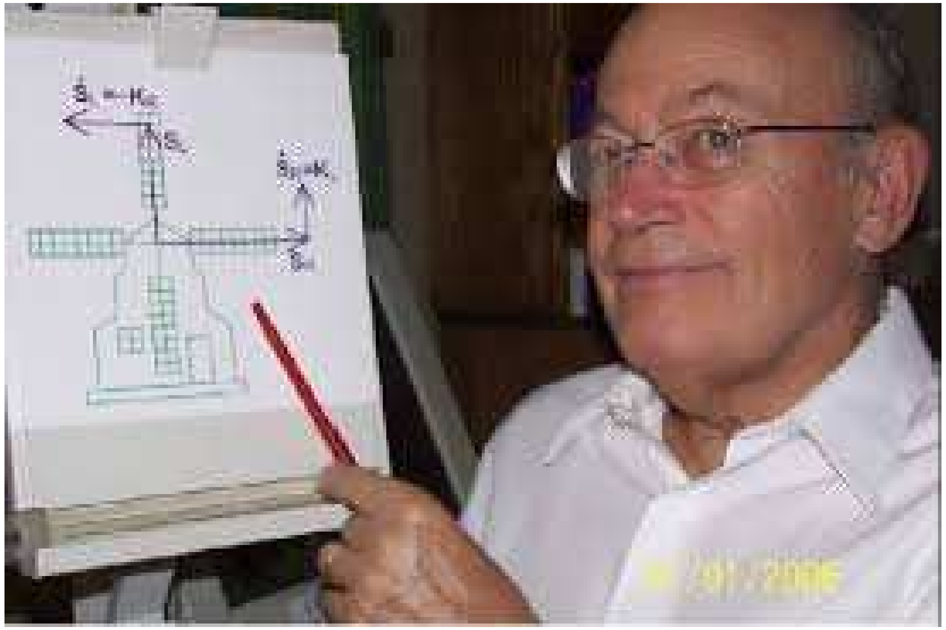






bernard.dieny@cea.fr

Spintronics tutorial Santander 20/06/2017



John Slonczewski

We will miss you, John

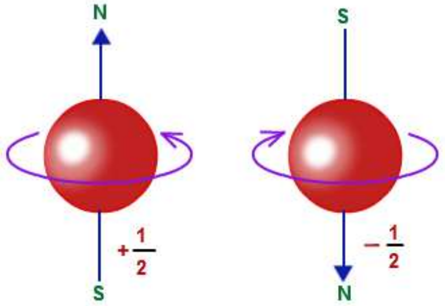
Spin-electronics

Electronics

Magnetism

Electron charge

Electron Spin

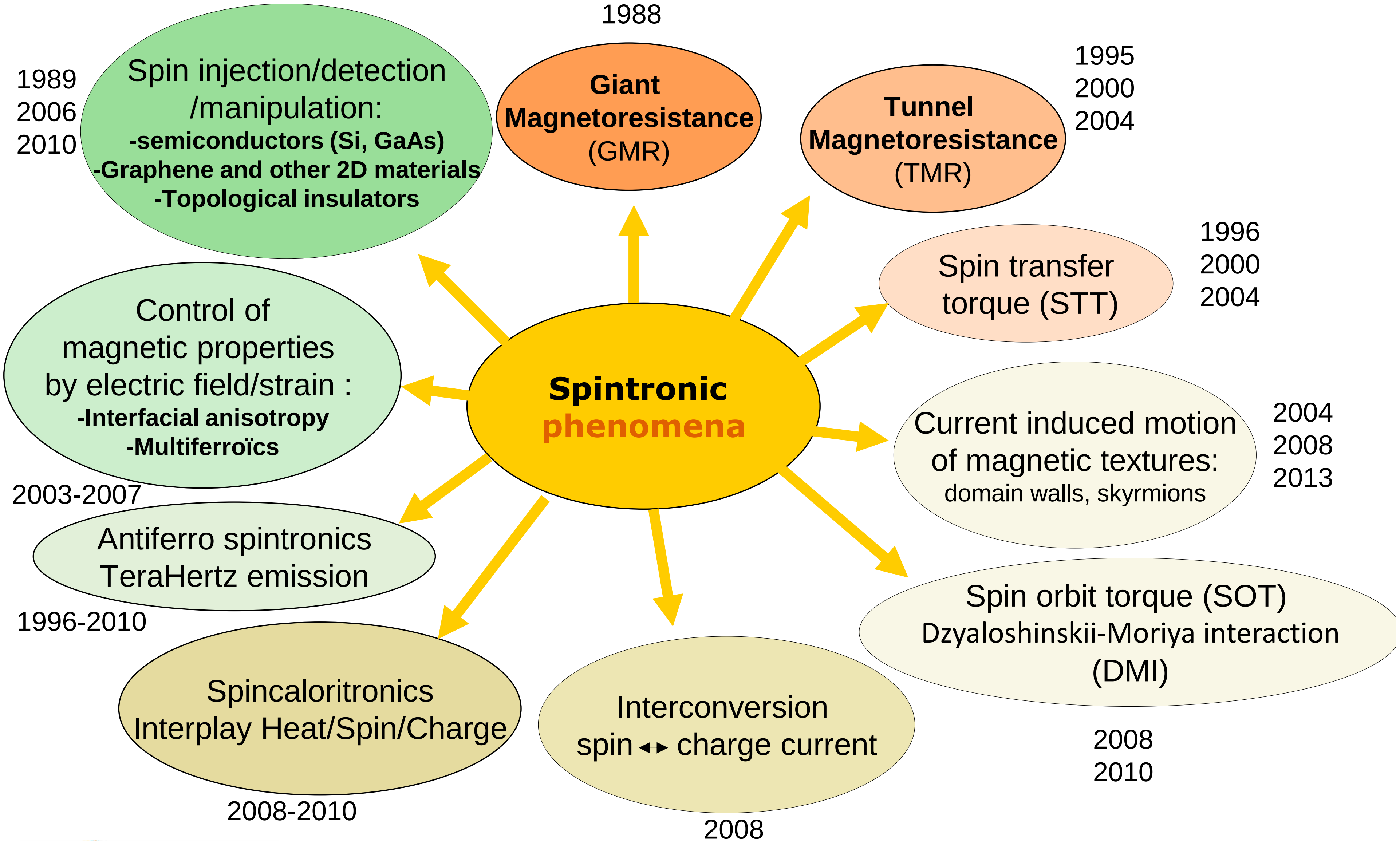


Main goal :

Discover new phenomena taking advantage of the electrons' spin and try to use them in devices having new functionalities or improved peformances (higher sensitivity, lower power consumption…etc).

Started in 1988 with the discovery of Giant Magnetoresistance

Spintronics/nanomagnetism broadening spectrum of interest



Spintronic phenomena

1989
2006
2010

Spin injection/detection /manipulation:
-semiconductors (Si, GaAs)
-Graphene and other 2D materials
-Topological insulators

1988

Giant Magnetoresistance (GMR)

Tunnel Magnetoresistance (TMR)

1995
2000
2004

Spin transfer torque (STT)

1996
2000
2004

Control of magnetic properties by electric field/strain :
-Interfacial anisotropy
-Multiferroïcs

2003-2007

Current induced motion of magnetic textures:
domain walls, skyrmions

2004
2008
2013

Antiferro spintronics
TeraHertz emission

1996-2010

Spin orbit torque (SOT)
Dzyaloshinskii-Moriya interaction (DMI)

2008
2010

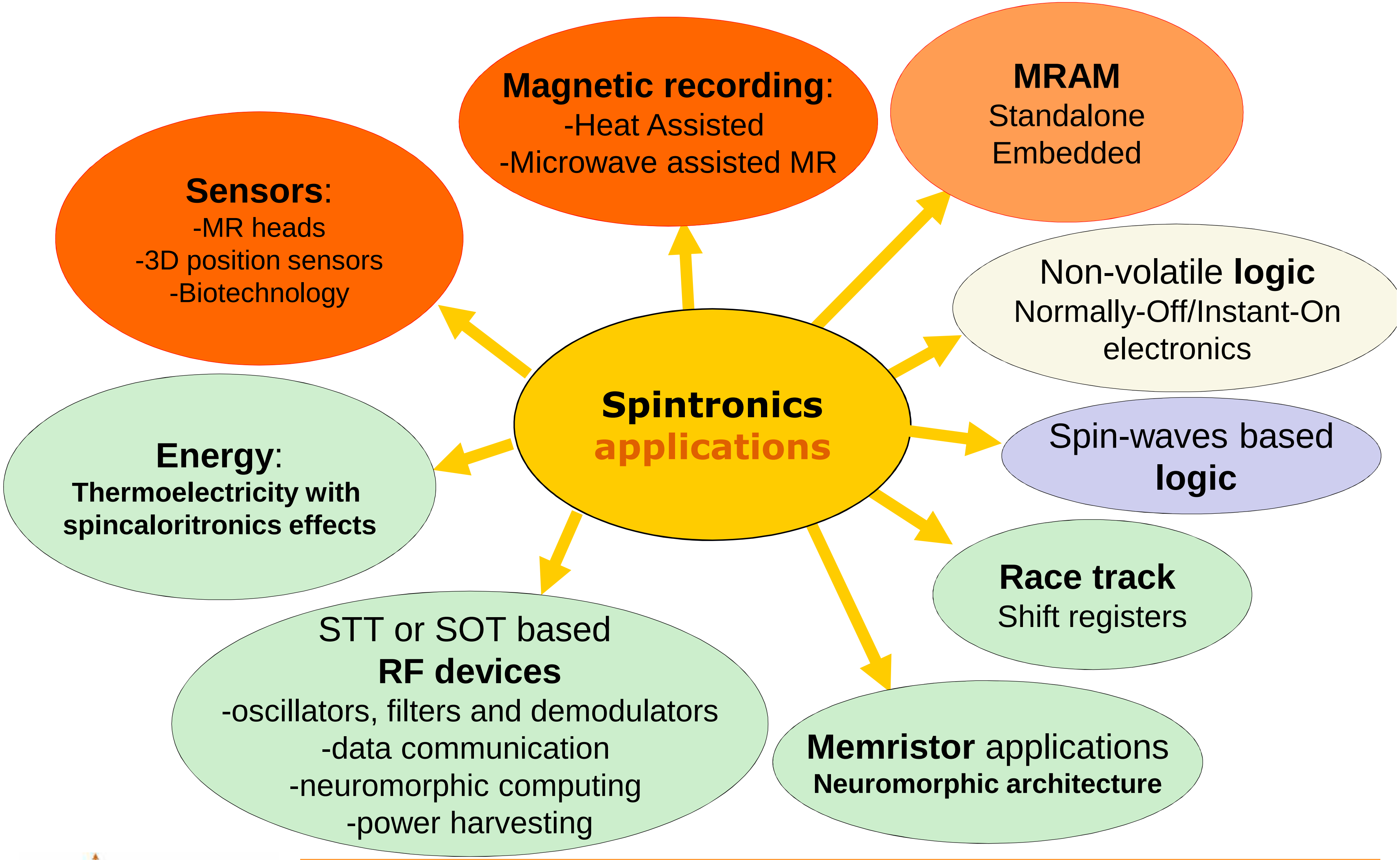
Spincaloritronics
Interplay Heat/Spin/Charge

2008-2010

Interconversion
spin ◂▸ charge current

2008

Spintronics/nanomagnetism broadening spectrum of interest



Spintronics applications

Magnetic recording:
-Heat Assisted
-Microwave assisted MR

MRAM
Standalone
Embedded

Sensors:
-MR heads
-3D position sensors
-Biotechnology

Non-volatile **logic**
Normally-Off/Instant-On electronics

Energy:
Thermoelectricity with spincaloritronics effects

Spin-waves based **logic**

Race track
Shift registers

STT or SOT based
RF devices
-oscillators, filters and demodulators
-data communication
-neuromorphic computing
-power harvesting

Memristor applications
Neuromorphic architecture

Spinelectronics:
From Basic Phenomena to Applications

OUTLINE

- Part 1 : Basic phenomena in spintronics:
  - Giant Magnetoresistance
  - Tunnel magnetoresistance (TMR)
  - Spin-Transfer Torque (STT)
  - Spin-orbit Torques (SOT)

- Part 2 : Spintronics main applications
  - Magnetic Recording (Hard disk drives Read-heads)
  - MRAMs
  - Magnetic field sensors
  - RF applications

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From Basic Phenomena to Applications

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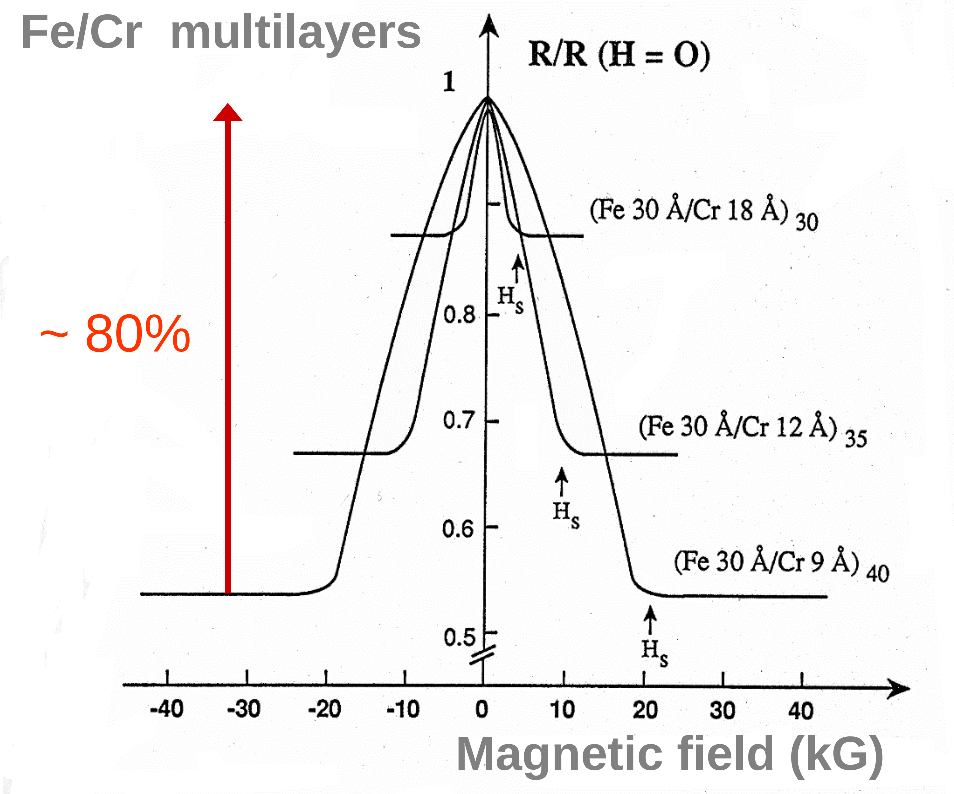
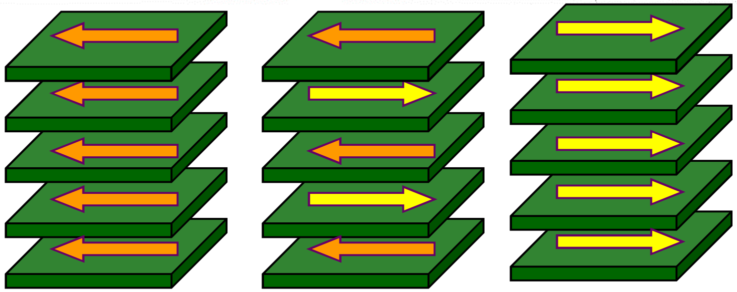
Giant magnetoresistance (1988)

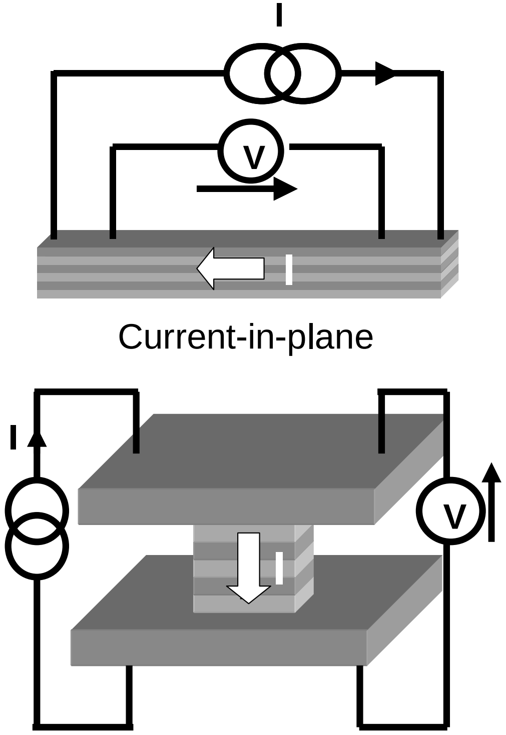
Baibich, M. et al, Phys.Rev.Lett., 61 (1988) 2472.





Antiferromagnetically coupled multilayers

Two geometries of measurement:



Current-in-plane

Current-perpendicular-to-plane

$$GMR = \frac{R_{AP} - R_P}{R_P}$$

NOBEL PRIZE IN PHYSICS IN 2007


Photo: U. Montan

Albert Fert

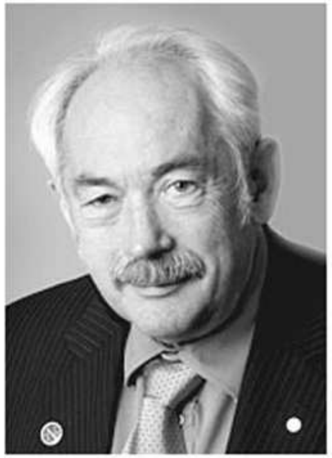


Photo: U. Montan

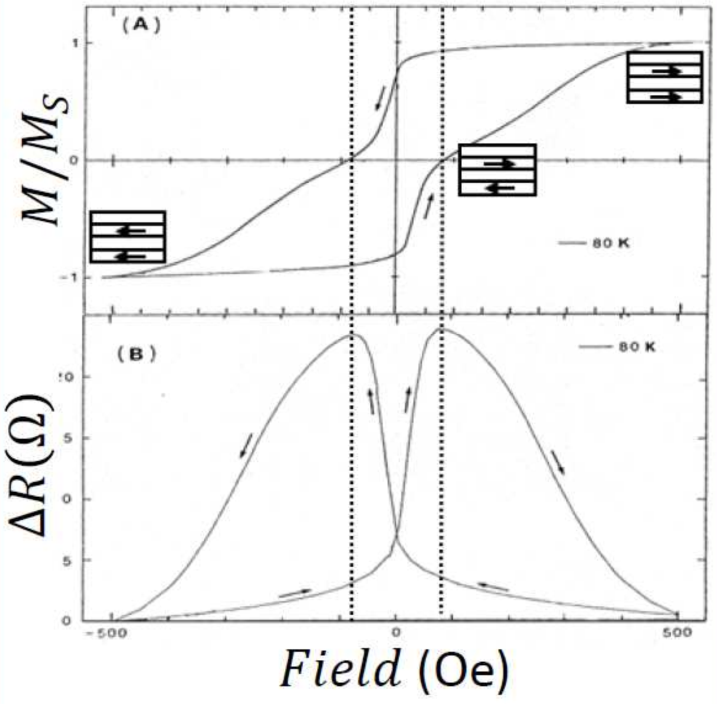
Peter Grünberg

Albert Fert & Peter Grünberg
received the Nobel Prize
from His Majesty King Carl XVI
Gustaf of Sweden
at the Stockholm Concert Hall,
10 December 2007.

Other GMR systems

Multilayers with two different switching fields

(Co 30 Å/Cu 55Å/NiFe 30 Å)$_5$

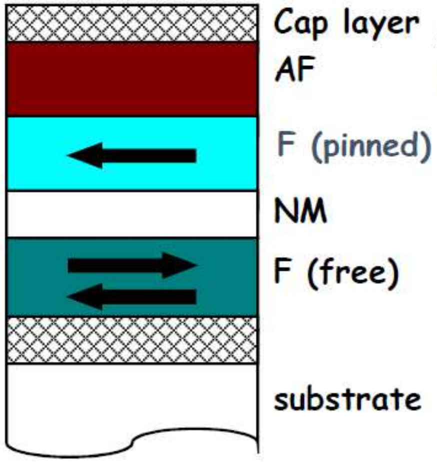


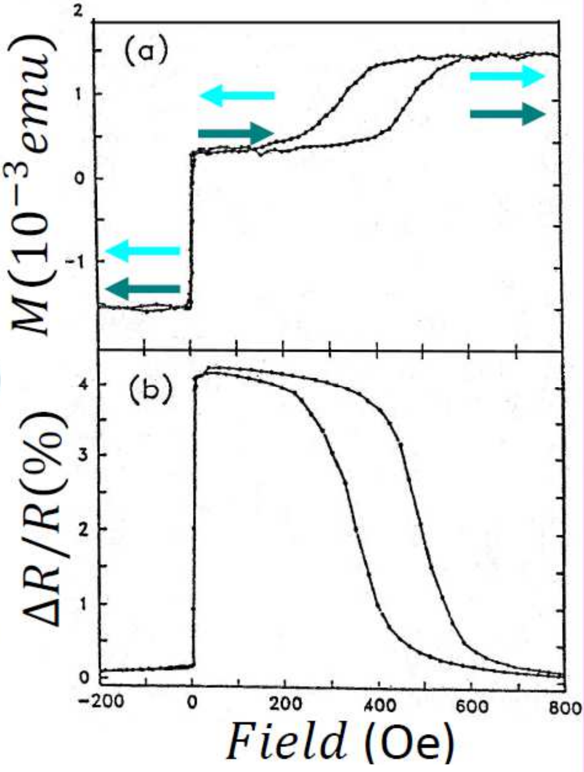
Yamamoto et al., JMMM 1991

Dupas et al, JAP 1990

Spin-valve structures

NiFe60Å/Cu22Å/NiFe40Å/FeMn70Å

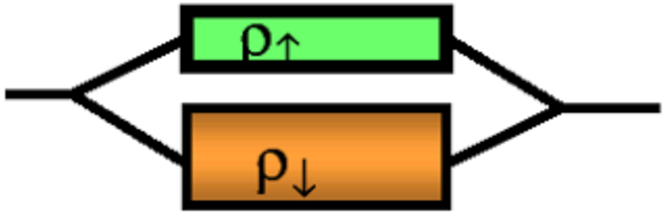




B.Dieny et al , Phys. Rev.B.(Condensed-Matter) 43 (1991)1297

Two current model (Mott 1930) for transport in magnetic metals

As long as spin-flip is negligible, current can be considered as carried in parallel by two categories of electrons: spin ↑ and spin ↓ (parallel and antiparallel to quantization axis)



$$\rho = \left(\frac{1}{\rho_\uparrow} + \frac{1}{\rho_\downarrow} \right)^{-1} = \frac{\rho_\uparrow \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow}$$

Sources of spin flip: magnons and spin-orbit scattering

Negligible spin-flip often crude approximation (spin diffusion length in NiFe~4.5nm, 30% spin memory loss at Co/Cu interfaces)

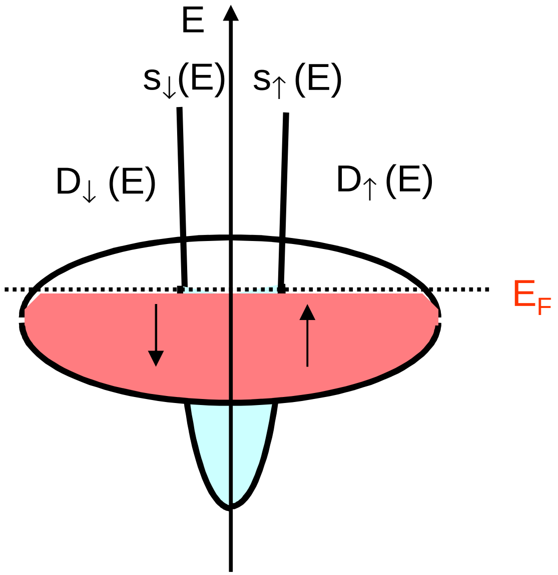
Mott N.F. and H.H.Wills, Proc.Roy.Soc.A156, 368 (1936).

Spin dependent transport in magnetic transition metals (1)

Band structure of 3d transition metals

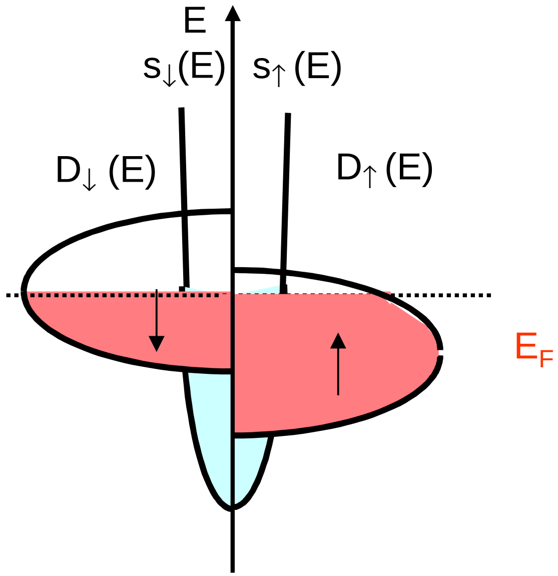
In transition metals, partially filled bands which participate to conduction are s and d bands

Non-magnetic Cu :



$D_{\uparrow}(E_F) = D_{\downarrow}(E_F)$

Magnetic Ni :



$D_{\uparrow}(E_F) \neq D_{\downarrow}(E_F)$

Most of transport properties are determined by DOS at Fermi energy

⇨ **Spin-dependent density of state at Fermi energy**

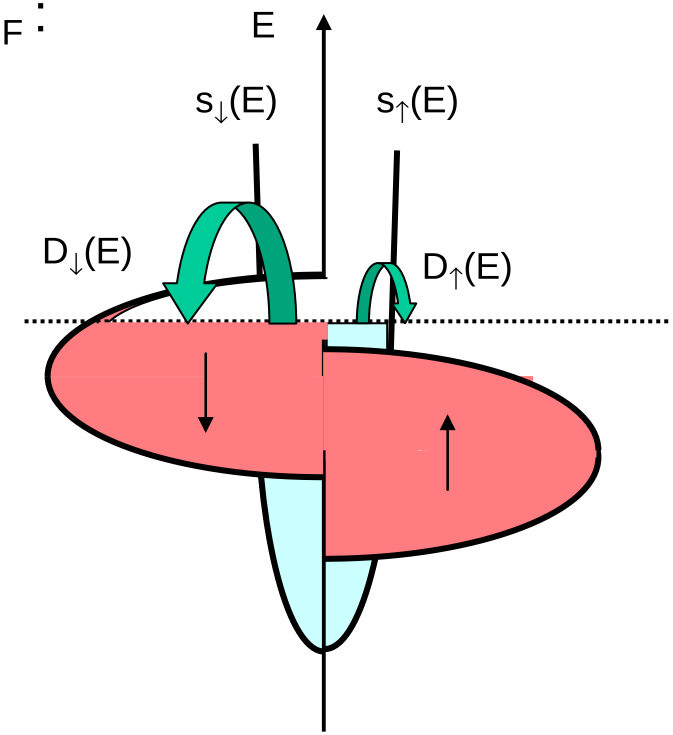
Fert, A., Campbell, I.A., J.Phys.F6, 849 (1976).

Spin dependent transport in magnetic metals (2)

$m^*(d) >> m^*(s)$ ⇨ J mostly carried by s electrons in transition metals

Scattering of electrons determined by DOS at E_F :

Fermi Golden rule : $P^{\sigma} \propto \langle i|W|f\rangle^2 D_f(E_F)$



$s_\uparrow \to s_\uparrow$

$s_\uparrow \to d_\uparrow$

$s_\downarrow \to s_\downarrow$

$s_\downarrow \to d_\downarrow$ Most efficient scattering channel

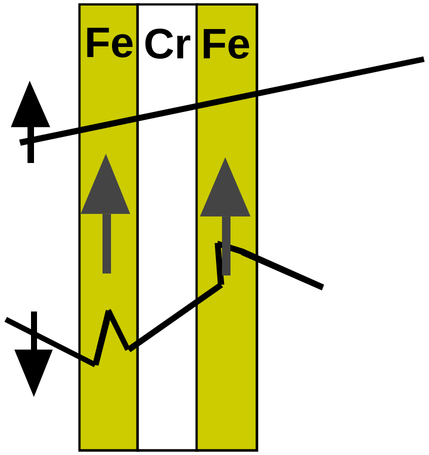
⇨ Spin-dependent scattering rates in magnetic transition metals

Example: $\lambda_{\uparrow Co} = 10nm; \lambda_{\downarrow Co} = 1nm$

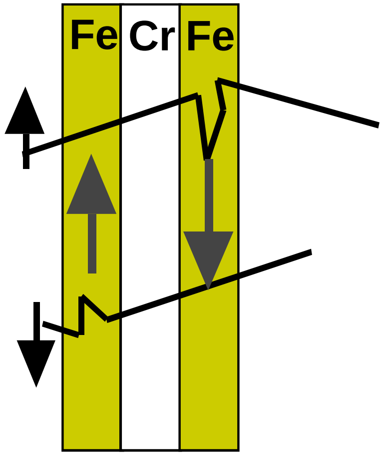
Fert, A., Campbell, I.A., J.Phys.F6, 849 (1976).

