ECE 495N

Fundamentals of Nanoelectronics

Fall 2008

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Lecture: 3
Title: Importance of Electrostatics
Date: August 29, 2008

Video Lectures posted at:
https://www.nanohub.org/resources/5346/

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Importance of electrostatics

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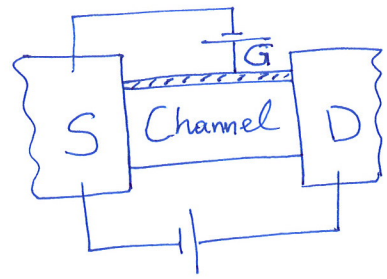
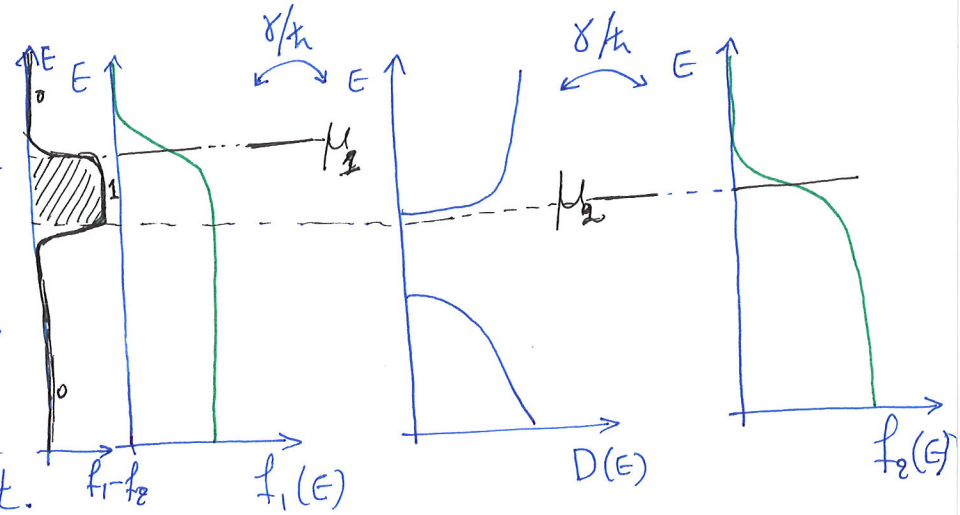
$$I = \frac{q}{h}\int \frac{\gamma}{2} dE \cdot D(E)\left[f_1 - f_2\right]$$



Given the DOS how we will calculate the current? Why we have current flow? Because the two contacts are held at different electrochemical potentials μ_1 and μ_2, which define the fermi functions. Contact one wants to put electrons in and contact two wants to pull them out.



Density of states (DOS), $D(E)$ tell us how many states are at this energy per energy. So, the $dE \cdot D(E)$ says how many states we have.

Current flows (look the fundamental relationship) if there is difference between the f_1 and f_2. If we apply voltage V_D then $\mu_1 \neq \mu_2$ and hence $f_1 \neq f_2$. In addition if $V_D = 0 \Rightarrow \mu_1 = \mu_2$ but there is temperature difference current might be flow. This is called thermoelectric current.

In this lecture we would like to describe current vs. voltage for big range in voltage like 1 Volt. The above formula needs to supplemented with something.

If the voltage is small enough then

$$I = \frac{q\gamma}{2h} D q V \Rightarrow \frac{I}{V} = G = \frac{q^2}{2h}(D\gamma)$$

$$= \frac{q^2}{h}(\pi D \gamma)$$

What we expect if we will go big conductor? To follow the Ohm's Law, that is

$$\boxed{G = \sigma \frac{A}{L}}$$

If we go to big conductors then D will be propotional to area and length $D \sim A \cdot l$. This happens only in big conductors where we have many states.

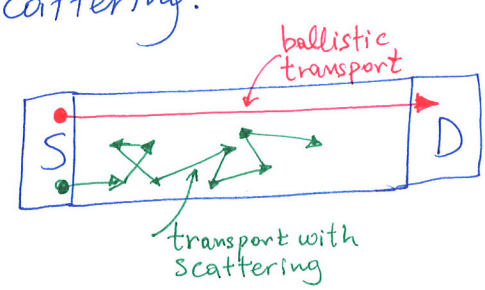
Then $\boxed{G \sim \frac{q^2}{h} (A \cdot L \pi \gamma)}$ but this doesn't follow Ohm's law in which $G \sim \frac{1}{L}$ and not $G \sim L$.

The answer is what is γ for large conductors. γ depends on concacts (how long it takes to get in) and on channel (how much time it take to go through the channel).

