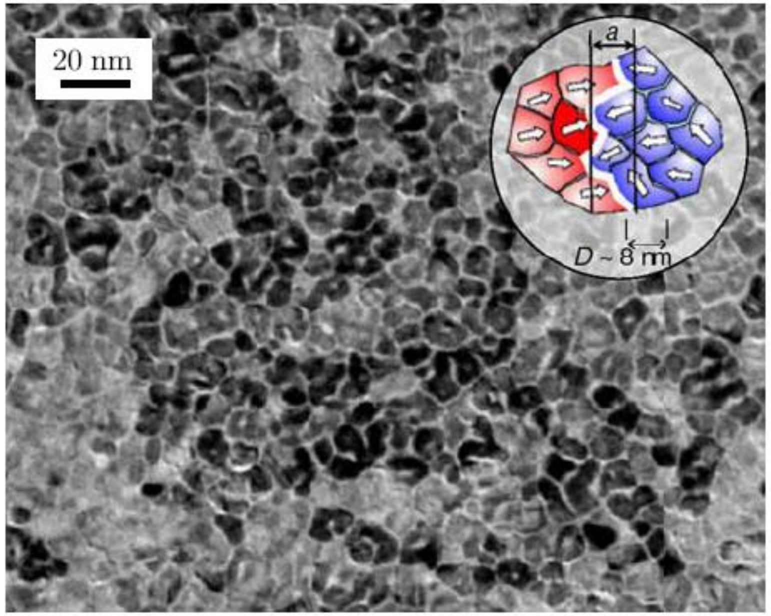
13

Spintronics

Some basic questions looking at this picture



CoCrPt recording layer

1) Why every grain has a magnetic moment?
2) How is the material chosen?
3) Why is every grain magnetically decoupled from the neighbors?
4) Why is the grain magnetization pointing in one specific direction?
5) Why does the magnetization direction change from grain to grain?
6) Why does the grain magnetization not fluctuate in time?
7) …

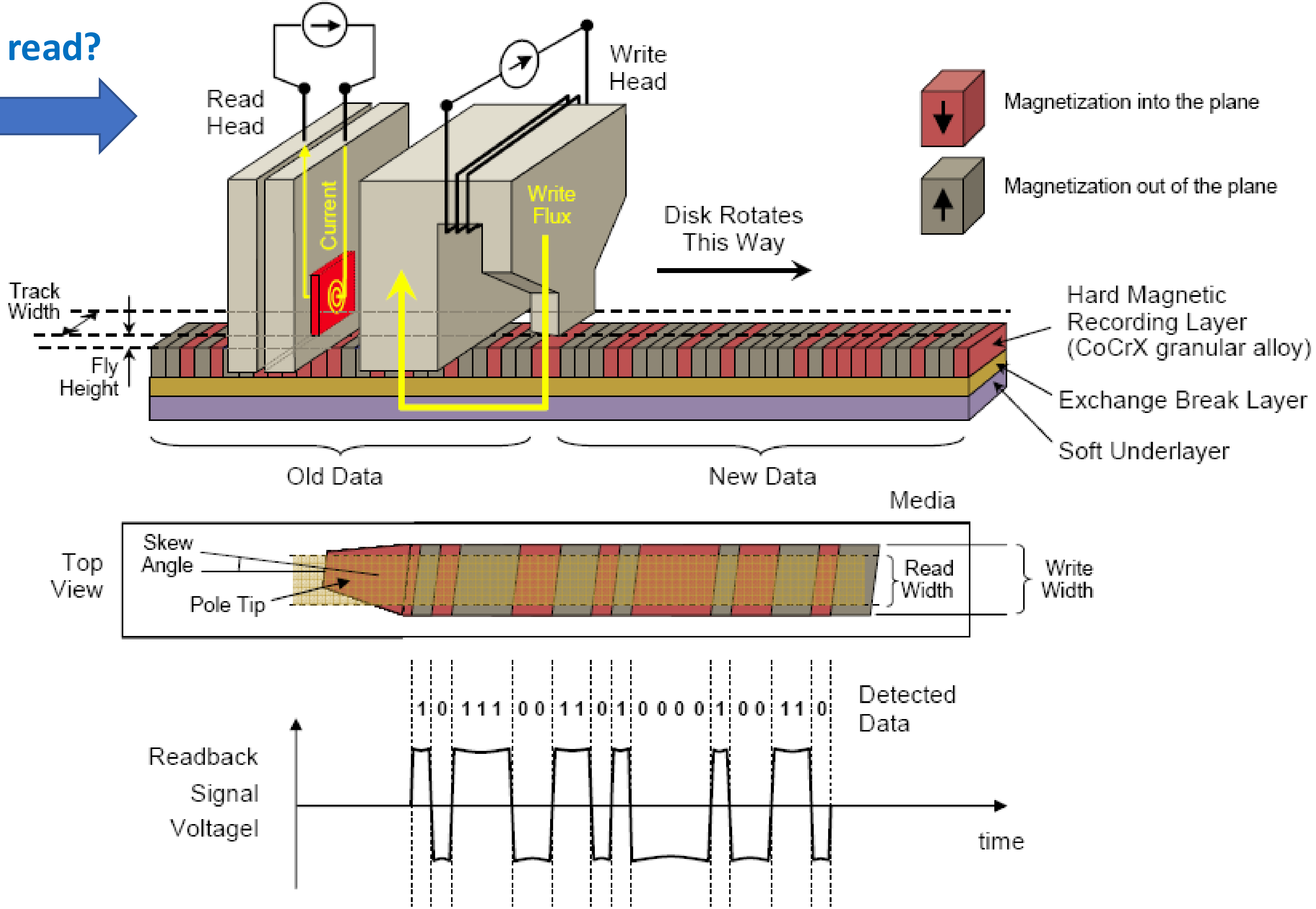
Atomic magnetism + Exchange coupling

Breaking of exchange coupling

Magnetic anisotropy:
- Crystalline
- Shape

The recording mechanism: a condensate of concepts

How to read?



Information storage and processing: electronics *vs* spintronics

1) Information storage

HDD: hard disk drive

High density magnetic storage

SSD: solid state drive (Flash memory)

Non-volatile memory

2) Fast access memory: temporary workspace in your device

Dynamic random-access memory (**DRAM**): random-access memory that stores each bit of data in separate capacitors within an integrated circuit (=> Single electron transistor to minimize the size of the capacitor)

Since the capacitors used in DRAM lose their charge over time, DRAM must refresh approximately 20 times a second

↓

Volatile

Spintronics: Combining electron charge and spin

Magnetic random-access memory (MRAM) never requires a refresh.
The memory will keep the information also with the power turned off

Much lower power consumption compared to DRAM

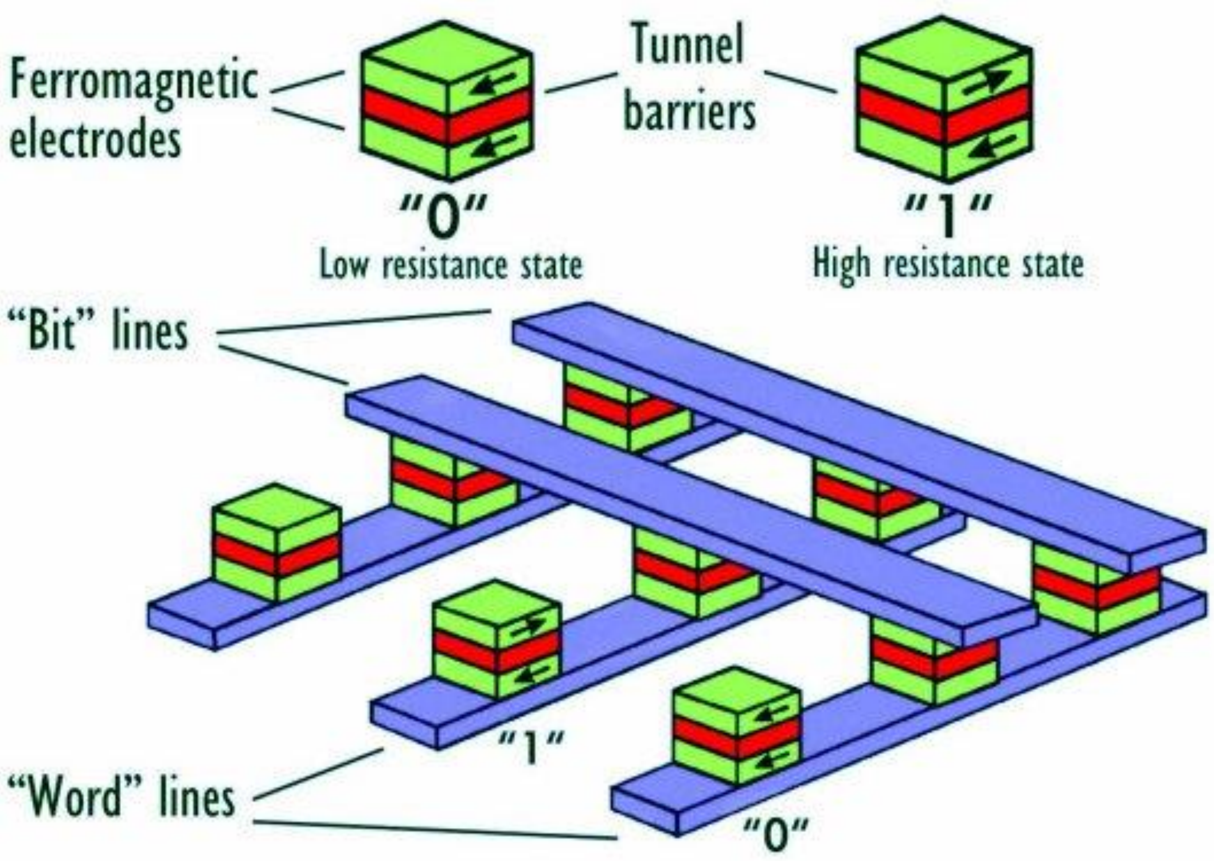
However, with storage density and capacity orders of magnitude smaller than a hard disk (HDD), MRAM is useful in applications where moderate amounts of storage with a need for very frequent updates are required

In production

EVERSPIN® TECHNOLOGIES

https://www.everspin.com/

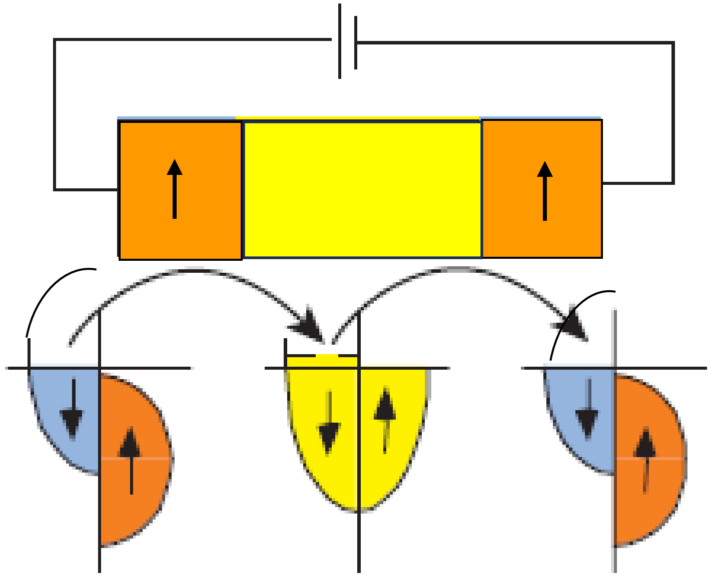
Ferromagnetic (FM) - nonmagnetic (NM) - ferromagnetic (FM) junction



Science **282**, 1660 (1998); Nat. mater. **6**, 813 (2007); doi.org/10.1016/j.mattod.2017.07.007

