

Fundamentals of Nanoelectronics

Prof. Supriyo Datta
ECE 453
Purdue University

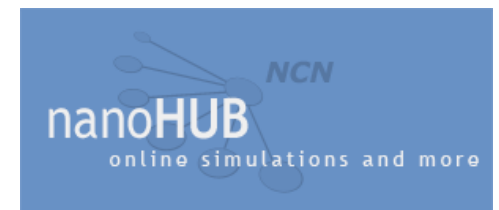
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Lecture 35: Transmission

Ref. Chapter

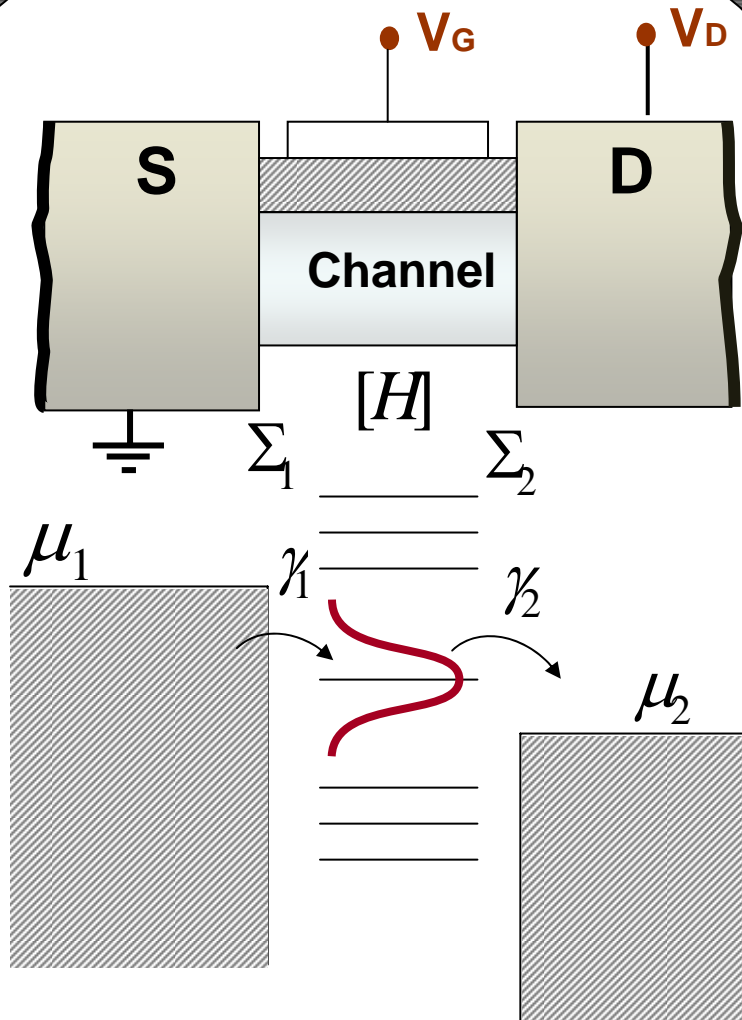


Network for Computational Nanotechnology



Review

00:05



- We've been studying the model of a nanotransistor drawn on the left. For a one level conduction we've been using these equations to get the current.

$$I_1 = \frac{q}{\hbar} \int dE \gamma_1 (D(E) f_1 - n(E))$$

$$I_2 = \frac{q}{\hbar} \int dE \gamma_2 (D(E) f_2 - n(E))$$

$$n(E) = D(E) \left(\frac{\gamma_1}{\gamma_1 + \gamma_2} f_1 + \frac{\gamma_2}{\gamma_1 + \gamma_2} f_2 \right)$$

$$I_1 = -I_2 = \frac{q}{\hbar} \int dE D(E) \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2} (f_1 - f_2)$$

- In general one deals with a Hamiltonian matrix which gives the energy levels of a device and the Sigma matrices which describe the effect of the coupling to the contacts. To solve the more general problem we've derived the matrix version of the above equations.

