DE LA RECHERCHE À L'INDUSTRIE

SPIN ELECTRONICS TUTORIAL

LASCAS 2016

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www.cea.fr

ACKNOWLEDGEMENTS

Myriam Pannetier-Lecoeur
Aurélie Solignac, CEA
Claude Chappert, IEF France
Andy Kent, New York University
Rolf Allenspach, IBM Zürich

who have directly or indirectly participated to this tutorial.

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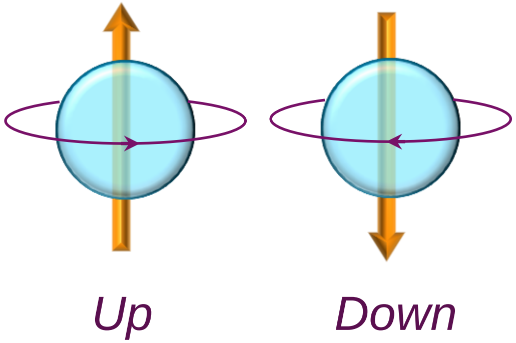
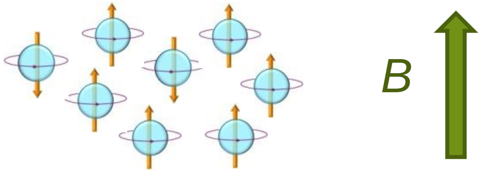
SPIN ELECTRONICS

Electron=Charge + magnetic moment (spin)



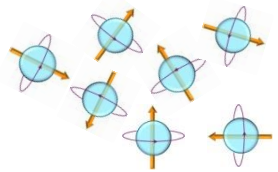
Spin electronics : to play with the spin
to differentiate and manipulate electrons.

Dream : to replace conventional electronics with a metallic electronics based on spin up and down instead of charges and holes.



THE FIRST STEP : POLARIZED ELECTRONS

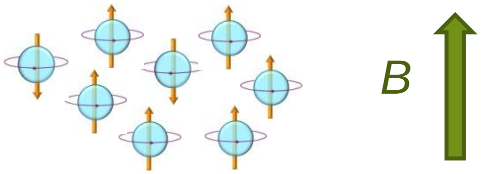
Electrons are naturally in a random direction.



In presence of a magnetic field, they acquire a small polarization, typically 10^{-3} under 1T at RT

In magnetic materials, the internal field is strong and is able to create a strong polarization.

→ The first ingredient is a magnetic material able to polarize spins.

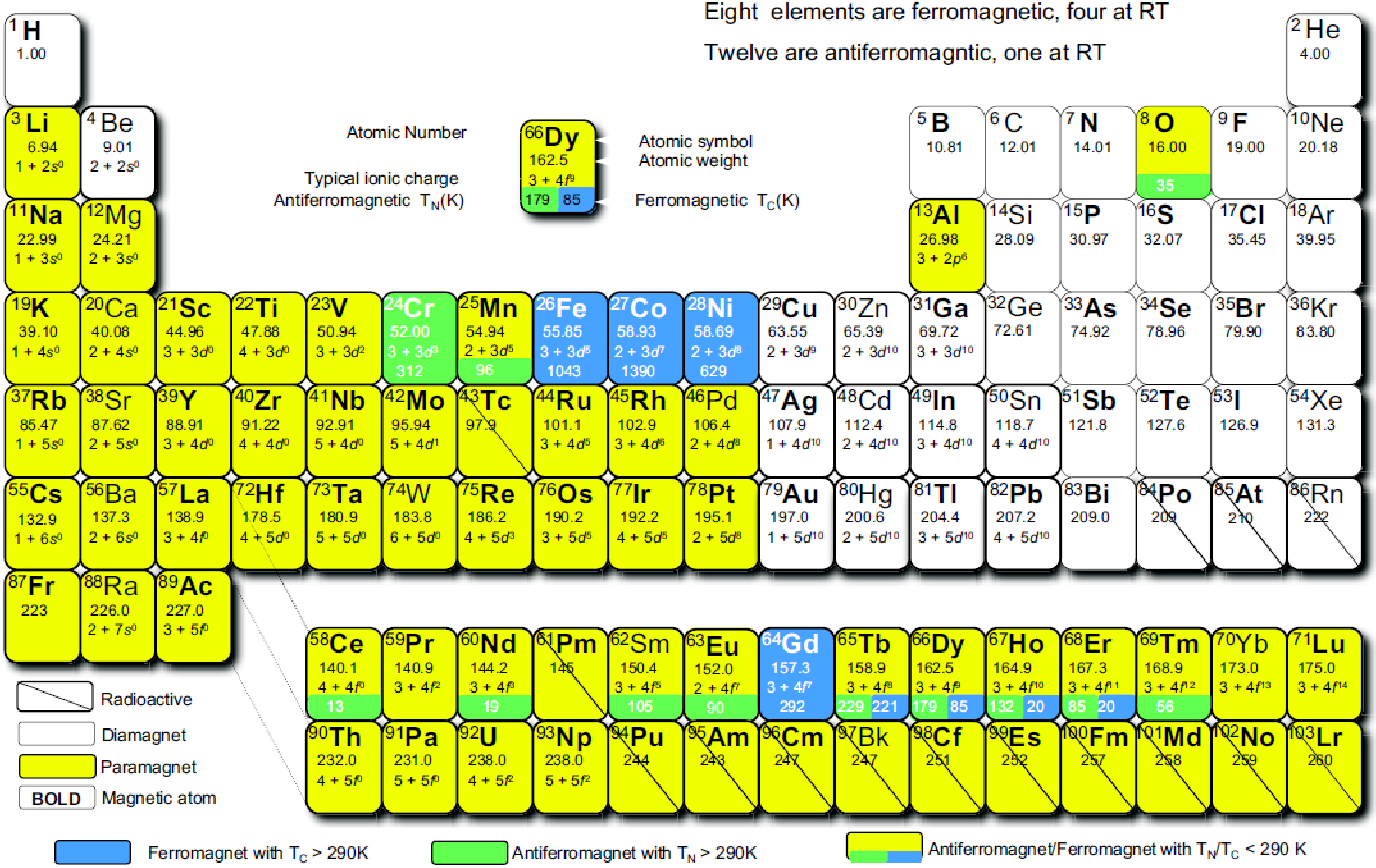


THE FIRST STEP : POLARIZED ELECTRONS

The Magnetic Periodic Table

Eight elements are ferromagnetic, four at RT

Twelve are antiferromagntic, one at RT



Atomic Number

Typical ionic charge

Antiferromagnetic T_N(K)

66 **Dy**
162.5
$3 + 4f^9$
179 85

Atomic symbol

Atomic weight

Ferromagnetic T_C(K)

1 **H** 1.00																	2 He 4.00
3 **Li** 6.94 $1 + 2s^0$	4 Be 9.01 $2 + 2s^0$											5 **B** 10.81	6 C 12.01	7 **N** 14.01	8 **O** 16.00 35	9 **F** 19.00	10 Ne 20.18
11 **Na** 22.99 $1 + 3s^0$	12 Mg 24.21 $2 + 3s^0$											13 **Al** 26.98 $3 + 2p^6$	14 Si 28.09	15 **P** 30.97	16 **S** 32.07	17 **Cl** 35.45	18 Ar 39.95
19 **K** 39.10 $1 + 4s^0$	20 Ca 40.08 $2 + 4s^0$	21 **Sc** 44.96 $3 + 3d^0$	22 **Ti** 47.88 $4 + 3d^0$	23 **V** 50.94 $3 + 3d^2$	24 **Cr** 52.00 $3 + 3d^3$ 312	25 **Mn** 54.94 $2 + 3d^5$ 96	26 **Fe** 55.85 $3 + 3d^5$ 1043	27 **Co** 58.93 $2 + 3d^7$ 1390	28 **Ni** 58.69 $2 + 3d^8$ 629	29 **Cu** 63.55 $2 + 3d^9$	30 Zn 65.39 $2 + 3d^{10}$	31 **Ga** 69.72 $3 + 3d^{10}$	32 Ge 72.61	33 **As** 74.92	34 **Se** 78.96	35 **Br** 79.90	36 Kr 83.80
37 **Rb** 85.47 $1 + 5s^0$	38 Sr 87.62 $2 + 5s^0$	39 **Y** 88.91 $3 + 4d^0$	40 **Zr** 91.22 $4 + 4d^0$	41 **Nb** 92.91 $5 + 4d^0$	42 **Mo** 95.94 $5 + 4d^1$	43 **Tc** 97.9	44 **Ru** 101.1 $3 + 4d^5$	45 **Rh** 102.9 $3 + 4d^6$	46 Pd 106.4 $2 + 4d^8$	47 **Ag** 107.9 $1 + 4d^{10}$	48 Cd 112.4 $2 + 4d^{10}$	49 **In** 114.8 $3 + 4d^{10}$	50 Sn 118.7 $4 + 4d^{10}$	51 **Sb** 121.8	52 **Te** 127.6	53 **I** 126.9	54 Xe 131.3
55 **Cs** 132.9 $1 + 6s^0$	56 Ba 137.3 $2 + 6s^0$	57 **La** 138.9 $3 + 4f^0$	72 **Hf** 178.5 $4 + 5d^0$	73 **Ta** 180.9 $5 + 5d^0$	74 W 183.8 $6 + 5d^0$	75 **Re** 186.2 $4 + 5d^3$	76 **Os** 190.2 $3 + 5d^5$	77 **Ir** 192.2 $4 + 5d^5$	78 **Pt** 195.1 $2 + 5d^8$	79 **Au** 197.0 $1 + 5d^{10}$	80 Hg 200.6 $2 + 5d^{10}$	81 **Tl** 204.4 $3 + 5d^{10}$	82 **Pb** 207.2 $4 + 5d^{10}$	83 **Bi** 209.0	84 **Po** 209	85 **At** 210	86 Rn 222
87 **Fr** 223	88 Ra 226.0 $2 + 7s^0$	89 **Ac** 227.0 $3 + 5f^0$															
				58 **Ce** 140.1 $4 + 4f^0$ 13	59 **Pr** 140.9 $3 + 4f^2$	60 **Nd** 144.2 $3 + 4f^3$ 19	61 **Pm** 145	62 Sm 150.4 $3 + 4f^5$ 105	63 **Eu** 152.0 $2 + 4f^7$ 90	64 **Gd** 157.3 $3 + 4f^7$ 292	65 **Tb** 158.9 $3 + 4f^8$ 229 221	66 **Dy** 162.5 $3 + 4f^9$ 179 85	67 **Ho** 164.9 $3 + 4f^{10}$ 132 20	68 **Er** 167.3 $3 + 4f^{11}$ 85 20	69 **Tm** 168.9 $3 + 4f^{12}$ 56	70 Yb 173.0 $3 + 4f^{13}$	71 **Lu** 175.0 $3 + 4f^{14}$
				90 **Th** 232.0 $4 + 5f^0$	91 **Pa** 231.0 $5 + 5f^0$	92 **U** 238.0 $4 + 5f^2$	93 **Np** 238.0 $5 + 5f^2$	94 **Pu** 244	95 **Am** 243	96 **Cm** 247	97 Bk 247	98 **Cf** 251	99 **Es** 252	100 **Fm** 257	101 **Md** 258	102 **No** 259	103 **Lr** 260

Radioactive

Diamagnet

Paramagnet

BOLD Magnetic atom

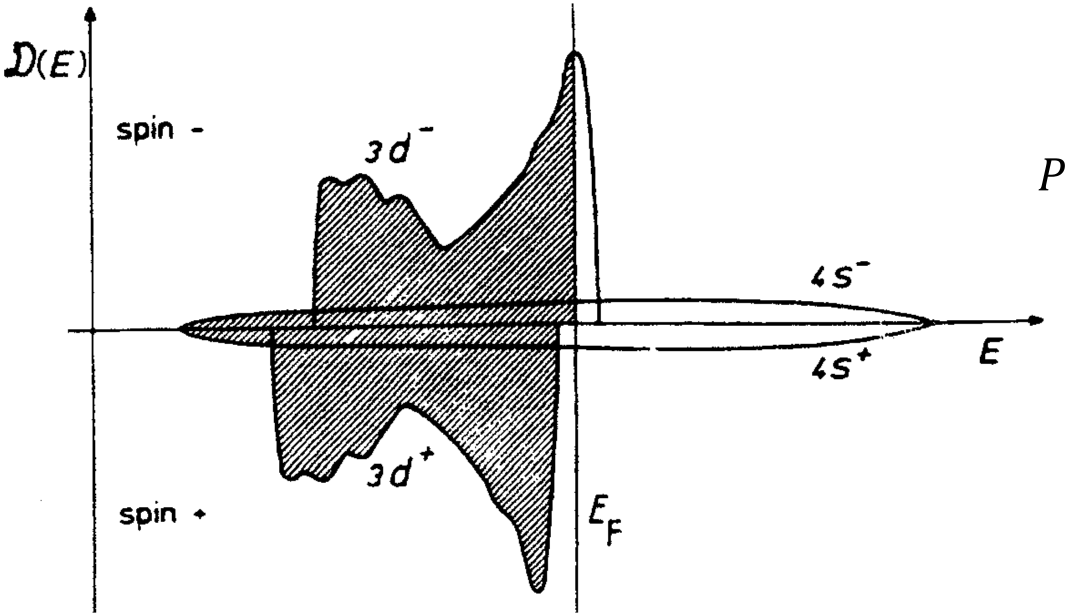
Ferromagnet with T_C > 290K

Antiferromagnet with T_N > 290K

Antiferromagnet/Ferromagnet with T_N/T_C < 290 K

THE FIRST STEP : POLARIZED ELECTRONS

The internal field is creating a displacement of the spin up and down bands



$$P = \frac{N^{+} - N^{-}}{N^{+} + N^{-}}$$

At the Fermi level, the up and down spin densities can be very different
→ Strong spin polarization.

THE FIRST STEP : POLARIZED ELECTRONS

Best candidate with 3D elements : CoFe with 70% of polarization

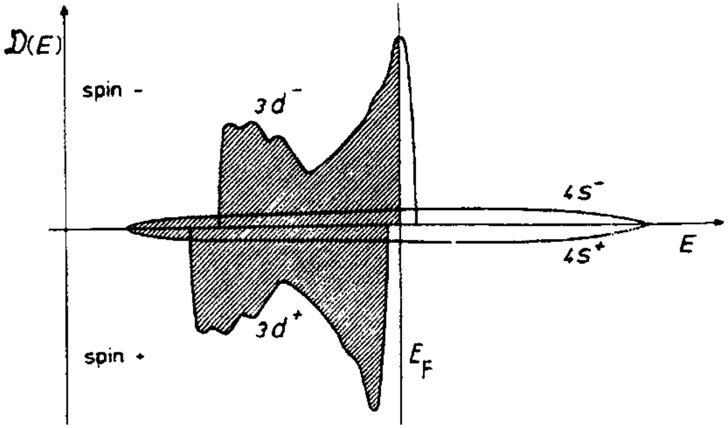
$LaSrMnO_3$ more than 90%

CrO_2, FE_3O_4, fully polarised but complicate to use.

NiMnSb and

New materials are appearing like Heusler Alloys Co_2MnSi, $Co_2Cr_{1-x}Fe_xAl$
more complicate to deposit in thin films but now mastered
They are well polarized and should be half metallic

Half metals : only one type of spin is conducting



THE SECOND STEP : TO PROPAGATE SPIN POLARIZED ELECTRONS

It is today a limitation of spin electronics

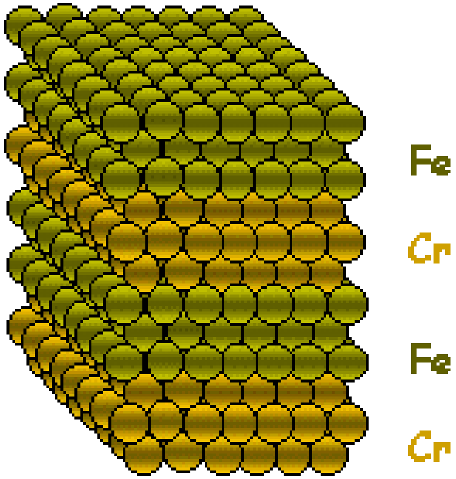
Polarised electrons can survive only on few nanometers in non magnetic metals.

They may survive longer in semiconductors and materials like graphene but there is a big loss of polarization at the entrance.

→ All spin electronics structures need to have at least one very small dimension.

THE SECOND STEP : TO PROPAGATE SPIN POLARIZED ELECTRONS

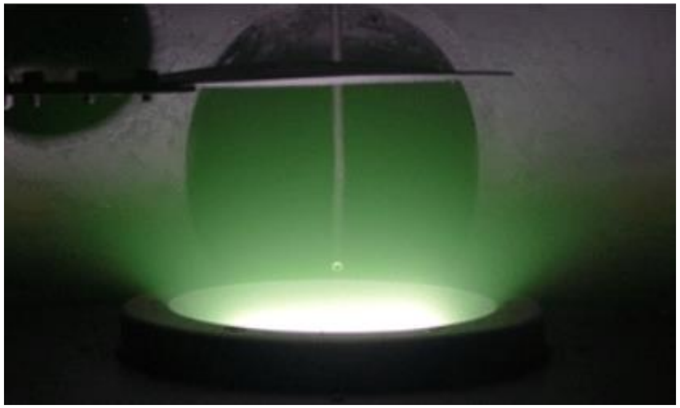
Thin film technology is used for spin electronics.



Multilayer of different materials with magnetic layers separated by non magnetic layers.

Control of the thickness required with atomic accuracy.

Sputtering techniques are mainly used for thin film deposition

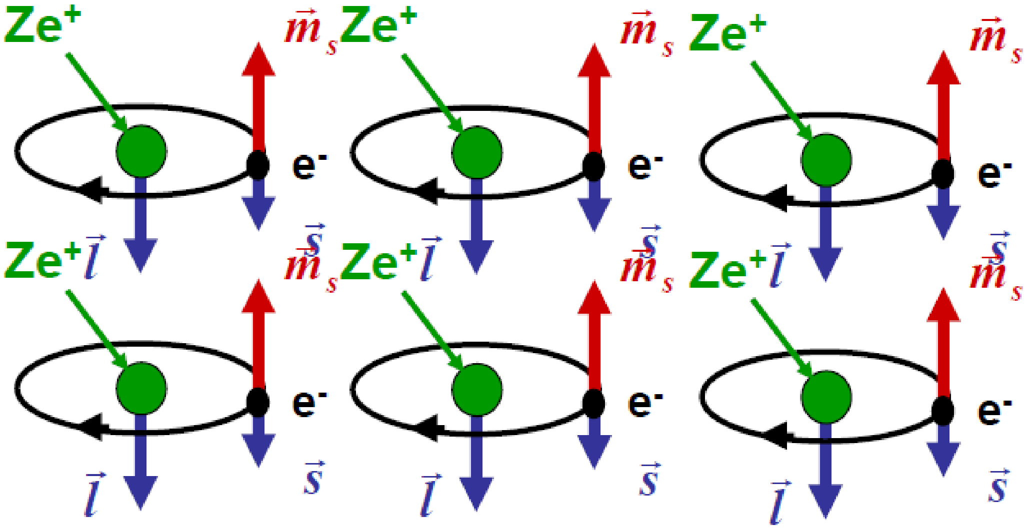


Magnetic material unit,NIMS tutorials

MAGNETIZATION OF THIN FILMS

Echange interaction:

- Pauli principle : 2 electrons cannot be in the same state.
- Coulomb interaction between electrons

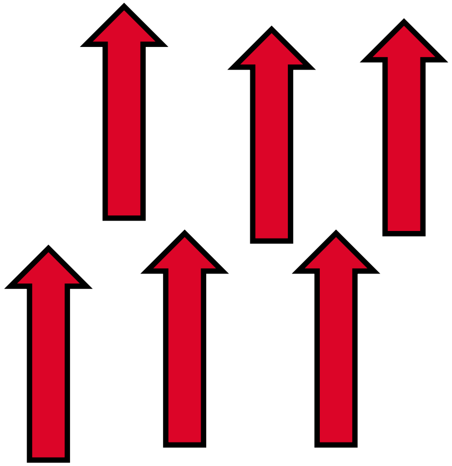


$$F_{1\to 2} = \frac{e^2}{4\pi\varepsilon_0 r^2}\frac{\vec{r}}{r}$$

Strength of the interaction is large 200T in Co/Fe/Ni

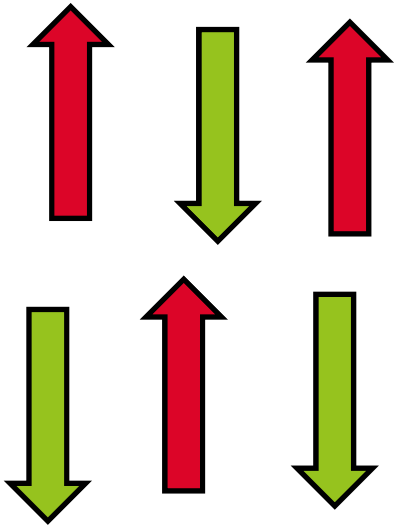
The interaction is AF for small distances and F for large distances. It is a short range interaction.

MAGNETIZATION OF THIN FILMS



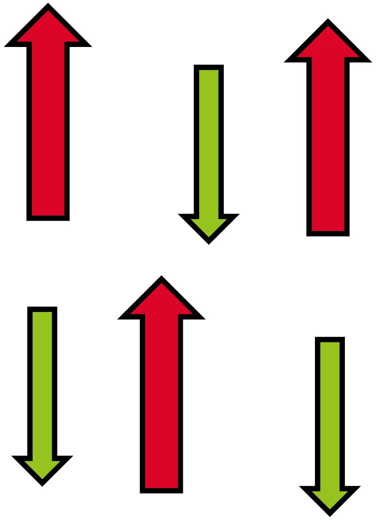
Ferromagnetism
All the moments are aligned

Co,Fe,Ni



Antiferromagnetism:
Moments are opposite

Cr, NiO, PtMn

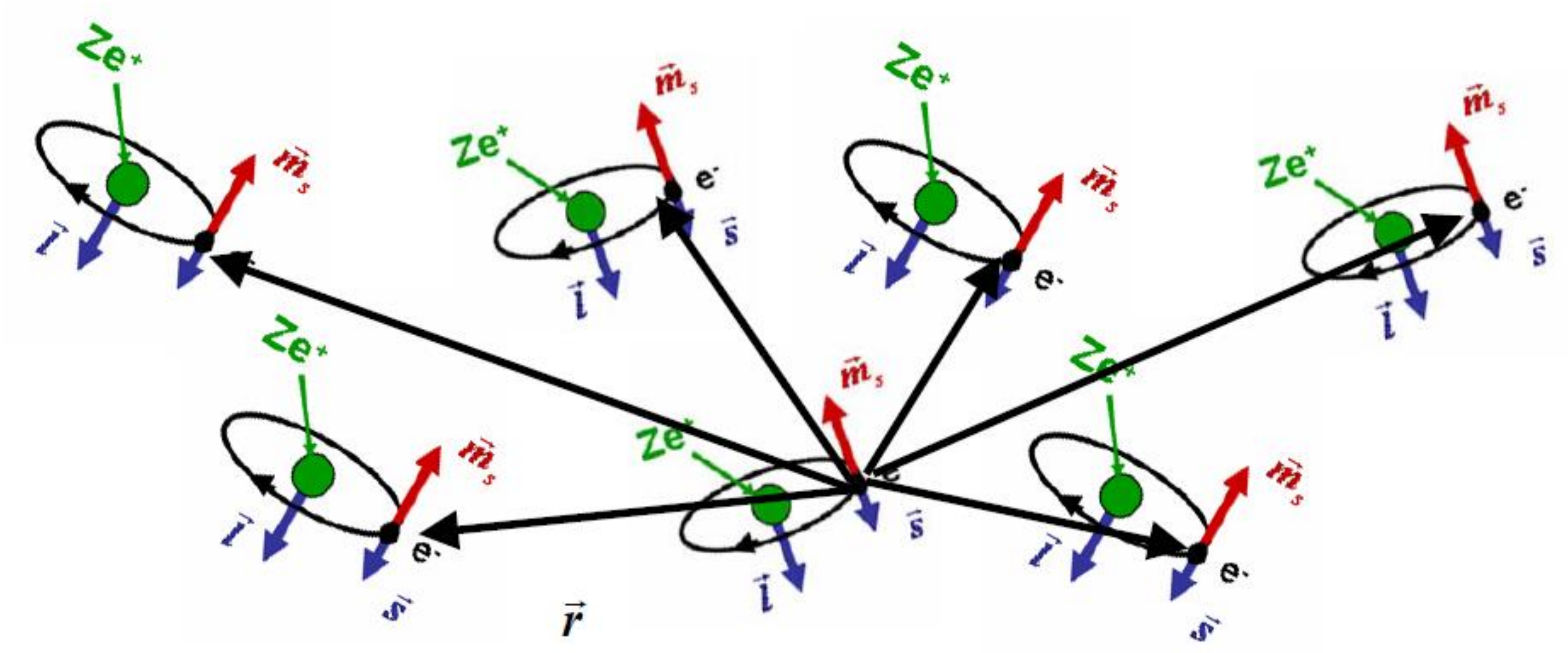


ferrimagnetism:
Moments are opposite but with different amplitudes

Fe_3O_4

MAGNETIZATION OF THIN FILMS

Dipolar coupling

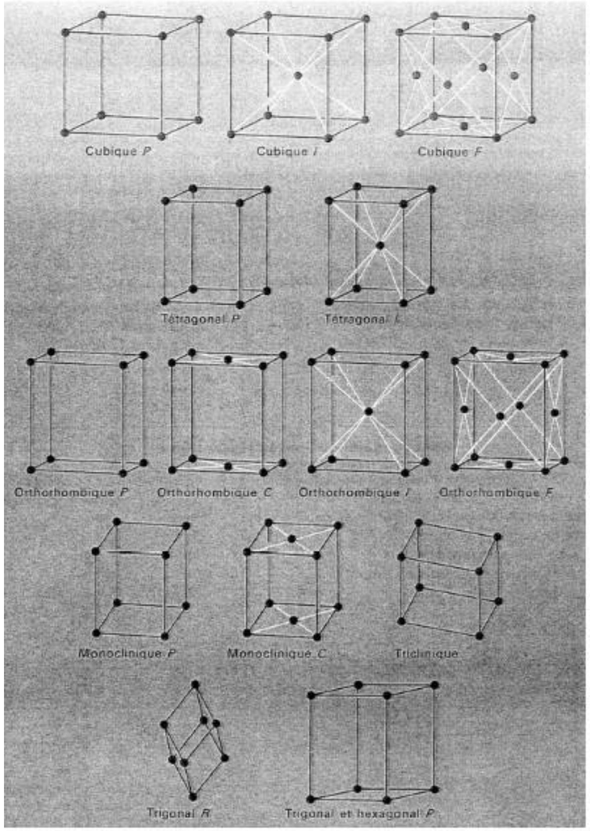


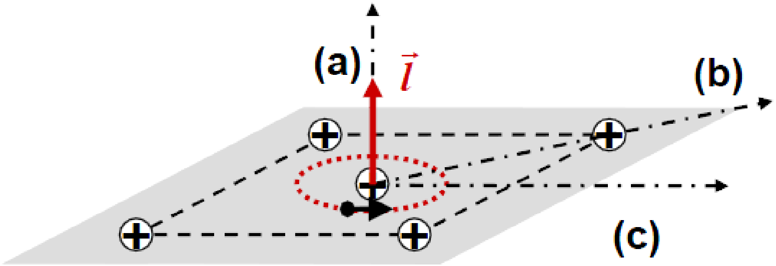
$$e_{dip} = \frac{\mu_0}{4\pi}\left[\frac{\vec{m}_1 \cdot \vec{m}_2}{r^3} - 3\frac{(\vec{m}_1 \cdot \vec{r})(\vec{m}_2 \cdot \vec{r})}{r^5}\right]$$

Field created by one atom on the others.
Long range and small

MAGNETIZATION OF THIN FILMS

Magnetocristalline anisotropy



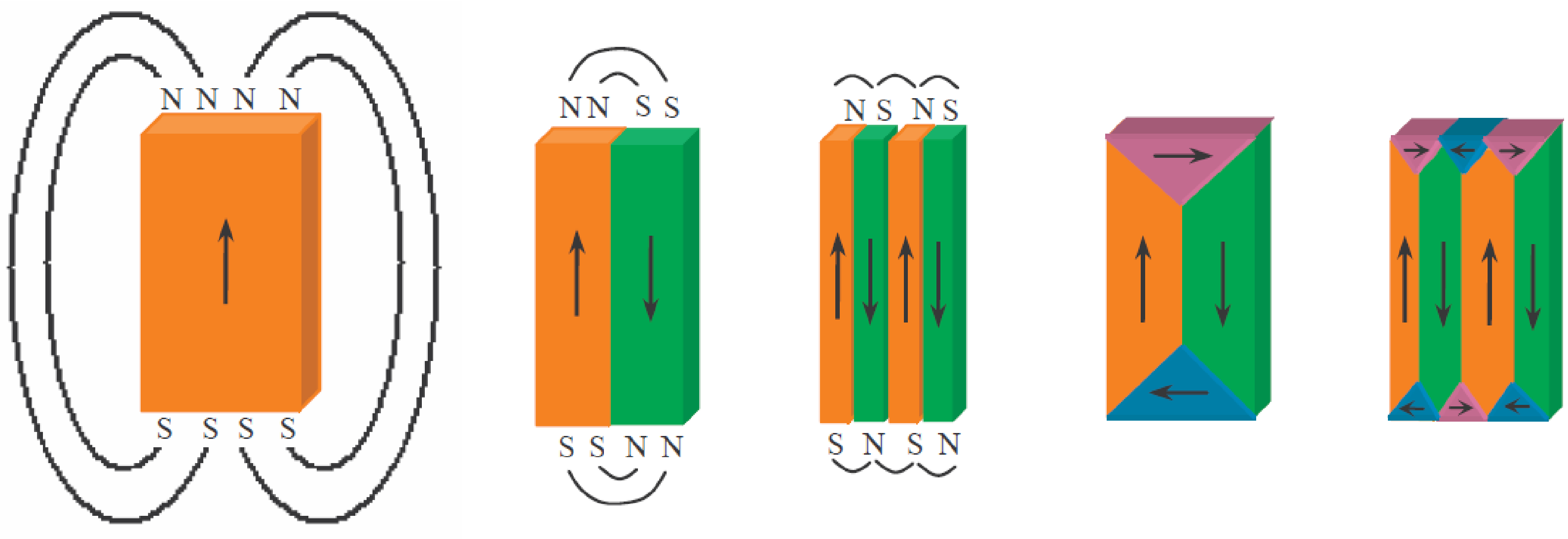


Induces specific easy and hard directions for the magnetization.

→ Requires textured or monocrystalline films.

MAGNETIZATION OF THIN FILMS

A infinite thin film has a uniform in plane magnetization.
In case of finite films, the dipolar energy is defining the main configuration of the film



The magnetization tends to never be perpendicular to a surface because it costs dipolar energy.

MAGNETIZATION OF THIN FILMS

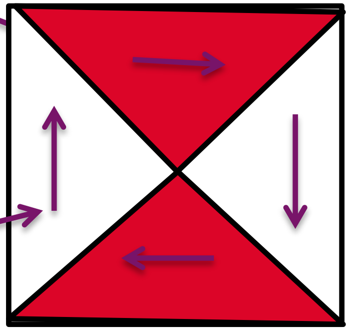
First consequence : in plane magnetization

Special case : Co/Pt or Fe/Pd where the magneto-crystalline interaction at the interface is strong enough to put the moments out of plane

Brown U.

