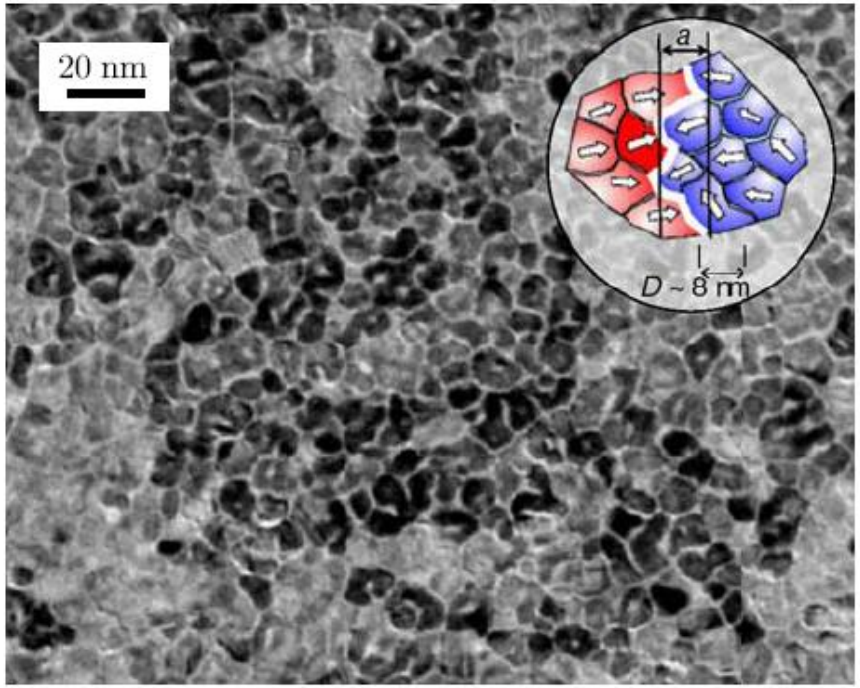
Some basic questions …..
… that need an answer



CoCrPt recording layer

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

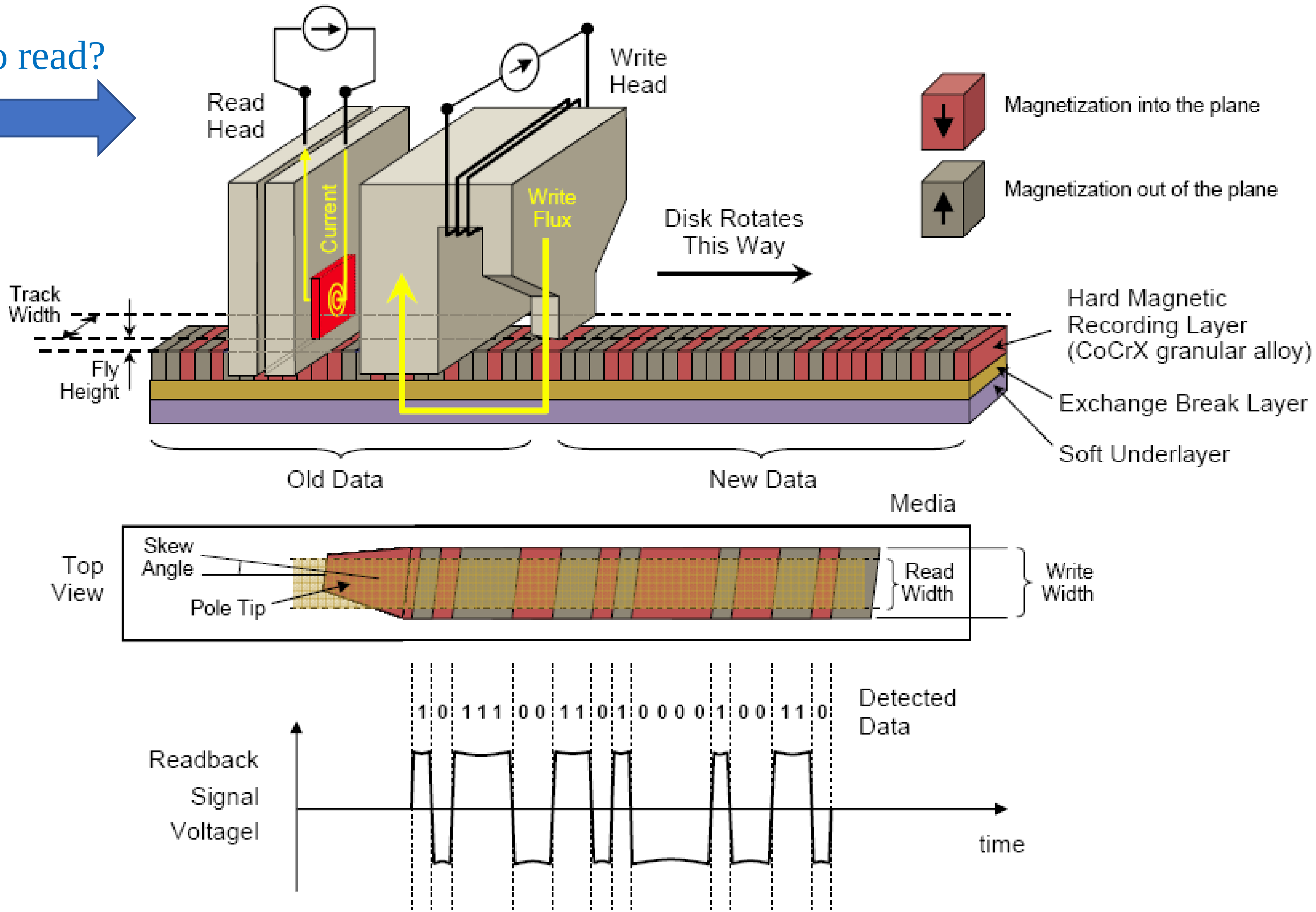
Atomic magnetism:
- Spin and orbital

Exchange energy

Magnetic anisotropy:
- Crystalline
- Shape

The recording mechanism: a condensate of concepts

How to read?



Information processing: electronics *vs* spintronics

1) Information storage

HDD: hard disk drive

High density magnetic storage

SSD: solid state drive

Solid state non volatile memory

2) Fast access memory: temporary work space 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

⇓

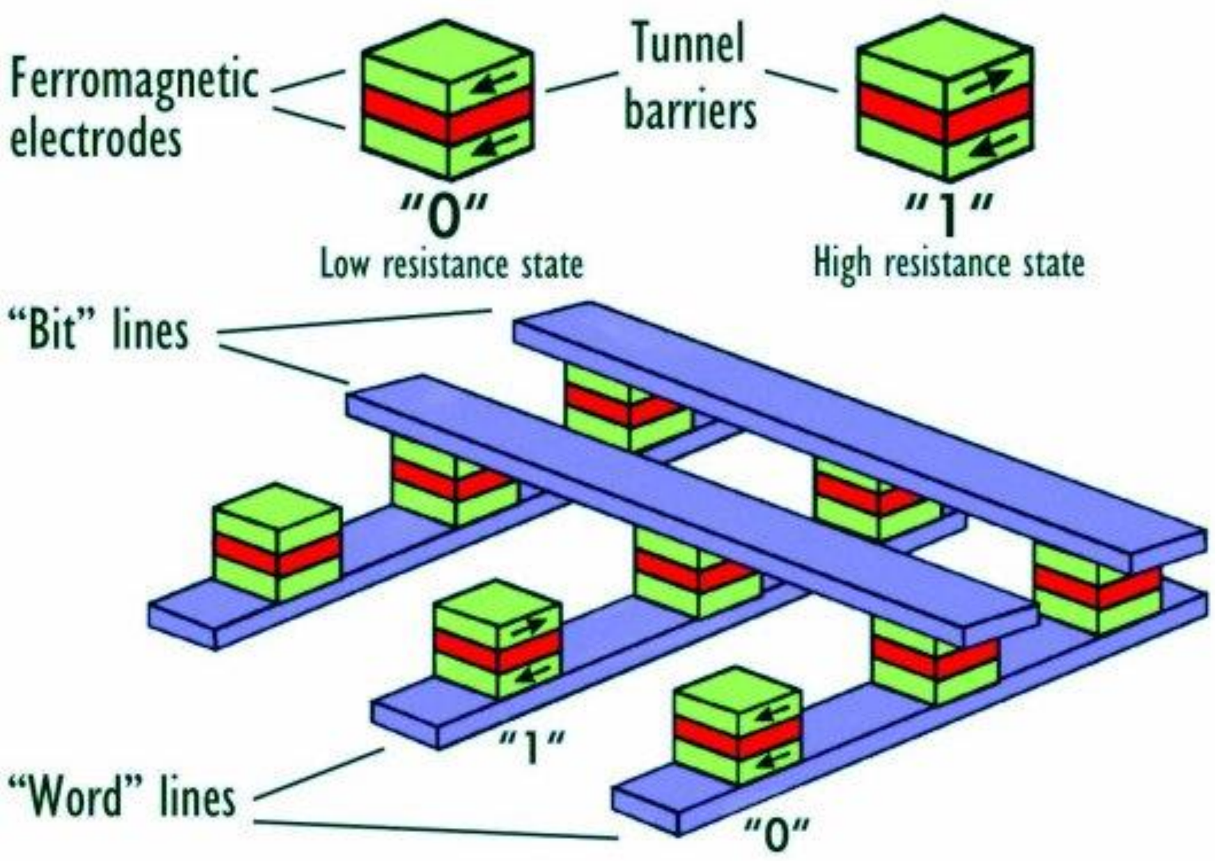
Volatile

Spintronics: combining the 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 (up to 99% less) compared to DRAM