Simple model of Giant Magnetoresistance

Parallel config



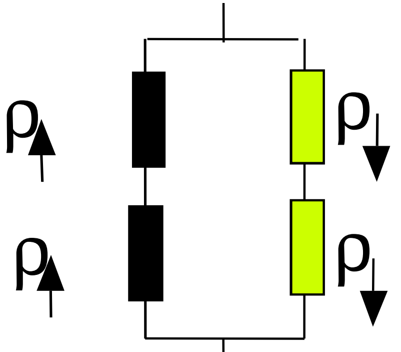
Antiparallel config



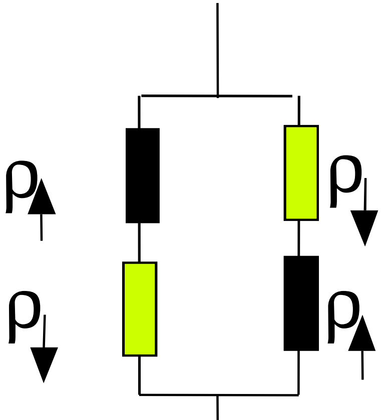
Baibich, M. et al,
Phys.Rev.Lett., 61 (1988) 2472.

$$\frac{\Delta\rho}{\rho_{ap}}=\left(\frac{\rho_{\uparrow}-\rho_{\downarrow}}{\rho_{\uparrow}+\rho_{\downarrow}}\right)^{2}=\left(\frac{\alpha-1}{\alpha+1}\right)^{2}$$

Equivalent resistances :



$$\rho_P=\frac{2\rho_{\uparrow}\rho_{\downarrow}}{(\rho_{\uparrow}+\rho_{\downarrow})}$$



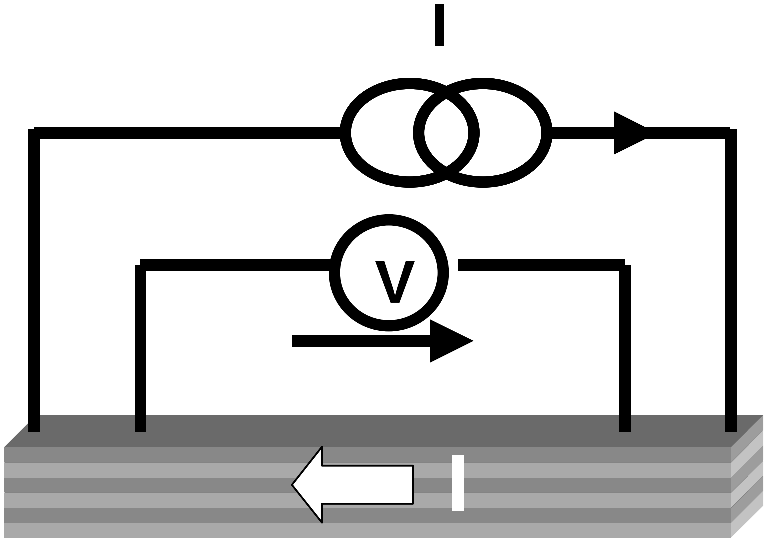
$$\rho_{AP}=\frac{(\rho_{\uparrow}+\rho_{\downarrow})}{2}$$

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

Key role of
scattering contrast α

Two configurations of GMR measurement

1) Current in-plane (CIP)



- Straightforward to measure at wafer level, no need for patterning
- Measured in 4 point probe geometry

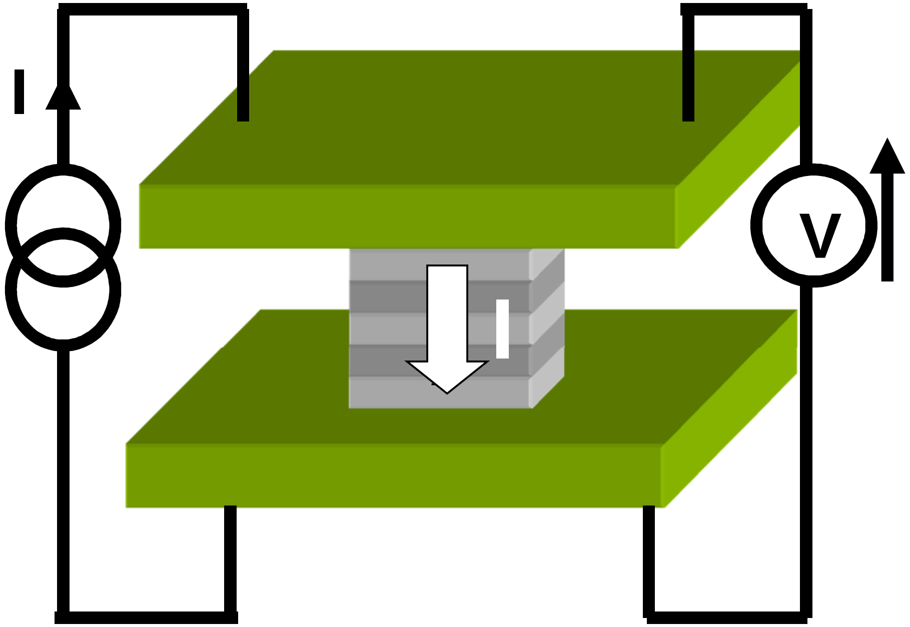
CIP-GMR described by Boltzman formalism

(R. E. Camley and J. Barnaś, Phys. Rev. Lett. ***63****, 664 (1989))*

- Important characteristic lengths : elastic spin-dependent mean free paths

e.g. $\lambda_{NiFe}^{\uparrow} = 7nm$; $\lambda_{NiFe}^{\downarrow} = 1nm$

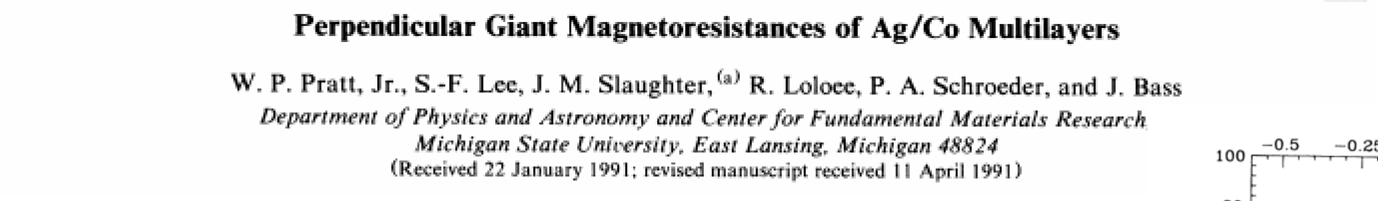
2) Current Perpendicular to Plane GMR (CPP-GMR)



Much more difficult to measure but richer physics,
Either on macroscopic samples (0.1mm diameter) with superconducting leads
(R~ ρ . thickness / area ~ $10^{-5}\Omega$)
or on patterned microscopic pillars of area <µm² (R~ a few Ohms)

Pratt,W.P.Jr, et al, Phys.Rev.Lett. 66 (1991) 3060
Eid, K.,Pratt Jr., W.P., and Bass, J. Journ.Appl.Phys.93, 3445 (2003). *Michigan State Univ*

Current Perpendicular to Plane GMR



VOLUME 66, NUMBER 23 PHYSICAL REVIEW LETTERS 10 JUNE 1991

Perpendicular Giant Magnetoresistances of Ag/Co Multilayers

W. P. Pratt, Jr., S.-F. Lee, J. M. Slaughter,(a) R. Loloee, P. A. Schroeder, and J. Bass
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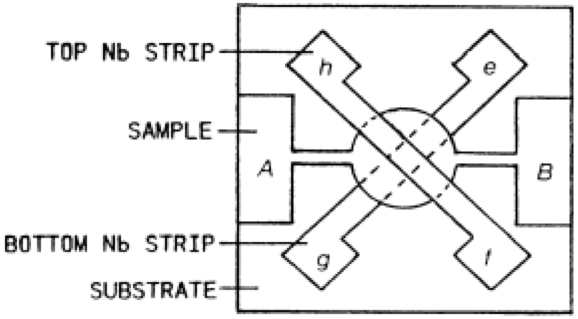
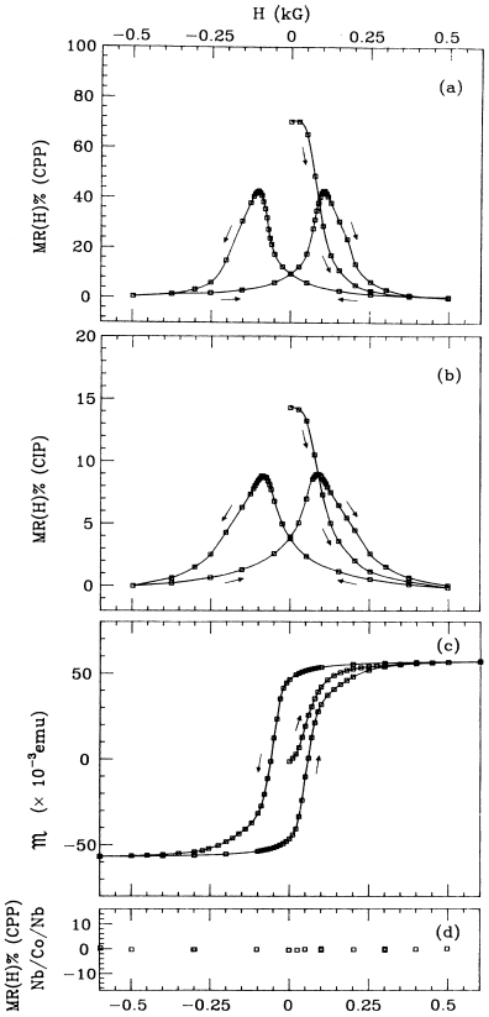
(Received 22 January 1991; revised manuscript received 11 April 1991)





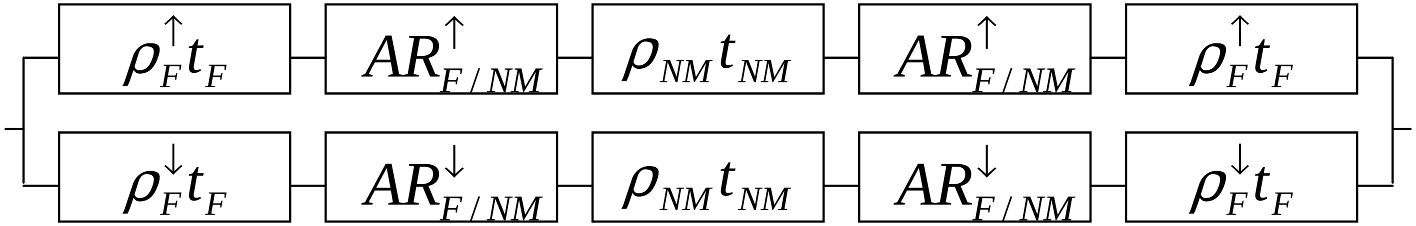
Measurement limited at 4K

Serial resistance model for CPP-GMR

Without spin-filp, serial resistance network can be used for CPP transport

CPP transport through F/NM/F sandwich described by:

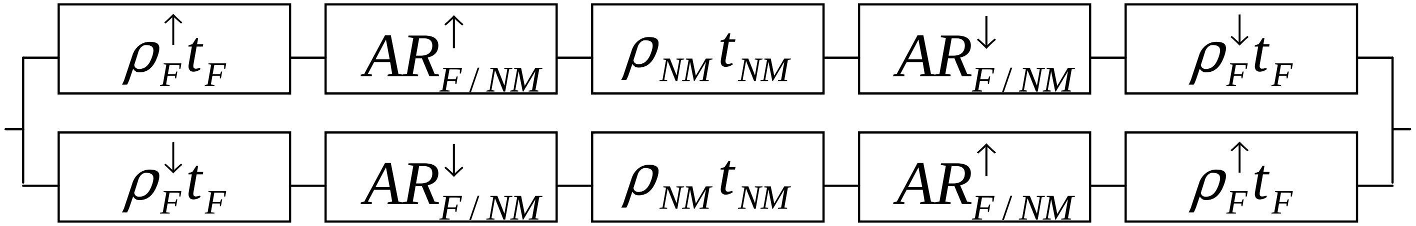
(a) Parallel magnetic configuration :



$\rho_F^{\uparrow} t_F$ — $AR_{F/NM}^{\uparrow}$ — $\rho_{NM} t_{NM}$ — $AR_{F/NM}^{\uparrow}$ — $\rho_F^{\uparrow} t_F$

$\rho_F^{\downarrow} t_F$ — $AR_{F/NM}^{\downarrow}$ — $\rho_{NM} t_{NM}$ — $AR_{F/NM}^{\downarrow}$ — $\rho_F^{\downarrow} t_F$

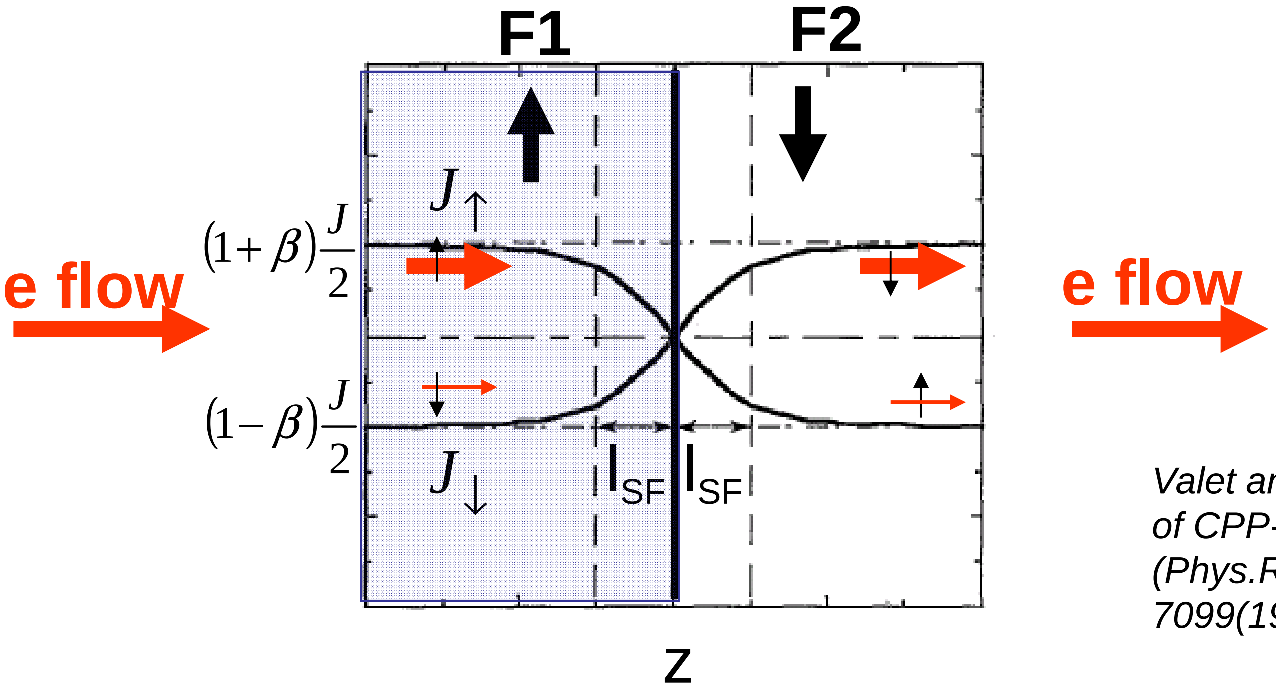
(b) Antiparallel magnetic configuration :



$\rho_F^{\uparrow} t_F$ — $AR_{F/NM}^{\uparrow}$ — $\rho_{NM} t_{NM}$ — $AR_{F/NM}^{\downarrow}$ — $\rho_F^{\downarrow} t_F$

$\rho_F^{\downarrow} t_F$ — $AR_{F/NM}^{\downarrow}$ — $\rho_{NM} t_{NM}$ — $AR_{F/NM}^{\uparrow}$ — $\rho_F^{\uparrow} t_F$

Spin accumulation – spin relaxation in CPP geometry



Valet and Fert theory of CPP-GMR (Phys.Rev.B48, 7099(1993))

In F1: Different scattering rates for spin ↑ and spin ↓ electrons
⇒ different spin ↑ and spin ↓ currents.
Larger scattering rates for spin ↓ : $J_\uparrow >> J_\downarrow$ far from the interface.

In F2: Larger scattering rates for spin ↑ : $J_\downarrow >> J_\uparrow$ far from the interface.

Majority of incoming spin ↑electrons, majority of outgoing spin↓ electrons
Building up of a spin↑accumulation around the interface balanced in steady state by spin-relaxation

Starting point : Valet and Fert theory of CPP-GMR (Phys.Rev.B48, 7099(1993))

μ_σ : spin-dependent chemical potential

In homogeneous material, $\mu=\varepsilon_F-e\phi$

Spin-dependent current driven by $\vec{\nabla}\mu$

$$\boxed{J_\sigma = \frac{1}{e\rho_\sigma}\frac{\partial \mu_\sigma}{\partial z}}$$

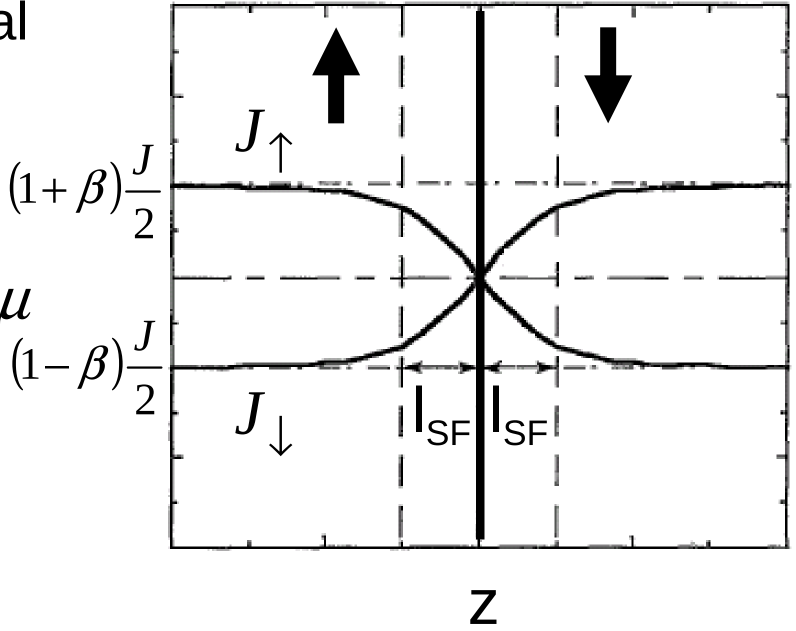
Generalization of Ohm law

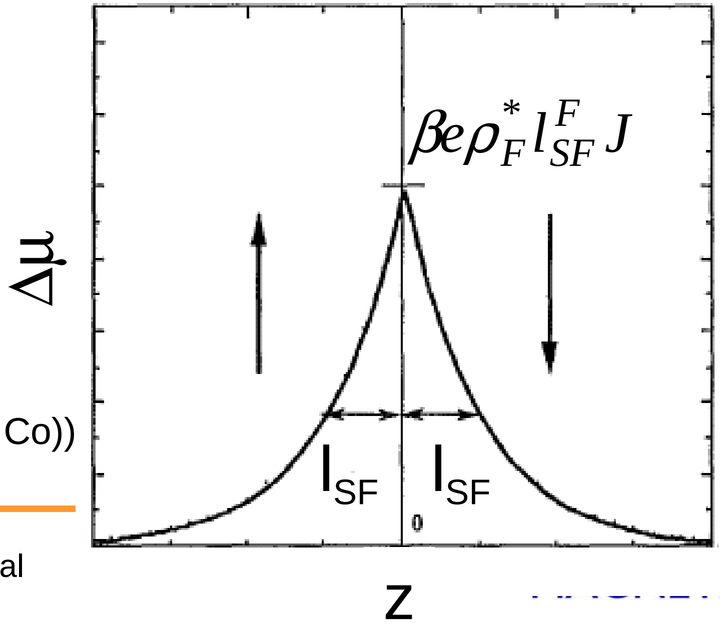
Spin relaxation :

$$\boxed{e\rho_\sigma \frac{\partial J_\sigma}{\partial z} = \frac{\mu_\sigma - \mu_{-\sigma}}{2 l_{SF}^2}}$$

l_{SF}=spin-diffusion length (~5nm in NiFe, ~20nm in Co))

Spin-relaxation at F↑/F↓ interface:





Interfacial boundary conditions

$$\mu_{i+1}^{\uparrow(\downarrow)}(z_{i+1}) - \mu_i^{\uparrow(\downarrow)}(z_{i+1}) = r_{i+1}^{\uparrow(\downarrow)} J_i^{\uparrow(\downarrow)}(z_{i+1})$$

(Ohm law at interfaces)

$$J_{i+1}^{\uparrow(\downarrow)}(z_{i+1}) = J_i^{\uparrow(\downarrow)}(z_{i+1})$$

(if no interfacial spin-flip is considered)

Note: Interfacial spin memory loss can be introduced by :

$$J_{i+1}^{\uparrow(\downarrow)}(z_{i+1}) = \delta\, J_i^{\uparrow(\downarrow)}(z_{i+1})$$

30% memory loss as at Co/Cu interface yields δ=0.7

Input microscopic transport parameters to describe macroscopic CPP properties

Within each layer :

-The measured resistivity ρ.

-The scattering asymmetry β.

-The spin diffusion length l_{sf}.

$$\rho_{\uparrow(\downarrow)} = 2\rho * [1-(+)\beta]$$

$$\rho_{measured} = \frac{\rho_\uparrow \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow} = \rho^*(1-\beta^2)$$

At each interface :

-The measured interfacial area*resistance product $r_{measured}$

-The interfacial scattering asymmetry γ.

$$r_{\uparrow(\downarrow)} = 2r * [1-(+)\gamma]$$

$$r_{measured} = \frac{r_\uparrow r_\downarrow}{r_\uparrow + r_\downarrow} = r*(1-\gamma^2)$$

Examples of bulk parameters

Material	Measured resistivity 4K/300K	β Bulk scattering asymmetry	l_{SF}
Cu	0.5-0.7μΩ.cm 3-5	0 0	500nm 50-200nm
Au	2μΩ.cm 8	0 0	35nm 25nm
$Ni_{80}Fe_{20}$	10-15 22-25	0.73-0.76 0.70	5.5 4.5
$Ni_{66}Fe_{13}Co_{21}$	9-13 20-23	0.82 0.75	5.5 4.5
Co	4.1-6.45 12-16	0.27 – 0.38 0.22-0.35	60 25
$Co_{90}Fe_{10}$	6-9 13-18	0.6 0.55	55 20
$Co_{50}Fe_{50}$	7-10 15-20	0.6 0.62	50 15
$Pt_{50}Mn_{50}$	160 180	0 0	1 1
Ru	9.5-11 14-20	0 0	14 12

Review on CPP-GMR: Bass, JMMM 408 (2016) 244–320

Examples of interfacial parameters

Review on
CPP-GMR:
Bass, JMMM 408 (2016) 244–320

Material	**Measured R.A interfacial resistance**	**γ Interfacial scattering assymetry**
Co/Cu	**0.21mΩ.μm^2** **0.21-0.6**	**0.77** **0.7**
$Co_{90}Fe_{10}$/Cu	**0.25-0.7** **0.25-0.7**	**0.77** **0.7**
$Co_{50}Fe_{50}$/Cu	**0.45-1** **0.45-1**	**0.77** **0.7**
NiFe/Cu	**0.255** **0.25**	**0.7** **0.63**
NiFe/Co	**0.04** **0.04**	**0.7** **0.7**
Co/Ru	**0.48** **0.4**	**-0.2** **-0.2**
Co/Ag	**0.16** **0.16**	**0.85** **0.80**

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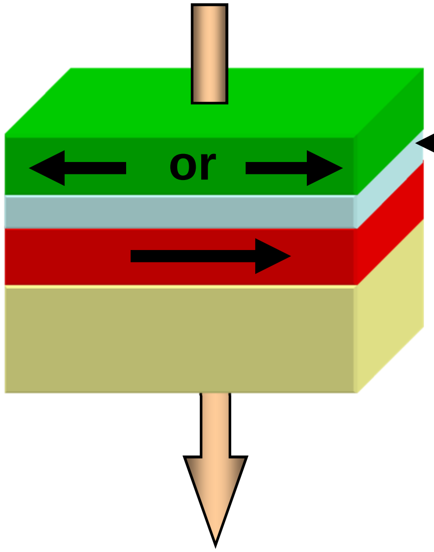
Magnetic tunnel junctions – Tunnel magnetoresistance

Structure of a magnetic tunnel junction



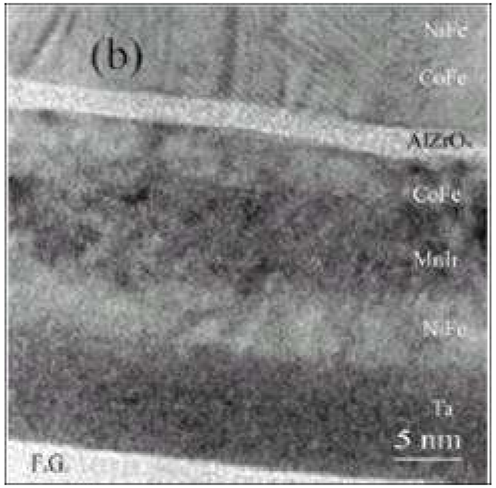
Storage layer: CoFe 4 nm

Al_2O_3 barrier 1.5nm

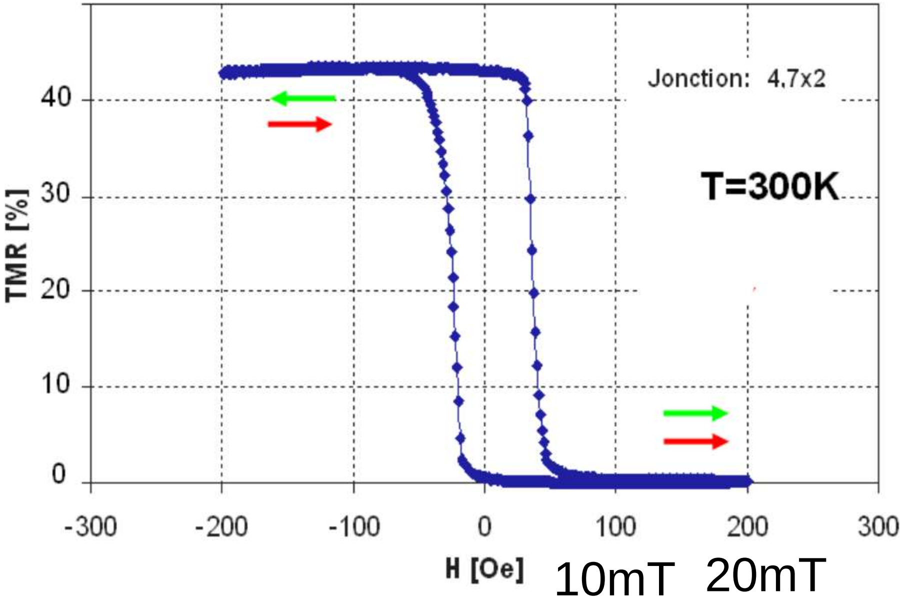
Reference layer :CoFe 3nm

IrMn 7nm

Acts as a couple polarizer/analyzer with the spin of the electrons.



$Al(Zr)O_x$



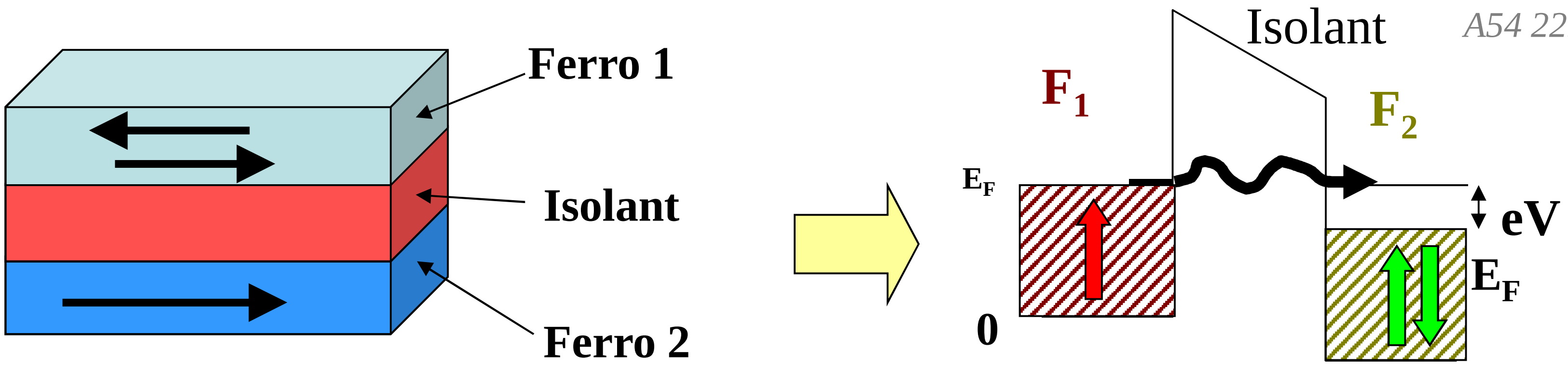
10mT 20mT

- First observation of TMR at low T in MTJ: Julliere (1975) (Fe/Ge/Co)
- TMR at 300K :
  Moodera et al, PRL (1995);
  Myazaki et al, JMMM(1995).
  in AlO_x based junctions

$\Delta R/R \sim 50\%$

Julliere model of tunnel magnetoresistance (TMR)

Jullière,Phys. Lett. A54 225 (1975)



Fermi Golden rule: proba of tunneling $\mathcal{P}^{\sigma} \propto \langle i|W|f \rangle^2 D_2(E_F)$

Nb of electrons candidate for tunneling $\propto D_1(E_F)$

$\Rightarrow$ tunneling current in each spin channel $J^{\sigma} \propto D_1^{\sigma}(E_F) \times D_2^{\sigma}(E_F)$

Parallel configuration

$$J^{parallel} \propto D_1^{\uparrow} D_2^{\uparrow} + D_1^{\downarrow} D_2^{\downarrow}$$

Antiparallel configuration

$$J^{antiparallel} \propto D_1^{\uparrow} D_2^{\downarrow} + D_1^{\downarrow} D_2^{\uparrow}$$

$$\boxed{P = \frac{D^{\uparrow}(E_F) - D^{\downarrow}(E_F)}{D^{\uparrow}(E_F) + D^{\downarrow}(E_F)}}$$

$$\boxed{TMR = \frac{\Delta R}{R_P} = \frac{2 P_1 P_2}{1 - P_1 P_2}}$$

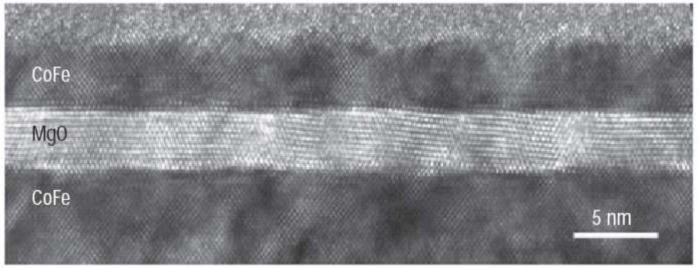
$$TMR = \frac{\Delta R}{R_{AP}} = \frac{2 P_1 P_2}{1 + P_1 P_2}$$

P~50% in Fe, Co
ΔR/R~40 - 70% with alumina barriers

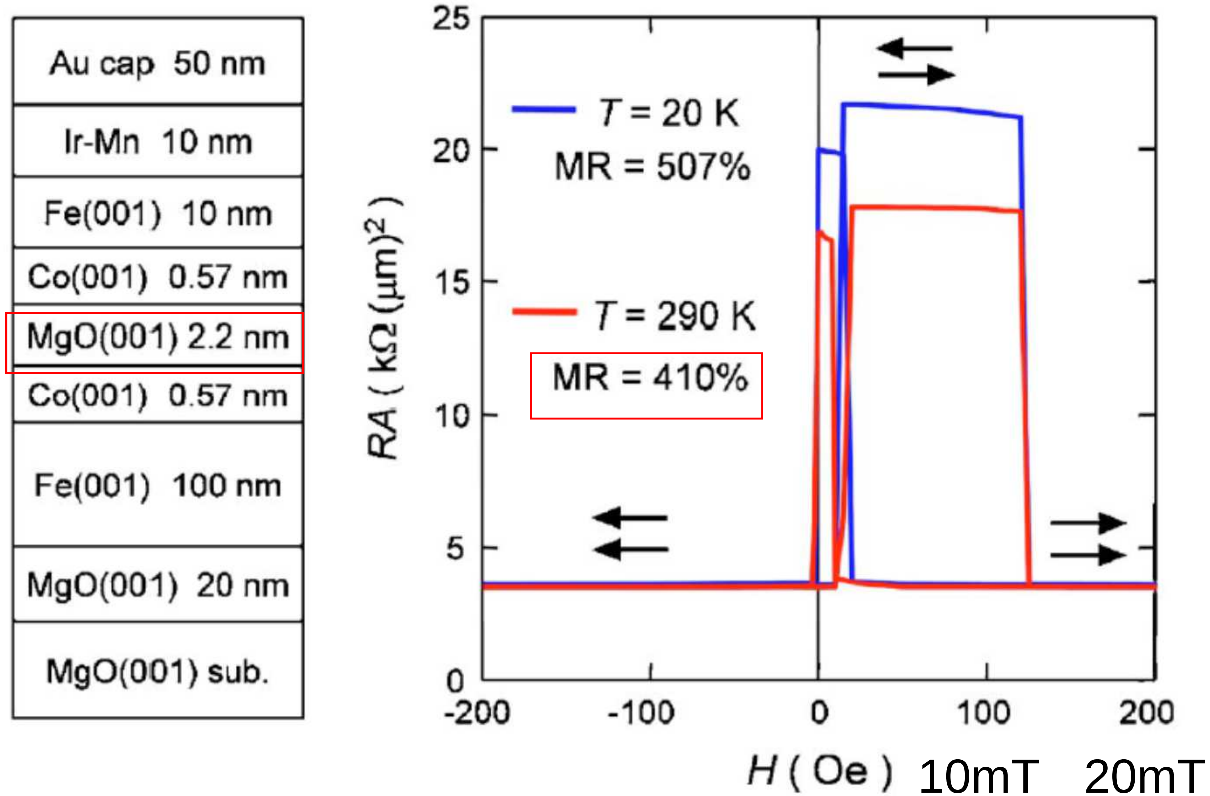
Giant TMR of MgO tunnel barriers

S.S.P.Parkin et al, Nature Mat. (2004), nmat1256.
S.Yuasa et al, Nature Mat. (2004), nmat 1257.

