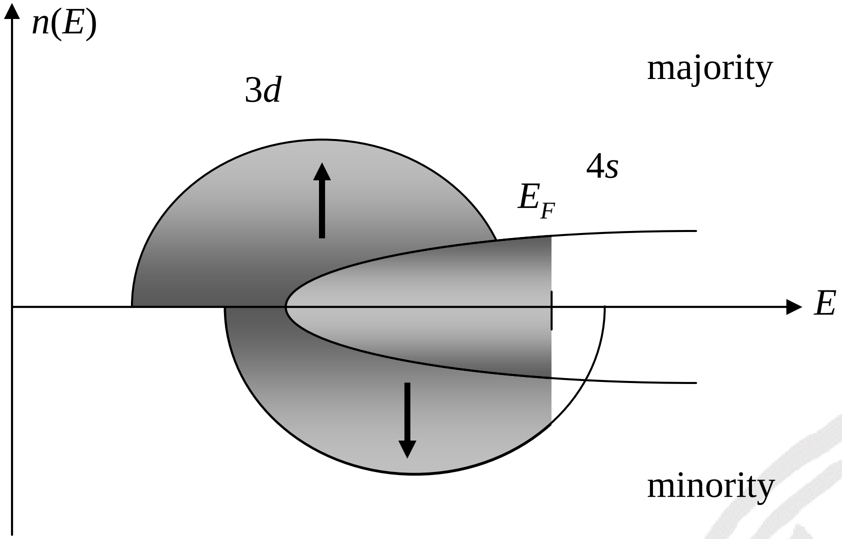
Spintronics – Basics electrical conduction in a ferromagnet

The *density of states* (DOS) in a ferromagnet is split into majority and minority bands due to the exchange interaction



- s- and d-electrons contribute to electrical conduction. The mobility of 3d-electrons is smaller (flat energy bands low velocity/high effective mass) than for 4s-electrons. Only electron-states close to the Fermi energy of importance.

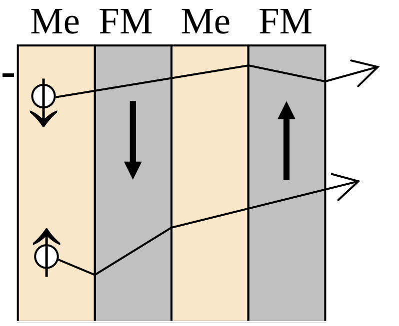
- In the example above, ↓ -electrons have more empty states to scatter to, the resistivity will be higher for these electrons; $\rho_\downarrow > \rho_\uparrow$, two independent electron conduction channels.

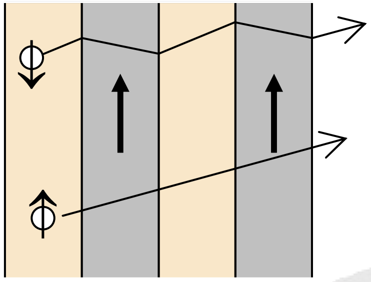
- Neglecting ρ_d, the resistivity of ↑ -electrons (majority electrons) will be $\rho_\uparrow \approx \rho_{\uparrow,s\to s}$, while the resistivity of ↓ -electrons (minority electrons) can be written as $\rho_\downarrow = \rho_{\downarrow s\to s} + \rho_{\downarrow s\to d}$, in most cases $\rho_{s\to d} > \rho_{s\to s}$.

Mechanism of GMR

Two current channels with different resistivities, the difference is mainly explained by the electronic structure and differences in the DOS for the majority and minority conduction electrons. In addition, we need to consider scattering centers, here we distinguish between bulk scattering and interface (FM/Me)

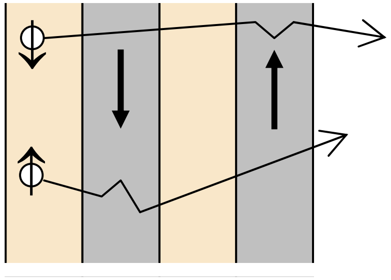
interface scattering





FM elements

bulk scattering



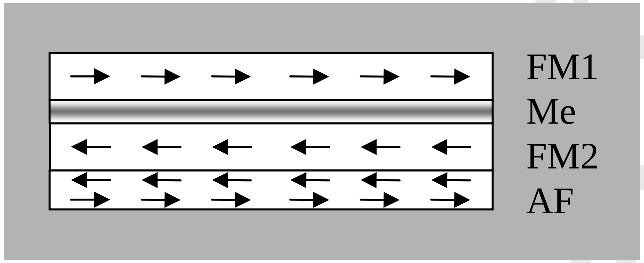
$\alpha = \rho_\downarrow / \rho_\uparrow > 1$ assumed

FM alloys

For applications, use two FM layers separated by a Me layer in a sandwich structure, one FM layer will be constrained by coupling to an adjacent antiferromagnetic layer (exchange anisotropy); FeMn ($T_N \approx$ 430 K), IrMn ($T_N \approx$ 470 K), CoO, ...

free layer

pinned layer



uni-directional anisotropy!

