

EECS 277C Nanotechnology HW #2

1. Find the relationship between the Fermi energy and the average energy of electrons in a box.
2. Same for the average wavelength.
3. Find the Fermi wavelength of electrons in a typical metal, e.g, Cu.

$$1) \langle E \rangle = \frac{1}{N} \int_0^{\infty} F(E) E N(E) dE$$

$F(E)$  is apprx. step function.

$$\approx \frac{1}{N} \int_0^{E_F} E N(E) dE$$

$$N(E) = \frac{L^3}{2\pi^2} \left( \frac{2m}{\hbar^2} \right)^{3/2} E^{1/2}$$

$$\begin{aligned} \langle E \rangle &= \frac{1}{N} \frac{L^3}{2\pi^2} \left( \frac{2m}{\hbar^2} \right)^{3/2} \int_0^{E_F} E^{3/2} dE \\ &= \frac{1}{N} \frac{L^3}{2\pi^2} \left( \frac{2m}{\hbar^2} \right)^{3/2} \frac{2}{5} E_F^{5/2} \quad (*) \end{aligned}$$

$$\text{Recall } E_F = \frac{\hbar^2}{2m} \left( 3\pi^2 \frac{N}{L^3} \right)^{2/3} \quad (**)$$

Combining  $(*)$ ,  $(**)$  yields

$$\langle E \rangle = \frac{3}{5} E_F$$



$$2) \langle \lambda \rangle = \frac{1}{N} \int_0^{\infty} \lambda F(E) N(E) dE$$

$$\approx \frac{1}{N} \int_0^{E_F} \lambda N(E) dE$$

$$E = \frac{\hbar^2 k^2}{2m} = \frac{\hbar^2 \left(\frac{2\pi}{\lambda}\right)^2}{2m}$$

$$= \frac{1}{N} \sqrt{\frac{\hbar^2}{2m}} 2\pi \int_0^{E_F} \frac{1}{\sqrt{E}} N(E) dE \quad \lambda = \sqrt{\frac{\hbar^2}{2mE}} 2\pi$$

$N(E)$  from before

$$= \frac{1}{N} \sqrt{\frac{\hbar^2}{2m}} 2\pi \frac{L^3}{2\pi^2} \left(\frac{2m}{\hbar^2}\right)^{3/2} \int_0^{E_F} \frac{1}{\sqrt{E}} \sqrt{E} dE$$

$$= \frac{1}{N} \sqrt{\frac{\hbar^2}{2m}} \cancel{2\pi} \frac{L^3}{2\pi^2} \left(\frac{2m}{\hbar^2}\right)^{3/2} E_F$$

$$= \frac{L^3}{N} \frac{1}{\pi} \left(\frac{2m}{\hbar^2}\right) E_F$$

$$= \frac{\frac{1}{\pi} \frac{2m}{\hbar^2} E_F}{E_F^{3/2} \frac{1}{3\pi^2} \left(\frac{2m}{\hbar^2}\right)^{3/2}} = 3\pi E_F^{-1/2} \left(\frac{2m}{\hbar^2}\right)^{-1/2} = \langle \lambda \rangle$$

