POLITECNICO DI MILANO

Spintronics: basic principles and emerging trends

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Outlook

1. **Introduction to classical (Mott) spintronics**
   - ✓ GMR, TMR
   - ✓ STT-MRAMs

2. **Magnon spintronics**
   - ✓ Spin waves and related devices
   - ✓ Thermally assisted magnetic scanning probe lithography" (tam-SPL)
   - ✓ Applications to magnonics

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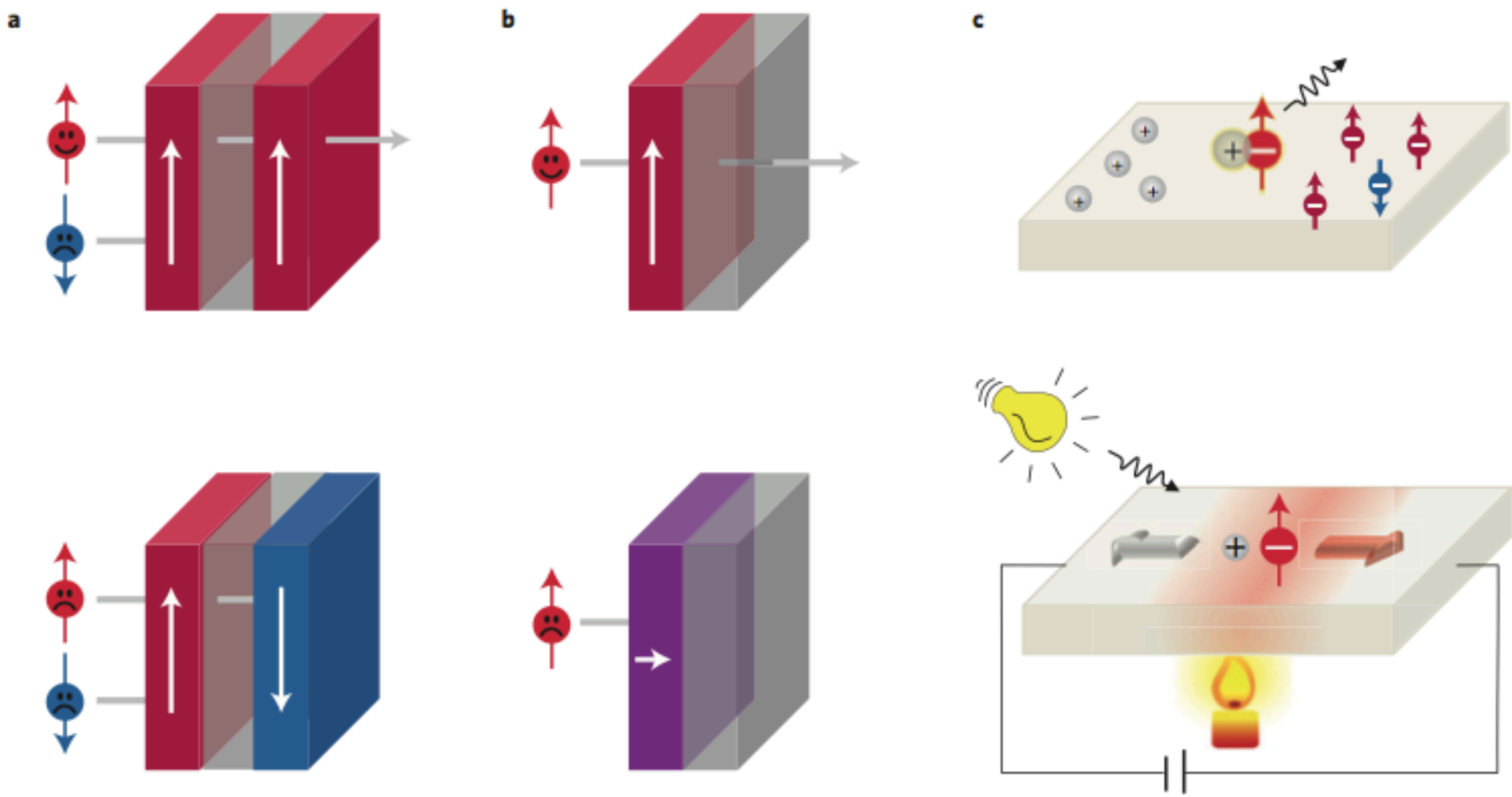
Spintronics paradigms

Mott | Dirac | Shockley



Sinova, J. and Žutic, I. Nat. Mater., 11 (5): 368–371, May 2012.

Mott spintronics: two currents model

Original idea: N. F. Mott, Proc. Roy. Soc. A153, 699 (1936)

First experimental evidence for spin dependent transport:
A. Fert and I. A. Campbell, Phys. Rev. Lett. 21, 1190 (1968) – Ni/Fe alloys

Basic idea: conduction in independent parallel channels by the spin↑ (majority) and spin↓ (minority) electrons. *The spin flip scattering of the conduction electrons by magnons is frozen out, the spin mixing rate is much smaller than the momentum relaxation rate.*

Eigenstates: $\psi_{j,s,\mathbf{k}}(\mathbf{r})$

j : layer in the structure
s: spin channel

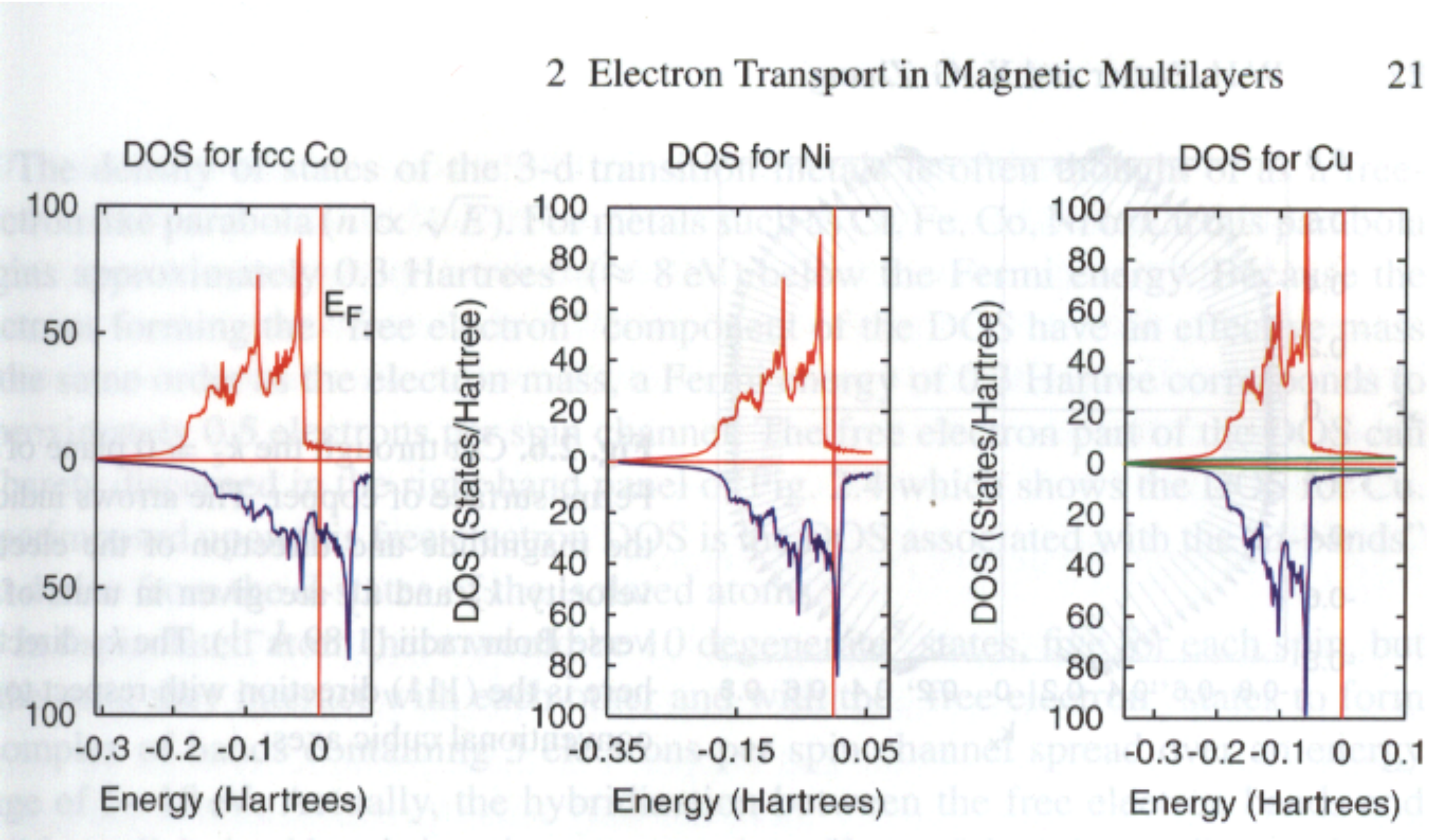
Eigenvalues: $\varepsilon_{j,s}(\mathbf{k})$

up and down bands

DOS (up and down): $$n_{j,s}(E) = \sum_{\mathbf{k}} \delta(E - \varepsilon_{j,s}(\mathbf{k}))$$

This is the Stoner description or band description of a ferromagnet

Spin dependent electronic structure



Ultrathin Magnetic Nanostructures III, Springer Verlag (2005)

The Nobel Prize in Physics 2007

Photo: U. Montan

Albert Fert

Prize share: 1/2

Photo: U. Montan

Peter Grünberg

Prize share: 1/2

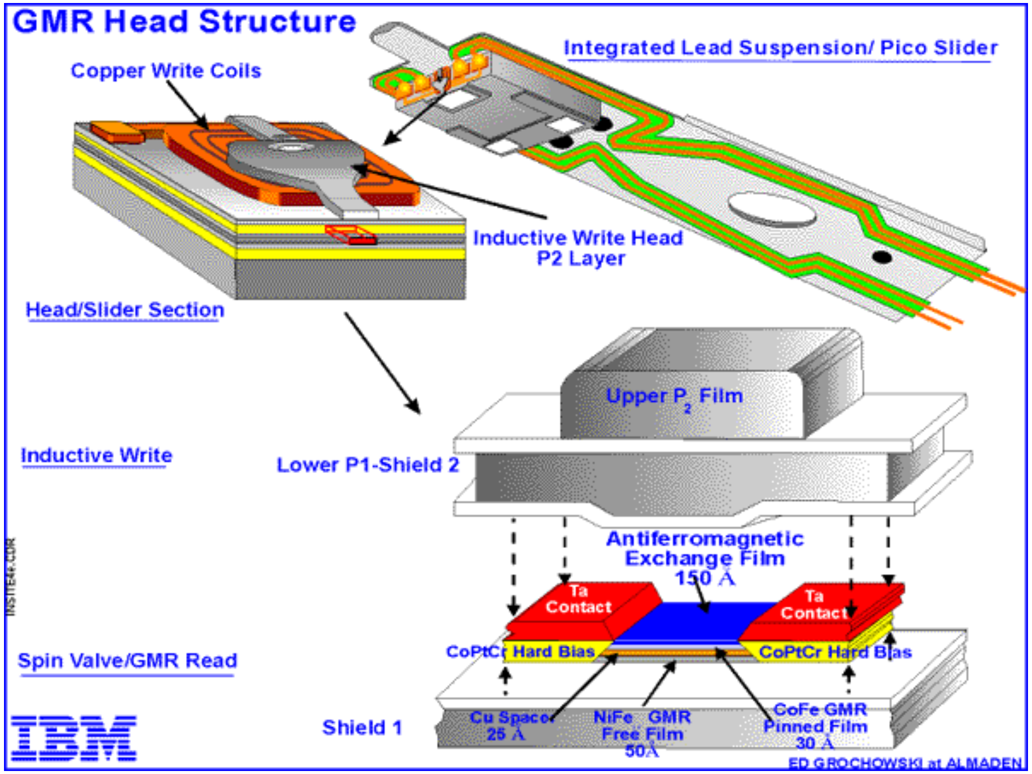
The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert and Peter Grünberg *"for the discovery of Giant Magnetoresistance"*

