TOWARD ULTRA LOW POWER SPINTRONICS DEVICES

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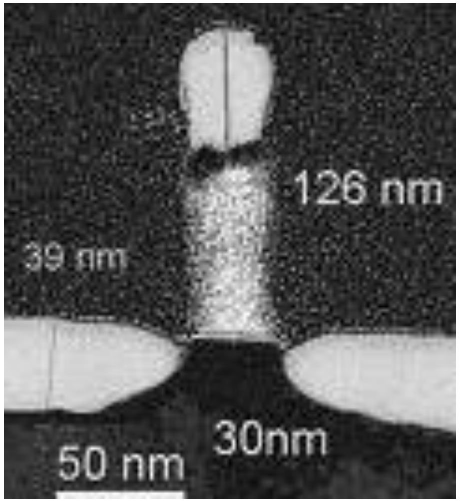
Nanoelectronics Vision for the Next Ten Years

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

MOSFET devices : significant increase in performance (node 20 nm)
…… *but* Leakage power consumption increases at an exponential rate



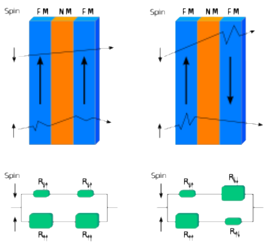
Demonstrate new low power concepts for calculation, data storage, sensors…..

Nanoelectronics Vision for the Next Ten Years

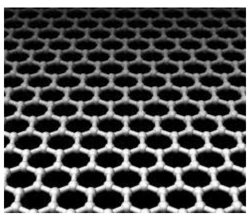
From how do we make devices smaller to how do we reduce power

Emerging nanodevices

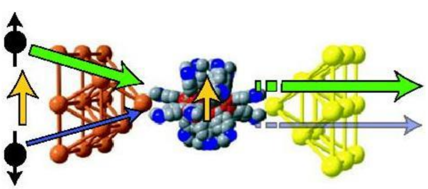
New functionalities on the nanometer scale



Spin Electronics



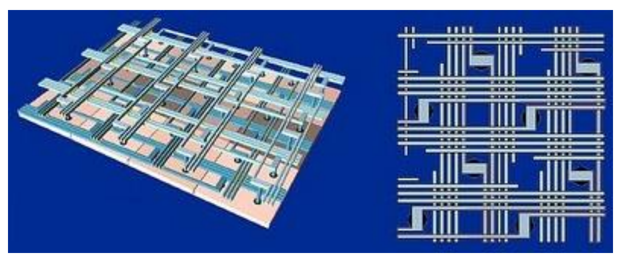
Carbon based electronics



Molecular Electronics

Emerging architectures

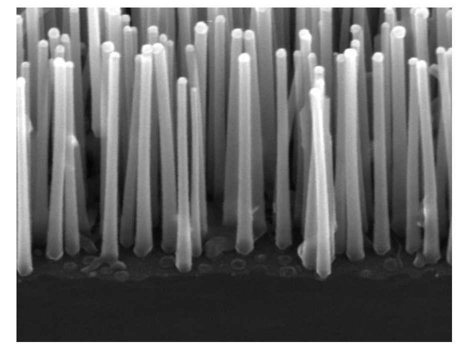
Circuits based on emerging nanodevices
New paradigm for calculation



Hybrid CMOS circuits`
Neuromorphic circuits

Energy harvesting

Photovoltaics/thermoelectricity based on new nano-objects



Nanomaterials

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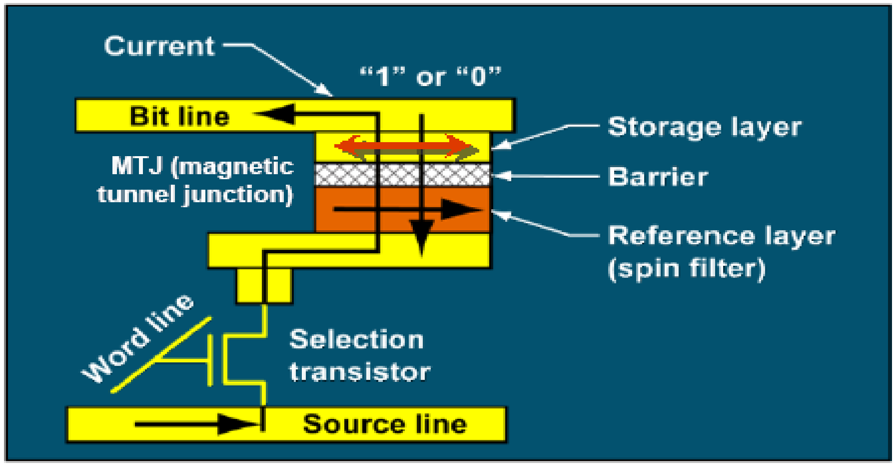
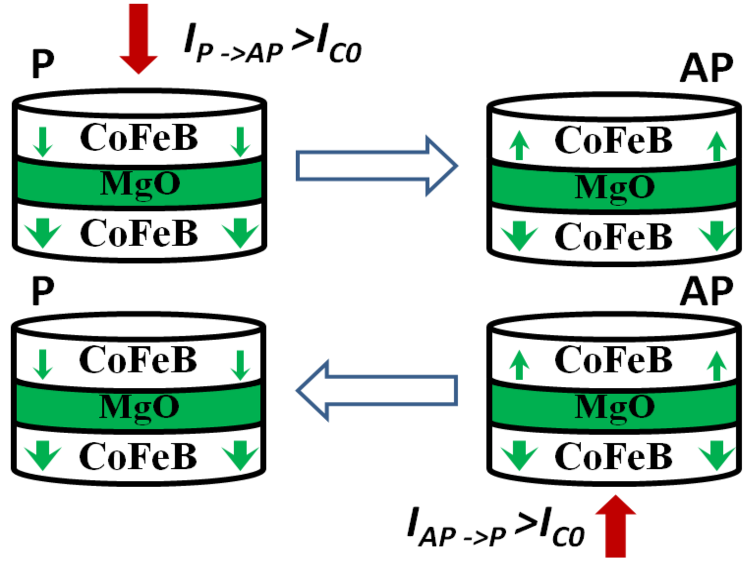
Spintronics : a new route to reduce power