If we define  $\lambda_F$  as  $\sqrt{\frac{2mE_F}{\hbar^2}}$  we get

$$\langle \lambda \rangle = \lambda_F \times \frac{\sqrt{2}}{2}$$



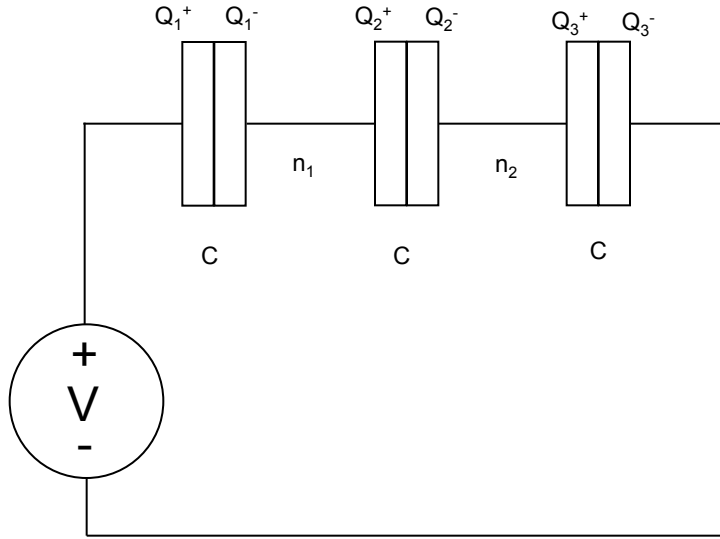
$$3) \quad E_F = \frac{\hbar^2}{2m} \left( 3\pi^2 \frac{N}{L^3} \right)^{2/3} \quad (*)$$

For copper, electron density  $\approx 1/\text{atom}$

Using  $\text{atom}/\text{m}^3$  for copper, we find

$$n \equiv \frac{N}{L^3} \approx 8.5 \times 10^{28} \frac{\text{electrons}}{\text{m}^3}$$

$$\text{Using } (*) \Rightarrow E_F \approx 7 \text{ eV}$$



**Definitions:**

C is the capacitance of each capacitor.

(They are all the same.)

$n_1$  is the number of excess electrons on island 1.

$n_2$  is the number of excess electrons on island 2.

$n_{1b} \equiv \#$  excess electrons on island 1 before the tunnel event

$n_{1a} \equiv \#$  excess electrons on island 1 after the tunnel event

$n_{2b} \equiv \#$  excess electrons on island 2 before the tunnel event

$n_{2a} \equiv \#$  excess electrons on island 2 after the tunnel event

$$Q_{before} \equiv \int_{-\infty}^{t_{before}} I(t') dt'$$

where  $I(t')$  is the current flowing out of the positive terminal of the battery.

$$Q_{after} \equiv \int_{-\infty}^{t_{after}} I(t') dt'$$

where  $I(t')$  is the current flowing out of the positive terminal of the battery.

**My calculations show that:**

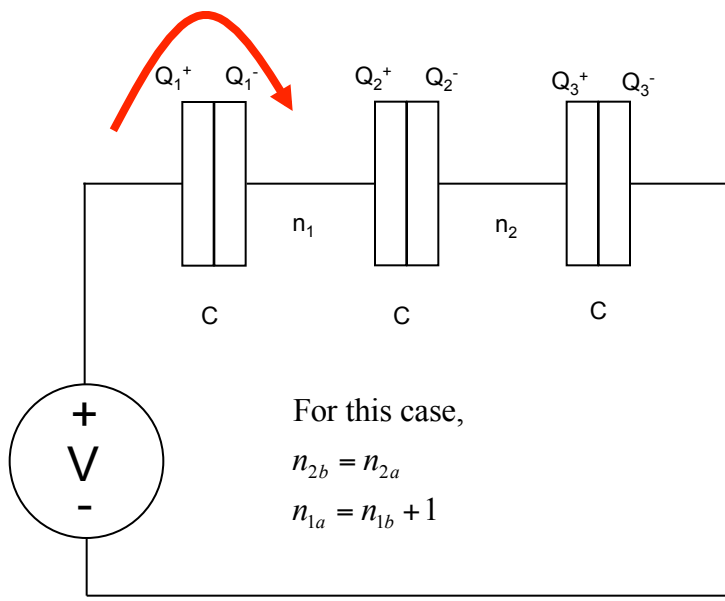
$$Q_1 = \frac{1}{3}(2en_1 + en_2 + CV)$$

$$Q_2 = \frac{1}{3}(-en_1 + en_2 + CV)$$

$$Q_3 = \frac{1}{3}(-en_1 - 2en_2 + CV)$$

$$E = \frac{Q_1^2}{2C} + \frac{Q_2^2}{2C} + \frac{Q_3^2}{2C} = \frac{1}{6C} [2e^2 n_1^2 + 2e^2 n_2^2 + (CV)^2 + e^2 n_1 n_2]$$