MAGNETIZATION OF THIN FILMS

Domain walls are large compared to atomic distances.



Domain wall

Domain

Large structures

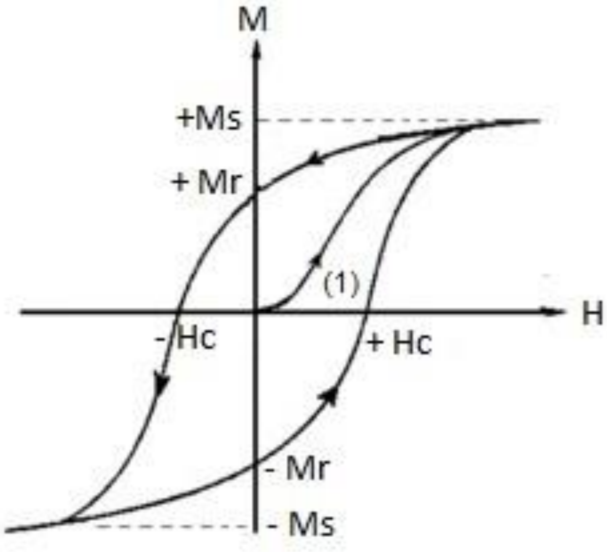
Domains Before Magnetization

Domains After Magnetization

Brown U.

Perpendicular films

MAGNETIZATION OF THIN FILMS



Hc coercitive field, Mr magnetization without field, Ms saturation magnetization.

Ms is fixed by the material. NiFe is 1Tesla, Co is 1.7T, Fe is 2T.
Hc depends on the material structure and anisotropies.

MAGNETIZATION OF THIN FILMS-UNITS

$$\boxed{\vec{B} = \mu_0\left(\vec{H} + \vec{M}\right) = \mu_0(1 + \chi)\vec{H} = \mu\vec{H}}$$

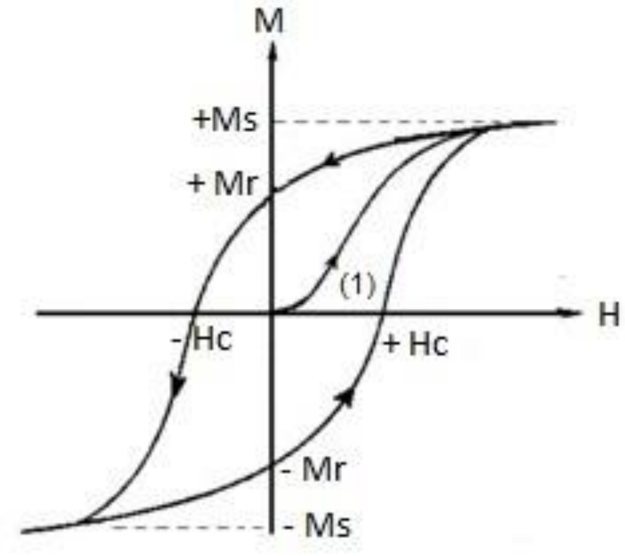
$\vec{B}$ is given in Tesla or Gauss (10^{-4}T)

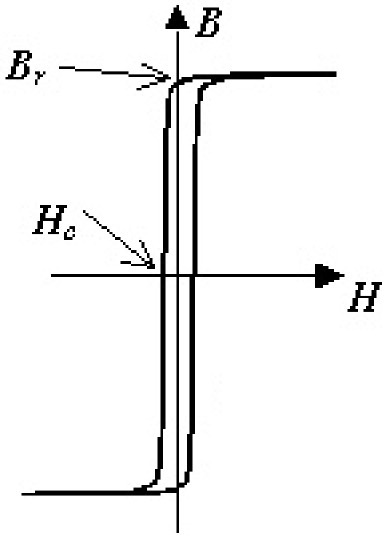
$\vec{H}$ is given in A/m or Oersted

μ_0 is $4\pi 10^{-7}$.

By extension, a lot of people are using the Tesla both for magnetic Induction and magnetic field.

MAGNETIZATION OF THIN FILMS





Hard materials

- H_c is large.

- Ex: permanent magnets

Hc can be as large as 1T

Soft material:

- H_c is low

Ex permalloy (NiFe allow)
$Hc<10^{-5}T$

THE THIRD STEP :TO MANIPULATE THE MAGNETIZATION

The way to change the polarization of electrons is to play with the magnetization of magnetic materials.

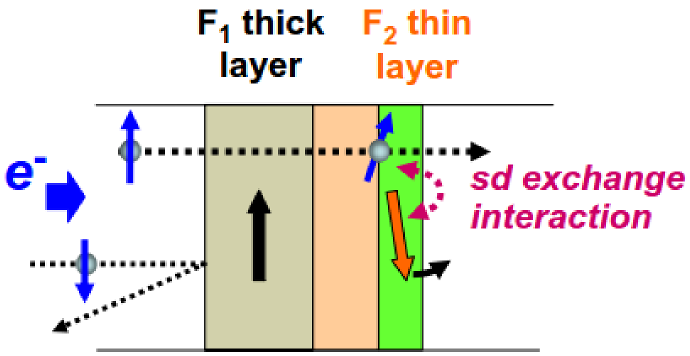
Three main ways :

- To apply a magnetic field. The magnetization of a soft material is following the magnetic field like a compass.

  → magnetic sensors
- To inject a current, spin torque effect

  →MRAMS
- To apply a strain.
  - → Magnetoelectric devices

THE THIRD STEP :TO MANIPULATE THE MAGNETIZATION



A polarized current is creating a torque on a magnetic layer.

If the layer is thin and the current large the thin layer can be rotated.

$$\vec{T} = \frac{J\hbar\varepsilon}{2e\delta {M_s}^2}\vec{M}\text{x}(\vec{M}\text{x}\vec{p})$$

Used for STT-MRAMS and STNOs

J. Slonczewski, Journal of Magnetism and Magnetic Materials, vol. 159, page L1 (1996)

THE THIRD STEP :TO MANIPULATE THE MAGNETIZATION

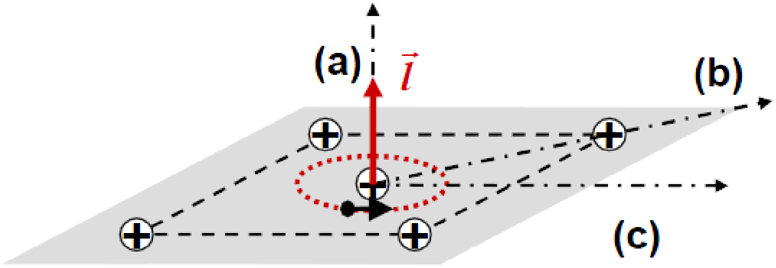
Playing with strains.

A strain changes the magnetocristalline anisotropy and hence may change the magnetization direction.

Piezoelectric films

Examples :

PZT, $BaTiO_3$, $BaFeO_3$ …

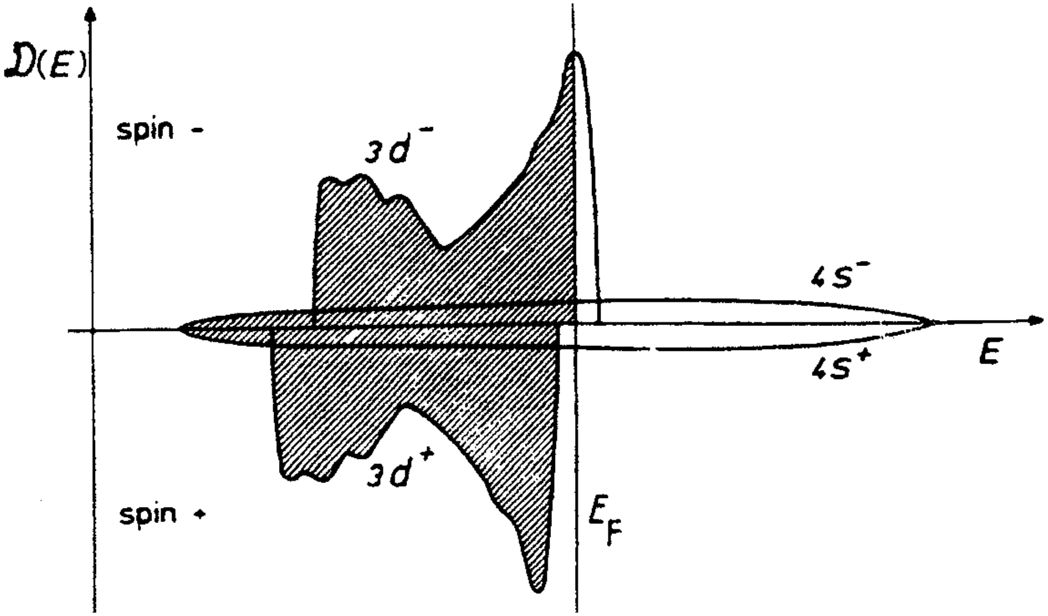


The strain has to be applied in the plane of a soft magnetic film

Requirements

- Rather large strain to induce a sizable effect
- A good mechanical coupling between the magnetic films and the piezoelectric film.

RESISTIVITY OF A MAGNETIC LAYER



At the Fermi level, the up and down spin densities can be very different

The spin diffusion length i.e. the mean distance where an electron is loosing its spin orientation is much larger than a mean free path

→ A model with 2 independent currents is valid with different densities

RESISTIVITY OF A MAGNETIC LAYER

2 currents model

$$\beta = \frac{\rho_\downarrow - \rho_\uparrow}{\rho_\downarrow + \rho_\uparrow}$$

β: asymmetry

-1< β <1 si β=-1 : $\rho_\downarrow$=0

si β=1 : $\rho_\uparrow$=0

In case of Ni, β>0, car $\rho_\uparrow < \rho_\downarrow$

Parallel channels:

$$\frac{1}{\rho} = \frac{1}{\rho_\downarrow} + \frac{1}{\rho_\uparrow}$$

ρ is the measured resistivity

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

with spin-flip:

$$\rho = \frac{\rho_\uparrow \rho_\downarrow + \rho_{\uparrow\downarrow}(\rho_\uparrow + \rho_\downarrow)}{\rho_\uparrow + \rho_\downarrow + 4\rho_{\uparrow\downarrow}}$$

In a simple model $\rho = \frac{m}{Ne^2\tau}$

The asymmetry can be large

RESISTIVITY OF A MAGNETIC LAYER

$$\rho(T) = \rho_i + \rho_{ph}(T) + \rho_{e-e}(T) + \rho_m(B,T)$$

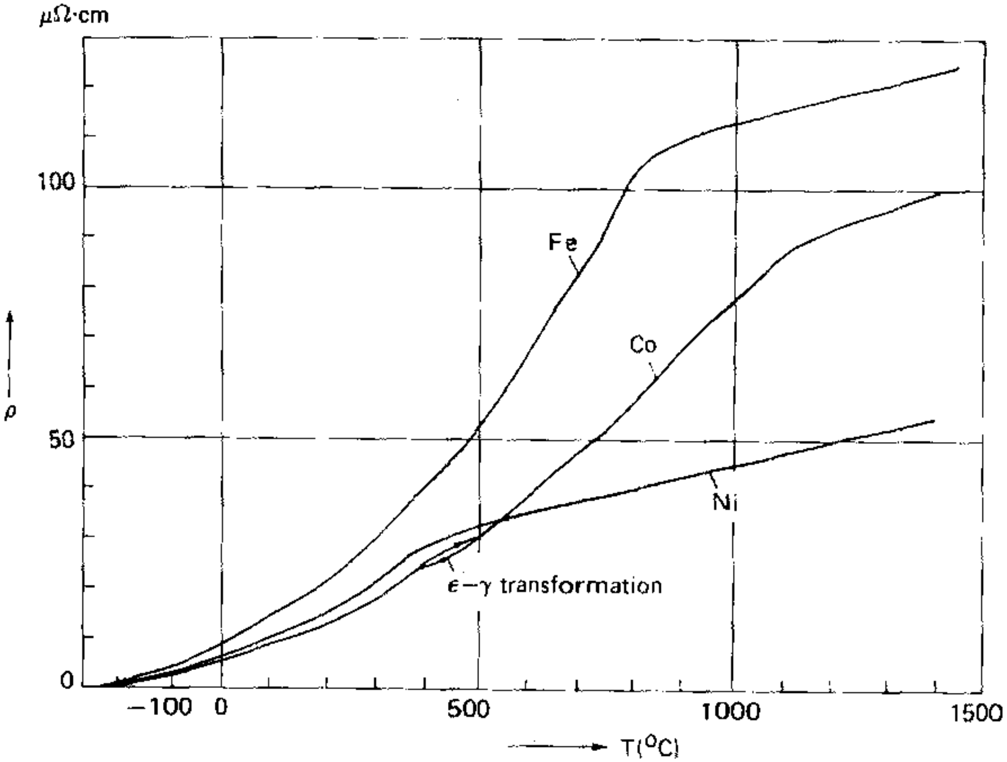
Impurities

Phonons
en T^5 puis T

e-e Interactions
T^2 à low Temp

Magnons
in T^2

3d metals experimental
ρ(T)



QUICK SUMMARY

Spin electronics requires

-A spin polarization made with magnetic thin films

- A propagation of these spin polarized electrons

- A manipulation of magnetic films by a magnetic field, a direct current or a strain

Magnetic films

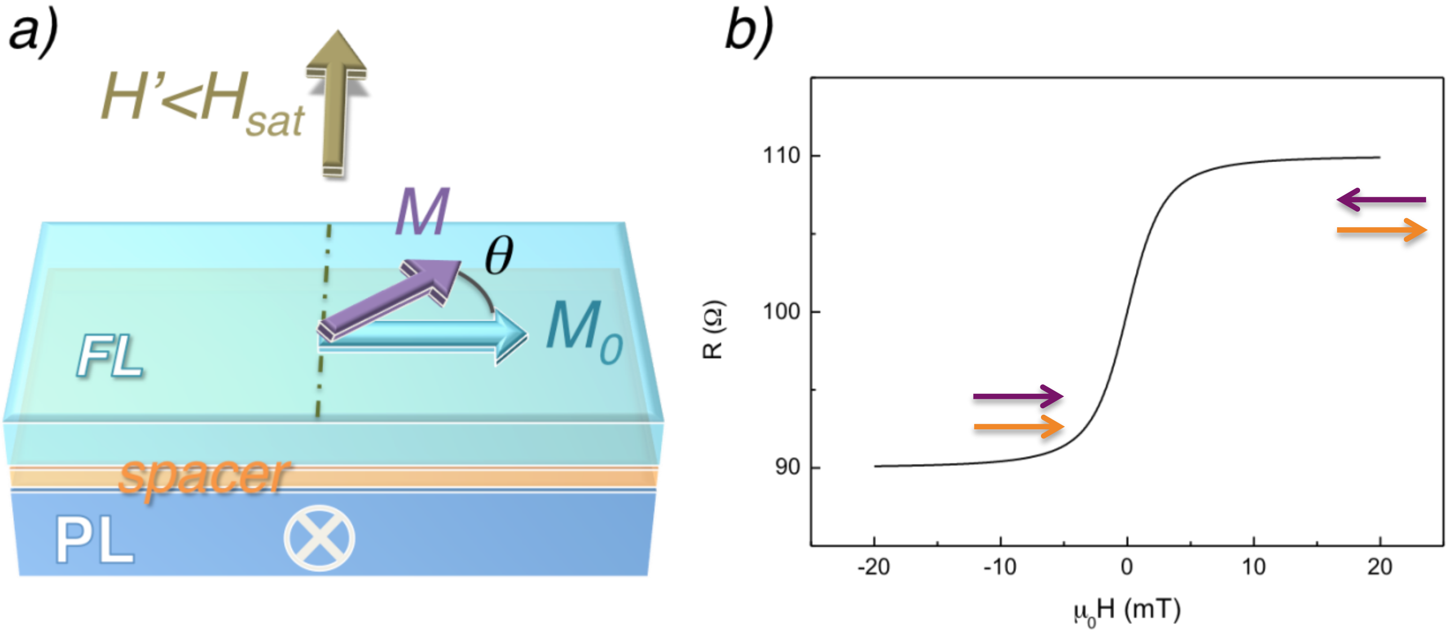
- can be ferromagnetic, antiferromagnetic, ferrimagnetic or not magnetically ordered

- their resistivity is similar to non magnetic metals but up and down spins have not the same density and resistivity.

-magnetic configuration is depending of the shape, crystallinity and applied field. We can have hard or soft magnetic films

A MAIN BUILDING BLOC : THE SPIN VALVE

Two ferromagnetic layers are separated by a thin non magnetic layer : giant magnetoresistance effect

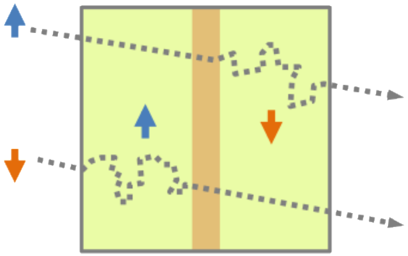


The resistance is low when the magnetization of the layers are parallel
High when they are anti parallel.

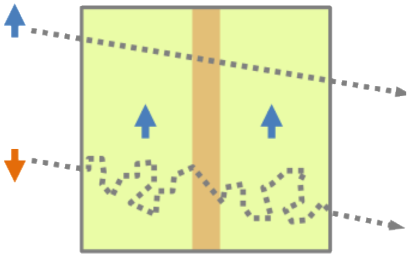
Fert and Grünberg Nobel prize

THE MAIN BUILDING BLOC : THE SPIN VALVE

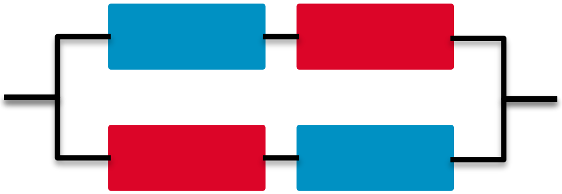
When a spin is parallel or antiparallel to the magnetization, the resistivity is changing

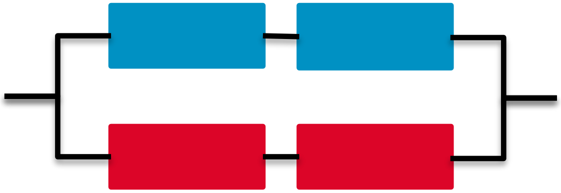


High resistance



Low resistance





Other way to understand the results :

- The first layer is a spin polarizer, the second one is a spin analyzer.

THE MAIN BUILDING BLOC : THE SPIN VALVE

In case of a metallic spacer→ GMR spin valve. G for Giant

In case of an insulating layer→ TMR spin valve. T for Tunnel

GMR spin valve has a typical effect of 10% of resistance change

TMR spin valve has now typical effect of 200%.

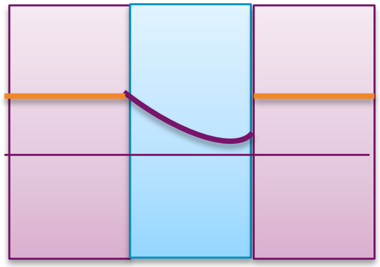
The origin of TMR is different from GMR.

TMR is really a reflection at the interface : the tunnel effect needs to couple two corresponding states.

THE MAIN BUILDING BLOC : THE SPIN VALVE

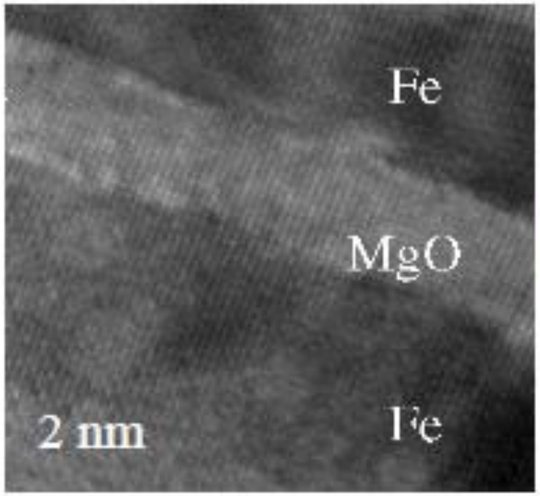
Julière Model : the TMR effect is directly related to the spin polarization of the two materials between the barrier

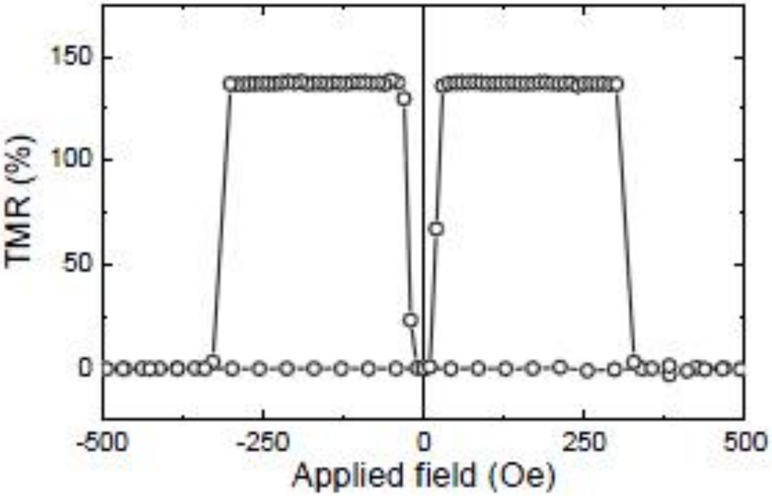
$$\boxed{TMR = \frac{2P_AP_B}{1 - P_AP_B}}$$

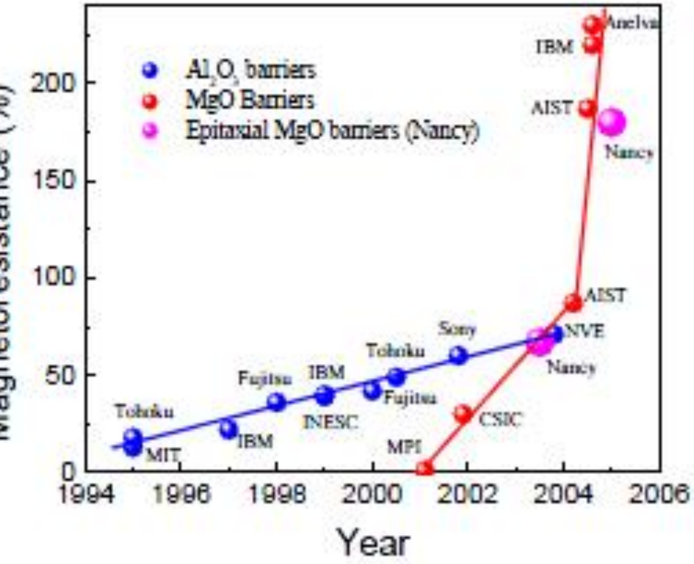


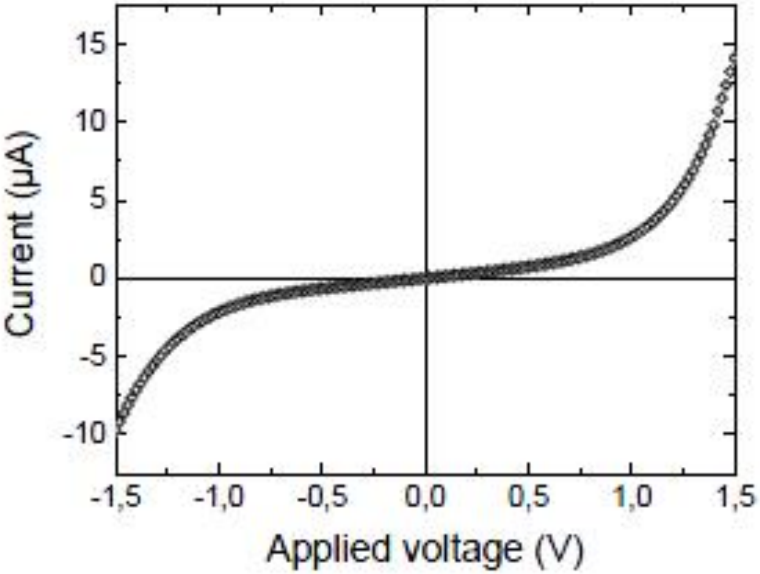
Jonction	**TMR$_{exp}$ (%)**	**TMR$_{Julière}$ (%)**
$Co_{75}Fe_{25}$ / Al_2O_3 / $Co_{75}Fe_{25}$	67-74	69
Co / Al_2O_3 / Co	42	37
Ni / Al_2O_3 / Ni	25	23
Fe/MgO/Fe	300	50
LSMO/STO/LSMO	2000	1000

THE MAIN BUILDING BLOC : THE SPIN VALVE









HISTORY

- 1951 & 1970 : GMR in granular materials (Co/Ag grains)
- 1980-1990 : Thin film technology
- 1975 : TMR principle & experiences at low temperature(Julliere)
- 1988 : First observation of the GMR effect in thin films(Baibich)
- 1991 : Spin valve (Dieny)
- 1994 : first AlOx based TMR (Miyazaki)
- 2001 : first MgO based TMR(Bowen)
- 2004 : perpendicular TMR
- 2007 : Nobel prize– A. Fert & P. Grünberg

THE MAIN BUILDING BLOC : THE SPIN VALVE

Summary of the spin valve

GMR : all metallic layers
10% of MR. Constant resistance

TMR : insulating barrier
200% of MR decreasing with current.
Parabolic dependence of the voltage versus current.

CONTENTS

I. Part 1 : Spin electronics, an introduction

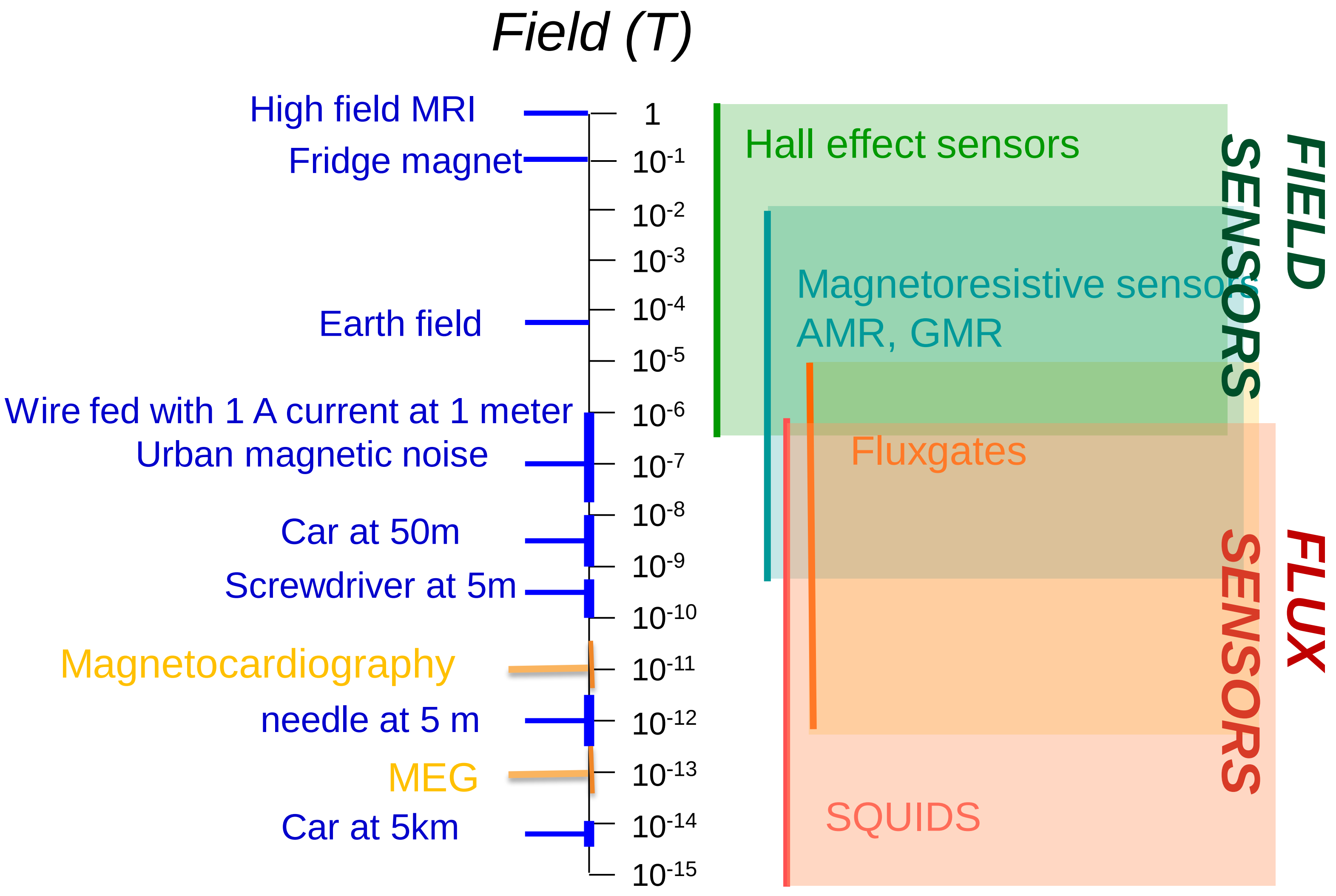
II. Part 2 : Magnetic sensors

III. Part 3 : A little more on spin electronics

IV. Part 4 : MRAMs, STNO, magnetic logics

V. Some perspectives

INTRODUCTION



Field (T)

High field MRI

Fridge magnet

Earth field

Wire fed with 1 A current at 1 meter

Urban magnetic noise

Car at 50m

Screwdriver at 5m

Magnetocardiography

needle at 5 m

MEG

Car at 5km

1

10^{-1}

10^{-2}

10^{-3}

10^{-4}

10^{-5}

10^{-6}

10^{-7}

10^{-8}

10^{-9}

10^{-10}

10^{-11}

10^{-12}

10^{-13}

10^{-14}

10^{-15}

Hall effect sensors

Magnetoresistive sensors
AMR, GMR

Fluxgates

SQUIDS

FIELD SENSORS

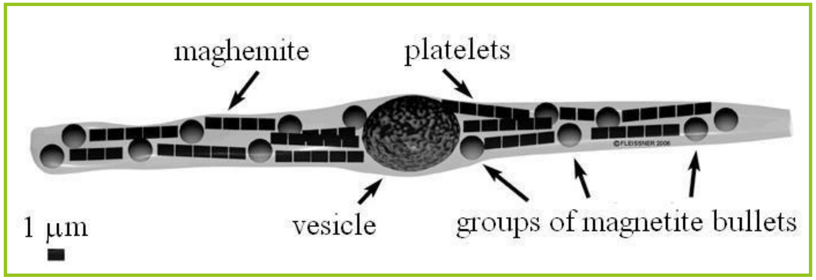
FLUX SENSORS

INTRODUCTION

The oldest magnetic sensor is the compass

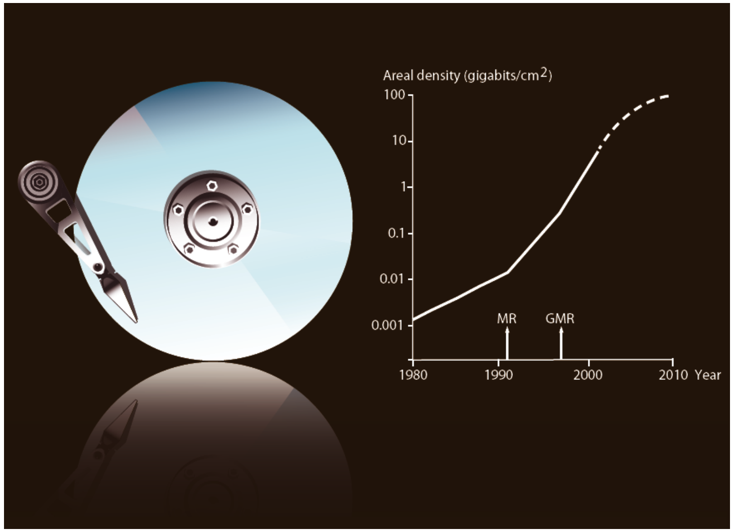
The market size is about 6 billions units.
They are every where.
in automotive, in your mobile, in domestic electrical..

