Physics 120 - David Kleinfeld - Spring 2017

1 Notes on diode analysis

1.1 Background

Mass action says that it is more probable for charge to move from a region with high charge carrier density to one with lower density. This gives rise to the notion of the diode, where current can flow more strongly in one direction than the other. The semiconductor diode is built by taking two blocks of pure semiconductor, like Si, and doping one block so that it has a net excess of negative carriers (n-side) and doping the other block so that it has a net excess of positive carriers (p-side) and then bringing the blocks in contact (Fig.)

Let N_n be the number of negative change carriers (electrons) and N_p be the number of positive charge carriers (holes). Right at the junction, the extra holes in the p-side will be swept toward the n-side and the extra electrons on the n-side will be swept onto the p-side. This results in a steady-state situation with a junction that has no free charge and a smooth transition in potential from one side to the other. The total potential drop, ϕ, can be expressed in terms of carrier density

$$\frac{N_p(n-side)}{N_p(p-side)} \;=\; e^{-e\phi/k_BT}. \tag{1}$$

Now the current of holes that flows is

$$\begin{aligned} \text{Current} \;&\propto\; \text{Hole from (p} - \text{side) moving to (n} - \text{side)} \;-\; \text{Hole from (n} - \text{side) moving to (p} - \text{side)} \\ &\propto\; N_p(\text{p} - \text{side})\; e^{-e\phi/k_BT} \;-\; N_p(\text{n} - \text{side}) \\ &=\; 0. \end{aligned} \tag{2}$$

Suppose that we now apply a potential, denoted V_D, to the n-side that lowers the potential; this is called the forward-biased condition as the applied potential is higher on the p-side than the n-side. The current is now

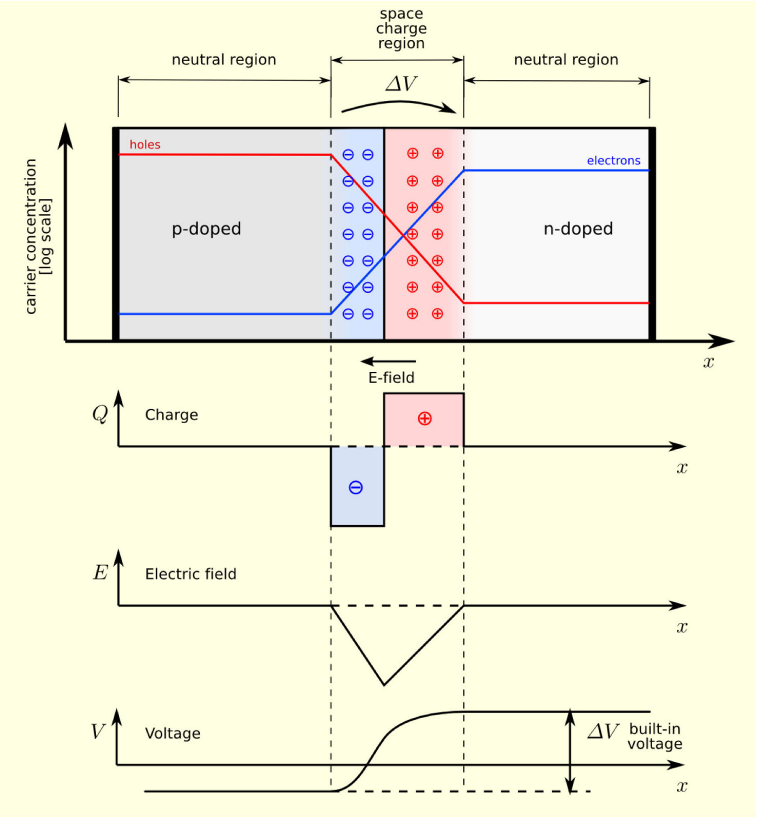
$$\begin{aligned} \text{Current} \;&\propto\; N_p(\text{p} - \text{side})\; e^{-e(\phi - V_D)/k_BT} \;-\; N_p(\text{n} - \text{side}) \\ &\propto\; N_p(\text{p} - \text{side})\; e^{-e(\phi - V_D)/k_BT} \;-\; N_p(\text{p} - \text{side})\; e^{-e\phi/k_BT} \\ &\propto\; \left[N_p(\text{p} - \text{side})\; e^{-e\phi/k_BT}\right] \left[e^{eV_D/k_BT} \;-\; 1\right]. \end{aligned} \tag{3}$$

We can repeat this argument in terms of electrons

$$\frac{N_n(p-side)}{N_n(n-side)} \;=\; e^{-e\phi/k_BT}. \tag{4}$$

The current of electrons that flows with $V_D > 0$ is again

$$\begin{aligned} \text{Current} \;&=\; \text{Electron from (n} - \text{side) moving to (p} - \text{side)} \;-\; \text{Electron from (p} - \text{side) moving to (n} - \text{side)} \\ &\propto\; N_n(\text{n} - \text{side})\; e^{-(\phi - V_D)/k_BT} \;-\; N_n(\text{p} - \text{side}) \\ &\propto\; N_n(\text{n} - \text{side})\; e^{-(\phi - V_D)/k_BT} \;-\; N_n(\text{n} - \text{side})\; e^{-e\phi/k_BT} \\ &\propto\; \left[N_n(\text{n} - \text{side})\; e^{-e\phi/k_BT}\right] \left[e^{eV_D/k_BT} \;-\; 1\right]. \end{aligned} \tag{5}$$



We can add the two currents up to get

$$\begin{aligned} I &\propto \left[N_p(\mathrm{p-side})\; e^{-e\phi/k_BT} + N_n(\mathrm{n-side})\; e^{-e\phi/k_BT}\right]\left[e^{eV_D/k_BT}\; - \;1\right] \\ &\propto \left[(N_p(\mathrm{p-side})\; + N_n(\mathrm{n-side}))\, e^{-e\phi/k_BT}\right]\left[e^{eV_D/k_BT}\; - \;1\right] \\ &= I_0\left[e^{eV_D/k_BT}\; - \;1\right]. \end{aligned} \tag{6}$$

The product $N_n N_p$ can be estimated as follows. In equilibrium, the numbers of holes and electrons are constant. There is a chance for an electron to leave the valence band and join the conduction band, thus forming an electron-hole pair. Thus the production of electron-hole pairs is given by the Boltzmann factor $exp(-E_{gap}/k_BT)$ where E_{gap} is the gap energy, about 1.1 eV for silicon. These charge pairs will not accumulate, but reach a steady state through the recombination of electron and hole pairs. The probability of decay depends on the product $N_n N_p$,

$$N_p\, N_n \approx e^{-E_{gap}/k_BT}. \tag{7}$$

The next order to business to to use the diode in a circuit. Let's see how we handle the nonlinearity!