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



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

In production

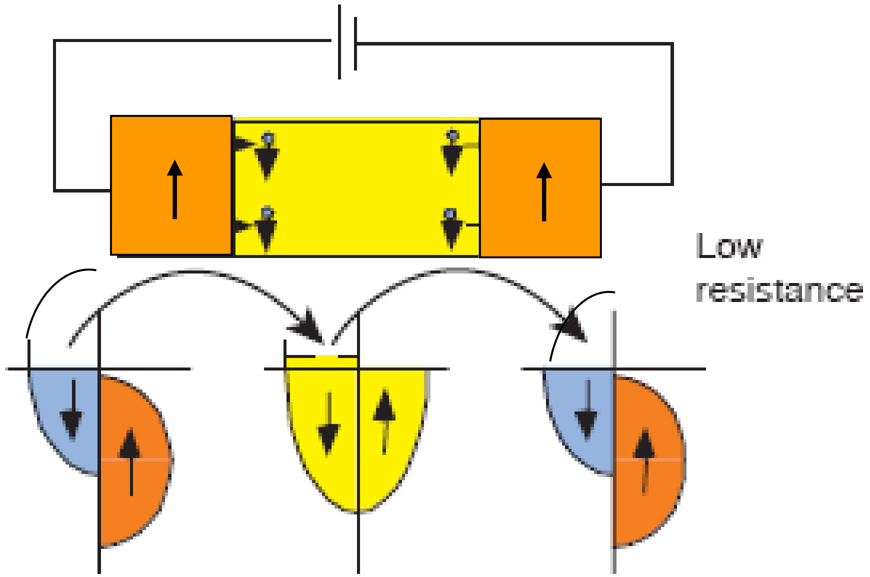
EVERSPIN TECHNOLOGIES

https://www.everspin.com/

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

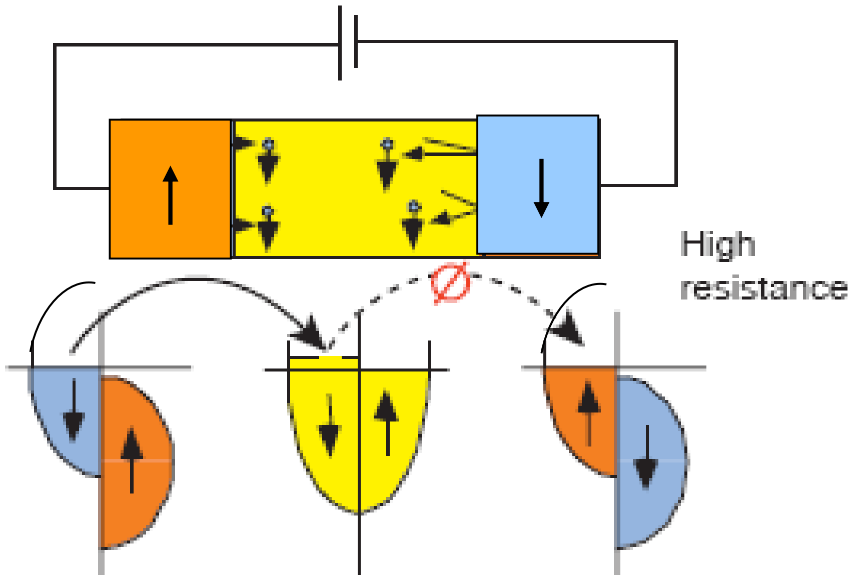
Spin transport

1



Available free states with the same spin:
Low resistance

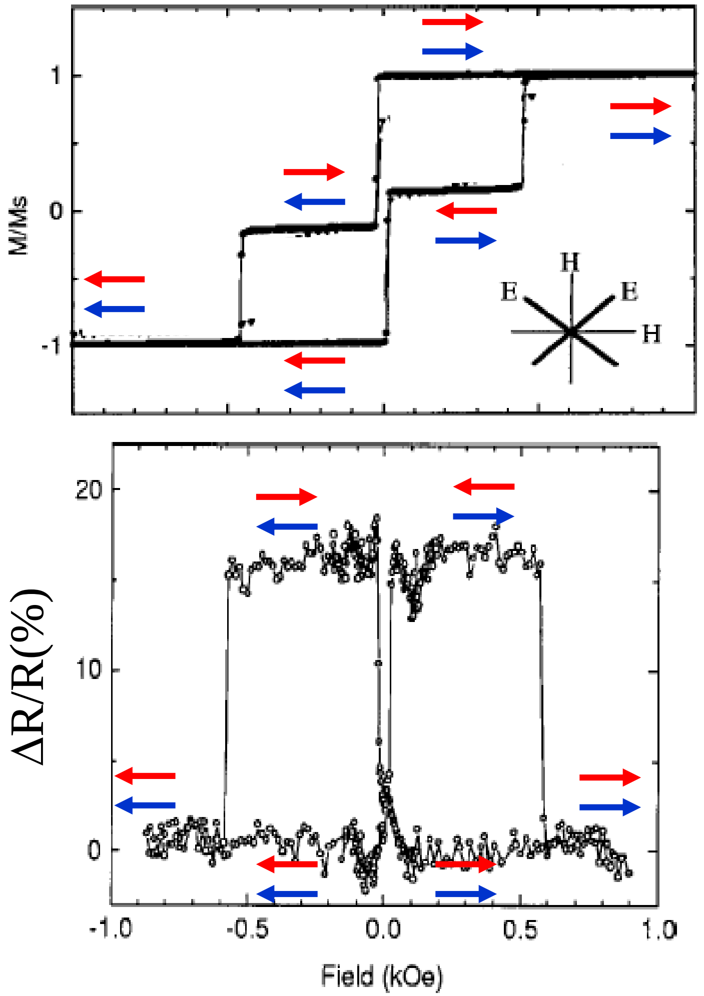
0



Absence of free states with the same spin:
High resistance

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

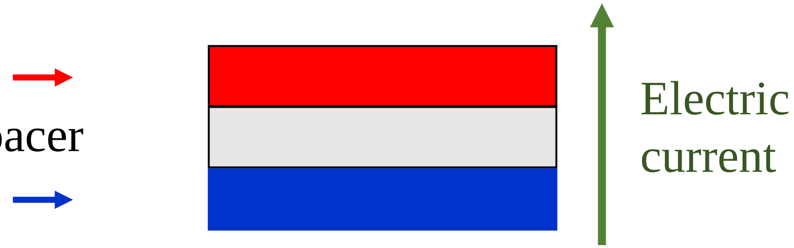
Magnetoresistance



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)

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

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

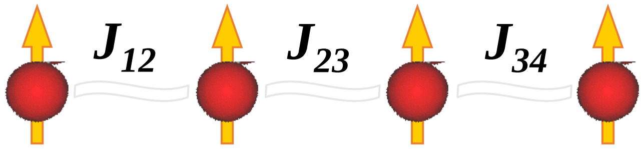
Role of the non magnetic spacer

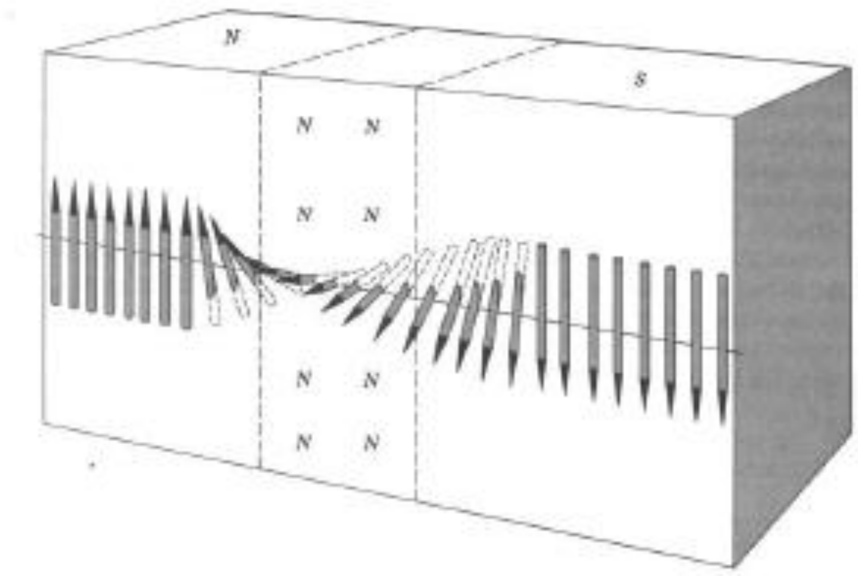
The atom spins are coupled together by
inter-atomic exchange

Inter-atomic exchange:

MAGNETIC ORDER

$$H_{exc} = -\sum_{i \neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

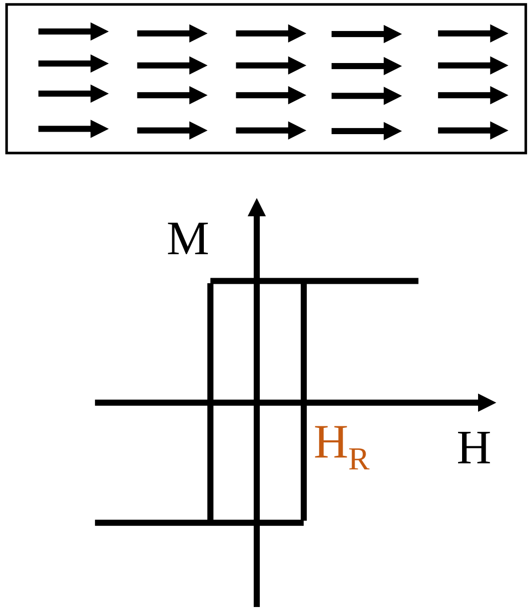




In non magnetic materials S = 0 thus H_{exc} = 0 i.e. decoupling of
free and pinned layer

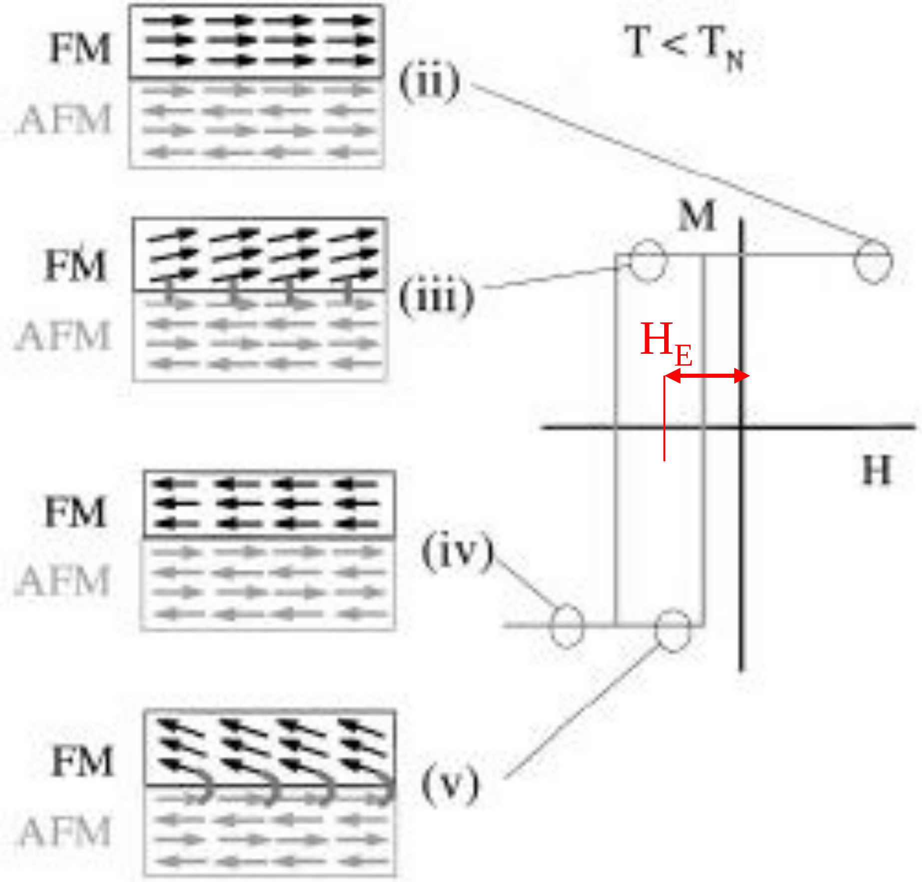
How to make the pinned layer: exchange bias

FM: ferromagnetic material; AFM: antiferromagnetic material



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

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 is the magnetic field shift of the hysteresis curve