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SPINTRONICS

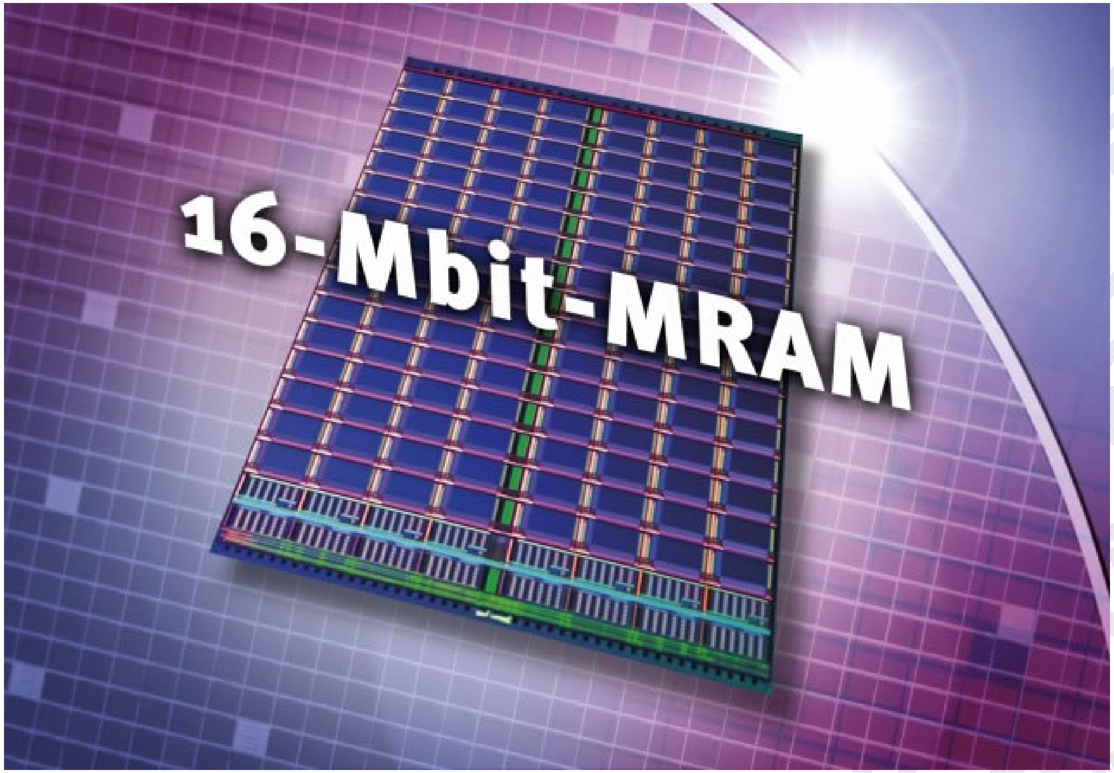
The acronym was originally used as name for a research program at DARPA **(**Defence Advanced Research Project Agency**)**

Overall goals

I. To produce a new generation of electronic devices where the spin of the carriers should play a crucial role in addition to or in place of the charge

II. To produce such materials that can be integrated with existing semiconductor materials

One example



Magnetoresistive
Random Access
Memory – MRAM

❑ IBM – Infineon in 2005 demonstrated a 16-Mbit magnetoresistive random access memory (MRAM) prototype

❑ Freescale Semiconductor Inc. summer 2006 introduced its first 4-Mbit MRAM as a commercial product

Magnetic tunnel junctions

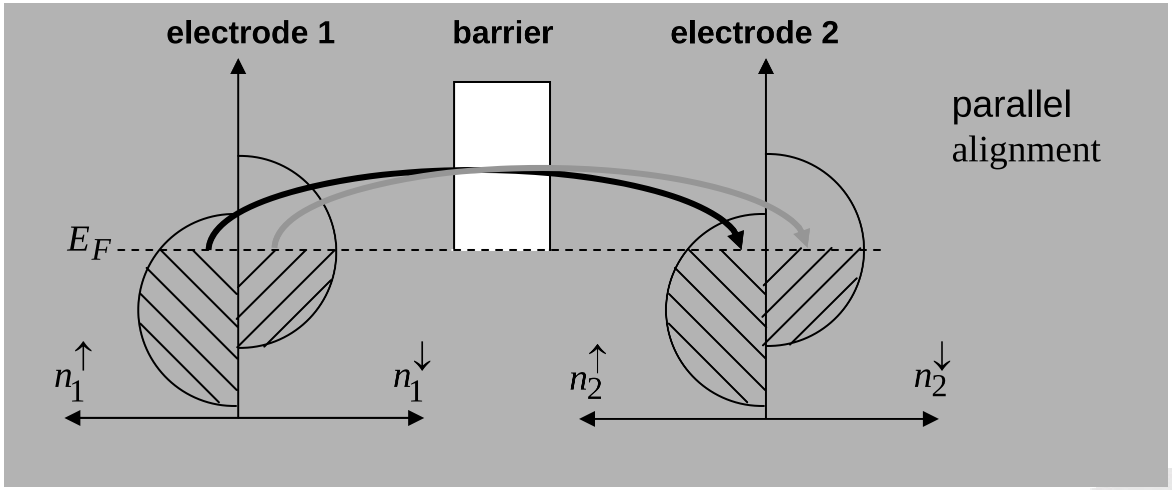
Quantum mechanics dictates that an electron in a metallic electrode has a certain probability to tunnel through an (insulating) potential barrier to another metallic electrode.

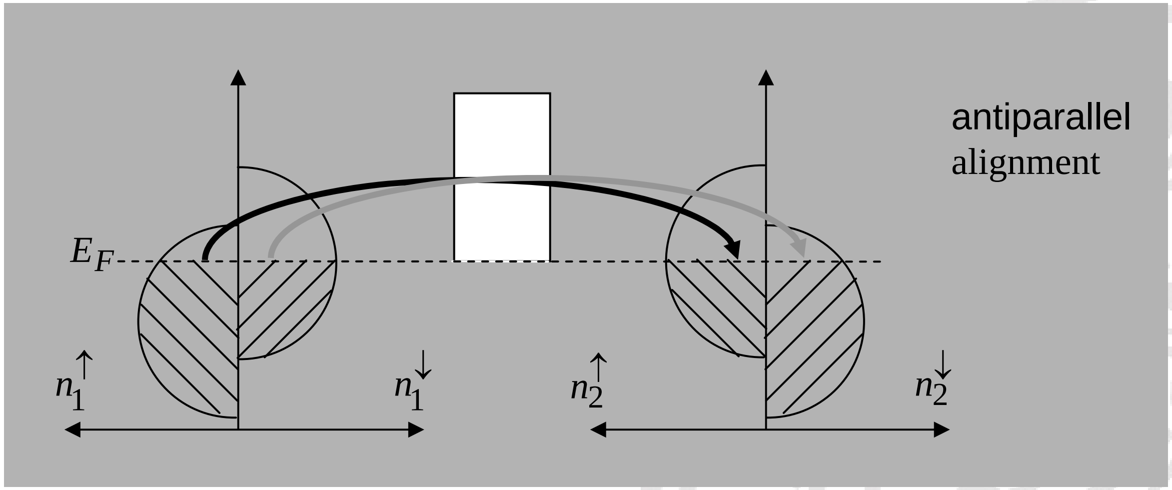
Important parameters – thickness of barrier, height of potential barrier and density of states (DOS) in the metallic electrodes. $n(E_F)$

Barrier height given by the energy difference between the metallic Fermi energy and lower Conduction band edge of the insulating barrier material

Tunnelling between two ferromagnetic electrodes

Schematic

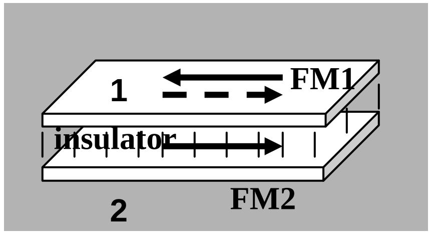




→ spin polarized transport, important parameter – spin polarization

$$P = \frac{n^\uparrow(E_F) - n^\downarrow(E_F)}{n^\uparrow(E_F) + n^\downarrow(E_F)}$$