Very well textured MgO barriers grown by sputtering or MBE on bcc CoFe or Fe magnetic electrodes, or on amorphous CoFeB electrodes followed by annealing to recrystallize the electrode.



Yuasa et al, APL89, 042505(2006)

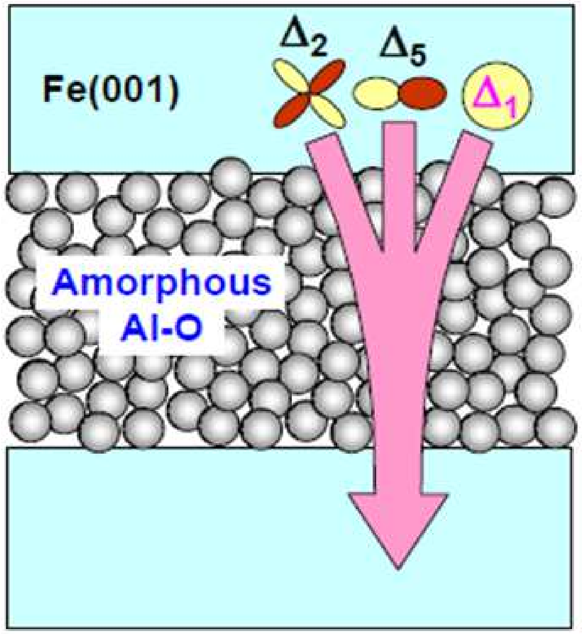


10mT 20mT

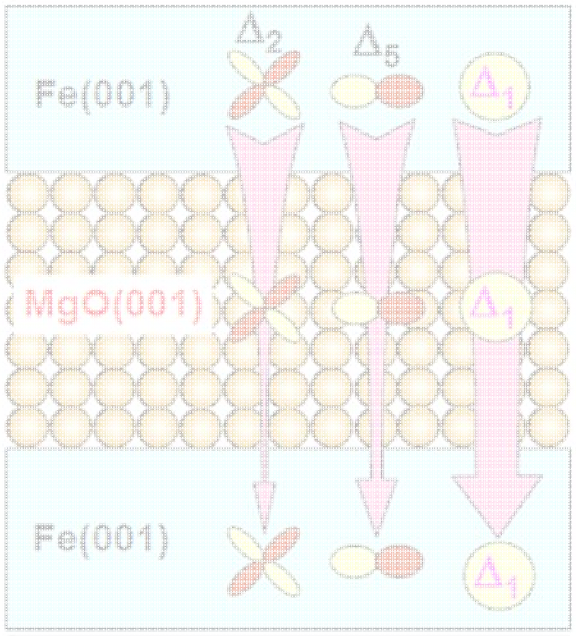
Amorphous barrier Vs Crystalline barrier

Amorphous barrier
ex: amorphous AlO

bcc



Crystalline barrier
ex: MgO(001)



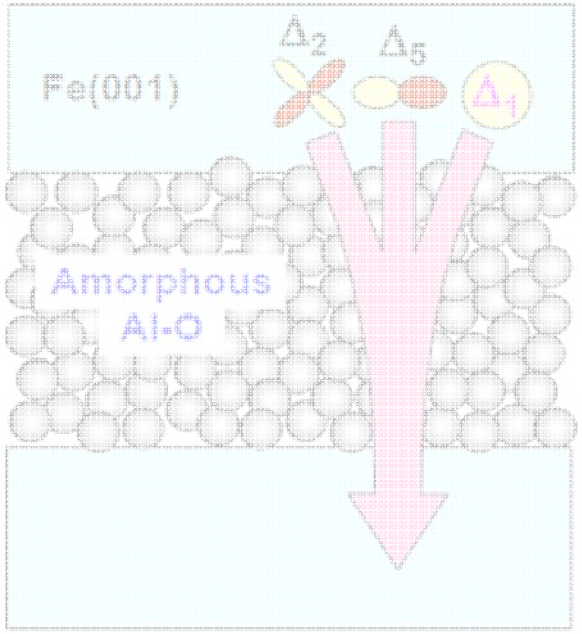
No crystallographic symmetry in the barrier:

- Incoherent tunneling: Bloch states are not conserved during tunneling.
- Every electron symmetry contributes equally to the tunneling process.
- Observed TMR < 100% @RT

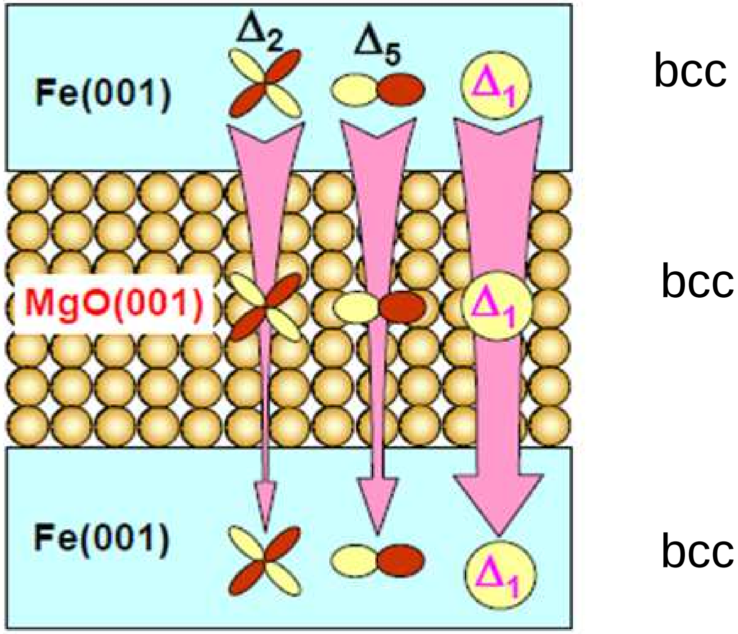
Butler et al., PRB 2001 ; Khvalkovskiy et al., J. Phys. D Appl. Phys 2013

Amorphous barrier Vs Crystalline barrier

Amorphous barrier
ex: amorphous AlO



Crystalline barrier
ex: MgO(001)

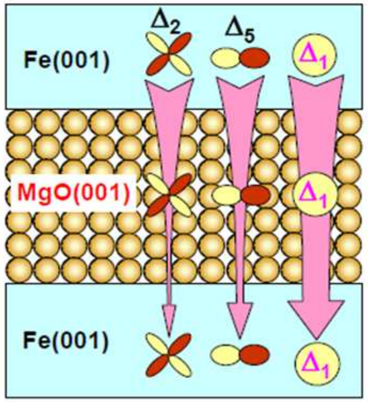


Epitaxially grown crystalline barrier:

- Coherent tunneling: the electrons' wave-functions in the FM are coupled with evanescent wave-functions having the same symmetry in the barrier.
- Tunneling probability of e^- strongly depends on its orbital symmetry
  → possible effective symmetry filtering of the tunneling current.

Butler et al., PRB 2001 ; Khvalkovskiy et al., J. Phys. D Appl. Phys 2013

Crystalline barrier – The example of Fe/MgO/Fe



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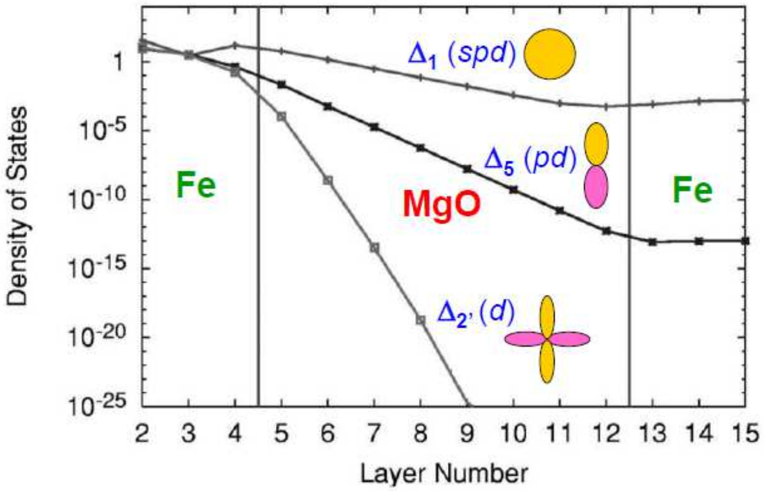

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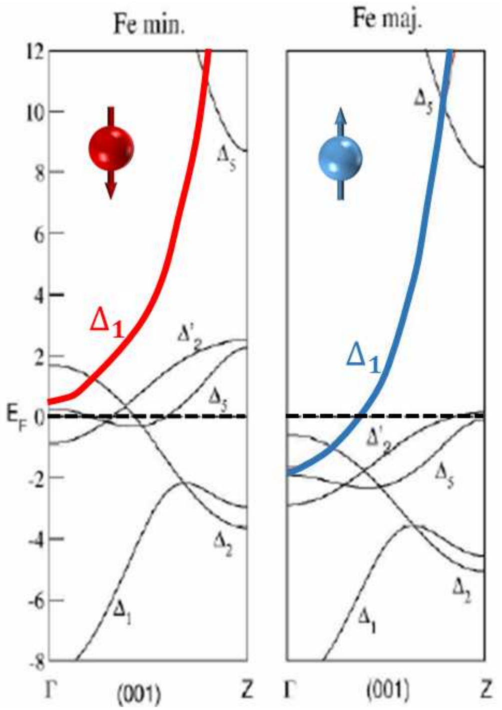
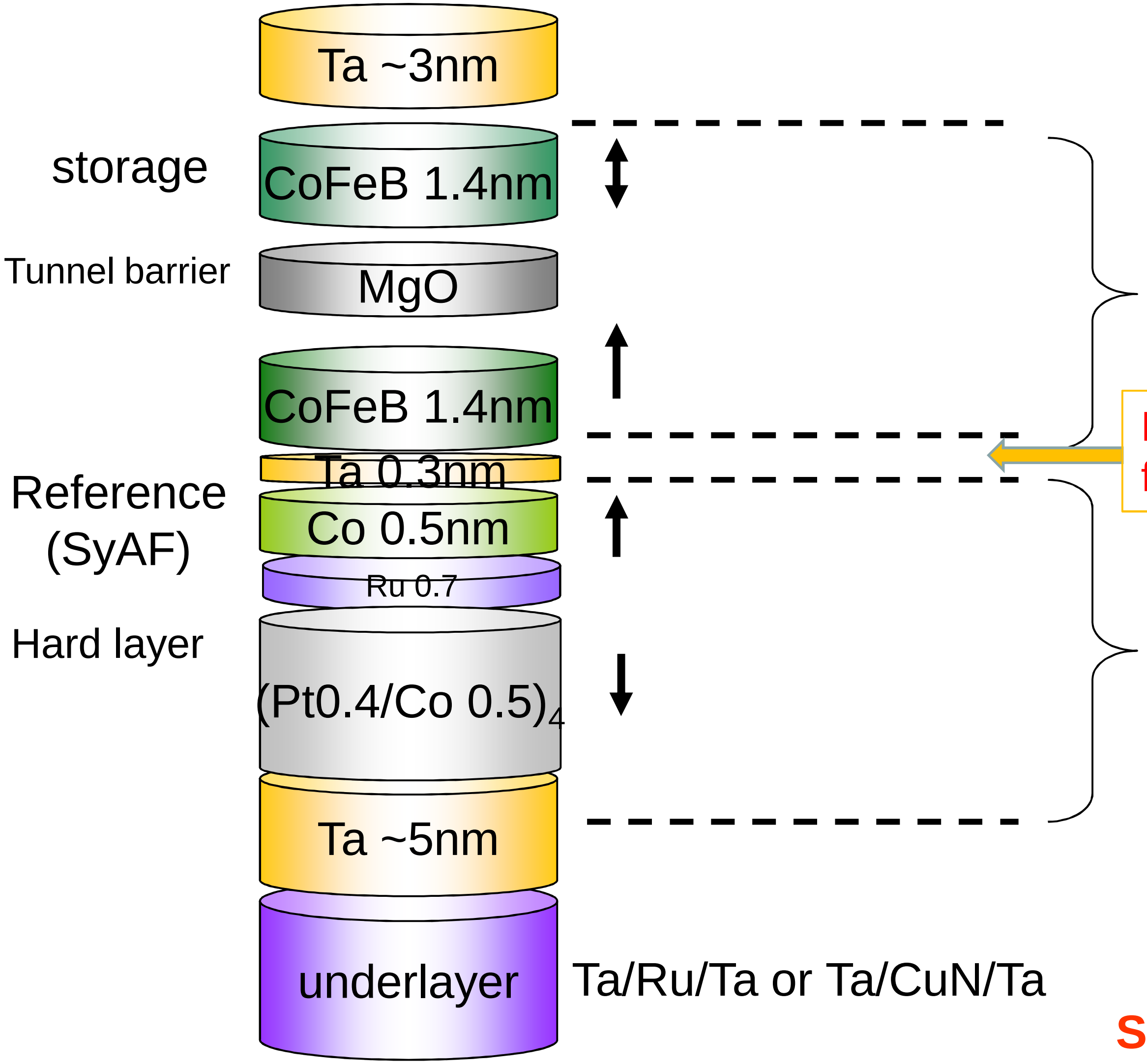


- ➢ Exponential tunneling decay is much stronger for Δ_2 and Δ_5 states than for Δ_1 states
- ➢ Both majority and minority Δ_2 and Δ_5 symmetry states can be found at the Fermi level → low P.
- ➢ Only majority electrons fill Δ_1 symmetry states, implying a full polarization $P_{\Delta_1} = 100\%$.

⇨ *Spin filtering* of the wave functions : large values of TMR expected in epitaxial or highly textured structures (TMR>1000% @RT).

Butler et al., PRB 2001 ; Khvalkovskiy et al., J. Phys. D Appl. Phys 2013

Standard out-of-plane MTJ stack



Ta/Ru/Ta or Ta/CuN/Ta

Must have a **bcc structure**
(001 textured)
for large TMR
(4-fold symmetry)

Nanocrystalline material to enable fcc/bcc structural transition

Must have a **fcc structure**
for strong perpendicular
anisotropy
(i.e. strong pinning)
(3-fold symmetry,
(111) texture)

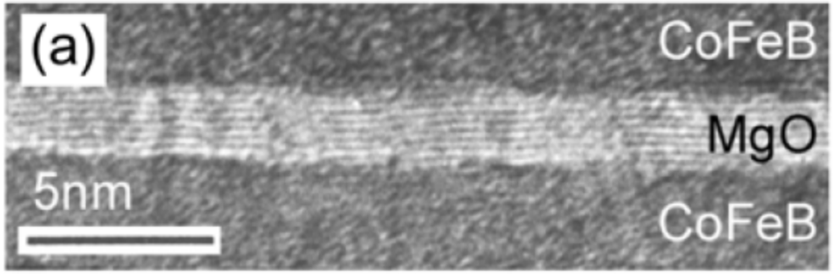
Same basic problem of in-stack symmetry compatibility

Growth and annealing of the tunnel barrier

Djayaprawira D D et al, Appl. Phys. Lett. 86 092502 (2005)

Problem of symmetry compatibility solved by using amorphous CoFeB electrodes during growth

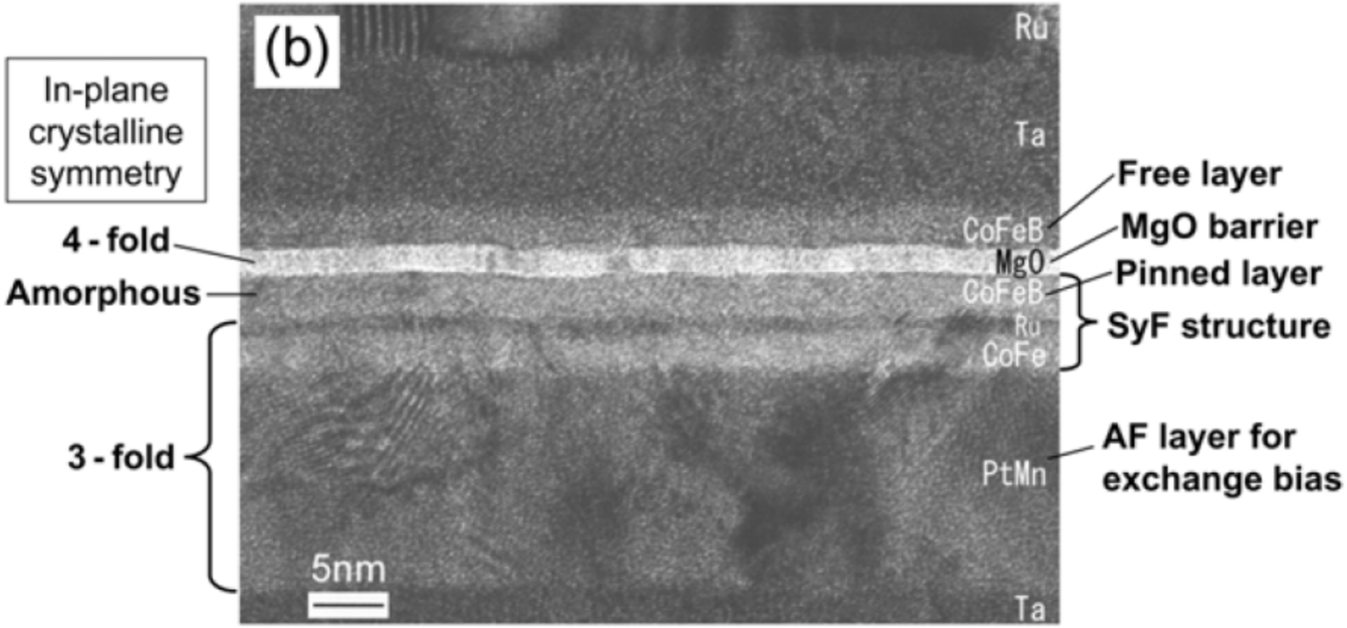
As-deposited



amorphous

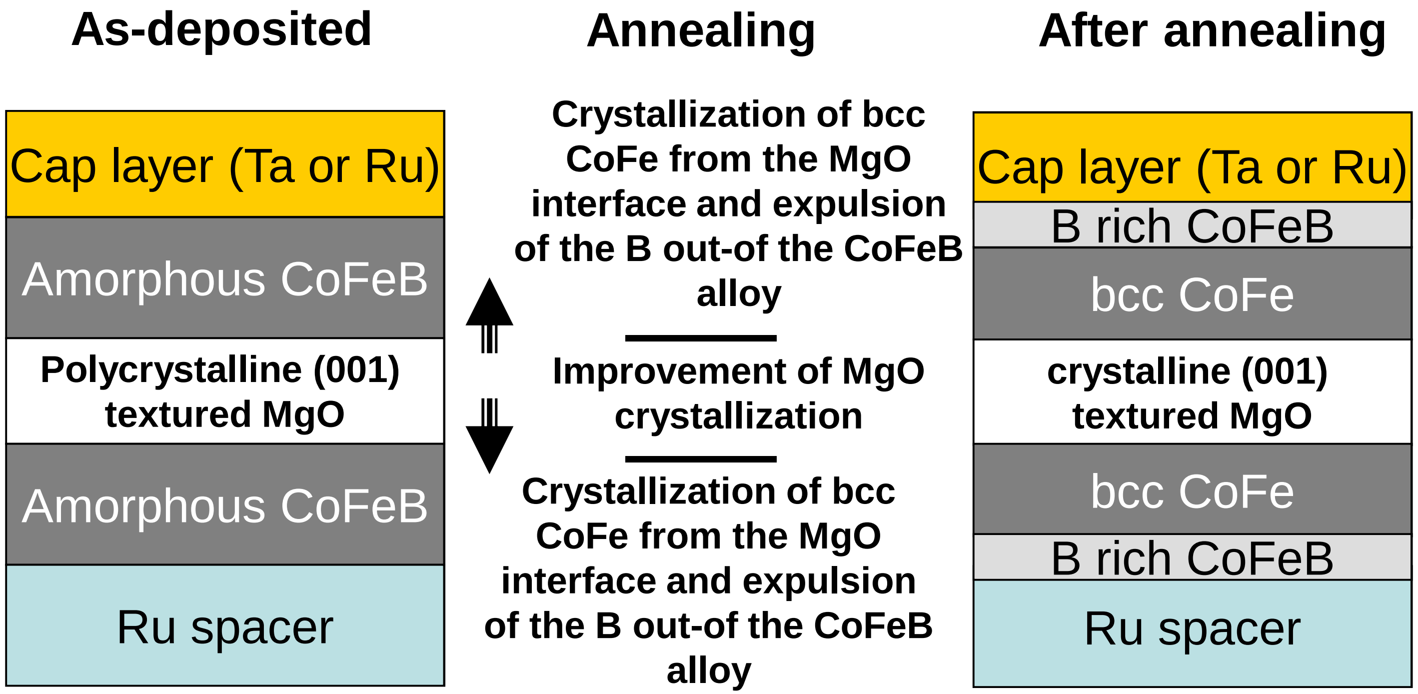
Polycrystalline
(001) bcc textured

amorphous



Annealing of the magnetic tunnel junction

Annealing at T_{anneal}~300ºC-400ºC.
The higher T_{anneal}, the better from the barrier formation standpoint



Crystallization of bcc CoFe from the MgO interface and expulsion of the B out-of the CoFeB alloy

Improvement of MgO crystallization

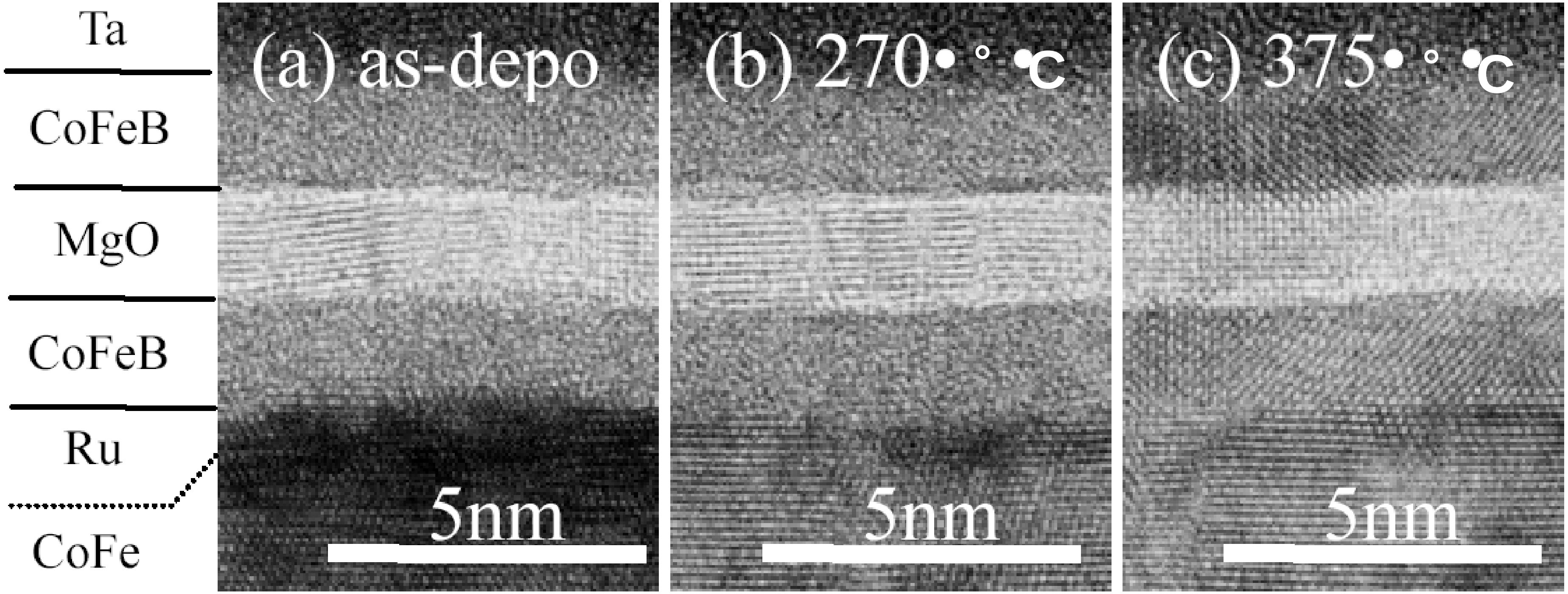
Crystallization of bcc CoFe from the MgO interface and expulsion of the B out-of the CoFeB alloy

- Important to attract B away from the tunnel barrier during the crystallization process. Choose materials which are **good B getters** on the opposite side of the free (storage) and reference layers (**Ta, Ru, W, Mo, Nb, Zr, Hf,**…).

Magnetic tunnel junctions based on MgO tunnel barriers

- As-deposited, CoFeB amorphous, MgO polycristalline
- Upon annealing, recrystallization of CoFeB from the MgO interfaces and improvement in MgO crystallinity with (100) bcc texture

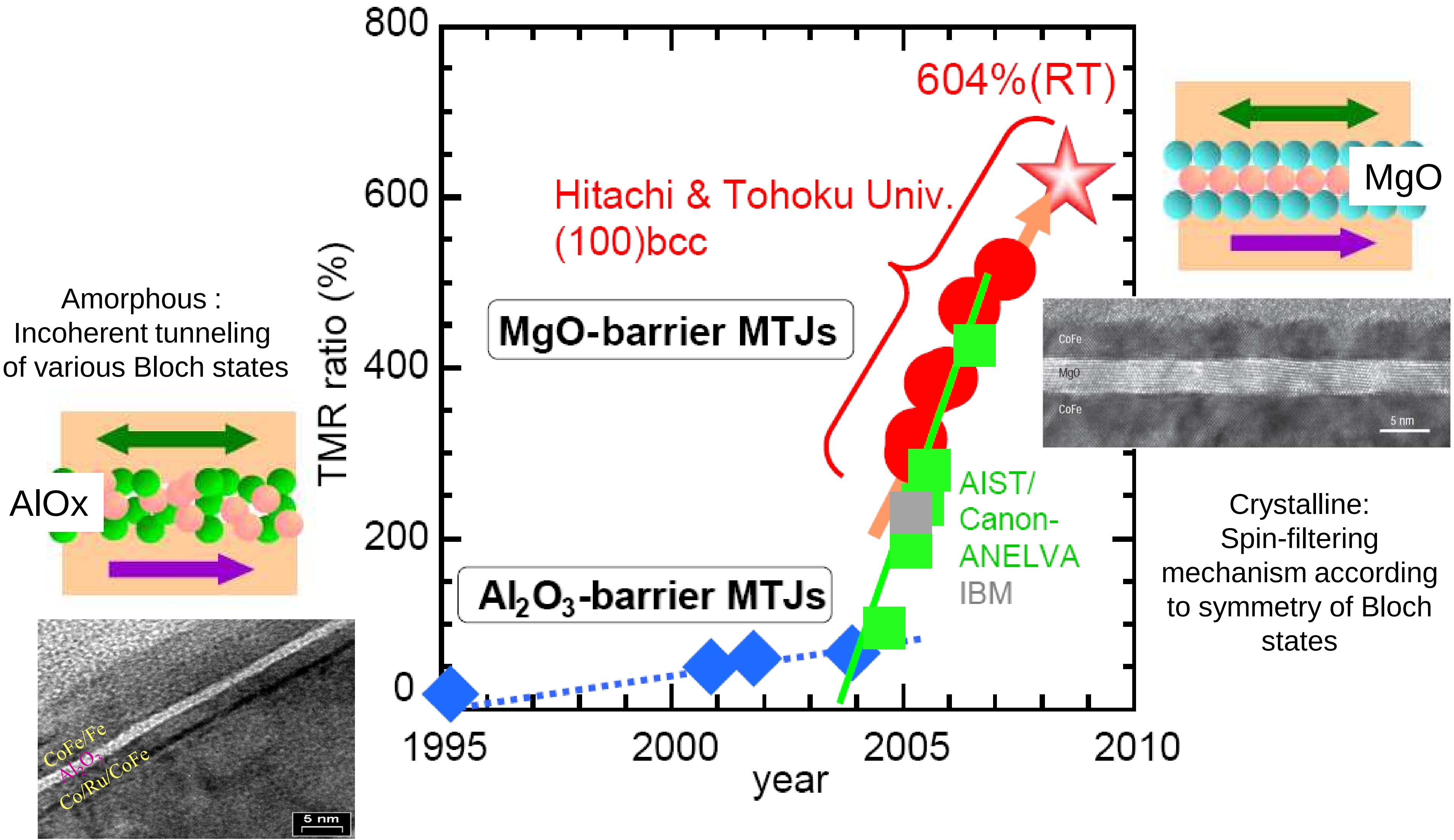
J. Hayakawa et al. Jap. J. Appl. Physics 2005