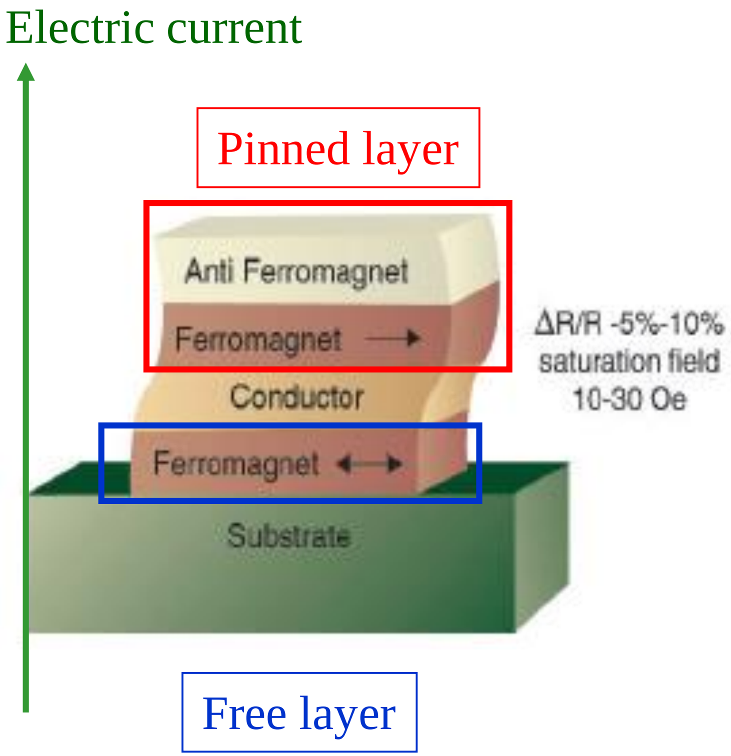
The magnetic field required to reverse the pinned layer becomes

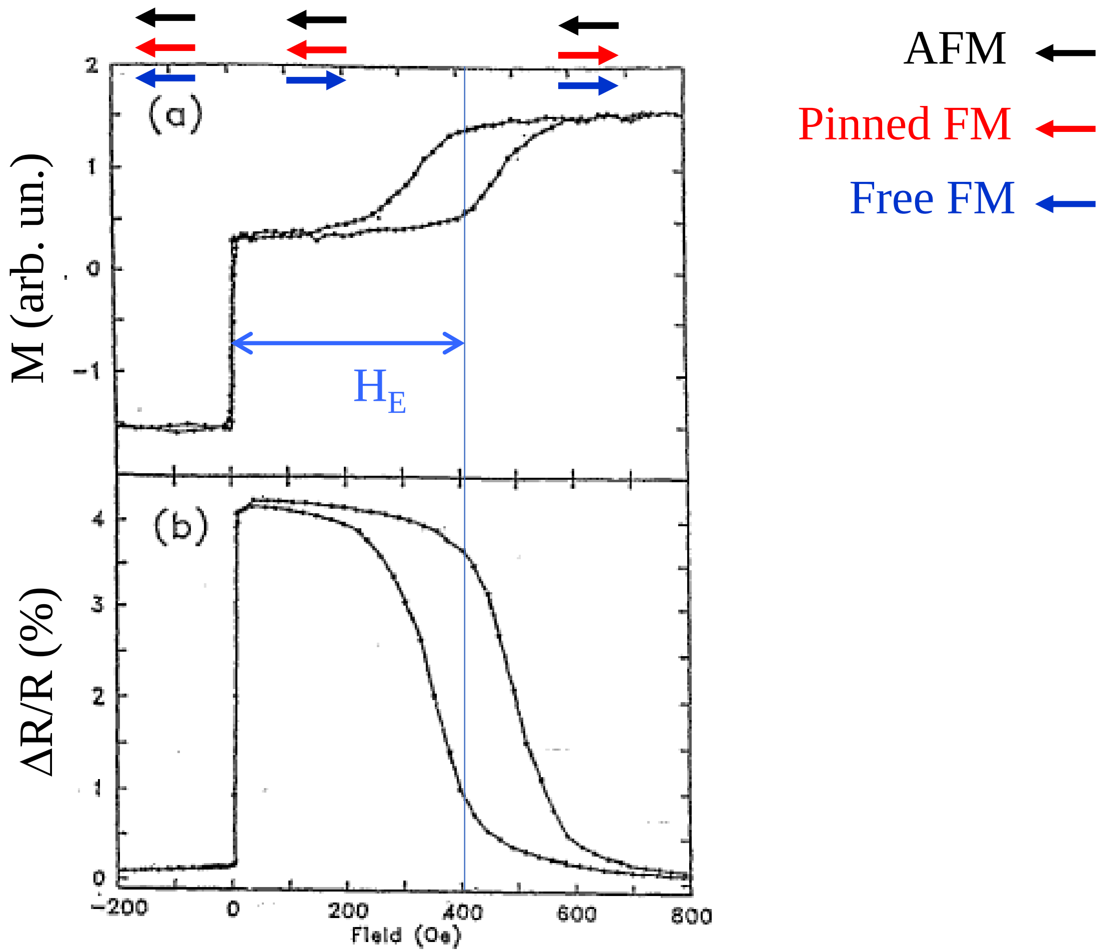
$H_R + H_E$

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

GMR: giant magneto resistance

The spacer is a metal

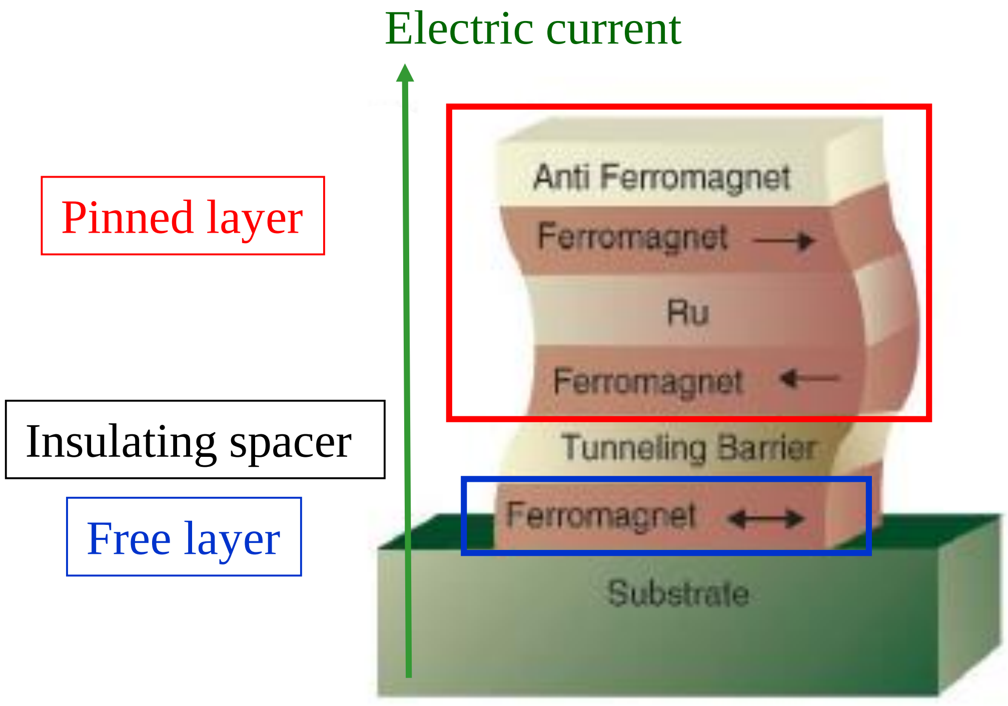


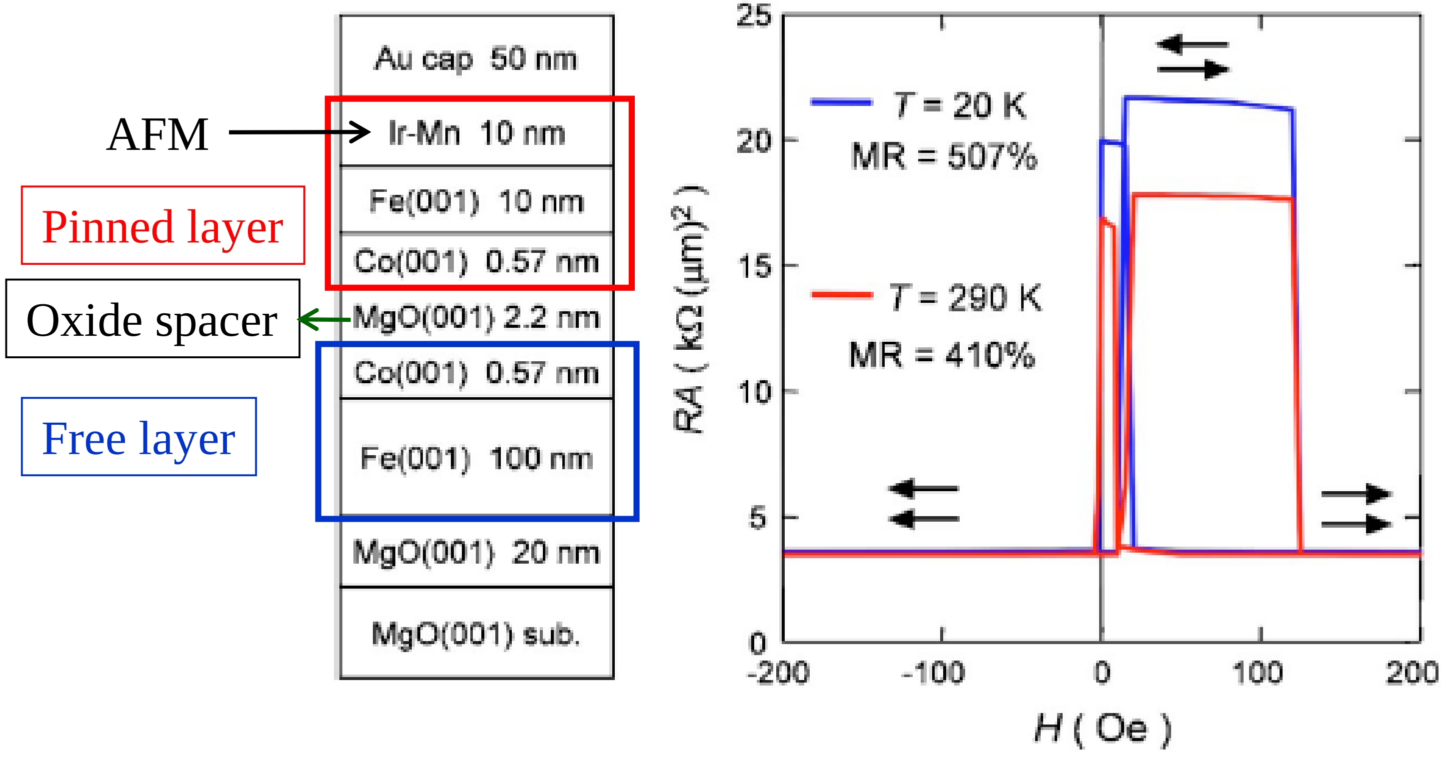


The electric resistance depends on the respective spin orientation of the two FM layers:
Low -> parallel alignment
High -> anti-parallel alignment