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**

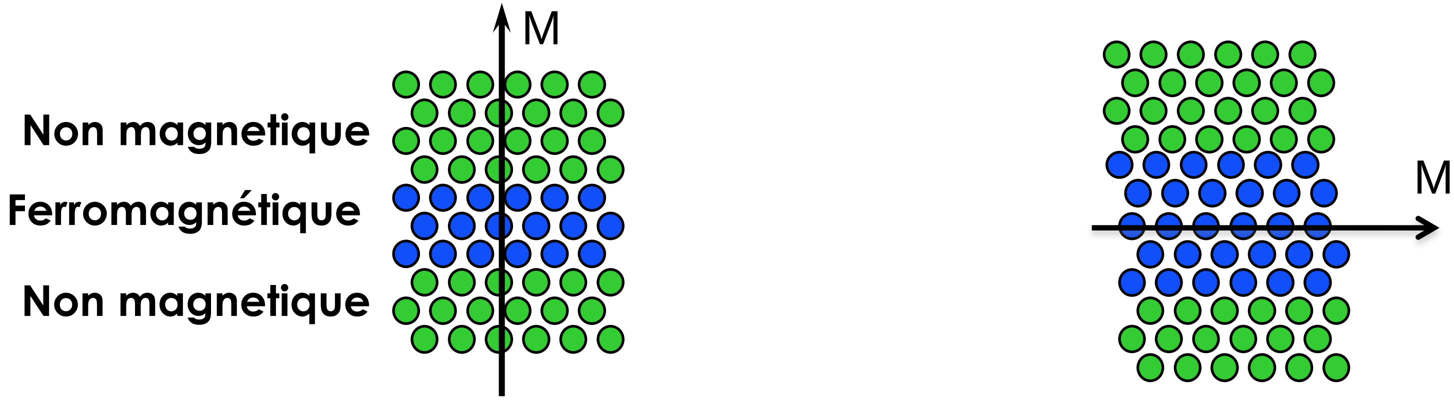
MgO Tunnel junction : TMR>200 %

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

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

Interface anisotropy

Magnetic properties are related to atomic short range order

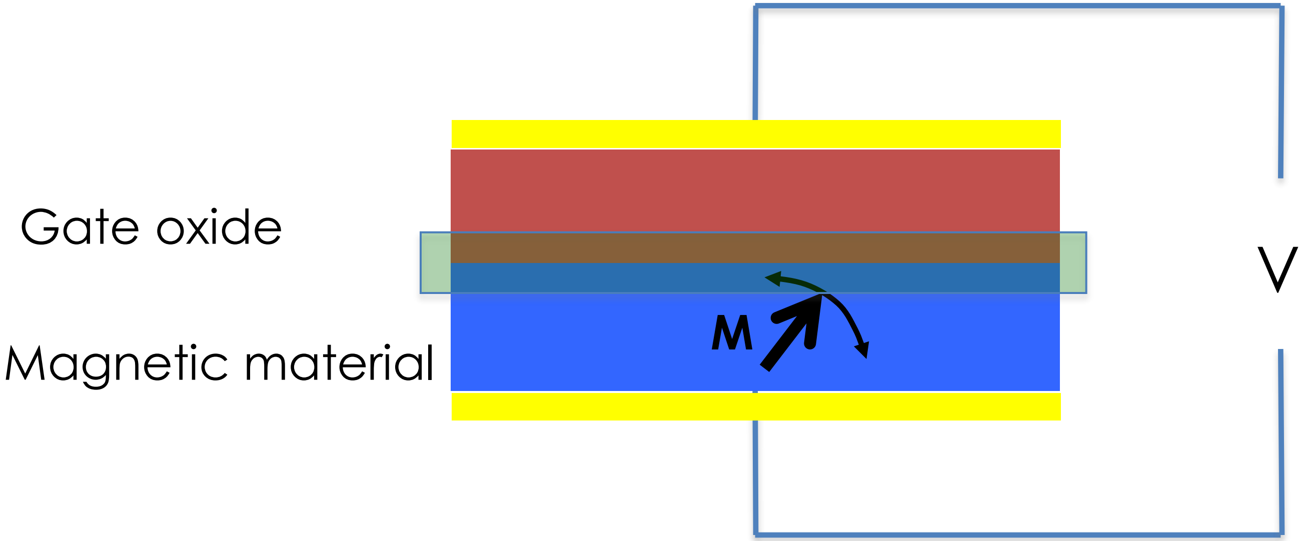


t<t* **t>t***

- Important role played by the interfaces : presence of interface anisotropy for thickness t<t*
- NRJ barrier **E_a ~ KV** where V is the magnetic volume and K the anisotropy
- Enought thermal stability for data retention (NRJ barrier **E_a> 50 kT** for 10 years)
- Writing current **Ic ~ E_a**

Can magnetic properties at interfaces be modulated ?

Electric field effect in hybrid Metal/Oxyde/Ferromagnetic structures

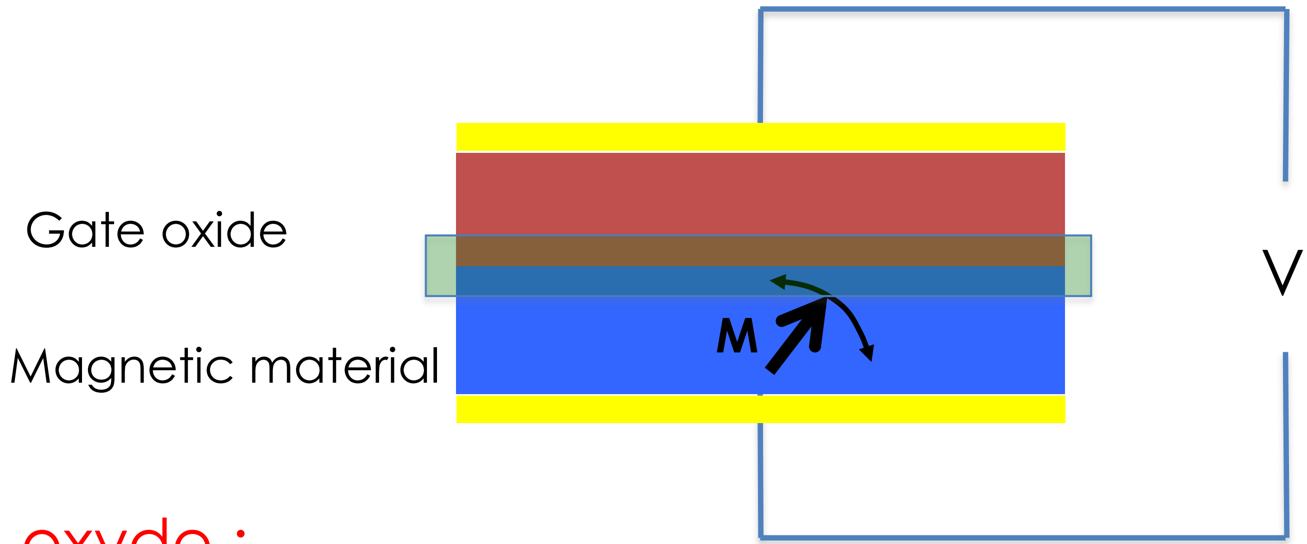


$$E_{dissipated} = \Delta Q x \Delta V = CV^2$$

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

- ➤ Voltage driven interface effect
- ➤ Dissipation << FemtoJoule

Strategy



Gate oxyde :