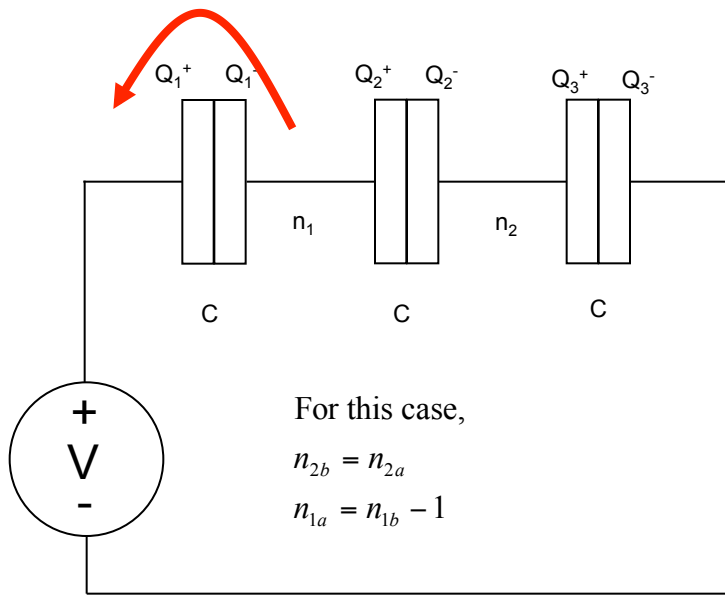
$$\Delta G = G_{before} - G_{after} = \{E_{before} - E_{after}\} - V \{Q_{before} - Q_{after}\}$$

$$\begin{aligned} & \{E_{before} - E_{after}\} \\ &= \frac{1}{6C} [2e^2 n_{1b}^2 + 2e^2 n_{2b}^2 + (CV)^2 + e^2 n_{1b} n_{2b}] - \frac{1}{6C} [2e^2 n_{1a}^2 + 2e^2 n_{2a}^2 + (CV)^2 + e^2 n_{1a} n_{2a}] \\ &= \frac{e^2}{6C} [2n_{1b}^2 + n_{1b} n_{2b}] - \frac{e^2}{6C} [2n_{1a}^2 + n_{1a} n_{2a}] = \frac{e^2}{6C} [2n_{1b}^2 + n_{1b} n_{2b} - 2(n_{1b} + 1)^2 - (n_{1b} + 1)n_{2b}] \\ &= \frac{e^2}{6C} [2n_{1b}^2 + n_{1b} n_{2b} - 2(n_{1b}^2 + 2n_{1b} + 1) - (n_{1b} + 1)n_{2b}] = \frac{e^2}{6C} [2n_{1b}^2 + n_{1b} n_{2b} - 2n_{1b}^2 - 4n_{1b} - 2 - n_{1b} n_{2b} - n_{2b}] \\ &= \frac{e^2}{6C} [-4n_{1b} - 2 - n_{2b}] \end{aligned}$$

$$\begin{aligned} \{Q_{before} - Q_{after}\} &= \int_{-\infty}^{t_{before}} I(t') dt' - \int_{-\infty}^{t_{after}} I(t') dt' = - \int_{t_{before}}^{t_{after}} I(t') dt' \\ &= - \int_{t_{before}}^{t_{after}} I_{tunnel}(t') dt' - \int_{t_{before}}^{t_{after}} I_{polarization}(t') dt' \\ &= e - \int_{t_{before}}^{t_{after}} I_{polarization}(t') dt' = e + (Q_{1before} - Q_{1after}) \end{aligned}$$