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

MTJ: magnetic tunnel junction





Improved performance with respect to GMR due to:

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

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

Role of the spacer thickness

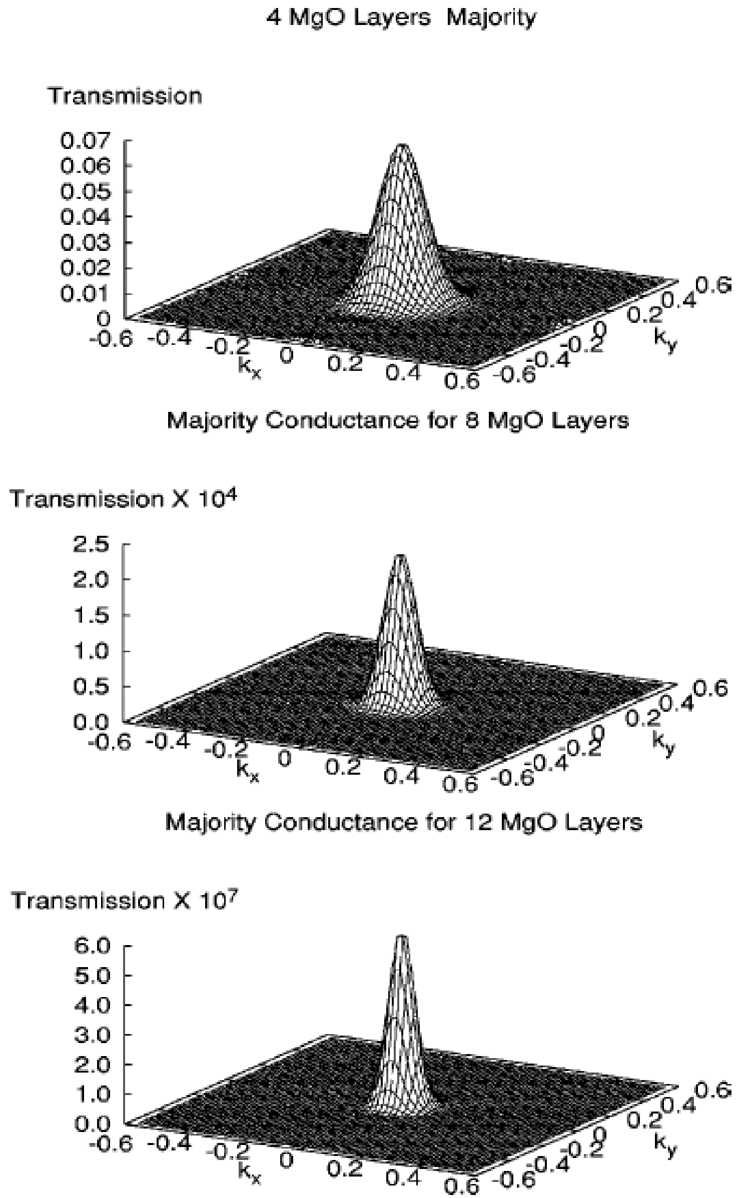


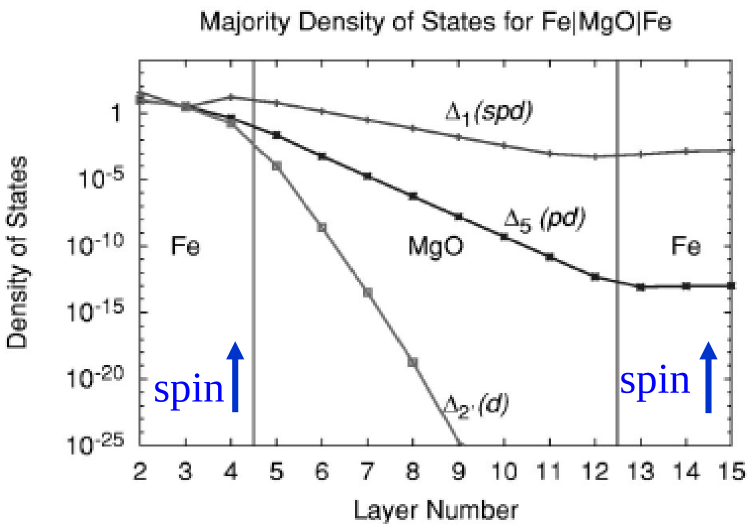
FIG. 6. Majority conductance for 4, 8, and 12 layers of MgO. Units for k_x and k_y are inverse bohr radii.

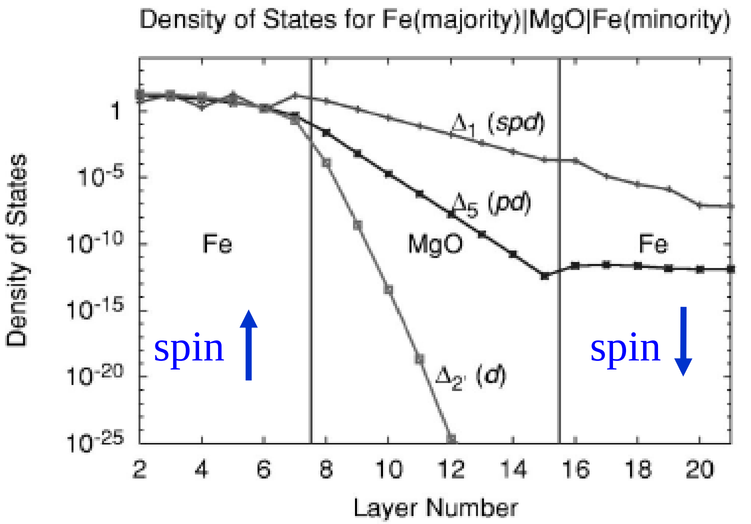
T = transmission trough the tunnel barrier

$$T \propto e^{-2d\sqrt{\frac{2m(\Phi - E_F)}{\hbar^2} + k_{//}^2}}$$

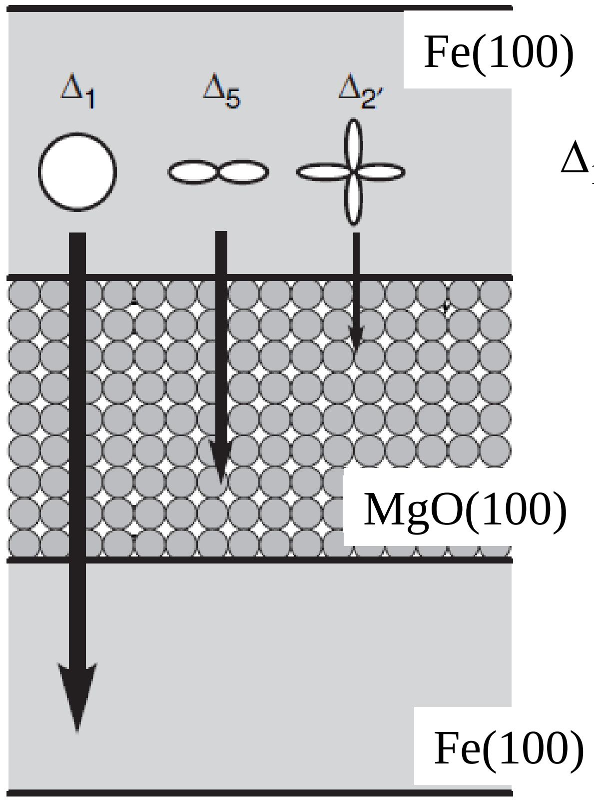
Transmission strongly dependent on MgO thickness d -> high control of MgO roughness to have flat interfaces and thus uniform current

Role of the spacer material and crystal structure





Electron wave function symmetries



Δ_1 -> totally symmetric wave function with respect to the normal to the tunnel barrier: s, p_z, d_{z^2}.

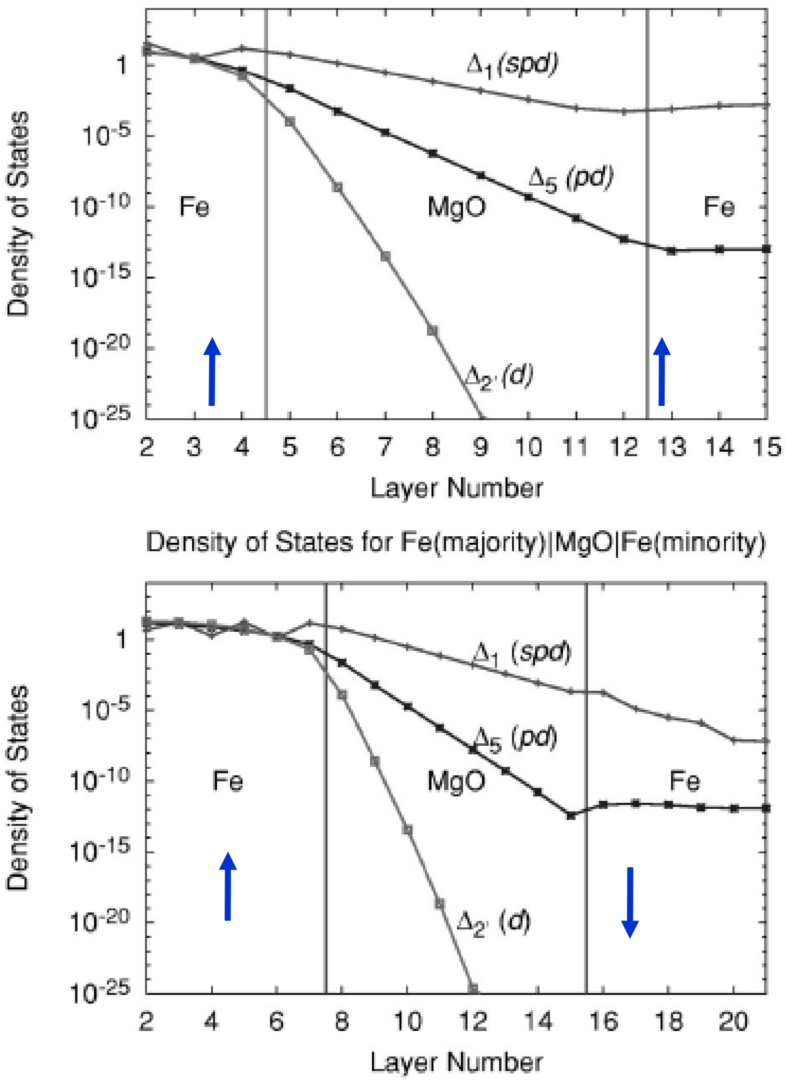
Δ_1 is a slowly decreasing evanescent state for majority spins.