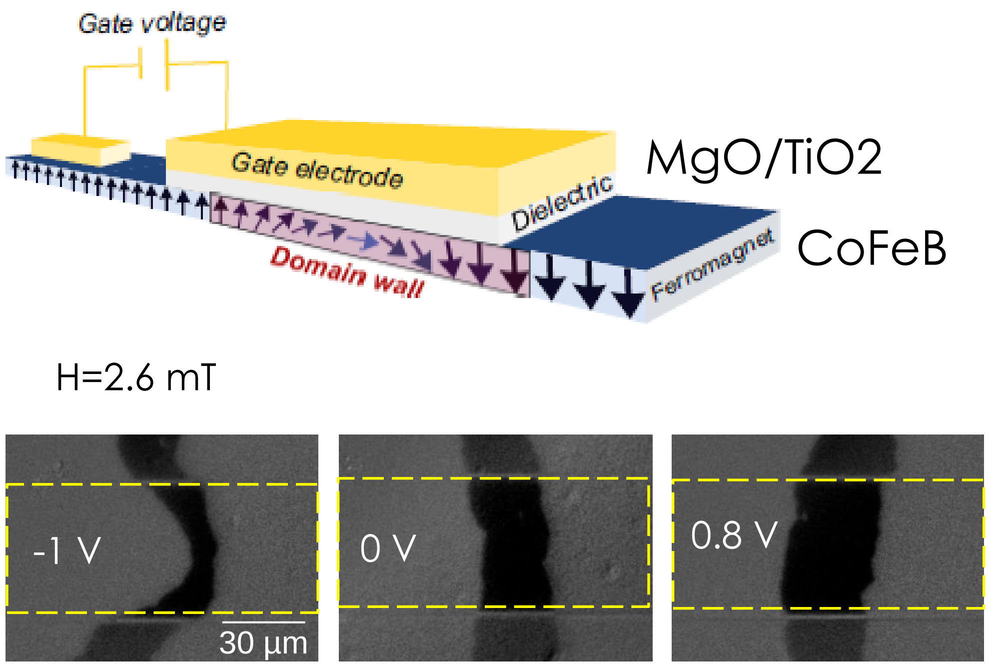
- ➤ Dielectric : Charge effect
- ➤ Piezoelectric : Strain effect

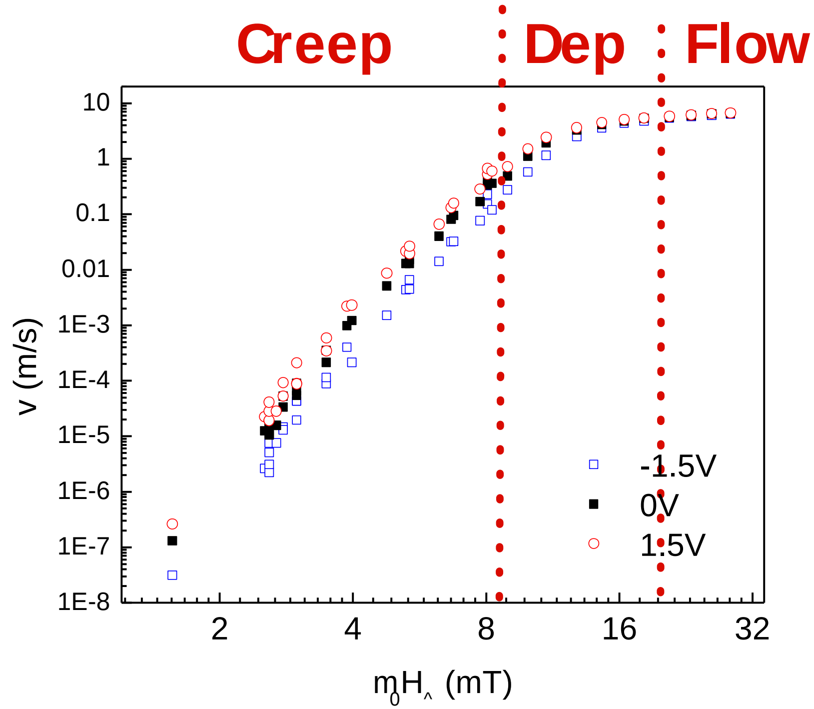
Magnetic Materials :

- ➤ Metal
- ➤ Semiconductors

Charge modulation in metals

Domain wall propagation under electric field

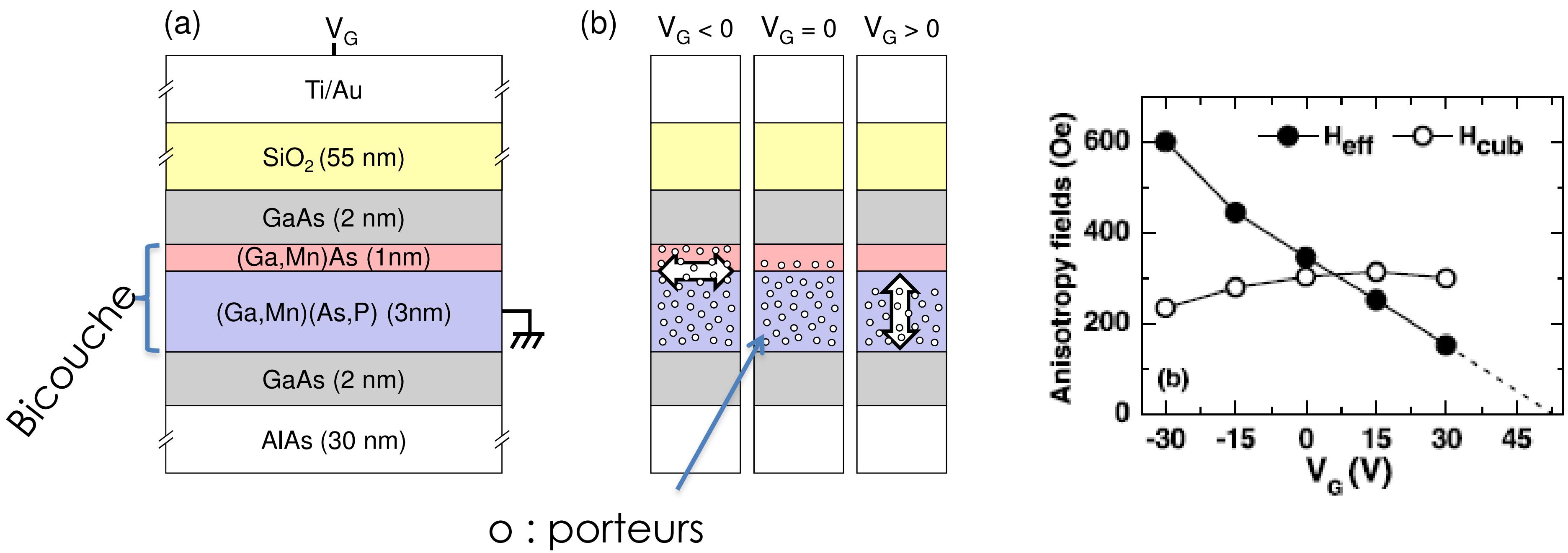




Electric field effect to assist domain wall propagation through anisotropy change (change of 1 mT under 1 V)

