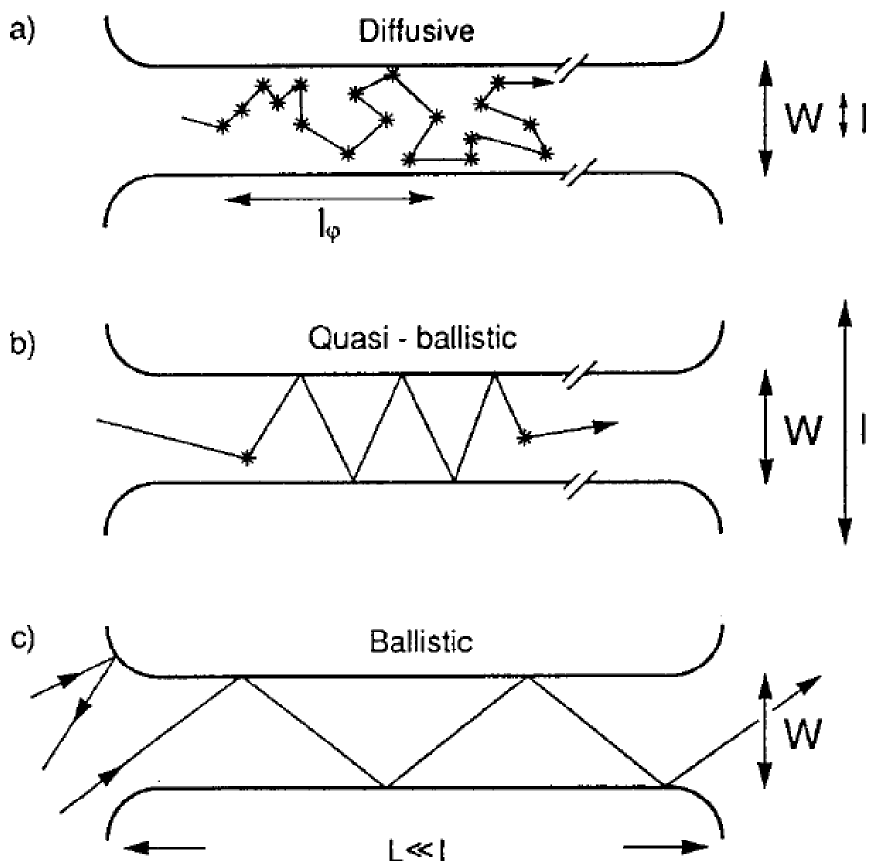
TRANSPORTE EN SISTEMAS MESOSCOPICOS Y NANOESTRUCTRADOS



λ<W,L

W<λ<L

W,L <λ

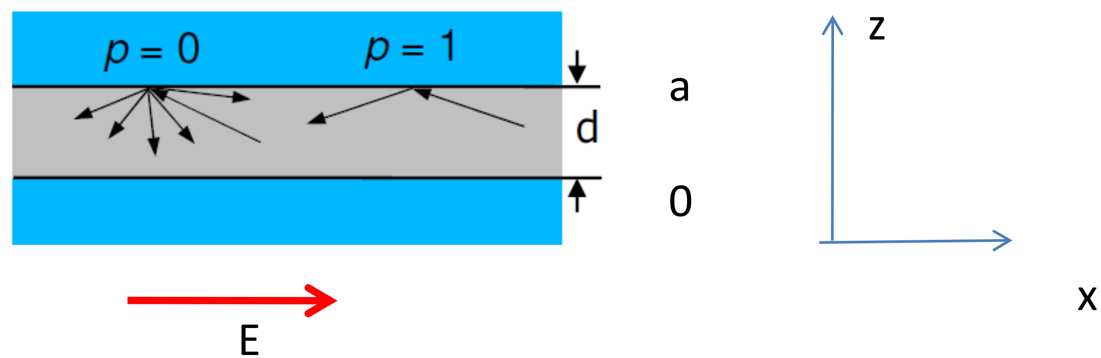
L: longitud,
W: ancho del hilo!

Primer abordaje al problema de transporte en un film delgado….

Espesor comparado con camino libre medio

Fuchs - Sondheimer (años 30-40, siglo pasado….)

$$f = f_0 + f_1(\mathbf{v}, z)$$



$$\frac{\partial f_1}{\partial z} + \frac{f_1}{\tau v_z} = \frac{\epsilon E}{m v_z}\frac{\partial f_0}{\partial v_x}.$$

$$f_1(\mathbf{v}, z) = \frac{\epsilon \tau E}{m}\frac{\partial f_0}{\partial v_x}\left\{1 + F(\mathbf{v})\exp\left(-\frac{z}{\tau v_z}\right)\right\}$$

Se buscan soluciones poniendo condiciones de contorno en 0 y a !

Ej: scattering difusivo en superficie: $f_1(z=a)=0$ para $vz<0$
$f_1(z=0)=0$ para $vz>0$

$$\left.\begin{aligned} f_1^+(\mathbf{v}, z) &= \frac{\epsilon \tau E}{m}\frac{\partial f_0}{\partial v_x}\left\{1 - \exp\left(-\frac{z}{\tau v_z}\right)\right\} \qquad (v_z > 0), \\ f_1^-(\mathbf{v}, z) &= \frac{\epsilon \tau E}{m}\frac{\partial f_0}{\partial v_x}\left\{1 - \exp\left(\frac{a - z}{\tau v_z}\right)\right\} \qquad (v_z < 0). \end{aligned}\right\}$$

$$J(z) = -\frac{2\epsilon^2 m^2 E}{h^3}\int_0^\infty \mathrm{d}v \int_0^{2\pi} \mathrm{d}\phi\, \tau v^3 \cos^2\phi \frac{\partial f_0}{\partial v}$$

$$\times \left[\int_0^{\pi/2} \sin^3\theta \left\{1 - \exp\left(-\frac{z}{\tau v \cos\theta}\right)\right\} \mathrm{d}\theta\right.$$

$$\left. + \int_{\pi/2}^{\pi} \sin^3\theta \left\{1 - \exp\left(\frac{a-z}{\tau v \cos\theta}\right)\right\} \mathrm{d}\theta\right].$$

$$\sigma = \frac{1}{Ea}\int_0^a J(z)\,\mathrm{d}z = \sigma_0\left[1 - \frac{3l}{2a}\int_0^{\pi/2} \sin^3\theta \cos\theta \left\{1 - \exp\left(-\frac{a}{l\cos\theta}\right)\right\} \mathrm{d}\theta\right]$$

Corriente total

Mas general: coef. P entonces la solución propuesta es:

$$f_0 + f_1^+(v_z, z=0) = p\{f_0 + f_1^-(-v_z, z=0)\} + (1-p)f_0, \qquad \text{en z=0}$$

$$f_0 + f_1^-(v_z, z=a) = p\{f_0 + f_1^+(-v_z, z=a)\} + (1-p)f_0. \qquad \text{en z=a}$$