Spin transport

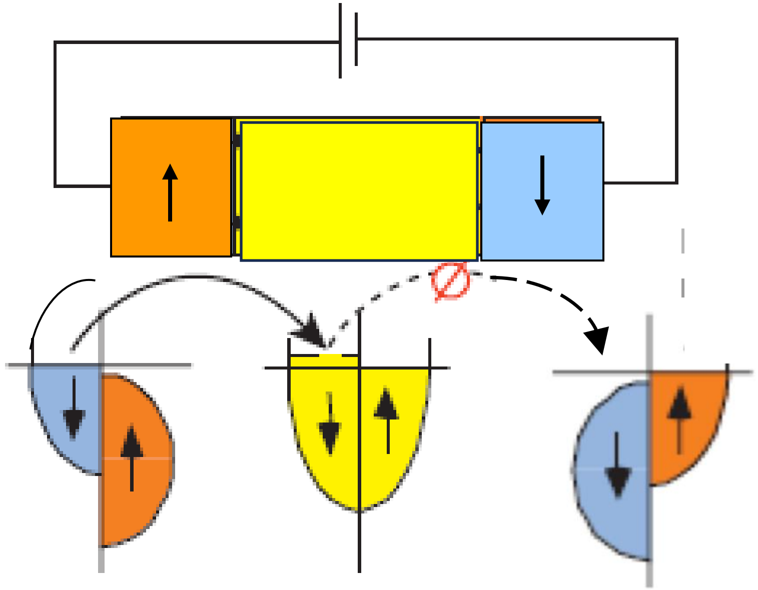
1



Available free states with the same spin

Low resistance

0

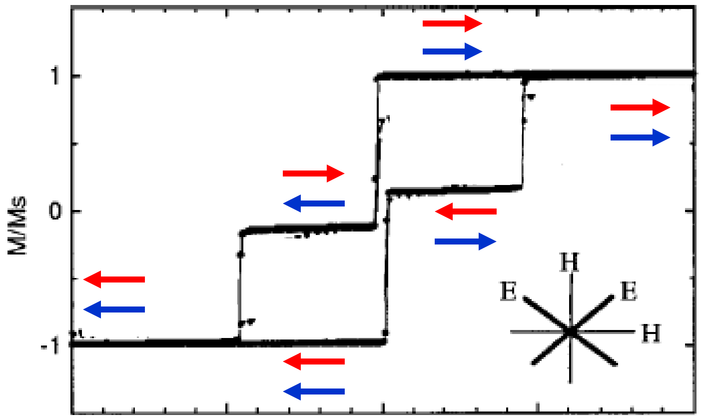


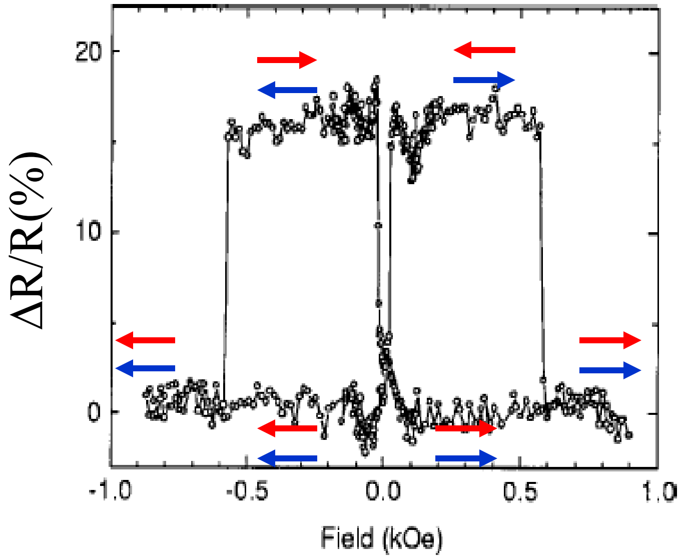
Absence of free states with the same spin

High resistance

Science **282**, 1660 (1998); Nat. Mater. **6**, 813 (2007)

Magnetoresistance

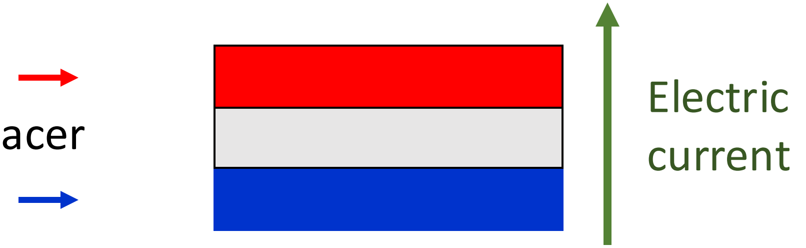




Pinned FM

metallic or insulating NM spacer

Free FM



Pinned layer: layer with high reversal field (i.e., high MAE)

Free layer: layer with low reversal field (i.e., low MAE)

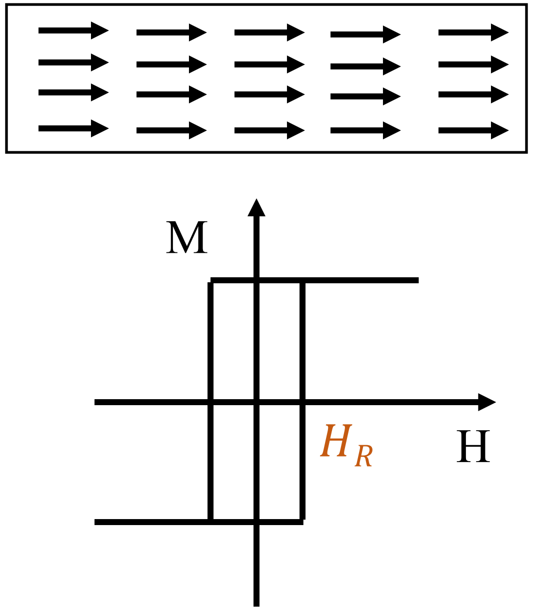
$$\frac{\Delta R}{R} = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}}$$

High (low) resistance for anti-parallel (parallel) alignment of the magnetization in the two ferromagnetic layers

Role of the non-magnetic spacer:
The atom spins are coupled by inter-atomic exchange
In non-magnetic materials, S = 0 thus $\mathcal{H}_{exc} = 0 \rightarrow$
decoupling of free and pinned layer

How to make the pinned layer: Exchange bias field

FM: ferromagnetic material
AFM: antiferromagnetic material

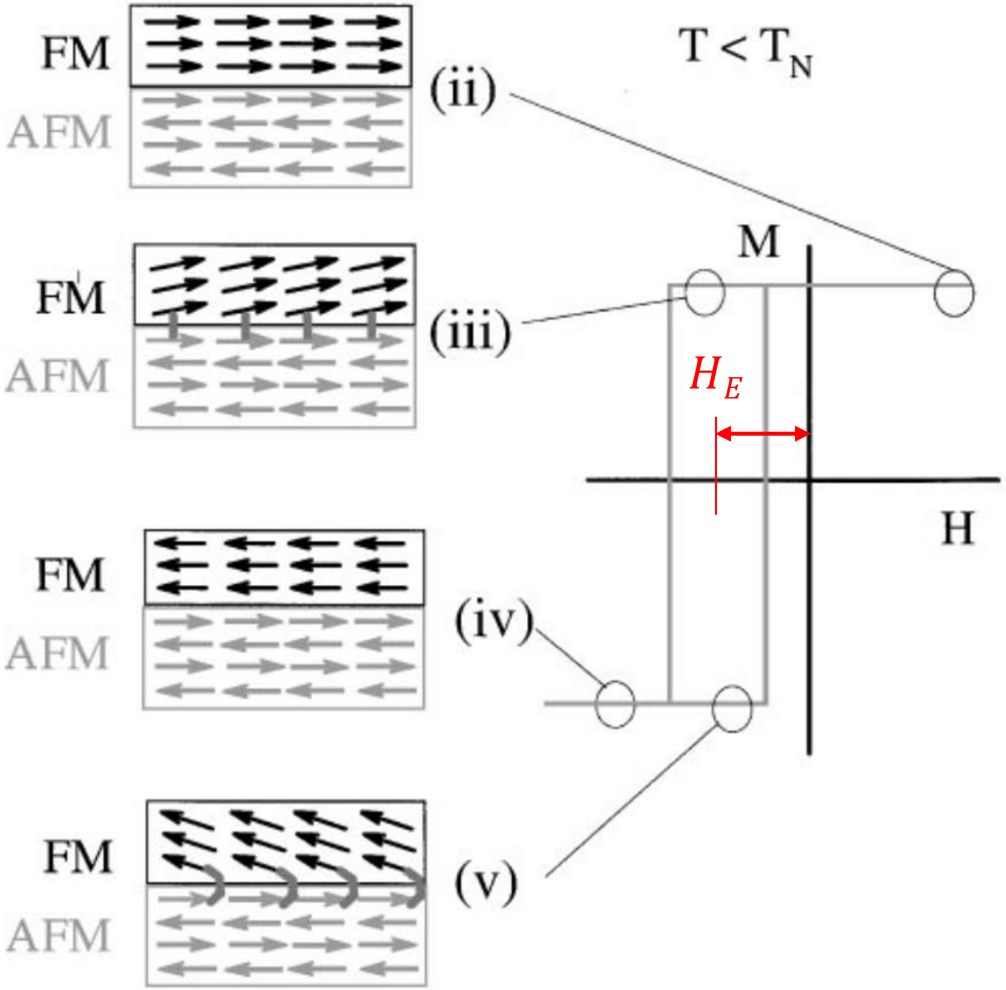


In a FM layer, the magnetization reverses at a field H_R (reversal or coercive field)

The magnetic field required to reverse the pinned layer becomes $H_R + H_E$

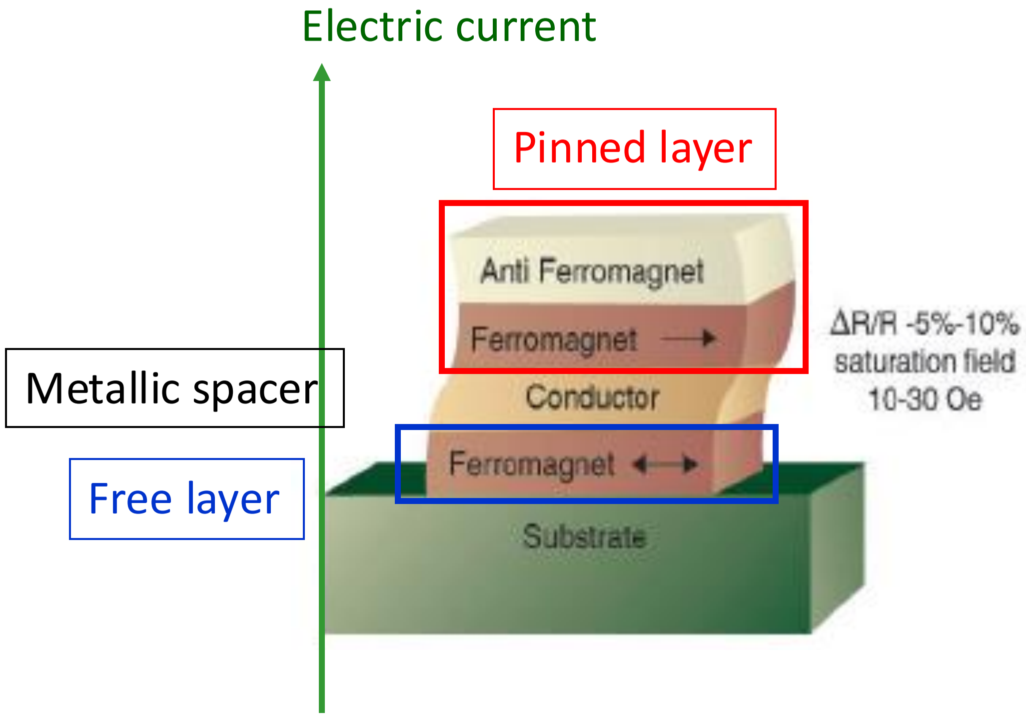
Due to the exchange interaction at the FM-AFM interface, the field necessary to orient the FM layer parallel to the direction of the surface AFM spins is reduced compared to the field necessary to force the anti-parallel alignment by an amount equal to H_E