Why?
Electromagnetic fields is the only interaction we are able to manipulate.

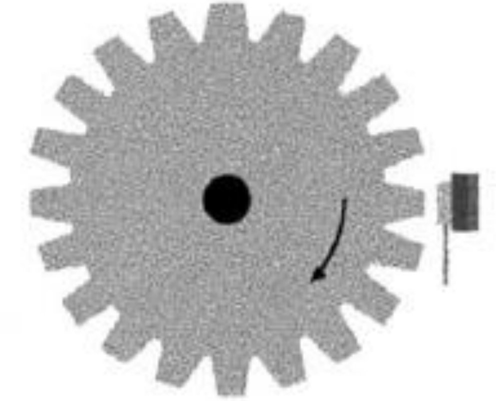


INTRODUCTION

Spin electronics sensors



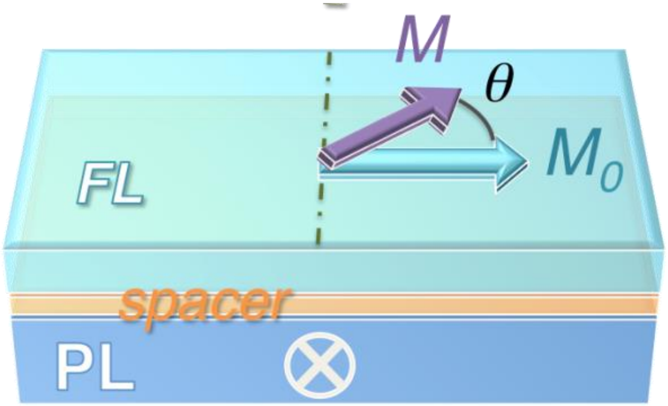
Read head application since 1994



More recently : Automotive applications (speed, angle..
, Compass, current sensors.

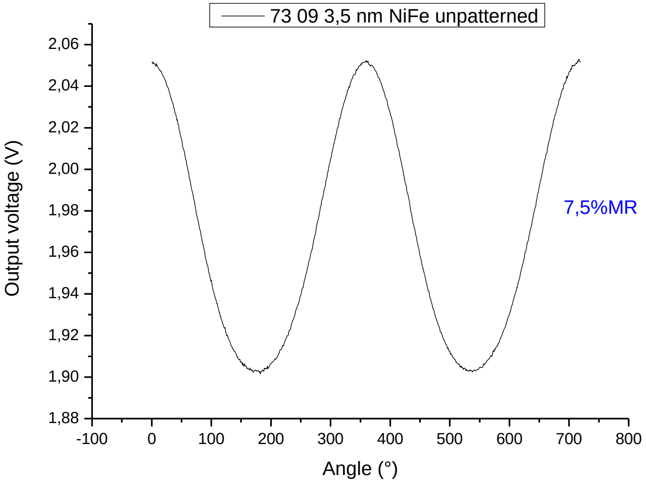
Today 10% of the global magnetic sensor market with more than 10% of increase/year

SPIN VALVE FOR SENSING

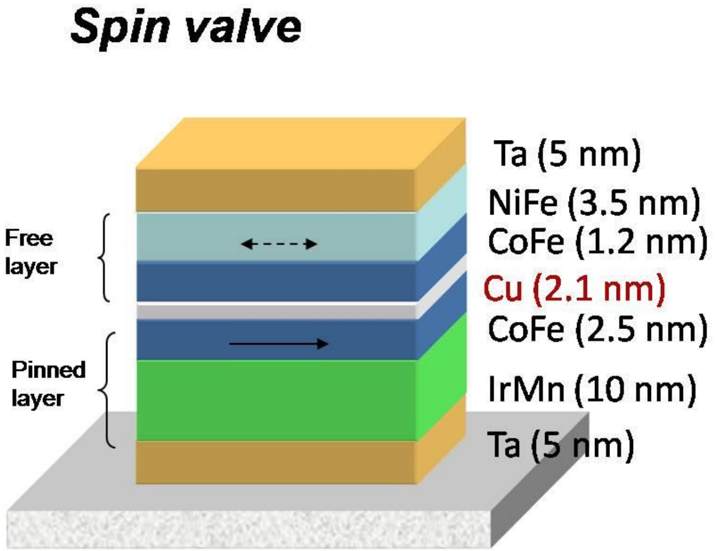


We create 2 kinds of magnetic layers
The first one called pinned layer or reference layer has a very high coercivity
The second one is a very soft and can follow an external magnetic field

The resistance varies as the cosine of the angle between the two magnetic layers



SPIN VALVE FOR SENSING



To increase the coercivity we use an Antiferromagnet coupled to a thin ferromagnet

The antiferromagnet has no net field and it is blocked below a T_b temperature.

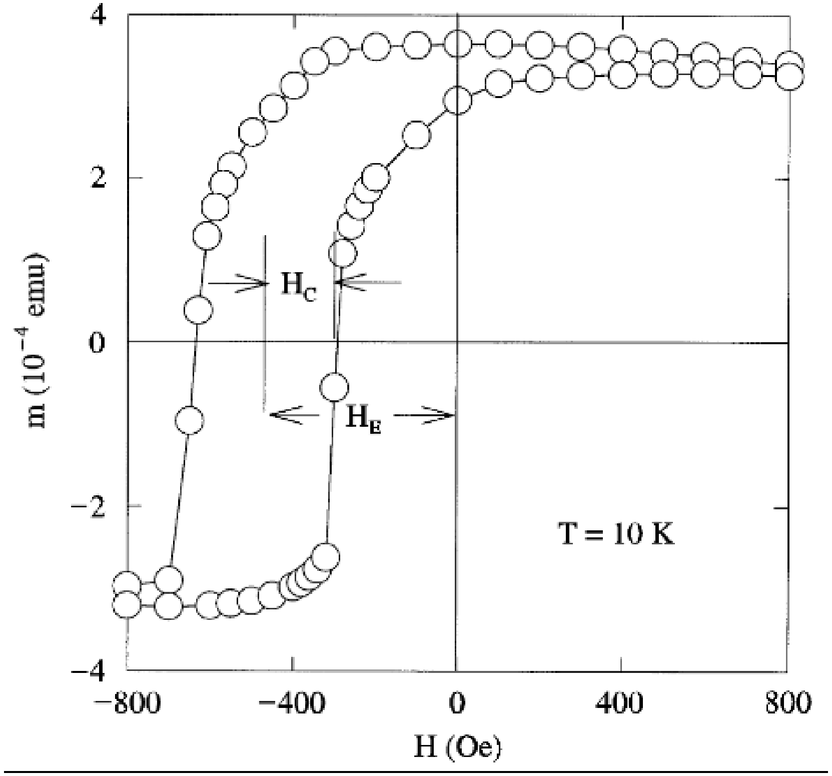
The reference layer is oriented by an annealing under high magnetic field.

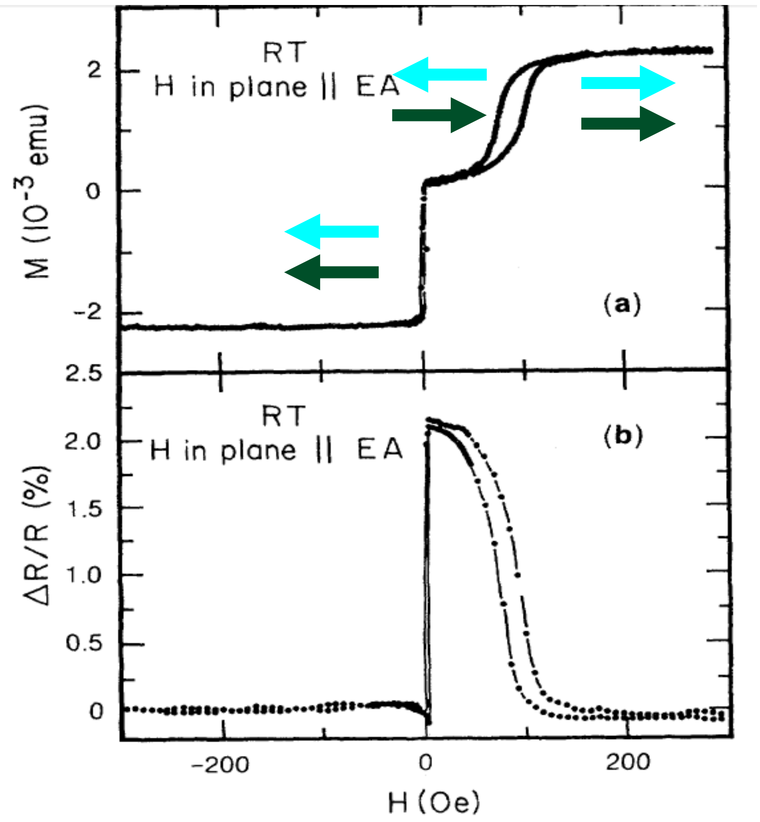
There is another interesting effect : the exchange bias field. The AF is creating through the interface the equivalent of a net field on the coupled layer.

SPIN VALVE FOR SENSING

Exchange bias

Nogues JMMM 1999,
Dieny 1991

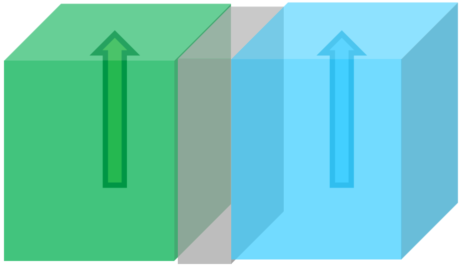


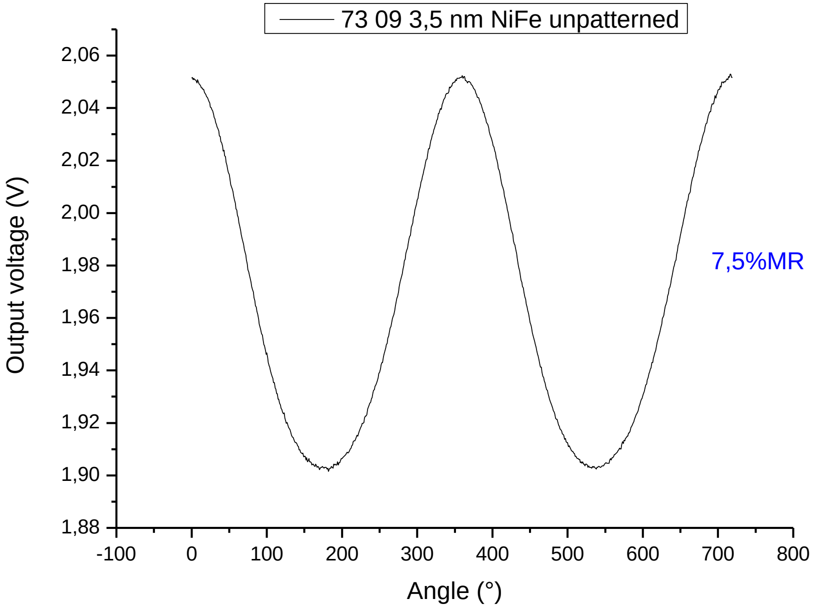


Today IrMn and PtMn are mainly used

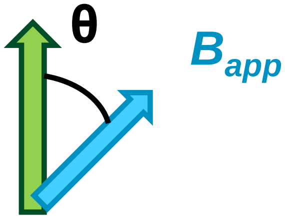
SPECIFIC SENSOR CONFIGURATIONS

A spin valve is first an angle sensor





Champ fixe appliqué avec un angle par rapport à la couche piégée.



$$R \propto \cos(\theta)$$

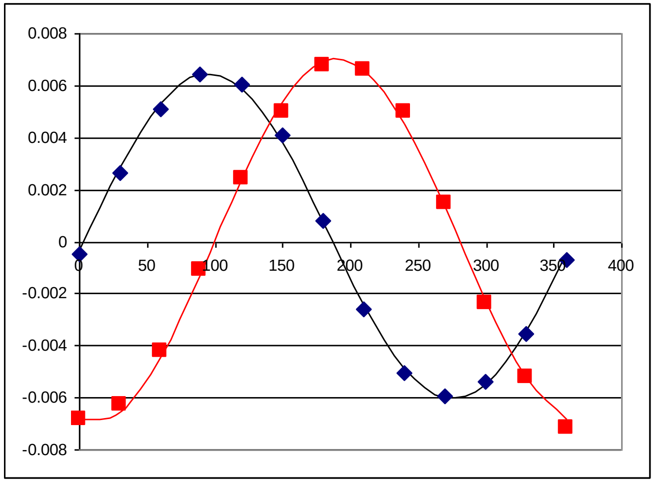
Natural application for angle sensing.
A magnet is rotating in front of a 2D magnetic sensor

In fact, not the easiest product.

ANGLE SENSORS AND COMPASS

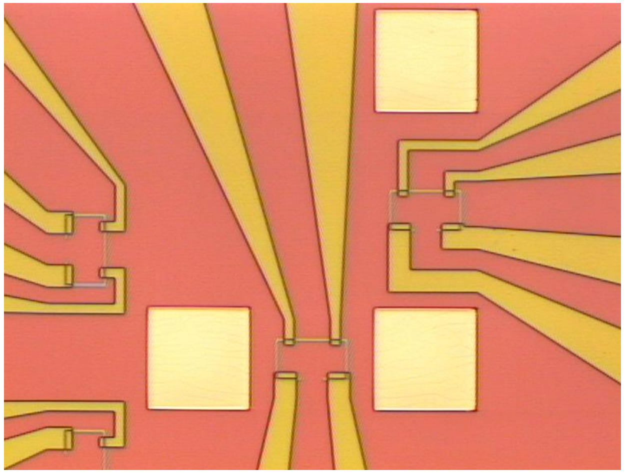
Requires

- A local reversal of the reference magnetization so a local heating or shaped reference layer.
- A very stable reference layer with external field for angle sensors.

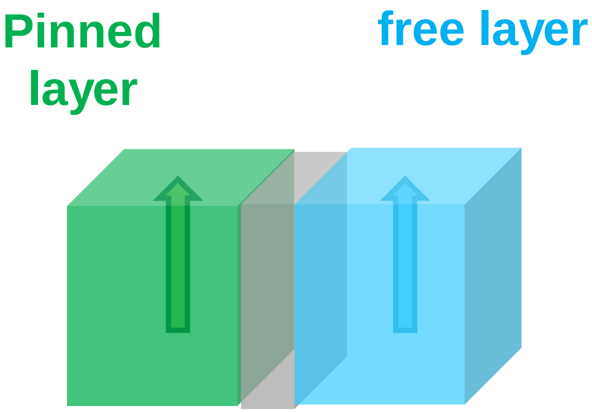


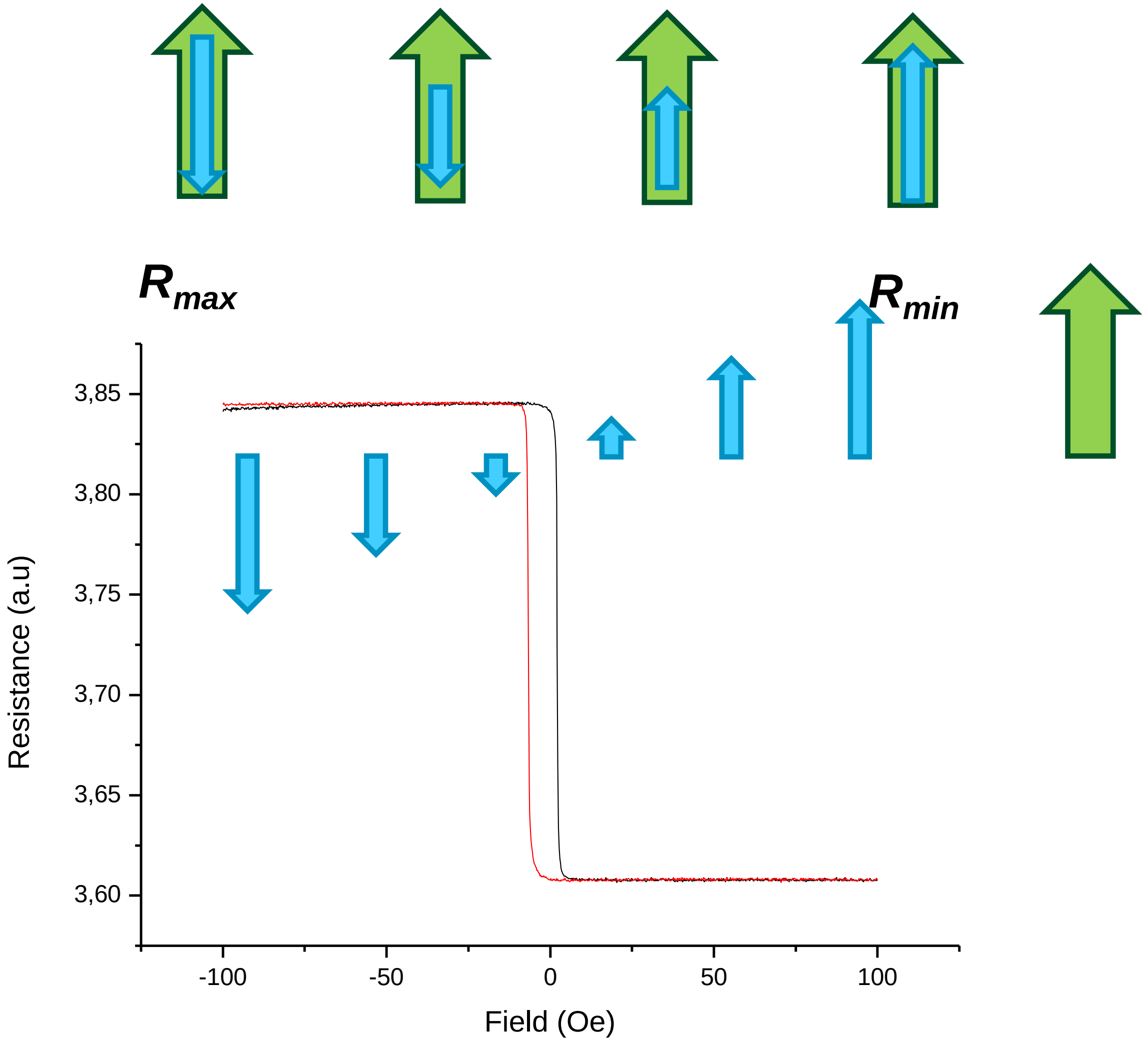
Injected current = 100µA.
Integration time ~ 0.3s.
Consumption power : 8 µW
Accuracy <3°

Example of a 2D compass



LINEARIZATION OF A SPIN VALVE

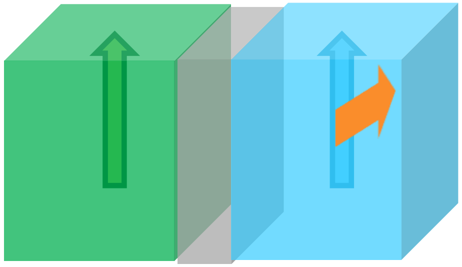


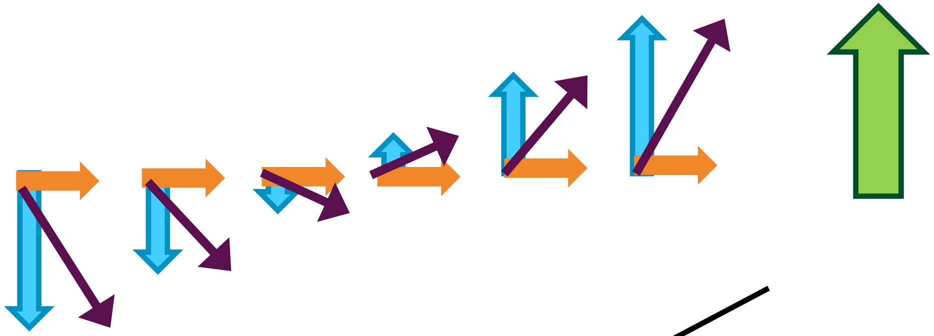


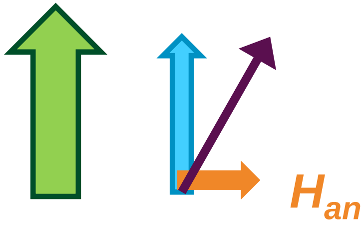
Field applied along the reference layer

Coercivity given by local anisotropy grains of the free layer

LINEARIZATION OF A SPIN VALVE







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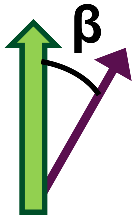
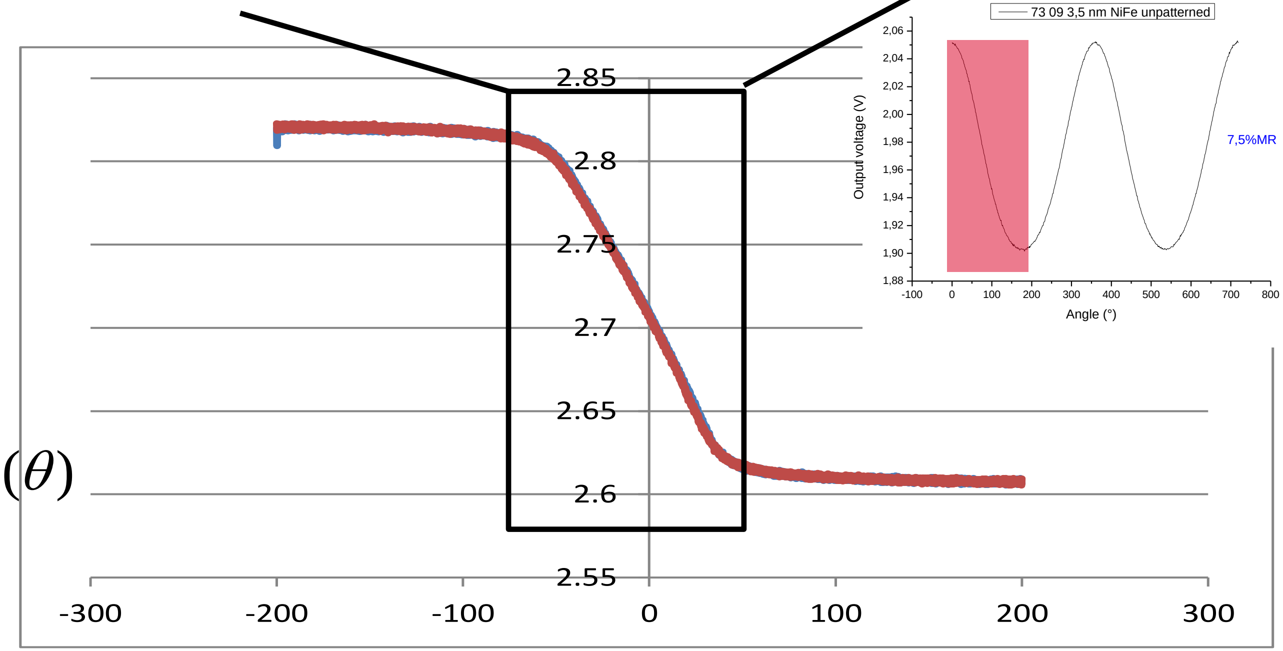


$$R \propto \cos(\theta)$$



$$\cos(\theta) = \frac{B_{app}}{\sqrt{B_{app}^2 + B_{an}^2}}$$

LINEARIZATION OF A SPIN VALVE

The anisotropy field can be

- **Shape anisotropy** : the dipolar field acts as an extra field.

Drawback→ The field is changing with the orientation of the layer. This creates hysteresis

- **External magnet with a proper direction.**

- **A weak coupling of the free layer** to a second AF aligned at 90° from the first one.

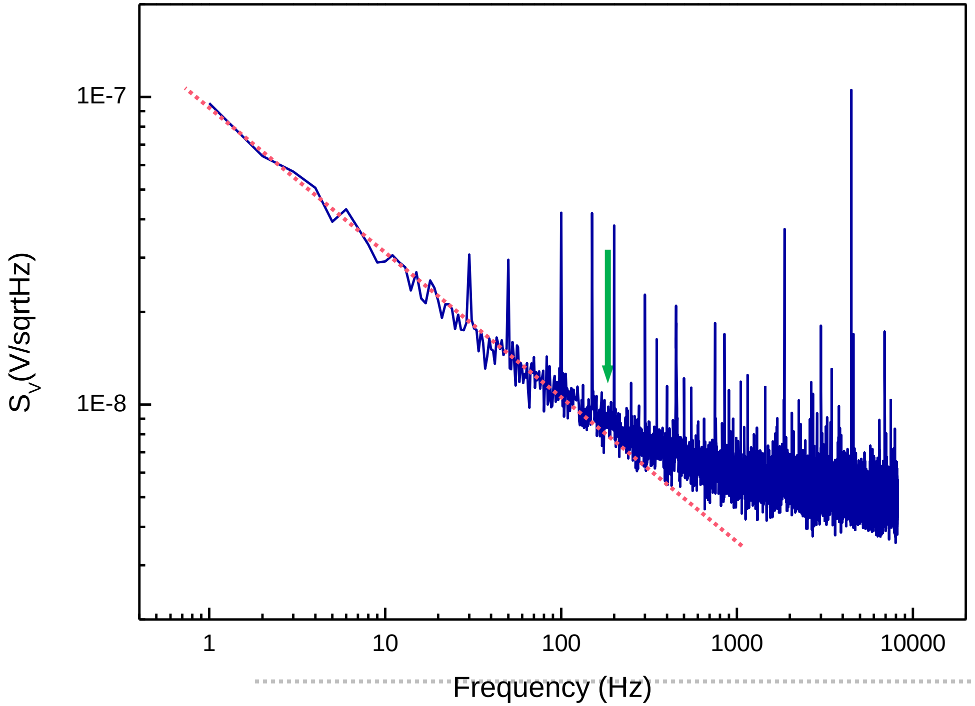
$$\cos(\theta) = \frac{B_{app}}{\sqrt{B_{app}^2 + B_{an}^2}}$$

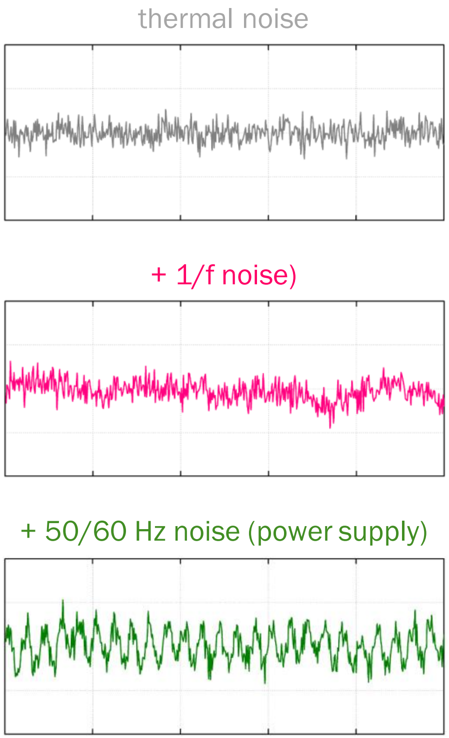
By playing on the strength of the magnetic anisotropy, we change the response

Typical sensitivity : 0.1%-10% of MR/mT for GMR

With 2V on the GMR we can vary the sensitivity from 2V/T with large field range to 200V/T with small field range.

NOISE OF A SPIN VALVE





$$S_V(f) \cong \boxed{\gamma \frac{I^2R^2}{N_C f}} + \boxed{RTN} + \boxed{4k_BTR}$$

1/f noise
N_c number of carriers
γ Hooge parameter

Random
Telegraph Noise

Thermal noise

NOISE OF A SPIN VALVE

1mm spin valve at 2V have a cross between 1/f noise and thermal noise at 10Hz
10µm spin valve has a cross at 1kHz.

With 100V/T and a thermal noise of 4nV/sqrt(Hz) (1kOhm)
This gives a field equivalent noise of 40pT/sqrt(Hz)

TMR devices

Gain in sensitivity by a factor of 20
1/f is typically 20-50 times larger than GMR 1/f noise. This is due to the barrier noise.

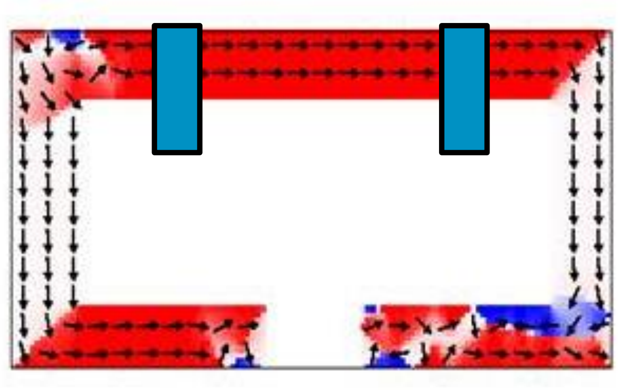
TMR should be selected for high frequency detection or when SNR is not critical i.e : external electric noise etc..
TMR is also very interesting for low consumption. For the same SNR you consume 20 times less than a GMR.

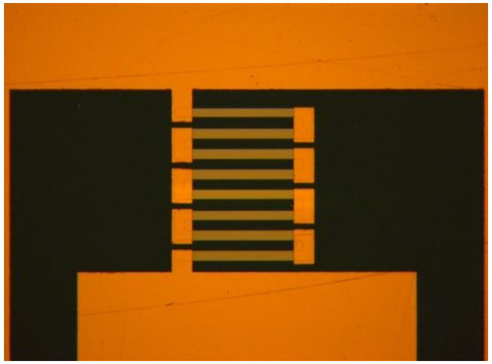
MAGNETIC NOISE

Shape is very important for magnetic sensor noise

If there are domains in the free layer, the fluctuations of domain size is creating a large low frequency noise.

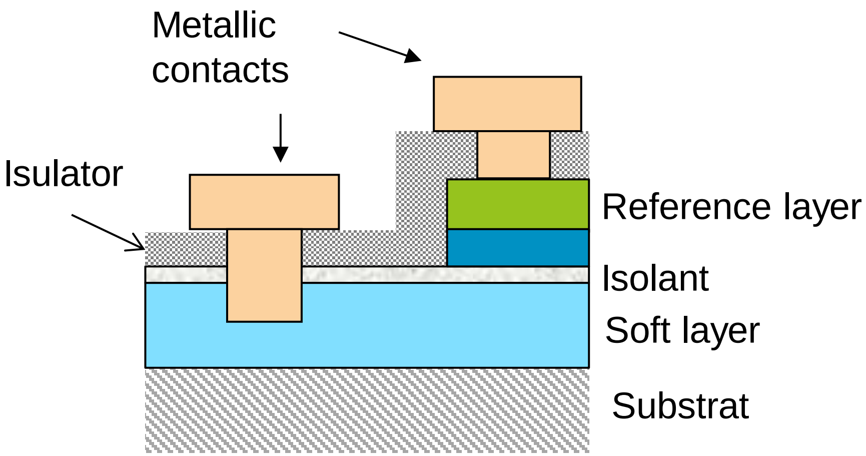
For GMR : C shape or short circuited meander





PRACTICAL DEVICES

CPP measurement for TMR, CIP measurement for GMR.