$$\begin{aligned} (Q_{1before} - Q_{1after}) &= \frac{1}{3} (2en_{1b} + en_{2b} + CV) - \frac{1}{3} (2en_{1a} + en_{2a} + CV) = \frac{1}{3} (2en_{1b}) - \frac{1}{3} (2en_{1a}) \\ &= \frac{2e}{3} (n_{1b} - n_{1a}) = \frac{2e}{3} (n_{1b} - (n_{1b} + 1)) = -\frac{2e}{3} \end{aligned}$$

$$\Delta G = \frac{e^2}{6C} [-4n_{1b} - 2 - n_{2b}] - V \left\{ \frac{e}{3} \right\}$$



$$\Delta G = G_{before} - G_{after} = \{E_{before} - E_{after}\} - V \{Q_{before} - Q_{after}\}$$

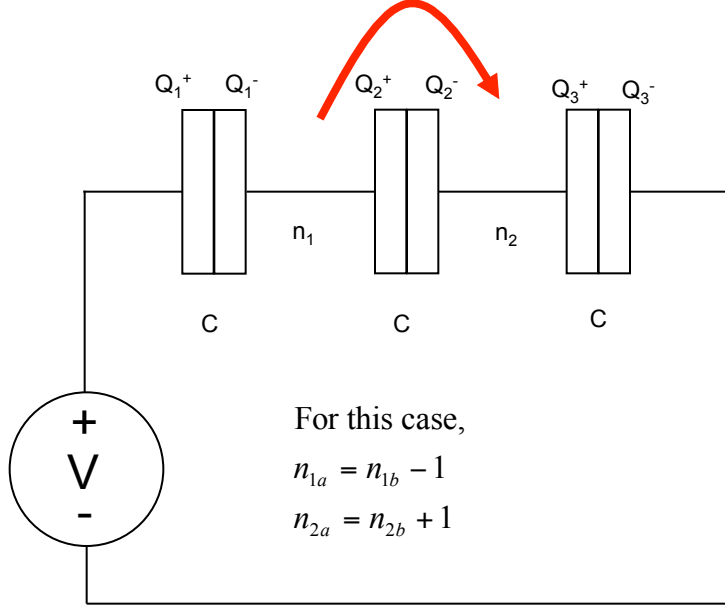
$$\begin{aligned} & \{E_{before} - E_{after}\} \\ &= \frac{1}{6C} [2e^2 n_{1b}^2 + 2e^2 n_{2b}^2 + (CV)^2 + e^2 n_{1b} n_{2b}] - \frac{1}{6C} [2e^2 n_{1a}^2 + 2e^2 n_{2a}^2 + (CV)^2 + e^2 n_{1a} n_{2a}] \\ &= \frac{e^2}{6C} [2n_{1b}^2 + n_{1b} n_{2b}] - \frac{e^2}{6C} [2n_{1a}^2 + n_{1a} n_{2a}] = \frac{e^2}{6C} [2n_{1b}^2 + n_{1b} n_{2b} - 2(n_{1b} - 1)^2 - (n_{1b} - 1)n_{2b}] \\ &= \frac{e^2}{6C} [2n_{1b}^2 + n_{1b} n_{2b} - 2(n_{1b}^2 - 2n_{1b} + 1) - (n_{1b} - 1)n_{2b}] = \frac{e^2}{6C} [2n_{1b}^2 + n_{1b} n_{2b} - 2n_{1b}^2 + 4n_{1b} - 2 - n_{1b} n_{2b} + n_{2b}] \\ &= \frac{e^2}{6C} [+4n_{1b} - 2 + n_{2b}] \end{aligned}$$

$$\begin{aligned} \{Q_{before} - Q_{after}\} &= \int_{-\infty}^{t_{before}} I(t') dt' - \int_{-\infty}^{t_{after}} I(t') dt' = - \int_{t_{before}}^{t_{after}} I(t') dt' \\ &= - \int_{t_{before}}^{t_{after}} I_{tunnel}(t') dt' - \int_{t_{before}}^{t_{after}} I_{polarization}(t') dt' \\ &= -e - \int_{t_{before}}^{t_{after}} I_{polarization}(t') dt' = -e + (Q_{1before} - Q_{1after}) \end{aligned}$$