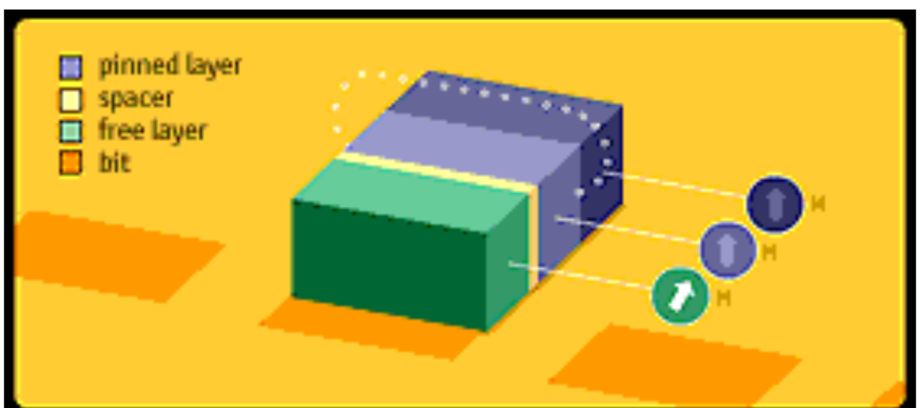
Giant

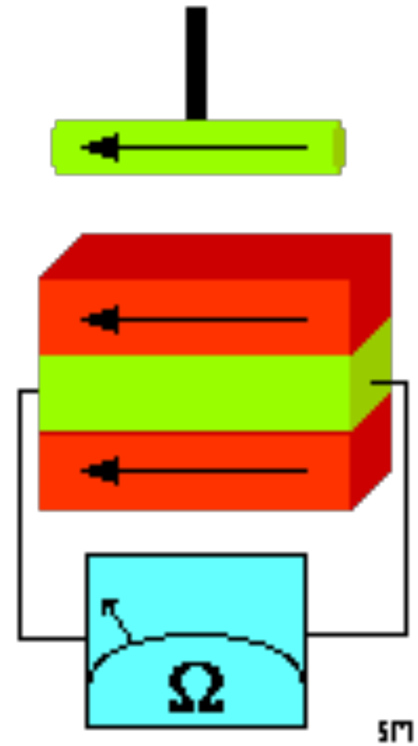
Magneto

Resistance

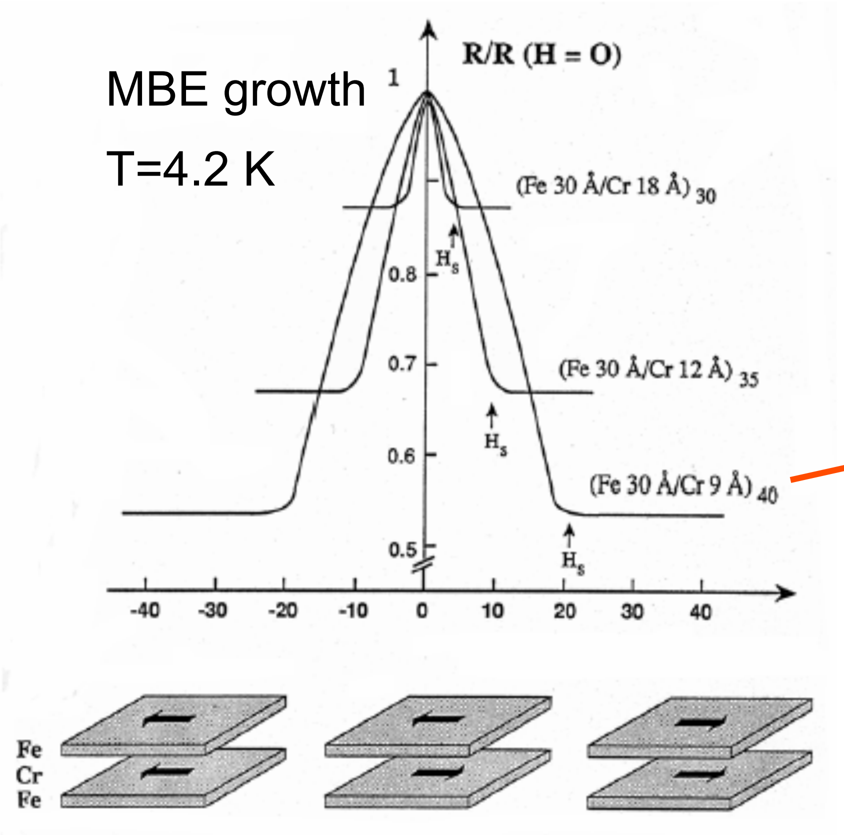
GMR and magnetic recording







The discovery of GMR (1988)



$$MR = \frac{\rho_{AP} - \rho_P}{\rho_P}$$

79% at 4.2 K
20% at 300 K

Record: 220%
Fe/Cr multilayers
Schad et al. (1994)

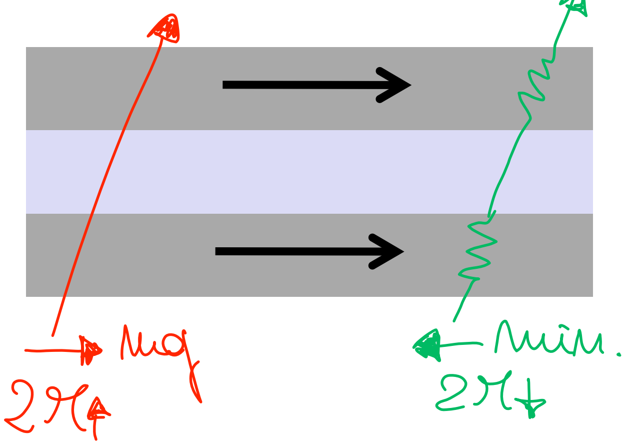
[1] M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J.Chazelas, Phys. Rev. Lett. **61**, 2472 (1988)

*[2] G. Binash, P. Grünberg, F. Saurenbach, and W. Zinn, Phys. Rev. B **39**, 4828 (1989) (trilayer)*

GMR: a simple model

- *Spin dependent scattering due to defects and impurities in magnetic layers as well as at interfaces*
- *CPP configuration*

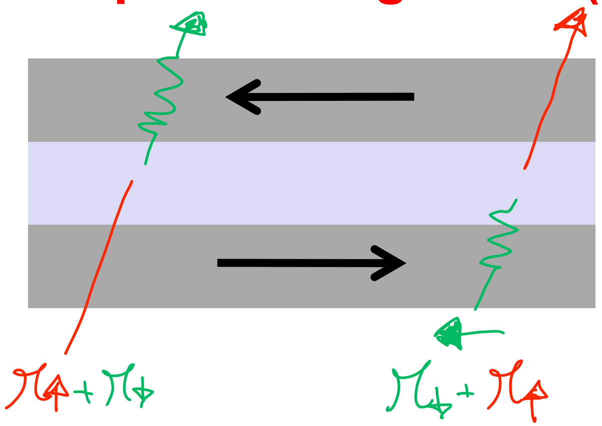
Parallel alignment (P)



$r_\uparrow << r_\downarrow$

(Co, Ni, ...)

Antiparallel alignment (AP)



$$r_P = \frac{2 r_\uparrow r_\downarrow}{r_\uparrow + r_\downarrow} \simeq 2 r_\uparrow$$

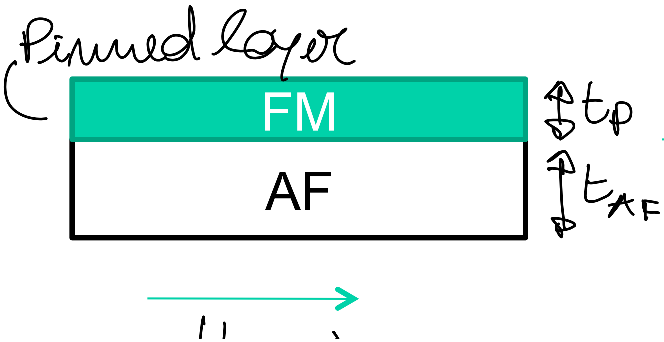
$$r_{AP} = \frac{r_\uparrow + r_\downarrow}{2}$$

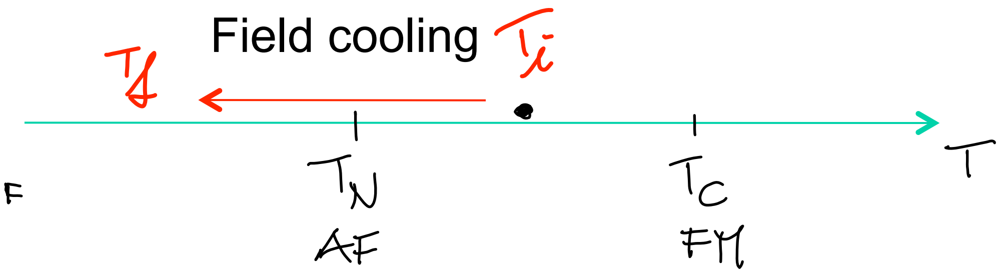
$$r_{AP} \gg r_P$$

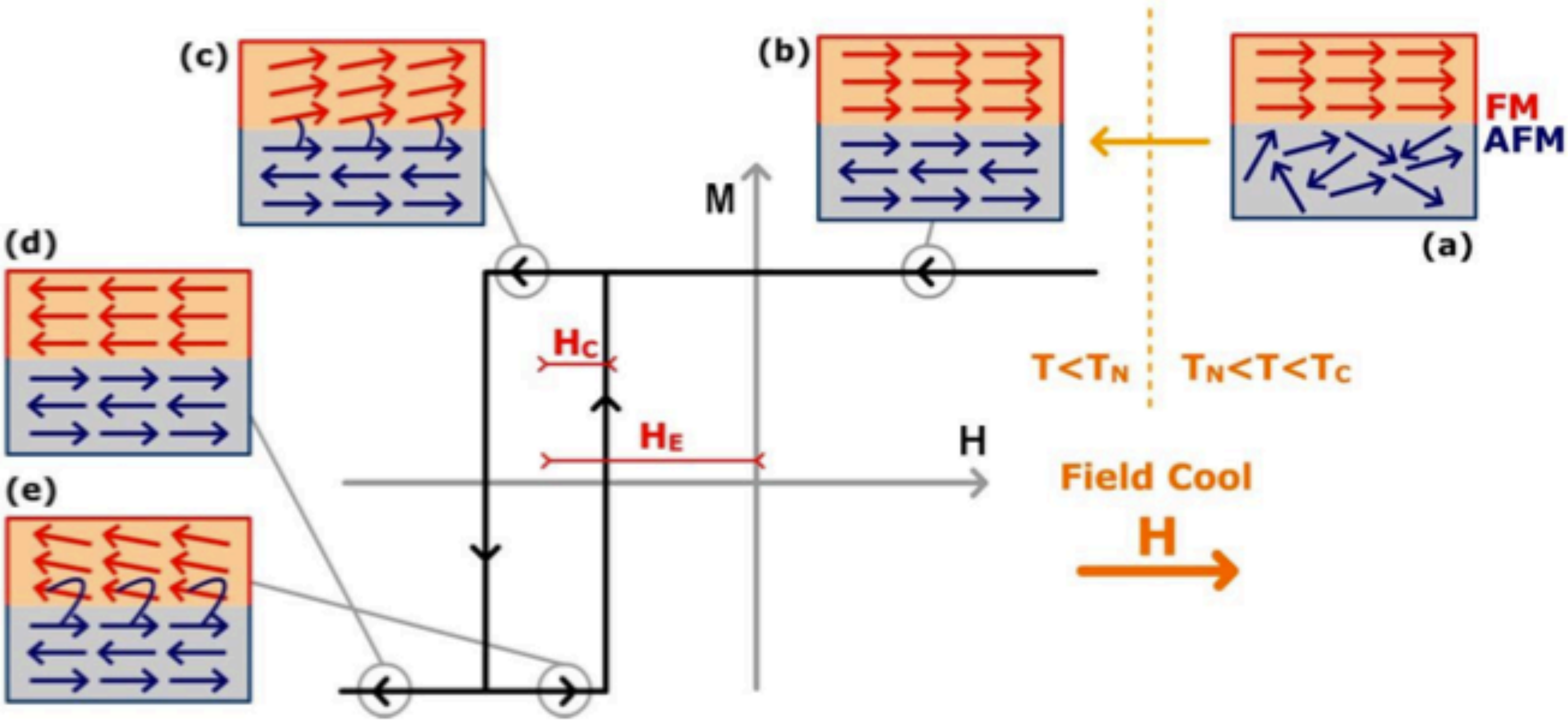
In the parallel configuration there is a short in the majority channel

$$GMR = \frac{r_{AP} - r_P}{r_P} = \frac{(r_\uparrow - r_\downarrow)^2}{4 r_\uparrow r_\downarrow}$$