Matrix Equations

07:50

$$2\pi D(E) \Rightarrow [A(E)] = i[G - G^+]$$

$$G(E) = (EI - H - \Sigma_1 - \Sigma_2)^{-1}$$

$$\Gamma_1 = i(\Sigma_1 - \Sigma_1^+)$$

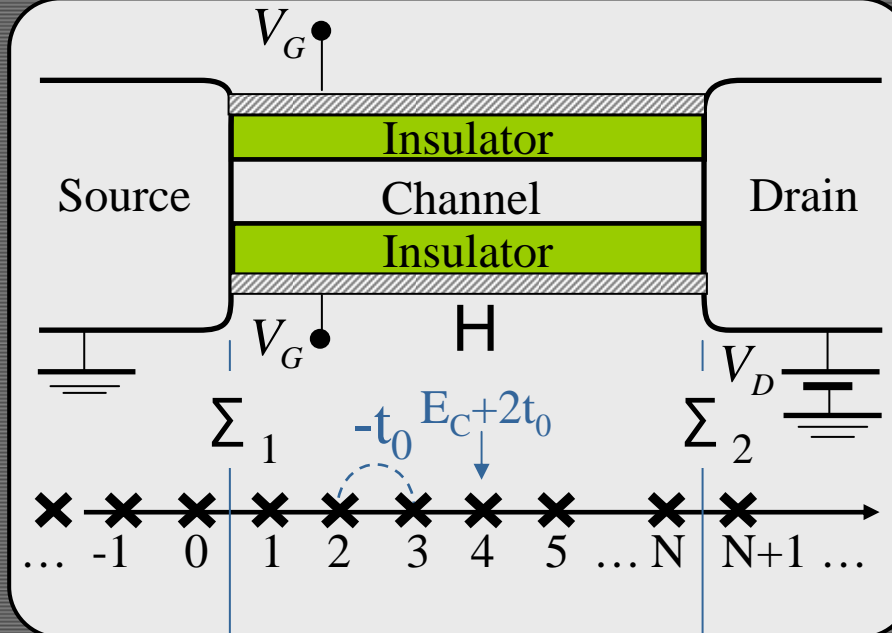
$$\Gamma_2 = i(\Sigma_2 - \Sigma_2^+)$$

$$2\pi n(E) = 2\pi D(E) \left(\frac{\gamma_1}{\gamma_1 + \gamma_2} f_1 + \frac{\gamma_2}{\gamma_1 + \gamma_2} f_2 \right)$$

$$I_1 = \frac{q}{h} \int dE 2\pi (\text{Tr}(\Gamma_1 A) f_1 - \gamma_1 n(E))$$

$$I_2 = \frac{q}{h} \int dE 2\pi (\text{Tr}(\Gamma_2 A) f_2 - \gamma_2 n(E))$$

$$[G^n] = [G\Gamma_1 G^+] f_1 + [G\Gamma_2 G] f_2$$



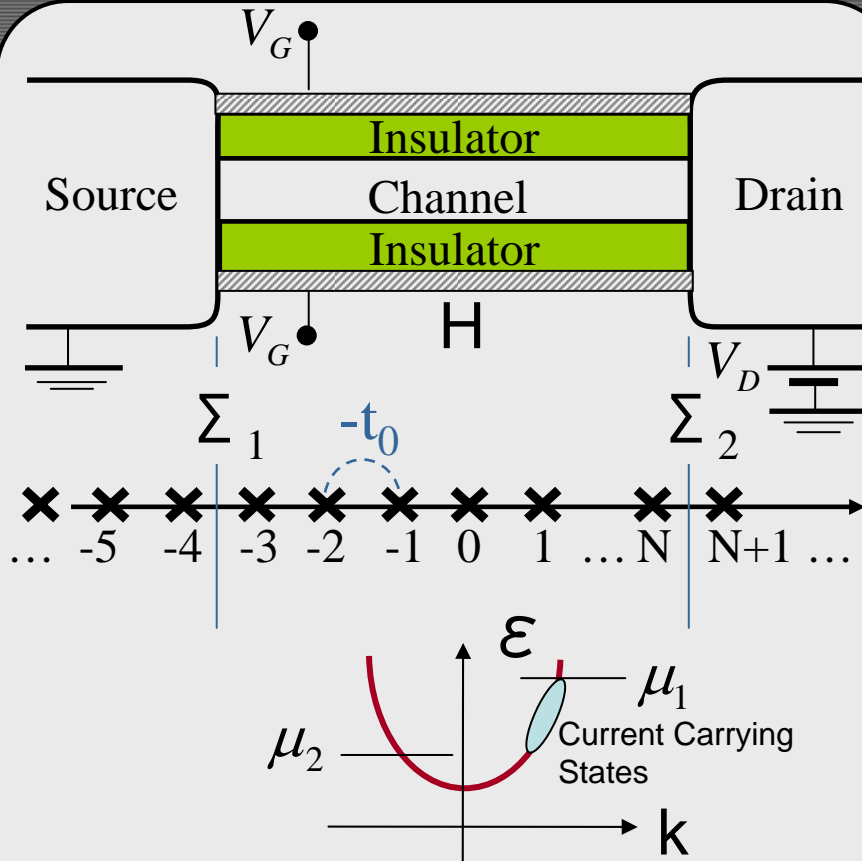
- We can rewrite current as:

$$I_1 = -I_2 = \frac{q}{h} \int dE \bar{T}(E) (f_1 - f_2)$$

$$\bar{T}(E) = \text{Trace}(\Gamma_1 G \Gamma_2 G^+)$$

Ballistic Wire

17:15



Ballistic Wire:
$$I = \frac{q}{\hbar} \int dE (f_1 - f_2)$$

- Note that the current for a ballistic wire can be obtained from the general formula with the transmission of 1. So ballistic wire is the one for which $T=1$.