W.Lin et al, submitted PRL 2014

Modulation of perpendicular anisotropy in bilayers (GaMnAsP)/(GaMnAs)

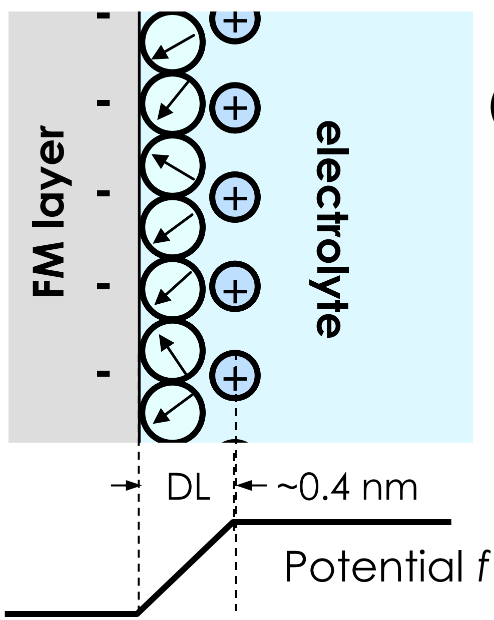


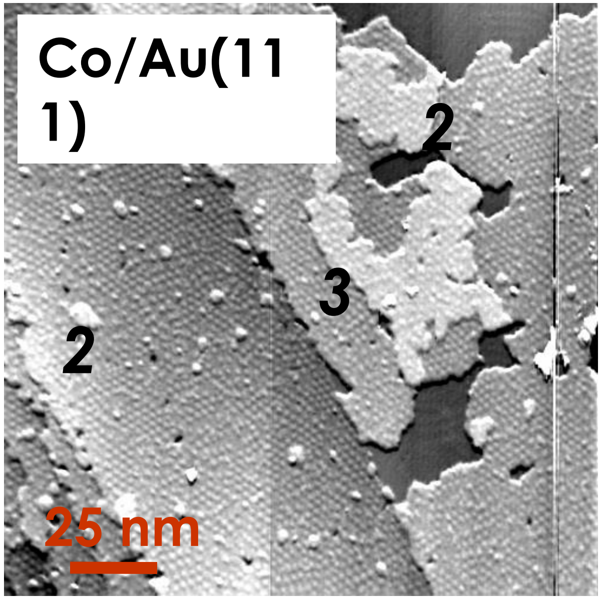
➤ Depending on the sign of Vg, either in-plane or out of plane anisotropy is favored

Niazi et al, APL 2013

Magnetoelectirc effect using an electrochemical approach

Modulation of perpendicular anisotropy in Au(111)/Co





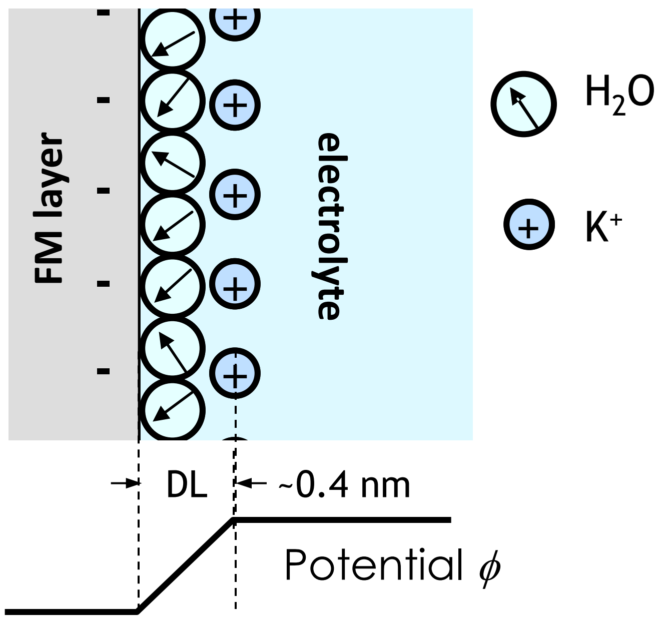
Solid/electrolyte contact:
- *No need of a dielectric layer.*
- *E*-field uniform and large (ca. 1 V/nm)
- No defects

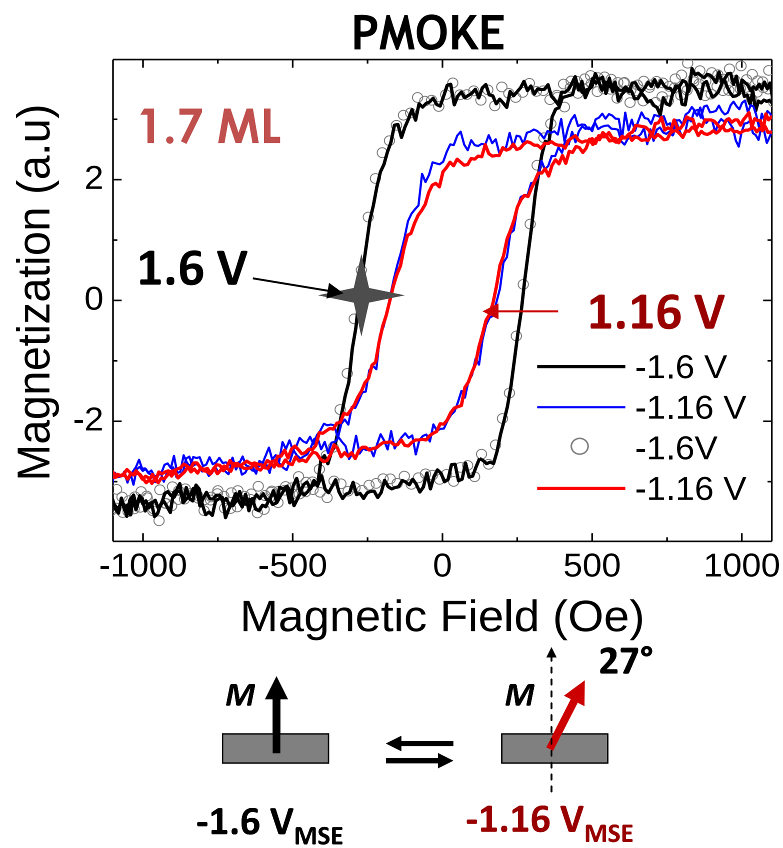
In situ Electrodeposition :
- Epitaxial layers
- Sample kept under potential control
- No oxide