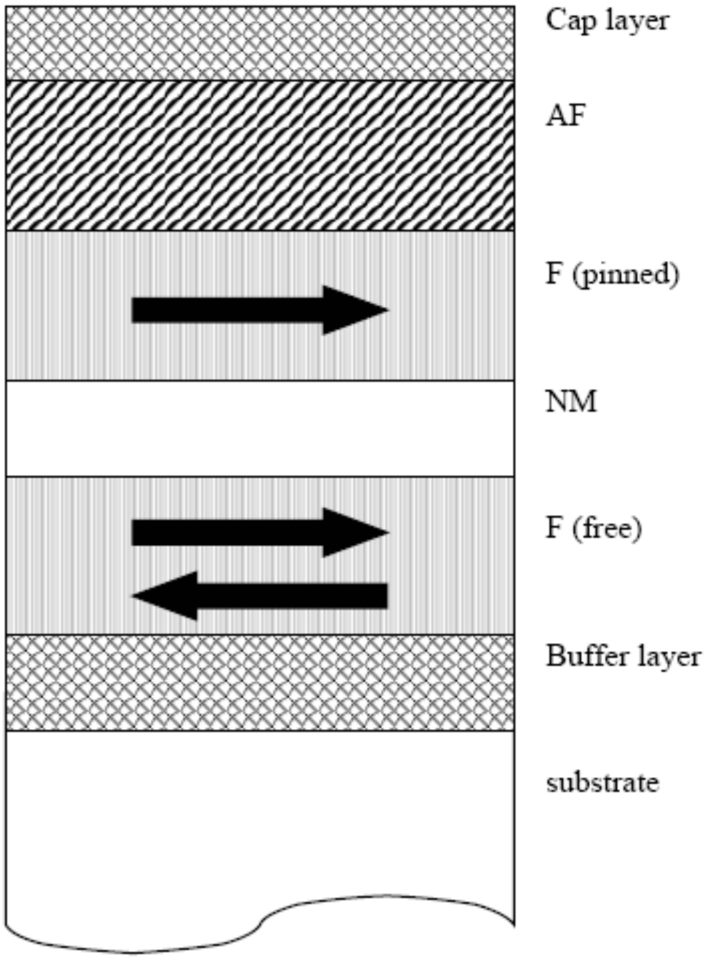
Exchange bias

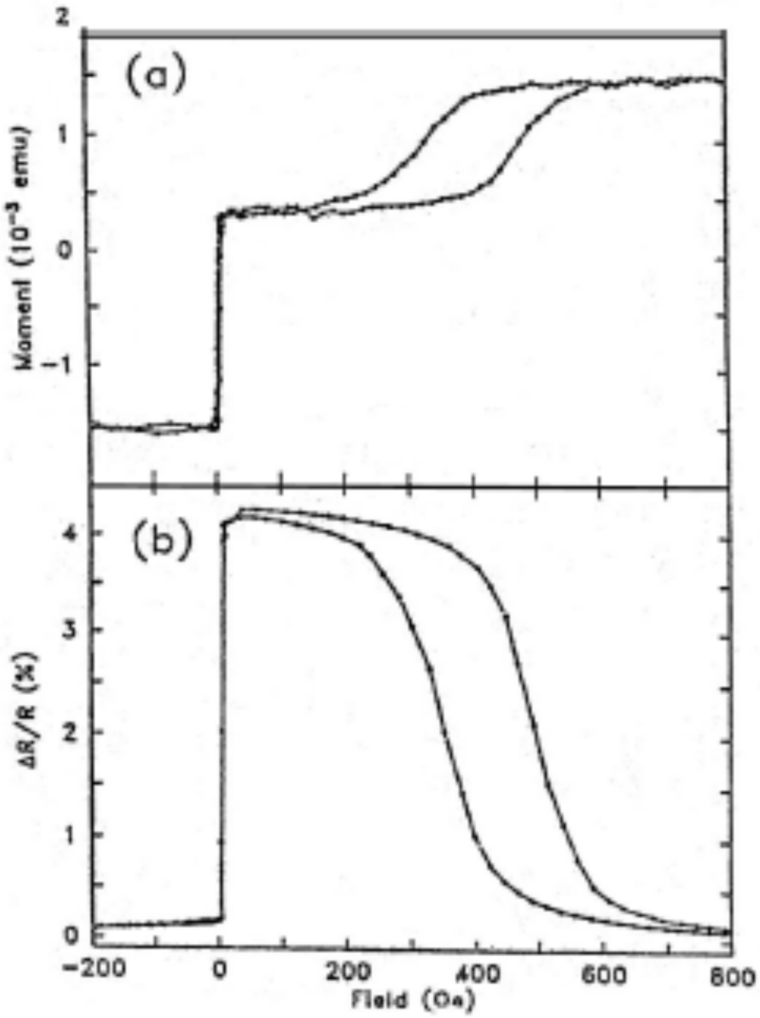




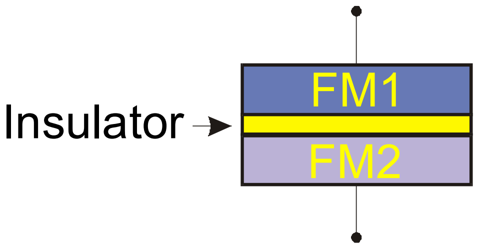


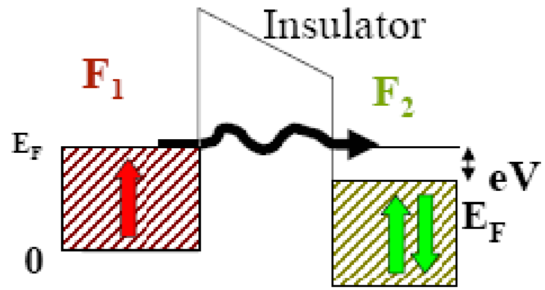
Spin valve (1991)

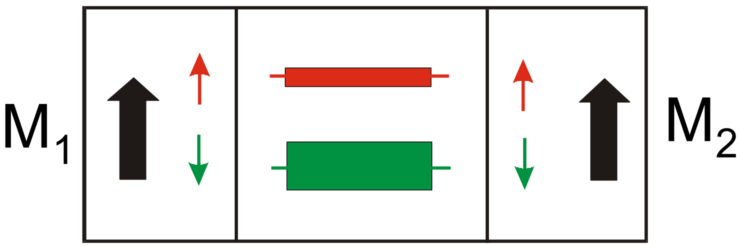


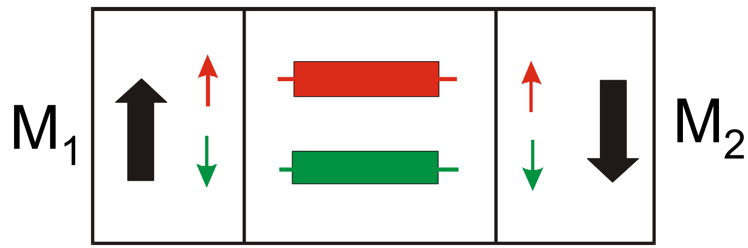


Tunneling magnetoresistance

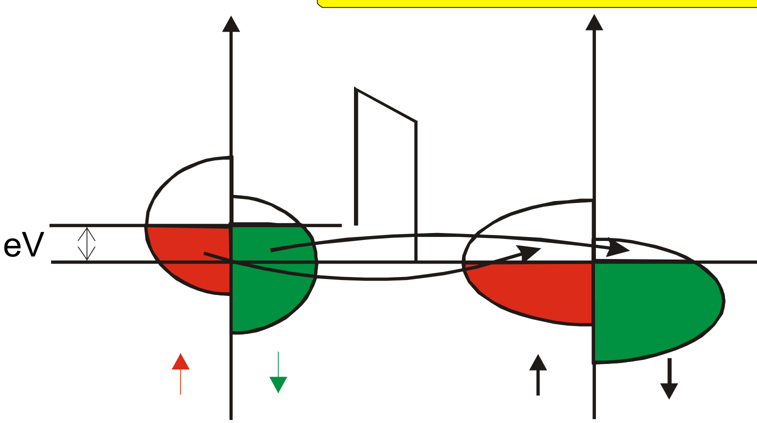


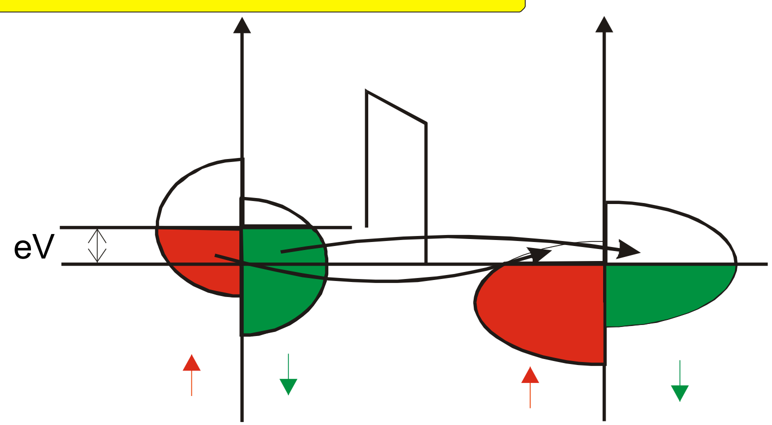




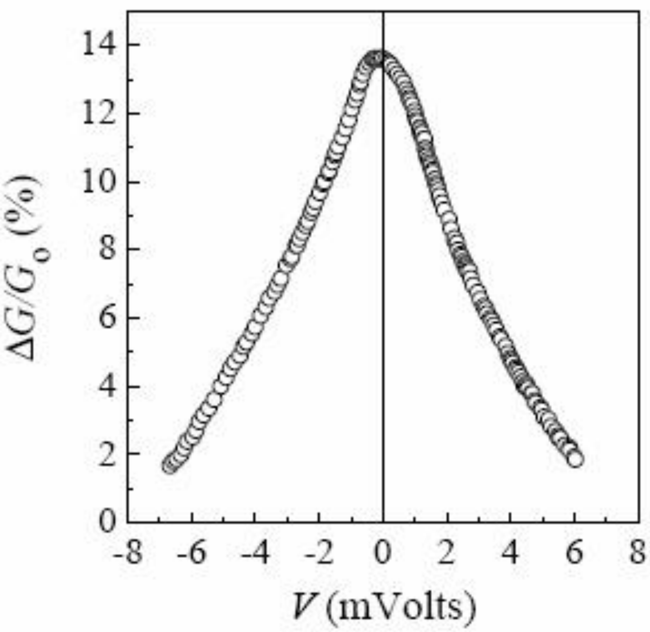


Rp < Rap





Jullière model for TMR (1975)



Fe/GeO_x/Co

Assumptions:
- Spin conservation during tunneling
- Constant transmission coefficients, independent on magnetization and energy
- Small applied voltage

$$G_P = G_{\uparrow\uparrow} + G_{\downarrow\downarrow} \propto D_{1\uparrow}D_{2\uparrow} + D_{1\downarrow}D_{2\downarrow}$$

$$G_{AP} = G_{\uparrow\downarrow} + G_{\downarrow\uparrow} \propto D_{1\uparrow}D_{2\downarrow} + D_{1\downarrow}D_{2\uparrow}$$

$$P_1 = \frac{D_{1\uparrow} - D_{1\downarrow}}{D_{1\uparrow} + D_{1\downarrow}}$$

$$TMR = \frac{R_{AP} - R_P}{R_P} = \frac{G_P - G_{AP}}{G_{AP}} = \frac{2P_1P_2}{1 - P_1P_2}$$

It works, especially in case of Al_2O_3 barriers.

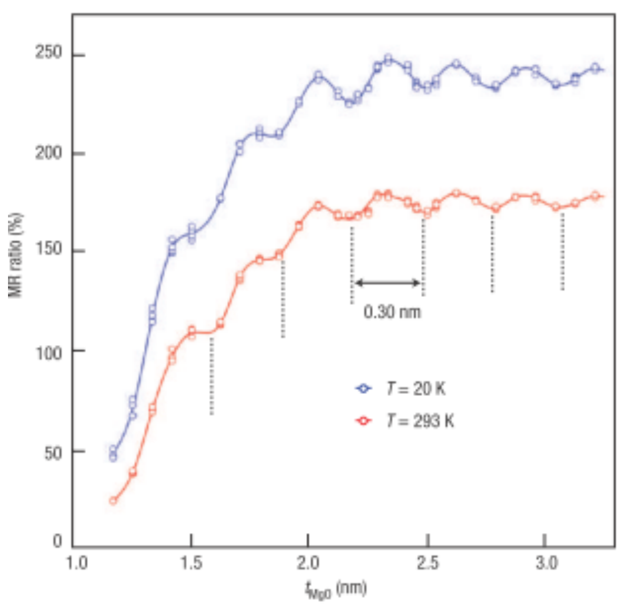
Fe/MgO/Fe: Coherent tunneling

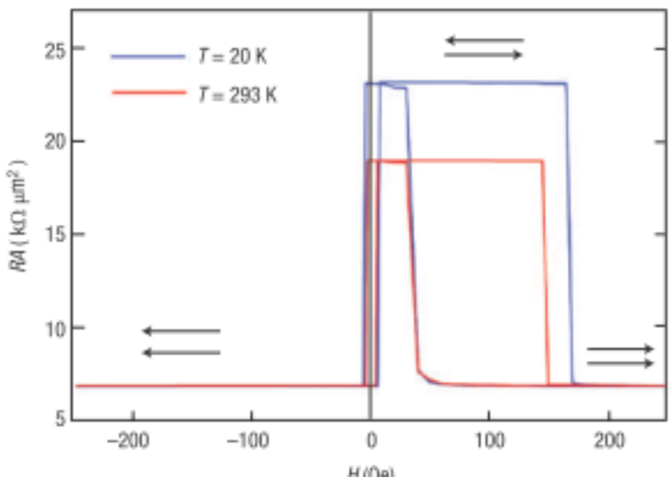
TMR (RT) MTJ conventional (Al2O3) ~ 70%

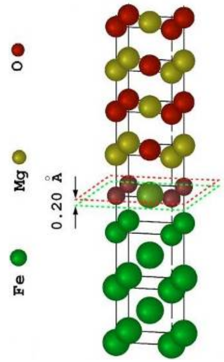
TMR (RT) MTJ Fe/MgO/Fe ~ 800% (theoretical value = **1000%**)

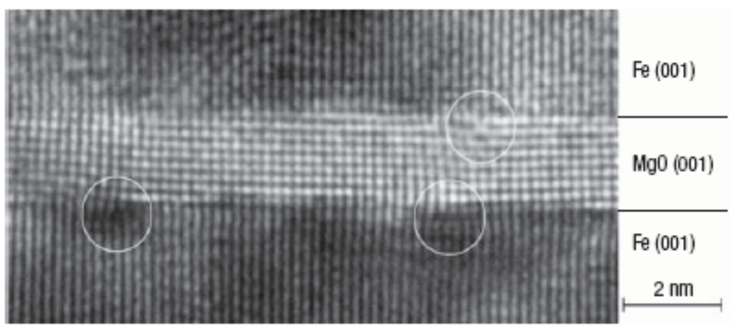
Giant room-temperature magnetoresistance in single-crystal Fe/MgO/Fe magnetic tunnel junctions

SHINJI YUASA[1,2]*, TARO NAGAHAMA[1], AKIO FUKUSHIMA[1], YOSHISHIGE SUZUKI[1] AND KOJI ANDO[1]
[1]NanoElectronics Research Institute, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki 305-8568, Japan
[2]PRESTO, Japan Science and Technology Agency, Kawaguchi, Saitama 332-0012, Japan
*e-mail: yuasa-s@aist.go.jp



