TOWARD ULTRA LOW POWER SPINTRONICS DEVICES

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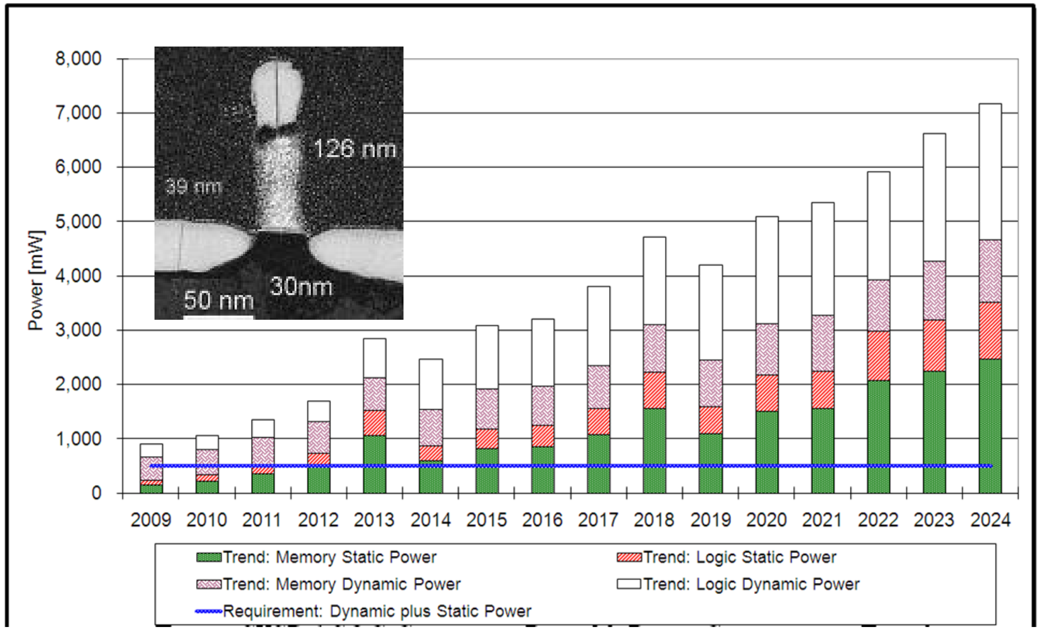
Campus Paris Saclay
FONDATION DE COOPERATION SCIENTIFIQUE

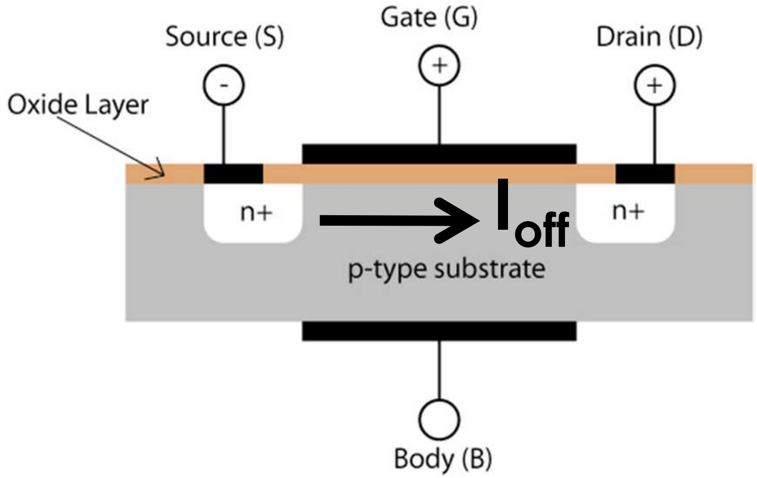
INVESTISSEMENTS D'AVENIR

Nanoelectronics Vision for the Next Ten Years

From how do we make devices smaller to how do we reduce power

MOSFET devices **: Leakage power consumption increases at an exponential rate**





Demonstrate novel computing devices capable of replacing the CMOS FET. These devices should show significant advantage over ultimate FET in power, performance, density, and/or cost to enable the semiconductor industry to extend the performance trends for IT

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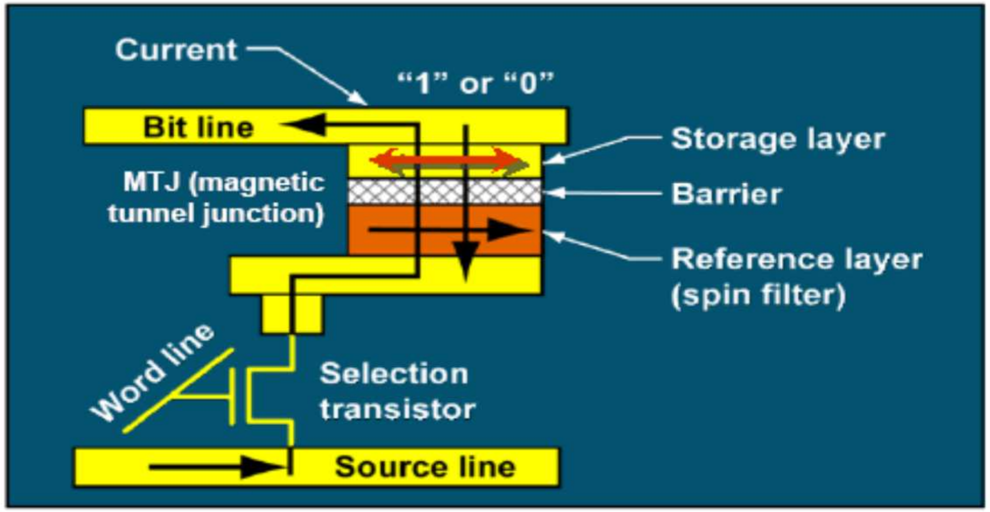
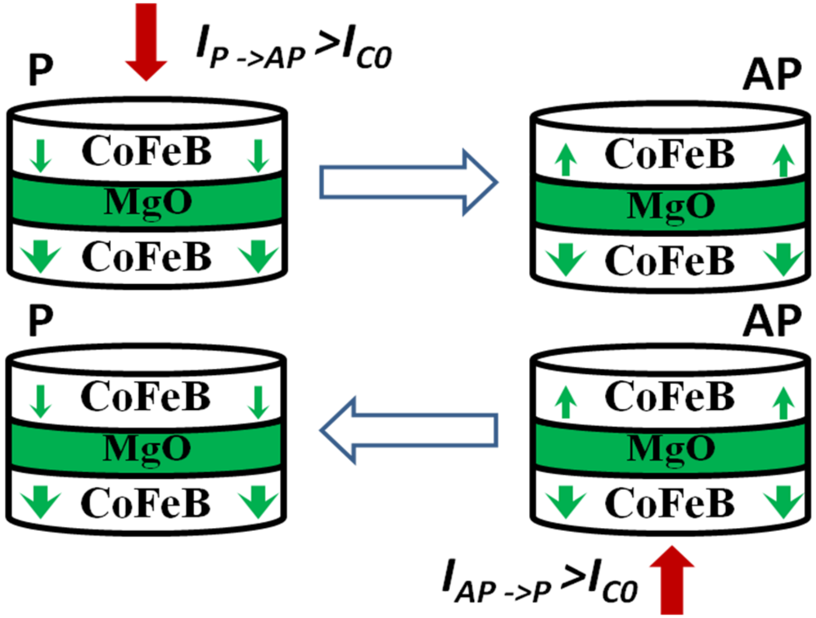
Spintronics : a new route to reduce power