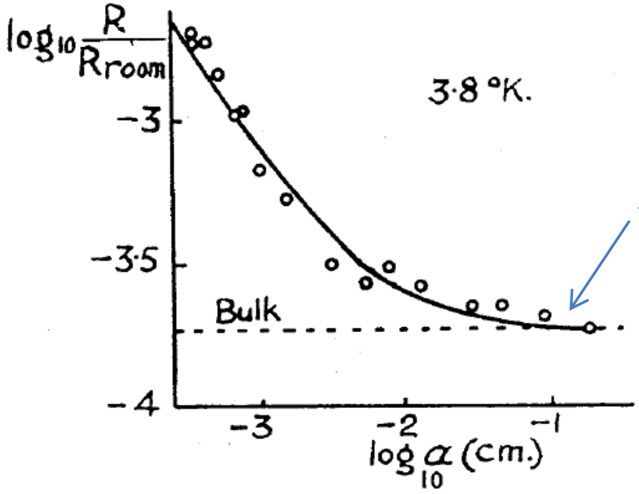
Aparece:

$$\left.\begin{aligned} f_1^+(\mathbf{v}, z) &= \frac{\epsilon\tau E}{m}\frac{\partial f_0}{\partial v_x}\left\{1 - \frac{1-p}{1-p\exp(-a/\tau v_z)}\exp\left(-\frac{z}{\tau v_z}\right)\right\} & (v_z > 0), \\ f_1^-(\mathbf{v}, z) &= \frac{\epsilon\tau E}{m}\frac{\partial f_0}{\partial v_x}\left\{1 - \frac{1-p}{1-p\exp(a/\tau v_z)}\exp\left(\frac{a-z}{\tau v_z}\right)\right\} & (v_z < 0). \end{aligned}\right\}$$

$$\frac{\sigma_0}{\sigma} = 1 + \frac{3}{8\kappa}(1-p) \qquad (\kappa \gg 1)$$

donde es κ= t/λ

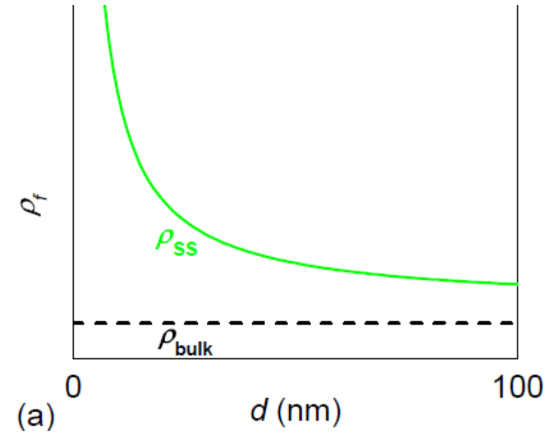
$$\frac{\sigma_0}{\sigma} = \frac{4}{3}\frac{1-p}{1+p}\frac{1}{\kappa\log(1/\kappa)} \qquad (\kappa \ll 1).$$



teoria con p=0

Figure 1. Experimental results on the resistivity of tin foils at 3.8°K, plotted logarithmically against the foil thickness. The full line is the theoretical curve for diffuse scattering ($p = 0$).

Calculo tomando en cuenta:
λ= 38nm Ag (1982)



Que pasa con metales magneticos?

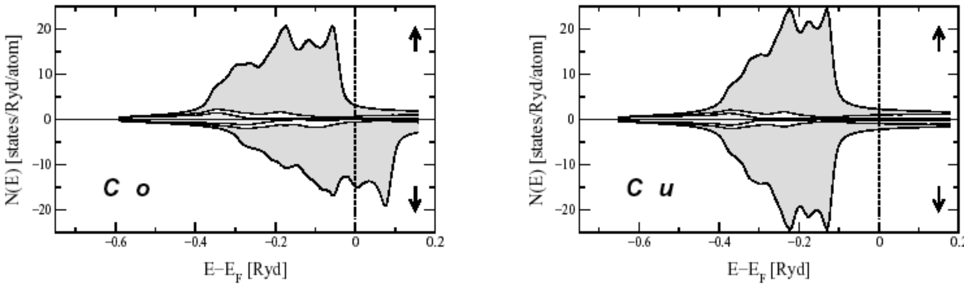


Figure 2.6: Spin-projected densities of states for Co and Cu; the differently shaded grey areas indicate the amount of s, p and d states.

Densidad de estados depende de espin y también en algunos casos el scattering (spin-orbita, e-magnones)

El enfoque para resolver el transporte en sistemas magneticos fue propuesto por Mott y consiste en plantear la conduccion a dos canales (↑,↓) que tienen distinta resistividad!

spin. When we exclude spin-flip scattering processes and make the gross yet conventional assumption that all k states for a spin direction scatter at the same rate we arrive at a particularly simple parameterization of conduction in which one assigns a scattering rate or resistivity to each spin channel of conduction (see also Eq. 2.30):

$$\boxed{\rho^{\uparrow,\downarrow} = \rho^{M,m} \equiv a \pm b,} \tag{2.77}$$

where the superscripts M and m, refer to electrons with spin parallel (Majority) and opposite (minority) to the magnetization. From Eq. (2.65) and the realization that for a homogeneous sample the effective fields are independent of spin, the total current in the two spin channels is,

$$\boxed{j = j^{\uparrow} + j^{\downarrow} = (\sigma^{\uparrow} + \sigma^{\downarrow})E,} \tag{2.78}$$

so that the resistivity is

$$\boxed{\begin{aligned} \rho &= \frac{1}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{\rho^{\uparrow}\rho^{\downarrow}}{\rho^{\uparrow +}\rho^{\downarrow}} \\ &= \frac{a^2 - b^2}{2a}. \end{aligned}} \tag{2.79}$$

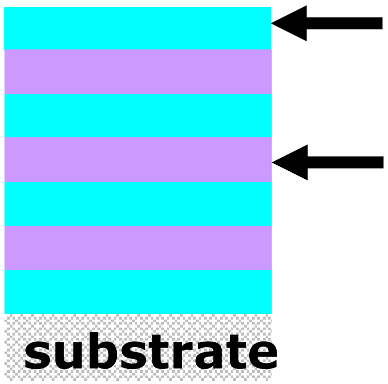
It is obvious that the resistance in ferromagnetic metals is less than in materials with comparable scattering rates, i.e., the average resistivity for each channel is a, so that for two channels conducting in parallel we find $\rho = 1/2a$, while from Eq. (2.79) we find $\rho < \frac{1}{2a}$. The channel with the lower resistivity conducts more of (shunts) the current, and creates the effect of a *short circuit*.

