# Spintronic components for memories, logic and RF applications

**OUTLINE**

**Giant MagnetoResistance (GMR),**

- **Benefit in magnetic recording technology**

**Tunnel Magnetoresistance (TMR)**

**Spin-transfer**

- **Magnetic Random Access Memories (MRAM)**
- **Hybrid CMOS/MTJ components for non-volatile and reprogrammable logic**
- **Radio Frequency oscillators based on spin-transfer**

**Conclusion**

# Acknowledgements


spintec SPIN IN ELECTRONICS

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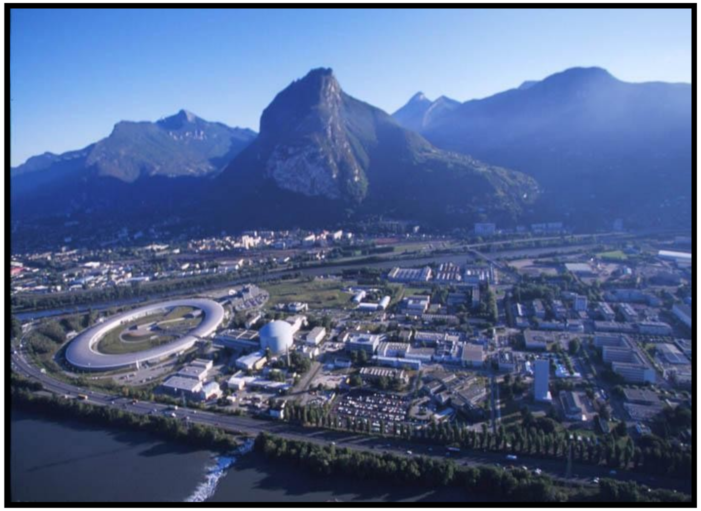


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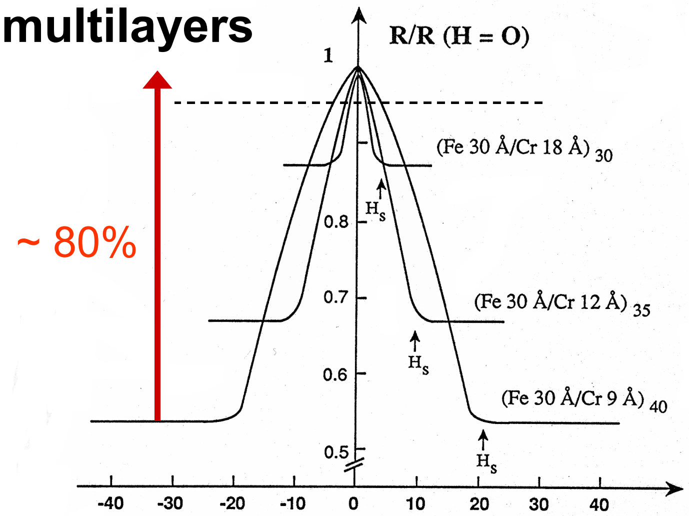
# Development of spin-electronics: strong synergy between basic research and applications

**Fe/Cr multilayers**




**Magnetic field (kOe)**

*A.Fert et al, PRL (1988); P.Grunberg et al, PRB (1989)*

$\Delta R/R_P$~80% at RT

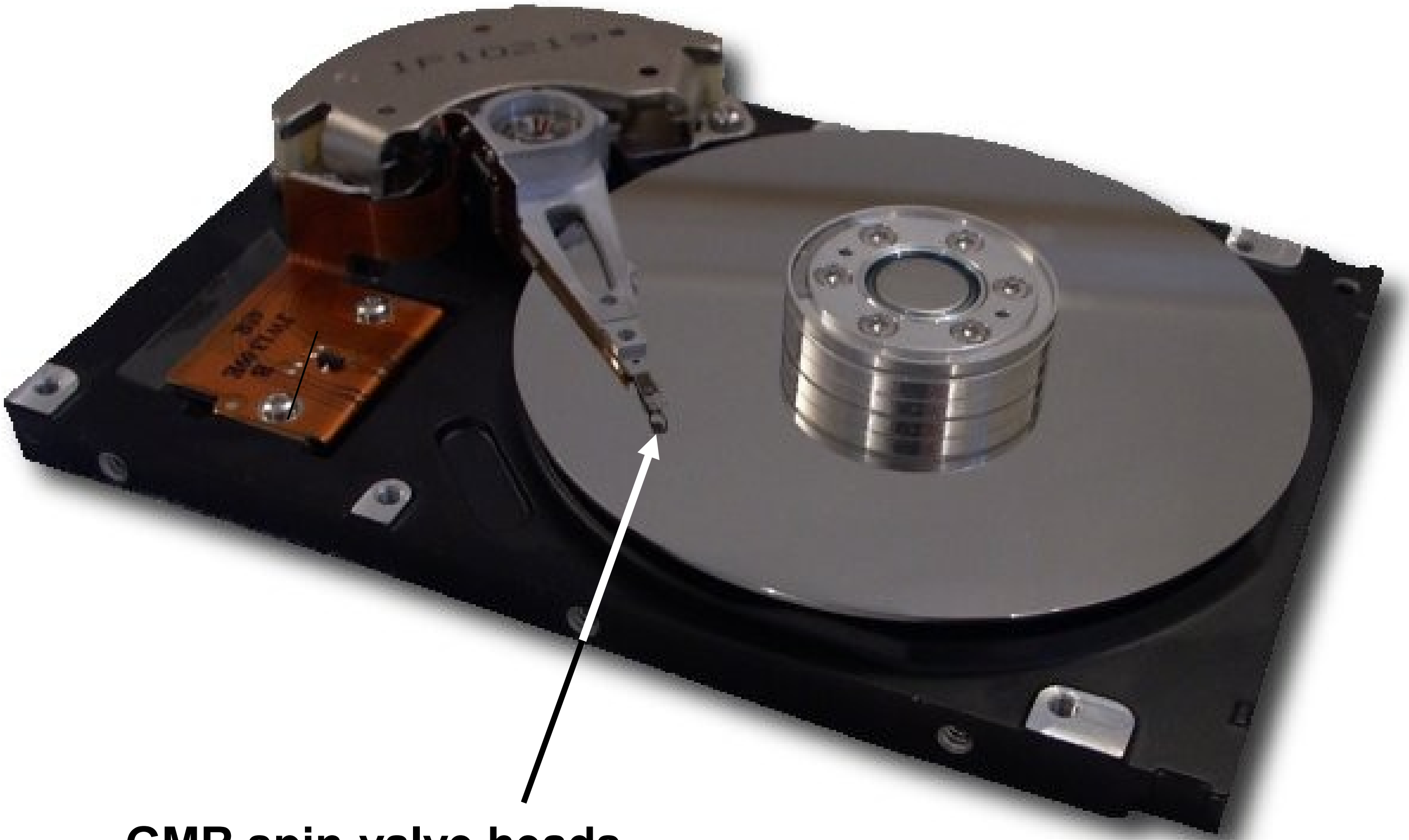
Development of spintronics paved with breakthrough discoveries:

-1) GMR ⇒ Hard disk drives (1990-2004)

-2) Tunnel MR ⇒ MRAM, hard disk drives (1995 - … for HDD, 2006-… for MRAM)

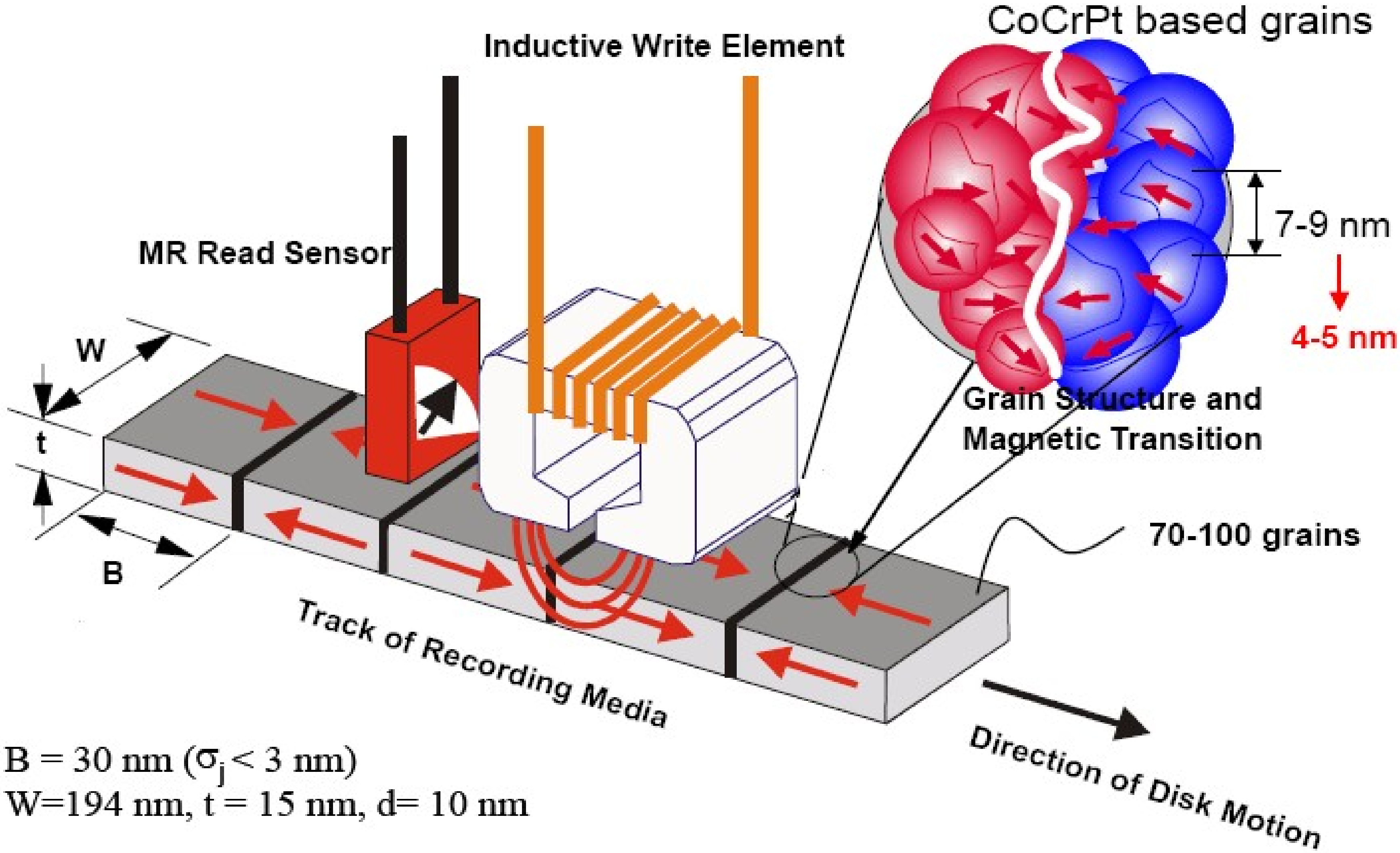
-3) Spin-transfer ⇒ MRAM, RF oscillators

# Benefit of GMR in magnetic recording



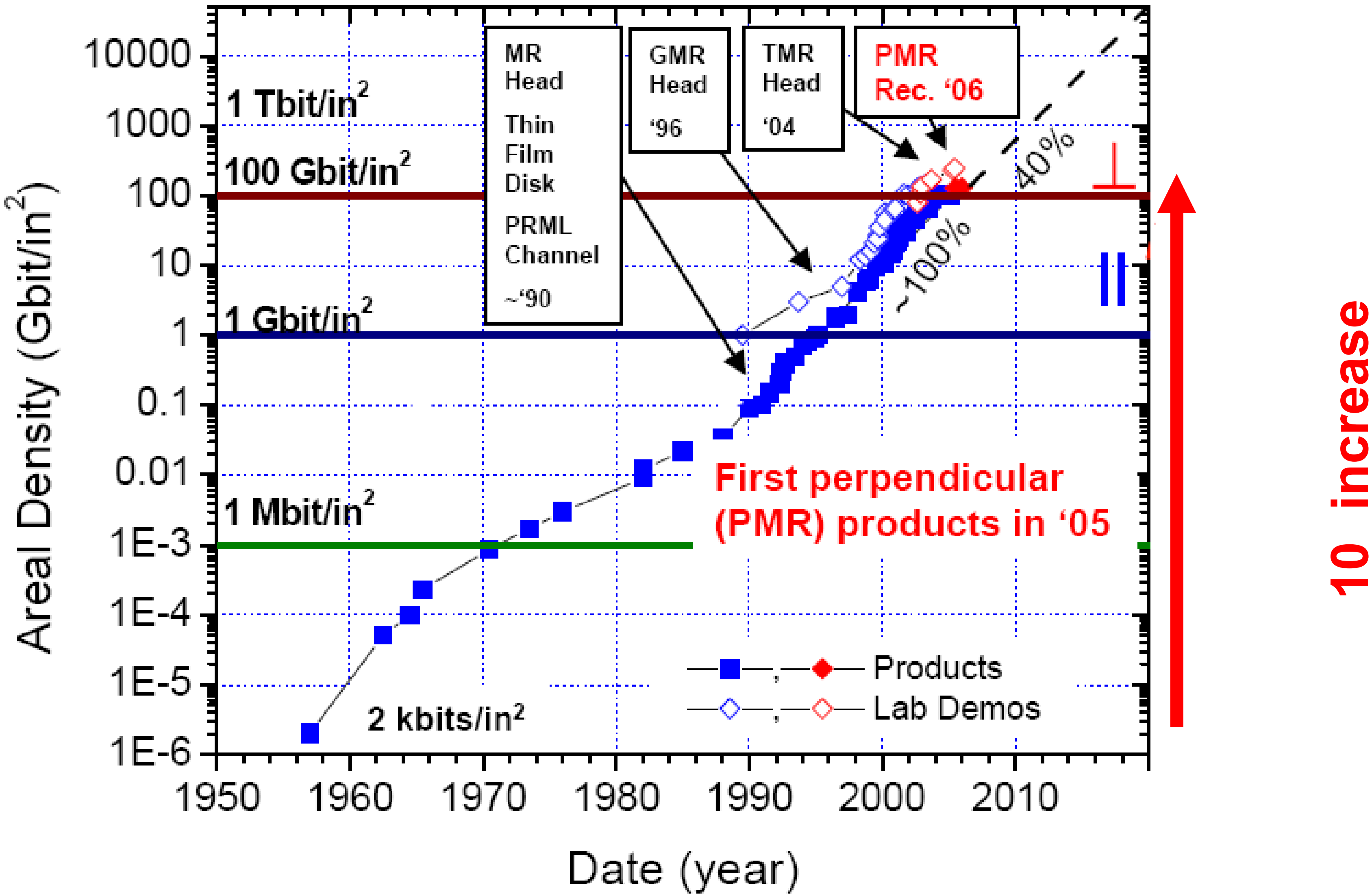
**GMR spin-valve heads from 1998 to 2004**