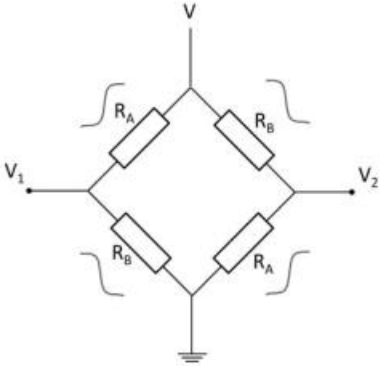
Resistance of the device is given for GMR by length/width
Resistance of a TMR is given by the barrier height

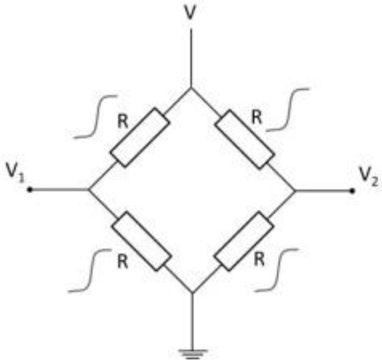
More freedom on the shape with TMR but accuracy of the resistance complicate
Today on 200mm wafer, there is a dispersion of 10%-30% of resistance.

PRACTICAL DEVICES

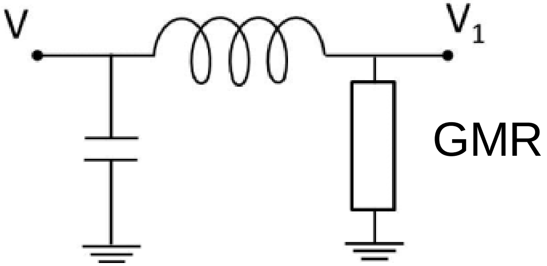
The main resistance of a spin valve varies as 0.2%/°C

Bridge configuration is required for DC detection





Filtering can be used for AC detection



PRACTICAL DEVICES

GMR/TMR is an in situ wideband modulator.

The external field is a sent with a frequency f_H
The bridge is biased with a f_G frequency.

V=RI.

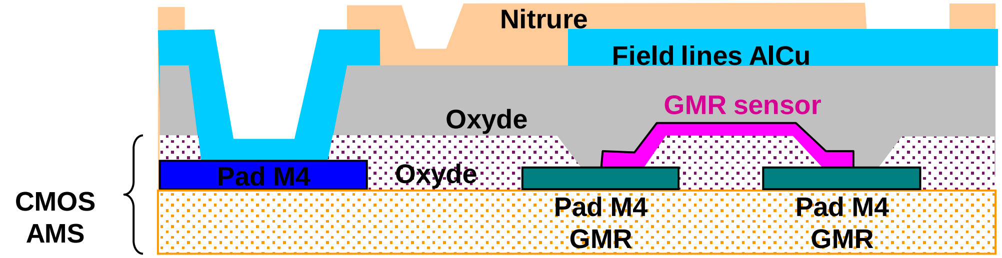
R varies as f_H, I varies as f_G.
V is varying as $f_H - f_G$ and $f_H + f_G$

Allows in RF devices to avoid direct coupling or direct capacitive coupling.

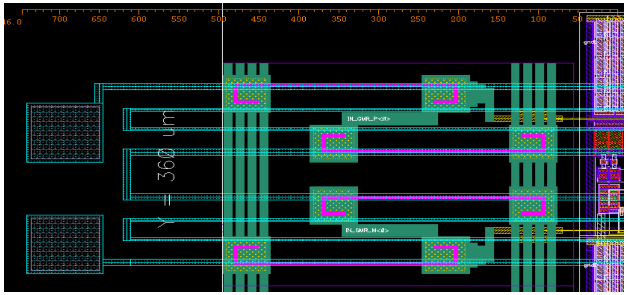
INTEGRATION OF GMR ON CMOS PROCESS

GMR-TMR contains metals non compatible with CMOS

→ Back end process.



Cut view on CMOS

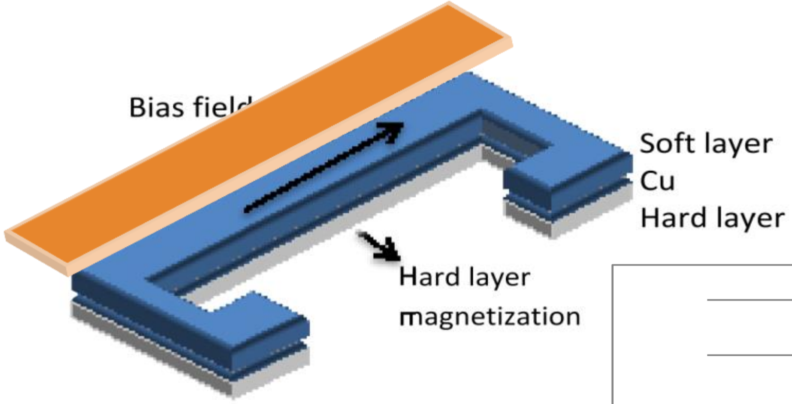


Top view on CMOS

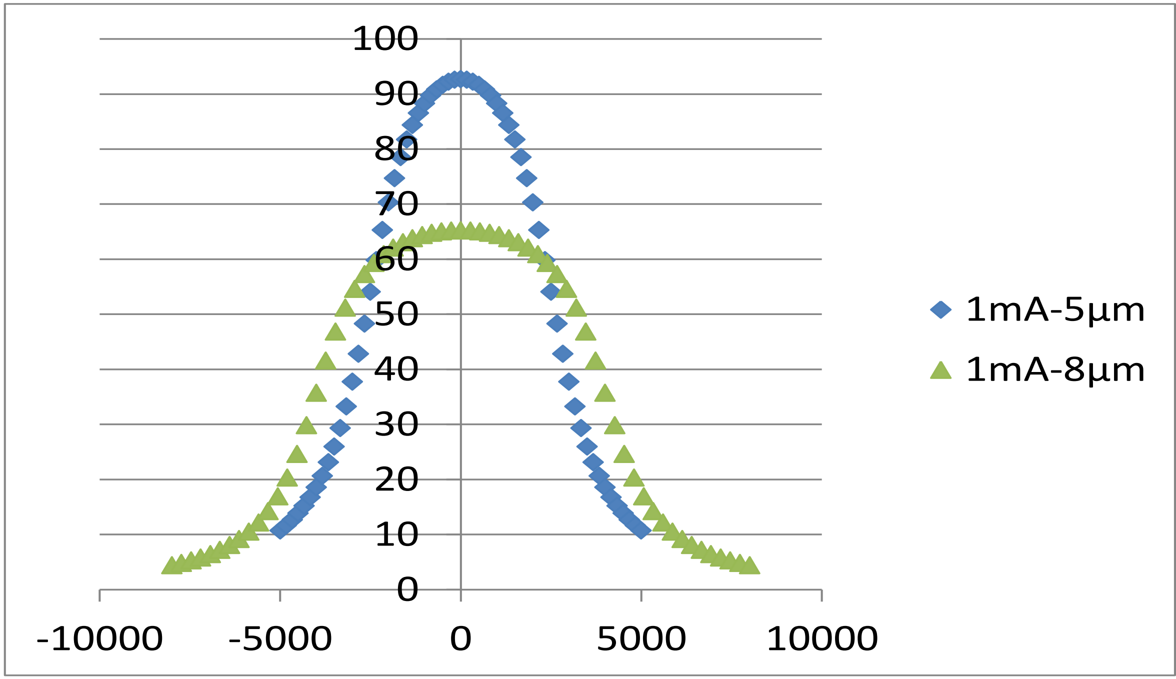
INTEGRATION OF GMR ON CMOS PROCESS

One example : current sensor for voltage fuel cell monitoring

Current line on top

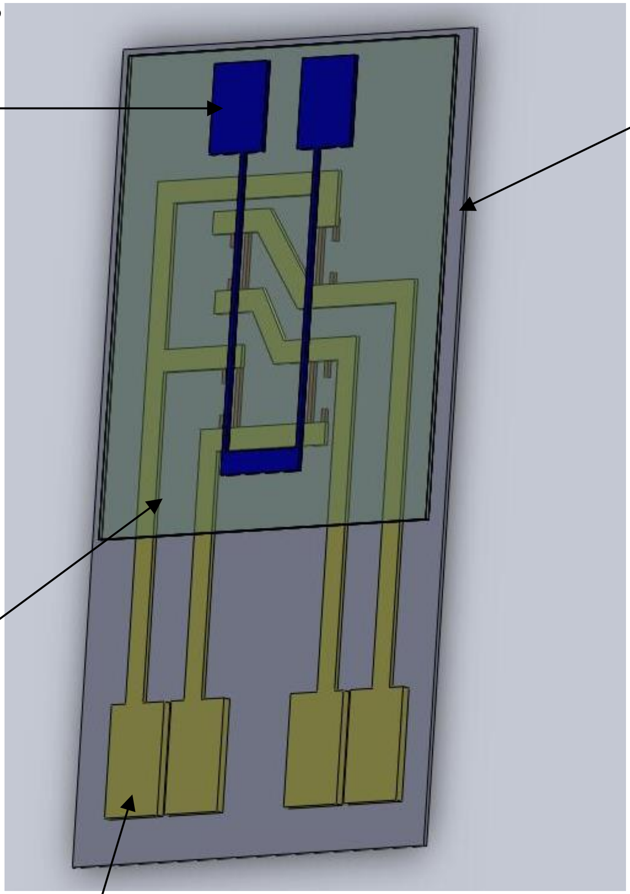


3kV means at least 5µm of separation with a good dielectric layer.



INTEGRATION OF GMR ON CMOS PROCESS

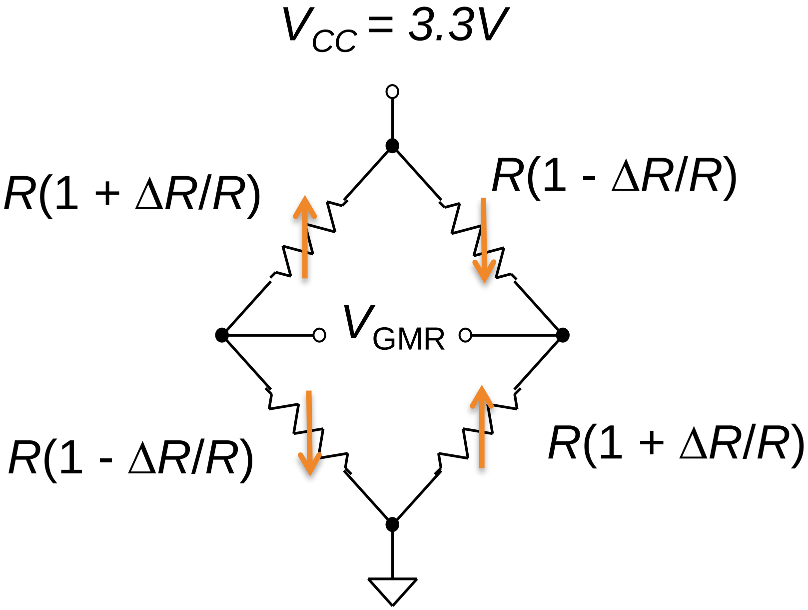
Calibrated current lines
20mA for 1.3V
$R_{current\ line}$=63 Ohms



Insulator

Bridge connections

4 GMR elements
4µmx100µm
R_{GMR}=1kOhm (single element)
3.3mA - 3.3V power supply
Sensitivity: 66mV/mT

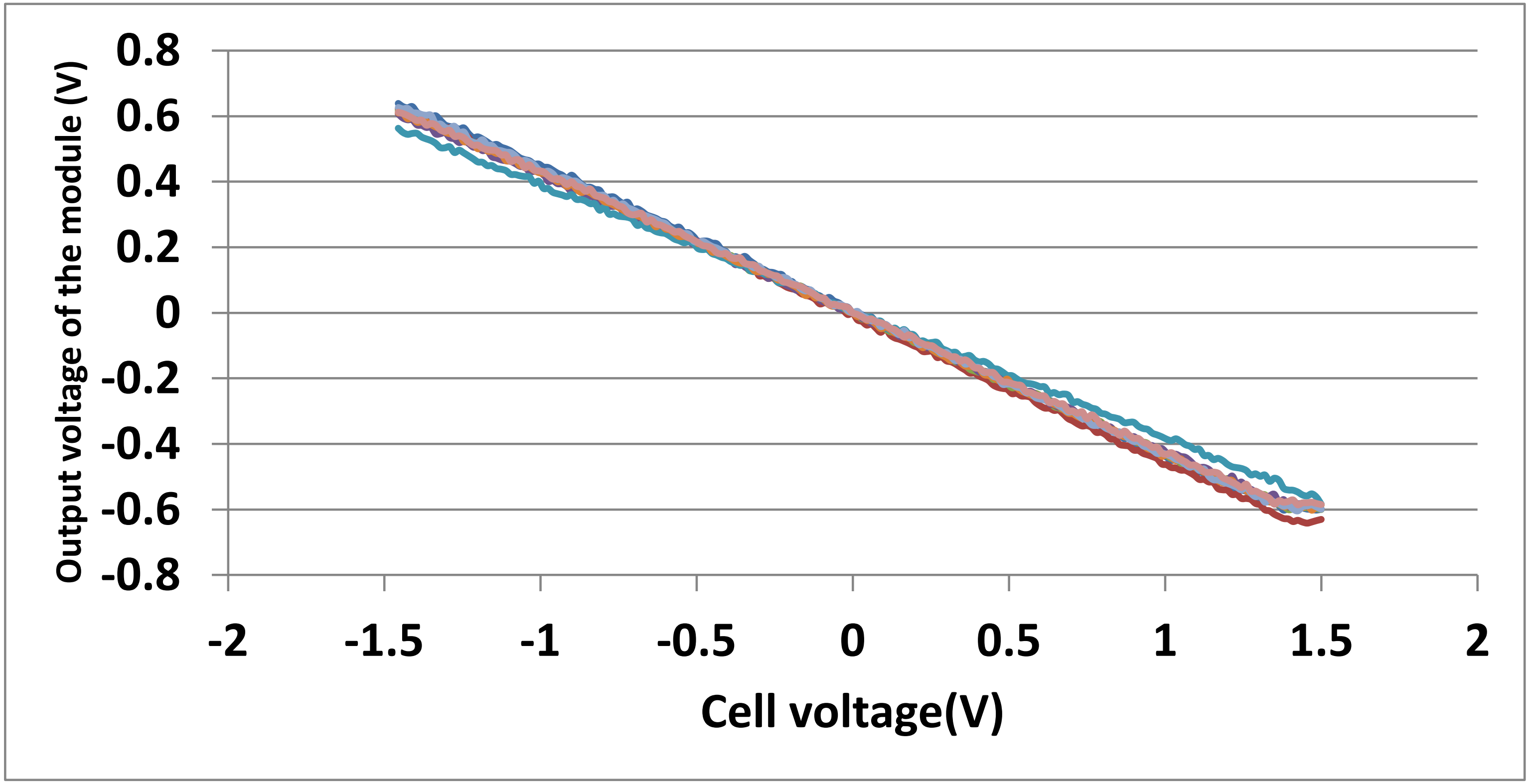


$$V_{GMR} = V_{CC} \frac{\Delta R(H)}{R}$$

Linear rang in open loop
Of +-20mA with +-0.5% of error

INTEGRATION OF GMR ON CMOS PROCESS

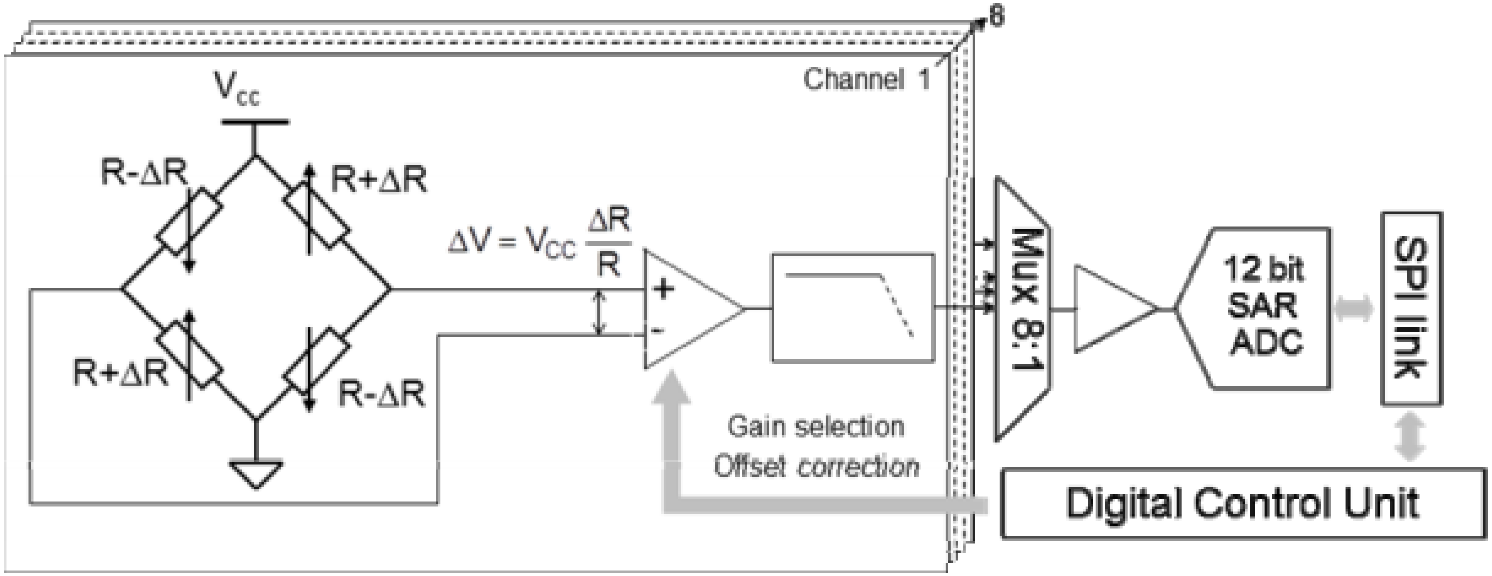
Temperature corrections



Variation of the response with temperature from -20°C to 85°C
before digital correction : 0.25% of sensitivity/°C

INTEGRATION OF GMR ON CMOS PROCESS

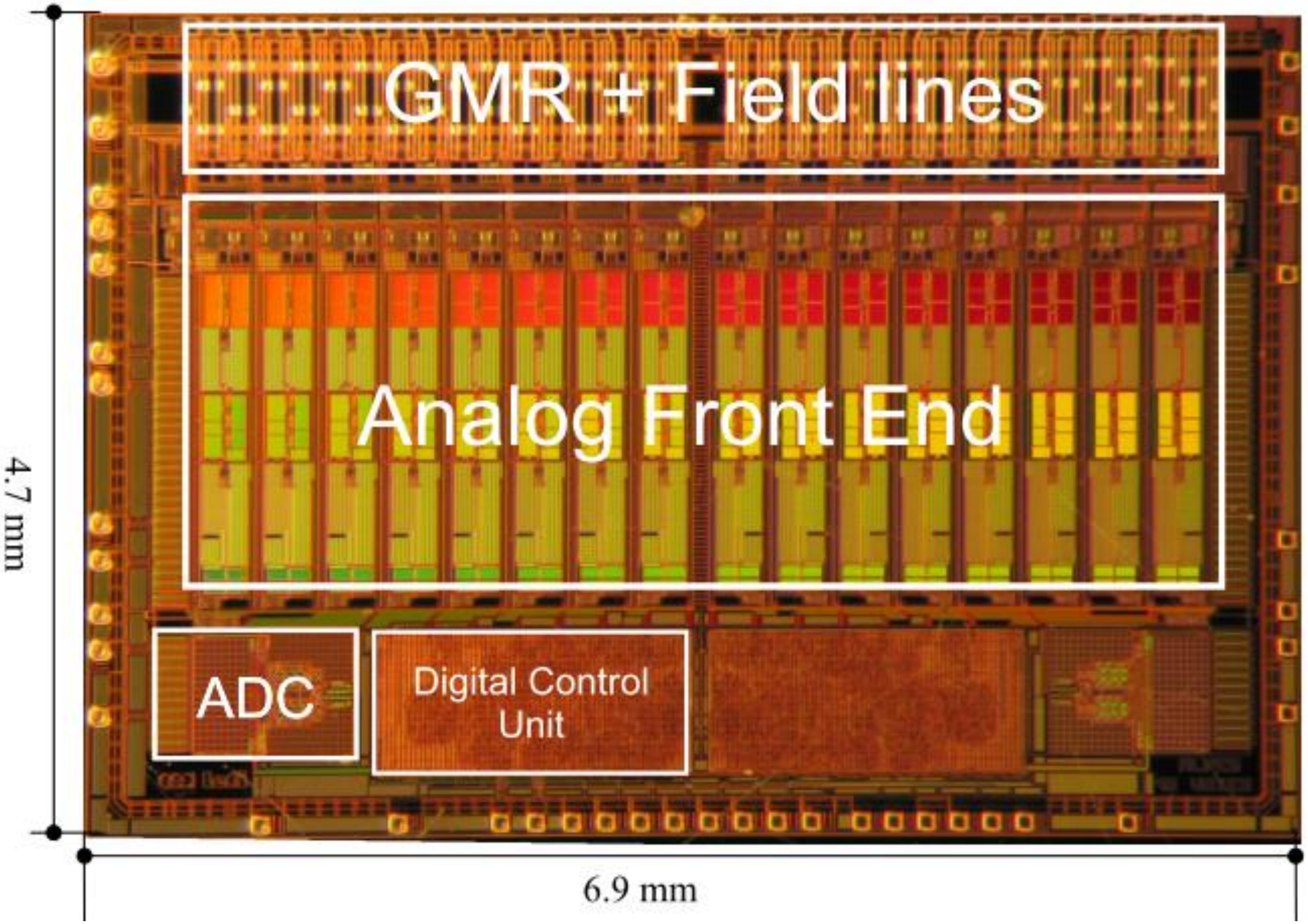
A first simple version



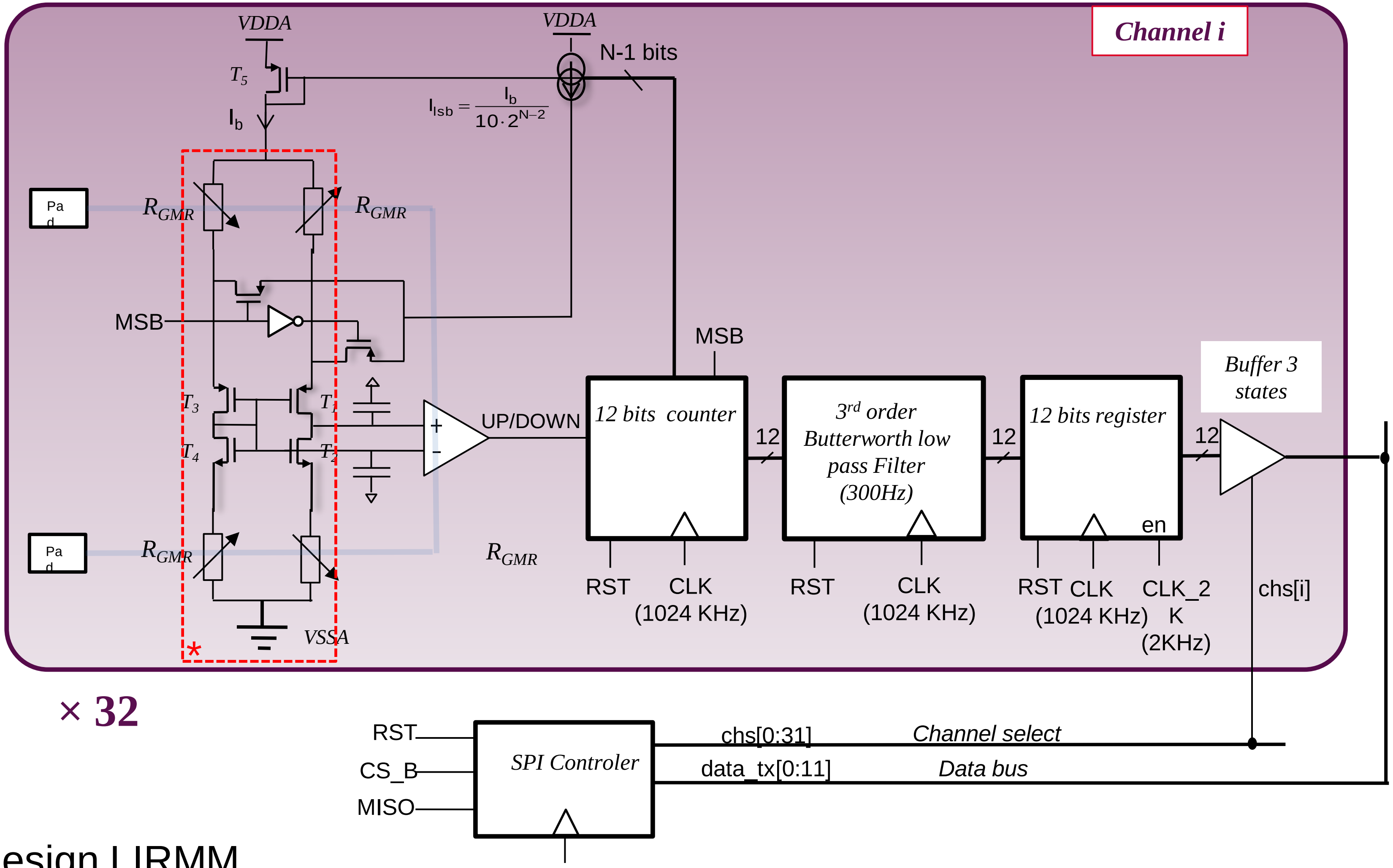
4x8 channels with 4 multiplexers and a SPI common line
10kHz acquisition speed.