Also, Yuasa et al. Applied Physics Letters, 2005

Giant TMR of MgO tunnel barriers

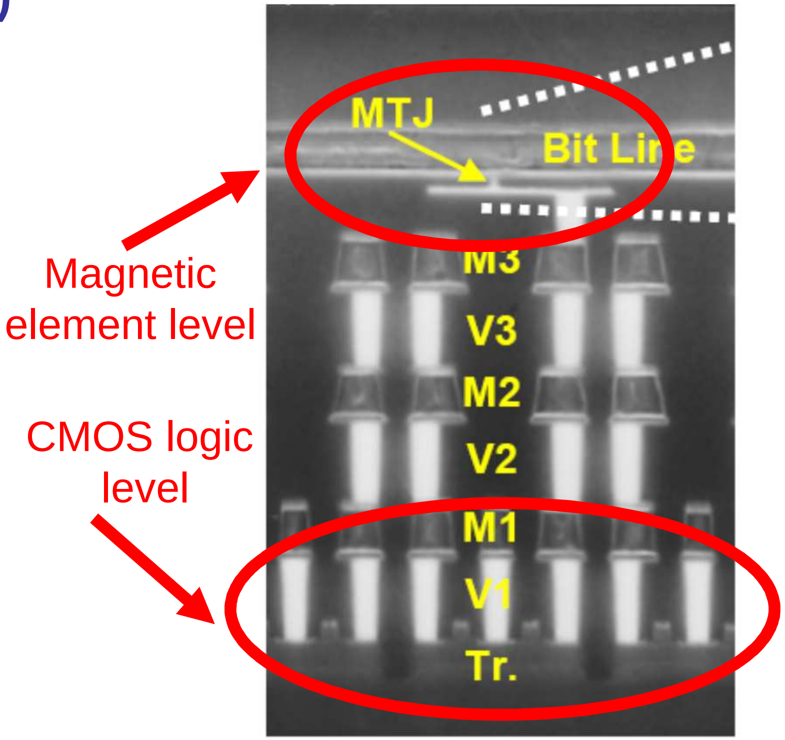
Amorphous :
Incoherent tunneling
of various Bloch states



Crystalline:
Spin-filtering
mechanism according
to symmetry of Bloch
states

MTJ : a reliable path for CMOS/magnetic 3D integration

- **Resistance compatible with CMOS (cell R ~ kΩ)**
- MTJ used as a variable resistance driven by field or current/voltage.
- MTJ can be deposited at any metallic level in the CMOS technology in replacement of a via.
- Above IC technology (‘end-of-back-end’ process)
- Front-end contamination under control
- Low-T BE process (250ºC-350ºC) compatible with Cu interconnect process
- Easy / cheap to embed (3 add-masks, no trade-off with logic process)



Magnetic element level

CMOS logic level

Rapid progress in technology maturity thanks to the involvement of major IDM and equipment manufacturers.
No CMOS contamination during the integration
Etching of MTJ remains the main difficulty at advanced nodes
More and more fabs now enabled with 200/300mm magnetic BEOL lines

Spinelectronics:
From Basic Phenomena to Applications

OUTLINE

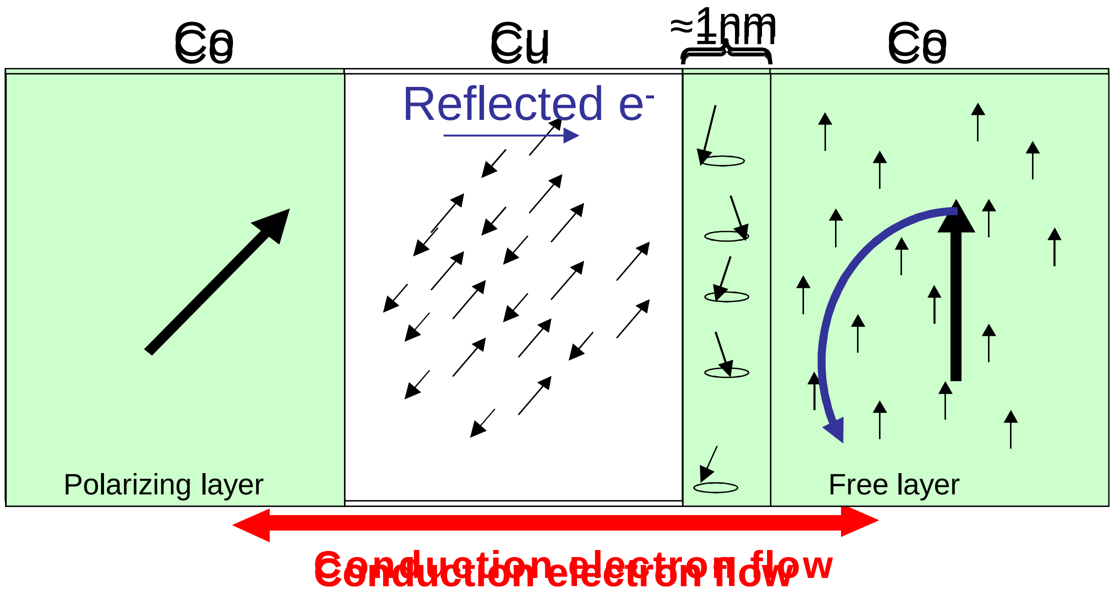
- **Part 1 : Basic phenomena in spintronics:**
  - Giant Magnetoresistance
  - Tunnel magnetoresistance (TMR)
  - **Spin-Transfer Torque (STT)**
  - Spin-orbit Torques (SOT)
- Part 2 : Spintronics main applications
  - Magnetic Recording (Hard disk drives Read-heads)
  - MRAMs
  - Magnetic field sensors
  - RF applications

Spin-Transfer Torque (STT)

Predicted by Slonczewski (JMMM.159, L1(1996)) and Berger (Phys.Rev.B54, 9359 (1996))

Giant or Tunnel magnetoresistance:
Acting on electrical current via the magnetization orientation

Spin transfer is the reciprocal effect:
Acting on the magnetization via the spin polarized current

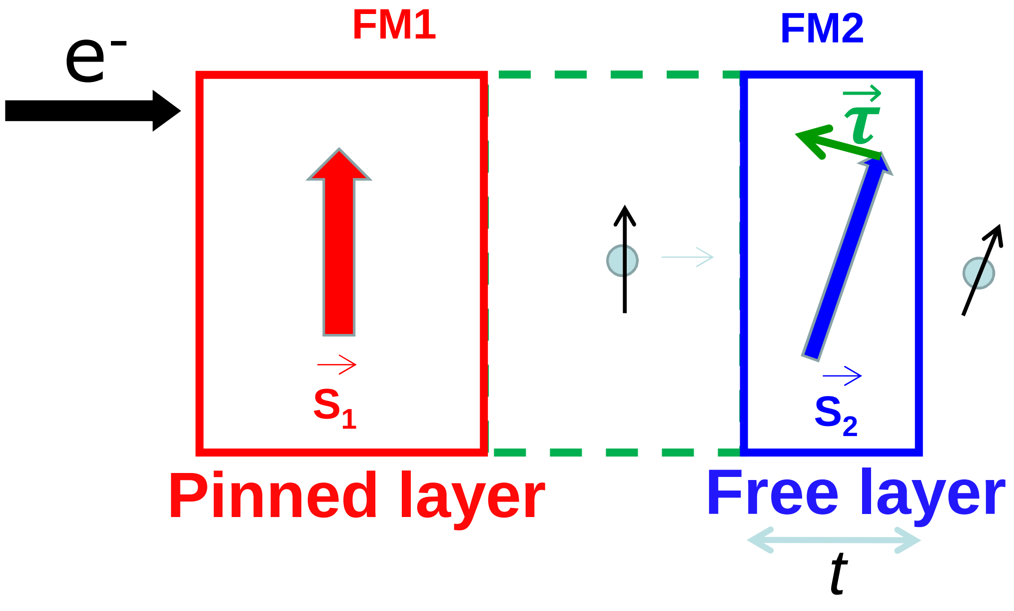


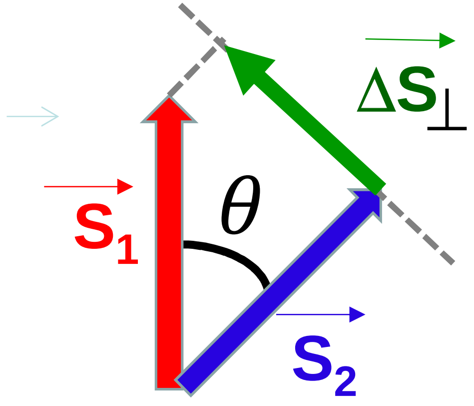
M.D.Stiles et al, Phys.Rev.B.66, 014407 (2002)

Reorientation of spin polarization ⇒ **Torque on the free layer magnetization**

A new way to manipulate the magnetization of magnetic nanostructures

Classical expression of the Spin Transfer torque





Bohr magneton

$$\vec{M} = -\frac{g\mu_B}{\hbar V}\vec{S} \qquad \mu_B = \frac{e\hbar}{2m_e}$$

g =electron gyromagnetic ratio

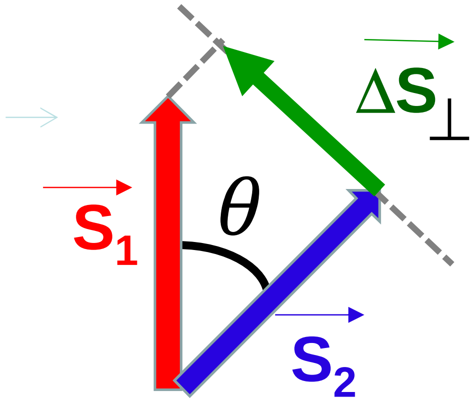
✓The whole transverse part of spin current is absorbed next to the interface

✓ Incident spin direction is aligned along the magnetization of the pinned layer FM_1

➢ Torque acting on the magnetization of FM_2 ?

Classical expression of the Spin Transfer torque

$$\overrightarrow{\tau_{STT}} = \frac{d\overrightarrow{M_2}}{dt} \propto \text{absorbed transverse spin current}$$



✓ Transverse spin component for one incoming electron :

$$\left.\begin{array}{c}\left|\overrightarrow{\Delta S_\perp}\right| = S\,sin(\theta)\\ \overrightarrow{\Delta S_\perp}\perp\overrightarrow{S_2}\end{array}\right\} \Longrightarrow \overrightarrow{\Delta S_\perp} = \frac{\hbar}{2}\overrightarrow{m_2}\times(\overrightarrow{m_2}\times\overrightarrow{m_1})$$

✓ Contribution to magnetization: $\overrightarrow{\Delta M} = -\frac{g\mu_B}{\hbar V}\overrightarrow{\Delta S}$

✓ Volume : $V = \mathcal{A}\cdot t = Area*thickness$

✓ Number of incoming electrons per second : $\frac{dN_{e^-}}{dt} = \frac{I}{e} = \frac{J\cdot\mathcal{A}}{e}$

✓ Number of incoming spins per second : $\frac{dN_S}{dt} = P_{spin}\frac{J\cdot\mathcal{A}}{e}$

$$\frac{d\overrightarrow{M_2}}{dt} = -P_{spin}\frac{J\mathcal{A}}{e}\frac{g\mu_B}{\hbar\mathcal{A}t}\frac{\hbar}{2}\left(\overrightarrow{m_2}\times(\overrightarrow{m_2}\times\overrightarrow{m_1})\right)$$

$$\vec{m}_{1(2)} = \frac{\vec{M}_{1(2)}}{\left\|\vec{M}_{1(2)}\right\|}$$

$$\boxed{\overrightarrow{\tau_{STT}} = \frac{d\overrightarrow{M_2}}{dt} = -P_{spin}\frac{J}{e}\frac{g\mu_B}{2t}\left(\overrightarrow{m_2}\times(\overrightarrow{m_2}\times\overrightarrow{m_1})\right)}$$

Expression derived by Slonczewski, JMMM 1996

Magnetization dynamics under Spin Transfer Torque (STT)

- Landau-Lifshitz-Gilbert-Slonczewski equation (LLGS) :

$$\frac{d\vec{m_2}}{dt} = \boxed{-\gamma_0\left(\vec{m_2} \times \vec{H_{eff}}\right)} + \boxed{\alpha\left(\vec{m_2} \times \frac{d\vec{_2}}{\mathrm{dt}}\right)} + \boxed{P_{spin}\frac{J}{e}\frac{g\mu_B}{2M_{S_2}t}\left(\vec{m_2} \times \left(\vec{m_2} \times \vec{m_1}\right)\right)}$$

✓ **Precessional torque (precession around H_{eff})**

$$\vec{H}_{eff} = \vec{H}_{applied} + \vec{H}_{anisotropy} + \vec{H}_{demag}$$

✓ **Damping torque (dissipation)**

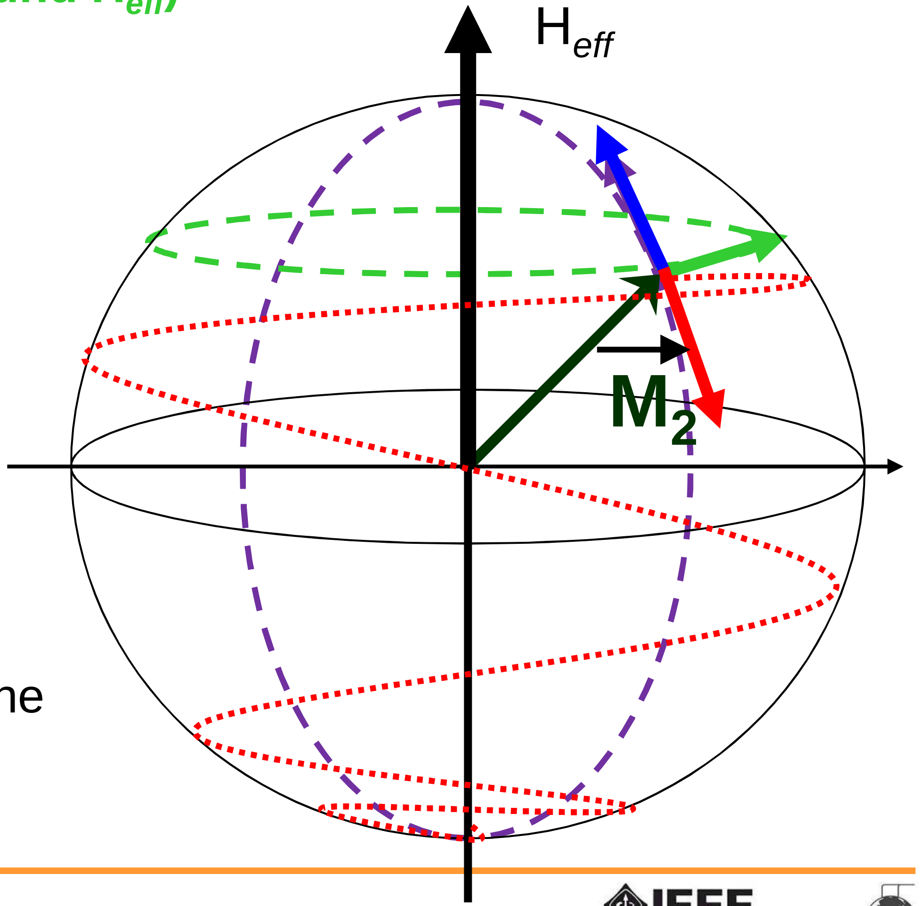
✓ **Spin transfer torque depends on the sign of the current**

- parallel to damping torque

- opposite to damping torque

→ Above a **threshold current**: the spin transfer torque causes the **effective damping to become negative**.

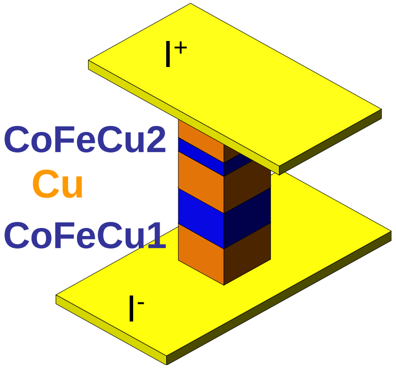
→ Equilibrium state becomes unstable: The magnetization spirals away from the direction of H_{eff} → *Switching*



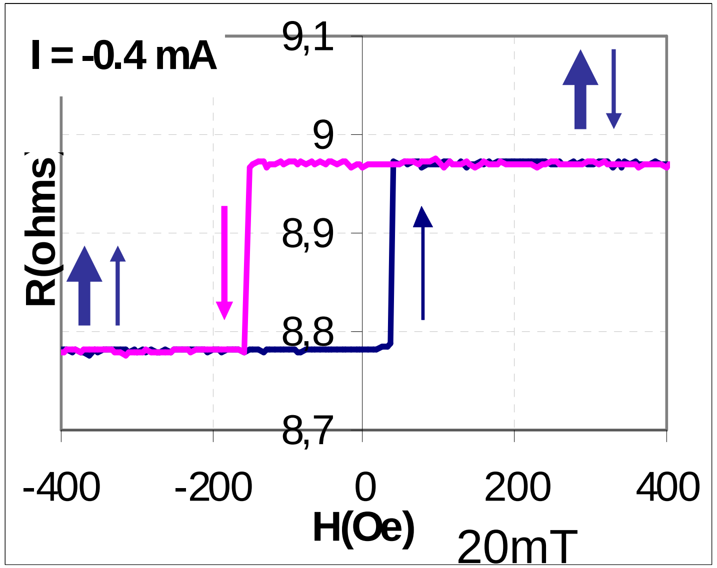
Magnetization switching induced by a polarized current

STT magnetization switching first observed in metallic pillars (2000)

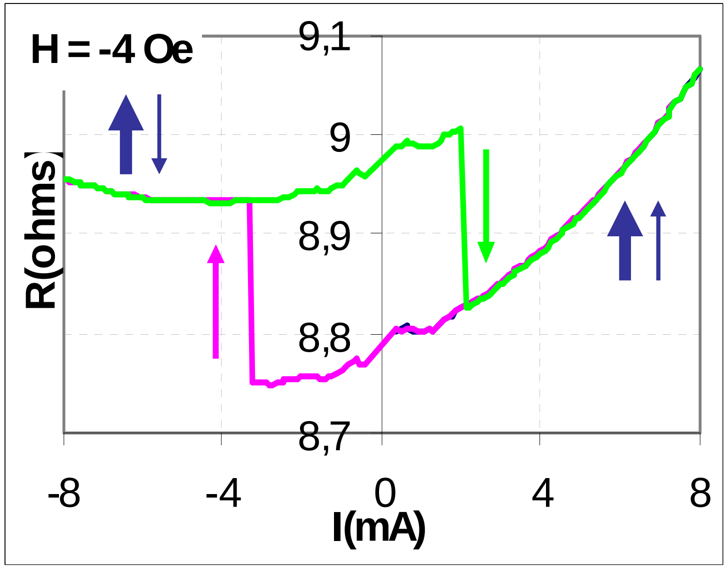
Katine et al, Phys.Rev.Lett.84, 3149 (2000) on Co/Cu/Co sandwiches (Jc ~2-4.107A/cm²)



Field scan



Current scan



$j_c^{P\text{-}AP}=1.9.10^7 A/cm^2$
$j_c^{AP\text{-}P}=1.2.10^7 A/cm^2$

By spin transfer, a spin-polarized current can be used to manipulate the magnetization of magnetic nanostructures instead of by magnetic field.

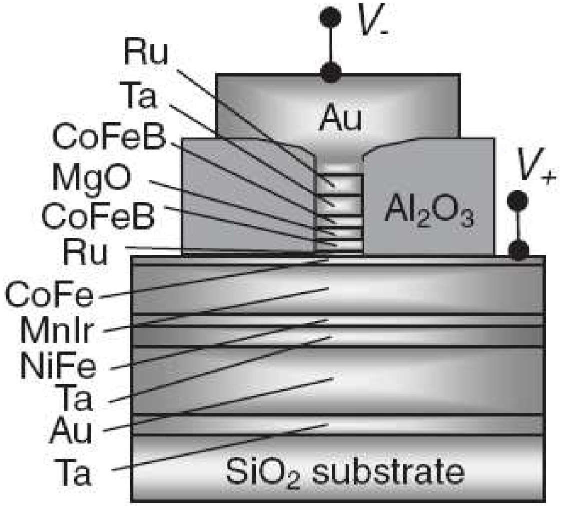
⇒ Can be used as a **new write scheme in MRAM**

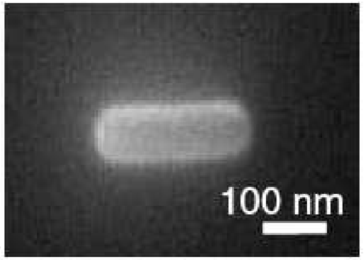
Magnetization switching induced by a polarized current

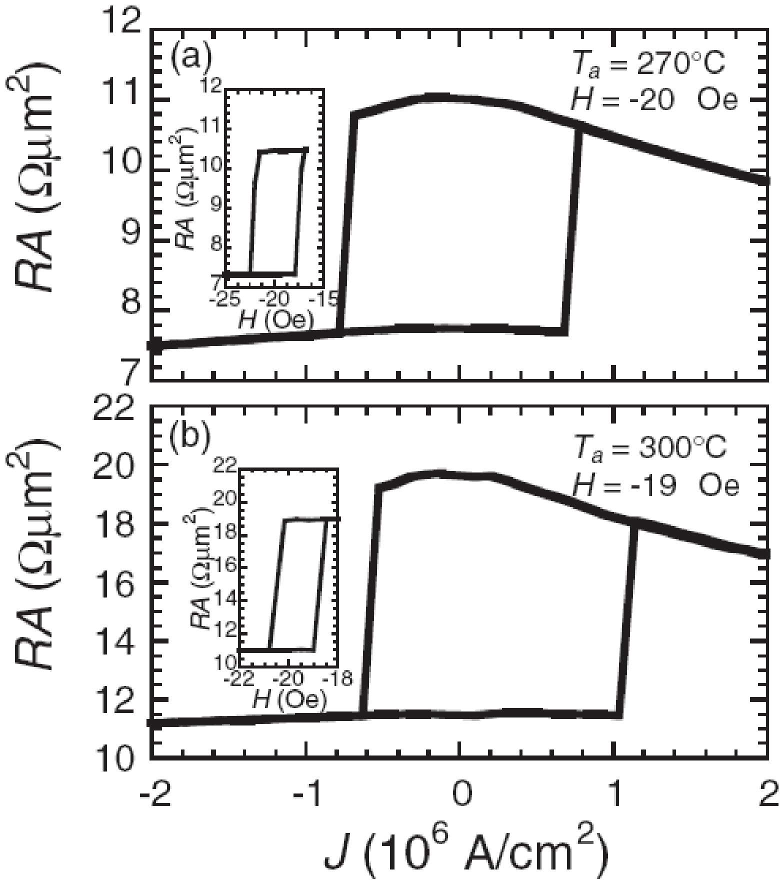
STT magnetization switching in MTJ (2004): *Huai et al, APL (2004); Fuchs et al, APL (2004)*

The bipolar current flowing through the MRAM cell is used to switch the magnetization of the storage layer.

Reading at lower current density then writing so as to not perturb the written information while reading.







Hayakawa et al,
Japanese Journal of Applied Physics
44, (2005),L 1267

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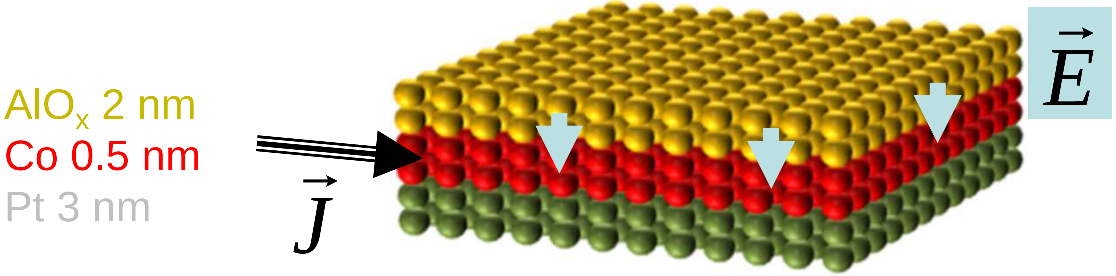
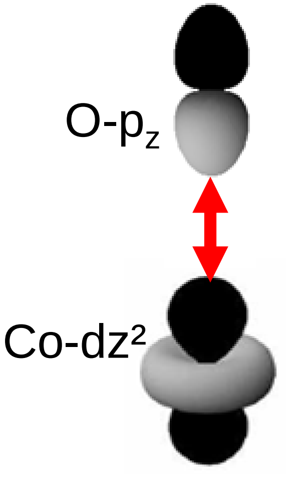
  - Magnetic field sensors
  - Others…

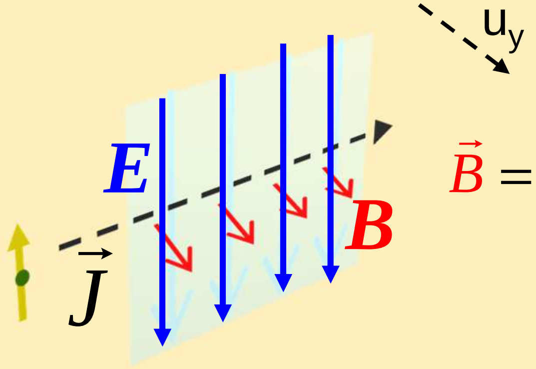
Rashba effect in thin MTJ electrodes with in-plane current



Breaking of inversion symmetry – Rashba effect
An interfacial effect due to the presence of an interfacial electrical field at metal/oxide interface



Charge transfer at Co/MOx interface
⇒
Interfacial E field



$$\vec{B} = \frac{1}{c}\frac{1}{\sqrt{1-v^2/c^2}}\vec{v}\times\vec{E}$$

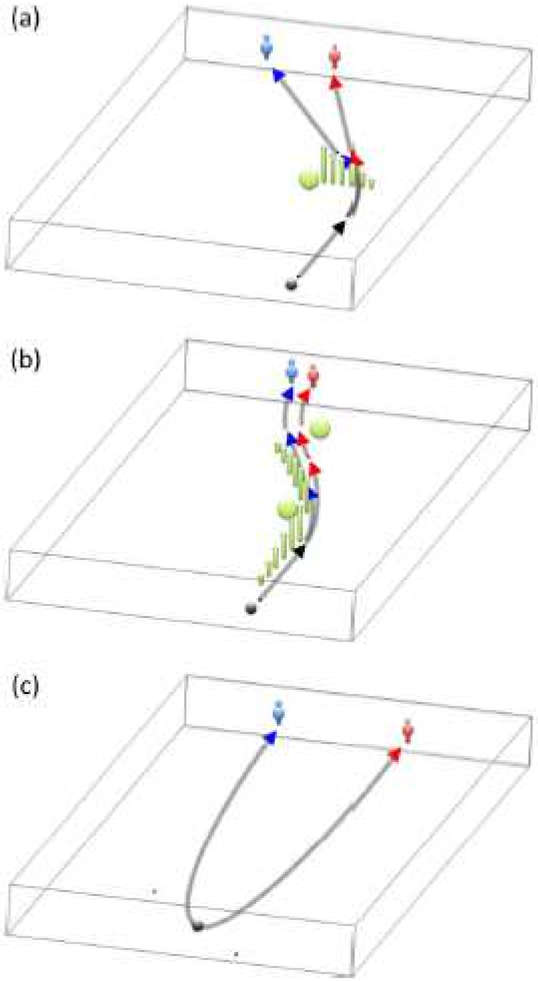
- 🕮 *Manchon et al., PRB 78, 212405 (2008)*
- 🕮 *Hane et. al .PRB (2013)*
- 🕮 *H. Yang et. al,PRL (2014)*

Pulse of in-plane current generates a pulse of in-plane transverse field

→ **Field like torque τ~J mxu_y**

Spin-Hall effect

In presence of spin-orbit interaction in heavy metals (Pt, Au, Bi etc),
spin-up and spin-down electrons are differently deviated during scattering.
Used in Mott detectors to measure the spin polarization of spin polarized electron beams.