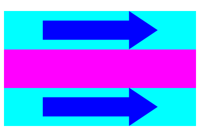
MAGNETORESISTENCIA GIGANTE

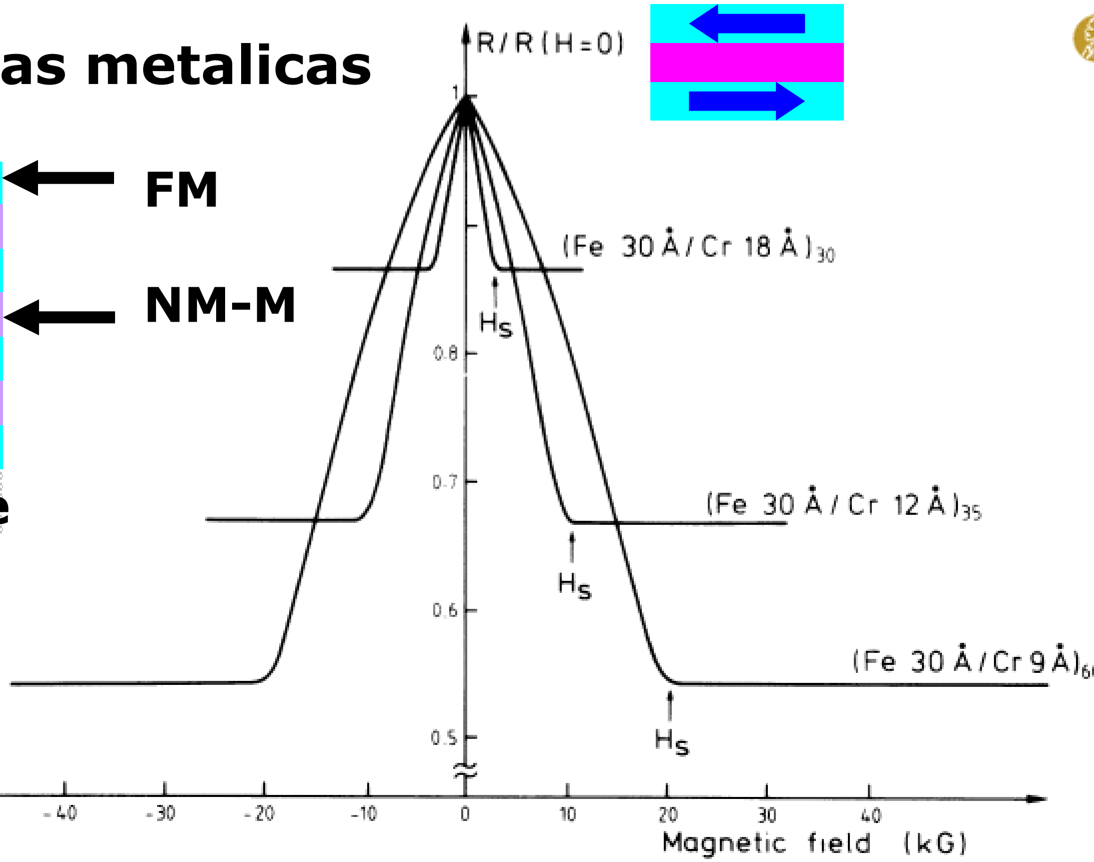
2007
Albert Fert &
Peter Grünberg

Nobelprize.org

multicapas metalicas







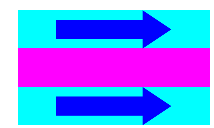


FIG. 3 Magnetoresistance of three Fe/Cr superlattices at 4.2 K. The current and the applied field are along the same [110] axis in the plane of the layers.

M.N. Baibich *et al.*, Phys. Rev. Lett. **61**, 2472 (1988).

MODELO A DOS CORRIENTES (propuesta inicial Mott 50's)

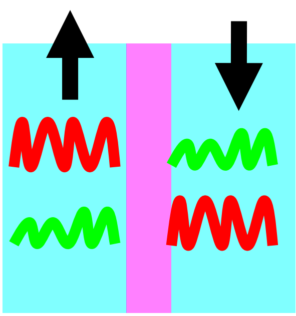
Conduccion electrica se realiza a traves de dos canales, correspondientes a cada direccion de espin (↑ y ↓) respectivamente.

$\rho^{\uparrow}$, $\rho^{\downarrow}$: resistencia electrones mayoritarios/ minoritarios

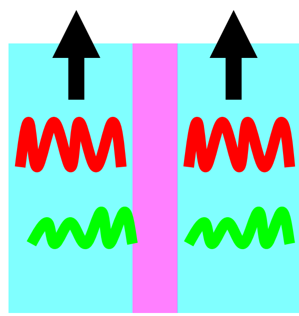
$j = j^{\uparrow} + j^{\downarrow} = (\sigma^{\uparrow} + \sigma^{\downarrow}).E$

Circuito resistivo equivalente

(a)



(b)



APM

$\rho=(\rho^{\uparrow}+\rho^{\downarrow})^2/[2.(\rho^{\uparrow}+\rho^{\downarrow})]$

PM

$\rho = \rho^{\uparrow}\cdot \rho^{\downarrow}/ (\rho^{\uparrow}+\rho^{\downarrow}) \sim \rho^{\downarrow}$

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Theory of Giant Magnetoresistance Effects in Magnetic Layered Structures with Antiferromagnetic Coupling

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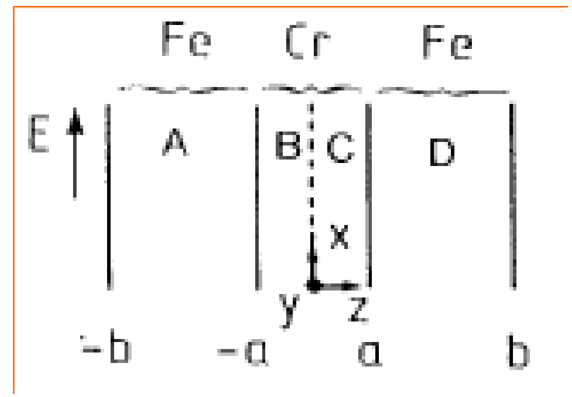
(Received 30 March 1989)

$$\frac{\partial g}{\partial z}+\frac{g}{\tau v_z}=\frac{eE}{m v_z}\frac{\partial f_0}{\partial v_x}$$

$$g=g_{A+\uparrow}(v_z,z)+g_{A+\downarrow}(v_z,z)\,.$$

$$g=g_{A-\uparrow}(v_z,z)+g_{A-\downarrow}(v_z,z)$$

$$g_{A\pm\uparrow}(v_z,z)=\frac{eE\tau}{m}\frac{\partial f_0}{\partial v_x}\left[1+A_{\pm\uparrow}\exp\left(\frac{\mp z}{\tau|v_z|}\right)\right]$$



En bordes periodo superred

$$g_{A+\uparrow}=R_0 g_{A-\uparrow}\quad \text{at}\quad z=-b\,,$$

$$g_{D-\uparrow}=R_0 g_{D+\uparrow}\quad \text{at}\quad z=+b\,.$$

$z=-a,$

$$G_{A-\uparrow}=T_\uparrow g_{B-\uparrow}+R_\uparrow g_{A+\uparrow}\,,$$

$$g_{B+\uparrow}=T_\uparrow g_{A+\uparrow}+R_\uparrow g_{B-\uparrow}\,.$$

$$g_{B-\uparrow}=T_{\uparrow\uparrow}g_{C-\uparrow}+T_{\uparrow\downarrow}g_{C-\downarrow}\,,$$

$$g_{B-\downarrow}=T_{\downarrow\downarrow}g_{C-\downarrow}+T_{\downarrow\uparrow}g_{C-\uparrow}\,,$$

$$g_{C+\uparrow}=T_{\uparrow\uparrow}g_{B+\uparrow}+T_{\uparrow\downarrow}g_{B+\downarrow}\,,$$

$$g_{C+\downarrow}=T_{\downarrow\downarrow}g_{B+\downarrow}+T_{\downarrow\uparrow}g_{B+\uparrow}\,,$$

en z=0

Idem en z=a y para spin down

$$T_{\uparrow\uparrow} = T_{\downarrow\downarrow} = \cos^2(\theta/2)$$

$$T_{\uparrow\downarrow} = T_{\downarrow\uparrow} = \sin^2(\theta/2) \, ,$$

Depende del campo el angulo!

