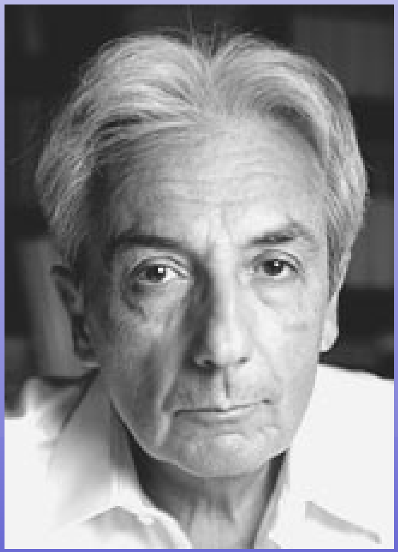
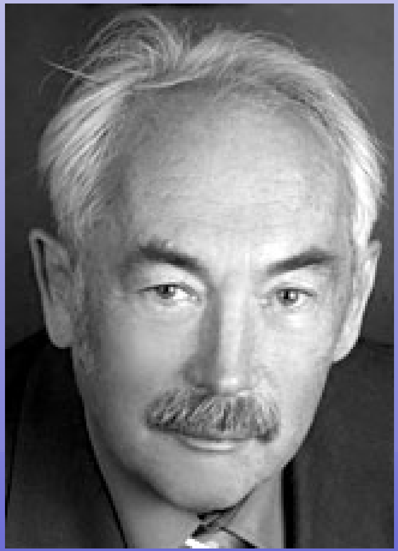
Premio Nobel del Física 2007

MAGNETO-RESISTENCIA GIGANTE: DEL LABORATORIO AL DISCO DURO DEL PC



- ***Descubrimiento de la magneto-resistencia gigante (GMR).***
- ***La GMR ha revolucionado las técnicas de lectura de datos en discos duros.***
- ***La GMR ha permitido desarrollar una nueva generación de sensores y dispositivos electrónicos.***
- ***La GMR constituye una de las primeras grandes aplicaciones de la nanotecnología.***

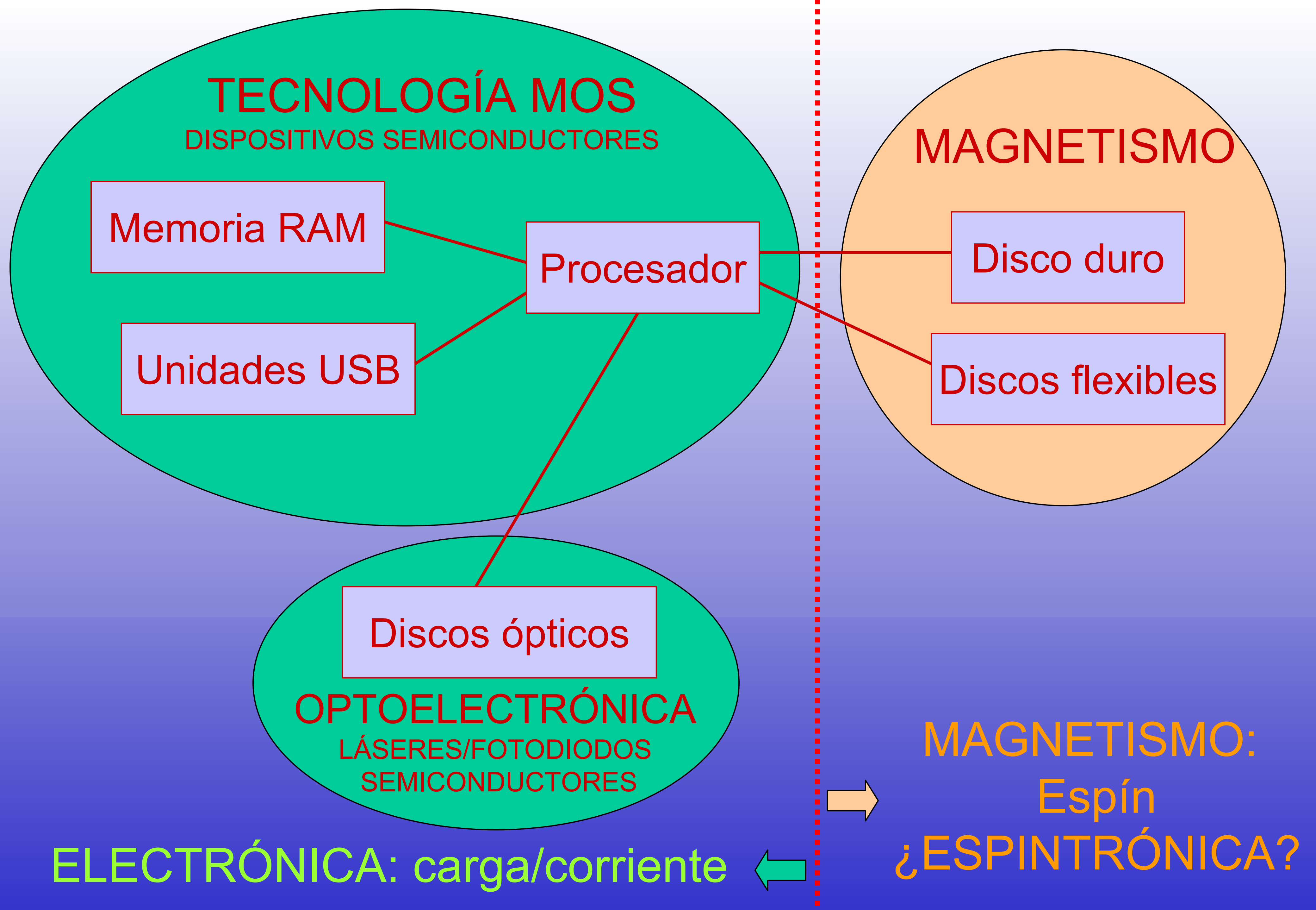


Albert Fert (1938)
Université Paris-Sud
Unité Mixte de Physique CNRS/THALES
Orsay, France

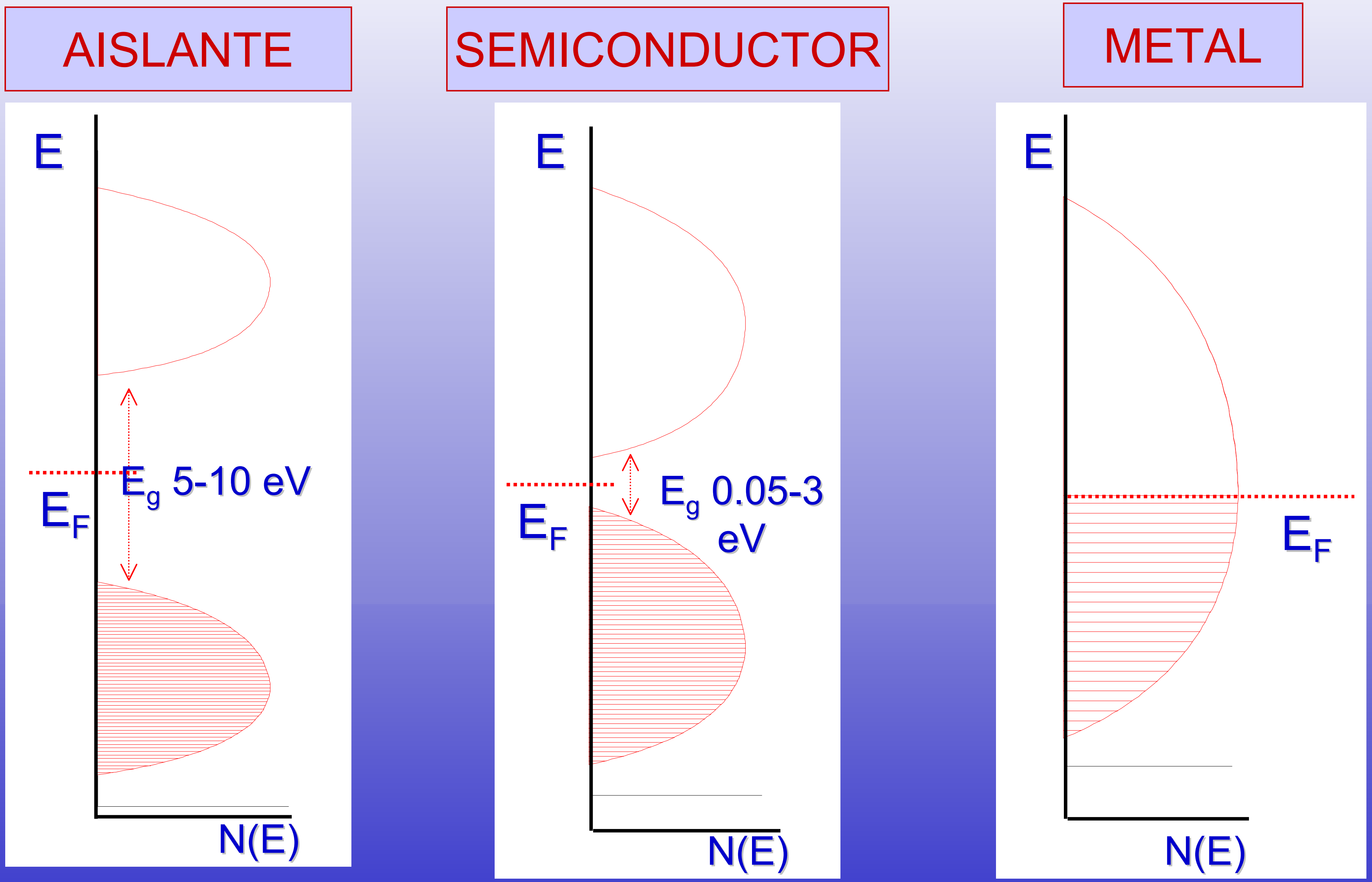
Peter Grünberg (1939)
Forschungszentrum Jülich
Jülich, Germany

Esquema de la charla

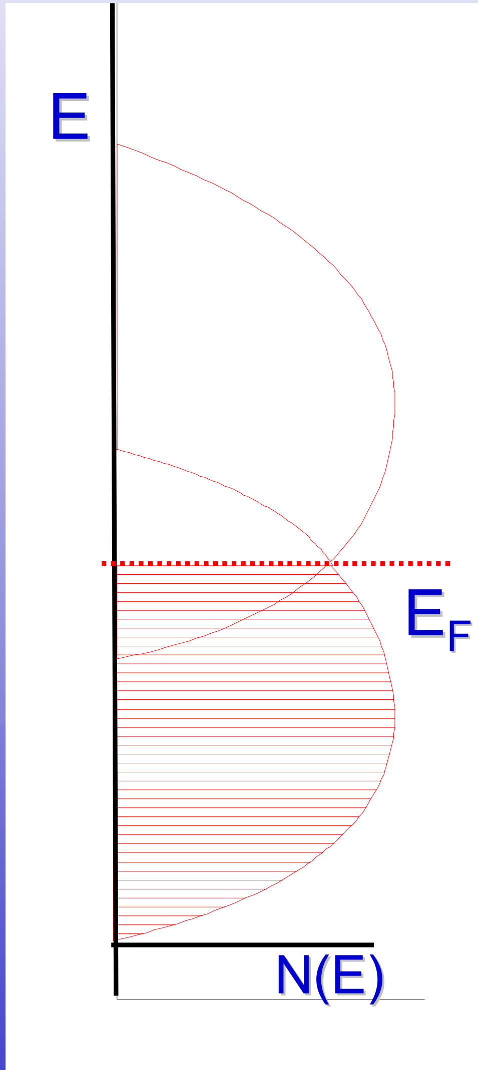
- Electrónica versus espintrónica
- Aislantes, semiconsuctores, metales
- Tecnología FET-MOS
- Materiales ferromagnéticos
- ¿Qué es la magnetorresistencia?
- Magnetorresistencia normal
- Magnetorresistencia gigante en multicapas magnéticas
- La válvula de spin
- Aplicaciones a la lectura de datos
- Memorias RAM basadas en válvulas de spin
- Otras consecuencias y desarrollos


TECNOLOGÍA MOS
DISPOSITIVOS SEMICONDUCTORES
Memoria RAM
Procesador
Unidades USB
MAGNETISMO
Disco duro
Discos flexibles
Discos ópticos
OPTOELECTRÓNICA
LÁSERES/FOTODIODOS SEMICONDUCTORES
MAGNETISMO: Espín
¿ESPINTRÓNICA?
ELECTRÓNICA: carga/corriente

