

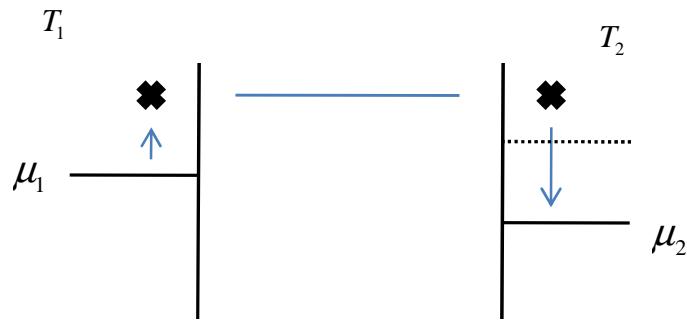
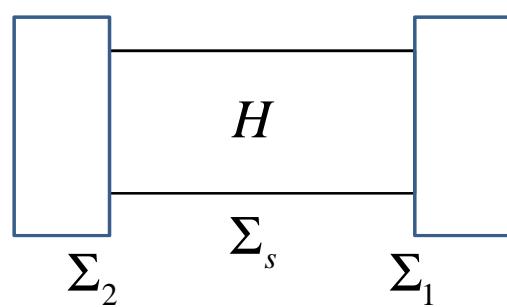
ECE 659 Quantum Transport: Atom to Transistor

Lecture 34: Second Law

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Notes prepared by Samiran Ganguly



$$I = \frac{q}{h} \int dE T(E) (f_1 - f_2)$$

$$I_{Q1,2} = \frac{1}{h} \int dE T(E) (E - \mu_{1,2}) (f_1 - f_2)$$

$$Q_1 - Q_2 = W \quad (\text{first law})$$

$$\frac{Q_1}{T_1} < \frac{Q_2}{T_2} \quad (\text{second law})$$

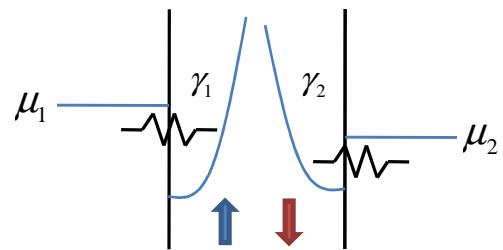
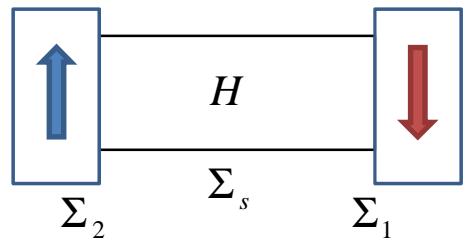
For current flow:

$$f_1 > f_2 \\ \frac{1}{e^{(E-\mu_1)/k_B T_1} + 1} > \frac{1}{e^{(E-\mu_2)/k_B T_2} + 1}$$

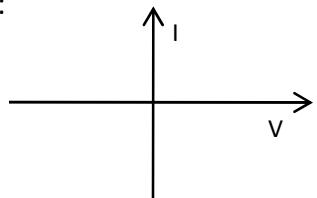
$$\frac{E - \mu_1}{T_1} < \frac{E - \mu_2}{T_2}$$

$$\frac{Q_1}{T_1} < \frac{Q_2}{T_2}$$

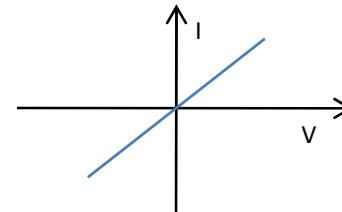
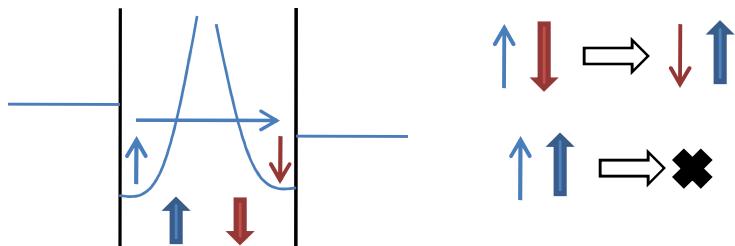
Anti-parallel spin valve device:



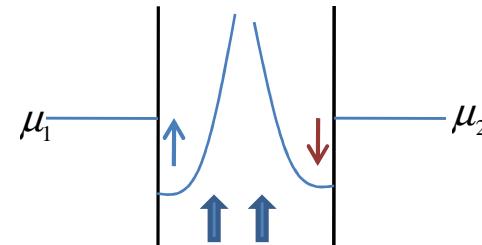
No impurities:



With spin flip impurities:

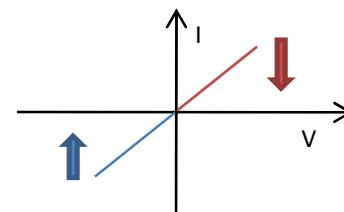


All impurities in up direction:



If $\mu_1 > \mu_2$ (V is positive): $I = 0$

If $\mu_1 < \mu_2$ (V is negative): $I \neq 0$

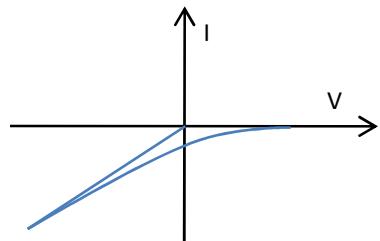


$$I \sim \int dE \begin{pmatrix} F_d f_u (1-f_d) \\ -F_u f_d (1-f_u) \end{pmatrix}$$

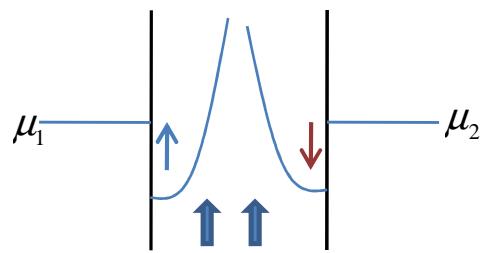
$$f_u = f_1, f_d = f_2$$

if $F_u = F_d$ we get $f_1 = f_2$

At non-zero temperatures:



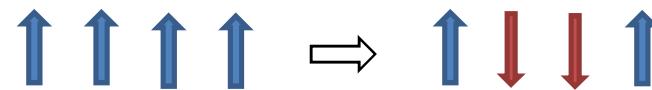
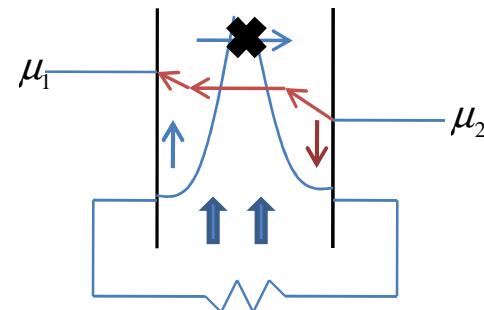
We get non-zero current for zero voltage



$$\frac{F_u}{F_d} = \frac{(1-f_2)f_1}{f_2(1-f_1)} = e^{(E-\mu_2)/kT} e^{-(E-\mu_1)/kT} * \\ = e^{(\mu_1-\mu_2)/kT}$$

$$(\mu_1 - \mu_2)_{oc} = kT \ln \frac{F_u}{F_d}$$

if $F_u \gg F_d$ we get $\mu_1 > \mu_2$



$$*f(E) = \frac{1}{e^{(E-\mu)/k_B T} + 1} \quad \frac{1-f}{f} = e^{(E-\mu)/k_B T}$$