H_E : exchange bias field
It describes the shift of the hysteresis curve



J. Magn. Magn. Mater. **192**, 203 (1999)

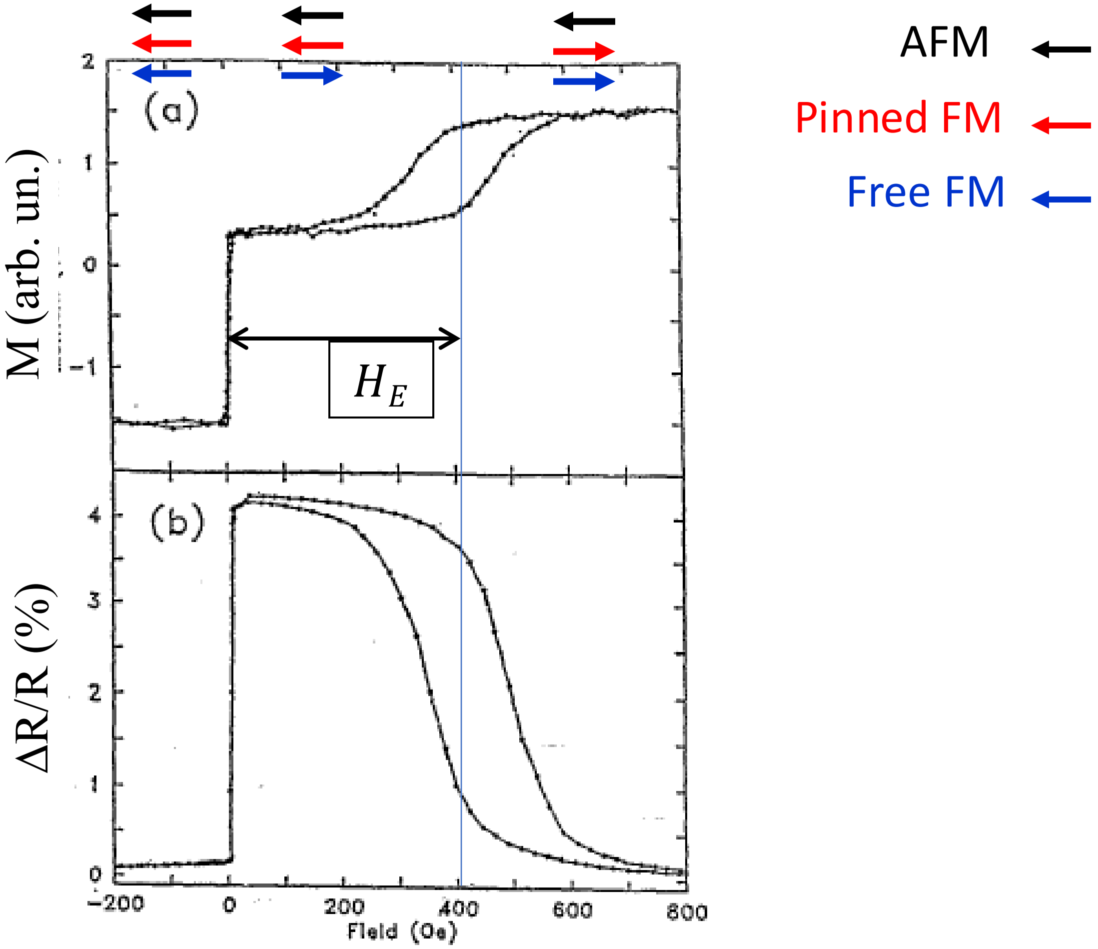
GMR: giant magneto-resistance


Electric current

Pinned layer

Metallic spacer

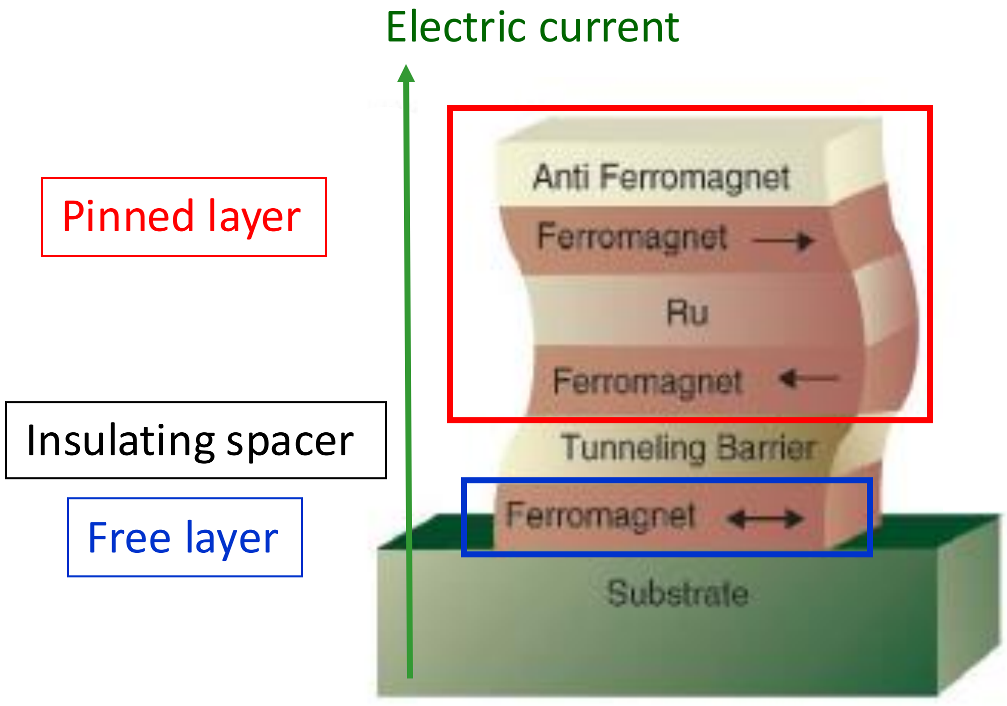
Free layer



J. Appl. Phys. **69**, 4774 (1991)

The electric resistance depends on the respective spin orientation of the two FM layers:
Low ⟶ parallel alignment
High ⟶ anti-parallel alignment

MTJ: magnetic tunnel junction and MTR

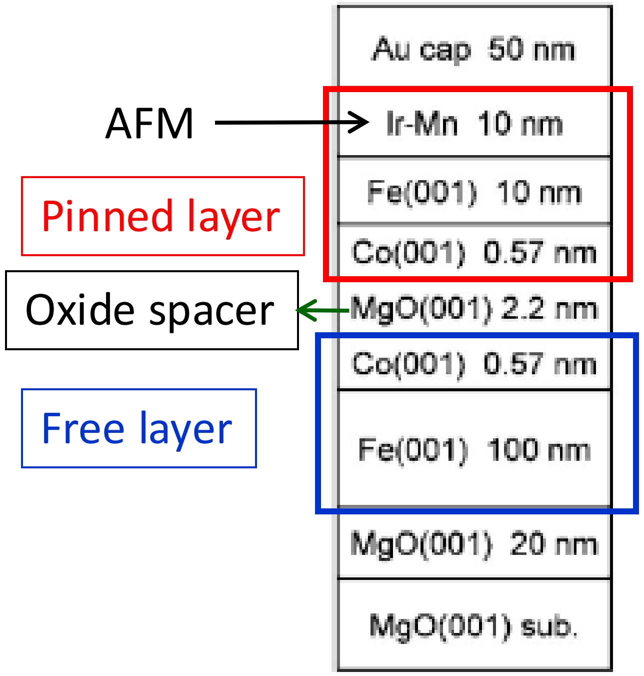


Electric current

Pinned layer

Insulating spacer

Free layer

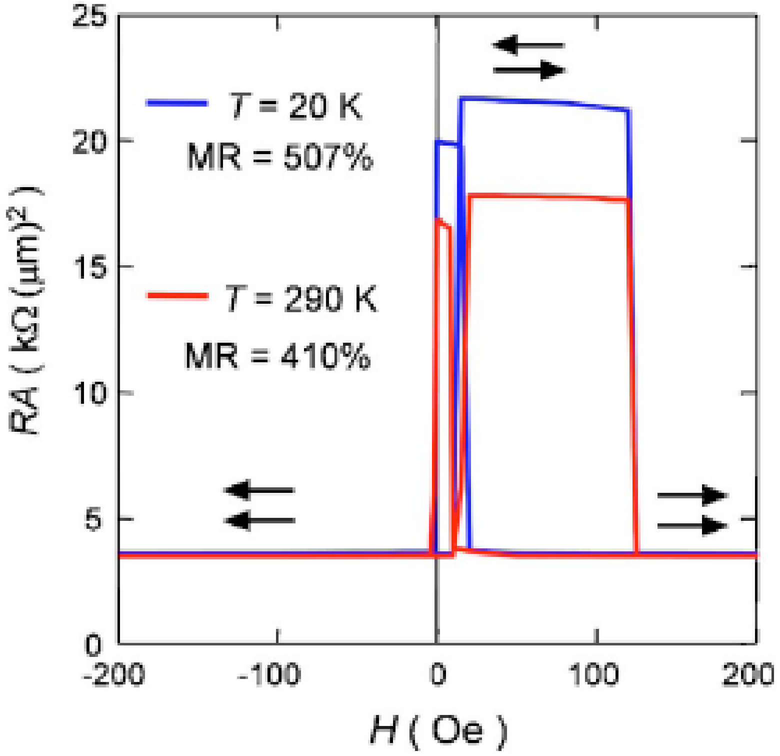


AFM

Pinned layer

Oxide spacer

Free layer



Improved performances with respect to GMR:
In the insulator, no spin-flip due to spin-electron scattering, spin-polarized current is preserved

And also thanks to:

1) precise control of layer thickness
2) high control of crystallographic structure and orientation
3) optimum choice of the materials

Appl. Phys. Lett. **89**, 042505 (2006)