Non volatile, highly scalable, high speed,unlimited undurance, high density

Spin Transfer Torque-RAM : use of a polarized current to switch magnetization





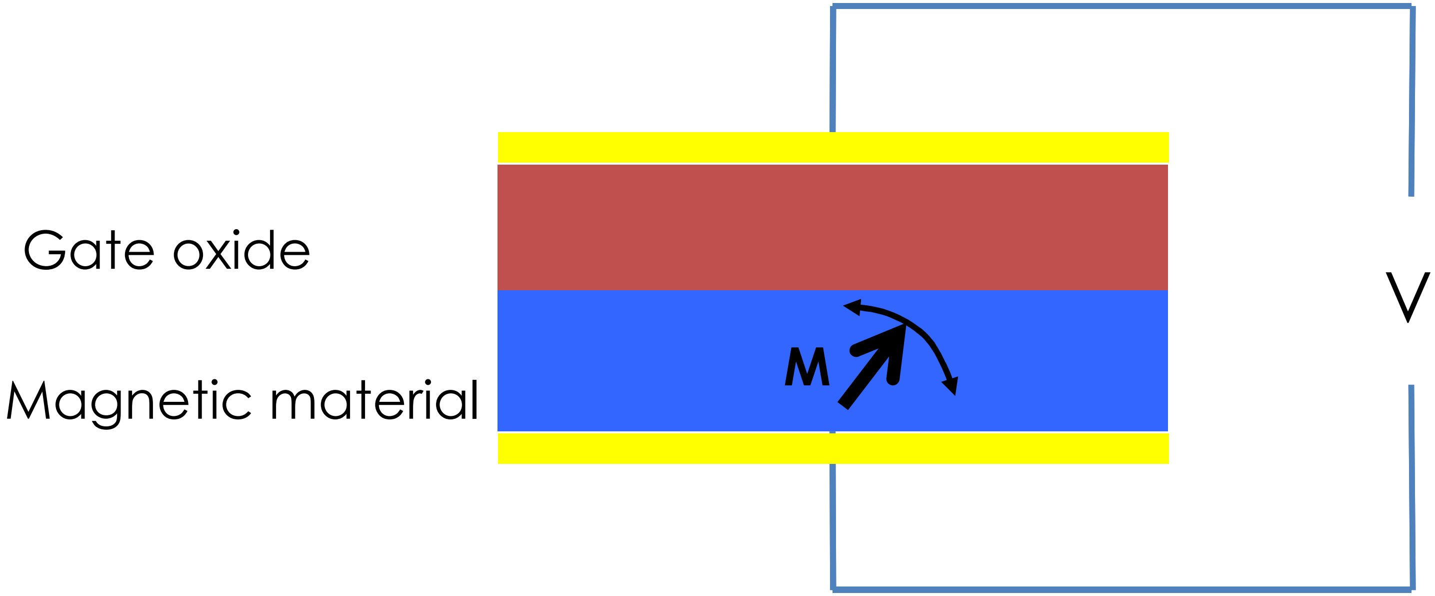
R_{MTJ}= 20 kΩ, F= 40 nm, j_C= 10^6 A/cm^2
Switching time 10 ns, I_{WR} ~20 μA

MgO Tunnel junction : TMR>500 %

Energy E_D dissipated in the switching process $E_D = RI^2 \times t_{switching}$

- Spin Transfer Torque RAM : $E_D \sim 10^6$-10^7 kT➛ 0.01-0.1 pJ, no passive dissipation
- Transistor : $E_D \sim 10^7$-10^8 kT ➛0.1-1 pJ

Electric field effect in hybrid Ferromagnetic/Oxyde structures



Gate oxide :

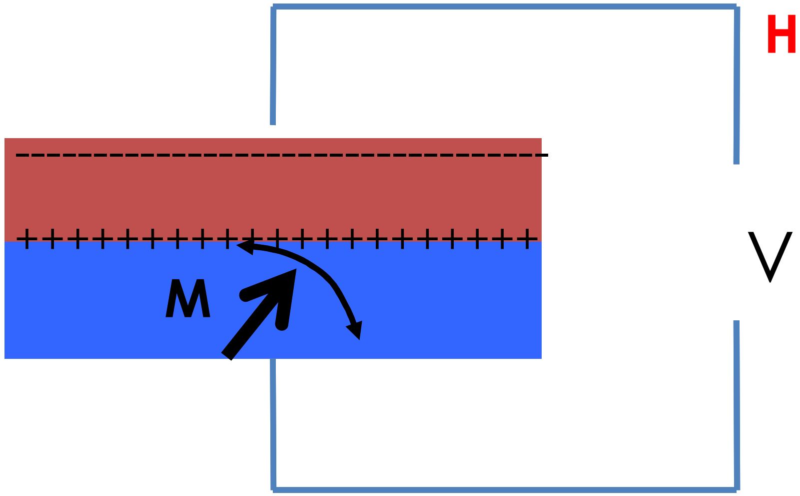
- Dielectric
- Ferroelectric
- Piezoelectric
- Multiferroic

$$E_{dissipated}=\Delta Q x \Delta V = CV^2$$

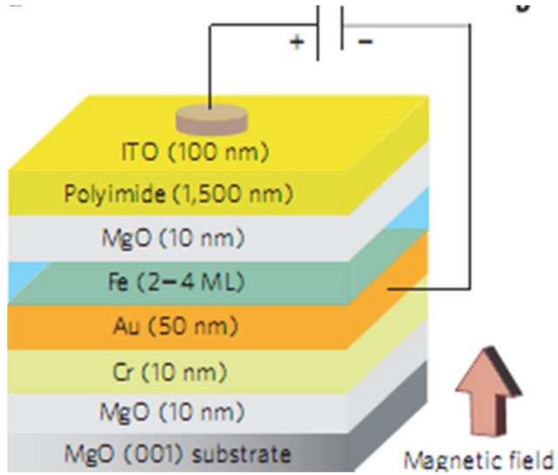
ΔQ :Amount of charges injected or extracted
ΔV : gradient of potential

- Dissipation in the range of Attojoule-FemtoJoule
- Compatibility with MOSFET technology