# 1) GMR in magnetic recording

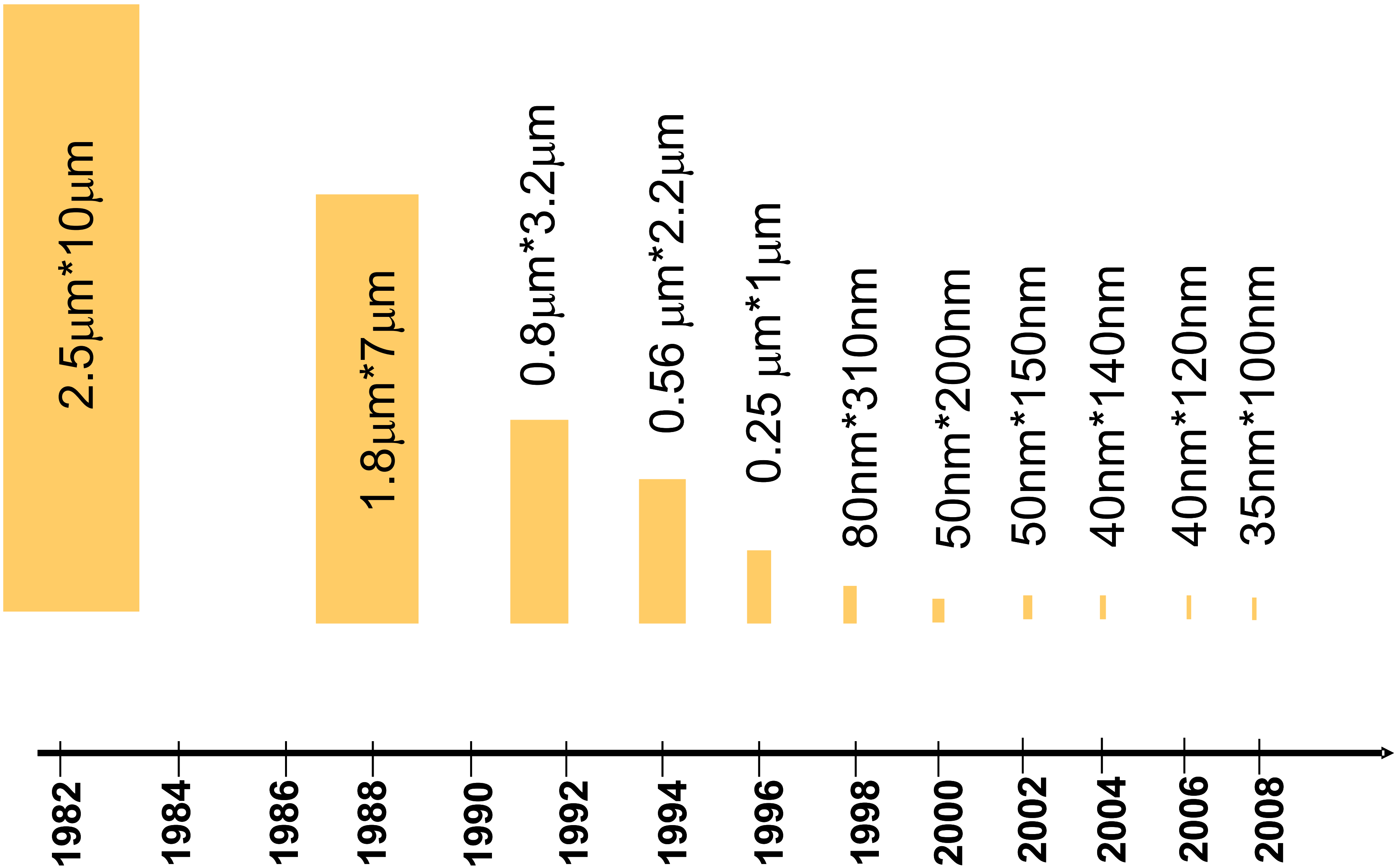



B = 30 nm ($\sigma_j$ < 3 nm)
W=194 nm, t = 15 nm, d= 10 nm

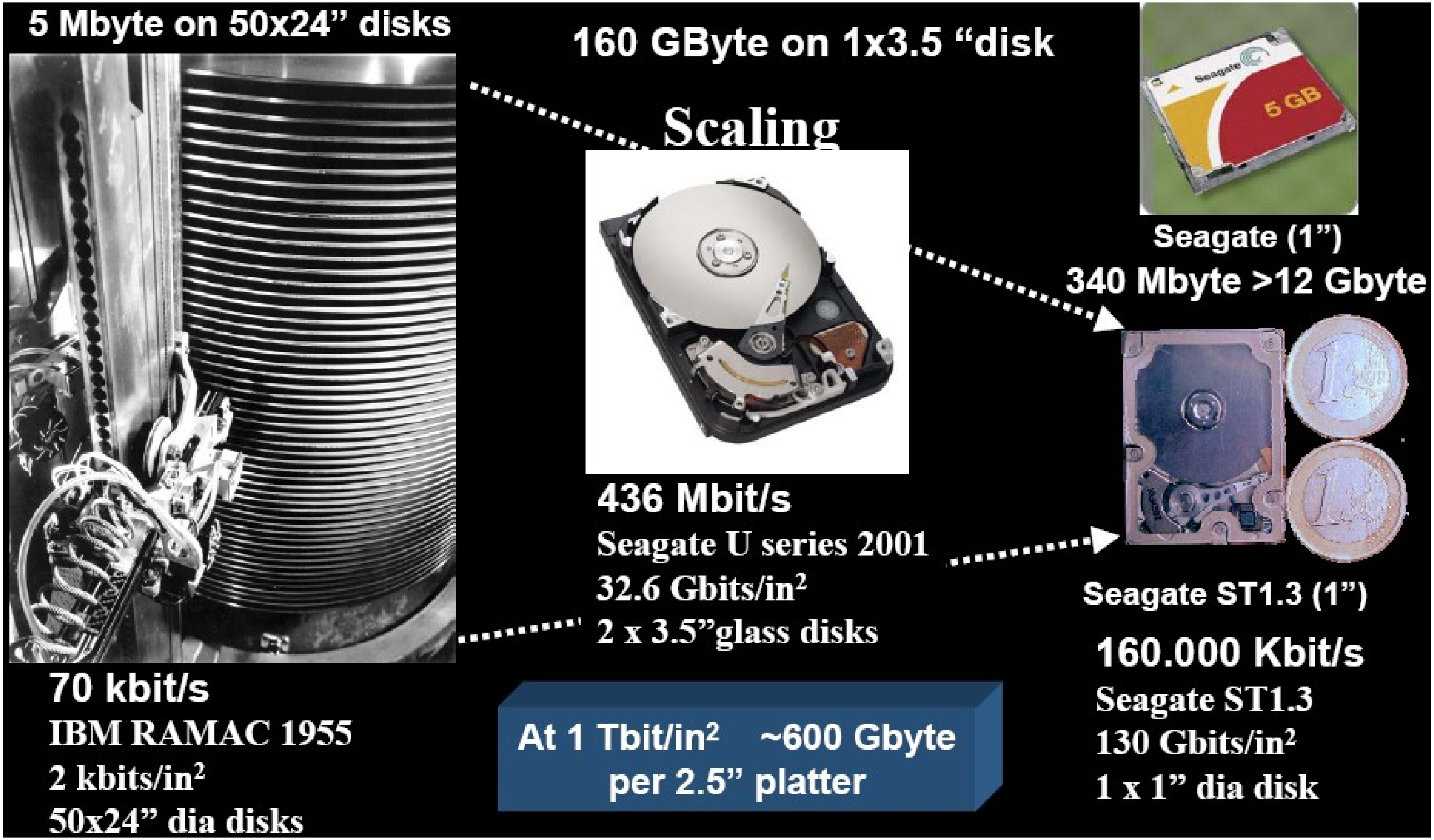
# Dramatic increase in areal storage density over the past 50 years



# Evolution of magnetic bit size in hard disk drives



## Reduction in size and increase in capacity




Areal storage density: +60%/year

# New applications of HDD made possible thanks to miniaturization

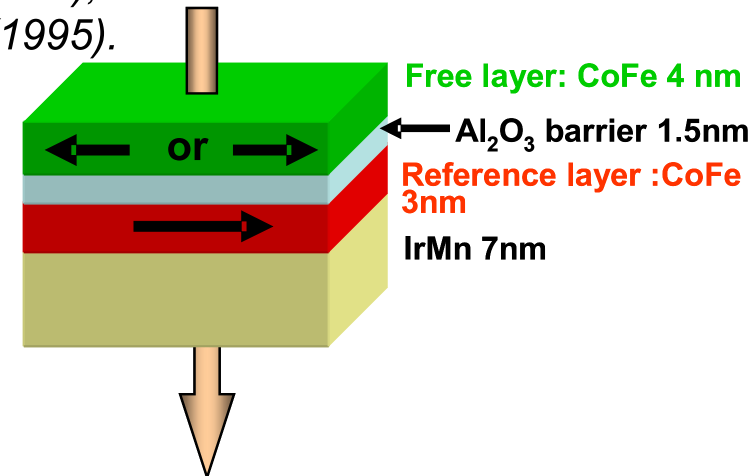
**GMR spin-valve heads from 1998 to 2004**

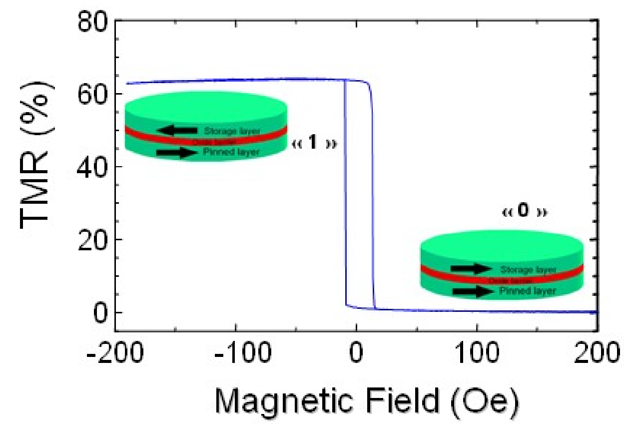

# 2) Magnetic tunnel junctions

***Tunnel magnetoresistance at 300K in amorphous Alumina based MTJ:***

*Julliere (1975) but at low T only*
*Moodera et al, PRL (1995);*
*Myazaki et al, JMMM(1995).*

TMR~40-70%



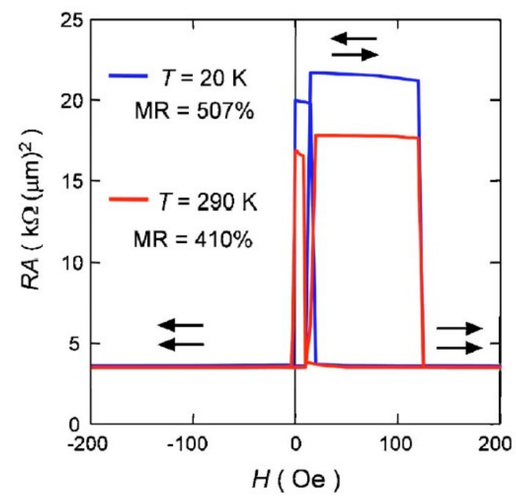




***« Giant » tunnel magnetoresistance at RT in crystalline MgO based MTJ:***

*Parkin et al, Nature Mat. (2004);*
*Yuasa et al, Nature Mat. (2004).*

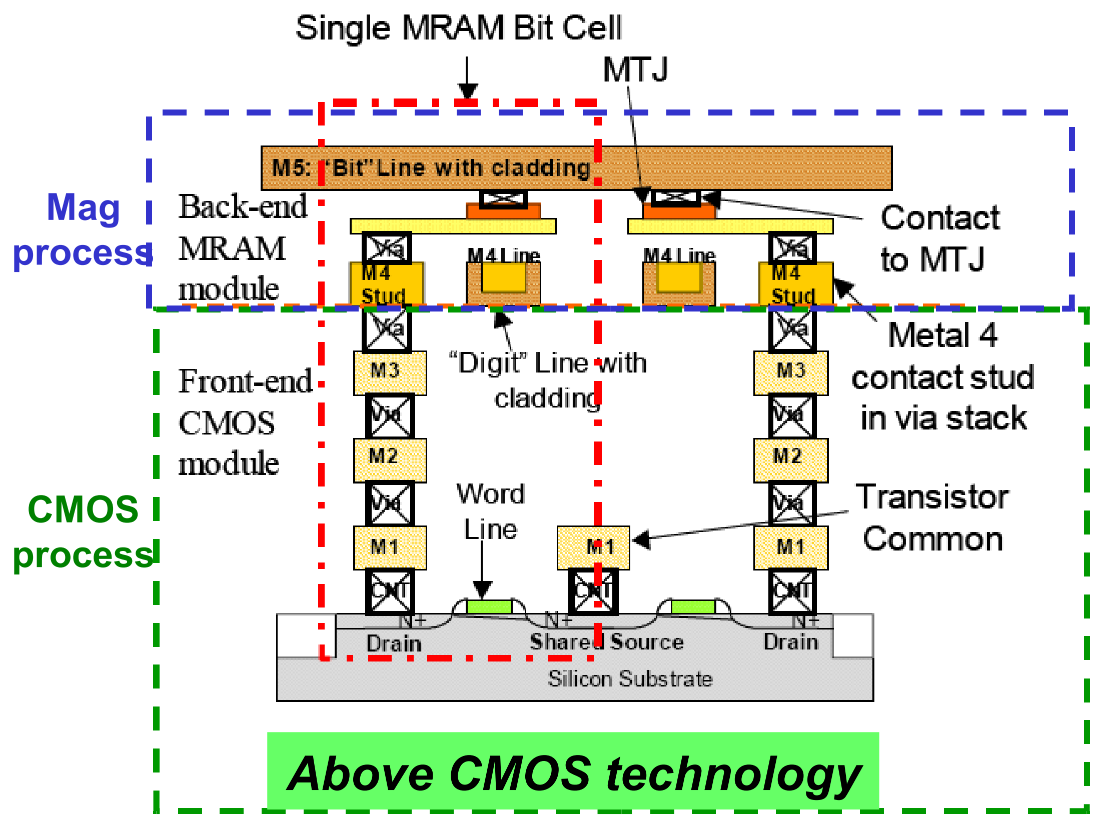
TMR~200-500%

| |
|---|
| Au cap 50 nm |
| Ir-Mn 10 nm |
| Fe(001) 10 nm |
| Co(001) 0.57 nm |
| MgO(001) 2.2 nm |
| Co(001) 0.57 nm |
| Fe(001) 100 nm |
| MgO(001) 20 nm |
| MgO(001) sub. |



# Magnetic Tunnel Junctions (MTJ): a new path for CMOS/magnetic integration

- Resistance of MTJ compatible with resistance of passing FET (few kΩ)
- MTJ can be deposited in magnetic back end process
- No CMOS contamination
- MTJ used as variable resistance controlled by field or current/voltage (Spin-transfer)



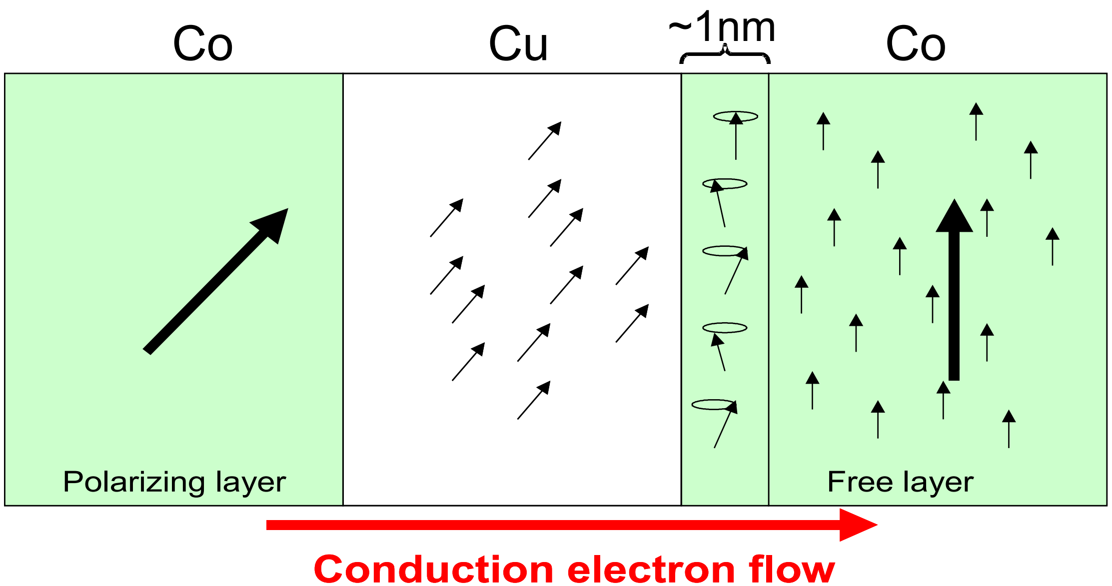

Cross-section of Freescale 4Mbit MRAM based on field switching

# 3) Spin-transfer

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 the direction of polarization of current via incoherent precession/relaxation of the electron spin around the local exchange field

$\Rightarrow$ **Torque on the Free layer magnetization**

# Magnetization dynamics: Effective field + spin-torque

Slonczewski (JMMM.159, L1(1996)) and Berger (Phys.Rev.B54, 9359 (1996)), Stiles, Levy, Fert, Barnas, Vedyaev

$$\frac{dM}{dt} = -\gamma M \times \left(H_{eff} + bI.M_p\right) + \gamma a I.M \times \left(M \times M_p\right) + \alpha M \times \frac{dM}{dt}$$

Polarizer M

Effective field term (conserve energy)

Spin-torque term: damping (or antidamping) term

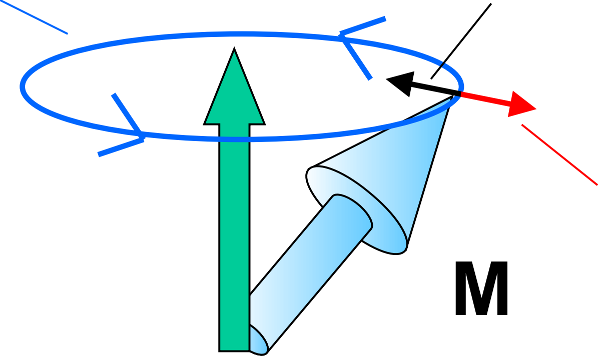
Gilbert Damping term

Non conservative

( Modified LLG)

a and b are coefficients proportional to the spin polarization of the current

Precession from effective field



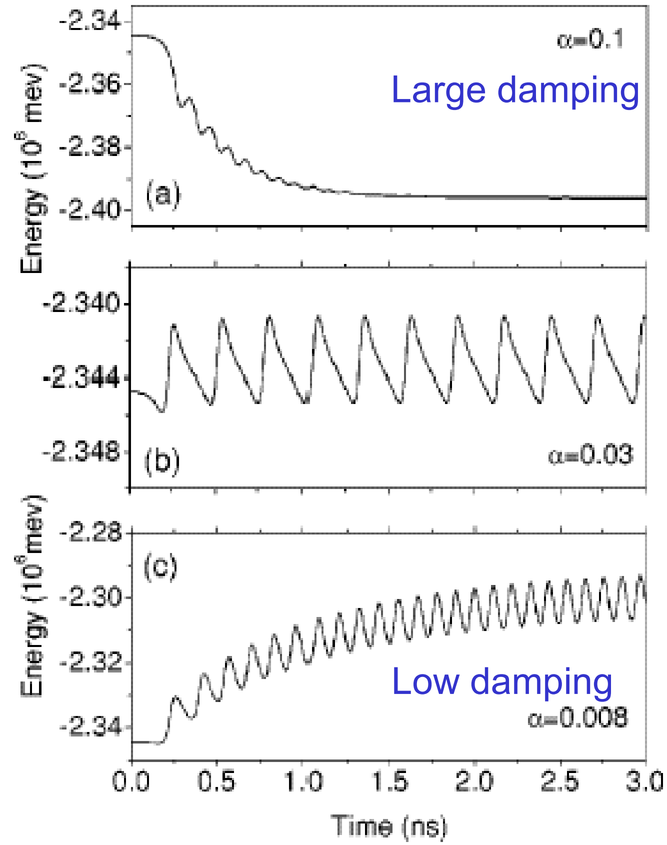

Effective field term seems weak in metallic pillars (<10% of spin-torque term) but more important in MTJ (~30% of spin-torque term)

# Energy dissipation and energy pumping due to spin transfer torque

Without spin torque (standard LLG)
$$\frac{dE}{dt} = -\frac{\alpha\gamma}{1+\alpha^2}\frac{1}{M_s}|\mathbf{H}_{eff}\times\mathbf{M}|^2 < 0$$

Dissipation, leading to relaxation towards effective field

*Z.Li and S.Zhang, Phys.Rev.B68, 024404 (2003)*




With spin torque term :

$$\frac{dE}{dt} = -\frac{\gamma}{1+\alpha^2}\frac{1}{M_s}[\alpha|\mathbf{H}_{eff}\times\mathbf{M}|^2 - a_J(\alpha M_s\hat{\mathbf{M}}_p - \mathbf{M}\times\hat{\mathbf{M}}_p)$$
$$\times(\mathbf{H}_{eff}\times\mathbf{M})],$$

dE/dt can be either>0 or <0

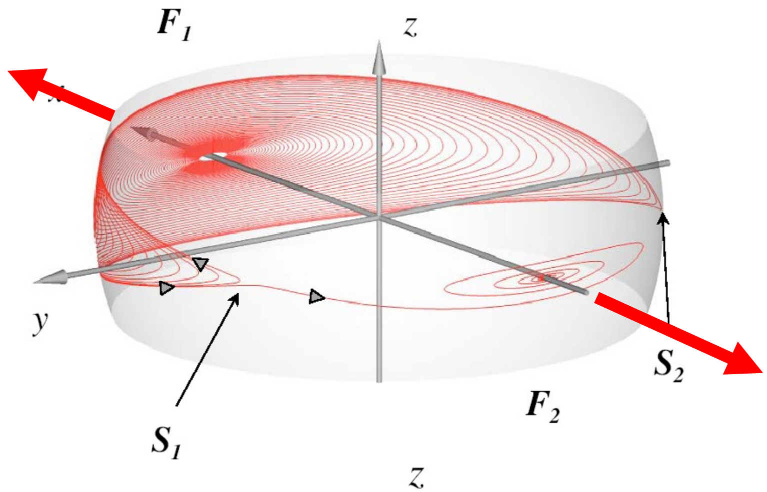
With Large damping: standard dynamical behavior,