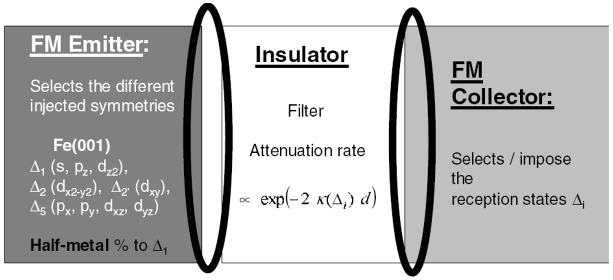






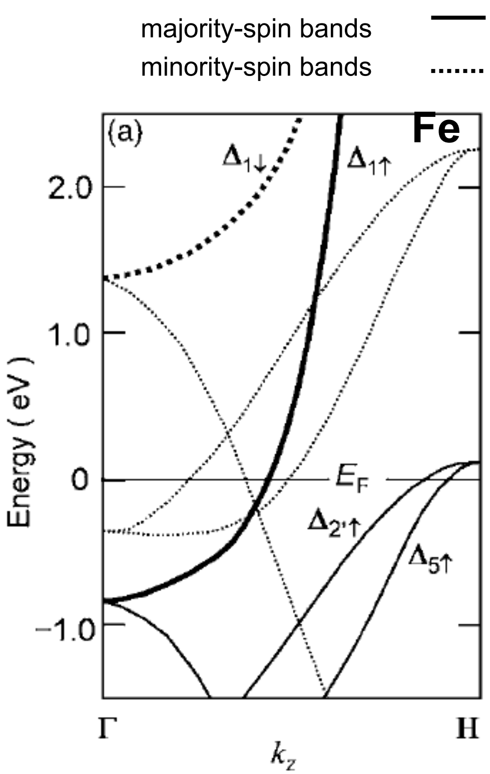
S. Yuasa et al, Nature Materials, **3** 868 (2004)

Symmetry based spin filtering

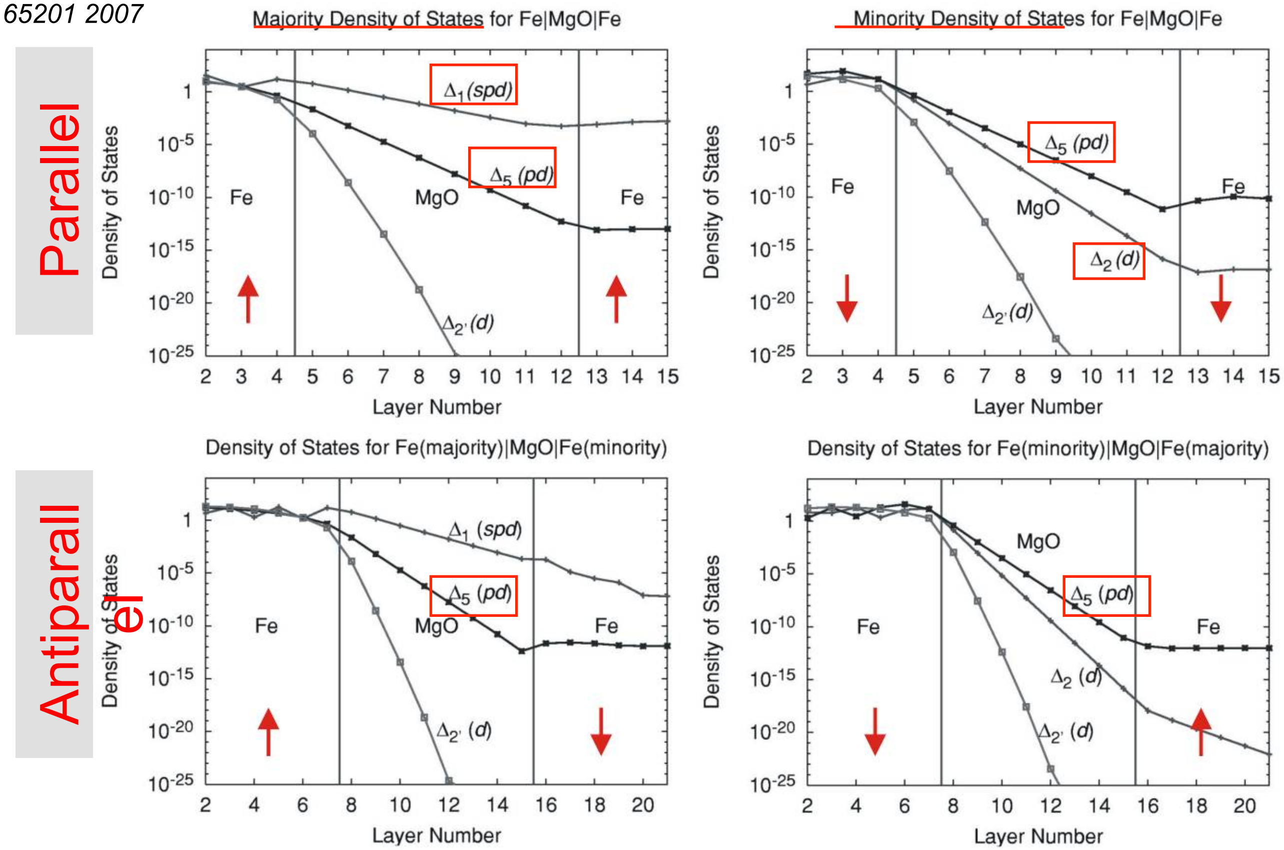


*C. Tiusan et al, J.Phys.:Cond. Matter **19** 165201 2007*

Different attenuation in the barrier depending on the symmetry of states



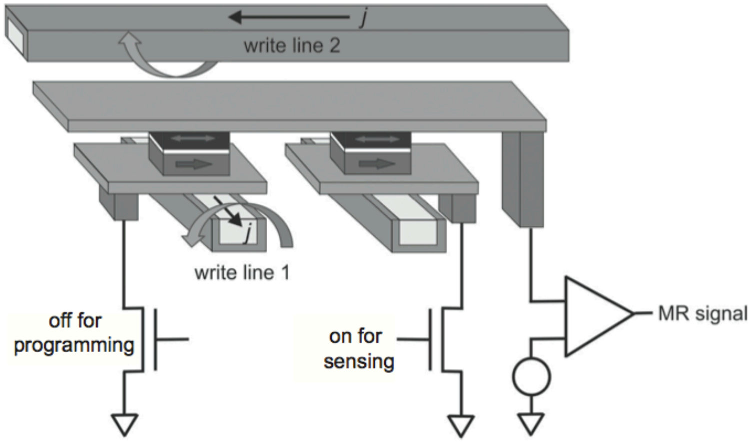
*S. Yuasa et al, APL **89** 042505 2006*



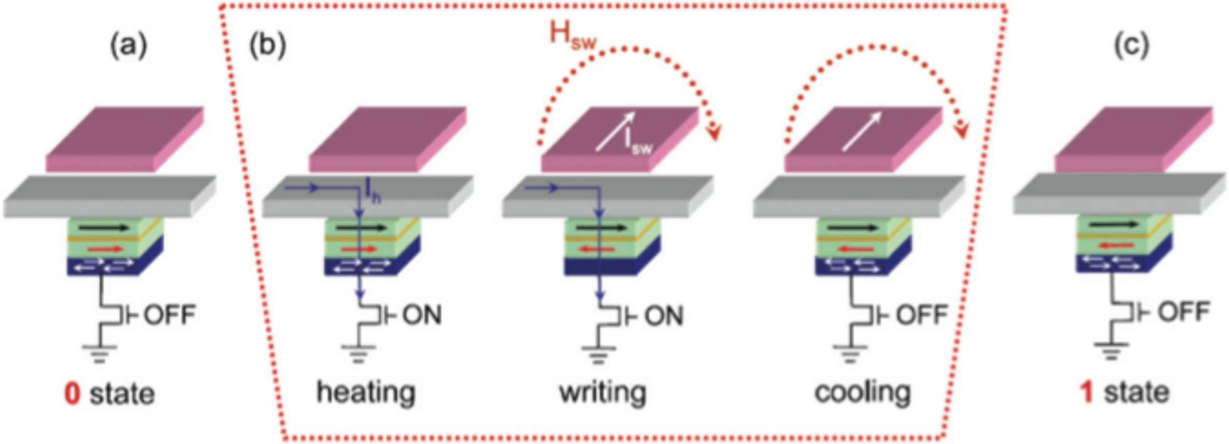
*W. H. Butler et al, PRB **63** 054416 (2001)*

Application to non-volatile MRAMs: the writing issue

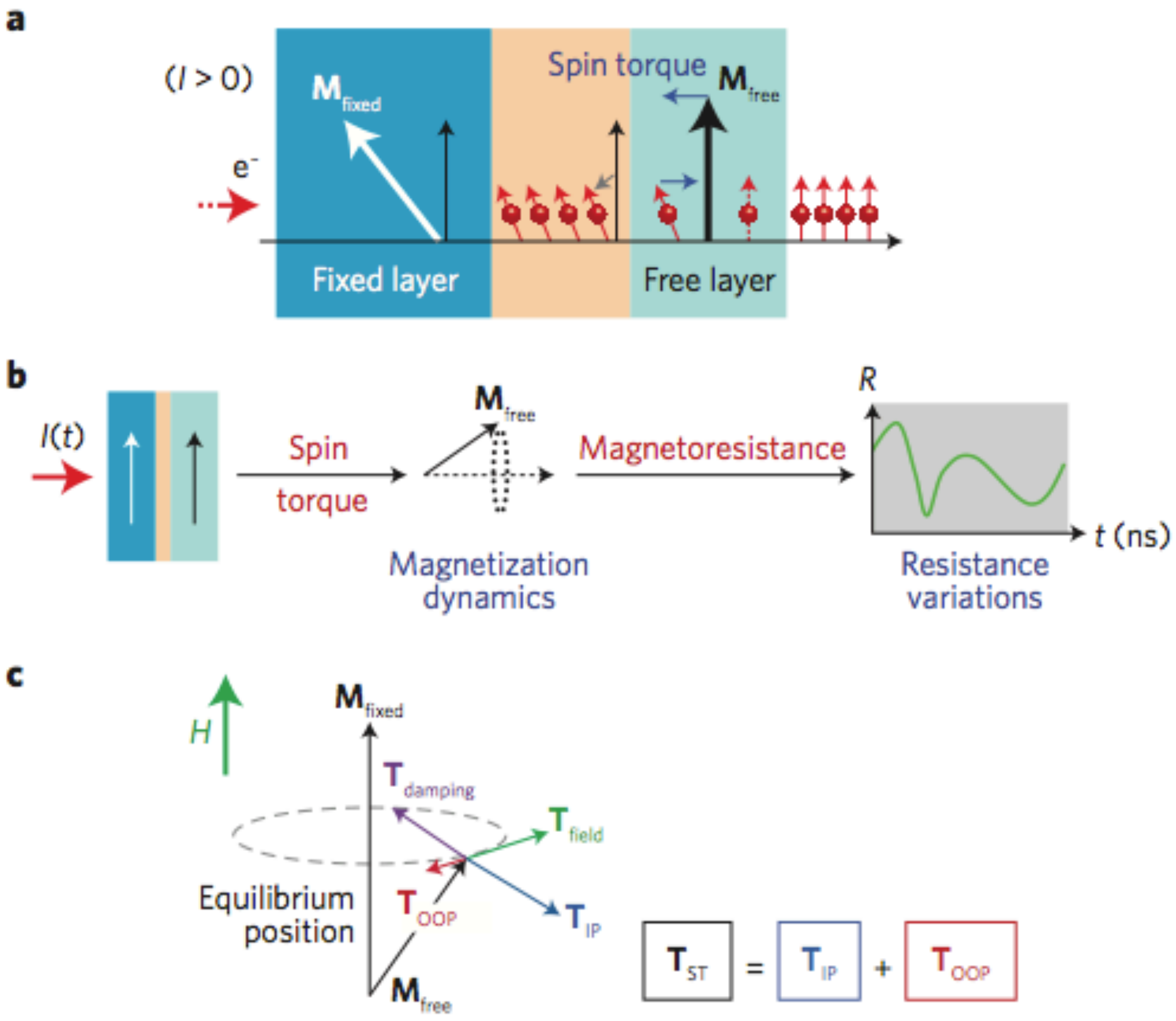
Current lines



Thermally assisted cell writing



Spin transfer torque (2001)

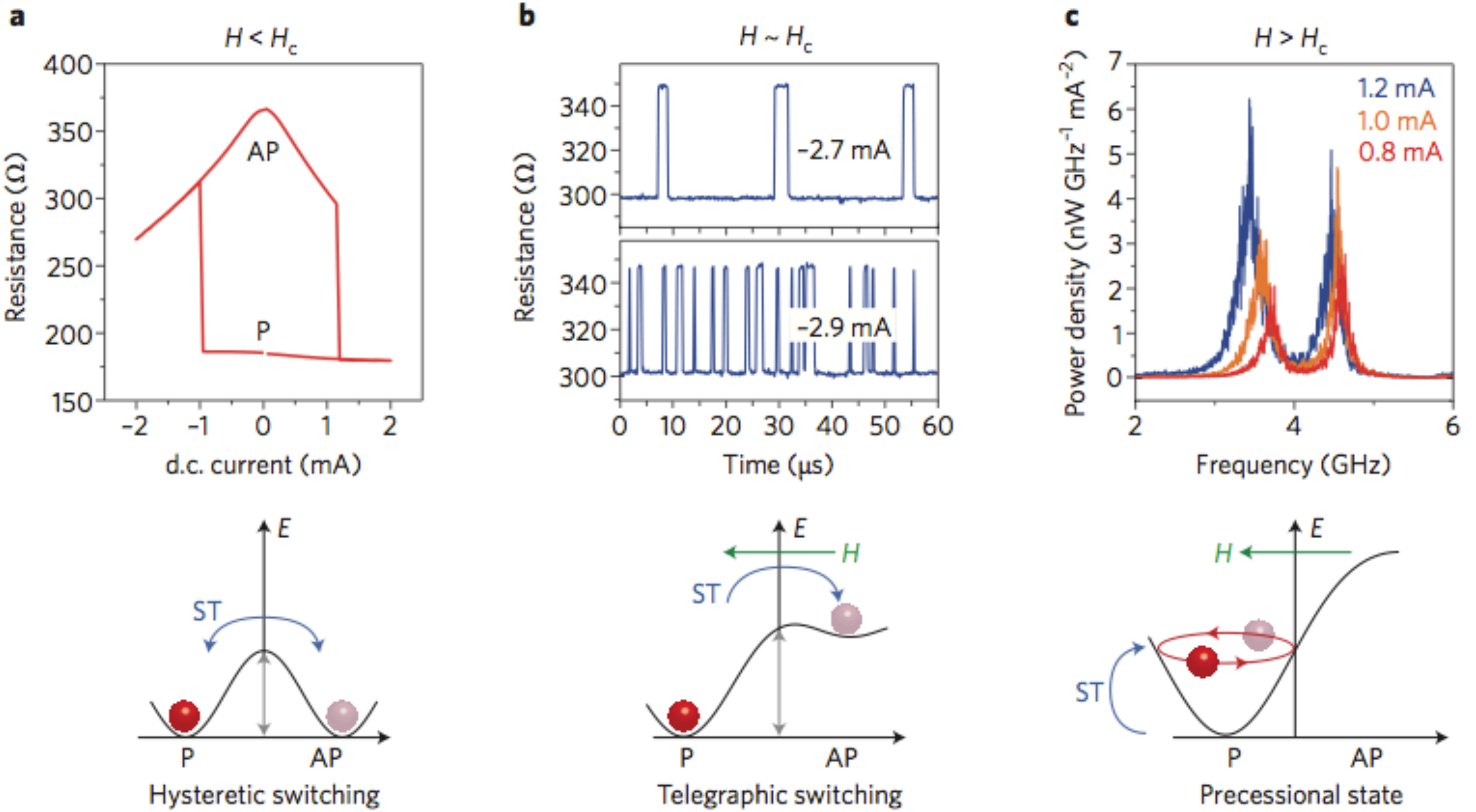


The in-plane torque is therefore useful for stabilizing the magnetization in its equilibrium position, or, on the contrary, to destabilize it to bring it to another equilibrium situation.