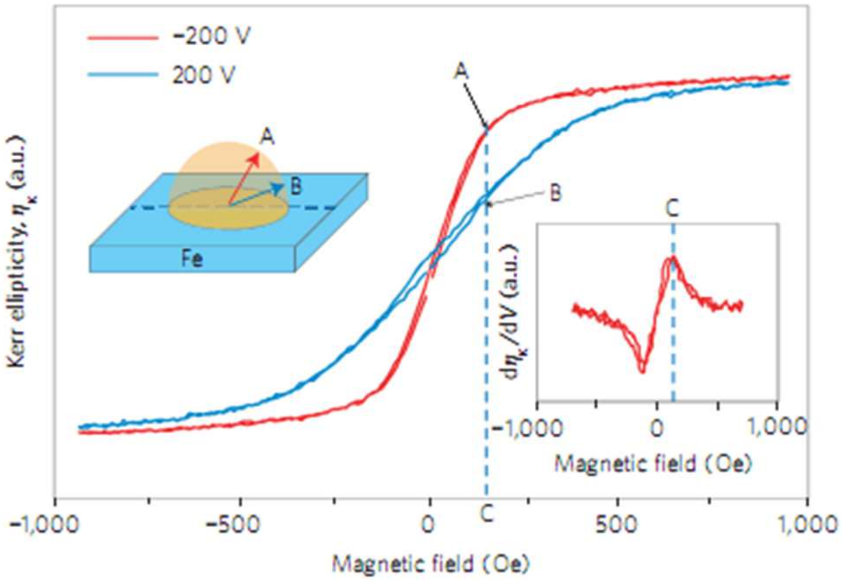
Charge modulation at interfaces



High-k gate Dielectric :
MgO, HfO_2, ZrO_2



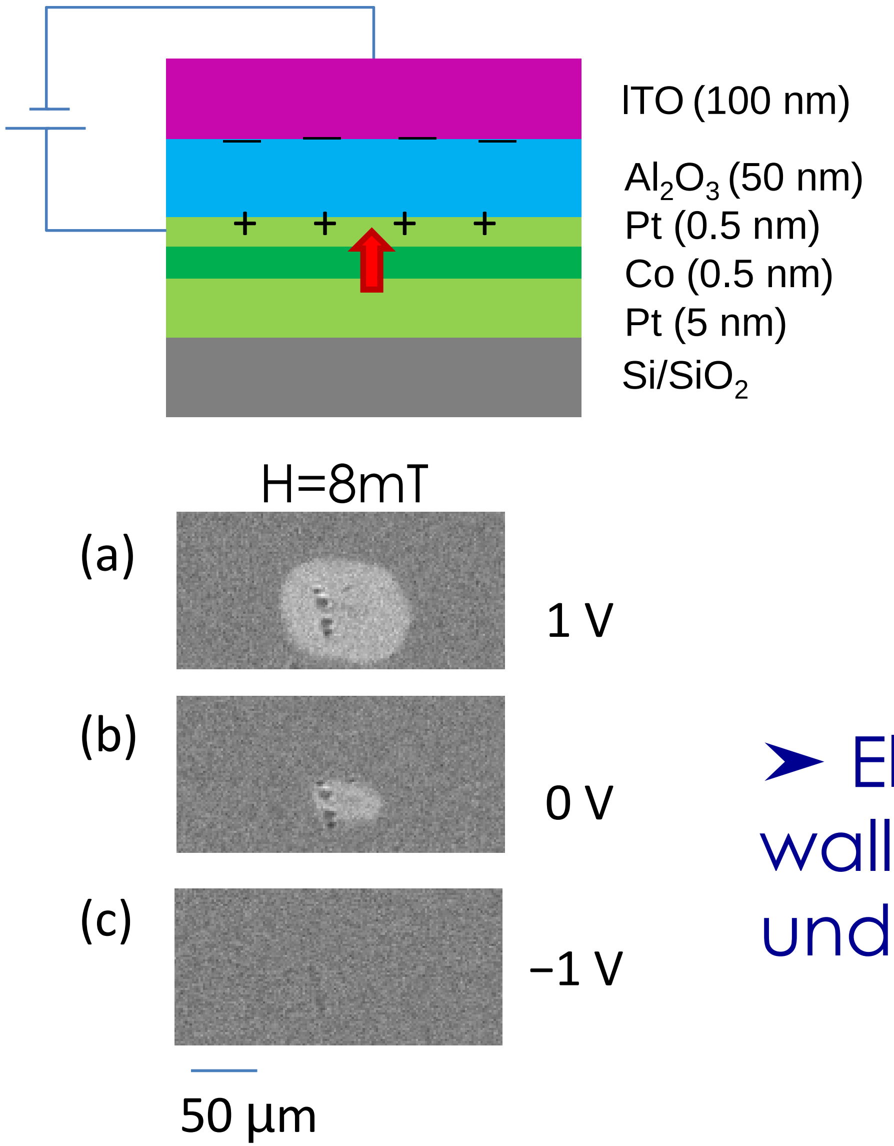
➤ Interface effect : efficient for ultra-thin magnetic films and close to a magnetic transition

