

FUNDAMENTALS OF NANO-ELECTRONICS

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 ..

4.4a One-level device

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

$$I_Q = G_P \Delta V + G_Q \Delta T$$

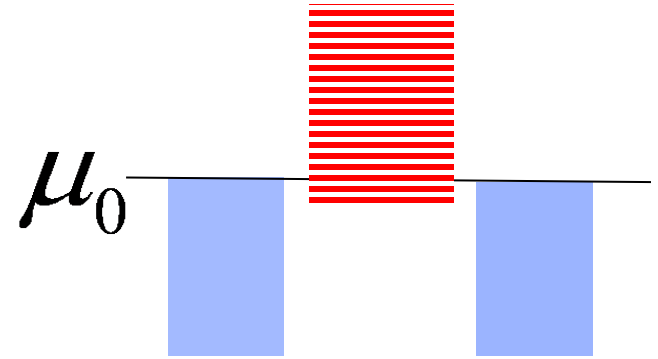
$$\Delta V = R I + S \Delta T$$

$$I_Q = -\Pi I + G_K \Delta T$$

$$S = -\frac{G_S}{G_0}$$

$$\Pi = -\frac{G_P}{G_0}$$

$$G_K = G_Q - \frac{G_P G_S}{G_0}$$



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

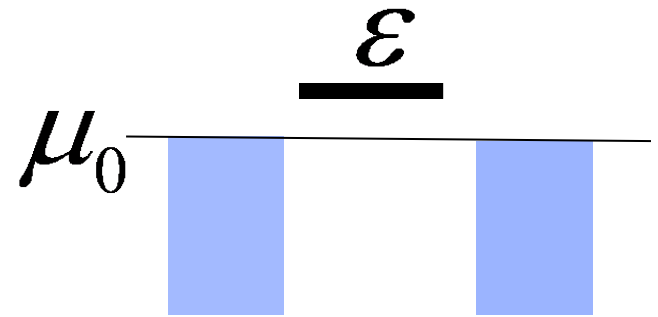
$$G_P = T_0 G_S = \int_{-\infty}^{+\infty} dE \left(-\frac{\partial f_0}{\partial E} \right) \frac{E - \mu_0}{q} G(E)$$

$$G_Q = \int_{-\infty}^{+\infty} dE \left(-\frac{\partial f_0}{\partial E} \right) \frac{(E - \mu_0)^2}{q^2 T_0} G(E)$$

4.4b One-level device

$$G_P = T_0 G_S = \frac{\varepsilon - \mu_0}{q} G_0$$

$$G_Q = \frac{(\varepsilon - \mu_0)^2}{q^2 T_0} G_0$$



$$S = -\frac{G_S}{G_0} = -\frac{\varepsilon - \mu_0}{q T_0}$$

$$\Pi = -\frac{G_P}{G_0} = -\frac{\varepsilon - \mu_0}{q}$$

$$G_K = G_Q - \frac{G_P G_S}{G_0} = 0$$

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

$$G_P = T_0 G_S = \int_{-\infty}^{+\infty} dE \left(-\frac{\partial f_0}{\partial E} \right) \frac{E - \mu_0}{q} G(E)$$

$$G_Q = \int_{-\infty}^{+\infty} dE \left(-\frac{\partial f_0}{\partial E} \right) \frac{(E - \mu_0)^2}{q^2 T_0} G(E)$$