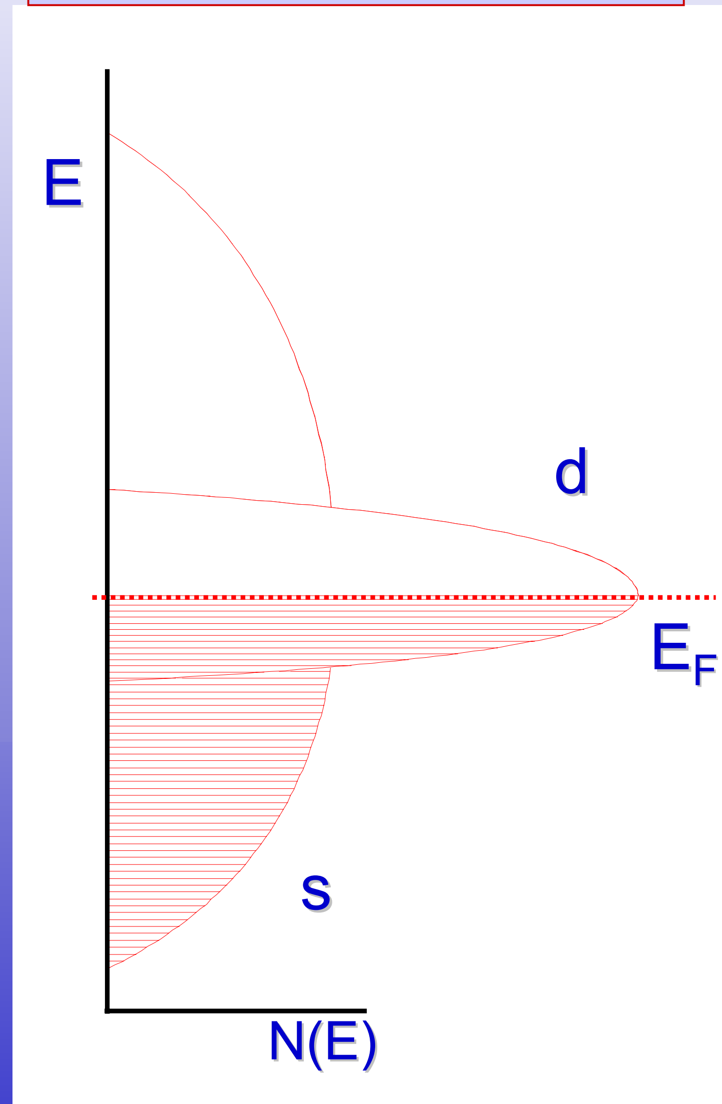
Bandas de energía en los sólidos



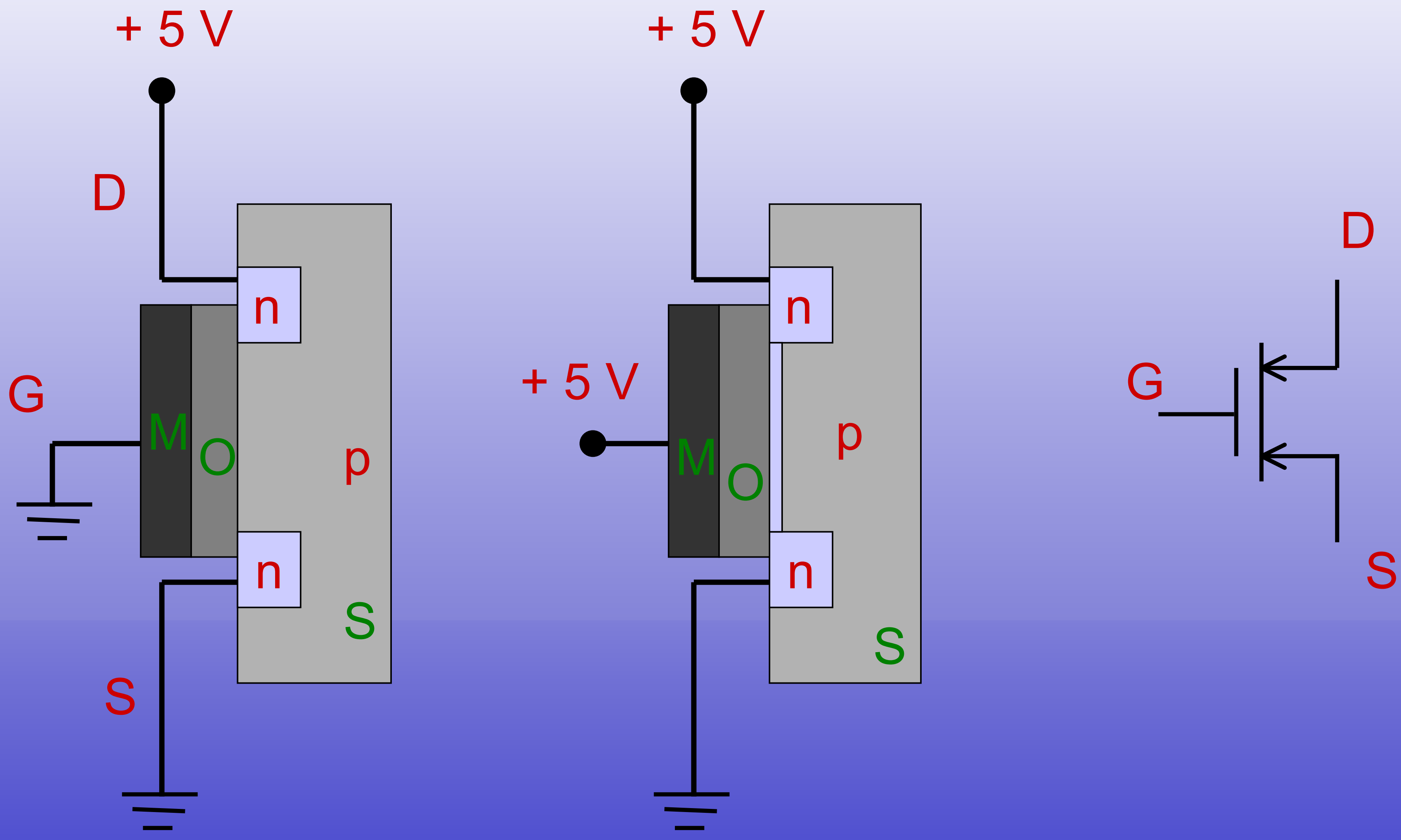
Metal o semimetal



Metales de transición



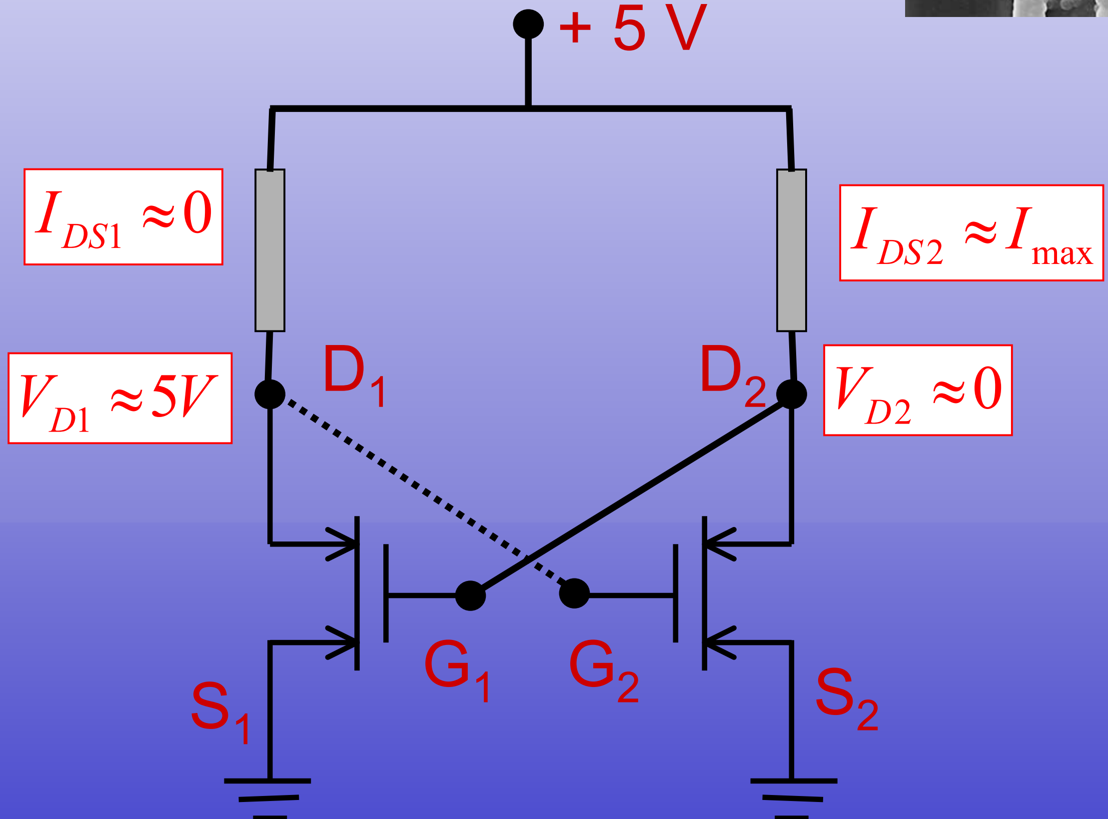
TECNOLOGÍA MOS: Transistor FET-MOS

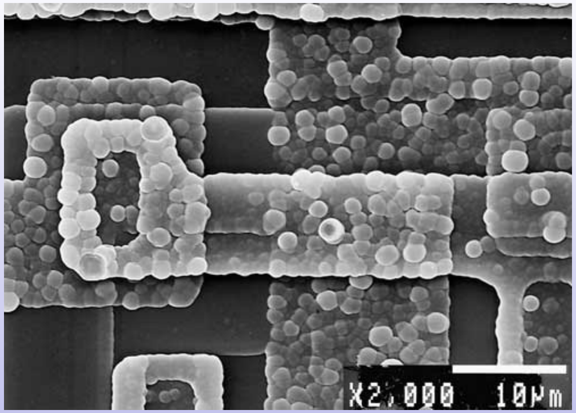


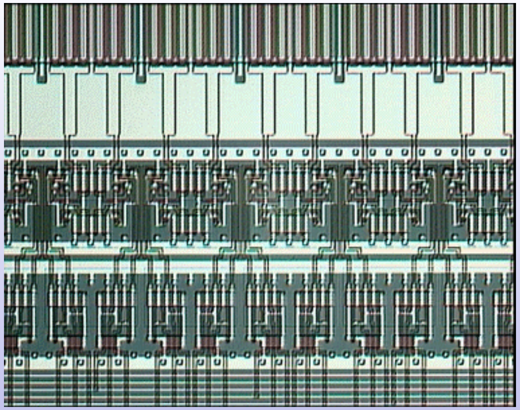
$R_{DS} > 10\,M\Omega$

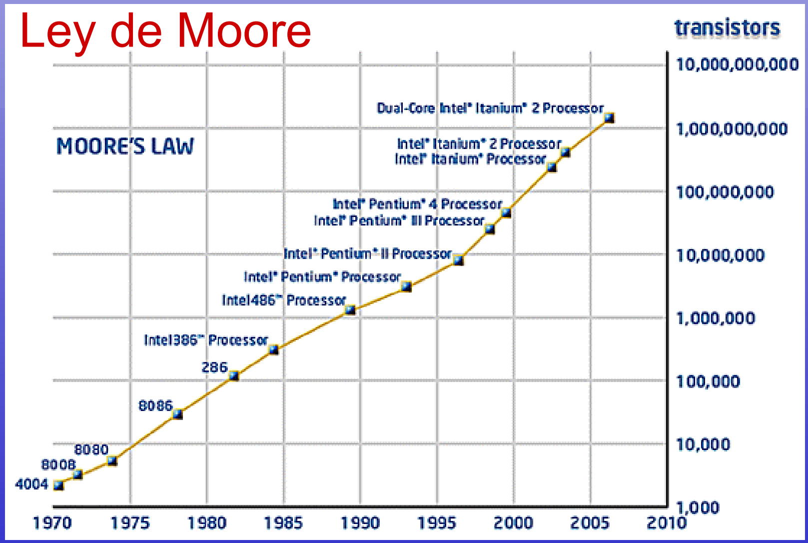
$R_{DS} \approx 0$

Bit MOS


+ 5 V
$I_{DS1} \approx 0$
$I_{DS2} \approx I_{max}$
$V_{D1} \approx 5V$
$V_{D2} \approx 0$
D_1
D_2
G_1
G_2
S_1
S_2

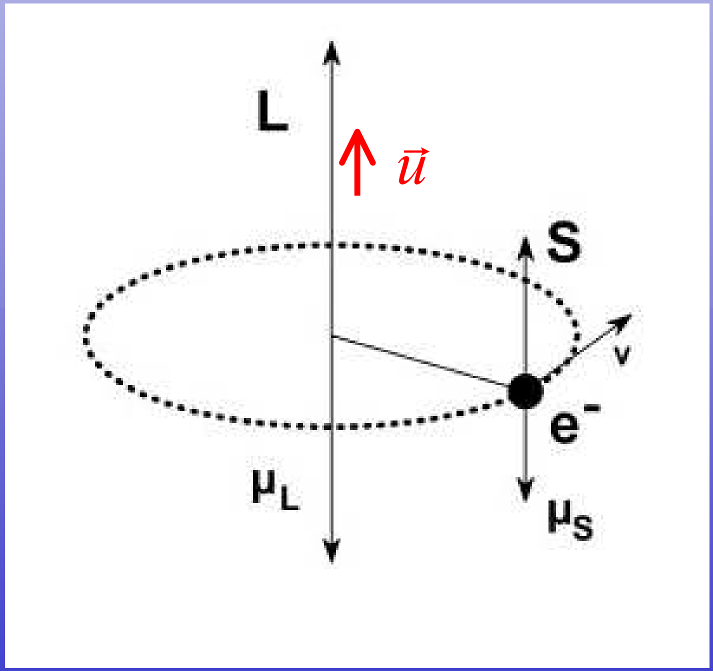

X2,000 10μm




Ley de Moore
transistors
MOORE'S LAW
Dual-Core Intel® Itanium® 2 Processor
Intel® Itanium® 2 Processor
Intel® Itanium® Processor
Intel® Pentium® 4 Processor
Intel® Pentium® III Processor
Intel® Pentium® II Processor
Intel® Pentium® Processor
Intel486™ Processor
Intel386™ Processor
286
8086
8080
8008
4004
10,000,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
1970
1975
1980
1985
1990
1995
2000
2005
2010

Materiales magnéticos

Contienen átomos de elementos de transición (capas *d* incompletas: Cr, Mn, Fe, Co, Ni) o tierras raras (capas *f* incompletas: Gd, Nd, Eu, etc)



$$\boxed{\vec{l} = m_e r^2 \omega \vec{u}}$$

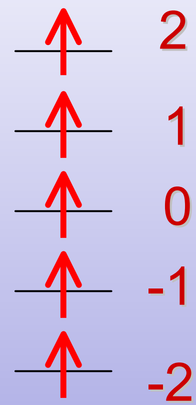
$$\boxed{\vec{m}_l = IS\,\vec{u} = e\,\frac{\omega}{2\pi}\,\pi\, r^2 \vec{u}}$$

$$\boxed{\vec{m}_l = \frac{e}{2m_e}\vec{l}}$$

$$\boxed{m_l = \frac{e}{2m_e}\hbar L = \mu_B L}$$

$$\boxed{m_S = g\mu_B S \cong 2\mu_B S}$$

Mn ($3d^5 4s^2$)

