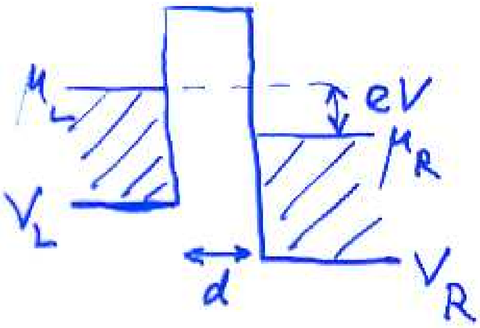
## Lecture 12.

# Spin-dependent tunneling in magnetic nanostructures

- Effect TMR
- Spin quantum well
- Transport in ferromagnetic wires with domain walls
- Negative resistance of the domain wall

# Effect TMR

Tunneling through the barrier (nonmagnetic)



$$I = e \int \frac{d^2 K_{\parallel}}{(2\pi)^2} N(K_{\parallel}) T(K_{\parallel})$$

$\hbar = 1$

$$N = 2 \cdot \frac{1}{2} \int_0^{eV} dE \; v_z \cdot \frac{1}{\pi v_z} = 2eV$$

$$T(K_{\parallel}) = \frac{16 K_L \varkappa^2 K_R e^{-2\varkappa d}}{(K_L^2 + \varkappa^2)(K_R^2 + \varkappa^2)}$$

$$K_L = \sqrt{2m(E - V_L) - k_{\parallel}^2}$$

$$K_R = \sqrt{2m(E - V_R) - K_{\parallel}^2}$$

$$\varkappa = \sqrt{K_{\parallel}^2 + 2m(V_B - E)}$$

## Conductance

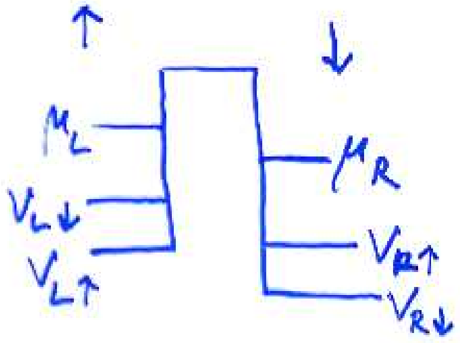
$$G = \frac{dI}{dV} = 2e^2 \int \frac{d^2 K_{\parallel}}{(2\pi)^2} T(K_{\parallel}) =$$

$$= 2e^2 \int_0^{\varepsilon_m} \nu_2(\varepsilon) T(\varepsilon) \, d\varepsilon$$

$$\nu_2(\varepsilon) = \frac{m}{2\pi}$$

$$\varepsilon_m = \frac{1}{2m} \min\{K_{LF}^2, K_{RF}^2\}$$

# Magnetic case



$V_L \to V_{L\sigma}$

$V_R \to V_{R\sigma}$ $\sigma = \uparrow, \downarrow$

$K_L \to K_{L\sigma}$, $K_R \to K_{R\sigma}$

$$I^F_{\uparrow(\downarrow)} = \frac{e}{2}\int \frac{d^2K_\parallel}{(2\pi)^2} N_{\uparrow(\downarrow)}(K_\parallel)\, T^F(K_\parallel)$$

$$I^{AF}_{\uparrow(\downarrow)} = \frac{e}{2}\int \frac{d^2K_\parallel}{(2\pi)^2} N_{\uparrow(\downarrow)}(K_\parallel)\, T^{AF}(K_\parallel)$$

$$TMR = \frac{G^F - G^A}{G^A}$$

For $\varkappa d \gg 1$ (large barrier)

$$TMR \simeq \frac{2P_{eff}^2}{1-P_{eff}^2}$$

$$P_{eff} = \frac{\varkappa_0^2 - k_{m0}K_{M0}}{\varkappa_0^2 + k_{m0}K_{M0}}\, P$$

