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Based on the energetics of the system, determine when electrons will tunnel into and out of the island, and how many extra electrons, n, that reside on the island.

$\Rightarrow$ we need to calculate $E_n(U)$; then $n \to n \pm 1$ if U is changed so that $E_{n\pm1}(U) < E_n(U)$

Total capacitance: $C_s^{-1} = C^{-1} + C_g^{-1} \Rightarrow C_s = \frac{CC_g}{C+C_g}$ (series)

Capacitance seen from island: $C_\Sigma = C + C_g$

Kirchhoff: $U = \frac{Q}{C} + \frac{Q_g}{C_g}$

Net charge on island: $q = Q - Q_g = -ne$

$\Rightarrow Q = C_s\left(U + \frac{q}{C_g}\right)$, $Q_g = C_s\left(U - \frac{q}{C}\right)$

Electrostatic energy: $E_{el} = \frac{Q^2}{2C} + \frac{Q_g^2}{2C_g} = \dots = \underbrace{\frac{1}{2} C_s U^2}_{\text{external part}} + \underbrace{\frac{q^2}{2C_\Sigma}}_{\text{internal part}}$

Work done by island (on external world) when $Q_g \to Q_g + dQ_g$:

$dW = U \cdot (+dQ_g)$

[Sign of dW: positive work done by island if positive charge dQ_g is moved from $\ominus$ to $\oplus$ terminal of voltage source, i.e., through a positive voltage U]

A tunneling event ($q \to q + dq$; $dq = -e$ if $n \to n+1$) brings the system out of equilibrium (with U fixed).

Equilibrium is reestablished via redistribution of Q and Q_g:

$$dQ = \frac{C_s}{C_g} dq = \frac{C}{C_\Sigma} dq = -\frac{C}{C_\Sigma} e$$

$$dQ_g = -\frac{C_s}{C} dq = -\frac{C_g}{C_\Sigma} dq = \frac{C_g}{C_\Sigma} e$$

The <u>total</u> change in equilibrium energy, dE, caused by a tunneling event is the sum of dE_{el}, the change in electrostatic energy, and $-dW$, the work done (on the island):

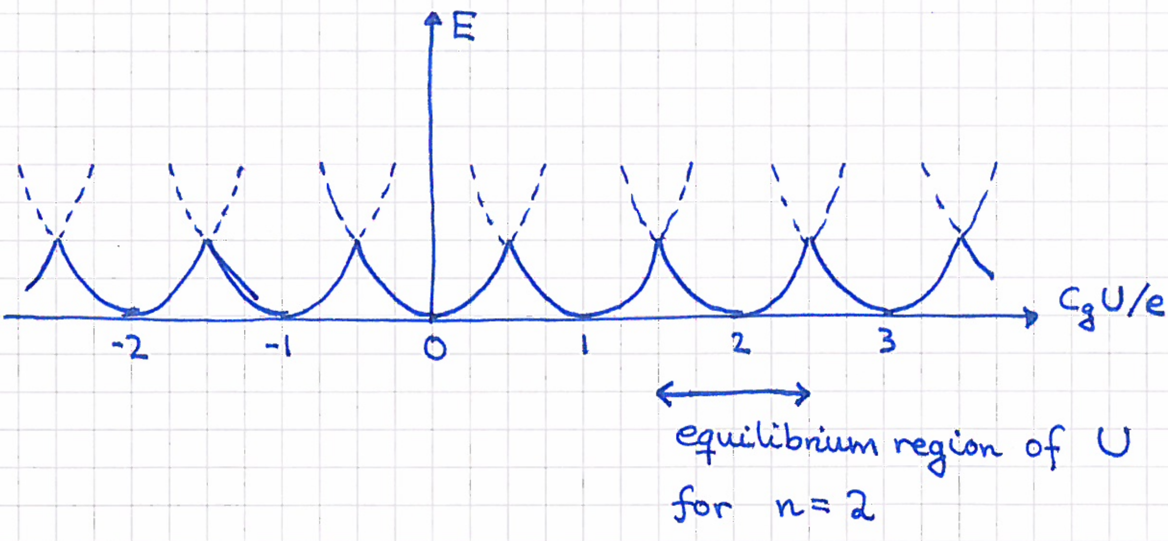
$$dE = dE_{el} - dW = \frac{q\,dq}{C_\Sigma} - U\,dQ_g = \frac{q\,dq}{C_\Sigma} + \frac{U C_g\,dq}{C_\Sigma}$$

Hence, the total equilibrium energy, with applied voltage U and n electrons on the island, is:

$$E_n(U) = \int dE = \int_0^q \frac{q + C_g U}{C_\Sigma}\,dq = \frac{(q + C_g U)^2}{2C_\Sigma} - \frac{(C_g U)^2}{2C_\Sigma}$$

$$\overset{(q=-ne)}{=} \frac{1}{2C_\Sigma}\left(C_g U - ne\right)^2 + \{n\text{-independent term}\}$$

