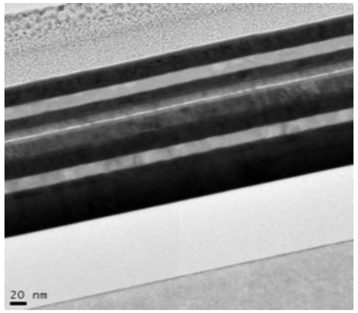
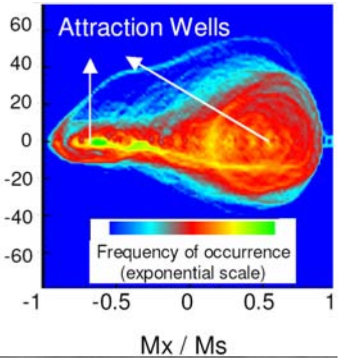
Spintronic phenomena and components

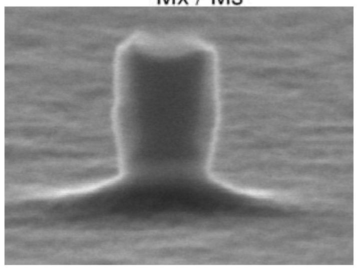
Material growth



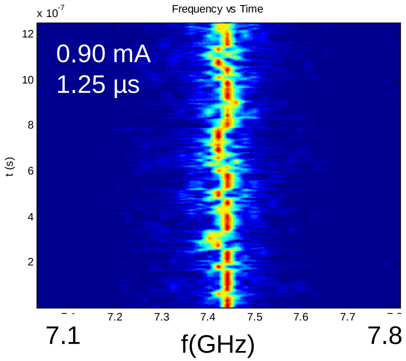
Theory/modeling



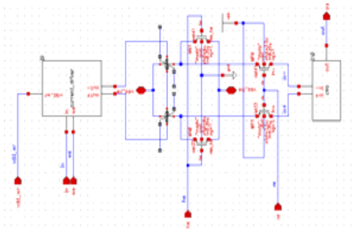
Technology



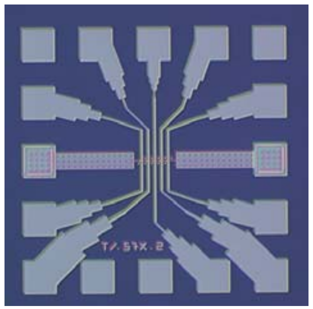
characterization

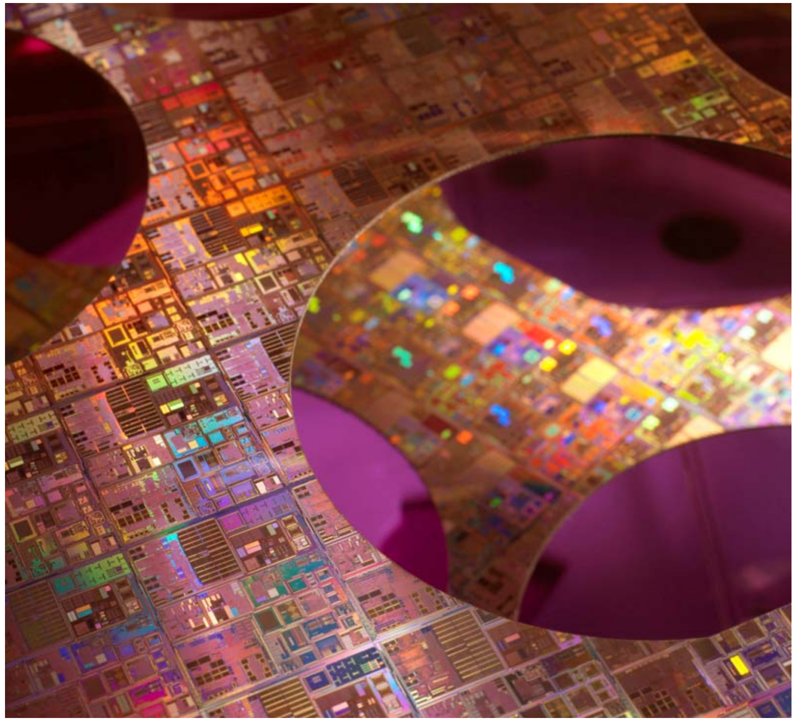


Design



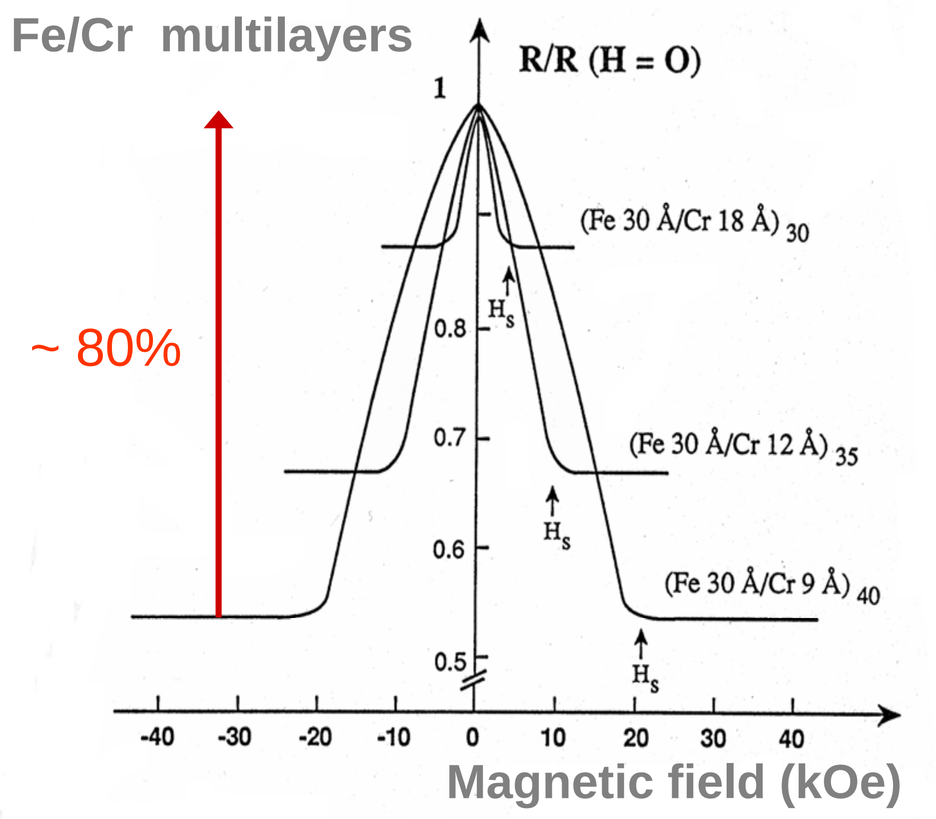
Device fabrication

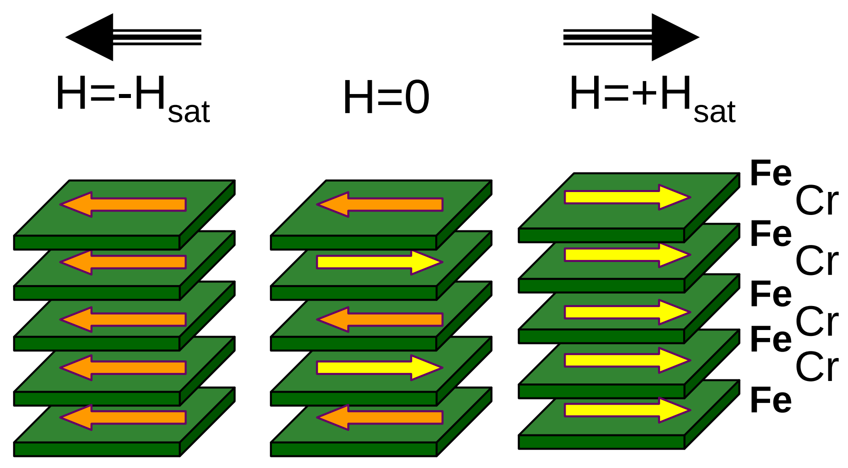




Functional chips / spintronics products

Birth of spin electronics : Giant magnetoresistance discovery (1988)





Antiferromagnetically coupled multilayers

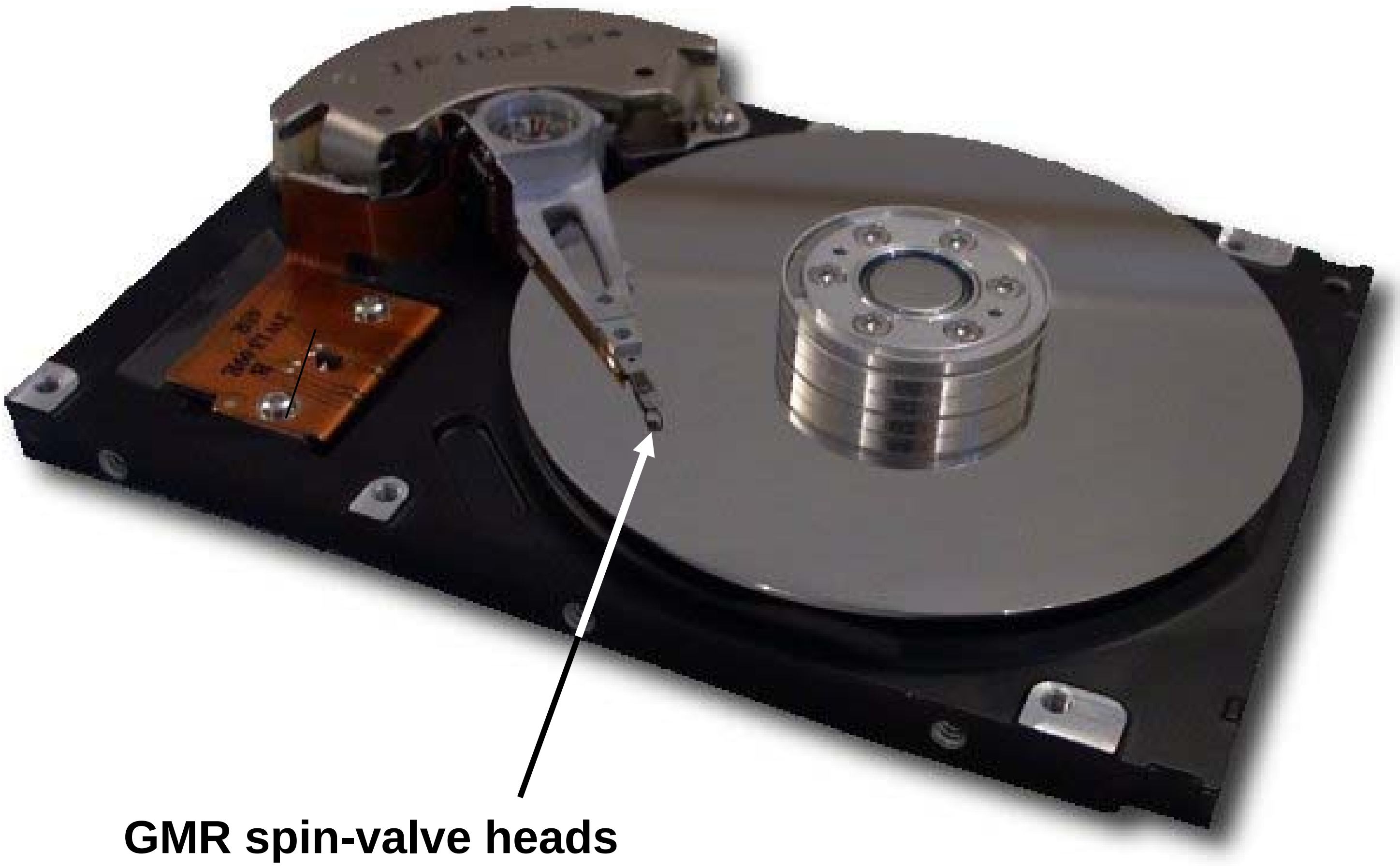
$$GMR = \frac{R_{AP} - R_P}{R_P}$$

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

Nobel Prize 2007

GMR due to spin-dependent scattering in the bulk or at the interfaces of the magnetic layers