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

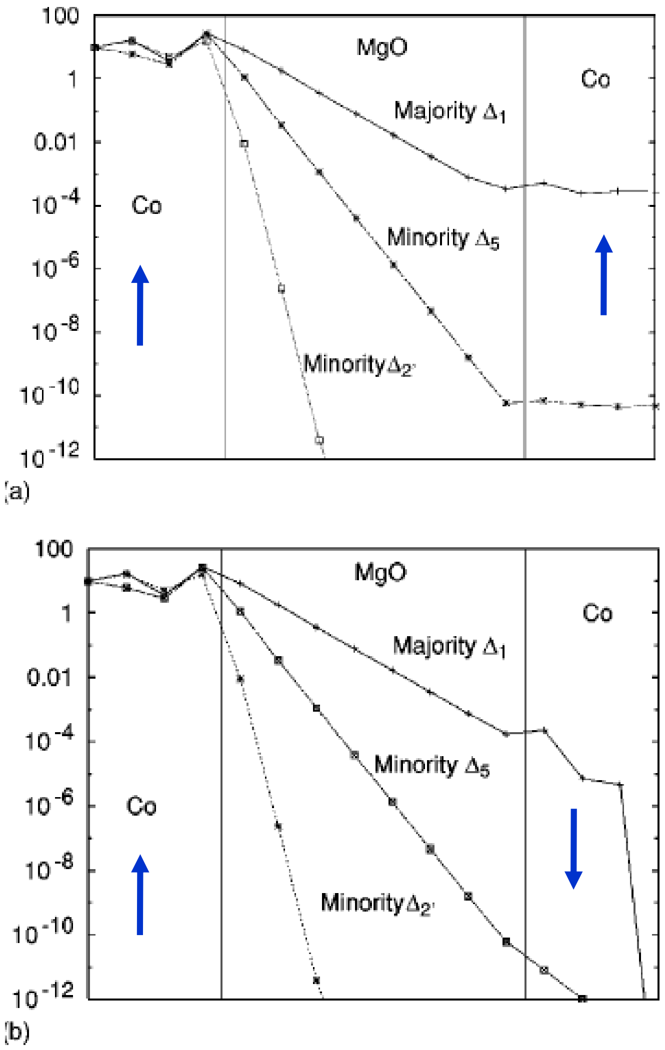
Phys. Rev. B **63**, 054416 (2001); Phys. Rev. B **70**, 172407 (2004); Encyclopedia of Materials: Science and Technology ISBN: 978-0-0804-3152-9

Role of the magnetic layer composition

Fe/MgO/Fe



Co/MgO/Co

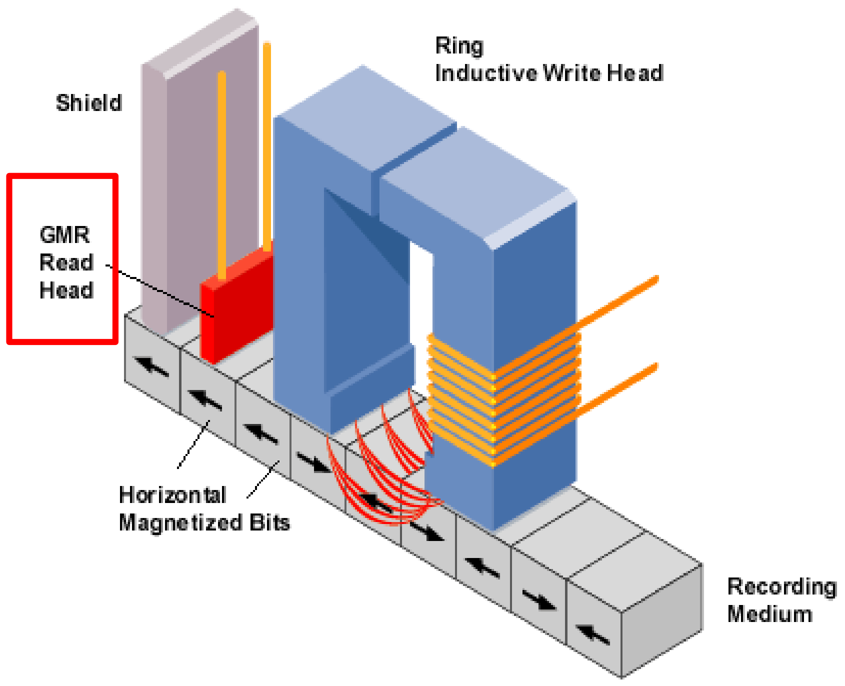


Total reflection of tunneling electrons for antiparallel spin alignment in Co/MgO/Co junction -> higher TMR in Co/MgO/Co than in Fe/MgO/Fe junction

The electronic DOS of the two electrodes determines the TMR

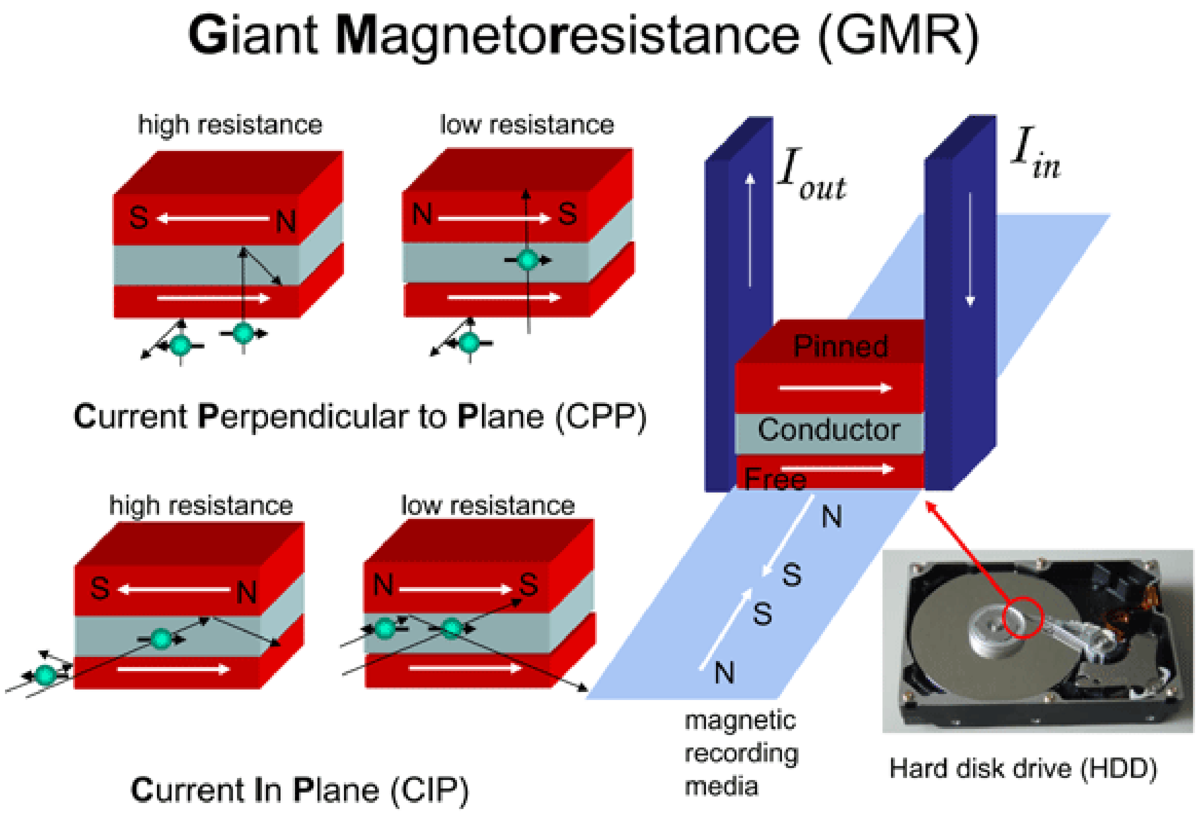
Phys. Rev. B **63**, 054416 (2001)
Phys. Rev. B **70**, 172407 (2004)

Reading-writing head in HDD

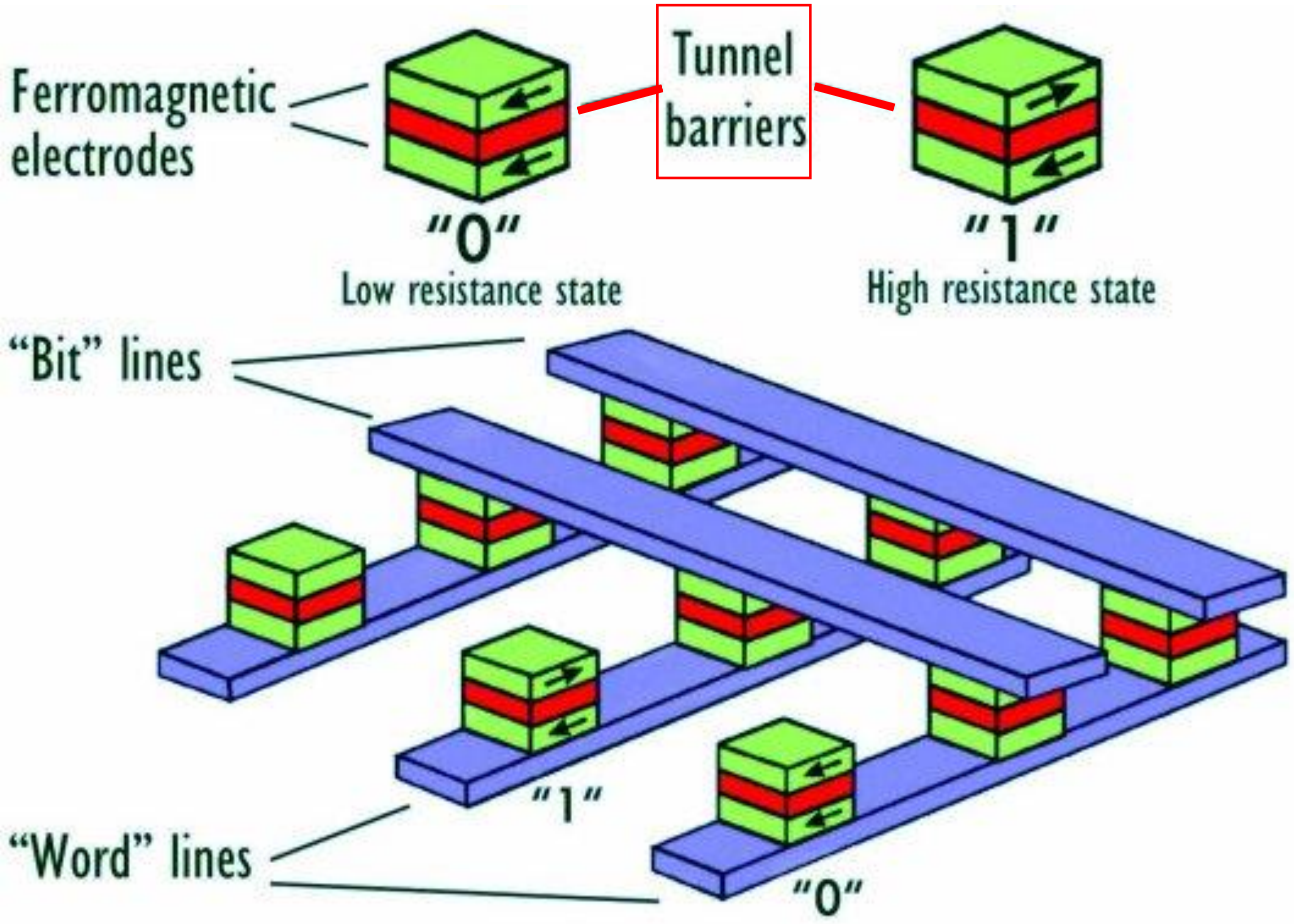


Writing:
the head stray field defines the magnetization direction of the recording medium