Skew scattering

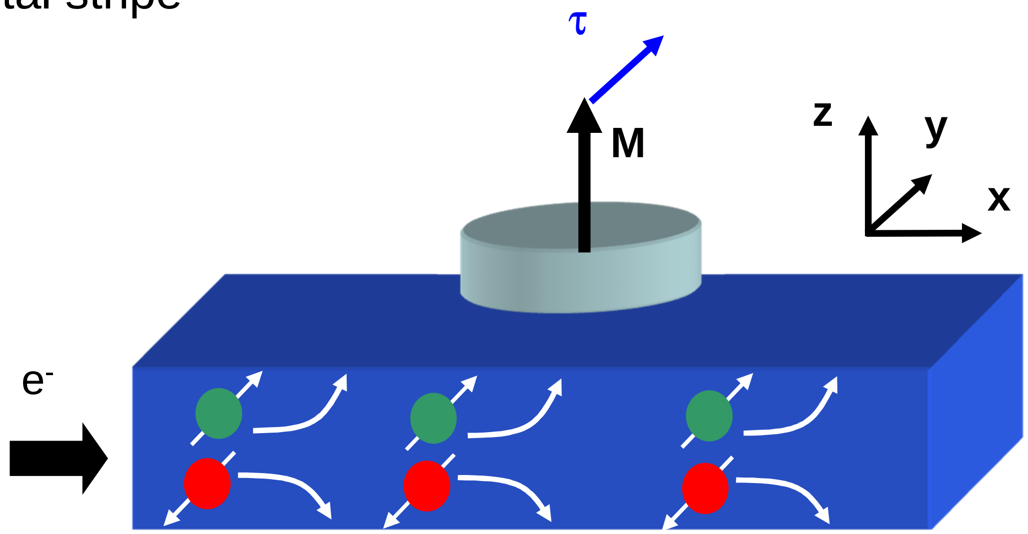
Side jump

Intrinsic Hall effect due to band structure

A.Hoffmann, IEEE TRANSACTIONS ON MAGNETICS, 49, 5172 (2013)

Switching by spin-Hall effect

Spin Hall effect provides another spin-torque contribution originating from the bulk of the heavy metal stripe



Pt, Ta, W, Re

→ Vertical spin-current with transverse polarisation $u_{y.}$

→ Spin-current related to Spin Hall angle θ_{SH} and charge current by: $J_s=\theta_{SH} J$

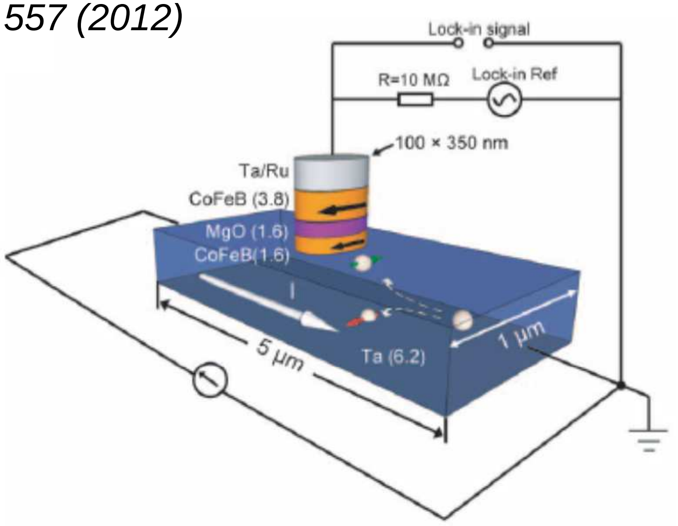
→ **Damping like torque** $\tau \sim \theta_{SH} J m \times (m \times u_y)$

📖*Liu et al., (Science 2012) , Liu et. al (2012); Kim, Hayashi et al. Nature Mater. (2013);*

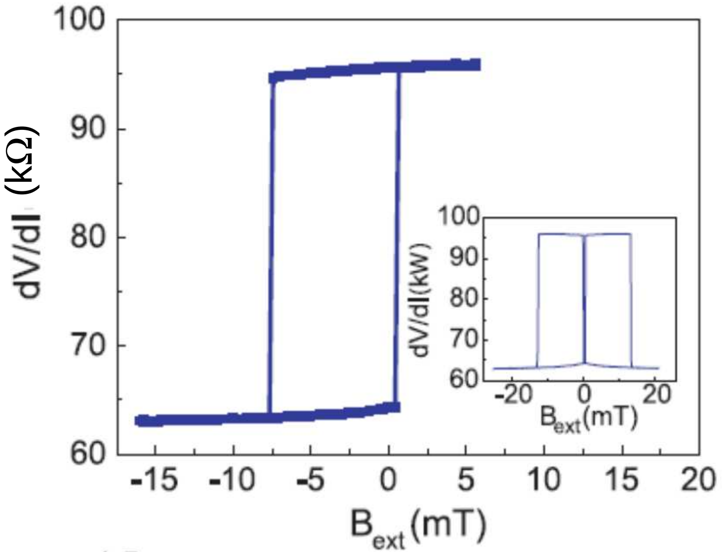
📖*X. Fan, J. Xiao et. al, NatCom (2014)*

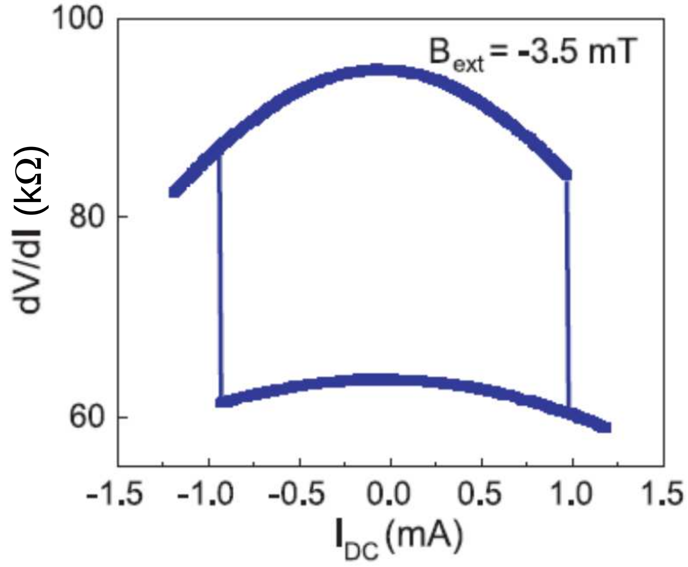
Switching by spin-Hall effect

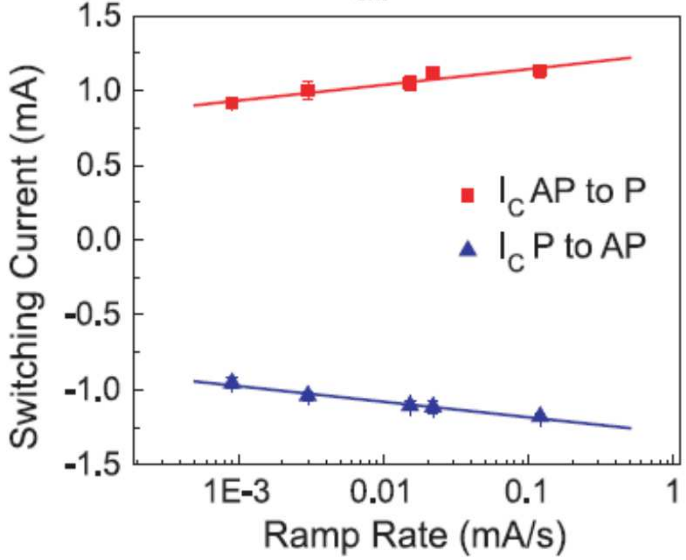
Liu et al, SCIENCE, 336, 557 (2012)



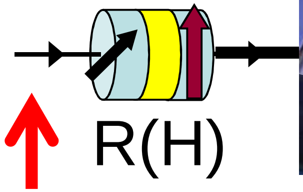
Switching by an in-plane current in a 3-terminal device

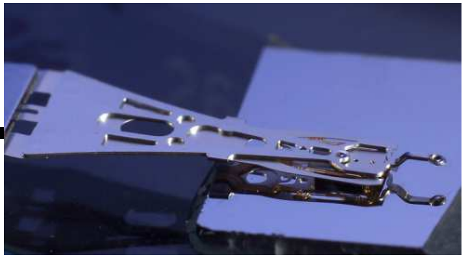






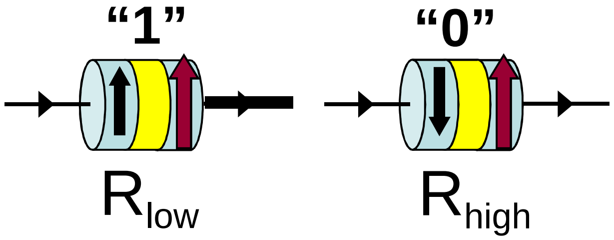
Spintronic components

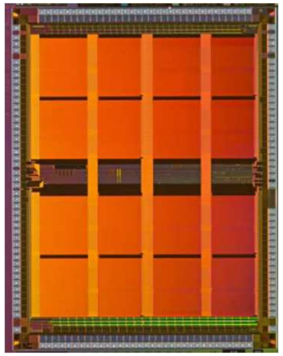




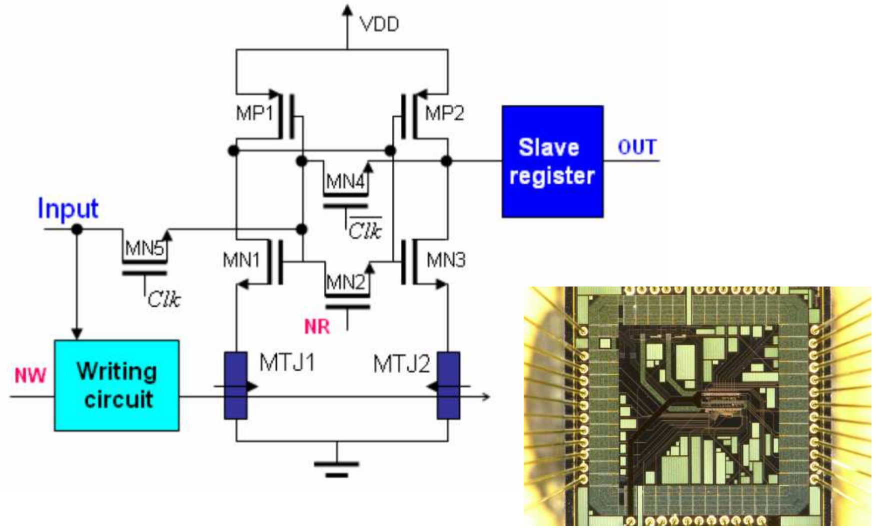
Write/read heads

Magnetic field sensors

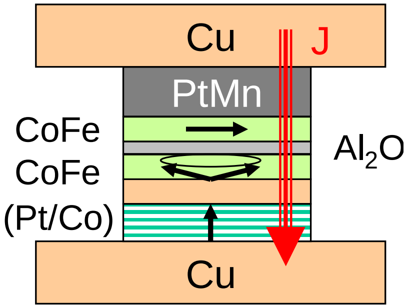


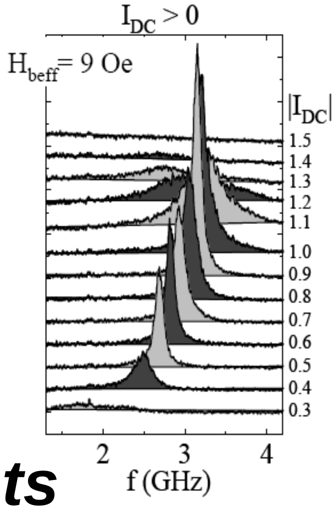


Memories



Logic circuits





RF components

End part I

Questions ?

Coffee break

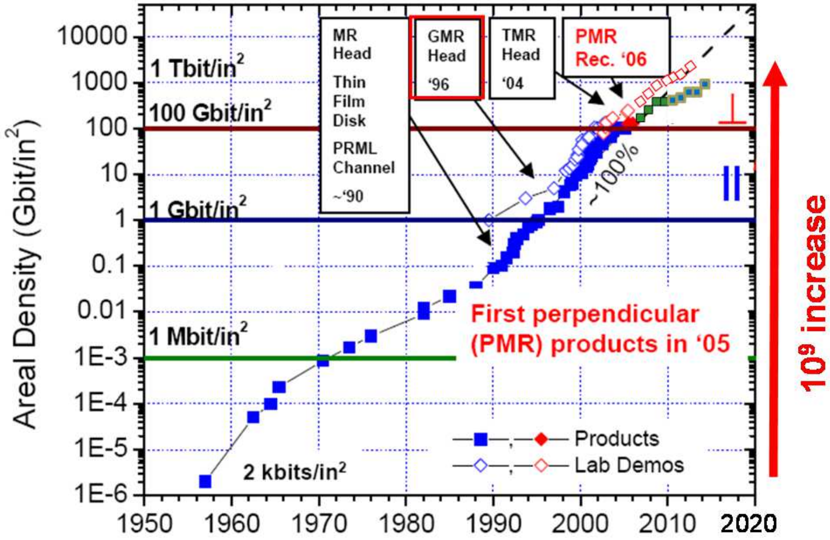
Spinelectronics:
From Basic Phenomena to Applications

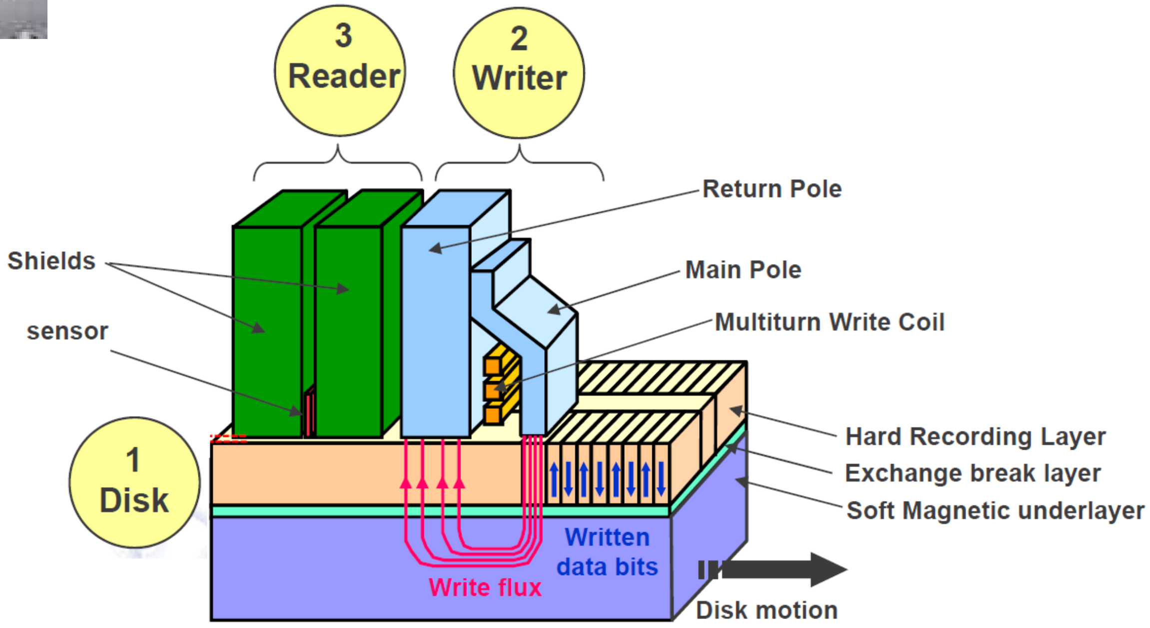
OUTLINE

- Part 1 : Basic phenomena in spintronics:
  - Giant Magnetoresistance
  - Tunnel magnetoresistance (TMR)
  - Spin-Transfer Torque (STT)
  - Spin-orbit Torques (SOT)
- **Part 2 : Spintronics main applications**
  - **Magnetic Recording (Hard disk drives Read-heads)**
  - MRAMs
  - Magnetic field sensors
  - RF applications

Magnetic recording technology has stimulated R&D in spintronics for more than 20 years

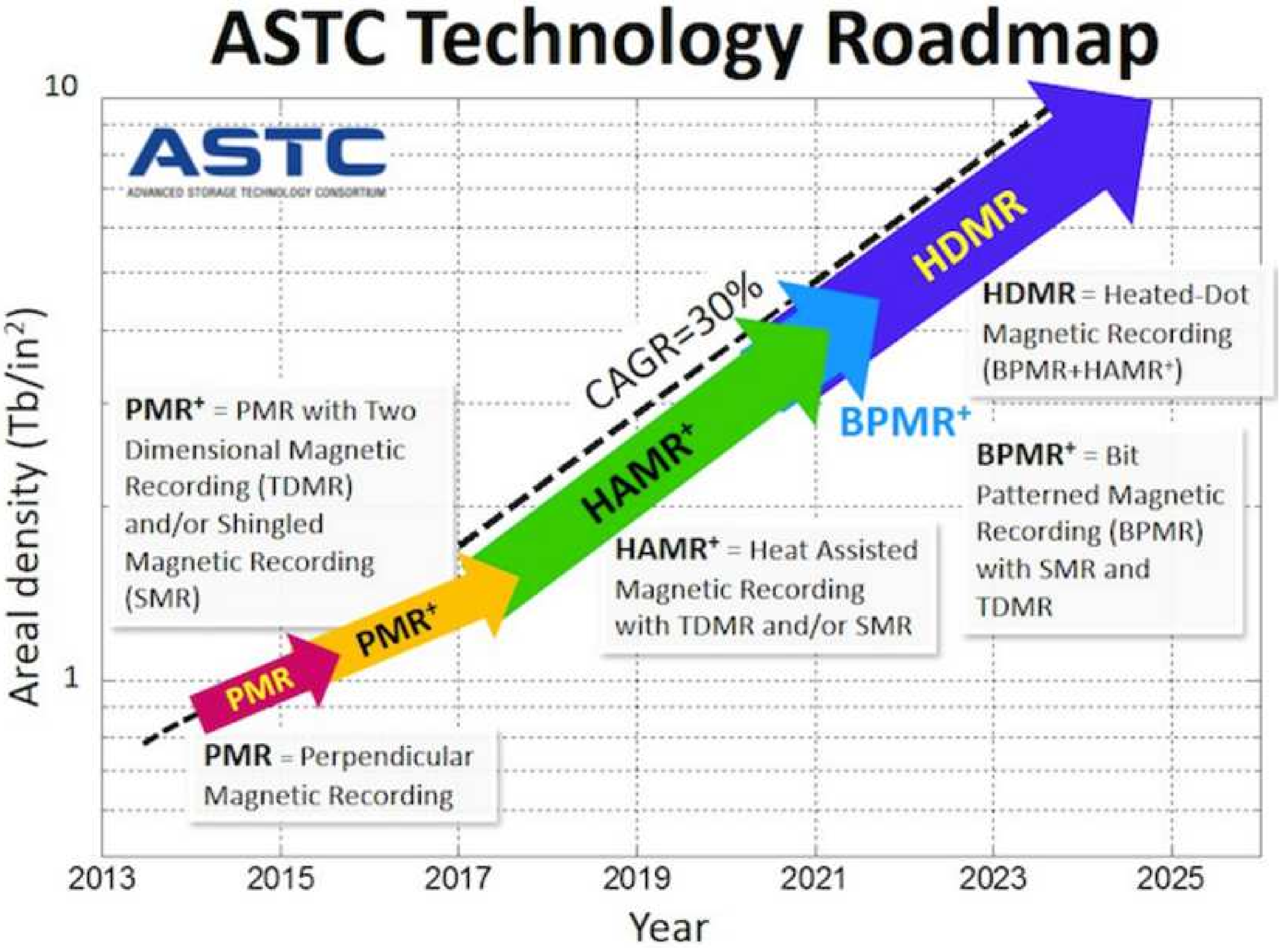
Hard Disk Drive (HDD)





GMR spin-valve heads from 1998 to 2004, TMR heads since 2004

Progresses in magnetic recording technology more and more difficult to achieve



PMR⁺ = PMR with Two Dimensional Magnetic Recording (TDMR) and/or Shingled Magnetic Recording (SMR)

PMR = Perpendicular Magnetic Recording

HAMR⁺ = Heat Assisted Magnetic Recording with TDMR and/or SMR

HDMR = Heated-Dot Magnetic Recording (BPMR+HAMR⁺)

BPMR⁺ = Bit Patterned Magnetic Recording (BPMR) with SMR and TDMR

HDD R&D increasingly difficult but increasing demand for data storage

Coexistence of **Solid State Drives** (based on Flash memories: charge based storage) and **Hard Disk Drives** (magnetic « cold » storage)

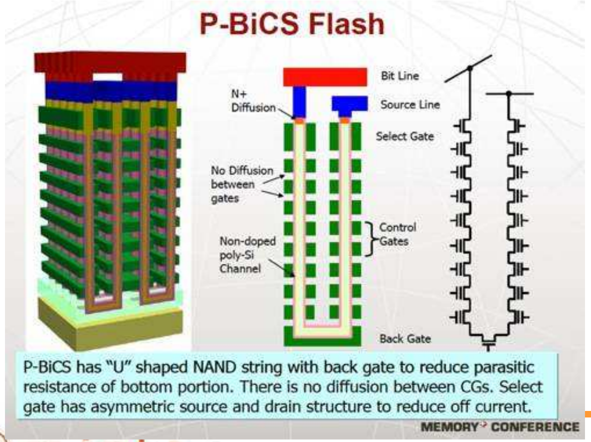
Handheld devices
Labtops, cell-phones…

SSD

Servers farms

SSD+HDD

3D-Flash allows significantly increase the density of Flash disks



P-BiCS Flash

P-BiCS has "U" shaped NAND string with back gate to reduce parasitic resistance of bottom portion. There is no diffusion between CGs. Select gate has asymmetric source and drain structure to reduce off current.

MEMORY CONFERENCE

HGST "Active Archive" System

Complete data storage system for cloud data centers

Need 4 racks to store all the books in the US Library of Congress !

Spinelectronics:
From Basic Phenomena to Applications

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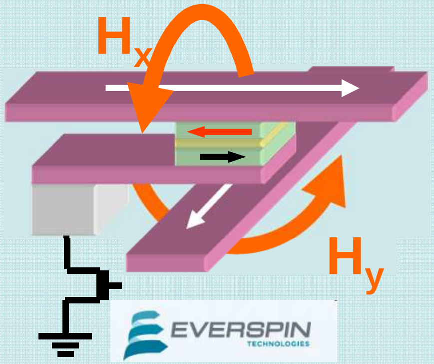
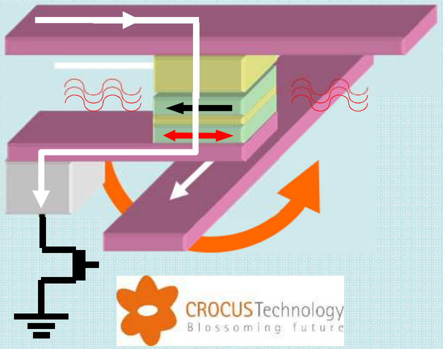
  - Magnetic field sensors
  - RF components

Various MRAM families

Field-driven

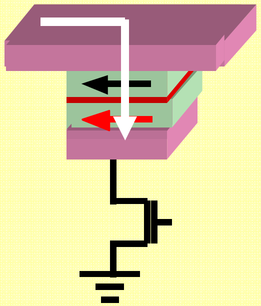


Thermally Assisted (TAS)

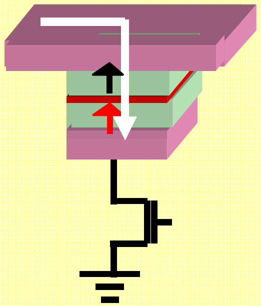


STT (STT MRAM)

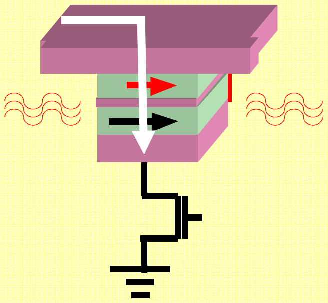
Planar



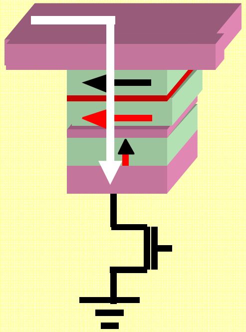
Perpendicular



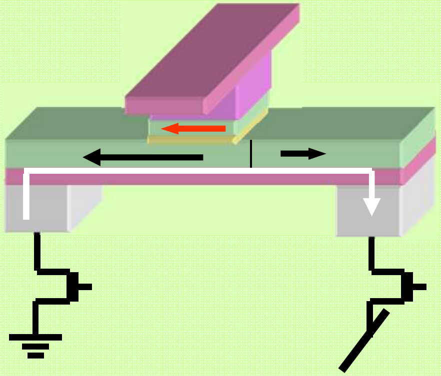
STT-TAS



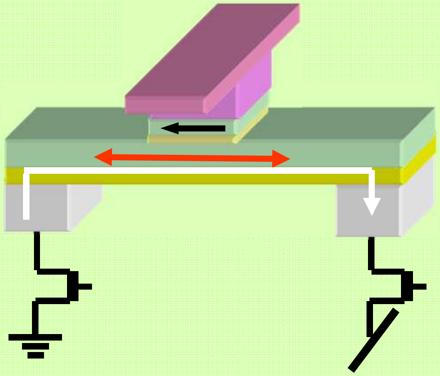
Precessional



DW motion

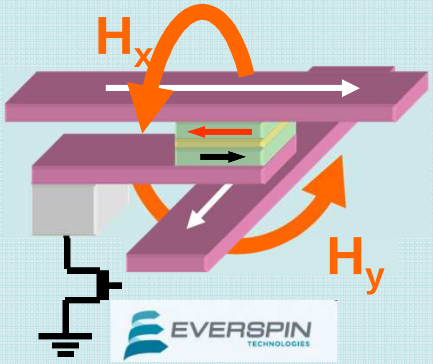


Spin-orbit torque (spin-Hall, Rashba)

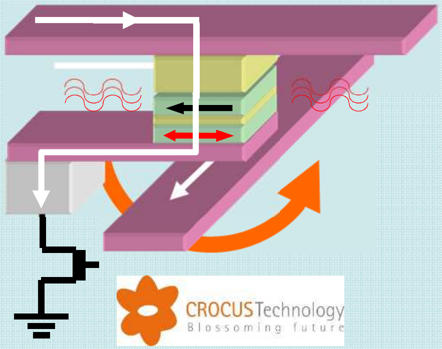


Various MRAM families

Field-driven

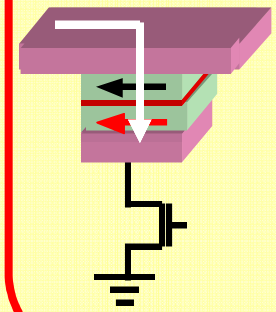


Thermally Assisted (TAS)

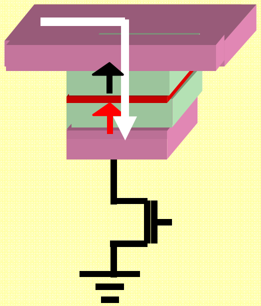


STT (STT MRAM)

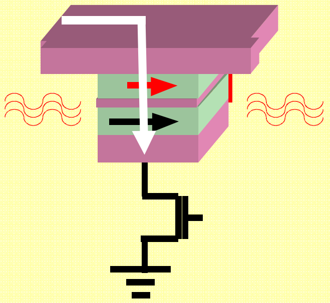
Planar



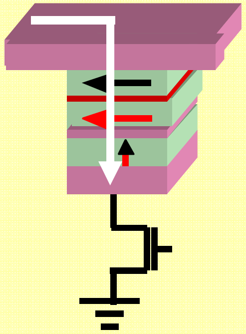
Perpendicular



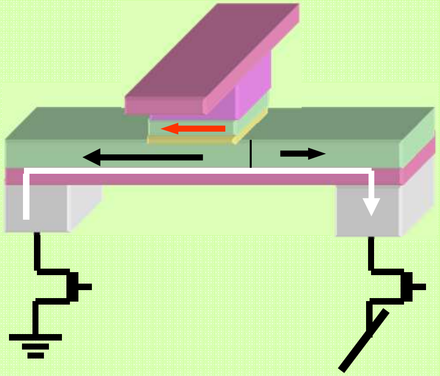
STT-TAS



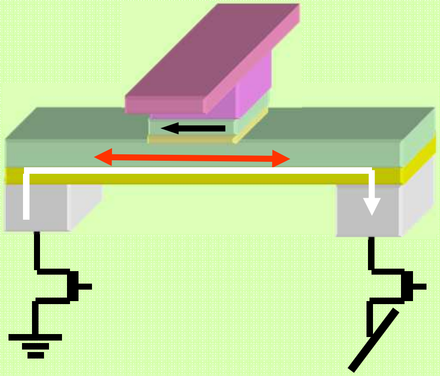
Precessional



DW motion

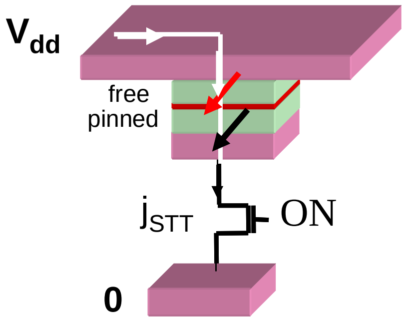


Spin-orbit torque (spin-Hall, Rashba)

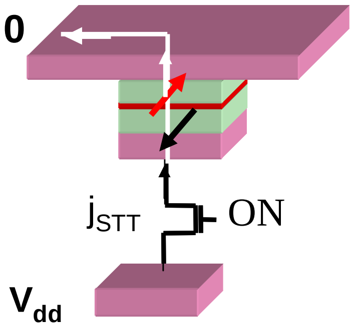


STT MRAM – scalability of write current

Writing “0”



Writing “1”



α: damping
P: polarization
t_F=F thickness
Ms: Magnetization
K: anisotropy

•Writing determined by a current density _:

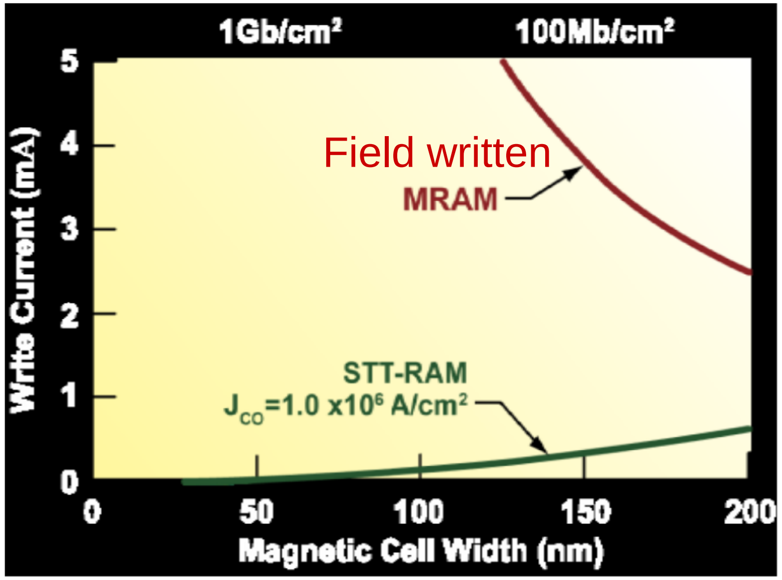
$$j_{WR\,in-plane} = \left(\frac{2e}{\hbar}\right)\frac{\alpha\, t_F}{P}\left(\frac{\mu_0 M_s^{\,2}}{2}+2K\right)$$

- **Current through cell proportional to MTJ area**

•$j_{write\ SST\ in\text{-}plane}$ ~ 8.10^5A/cm² quasistatic

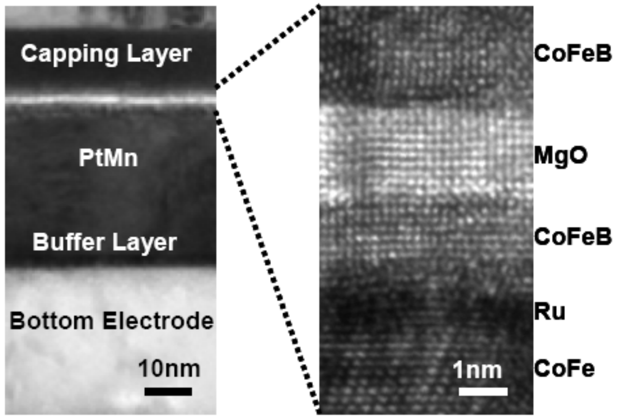
~ 3.10^6A/cm² @10ns

Huai et al, Appl.phys.Lett.87, 222510 (2005) ;
Hayakawa, Jap.Journ.Appl.Phys.44 (2005) L1246



Write current ~15-40µA at sub-20nm node

STT-MRAM – Write – influence of current pulse width



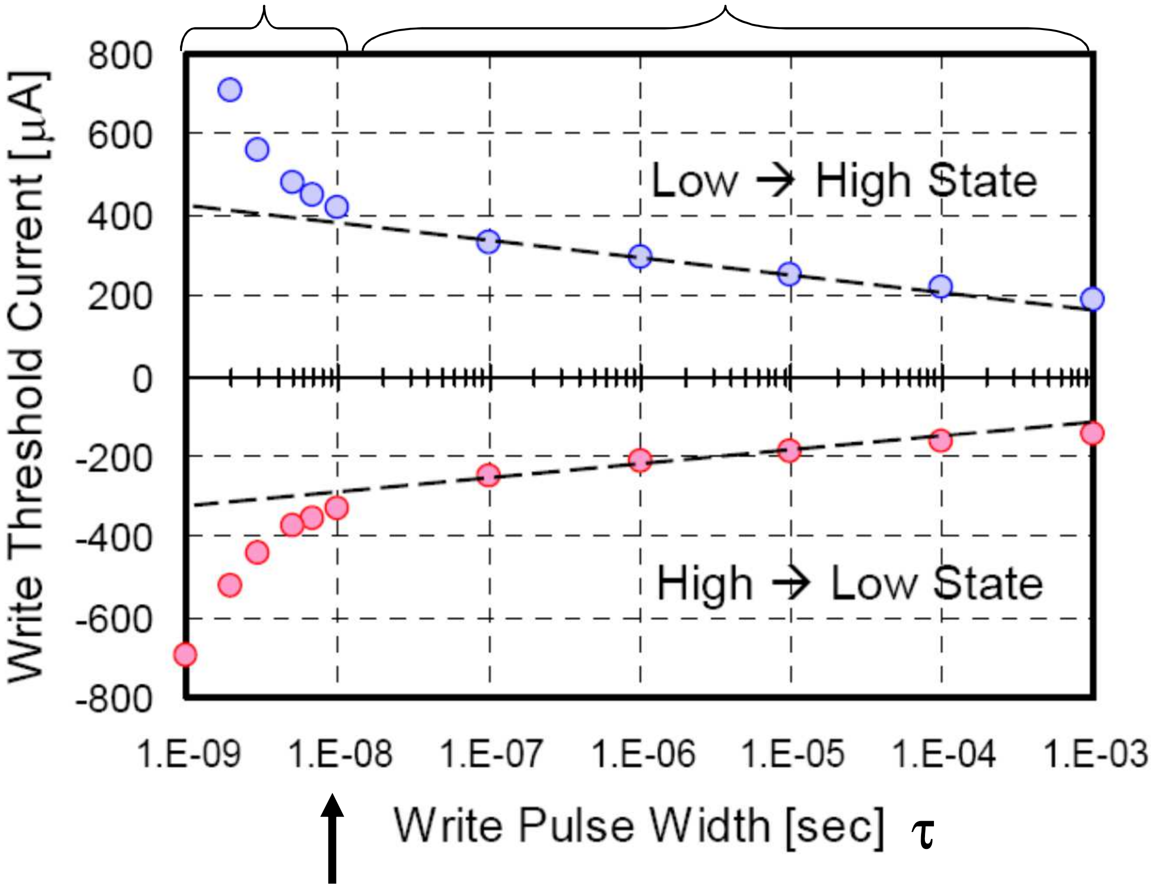
In-plane magnetized MTJ

Elliptical shape
115nm*155nm

Hosomi et al, Sony, 4Kbit demo (2005)