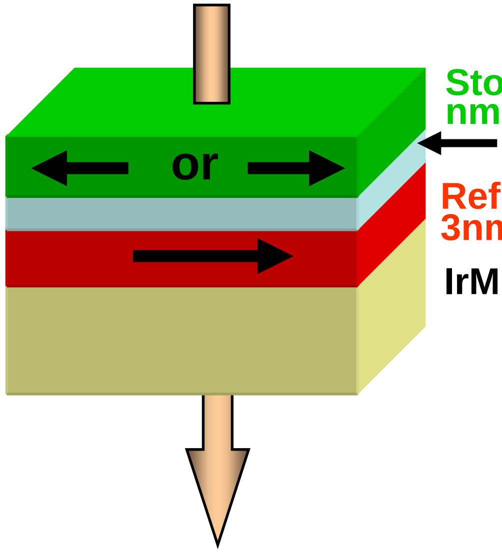
Benefit of GMR in magnetic recording



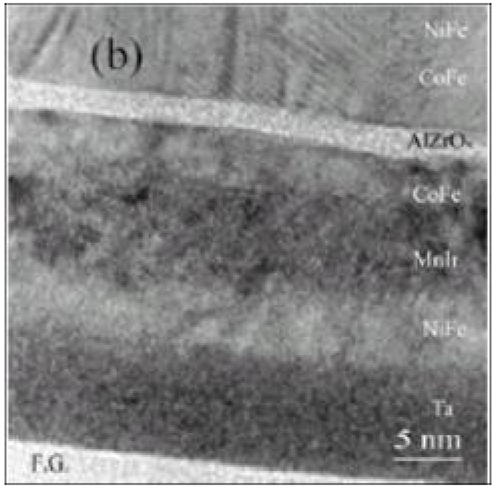
GMR spin-valve heads from 1998 to 2004

Magnetic tunnel junctions – Tunnel magnetoresistance

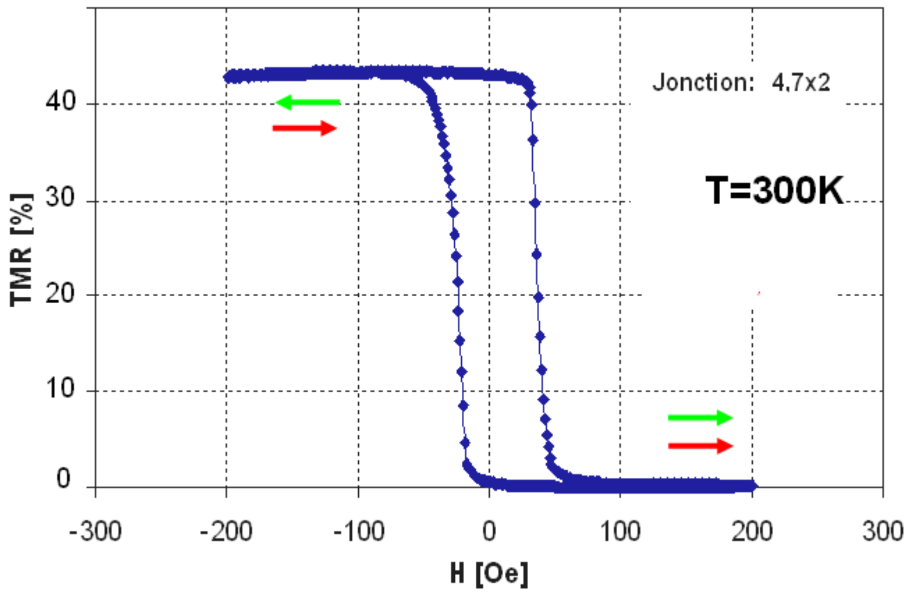
Structure of a magnetic tunnel junction



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



Al(Zr)O_x



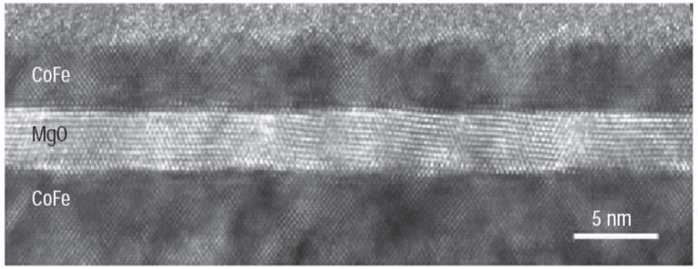
•First observation of TMR at low T in MTJ: Julliere (1975) (Fe/Ge/Co)

•TMR at 300K :
Moodera et al, PRL (1995);
Myazaki et al, JMMM(1995). $\Delta R/R \sim 50\%$
in AlO_x based junctions

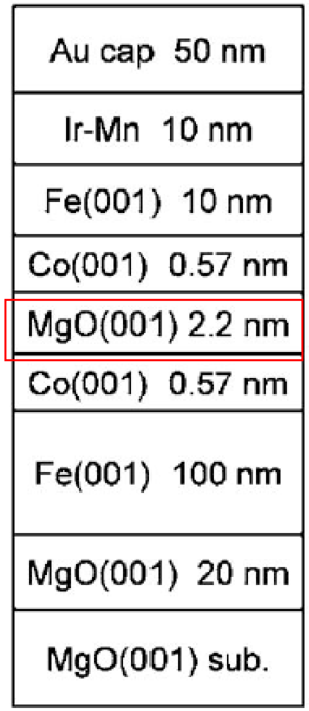
Giant TMR of MgO tunnel barriers

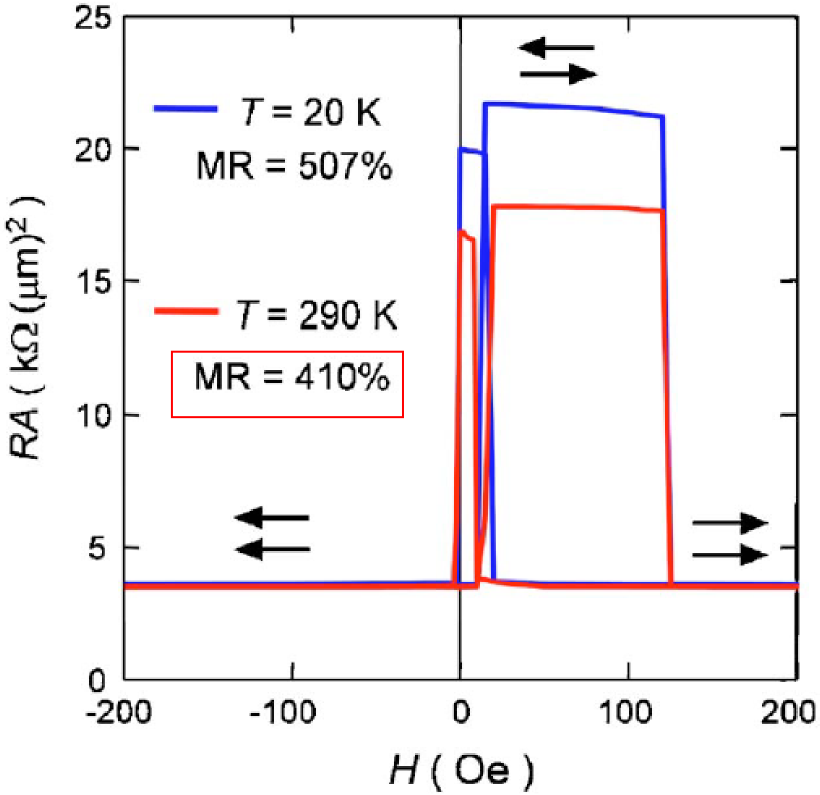
S.S.P.Parkin et al, Nature Mat. (2004), nmat1256.
S.Yuasa et al, Nature Mat. (2004), nmat 1257.