with $n = 0, \pm 1, \pm 2, \ldots$ = net nr of electrons on island



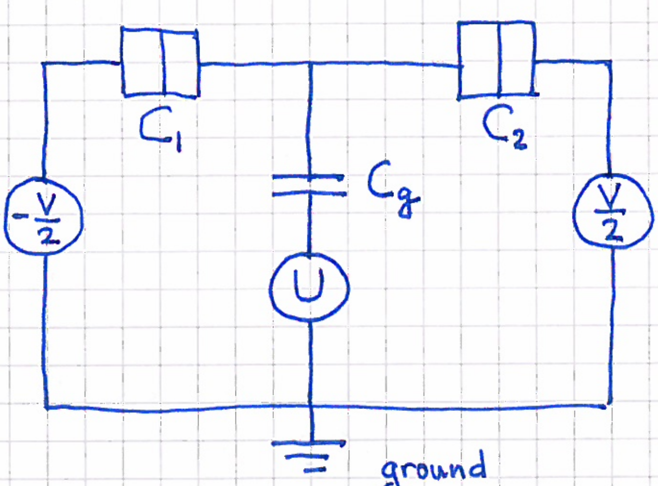
Tunneling will only happen if $\Delta E_n < 0$

$$\Rightarrow \Delta E_n = E(n+1) - E(n) = -\frac{e}{C_\Sigma}\left(C_g U - ne - \frac{e}{2}\right) < 0$$

$\Rightarrow$

We may increase / decrease U, fast or slowly, and make electrons tunnel, <u>one by one</u>, into or out of the island. "Single electron tunneling"!

Single Electron Transistor



V = applied voltage
U = gate voltage

A similar analysis yields $E(U, V, q)$; $q = -ne$ = net charge on island.

$\Rightarrow$ We may discuss "stability vs tunneling" in terms of U and V.

See Exercise 12!

Spintronics

Particles with <u>charge</u> and <u>spin</u> $\Rightarrow$

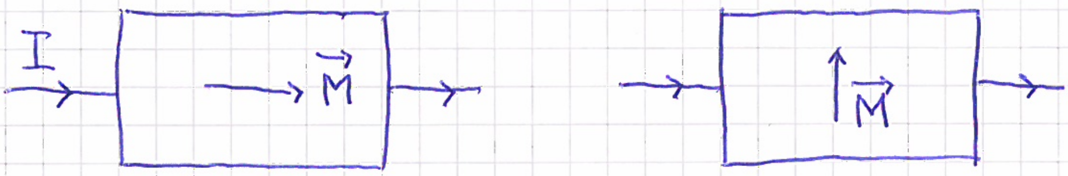
possible applications based on both charge transport (<u>electronics</u>) and spin transport (<u>spintronics</u>).

Electrons have spin $s = 1/2$; $m_s = +1/2$ ("spin up", $\uparrow$) or $m_s = -1/2$ ("spin down", $\downarrow$)

Brief historical account:

AMR: Anisotropic MagnetoResistance

- W. Thomson (= Lord Kelvin), Proc Roy Soc London <u>8</u>, 546 (1857): Experiments on Fe and Ni (and brass), $R(I \parallel \vec{M}) > R(M=0) > R(I \perp \vec{M})$

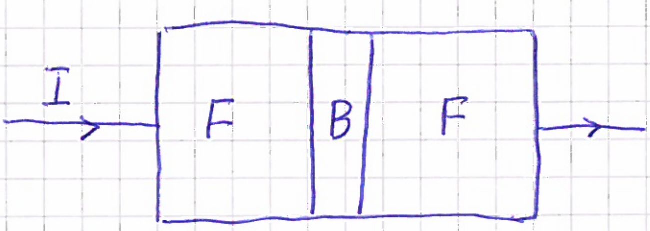


$R_{\parallel}$ $\qquad$ $R_{\perp} < R_{\parallel}$

- AMR caused by spin-orbit coupling, $V \sim \vec{L} \cdot \vec{S}$,

  see T.R. McGuire and R.I. Potter, IEEE Trans Magn <u>11</u>, 1018 (1975).

TMR : Tunneling MagnetoResistance



F : ferromagnetic conductor

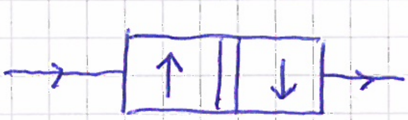
B : tunnel barrier

M. Jullière, Phys Lett 54A, 225 (1975), exp. on Fe/Ge/Co and Fe/Ge/Pb structures

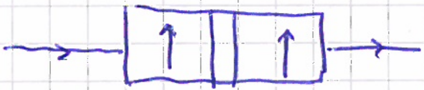
$R_0 = R(B=0)$

$\Delta R = R(B) - R_0$ $\quad (\vec{B} =$ external magn. field$)$

$|\Delta R / R_0| \sim 14\,\%$

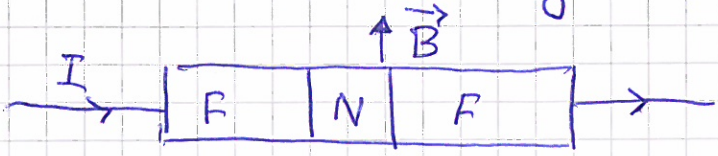


R_{ap}



$R_p < R_{ap}$

GMR : Giant MagnetoResistance



F = ferromagnet

N = non-magnetic

$\Delta R(B) = R(B) - R(0) < 0$

"giant" effect

Nobel prize 2007:

G. Binasch et al, PRB 39, 4828 (1989) ↔ P. Grünberg

M. N. Baibich et al, PRL 61, 2472 (1988) ↔ A. Fert

End 17.04.12