FUNDAMENTALS OF NANOELECTRONICS

Basic Concepts

1. The New Perspective
2. Energy Band Model
3. What and Where is the Voltage?

Heat & Electricity:
Second Law & Information

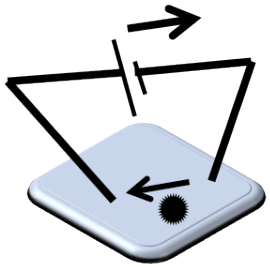
4.1. Introduction
4.2. Seebeck Coefficient
4.3. Heat Current
4.4. One-level Device
4.5. Second Law
4.6. Entropy
4.7. Law of Equilibrium
4.8. Shannon Entropy
4.9. Fuel Value of Information
4.10. Summing up ..

$$I \sim G(E)\left(f_1(E) - f_2(E)\right)$$

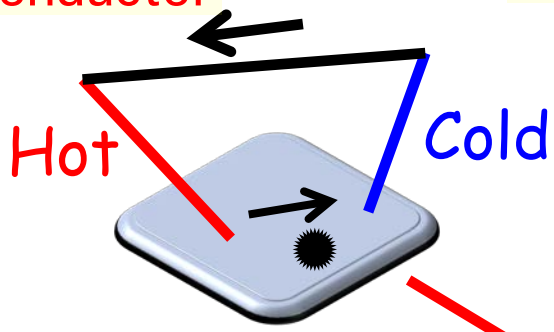
4.2a Seebeck Coefficient

All conductors

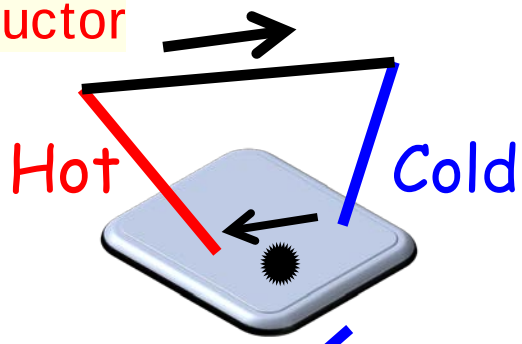
Electron Current



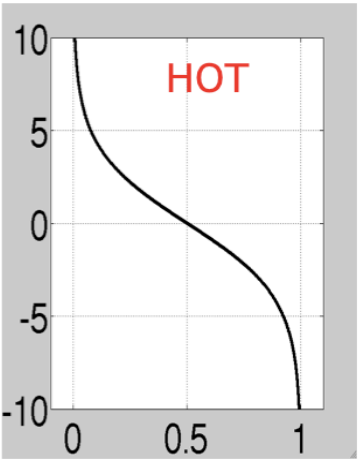
(a) n-type conductor



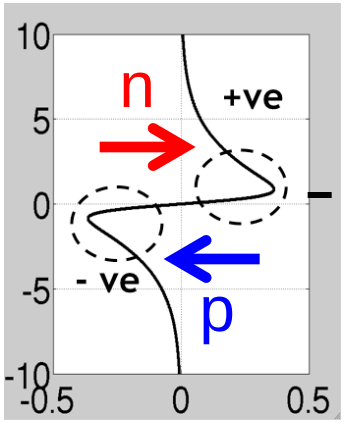
(b) p-type conductor



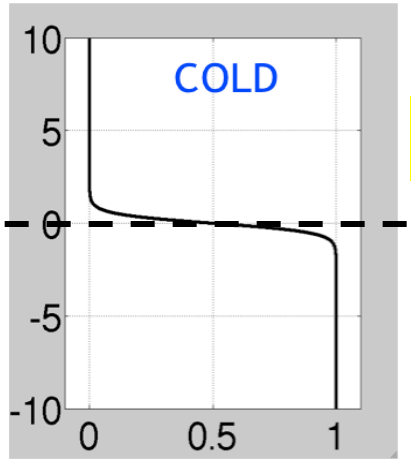
$$\frac{E-\mu}{kT}$$



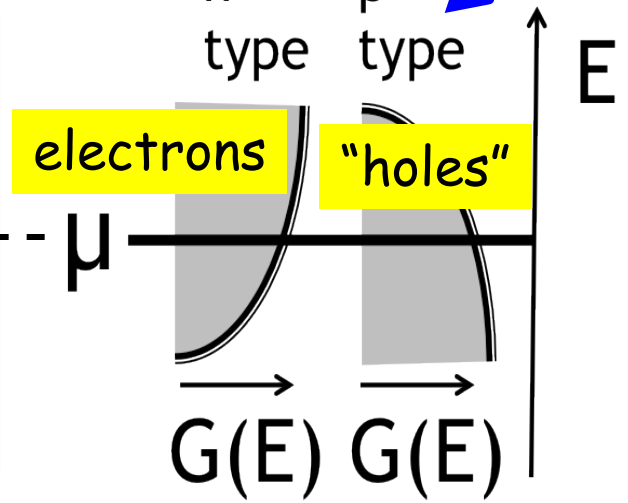
$f_1(E)$



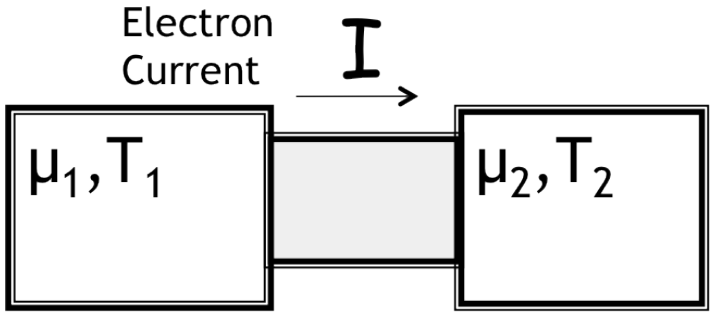
$f_1 - f_2$



$f_2(E)$



4.2b Seebeck coefficient



Fermi function

$$f(E,\mu,T)=\frac{1}{1+e^{x}} \qquad x\equiv\frac{E-\mu}{kT}$$

$$I \sim G(E)\left(f_1(E)-f_2(E)\right)$$

