Information storage: electronics vs. spintronics

HDD: hard disk drive
High density magnetic storage

SD: secure digital
Solid state non volatile memory

Electronics: Using electron charge to determine high-low levels

Dynamic random-access memory (DRAM) is a type of random-access memory that stores each bit of data in a separate capacitor within an integrated circuit (=> Single electron transistor to reduce as much as possible the size of the capacitor)

Since the capacitors used in DRAM lose their charge over time, memory assemblies that use DRAM must refresh all the cells in their chips approximately 20 times a second

Volatile
Spintronics: Using electron spin to determine high-low levels

**Magnetic random access memory (MRAM)** never requires a refresh. This means that not only does it retain its memory with the power turned off but also there is no constant power-draw much lower power consumption (up to 99% less) compared to DRAM.

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.

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

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

Spin up and spin down states are split by an external magnetic field $\mathbf{H}$ (Zeeman energy). If $\mathbf{H}$ is removed, the system relax in a non magnetic state ($N^\uparrow = N^\downarrow$) with a relaxation time of about $10^{-11}$ seconds.

Ferromagnetism

Spin up and spin down states are split by an external magnetic field $\mathbf{H}$ (Zeeman energy). If $\mathbf{H}$ is removed, the system relax in a magnetic state ($N^\uparrow \neq N^\downarrow$) with a relaxation time of about $10^{-11}$ seconds.
**Single atom**
Due to the electron spin and the electronic processional motion an isolated atom has a non zero magnetic moment.

**Paramagnetism**
In a paramagnet, the magnetic moments tend to be randomly oriented due to thermal fluctuations when there is no magnetic field. In an applied magnetic field these moments start to align parallel to the field such that the magnetisation of the material is proportional to the applied field.

**Ferromagnetism**
The magnetic moments in a ferromagnet have the tendency to become aligned parallel to each other under the influence of a magnetic field. However, unlike the moments in a paramagnet, these moments will then remain parallel when a magnetic field is not applied.

**Antiferromagnetism**
Adjacent magnetic moments from the magnetic ions tend to align anti-parallel to each other without an applied field. In the simplest case, adjacent magnetic moments are equal in magnitude and opposite therefore there is no overall magnetization.
Available states with the same spin:
Low resistance

Absence of 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 →

Electric current

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

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

In non magnetic materials $J = 0$

Domain wall between two pinned ferromagnetic materials with opposite orientation of the magnetization

Without the spacer two (negative) scenarios depending on the strength of the exchange force in respect to the pinning force:

a) The free layer magnetization always aligns parallel to the magnetization of the pinned layer

b) A domain wall forms which produces the spin current depolarization
Exchange bias

FM: ferromagnetic material; AFM: antiferromagnetic material

$H_E$ : exchange bias is the shift of the hysteresis curve

Due to the interaction (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 in respect to the field necessary to force
the anti-parallel alignment by $H_E$

N.B.: the magnetic field necessary to invert the spin orientation in the
AFM is several tens of Tesla
GMR based devices

GMR: Giant Magnetic 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
MTJ based devices

MTJ: Magnetic Tunnel Junction

Improved performance with respect to GMR

Spin-dependent tunneling

Transmission through a crystalline MgO tunneling barrier: Because of the two-dimensional periodicity, the crystal momentum parallel to the layers is conserved.

For the majority channel the conductance has a rather broad peak centered at $k_{||} = 0$.

$$T = \text{transmission through the tunnel barrier}$$

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

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

The transmission depends on the electronic state symmetry

Tunneling DOS for $k_{//} = 0$ for Fe(100)/8MgO/Fe(100).

\[ \Delta_1 \rightarrow \text{totally symmetric wave function with respect to the normal to the tunnel barrier: } s, p_z, d_{2z^2-x^2-y^2}. \]

\[ \Delta_1 \text{ is a slowly decreasing evanescent state for majority spins.} \]

\[ \Delta_1 \text{ is absent for the minority spins.} \]

The symmetry of the wave functions depend on the crystallographic structure of electrodes and barrier $\rightarrow$ optimization of the structure to optimize the spin valve performance

Tunneling DOS

When the spins are parallel, $\Delta_1$ can get through the barrier and enter the electrode on the other side. When the spins are anti-parallel, $\Delta_1$ can not enter the other electrode.