$$\frac{\gamma}{h} = \frac{v}{L}$$

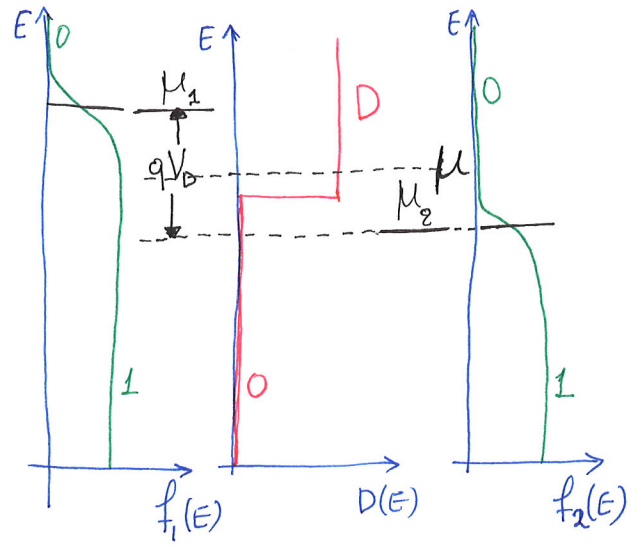
Then $G \sim \frac{q}{\cancel{h}} A \cdot \cancel{L} \pi \frac{v}{\cancel{L}} \cancel{h} \Rightarrow \boxed{G \sim q \cdot A \cdot \pi \cdot v}$ which is also not Ohm's law.

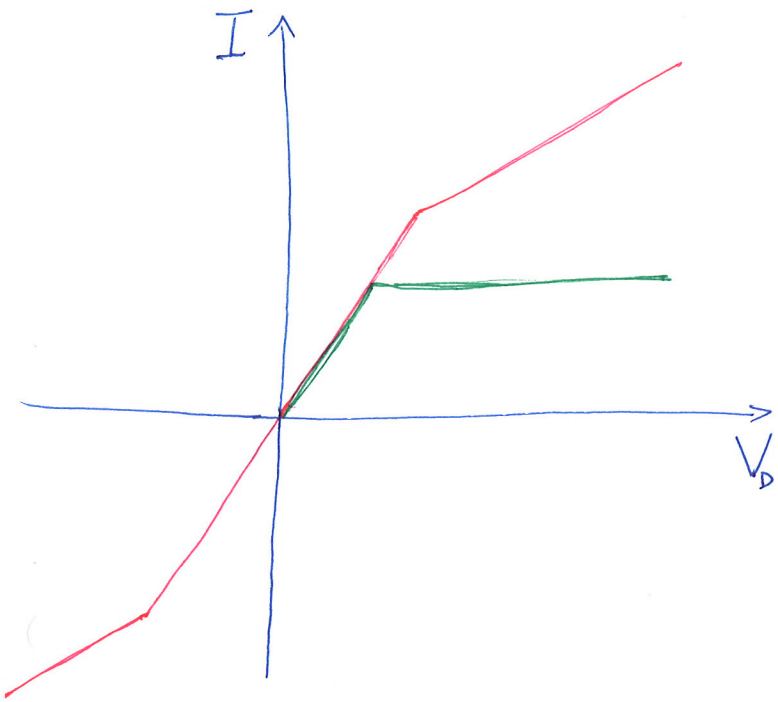
The reason is that we have assumed that the conductor is ballistic, in the sense that an electron pass from one contact to the other like a bullet, straight, without scattering.

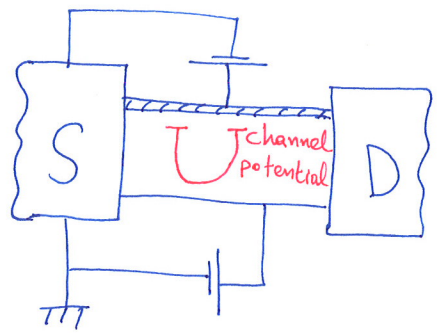


If an electron is moving with scattering then the time it takes to pass through is propotional to L^2 (diffusive motion) so $\frac{\gamma}{h} \sim \frac{2D}{L^2}$ and hence we have the Ohm's law.

So now, suppose that we have a material with DOS like this one in the figure below. This is a good approximation of an nmos transistor. The question is what current vs. voltage is.





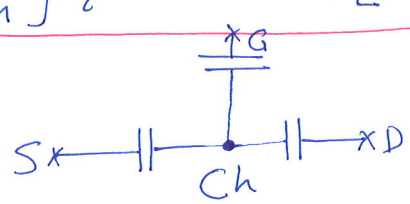


A good transistor is that which controls the channel potential from the gate and not from the drain or source.

Due to the potential in the channel U we have to modify our relationship for the current in order to take it into account.

Hence

$$\boxed{I = \frac{q}{h}\int \frac{\gamma}{2}\, dE \cdot D(E-U)\left[f_1(E) - f_2(E)\right]} \quad (1)$$



$$C = \frac{\epsilon A}{d}$$

$U = U_L$ ← Laplace potential

Suppose that we have a perfect transistor which only the gate contact controls the channel.

Suppose also that <u>in equilibrium</u> we have 100 electrons in the channel. <u>In non-equilibrium</u> one gets in one gets out, so in average the number of electrons is no anymore 100 but something like 50. So the potential in the channel will become more positive. And positive potential means to slip the D(E) down a little bit.

$$\boxed{U = U_L + \underbrace{U_0}_{\text{average potential per electron}} (N - N_{eq})} \quad (2)$$

And to complete the system description we need an equation for N, that is

$$N = \int dE\, D(E)\, f(E), \quad \text{for equilibrium}$$

$$\boxed{N = \int dE \cdot D(E)\, \frac{\gamma_1 f_1 + \gamma_2 f_2}{\gamma_1 + \gamma_2}} \quad (3), \quad \text{for non-equilibrium}$$

Equations (1), (2), (3) describe the whole system.