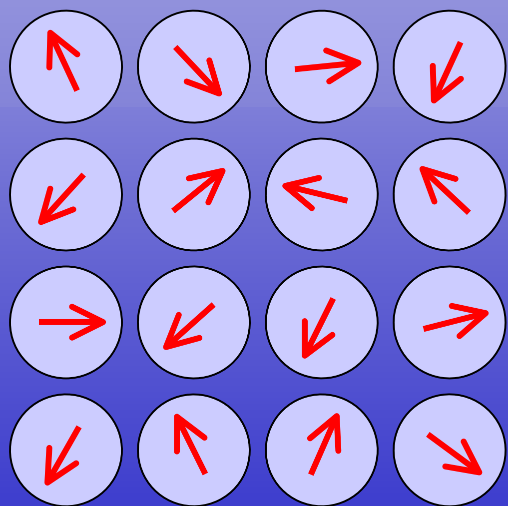


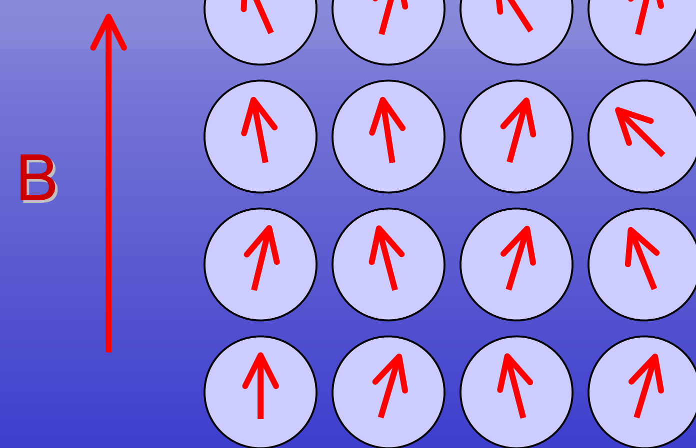
$$\boxed{L = 0 \quad S = \frac{5}{2} \quad J = \frac{5}{2}}$$

$$\boxed{m = 5\mu_B}$$

Materiales paramagnéticos

$$\boxed{\begin{array}{l} \vec{B} = 0 \\ \vec{M} = 0 \end{array}}$$

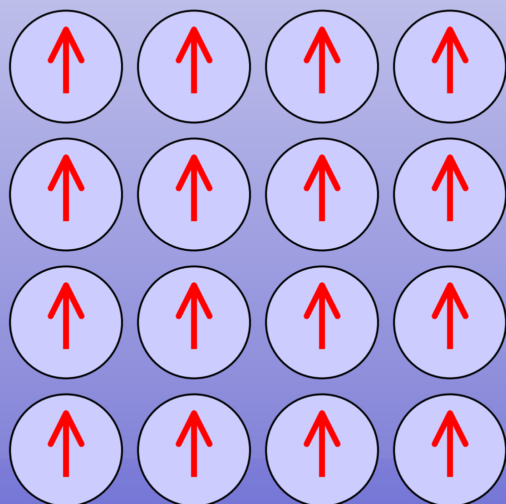




$$\boxed{\begin{array}{l} \vec{B} \neq 0 \\ \vec{M} \neq 0 \end{array}}$$

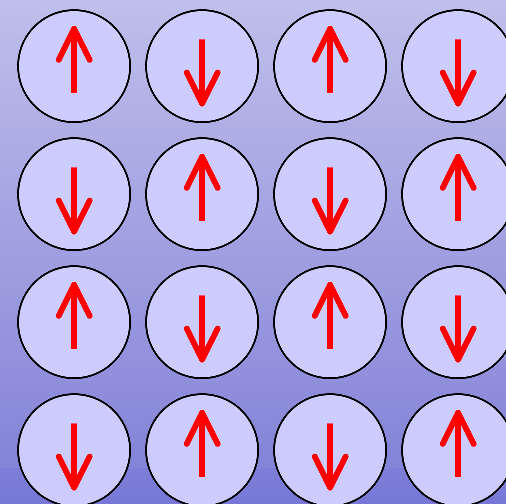
Materiales ferromagnéticos

$$\vec{B} = 0$$
$$\vec{M} \neq 0$$

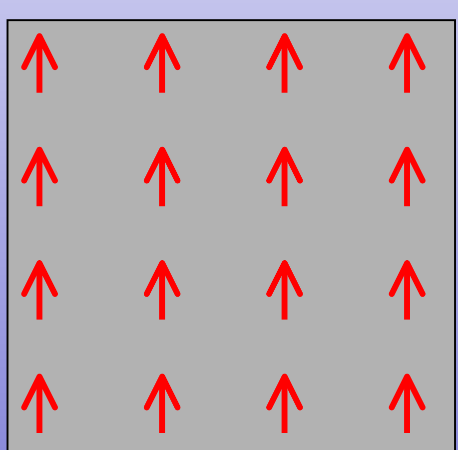


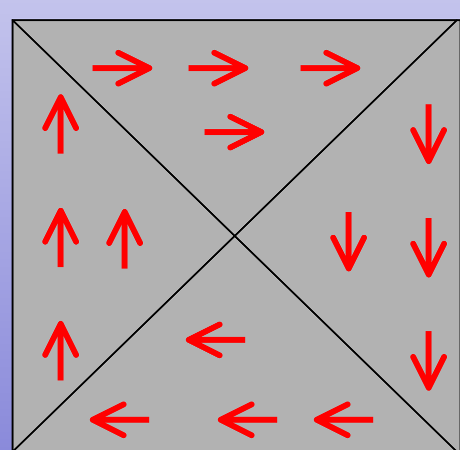
Materiales antiferromagnéticos

$$\vec{B} = 0$$
$$\vec{M} = 0$$



Dominios magnéticos

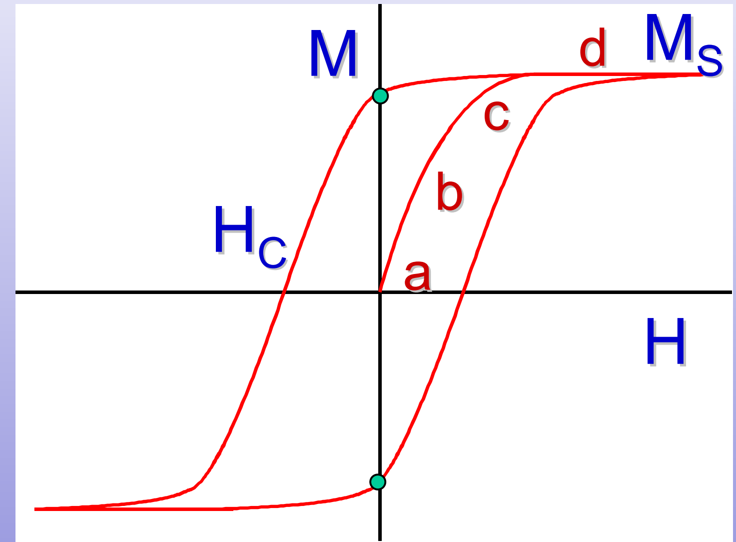


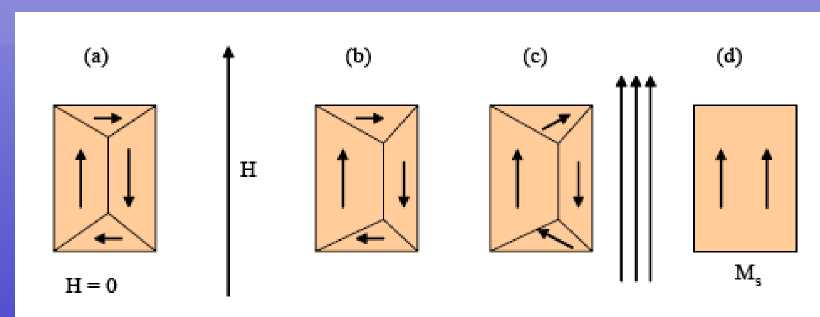


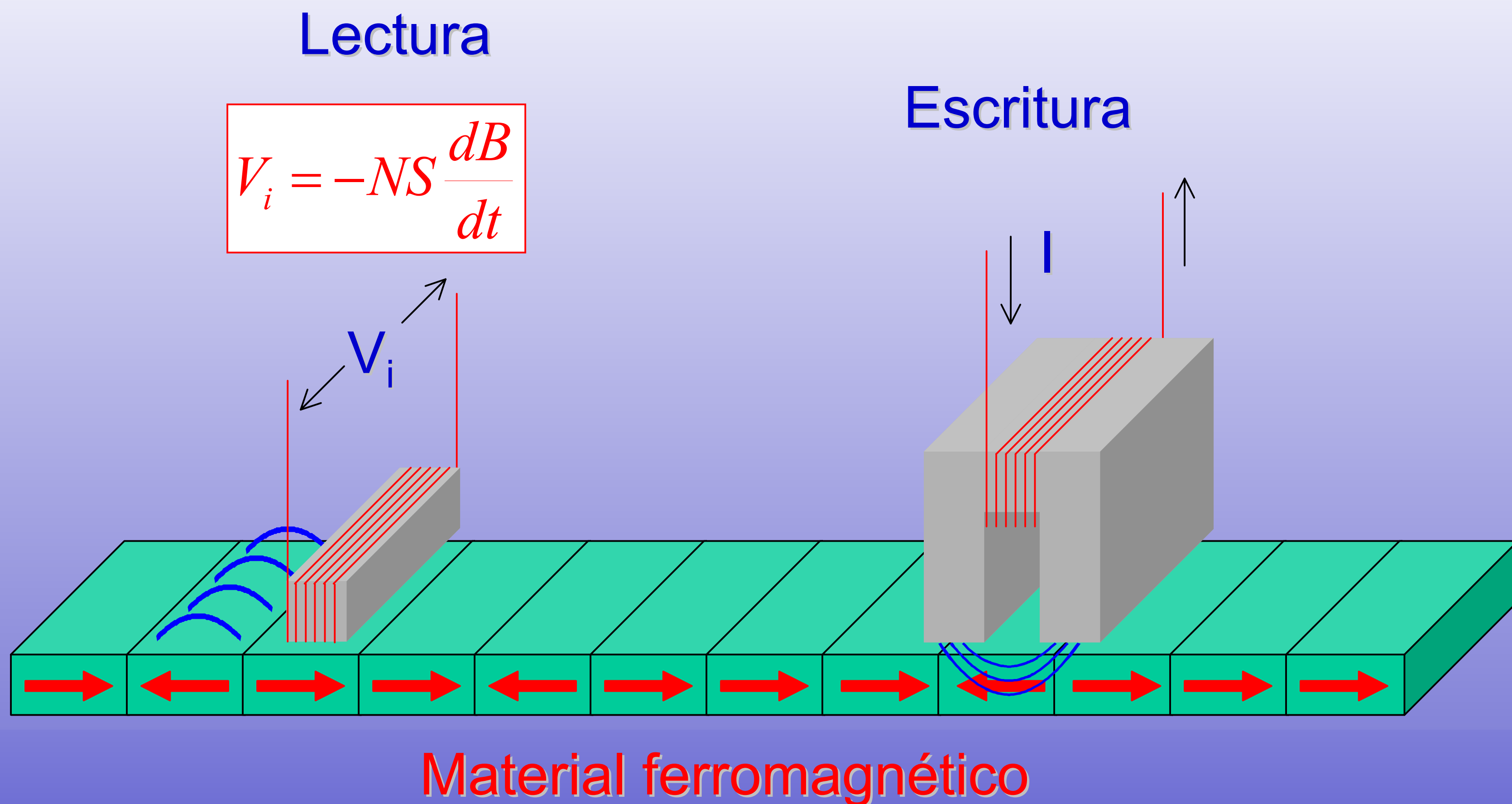
$$\vec{B} = 0$$
$$\vec{M} \neq 0$$

$$\vec{B} = 0$$
$$\vec{M} = 0$$

Histéresis



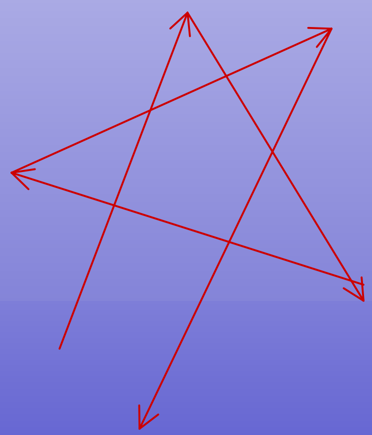


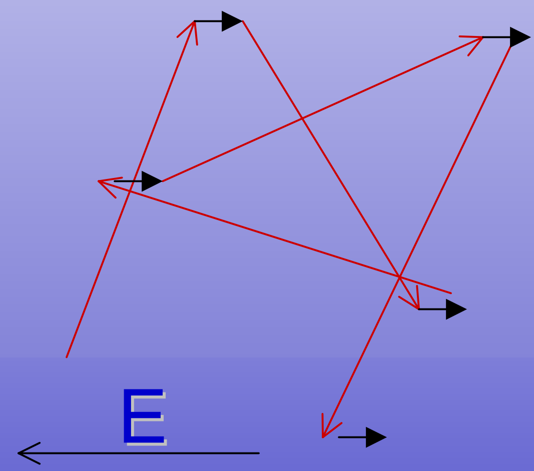

Lectura
$V_i = -NS\frac{dB}{dt}$
V_i
Escritura
I
Material ferromagnético

¿Qué es la magnetorresistencia?