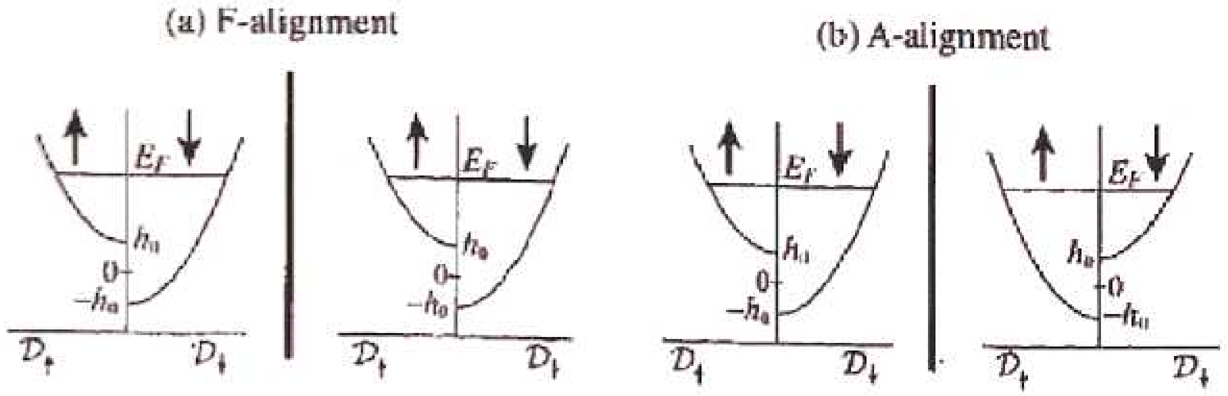
$$P = \frac{K_{M0} - k_{m0}}{K_{M0} + k_{m0}}$$ – spin polarization in ferromagnet

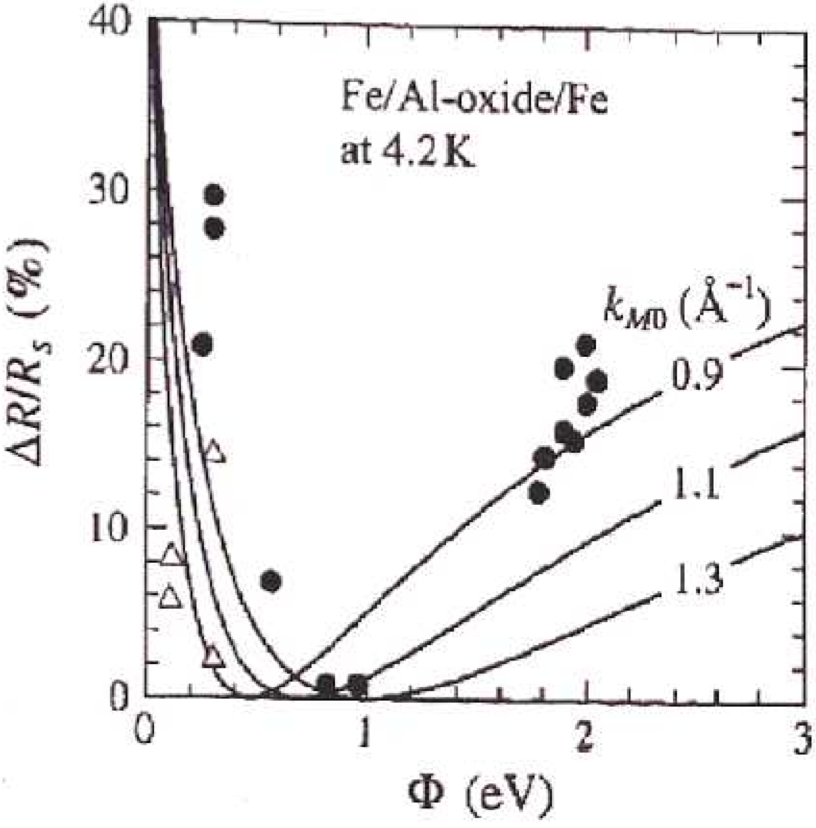
$K_{M0} = \sqrt{2mE_{F\uparrow}}$

$k_{m0} = \sqrt{2mE_{F\downarrow}}$

For $\varkappa_0$ large:

$$TMR \simeq \frac{2P^2}{1-P^2}$$


(a) F-alignment
(b) A-alignment
$E_F$
$h_0$
0
$-h_0$
$D_\uparrow$
$D_\downarrow$


Fe/Al-oxide/Fe
at 4.2 K
$k_{M0}$ (Å$^{-1}$)
0.9
1.1
1.3
$\Delta R/R_S$ (%)
$\Phi$ (eV)
0
10
20
30
40
0
1
2
3