Transmission: Role of the spacer thickness

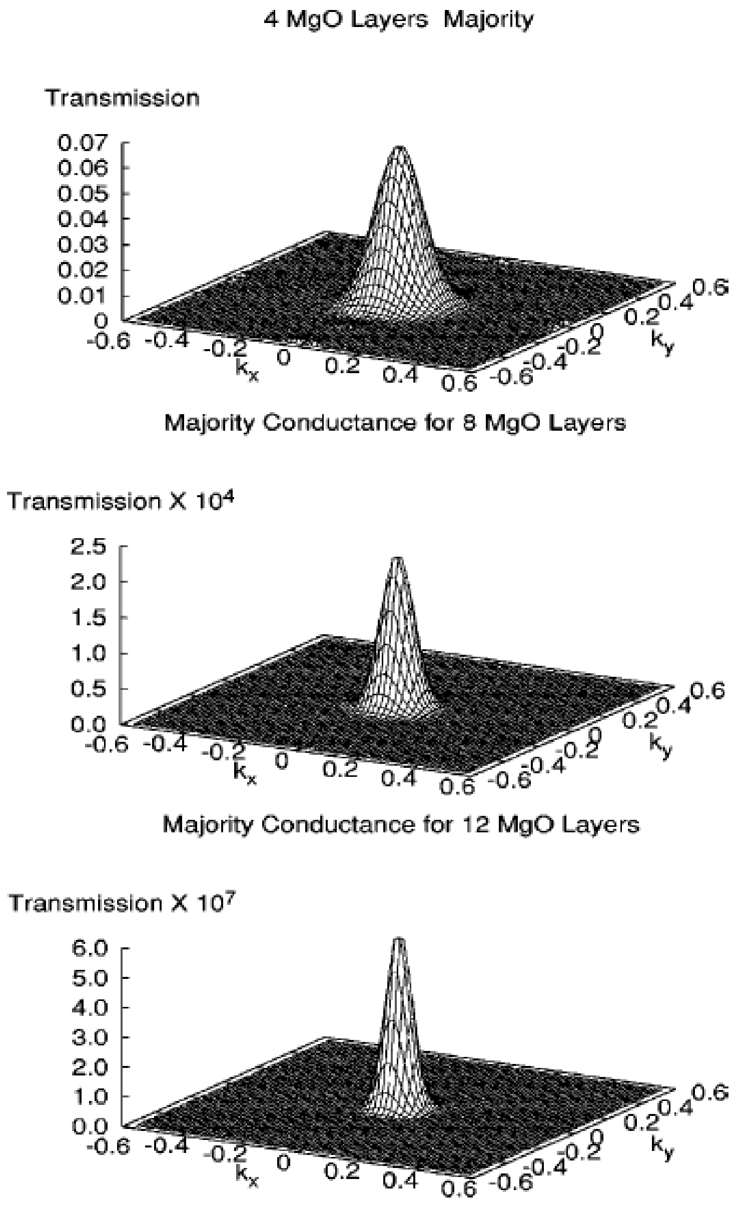


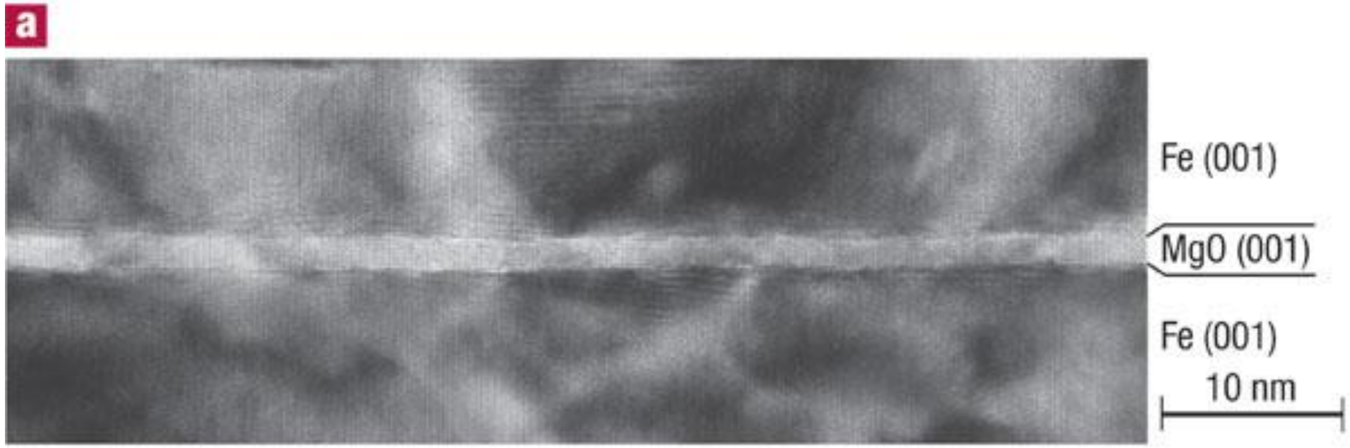
FIG. 6. Majority conductance for 4, 8, and 12 layers of MgO. Units for k_x and k_y are inverse bohr radii.

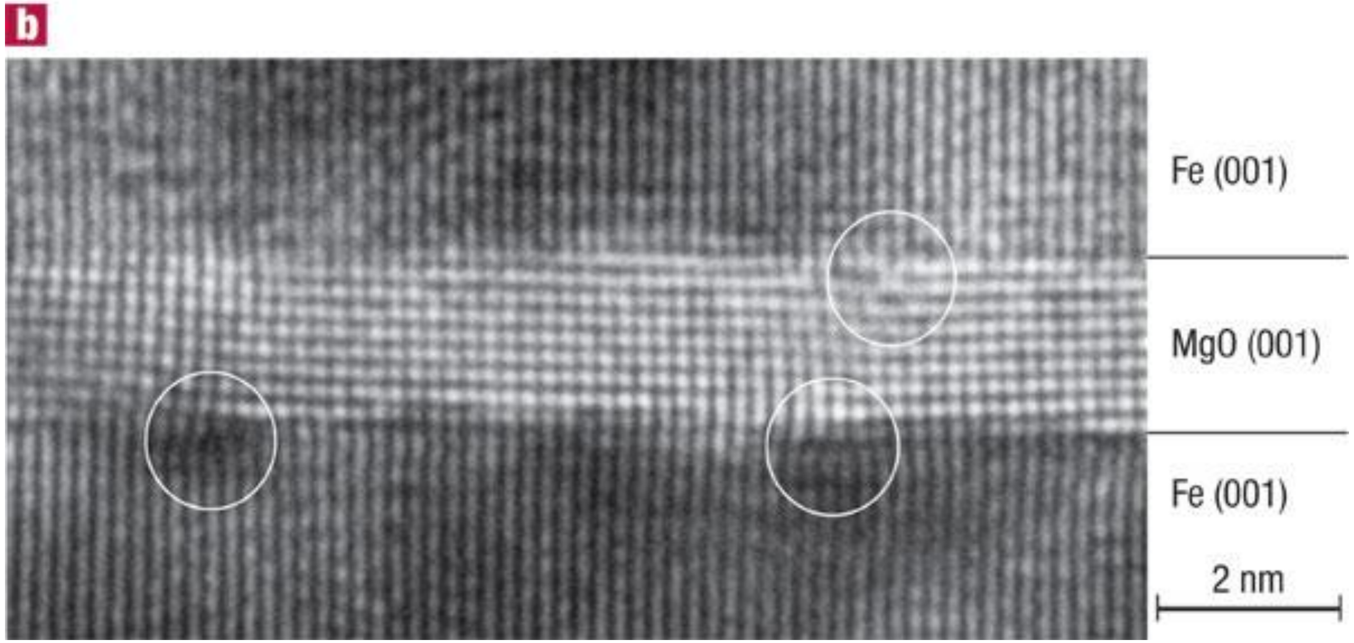
T = transmission through the tunnel barrier

$$T \propto \exp\left(-2d\sqrt{\frac{2m(\Phi - E_F)}{\hbar^2} + k_\parallel^2}\right)$$

Transmission strongly dependent on MgO thickness d
→
need of high control of MgO roughness to have flat interfaces and thus uniform current

Epitaxial heterostructures for MTJ





High-resolution TEM images

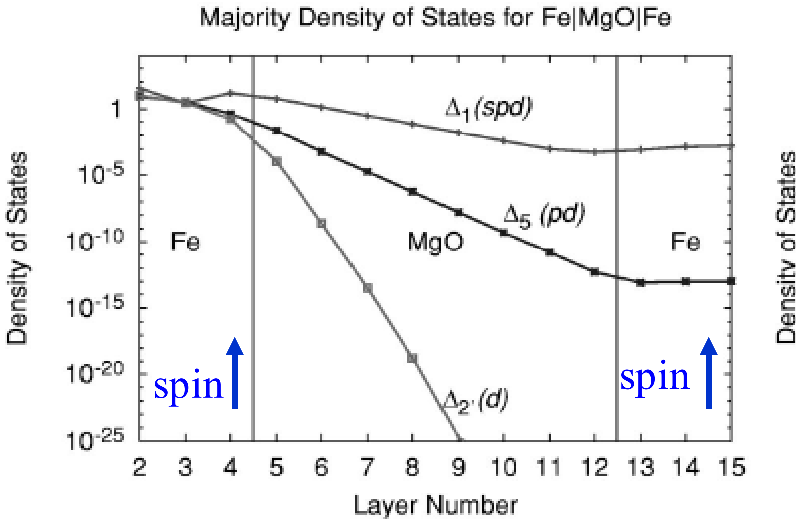
Fe(001)/MgO(001)(1.8 nm)/Fe(001) structure

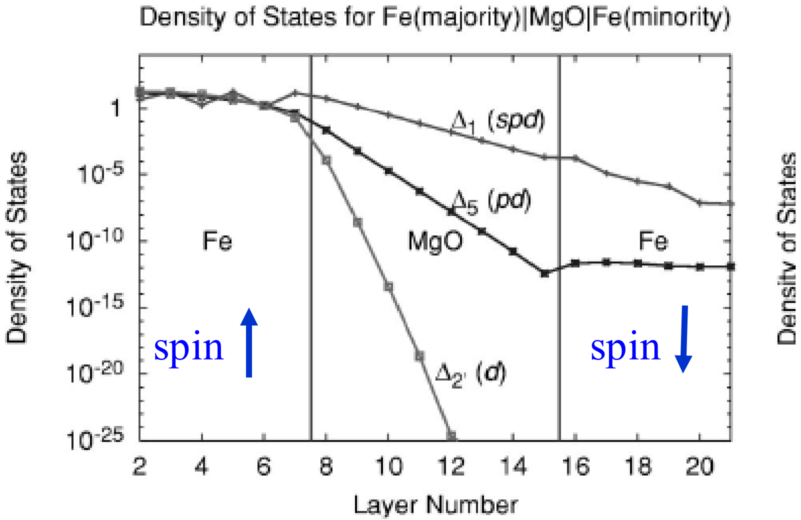
b is a magnification of **a**.
Lattice dislocations are encircled.

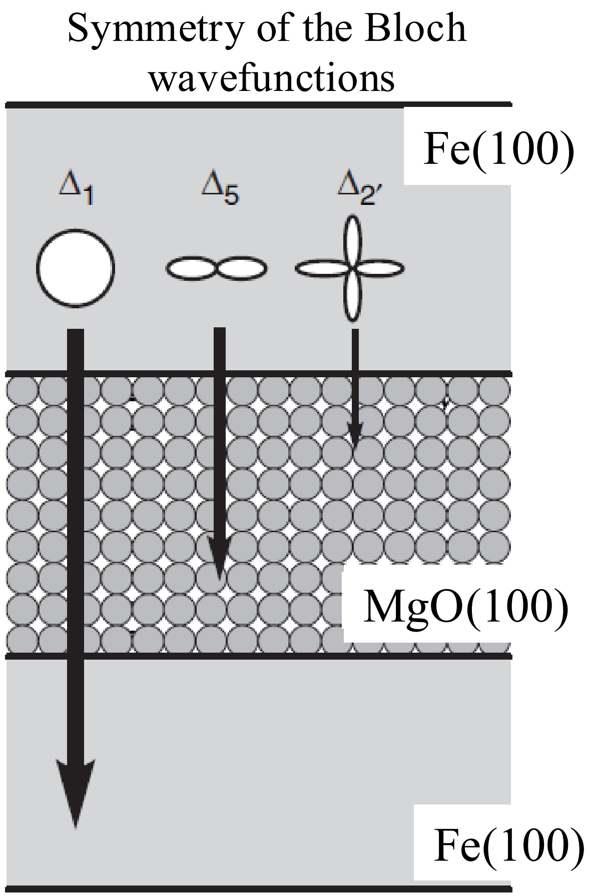
Very good control of thickness and orientation can be achieved

Nature Materials **3,** 868–871 (2004)

Role of barrier crystal structure and wavefunction symmetry







The tunneling conductance depends strongly on the symmetry of Bloch states in the FM electrodes and of the evanescent states in the barrier.
Bloch states of different symmetry decay at different rates within the barrier.