The out-of-plane torque, often called field-like torque, it can emulate the action of a field on M_{free}, which means that it can modify the energy landscape seen by the magnetization.

N. Locatelli, V. Cros and J. Grollier, Nature Materials, 13,11 (2014)

Magnetization dynamics with in-plane spin torque

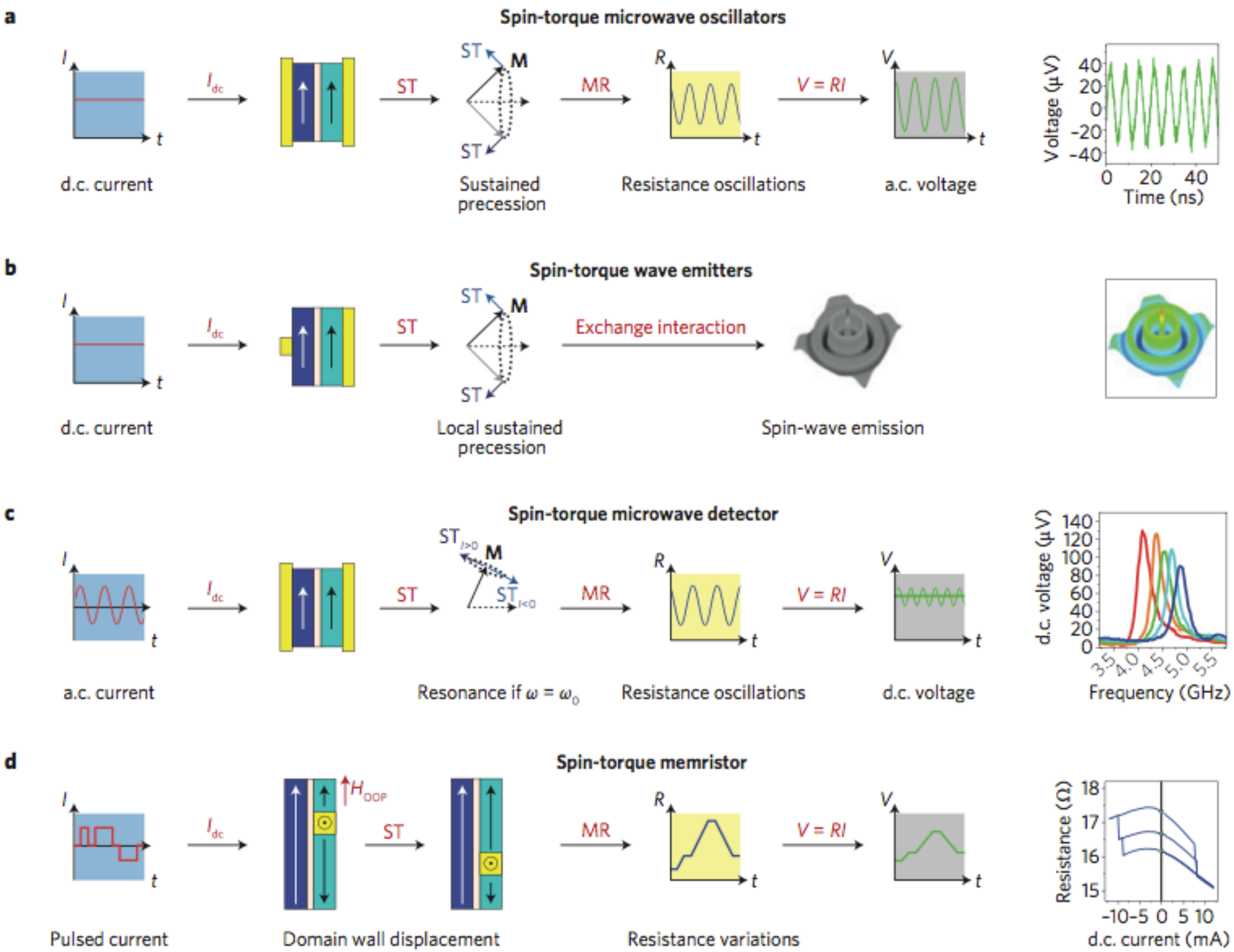


STT- MRAMs

Stochastic devices

MW and SW generators, detectors

Spin-torque building blocks



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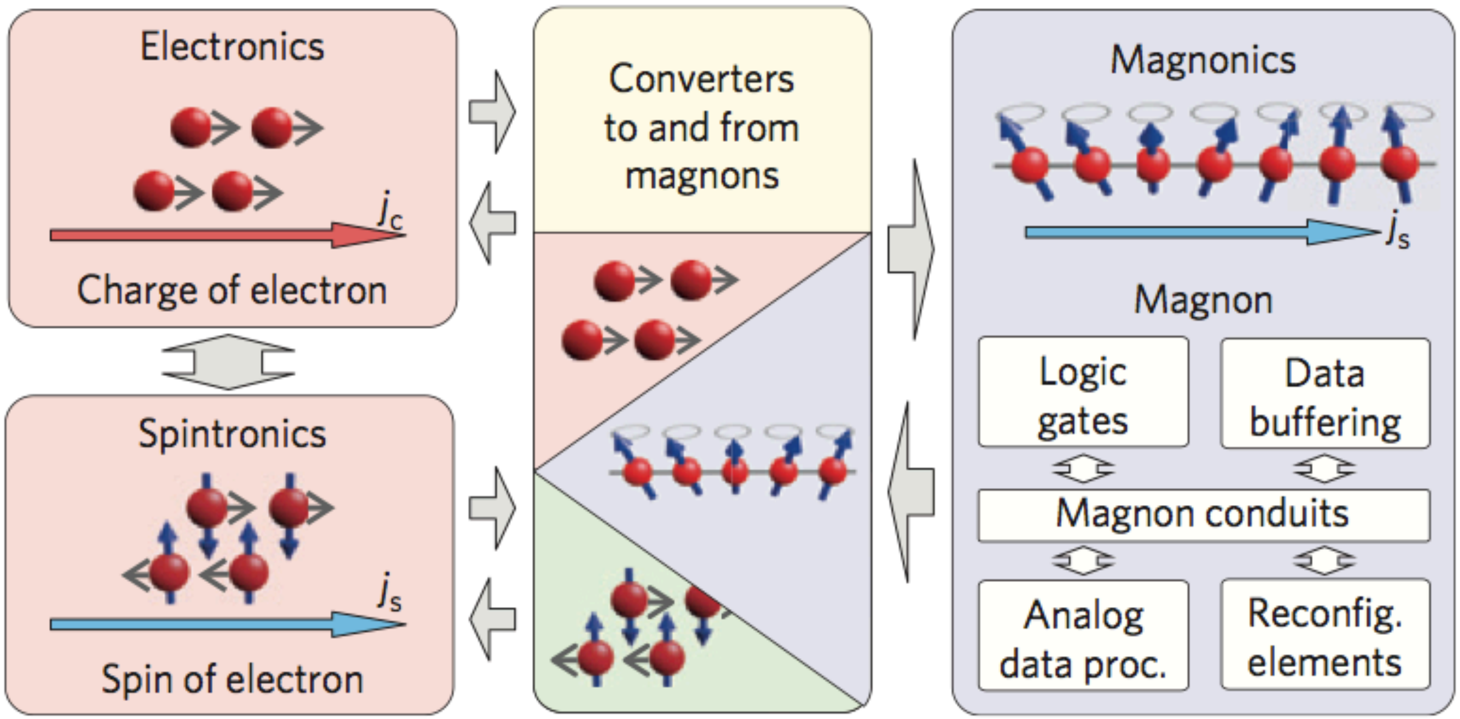
Magnon spintronics

nature physics
REVIEW ARTICLE
PUBLISHED ONLINE: 2 JUNE 2015 | DOI: 10.1038/NPHYS3347

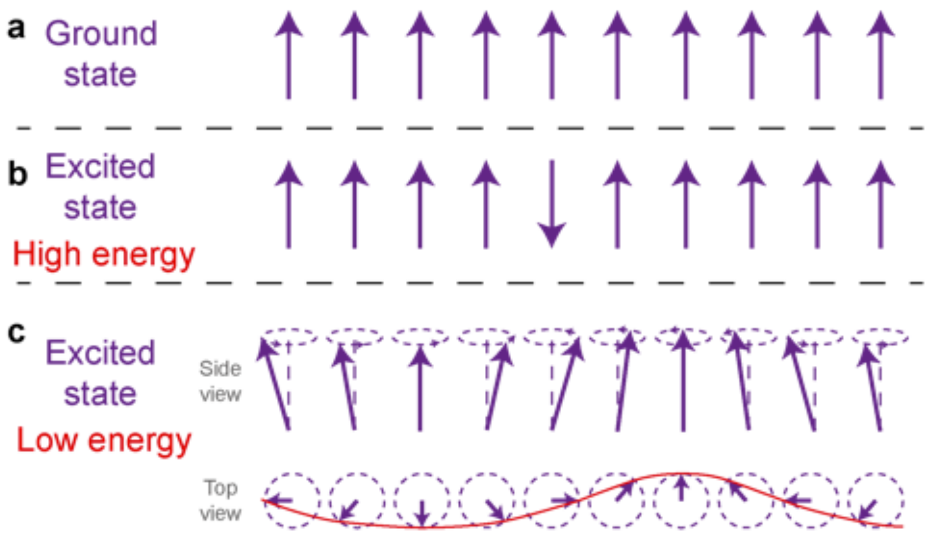
Magnon spintronics

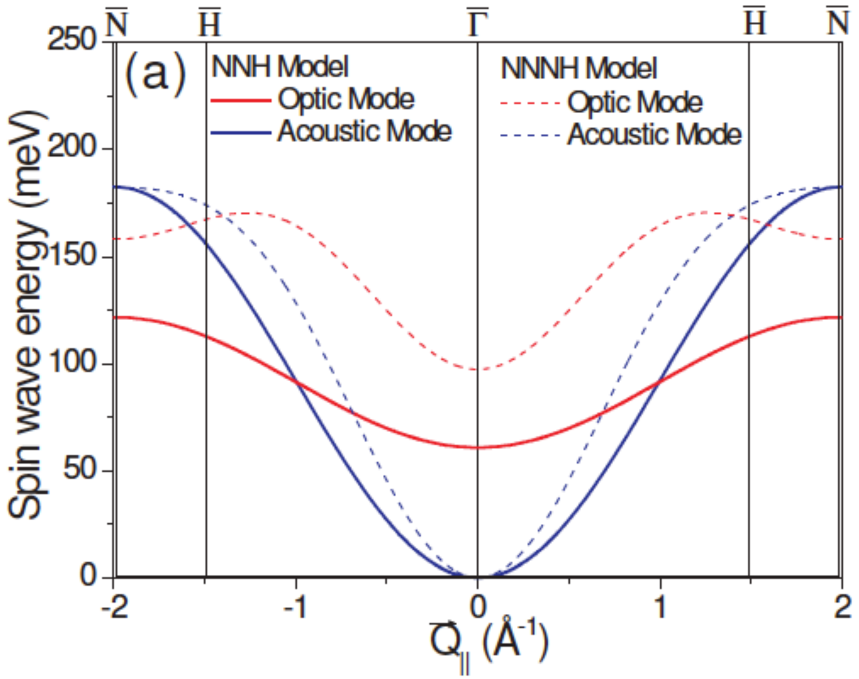
A. V. Chumak*, V. I. Vasyuchka, A. A. Serga and B. Hillebrands



Exchange SW: spin flip delocalized over the entire lattice, strong short range exchange interaction (λ<1mm)

