Serie 03

Preamble

Space Charge Region

As discussed during the lecture, in an intrinsic semiconductor, each electron promoted to the conduction band leaves a hole in the valence band. Both of these carriers can move more or less freely within the semiconductor. Even though theoretically, the random motion of free carriers can generate localized regions containing slightly more holes or electrons, the electric field generated by this charge difference will immediately attract the needed charge and neutralize these regions. Therefore, such phenomena are never observed in practice.

In the case of a uniformly doped semiconductor, the concept remains similar. For example, when a donor dopant is ionized, the atoms donate one of their electrons to the conduction band, generating a free electron and becoming slightly positive themselves. Unlike the electrons or holes generated by dopant ionization, the dopants themselves, being part of the crystal structure, cannot move easily. Nevertheless, the principle remains the same as for intrinsic semiconductors: if theoretically, the random motion of free carriers can generate localized regions with a slight charge, these regions will be immediately neutralized by the electric field generated.

In the case of an n-type non-uniformly doped semiconductor, the electron density depends on the donor concentration, but not only. Similar to many other phenomena, free carriers tend to flow towards regions where the carrier density is lower. The formulas that describe this flow (F_n and F_p) are as follows:

$$F_n = -D_n \frac{dn}{dx} \qquad\qquad F_p = -D_p \frac{dp}{dx} \tag{1}$$

This flux of carrier diffusion will create what is known as the diffusion current. In our case, electrons flow towards regions with lower electron density, while the donors, being part of the crystal structure, remain immobile. Consequently, the region from which the electrons flow has a higher concentration of ionized donors (positive) compared to electrons (negative), resulting in a positive charge in that region. Conversely, the region into which the electrons flow has a higher electron (negative) concentration than the ionized donor (positive) concentration, creating a negatively charged region. These charged regions generate an electric field that counteracts the diffusion current, leading to a drift current. A similar reasoning can be applied to p-type semiconductors.

The best example of such a phenomenon is, of course, the p-n junction. In all cases, the overall structure must remain neutral at thermal equilibrium. This is evident from the preceding paragraph, but it is also essential to prevent the generation of an electric field within the structure.

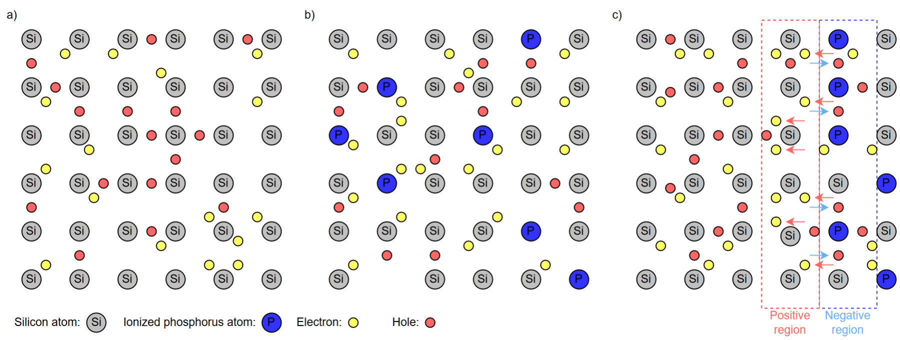

Figure 1: a) Intrinsic semiconductor. b) Uniformly doped n-type semiconductor. c) Non-uniformly doped n-type semiconductor.

Overall charge neutrality

During the formation of the space charge region, charges are moved around, but none appear or disappear. This leads to an overall neutrality of the PN-junction. In other words, even if space charge regions are created, the total amount of positive and negative charge will be zero. By applying Maxwell's equations (Gauss's law), we can therefore say that outside of the space charge region, no electric field will exist. Another way to see this is that if the overall structure of the PN-junction is not neutral, an electric field will be created, attracting any possible charge in the outside world to cancel out these non-balanced charges.

Given constants

$n_i(Si) = 1.5 \cdot 10^{10}\,[cm^{-3}] \quad @ \quad T = 300\,[K]$
$k = 8.62 \cdot 10^{-5}\,[eV/K]$
$q = 1.60 \cdot 10^{-19}\,[C]$
$\epsilon_0 = 8.85 \cdot 10^{-14}\,[F/cm]$
$\epsilon_{Si} = 11.7 \cdot \epsilon_0$

Exercise 01

A silicon bar is doped with acceptor dopants following a profile shown in Fig. 2. The dopant density, N_a, increases quasi-monotonically from $N_{amin} \ll n_i$ at $x = 0$ to $N_{amax} = \text{cst}$ at $x = L$. It is considered that $N_a = n_i$ at $x = L/2$, the dopant concentration saturates to a constant value near $x = L$, the donor concentration is $N_d = 0$ throughout the bar, and finally, thermal equilibrium is assumed.

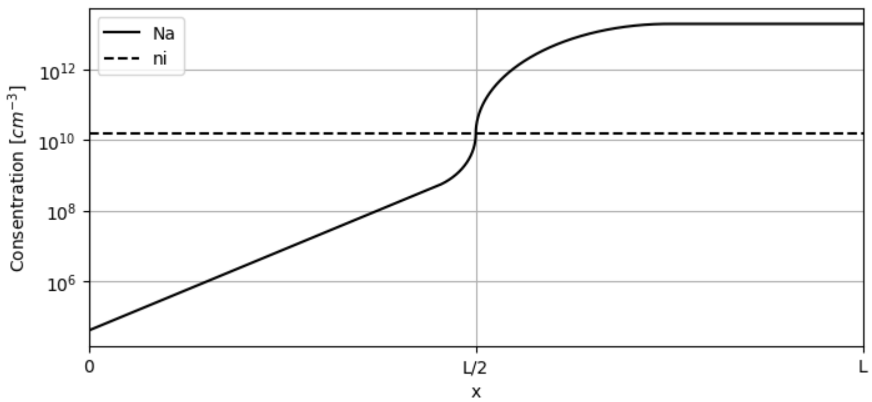

Figure 2: Non-uniform doping profile.