$$\begin{aligned} (Q_{1before} - Q_{1after}) &= \frac{1}{3} (2en_{1b} + en_{2b} + CV) - \frac{1}{3} (2en_{1a} + en_{2a} + CV) = \frac{1}{3} (2en_{1b}) - \frac{1}{3} (2en_{1a}) \\ &= \frac{2e}{3} (n_{1b} - n_{1a}) = \frac{2e}{3} (n_{1b} - (n_{1b} - 1)) = + \frac{2e}{3} \end{aligned}$$

$$\Delta G = \frac{e^2}{6C} [+4n_{1b} - 2 + n_{2b}] - V \left\{ \frac{-e}{3} \right\}$$





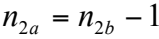
$$\Delta G = G_{before} - G_{after} = \{E_{before} - E_{after}\} - V \{Q_{before} - Q_{after}\}$$

$$\begin{aligned} & \{E_{before} - E_{after}\} \\ &= \frac{1}{6C} [2e^2 n_{1b}^2 + 2e^2 n_{2b}^2 + (CV)^2 + e^2 n_{1b} n_{2b}] - \frac{1}{6C} [2e^2 n_{1a}^2 + 2e^2 n_{2a}^2 + (CV)^2 + e^2 n_{1a} n_{2a}] \\ &= \frac{1}{6C} [2e^2 n_{1b}^2 + 2e^2 n_{2b}^2 + (CV)^2 + e^2 n_{1b} n_{2b}] - \frac{1}{6C} [2e^2 (n_{1b} - 1)^2 + 2e^2 (n_{2b} + 1)^2 + (CV)^2 + e^2 (n_{1b} - 1)(n_{2b} + 1)] \\ &= \frac{1}{6C} [2e^2 n_{1b}^2 + 2e^2 n_{2b}^2 + (CV)^2 + e^2 n_{1b} n_{2b}] - \frac{1}{6C} [2e^2 (n_{1b}^2 - 2n_{1b} + 1) + 2e^2 (n_{2b}^2 + 2n_{2b} + 1) + (CV)^2 + e^2 (n_{1b} n_{2b} + n_{1b} - n_{2b} - 1)] \\ &= \frac{1}{6C} [2e^2 n_{1b}^2 + 2e^2 n_{2b}^2 + (CV)^2 + e^2 n_{1b} n_{2b}] - \frac{1}{6C} [2e^2 n_{1b}^2 - 4e^2 n_{1b} + 2e^2 + 2e^2 n_{2b}^2 + 4e^2 n_{2b} + 2e^2 + (CV)^2 + e^2 n_{1b} n_{2b} + e^2 n_{1b} - e^2 n_{2b} - e^2] \\ &= -\frac{1}{6C} [-4e^2 n_{1b} + 2e^2 + 4e^2 n_{2b} + 2e^2 + e^2 n_{1b} - e^2 n_{2b} - e^2] \\ &= -\frac{1}{6C} [-3e^2 n_{1b} + 3e^2 + 3e^2 n_{2b}] = -\frac{3e^2}{6C} [-n_{1b} + 1 + n_{2b}] = -\frac{e^2}{2C} [-n_{1b} + 1 + n_{2b}] = \frac{e^2}{2C} [n_{1b} - n_{2b} - 1] \end{aligned}$$

$$\begin{aligned} \{Q_{before} - Q_{after}\} &= \int_{-\infty}^{t_{before}} I(t') dt' - \int_{-\infty}^{t_{after}} I(t') dt' = -\int_{t_{before}}^{t_{after}} I(t') dt' \\ &= -\int_{t_{before}}^{t_{after}} I_{tunnel}(t') dt' - \int_{t_{before}}^{t_{after}} I_{polarization}(t') dt' \\ &= 0 - \int_{t_{before}}^{t_{after}} I_{polarization}(t') dt' = (Q_{1before} - Q_{1after}) \end{aligned}$$