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# 230% room-temperature magnetoresistance in CoFeB/MgO/CoFeB magnetic tunnel junctions

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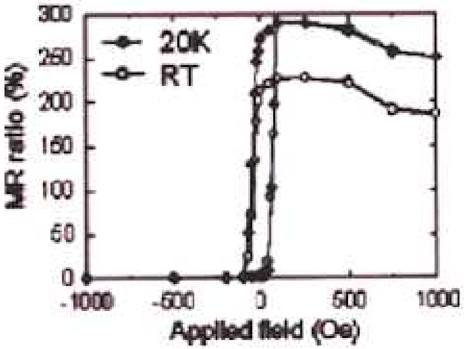


FIG. 1. MR curves of CoFeB/MgO/CoFeB MTJs evaluated at RT and 20 K.

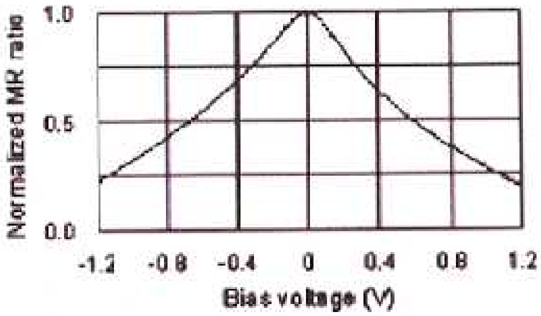
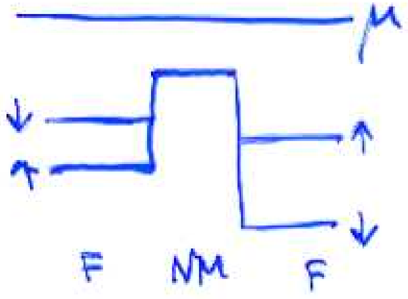
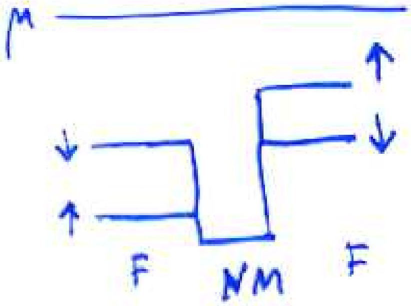


FIG. 4. Bias voltage dependence of normalized MR ratio evaluated at RT in CoFeB/MgO/CoFeB MTJs.

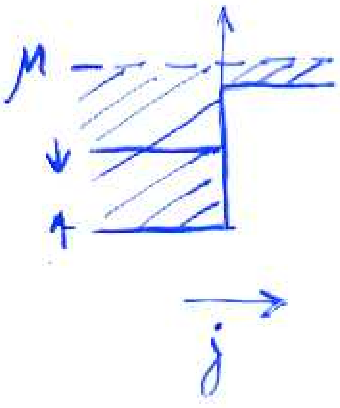
How to use magnetic profile?





structure with
spin quantum well

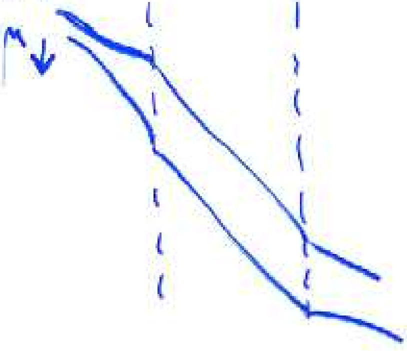
## Ferromagnet - Semiconductor

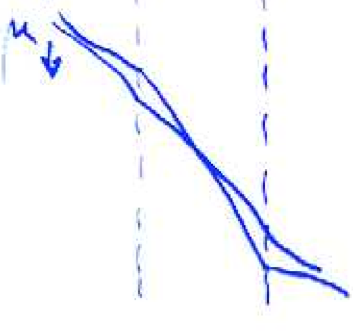


spin injection
into semiconductor

Experimentally: no spin injection!