Δ_1 : totally symmetric wave function with respect to the direction perpendicular to the tunnel barrier: s, p_z, d_{z^2}

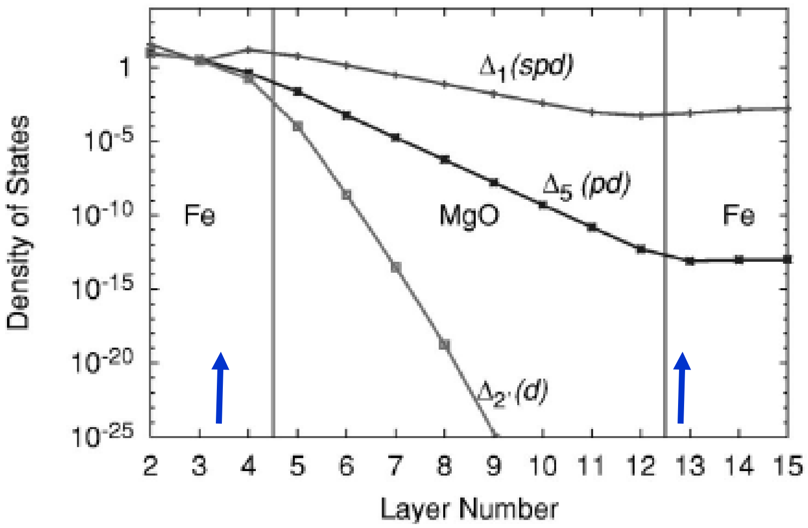
Δ_1 are slowly decreasing evanescent states for majority spins.

Transmission depends on the electronic state symmetry, materials and crystal structure
→ optimization of material crystal structure to optimize the spin junction performance

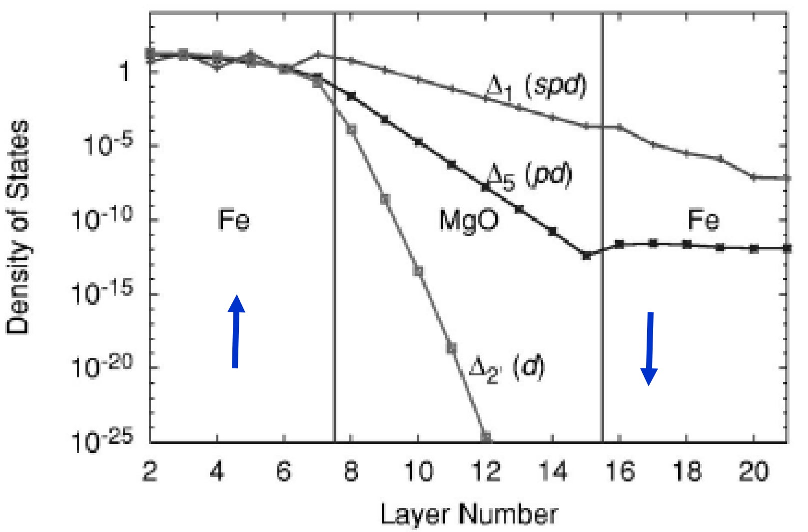
Phys. Rev. B **63**, 054416 (2001); Phys. Rev. B **70**, 172407 (2004); Sci. Technol. Adv. Mater. **9,** 014106 (2008);
Encyclopedia of Materials: Science and Technology ISBN: 978-0-0804-3152-9

Role of the magnetic layer composition

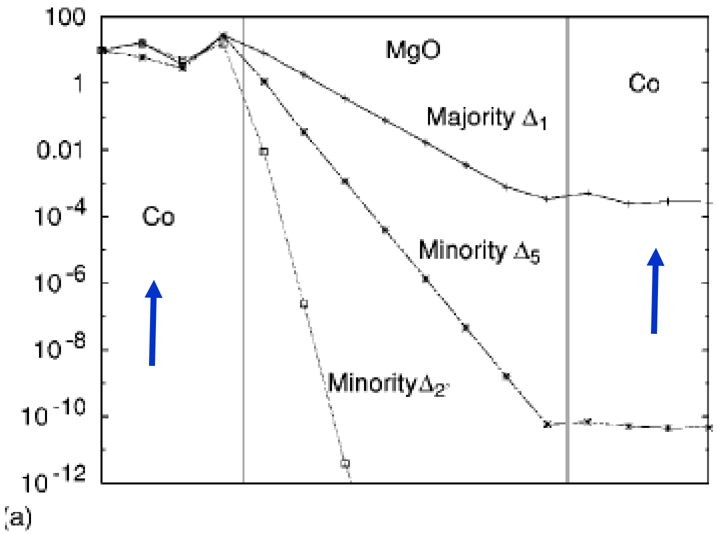
Fe/MgO/Fe

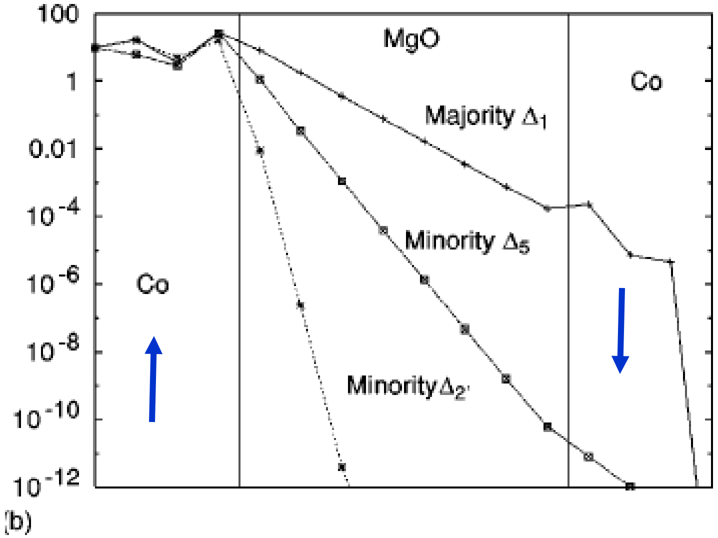


Density of States for Fe(majority)|MgO|Fe(minority)



Co/MgO/Co





Total reflection of tunneling electrons for antiparallel spin alignment in Co/MgO/Co junction

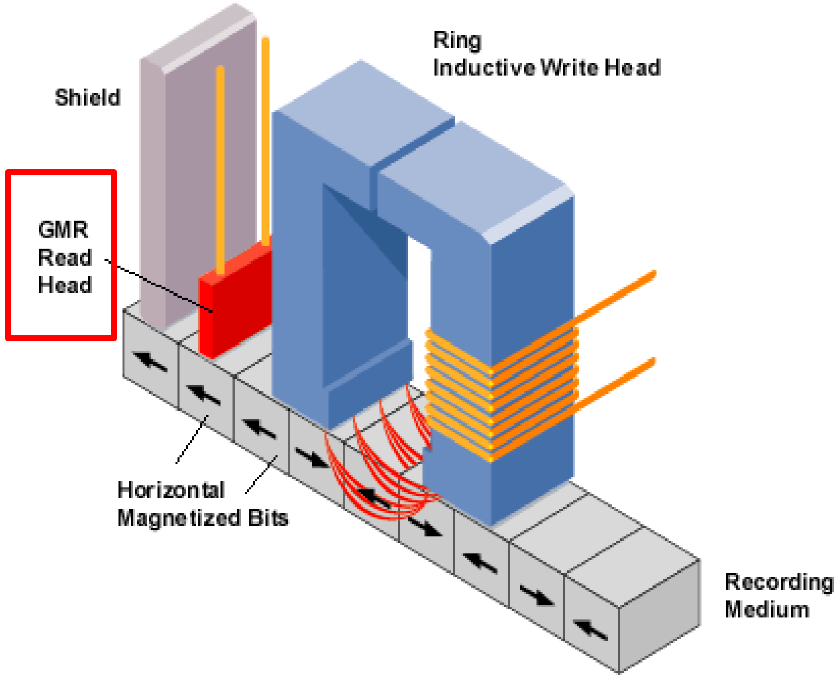
→

Higher TMR in Co/MgO/Co than in Fe/MgO/Fe junction

The DOS and band structure of the two electrodes determine the TMR

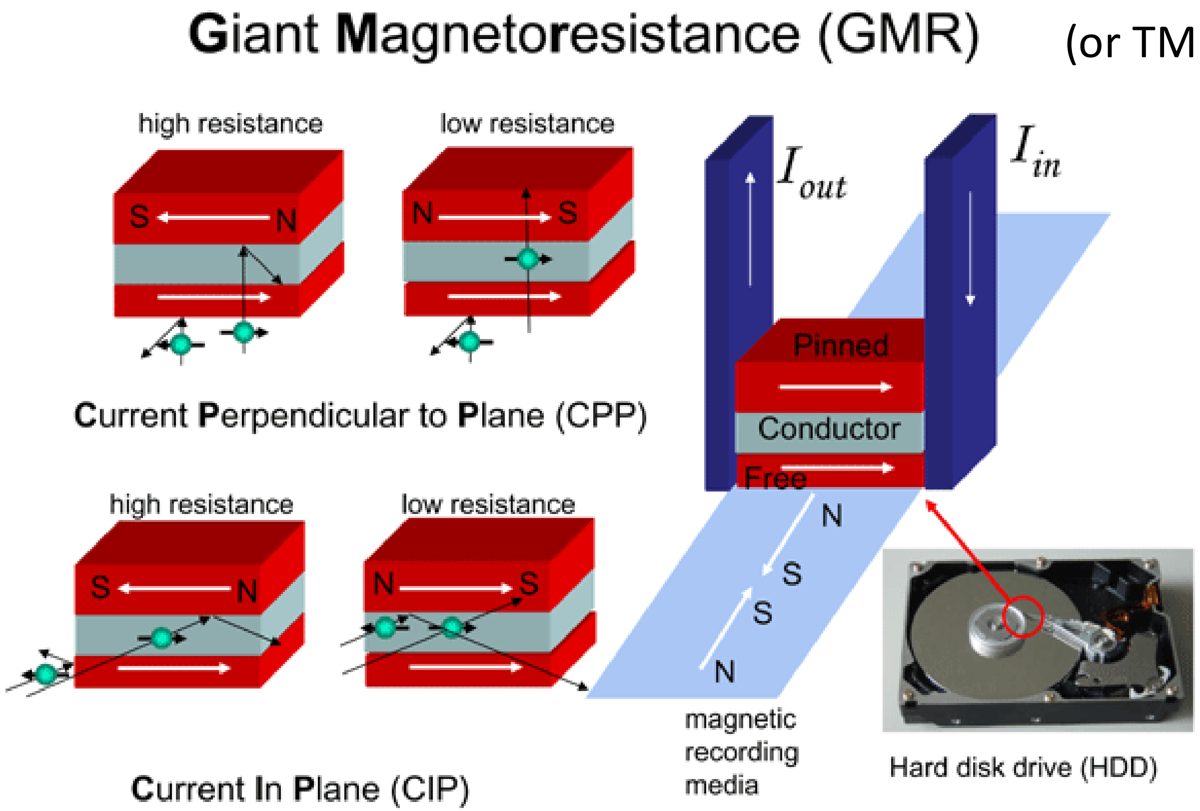
Phys. Rev. B **63**, 054416 (2001)
Phys. Rev. B **70**, 172407 (2004)