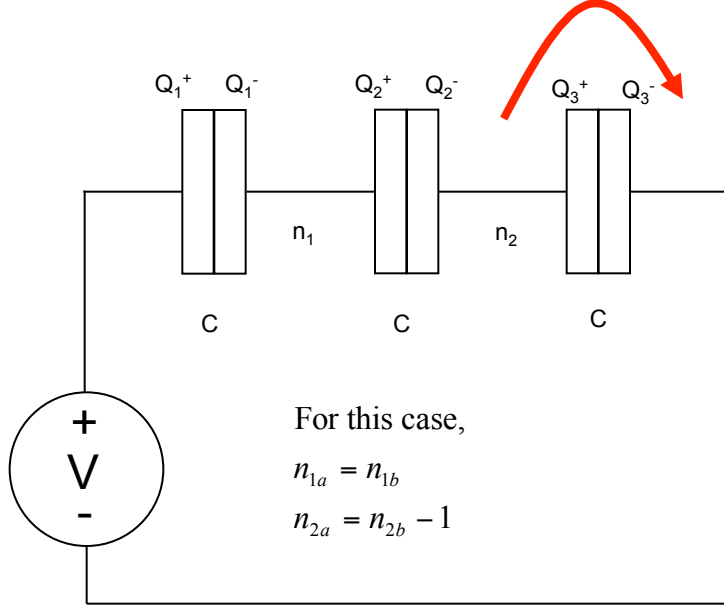
$$\begin{aligned} (Q_{1before} - Q_{1after}) &= \frac{1}{3} (2en_{1b} + en_{2b} + CV) - \frac{1}{3} (2en_{1a} + en_{2a} + CV) = \frac{1}{3} (2en_{1b} + en_{2b} + CV) - \frac{1}{3} (2e(n_{1b} - 1) + e(n_{2b} + 1) + CV) \\ &= \frac{1}{3} (2en_{1b} + en_{2b} + CV) - \frac{1}{3} (2en_{1b} - 2e + en_{2b} + e + CV) = \frac{1}{3} (2en_{1b} + en_{2b} + CV) - \frac{1}{3} (2en_{1b} - e + en_{2b} + CV) \\ &= \frac{1}{3} (2en_{1b} + en_{2b} + CV - 2en_{1b} + e - en_{2b} - CV) = \frac{+e}{3} \end{aligned}$$

$$\Delta G = \frac{e^2}{2C} [n_{1b} - n_{2b} - 1] - V \left\{ \frac{e}{3} \right\}$$



$$\Delta G = \frac{e^2}{2C}[-n_{1b} + n_{2b} - 1] + V \left\{ \frac{e}{3} \right\}$$