Tournerie et al, Phys. Rev. B 86 (2012) 104434

Magnetoelectirc effect using an electrochemical approach

ÉCOLE POLYTECHNIQUE ParisTech

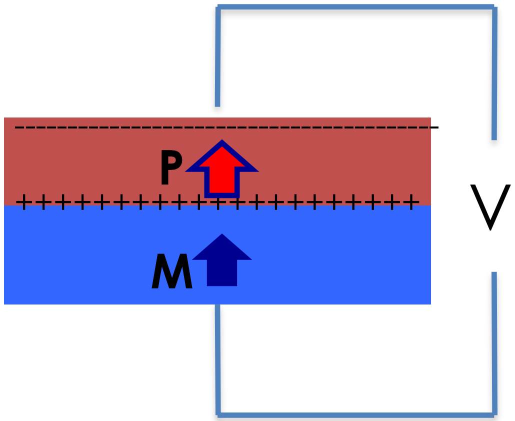


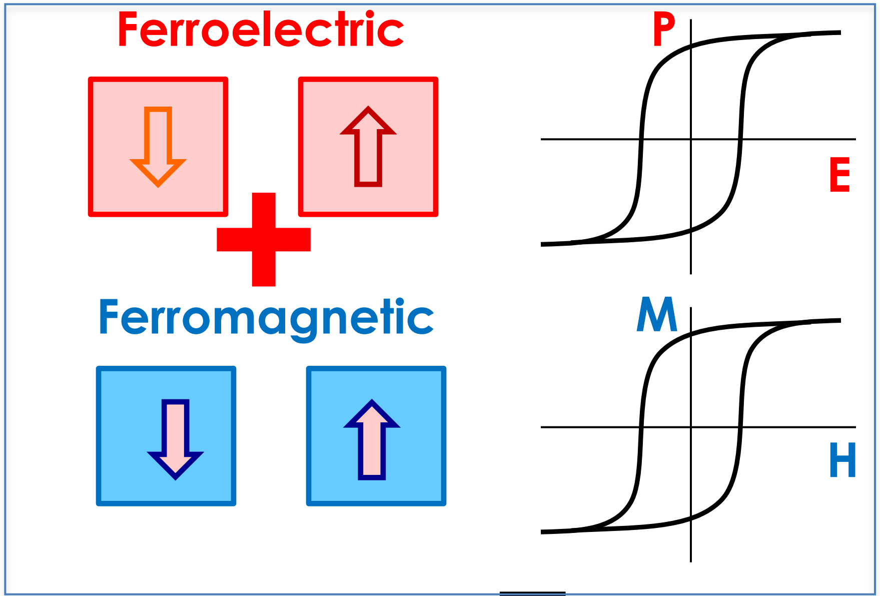


➢ **Voltage effect in out of plane magnetized H-Co/Au(111) :**
Linear (E-field effect), ***pure surface*** **phenomenon, large ($\Delta K_S/\Delta U$ = -130 μJ/m^2/V)**

➢ **Voltage effect (sign + amplitude) depends on adsorbate on Co/Au(111)**

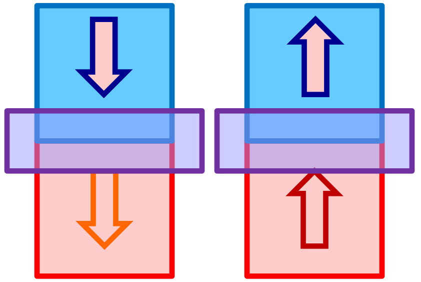
Ferromagnetic/Ferroelectric structures

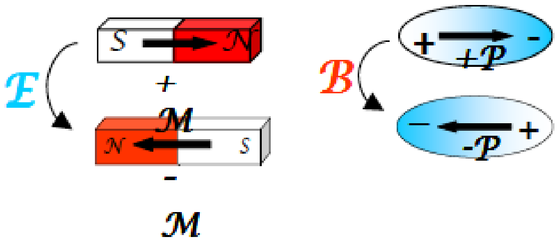




- Electric control of magnetization
- Magnetic control of polarization
- Induced magnetism in the ferroelectric
- New states at ferroelectic/ferromagnetic interfaces