Reading-writing head in HDD



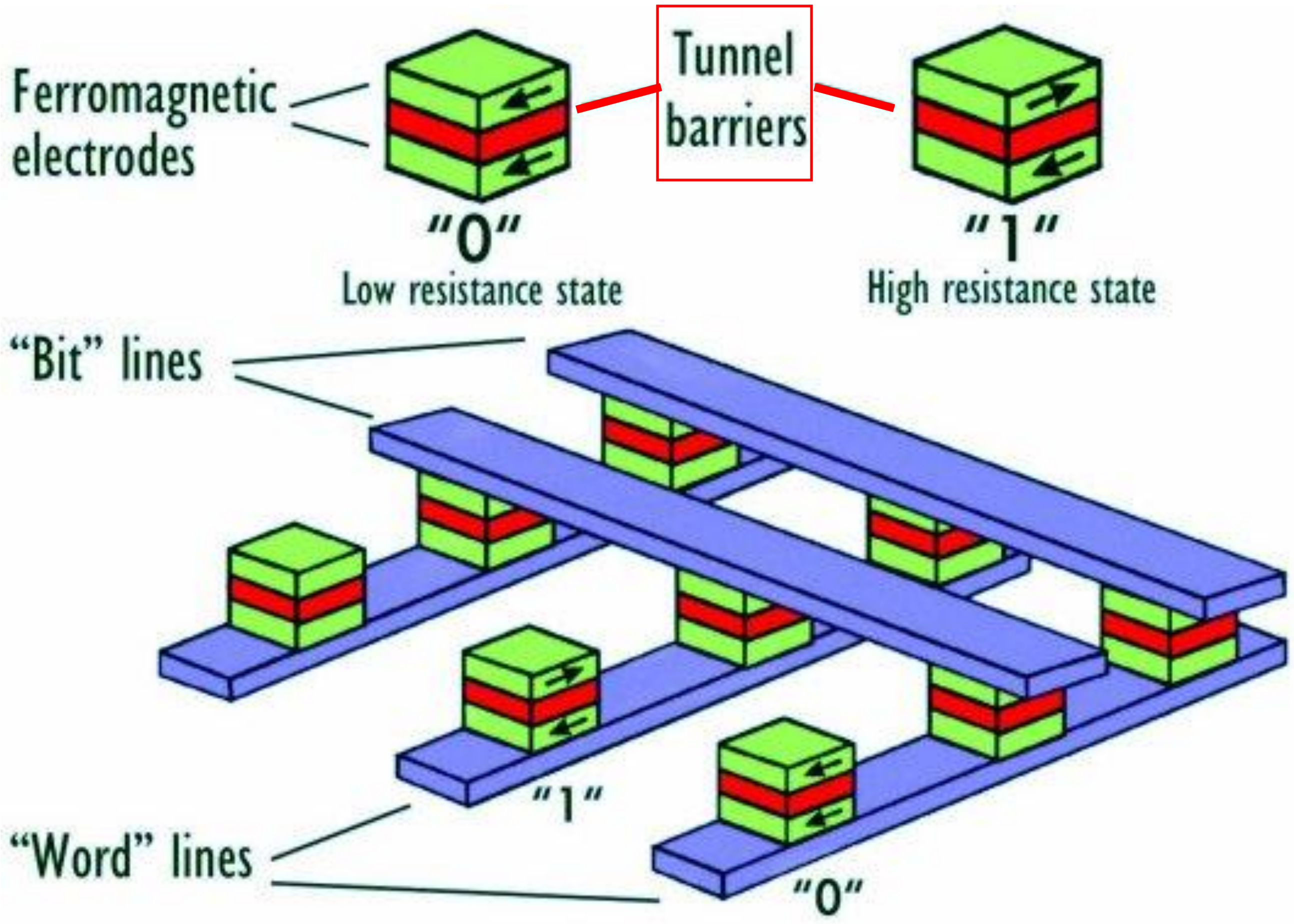
Writing:
the head stray field defines the magnetization direction of the recording medium

Reading:
the bit stray field defines the magnetization direction of the free layer



(or TMR)

Magnetic random-access memory (MRAM)

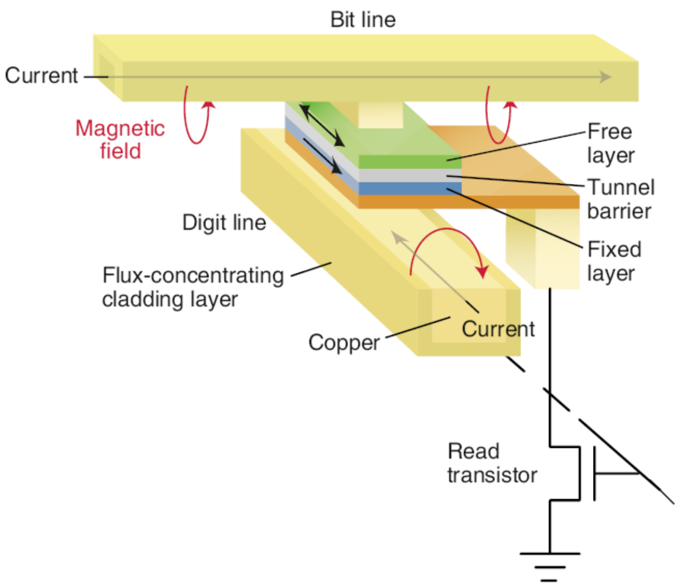


Reading: by measuring the point contact resistance between a bit and a word line

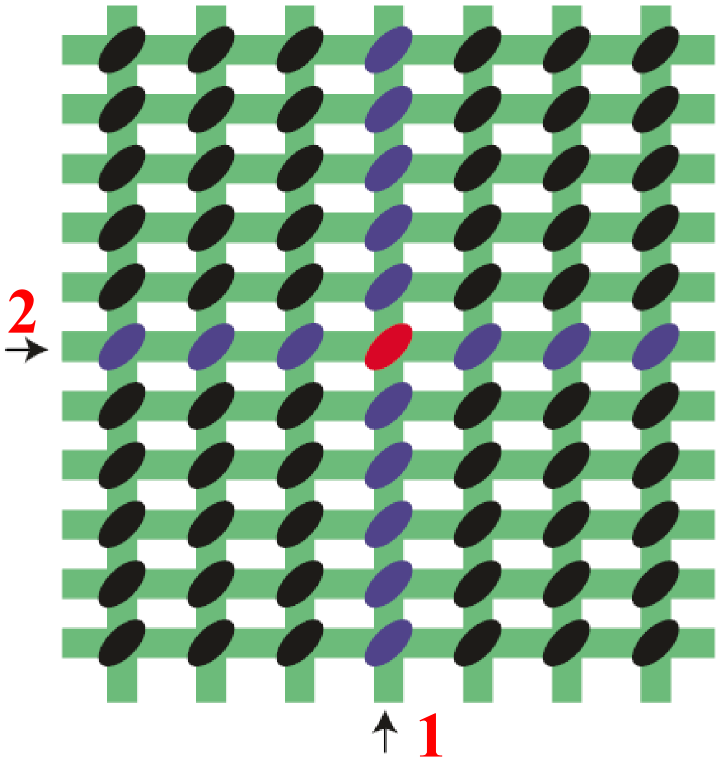
Writing: by induced magnetic fields or by injecting spin polarized current thought the point contact

Science **282**, 1660 (1998); Nat. Mater. **6**, 813 (2007)

MRAM writing by a magnetic field



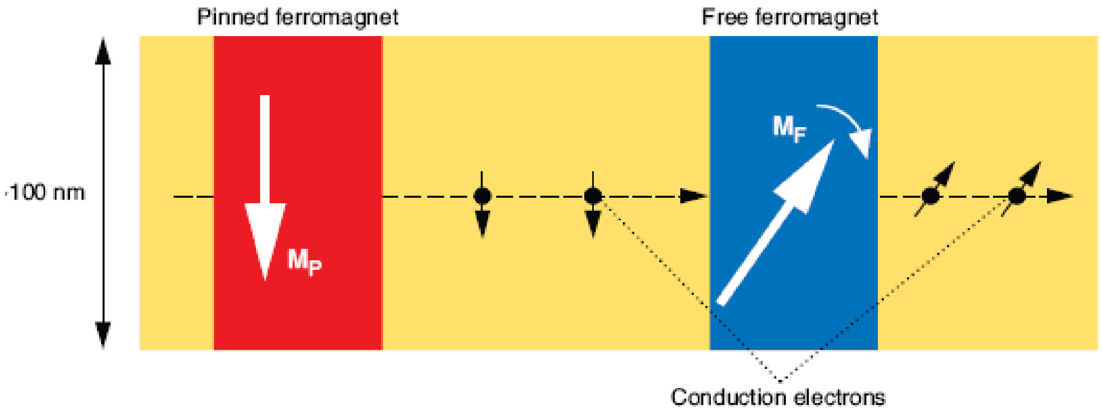
The MRAM is engineered in such a way that the bit easy axis points at 45° to the bit and digit lines



Line 1 produces the magnetic field necessary to turn by 45° the bit magnetization
Line 2 produces the magnetic field necessary to complete the reversal of the magnetization of the selected (red) bit
Switching off the magnetic fields generated by bit and digit lines, the magnetization of the non selected bits relax back to the original direction

J. Akerman, Science **308**, 508 (2005)

MRAM writing by a spin-polarized current: spin-transfer torque



Simple picture (classical)

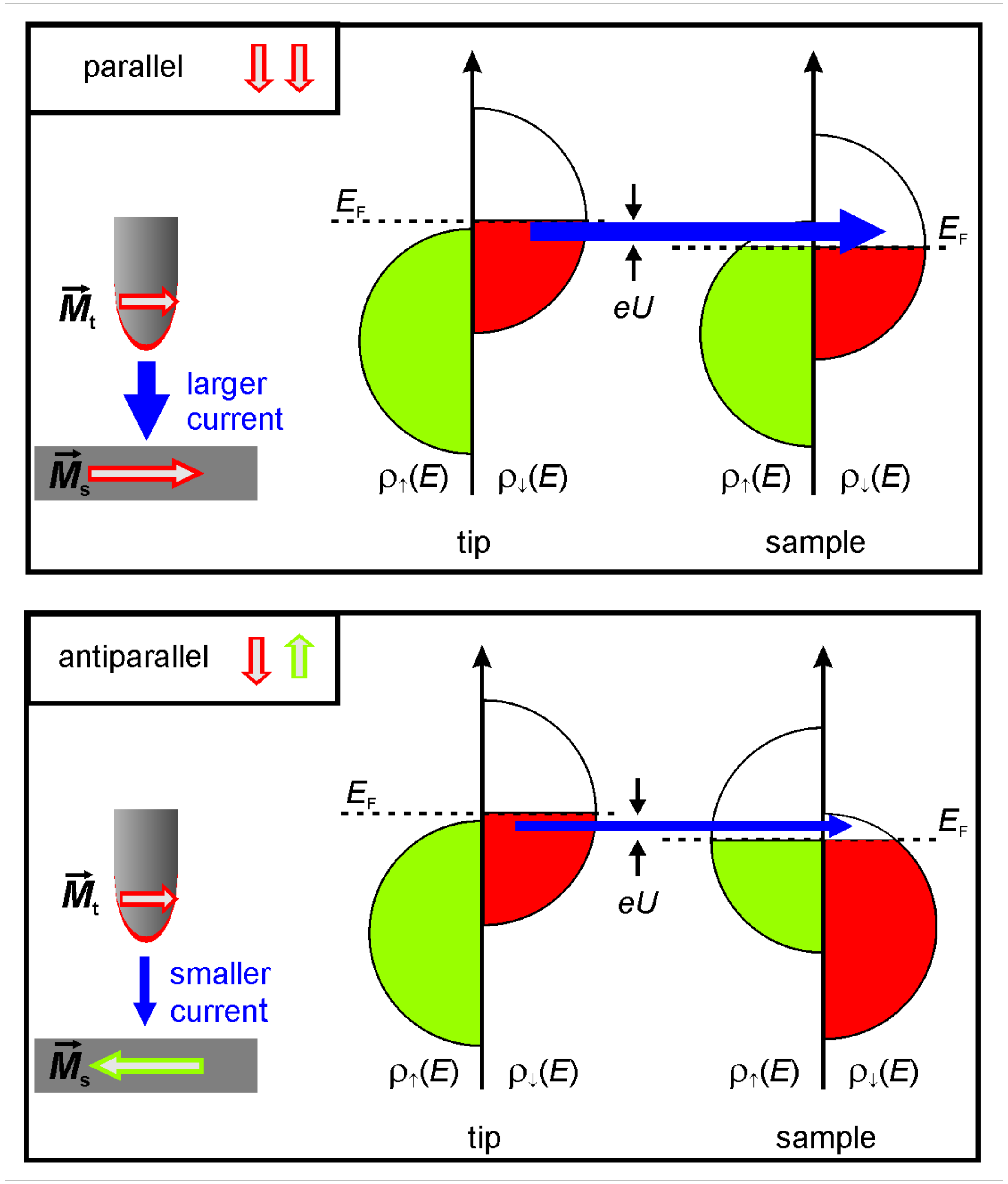
A current flowing through the pinned layer get spin polarized.
The free layer exerts a torque on the spin electrons flowing through it; the electrons exert an equal and opposite torque on the magnet, causing the magnetization reversal (conservation of angular momentum)

The torque depends on the direction of the current
→
parallel or antiparallel alignment of the magnetization of pinned and free layer can be selected

Spin-polarized STM

In this sketch, tip and sample magnetization are in-plane.