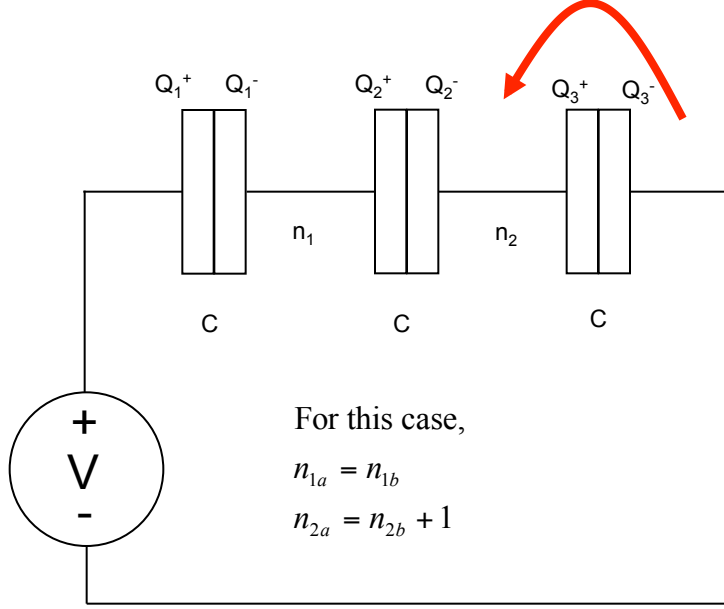
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$$\begin{aligned} \{Q_{before} - Q_{after}\} &= \int_{-\infty}^{t_{before}} I(t') dt' - \int_{-\infty}^{t_{after}} I(t') dt' = - \int_{t_{before}}^{t_{after}} I(t') dt' \\ &= - \int_{t_{before}}^{t_{after}} I_{tunnel}(t') dt' - \int_{t_{before}}^{t_{after}} I_{polarization}(t') dt' \\ &= 0 - \int_{t_{before}}^{t_{after}} I_{polarization}(t') dt' = (Q_{1before} - Q_{1after}) \end{aligned}$$

$$\begin{aligned} (Q_{1before} - Q_{1after}) &= \frac{1}{3} (2en_{1b} + en_{2b} + CV) - \frac{1}{3} (2en_{1a} + en_{2a} + CV) = \frac{1}{3} (2en_{1b} + en_{2b} + CV) - \frac{1}{3} (2en_{1b} + e(n_{2b} - 1) + CV) \\ &= \frac{1}{3} (2en_{1b} + en_{2b} + CV) - \frac{1}{3} (2en_{1b} + en_{2b} - e + CV) \\ &= \frac{1}{3} (2en_{1b} + en_{2b} + CV - 2en_{1b} + e - en_{2b} - CV) = \frac{+e}{3} \end{aligned}$$

$$\Delta G = \frac{e^2}{6C} [4n_{2b} - 2 - n_{1b} n_{2b} + n_{1b}] - V \left\{ \frac{e}{3} \right\}$$



$$\Delta G = G_{before} - G_{after} = \{E_{before} - E_{after}\} - V \{Q_{before} - Q_{after}\}$$

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$$\begin{aligned} \{Q_{before} - Q_{after}\} &= \int_{-\infty}^{I_{before}} I(t') dt' - \int_{-\infty}^{I_{after}} I(t') dt' = -\int_{I_{before}}^{I_{after}} I(t') dt' \\ &= -\int_{I_{before}}^{I_{after}} I_{tunnel}(t') dt' - \int_{I_{before}}^{I_{after}} I_{polarization}(t') dt' \\ &= 0 - \int_{I_{before}}^{I_{after}} I_{polarization}(t') dt' = (Q_{1before} - Q_{1after}) \end{aligned}$$

$$\begin{aligned} (Q_{1before} - Q_{1after}) &= \frac{1}{3} (2en_{1b} + en_{2b} + CV) - \frac{1}{3} (2en_{1a} + en_{2a} + CV) = \frac{1}{3} (2en_{1b} + en_{2b} + CV) - \frac{1}{3} (2en_{1b} + e(n_{2b} + 1) + CV) \\ &= \frac{1}{3} (2en_{1b} + en_{2b} + CV) - \frac{1}{3} (2en_{1b} + en_{2b} + e + CV) \\ &= \frac{1}{3} (2en_{1b} + en_{2b} + CV - 2en_{1b} - e - en_{2b} - CV) = \frac{-e}{3} \end{aligned}$$

$$\Delta G = \frac{e^2}{6C} [-4n_{2b} - 2 - n_{1b} n_{2b} - n_{1b}] + V \left\{ \frac{e}{3} \right\}$$



For current to flow from left to right, we need the following transitions to be allowed, for example, if the initial state of the system is (0,0), i.e.  $n_1=0$ ,  $n_2=0$ :

0,0  $\rightarrow$  1,0

1,0  $\rightarrow$  0,1

0,1  $\rightarrow$  0,0

For the first, we require  $V < -e/C$ .