INTEGRATION OF GMR ON CMOS PROCESS

A large die for 32 channels

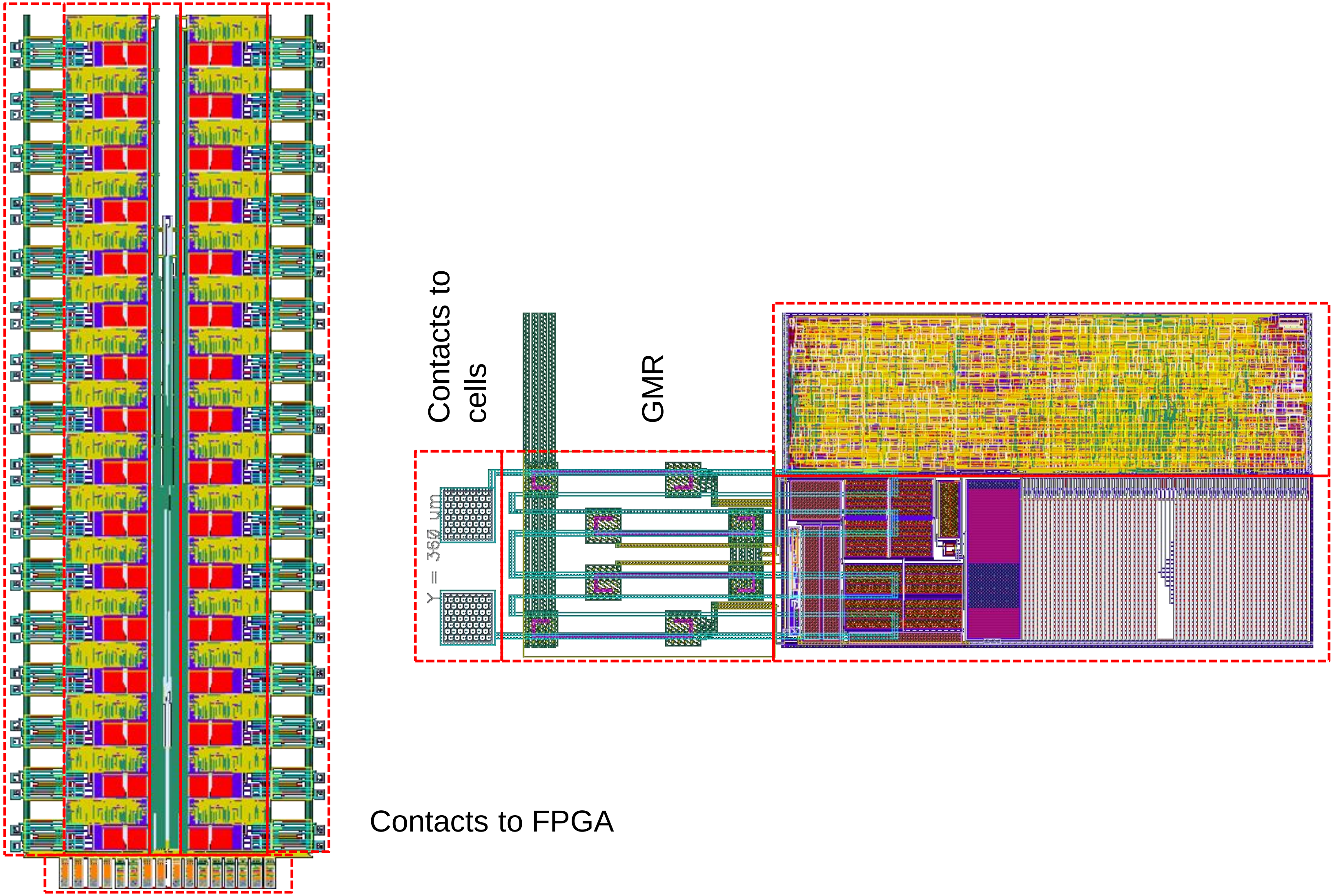


INTEGRATION OF GMR ON CMOS PROCESS



Design LIRMM

INTEGRATION OF GMR ON CMOS PROCESS

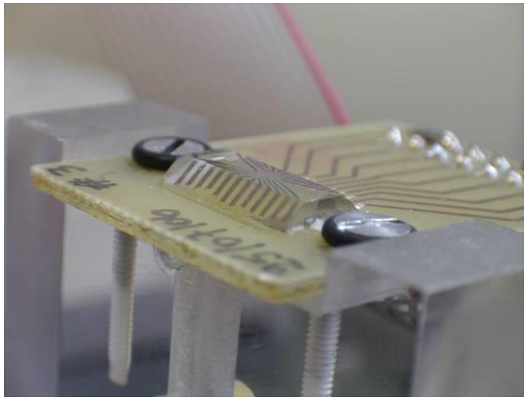


Contacts to cells

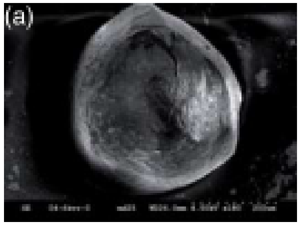
GMR

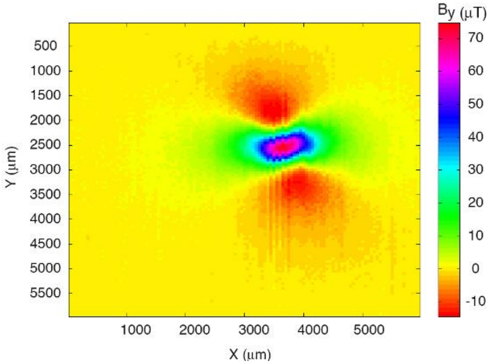
Contacts to FPGA

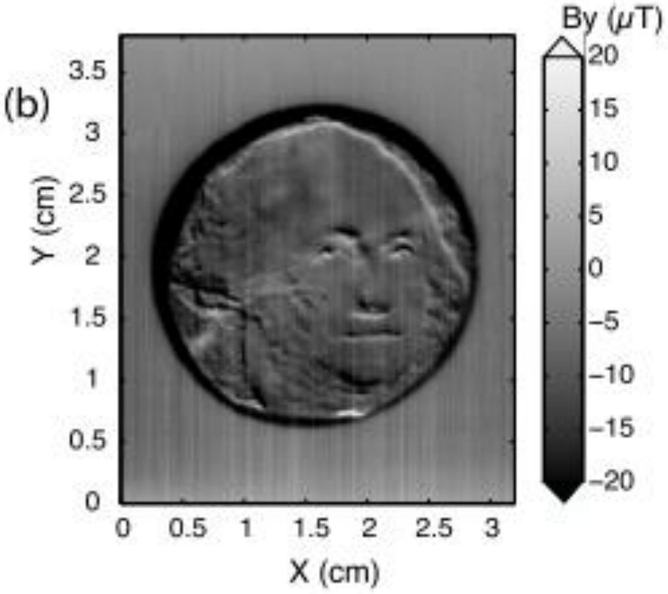
SOME SENSORS EXAMPLES

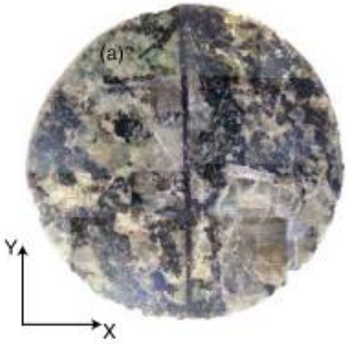


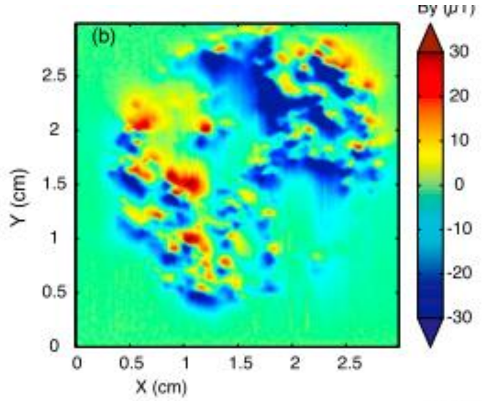
Magnetic mapping-NDE

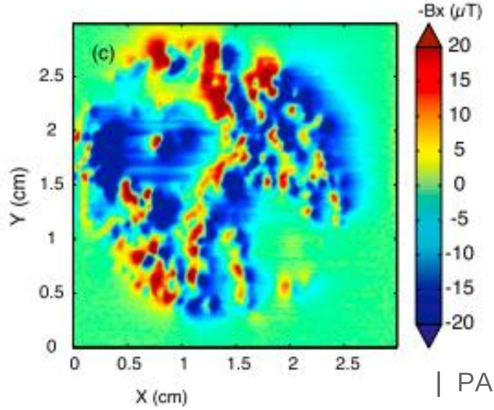








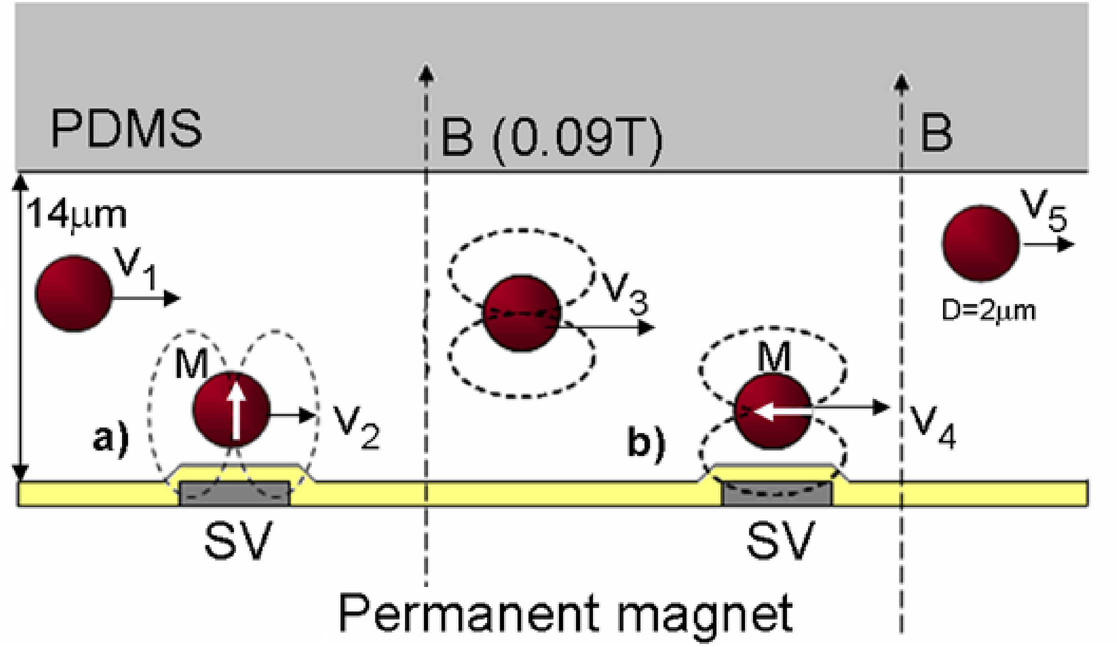


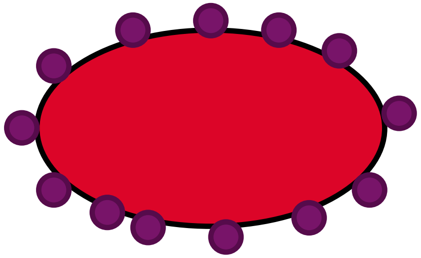


Hankard *et al*.
GEOCHEMISTRY
GEOPHYSICS
GEOSYSTEMS
10 (2009)

Now arrays of 256 sensors with ASIC

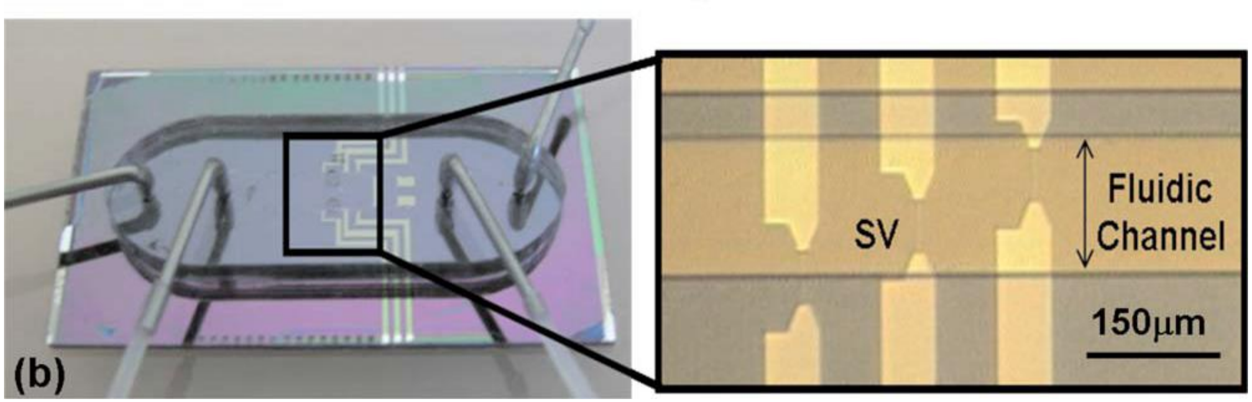
BIOCHIPS-DYNAMIC APPROACH

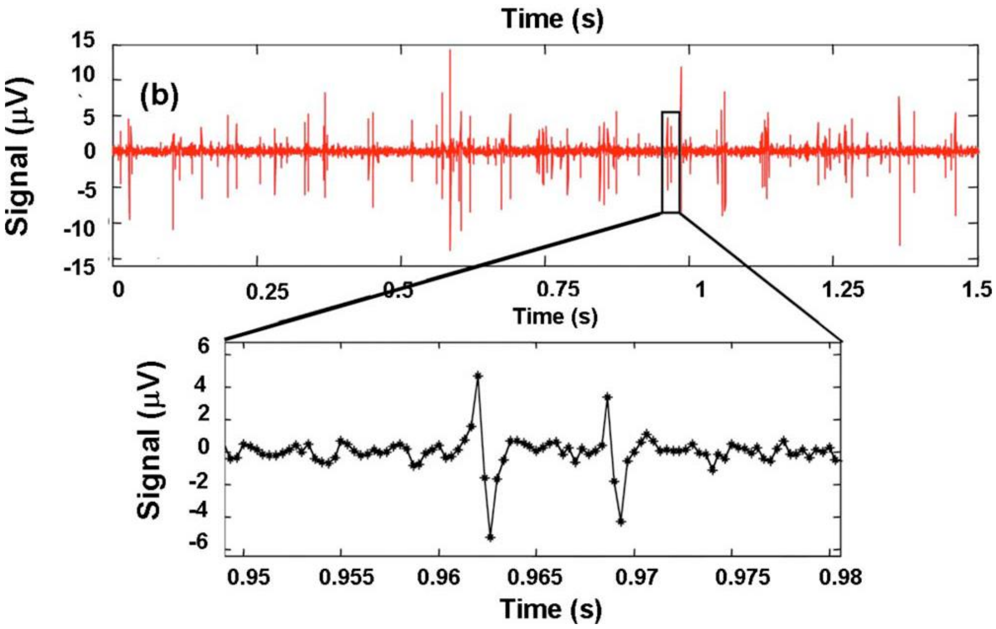




Cell labelling

BIOCHIPS-DYNAMIC APPROACH

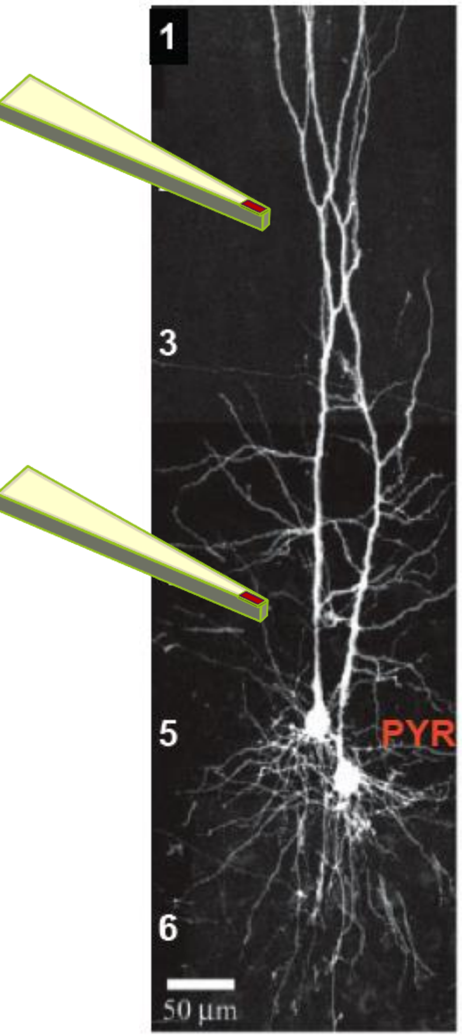




INESC-MN collaboration

Appl. Phys. Lett. ***95***, *034104 2009*

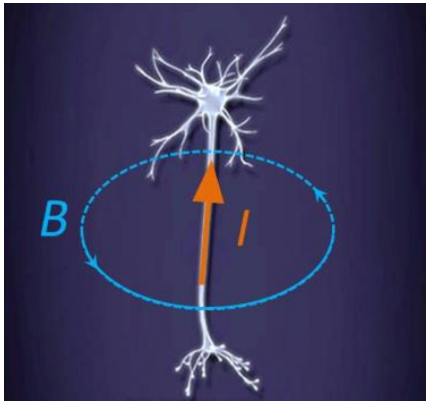
MAGNETRODES



- Develop room temperature tools for local recordings of the neuromagnetic field

- Give an electromagnetic description of the neurons (theoretical and experimental)

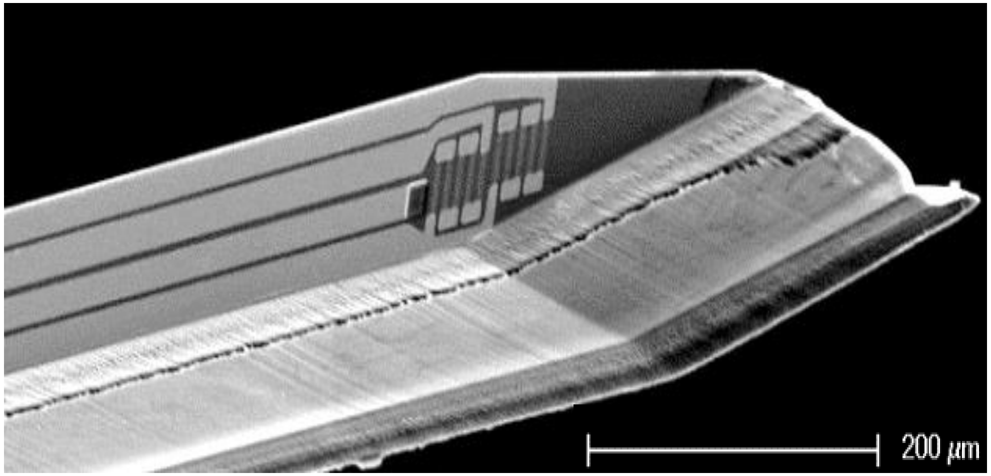
- Access to the axial currents (not accessible by electrophysiology)
- Perform local NMR spectroscopy



CEA France
ESI Germany
INESC-MN portugal
CNRS France
Aalto University Finland

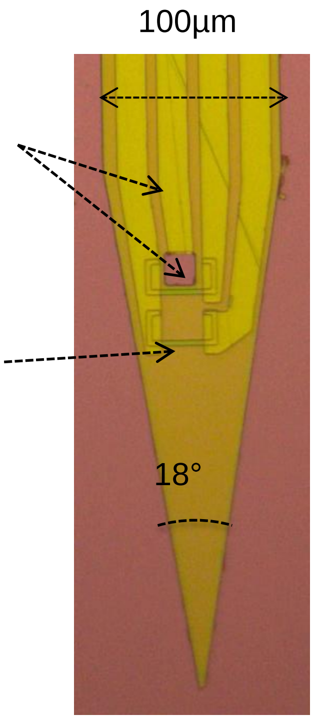
MAGNETRODES

- State of the art micrometer GMR sensor (typ. 40V/V/T)
- Needle shape – 200µm thick substrate
- Embedded reference electrode
- Compatible with *in vivo / in vitro*



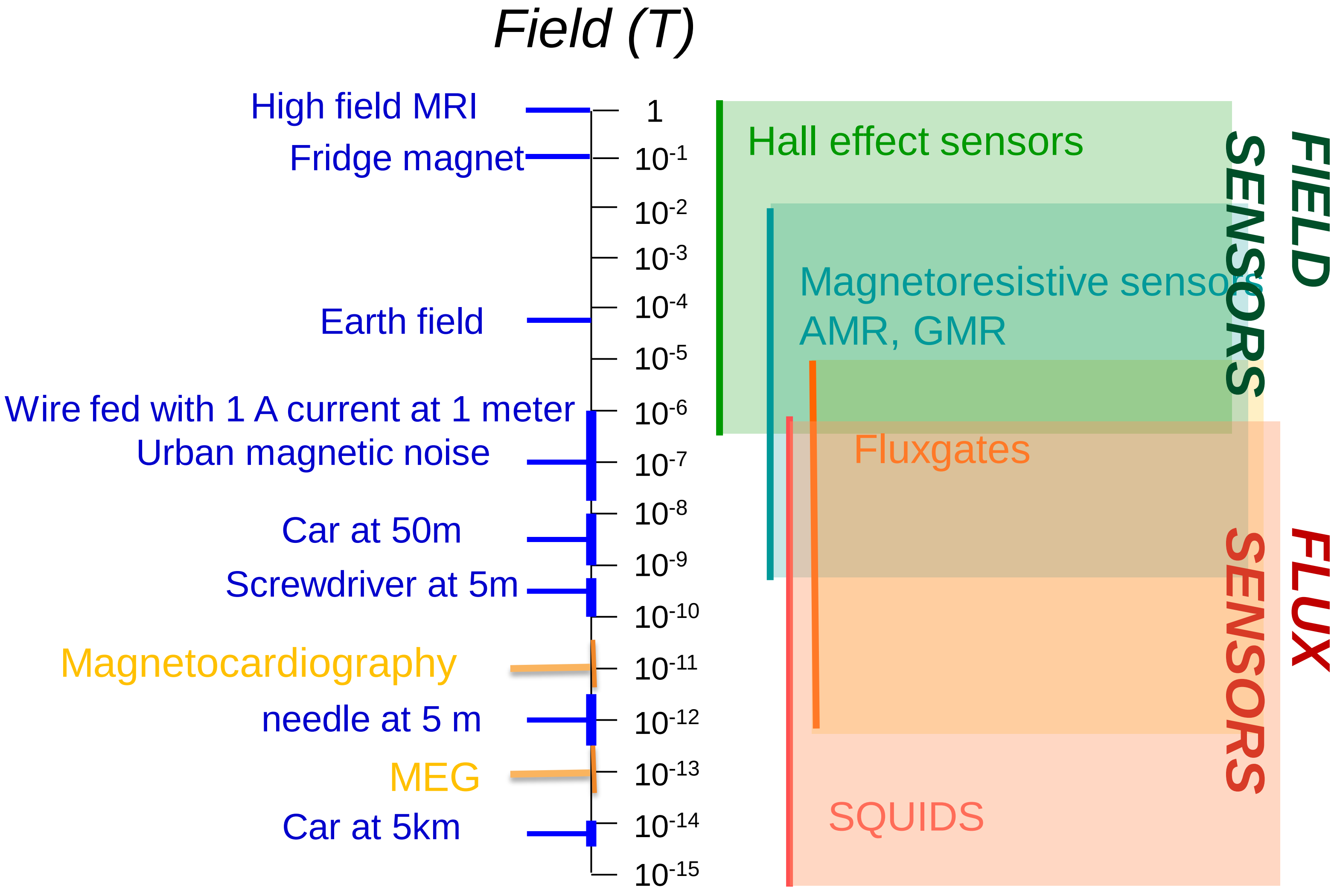
Contacts +
Electrode

2 GMR
sensors



- First recordings obtained *in vitro* on muscle fibers and *in vivo* on the cat's visual cortex.
- Fields detected between 0.5nT to 2nT under validation and model comparison

MAGNETIC FIELD SENSING



Field (T)

High field MRI

Fridge magnet

Earth field

Wire fed with 1 A current at 1 meter

Urban magnetic noise

Car at 50m

Screwdriver at 5m

Magnetocardiography

needle at 5 m

MEG

Car at 5km

Hall effect sensors

Magnetoresistive sensors
AMR, GMR

Fluxgates

SQUIDS

FIELD SENSORS

FLUX SENSORS

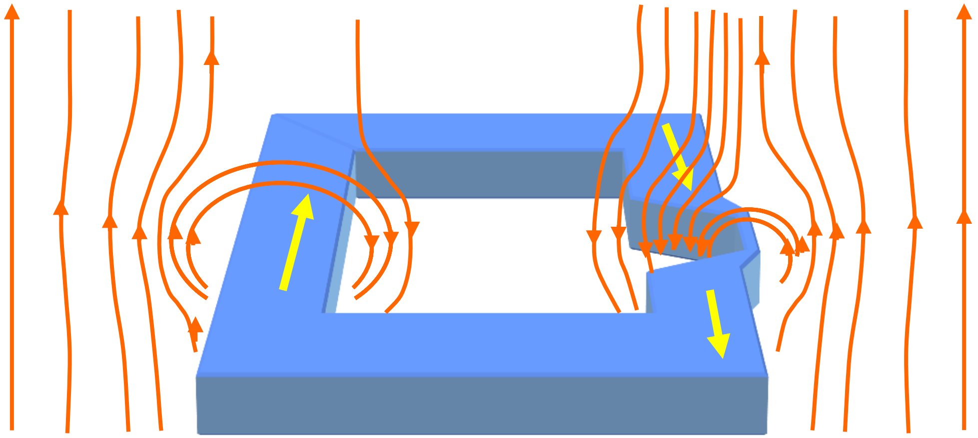
MIXED SENSORS PRINCIPLE

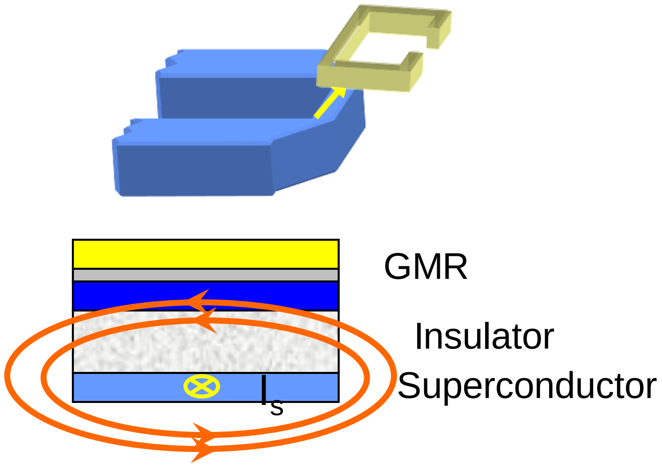
- Most sensitive magnetometers (coils and SQUIDs) are **flux** sensors
- Giant Magneto-Resistance (GMR) or Tunnel Magneto-Resistance (TMR) are **field** sensors

- A SQUID of 5µm² is less sensitive than a GMR sensor of the same size

=> Couple a magnetoresistive sensor to an efficient flux-field transformer.

MIXED SENSORS PRINCIPLE



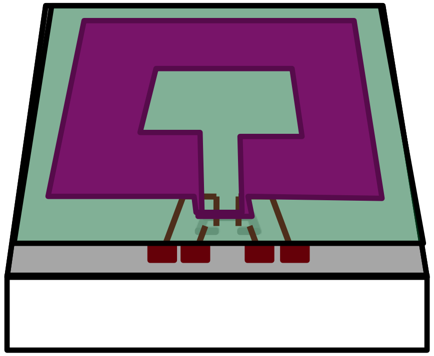


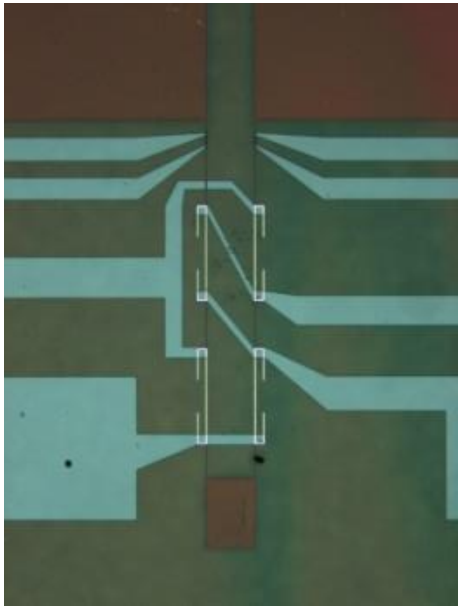
Gain related to the ratio of the main loop size to the constriction size

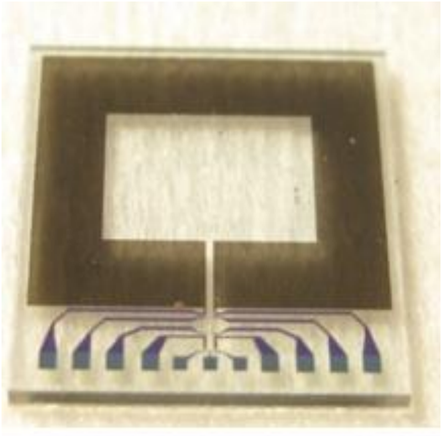
M. Pannetier, C. Fermon, G. Le Goff, J. Simola, E. Kerr, Science, 304 (2004) 1648

MIXED SENSORS PRINCIPLE

YBCO or Nb based mixed sensors





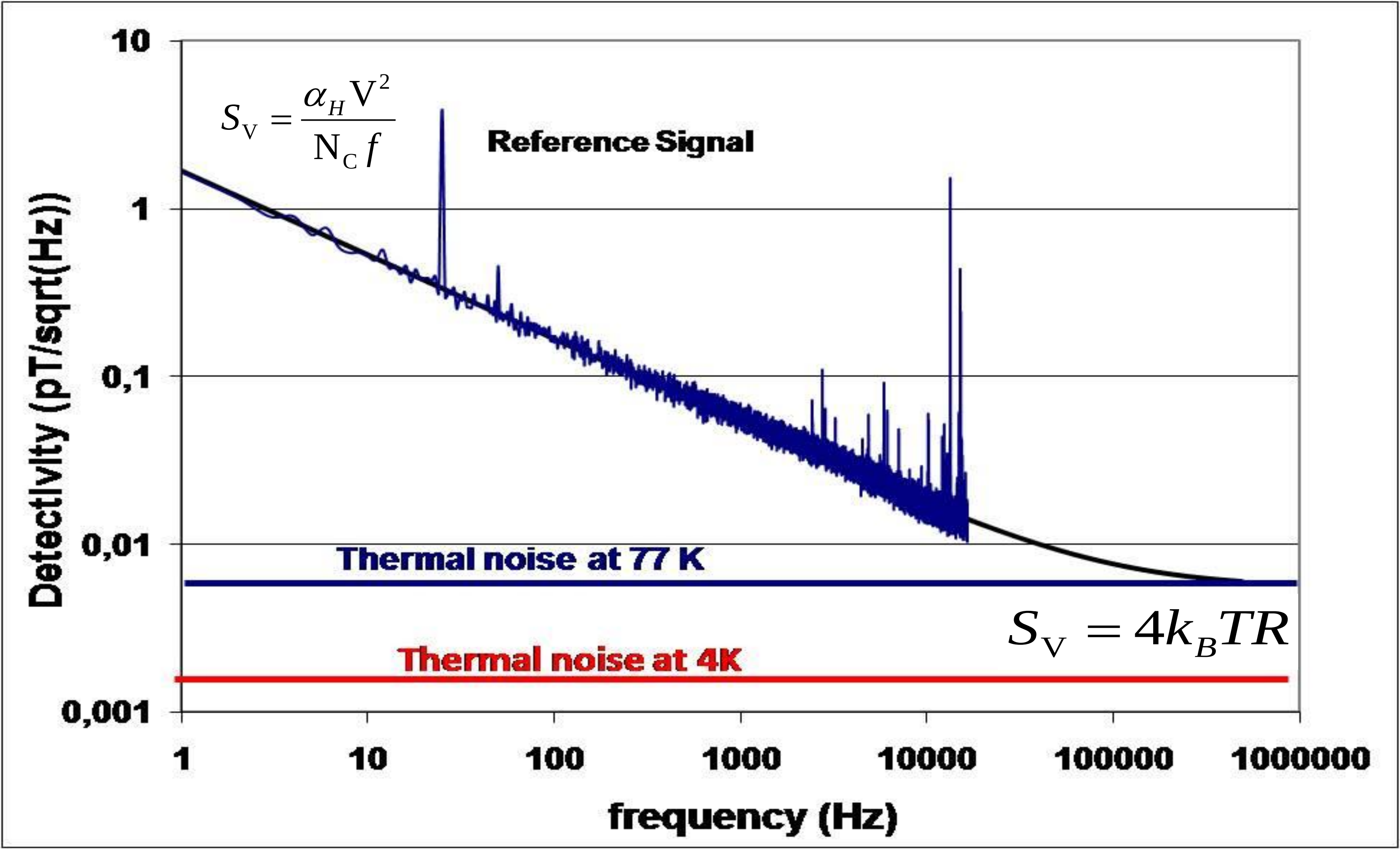


MIXED SENSORS PRINCIPLE

Sensor	Gain measured	Surface (mm^2)	Maximal bias current	Detectivity * at 77K (fT/√Hz)	Detectivity * at 4K (fT/√Hz)
Nb	108	7x7	1mA	n.a.	600
Nb	500	15x15	1mA	n.a.	140
YBCO	160	9x9	15mA	150	32
YBCO	600	17x17	10mA	25	5
YBCO	1300	25x25	10mA	8	1.5
SQUIDS	-	25x25	-	30 (High T_c)	1 (Low T_c)

** In the thermal noise*

MIXED SENSORS DETECTIVITY



BIOMAGNETISM APPLICATIONS

MagnetoCardiography(MCG)

Magnetic signature of the heart electrical activity

Amplitude: 10^{-11} T (=10pT)

Frequency: 0,1 – 100 Hz

Temporal resolution: 1ms

Rather poor spatial resolution

Few sensors

Contactless - non invasive

Additional information to ECG

MagnetoEncephalography (MEG)

Aligned and synchronized neurons signal

Amplitude: 10^{-14}-10^{-13}T (=10-100fT)