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



Yuasa et al, APL89, 042505(2006)

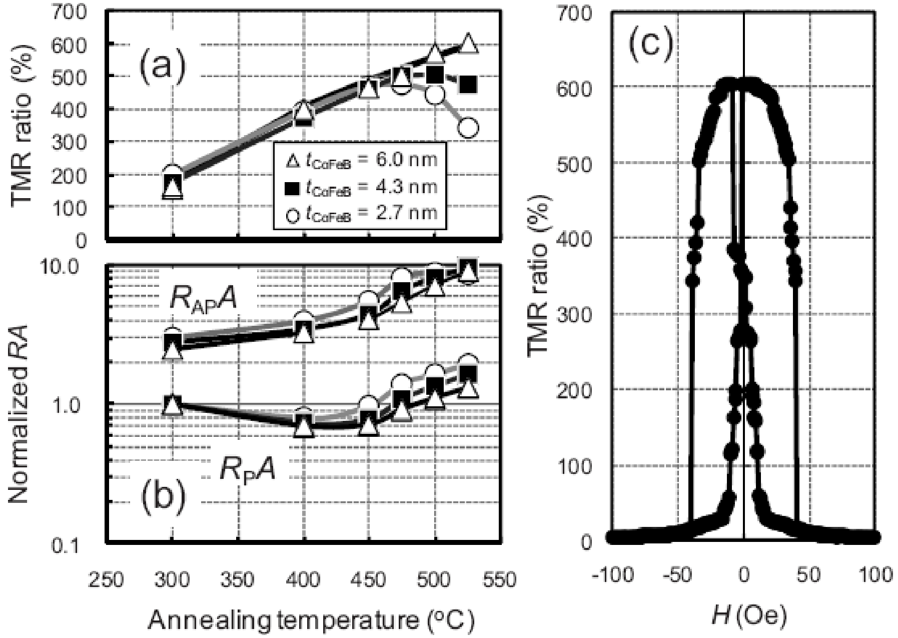




APPLIED PHYSICS LETTERS **93**, 082508 (2008)

Tunnel magnetoresistance of 604% at 300 K by suppression of Ta diffusion in CoFeB/MgO/CoFeB pseudo-spin-valves annealed at high temperature

S. Ikeda,[1,a)] J. Hayakawa,[2] Y. Ashizawa,[3,b)] Y. M. Lee,[1,c)] K. Miura,[1,2] H. Hasegawa,[1,2] M. Tsunoda,[3] F. Matsukura,[1] and H. Ohno[1,d)]



Applied Physics Express **2** (2009) 083002

Large Tunnel Magnetoresistance of 1056% at Room Temperature in MgO Based Double Barrier Magnetic Tunnel Junction

Lixian Jiang, Hiroshi Naganuma*, Mikihiko Oogane, and Yasuo Ando

Department of Applied Physics, Graduate School of Engineering, Tohoku University, Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan

Received June 29, 2009; accepted July 2, 2009; published online July 17, 2009

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

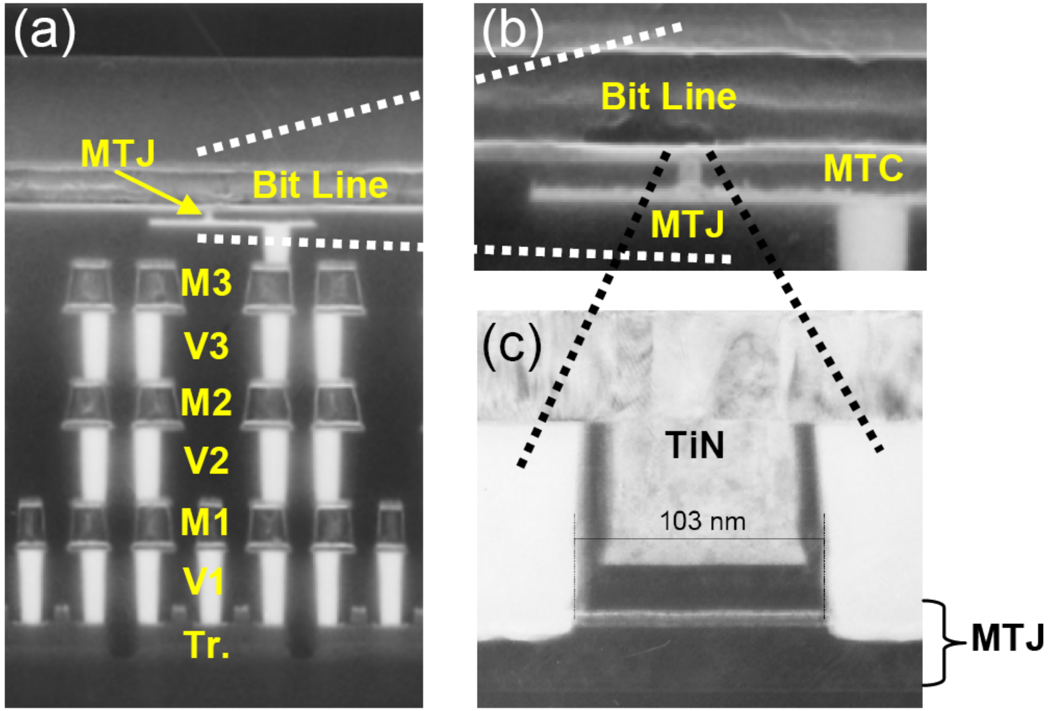
• Resistance of MTJ compatible with resistance of passing FET (few kΩ)

• 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)

•Commercial CMOS/MTJ products available from EVERSPIN since 2006 (4Mbit MRAM)
Implemented in Airbus flight controller

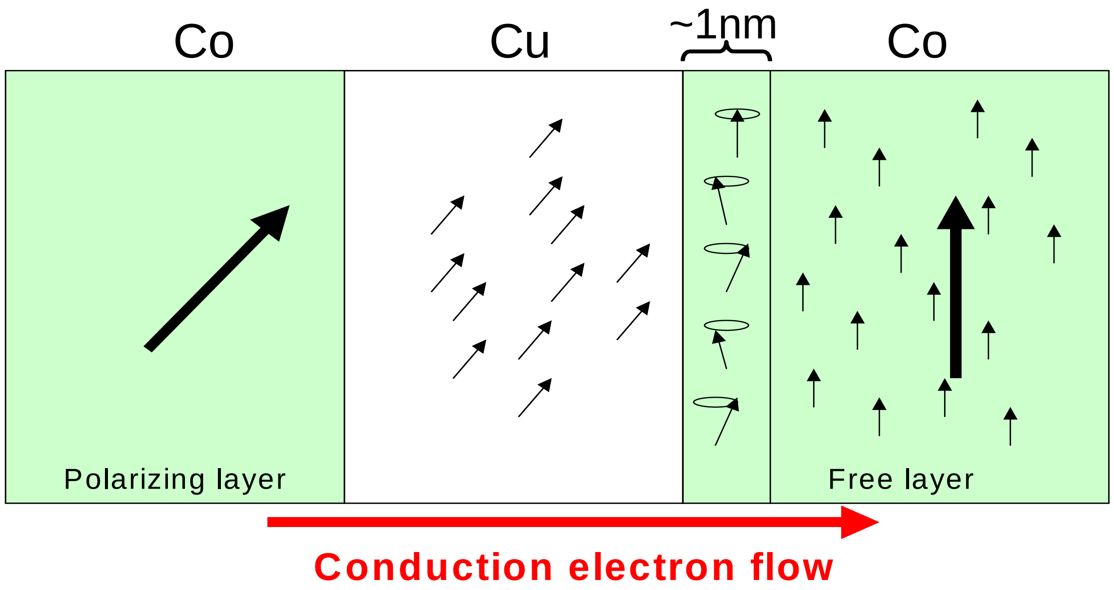


Spin-transfer

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

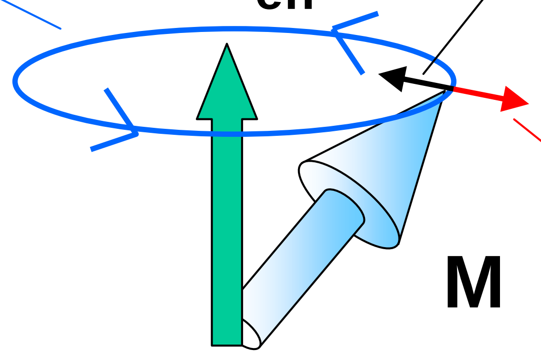
Effective field term (conserves energy)

Spin-torque term: damping (or antidamping) term

Gilbert Damping term

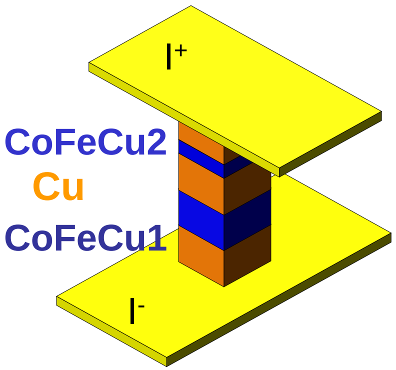
Non conservative

(Modified LLG)

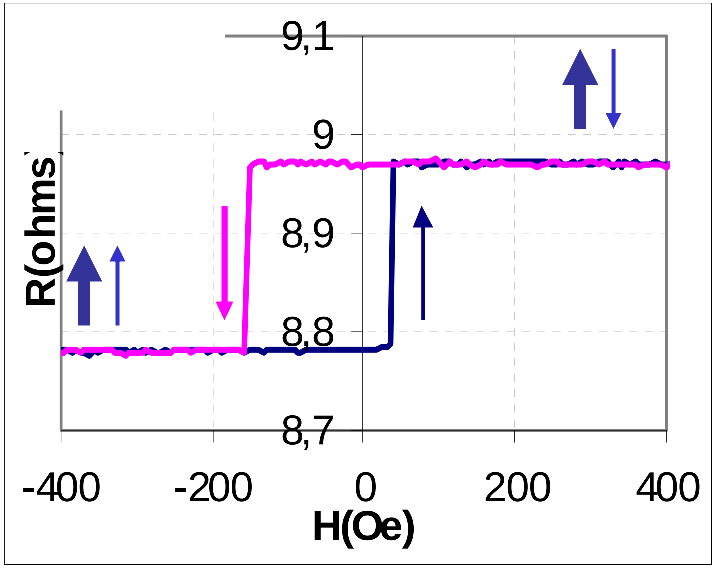


Magnetization switching induced by a polarized current

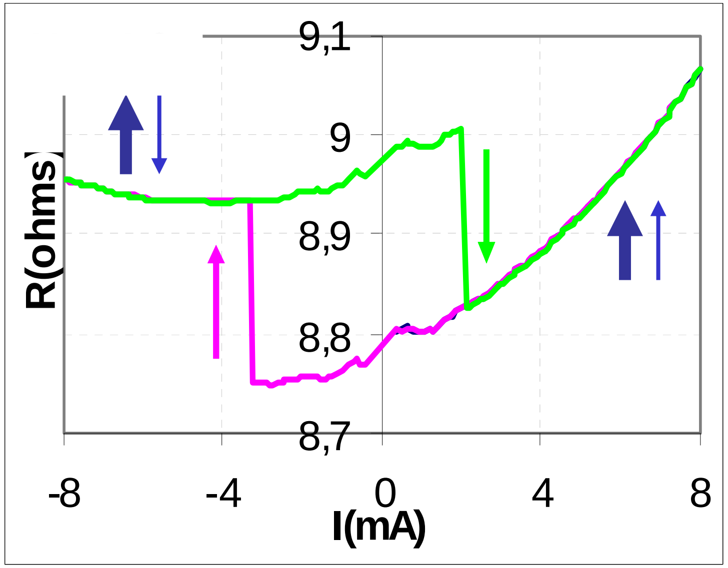
Katine et al, Phys.Rev.Lett.84, 3149 (2000) on Co/Cu/Co sandwiches (Jc ~2-4.107A/cm^2)