Total reflection of the tunneling electrons at $k_{//}=0$ for antiparallel spin alignment in the case of Co/MgO/Co junction -> higher TMR than in Fe/MgO/Fe junction

The electronic DOS of the two electrodes determines the TMR

Electronic and magnetic properties are strictly correlated

Reading: the bit stray field defines the magnetization direction of the free layer
MRAM: Magnetic Random Access Memory

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

MRAM advantage over electronic based RAM: the data are retained after the power is turned off
2D write selection with MRAM

The MRAM is engineered in such a way that the bit easy axis points at 45° in respect 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
Writing by spin polarized current switching

Directions of torque on the magnetic moments in layer 1, due to spin transfer by current flow. Parallel alignment of the moments in the two layers is unstable for sufficiently large positive currents, whereas antiparallel alignment is unstable for large negative currents.

\[ \mathbf{\tau}_{1,2} \propto I s_{1,2} \times (s_1 \times s_2) \]

If an electron travels through a thin film of magnetic material, the magnet exerts a torque on the electron tilting its spin. According to the Newton’s third law, the electron must exert an equal and opposite torque on the magnet, which causes the magnet moment vector to tilt as well (angular momentum conservation).

Electrons polarized by the pinned ferromagnet exert a torque on the free ferromagnet. Motion of the free layer magnetization, \( \mathbf{M}_F \), is monitored through the resistance, which depends on the relative orientation of \( \mathbf{M}_F \) and the pinned-layer magnetization, \( \mathbf{M}_P \). The resistance continuously varies from low to high resistance as \( \mathbf{M}_F \) and \( \mathbf{M}_P \) go from parallel to antiparallel, respectively.
Writing by spin polarized current switching

An external magnetic field first switches the soft (thin) film and than the hard (thick) one.

The same high-low conductance level can be reached by applying an external magnetic field or by injecting spin polarized current.

Magneto-resistance change induced by a spin polarized current.

Spintronics with semiconductor

(a,b) Spin injection from a magnetic spin emitter (metal or semiconductor) into a semiconductor (2DElectron gas channel) and spin detection by a magnetic collector (spin analyser). Injection and detection are through tunnel barriers. For a parallel (P) configuration of magnetic moments in the emitter and collector (a), a spin-polarized current is injected and transmitted to the collector. For an antiparallel (AP) configuration (b), spin up electrons are injected and accumulated in the semiconductor (due to the poor transmission to the collector) and rejected in major part into the emitter. The condition for strong accumulation is that the spin lifetime in the semiconductor be longer than the time spent by the particle in the semiconductor. (e) Magnetoresistance of a heterostructure of the type of (d). (f) Temperature dependence of the spin life time in a GaAs QW from magnetoresistance measurements on a heterostructures of the type of (d).
The electrons moving in the 2DEG have near-relativistic velocities so that in their system the gate electrical field appears as a magnetic field oriented perpendicularly to the spin velocity.

**Spin field effect transistor**

Electron spin precession around the magnetic field

Depending on the gate voltage the electron spins invert the direction during the source-drain displacement.

The gate voltage can be used to tune the 2DEG conductivity leaving unchanged the magnetic state of source and drain.