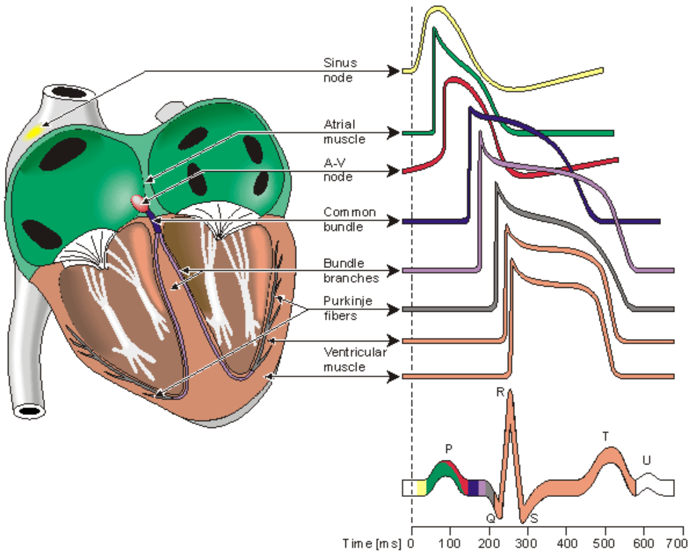
Temporal resolution: ms

Information on cognitive architecture and on algorithms used by the brain

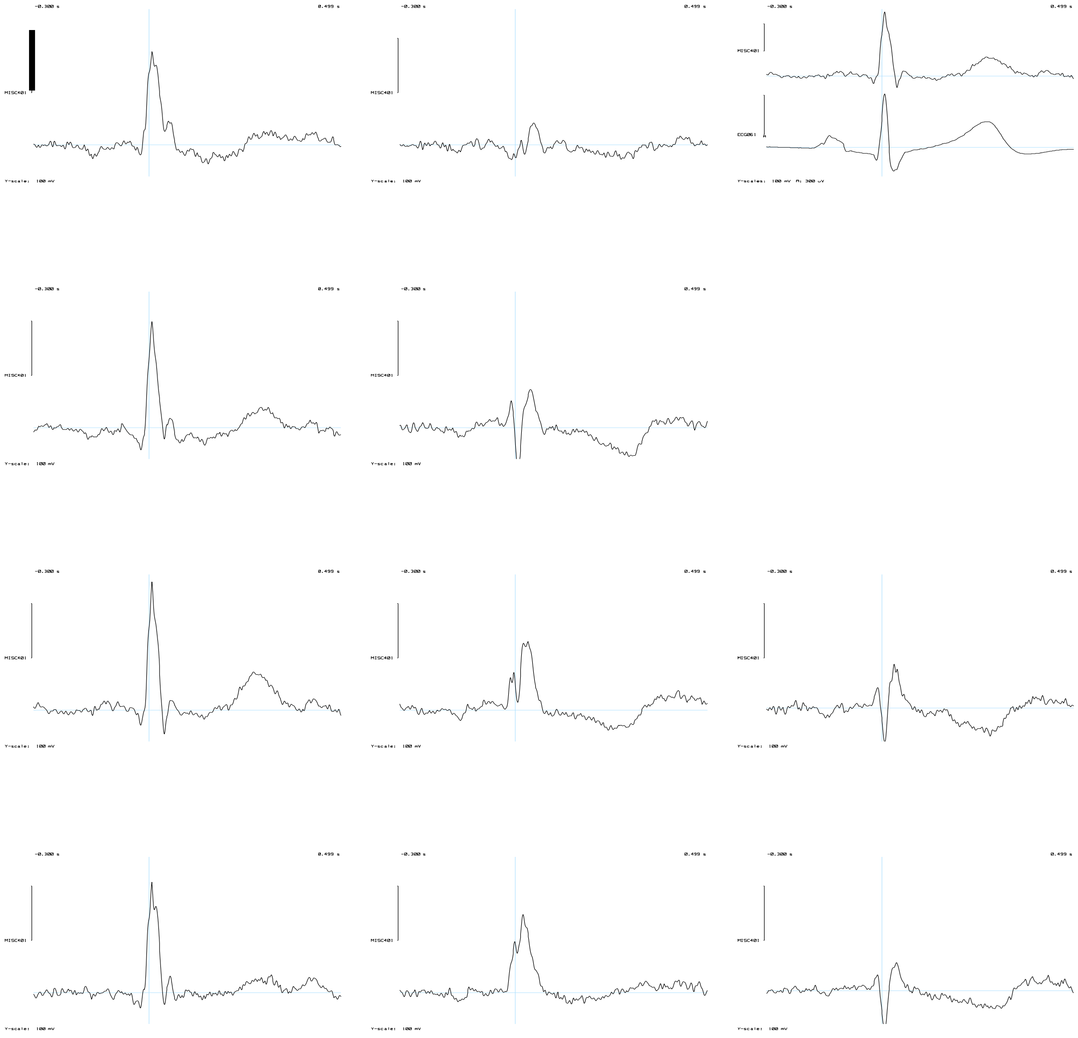
Spatial resolution: 2-4mm (depends on SNR)
Up to 300 sensors

Brain noise: 10-25 fT/√Hz (0,1-30Hz)
Sensor noise < 5 fT /√Hz *(low-Tc SQUIDS)*

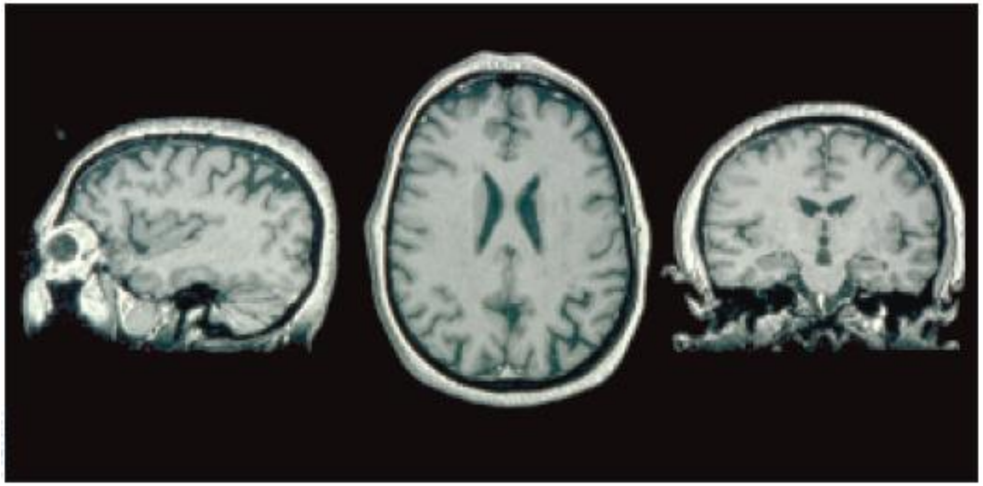
BIOMAGNETISM APPLICATIONS

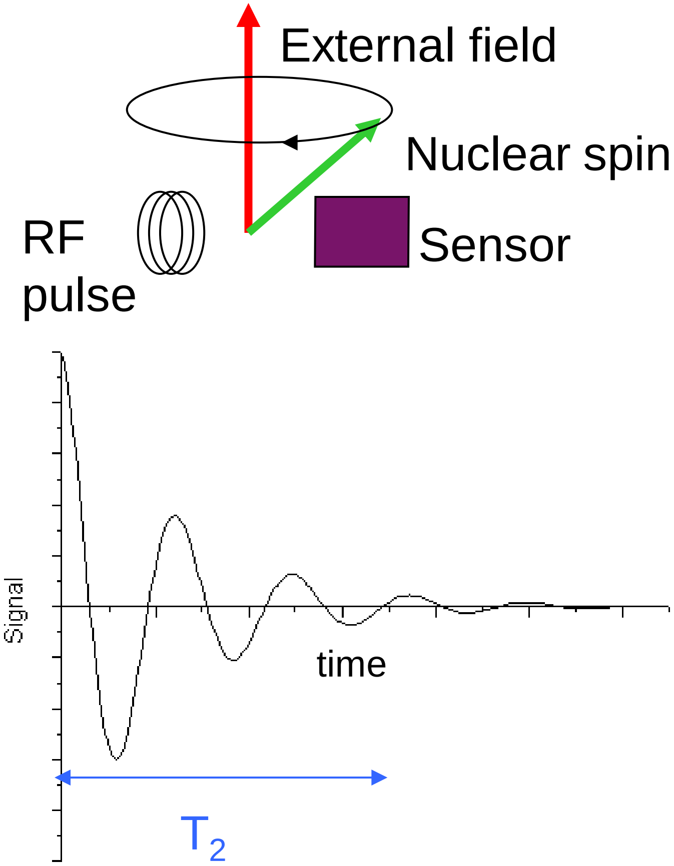


10pT



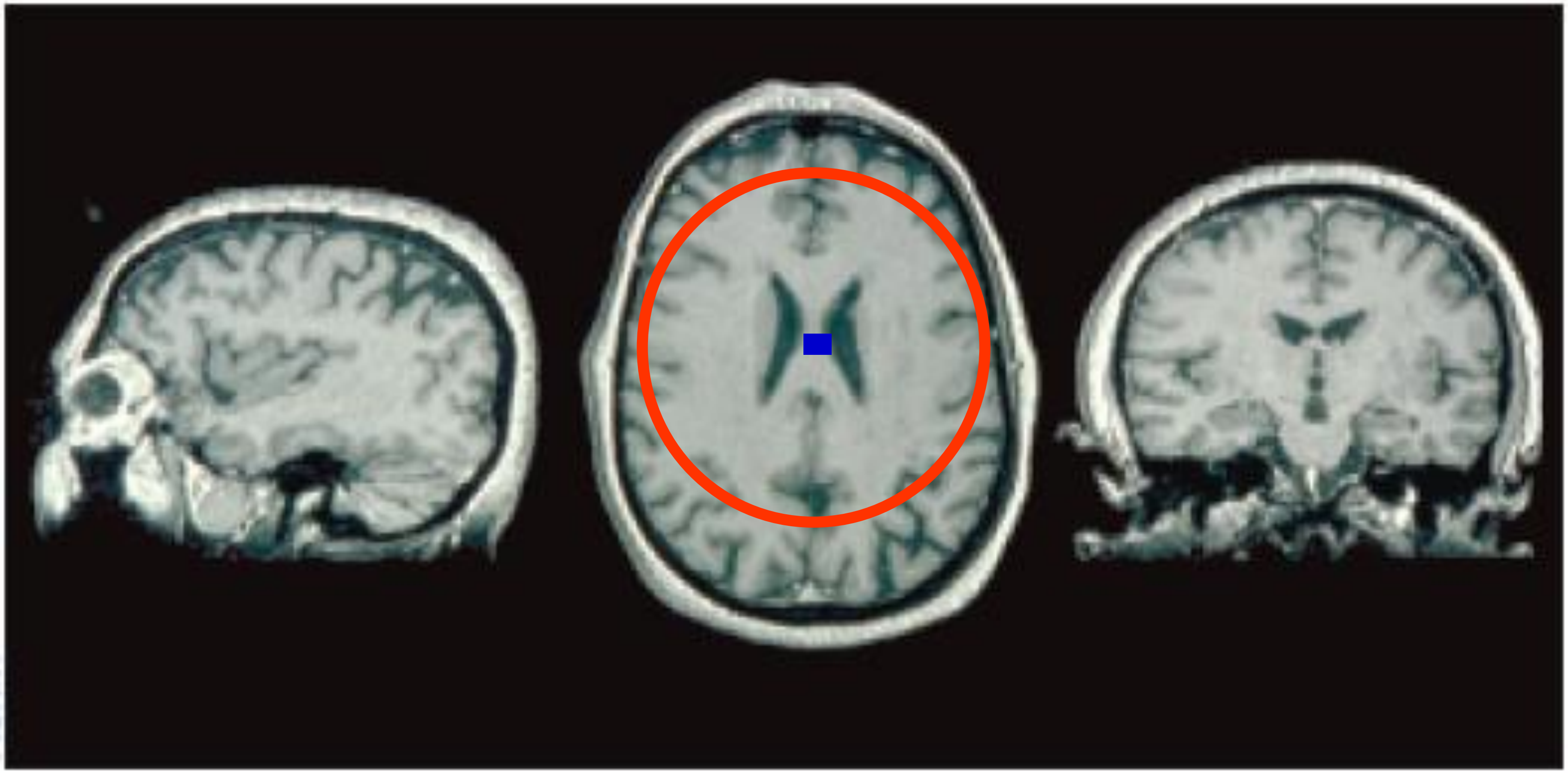
Magnetic Resonance Imaging





Signal is proportional to
an external applied field
Detection at a frequency related to the field
1Tesla : 42.57MHz

LOW FIELD MRI



At 1 Tesla a 1mm^3 voxel create a mean field of 10fT in the coil
At 10mT it is 0.1fT

LOW FIELD MRI

Advantages

- ➢ Low cost system
- ➢ Open system with no noise
- ➢ Can accept metallic implants
- ➢ transportable system is possible
- ➢ Contrasts are different
- ➢ noise is not limited by the body noise.

Drawbacks

- ➢ Signal is smaller→ has to be compensated by sensor noise

LOW FIELD MRI SNR CONSIDERATIONS

At 10mT signal is 150 times smaller than at 1.5T

But

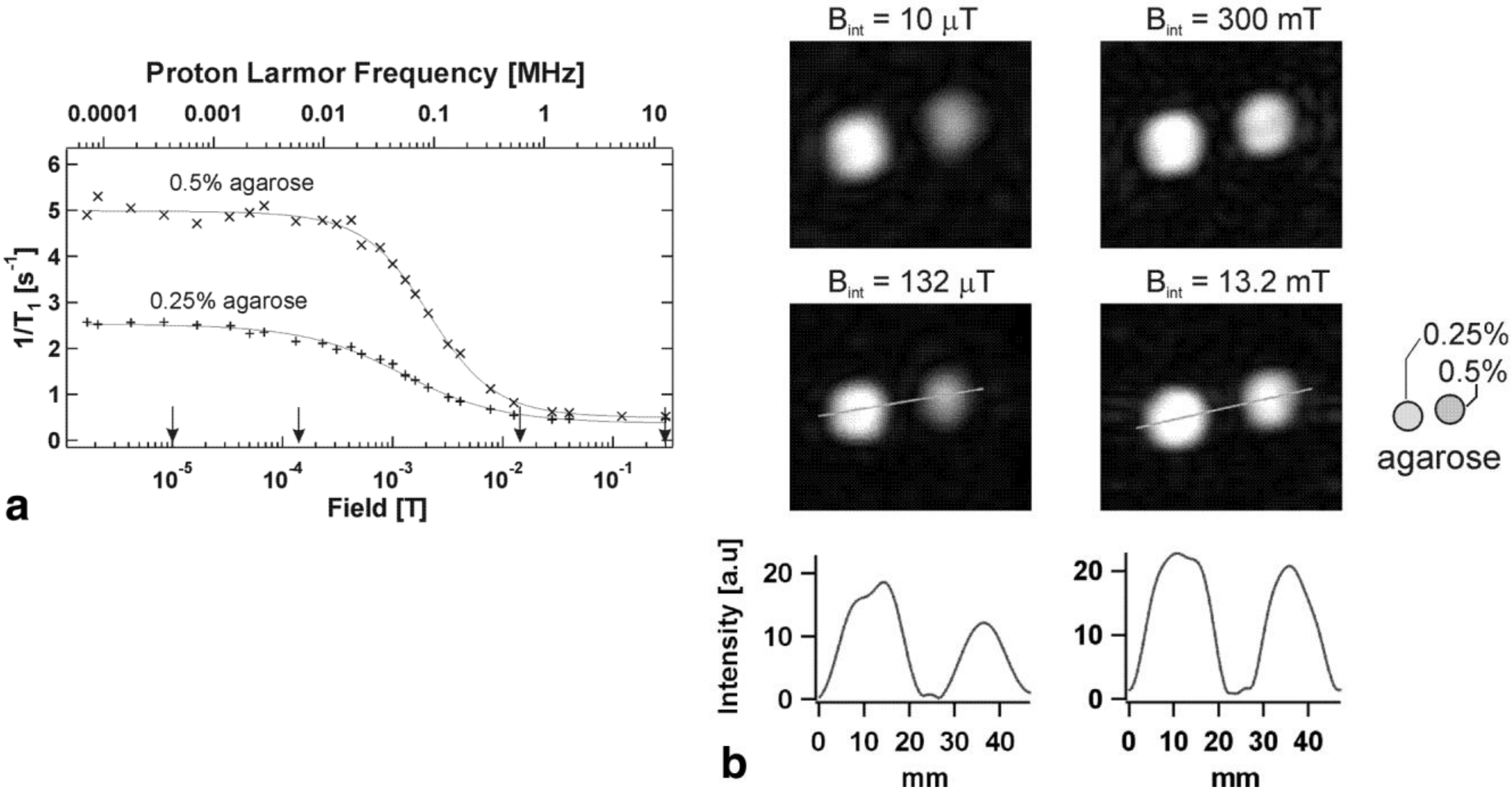
Bandwidth is sqrt(150) smaller→ 12 times gain
Contrasts may be different.
Body noise is smaller (30% less)

A factor of 8-10 is SNR is just a factor of 2 in resolution.

Requirement

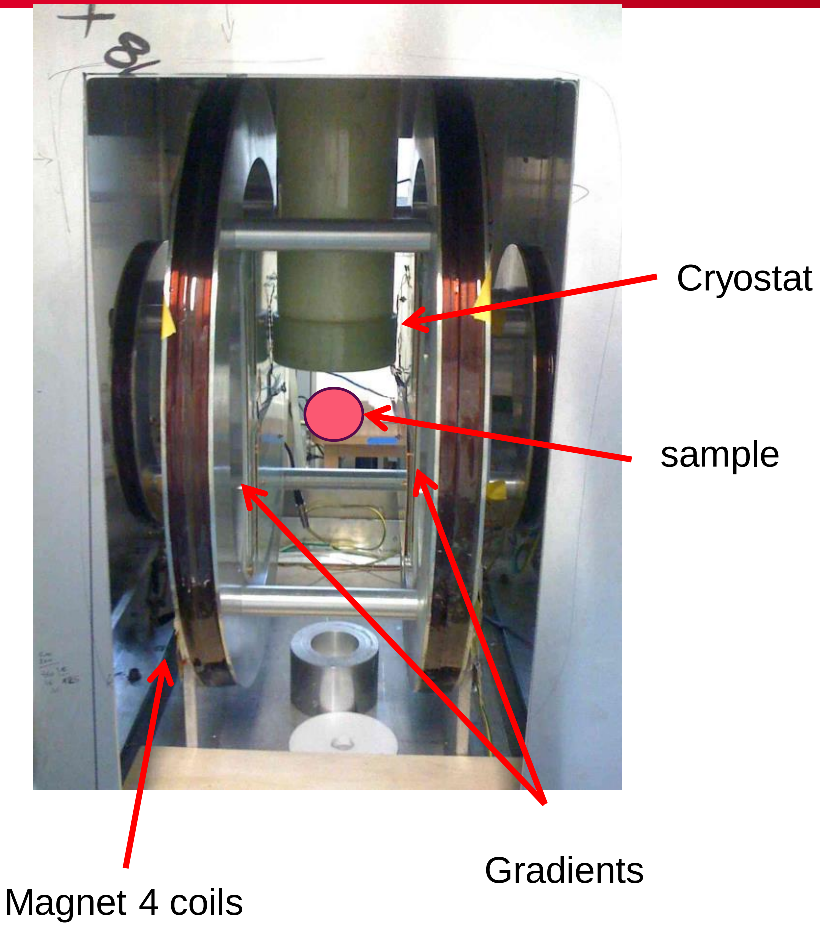
The noise of the sensor should be low enough.

LOW FIELD MRI

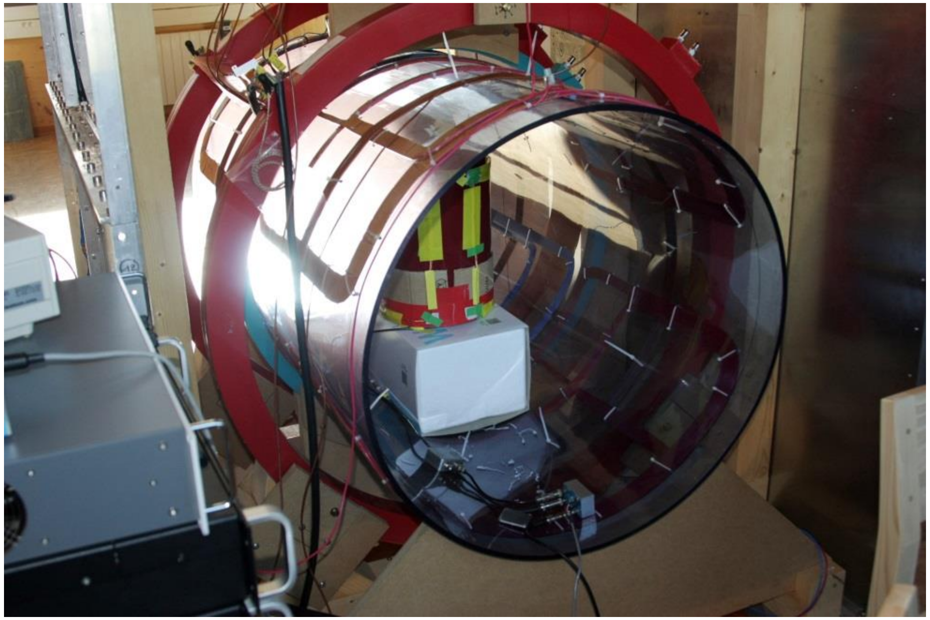


Courtesy John Clarke

LOW FIELD MRI SETUPS

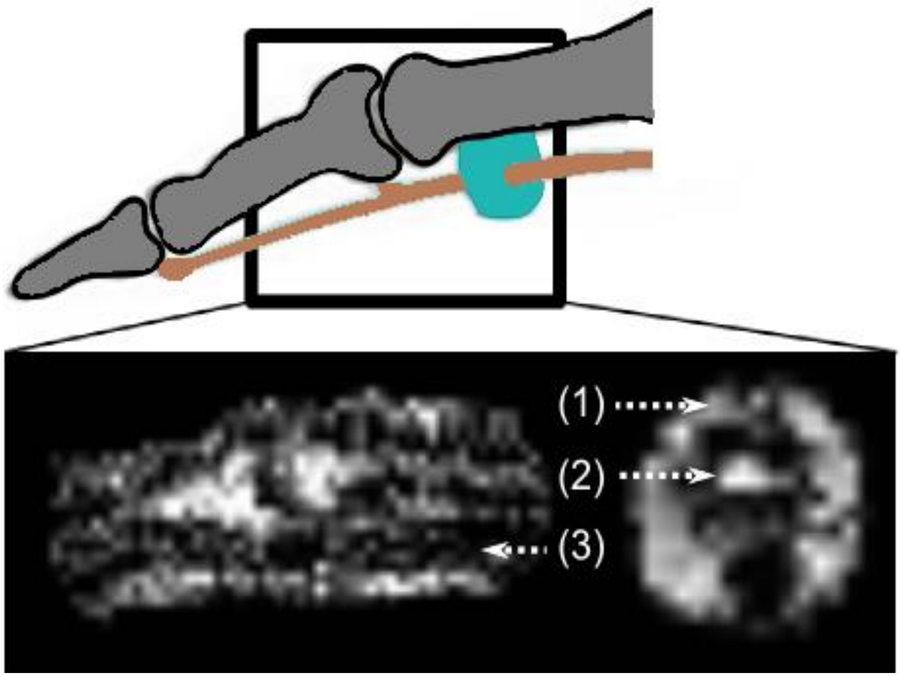


Small size device.
Direct mixed sensor detection

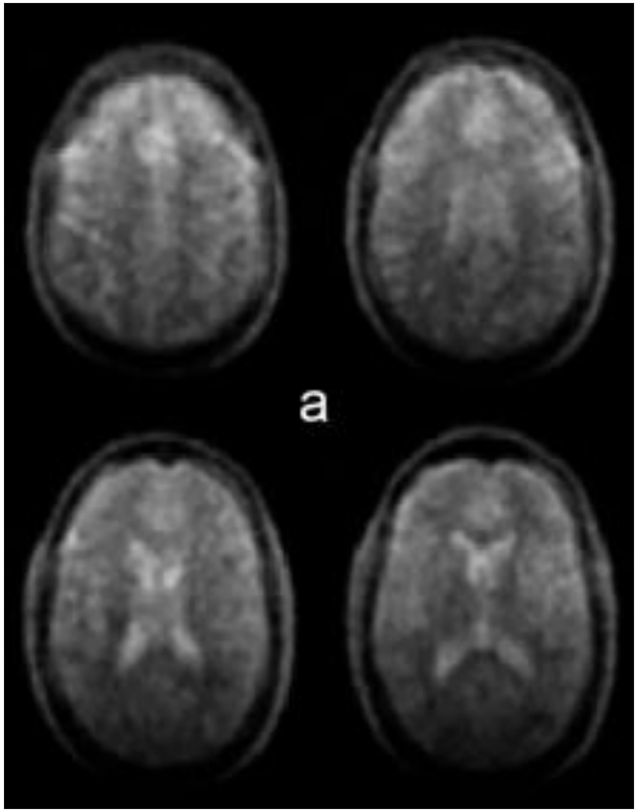


Full head device
Flux coupled mixed sensors detection

LOW FIELD MRI

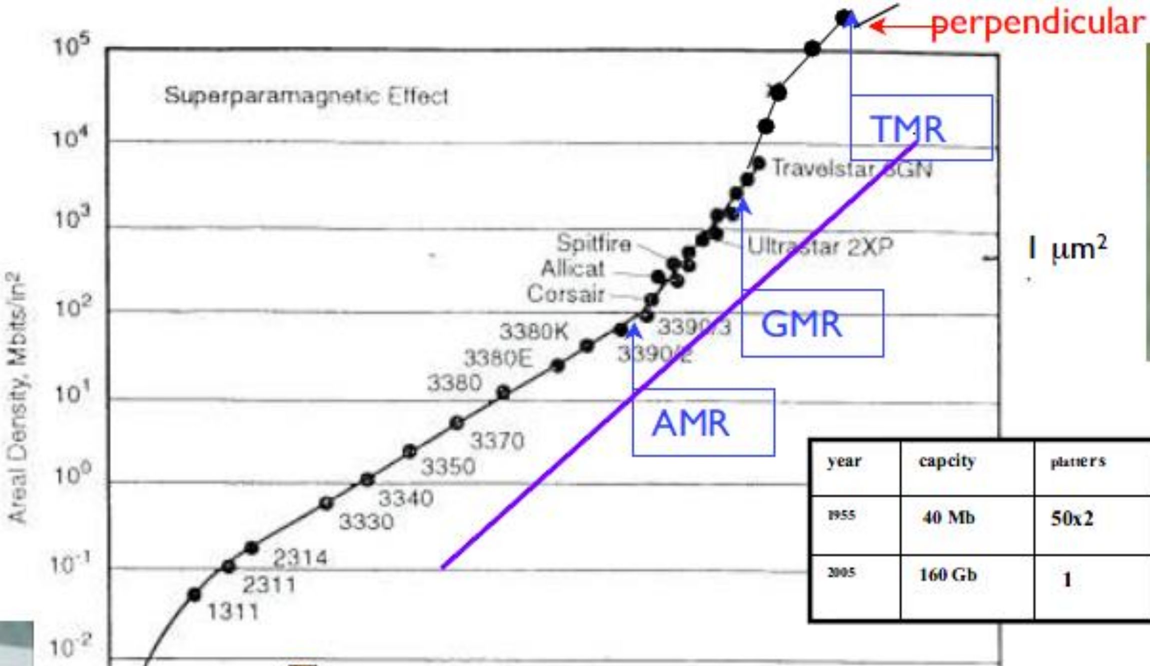


3D MRI of a finger at 7mT with 1x1x2mm resolution

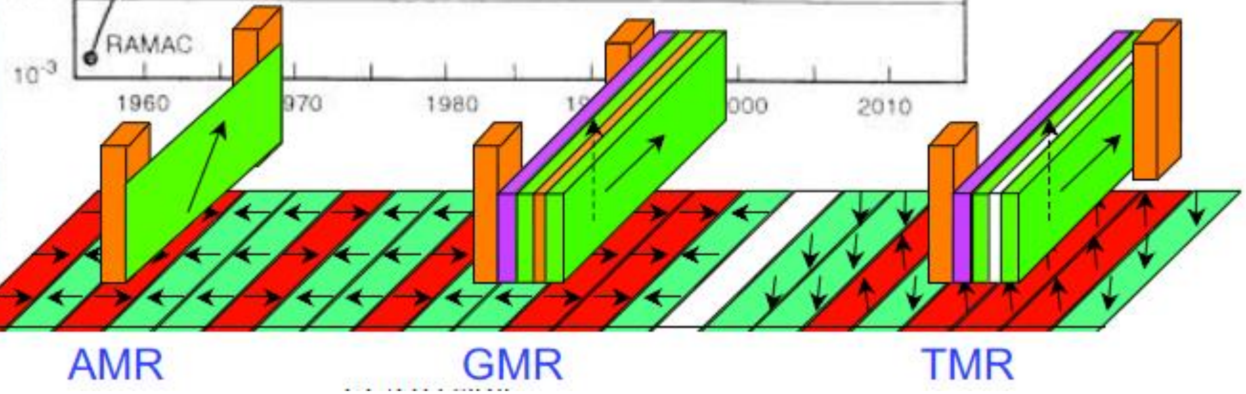


Sarracanie et al, nature scientific Reports 2015. brain images.
6 minutes

AND THE HARD DISKS



year	capcity	platters	size	rpm
1955	40 Mb	50x2	24"	1200
2005	160 Gb	1	2.5"	18000



Typical size is 50nm and frequency >100MHz
CPP GMR begins to be competitive (less noise)

MAGNETIC SENSOR PART SUMMARY

TMRs and GMRs have different advantages and drawbacks.

Spin electronics based sensor are covering a lot of existing applications down to femtoTesla range

They are bringing sensitivity compared to Hall technology but design is essential as their response is an angle between two layers

Now integration with CMOS is fully operational on 200mm.

CONTENTS

AND THE DYNAMICS?

The Dynamics of the magnetic layer is controlled by the Landau-Lifshitz-Gilbert equation.

$$\frac{d\vec{M}}{dt} = -|\gamma|\mu_0\left(\vec{M}\times\vec{H}_{eff}\right) + \frac{\alpha}{\left\|\vec{M}\right\|}\left(\vec{M}\times\frac{d\vec{M}}{dt}\right)$$

28GHz/T

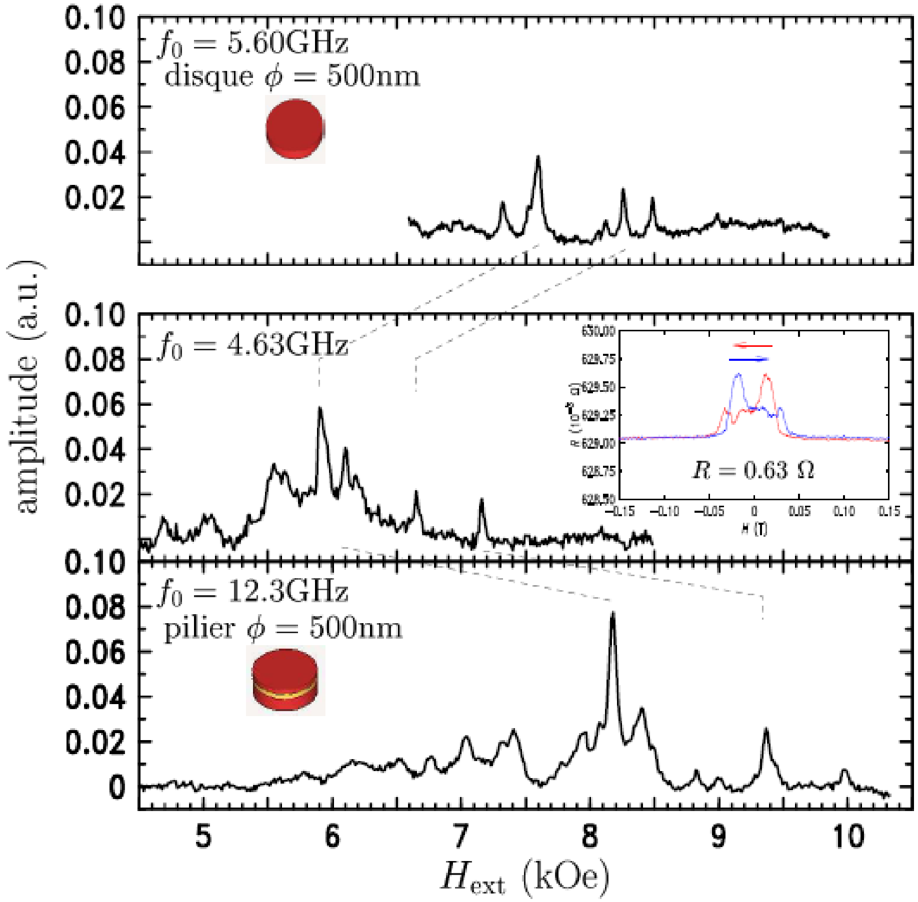
Damping

Precession

The magnetic excitations, magnons, are controlled by that equation.
Several modes : a fundamental modes and a lot of excitations.

A new field of spintronics called magnonics try to exploit these excitations to transport information and perform logics

AND THE DYNAMICS?



At 0 external field, there are also excitations due to internal field.

The response of a sensor will be linear up to GHz frequencies.
The GMR effect is still constant.
The time reversal of a MRAM is in the range of ns.

AND THE DYNAMICS?