Jullière's model (M. Julliere, Physics Letters **54A**, 225 (1975))



spin conservation

the conductance is proportional to products like $n_1^{\uparrow} n_2^{\uparrow}$

Relation between conductivity and resistivity changes ($G_{\uparrow\uparrow}\left(R_{\uparrow\uparrow}\right)$ conductivity (resistivity) for parallel magnetizations …)

$$\frac{\Delta G}{G_{\uparrow\downarrow}} = \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}} = \frac{\dfrac{1}{R_{\uparrow\uparrow}} - \dfrac{1}{R_{\uparrow\downarrow}}}{\dfrac{1}{R_{\uparrow\downarrow}}} = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}} = \frac{\Delta R}{R_{\uparrow\uparrow}}$$

Conductance when the magnetizations in the two FM electrodes are parallel ($f(E) =$ Fermi-Dirac distribution)

$$G_{\uparrow\uparrow} \propto n_1^{\uparrow}(E_{F-}) f(E_{F-}) \cdot n_2^{\uparrow}(E_{F+})\left(1 - f(E_{F+})\right) +$$

$$+ n_1^{\downarrow} f(E_{F-}) \cdot n_2^{\downarrow}\left(1 - f(E_{F+})\right) = \left\{\begin{matrix} n_1 = n_2 = n \text{ and} \\ f(E_{F-}) \approx 1;\ f(E_{F+}) \approx 0 \end{matrix}\right\} =$$

$$= n^{\uparrow 2} + n^{\downarrow 2}$$

and the corresponding result when the magnetizations are in opposite directions

$$G_{\uparrow\downarrow} \propto 2n^{\uparrow} \cdot n^{\downarrow}$$

Using the definition of spin polarization, we obtain

$$G_{\uparrow\uparrow} \propto \frac{1}{2}\left(1+P^2\right)\left(n^{\uparrow}+n^{\downarrow}\right)^2 \quad \text{and}$$

$$G_{\uparrow\downarrow} \propto \frac{1}{2}\left(1-P^2\right)\left(n^{\uparrow}+n^{\downarrow}\right)^2$$

and

$$\text{i)}\ \frac{G_{\uparrow\uparrow}-G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}} = \frac{\Delta R}{R_{\uparrow\uparrow}} = \frac{2P^2}{1-P^2}$$

can be generalized to two different FM materials with two different spin polarizations; P_1 and P_2

$$\text{ii)}\ \frac{\Delta R}{R_{\uparrow\downarrow}} = \frac{2P^2}{1+P^2}$$

A more complete theory by Slonczewski (Phys. Rev. B **39**, 6995 (1989)) describes how e.g. the tunneling conductance depends on barrier height and barrier thickness.

Typical dimensions

FM electrodes of sub-micron lateral size, thickness 10-20 nm

Tunnel barrier one or a few nm thick, barrier height 2-3 eV, junction resistance from < 100 Ω to tens of kΩ, depends exponentially on barrier thickness (and barrier height)

A spintronics material should *i*) exhibit FM properties at room temperature, *ii*) exhibit LARGE spin polarization and *iii*) preferably be compatible with existing semiconductor-based electronics.

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FM materials

Half-metallic ferromagnets

Fermi-level intersects the majority spin electron band, while the minority electron band has a gap at the Fermi-level ($P = 1$)

Heusler alloys – Ni_2MnGa ($T_c \approx 340$ K), Ni_2MnGe ($T_c \approx 320$ K)

Half-metallic oxides – CrO_2 ($T_c \approx 390$ K), Fe_3O_4 ($T_c \approx 860$ K)

Transition metal pnictides – MnAs ($T_c \approx 320$ K), MnSb ($T_c \approx 850$ K), CrSb ($T_c > 400$ K)
(all easily incorporated in existing semiconductor technology)

Magnetic semiconductors
(see e.g. A.H MacDonald, P. Schiffer, and N. Samarth, Nature Materials **4**, 195 (2005))
<u>III-V</u> diluted magnetic semiconductor ($Ga_{1-x}Mn_x$)As, $0.02 < x < 0.1$; Mn^{2+} substitutes for Ga, has five 3*d* electrons and gives a localized magnetic moment of $5\mu_B$, in addition acts as a hole dopant in that every Mn^{2+} contributes with one hole. BUT, $T_c \sim 170$ K.

<u>II-VI</u> systems, like 3*d*-doped ZnO; at present, despite claims made, no convincing evidence of a FM ground-state.

3d FM materials – Co, Fe, Ni, NiFe, CoFe, CoFeB

Barriers

Amorphous oxide tunnel barrier NiO, CoO, Al_2O_3.

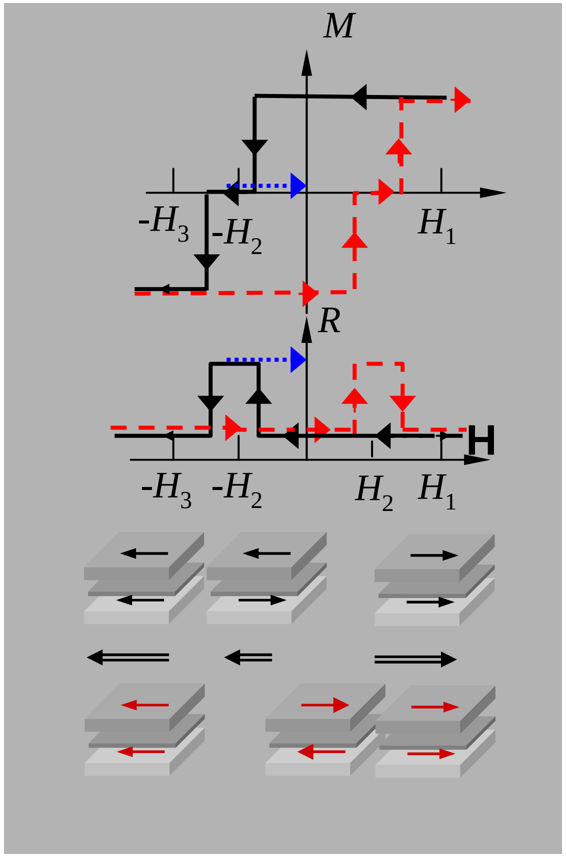
Important – Interfaces

Sharp interfaces without interdiffusion, minimum of spin-flip scattering at interfaces