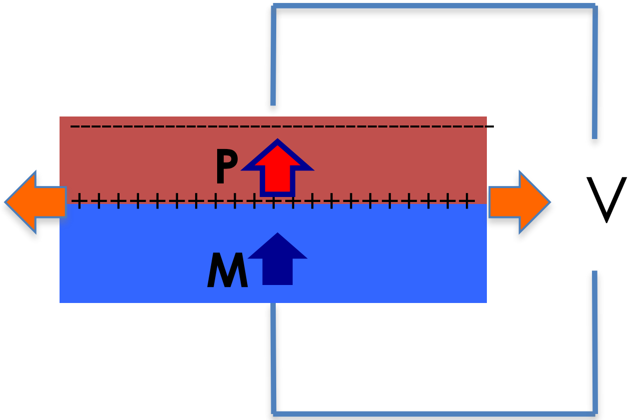
Magnetoelectric Coupling at interfaces

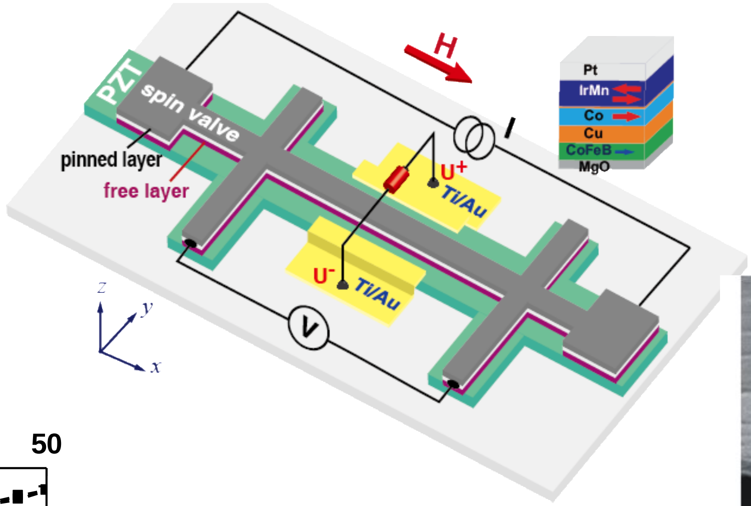


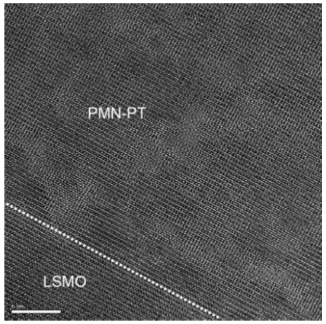


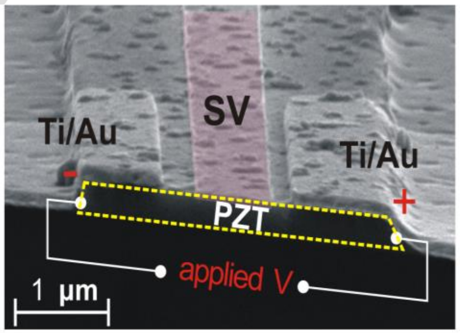
Ferromagnetic/piezoelectric structures

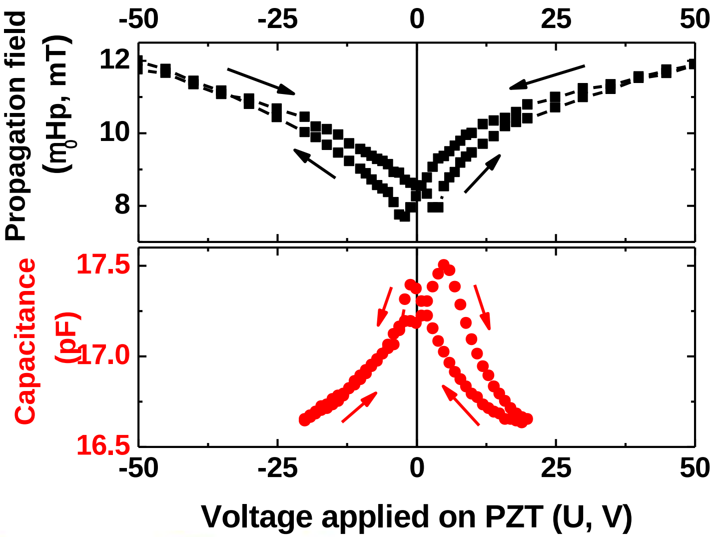
All electrical integrated Ferromagnetic/Piezoelectric nanodevices









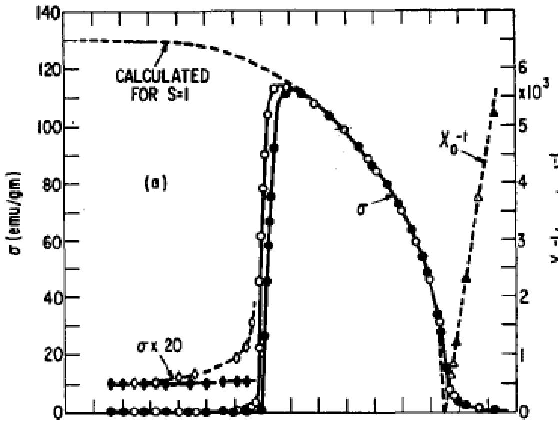


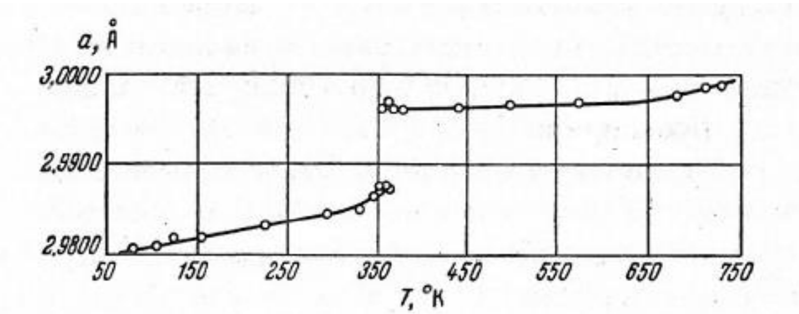
- ➤80% variation of Hc in an integrated nanodevice
- ➤Demonstration of a domain wall gate under electric field

Lei et al, *Nature Materials 2013*

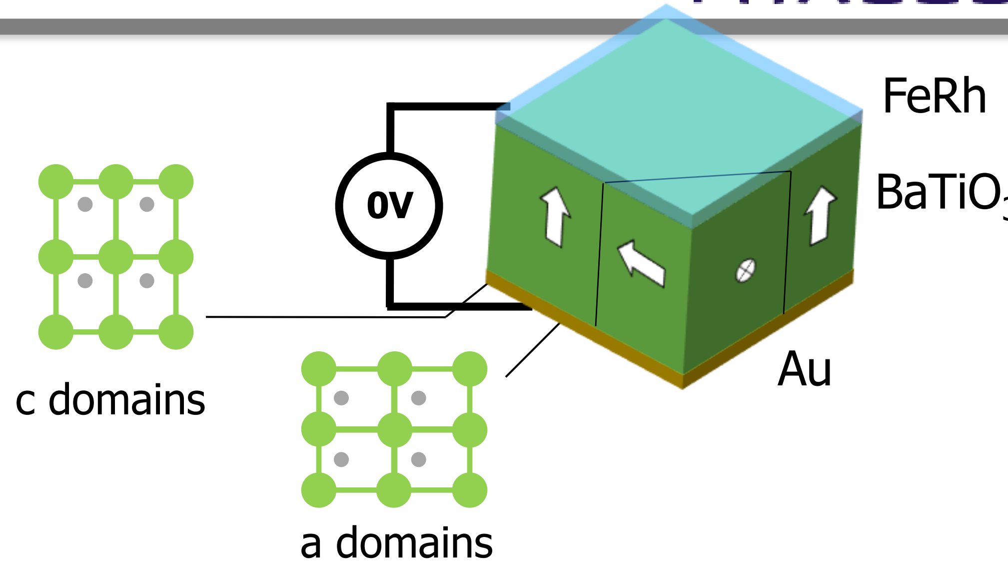
Electric field control of magnetic order

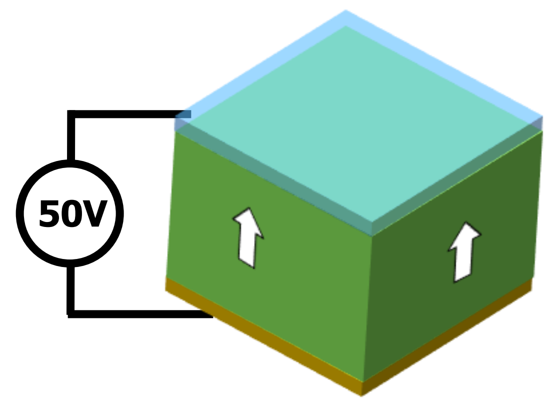
FeRh alloys : near 50/50 composition, transition from **AF to FM** at T*≈370 K





Kouvel et al, JAP 33, 1343 (1962) ; Maat et al, PRB 72, 214432 (2005)



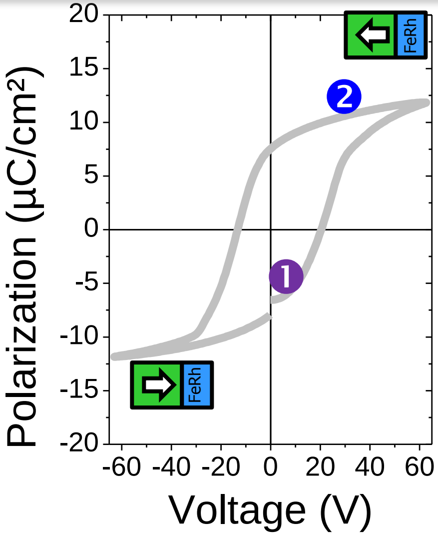


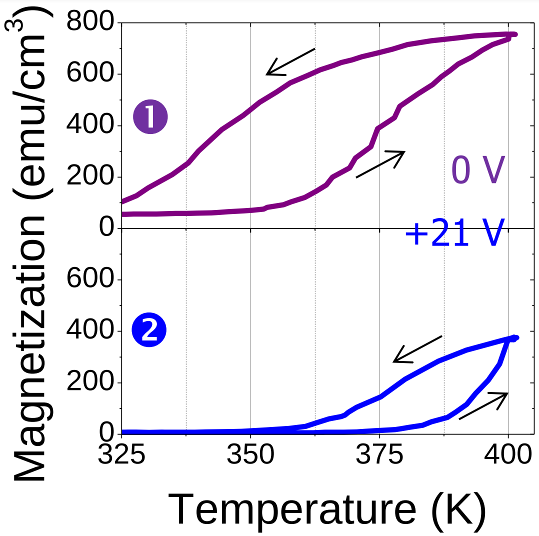
⊙ Transition is first order ⊙ Jump of cell volume at T*