$$\frac{R(B)-R(0)}{R(0)} = \frac{\Delta R}{R(0)} = CB^2$$

Origen de la magnetorresistencia “normal”





$$J = en\Delta v = en\mu E$$

$$J = \sigma E$$

$$J = \frac{I}{S} \qquad E = \frac{V}{L}$$

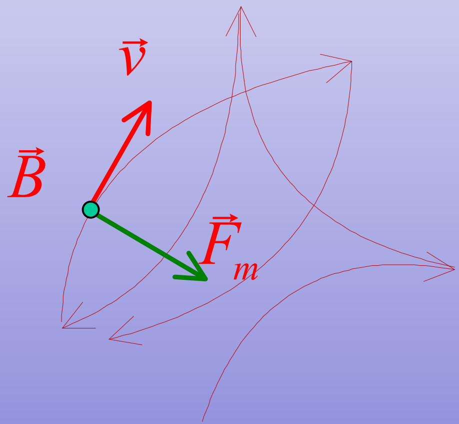
$$E = 0 \qquad \langle v \rangle = 0$$

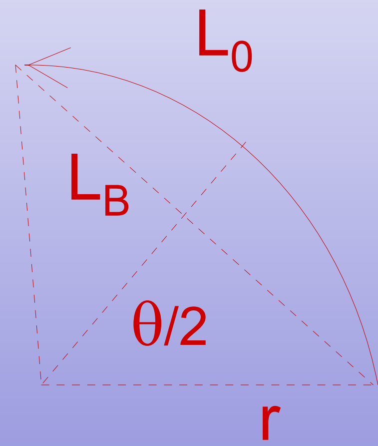
$$\Delta v = a\tau = \frac{eE}{m^*}\tau = \frac{e\tau}{m^*}E = \mu E$$

$$R = \frac{V}{I} = \frac{L}{\sigma S}$$

Origen de la magnetorresistencia “normal”

$$\boxed{\vec{F} = -e\vec{v}\times\vec{B}}$$





$$L_0 = r\theta$$

$$L_B = 2r\sin\frac{\theta}{2} \approx 2r\left(\frac{\theta}{2} - \frac{\theta^3}{8}\right)$$

$$\frac{\Delta L}{L_0} = \frac{L_0 - L_B}{L_0} \propto \theta^2$$

$$\frac{\Delta R}{R_0} = \frac{\Delta L}{L_0} \propto (\mu B)^2$$

$$\omega^2 r = \frac{evB}{m} = \frac{e\omega r B}{m}$$

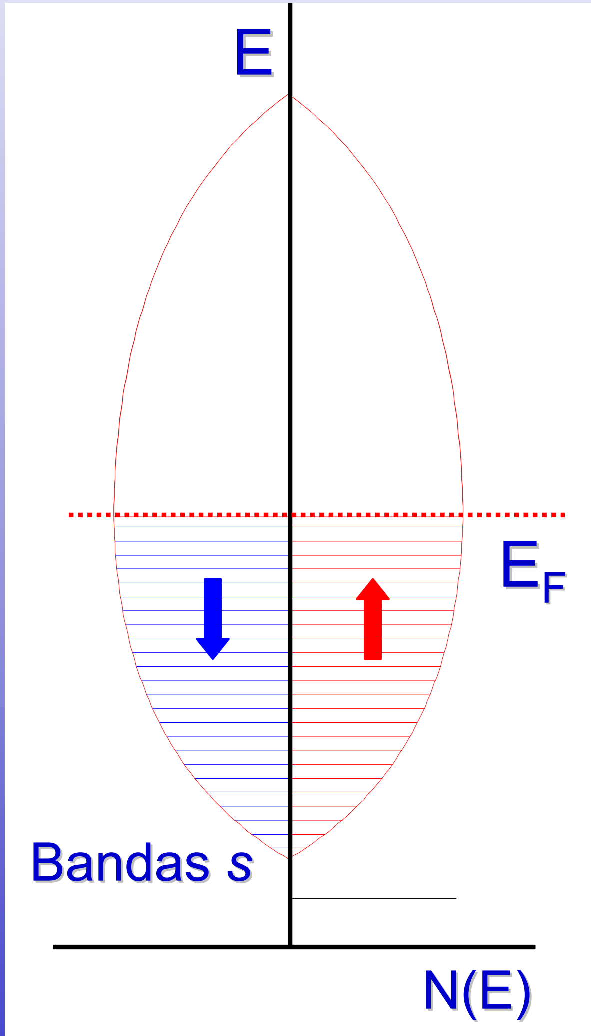
$$\omega_C = \frac{eB}{m}$$

$$\theta = \omega_C\tau = \frac{eB}{m}\tau = \frac{e\tau}{m}B = \mu B$$

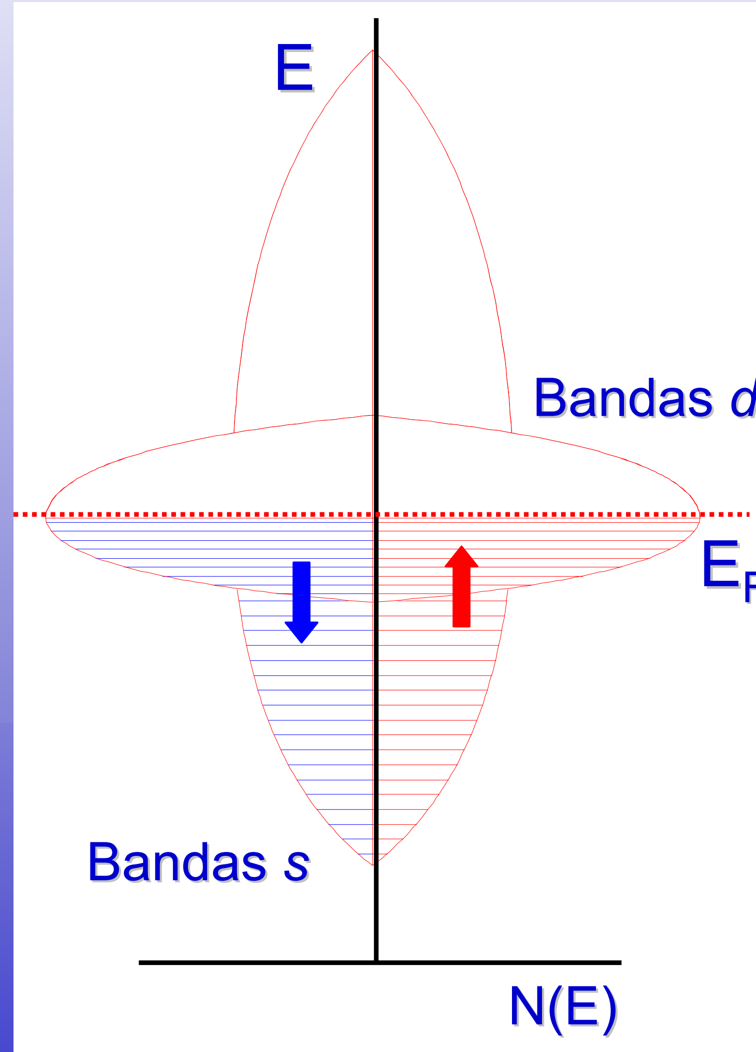
$$\mu \approx 0.5\, m^2/Vs \qquad B = 0.1\, T$$

$$\frac{\Delta R}{R_0} \approx 2.5\times10^{-3}$$

Metales normales



Metales de transición (Mn, Fe, Co, Ni)



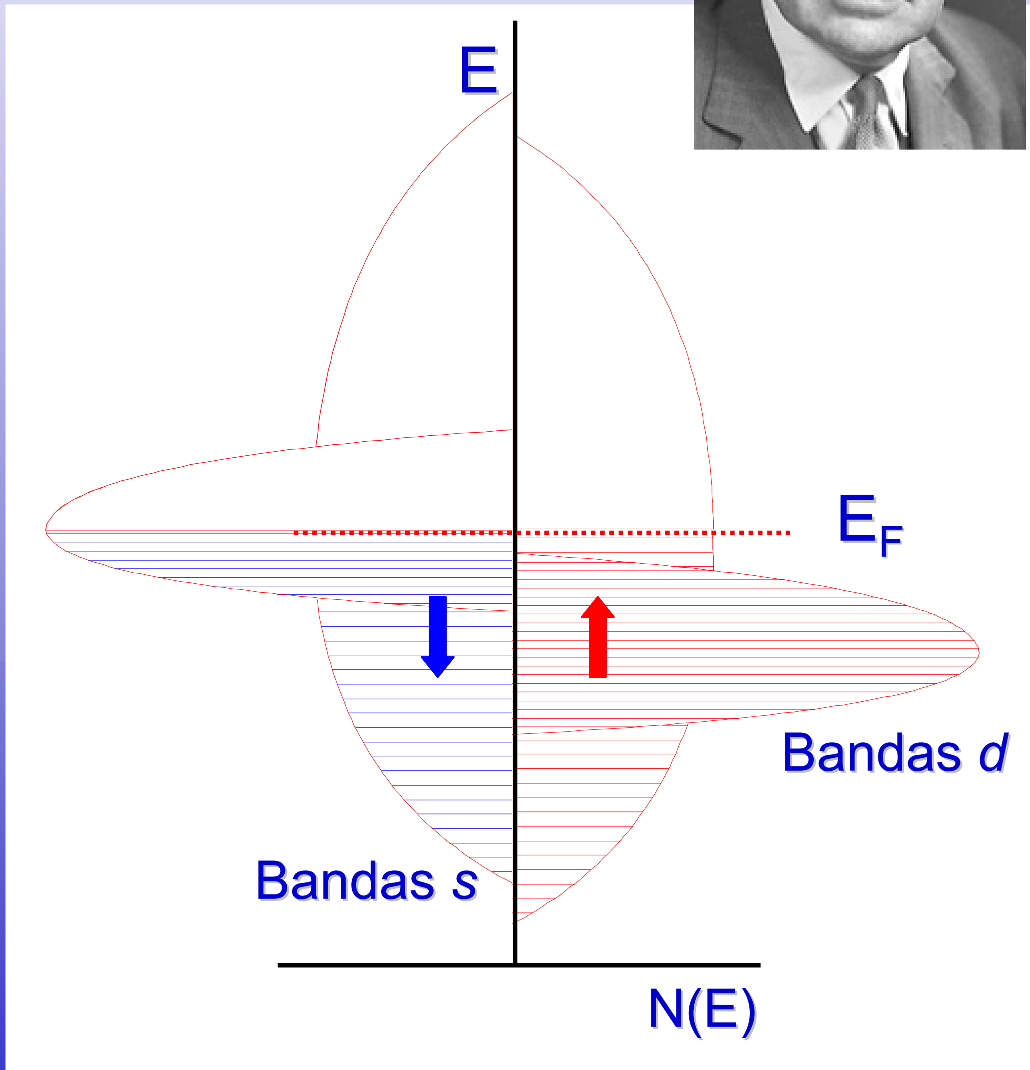
Sir Nevill F. Mott

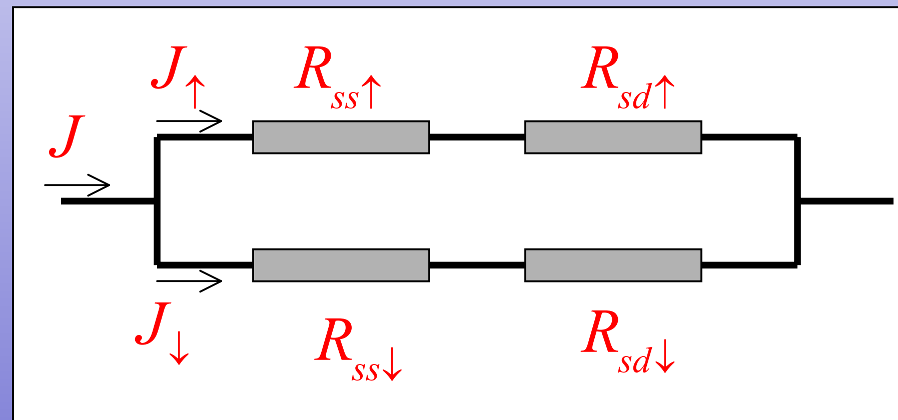
Premio Nobel de Física 1977

$$\boxed{J = \sigma E}$$

$$\boxed{J = J_{\uparrow} + J_{\downarrow} = \left(\sigma_{\uparrow} + \sigma_{\downarrow}\right) E}$$

$$\boxed{\sigma_{\uparrow} = \frac{e^2 n_{\uparrow} \tau_{\uparrow}}{m^*}} \qquad \boxed{\sigma_{\downarrow} = \frac{e^2 n_{\downarrow} \tau_{\downarrow}}{m^*}}$$



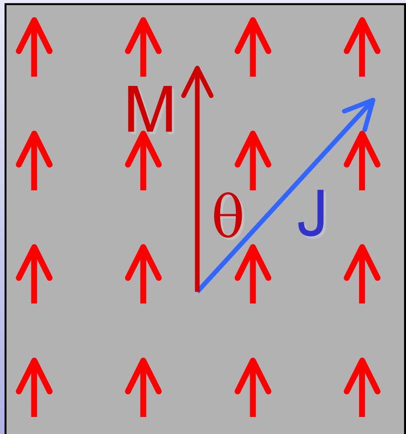


Espín mayoritario: "up" ↑

$R_{ss} < R_{sd} \qquad R_{sd\uparrow} < R_{sd\downarrow}$

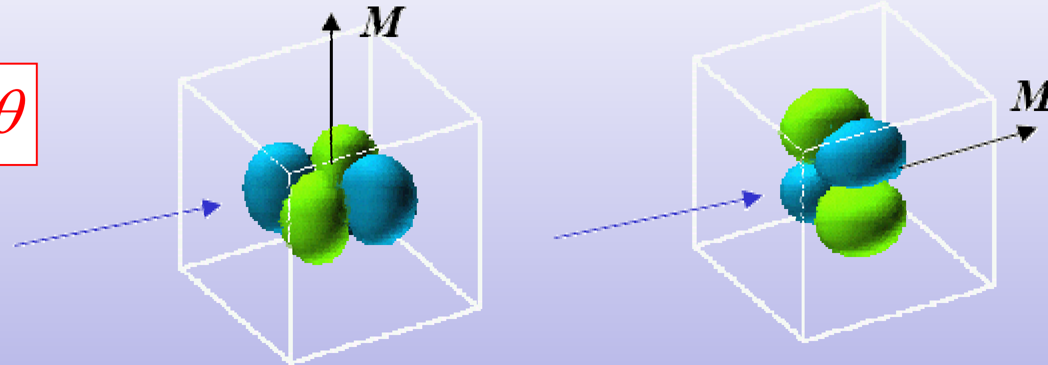
$$\boxed{\tau_{\uparrow} >> \tau_{\downarrow}}$$