With low damping: New dynamical effects such as spin current induced excitations

# Current induced switching: Macrospin approximation

Initial orientation

Polarisation of spin-current




*From J.Miltat*

Final orientation

Three steps:
- -Increase in precession angle
- -switching in the opposite hemisphere
- -fast relaxation

Analysis of stability of LLG equation : initial state becomes unstable for

$$(a_J)_{crit} = \pm\alpha(2\pi M_s + H_K) + \alpha H_{ext} \approx \alpha 2\pi M_s$$

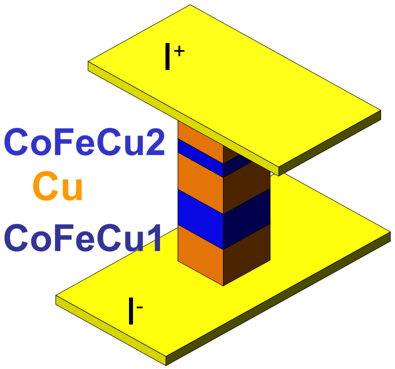
Where $a_J$ is prefactor of ST term:

$$(a_J) = -\frac{|g|}{2}\frac{\mu_B}{M_s^2}\frac{1}{d}\frac{J}{e}P$$

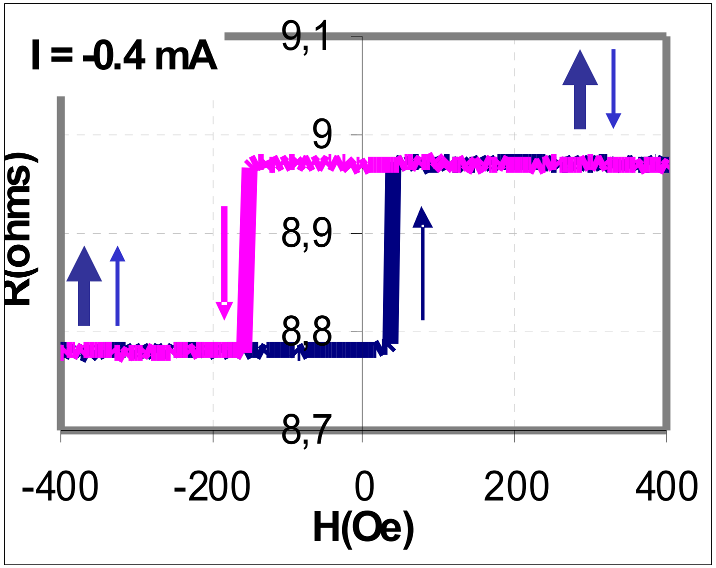
Switching of a 2.5nm Co layer for j~2-4.$10^7$A/$cm^2$

# Magnetization switching induced by a polarized current

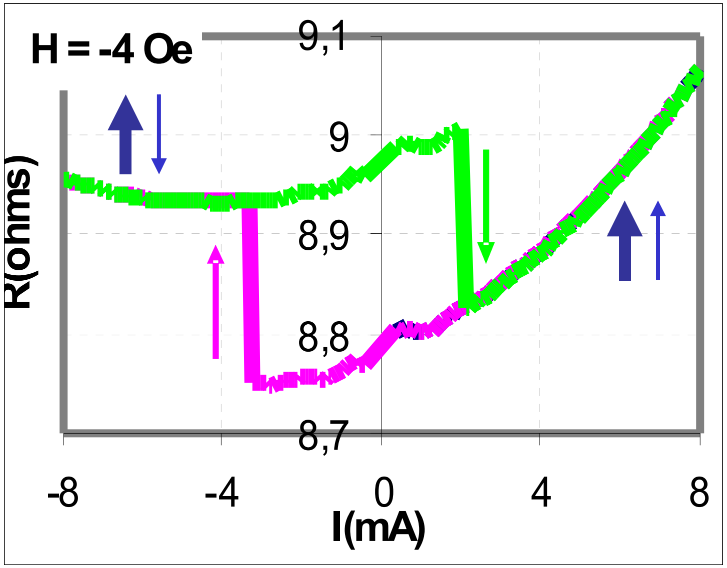
*Katine et al, Phys.Rev.Lett.84, 3149 (2000) on Co/Cu/Co sandwiches (Jc ~2-4.107A/$cm^2$)*




**Field scan**




**Current scan**




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

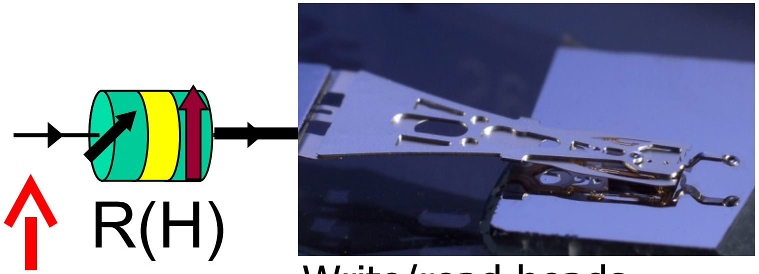
$j_c^{AP\text{-}P} = 1.2.10^7 A/cm^2$

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**

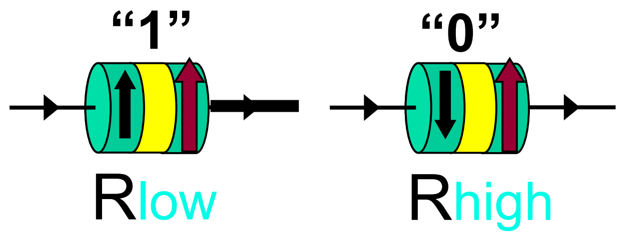
⇒Or to generate steady state oscillations leading to **RF oscillators**

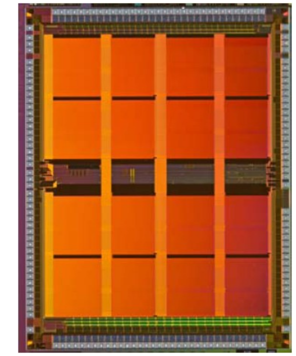
# Spintronic components




Write/read heads

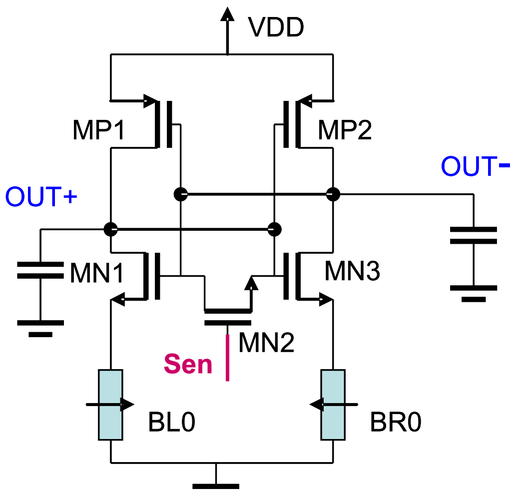
## *Magnetic field sensors*



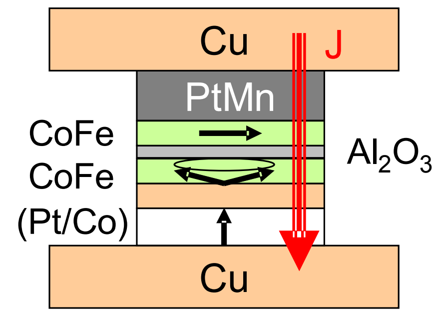



Freescale 4Mbit

## *Memories*



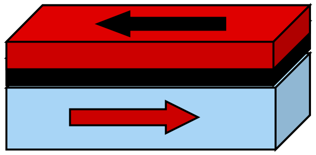

## *Logic circuits*

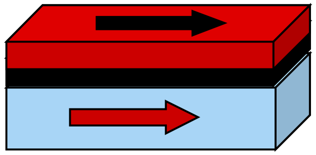



## *RF components*

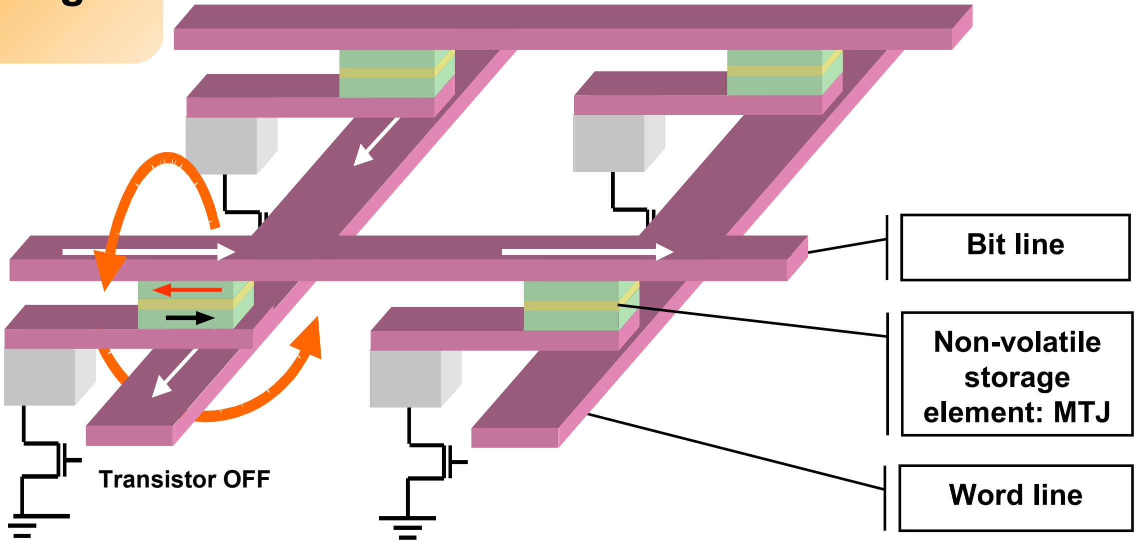
# Field induced magnetic switching (FIMS) MRAM

Principle :
Store data by the direction (parallel or antiparallel) of magnetic layers in MTJ

"1"


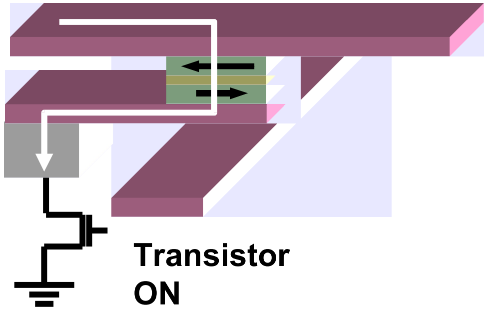
"0"


**Writing**




**Selectivity achieved by combination of two perpendicular magnetic fields**

**Reading**

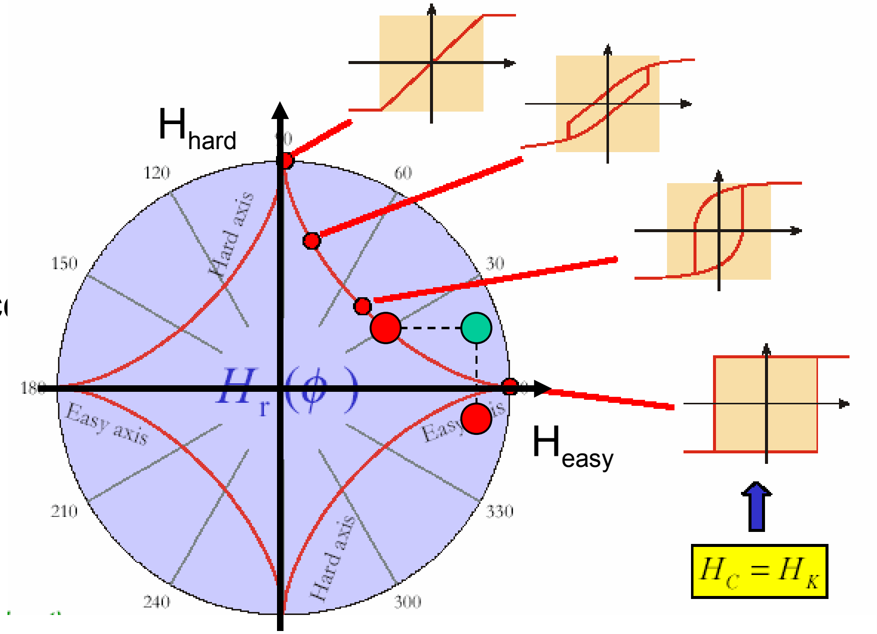


# Field induced switching MRAM Write Operation

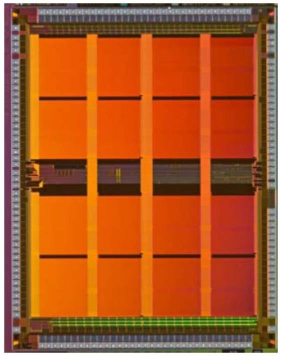
**Stoner-Wohlfarth switching**

- Selectivity based on Astroïd diagram
- With proper adjustment of Hx and Hy, only the c simultanously submitted to Hx and Hy switches, and not the half selected cell
- Requires narrow distributions of switching field

➔ manufacturing issues




4Mbit product from FREESCALE launched in 2006.
Great achievement which demonstrates that CMOS/MTJ integration is possible in a manufacturable process.



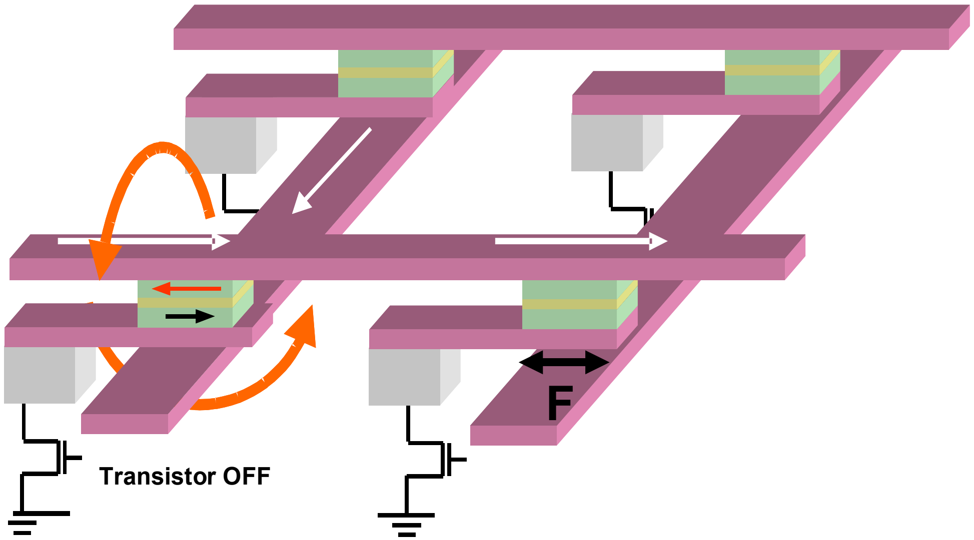
Freescale 4Mbit

However,

High power consumption as large magnetic fields (~50-70Oe) required for switching: I~5mA/Line.

Power consumption will increase upon scaling down due to increasing shape anisotropy necessary for thermal stability.

# Poor scalability of field induced switching MRAM



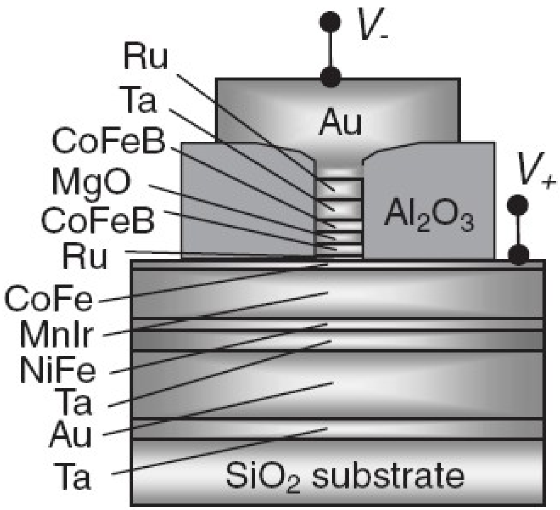

**Limited scalability due to electromigration in bit/word lines**

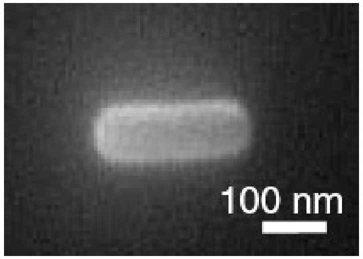
# Solution 1: Spin-Transfer Torque MRAM

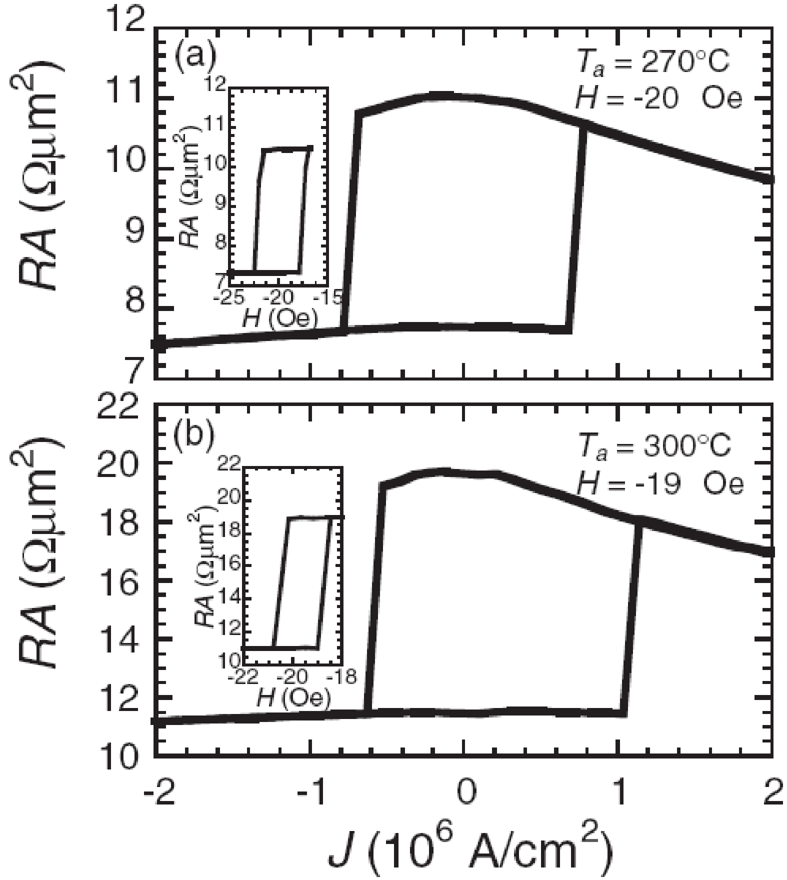
*Slonczewski, Berger (1996); STT in MTJ: Huai et al, APL (2004); Fuchs et al, APL (2004)*

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.