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



Magnetic random access memory (MRAM)

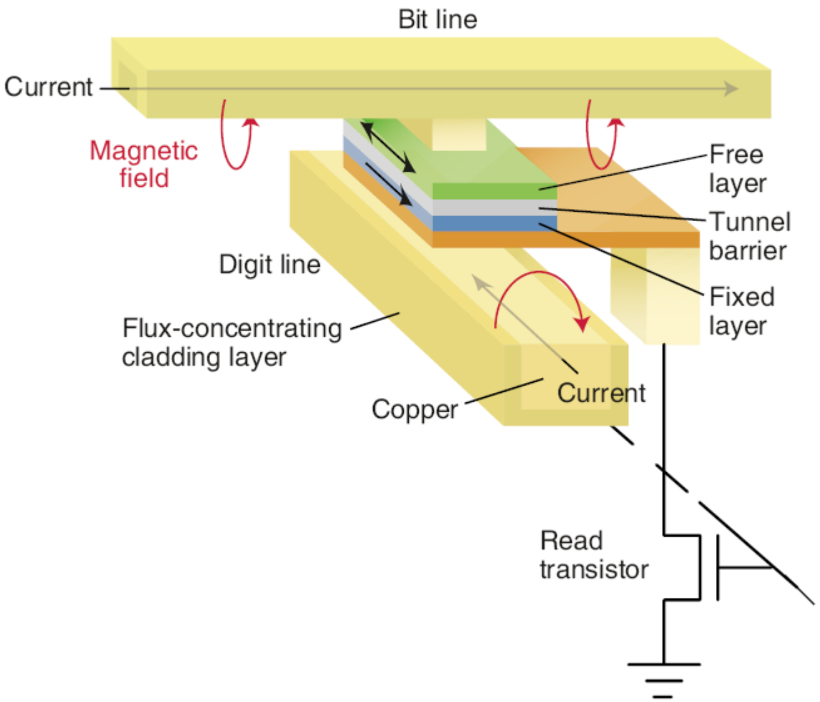


Reading: by measuring the point contact resistance between a bit and a word line

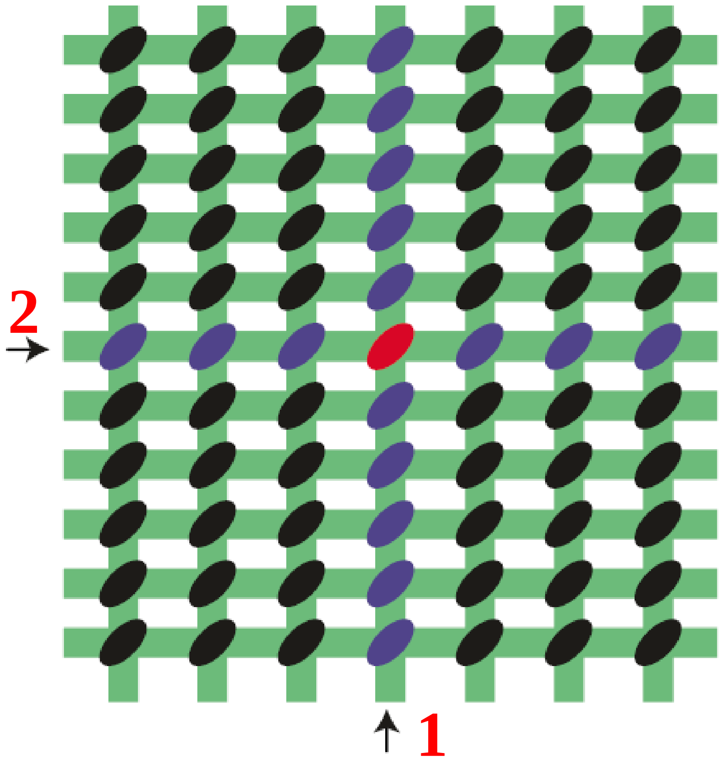
Writing: by induced magnetic fields or by injecting spin polarized current thought the point contact

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

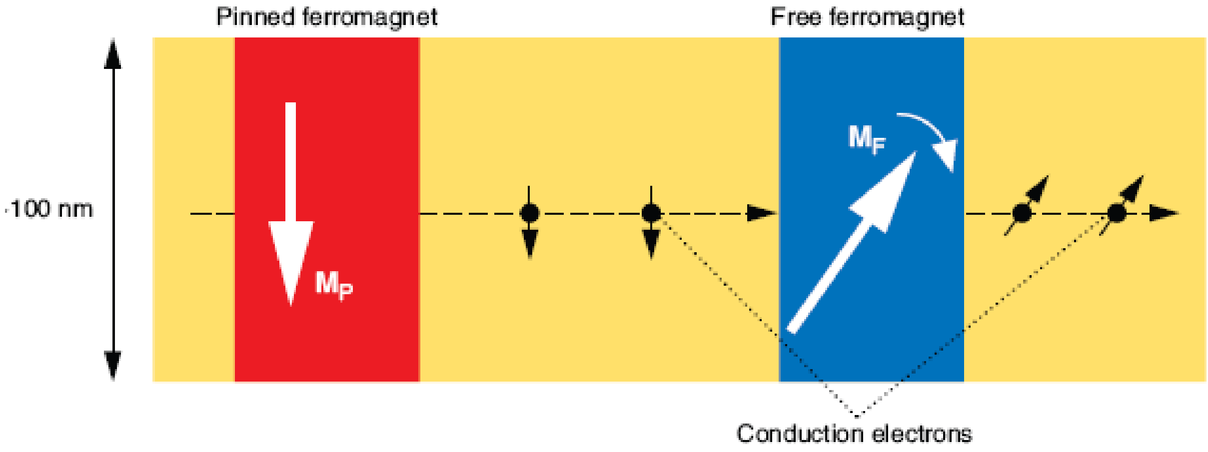


Word line = digit line

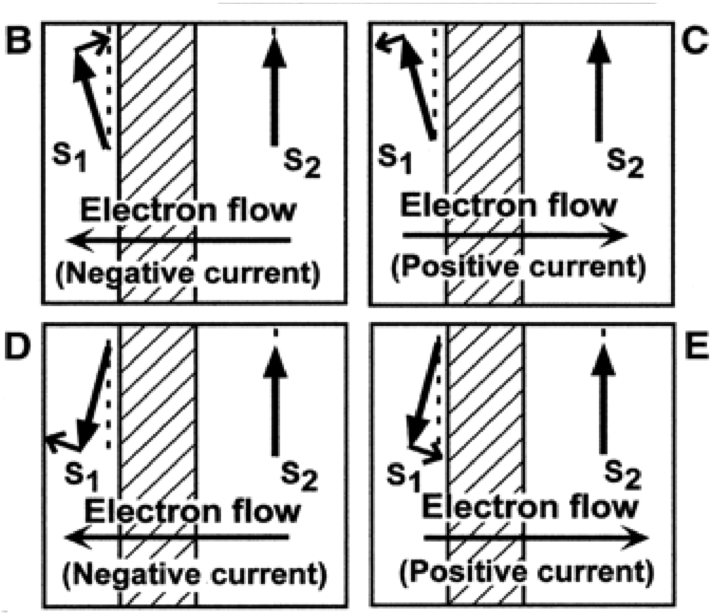
Line 1 produces the magnetic field necessary to turn by 45° the bit magnetization
Line 2 produces the magnetic field necessary to complete the reversal of the magnetization of the selected (red) bit
Switching off the magnetic fields generated by bit and digit lines, the magnetization of the non-selected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

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

MRAM writing by a spin polarized current



- The current flowing through the pinned layer gets spin polarized
- The free layer exerts a torque on the spin of electrons flowing through it
- According to the Newton's third law, the electron must exert an equal and opposite torque on the magnet, which causes the magnetization reversal

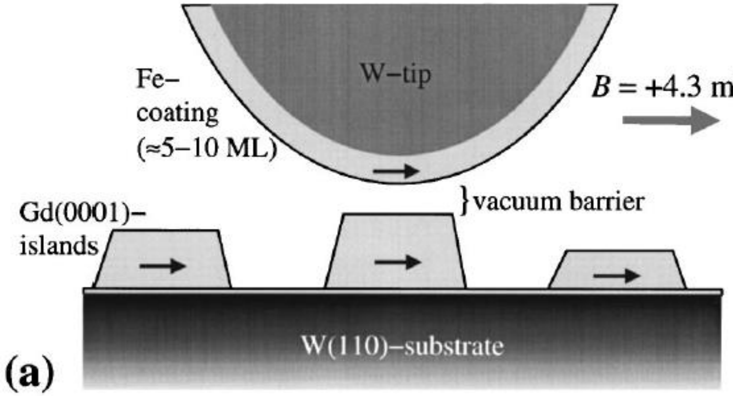


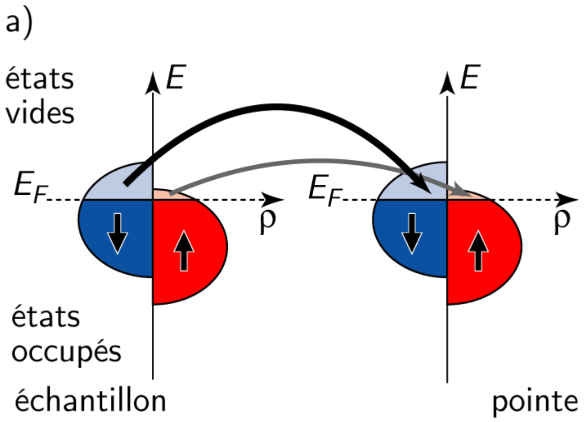
$$\underline{\tau}_{1,2} \propto I\underline{s}_{1,2} \times (\underline{s}_1 \times \underline{s}_2)$$

Torque depends on the current direction:
parallel or antiparallel alignment of the magnetization of pinned and free layer can be selected