In general, they can also be out-of-plane

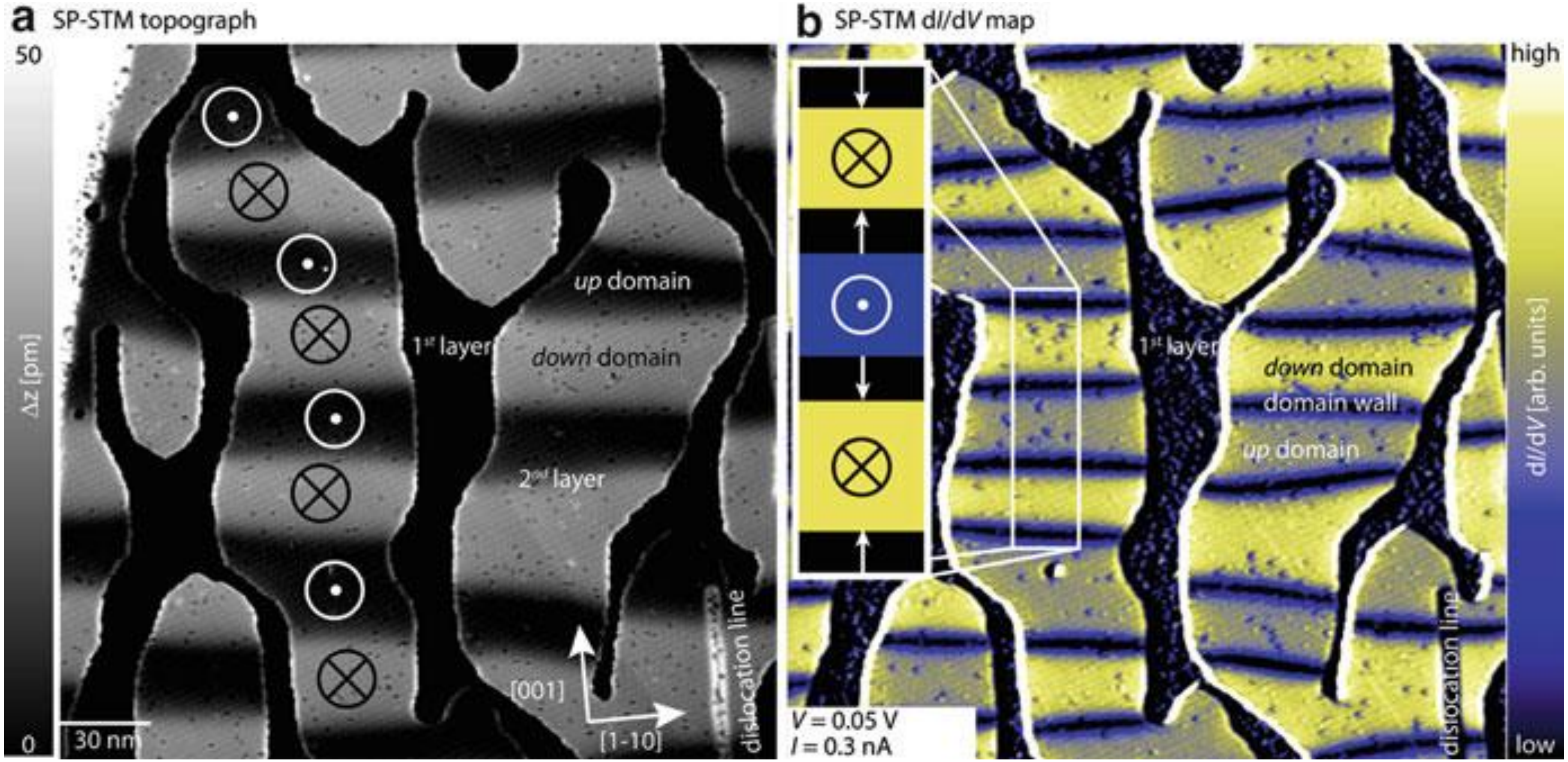


high current

low current

R. Wiesendanger group
http://www.nanoscience.de/HTML/methods/sp-stm.html

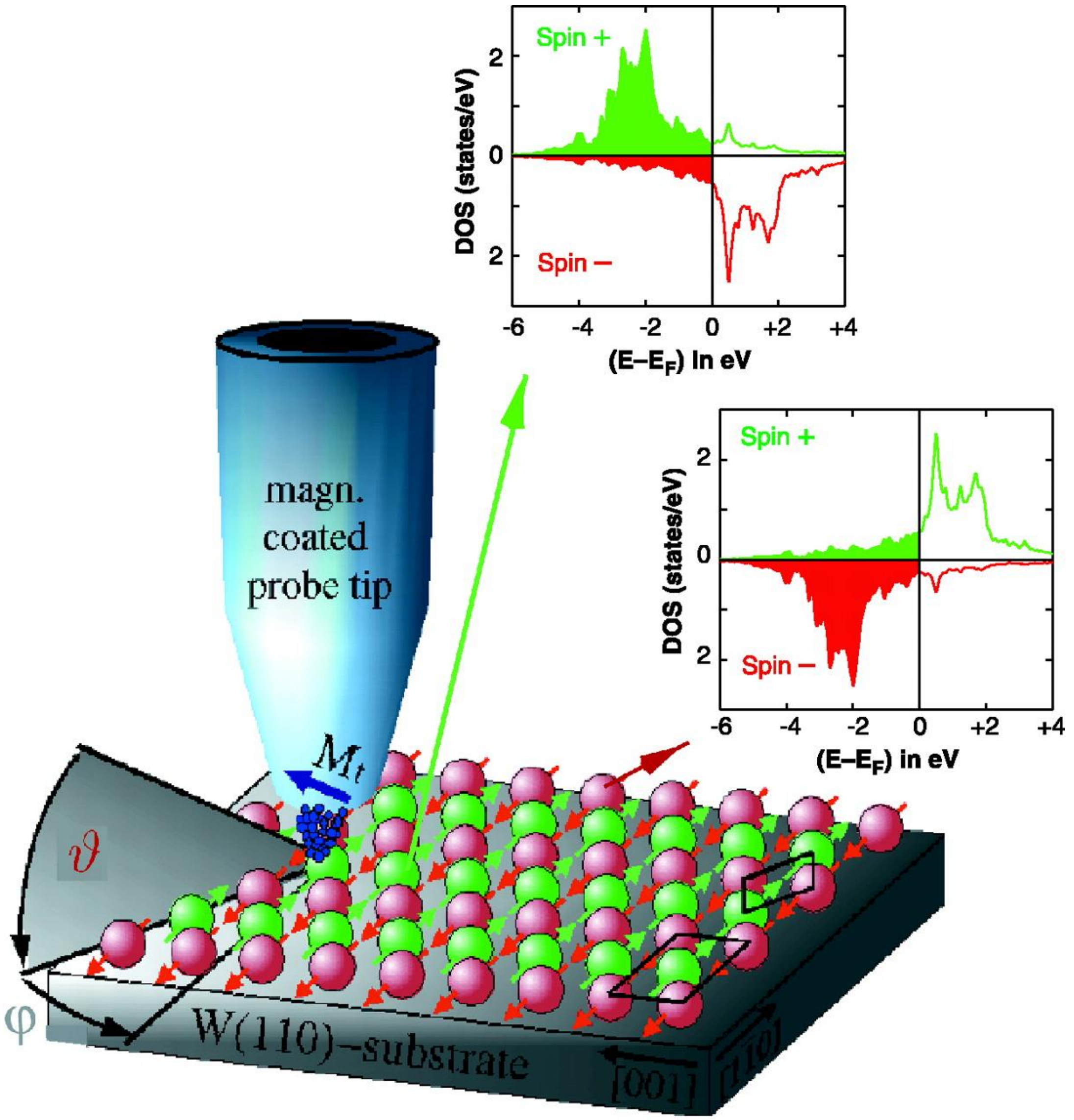
Example: magnetic domain structure of Fe/W(110)



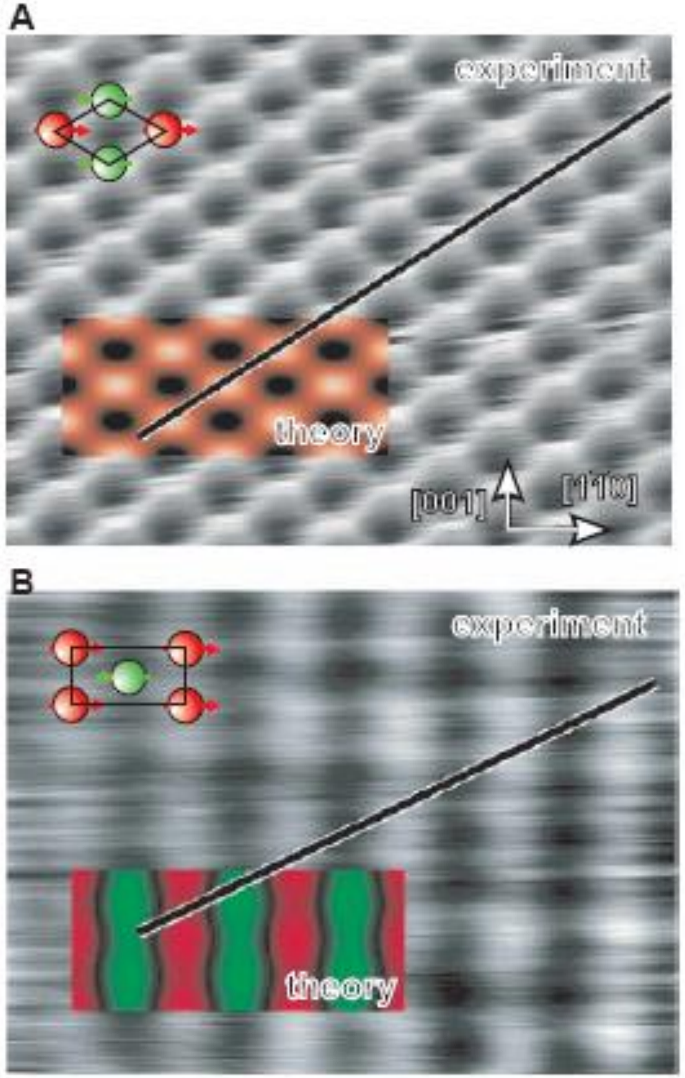
The magnetic domain structure of two atomic layers of Fe grown on W(110) revealed by SP-STM. A Cr-coated W-tip with out-of-plane spin sensitivity has been used. Alternating magnetic domains (up (⨀) or down (x)) are clearly in both, the constant-current SP-STM topography (a) and the map of the spin-resolved differential tunneling conductance (b)