Ballistic
STT switching

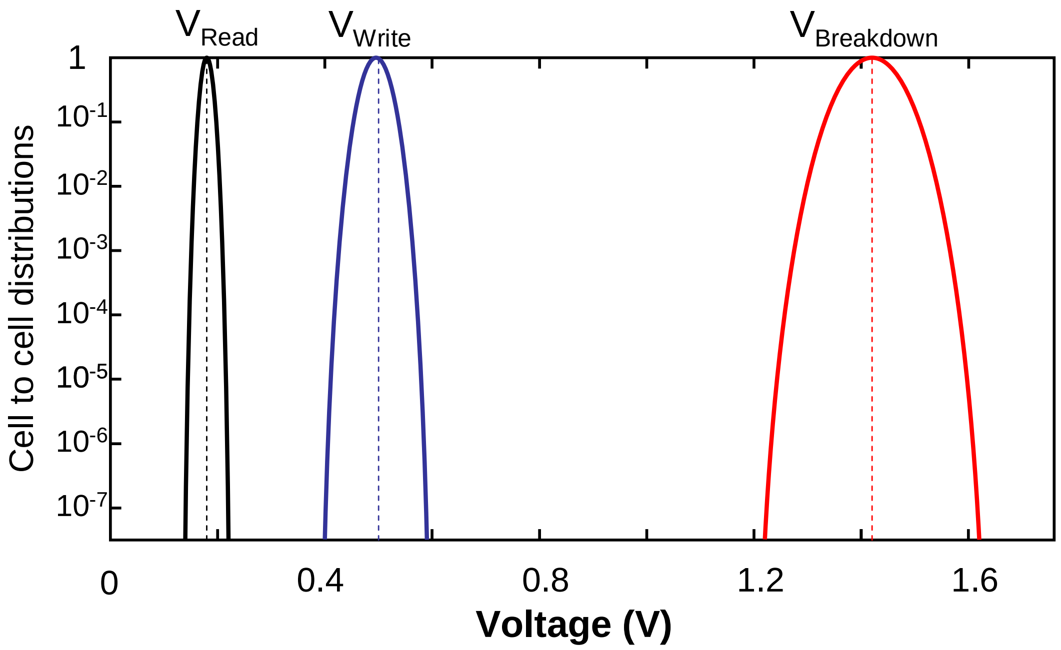
Thermally activated
STT switching

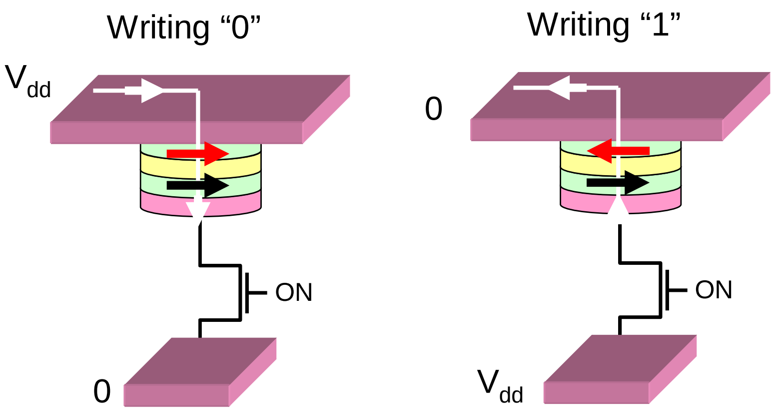


~10ns

STT-MRAM – Distributions consideration

Read **STT Write** **Breakdown**





0.15-0.2V 0.40-0.50V 1.2V-1.6V

V_{switch}<<$V_{breakdown}$ for good write endurance

V_{read}<<V_{switch} to avoid disturb during read

V_{read} large enough for reasonable read speed (~10ns).

STT-MRAM – Key parameters

- Δ (**thermal stability factor**) $\Rightarrow$ data retention, read disturb, operating temperature range, downsize scalability

Δ should be between 30 and 90 depending on chip density and retention.

- **TMR** (**read signal**) $\Rightarrow$ read speed, sense margin, tolerance on RA dispersion

TMR above 200% to achieve fast (sub 10ns) read-out. The larger, the better.

- **J_{c0} (write current density)** $\Rightarrow$ cell size, write speed, write consumption, reliability

J_c below 1.10^6A/cm² is desirable to insure select transistor size smaller than MTJ.

- **V_{bd} (MTJ breakdown voltage)** $\Rightarrow$ reliability, endurance

V_{bd} should be above 3 times write voltage (typically V_{bd}~1.5V at 10ns and V_{write}~0.5V) to achieve a write endurance above 10^{16} cycles.

2013: 1st STT-MRAM product

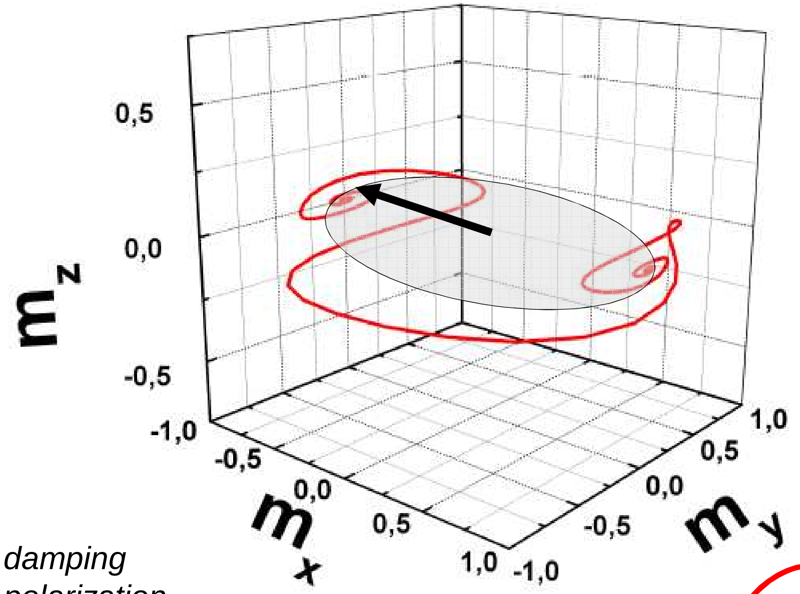
Everspin Introduces
The 64Mb DDR3 ST-MRAM

EVERSPIN®
TECHNOLOGIES
The MRAM Company™

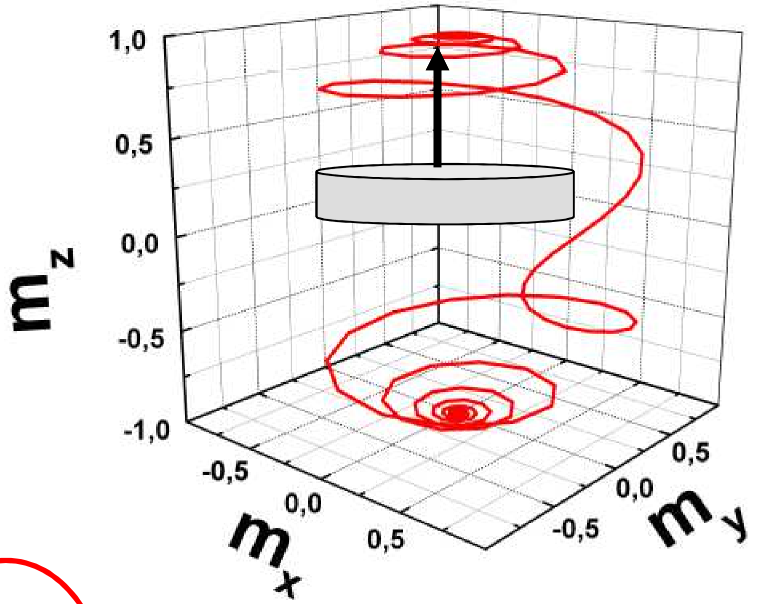
November 2012

In-plane versus out-of-plane STT switching

In-plane magnetized MTJ



Out-of-plane magnetized MTJ



α = damping
P = polarization
A = Area
g(0)~1

$$j_c^{in-plane} = \left(\frac{4e}{\hbar}\right)\frac{\alpha k_B T}{g(0)pA}\left(\Delta + \boxed{\frac{\pi M_s^2 V}{k_B T}}\right)$$

$$j_c^{perp} = \left(\frac{4e}{\hbar}\right)\frac{\alpha k_B T}{g(0)pA}\Delta$$

Thermal stability determined by in-plane anisotropy (shape anisotropy)

Simpler materials but additional penalty in jc due to out-of plane precession

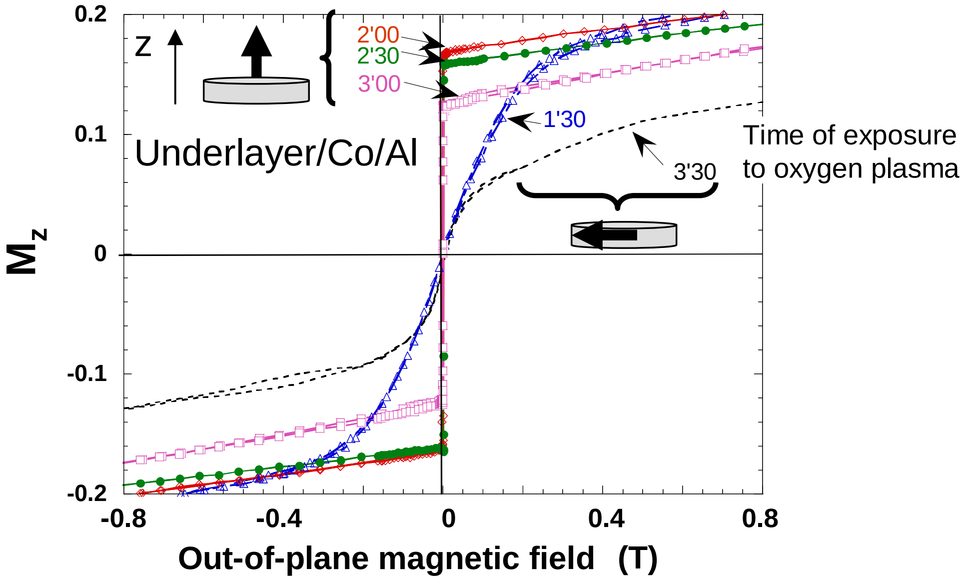
More complex materials but lower jc expected thanks to direct proportionality between Jc and thermal stability Δ

Perpendicular Magnetic Anisotropy (PMA) at magnetic metal/oxide interface

Surprisingly large perpendicular anisotropy at magnetic metal/oxide interface

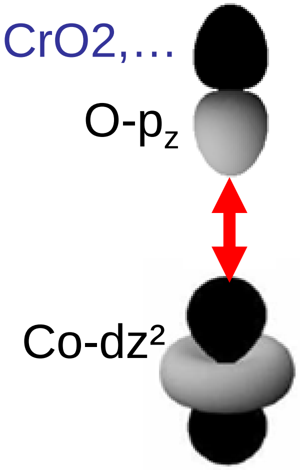
(Monso et al APL 2002)

S.Monso, et al, APL 80 (2002), 4157-9.	*First observation of PMA at Co/AlOx*
B.Rodmacq et al,Journ.Appl.Phys.93, (2003), 7513.	*PMA at Co or CoFe/MgO, CrO, TaO*
A.Manchon et al, Journ. Appl. Phys. 104, 043914 (2008).	*XPS, XAS, interpretation of PMA at M/Ox*
B.Rodmacq et al, Phys.Rev.B79, 024423 (2009)	Influence of annealing on PMA at Co/AlOx
L.Nistor et a, IEEE Trans Mag., 46 (2010), 1412	Correlation PMA -TMR at CoFe(B)/MgO



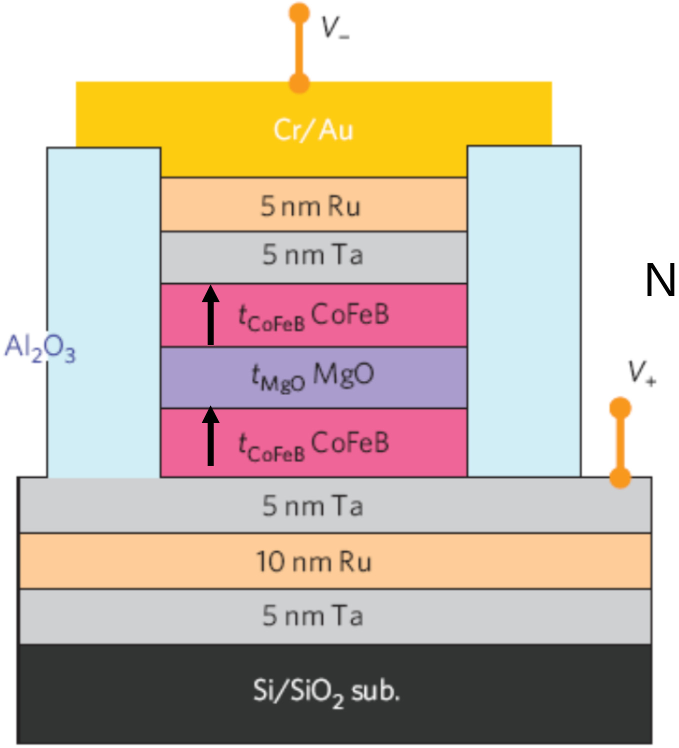
Very general phenomenon of perpendicular anisotropy observed at a wide variety of M/Ox interfaces with M=Co, CoFe, CoFeB and Ox= AlOx, MgO, TaOx, CrO2,…

Due to hybridization between Co dz² and O sp orbitals

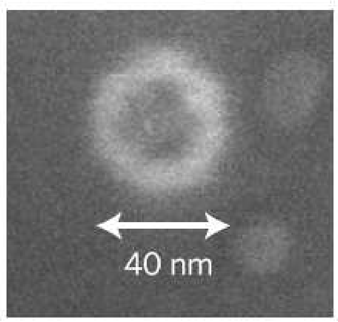


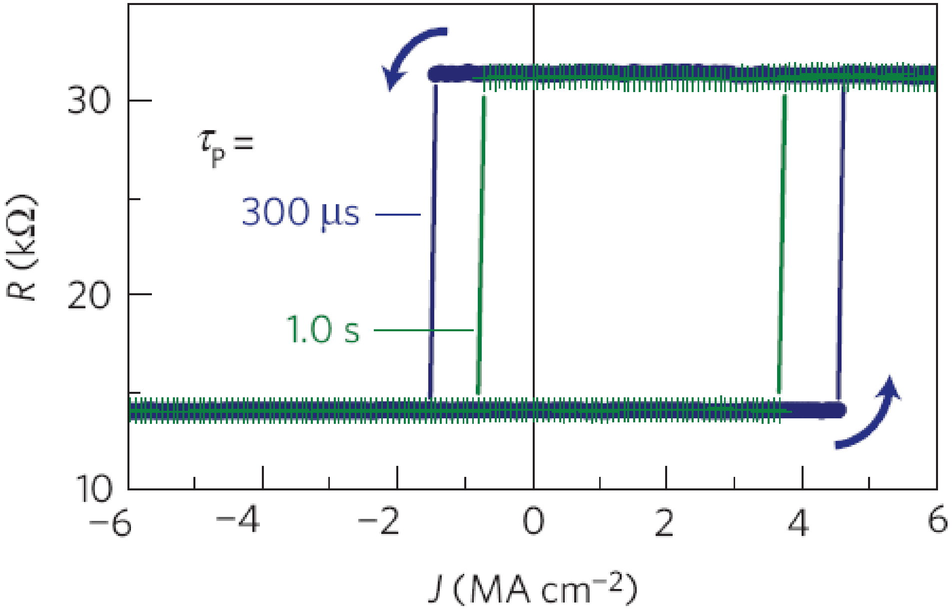
P-MTJ based on interfacial PMA (i-PMA)

Ikeda et al, Nat.Mat.2804 (2010)



No Pt nor Pd in the stack



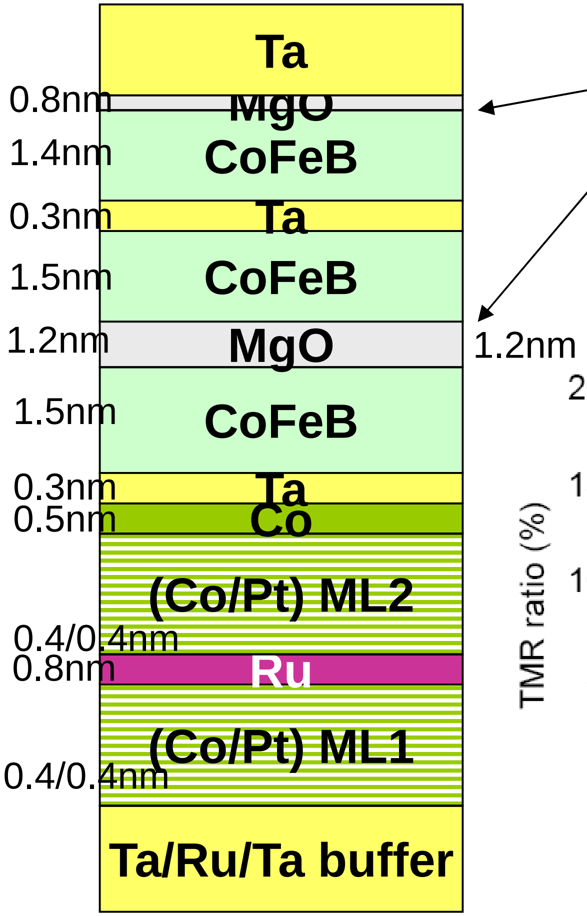


TMR=124%
RA=18Ω.µm²

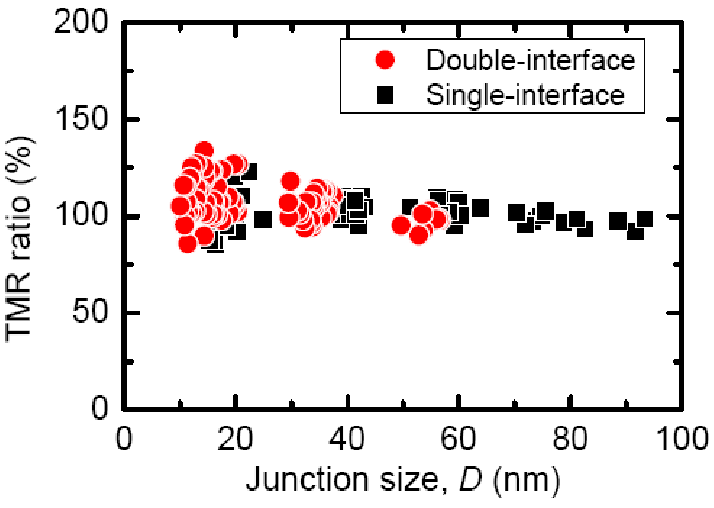
Δ=43
(70 required for 1Gbit)

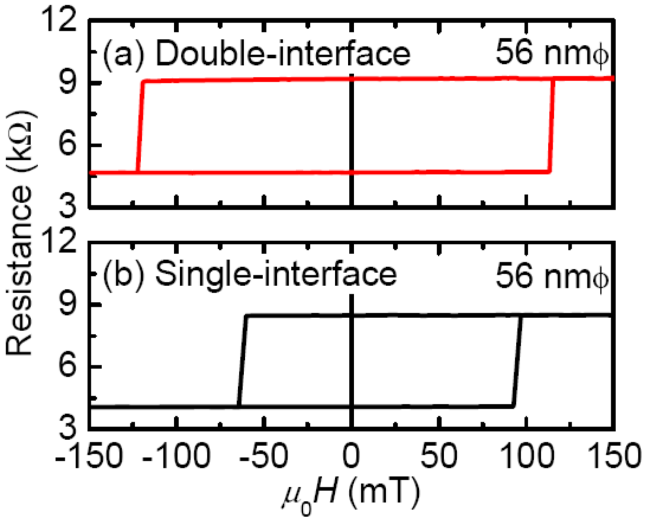
Sub-20nm STT-MRAM

Bottom pinned with double MgO barrier:



Benefit from the PMA at these two interfaces.
Increases the thermal stability of the free layer.



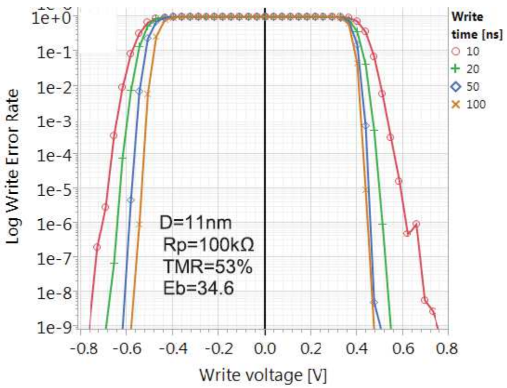


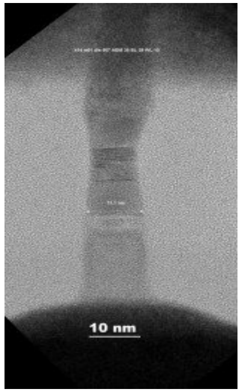
H.Ohno's group (Tohoku Univ 2013), IEDM 2014

TMR ~100-130%

STT-MRAM assets

- **Non-volatility**

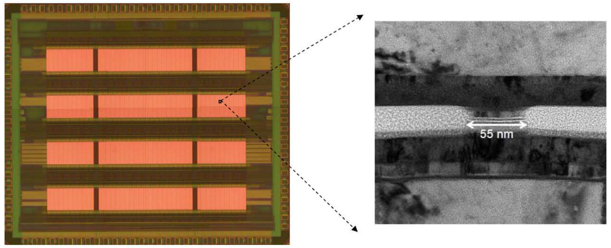


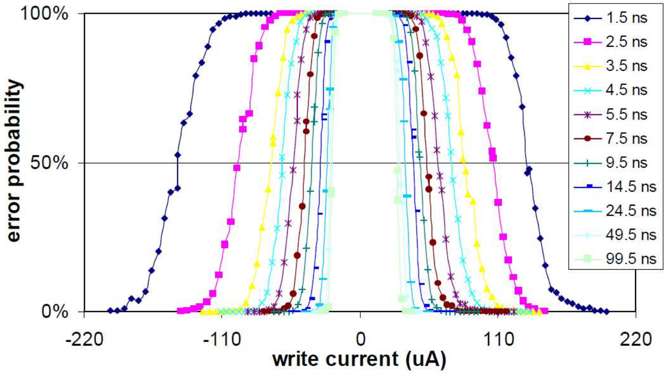


11nm STT-MRAM cell
(IBM)
Janusz et al, IEEE Mag.Lett.7, 3102604(2016)

- **Downsize scalability**

8 Mbit fully functional demo from TDK/Headway
Techno now transfered to TSMC

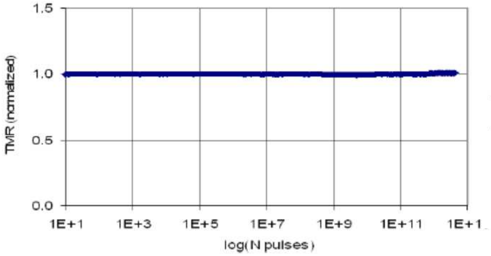


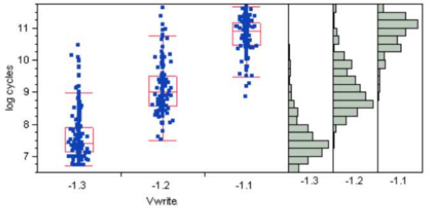


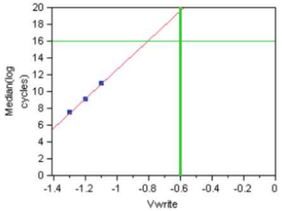
- **Write speed**

- **Write endurance**

(at least for pulse duration >20ns)







10^{20} cycles à 0.6V

➡ 1) e-FLASH, 2) non-volatile SRAM …. 3) Non-volatile DRAM

An increasing number of industrial actors active in the MRAM arena

EVERSPIN TECHNOLOGIES

NEC

intel

TDK

AvalancheTechnology

IBM

Spin Transfer Technologies

tsmc

RENESAS Everywhere you imagine.

Micron

CROCUS Technology Blossoming future

SAMSUNG

SONY

FUJITSU

TOWERJazz

GRANDIS

TEL

QUALCOMM

TOSHIBA

KEYSIGHT TECHNOLOGIES

SINGULUS

APPLIED MATERIALS

hynix

Canon CANON ANELVA CORPORATION

SAMSUNG Newsroom

https://news.samsung.com/global/samsung-electronics-starts-commercial-shipment-of-emram-product-based-on-28nm-fd-soi-process

Samsung Electronics Starts Commercial Shipment of eMRAM Product Based on 28nm FD-SOI Process

Korea on March 6, 2019

Samsung's eMRAM will further strengthen the company's technology leadership in embedded memory

Samsung Electronics the world leader in semiconductor technology, today announced that it has commenced mass production of its first commercial embedded magnetic random access memory (eMRAM) product based on the company's 28-nanometer(nm) fully-depleted silicon-on-insulator (FD-SOI) process technology, called 28FDS.

As eFlash has faced scalability challenges due to a charge storage-based operation, eMRAM has been the most promising successor since its resistance-based operation allows strong scalability while also possessing outstanding technical characteristics of memory semiconductors such as nonvolatility, random access, and strong endurance. With today's announcement, Samsung has proved its capability to overcome technical hurdles and demonstrated the possibility for further scalability of embedded memory technology to 28nm process node and beyond.

Samsung's 28FDS-based eMRAM solution offers unprecedented power and speed advantages with lower cost. Since eMRAM does not require an erase cycle before writing data, its writing speed is approximately a thousand times faster than eFlash. Also, eMRAM uses lower voltages than eFlash, and does not consume electric power when in power-off mode, resulting in great power efficiency.

Conclusion on p-STT-MRAM

- Perpendicular MTJs offer better downsize scalability than in-plane magnetized MTJs due to larger anisotropy and lower write current for a given thermal stability factor.

- In p-MTJs, taking advantage of the interfacial anisotropy at CoFe/MgO interface allows to circumvent the issue of combining large PMA with low Gilbert damping.

- Etching of the MTJ stack remains the main technological difficulty at sub-28nm node yielding too large variability. However, great progress are made and demonstrators of embedded STT-MRAM at 28nm node have been successfully realized.

- Main foreseen applications:
    - Replacement of embedded FLASH
    - Replacement of SRAM
    - Remplacement of DRAM (longer time goal….)