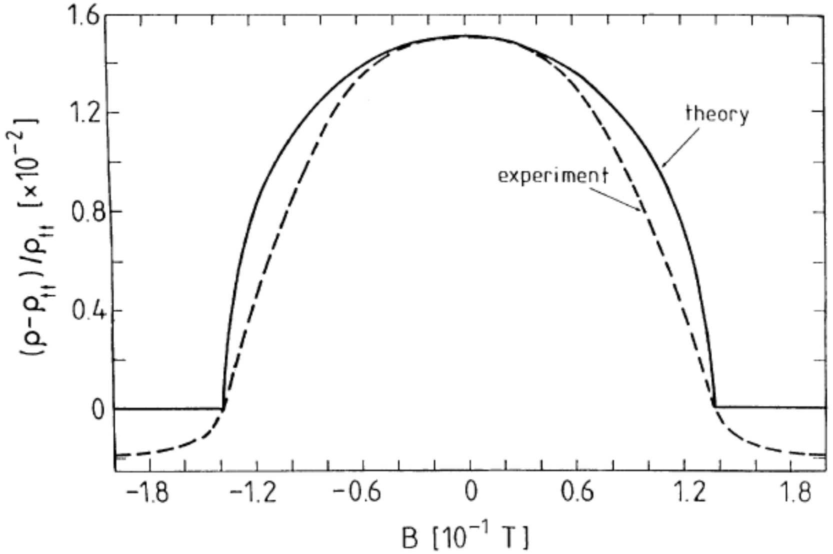


FIG. 2. The percentage change in resistance as a function of applied field. The deviation of the experimental data from zero at high field is a measure of the size of the magnetoresistance anisotropy effect, neglected in the theory. The parameters for the figure are $N=6$ and $D_{\uparrow}=0.48$.

Calculan:

$$J(z) = \int v_x g(v_z, z) d^3v$$

Y despues se integra en z

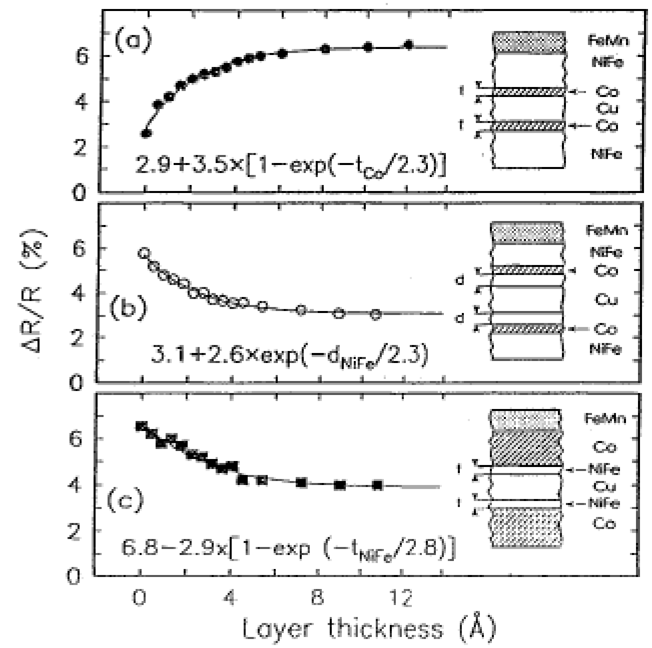
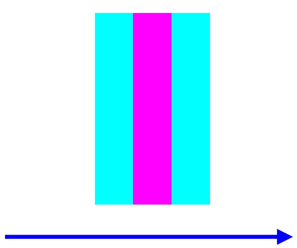
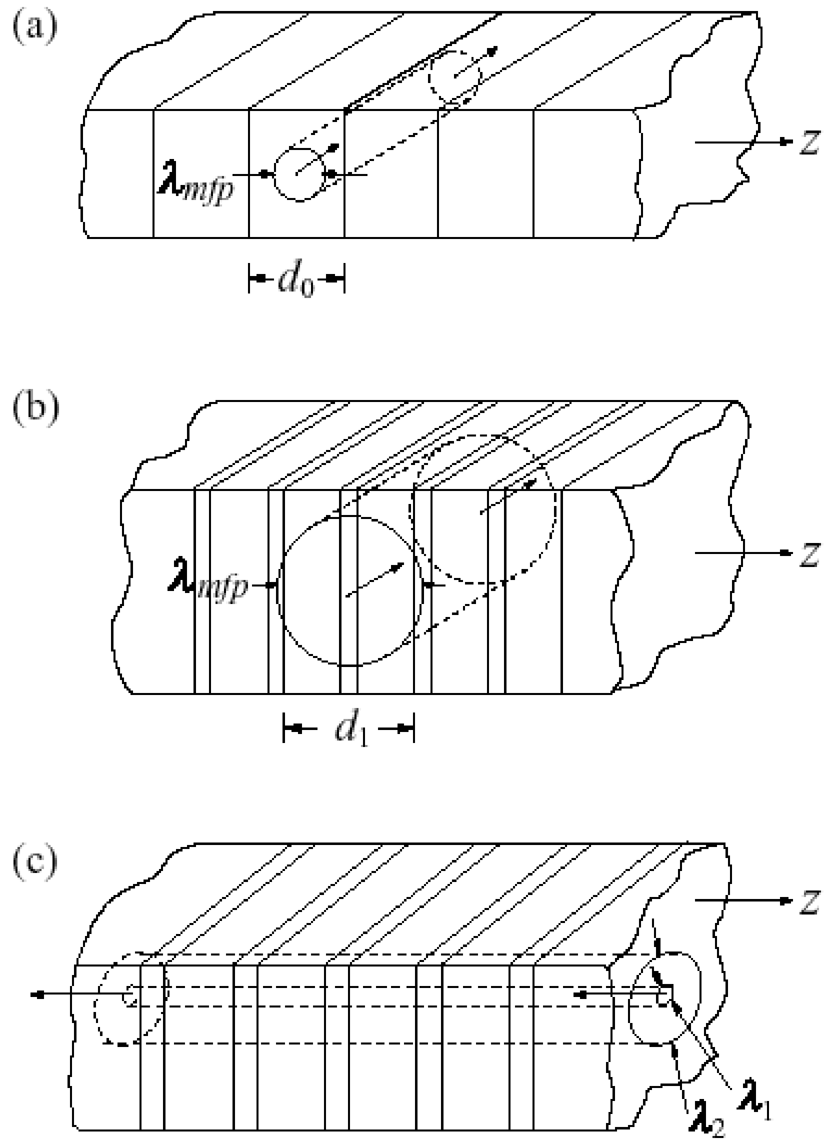