Spin polarized elastic tunneling

Junction magnetoresistance: \( R_{\text{JMR}} = \frac{\Delta R_J}{R_J} = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\downarrow}} = \frac{2P_T P_S}{1 + P_T P_S} \)

Spin polarization at \( E_F \) (describes the asymmetry between spin up and down)

\[ P_{T,S}(E_F) = \frac{\rho_{T,S}^{\uparrow}(E_F) - \rho_{T,S}^{\downarrow}(E_F)}{\rho_{T,S}^{\uparrow}(E_F) + \rho_{T,S}^{\downarrow}(E_F)}. \]

\( \rho_{T,S}^{\uparrow}(E_F) \) is the Tip (T) or Sample (S) at the Fermi level

Conductivity at zero bias:

\[ \frac{dI}{dU} \propto \rho_T^{\uparrow}(E_F) \rho_s^{\uparrow}(E_F) + \rho_T^{\downarrow}(E_F) \rho_s^{\downarrow}(E_F). \]

\[ I(\vec{r}_0, V) = I_0(\vec{r}_0, V) + I_{SP}(\vec{r}_0, V, \theta) \]

\( I_{sp} \approx P_T P_s \cos (M_t M_s) \) -> spin polarized tunneling current which depends on the mutual orientation of tip and sample magnetization

SP-STM review:
Spin polarized STM (SP-STM)

STM with a magnetic tip

Topological antiferromagnetic order of the Cr(001) surface with terraces separated by monoatomic steps. Different terraces are magnetized in opposite directions.

FIG. 3. Arbitrarily chosen (not successive) single-line scans over the same three monatomic steps taken from the STM image of Fig. 2(b), which was obtained with a CrO$_2$ tip. The same alternation of the step-height values (0.16, 0.12, and again 0.16 nm) in all single-line scans is evident. The line scans are 22 nm long. Inset: For comparison, a single-line scan over two monatomic steps taken from the STM image of Fig. 2(a), which was obtained with a tungsten tip. In this case, the measured step-height value is constant and corresponds to the topographic monatomic step height. This line scan is 70 nm long.

FIG. 4. Schematic drawing of a ferromagnetic tip scanning over alternately magnetized terraces separated by monatomic steps of height $h$. An additional contribution from SP tunneling leads to alternating step heights $h_1 = h + \Delta s_1 + \Delta s_2$ and $h_2 = h - \Delta s_1 - \Delta s_2$.
By applying an alternating current of frequency $f$ through a small coil wound around the magnetic tip, the magnetization of a soft magnetic tip is switched periodically without affecting the sample magnetization.

The frequency is set well above the cut-off frequency of the feedback loop.

The high frequency signal is detected with a lock-in amplifier.

The tunnel probability due to the magneto-tunnel effect is maximal for parallel and minimal for antiparallel orientation between tip and sample magnetization.

The low frequency signal gives the topography information.

The high frequency signal gives the magnetization information.

Topography and magnetization available at the same time.

Schematic drawing of the experimental setup for measuring the vacuum-tunneling magnetoresistance between an Fe-coated W tip and a Gd(0001) island.

a) Tunneling conductance as measured with an Fe-coated W tip above a Gd (0001) island magnetized in two opposite directions. An asymmetry of the dI/dU signal between the two spin components of the exchange-split Gd (0001) surface state can clearly be recognized. b) Tunnel resistance changes at the bias voltages corresponding to the energetic positions of the two spin components of the exchange-split surface state are found to be as high as 31% for the filled state part and 13% for the empty state part.

Tunneling spectra of a Fe-coated tip on a Cr(001) surface

Best magnetic contrast during a constant current scan

LDOS peak due to minority surface state of Cr(001)

Sub nm resolution of magnetic domains

Structure of a domain wall between two ferromagnetic domains with opposite orientation of the local magnetization (180° wall)

1.3 monolayers Fe / stepped W(110)

- Real-space observation of dipolar induced antiparallel domain orientation
- Atomically narrow domain walls

Atomically resolved anti-ferromagnetic order

1 monolayer Mn/W(110)

1x1 unit cell

c 2x2 magnetic unit cell

Ultradense AFM data storage. (A) Non-spin-polarized STM image, 24×8 nm, of eight (2×6) arrays assembled from Fe atoms on Cu$_2$N. (B) Schematic of the bits in (A), with colors. Jb and Jb': pairwise canceling exchange couplings between atoms in neighboring bits.

**Temperature stability**

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