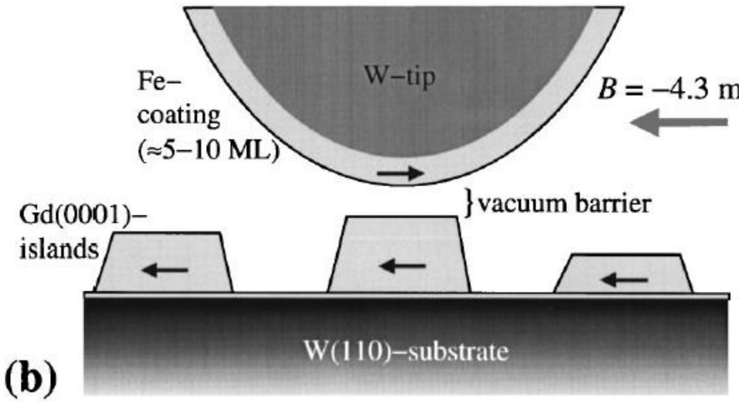
Spin polarized STM

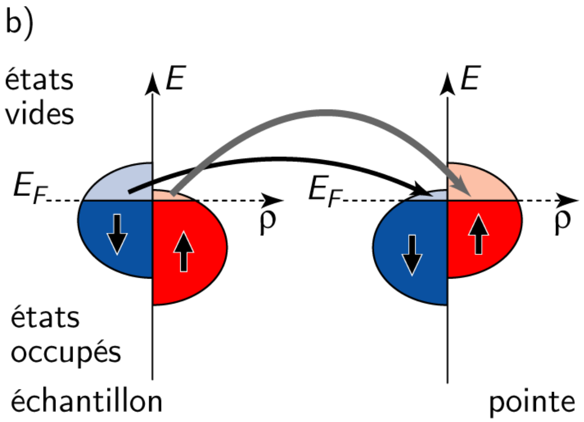
High current



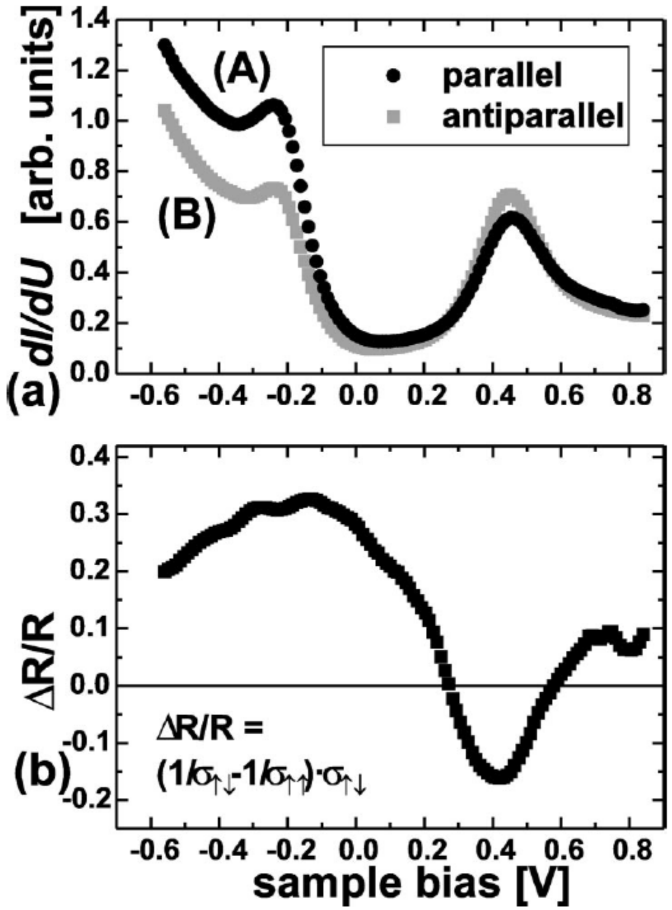


Low current



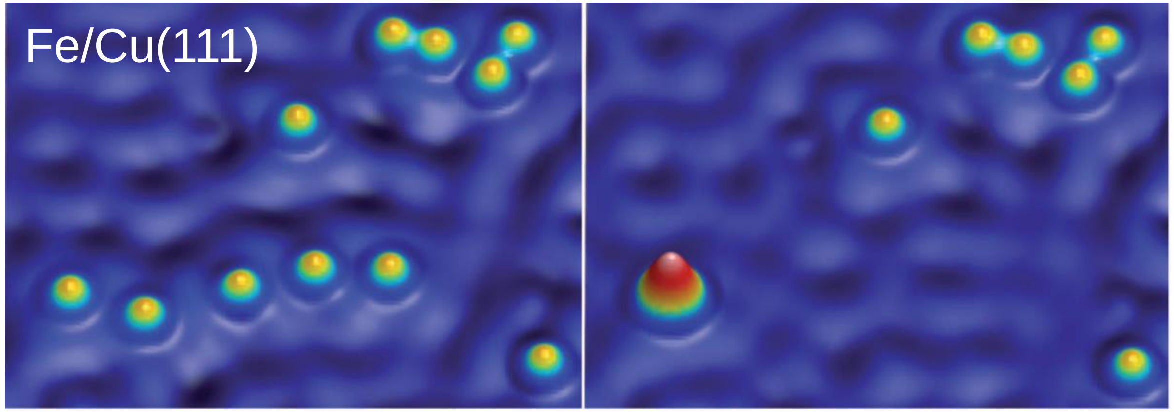


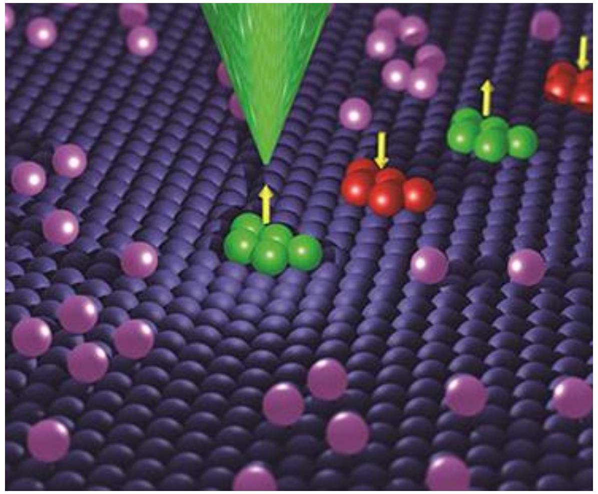
In Practice: the bias voltage defines the optimum sensitivity by selecting the spin polarized states



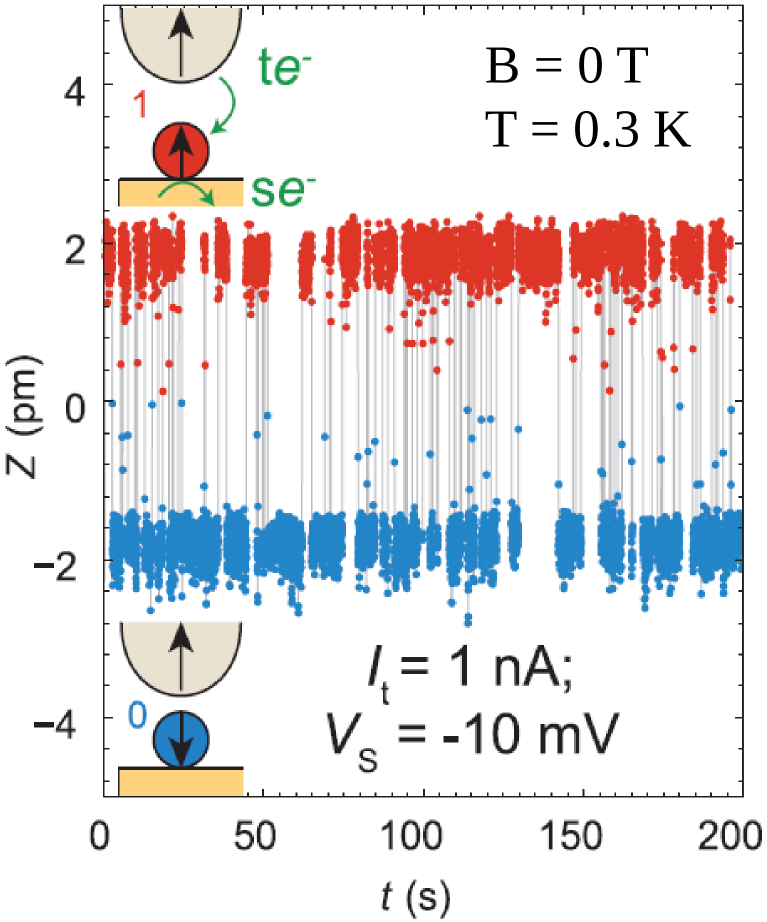
R. Wiesenganger, Appl. Phys. Lett. **75,** 124 (1999)