$$\Delta V = RI + S \Delta T$$

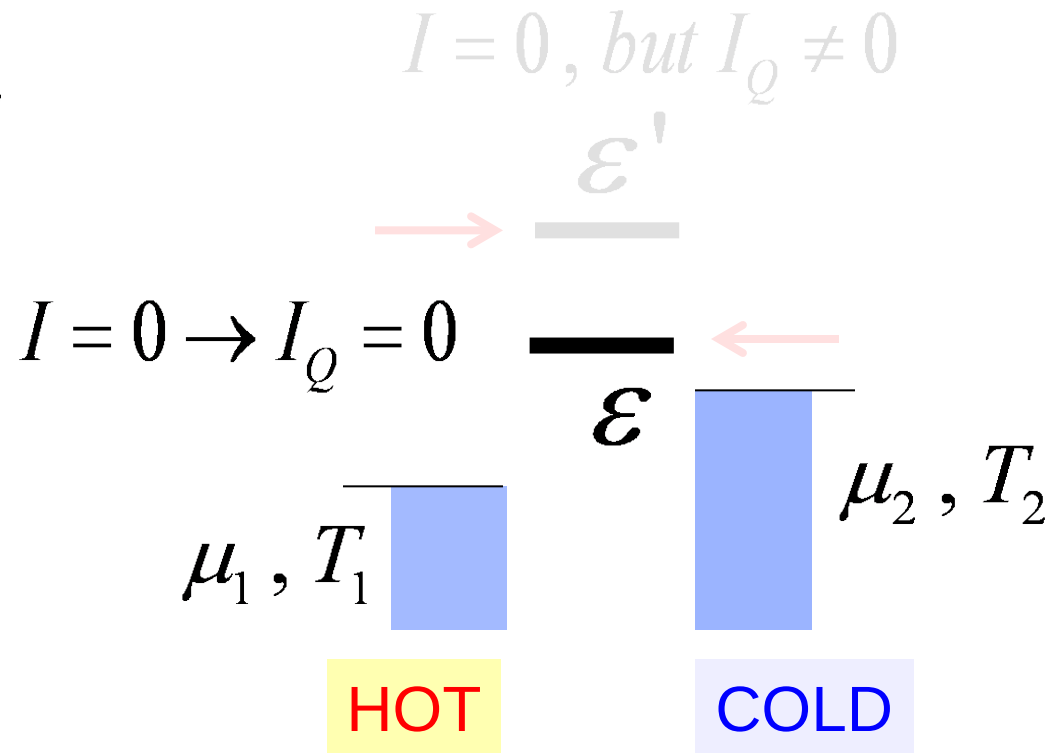
4.4c One-level device

$$I_Q = -\Pi I + G_K \Delta T + G_{K, \text{phonons}} \Delta T$$

$$S = -\frac{G_S}{G_0} = -\frac{\varepsilon - \mu_0}{qT_0}$$

$$\Pi = -\frac{G_P}{G_0} = -\frac{\varepsilon - \mu_0}{q}$$

$$G_K = G_Q - \frac{G_P G_S}{G_0} = 0$$



4.4d One-level device

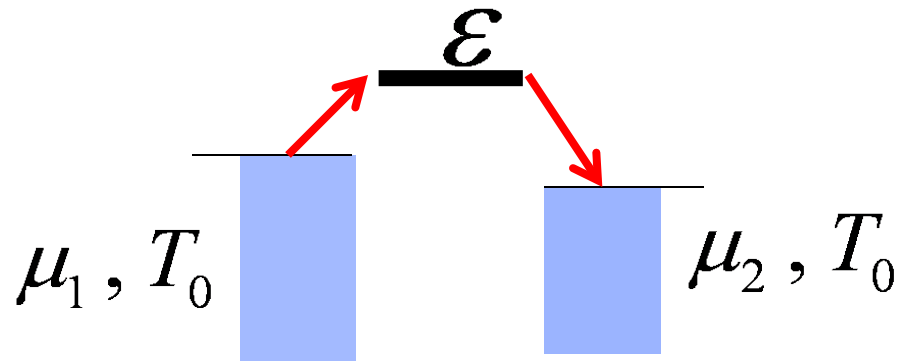
$$\Delta V = R I + S \Delta T$$

$$I_Q = -\Pi I + G_K \Delta T$$

$$S = -\frac{G_S}{G_0} = -\frac{\varepsilon - \mu_0}{q T_0}$$

$$\Pi = -\frac{G_P}{G_0} = -\frac{\varepsilon - \mu_0}{q}$$

$$G_K = G_Q - \frac{G_P G_S}{G_0} = 0$$



Every electron transfers
charge q
energy $\varepsilon - \mu$

4.4e One-level device

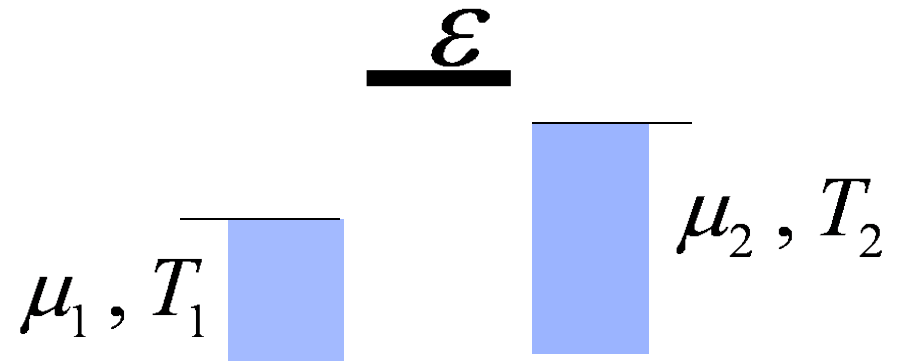
$$\Delta V = R I + S \Delta T$$

$$I_Q = -\Pi I + G_K \Delta T$$

$$S = -\frac{G_S}{G_0} = -\frac{\varepsilon - \mu_0}{q T_0}$$

$$\Pi = -\frac{G_P}{G_0} = -\frac{\varepsilon - \mu_0}{q}$$

$$G_K = G_Q - \frac{G_P G_S}{G_0} = 0$$



$$I = 0 \rightarrow f_1(\varepsilon) = f_2(\varepsilon)$$

$$\begin{aligned} \frac{\varepsilon - \mu_1}{T_1} &= \frac{\varepsilon - \mu_2}{T_2} = -\frac{\mu_1 - \mu_2}{T_1 - T_2} \\ &= -\frac{q \Delta V}{\Delta T} \end{aligned}$$