The reversal of a magnetic layer is also related to LLG equation.
Hence reversal in ns range is possible, ps range not.

Except in one case : insulating antiferromagnet have a dynamics in the THz range

Some materials have a small damping : NiFe, Heusler alloys
The propagation of spin waves is in the range of 10-100µm.

Damping is mainly due to the interaction of spin waves and conduction electrons.

One specific material YIG and magnetic insulator has a spin wave propagation of cm.

DYNAMICS AND SPIN TORQUE

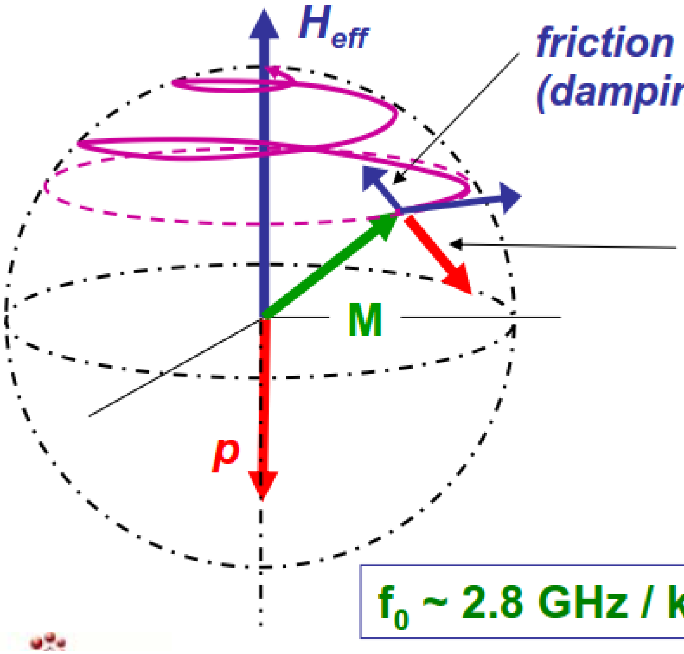
the Landau-Lifshitz-Gilbert (LLG) equation

$$\frac{d\vec{M}}{dt} = -|\gamma|\mu_0\left(\vec{M}\times\vec{H}_{eff}\right)+\frac{\alpha}{\left\|\vec{M}\right\|}\left(\vec{M}\times\frac{d\vec{M}}{dt}\right)$$

+ the "spin transfer torque"

$$\underbrace{-\,G\;j\;\vec{M}\times\left(\vec{M}\times\vec{p}\right)}$$

≠ 0 only
if *M* and *p* are
non colinear



friction torque
(damping)

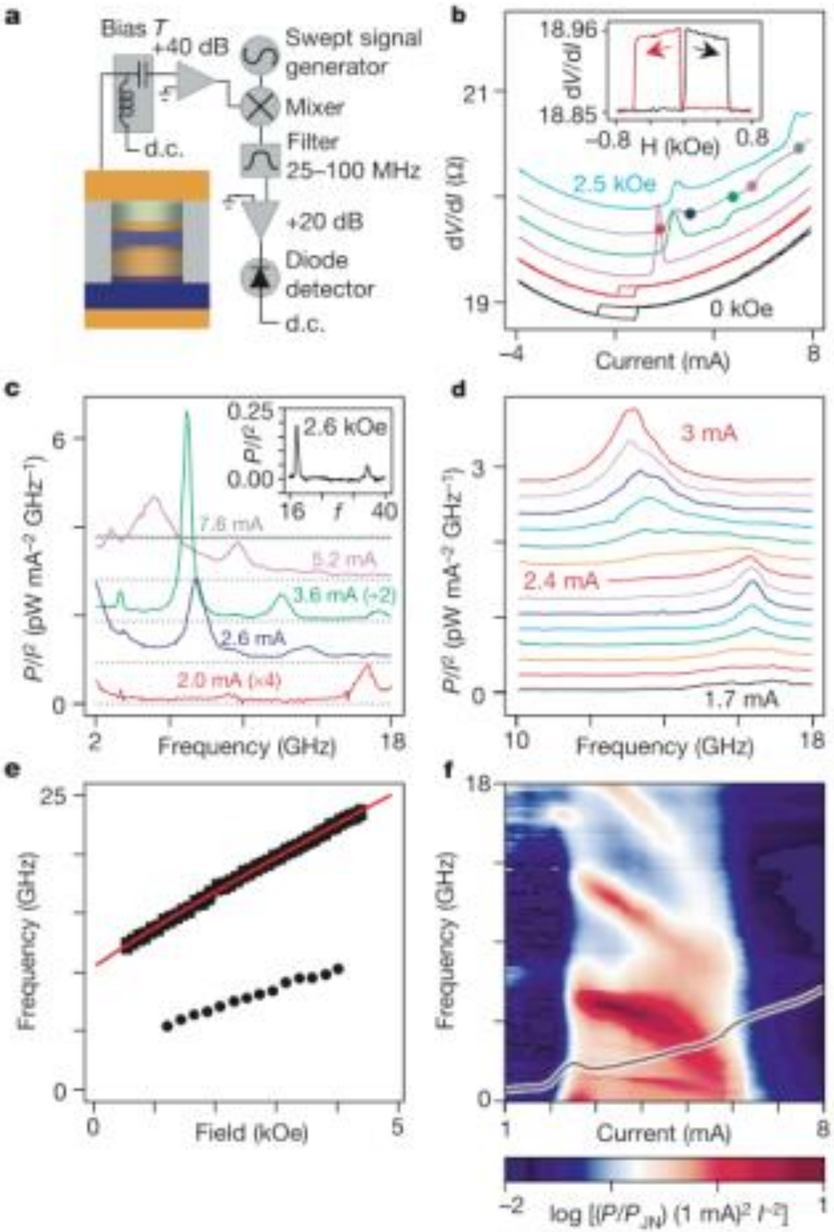
"negative friction" torque induced by spin transfer

f_0 ~ 2.8 GHz / kOe

We can have a state where the torque compensate the friction

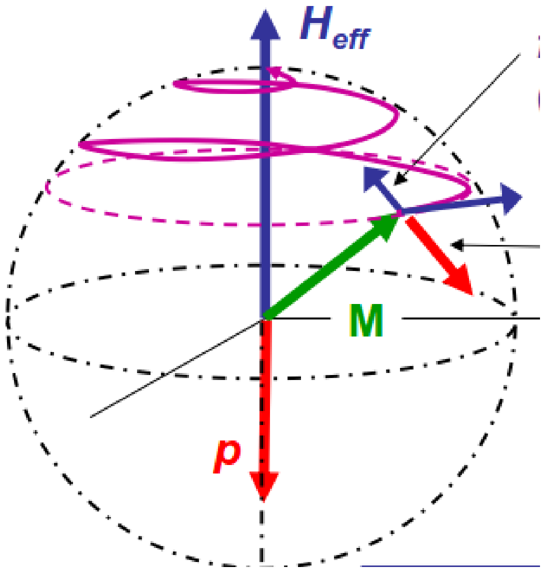
CONTENTS

SPIN TORQUE NANO OSCILLATORS (STNOS)



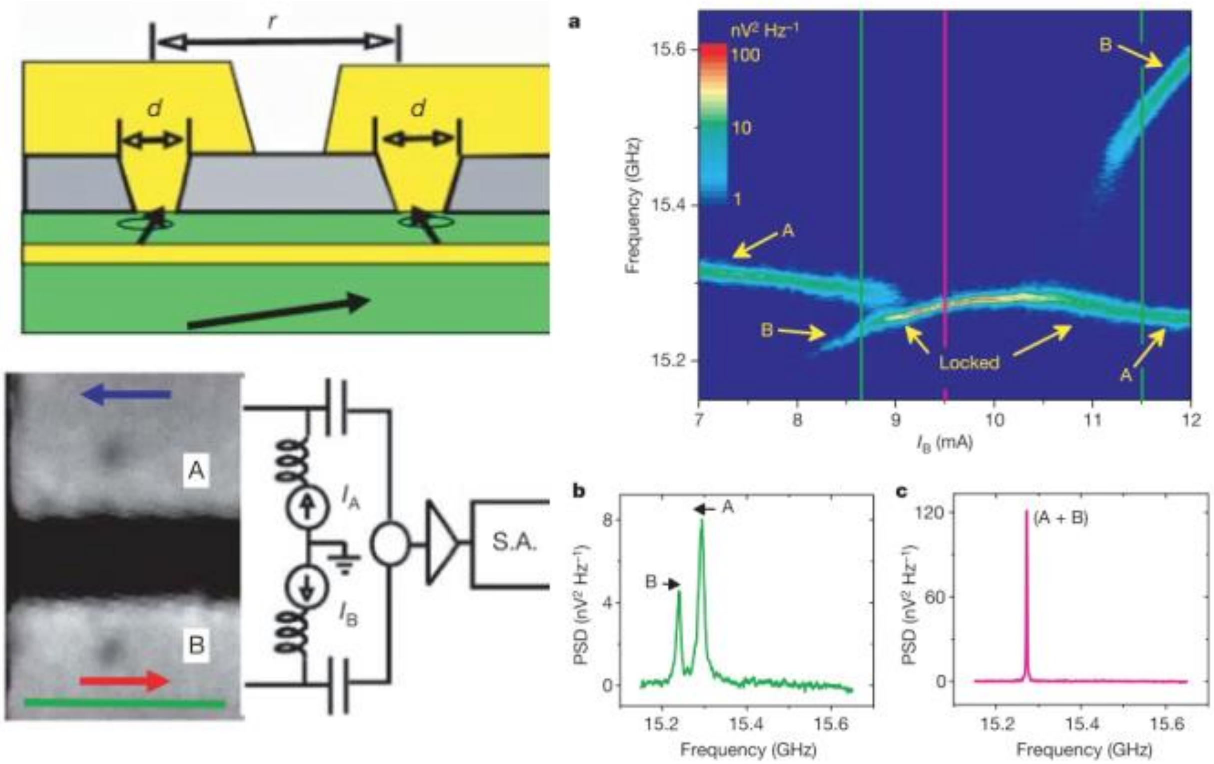
Liselev et al, Nature 2003

Generation of a GHz field with a DC current. The frequency is controlled by the external field→ excitation mode of the pilar.



SPIN TORQUE NANO OSCILLATORS (STNOS)

Synchronization of oscillators

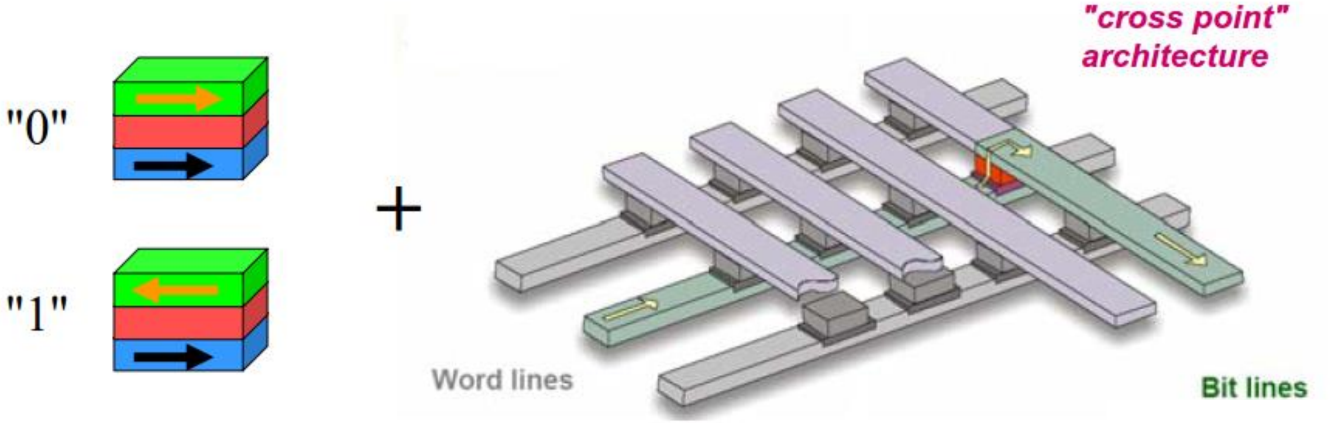


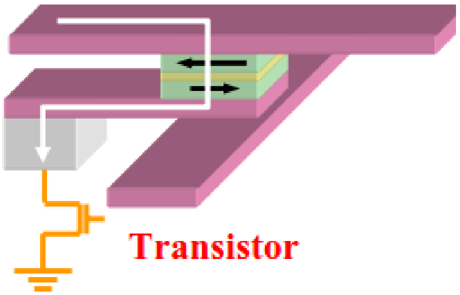
Kaka et al., Nature 2005 and Mancoff et al. Nature 2005

Now power of about 1µW achieved but good agility.

MRAMS

MRAM principle. A MTJ cell stores the bit

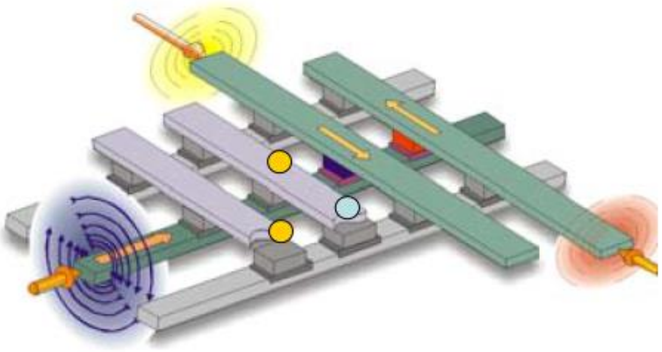


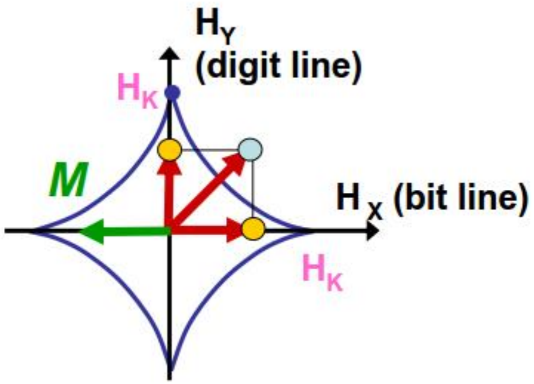


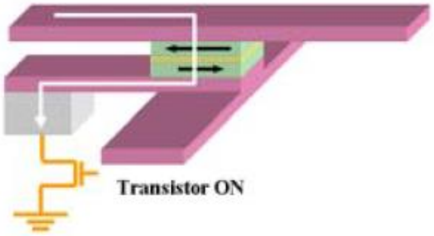
The MR ratio is large enough so the reading is easy and fast.
The writing is more complicate.
Just sending a field through a current line is not enough accurate and corresponds to a large consumption.
2 opposite requests : a easy writing and a high stability.

MRAMS CONVENTIONAL APPROACH

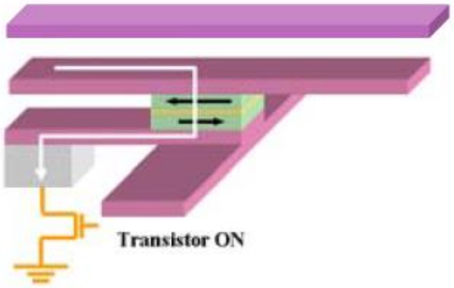
Everspin approach for conventional MRAM
2 current lines are used and rotation is done by several pulses





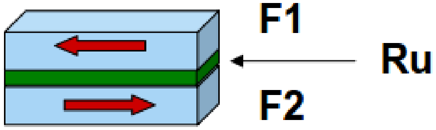


OR



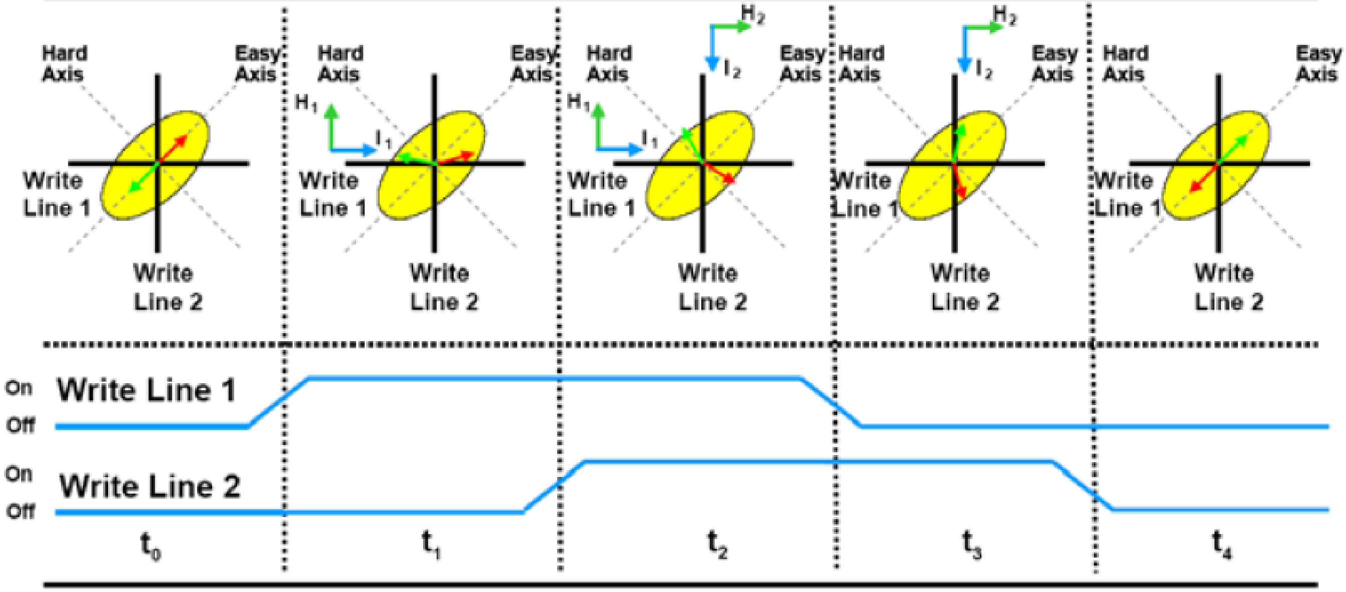
...

MRAMS CONVENTIONAL APPROACH



- *free layer = synthetic antiferromagnet*
- *current lines at 45 deg. of easy axis*

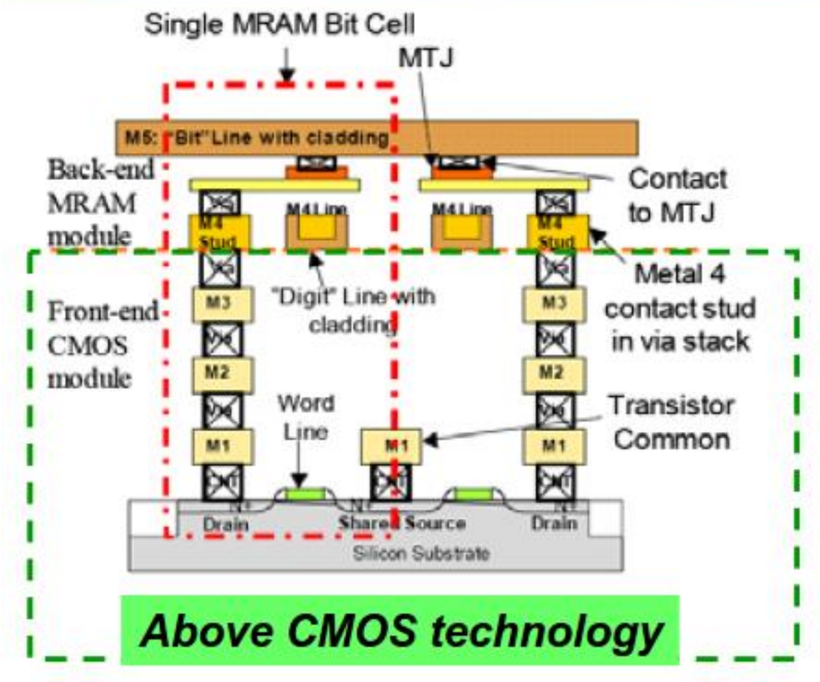
➔ toggle switching mode

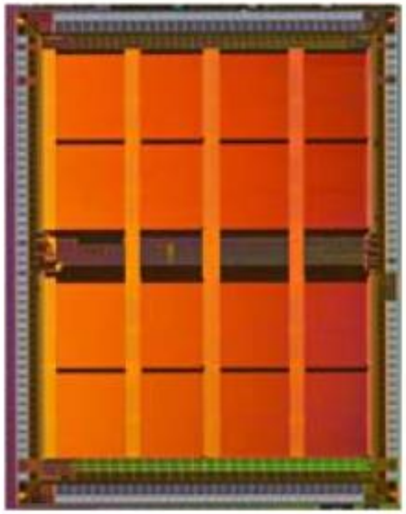


B. N. Engel et al., IEEE Trans. Magn. 41, 132 (2005)

Robust writing but a large consumption.

MRAMS CONVENTIONAL APPROACH





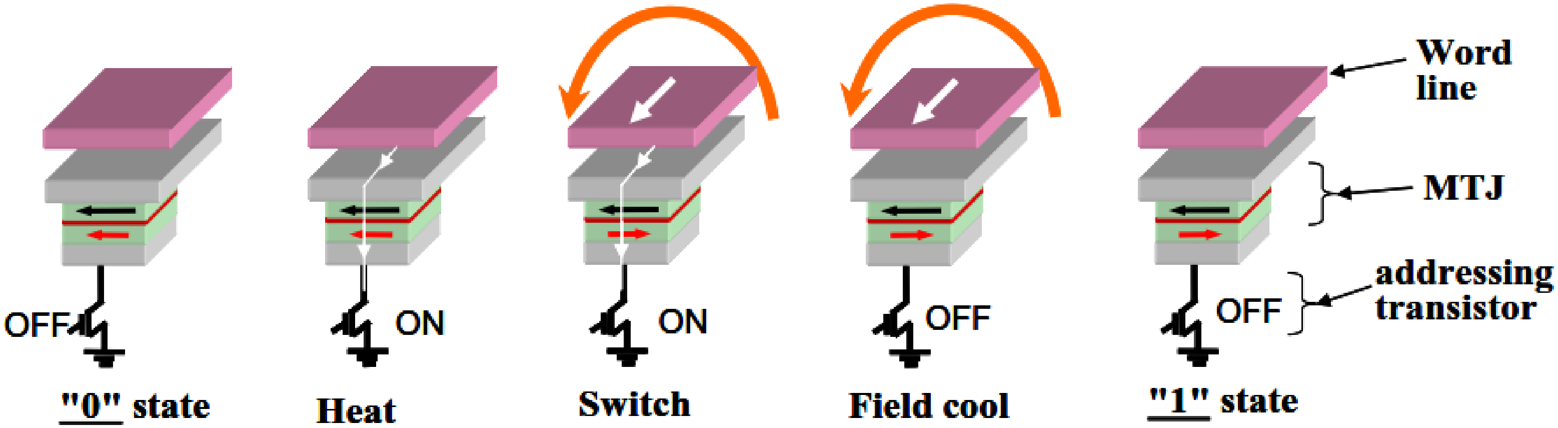
64 Mbits memory
Everspin

Specific markets where reliability is important and size, consumption not critical.

MRAMS TAS

Principle : heat allows less current consumption for switching

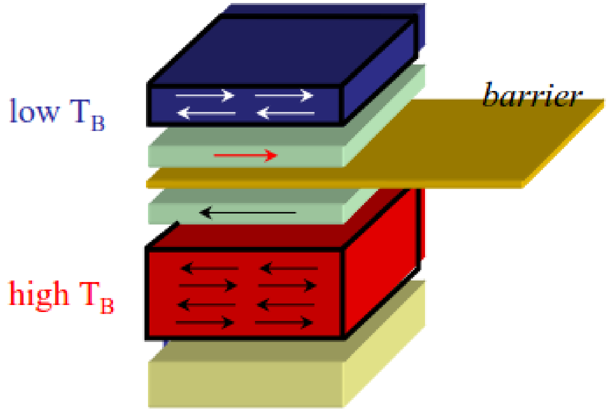
From a "0" ….. **… to a "1"**



spintec
SPIN IN ELECTRONICS

CROCUS Technology
Blossoming Future

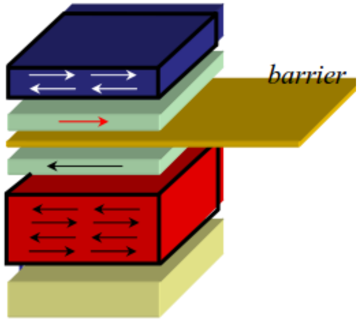
Exchange biased storage layer is SAF/AF multilayer

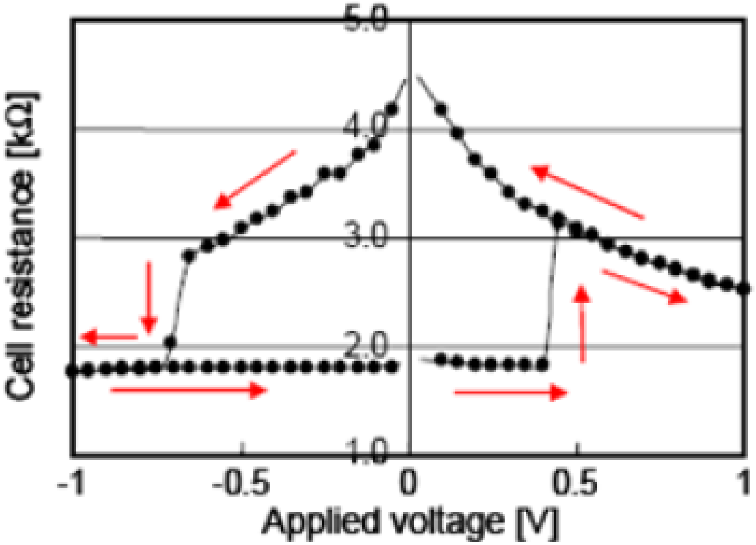


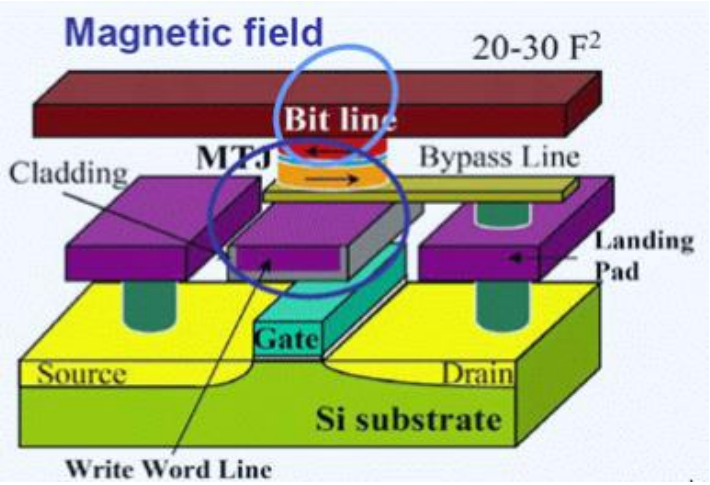
Better than conventional MRAM but not enough for scalability

STT-RAM

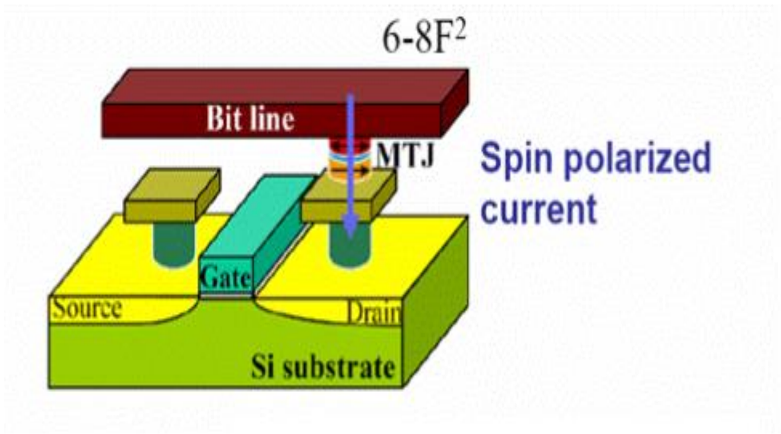
Principle : use the spin torque effect to rotate the magnetization of the second layer







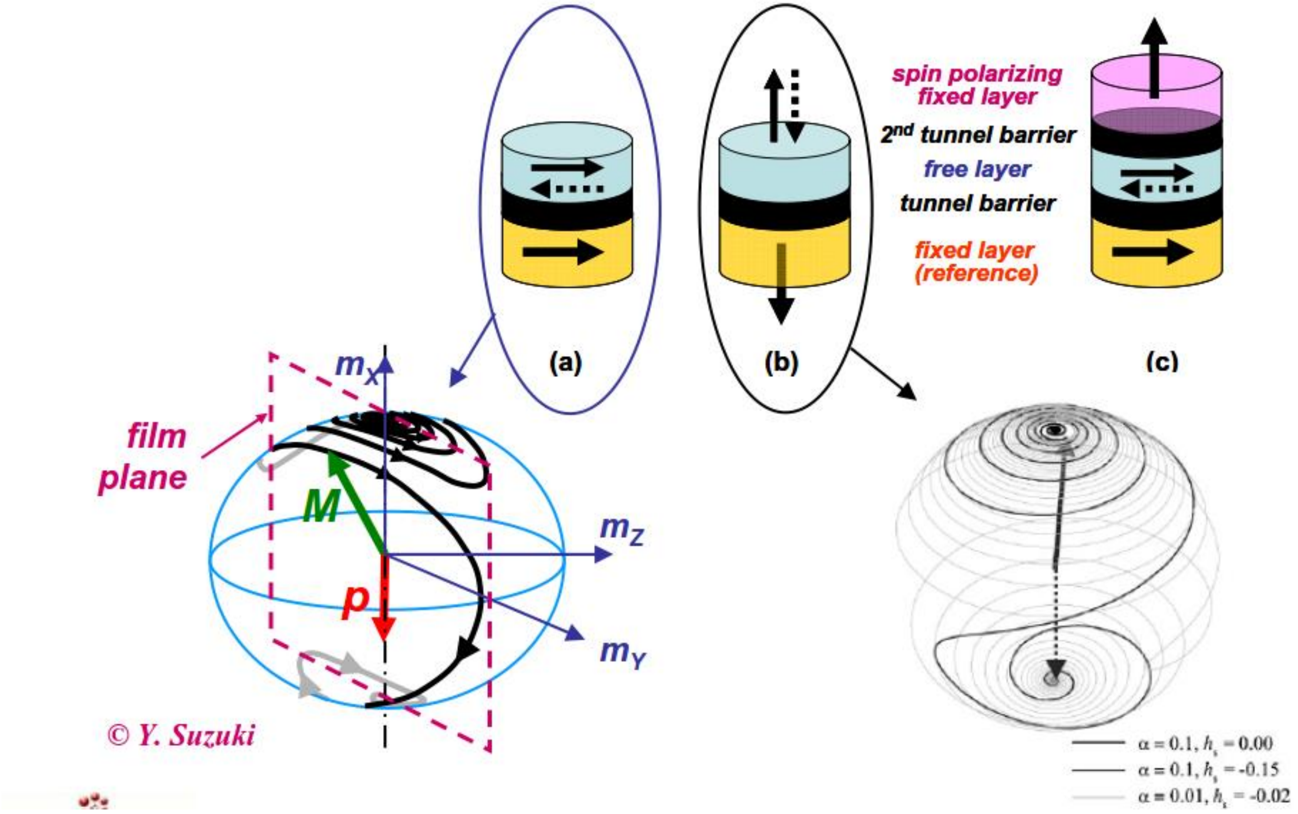
Conventional cell



STT-Cell

STT-RAM

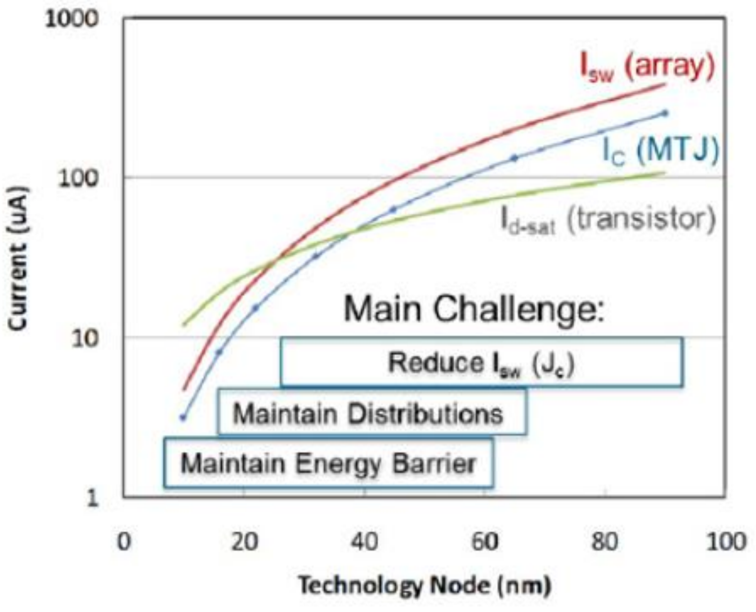
Various configurations for STT-RAM



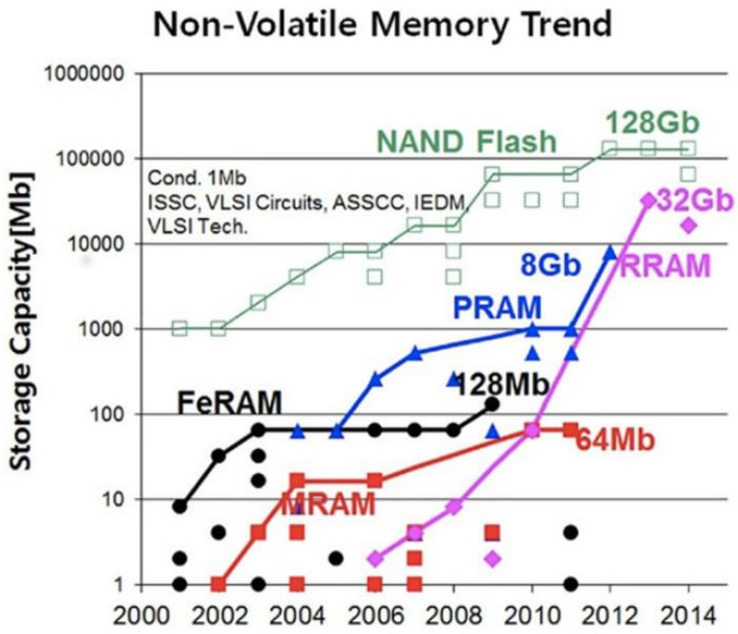
Perpendicular configuration is presently the most promising

In 2010 Toshiba presented a 256kbits perpendicular STT RAM

STT-RAM



$6F^2$ cell is possible with scaling

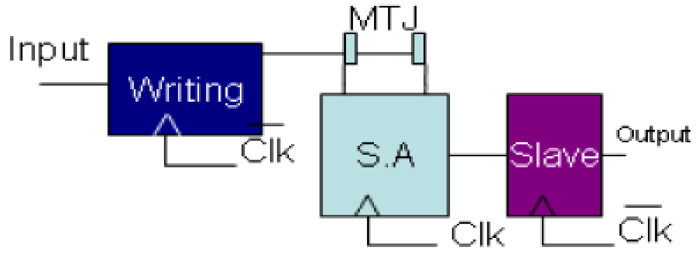


Storage capacity trend of emerging non-volatile memories.