Measured spin polarizations *P* (Meservey and Tedrow, Phys. Rep. **238**, 173 (1994))

Material	Ni	Co	Fe	NiFe	CoFe
P	+23%	+35%	+40	+32%	~50%

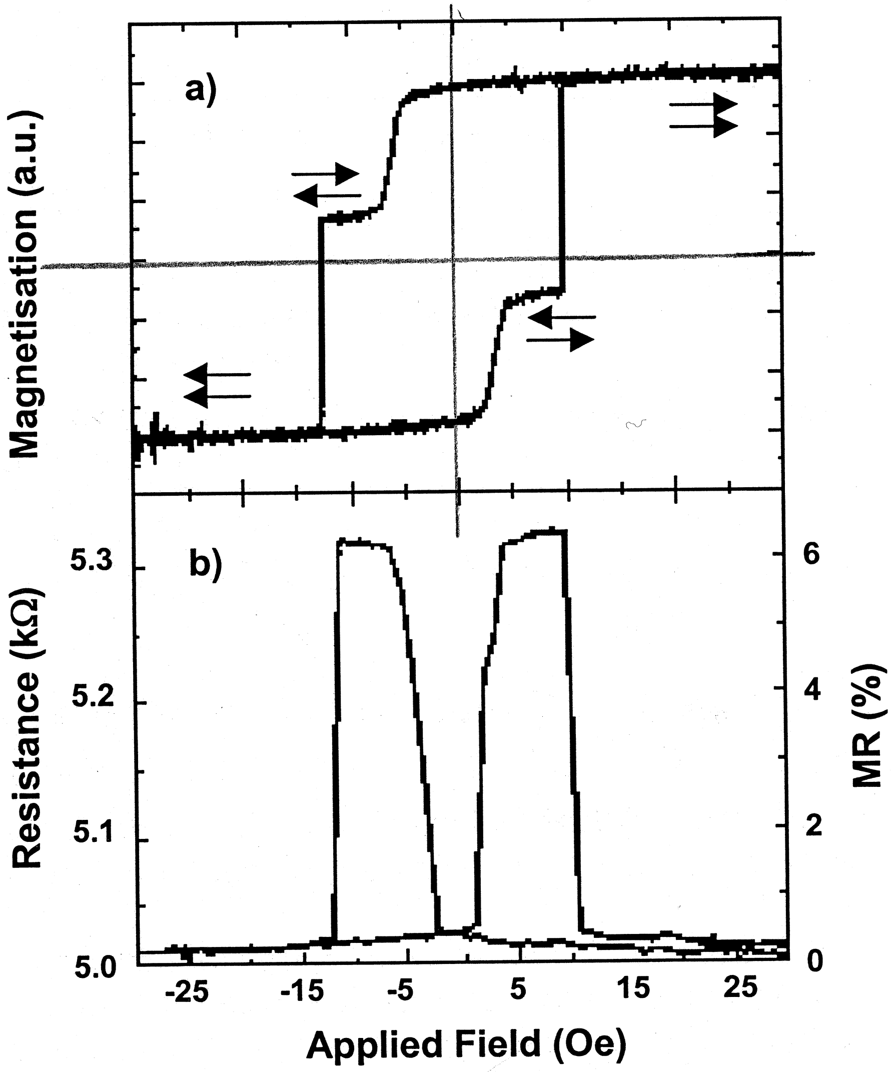
How to prepare a junction in low / high resistance states



one FM electrode may be pinned by an AF layer or the FM layers may have different H_c

TMR-results for Co/Al_2O_3/NiFe junctions $\Delta R / R_{\uparrow\uparrow}$

20.2%	27.1%	27.3%
RT	77K	4.2K



‘Recent’ advances – *epitaxial barriers or barriers with texture*

First-principle calculations (complex energy bands and Landauer conductance formula) of the tunneling conductance in Fe(100) | MgO(100) | Fe(100) junctions

W.H. Butler et al., Phys. Rev. B **63**, 054416 (2001)

I. Tunneling conductance depends strongly on the symmetry of Bloch states in the FM electrodes and of the evanescent states in the barrier.

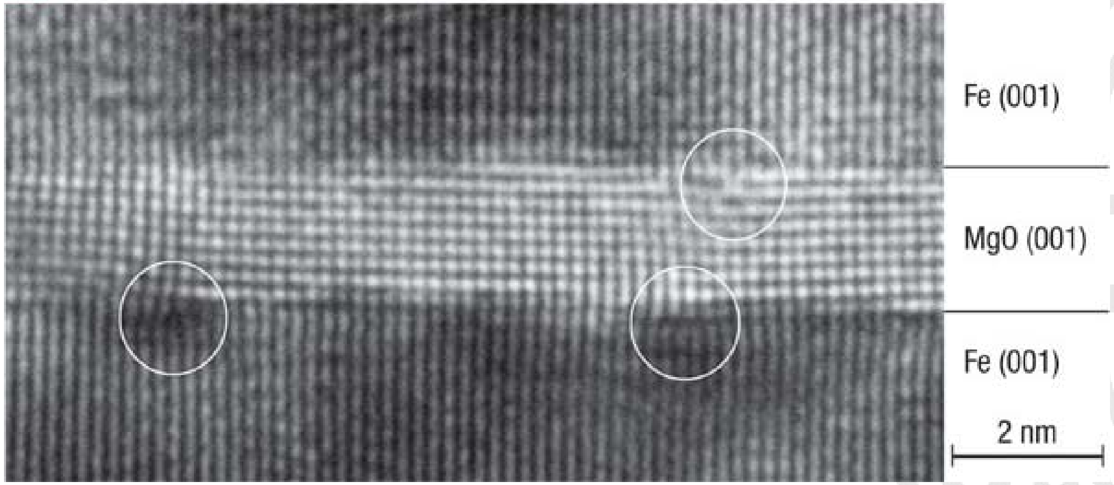
II. Bloch states of different symmetry decay at different rates within the barrier.

III. For Fe(100) | MgO(100) | Fe(100) a state of Δ_1 symmetry effectively couples electrons in the *majority* channel from Fe into MgO.

IV. For the minority channel, states of Δ_1 symmetry do not exist, and it is instead states of Δ_5 symmetry that dominate the conductance. However, the decay rate of Δ_5 inside the barrier is much larger than that of Δ_1.