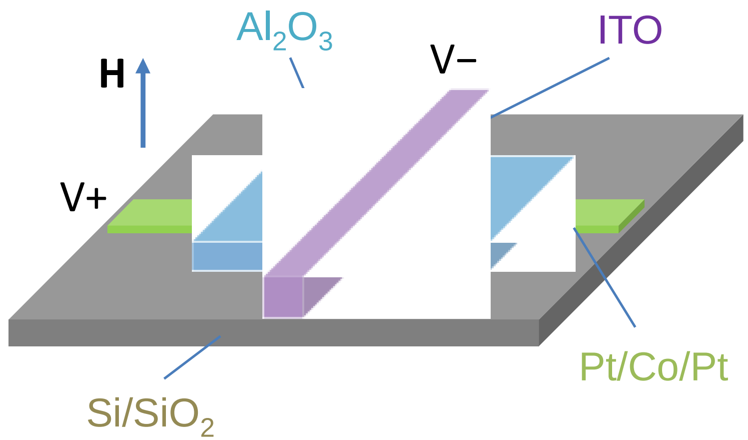


T. Maruyama *et al*. Nat. Nano. **4**,158 (2009)

Charge modulation in Co/Pt

Modulation of perpendicular anisotropy in Co/Pt multilayers

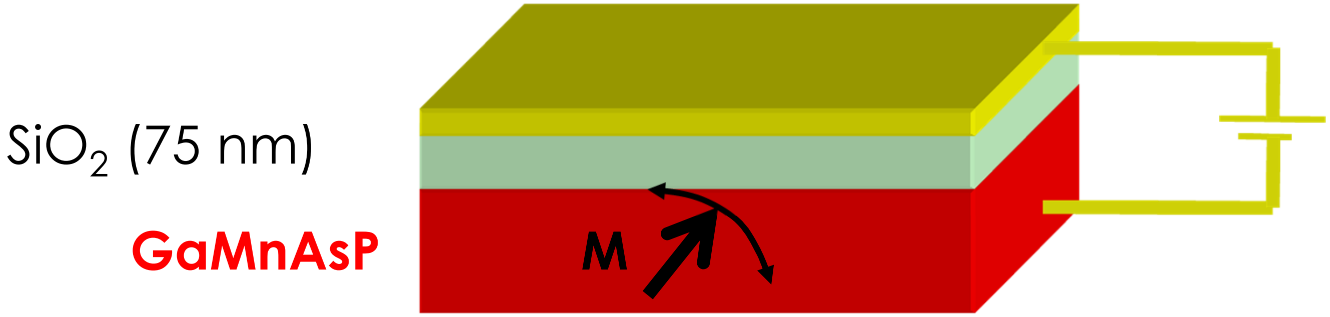


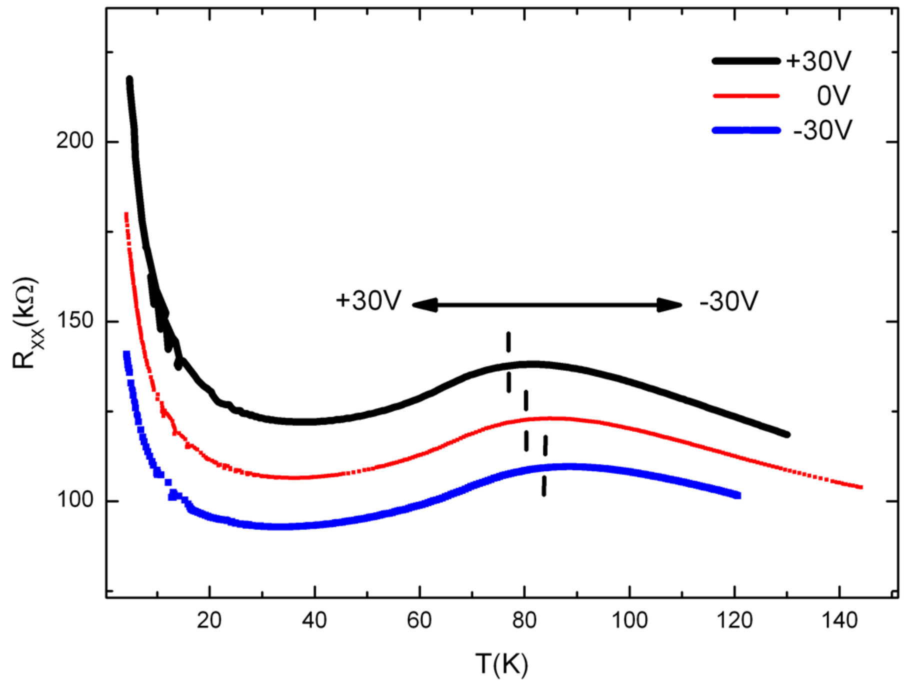


➤ Electric field assisted domain wall nucleation (change of 1 mT under 1 V : 10 %)

Charge modulation in (Ga,Mn)(As,P)

Modulation of perpendicular anisotropy in (Ga,Mn)(As,P)



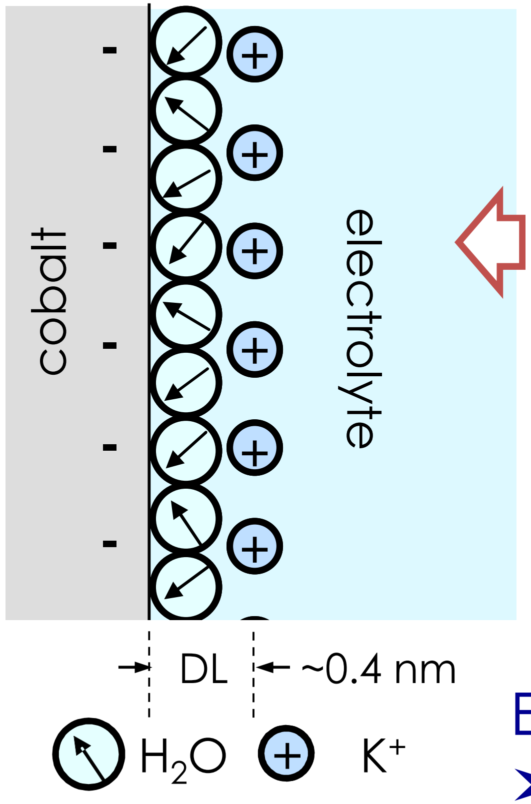


- Small variation of Tc
- High k gate dielectric : HfO_2

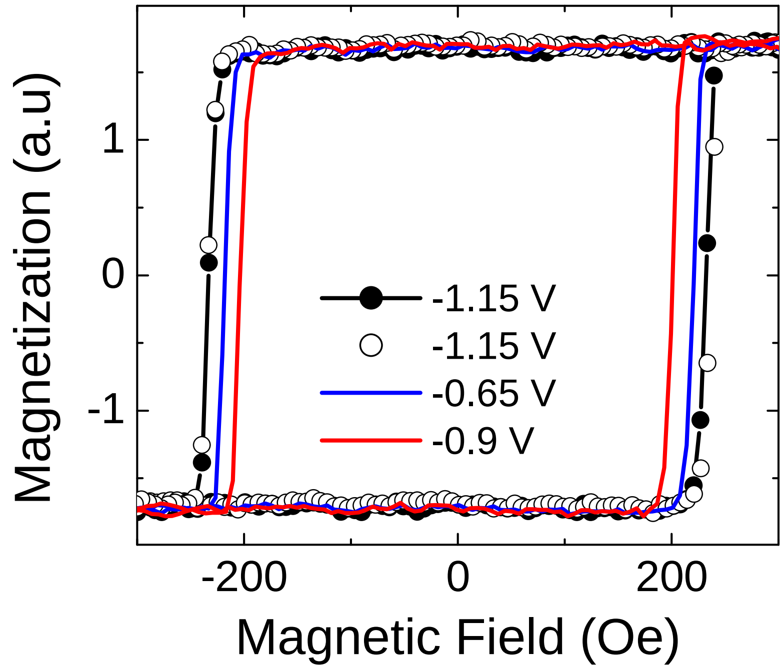
Charge modulation in electrolyte

Modulation of perpendicular anisotropy in Au(111)/Co

contact solide / électrolyte



- Electric field > 1 V/nm for voltages < 1 V
- No short circuits
- No structural defects



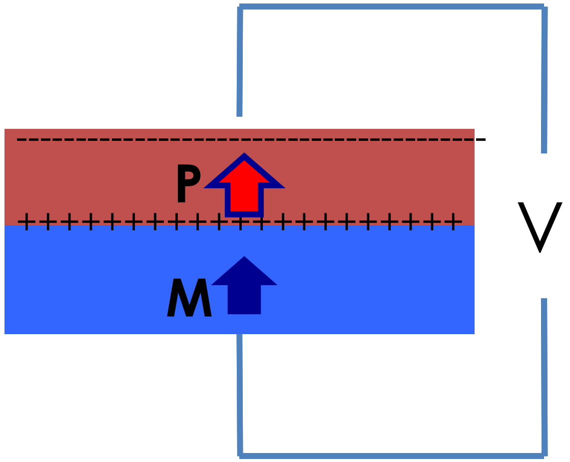
E-field effect on magnetocristalline anisotropy

