FUNDAMENTALS OF NANOELECTRONICS

Basic Concepts

1. The New Perspective
2. Energy Band Model
3. What & Where is the "Voltage"?
4. Heat & Electricity: Second Law & Information

3.1. Introduction

3.2. A New Boundary Condition

3.3. Quasi-Fermi Levels (QFL's)

3.4. Current from QFL's

3.5. Landauer Formulas

3.6. What a Probe Measures

3.7. Electrostatic Potential

3.8. Boltzmann Equation

3.9. Spin voltages

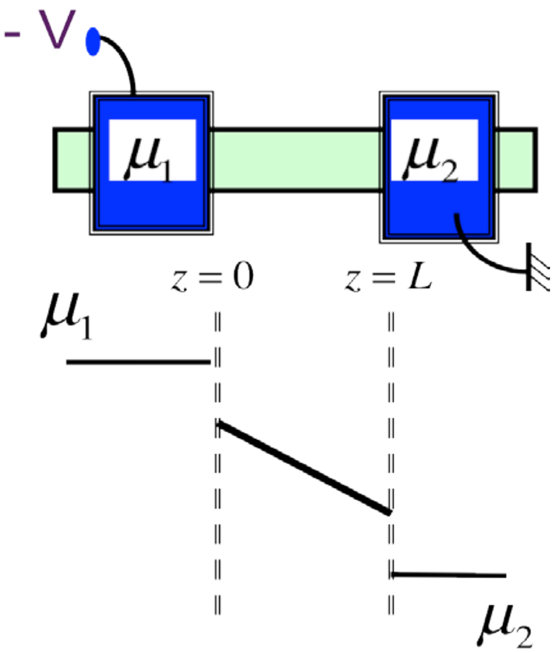
3.10. Summing up ..

Supriyo Datta

Spring 2015

http://nanohub.org/groups/lnebook

3.8a Boltzmann Equation



$$\boxed{v_z \frac{\partial f}{\partial z} + F_z \frac{\partial f}{\partial p_z} = -\frac{f - \bar{f}}{\tau}}$$

Newton's Law

$$\frac{dz}{dt} = v_z \quad , \quad \frac{dp_z}{dt} = F_z$$

$$J = -\frac{\sigma_0}{q}\frac{d\mu}{dz}$$

$$\mu(z=0) = \mu_1 - \frac{qIR_B}{2}$$

$$\mu(z=L) = \mu_2 + \frac{qIR_B}{2}$$

$$\cancel{\frac{\partial f}{\partial t}} + v_z \frac{\partial f}{\partial z} + F_z \frac{\partial f}{\partial p_z} = 0 + S_{op} f$$

$$\cancel{f(z, p_z, t)} = f(z - v_z \Delta t, p_z - F_z \Delta t, t - \Delta t)$$

$$\cong \cancel{f(z, p_z, t)} - \frac{\partial f}{\partial t}\Delta t - \frac{\partial f}{\partial z} v_z \Delta t - \frac{\partial f}{\partial p_z} F_z \Delta t$$

3.8b Boltzmann Equation

$$f(z, p_z, E) = \frac{1}{1 + e^{(E-\mu(z,p_z))/kT}}$$

Occupation

QFL's

$$v_z \frac{\partial f}{\partial z} + F_z \frac{\partial f}{\partial p_z} = -\frac{f - \bar{f}}{\tau}$$

$$\frac{\partial f}{\partial z} \approx \left(-\frac{\partial f_0}{\partial E}\right)\frac{\partial \mu}{\partial z} \qquad \Delta\mu \approx qV\,\Delta f$$

$$v_z \frac{\partial \mu}{\partial z} + \cancel{F_z \frac{\partial \mu}{\partial p_z}} = -\frac{\mu - \bar{\mu}}{\tau}$$

$$\frac{\partial f}{\partial p_z} \approx \left(-\frac{\partial f_0}{\partial E}\right)\frac{\partial \mu}{\partial p_z}$$

$$v_z \frac{\partial \mu(z, p_z)}{\partial z} = -\frac{\mu(z,p_z) - \bar{\mu}(z)}{\tau}$$