Magnetorresistencia anisotrópica



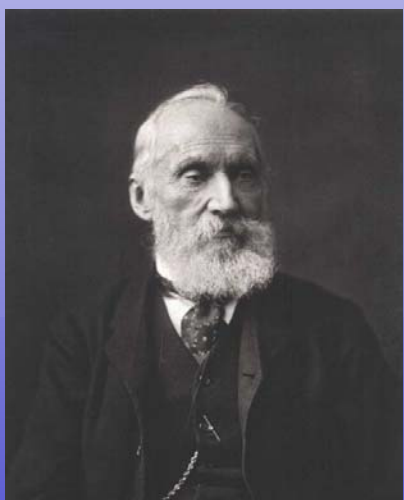
$$\rho = \rho_0 + \Delta\rho \cos^2\theta$$

$$\frac{\Delta\rho}{\rho} \approx 0.01$$



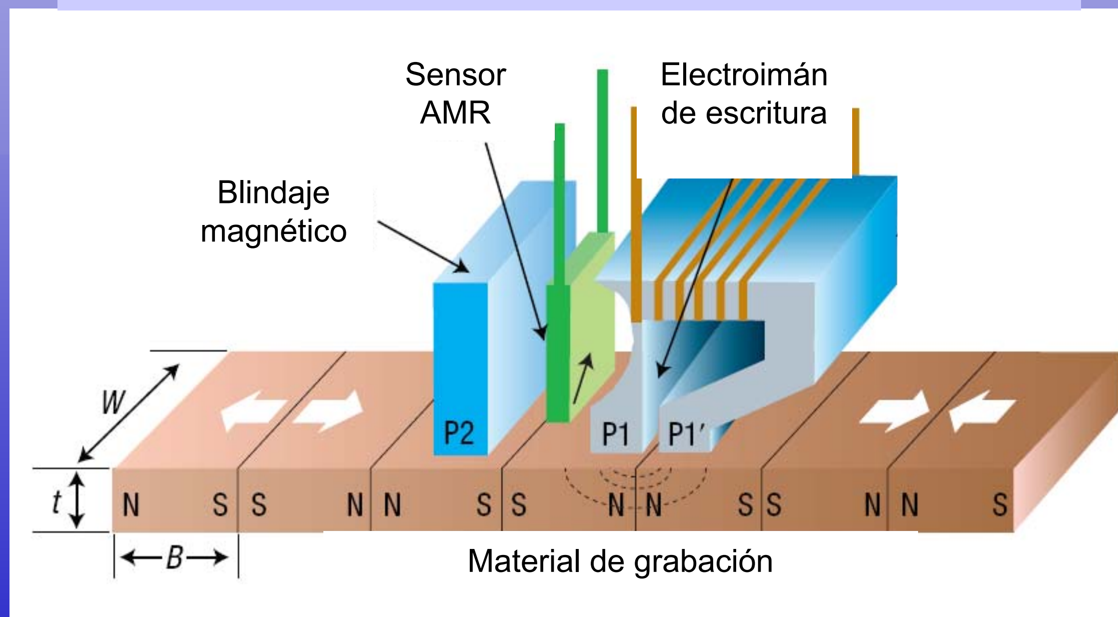
**Menor sección eficaz:
Menor resistencia**

**Mayor sección eficaz:
Mayor resistencia**

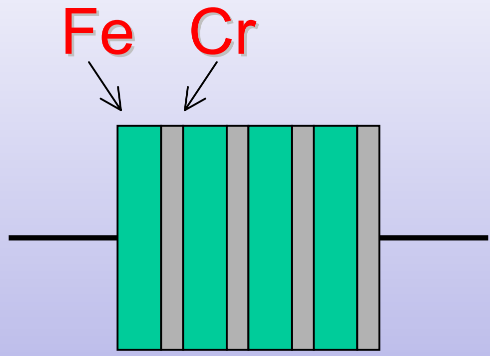


1856 William Thomson (Lord Kelvin)

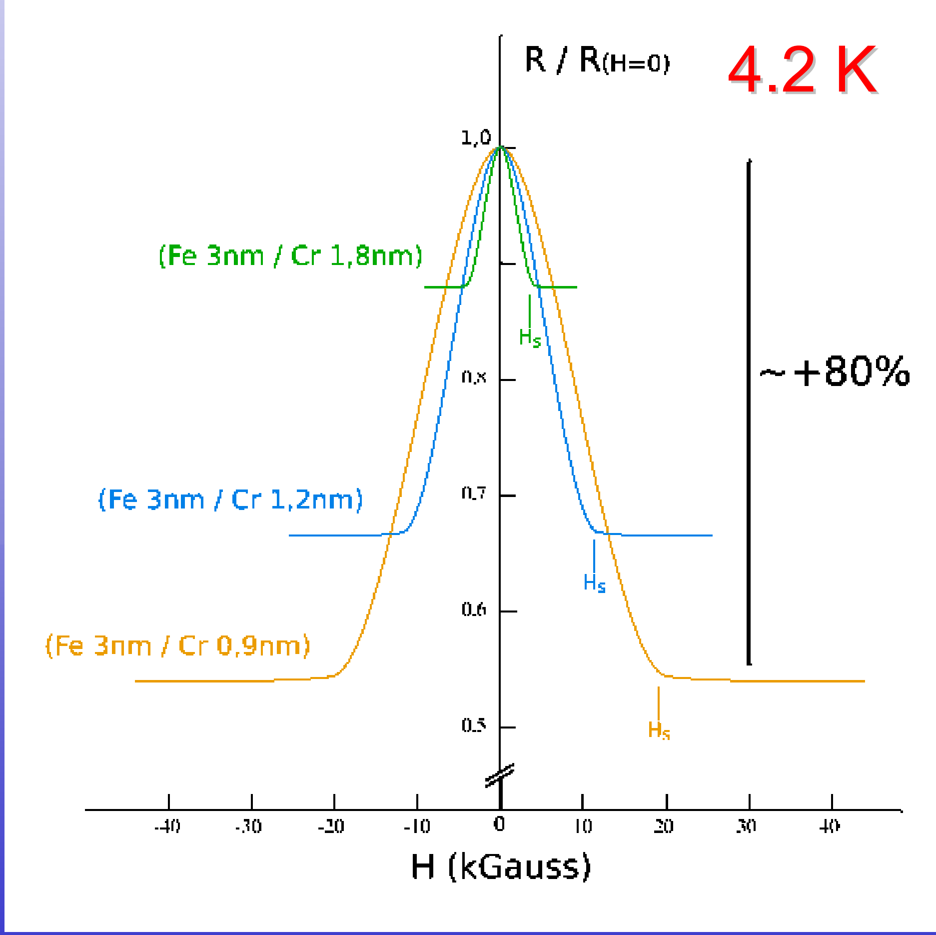
Sensores de lectura AMR 1960-1997



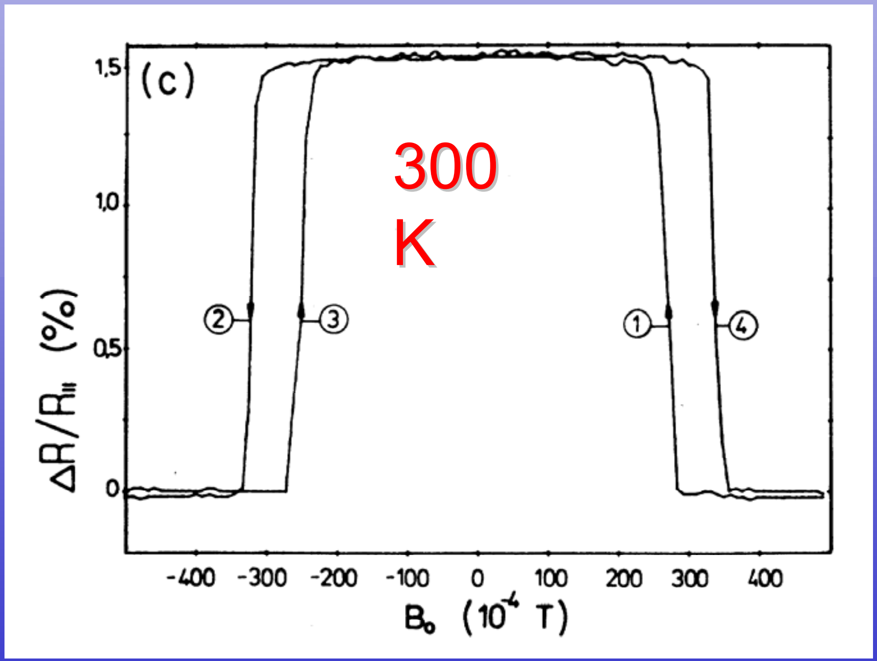
Magnetorresistencia gigante

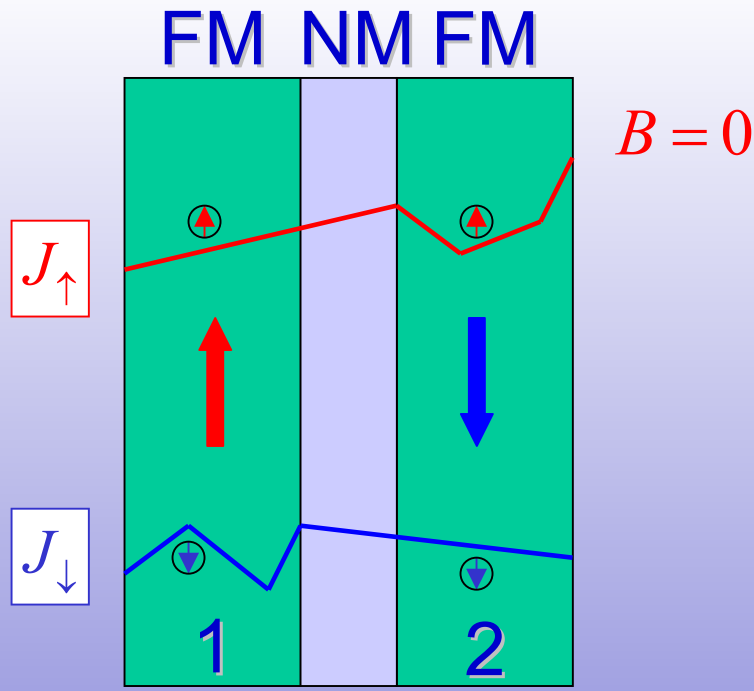


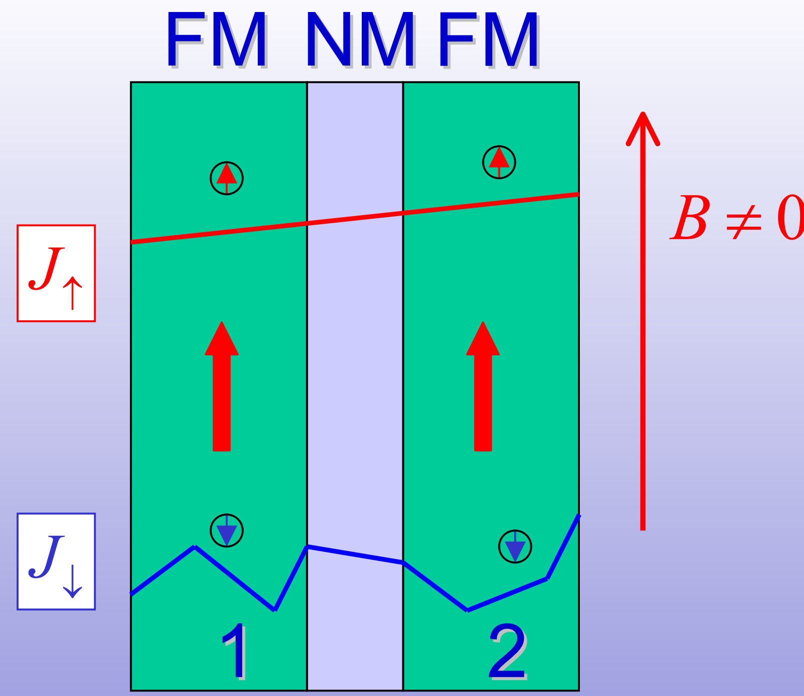
Baibich et al., Phys. Rev. Lett. 61, 2472 (1988) (FERT)

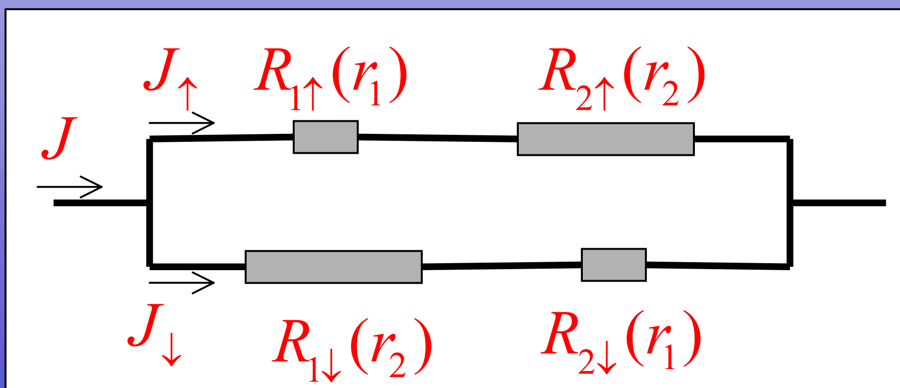


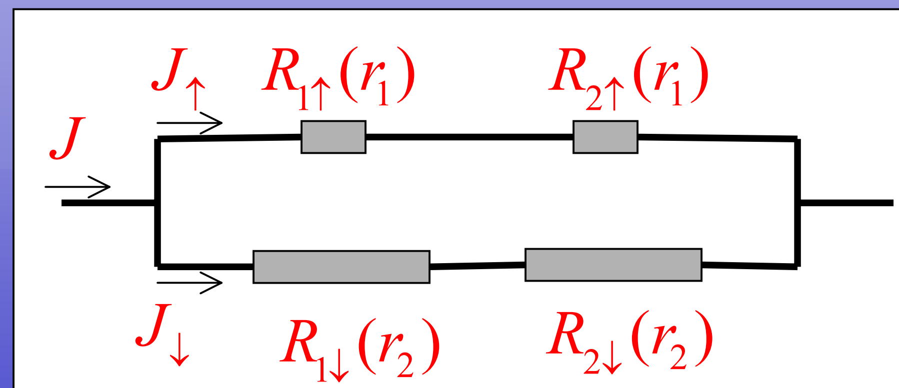
Binasch et al., Phys. Rev. B 38, 4828 (1989) (GRÜNBERG)