Artificially constructed quantum magnet

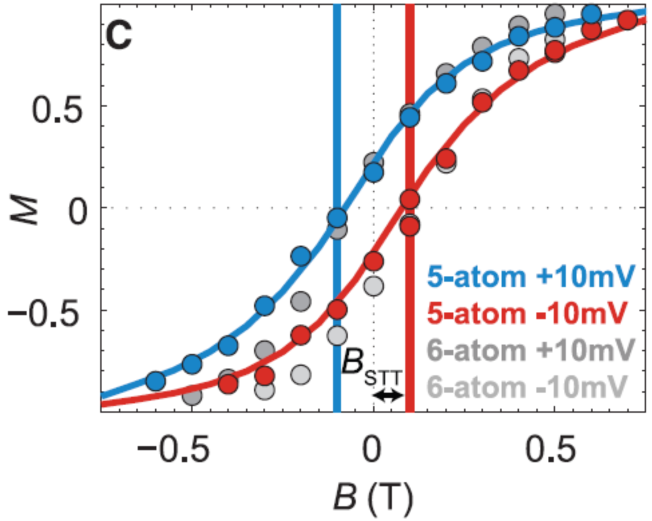




Spin life time: switching between the two spin states

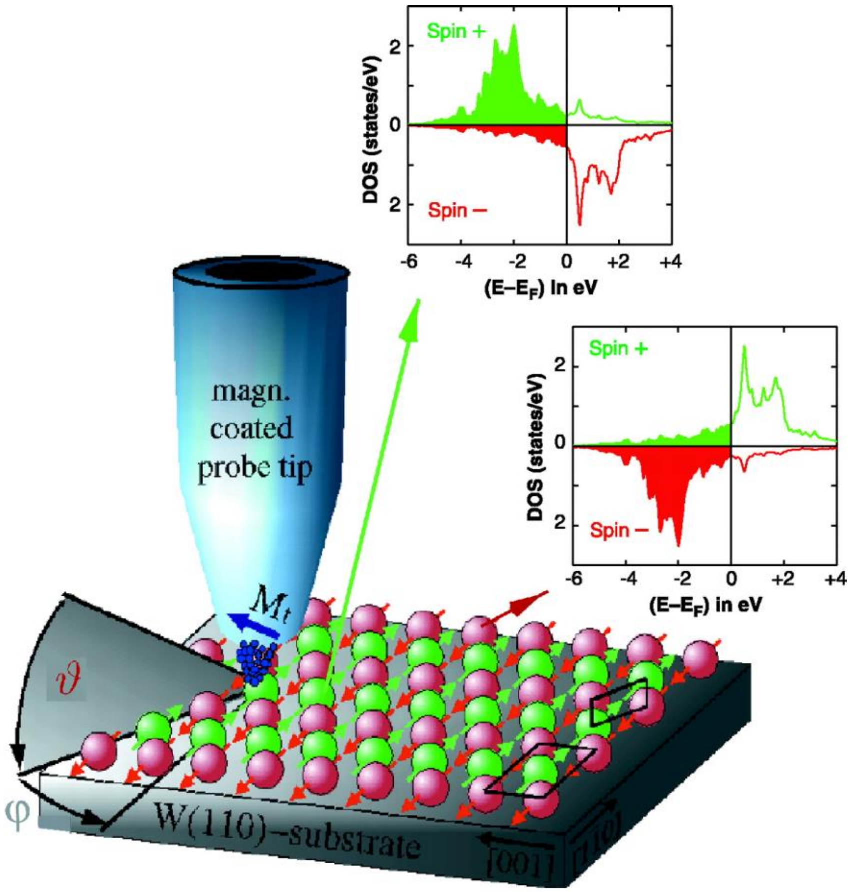


Magnetization curve



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

Real-Space Imaging of Two-Dimensional Antiferromagnetism on the Atomic Scale



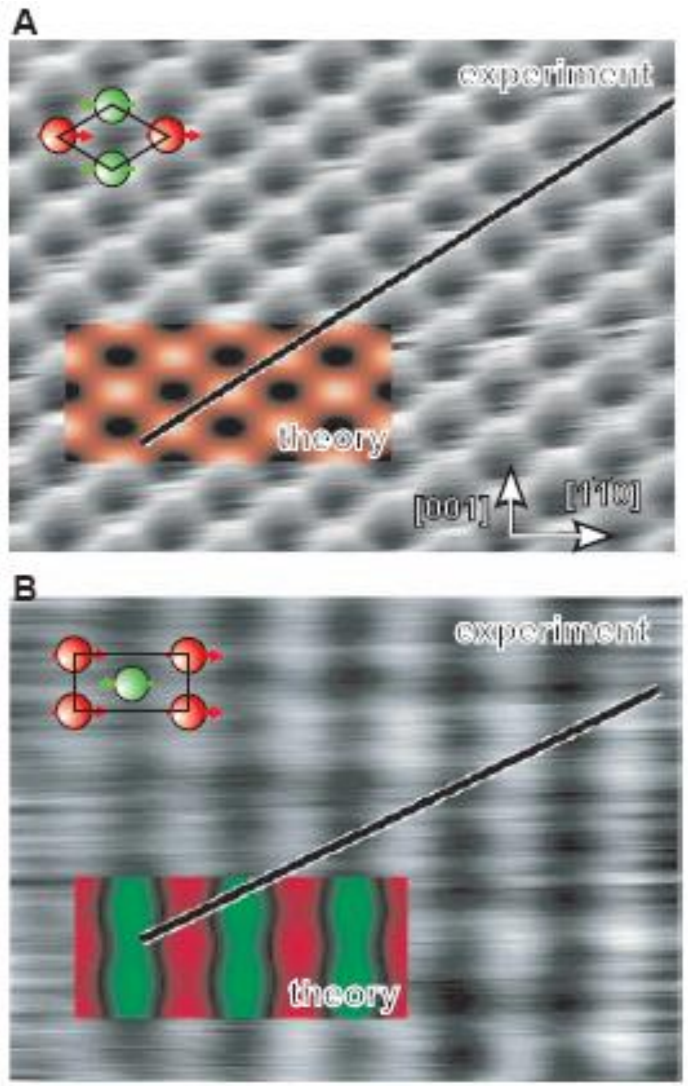
1 monolayer Mn/W(110)

W tip

1x1
unit cell

Fe coated tip

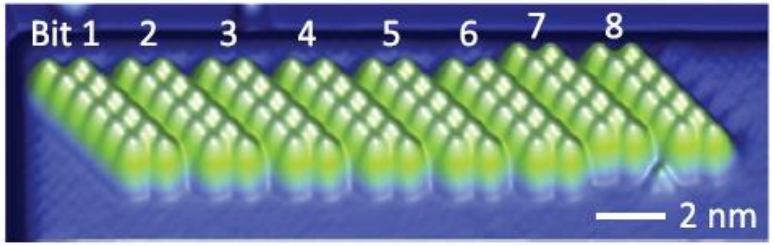
c 2x2
magnetic
unit cell

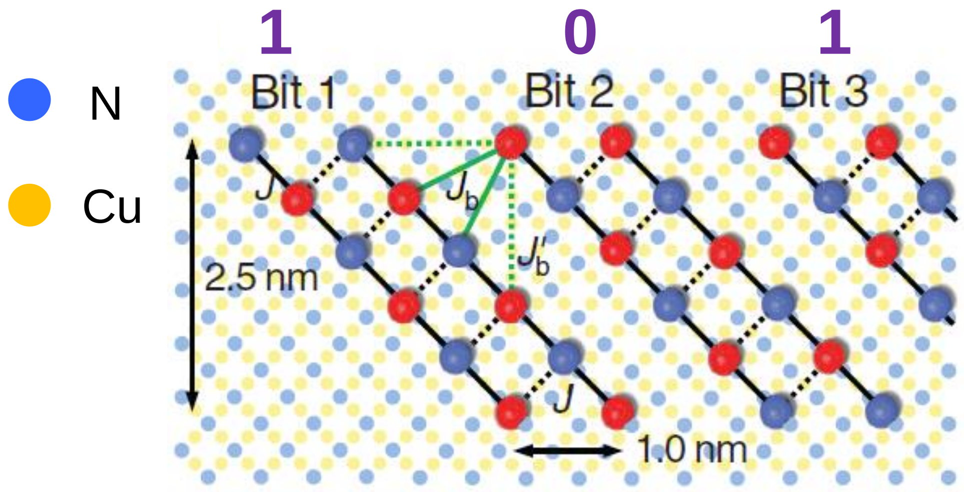


S. Heinze et al., Science 288, 1808 (2000)

Bistability in Atomic-Scale Antiferromagnets

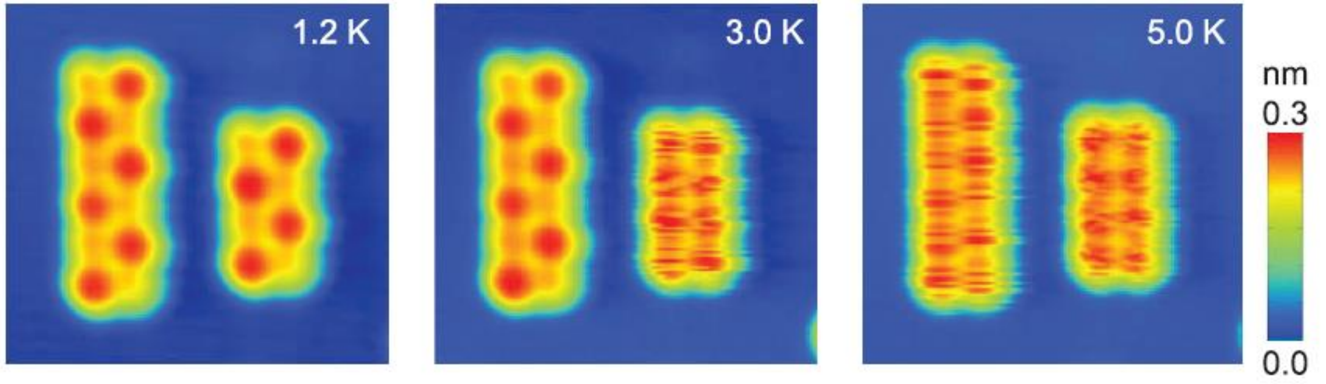
Fe nanostructures on Cu_2N

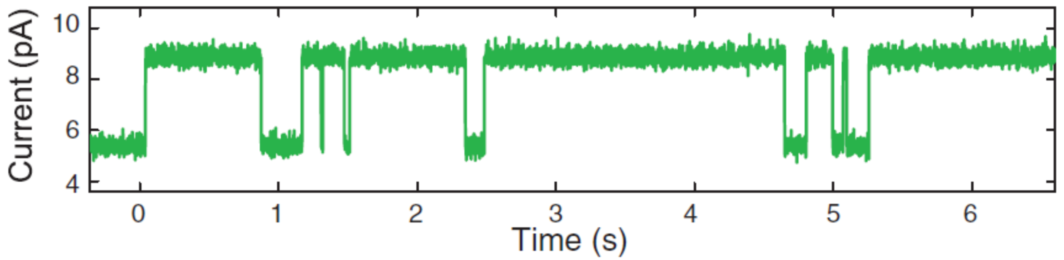




J : exchange coupling between atoms in a bit
J_b , $J_{b'}$: exchange couplings between atoms in neighboring bits.

Temperature stability

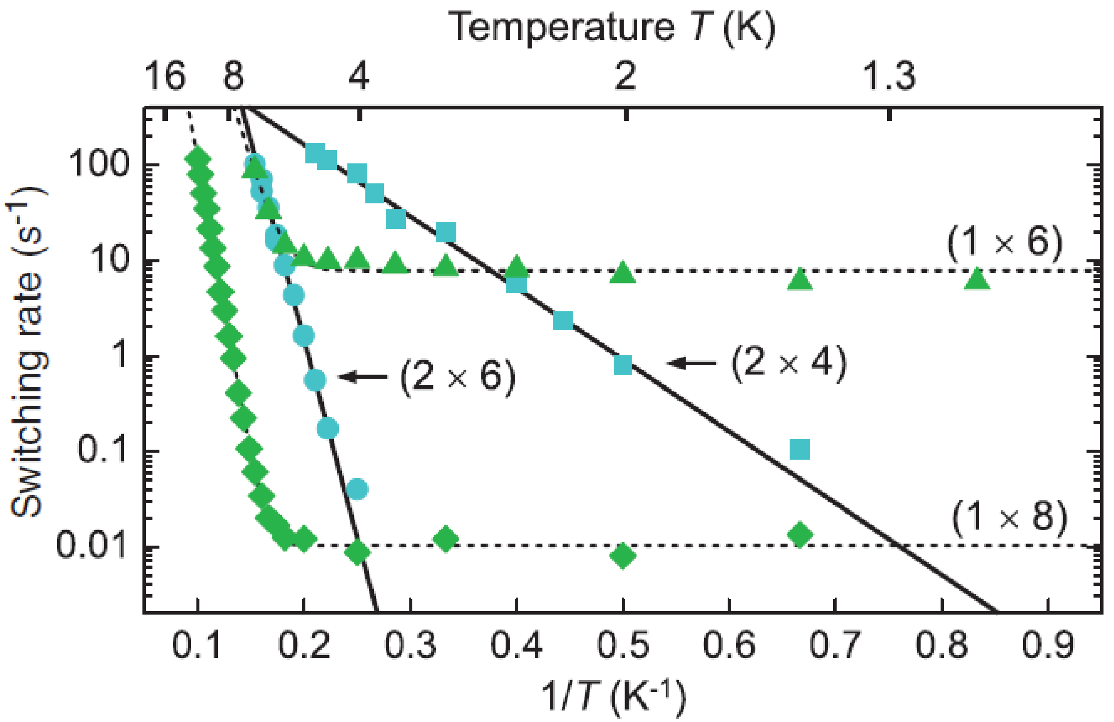




Switching between the two Néel states

S. Loth et al., Science 335, 196 (2012)

Size dependent spin-reversal mechanism



Reversal mechanism depends on the bit size and on T

Reversal over the top of the barrier or via excited state (assisted QT) is T dependent: $\tau = \tau_0 \exp(\Delta E/k_B T)$

QT is temperature independent