$$\frac{\partial f}{\partial \mu}=\frac{df}{dx}\frac{\partial x}{\partial \mu}=-\frac{1}{kT}$$

$$\frac{\partial f}{\partial E}=\frac{df}{dx}\frac{\partial x}{\partial E}=+\frac{1}{kT}$$

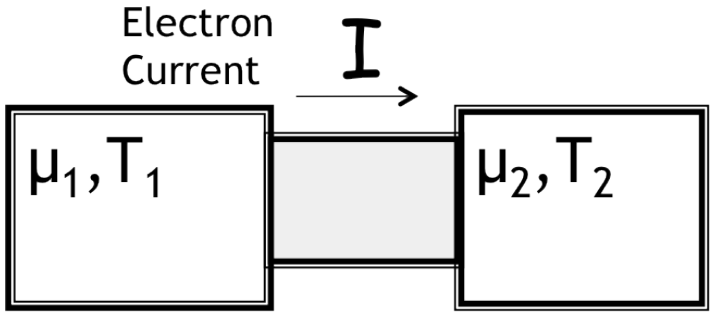
$$\frac{\partial f}{\partial T}=\frac{df}{dx}\frac{\partial x}{\partial T}=-\frac{E-\mu}{kT^2}$$

$$f(E,\mu_1,T_1)-f(E,\mu_2,T_2)$$

$$\approx \left(\frac{\partial f}{\partial \mu}\right)_{\mu=\mu_0,\,T=T_0}(\mu_1-\mu_2)+\left(\frac{\partial f}{\partial T}\right)_{\mu=\mu_0,\,T=T_0}(T_1-T_2)$$

$$=\left(-\frac{\partial f_0}{\partial E}\right)\times\left(\Delta\mu+\frac{E-\mu_0}{T_0}\Delta T\right)$$

4.2c Seebeck coefficient



Fermi function

$$f(E,\mu,T)=\frac{1}{1+e^{x}} \qquad x\equiv\frac{E-\mu}{kT}$$

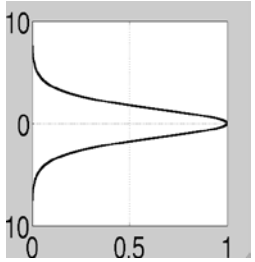
$$I=\frac{1}{q}\int_{-\infty}^{+\infty}dE\,G(E)\,\left(f_1(E)-f_2(E)\right)$$

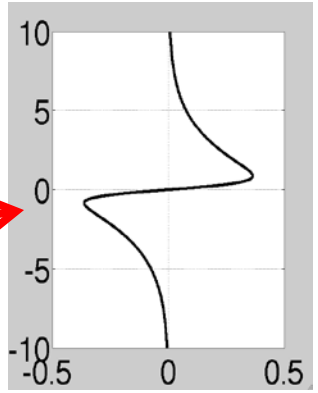
$$I\approx G_0\,\Delta V+G_S\,\Delta T$$

$$f(E,\mu_1,T_1)-f(E,\mu_2,T_2)=\left(-\frac{\partial f_0}{\partial E}\right)\times\left(\Delta\mu+\frac{E-\mu_0}{T_0}\Delta T\right)$$