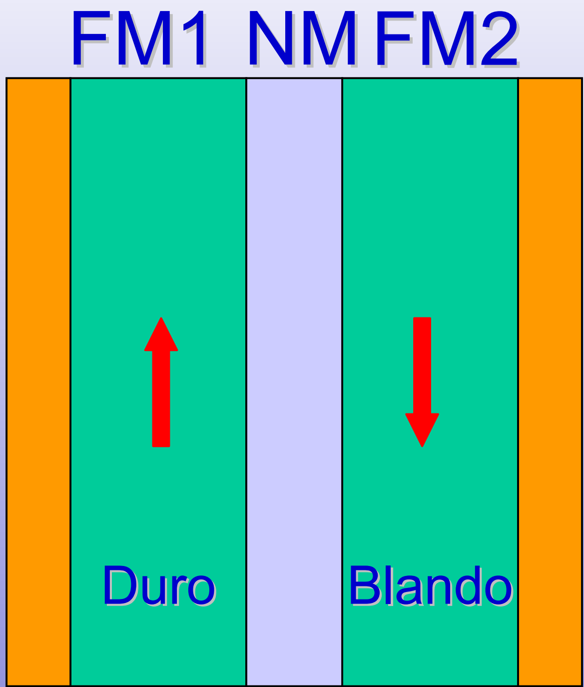




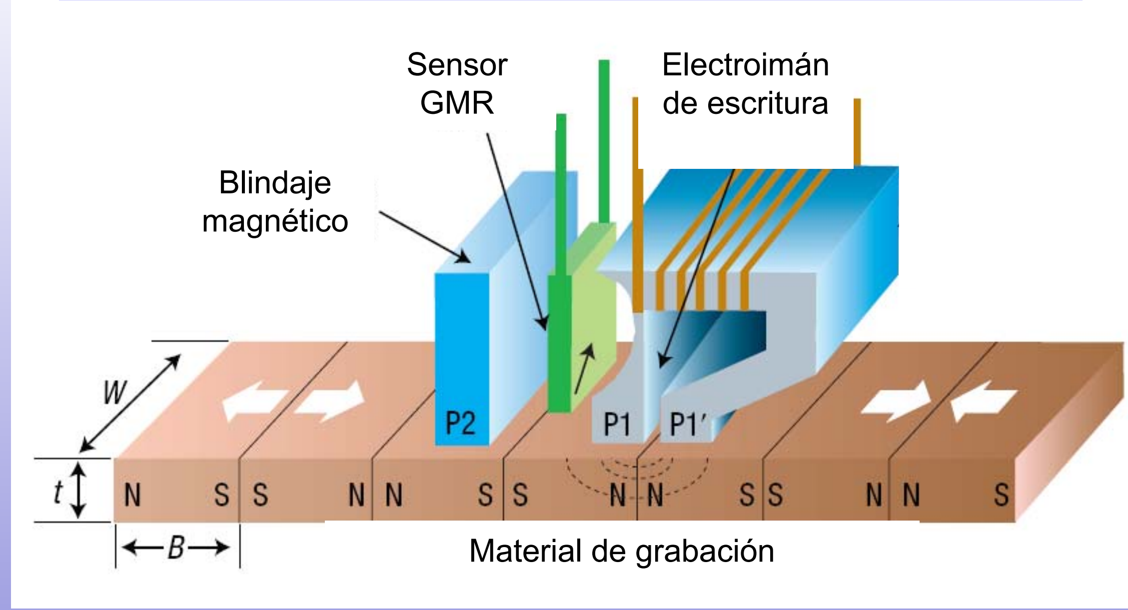
$$R_{B=0}=\frac{r_1+r_2}{2}\approx\frac{r_2}{2}\quad(r_1<<r_2)$$

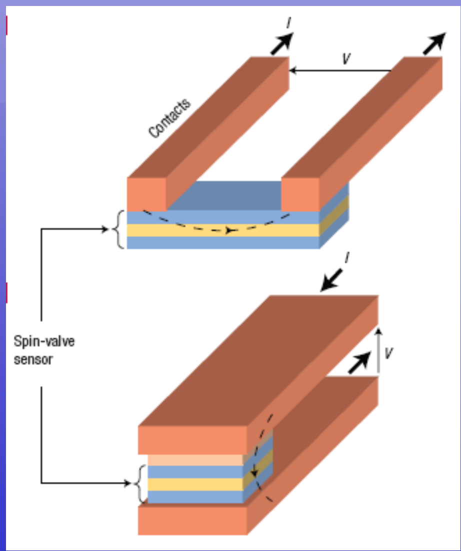
$$R_{B\neq 0}=\frac{2r_1\times 2r_2}{2r_1+2r_2}\approx 2r_1\quad(r_1<<r_2)$$