Experimental confirmation

Stuart S.P. Parkin et al, Nature Materials **3**, 862 (2004); Shinji Yuasa et al, Nature Materials **3**, 868 (2004)



Good results both for *epitaxial* junctions and *polycrystalline* but *highly* (001) *oriented* junctions.

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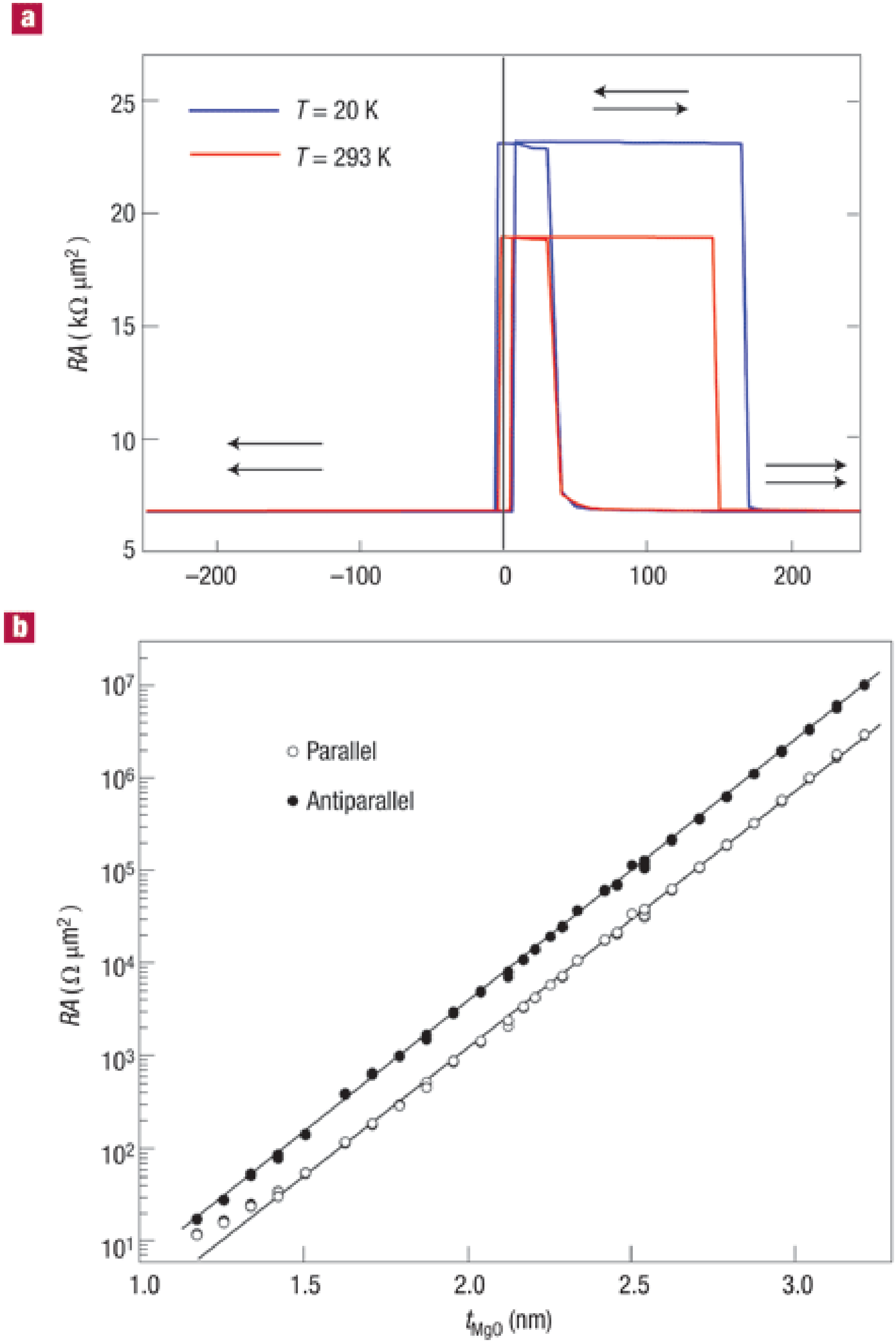
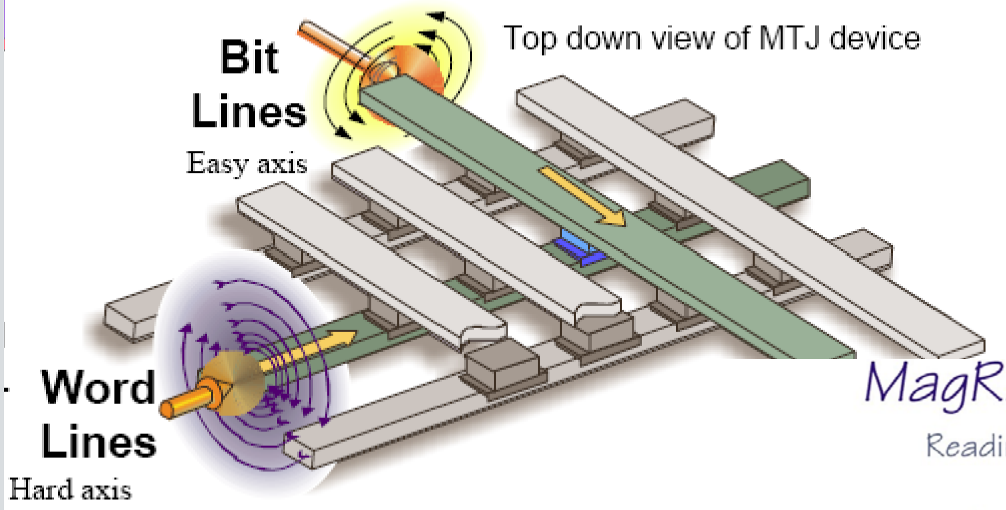