Spinelectronics:
From Basic Phenomena to Applications

OUTLINE

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  - Spin-orbit Torques (SOT)

- **Part 2 : Spintronics main applications**

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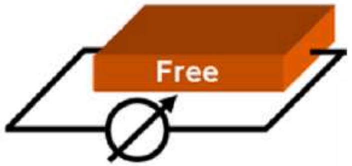
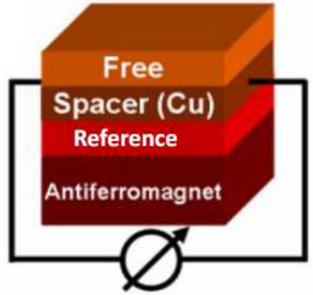
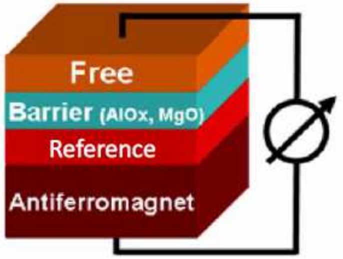
  - MRAMs
  - **Magnetic field sensors**
  - RF components

Different kinds of magnetoresistive sensors

Freitas, P.; Ferreira, R., Cardoso, S. ; PROCEEDINGS OF THE IEEE, 104, 1894-1918 (2016)

TYPICAL KEY PROPERTIES OF MAGNETORESISTIVE SENSORS

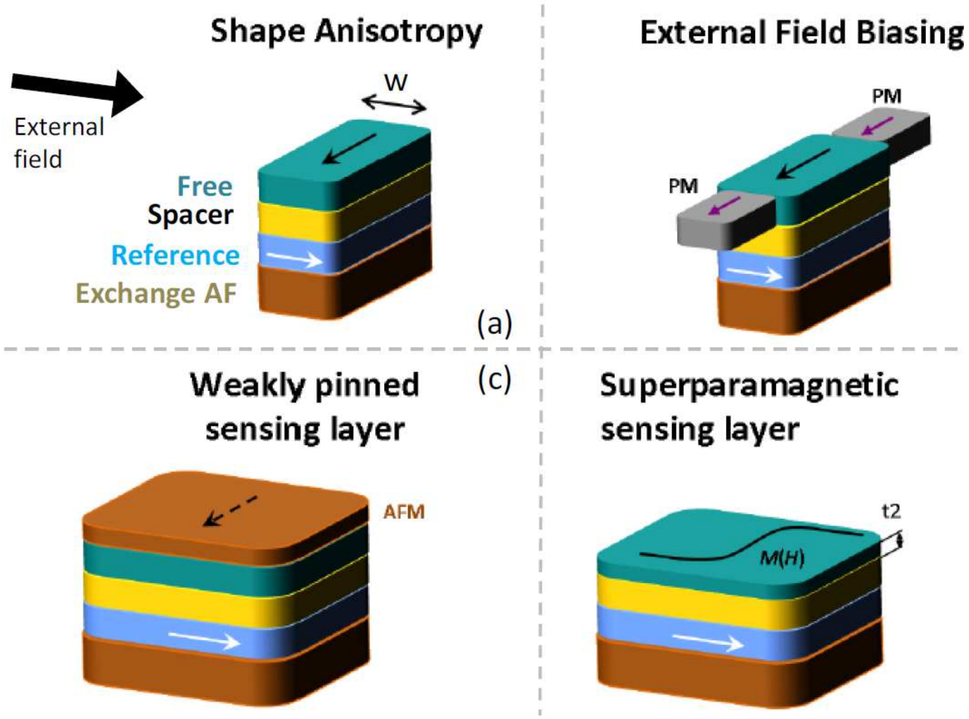
	AMR	**GMR** Spinvalves	**TMR** - Magnetic Tunnel Junctions
Physical principle	*Anisotropic MR*	*Giant MR*	*Spin dependent tunneling*
Thin film structure	*Simple* *Buffer/free/cap*	*Multilayers, several material compositions* *Buffer/free/spacer/reference/pinning/cap*	*Complex multilayers, several material compositions* *Buffer/free/barrier/reference/pinning/cap*
Magnetoresistance (MR) [%]$^{\#}$	*2-6*	*6-20*	*50% (Al_2O_3 amorphous barrier)* *300% (MgO crystalline barrier)*
Sensor linear range [mT]$^{\&}$	*0.1-1*	*1-5*	*2-10*
Thermal treatment [°C] $^{\$}$	*Not required*	*Typically 220-280°C*	*Typically 280-340°C*
Reference layer	*No, needs external*	*Yes (interface exchange biased trough an antiferromagnetic film)*	*Yes (interface exchange biased trough an antiferromagnetic film)*
Electrical robustness against electrostatic discharge	Excellent	Excellent	Good
General geometry and readout scheme			

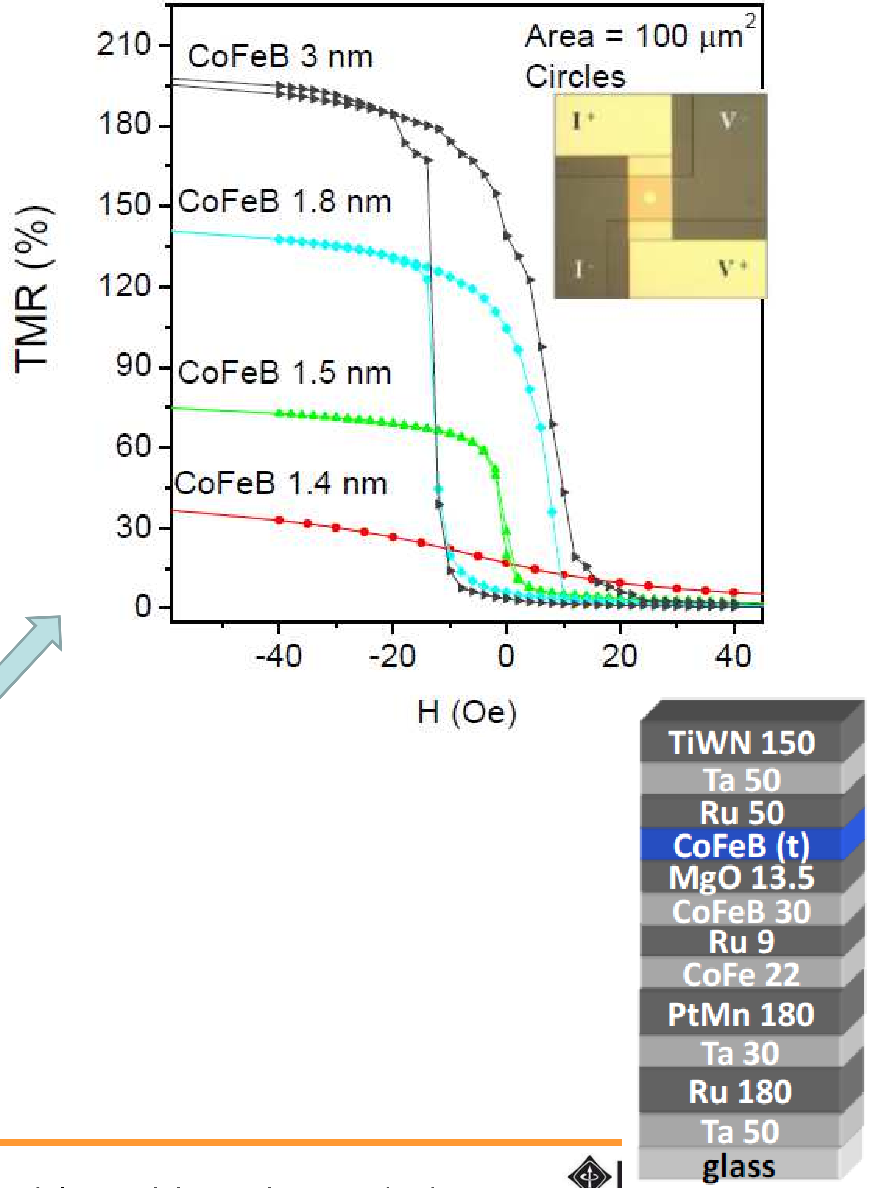
Sensors matrix (from NIST, 2003)

Sensor type	Sensitivity/ Field range	Frequency Range	Operation Temperature	Minimum sensor size/ Scalability	Vectorial/ scalar	Cost	Advantages	Disadvantages	Status
Search coil	30 fT	>1 Hz	RT	1 mm	vector	Moderate	Low cost for the sensitivity	Limited to > 1Hz, sensitive to angular vibrations, Loose sensitivity as decrease size	Mature
Hall probe/EMR	100 nT/ 1nT	< 1kHz	RT	< 1µm	Vector	Moderate	Large range, linear	Temperature dependent	Mature
Fluxgate	1 pT/Hz)$^{0.5}$ @ 1Hz	< 1kHz	RT	Loose S/N scaling down	Vector	Moderate	High sensitivity	Cost, size, energy consumption	Bulk films versions possible
SQUID	1 fT	<1kHz	<77K	< 1µm (system large)	Vector	Expensive	Sensitivity	Need for low temperature	mature
GMR	20 nT	0- 5 GHz	RT	< 1µm	Vector	Cheap	Low cost in large quantities. Small sensors. Wide frequency range		
TMR	1 nT	0-1 GHz	RT	< 1µm	Vector	Cheap	Large MR, low cost in large quantities	High 1/f noise, hysteretic	
GMI	100 pT	<500 kHz	RT	1 mm	Vector	Moderate		Cost, size, high power	
Magneto-optic	100 pT	0-5GHz	RT	. 1 mm	Vector	Moderate	No electrical connection		
Resonance		DC	RT		Scalar	Expensive			
Optical pumping	10-1000 fT	< 100 Hz	RT	10 mm	Scalar or vector	Expensive	Insensitive to angular vibrations	Cost, power consumption, loss of sensitivity at higher frequencies	
Magnetostrictive /	1 nT		RT	10 µm	Vector	Moderate	Low power Large output	Sensitive to vibrations	

Various approaches for linearization of magnetoresistive sensors

Aspect ratio >20

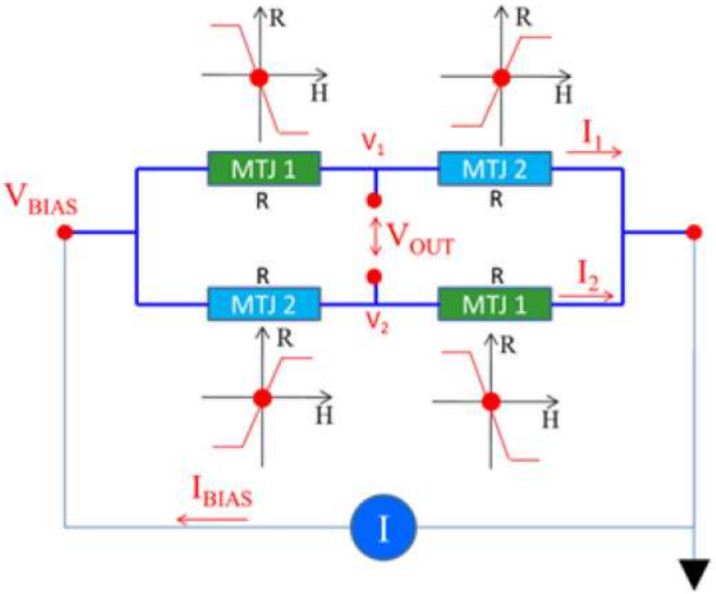


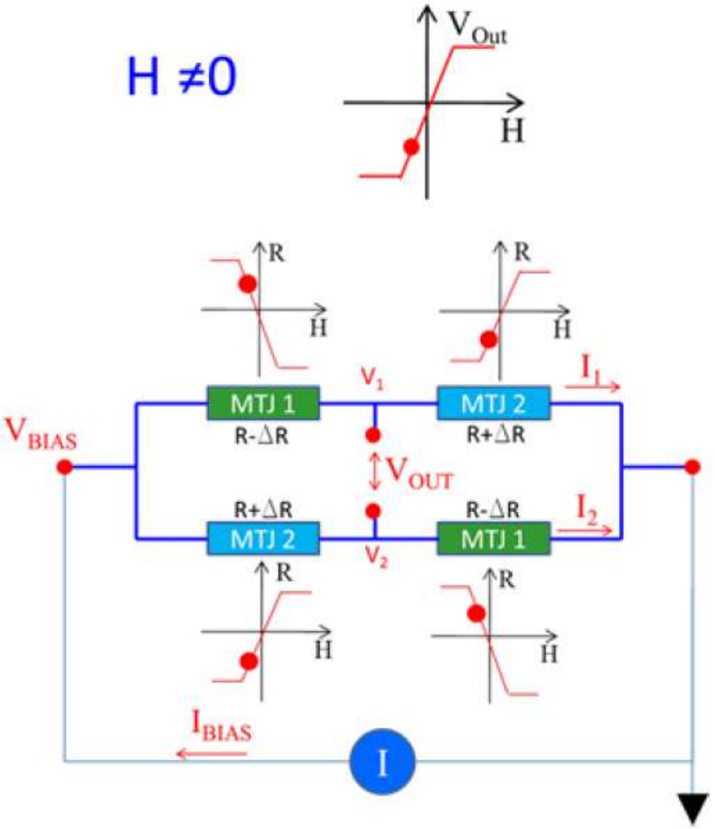


P. Wisniowski, et al, J. Appl. Phys. ***103****, 07A910 (2008).*

Magnetoresistive sensors often used in Wheastone bridge configuration

H =0 ; V_{out}=0



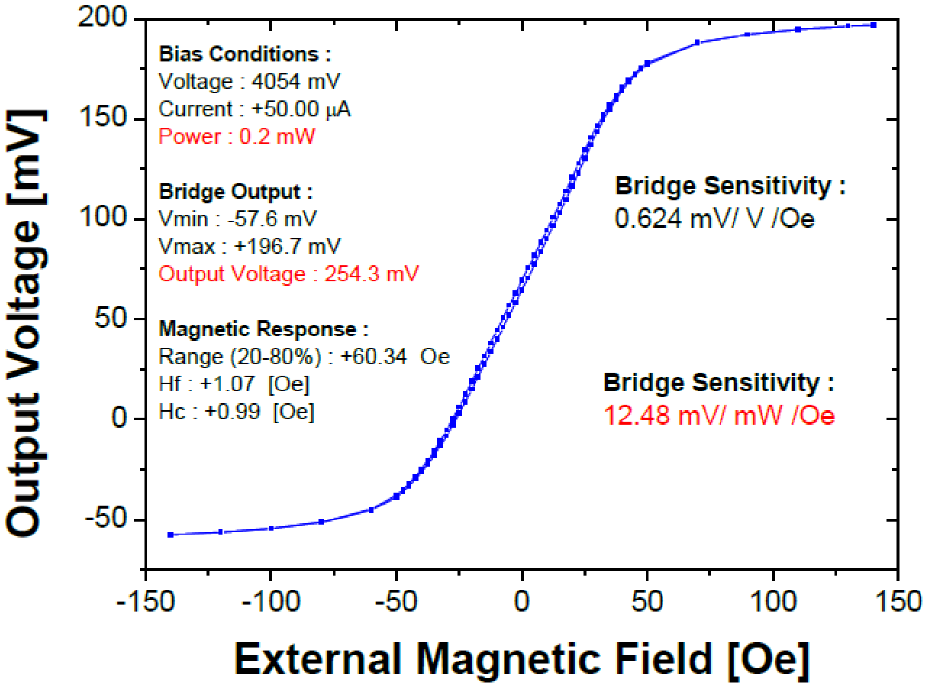


Difficulty is to set the two pairs of sensors in opposite pinning directions:
-Use different deposits (different field during deposition or AF with different TB or SAF differently compensated…)
-Or use local heating lines
-Or use local field generating lines

P.P.Freita et al, SPIN, Vol.1, 71 (2011)
J.Cao et al, J.Appl.Phys.107, 9 (2010)

Example of bridge magnetoresistive sensor

Example: spin-valve based bridge sensor
Glass/Ta 2nm /NiFe 3nm / CoFe 2 / Cu 1.9 / CoFe 2 / Ru 8 / CoFe 1.5 / MnIr 6 / Ta 3nm
GMR=8%
30 GMR elements in series in each branch with individual dimension 3*170mm
Very elongated shape to insure single domain behavior



J.Cao and P.P.Freitas, Wheatstone bridge sensor composed of linear MgO magnetic tunnel junctions, Journal of Applied Physics , 107, 9, (2010)

With TMR : bridge sensitivity 32mV/V/Oe or 26.7 mV/mW/Oe

Spintronics sensors for ultra-low field detection

S.Cardoso et al, Microsyst .technol (2014) 20, 793.

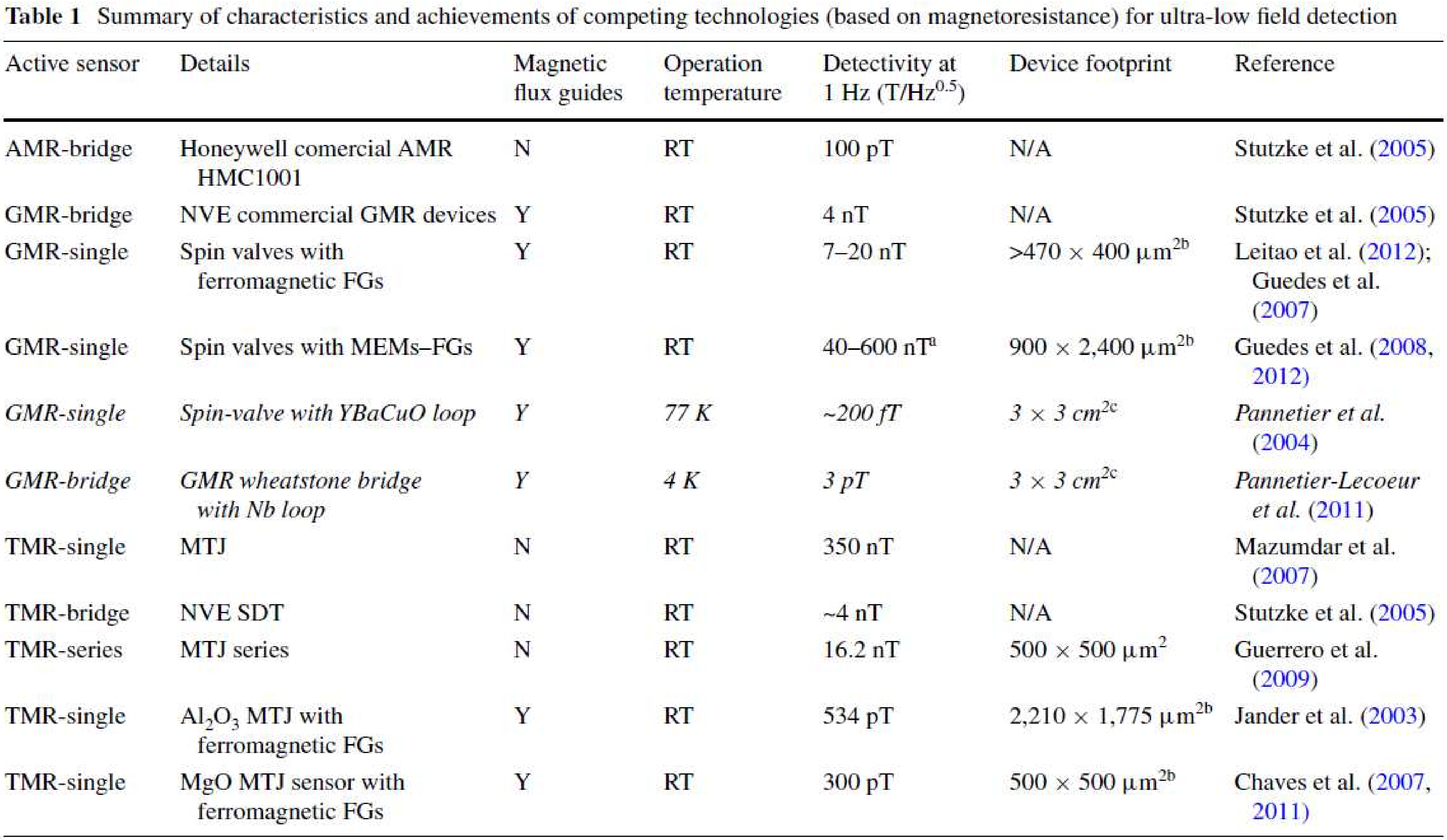
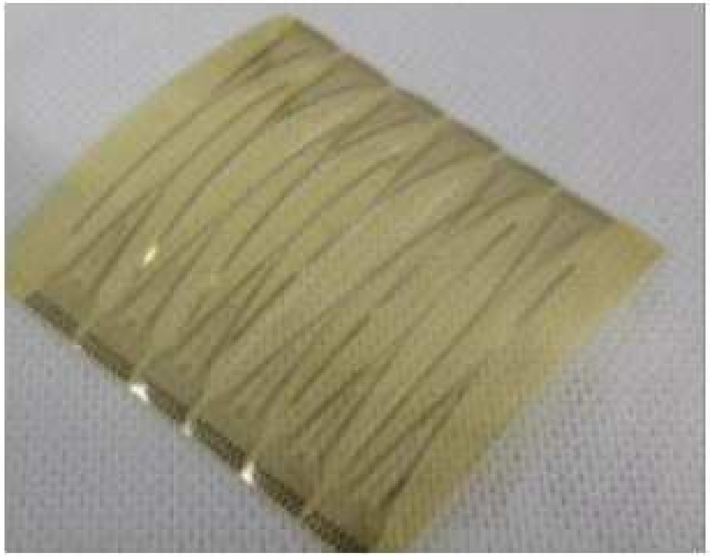


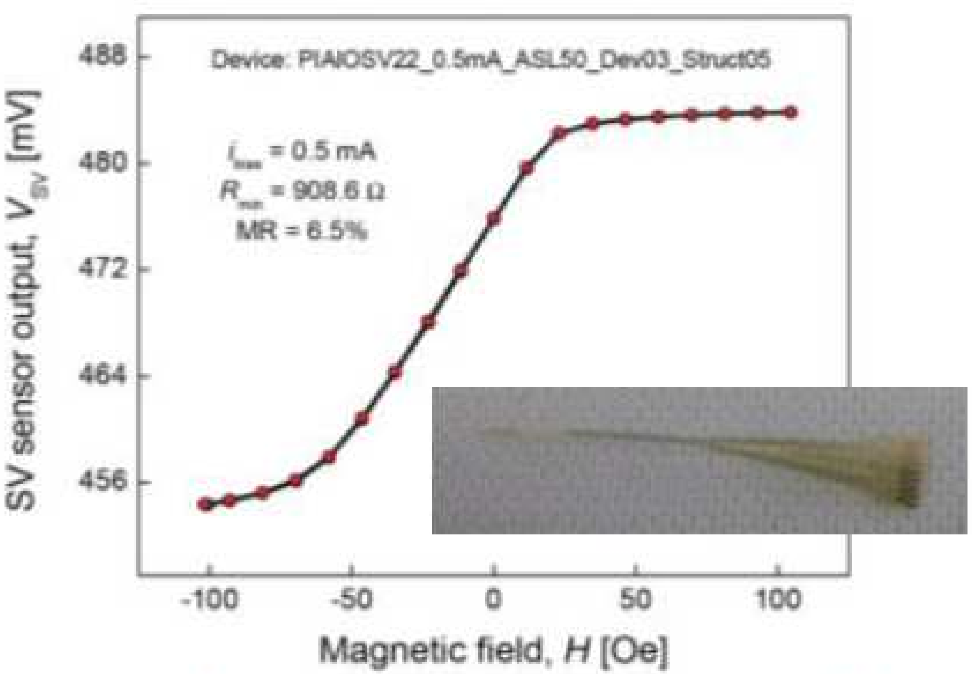
Table 1 Summary of characteristics and achievements of competing technologies (based on magnetoresistance) for ultra-low field detection

Active sensor	Details	Magnetic flux guides	Operation temperature	Detectivity at 1 Hz (T/Hz$^{0.5}$)	Device footprint	Reference
AMR-bridge	Honeywell comercial AMR HMC1001	N	RT	100 pT	N/A	Stutzke et al. (2005)
GMR-bridge	NVE commercial GMR devices	Y	RT	4 nT	N/A	Stutzke et al. (2005)
GMR-single	Spin valves with ferromagnetic FGs	Y	RT	7–20 nT	>470 × 400 μm^{2b}	Leitao et al. (2012); Guedes et al. (2007)
GMR-single	Spin valves with MEMs–FGs	Y	RT	40–600 nT^{a}	900 × 2,400 μm^{2b}	Guedes et al. (2008, 2012)
GMR-single	*Spin-valve with YBaCuO loop*	*Y*	*77 K*	*~200 fT*	*3 × 3 cm*^{2c}	*Pannetier et al.* (2004)
GMR-bridge	*GMR wheatstone bridge with Nb loop*	*Y*	*4 K*	*3 pT*	*3 × 3 cm*^{2c}	*Pannetier-Lecoeur et al.* (2011)
TMR-single	MTJ	N	RT	350 nT	N/A	Mazumdar et al. (2007)
TMR-bridge	NVE SDT	N	RT	~4 nT	N/A	Stutzke et al. (2005)
TMR-series	MTJ series	N	RT	16.2 nT	500 × 500 μm^{2}	Guerrero et al. (2009)
TMR-single	Al_2O_3 MTJ with ferromagnetic FGs	Y	RT	534 pT	2,210 × 1,775 μm^{2b}	Jander et al. (2003)
TMR-single	MgO MTJ sensor with ferromagnetic FGs	Y	RT	300 pT	500 × 500 μm^{2b}	Chaves et al. (2007, 2011)

Integration of sensors on flexible substrates possible

Interesting for instance for implantable devices, bendable electrodes (neurosciences).
Example: GMR spin-valves on polyimide



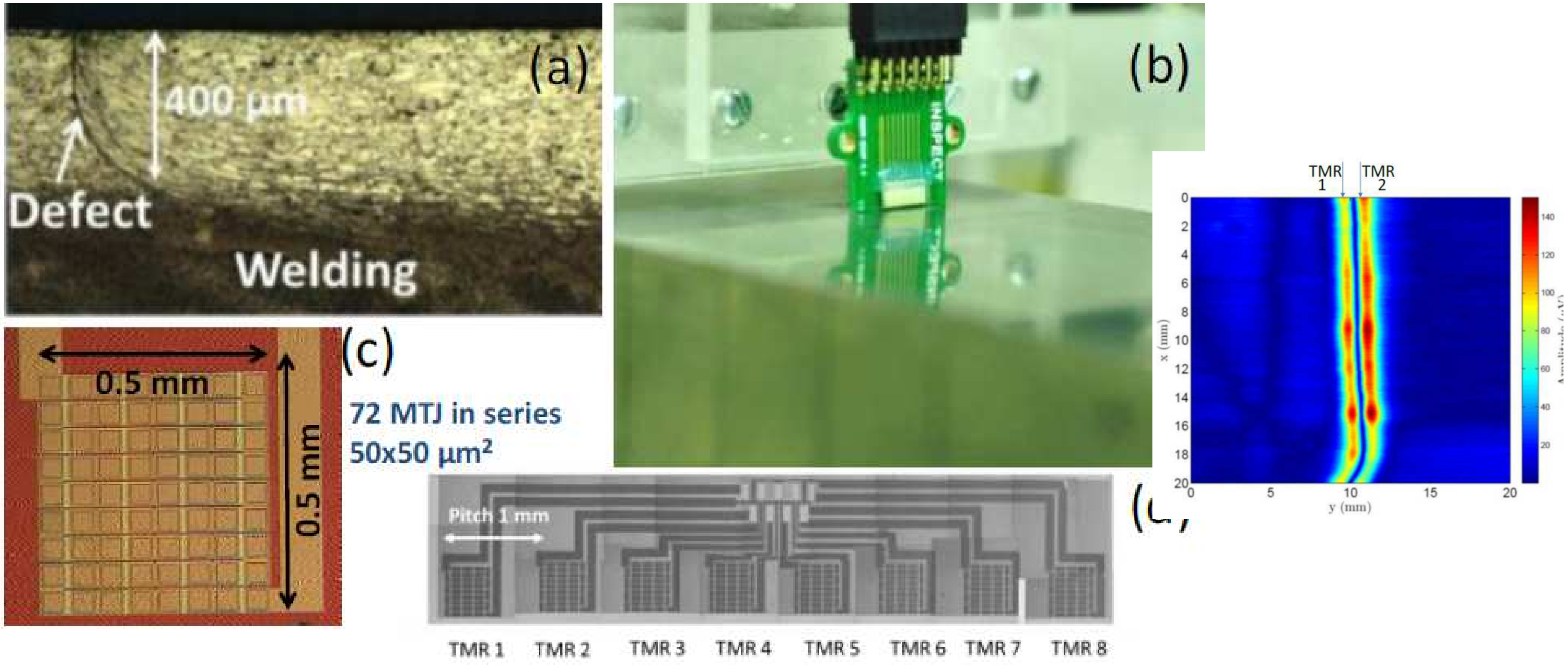


-M.Melzer, G. Lin, O. G. Schmidt, Adv. Mater. 2012, DOI: 10.1002/adma.201201898
-C. Barraud et al, Appl. Phys. Lett. 96, 072502 (2010)
-M. Melzer, D. Makarov, A. Calvimontes, et.al, Nano Lett. (2011), 11, 2522–2526
-J. Gaspar et al, presented at INTERMAG conference, Beijing (2015)

Applications: 1) metal surface inspection

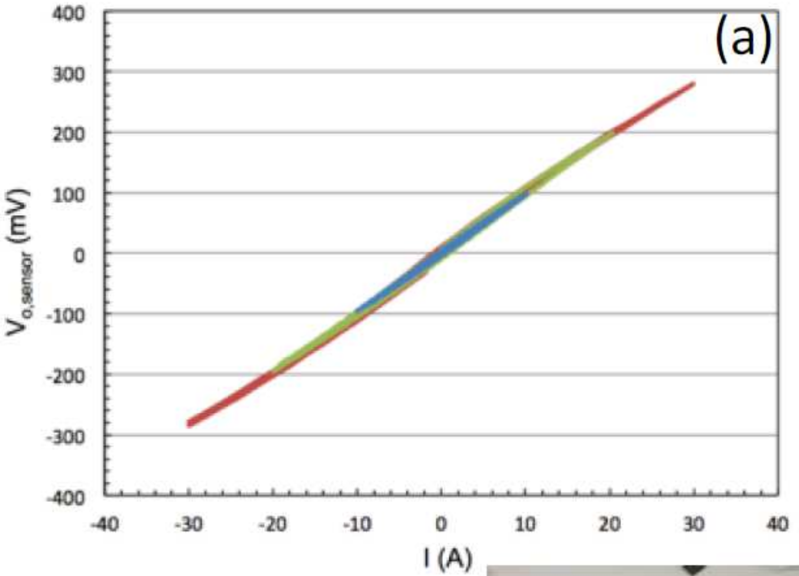
<u>Principle</u>: To excite the metal surface with a RF field at ~1MHz and detect the stray field due to eddy current from the metal surface. Eddy currents are very sensitive to local resistivity which changes significantly if a defect is present.

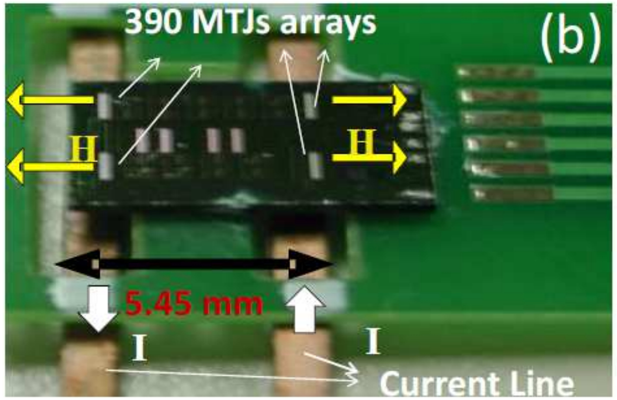
Al plate to
be tested



E. E. Kriezis et al, Proceedings of the IEEE, 80(10), 1559-1589, 1992
T. Dogaru et al, IEEE Trans.Magn., 37, 3831 (2001).
Y. Dalichaouch, et al, Proc. SPIE, 3994, 2 (2000).
L. Rosado et al, Sensors and Actuators A:Physical, 212, 58 (2014).
F. Cardoso et al, J.Appl.Phys.115, 17E516 (2014).