Field scan



Current scan



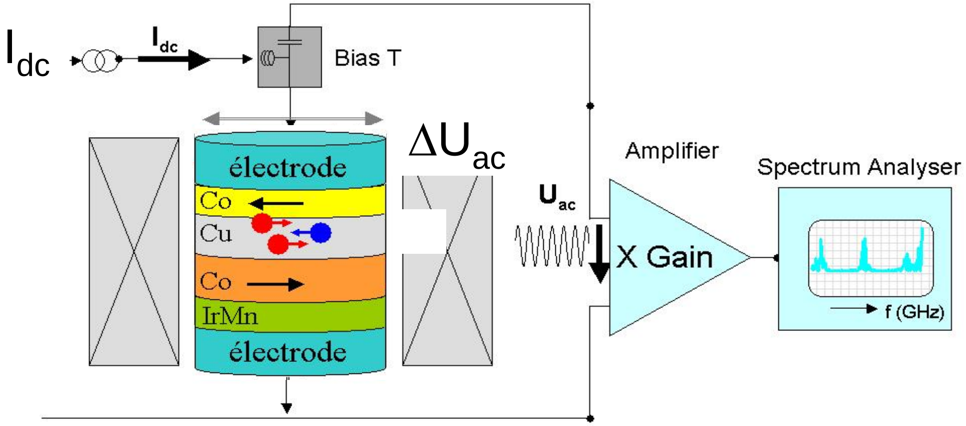
$j_c^{P\text{-}AP} = 1.9.10^7 A/cm^2$
$j_c^{AP\text{-}P} = 1.2.10^7 A/cm^2$

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**

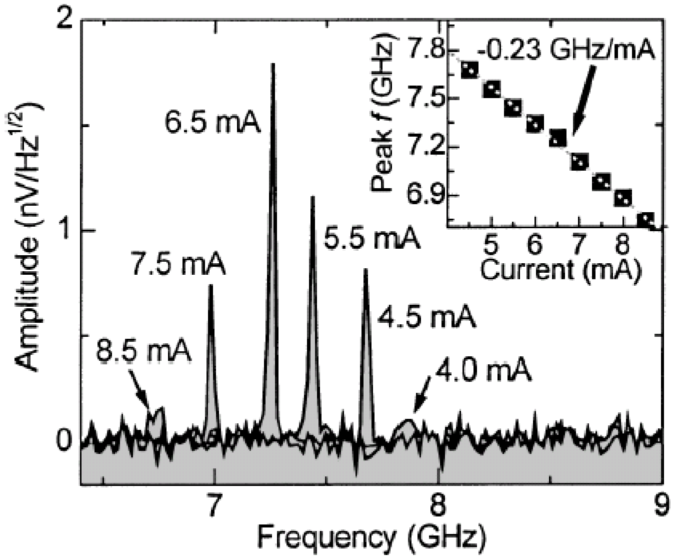
⇒Or to generate steady state oscillations leading to **RF oscillators**

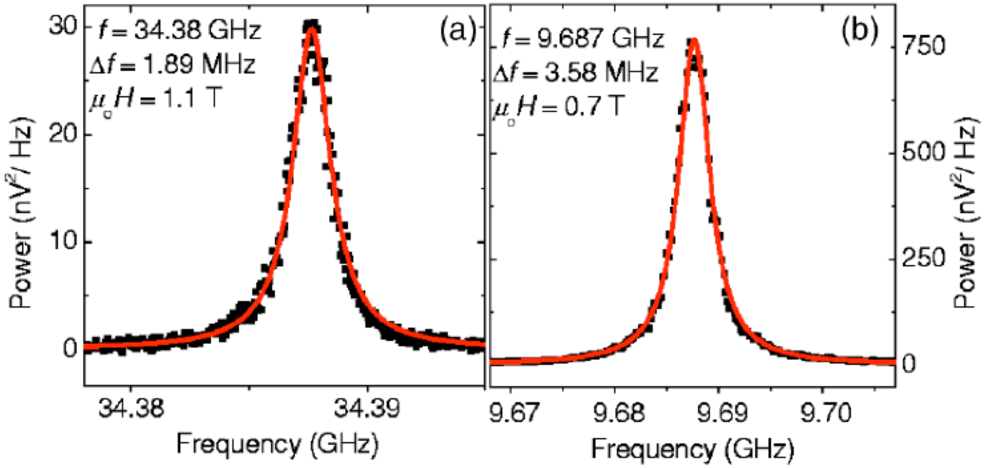
Steady magnetic excitations induced by a polarized current



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

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

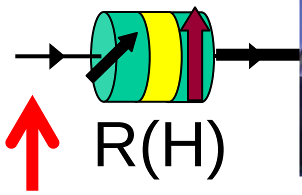


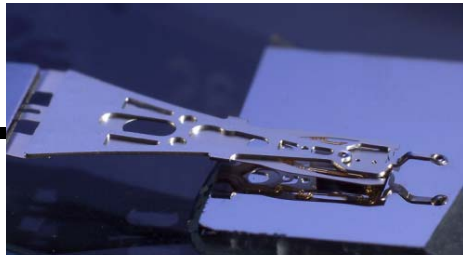


Q=18200 *Q=2700*

Interesting for RF components (frequency tunable RF oscillators, RF spin-diodes)

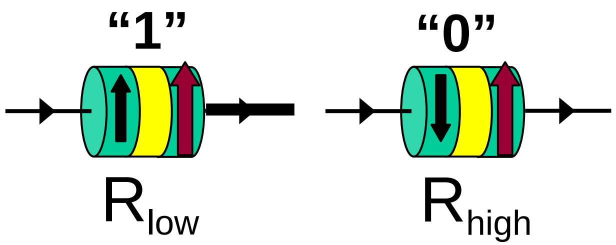
Spintronic components

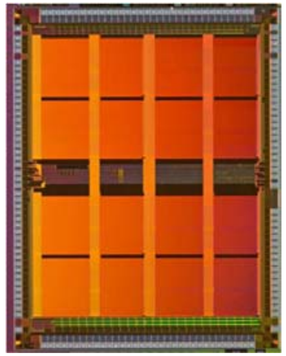




Write/read heads

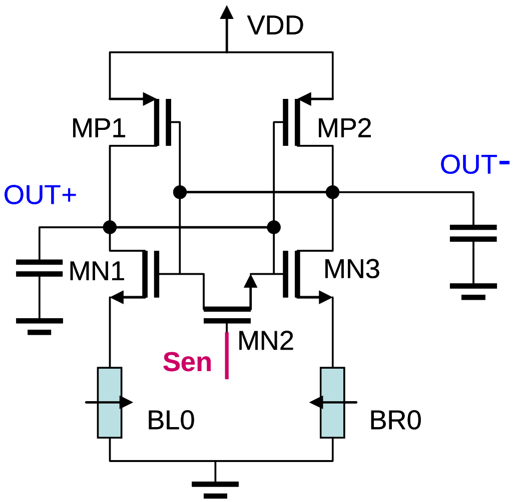
Magnetic field sensors



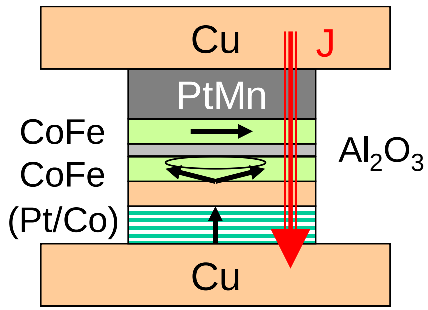


Freescale 4Mbit

Memories



Logic circuits

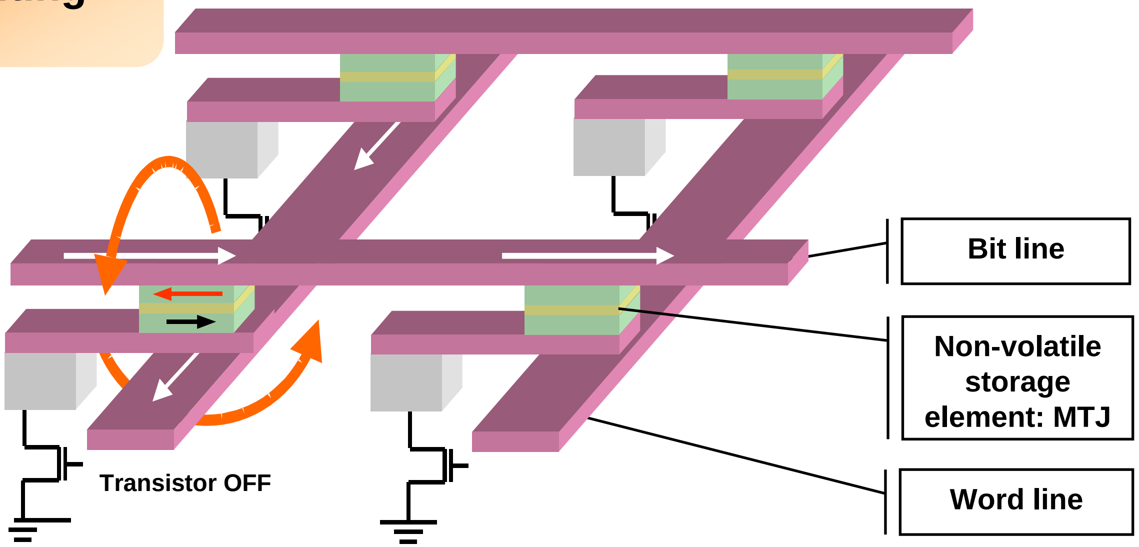


RF components

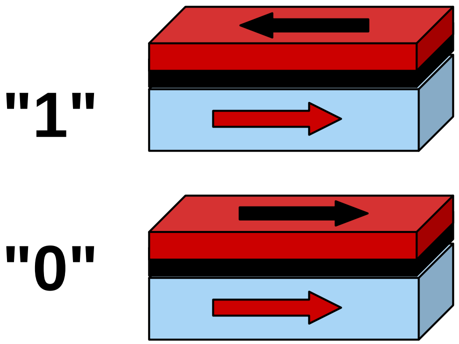
Field induced magnetic switching (FIMS) MRAM