Syed M. Alam (salam@alum.mit.edu)
Everspin Technologies, Inc.

2015 : Avalanche technologies has produced 64Mbits pSTT-MRAM

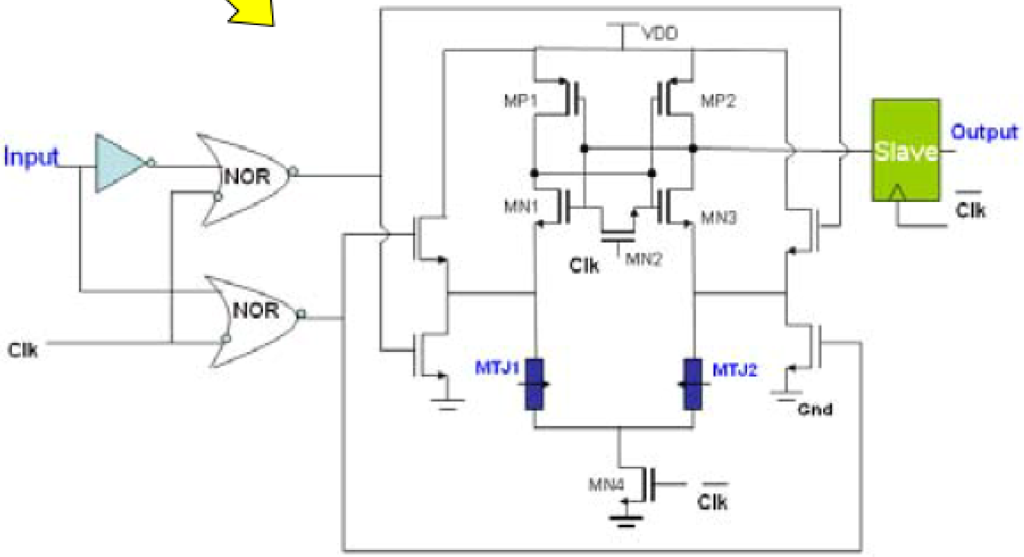
MAGNETIC LOGIC-MRAM EXTENSION

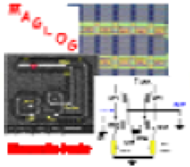


master slave flip-flop based on spin transfer switching
➔ non volatile,
➔ instant on/off
➔ record all intermediate calc. steps

if :
- CMOS compatible I_{WR}
- writing speed at processor's rate (~3 GHz)

➔ e-MRAM could enter the CPU !!!





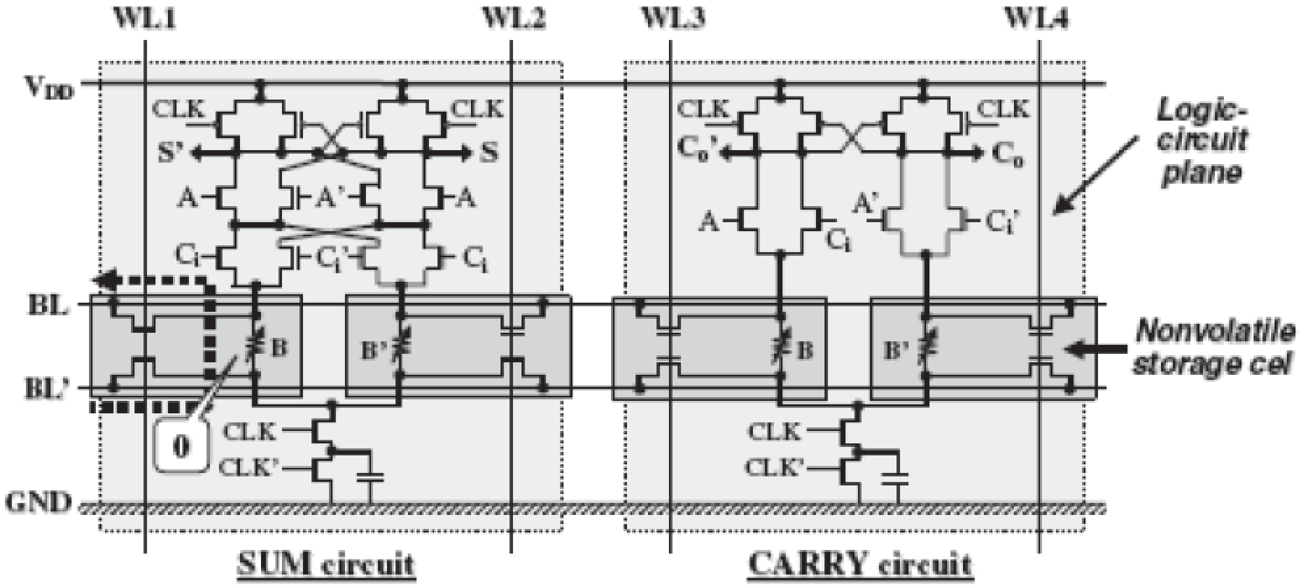
STREP
MAGLOG
W. Zhao, E. Belhaire (IEF), V. Javerliac, B. Dieny (SPINTEC)
P. Mazoyer, F. Jacquet (ST Microelectronics)

MAGNETIC LOGIC-MRAM EXTENSION

Fabrication of a Nonvolatile Full Adder Based on Logic-in-Memory Architecture Using Magnetic Tunnel Junctions

Shoun Matsunaga, Jun Hayakawa[1], Shoji Ikeda[2], Katsuya Miura[1,2],
Haruhiro Hasegawa[2], Tetsuo Endoh[3], Hideo Ohno[2], and Takahiro Hanyu*

(a)



MRAM SUMMARY

MRAM technology is very promising

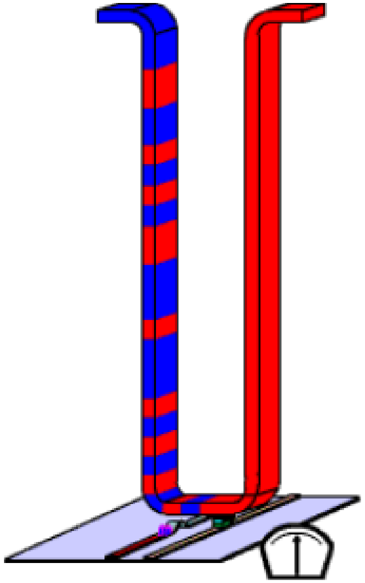
Path to real products with large storage capacity is longer than first expected but they arrive.

pSTT-MRAM is the most promising technology for scalability

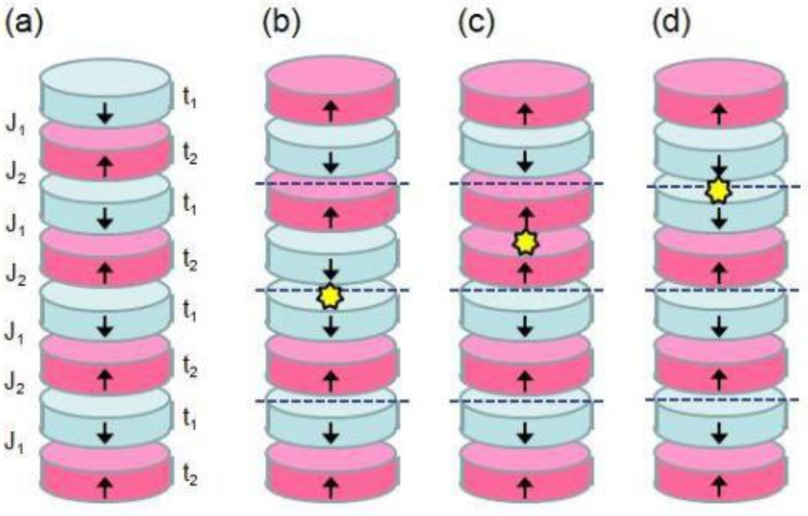
MRAM-FPGA combination will also be implemented in the future for local storage and reconfiguration.

DOMAIN WALL MOTION AND STORAGE

Principle : still based on spin torque effect.
In a domain wall, the magnetization is rotating and hence a current can apply a force able to move a domain wall.



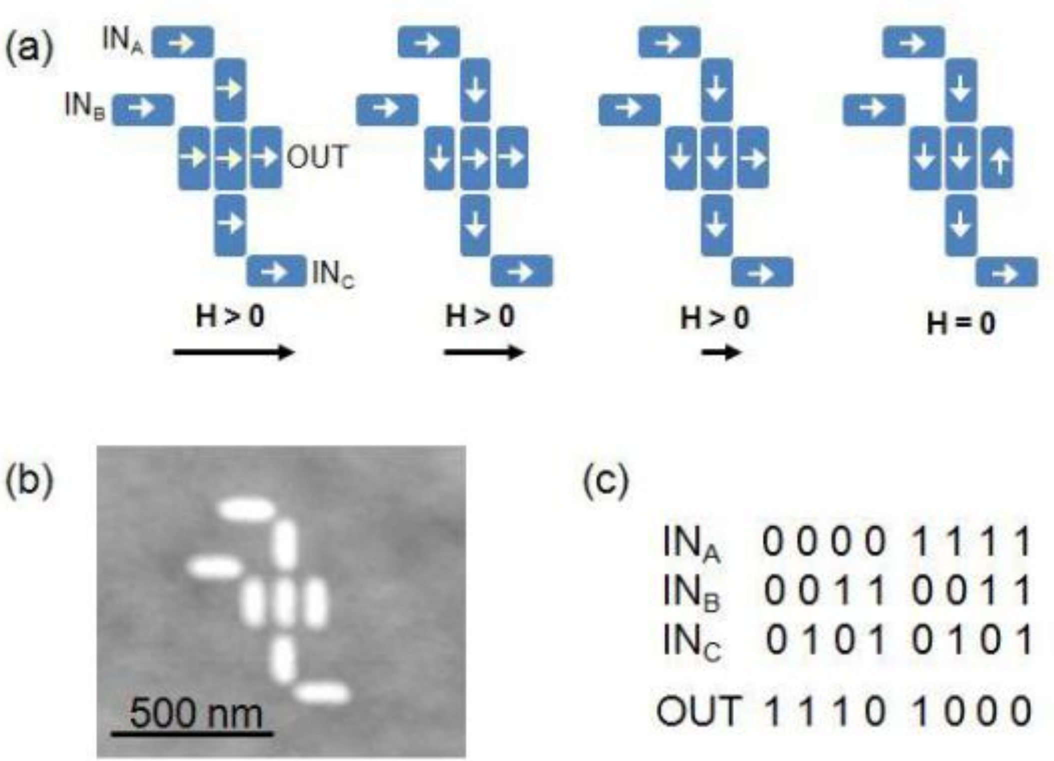
Racetrack proposed by Parkin 2008



Lavrijsen et al, Nature 2013

NANOMAGNET LOGIC

Principle small ferromagnetic dots are coupled and a reversal of one dot is propagating. Logic computing can then be made
Lower consumption than similar operation in cmos devices

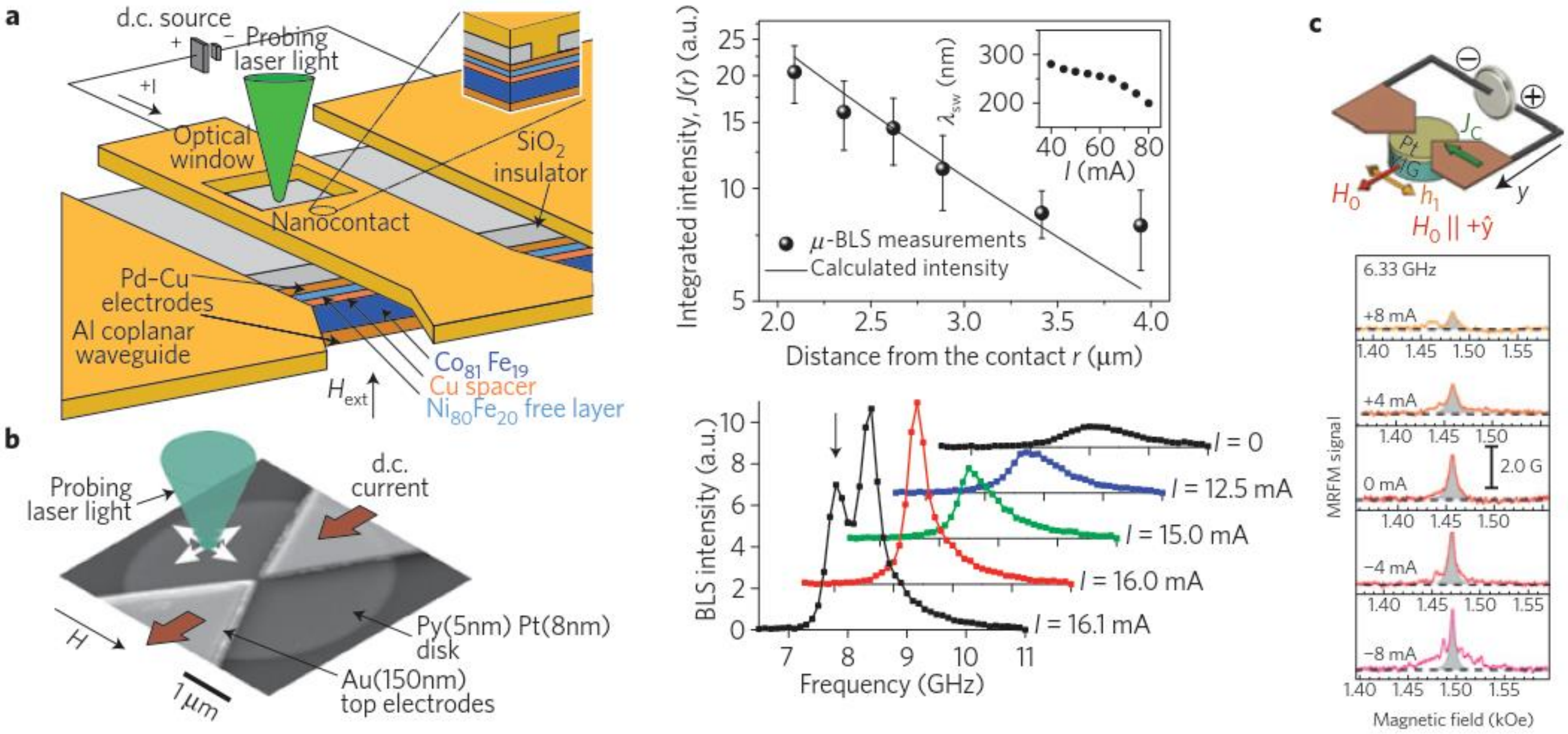


IN_A	0	0	0	0	1	1	1	1
IN_B	0	0	1	1	0	0	1	1
IN_C	0	1	0	1	0	1	0	1
OUT	1	1	1	0	1	0	0	0

Imre A et al, science 2006

MAGNON SPINTRONICS

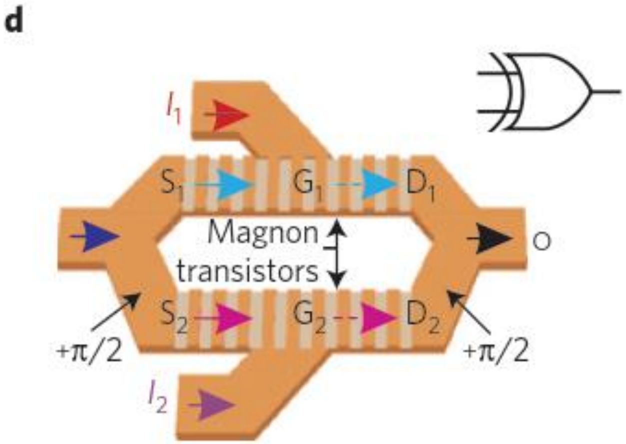
First step : creation of spin waves by STNOs



Chumak A.V. et al, Nature physics 2015

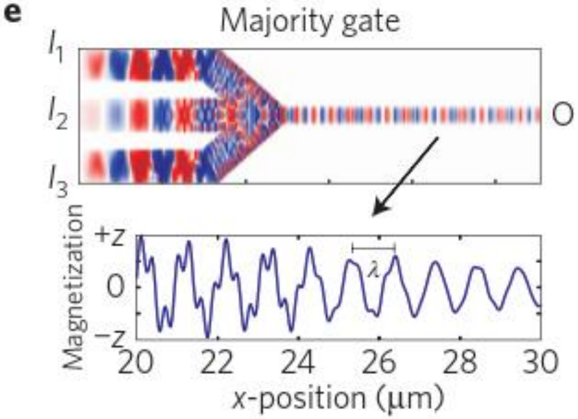
MAGNON SPINTRONICS

second step : operations with spin waves

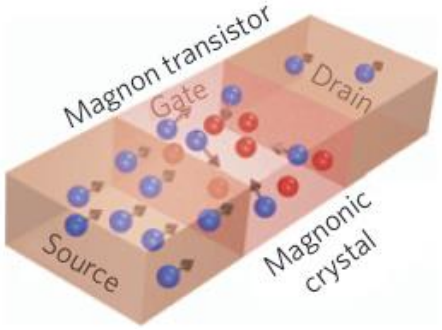


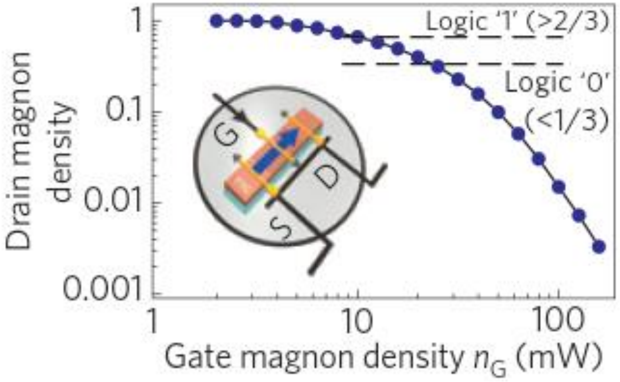
XOR

I_1	I_2	O
0	0	0
0	1	1
1	0	1
1	1	0



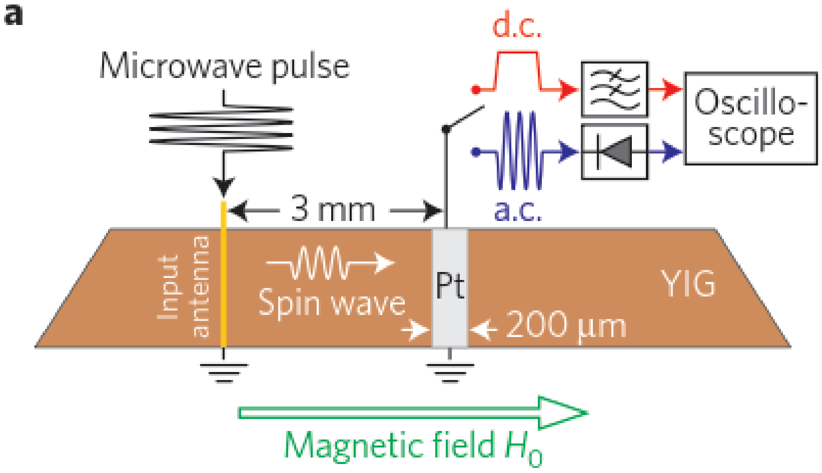
Magnon transistor

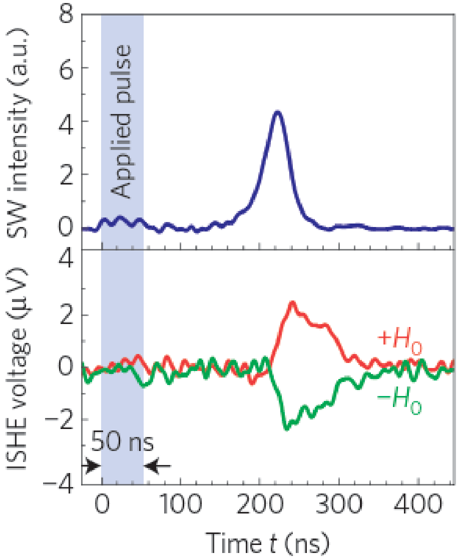




MAGNON SPINTRONICS

Last step conversion to charge information

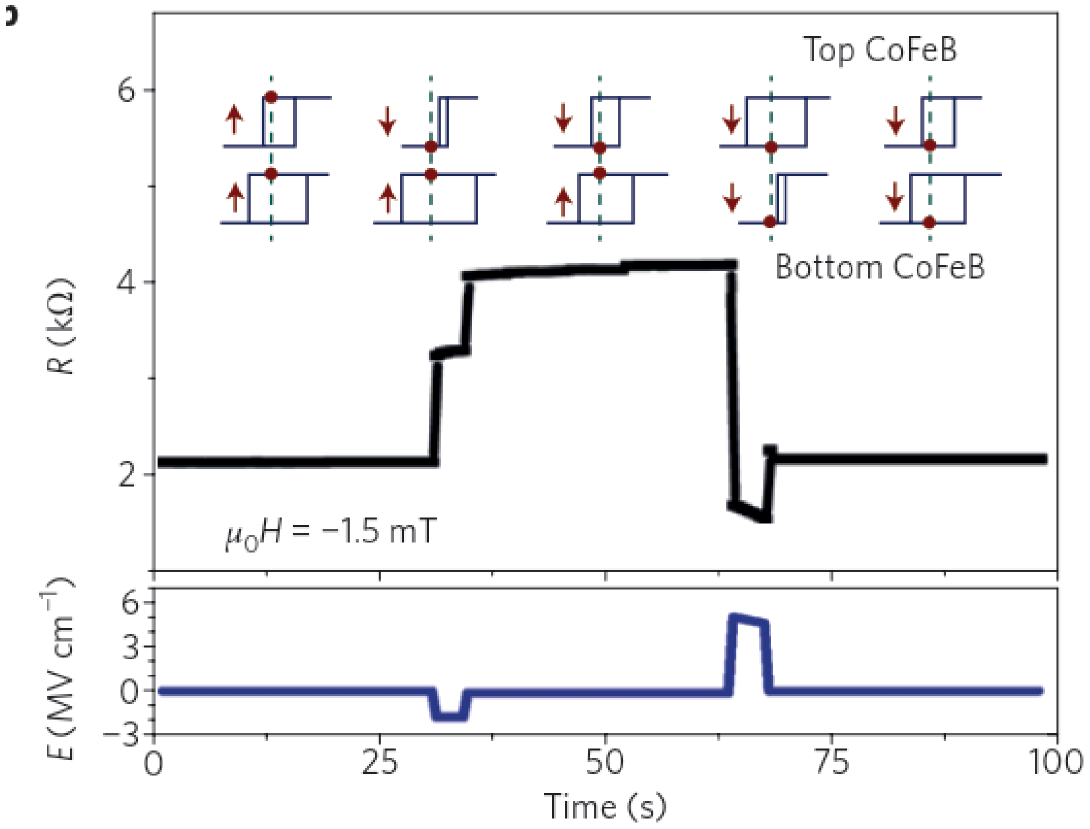




Today, all steps are existing but the energy loss are too high to be applicable

CONTROL OF MAGNETISM BY ELECTRIC FIELDS

Large electric fields can modulate the switching of a CoFe/Mgo/COFe barrier



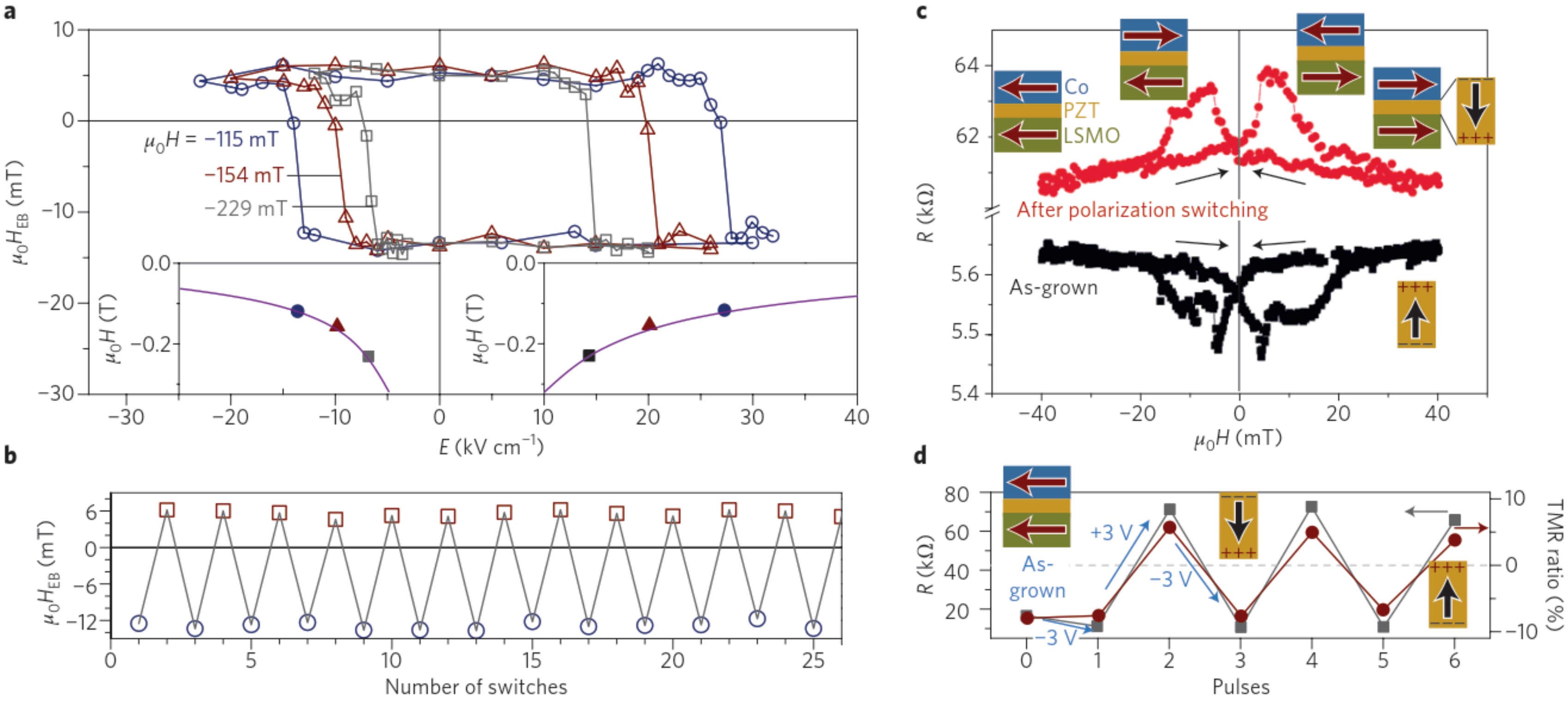
Wang W. Nature mat 2012

CONTROL OF MAGNETISM BY ELECTRIC FIELDS

New materials called multiferroics where piezzo-electricity and magnetism are coupled

BiFeO3 is the most studied.

Another example Co/PZT/LSMO tunnel junction



HE, X. ET. AL. NATURE MATER. (2010).,PANTEL D ET AL, NATURE MAT (2012)

CONCLUSIONS

Still a lot of other aspects of spintronics

- Spin hall effects,
- pure spin current generation
- skyrmions and topological magnetic objects

Every month a new concept appears in spintronics. It is however difficult to predict what will be effectively applied in devices.

Despite a large number of proposals, a real spin transistor with an effective gain is still missing. Perhaps the electric field manipulation of magnetization will open that way.

But spintronic magnetic sensors are now largely implemented,
MRAMs is also a reality.