Fig. 2.73. Dependence of room temperature saturation magnetoresistance on (**a**) Co interface layer thickness, t_{Co}, in sandwiches of the form $Si/Ni_{81}Fe_{19}(53 - t_i)/Co(t_i)/Cu(32)/Co(t_i)/Ni_{81}Fe_{19}(22 - t_i)/FeMn(90)/Cu(10)$, (**b**) distance of a 5 Å thick Co layer from the $Ni_{81}Fe_{19}/Cu$ interfaces in sandwiches of the form $Si/Ni_{81}Fe_{19}(49 - d)/Co(5)/Ni_{81}Fe_{19}(d)/Cu(30)/Ni_{81}Fe_{19}(d)/Co(5)/Ni_{81}Fe_{19}(18 - d)/FeMn(90)/Cu(10)$, and (**c**) $Ni_{81}Fe_{19}$ interface layer thickness, t_i, in sandwiches of the form $Si/Co(57 - t_i)/Ni_{81}Fe_{19}(tNi_{81}Fe_{19})/Cu(24)/Ni_{81}Fe_{19}(t_i)/Co(29 - t_i)/FeMn(100)/Cu(10)$. Note layer thicknesses are in angstroms

GEOMETRIAS DE MEDICION





Comparacion resultados CPP y CIP en Co/Cu

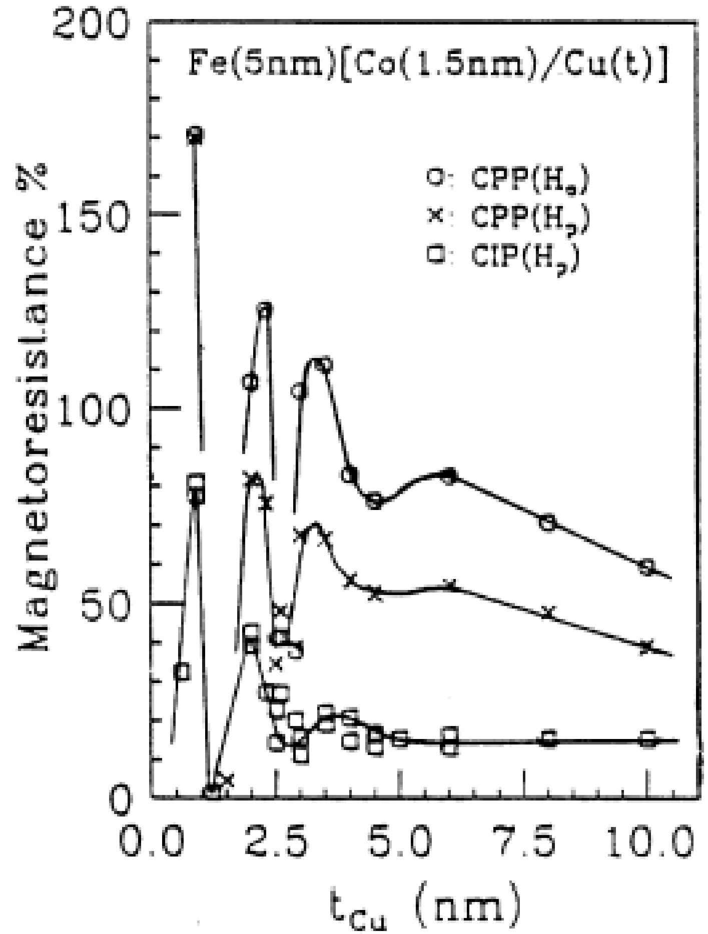


Fig. 2. CIP-MR and CPP-MR for a series of [Co(1.5 nm)/ Cu(t)]$_N$ multilayers. The open squares are the CIP-MR at H(Pk); the crosses the CPP-MR at H(Pk); and the open circles the CPP-MR at H(0). The curves are just guides to the eye (from Ref. [10,11]).

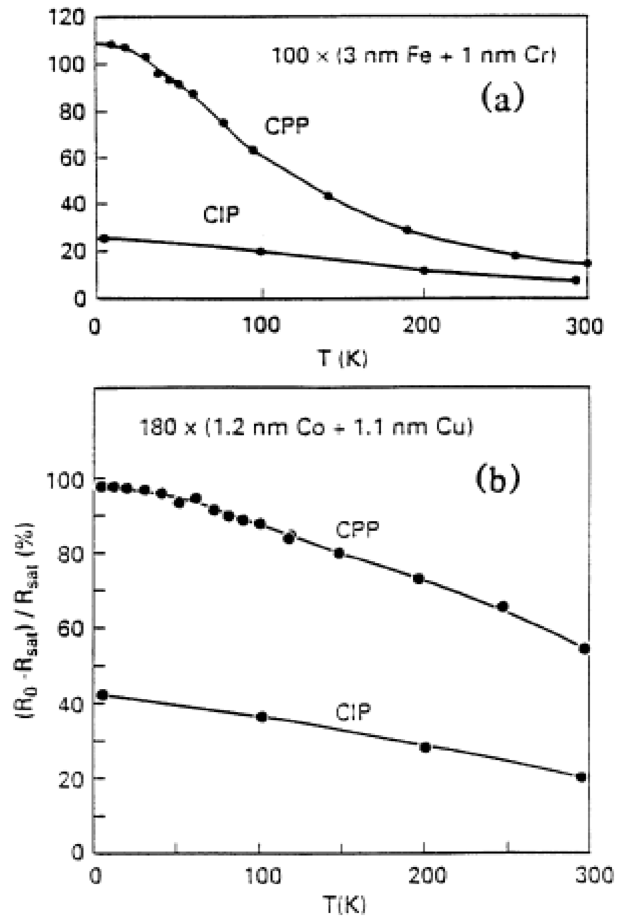
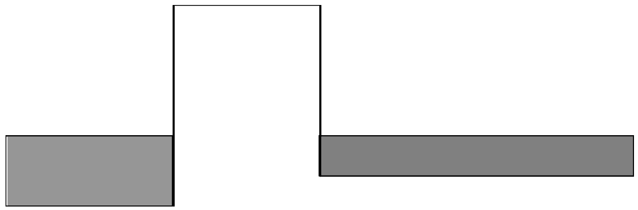


Fig. 3. CPP-MR and CIP-MR versus temperature T for: (a) $[Fe(3\ nm)/Cr(1\ nm)]_{100}$ and (b) $[Co(1.2\ nm)/Cu(1.1\ nm)]_{180}$ multilayers. The curves are just guides to the eye (After, Refs. [12,13]).

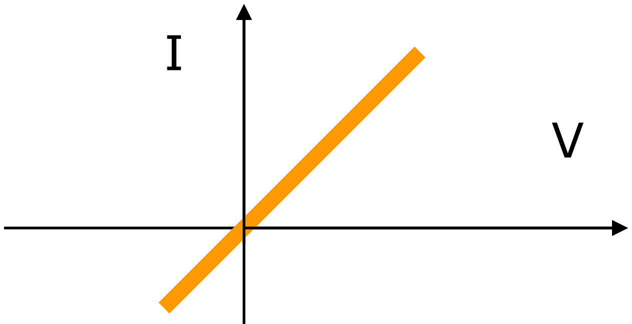
[12] M.A.M. Gijs et al., Phys. Rev. Lett. 70 (1993) 3343.
[13] M.A.M. Gijs et al., J. Appl. Phys. 75 (1994) 6709.