Handbook of Spintronics DOI 10.1007/978-94-007-7604-3_30-1

Example: Atomic-scale imaging of a two-dimensional antiferromagnet



1 monolayer Mn/W(110)



W tip

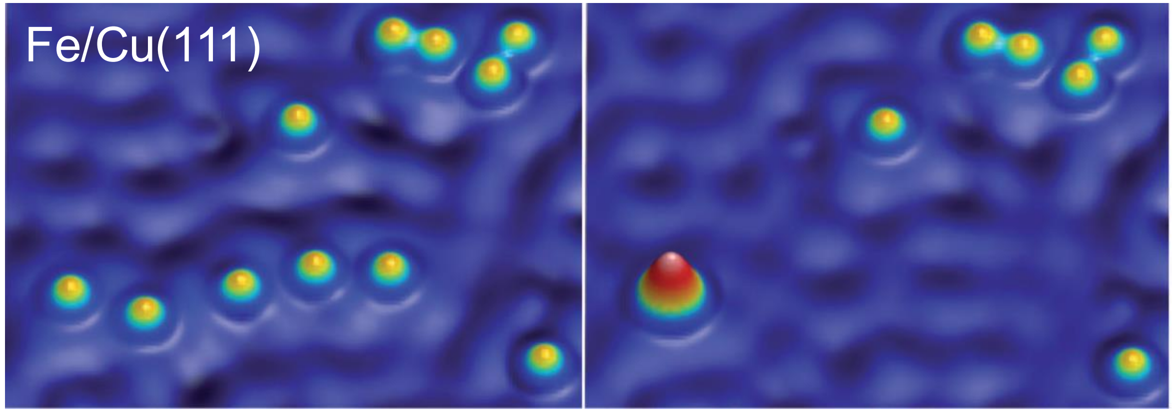
1x1 apparent unit cell

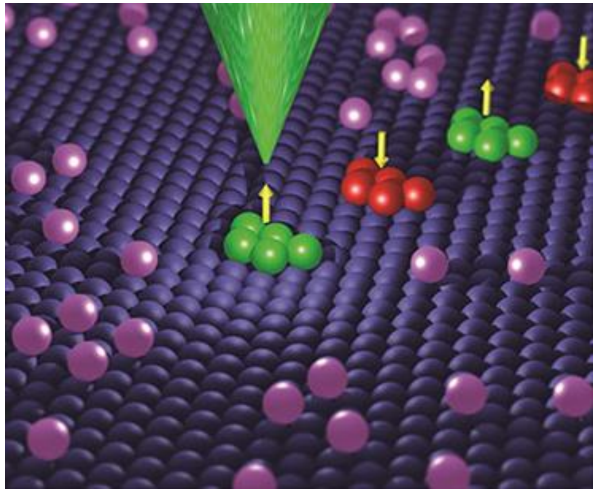
Fe-coated tip

c(2x2) magnetic unit cell

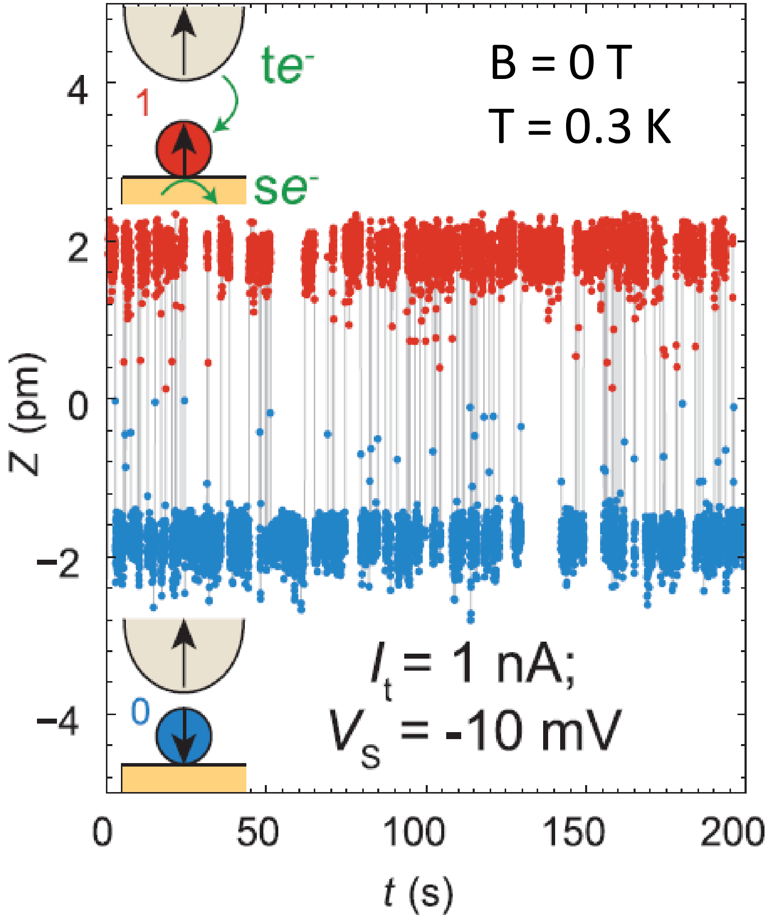
S. Heinze et al., Science **288**, 1808 (2000)

Example: Fe_5 quantum magnet built by atomic manipulation

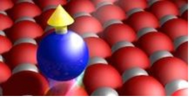




Spin lifetime: switching between the two spin states



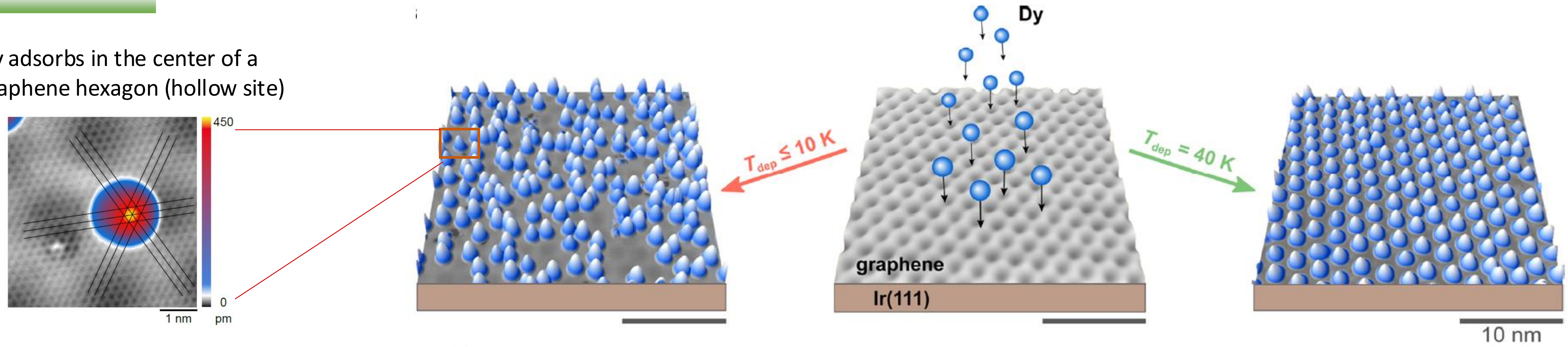
A.A. Khajetoorians *et al.* , Science **339**, 55 (2013)



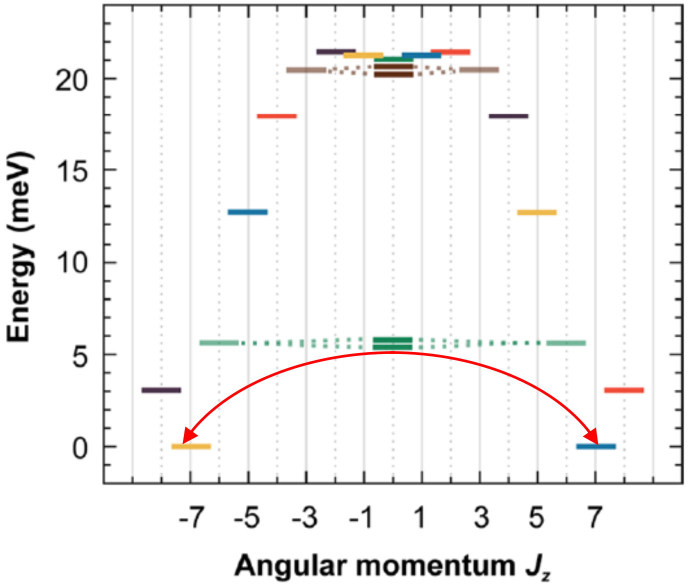
Example: Dy/graphene, a superlattice of single atom magnets

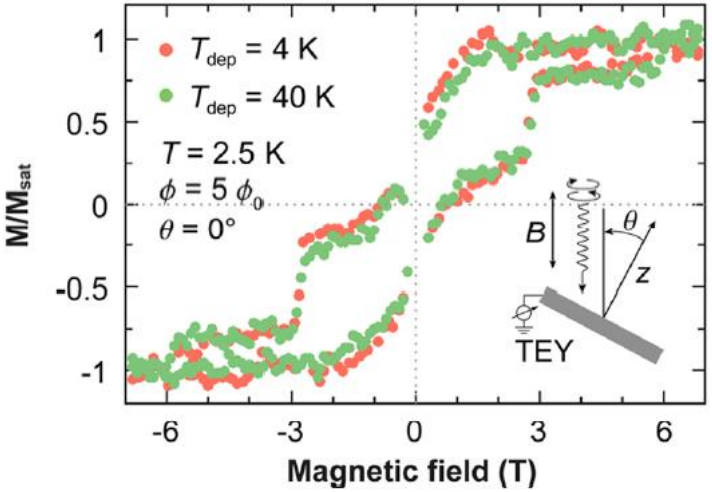
Exercise 13.1

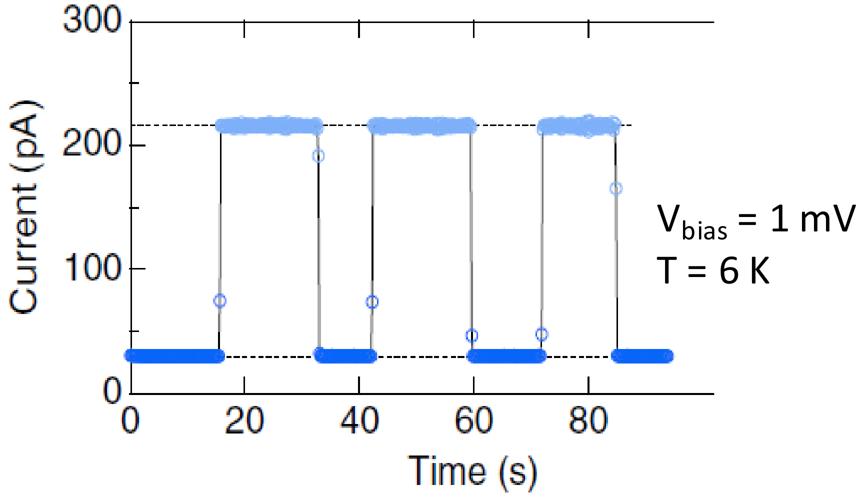
Dy adsorbs in the center of a graphene hexagon (hollow site)



CF with C_{6v} symmetry







R. Baltic *et al.*, Nano Letters **16**, 7610 (2016); M. Pivetta *et al.*, Phys. Rev. X **10**, 031054 (2020)