Válvula de espín

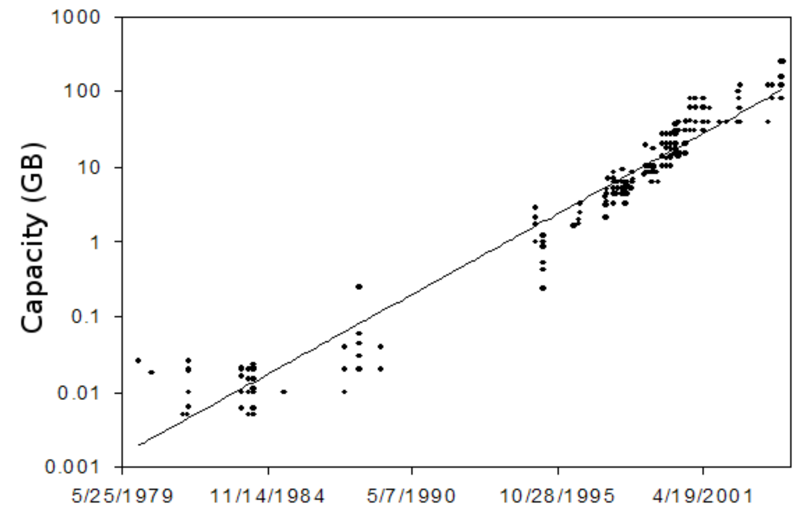


Sensores de lectura GMR 1997

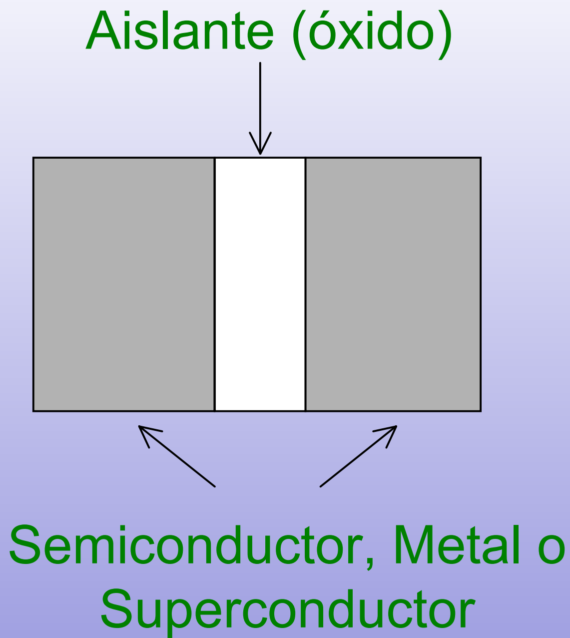


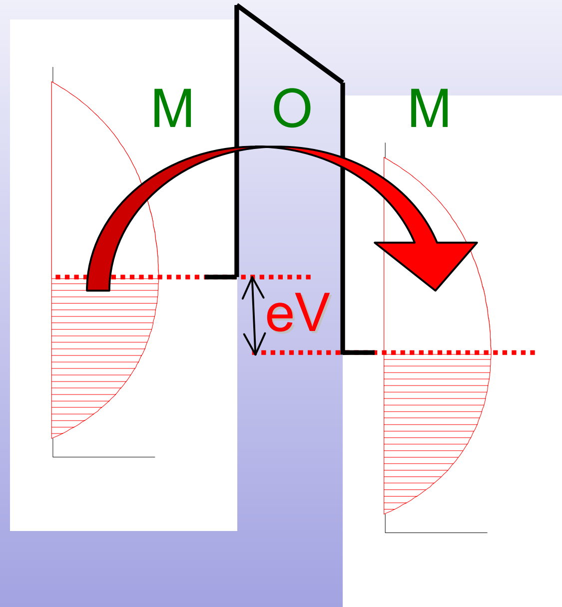


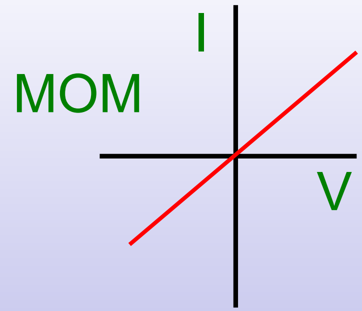
Ley de Kryder

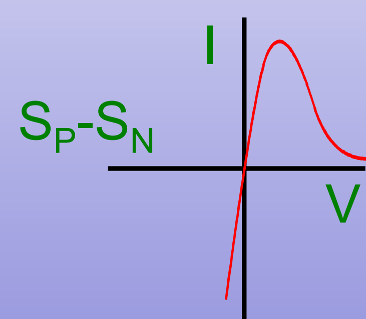


Efecto túnel en sólidos



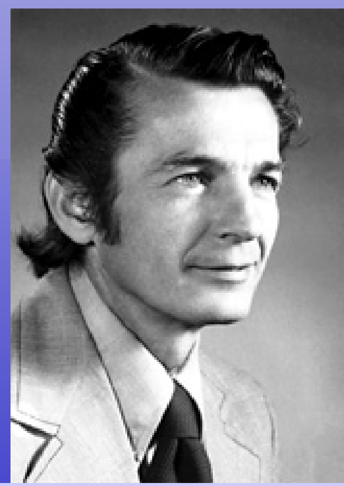






Premio Nobel de Física 1973

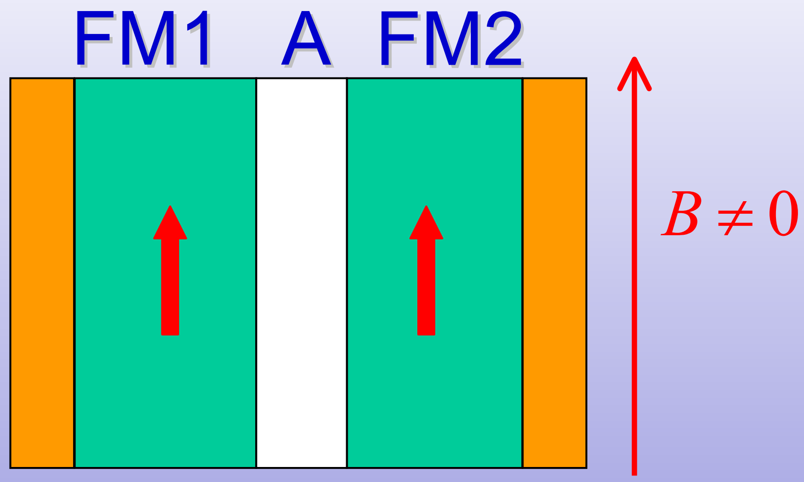
Leo Esaki

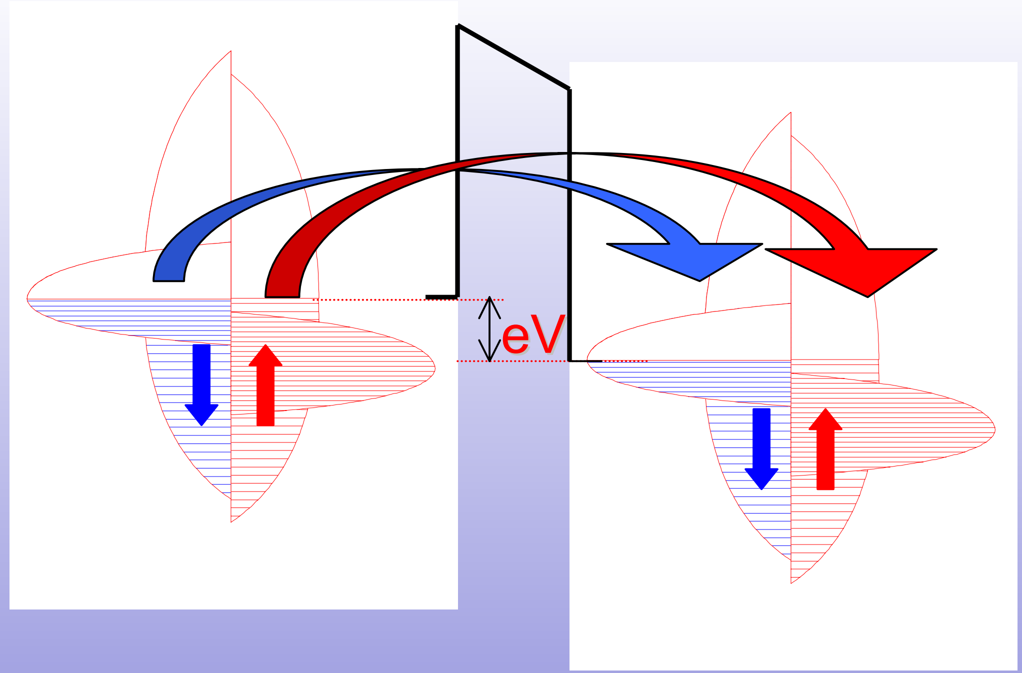


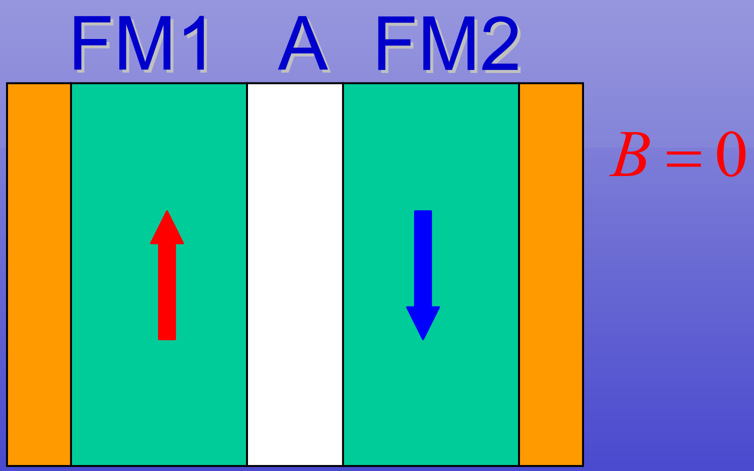
Ivar Giaever

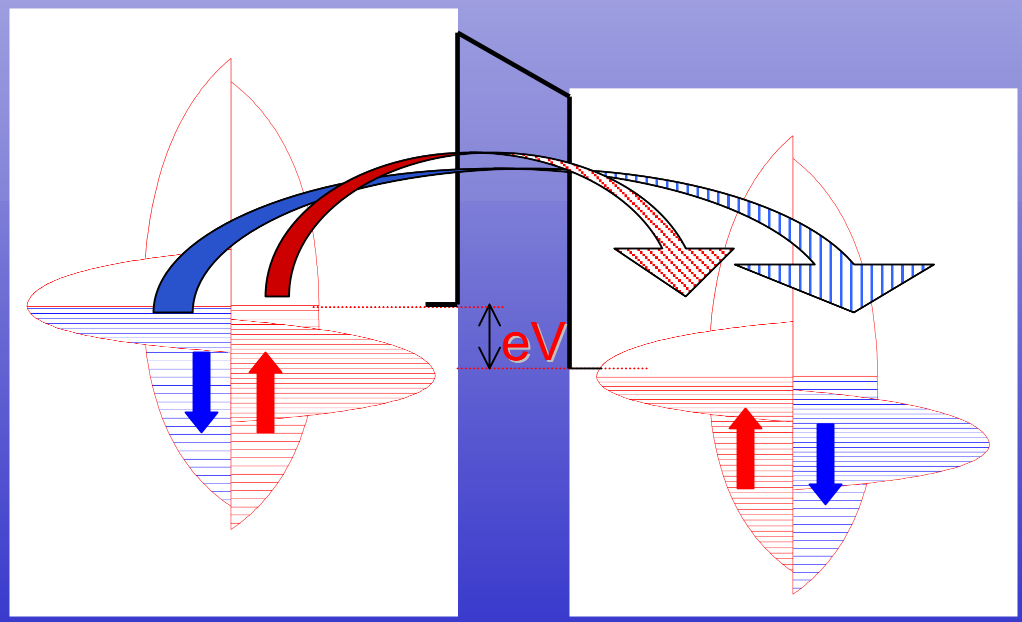
Brian D. Josephson

Unión túnel magnética



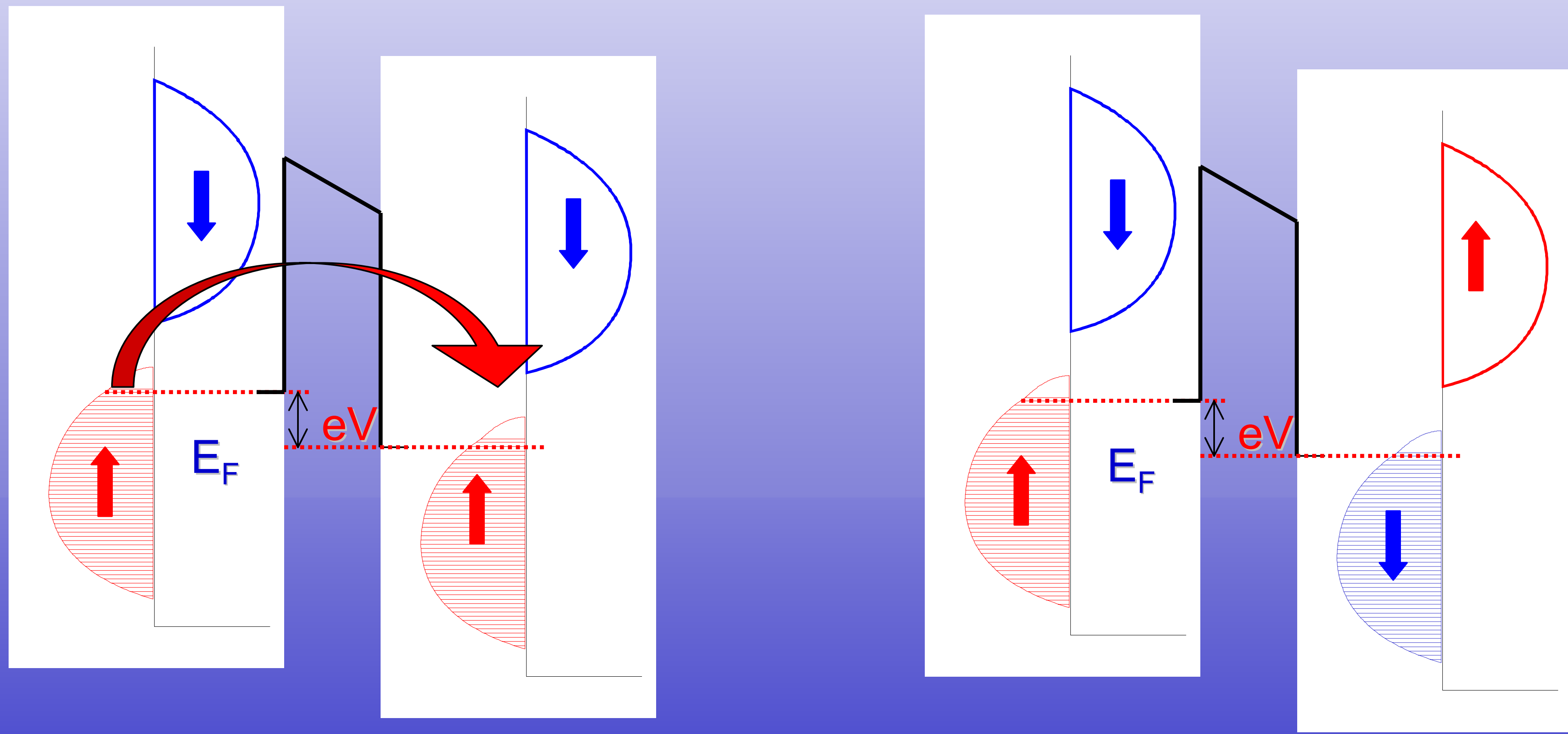




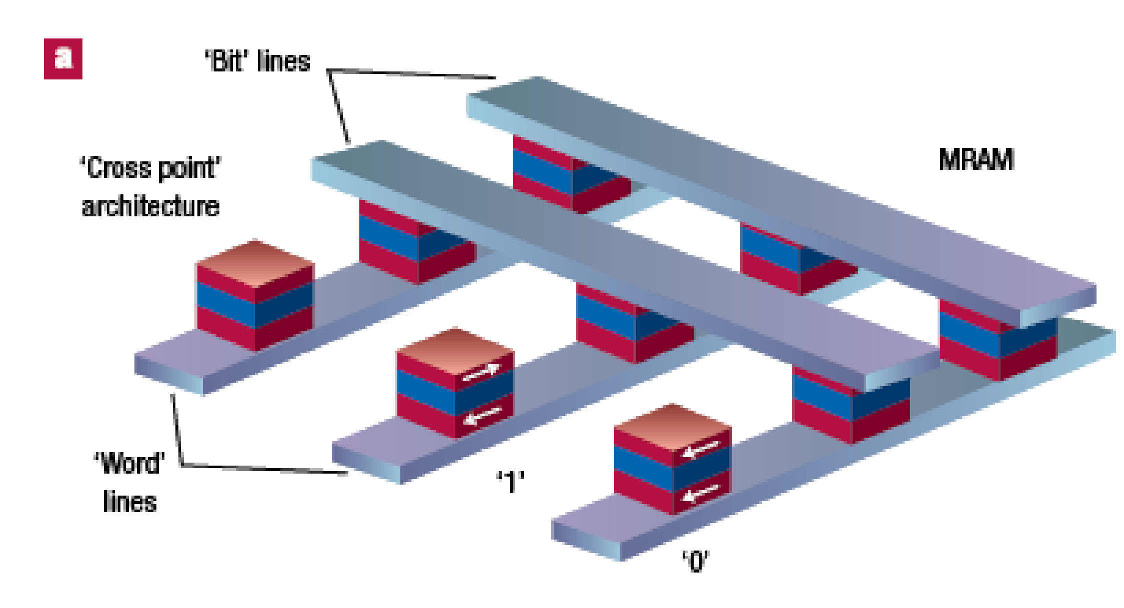


Aumentando el efecto GMR: corrientes con 100% de polarización de espín en semimetales o semiconductores ferromagnéticos