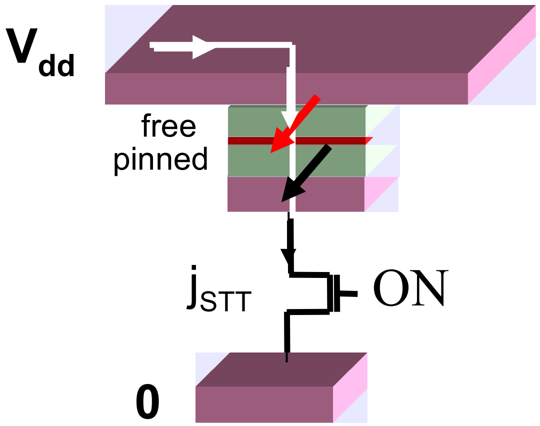



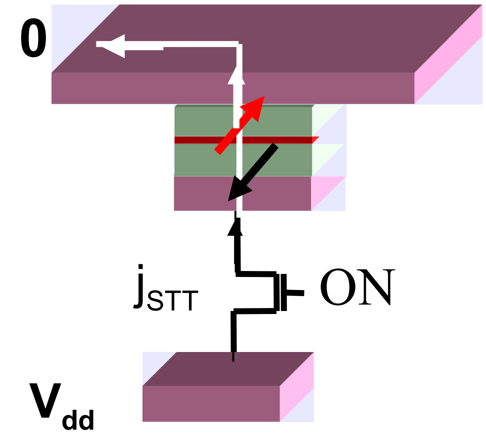

***Hayakawa et al,***
*Japanese Journal of Applied Physics*
*44, (2005),L 1267*

# STT MRAM scalability

**Writing "0"**




**Writing "1"**




- **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**

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

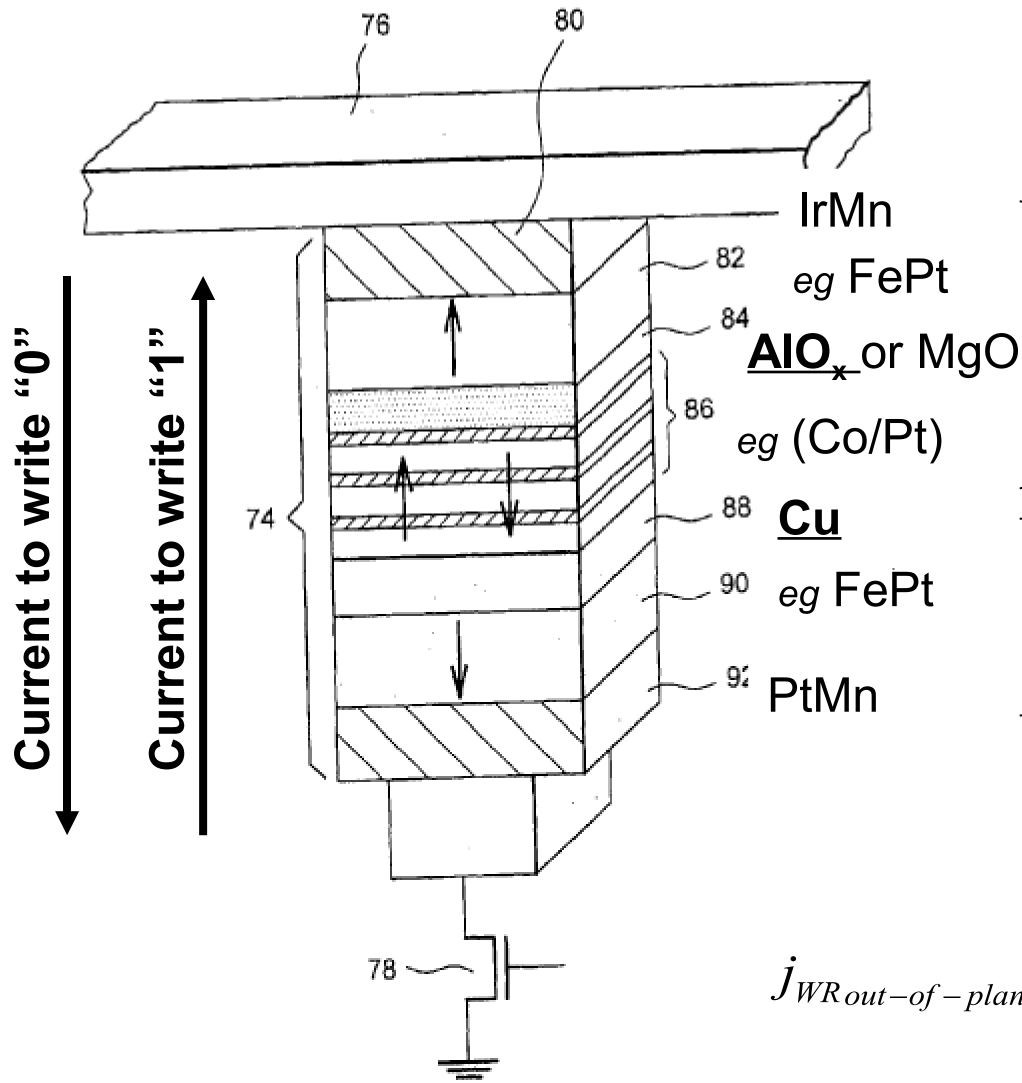
- **Concern with thermal stability of the cell below 45nm (superparamagnetic limit)**

  Increasing aspect ratio inefficient for AR>2 (nucleation/propagation)

  Increasing intrinsic anisotropy often increases Gilbert damping

# Perpendicular-to-plane STT MRAM

FR2832542 filed 16th Nov.2001, US6385082




MTJ provides the TMR signal

Additional spin-polarizer to reinforce STT

Opposite sign in perpendicular anisotropy.

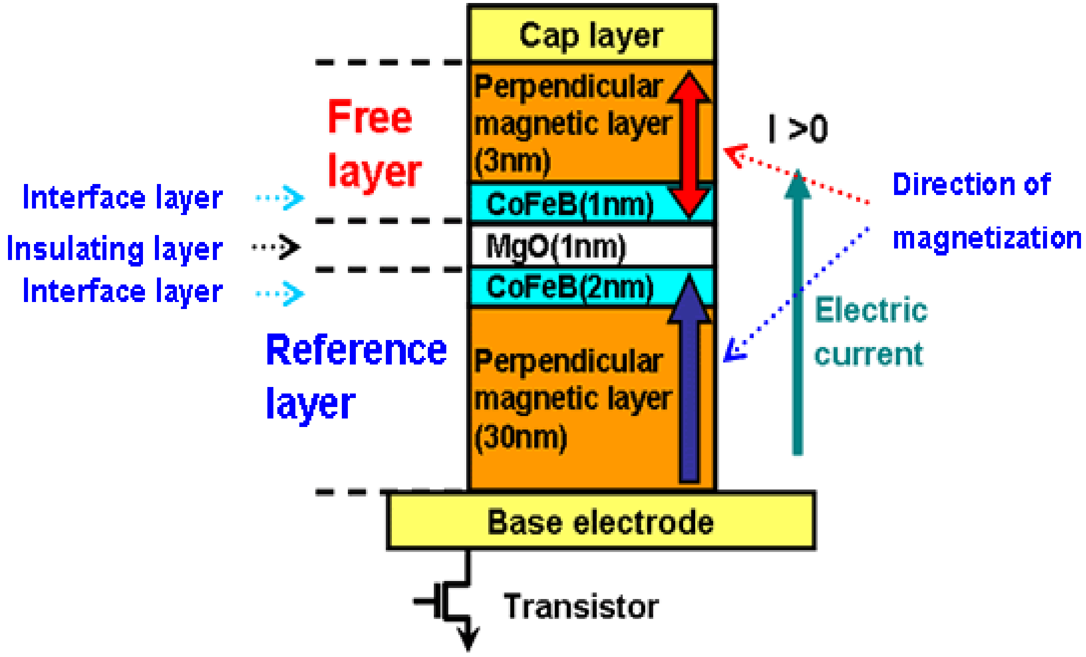
$$j_{WR\,out-of-plane} = \left(\frac{2e}{\hbar}\right)\frac{\alpha\, t_F}{P}\left(\frac{\mu_0 M_S^{\,2}}{2} + 2K\right)$$

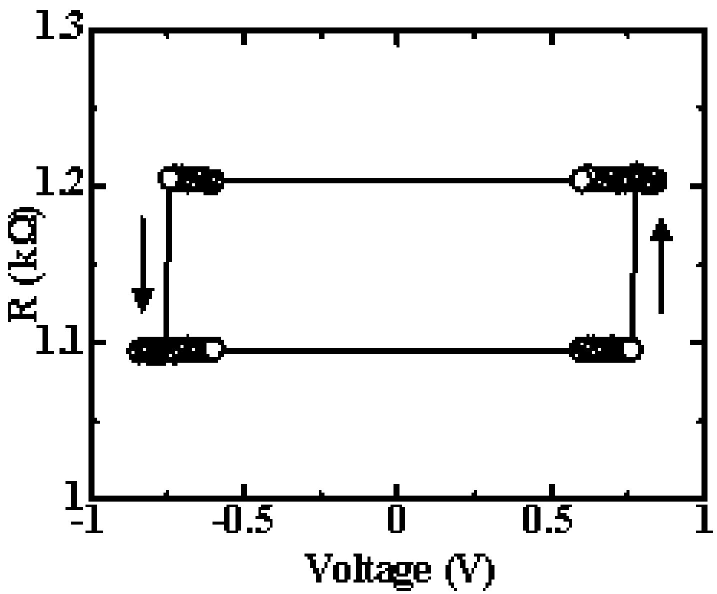
Switching current can be lower than with in-plane magnetized material

# Toshiba develops new MRAM device which opens the way to giga-bits capacity

www.toshiba.co.jp/about/press/2007_11/pr0601.htm

06 November, 2007




$j_c \sim 3.10^6 A/cm^2$

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

Ability to maintain low $\alpha/P$ factor with out-of plane anisotropy (?)

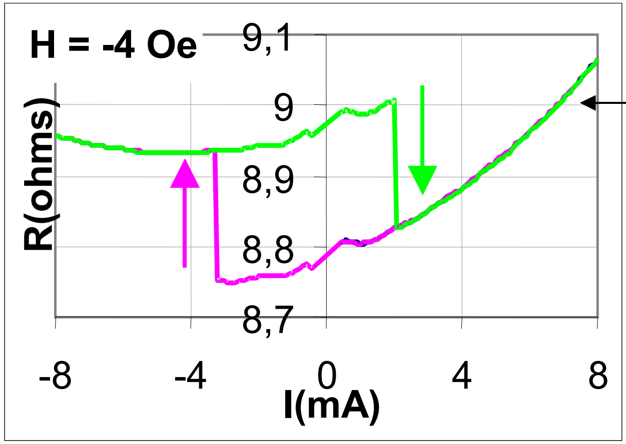
# Heating effects in STT cells

Heating does take place in metallic and MTJ cells during STT writing

NiFe/Ta5nm/IrMn 7nm/CoFe3nm/Ru0.6nm/CoFeCu2.5nm/Cu3nm/CoFeCu3nm/Ta5nm/Cu

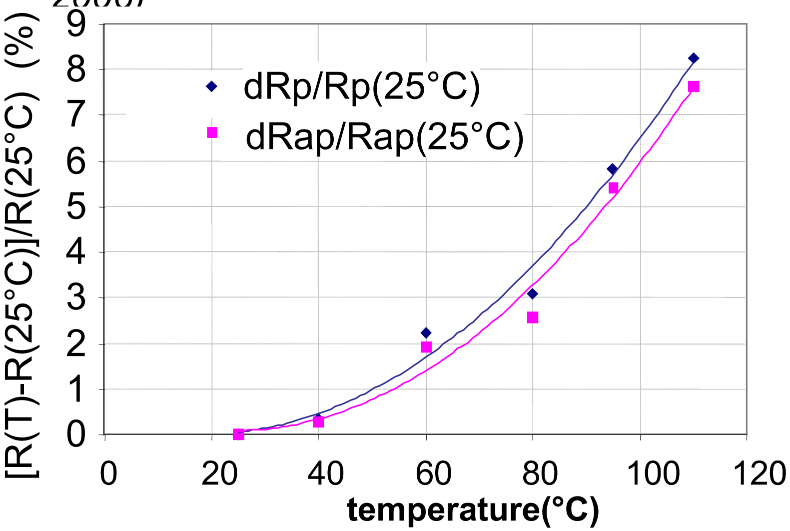
*Deac et al, Phys.Rev.B73 (6), 064414 (2006)*

**CPP SV:**




ΔT=+50°C

$J_c$~2.10⁷A/cm²




**MTJ:**

$$P_{heating} = RA.j^2$$

**10 times lower $j_c$ than in CPP SV but >$10^3$* higher RA**

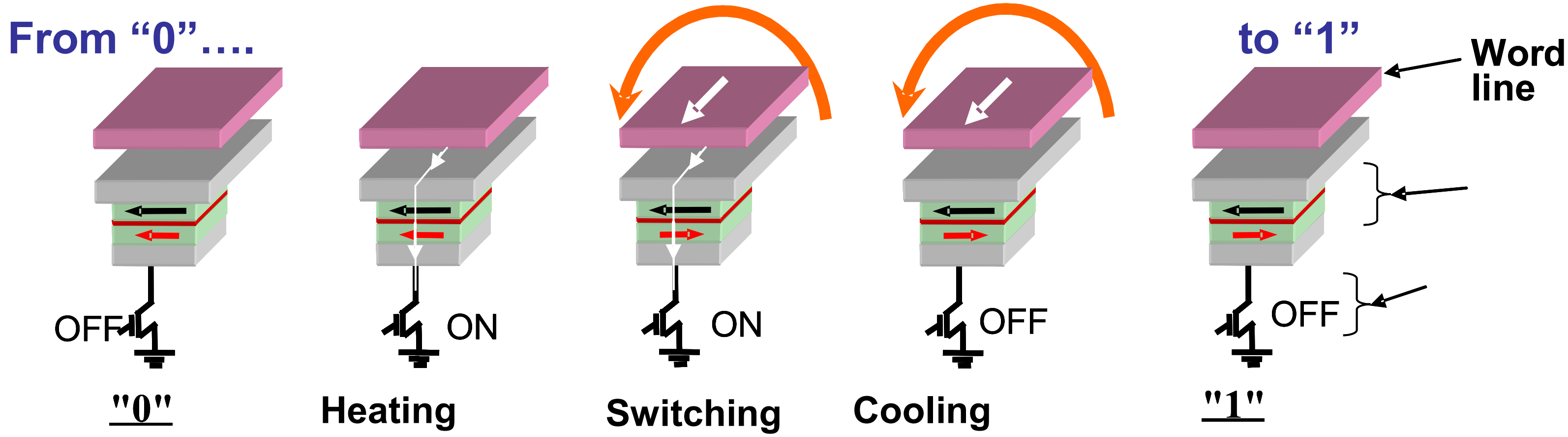
**so that comparable or even larger heating power in MTJ than in metallic CPP SV.**

**Stochastic switching + Possible drift in temperature upon repeated write**

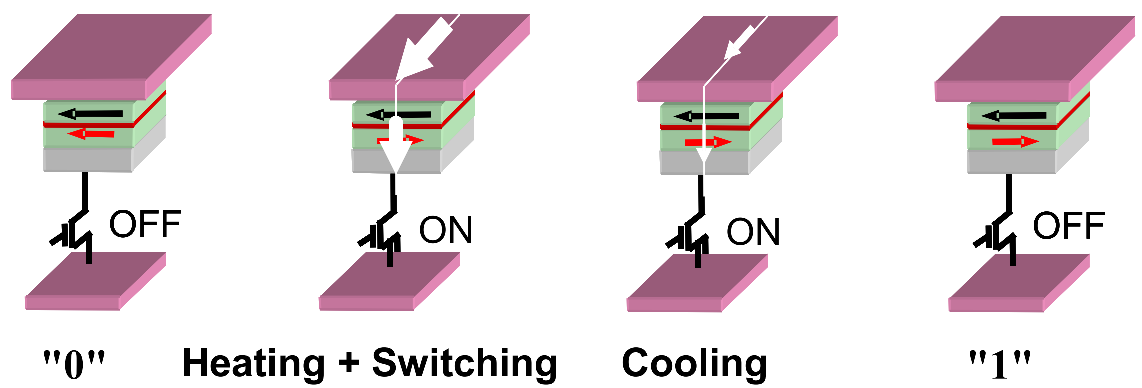
# Solution 2 : Thermally assisted MRAM

Very similar to Heat Assisted Magnetic Recording (HAMR)
Write at elevated temperature – Store at room temperature
**In TA-MRAM: Heating by current flowing through the cell**