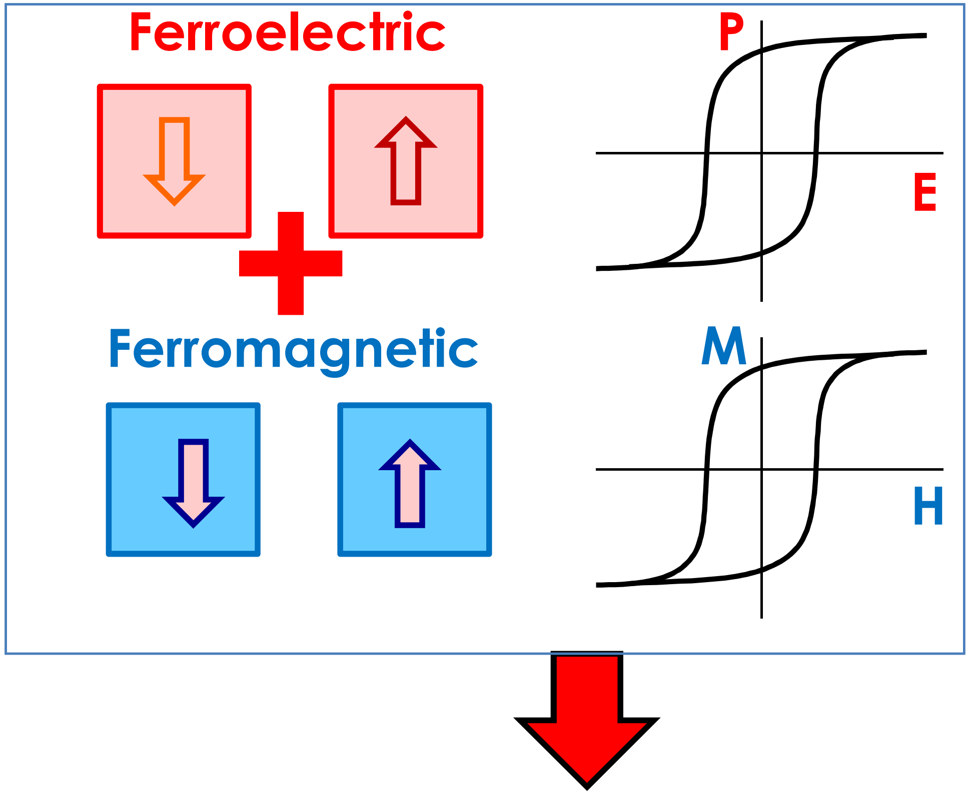
➤ Linear and reversible change

➤ 1/t Dependence → surface effect

➤ Large variation : $\Delta K_S^{Surf\text{–}H}/\Delta U = -0.13$ erg cm^{-2} V^{-1}.

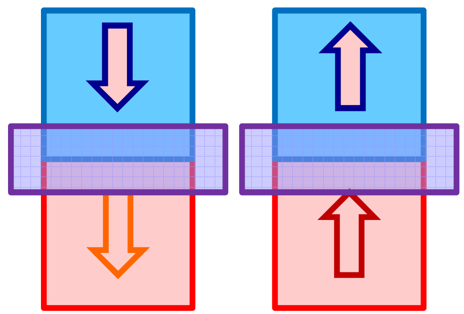
Ferromagnetic/Ferroelectric structures

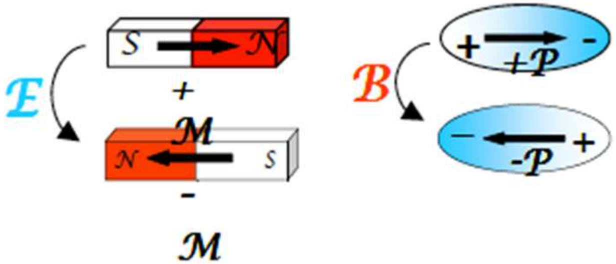




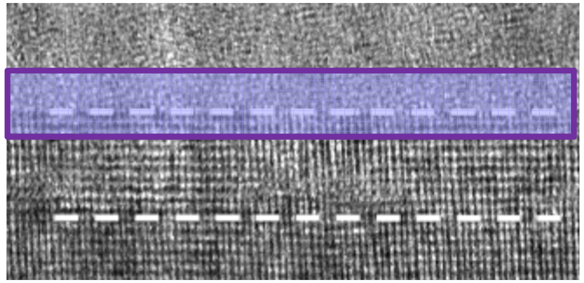
- Electric control of magnetization
- Magnetic control of polarization
- Induced magnetism in the ferroelectric
- New states at ferroelectic/ferromagnetic interfaces