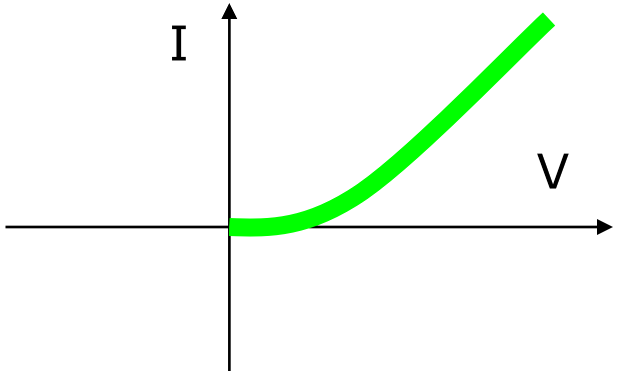
JUNTURAS TUNEL

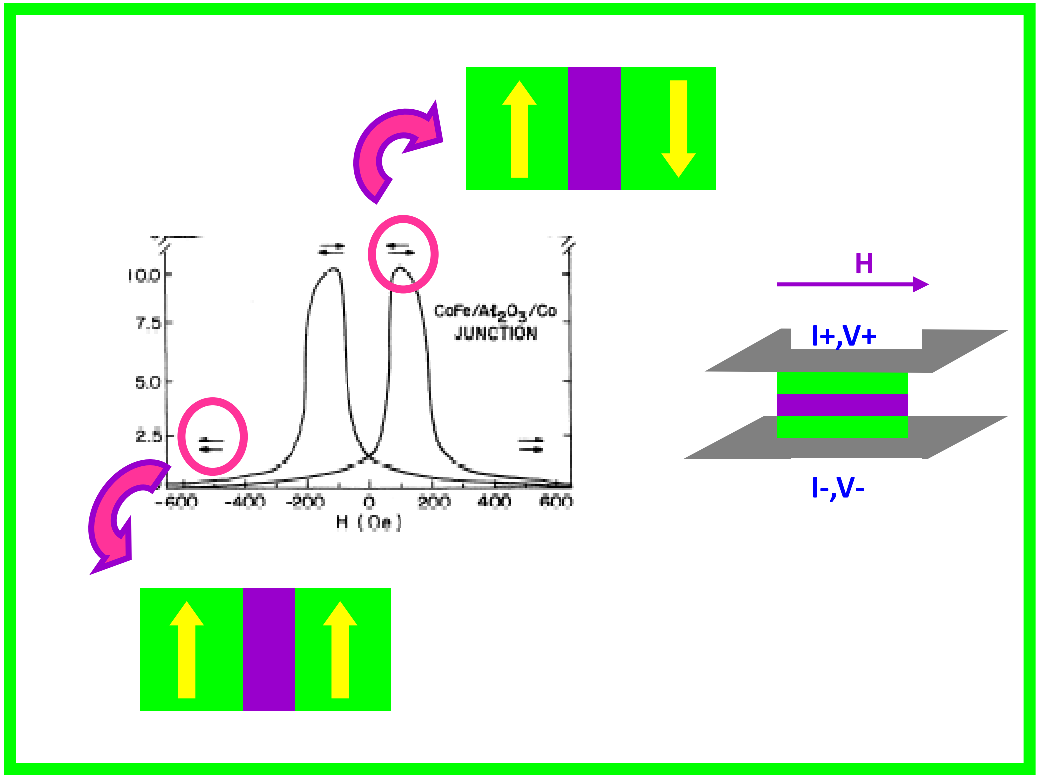
Dos electrodos metalicos separados por un aislador. El transporte esta controlado por el efecto tunel.

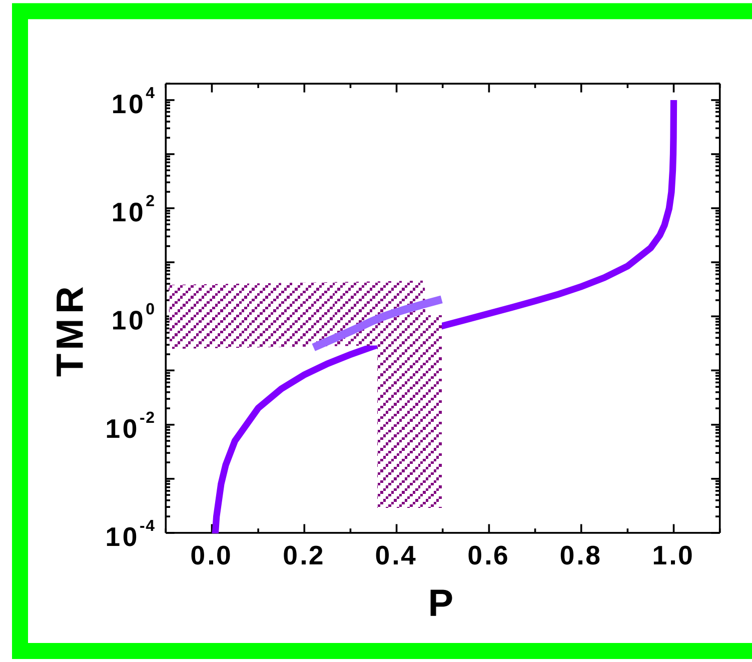


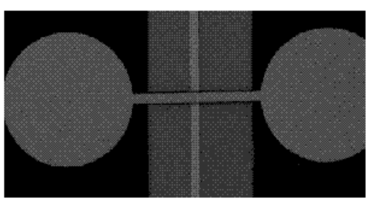
Diferencia crucial con la conduccion en sistemas metalicos



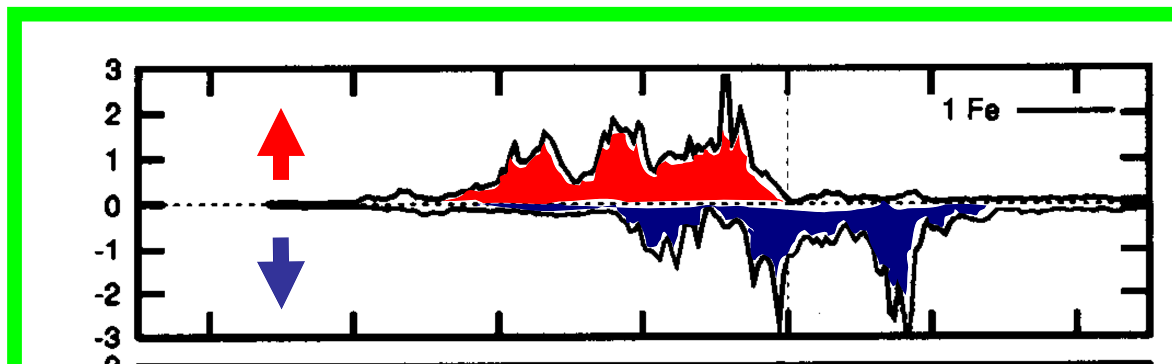






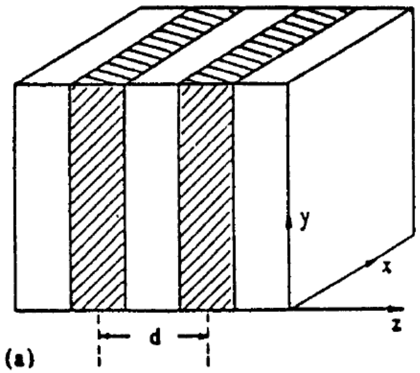


Scanning electron microscope image of typical metal-masked magnetic tunnel junction, 80 µm x 80 µm in area.