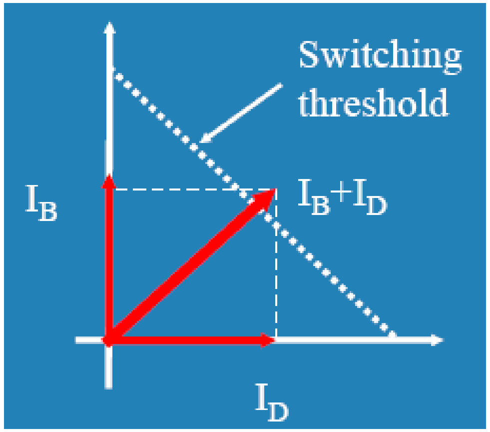
Fe | MgO | Fe | IrMn epitaxial junctions

$$\frac{\Delta R}{R_{\min}} = 180\% \text{ at 293 K and}$$

$$\frac{\Delta R}{R_{\min}} = 247\% \text{ at 20K.}$$

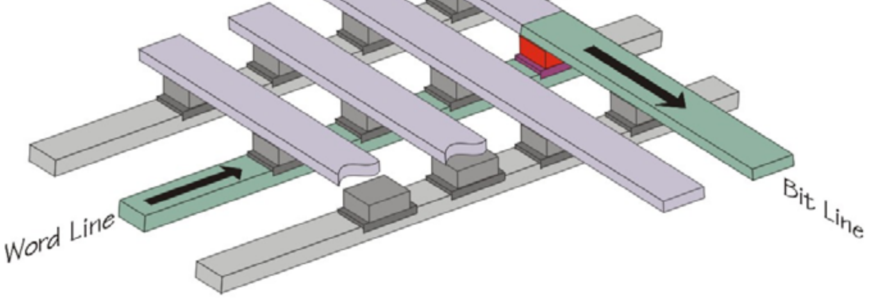


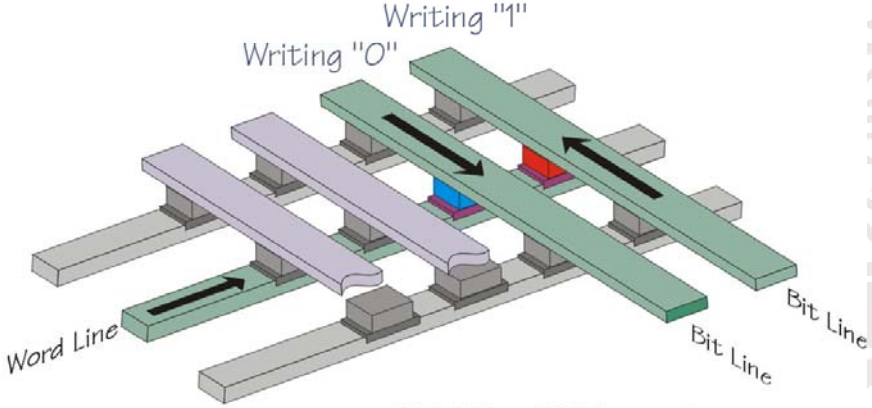
MagRAM Architecture



- ❑ Writing by currents in one word and one bit line (the total field is large enough to switch the magnetization in one electrode)
- ❑ Reading by probing the resistance over one TMR junction

Reading a bit





MTJ MagRAM promises
- density of DRAM
- speed of SRAM
- non-volatility

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Comparison of memory technologies for the Year 2011

	CMOS			
Technology	DRAM	Flash	SRAM	MRAM
Reference	SIA 1999	SIA 1999	SIA 1999	
Generation at introduction	64 GB	64 GB	180 MB/cm^2	64 GB
Circuit speed	150 MHz	150 MHz	913 MHz	>500 MHz
Feature size	50 nm	50 nm	35 nm	<50 nm
Access time	10 ns	10 ns	1.1 ns	<2 ns
Write time	10 ns	10 ns	1.1 ns	<10 ns
Erase time	<1 ns	10 µs	1.1 ns	N/A
Retention time	2-4 s	10 years	N/A	Infinite
Endurance cycles	Infinite	10^5	Infinite	Infinite
Operating voltage	0.5-0.6 V	5 V	0.5-0.6 V	<1 V
Voltage to switch state	0.2 V	5 V	0.5-0.6 V	<50 mV

SIA – Securities Industry Association

Access time – defined by how quickly the memory can respond to a read or write request

Retention time – memory is retention of information over this period of time

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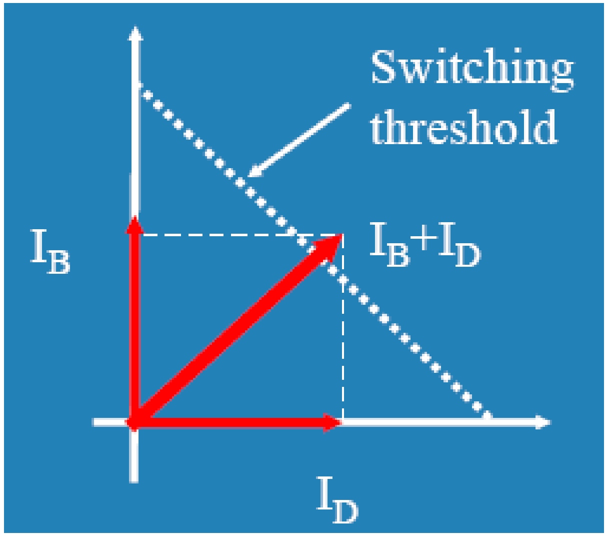
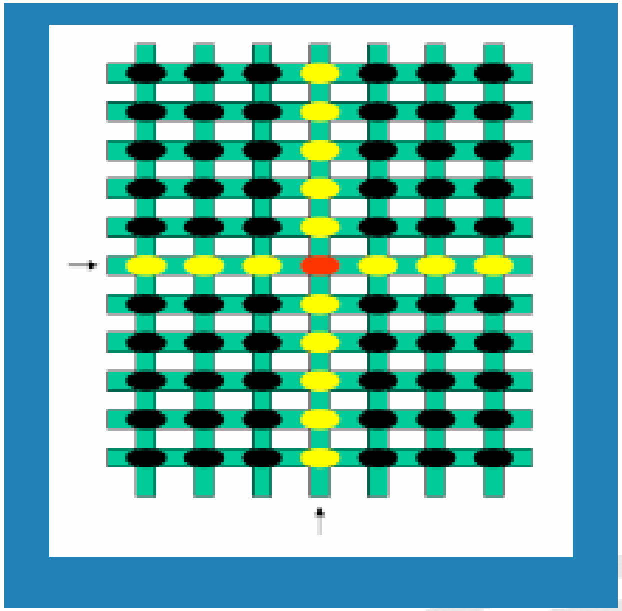




Major limitations of FW MRAM:

Because writing is i-field based (2D magnetic selection), it has the following limitations:

- 1/2 selected lines could cause addressing errors due to switching field distribution of the cells.
- FW limits the level of integration, difficult to implement at high density due to stray field cross interference.
- No parallel writing at high density due to cross interferences.
- High power consumption due to inductive writing, increasing with reduction of cell sizes, typical writing current more than 10 mA.