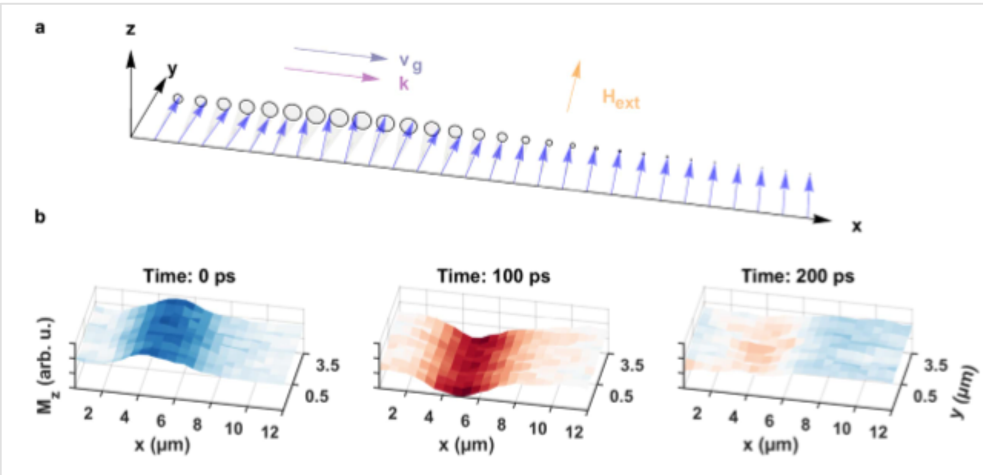
$$\mathcal{H} = -\frac{1}{2} J \sum_{i,j} \mathbf{S}_i \cdot \mathbf{S}_j - g\mu_B \sum_i \mathbf{H} \cdot \mathbf{S}_i \qquad |\mathbf{Q}\rangle = \frac{1}{\sqrt{N}} \sum_j e^{i\mathbf{Q}\cdot\mathbf{r}_j} |\downarrow_j\rangle$$





Dipolar or magnetostatic waves (MSWs)

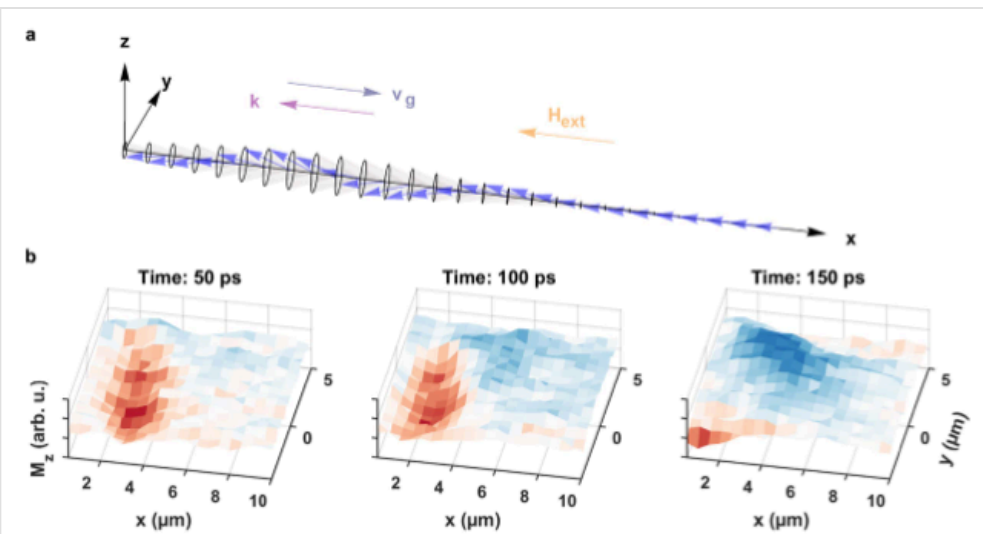
Long-range dipolar interaction (λ>1mm), excitation/detection via antennas



For in plane magnetization

Magnetostatic surface waves (MSSWs, also known as Damon–Eshbach waves)

k parallel to M

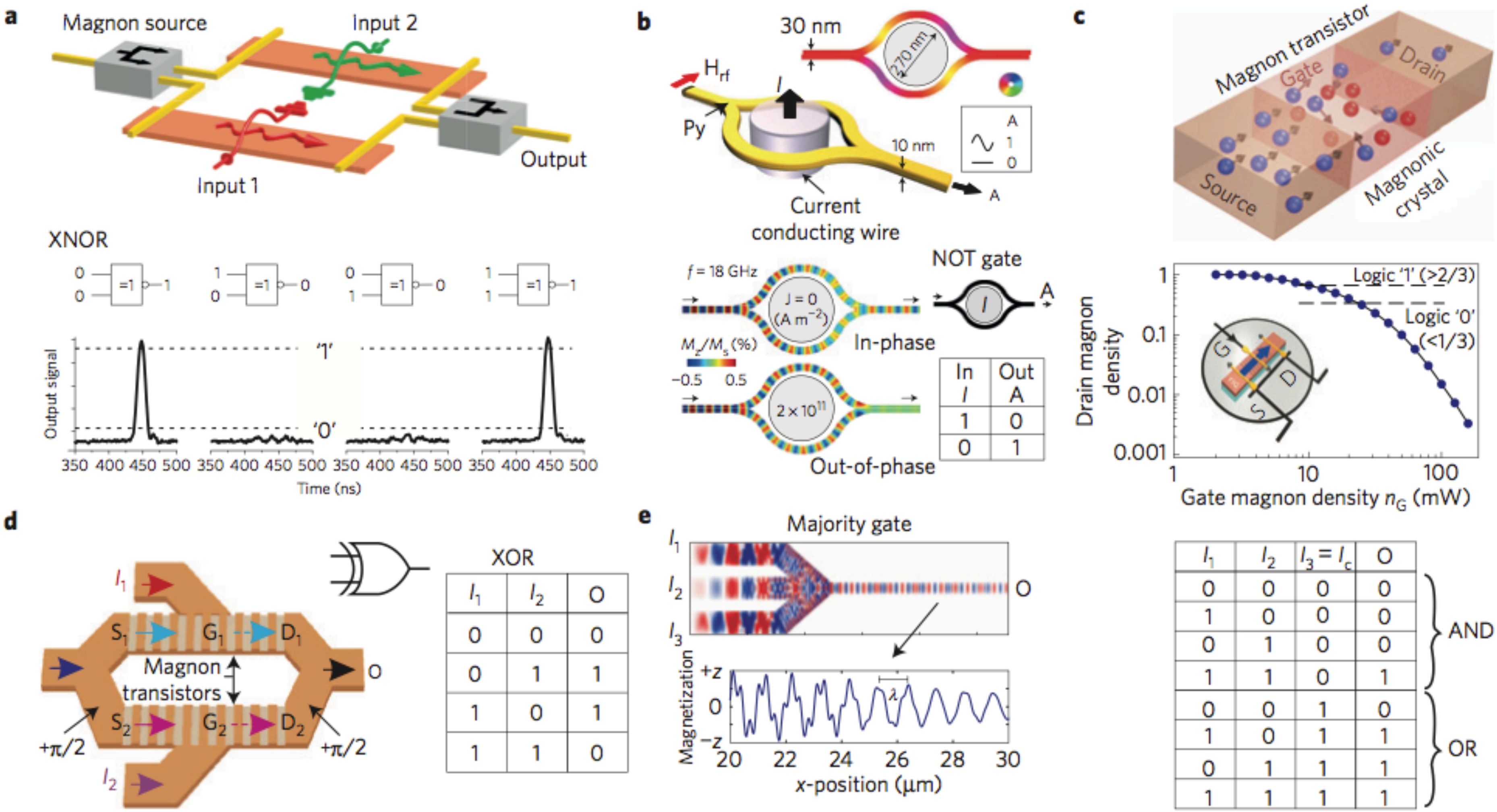


Backward volume magnetostatic waves (BVMSWs)

k perpendicular to M

Philipp Wessels et al., Sci. Rep. 6:22117 | DOI: 10.1038/srep22117

Proposed devices



In I	Out A
1	0
0	1

XOR

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

I_1	I_2	$I_3 = I_c$	O	
0	0	0	0	AND
1	0	0	0	
0	1	0	0	
1	1	0	1	
0	0	1	0	OR
1	0	1	1	
0	1	1	1	
1	1	1	1	

Thermally assisted magnetic scanning probe lithography" (*tam*-SPL)

nature nanotechnology

ARTICLES

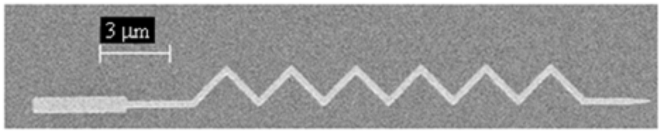
PUBLISHED ONLINE: 7 MARCH 2016 | DOI: 10.1038/NNANO.2016.25

Nanopatterning reconfigurable magnetic landscapes via thermally assisted scanning probe lithography

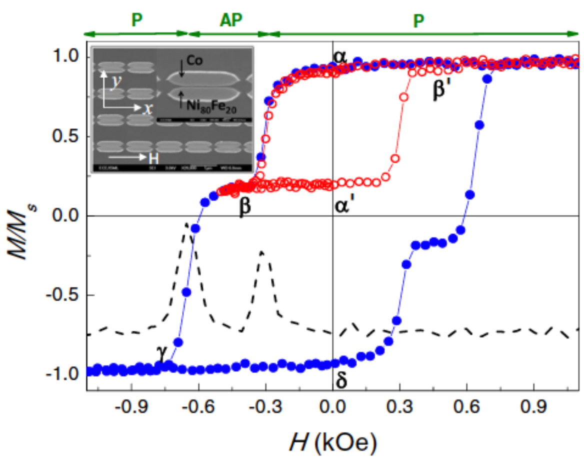
E. Albisetti[1,2]*, D. Petti[1], M. Pancaldi[3], M. Madami[4], S. Tacchi[5], J. Curtis[2], W. P. King[6], A. Papp[7], G. Csaba[7], W. Porod[7], P. Vavassori[3,8], E. Riedo[2,9]* and R. Bertacco[1,10]*

Conventional technologies for magnetic patterning

Top-down: lithography



M. Donolato et al., Adv. Mater. 2010, 22, 2706/2710



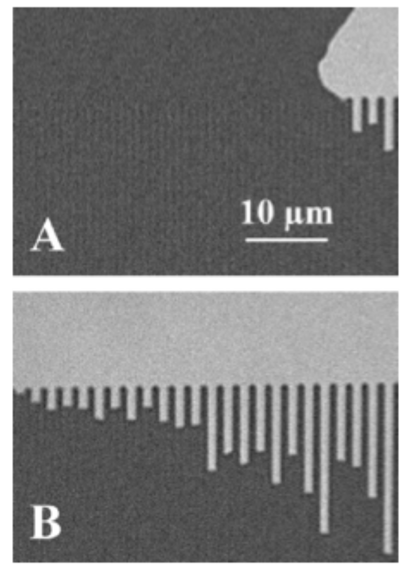
Gubbiotti, G. *et al*. *Phys. Rev. B* **90,** 024419 (2014)

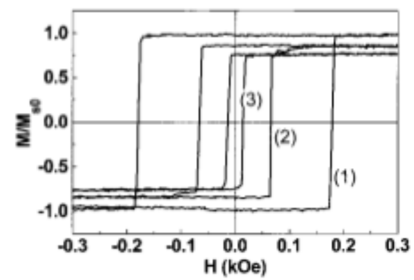
Ion irradiation

Planar Patterned Magnetic Media Obtained by Ion Irradiation

C. Chappert, H. Bernas, J. Ferré, V. Kottler, J.-P. Jamet, Y. Chen, E. Cambril, T. Devolder, F. Rousseaux, V. Mathet, H. Launois

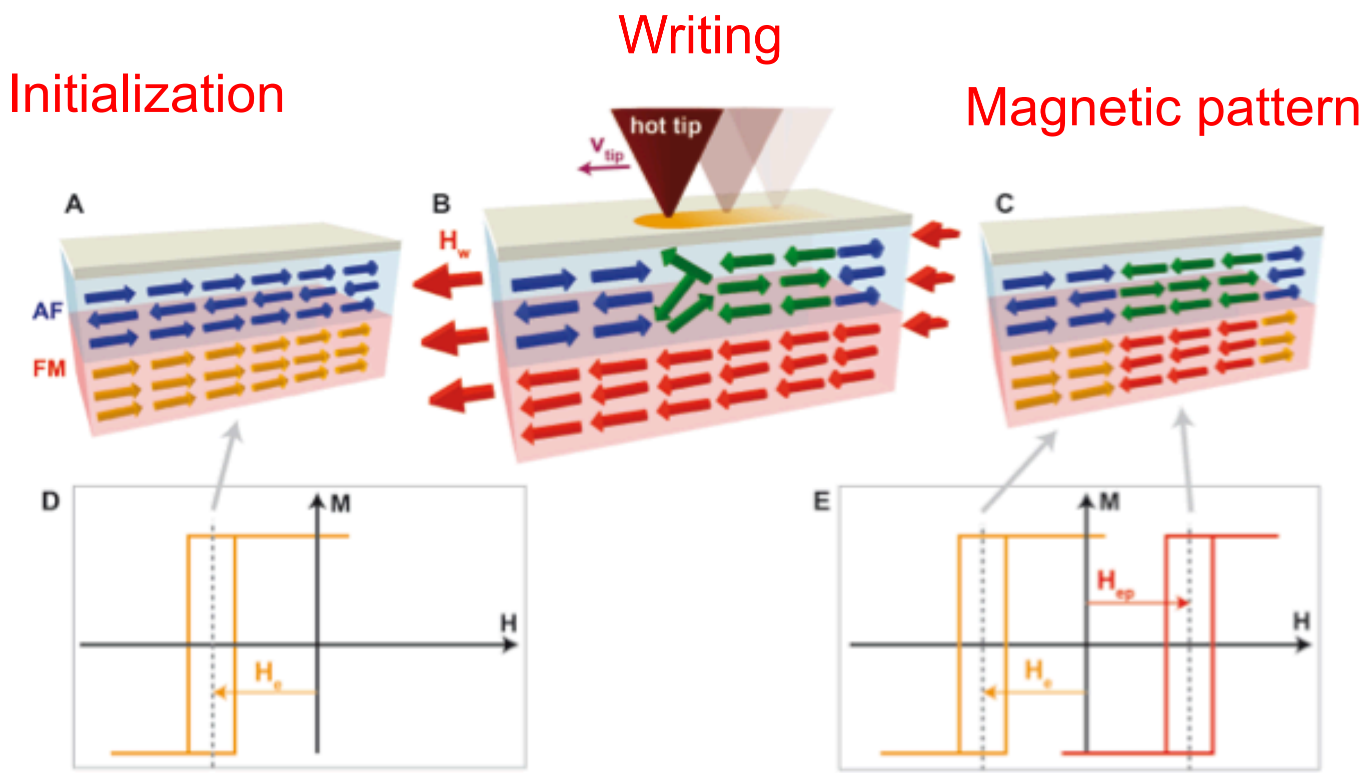
SCIENCE VOL. 280, 19 JUNE 1998





Destructive, irreversible and not suitable to easily produce a vectorial modulation of the magnetic properties within the pattern.