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

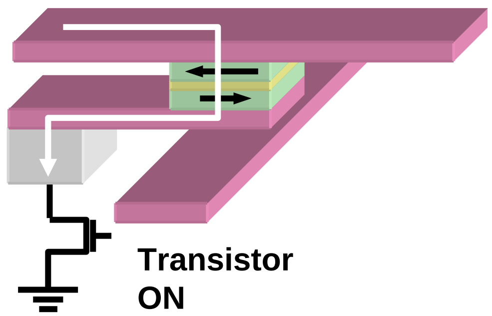
Writing

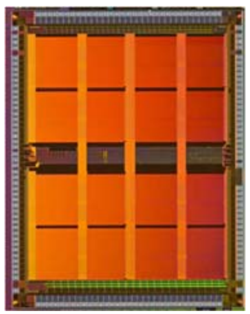


Selectivity achieved by combination of two perpendicular magnetic fields



Reading



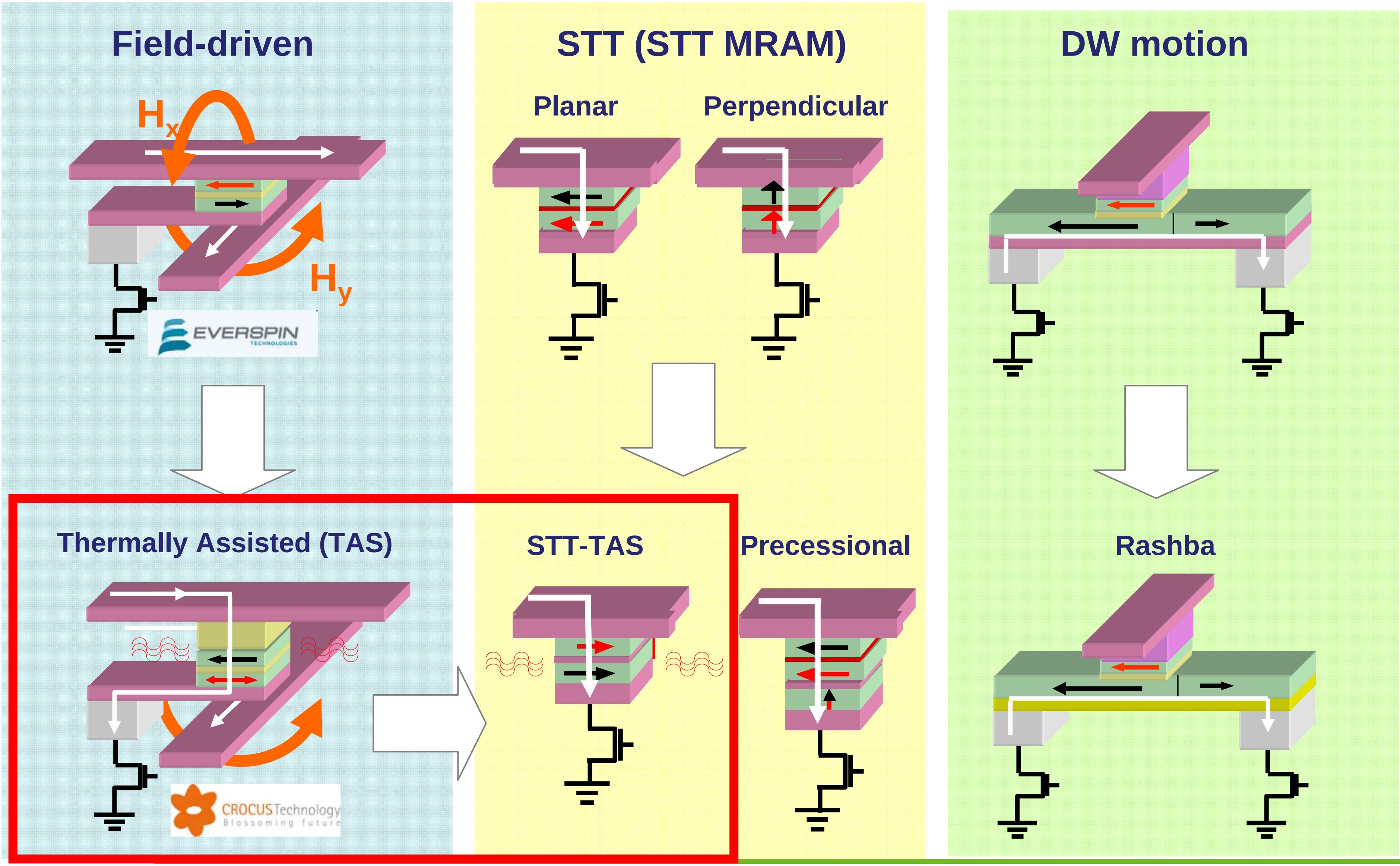


Freescale 4Mbit (2006)

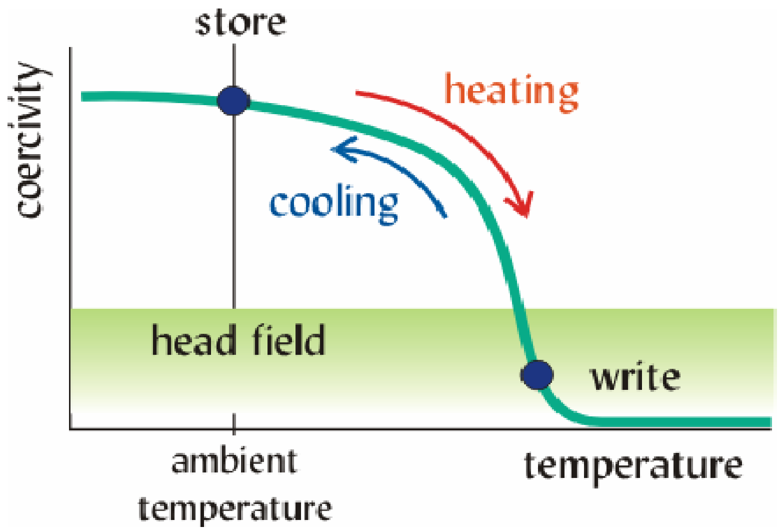
In Airbus flight controllers

Not scalable below 65nm because of electromigration issues

Several new generations of MRAM



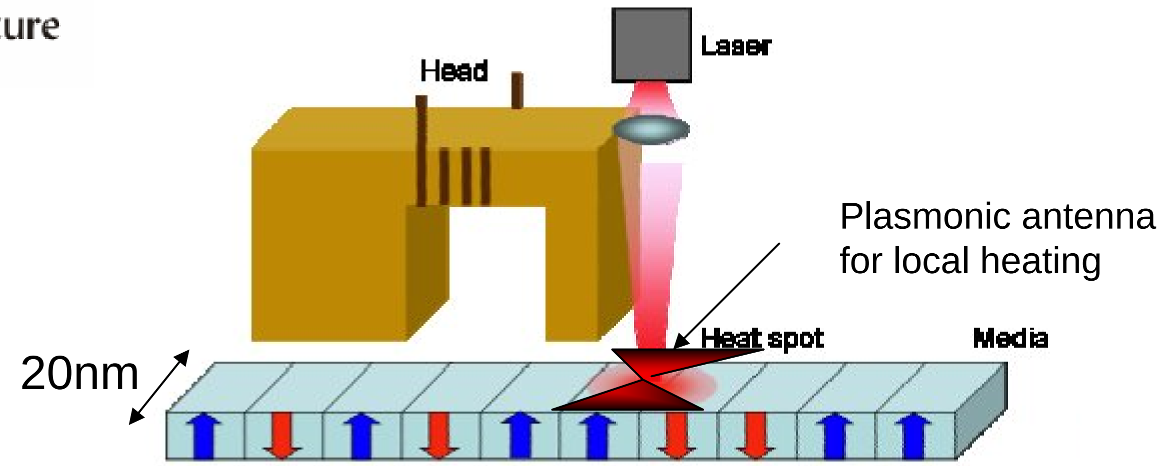
Thermally Assisted switching (TAS)



•Use temperature-dependence of switching ability

- ➢ **Write at elevated temperature**
- ➢ **Store / read at room temperature**

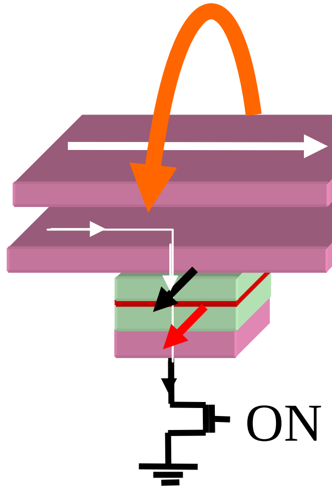
•Same basic concept as in **Heat Assisted Magnetic Recording.** Allows extending the areal density of stored information (smaller bits) without requiring higher field to write

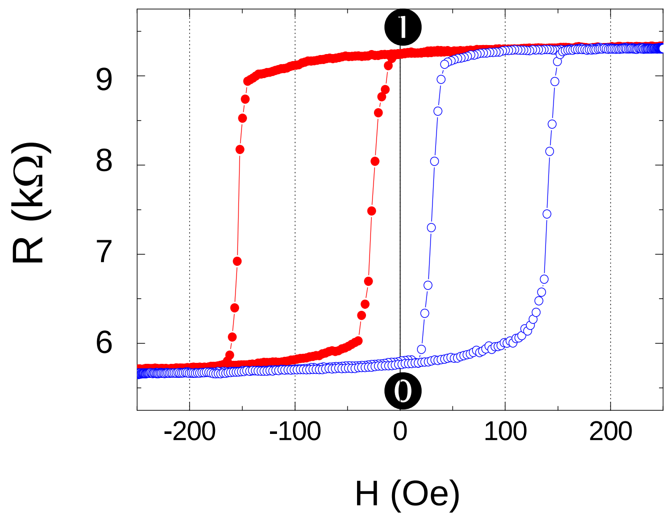


• In MTJ for MRAM, heating produced by Joule dissipation around the tunnel barrier.
• Write temperature~250°C