**Heating+ pulse of magnetic field:**



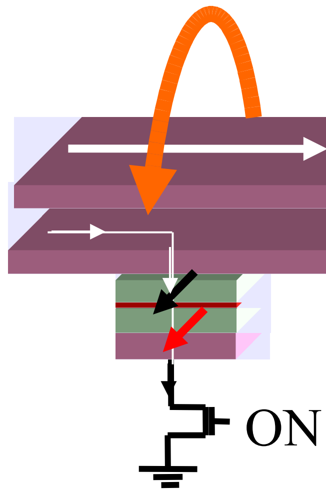

**Heating + STT:**

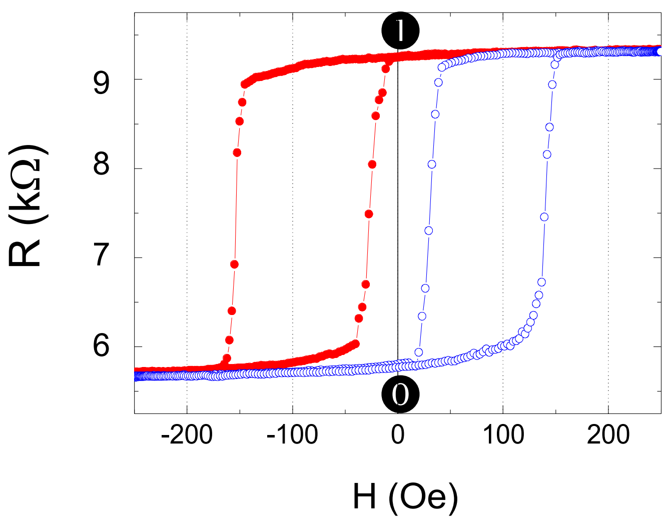



FR2832542 filed 16th Nov.2001, US6385082

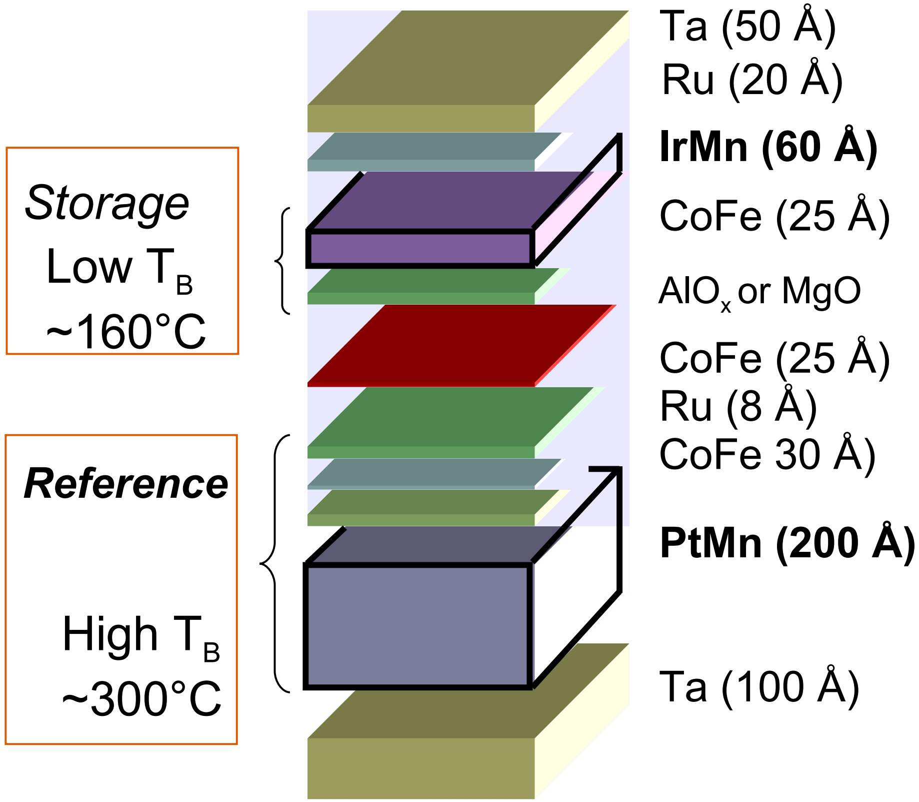
# Thermally assisted writing in TA-MRAM

**Heating + Field~2.5mT**



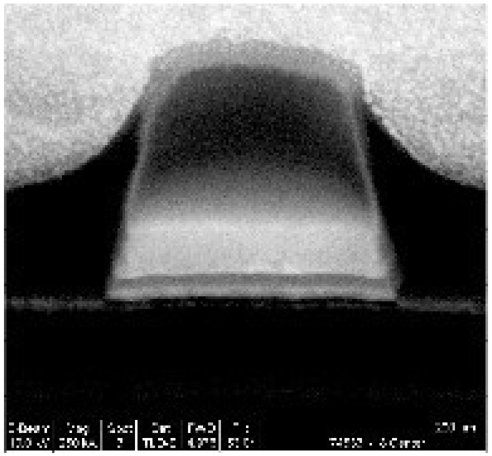




## Exchange biased storage layer




- heat the storage layer above the **low $T_B$**

# Heating Dynamics in TA-MRAM

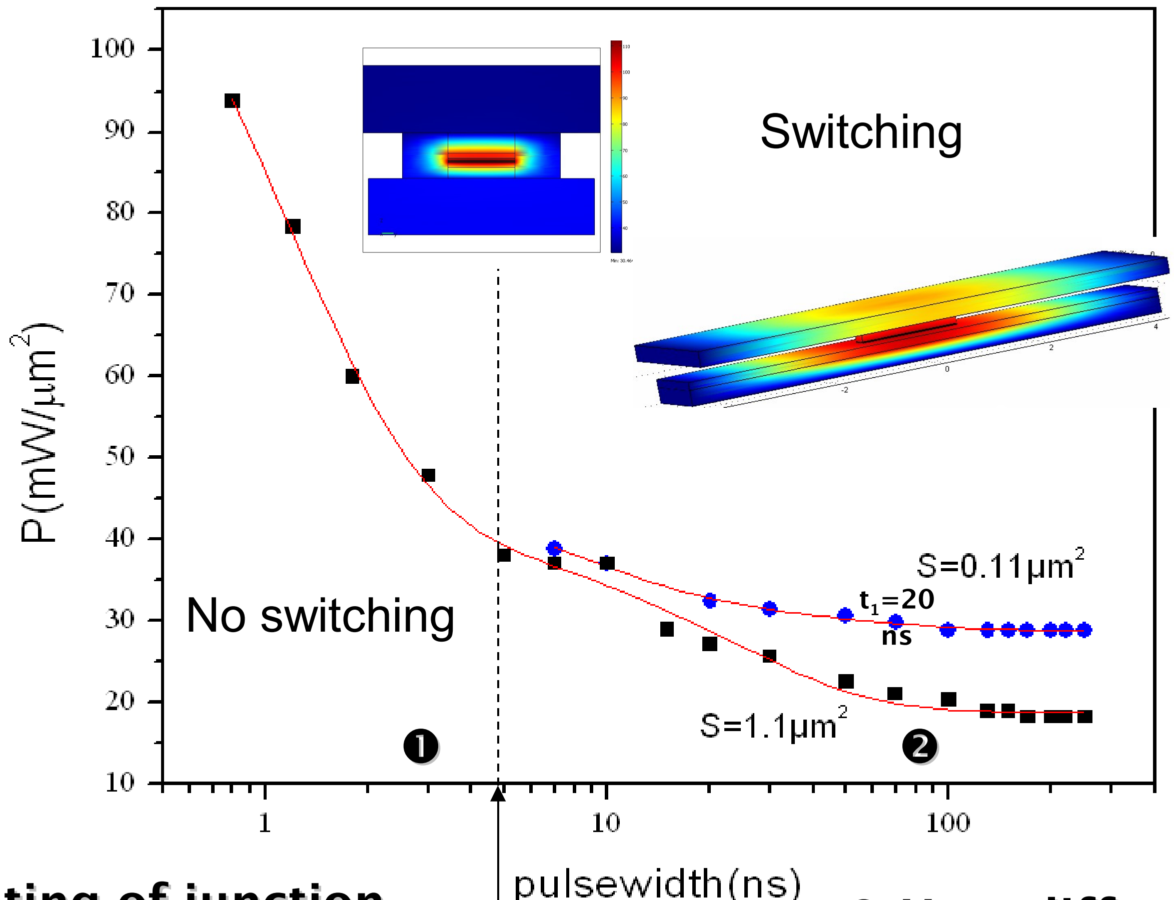


100nm

MTJ pillar etched by RIE

CROCUS Technology

Blossoming Future



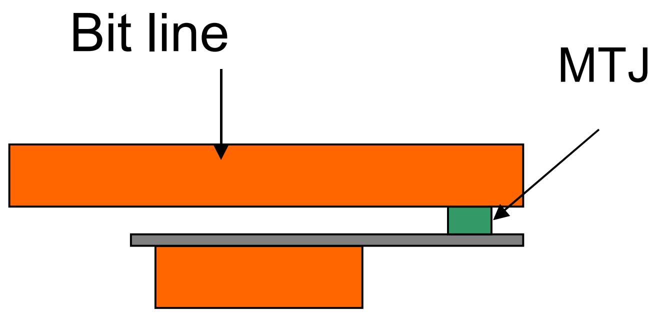

❶ **Adiabatic heating of junction**

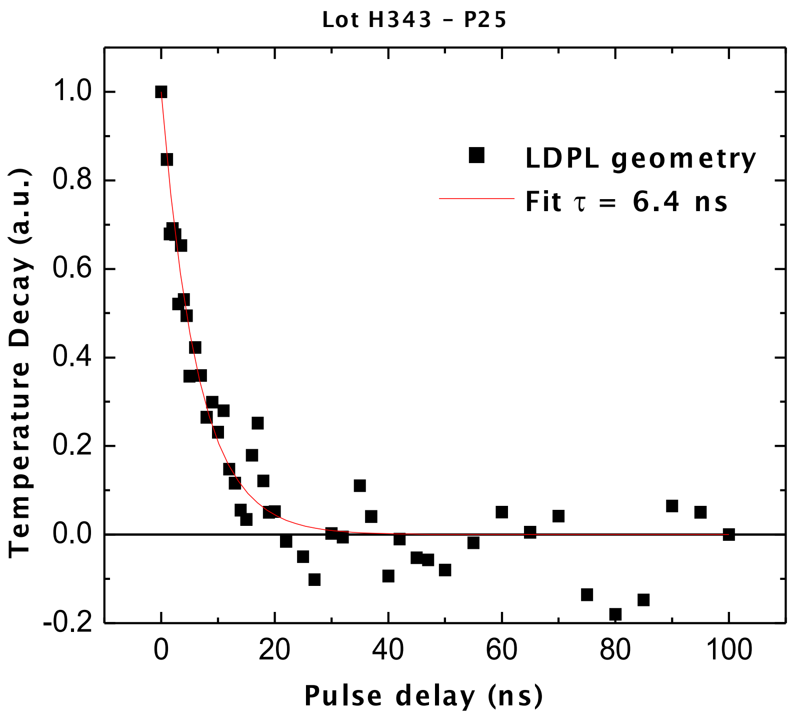
$E_{write} = C\Delta T \Rightarrow P_{write} = C\Delta T/t$

**Best operating region**
**$J_{heating} \sim 10^6 A/cm^2$**

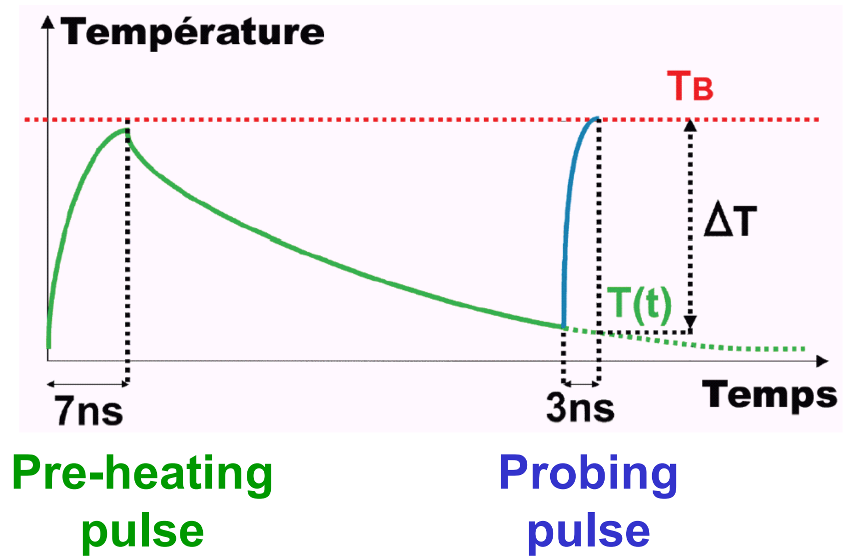
❷ **Heat diffusion towards the leads**

# Cooling dynamics in TA-MRAM




Double-pulse method for measuring cooling dynamics *(C.Papusoi, J.Hérault)*:

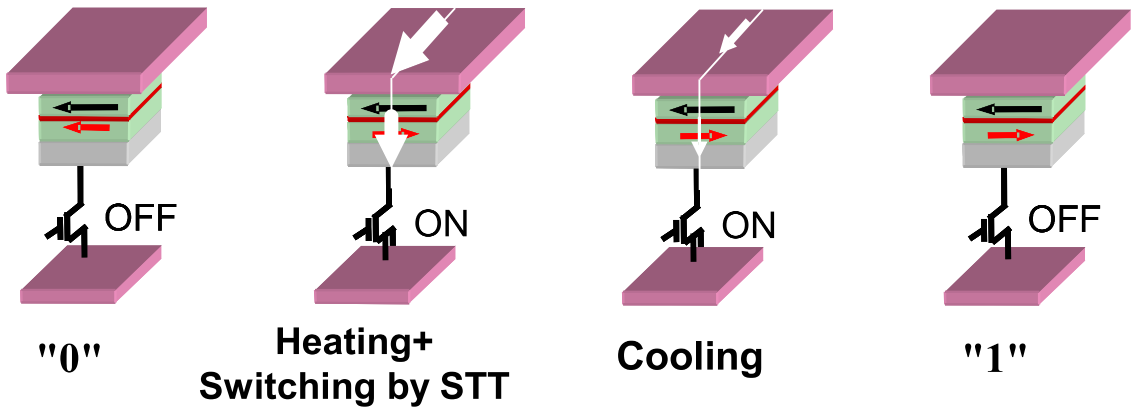



**Characteristic cooling time~15ns.**

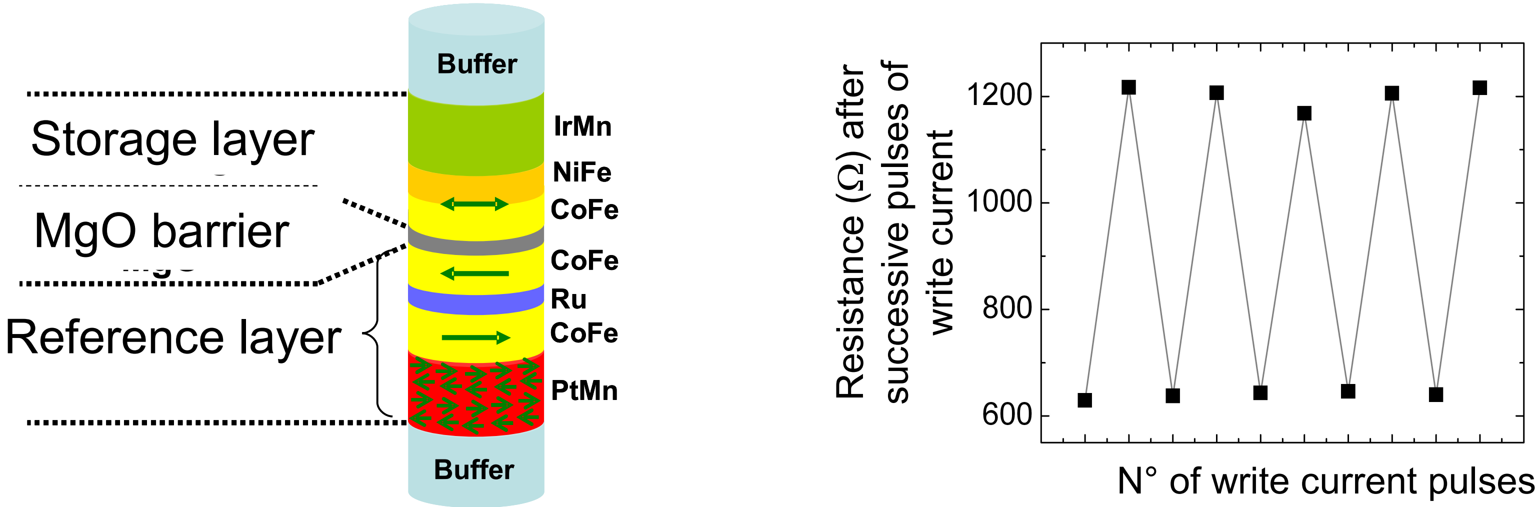
**TA-MRAM cycle time ~30ns**

# Combining spin-transfer with thermally assisted writing

The same bipolar current flowing through the cell is used to both temporarily heat the cell and apply a spin transfer torque to switch the magnetization of the storage layer.