2007 R&D moving to spin transfer torque RAM (STTRAM) !

Spin transfer switching (Slonczewski, JMMM **159**, L1-L7 (1996))

Manipulation of magnetic moments in a nano-scale ferromagnet by a current is one of the most important techniques for the future spintronics devices.

Especially, current induced magnetization switching in MgO-based magnetic tunnel junctions (MTJs) are expected as a method of writing in high density magnetoresistive random access memory (MRAM).

The necessary critical current for spin transfer switching decreases as the free-layer volume decreases, implying a smaller writing current in MRAM with decreasing bit size, while conventional writing method using the magnetic field generated by a current needs a larger current with decreasing bit size.

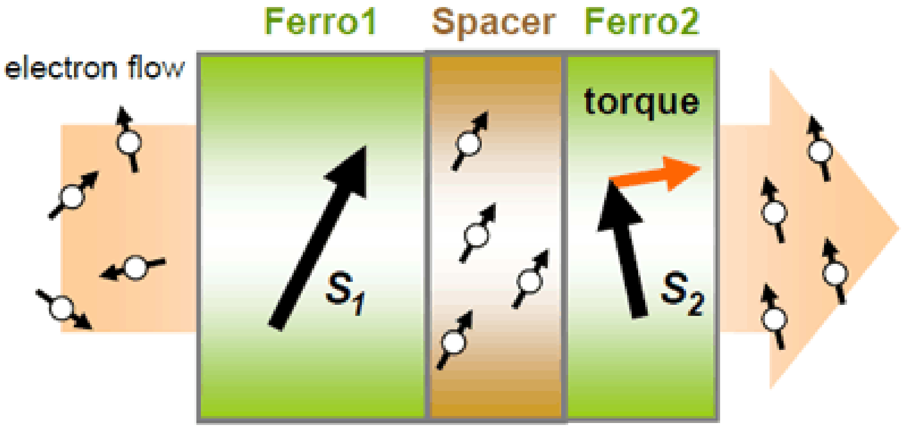


Fig. 1 Schematic illustration of spin transfer torque

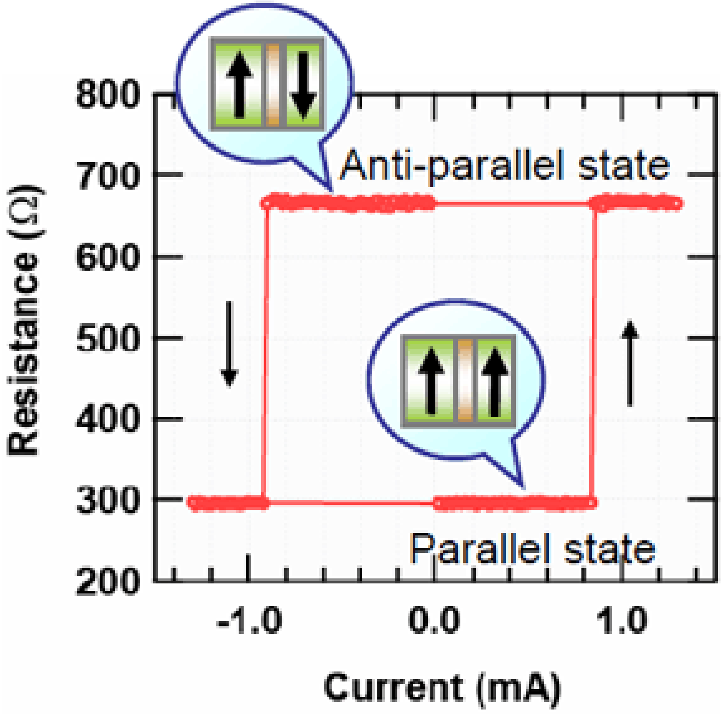


Fig. 2 Typical TMR loop driven by a pulse current.

Electrons flowing through a magnetic layer in a magnetoresistive device are spin polarized along the magnetization of F1.

When these spin-polarized electrons pass through another magnetic layer (F2), the polarization direction of the carriers will rotate towards mangetization direction of F2.

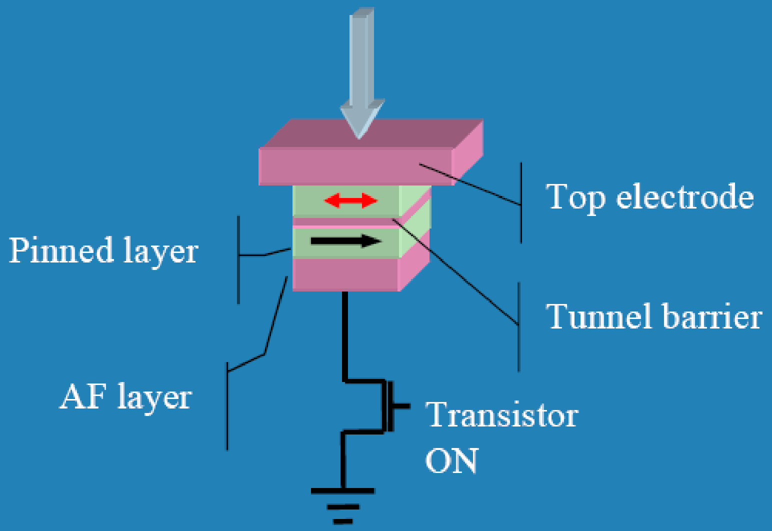
In this repolarization process, F2 experiences a torque (spin torque) associated with the transfer of spin angular momentum from the spin polarized carriers.

For large enough current, the spin torque amplifies the spin precession and magnetization switching occurs;

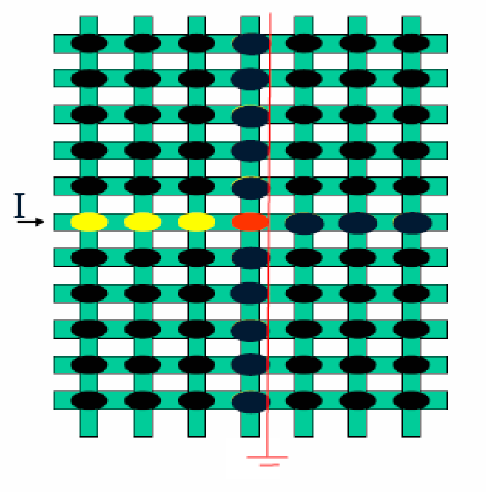
spin transfer torque $\propto b(P)\, J\, \underline{S}_1 \times \underline{S}_2$

Spin torque MRAM

Basic principle:
If a highly spin polarised current flows into a ferromagnetic layer, there is a 'torque' applied by the injected electron spins on the local moment that tends to induce a precession of the local magnetisation along this spin direction.