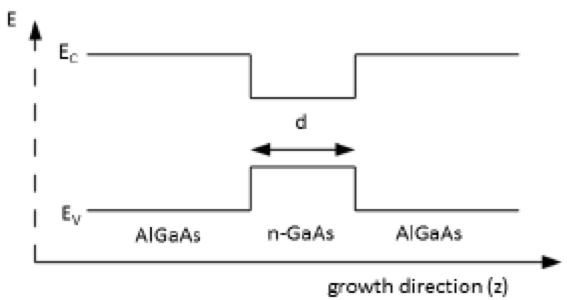
P= (DOS(↑) - DOS(↓))/(DOS(↑) + DOS(↓))

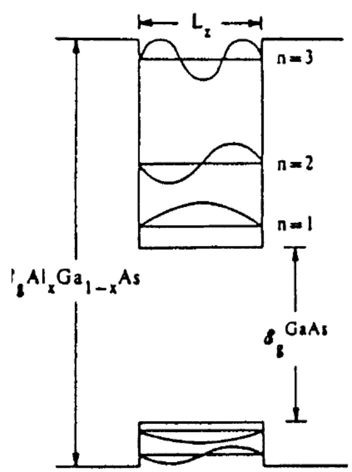
Pozos cuanticos – Gases de electrones 2D

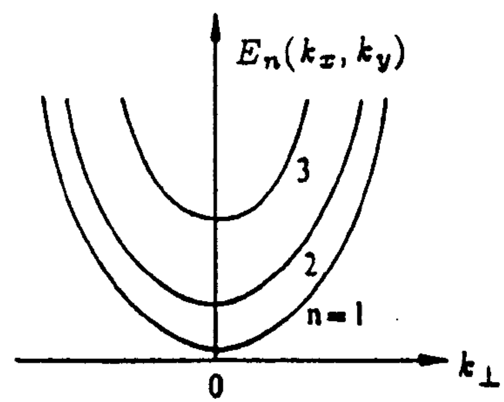


$$\Psi_{n,k_x,k_y} = e^{ik_x x} e^{ik_y y} f_n(z)$$

$$E = E(k_x,k_y) + E_n = \frac{\hbar^2}{2m_e}\left(k_x^2 + k_y^2 + \frac{\pi^2 n^2}{d^2}\right)$$



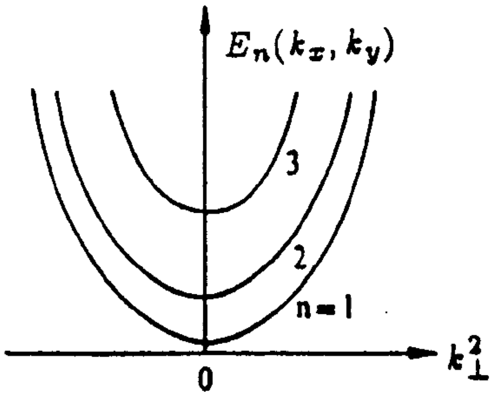




Densidad de estados del gas 2D

En cada disco de energia En el numero de estados es:

$$N_{2D} = \frac{2}{(2\pi)^2}\pi k_\perp^2 \qquad k_\perp^2 = k_x^2 + k_y^2$$



Puesto que $E_\perp = \dfrac{\hbar^2 k_\perp^2}{2m^*}$

entonces la densidad de estados por energia es:

$$\frac{\partial N_{2D}}{\partial E} = g_{2D}(E) = \frac{m^*}{\pi\hbar^2}.$$

Por cada n da constante!

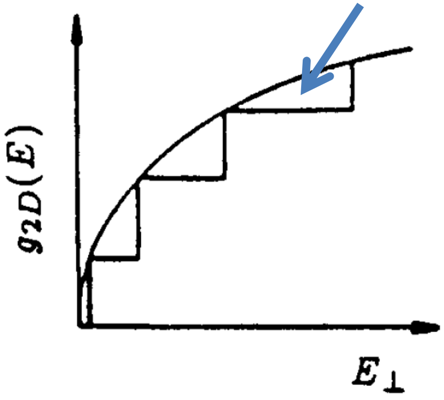
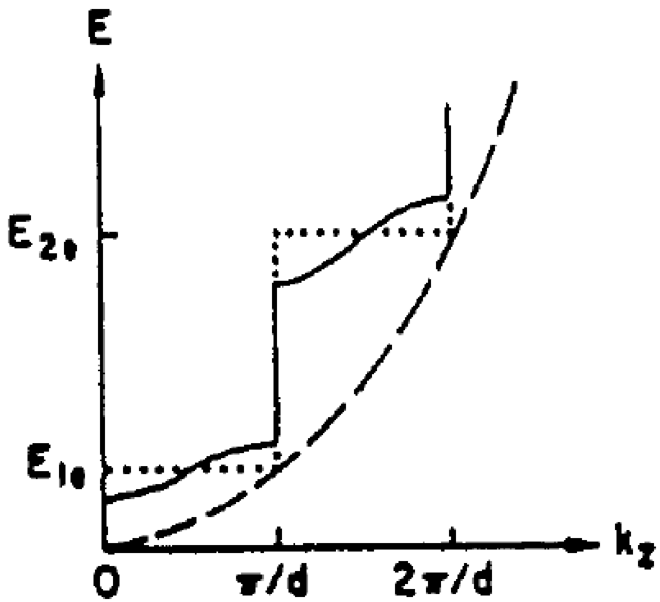
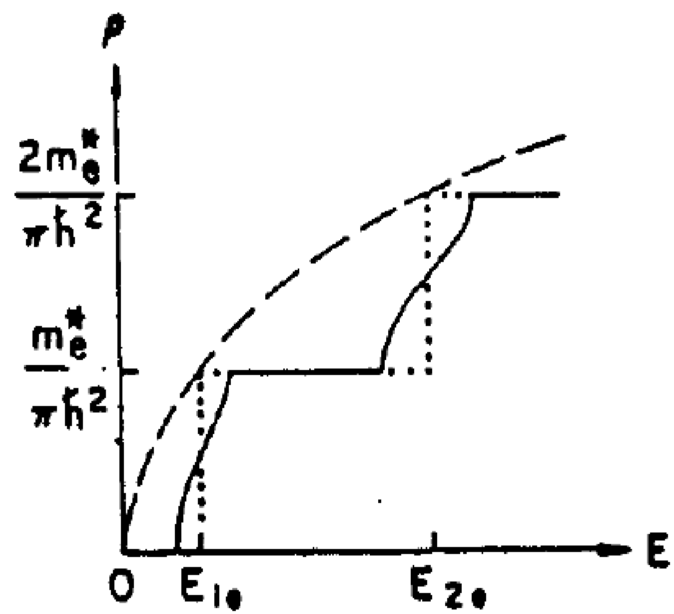


Figure 9.14: Two dimensional density of states $g_{2D}(E)$ for rectangular quantum well structures.