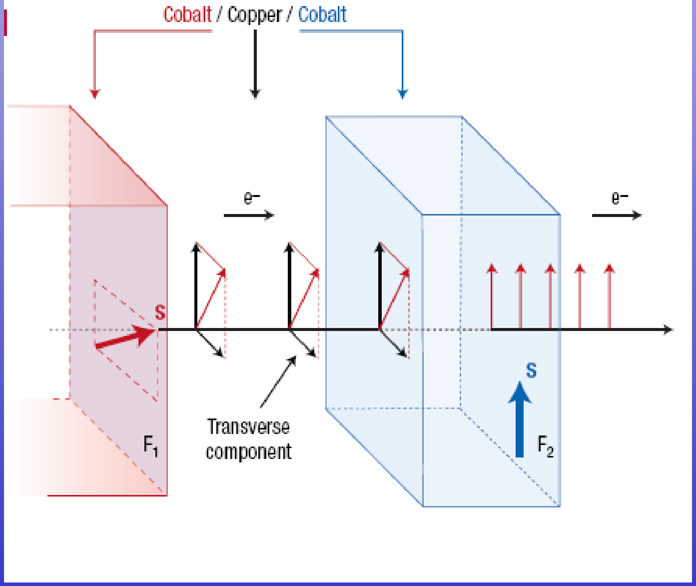
CrO_2 , $La_{2/3}Sr_{1/3}MnO_3$

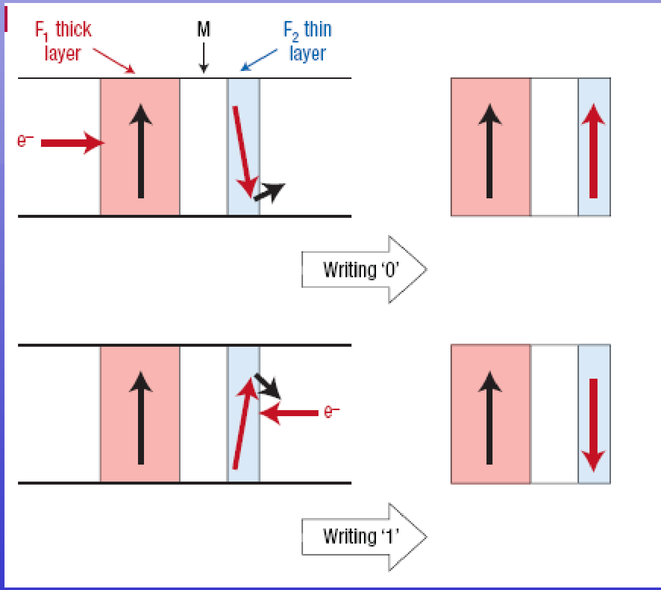


Memoria RAM magnética



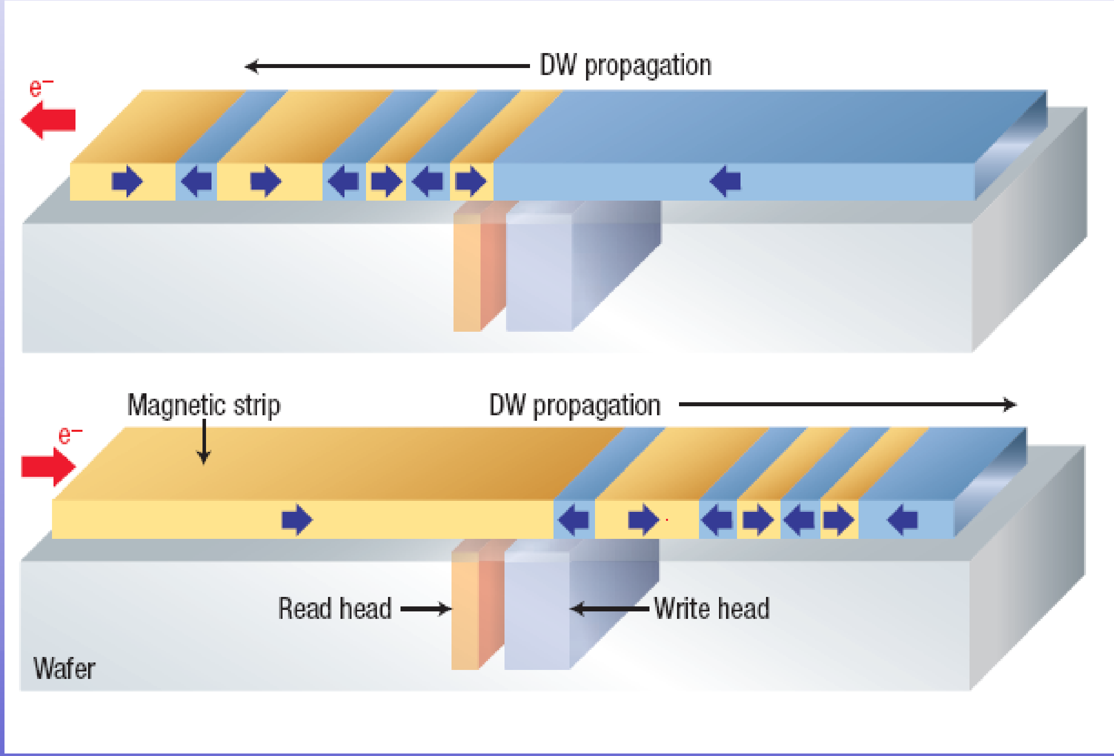
Conmutación por transferencia de spin



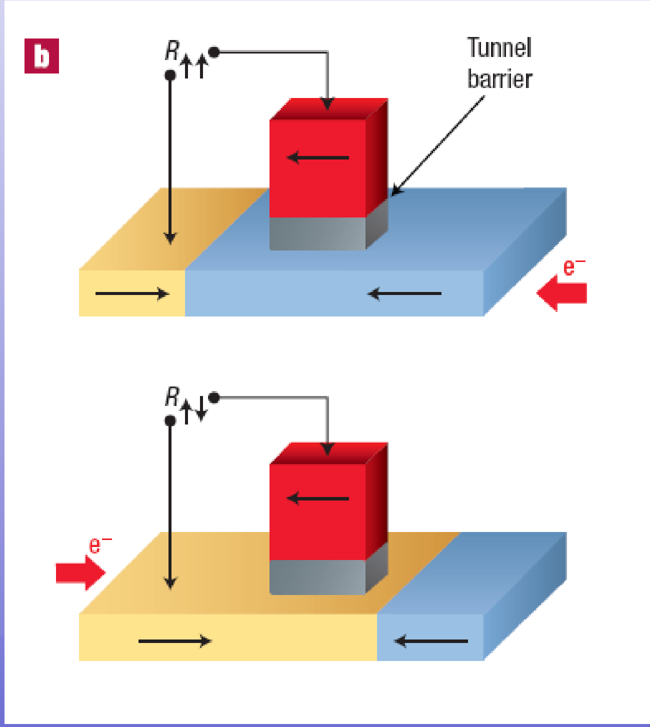


Arrastre de paredes de los dominio ferromagnéticos

Lectura/escritura

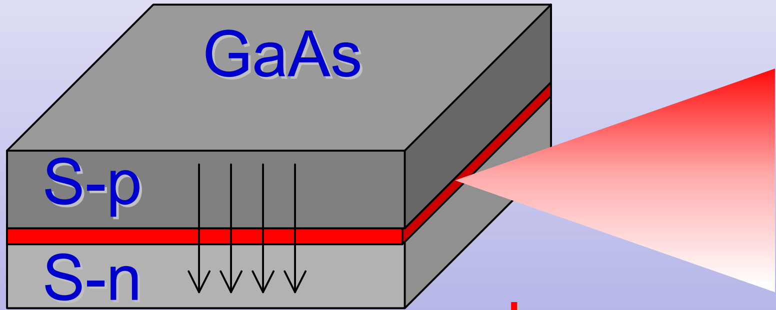


Bit MRAM



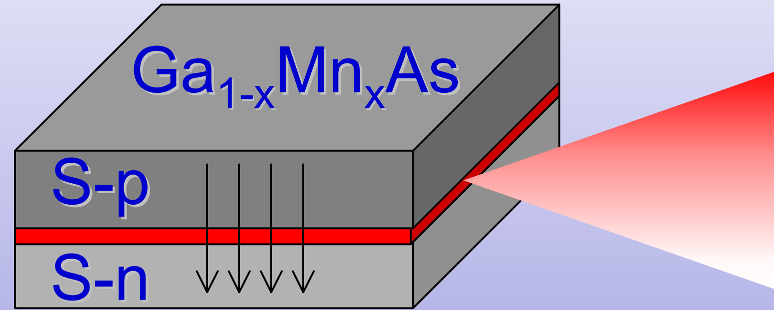
Otros dispositivos: LED de espín

LED

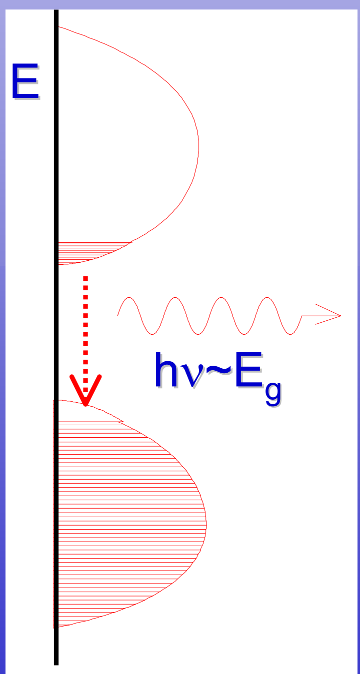


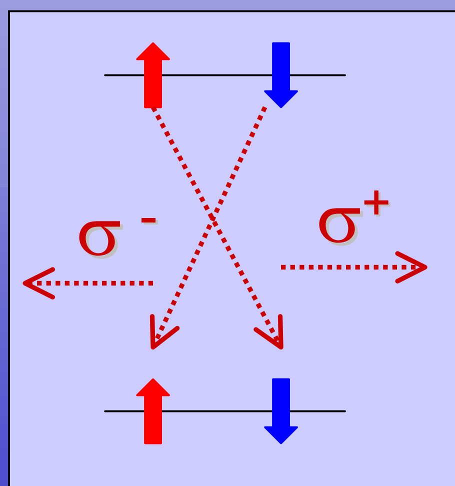
Luz no polarizada

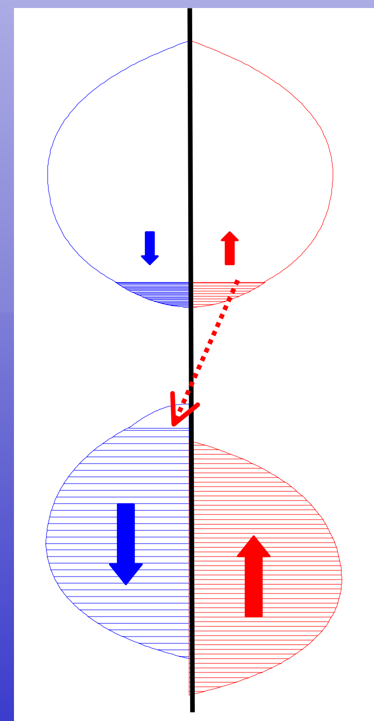
LED de espín



Luz polarizada circularmente







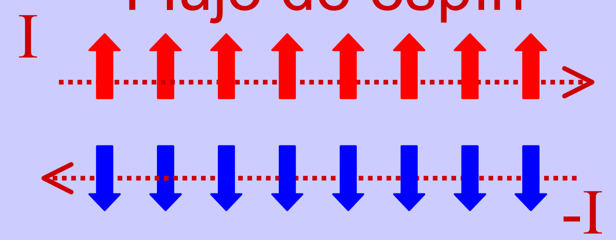
Electrónica versus espintrónica

Corriente eléctrica:
flujo de carga

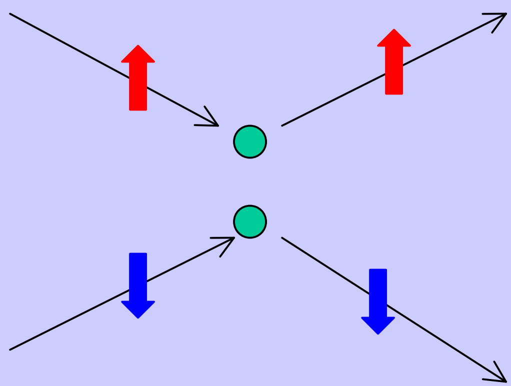
"Corriente" de espín:
flujo de espín

Válvulas de espín:
Flujo de electrones con polarización de espín

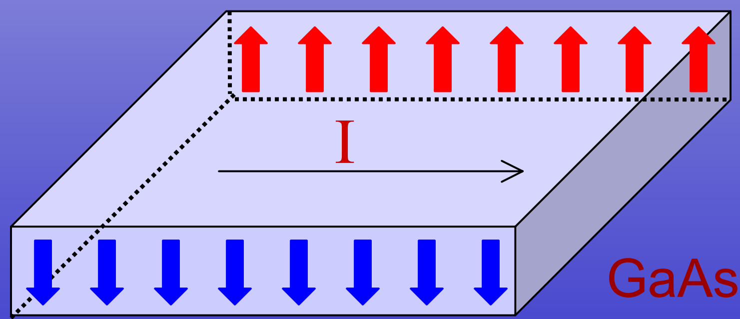
Flujo de espín



Asimetría en la dispersión

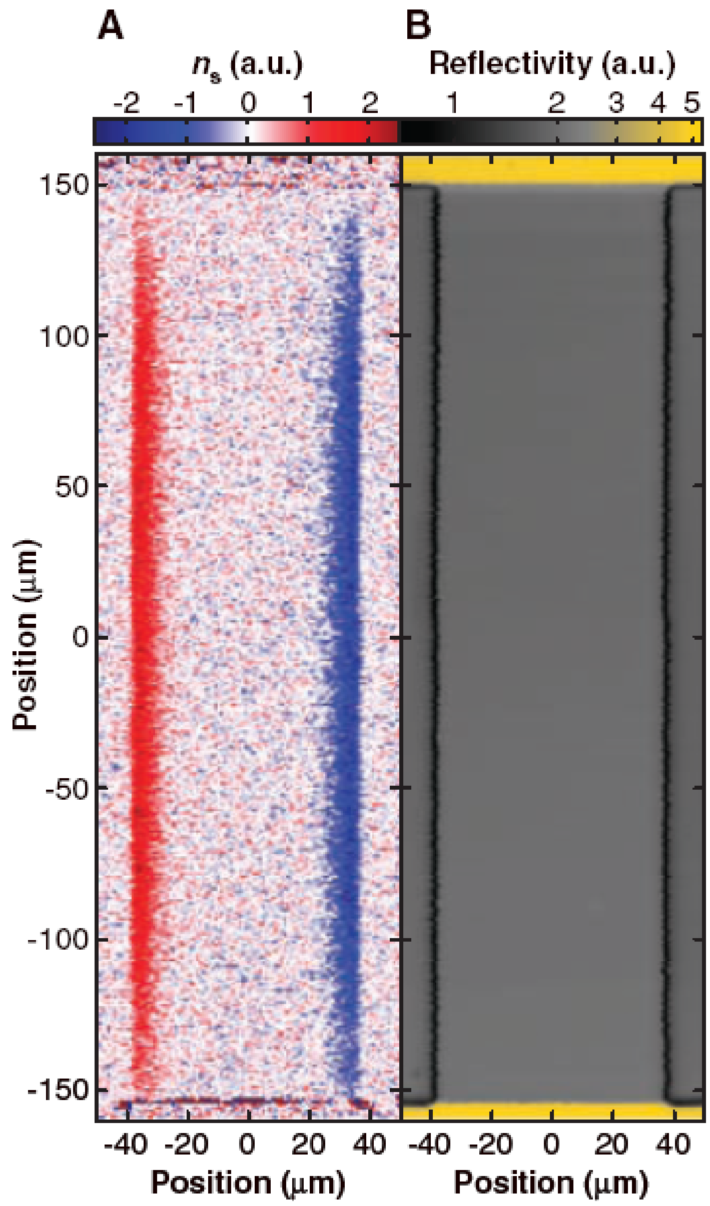


Efecto Hall de espín



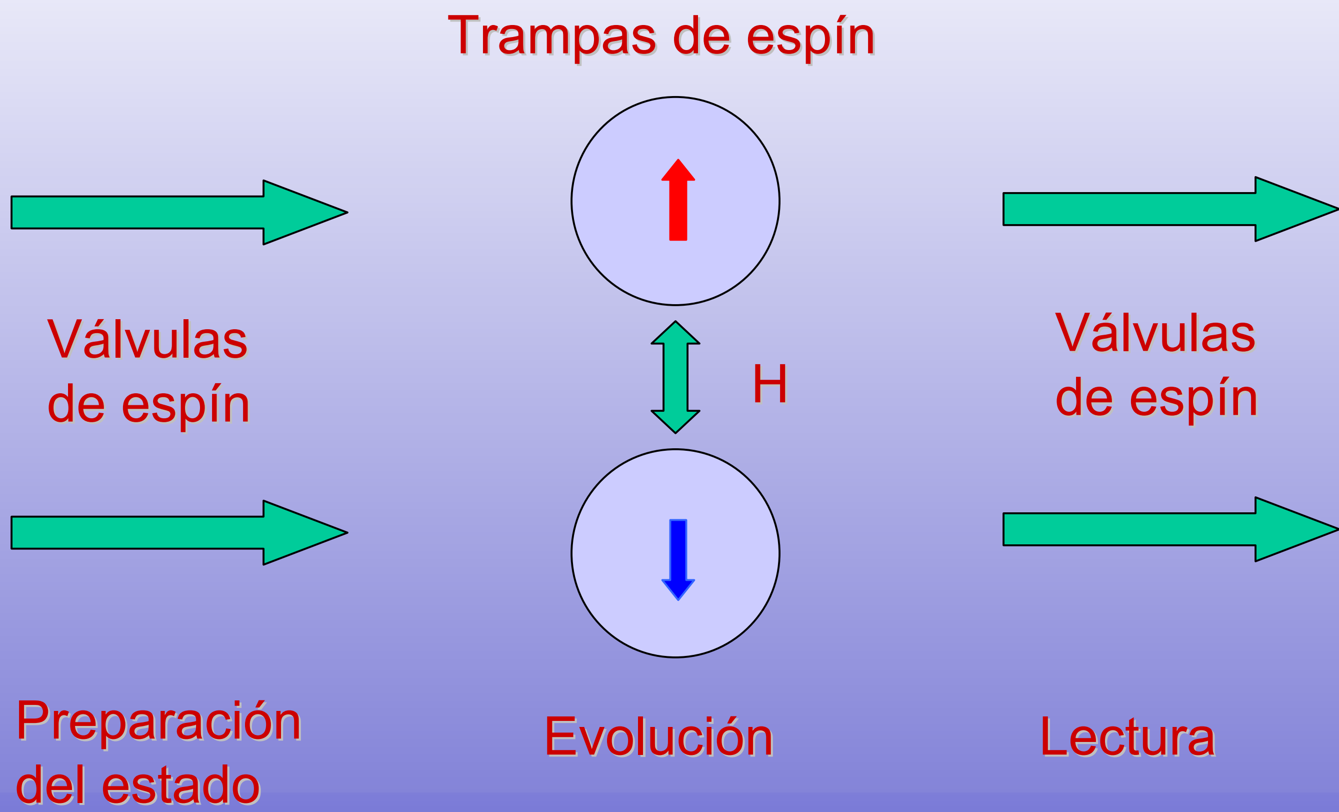
M. I. D'yakonov, V. I. Perel, JETP Lett. 13, 467 (1971)

Detección del efecto Hall de espín mediante efecto Kerr



Y. K. Kato, *et al. Science* 306, 1910 (2004)

Otros dispositivos: QUBITS



Qubits atómicos:
Trampas magnéticas
en vacío

Qubits sólidos:
Puntos cuánticos en
semiconductores