1-D magnetic selection, spin torque writing with much less current.



Advantages of spin torque writing

- **Retaining all the good features of** the previous versions of MRAM
- **No addressing errors**: The writing process uses a much smaller current that is only flowing through the addressed cell.
- **Multi-bit (parallel) writing**: As it has no half selection issue, it will not affect adjacent cells, fully compatible with parallel writing, whatever the integration level.
- **Low power consumption**: The write current being significantly reduced, the power consumption of writing and reading operation is minimised.
- **Potentially high integration level:** if writing current can be significantly reduced.

Some recent news

2007
R&D moving to spin transfer torque RAM (STTRAM)

February - Tohoku University and Hitachi developed a prototype 2 Mbit Non-Volatile RAM Chip employing spin-transfer torque switching

August - IBM, TDK Partner In Magnetic Memory Research on Spin Transfer Torque Switching to lower the cost and boost performance of MRAM

November - Toshiba applied and proved the spin transfer torque switching with perpendicular magnetic anisotropy MTJ device – is expected to yield smaller critical currents

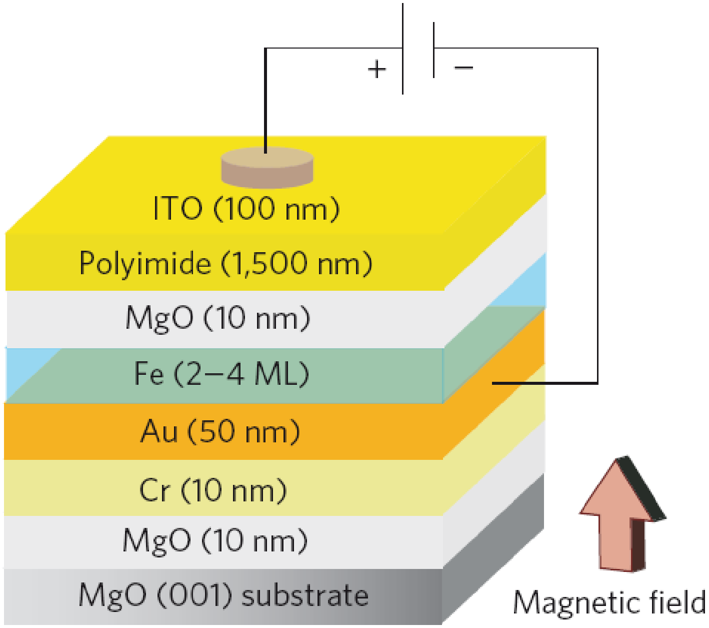
November - NEC Develops World's Fastest SRAM-Compatible MRAM With Operation Speed of 250MHz

2008
Japanese satellite, Sprite Sat, to use Freescale MRAM to replace SRAM and FLASH components, collaboration including Ångström Aerospace Corporation who has developed a MEMS unit including a magnetometer to study Earth's magnetic field.

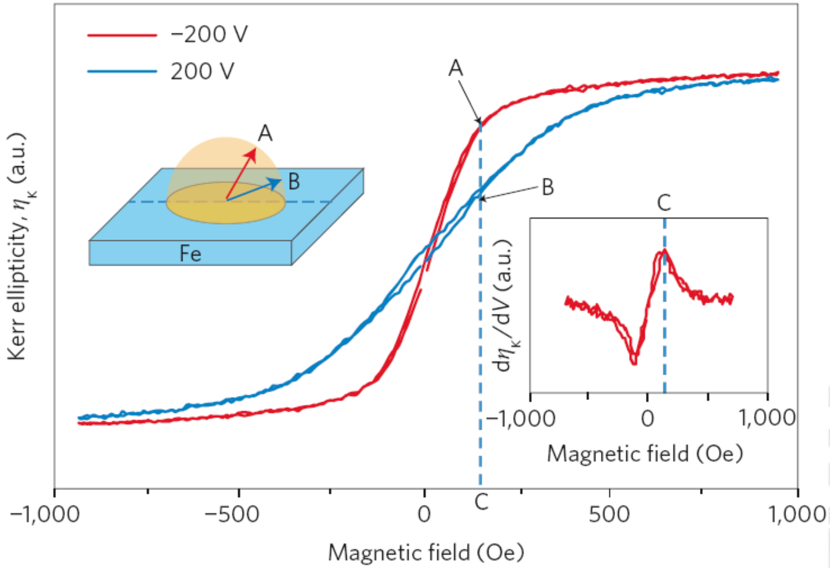
August - Scientists at the Physical-Technical Federal Laboratory of Germany (Serrano-Guisan and Schumacher), in collaboration with researchers at University of Bielefeld and Singulus Nano-Deposition Technologies, have built a spin-torque system much faster than others, is said to operate as fast as fundamental performance limits allow, with write cycles below 1 nanosecond.

Voltage induced magnetic anisotropy change – the very LATEST news

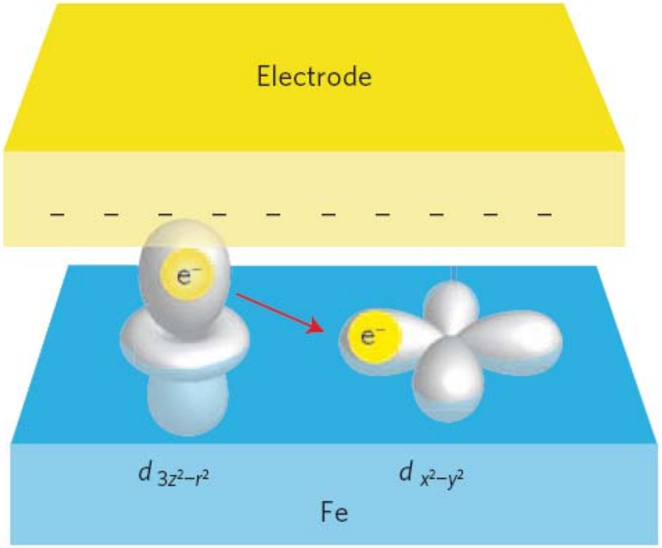
Maruyama et al., Nature Nanotechnology, Advance Online publication, 18 January 2009



Result



Explanation



Simulation