$$Equilibrium: \quad \mu = \mu_0$$

$$f_{eq}(E) = \frac{1}{1 + e^{(E-\mu_0)/kT}}$$

$$\bar{\mu} = \frac{\mu^+ + \mu^-}{2}$$

$$|v_z| \frac{d\mu^+}{dz} = -\frac{\mu^+ - \bar{\mu}}{\tau}$$

$$-|v_z| \frac{d\mu^-}{dz} = -\frac{\mu^- - \bar{\mu}}{\tau}$$

3.8c Boltzmann Equation

$$f(z, p_z, E) = \frac{1}{1 + e^{(E - \mu(z, p_z))/kT}}$$

Occupation

QFL's

$$v_z \frac{\partial \mu(z, p_z)}{\partial z} = -\frac{\mu(z, p_z) - \bar{\mu}(z)}{\tau}$$

$$-|v_z| \frac{d\mu^-}{dz} = -\frac{\mu^- - \bar{\mu}}{\tau}$$

$$\bar{\mu} = \frac{\mu^+ + \mu^-}{2}$$

$$|v_z| \frac{d\mu^+}{dz} = -\frac{\mu^+ - \bar{\mu}}{\tau}$$

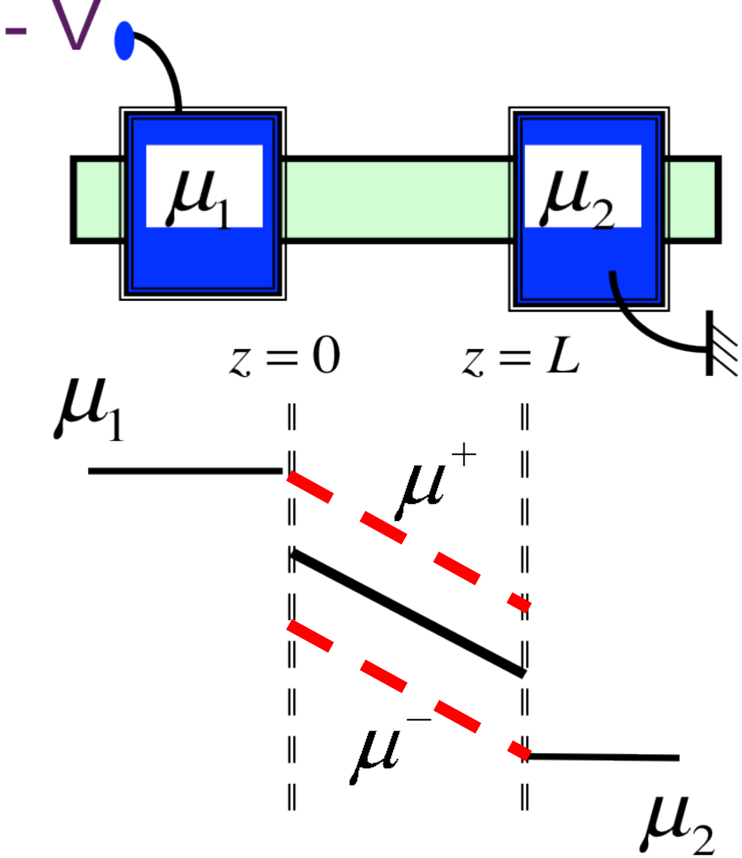
$$\frac{d\mu^+}{dz} = \frac{d\mu^-}{dz} = -\frac{\mu^+ - \mu^-}{2|v_z|\, \tau}$$

$$\frac{d\mu^+}{dz} = \frac{d\mu^-}{dz} = -\frac{1}{\lambda} \frac{qI}{G_B}$$

$$I = -\frac{G_B \lambda}{q} \frac{d\mu^+}{dz} = -\frac{G_B \lambda}{q} \frac{d\mu^-}{dz}$$

$\sigma_0 A$

3.8d Boltzmann Equation



$\sigma_0 A$

$$I = -\frac{G_B \lambda}{q}\frac{d\mu^+}{dz} = -\frac{G_B \lambda}{q}\frac{d\mu^-}{dz}$$

$$I = -\frac{\sigma_0 A}{q}\frac{d\mu}{dz}$$

$$\mu(z=0) = \mu_1 - \frac{qIR_B}{2}$$

$$\mu^+(z=0) = \mu_1$$

$$\mu^-(z=L) = \mu_2$$

$$\mu(z=L) = \mu_2 + \frac{qIR_B}{2}$$

Coming up next ..