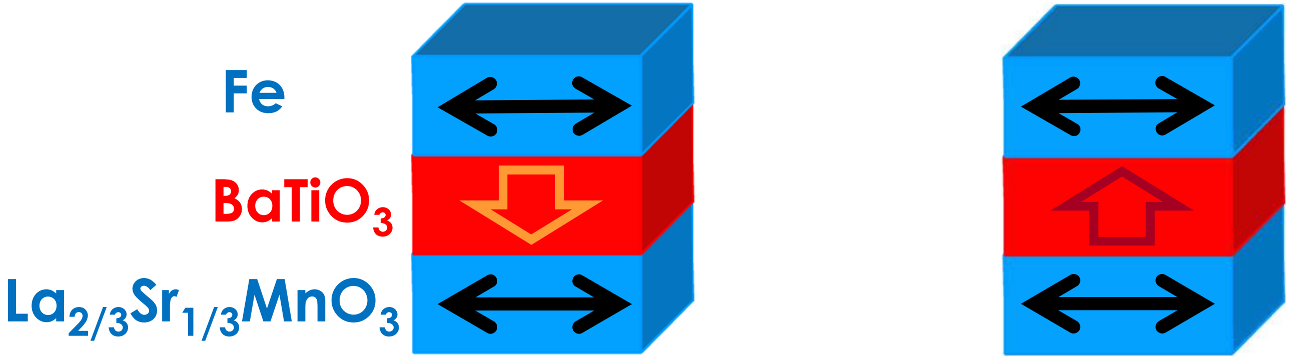
Magnetoelectric Coupling at interfaces



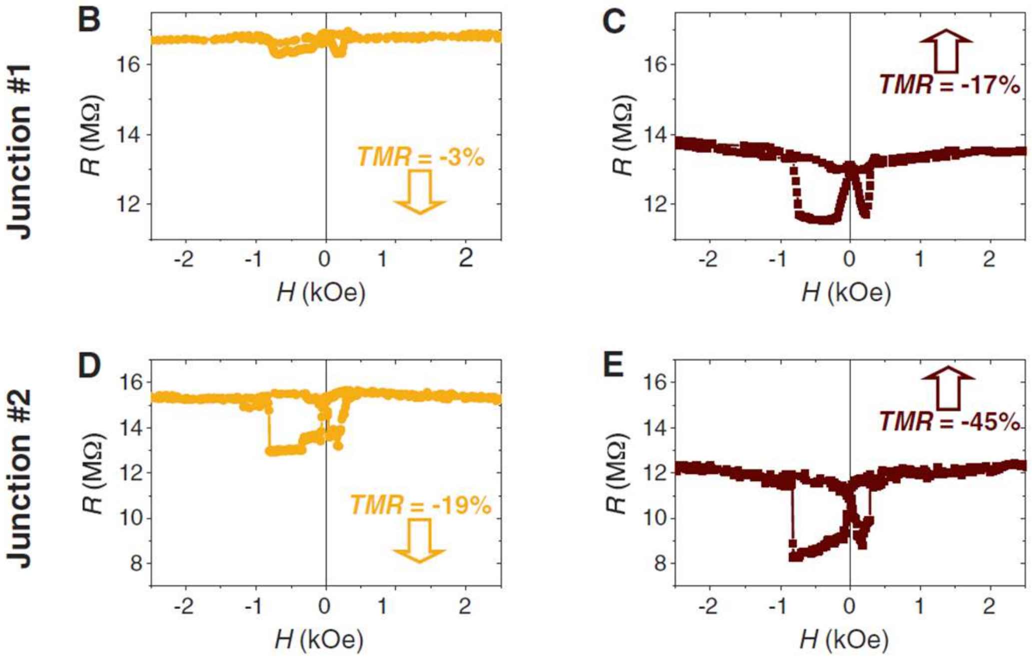


Ferromagnetic/Ferroelectric structures





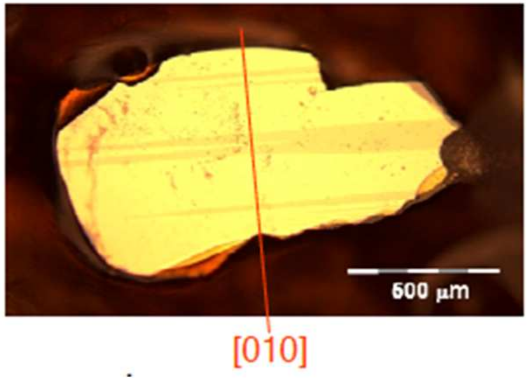
The TMR depends on the direction of the electric polarization in $BaTiO_3$
➤ Electrical control of spin polarization
➤ Low writing power (10^4 A/cm²)



Garcia et al, *Science* 327, 1106 (2010)
Valencia et al, *Nature Mater.* 10, 753 (2011)

Ferromagnetic/Multiferroic structures

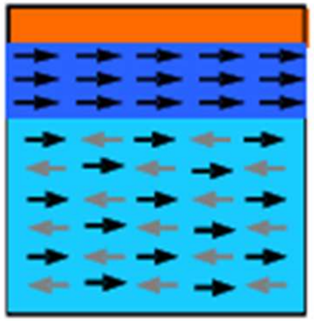
Ferromagnetic film grown on a $BiFeO_3$ crystal (Ferroelectric+Antiferromagnetic)

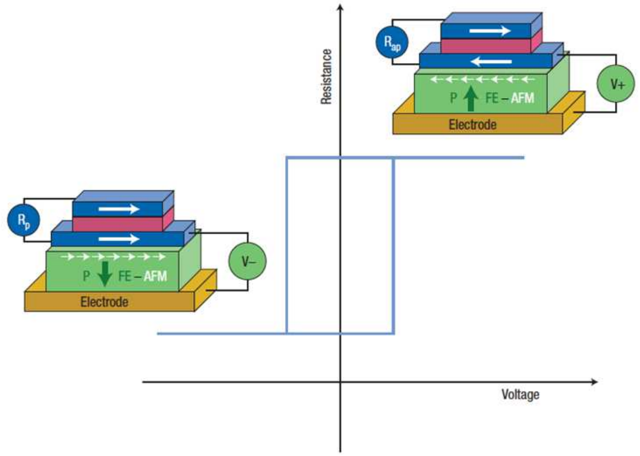


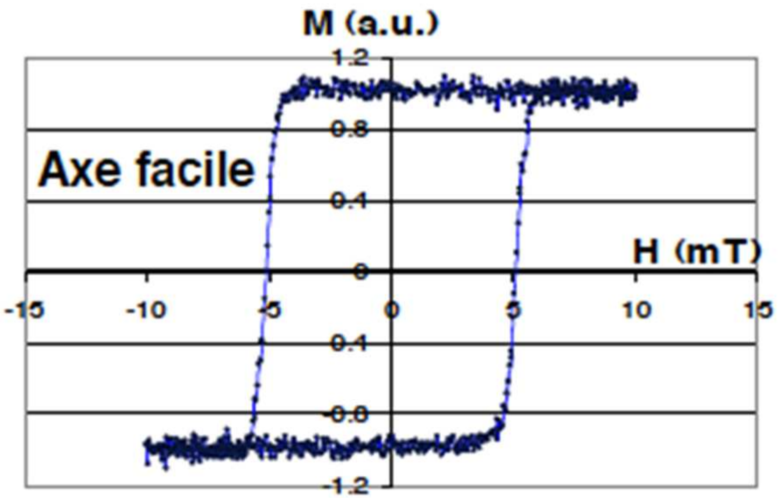
Au (4nm)

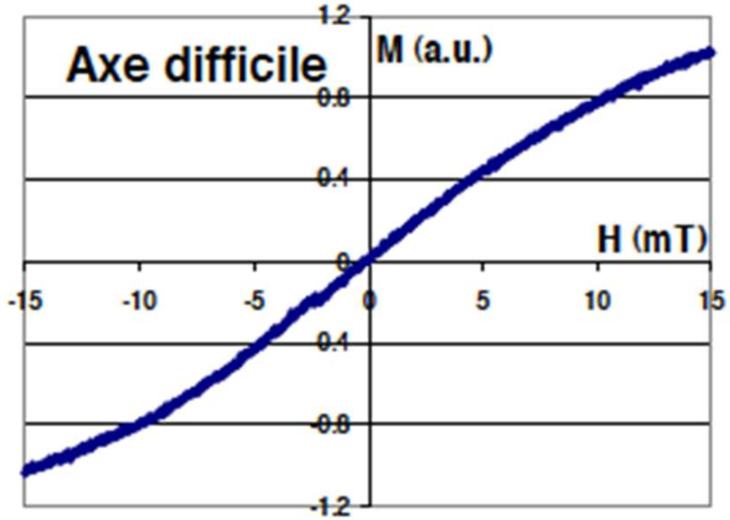
NiFe (10nm)