Relacion de dispersion y densidad de estados para un 3D, 2D y una muestra real





En realidad, el tamaño finito del pozo hace que el sistema no sea totalmente 2D, ademas que en los semiconductores las bandas de valencia no son perfectamente parabolicas

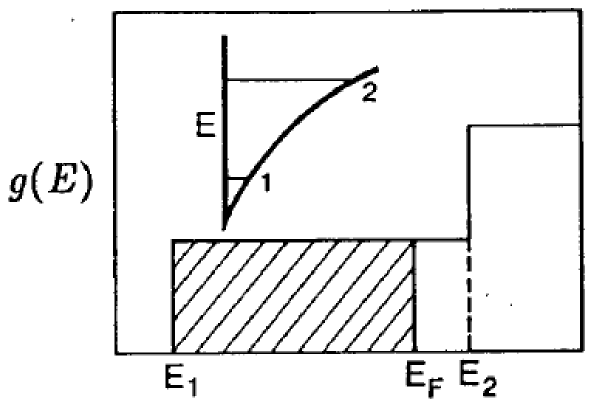
Gas 1D

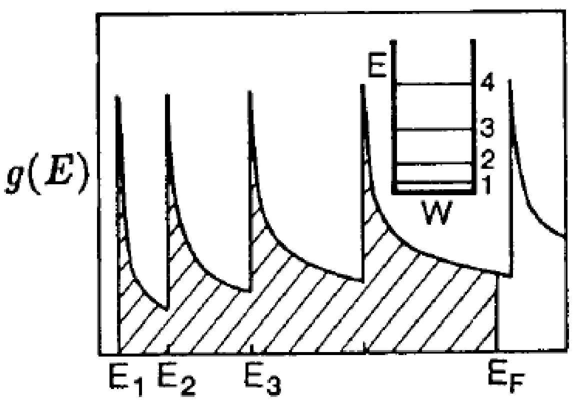
Alambre.... $E = E_n + \hbar^2 k^2/(2m^*)$

$$N_{1\mathrm{D}} = \frac{2}{2\pi}(k) = \frac{1}{\pi}\left(\frac{2m^*(E - E_n)}{\hbar^2}\right)^{1/2}$$

$$g_{1\mathrm{D}}(E) = \frac{1}{2\pi}\left(\frac{2m^*}{\hbar^2}\right)^{1/2}(E - E_n)^{-1/2}.$$

Por cada sub-banda



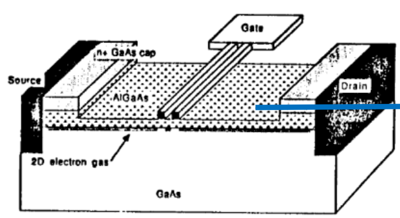


2D y 1D a la derecha.
En la fig. izq solo se ocupa una sub-banda, en la derecha hasta la cuarta

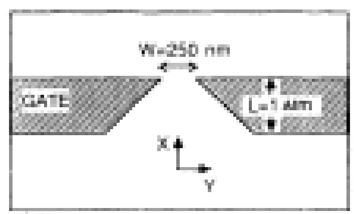
Que pasa en la conduccion balística en un sistema 1D?

Experimento para ver paso difusivo/balistico….

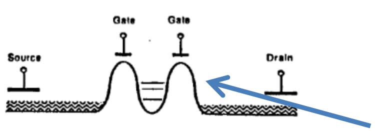
Se confina un gas 2D a fluir por un canal muy angosto*. Calculo la corriente a través del canal, aplicando el voltaje sobre el gas 2D (electrodos, source-drain)



(a)



Ancho máximo del hilo: W= 250nm



* Con un voltaje tipo gate se controla el ancho del gas 1D (ancho pozo). No lo pueden hacer en un metal, lo hicieron sobre un gas GaAs-AlGaAs

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Quantized Conductance of Point Contacts in a Two-Dimensional Electron Gas

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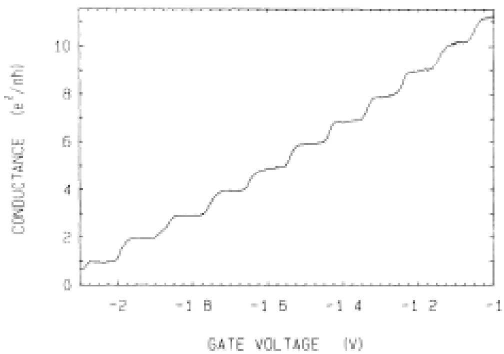

FIG. 2. Point-contact conductance as a function of gate voltage, obtained from the data of Fig. 1 after subtraction of the lead resistance. The conductance shows plateaus at multiples of $e^2/\pi\hbar$.

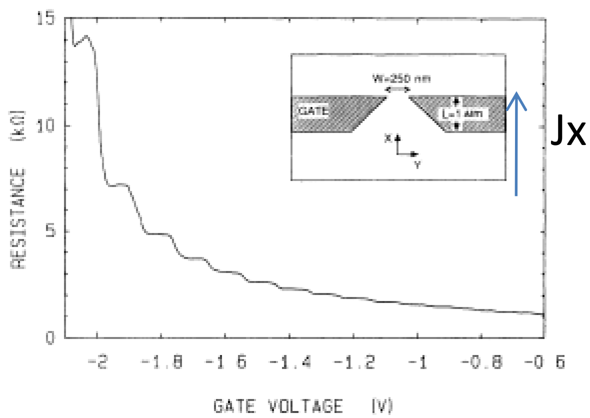

FIG. 1. Point-contact resistance as a function of gate voltage at 0.6 K. Inset: Point-contact layout.

Calculo $j_x = n.e.\delta v$ **balistico**

Pero 1D $N = 2k_F / (2\pi/L) \rightarrow n = k_F / \pi$ y

$eV = 1/2m^*(v_F + \delta v)^2 - 1/2m^* v_F^2 = m^* v_F \delta v \cancel{+1/2\, m^* \delta v^2}$

Entonces: $J_x = e\, k_F / \pi \,.\, eV / (m^* v_F) = e^2 / \pi\hbar\, V$, pero

$G = W/L\, \sigma$ => $G_i = e^2 / \pi\hbar$

$$G = \sum_{n=1}^{N_c} \frac{e^2}{\pi\hbar},$$ Sumo sobre sub-bandas o canales

Sumo sobre canales o sub-bandas,
donde Nc entero mayor valor, que sea menor
a $k_F W / \pi$ (en direc. y: **$k_y = n\, \pi / W$**) OJO n entero

Si me muevo en $\delta W = \lambda_F/2 = \pi / k_F$ entonces agrego un canal de conduccion y G sube en un numero entero de e2 / $\pi\hbar$

Limites $l \gg W$, $\lambda_F \ll W$
Wmax 250nm, le≅ 8.5μm λ_F=42nm