Goal : drive AF to FM transition by electric field
➔ Grow FeRh on $BaTiO_3$ crystals
(ferroelectric & ferroelastic)

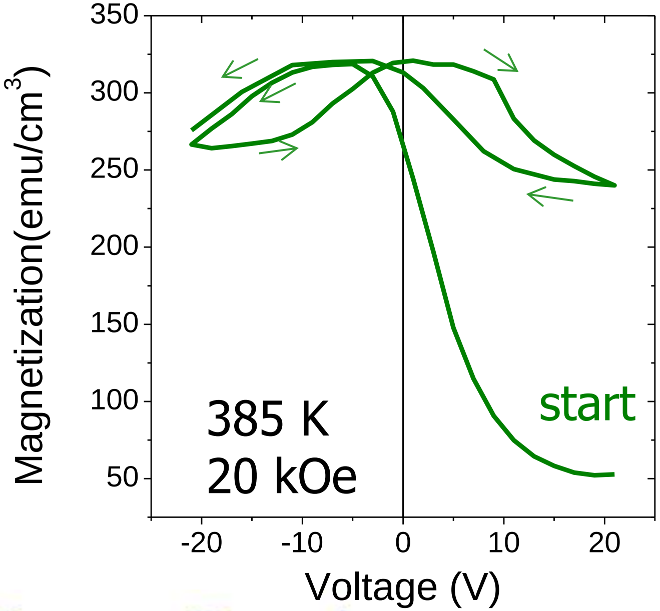
⊙ At 0 V, coexistence of a and c domains
⊙ Applied voltage : increase of c domain fraction (up to ~100%)
⊙ Compressive strain applied to FeRh

Electric field control of magnetic order





- At 0V at 20 kOe, T*≈360 K
- Voltage shifts T* by ~20K



- Huge voltage induced magnetization change
- First branch : largest effect (1st order transition)
- Then, hysteretic, reversible magnetoelectric effect
- Effect roughly symmetric
- → Mainly driven by strain
- Supported by first principles calculations

Nature Materials 13, 345 (2014)

Conclusion

- ➤ Proof of concepts of electric field effect have been realized using innovative approaches

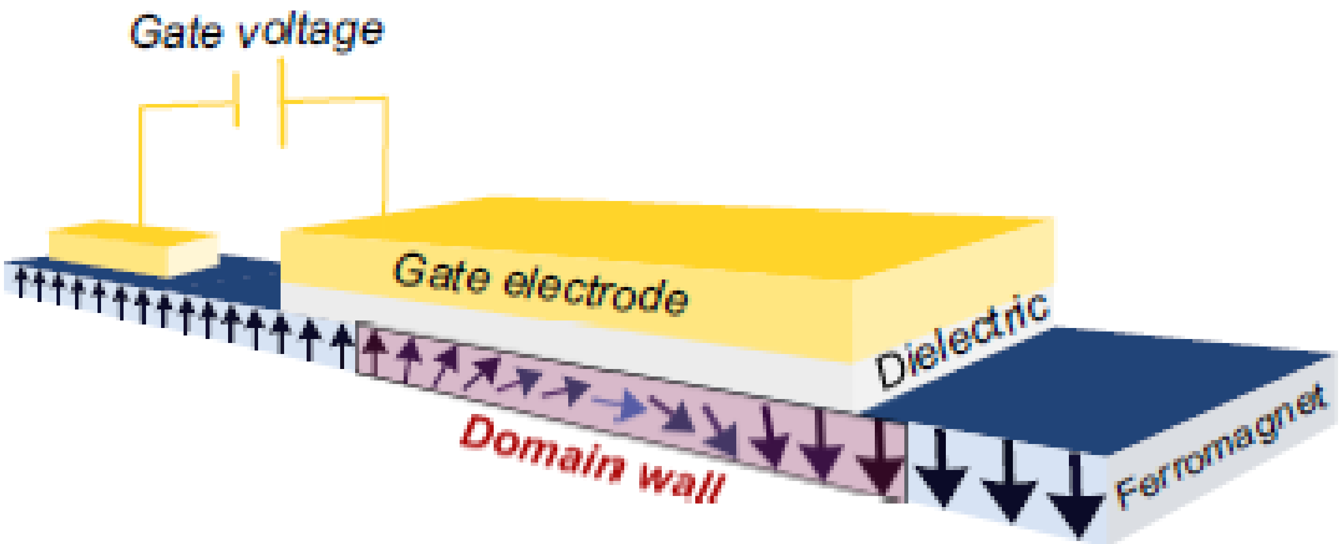
- ➤ 4 meetings of Axe 2 have been organized

- ➤ 1 Japanese-French workshop has been organised

- ➤ Call for 3 postdocs to further investigate the best approaches for low power spintronics