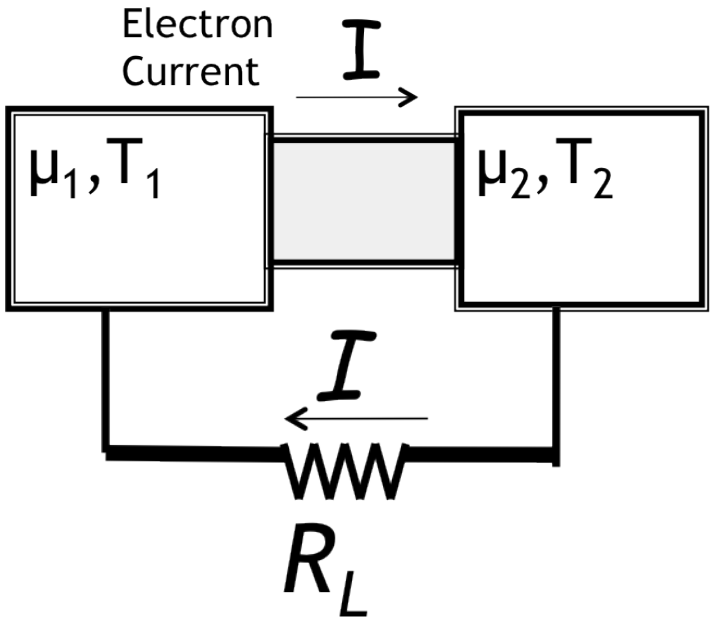
$$G=\int_{-\infty}^{+\infty}dE\,\left(-\frac{\partial f_0}{\partial E}\right)G(E)$$

$$G_S=\int_{-\infty}^{+\infty}dE\,\left(-\frac{\partial f_0}{\partial E}\right)\frac{E-\mu_0}{qT_0}\,G(E)$$





4.2d Seebeck coefficient



(Temperature Difference)

Heat → Electricity

Electricity → Temperature Difference

$$I \approx G_0 \Delta V + G_S \Delta T$$

$$I = 0$$

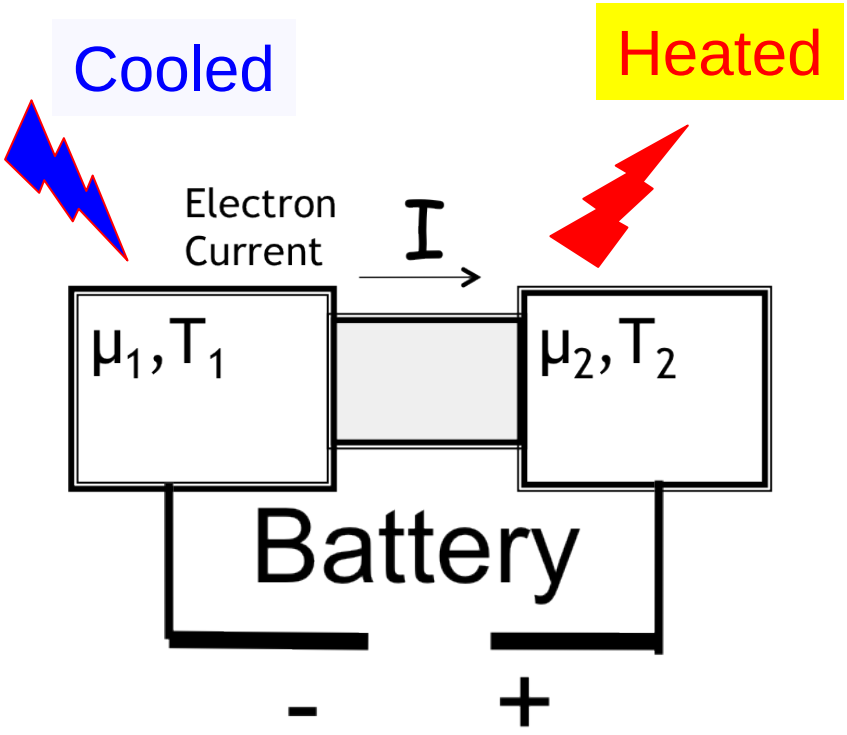
$$S \equiv \frac{\Delta V}{\Delta T} \approx -\frac{G_S}{G_0}$$

$$G_0 = \int_{-\infty}^{+\infty} dE \left(-\frac{\partial f_0}{\partial E}\right) G(E)$$

$$G_S = \int_{-\infty}^{+\infty} dE \left(-\frac{\partial f_0}{\partial E}\right) \frac{E-\mu_0}{qT_0} G(E)$$

$$\frac{\textit{Open circuit voltage}}{\textit{Temperature difference}}$$

Coming up next ..



Electricity → Temperature Difference