Applications: 2) MR sensors for Power measurements



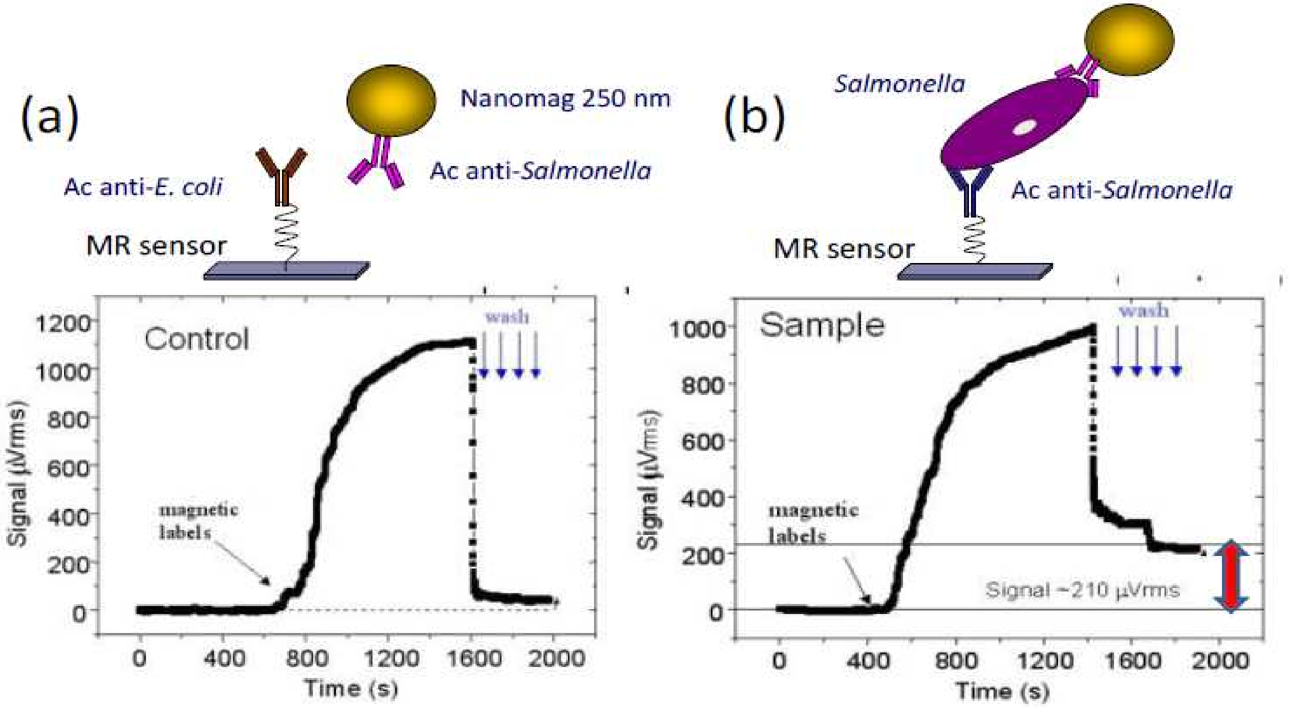


Contactless measurement of the stray field created by a current flowing in a wire

D. Ramírez Muñoz et al "Active power analog front-end based on a Wheatstone-type magnetoresistive sensor", Sensors & Actuators A 169 (2011), 83-88
J. Sánchez et al, "Magnetic tunnel junction current sensor for industrial applications", IEEE Trans. Magn. 48 (11), pp. 2823-2824 (2012)

Applications: 3) Medical/biological diagnosis
Biosensing through magnetic nanoparticles labelling

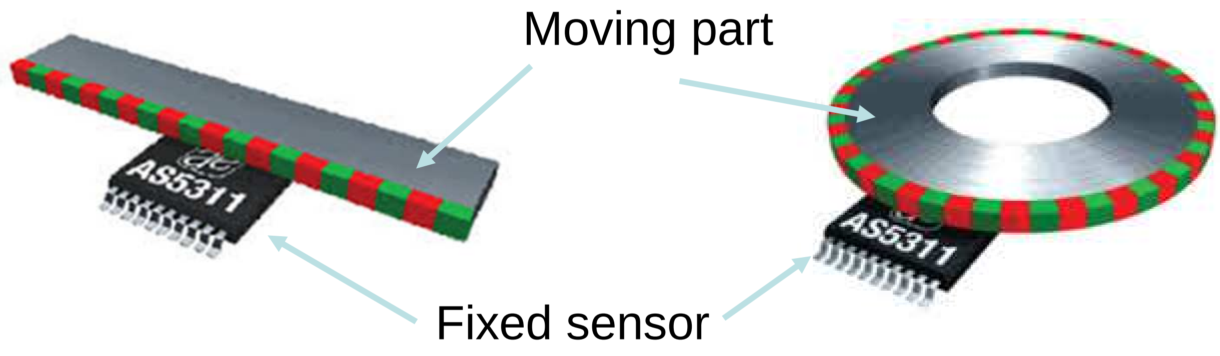
Use MR sensors to detect magnetic particles flowing in a microfluidic channel



Startups:
http://www.magarray.com (Stanford, Pr S.Wang)
http://www.zeptolife.com (Minnesota)
http://www.magnomics.pt (INESC, Portugal)

P.P. Freitas et al, Spintronic platforms for biomedical applications, Lab-on-Chip, 2012, 12 (3), 546 – 557
G.Li et al, Model and experiment of detecting multiple magnetic nanoparticles as biomolecular labels by spin valve sensors. *IEEE Transactions on Magnetics,* 40, 3000-3002 (2004)
V. C Martins et al, Femtomolar Limit of Detection with a Magnetoresistive Biochip, Biosensors and Bioelectronics 24, 2690 (2009),
Ferreira, H.A. et al. Rapid DNA hybridization based on ac field focusing of magnetically labeled target DNA, Appl. Phys. Lett. 87, 013901 (2005)
Germano, J.et al., Sensors 9(6), 4119-4137 (2009).

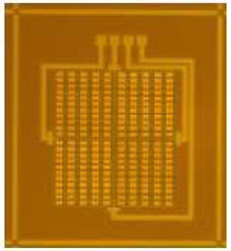
Applications: 4) Position/rotation encoders

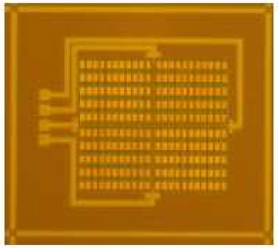


- MR sensors used as linear or rotation encoders
- More than 100 of them in a car. Often based on Hall sensors but GMR increasingly used.
- One difficulty with GMR or TMR is the temperature sensitivity. Must be somehow compensated (example: anisotropy field $H_k(T)$ decreasing at same rate as GMR(T) amplitude versus T so that dR/R/dH remains constant vs T)
- Must be very low cost.

Applications: 5) MR sensors used as compass

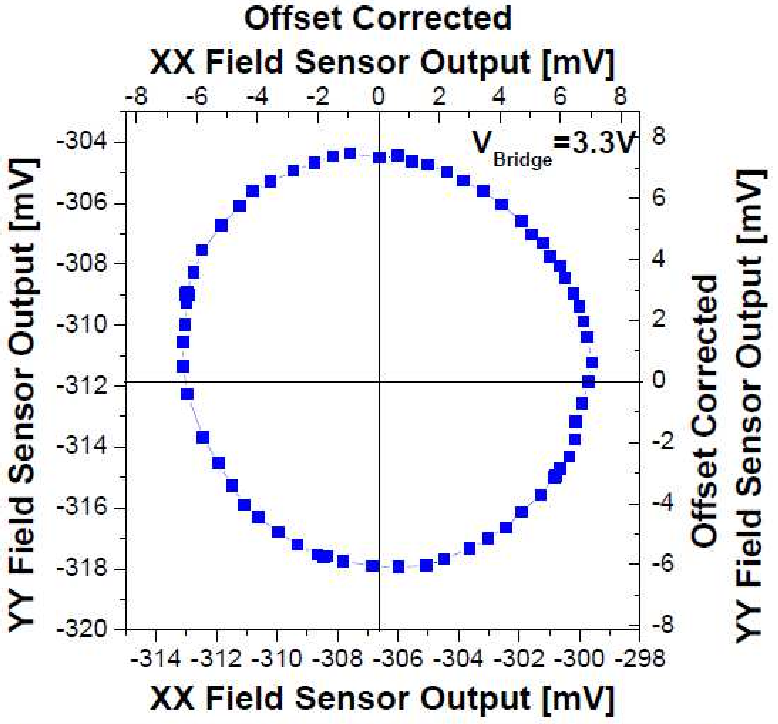
XX Component Sensor





YY Compone Sensor

Sensor output during a 360° rotation



13.3 mV/V/Oe sensitivity → 0.31 Oe field

Sensitive to earth field

R. Ferreira, E.Paz, P.P.Freitas, 2-Axis Magnetometers Based on Full Wheatstone Bridges Incorporating Magnetic Tunnel Junctions Connected in Series, IEEE Transactions on Magnetics, 48, 4107 (2012)

Can complement GPS signal when the latter is not available (tunnels, underground parking lot, GPS breakdown…)

3D sensing also developed: Difficulty is to measure B_z with integrated components (these sensors must be low cost)

Industrial actors in MR sensors

Allegro™ MicroSystems, LLC

High-Performance Semiconductors

(USA)

PRODUCTS

- Current Sensor ICs
- Magnetic Digital Position Sensor ICs
- Magnetic Speed Sensor ICs
- Sanken Products
- Magnetic Linear and Angular Position Sensor ICs
- Motor Driver and Interface ICs
- Regulators and Lighting

AsahiKASEI

(Japan)

Honeywell

(USA)

MEMSIC Powerful Sensing Solutions

(USA)

Infineon

(Germany)

Melexis Microelectronic Integrated Systems

(Belgium)

MICRONAS

(Switzerland)

NXP

(Netherland)

ams

(Austria)

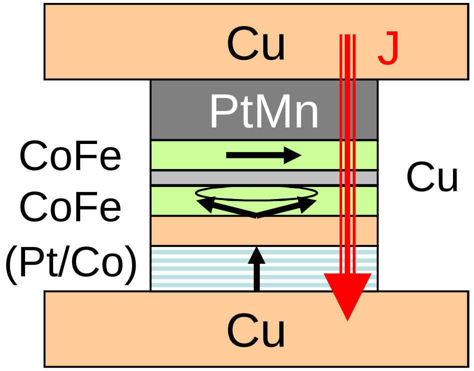
Spinelectronics:
From Basic Phenomena to Applications

OUTLINE

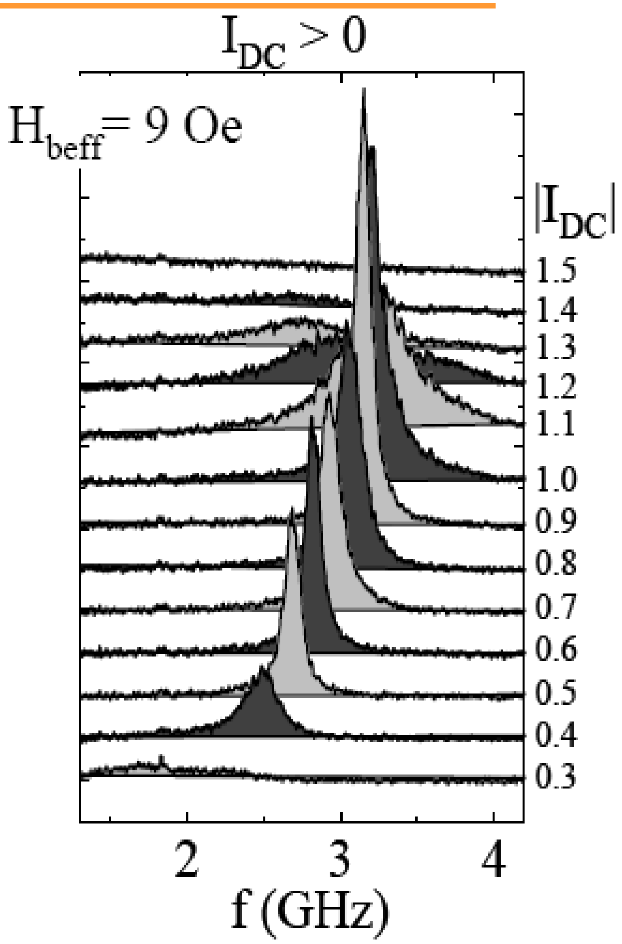
- Part 1 : Basic phenomena in spintronics:
  - Giant Magnetoresistance
  - Tunnel magnetoresistance (TMR)
  - Spin-Transfer Torque (STT)
  - Spin-orbit Torques (SOT)

- **Part 2 : Spintronics main applications**
  - Magnetic Recording (Hard disk drives Read-heads)
  - MRAMs
  - Magnetic field sensors
  - **RF components**

RF oscillators based on spin-transfer torque



D.Houssamedine et al, Nat.Mat 2007



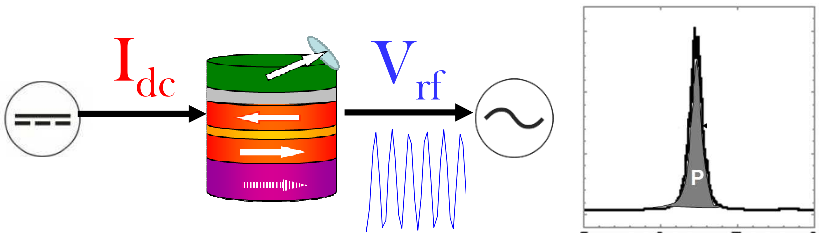
- Injection of electrons with out-of-plane spins in a layer of in-plane magnetization;
- Steady precession of the magnetization of the soft layer adjacent to the tunnel barrier.

Precession (2GHz-40GHz) + Tunnel MR $\Rightarrow$ RF voltage
Large-band frequency tunable RF oscillators

Spintronics RF Functions

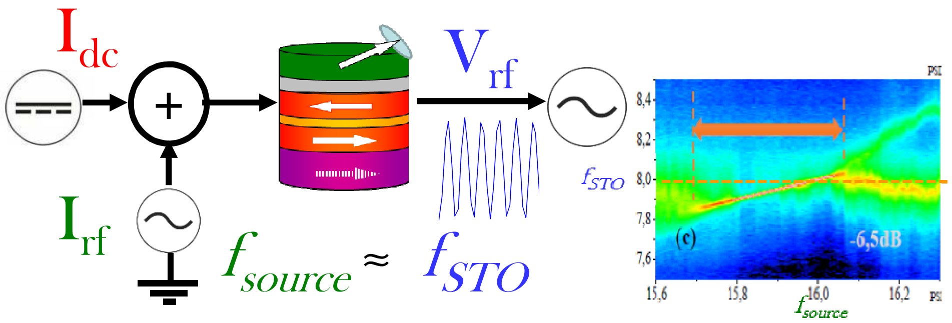
Function 1: **DC-to-RF converter**

RF Signal generation



Function 2: **Injection locking**

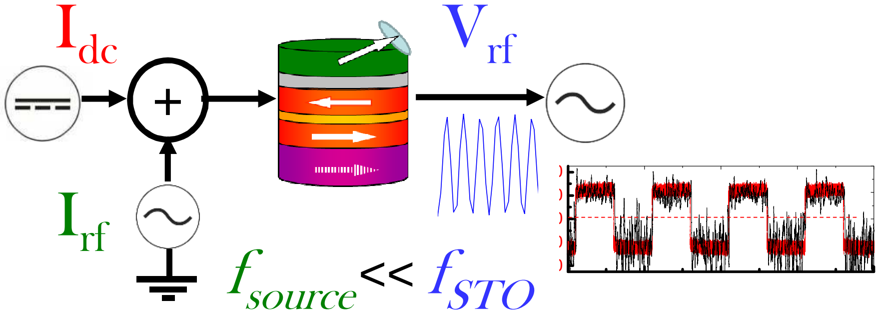
Signal synchronisation



$f_{source} \approx f_{STO}$

Function 3: **Modulation and Mixing**

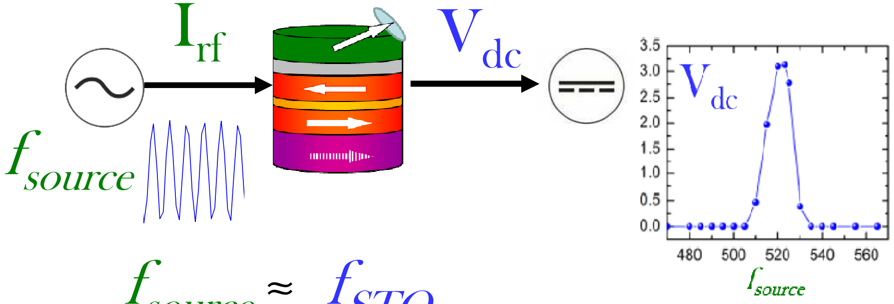
Communication



$f_{source} << f_{STO}$

Function 4: **RF-to-DC conversion**

Frequency selective microwave detection

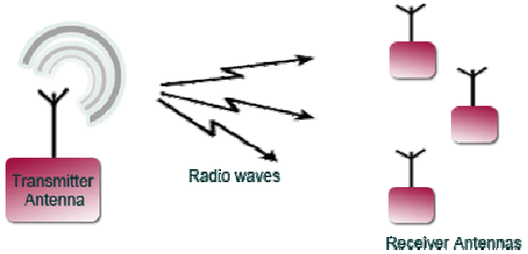


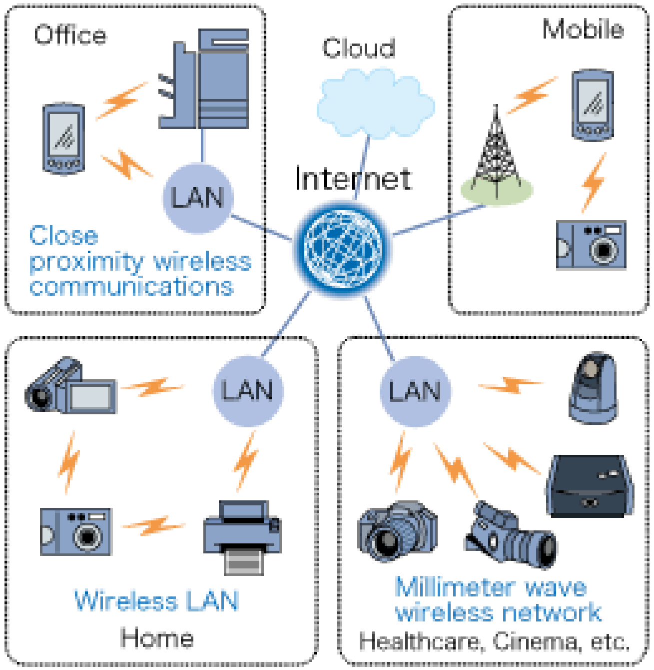
$f_{source} \approx f_{STO}$

Assets of spintronics RF components

- **Low power**, active device
- **Nanoscale dimension** – small chip size, compact alternative to LC tanks
- **Large range of base frequencies** (configuration)
- **Frequency tuning** via I and H – reconfigurable communication
- **Multifunctional** (signal generation, injection locking, modulation, detection)
- **CMOS compatible** and radiation hard

Wireless communications





Wireless sensors network

However, not yet ready for practical applications….

Remaining problems towards practical spintronics RF oscillators

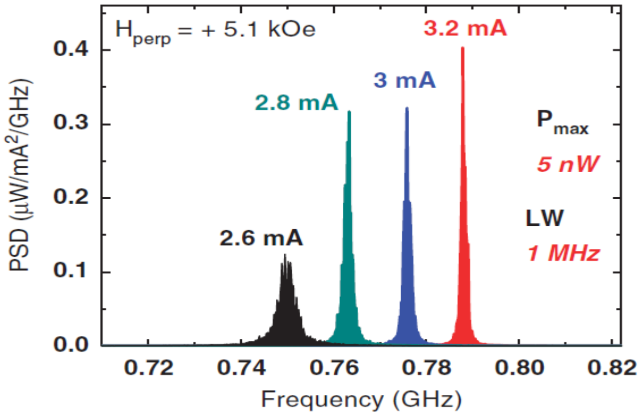
1) RF power still too low :

Large microwave generation from current-driven magnetic vortex oscillators in magnetic tunnel junctions, A.Dussaux et al, Nature Com.2010, **DOI: 10.1038/ncomms1006**

PtMn 15 nm / CoFe 2.5 nm / Ru 0.85 nm / CoFeB 3 nm / MgO 1.075 nm / NiFe 15 nm / Ru 10 nm.

170nm pillar diameter

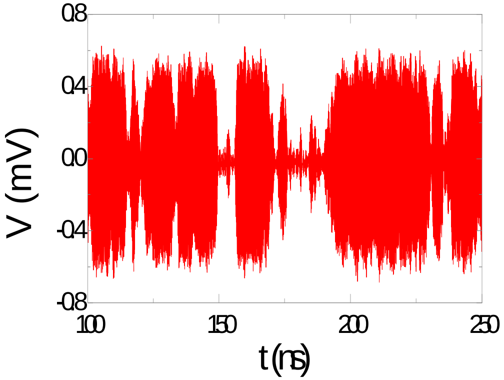
Free layer in vortex configuration



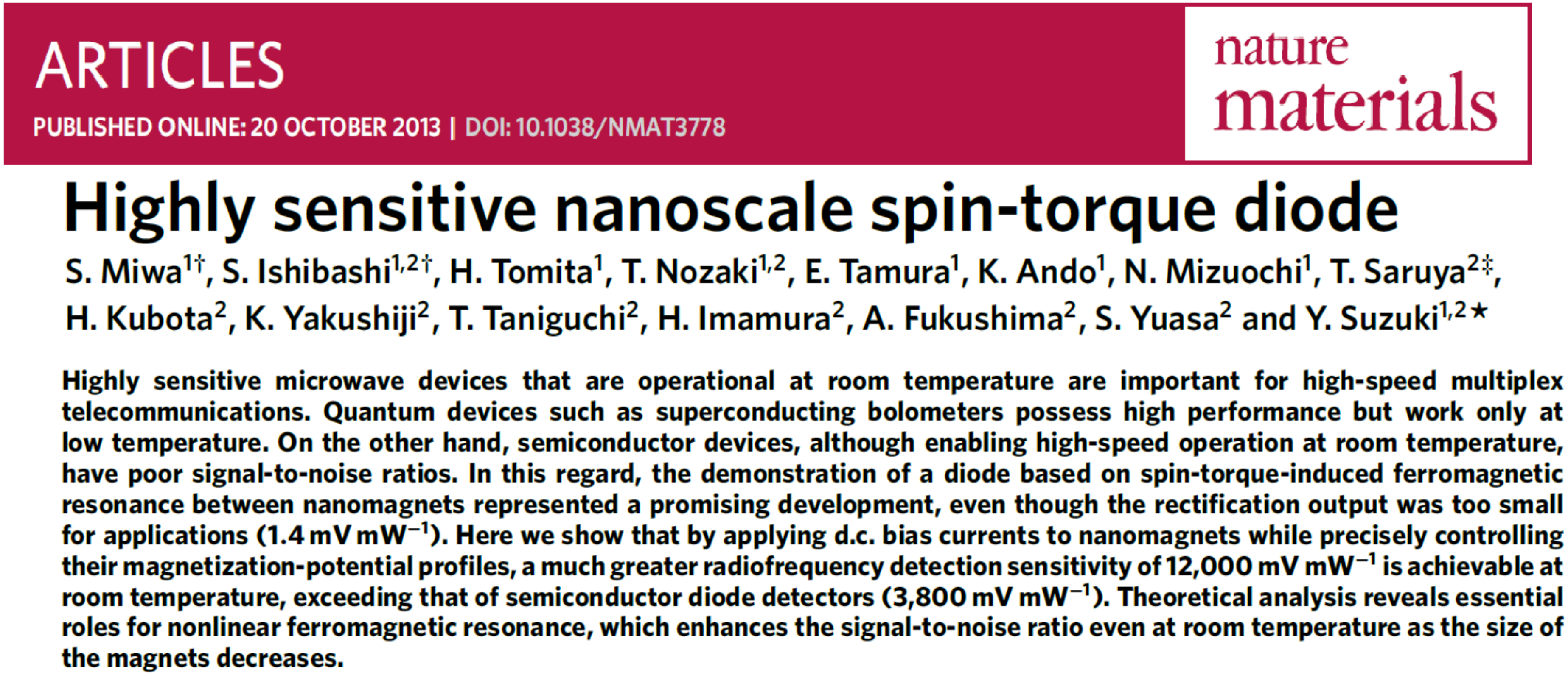
Vortex oscillators provide the largest output power among all STO but weak tunability and power still too low for practical applications (by several orders of magnitude).

2) Instability of the precessional motion:

Large tunability is intrinsically associated with large non-linearity in magnetization dynamics (frequency depends on magnetization trajectory amplitude). But then thermal fluctuations, by perturbing the magnetization trajectories, more strongly hamper the coherence of the magnetization dynamics yielding large noise.



Most probable first application :
RF rectifiers: spin-torque diodes



ARTICLES

PUBLISHED ONLINE: 20 OCTOBER 2013 | DOI: 10.1038/NMAT3778

nature materials

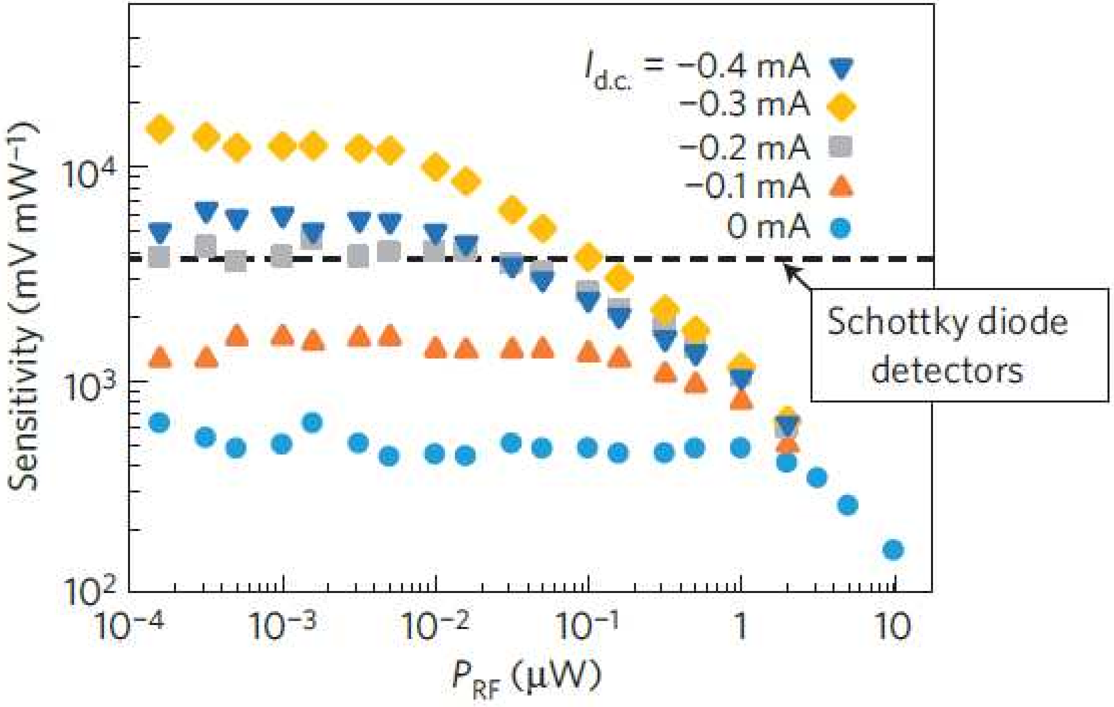
Highly sensitive nanoscale spin-torque diode

S. Miwa[1†], S. Ishibashi[1,2†], H. Tomita[1], T. Nozaki[1,2], E. Tamura[1], K. Ando[1], N. Mizuochi[1], T. Saruya[2‡], H. Kubota[2], K. Yakushiji[2], T. Taniguchi[2], H. Imamura[2], A. Fukushima[2], S. Yuasa[2] and Y. Suzuki[1,2]*

Highly sensitive microwave devices that are operational at room temperature are important for high-speed multiplex telecommunications. Quantum devices such as superconducting bolometers possess high performance but work only at low temperature. On the other hand, semiconductor devices, although enabling high-speed operation at room temperature, have poor signal-to-noise ratios. In this regard, the demonstration of a diode based on spin-torque-induced ferromagnetic resonance between nanomagnets represented a promising development, even though the rectification output was too small for applications (1.4 mV mW^{-1}). Here we show that by applying d.c. bias currents to nanomagnets while precisely controlling their magnetization-potential profiles, a much greater radiofrequency detection sensitivity of 12,000 mV mW^{-1} is achievable at room temperature, exceeding that of semiconductor diode detectors (3,800 mV mW^{-1}). Theoretical analysis reveals essential roles for nonlinear ferromagnetic resonance, which enhances the signal-to-noise ratio even at room temperature as the size of the magnets decreases.

RF diodes are important components in RF communications for frequency detection.

RF rectifiers: spin-torque diodes

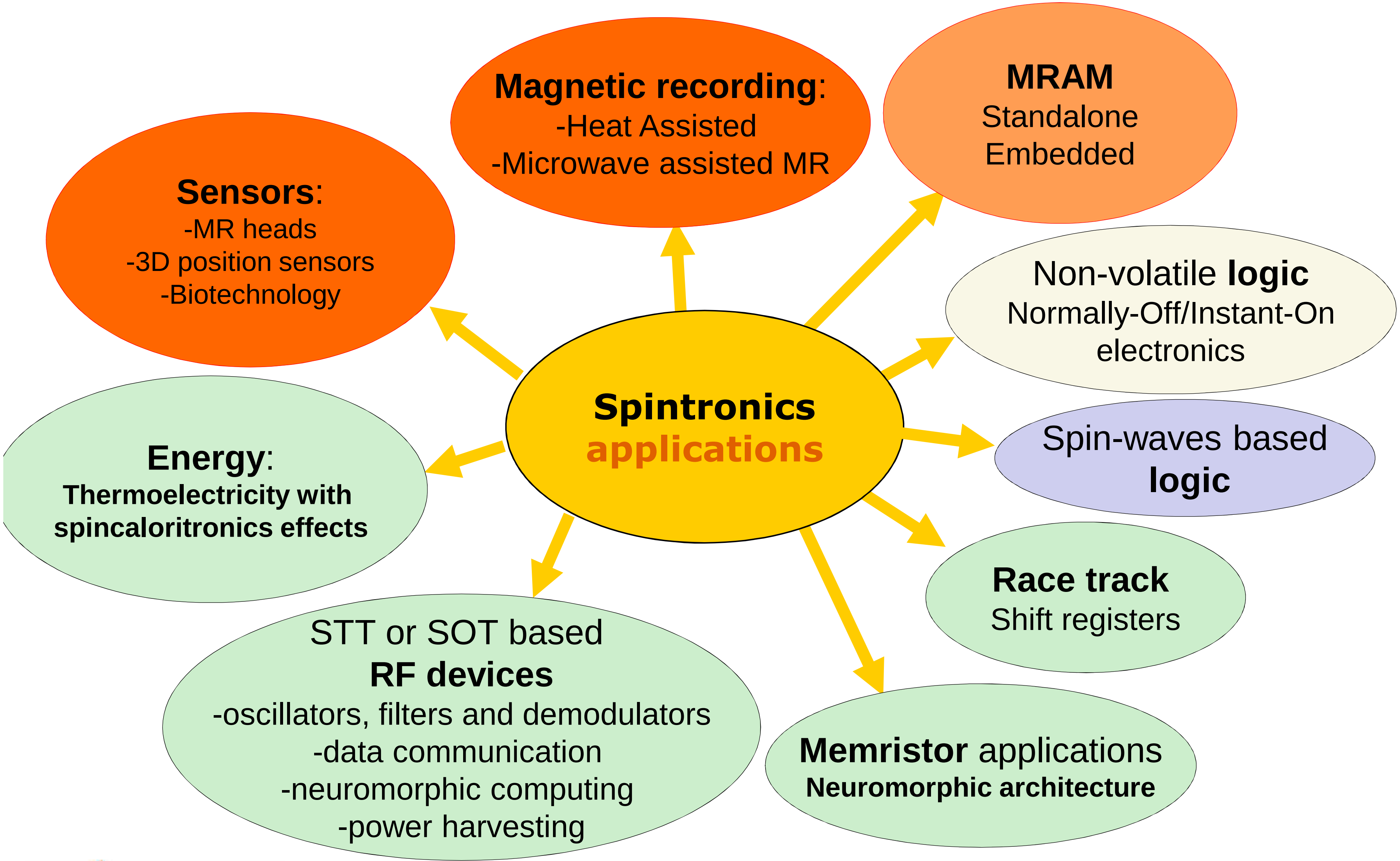


S.Miwa et al, Nat.mat (2013) NMAT 3778

In the sub-threshold regime (just before magnetization switching), high sensitivity of magnetization trajectory on RF power.

In Japan, spin-torque diodes considered as a promising RF application of STT.

Spintronics/nanomagnetism broadening spectrum of interest



Spintronics applications

Magnetic recording:
-Heat Assisted
-Microwave assisted MR

MRAM
Standalone
Embedded

Sensors:
-MR heads
-3D position sensors
-Biotechnology

Non-volatile **logic**
Normally-Off/Instant-On electronics

Spin-waves based **logic**

Energy:
Thermoelectricity with spincaloritronics effects

Race track
Shift registers

STT or SOT based
RF devices
-oscillators, filters and demodulators
-data communication
-neuromorphic computing
-power harvesting

Memristor applications
Neuromorphic architecture

Thank you !

Work partly supported by the project

HYMAGINE (ERC2010-2015)

MAGICAL (ERC2015-2020)