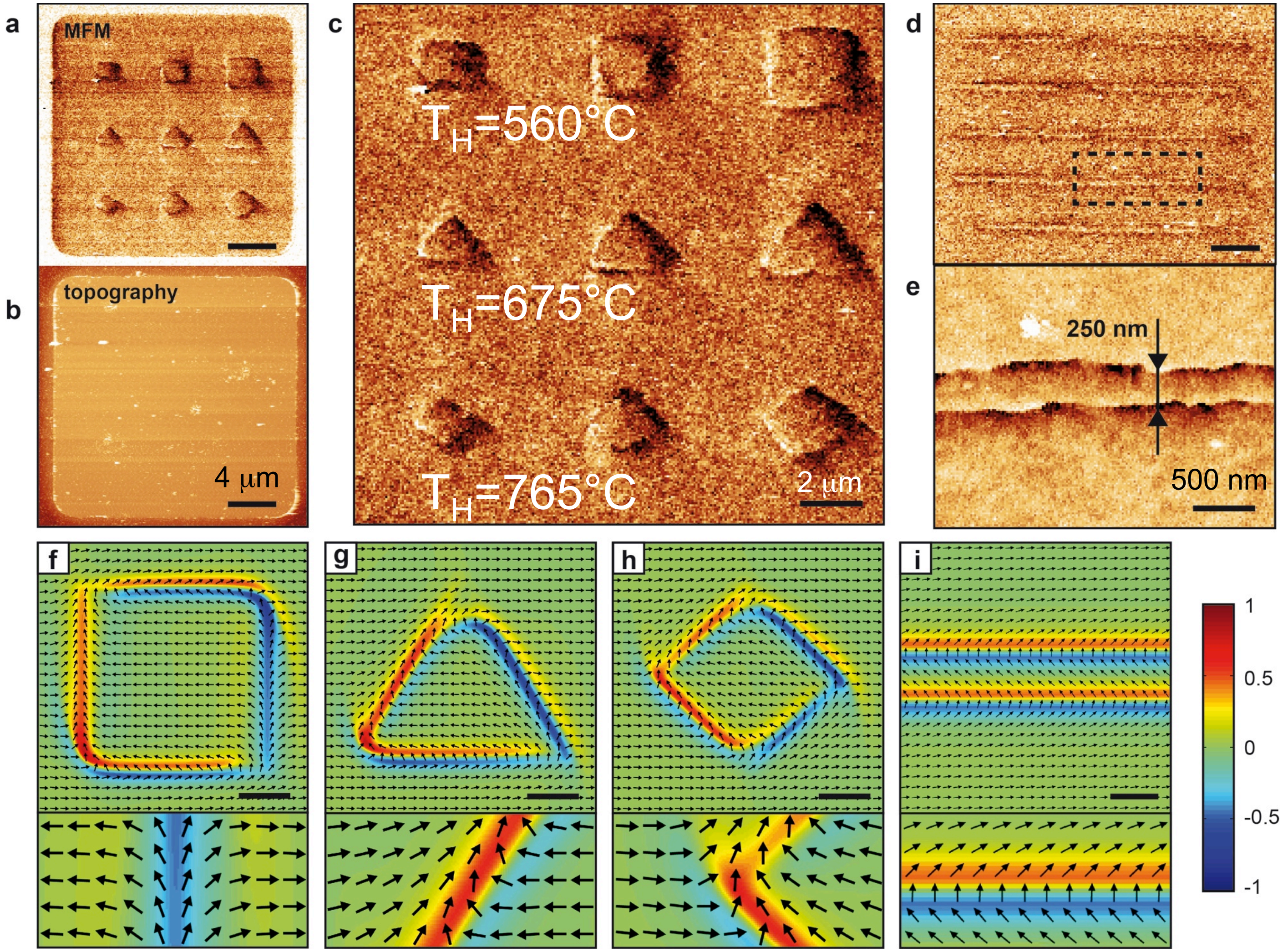
Concept of *tam*-SPL



- ✓ Non destructive and single step
- ✓ Extremely robust upon application of external magnetic fields
- ✓ Fine tuning of magnetic anisotropy for patterning magnetic landscapes
- ✓ Fully reversible (cancel and re-write)

Magnetic patterning via tam-SPL

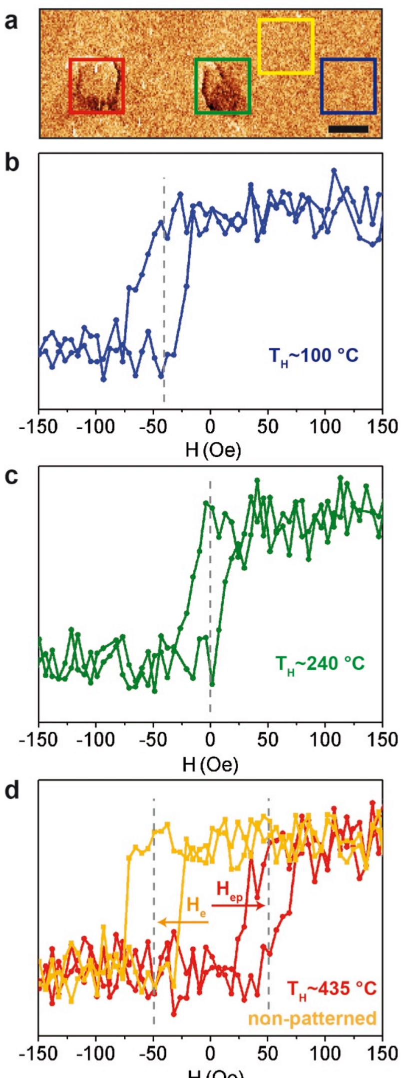
H_W=700 Oe



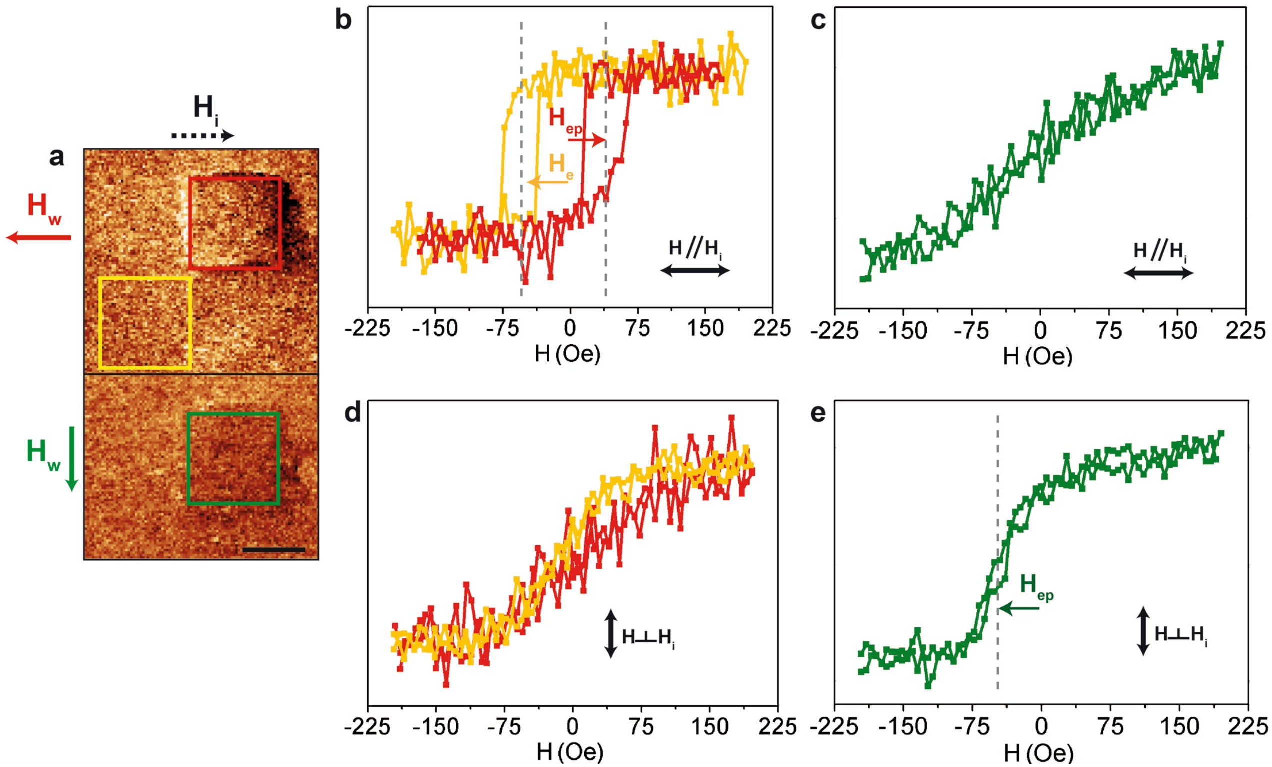
$$F_z = \mu_0 m_z \cdot (\nabla H_z)_z$$

Tunability

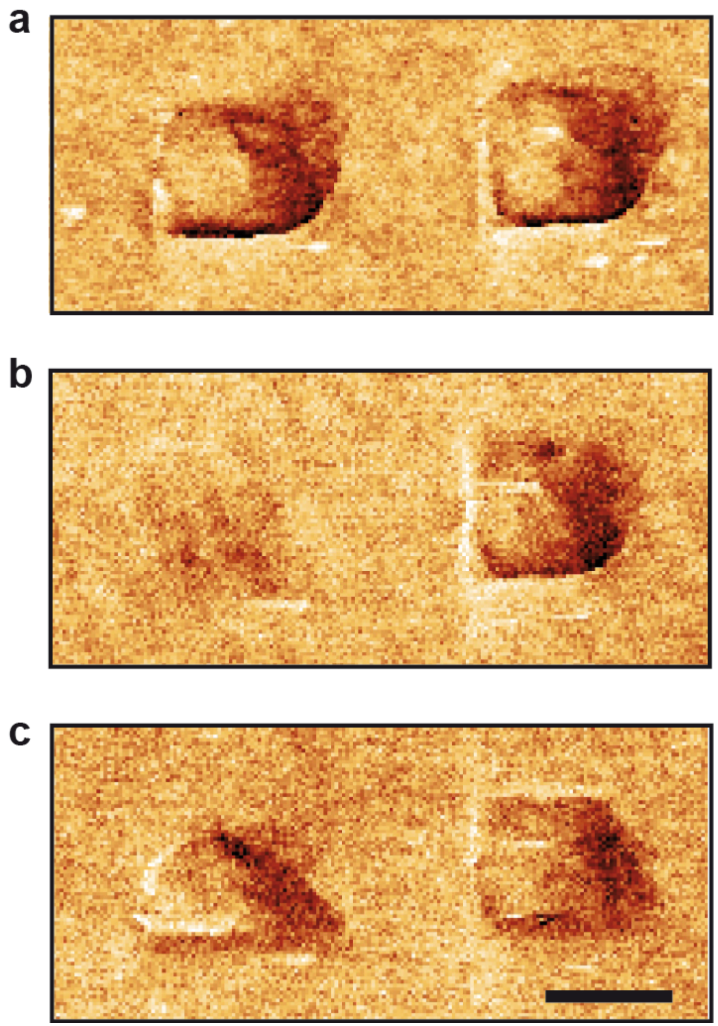
Tuning the exchange bias field



Tuning the exchange bias direction



Rewritability



T_H=600°C — writing — H_w ← — H_W=700 Oe

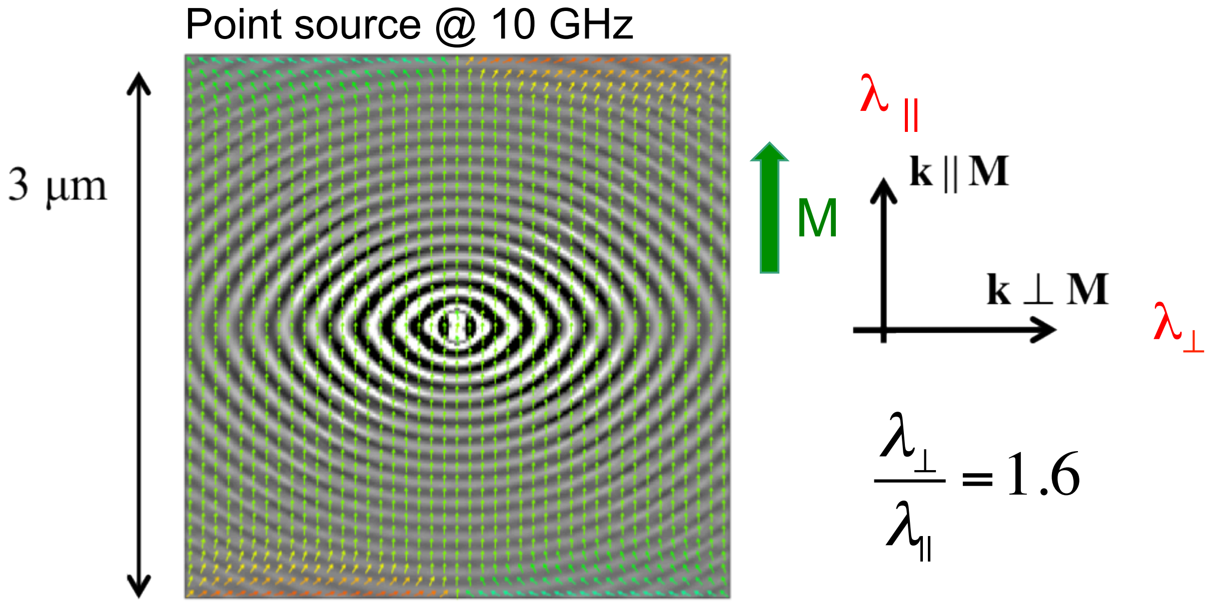
T_H=600°C — erasing — H_{er} → — H_{er}=-700 Oe