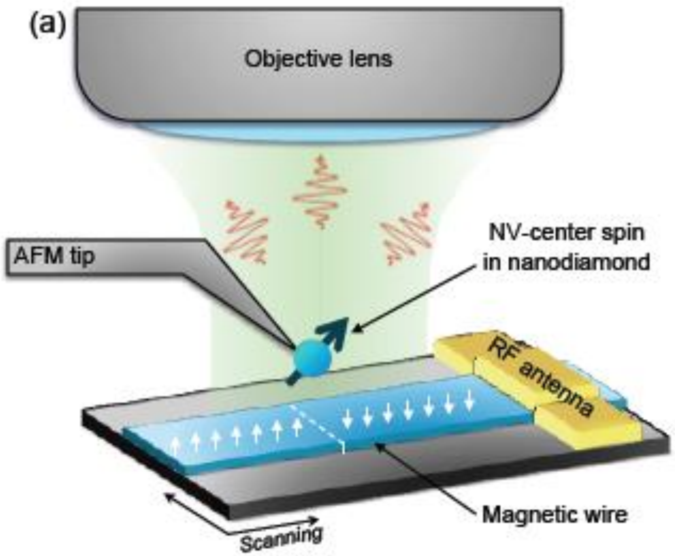
Domain wall motion in nanodevices

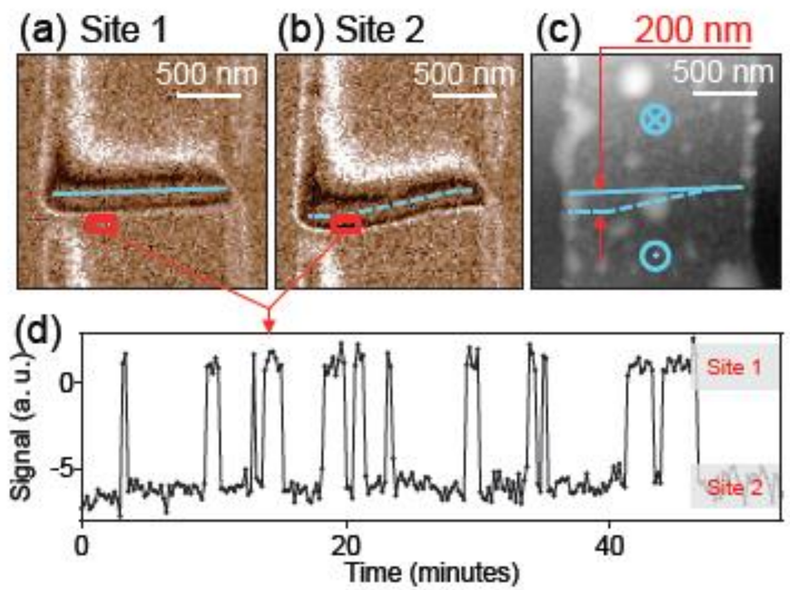
Combine polarized current and electric field effect to assist DW motion in nanowires (propagation, nucleation, depinning)



Domain wall motion in nanodevices

Observe DW structure under electric field using NV center microscopy



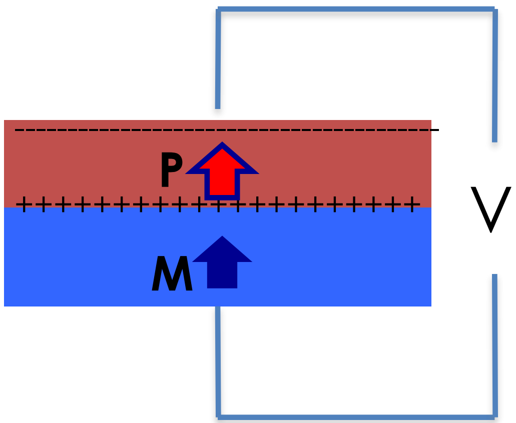


J.P.Tetienne, T.Hingant, J.F roch, V.Jacques, ENS CACHAN

J.P.Tetienne et al, Science 2014

Artificial multiferroics

- Drive AF to FM transition in a non-volatile way
- Dope FeRh with different elements to tune T* to be at 300K
- Extend approach to other systems



Oxide electronics :

- Induce multiferroicity in oxides through strain and interface engineering
- Explore new approaches for magnetoelectric coupling

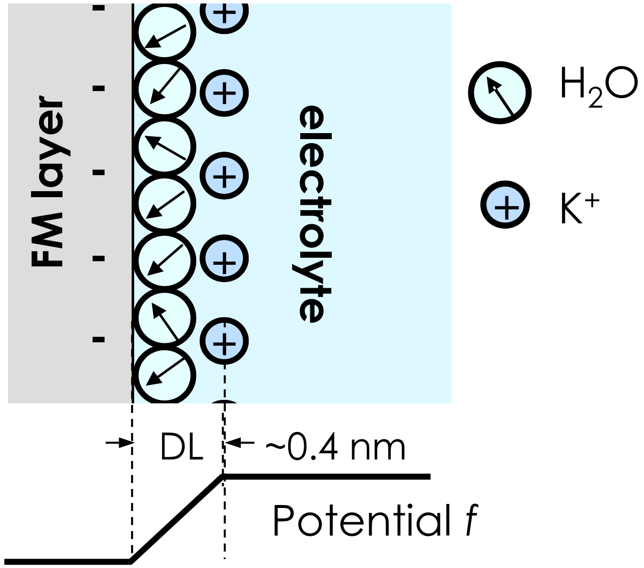
Electrochemical approach

Running collaboration IEF – PMC:

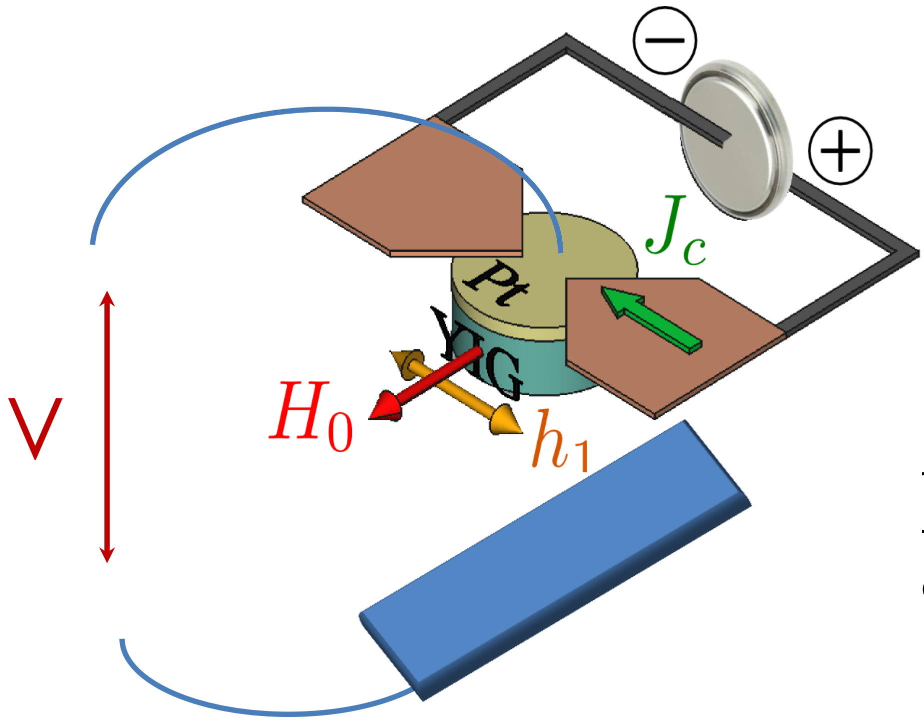
- Control of anisotropy via light induced charge transfer between Adsorbed photochromes and a ferromagnetic ultrathin layer

Future collaboration IEF – LPS - PMC:

- In situ MOKE microscopy to investigate the influence of E-field on the DMI in asymmetric systems Au/cobalt/solution.



Electric field control of FMR



-FMR in YIG/Pt measured by MRFM
-FMR is particularly sensitive to any change in damping and anisotropy

➢A current flowing in the Pt will generate a spin current by Spin Hall effect. Spins will accumulate at the interface and affect the YIG surface anisotropy.
➢A voltage will be applied between top and bottom electrodes of the insulating YIG. The internal electric field generated should affect the ferromagnetic anisotropy