The reason is different resistivity





$$\alpha = \frac{j_\uparrow - j_\downarrow}{j_\uparrow + j_\downarrow}$$

Spin-polarized current

RAPID COMMUNICATIONS

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# Fundamental obstacle for electrical spin injection from a ferromagnetic metal into a diffusive semiconductor

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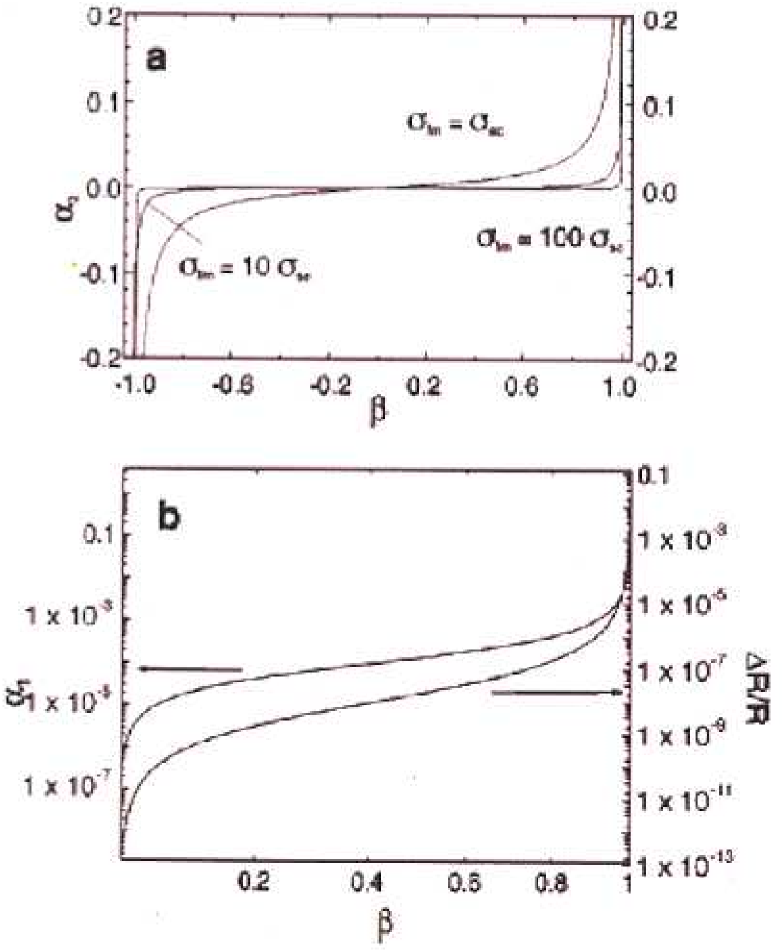
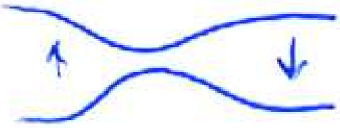


# Ferromagnet with domain wall

Two main types

- smooth DW, $k_F L \gg 1$ (classical ferro)
- sharp DW, $k_F L \lesssim 1$ (constriction)
  - $k_F L \ll 1$ (magn. semicond.)

In nanoconstriction:



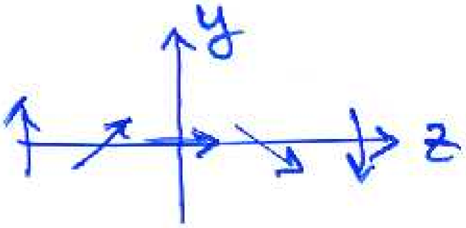
$L \sim$ at. size

(P. Bruno, 1999)

Applications:

- controllable using magn. field
- easy to move
- current-induced motion

## Resistance of smooth DW



$$\mathcal{H} = -\frac{1}{2m}\frac{\partial^2}{\partial z^2} - J\,\vec{\sigma}\cdot\vec{n}(z)$$

Unitary transformation:

$$T^+(z)\,\vec{\sigma}\cdot\vec{n}(z)\,T(z) = \sigma_z$$

$$\frac{\partial}{\partial z} \to \frac{\partial}{\partial z} + A_z(z)$$

Gauge potential:

$$\vec{A}(z) = T^{+}(z)\,\frac{\partial}{\partial z}\,T(z)$$

Parametrization:

$$\vec{n}(z) = (\sin\varphi(z),\ 0,\ \cos\varphi(z))$$

$$\vec{A}(z) = \Big(0,\ 0,\ \underbrace{-\frac{i}{2}\sigma_y\,\varphi'(z)}_{\text{small for smooth DW}}\Big)$$