Questions

Choose the correct answer to the following questions:

Q1. Where is the maximum hole concentration reached in this structure?

a) $x = 0$
b) $0 < x < L/2$
c) $x = L/2$
d) $L/2 < x < L$
e) $x = L$

Q2. Where is the maximum electron concentration reached in this structure?

a) $x = 0$
b) $0 < x < L/2$
c) $x = L/2$
d) $L/2 < x < L$
e) $x = L$

Q3. In which direction is the diffusion current of holes oriented?

a) $-\vec{x}$
b) $\vec{x}$
c) There is no diffusion current of hole.

Q4. In which direction is the drift current of holes oriented?

a) $-\vec{x}$
b) $\vec{x}$
c) There is no drift current of hole.

Q5. In which direction is the diffusion current of electron oriented?

a) $-\vec{x}$
b) $\vec{x}$
c) There is no diffusion current of electron.

Q6. In which direction is the drift current of electron oriented?

a) $-\vec{x}$
b) $\vec{x}$
c) There is no drift current of electron.

Q7. In which direction is the electric field oriented?

a) $-\vec{x}$
b) $\vec{x}$
c) There is no electric field.

Q8. At which point in the structure is the internal electric potential maximum in absolute value? Considering that $\phi(x = 0) = 0$.

a) $x = 0$
b) $0 < x < L/2$
c) $x = L/2$
d) $L/2 < x < L$
e) $x = L$

Q9. At which point in the structure is the internal electric field maximum in absolute value?

a) $x = 0$
b) $0 < x < L/2$
c) $x = L/2$
d) $L/2 < x < L$
e) $x = L$

Q10. If the doping level N_a increases according to a new profile shown in Fig. 3, what happens to the absolute maximum internal electric potential?

a) It increase.
b) It decrease.
c) It doesn't change.

Q11. If the doping level N_a increases according to a new profile shown in Fig. 3, what happens to the absolute maximum internal electric field?

a) It increase.
b) It decrease.
c) It doesn't change.

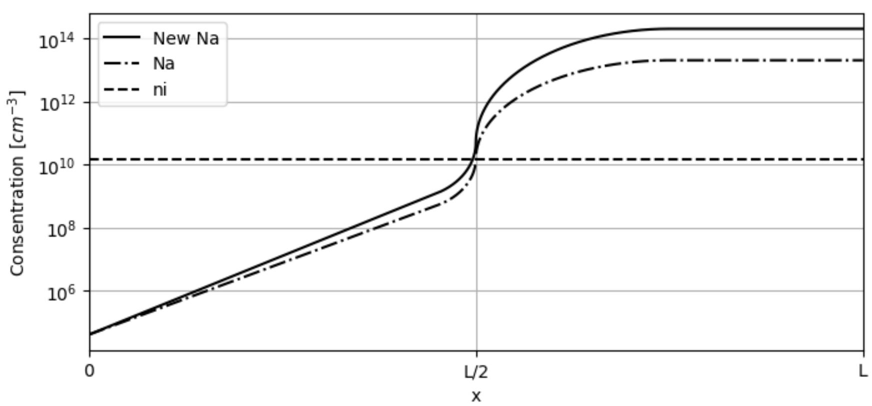

Figure 3: New non-uniform doping profile.

Exercise 02

We have a p-n junction at room temperature and thermal equilibrium. The p-type region of the junction is doped with $N_a = 10^{16}\left[cm^{-3}\right]$ and $N_d = 0\left[cm^{-3}\right]$. The n-type region of the junction is doped with $N_a = 0\left[cm^{-3}\right]$ and $N_d = 10^{17}\left[cm^{-3}\right]$. Use the depletion approximation for this exercice.

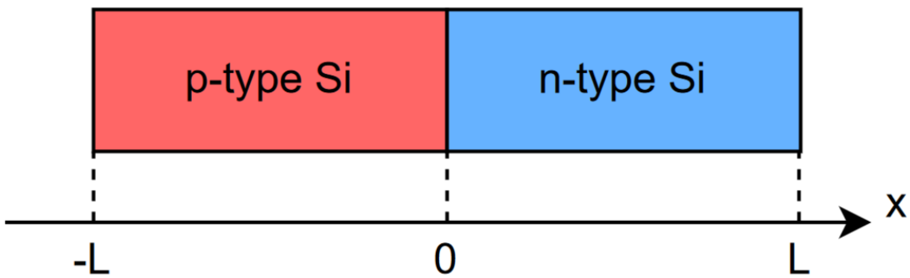

Figure 4: Exercise 02 p-n junction draw.

a) Calculate ϕ_n, ϕ_p, and ϕ_B the built-in potential.

b) Using the depletion approximation, draw and calculate the charge distribution in the p-n junction $\rho(x)$. Let x_{n0} and x_{p0} represent the unknown depletion widths on each side of the p-n junction.

c) Based on the calculated charge distribution, draw and calculate the electric field $E(x)$.

d) Based on the calculated electric field, draw and calculate the electric potential.

e) Use the built-in potential calculated at point **a)** and the potential calculated at point **d)** to determine the depletion widths on each side of the p-n junction, x_{n0} and x_{p0}.

Exercise 03

Considering the junction calculated in the preceding exercise with depletion approximation, if Q is the charge in the n-Type part of the space charge region, and $-Q$ is the charge in the p-Type part of the space charge region, calculate $\frac{\partial Q(\phi_B)}{\partial \phi_B}$.