Experimental demonstration:




**Approach offering the ultimate scalability (sub-15nm cell-size possible)**
**With stability of information over 10 years.**

spintec SPIN IN ELECTRONICS

# Scalability of TA-MRAM

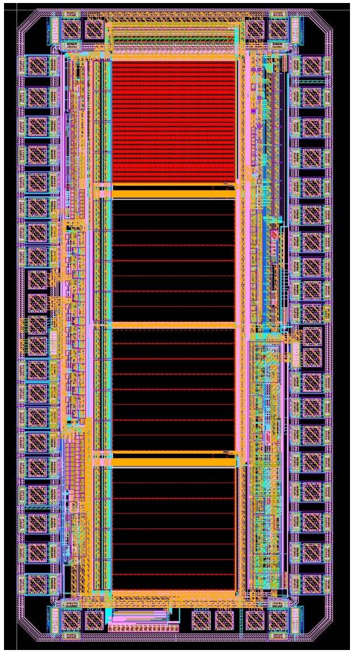
**Heating+ pulse of magnetic field~2.5mT:**

Scalability limited by electromigration in bit line (field generation) @ 45nm

**Heating+ STT:**

Same bipolar CPP current used to heat and switch;
No Physical limit in downscaling from magnetic point of view down a few nm;

Can be implemented with :
-in-plane magnetized material (exchange biased storage layer)
-perpendicular-to-plane magnetized material (variation of $M_s$ or K with T)



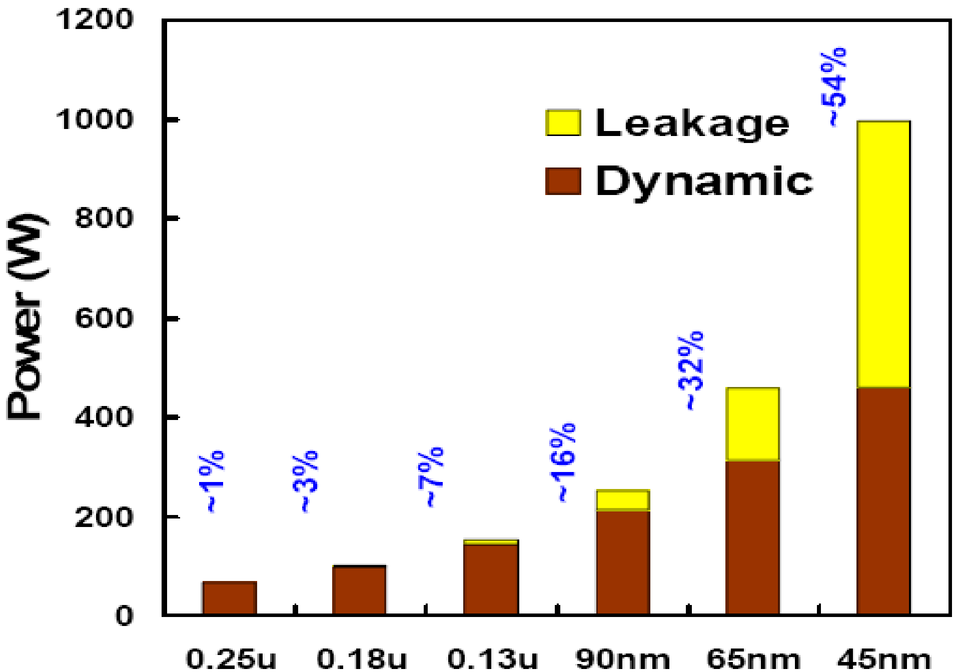
*Layout of 1Mbit TA-MRAM demonstrator from Crocus Technology*

# New hybrid CMOS/MTJ architectures for non-volatile logic

DRAM, SRAM: volatile. Cannot be switched off without loosing information

However, increasing leakage current with downsizing (thinner gate oxide)

**Power consumption in CMOS electronic circuit per inch²**



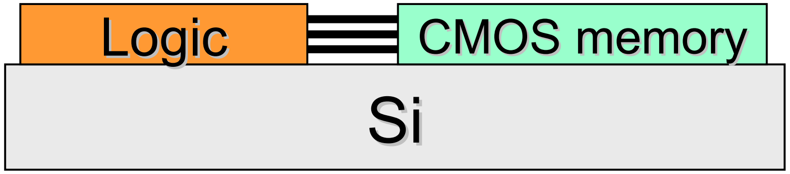

Major benefit in introducing non-volatility in CMOS components in terms of energy savings

# Tighter integration between logic and memories

**Same technology as for MRAM**

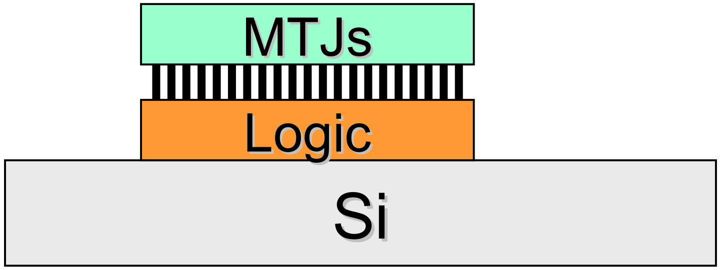
**Benefit from "Above IC" technology**

**With CMOS technology only:**




Slow communication between
logic and memory
-few long interconnections
-complexity of interconnecting paths
-larger occupancy on wafer

**With hybrid CMOS/magnetic:**




Non-volatility in logic
Large energy saving
Fast communication between
logic and memory
-numerous short vias
-simpler interconnecting paths
-Smaller occupancy on wafer

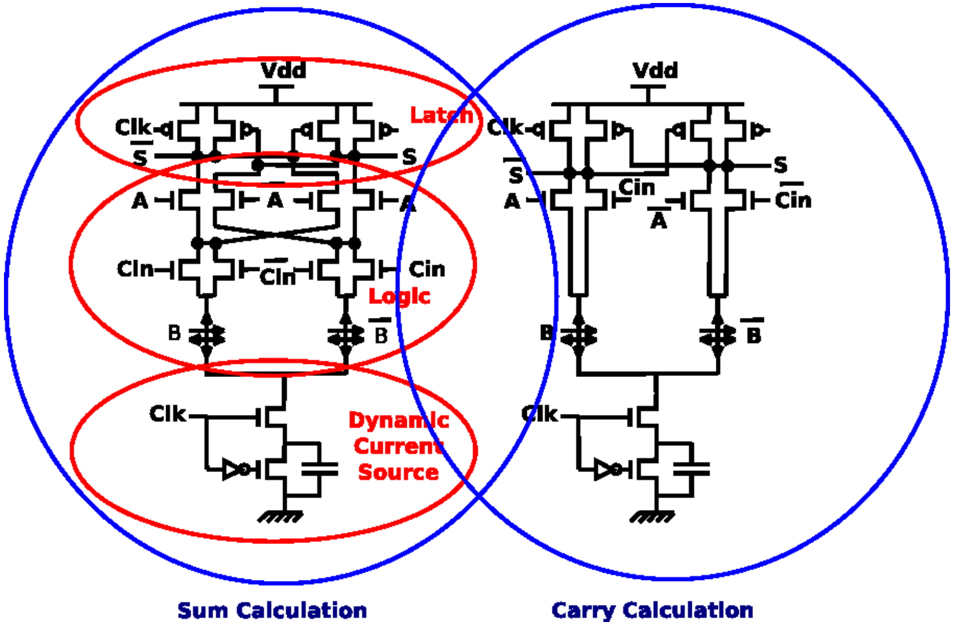
**New paradigm for architecture of complex electronic circuit (microprocessors...)**

# Magnetic Full Adder (Hitachi, Tohoku University)

S.Matsunaga et al, *Applied Physics Express*, vol. 1, 2008.

- Based on
  - Dynamic Current Mode Logic
    - Dynamic consumption reduction
    - Footprint reduction
  - MTJs
    - One input is made non-volatile (instant startup, security)
    - Drastic static consumption reduction
    - Footprint reduction
- Demonstrator : CMOS 0.18µm,
- MTJs size: 200X100nm²

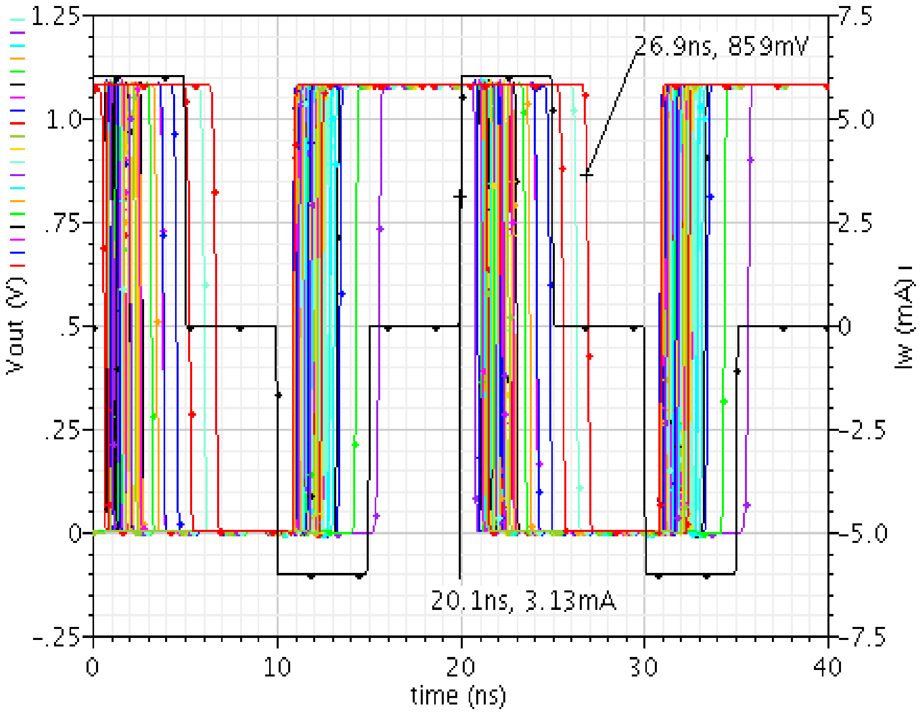
| | CMOS | Hybrid |
|---|---|---|
| Delay | 224 ps | 219 ps |
| Dynamic Power | 71.1 µW | 16.3 µW |
| Writing Time | 2 ns/bit | 10 (2) ns/bit |
| Writing Energy | 4 pJ/bit | 20.9 (6.8) pJ/bit |
| Standby Power | 0,9 nW | 0 nW |
| Surface | 333 µm² | 315 µm² |

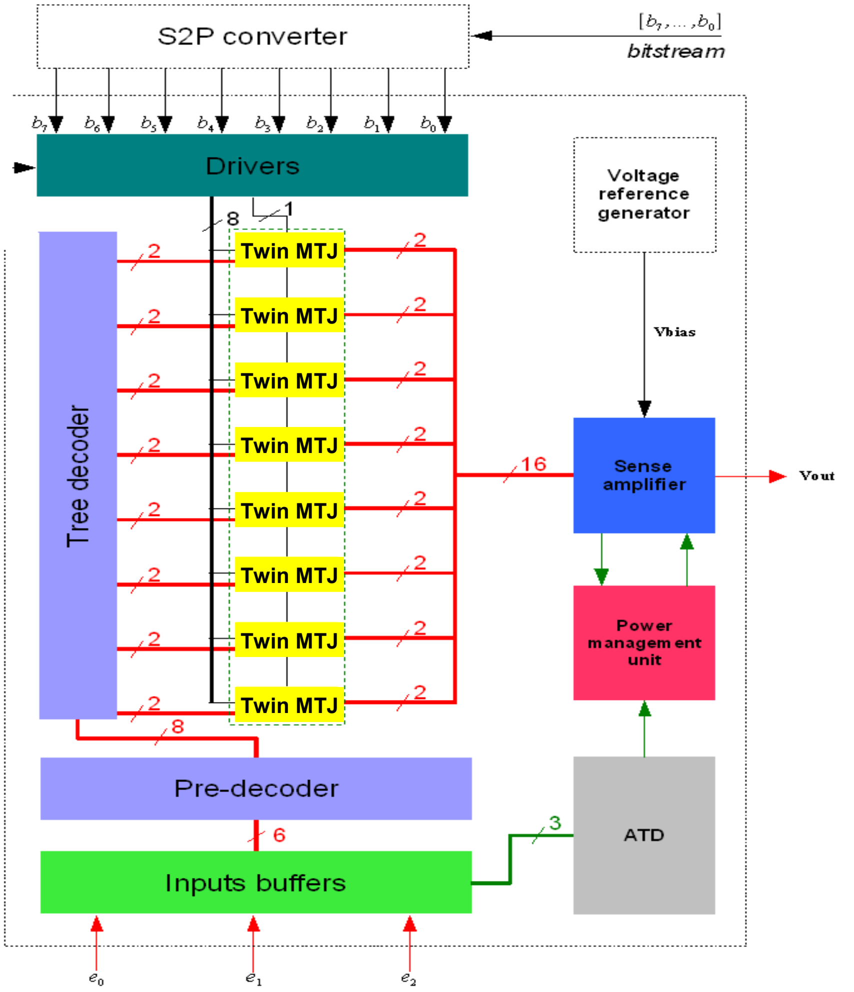


# Reprogrammable hybrid CMOS/MTJ logic gates

MTJ used as variable resistances to change the switching threshold of CMOS components

**Simulations of reprogrammability taking into account CMOS and magnetic process variations**

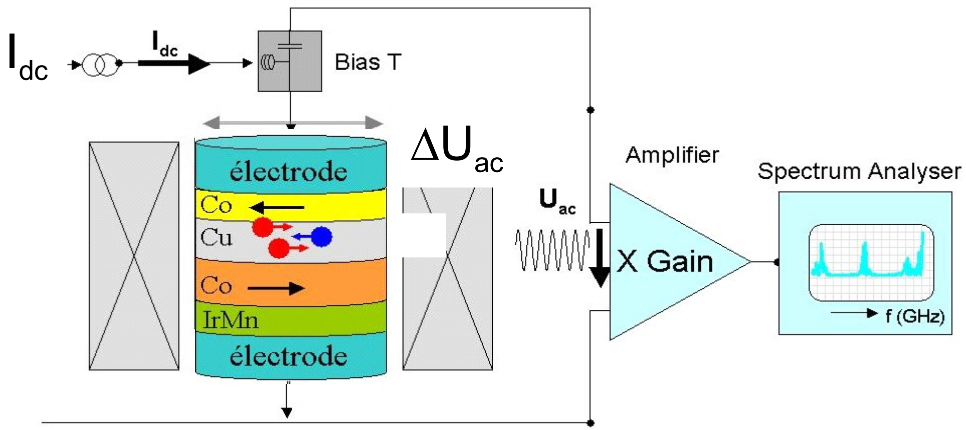



Extremelly fast reprogrammation

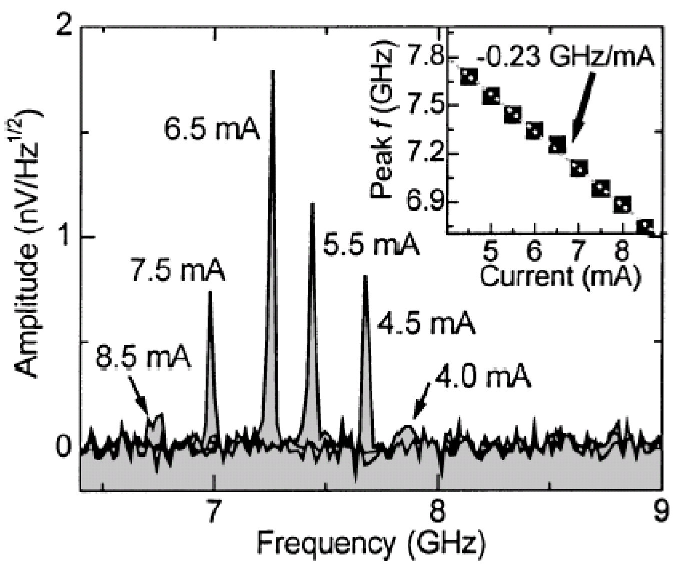
# RF components based on spin transfer

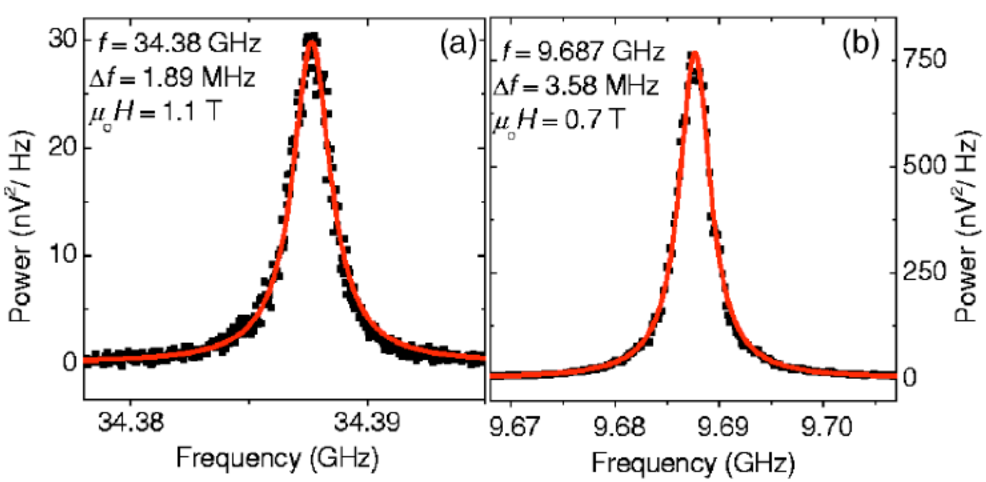
## Current Induced Steady State Oscillations




Kiselev et. al., *Nature* **425**, p. 380 (2003)

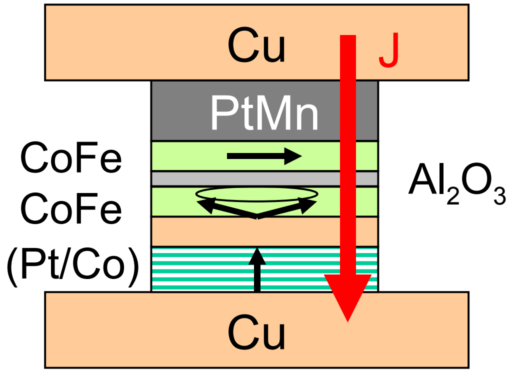
Rippard et. al., *Phys. Rev. Lett.* **92**, p. 27201 (2004)



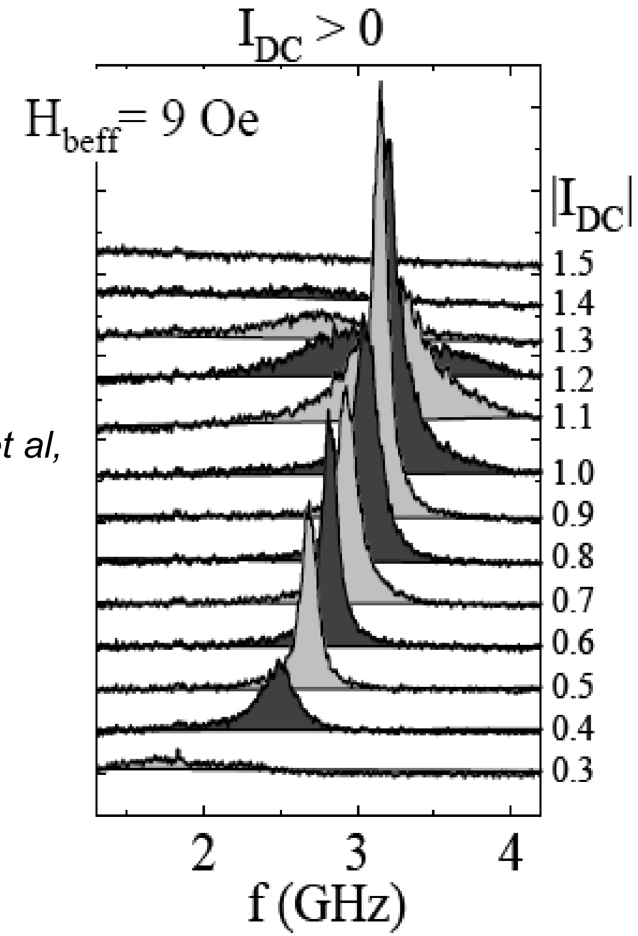




*Q=18200* *Q=2700*

# RF oscillator with perpendicular to plane polarizer




*D.Houssamedine et al, Nat.Mat 2007*

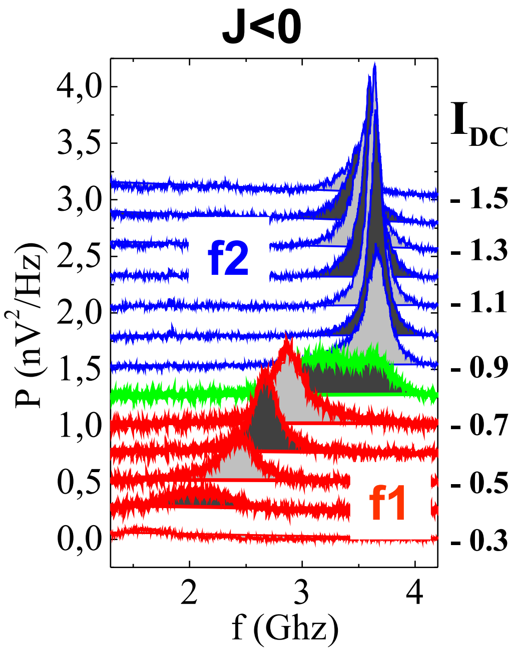



Injection of electrons with out-of-plane spins;
Steady precession of the magnetization
of the soft layer adjacent to the tunnel barrier.