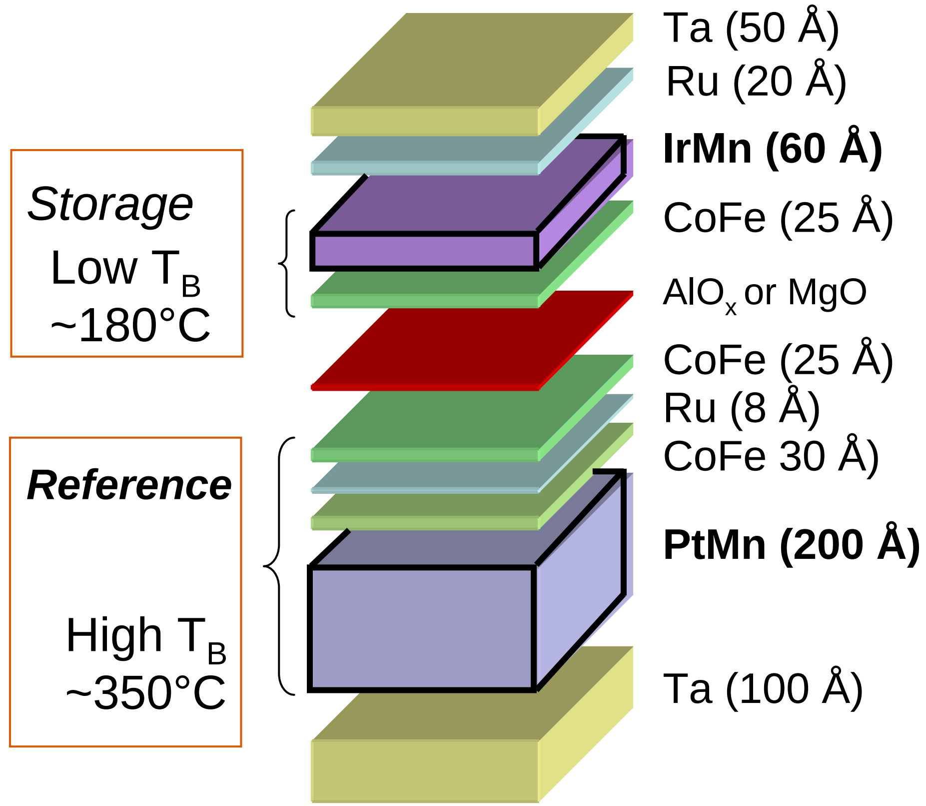
Thermally assisted writing in TA-MRAM

Heating + Field~2.5mT





Exchange biased storage layer

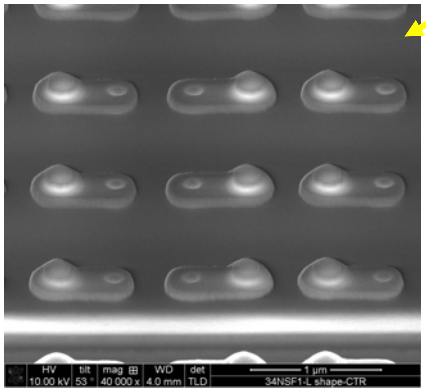


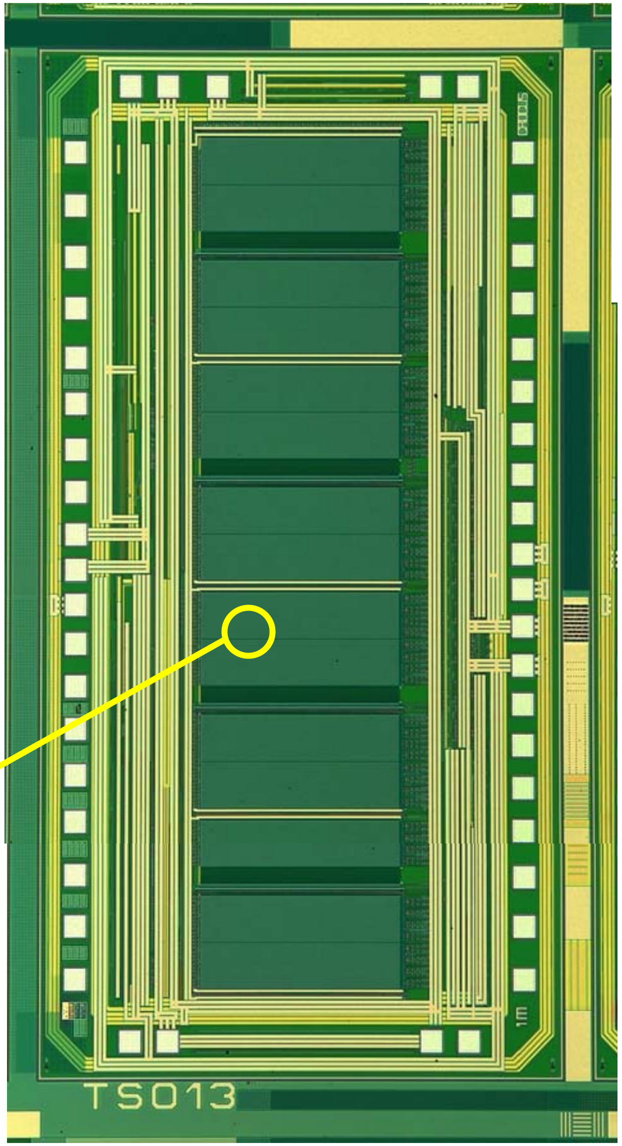
- heat the storage layer above the **low T_B**

CROCUS 1-4MB PRODUCT (Field-TAS)

TOWERJAZZ CROCUS Technology Blossoming future

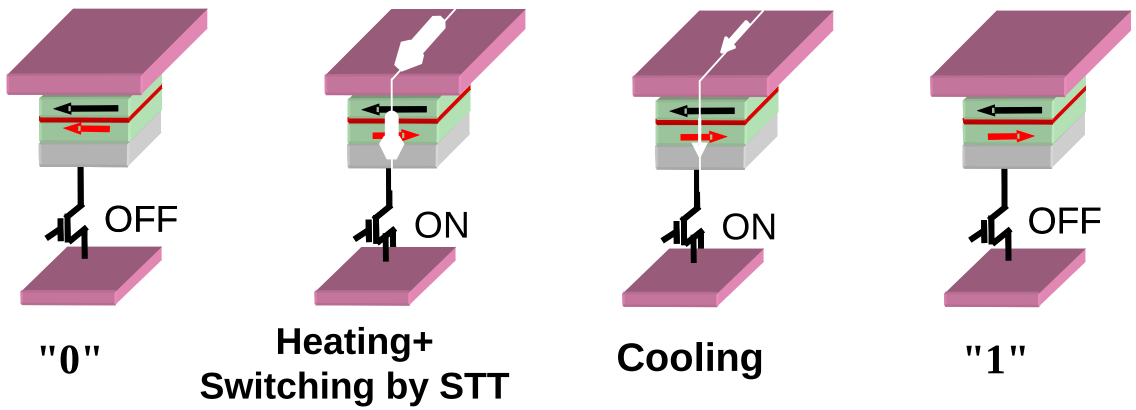
- Agreement to manufacture Crocus TA-MRAM products on Tower Semiconductors 130nm Cu Fab2
- Both standalone and embedded products will be addressed
- Start with 1Mb stand-alone SRAM compatible product, sampling in progress (1H'11)
  - 128Kx8 1Mbit MRAM w/ asynchronous SRAM interface
    130nm / 3.3V industry-standard CMOS front-end
    4 metals + magnetics
  - Timings comparable to C3 SRAM
    Read cycle time ~20ns, write cycle time 40ns
  - Low power architecture specific to TAS cell operation
    Icc Write ~35mA
  - Commercial T-range (0-85°C)
- Migrating to 4Mb 2H'11
- Potentially going down to
  - ~10F^2
  - Icc write ~5mA
  - 10ns R/W cycle



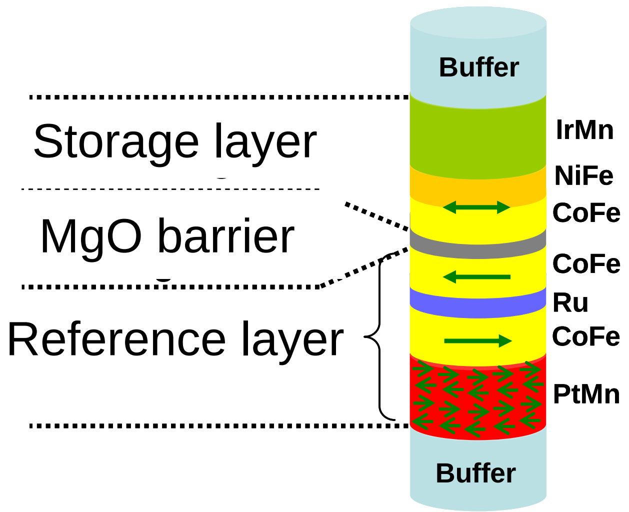


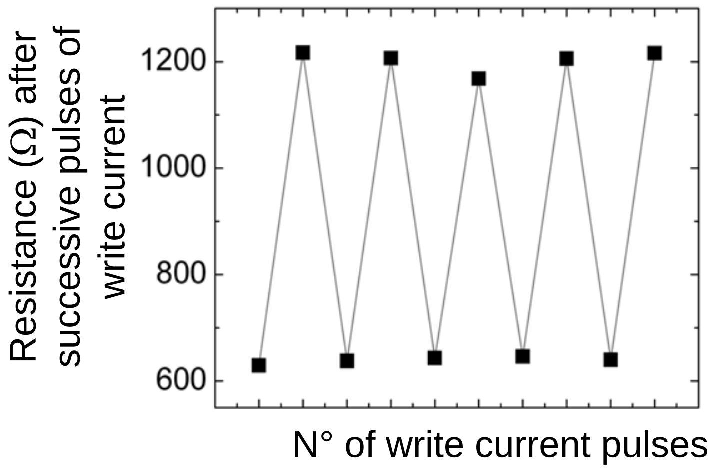
Combining spin-transfer with thermally assisted writing

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:

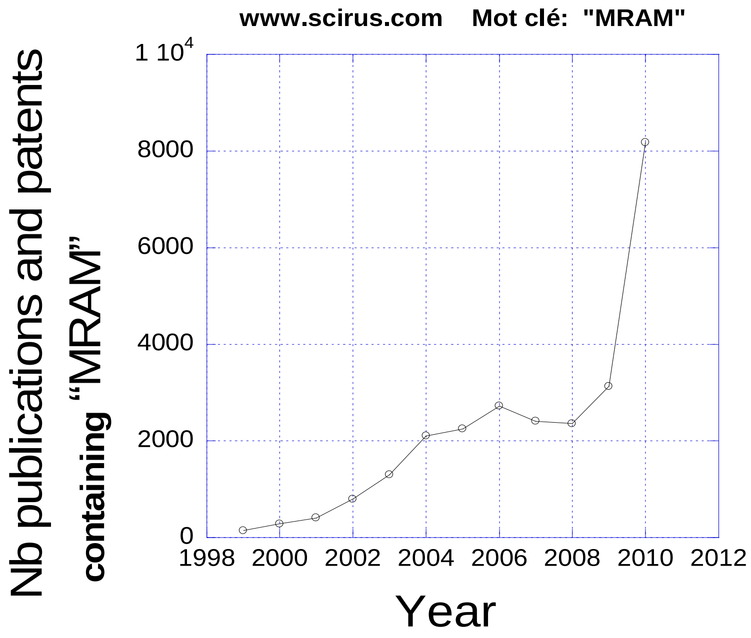




Approach offering the ultimate scalability (sub-15nm cell-size possible) with stability of information over 10 years.

spintec
SPIN IN ELECTRONICS

Increasing interest for MRAM in microelectronics industry



International Technology Roadmap of Semiconductors-ERD 2010:

Assessment of the Potential & Maturity of Selected Emerging Research Memory Technologies
Workshop & ERD/ERM Working Group Meeting (April 6-7, 2010)

Jim Hutchby & Mike Garner
July 23, 2010

The outcome of this study is the ERD/ERM working groups identified Spin Transfer Torque MRAM and Redox RRAM as emerging memory technologies recommended for accelerated research and development leading to scaling and commercialization of Non-volatile RAM to and beyond the 16nm generation.