For the second, we require  $V < 0$ .

For the third, we require  $V < e/C$ .

However, all 3 transitions must be allowed, so the only way to satisfy this is if  $V < -e/C$ .

Thus, no current can flow in that direction unless  $V < -e/C$ .

By a similar consideration, you can show that no current can flow in the opposite direction unless  $V > e/C$ .

Problem 2:

In a 2d gas, the Fermi energy is well defined,  
and so is the Fermi wavevector.

The answers are: 3.5 meV  
and 80 nm.



Prob 3

$$R_T \sim \frac{e^{-\alpha}}{A}$$

$$e \sim A$$

$R_T \propto$  ~~the~~ independent  
of area

Prob 4

$$C \approx \frac{\epsilon A}{d} \quad A = (1 \text{ cm})^2$$

$$d = 1 \text{ nm}$$

$$\Rightarrow C = 1 \mu\text{F} \quad R = 10 \Omega$$

$$\Rightarrow \tau = 10 \text{ ps}$$

Prob 5

$$R_T > h/e^2 = 25 \text{ k}\Omega \quad \text{Take } R_T = 250 \text{ k}\Omega$$

$$e^2/C > kT$$

$$\text{Take } \frac{e^2}{C} = 10 kT \Rightarrow C = 0.1 \text{ fF}$$

$$\Rightarrow R_T C = 40 \text{ ps}$$

These are one very rough estimates.

**EECS 277C Nanotechnology**  
**Homework #3 Solutions**

What is the Fermi wavelength of electrons in aluminum? Is it possible to fabricate 1d Al wires using photolithography? Is it possible to fabricate Al wires using electron beam lithography?

3.6 angstroms.

No.

Find the resistivity of pure copper at room temperature. Now, find the density of electrons in copper, assuming one free electron per atom. Now, calculate the scattering time and the mean free path of the electrons from the Drude model. Is it possible to fabricate copper wires in the ballistic limit using photolithography? Is it possible to fabricate copper wires in the ballistic limit using electron beam lithography?

$$10 \text{ microhm-cm} \quad 8.45 \cdot 10^{22} \text{ cm}^{-3} \quad \frac{1}{\rho} = \sigma = \frac{ne^2\tau}{m}$$

$$\tau = 4 \cdot 10^{-15} \text{ s} \quad l = v_{\text{Fermi}}\tau$$

$$v_{\text{Fermi}} = 1.6 \times 10^8 \text{ cm/s} \quad \text{so } l = 6.4 \text{ nm}$$

No

No

For a 2DEG in GaAs with  $n=10^{11} \text{ cm}^{-2}$  and a mobility of 8,000  $\text{cm}^2/\text{V-s}$  (typical of room temperature HEMT operation), calculate the scattering time and the mean free path from the Drude model. Is it possible to fabricate devices using lithography that are smaller than the mean free path? Remember you must use the effective mass of electrons for the Fermi energy, etc.

$$\mu = \frac{e\tau}{m^*} \quad \tau = 0.3 \text{ ps} \quad l = v_{\text{Fermi}}\tau \quad \text{so } l = 1.3 \cdot 10^5 \text{ m/s} \times 0.3 \text{ ps} = 40 \text{ nm}$$

Yes

- 9.) A ballistic wire has a long length, but the height is one Fermi wavelength tall, and the width is 10 Fermi wavelengths wide. What is the resistance?

Need to find number of modes. Each mode will carry  $e^2/h$  of current/conductance.

Approximately 10 Fermi wavelengths fit in the horizontal direction, so there are approximately 10 modes. Each mode carries spin up and spin down.

So total conductance is  $10 \times 2 \times e^2/h$ . Total resistance is  $h/(20 e^2) = 1.25 \text{ kohm}$