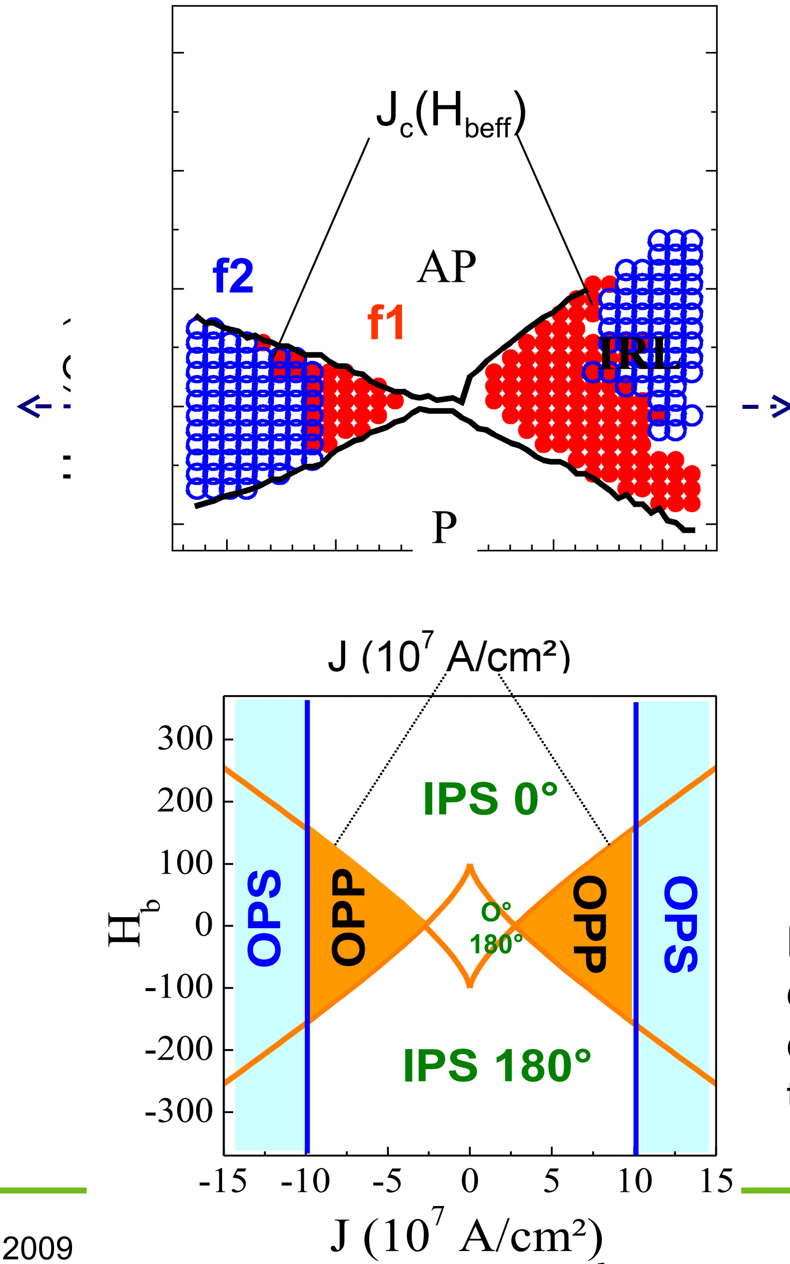
Precession (2GHz-40GHz) + Tunnel MR ⇒ RF voltage
Interesting for frequency tunable RF oscillators ⇒ Radio opportunism

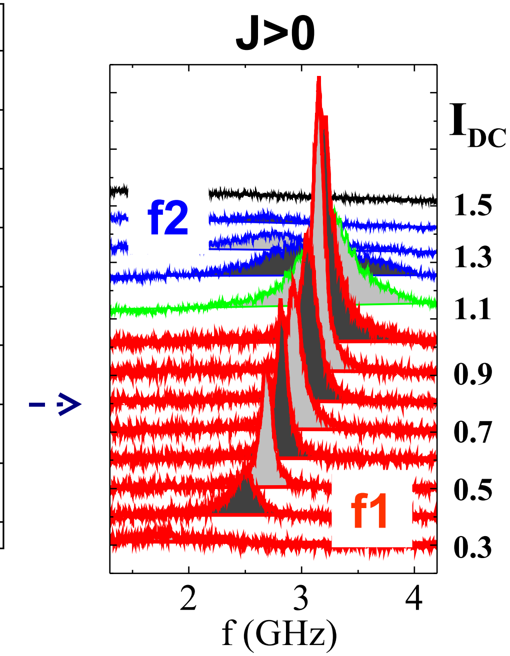
(SPINTEC patent + Lee et al, Appl.Phys.Lett.86, 022505 (2005) )

# Dynamic Spectra and Dynamic Diagram




$H_{beff}$= 9 Oe



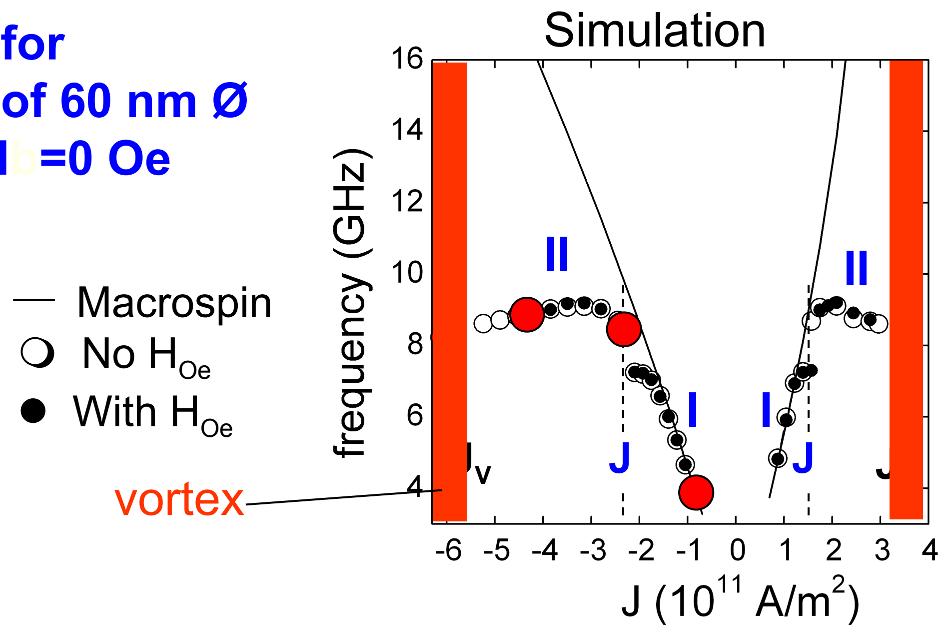

$H_{beff}$= 9 Oe

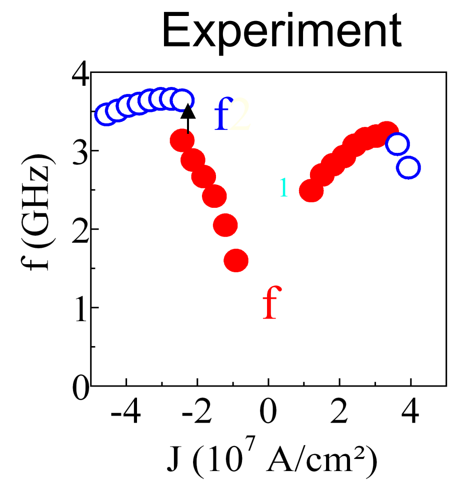
D. Houssameddine et al. Nature Materials **6**, 447 (2007)

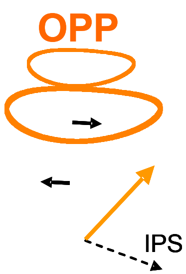
Macrospin simulated phase diagram calculated from LLG equation with spin-transfer term

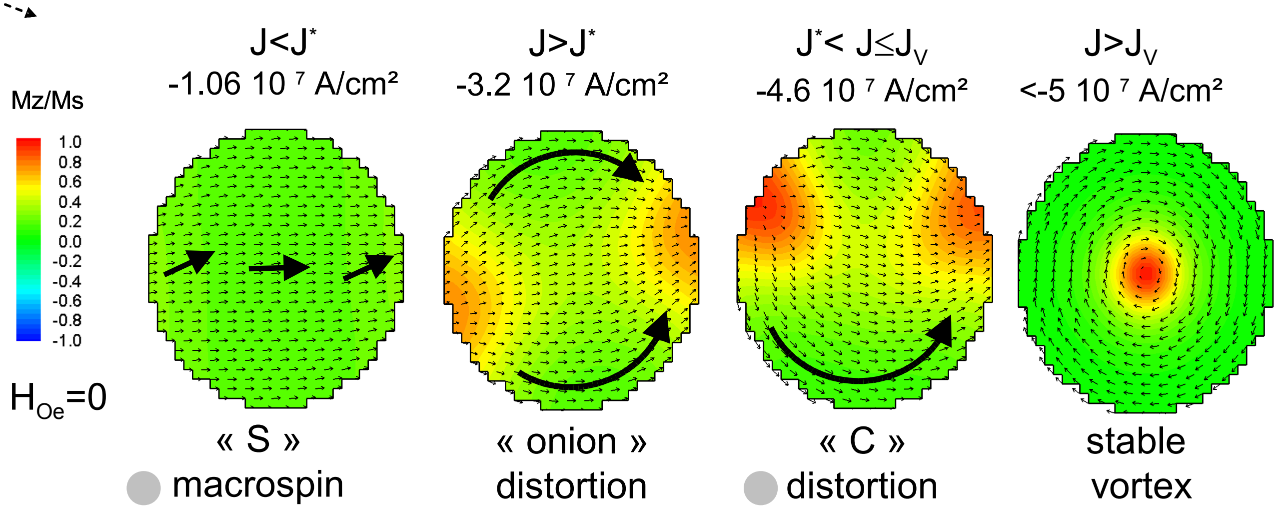
# Micromagnetic simulations with perpendicular polarizer

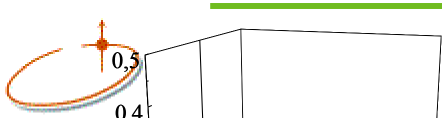
**Simulations* for**
**- circular dot of 60 nm Ø**
**- H =15 Oe, H =0 Oe**
**- α=0.01**