Increasing interest for MRAM in microelectronics industry

The Register®

Samsung dives into spin-transfer torque

Next generation tech: Korean company buys DARPA-funded Grandis

By **Chris Mellor**

Posted in Storage, 3rd August 2011 09:26 GMT

CROCUS Technology
Blossoming future

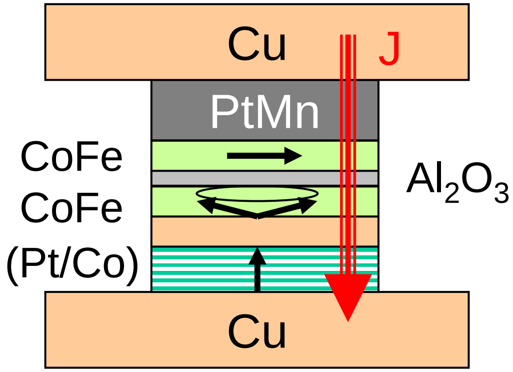
Crocus Technology Strikes $300 Million Financing Deal with RUSNANO to Build Advanced MRAM Manufacturing Facility in Russia

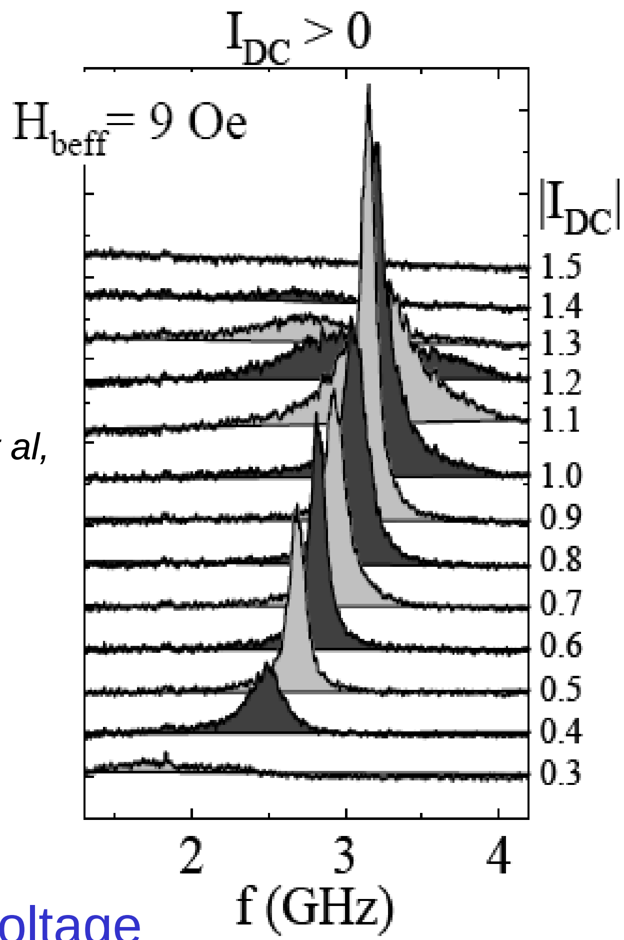
For Immediate Release

SUNNYVALE, Calif. — May 17, 2011 — Crocus Technology, a leading developer of MRAM technology, and RUSNANO, a premier nano-technology investment fund, today announced that they have closed an agreement to create an MRAM manufacturing company, with a combined investment totaling $300 million.

RF components based on spin transfer

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.

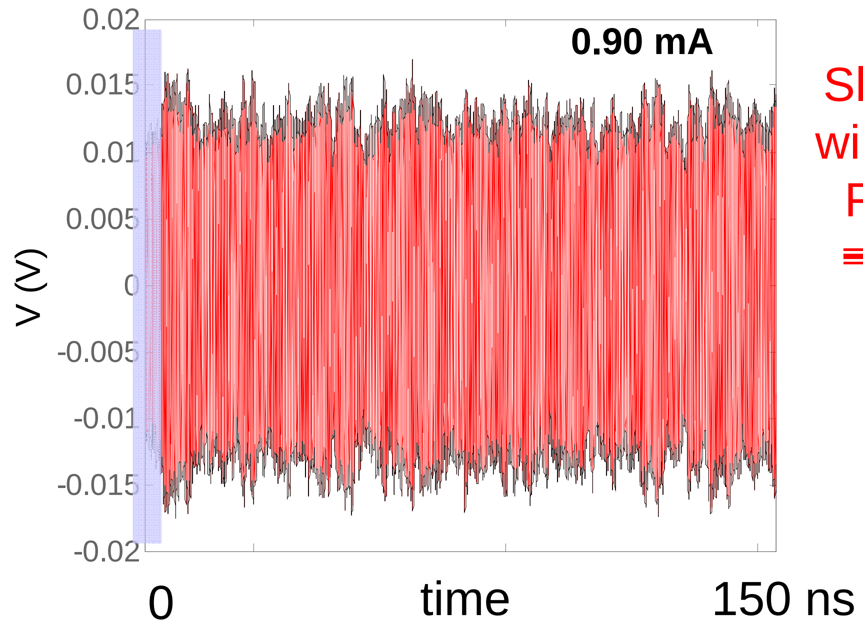
Precession (2GHz-40GHz) + Tunnel MR ⇒ RF voltage
Interesting for frequency tunable RF oscillators ⇒ Radio opportunism

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

Spin-transfer RF oscillators: linewidth and phase noise

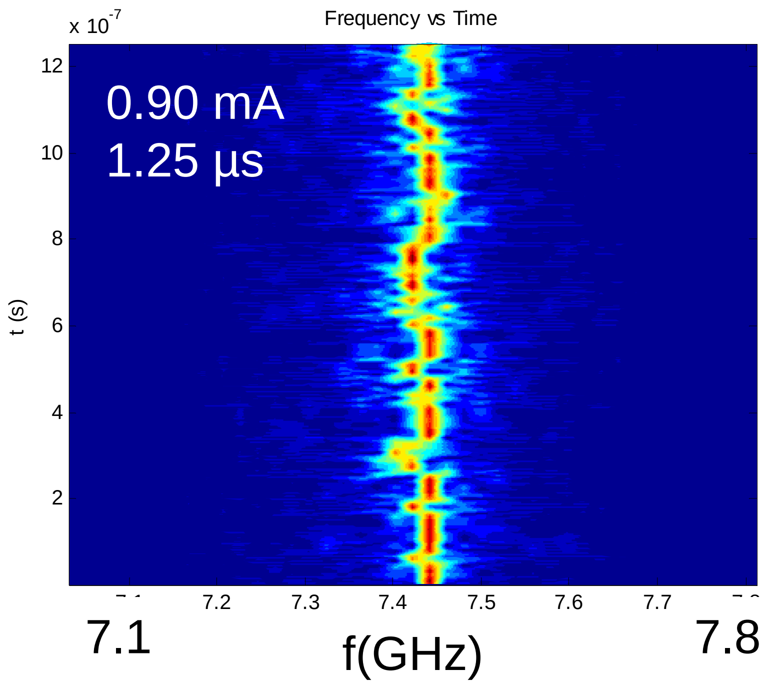
Still too large for practical applications but steady progress thanks to optimization of stack composition and shape

Time domain measurement



Sliding window FFT

Time evolution of spectrum



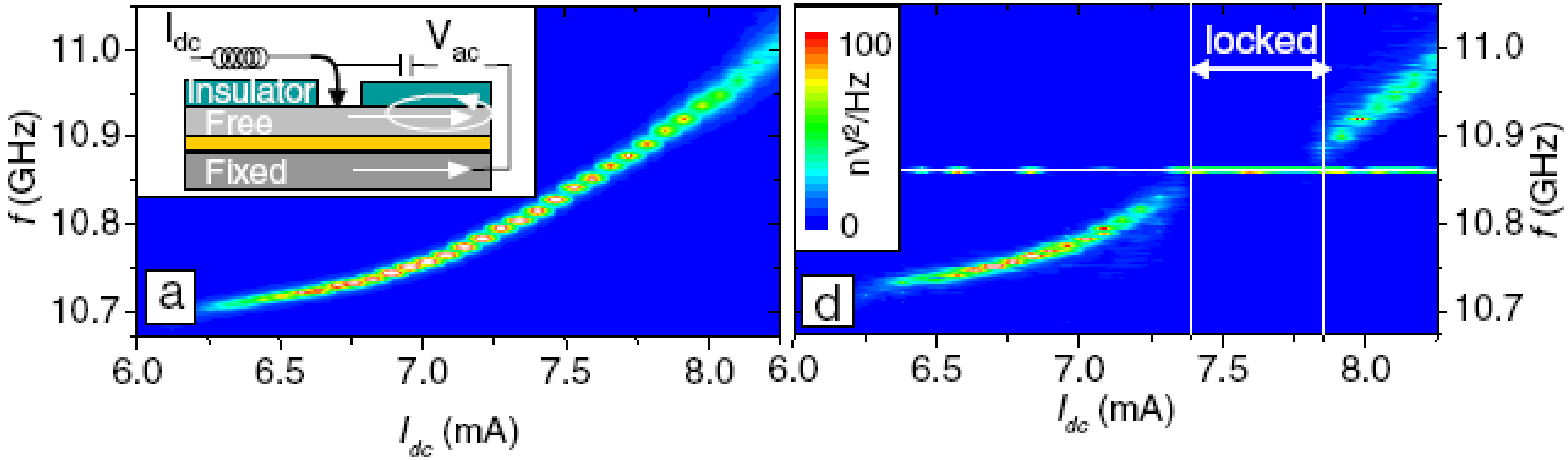
Influence of thermal fluctuations on magnetization dynamics and pillar edge modes

Increasing magnetic volume of oscillator, locking of several oscillators, locking on external source, feedback with PLL…

RF components based on spin transfer

Phase locking phenomenon: Locking on an external source

CoFe 20nm (fixed)/Cu 4nm/NiFe 5nm (free)