Semiclassical approximation

$$\varphi'(z) \equiv \beta \simeq \text{const}$$

$$H_{\text{eff}} \simeq -\frac{1}{2m}\frac{\partial^2}{\partial z^2} - \mu\sigma_z + \frac{m\beta^2}{2} + i\sigma_y\,\beta\,\frac{\partial}{\partial z}$$

Conductivity

$$\sigma_{zz} = \frac{e^2}{2\pi m^2}\,\mathrm{Tr}\int\frac{d^3k}{(2\pi)^3}\,(k_z - m\beta\sigma_y)\,G^R\,(k_z - m\beta\sigma_y)\,G^A$$

Resistance of DW can be *negative*

(and very small!)

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# Ballistic magnetoresistance over 3000% in Ni nanocontacts at room temperature

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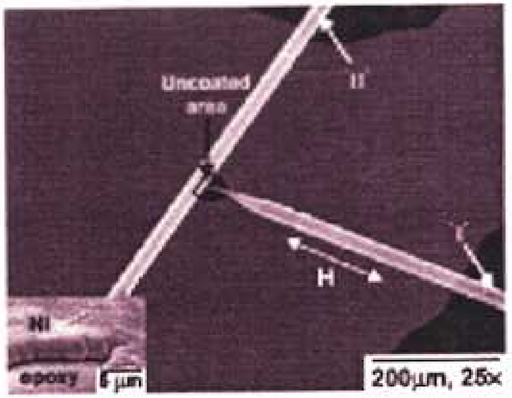


FIG. 1. Scanning electron micrograph of the 125-$\mu$m-diameter Ni wires in a *T* configuration. The electrodeposited Ni nanocontact is deposited in the gap between the tip of the Ni wire labeled I and the wire labeled II. The inset shows the columnar growth of the electrodeposited Ni.

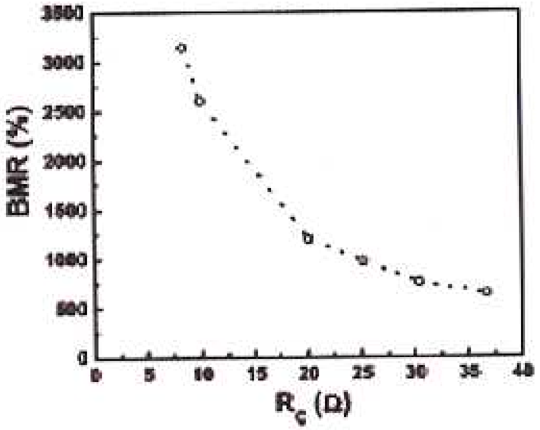
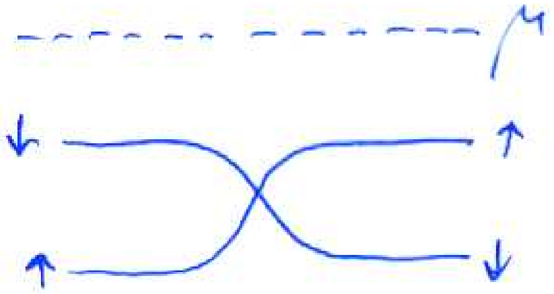
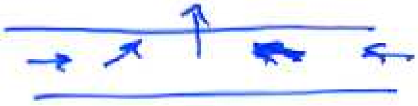


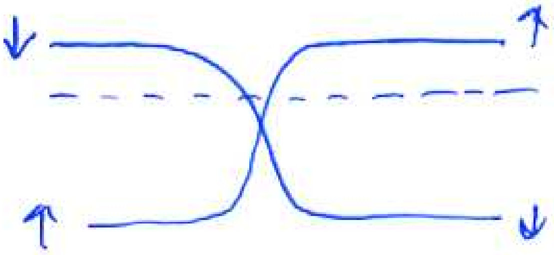
FIG. 4. Variation in BMR as a function of contact radius, as inferred from change in low-field resistance over successive cycles in Fig. 3 and several other measurements taken from the same sample.

# Reflection from a sharp domain wall





In case of 100% polarization:



$MR = \infty$