$BiFeO_3$ crystal







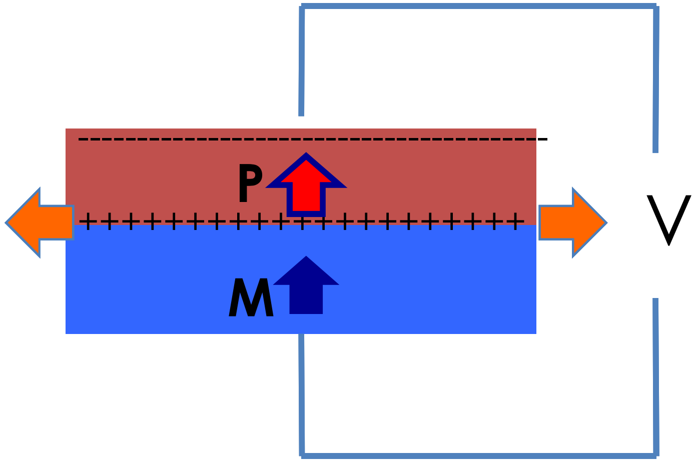


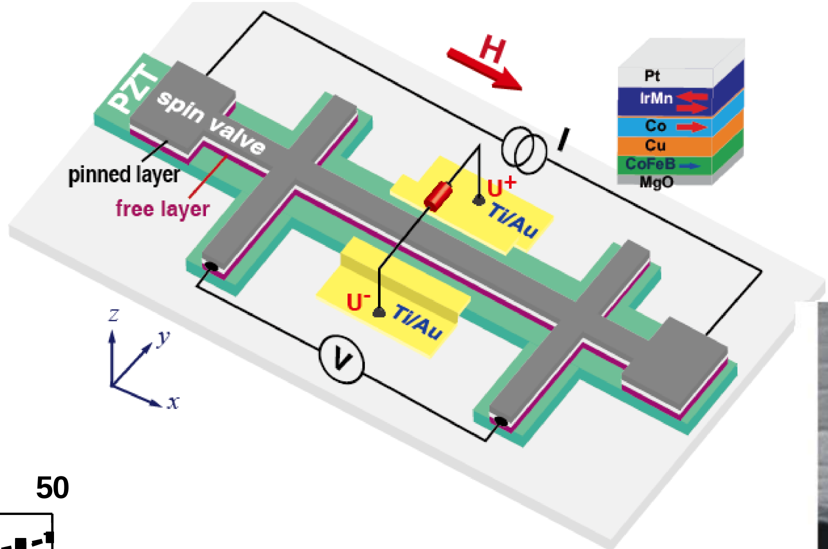
➤ Evidence of a coupling between ferromagnetic and ferroelectric order

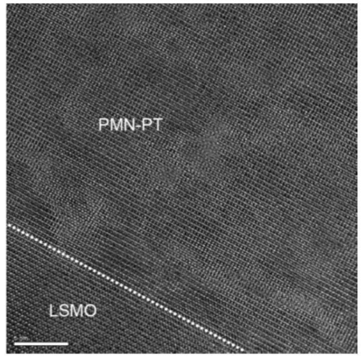
D.Lebeugle, Phys. Rev. Lett. 103, 257601 (2009)

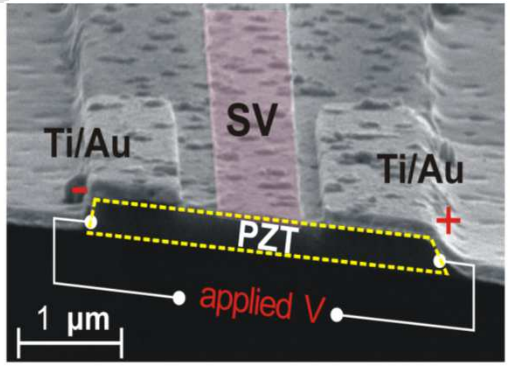
Ferromagnetic/piezoelectric structures

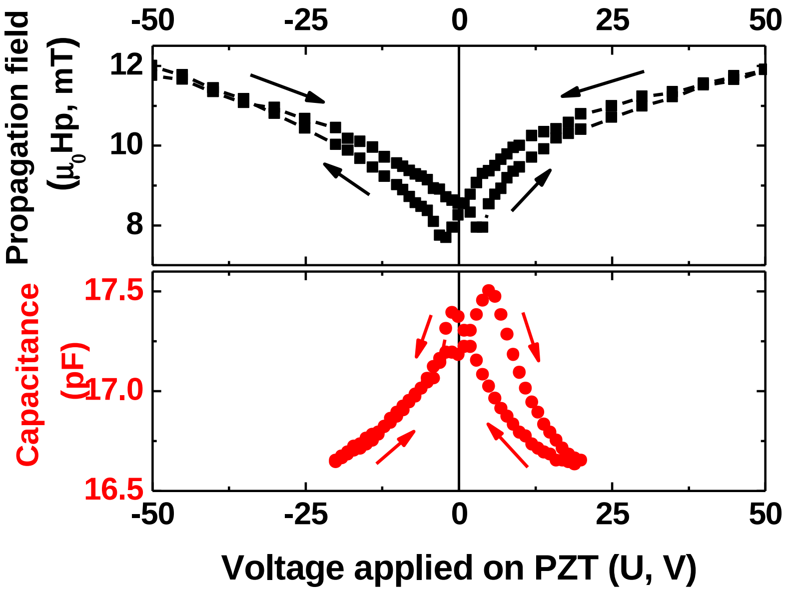
All electrical integrated Ferromagnetic/Piezoelectric nanodevices