DC current, no AC drive

$I_{DC}+I_{AC}$ 10.86GHz 410µA RMS

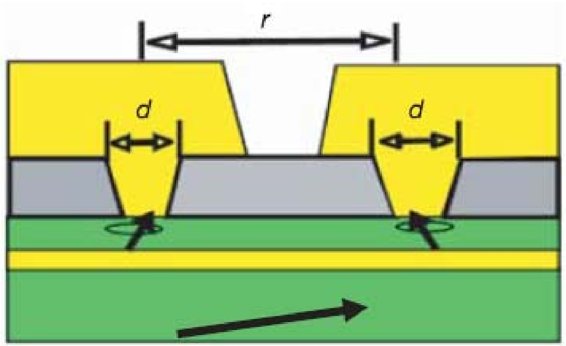
Rippard et al, PRB70, 100406 (2004)

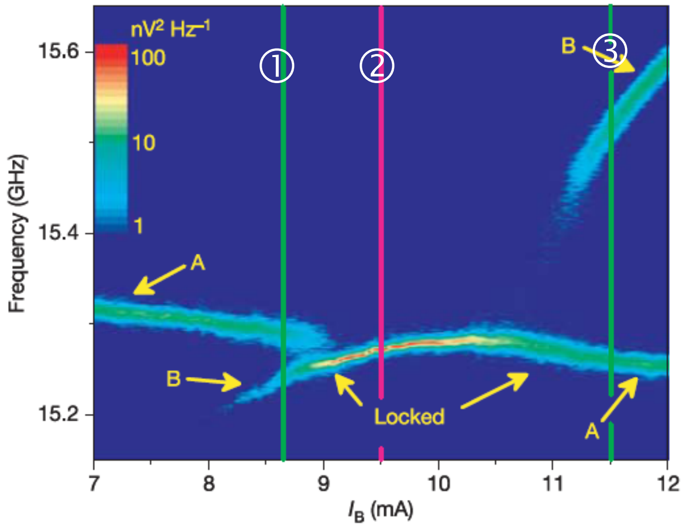
RF components based on spin transfer (cont'd)

Phase locking phenomenon:

S.Kaka et al, Nature 437, 389(2005)

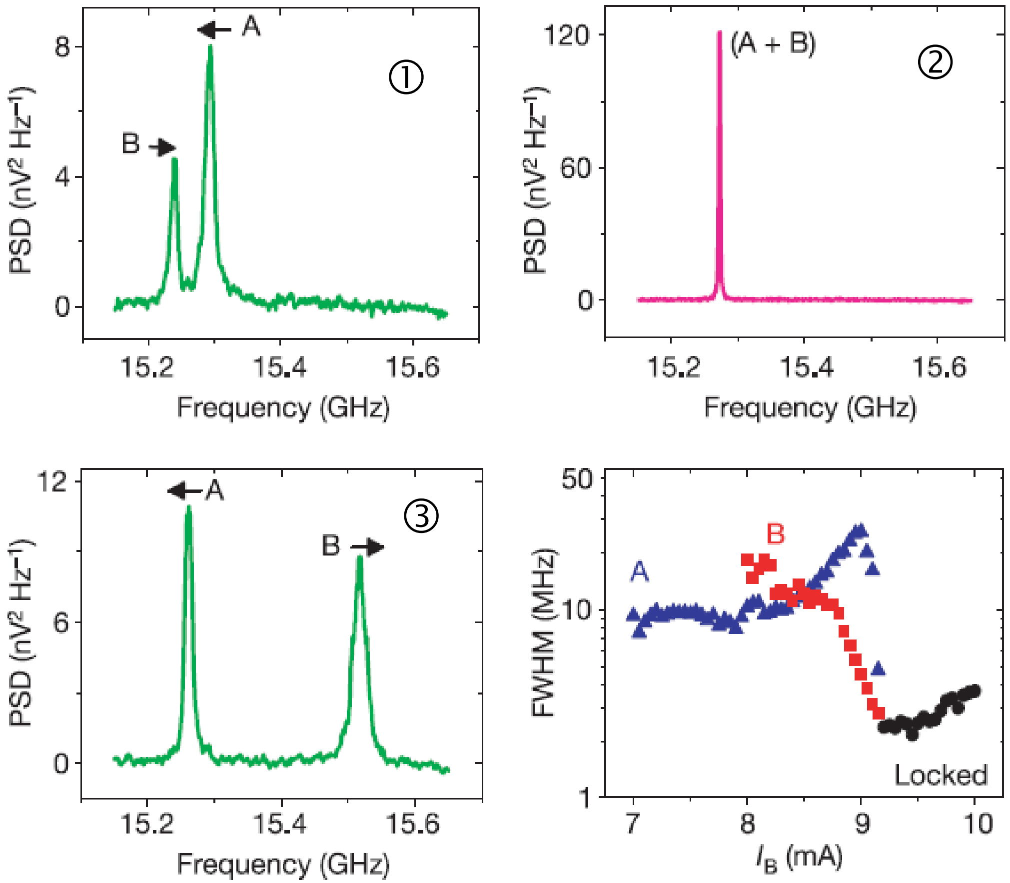
NiFe 5nm
Cu 2nm
Co 20nm





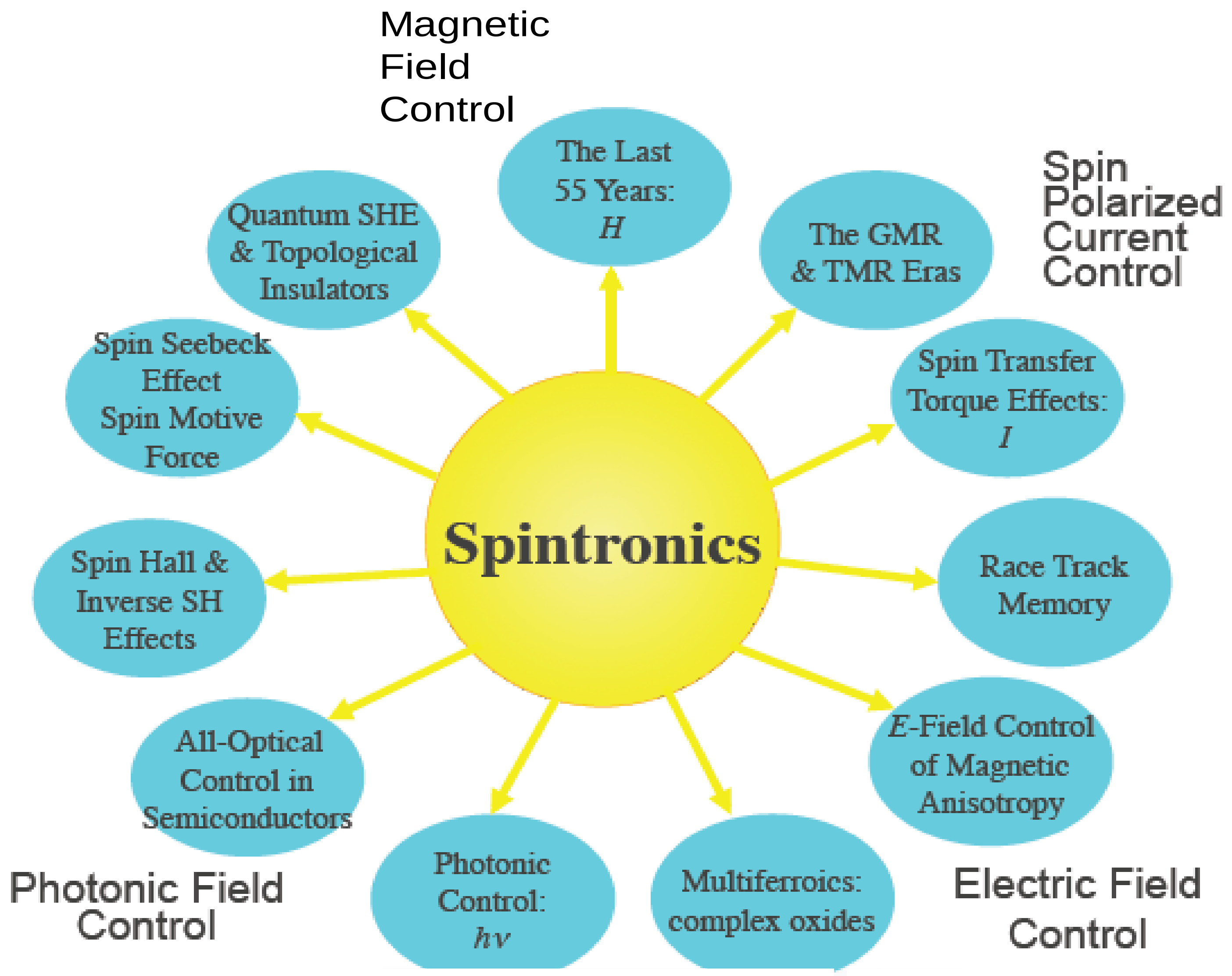
Locking of two oscillators together

Locking via spin-waves propagating from one STO to the other



Larger emitted power and narrower linewidth when the STOs are locked

WHAT'S NEXT ?



Courtesy Sam Bader

Conclusion

- GMR discovery has triggered the development of spin-electronics.

  Played a key role in magnetic recording and other sensor applications;
- For CMOS/magnetic integration, MTJ offers more suitable impedance

  ~ few kΩ and larger magnetoresistance than GMR;
- Spin-transfer offers a new way to manipulate the magnetization of magnetic nanostructures (switching, steady excitations);
- Increasing interest for MRAM in microelectronics industry; renewal of magnetism industry in particular in Europe.
- Besides MRAM, CMOS/MTJ integration quite interesting for logic, innovative computer architecture, frequency tunable RF oscillators.
- Lot of emerging topics in spin-electronics covering a broad spectrum from basic research to applications.

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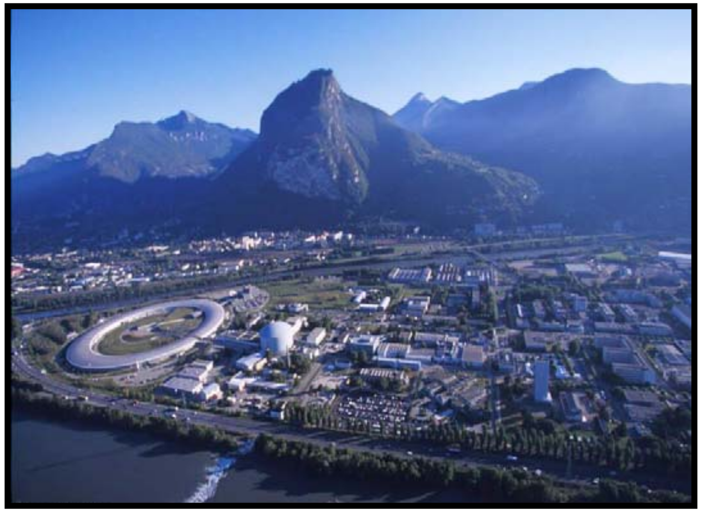

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