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

- What if there is a delta function potential scatterer in the wire? There is another method to calculate the current. In this method, we view electrons as waves incident on the delta function potential (located at $x=0$) from left (right). We then use the Schrödinger equation to calculate the transmission amplitude. Transmission probability is the squared module of transmission amplitude. Although this method gives us good physical insight about the problem, it won't be convenient for real practical problems.

Incident wave from left $U_0\delta(x)$

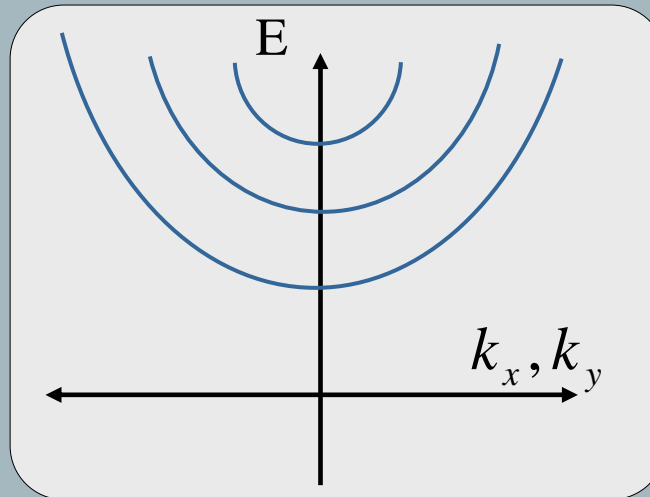
$1 - |r|^2$ $e^{ikx} \longrightarrow$ $\longleftarrow re^{-ikx}$ $\xrightarrow{te^{ikx}}$ $|t|^2$

(x)

t: Transmission amplitude
T: Transmission Probability $T = |t|^2$

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

- If we have a wire with a cross section that allows multiple number of modes we have:

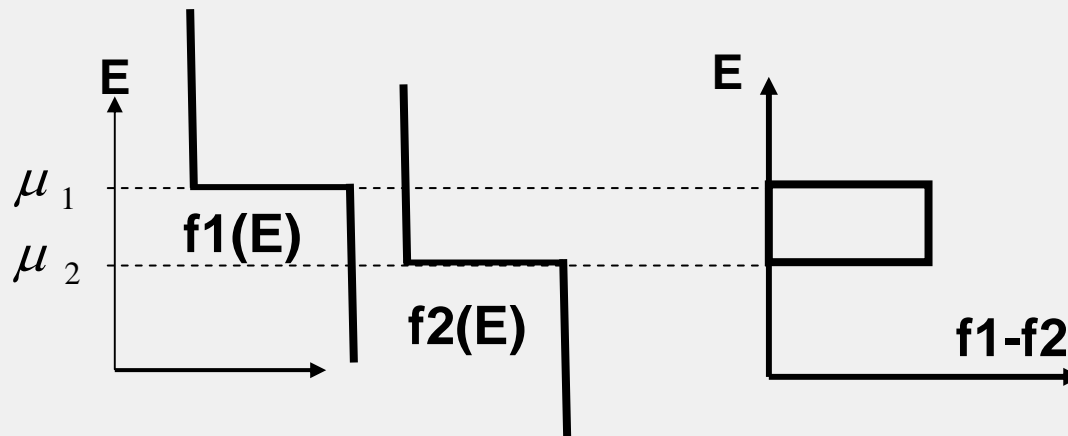


$$I = \frac{q}{h} \int dE \bar{T}(E) (f_1 - f_2)$$
$$\bar{T} = MT(E)$$

Landauer Formula

32:45

- Consider the case where a small drain voltage has been applied to contact 2.



$$I = \frac{q}{h} \int dE \bar{T}(E) (f_1 - f_2) = \frac{q}{h} \bar{T} (\mu_1 - \mu_2) = \frac{q^2}{h} \bar{T} V_D$$

$$G = \frac{I}{V_D} = \frac{q^2}{h} \bar{T}$$

Where is the heat dissipated?

40:27

- So what happens if we make a wire ballistic? Will the resistance go to 0? Are we NOT going to have any dissipation? These issues caused a lot of controversy in the 1980's. Today we know that what the Landauer formula predicts is correct. The maximum conductance is:

$$G_{\max} = (q^2 / h)$$

- If this correct, then there is a minimum resistance and that should cause heating. But since the conductor is ballistic, resistance and the associated heating cannot be in the channel. So where is the heat dissipation?
- As the figure below shows once an electron gets onto the drain contact it loses its energy and relaxes down whereby it generates heat. On the other hand the hole left in drain floats up to the top. Describing these processes are very difficult. We've bypassed them by stating that certain forces keep holes and electrons in equilibrium with the Fermi levels in the contacts.

