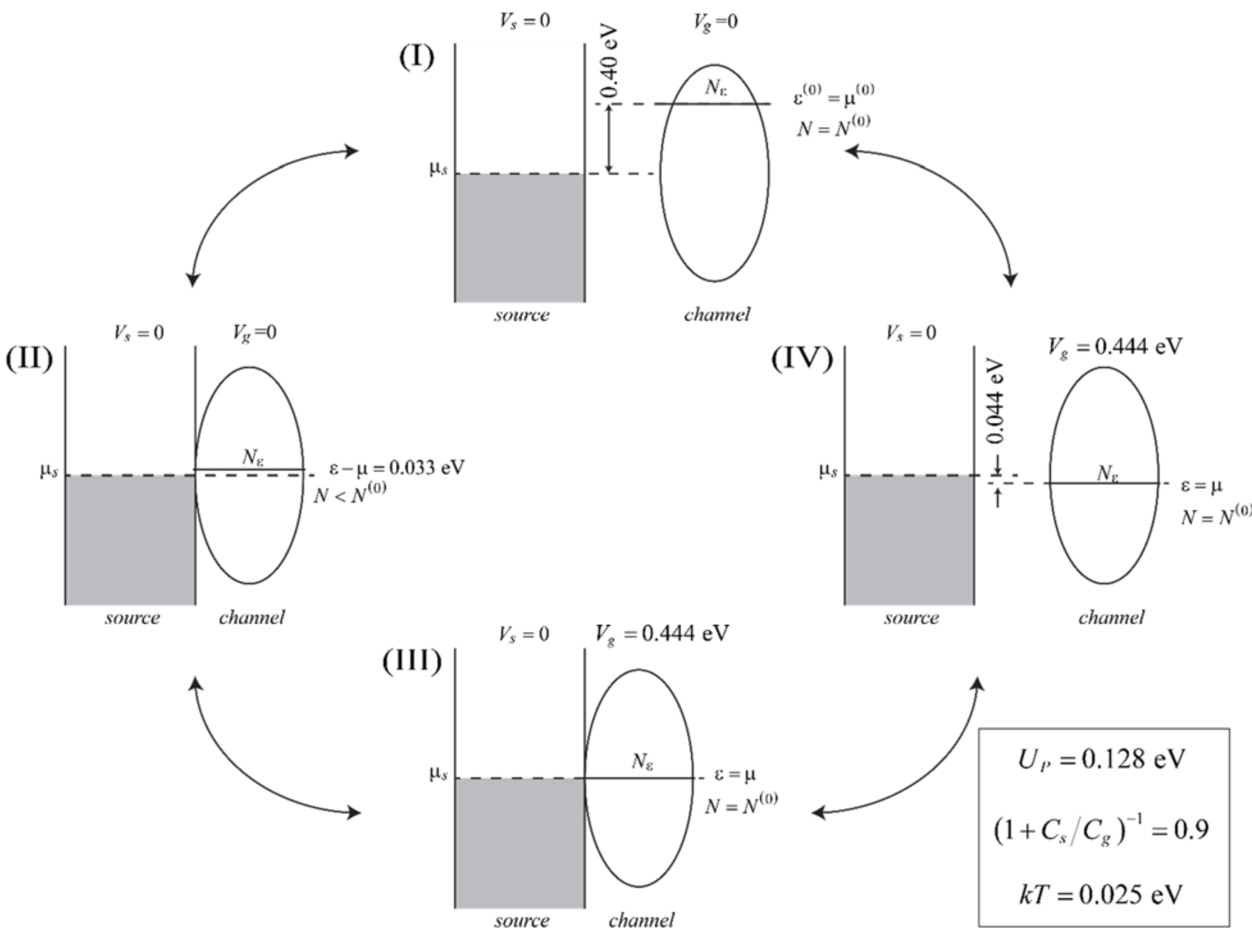
NANO 705-Notes

<u>Nanocapacitor</u>

Cyclic process

Consider the charging and neutralizing of a nanocapacitor shown in the energy diagram below.



In the neutral, isolated channel, we will call the energy level $\varepsilon^{(0)}$ and the chemical potential $\mu^{(0)}$. The energy level in the channel has a degeneracy of N_ε. In its netural state, the level contains $N^{(0)}$ electrons.

Explanation

Let's take the channel potential to be

$$U = U_P \cdot \Delta N - U_L$$

When the channel is in contact with the source, the potential terms are

$$U_P \cdot \Delta N = -\frac{qQ}{C_s + C_g} = \frac{q^2}{C_s + C_g} \cdot \left(N - N^{(0)}\right) \text{ and } U_L = \frac{qV_g}{1 + C_s/C_g}$$

When the channel is isolated from the source, the potential terms are

$$U_P \cdot \Delta N = -\frac{qQ}{C_g} = \frac{q^2}{C_g} \cdot \left(N - N^{(0)}\right) \text{ and } U_L = qV_g$$

It is given in this example that $\varepsilon^{(0)} = \mu^{(0)}$, so $N^{(0)} = (0.5)\,N_\varepsilon$.