➤80% variation of Hc in an integrated nanodevice

➤Demonstration of a domain wall gate under electric field

Lei et al, *submitted to Nature Materials*

Lei et al, PRB 2011

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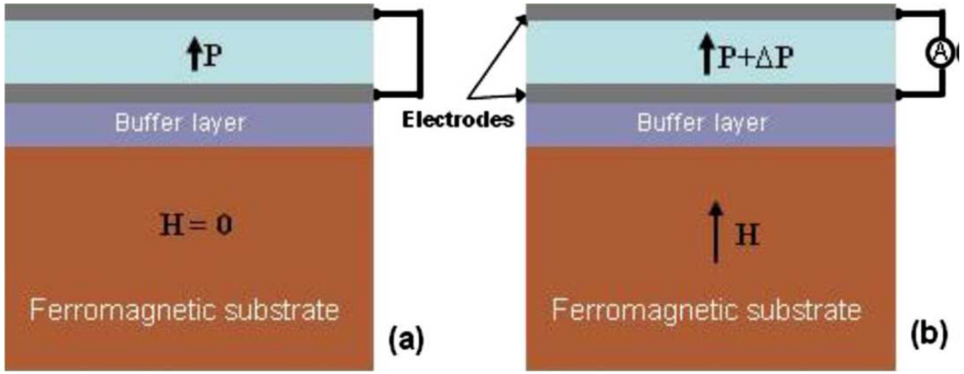
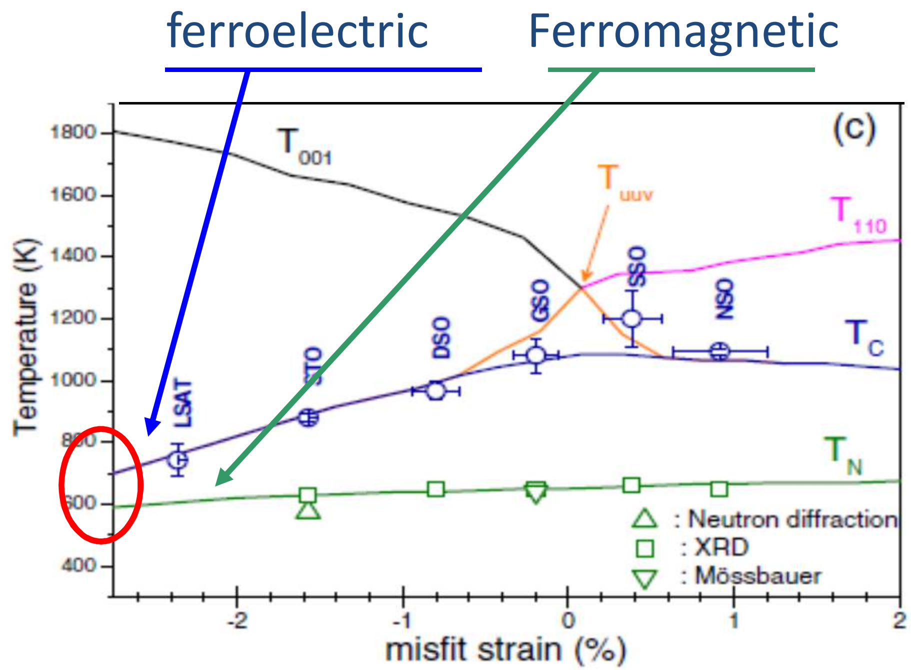
Strain induced magnetoelectric effect



Strong enhancement of the direct magnetoelectric effect in strained ferroelectric-ferromagnetic thin-film heterostructures



Bridging multiferroic phase transitions by epitaxial strain in $BiFeO_3$

N. A. Pertsev et al, Phys. Rev. B 80, (2009)
I.C. Infante, Phys. Rev. Lett. 105, 057601 (2010)

Goals

State of the art : >50 presentations at the last MMM 2011 conference, 10 high impact factor papers over last 4 months

nature materials

ARTICLES

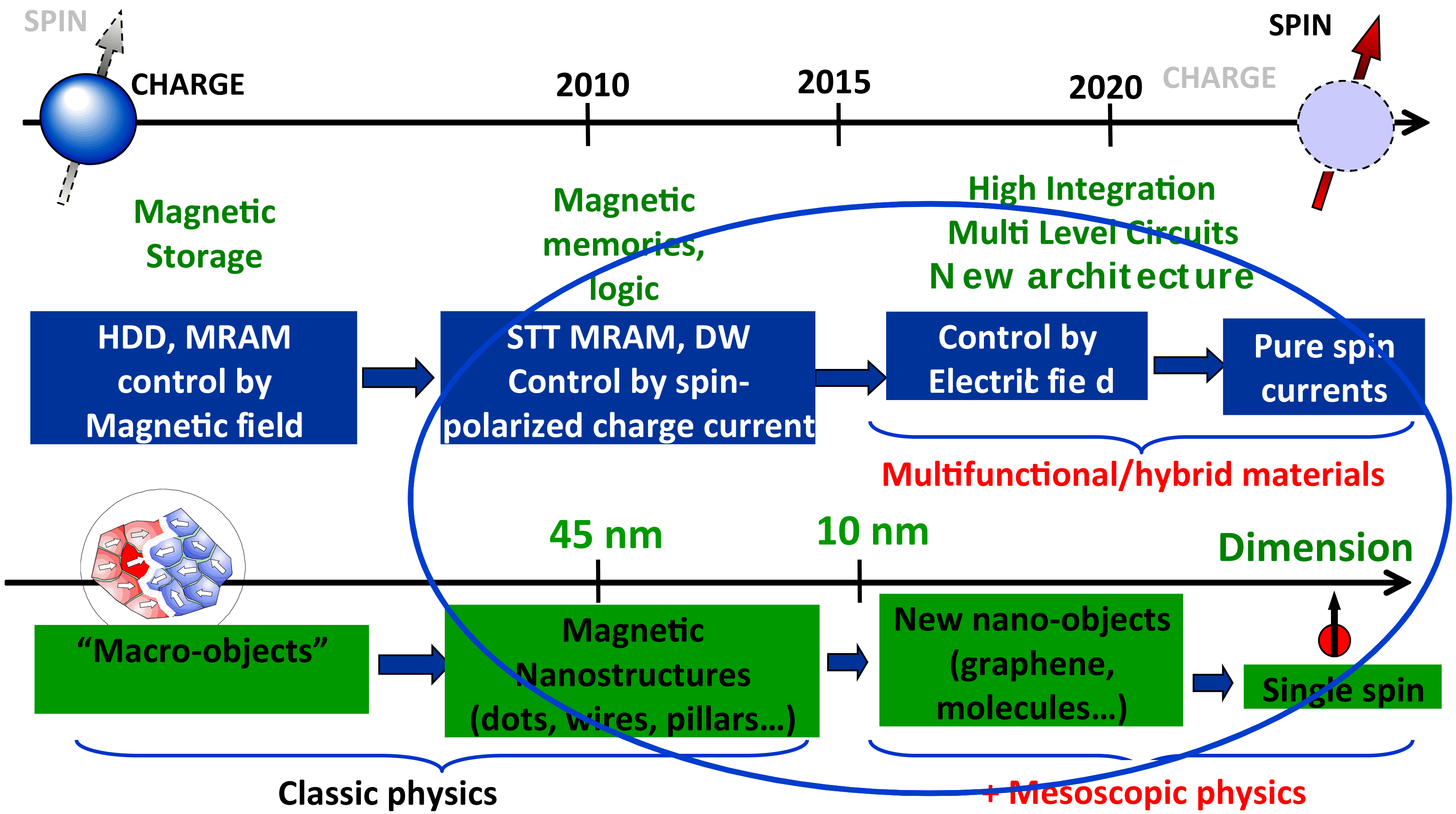
PUBLISHED ONLINE: 13 NOVEMBER 2011 | DOI: 10.1038/NMAT3171

Electric-field-assisted switching in magnetic tunnel junctions

Wei-Gang Wang*, Mingen Li, Stephen Hageman and C. L. Chien*

- ➤ Systematically investigate the E-field effects on magnetic properties
- ➤Combine electric field and spin current driven effects to optimize the dynamics of magnetization reversal (sub-ns time scale) and to reach ultra low power consumption (<pJ)
- ➤Exploit E-field control of magnetism to develop new functionalities in solid state spin based devices

Toward ultra low power spintronics devices



Novel multifunctional materials, new writing schemes, innovative architectures, new nanoscale devices

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