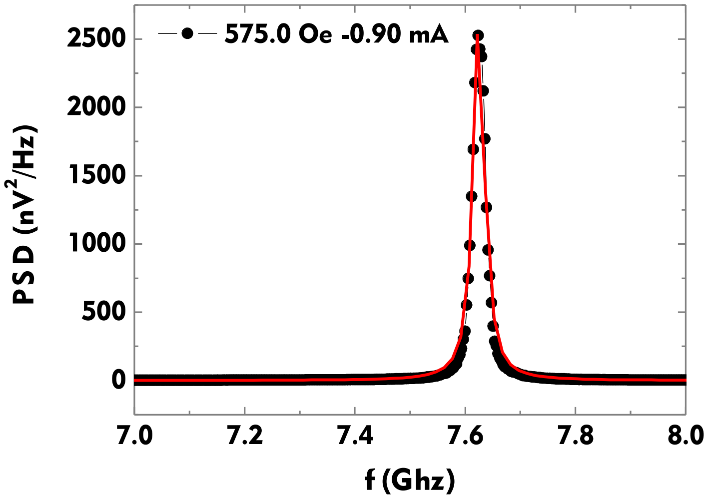



# Time domain versus spectral domain characterization of STT oscillators

## Spectral measurement

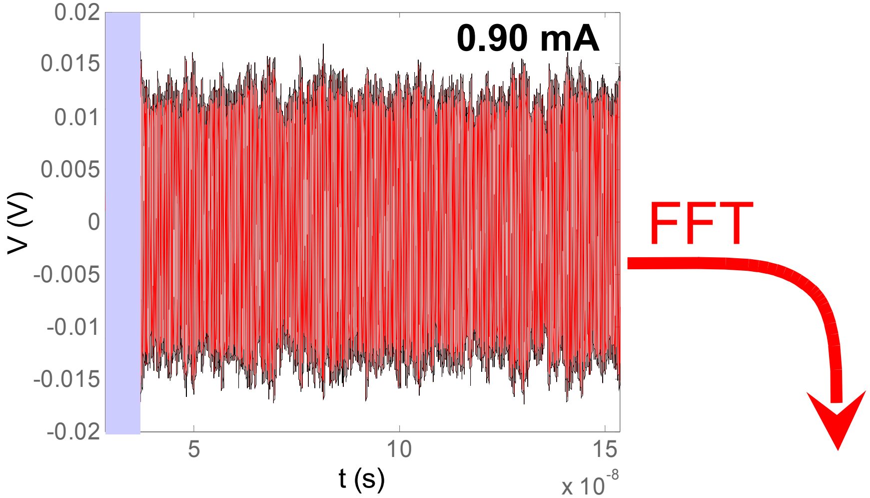
Several ms

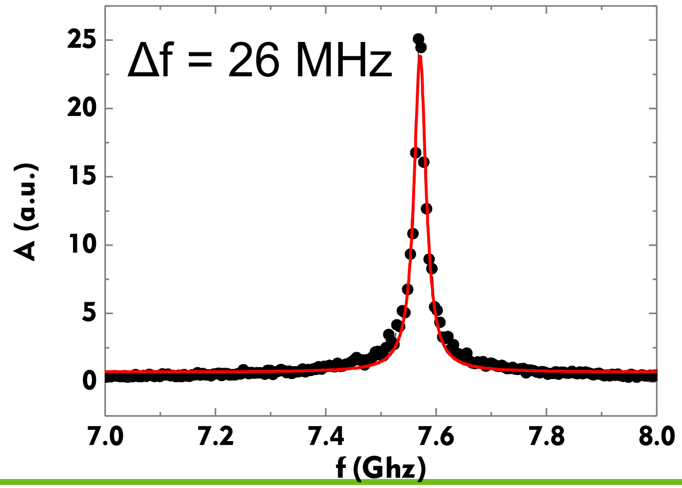



$\Delta f$ = 25 MHz

## Time domain measurement

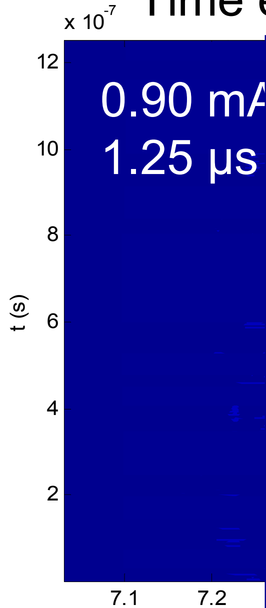
Few µs

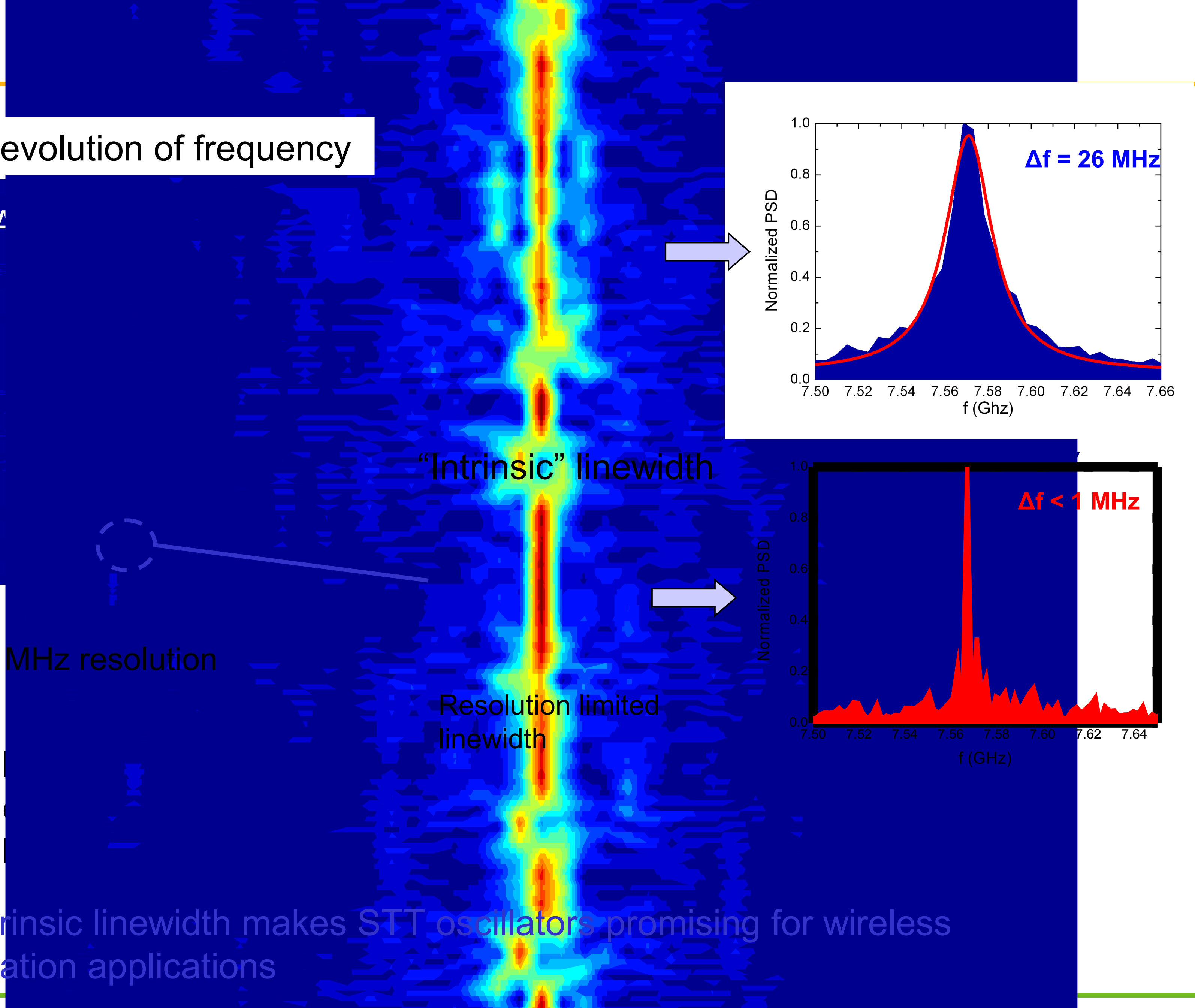



Spectrum analyzer linewidth = long time scale linewidth

## Time evolution of frequency




10 MHz resolution

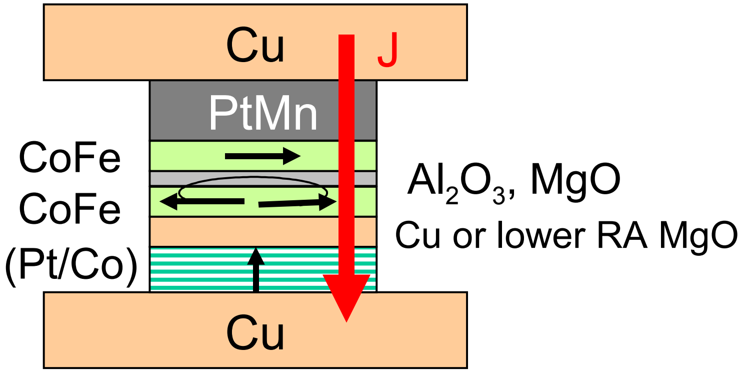
Two contri

- Frequen
- Intrinsic l

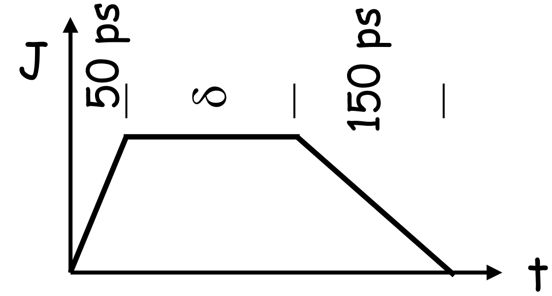
Narrow intrinsic linewidth makes STT oscillators promising for wireless communication applications

# Precessional switching in MRAM cell with perpendicular polarizer

**MRAM cell:**
**planar MTJ+perpendicular polarizer**



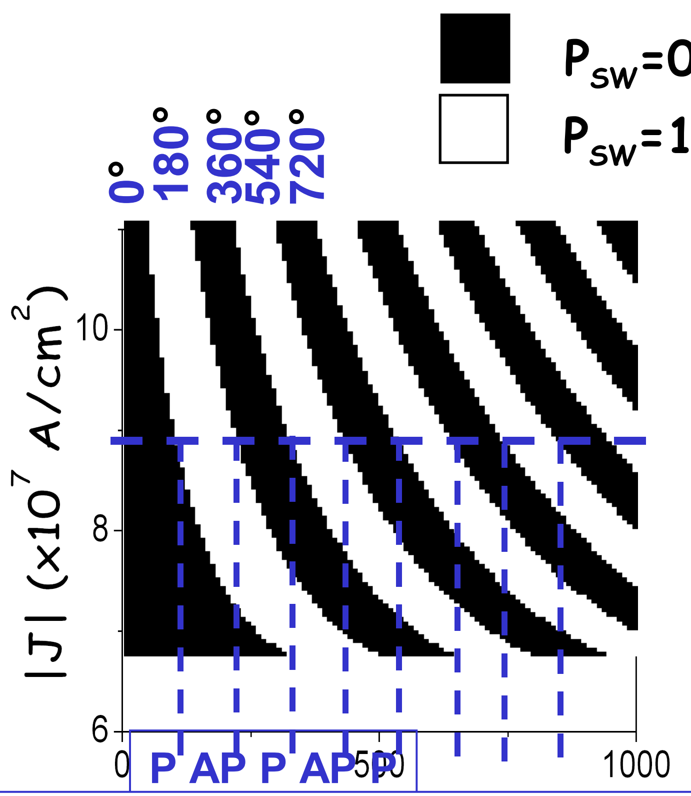

Current pulse shape




**Switching by monopolar pulse of current of duration ~half precession period (30ps-300ps)**

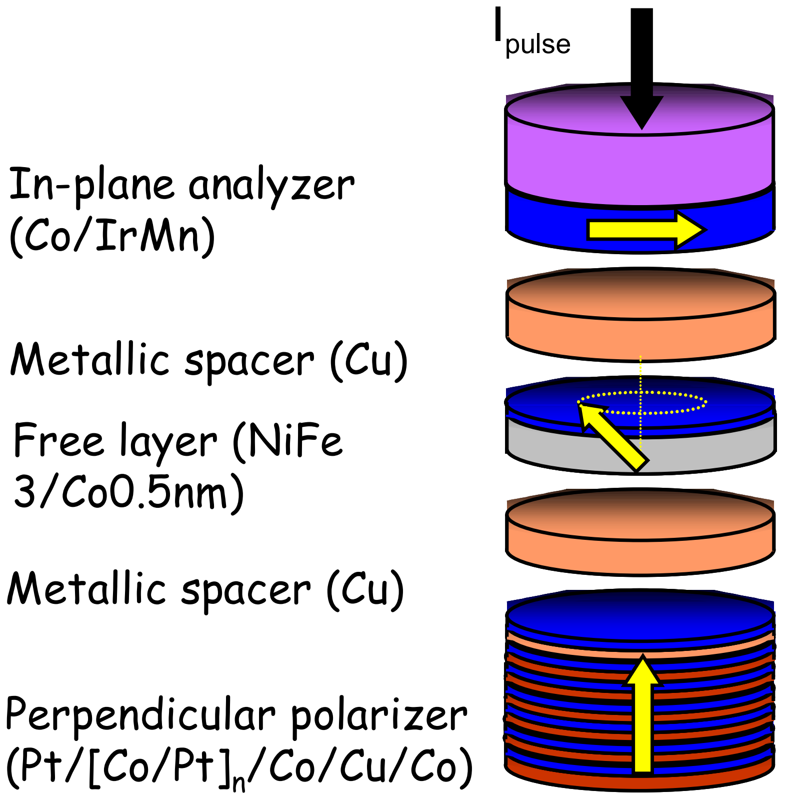
Macrospin LLG calculation at 0K assuming STT from perpendicular polarizer only.

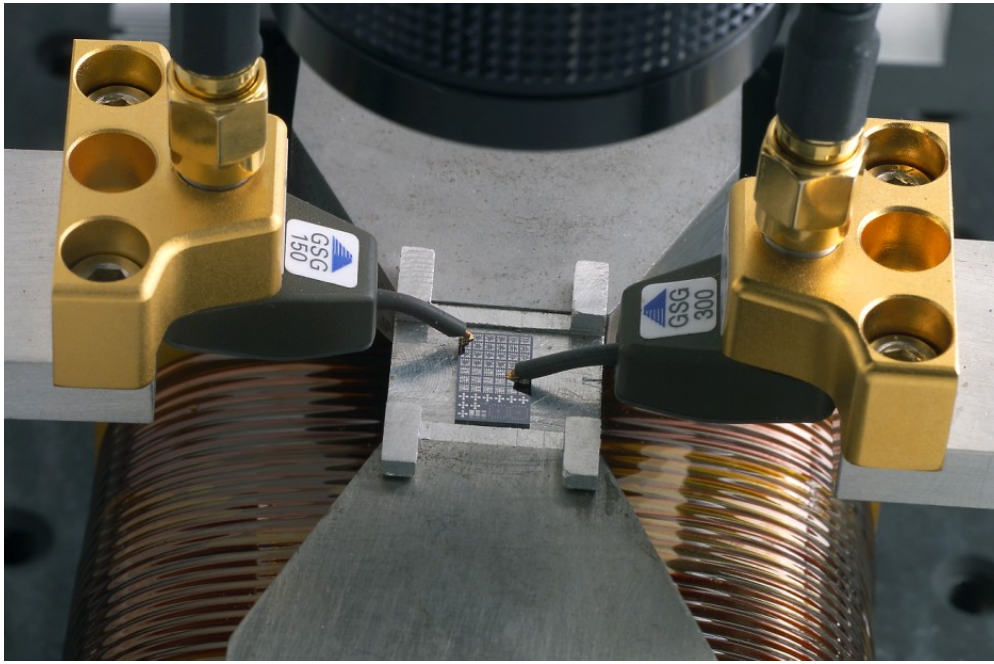
*70nm*140nm elliptical , CoFe 3nm*




**Same pulse duration for P⇒AP and AP⇒ P**

# Precessional switching in MRAM cell with perpendicular polarizer (cont'd)



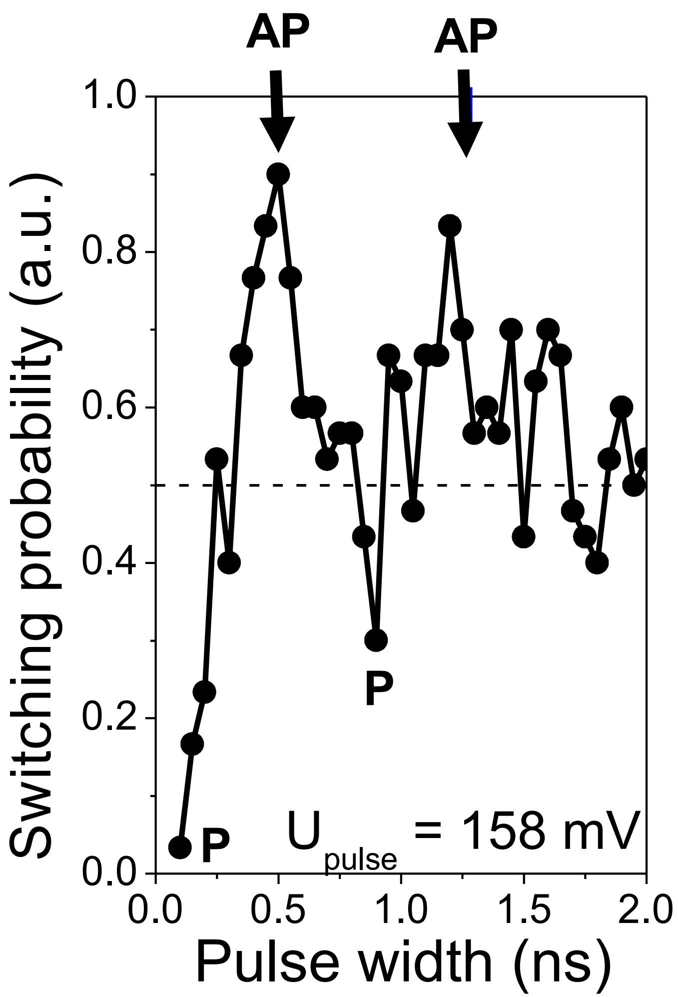




- Set a given configuration (P or AP)
- Apply a pulse of current of given amplitude and duration.
- Measure a posteriori the resistance of the stack to determine its magnetic state.
- Repeat 100 times for statistics of switching probability

# Precessional switching in MRAM cell with perpendicular polarizer (cont'd)

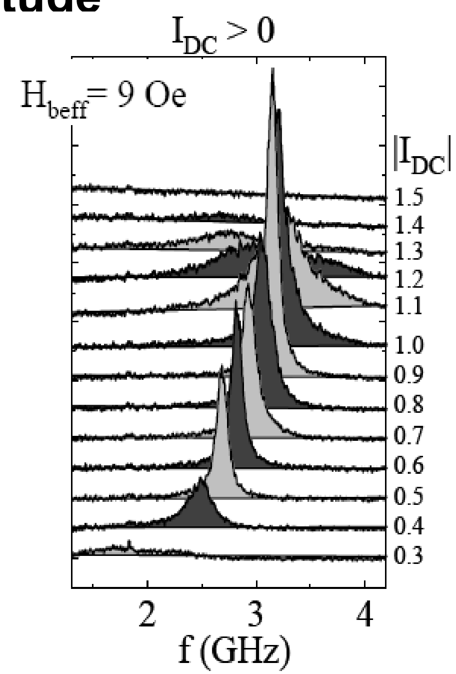
**Ultrafast switching at RT**

**Experiment repeated 100 times for each pulse width and amplitude**




ellipse 200x100 nm

$Ni_{80}Fe_{20}$ 3/Co 0.5 **nm**




**<u>Switching in 400ps</u>. Reasonable order of magnitude considering that precession frequency~2-3GHz**

**Damped oscillation in the switching probability at RT:**
**-Influence of thermal fluctuations which induces a loss of coherence;**
**-Influence of Oersted field during the current pulse**

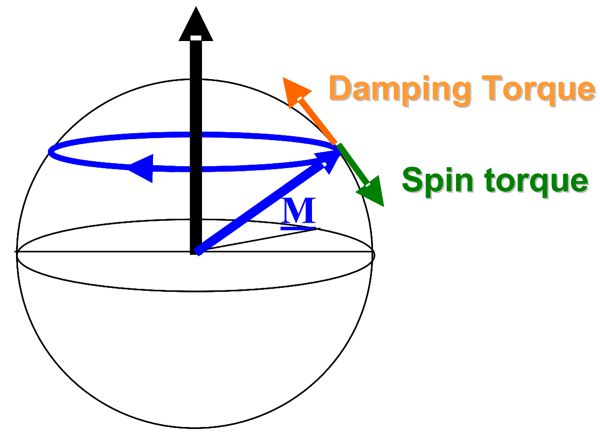
# Conclusion

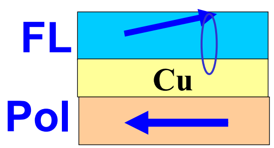
- GMR discovery has triggered the development of spin-electronics.
  Played a key role in magnetic recording and other sensor applications;
- Spin-valve magnetic concept (free/pinned by exchange anisotropy) also used in MTJ $\Rightarrow$ Spin engineering;
- Spin-transfer offers a new way to manipulate the magnetization of magnetic nanostructures (switching, steady excitations)
- For CMOS/magnetic integration, MTJ offers more suitable impedance ~few k$\Omega$ and larger magnetoresistance than GMR;
- Increasing interest for MRAM in microelectronics world;
- Besides MRAM, CMOS/MTJ integration quite interesting for logic, reprogrammable logic, innovative architecture.
- Frequency tunable RF oscillators interesting for wireless communications, RF interconnects.

# Perpendicular versus Planar Polarizer

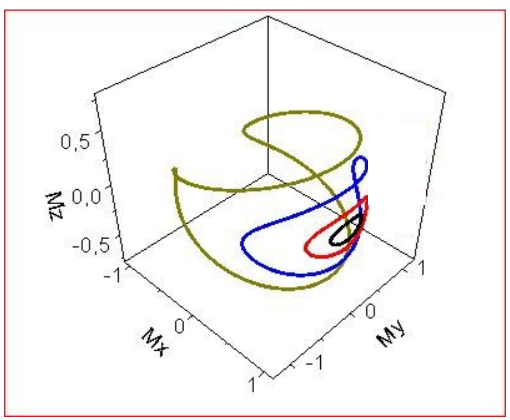
$$\frac{d\mathbf{M}}{dt} = -\gamma(\mathbf{M}\times\mathbf{H}_{eff}) + \frac{\alpha}{Ms}\mathbf{M}\times\frac{d\mathbf{M}}{dt} + \frac{\gamma\, a_J(\theta)}{Ms}\mathbf{M}\times(\mathbf{M}\times\mathbf{P})$$

Precession Damping Spin torque (ST)



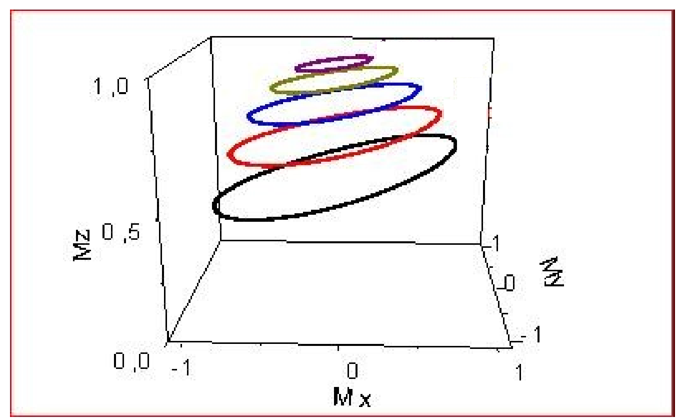




**In-Plane Precession IPP**

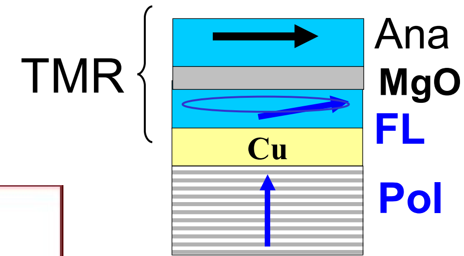



**Small angle precession around polarizer axis**

**Out-of-Plane Precession OPP**




**Large angle precession around out-of- plane axis**





- J. C. Slonczewski JMMM 157, (1996)
- O. Redon, B.Dieny US6,532,164 (2002)
- A. Kent et al. APL 84 (2004)
- K. J. Lee et al. APL 86 (2005)


 A. N. Slavin et al PRB **72**, 94428 (2005)