(I) No contact, no bias, neutral
Starting in isolation with $V_g = 0$ and $Q = 0$. Then

$$\varepsilon = \varepsilon^{(0)},\ \mu = \mu^{(0)} \text{ and } N = N^{(0)}.$$

So $U_P \cdot \Delta N = 0$ and $U_L = 0$, giving $U = 0$.

(II) Contact, no bias
Contact between the source and channel gives $\mu = \mu_s$. In general, we still have $\varepsilon \neq \varepsilon^{(0)}$ and $N \neq N^{(0)}$. Their exact values require a self-consistent solution. Now $U_P \cdot \Delta N \neq 0$, but $U_L = 0$, so $U = U_P \cdot \Delta N$

(III) Contact, bias, neutral
Now let's find the exact bias that gives $N = N^{(0)}$ ($Q = 0$). We still have $\mu = \mu_s$. For neutrality, we must have $\varepsilon - \mu = \varepsilon^{(0)} - \mu^{(0)} = \left(\varepsilon^{(0)} + U\right) - \mu$. This indicates that $\mu - \mu^{(0)} = U$. Since $U_P \cdot \Delta N = 0$, we have

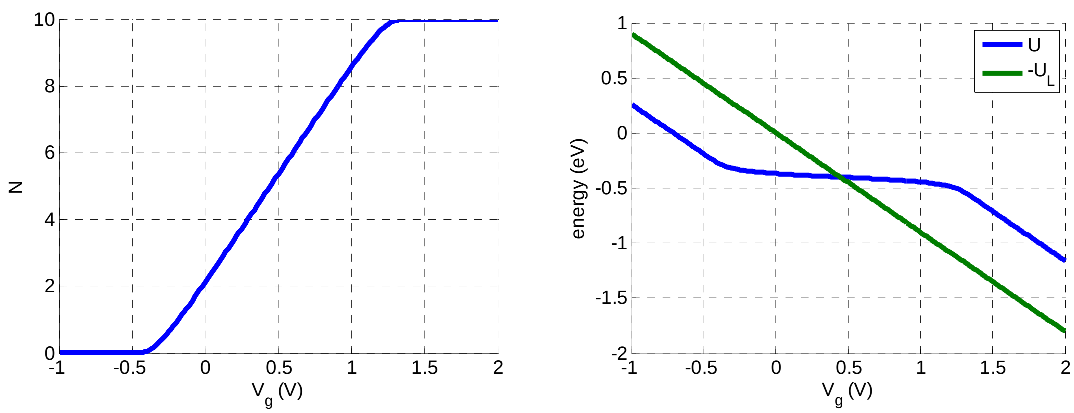
$$U = -U_L = -\frac{qV_g}{1 + C_s/C_g}$$

So the needed gate bias is

$$V_g = (1 + C_s/C_g)\cdot\left(\mu - \mu^{(0)}\right)/q$$

(IV) No contact, bias, neutral
Now let's keep the same gate voltage and break contact with the source. We will have $Q = 0$ and $N = N^{(0)}$. So $U_P \cdot \Delta N = 0$, but without the source-channel capacitance, we have $U_L = qV_g$. Then $U = -U_L = -qV_g$. We have $\varepsilon - \mu = \varepsilon^{(0)} - \mu^{(0)}$, so $\varepsilon - \varepsilon^{(0)} = \mu - \mu^{(0)} = -qV_g$. Also $\mu - \mu_s = \mu^{(0)} - \mu_s - qV_g$.

Self-consistent solutions
Let's evaluate the channel charge and energy level as functions of gate voltage when in contact with the source using the numbers in the figure: $U_P = 0.128$ eV, $1/(1 + C_s/C_g) = 0.9$, $kT = 0.025$ eV.



In case (I), we have $\mu^{(0)} - \mu_s = 0.40\ \text{eV}$. In case (II), the self-consistent solution tells us that, with $V_g = 0$, we have $N = (0.213) \cdot N_\varepsilon$ and $\varepsilon - \mu_s = 0.033\ \text{eV}$. In case (III), we find the exact gate voltage to neutralize the channel is $V_g = (0.40\ \text{eV})/0.9 = 0.444\ \text{eV}$. In case (IV), $\varepsilon = \varepsilon^{(0)} - 0.444\ \text{eV}$, which is $0.044\ \text{eV}$ below μ_s .