4.4f One-level device

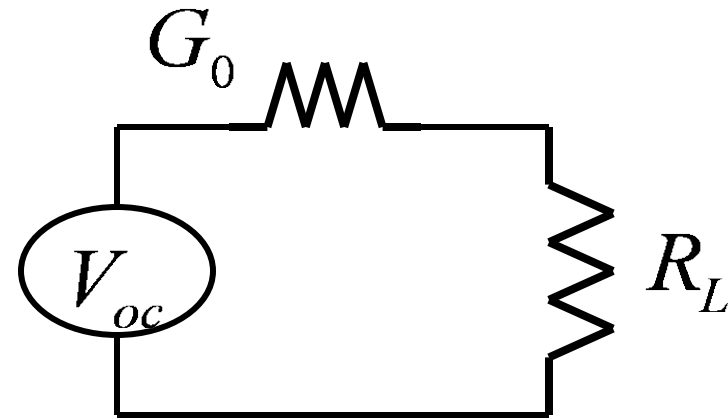
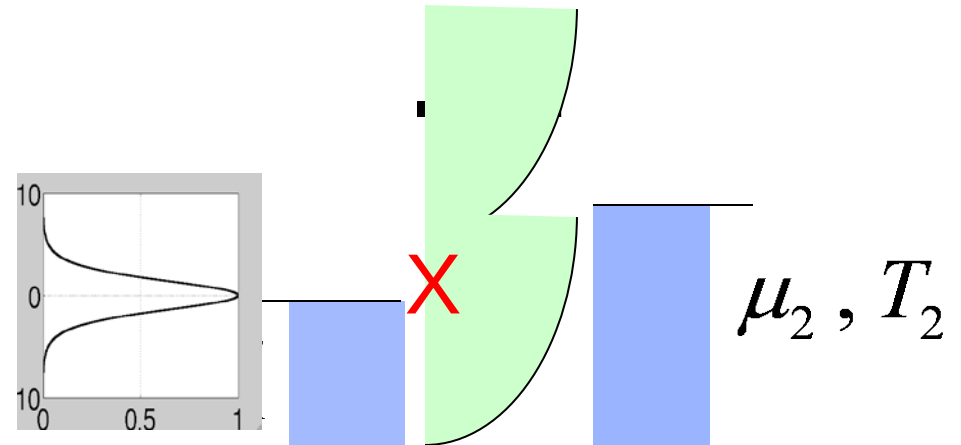
$$|S| \sim \frac{kT_0}{qT_0} \approx 85 \frac{\mu V}{K}$$

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

$$S = -\frac{G_S}{G_0} = -\frac{\varepsilon - \mu_0}{qT_0}$$

$$\Pi = -\frac{G_P}{G_0} = -\frac{\varepsilon - \mu_0}{q}$$

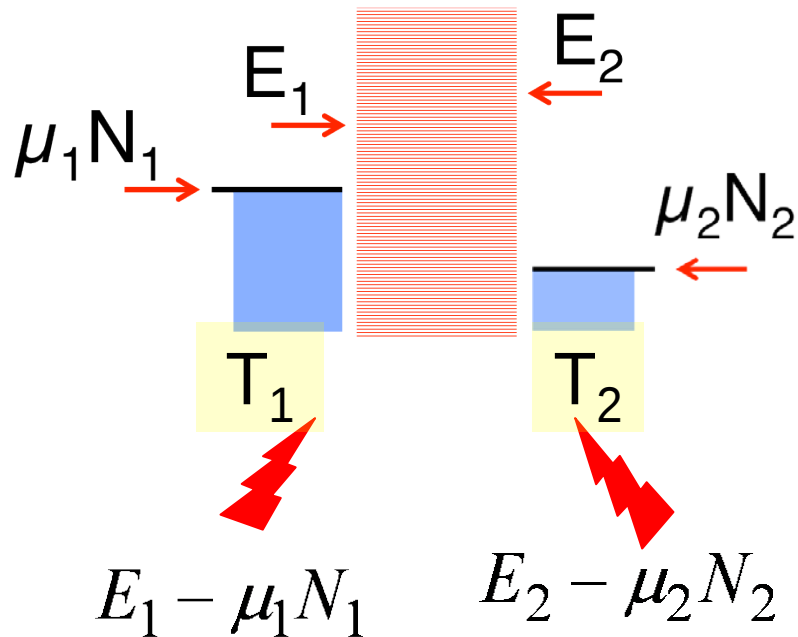
$$G_K = G_Q - \frac{G_P G_S}{G_0} = 0$$



Coming up next ..

$$\frac{E_0}{T_0} + \frac{E_1 - \mu_1 N_1}{T_1} + \frac{E_2 - \mu_2 N_2}{T_2} \leq 0$$

Second Law



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 ..