T_H=470°C — re-writing — H_w ← — H_W=700 Oe

Endurance & rewritability

An example of application to magnonics

Anisotropic propagation of spin-waves (OOMMF simulation)

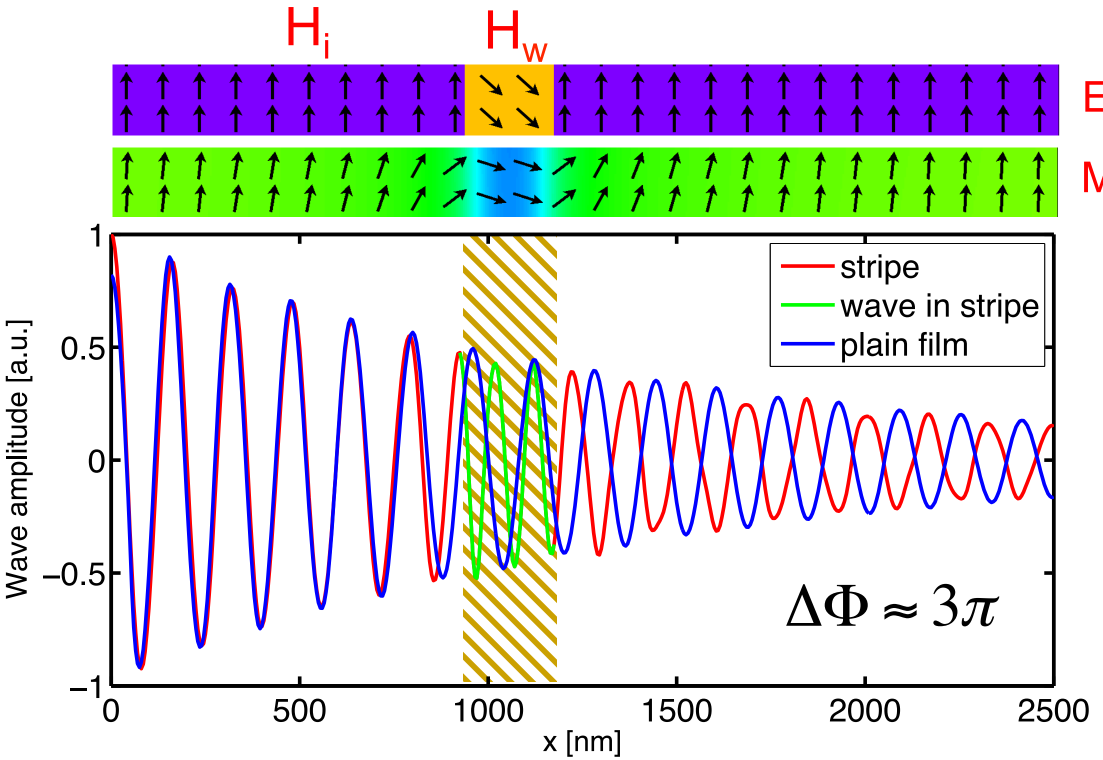


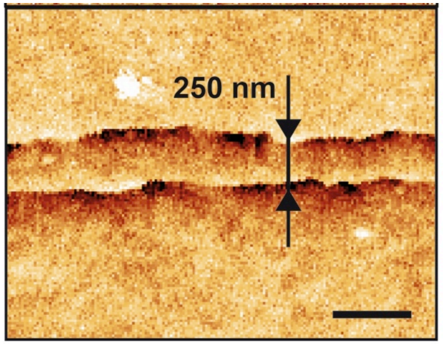
$$\frac{\lambda_\perp}{\lambda_\parallel} = 1.6$$

In terms of the refractive index seen by magnons:

$$\frac{n_\parallel}{n_\perp} = 1.6$$

How to implement a phase shifter



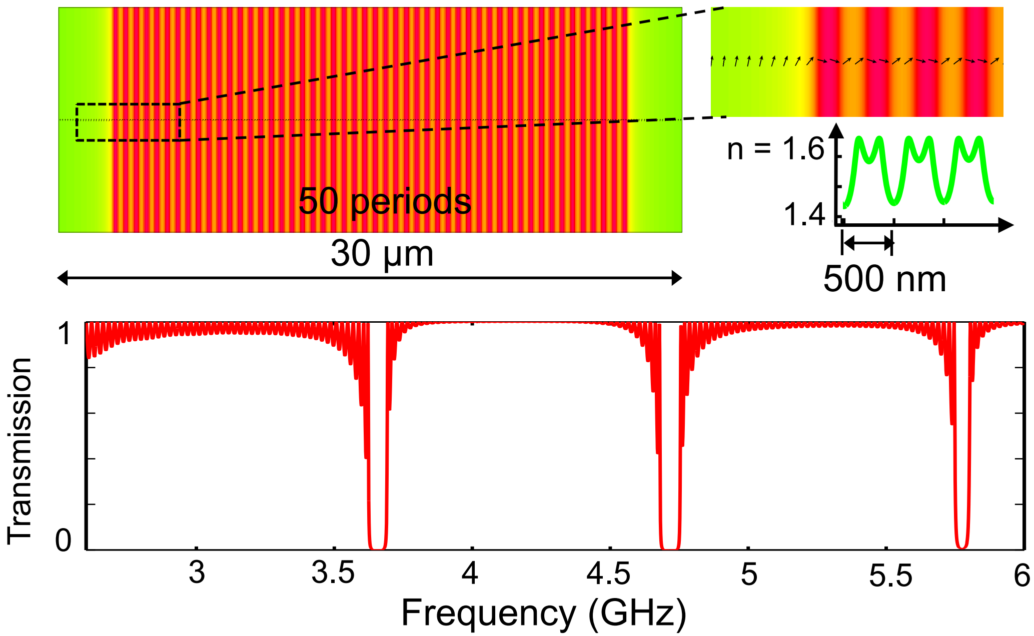


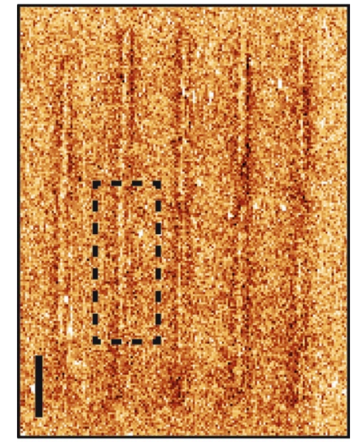
The basic building block of a Mach-Zehnder SW interferometer, where one of the two branches contains a phase shifter.

Magnonic crystals (MCs) patterned via tam-SPL

OOMMF

one-dimensional transfer matrix method

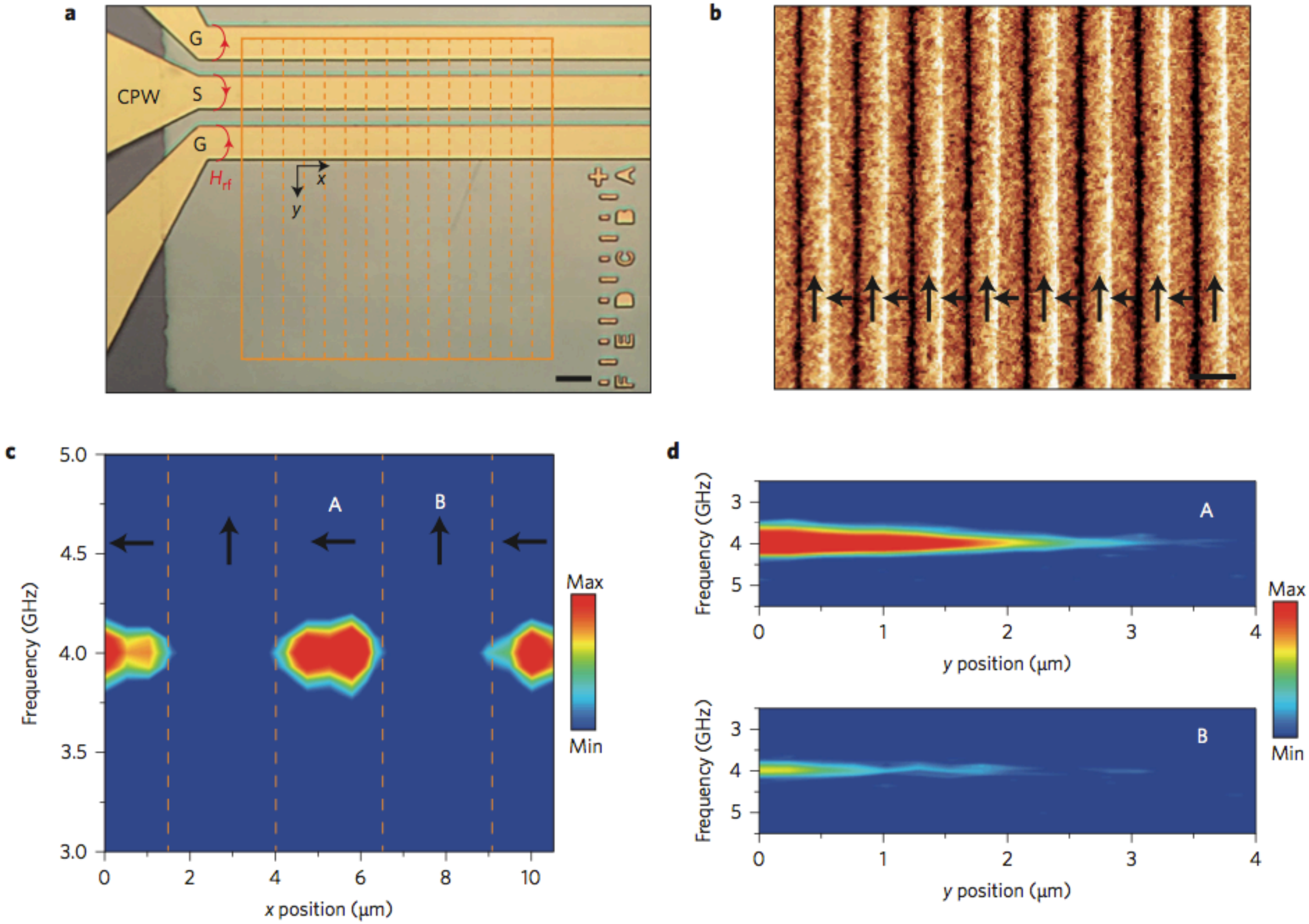




Advantages

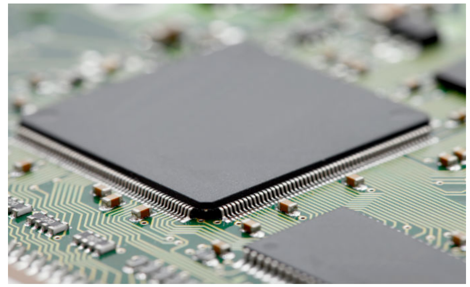
1. MCs patterned in a continuous film: lower SW attenuation expected.
2. Fine tailoring of magnetic anisotropy or refractive index easily implemented
3. AFM fabrication: suitable for concept development
4. Flexibility and rewritability: ideal tool for scientists
5. Reprogrammability via external magnetic fields

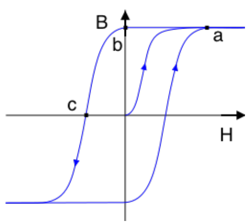
Selective excitation and propagation of SWs in patterned magnetic tracks



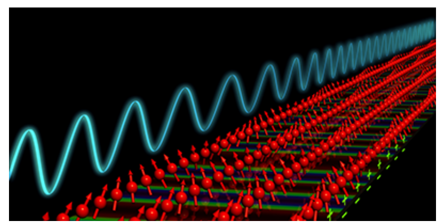
Plenty of room ?

CMOS

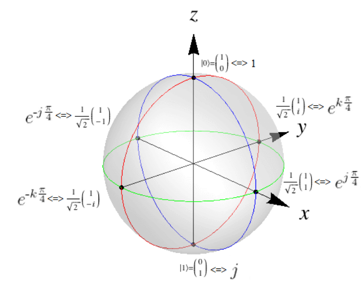




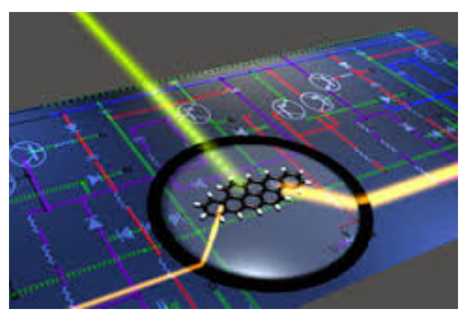
Non volatility
(memory)



Coherent and non-linear phenomena
(wave computing)



Bloch sphere
(quantum)



Photonics

Conclusions

Thank you for your attention!