Exercise 1 (online: 24.04.2023. Return by: **Mo 01.05.2023 10:00**) **20P**

1. **Schottky Contact** 3P

   Consider a contact between Al and n-Si doped at $N_d = 10^{16}\,\mathrm{cm}^{-3}$ at $T = 300\,\mathrm{K}$. The work function of Al is $4.28\,\mathrm{eV}$, the electron affinity for Silicon is $4.01\,\mathrm{eV}$, the energy separation between the conduction band edge and the Fermi energy in the n-Si is $206\,\mathrm{meV}$ and the relative permittivity of Silicon $\varepsilon_r = 11.68$.

   (a) Draw the energy-band diagrams of the two materials before the junction is formed.(1P)

   (b) Draw the energy-band diagrams after the junction is formed.(1P)

   (c) What are the values of the Schottky barrier height $e\Phi_{\mathrm{SB}}$ and the built-in potential eV_B? (1P)

2. **Semiconductor Doping** 3P

   In a doped semiconductor with a donor concentration N_d and an acceptor concentration N_a the densities of the majority and minority charge carriers, n_c and p_v, can be determined by taking the "Law of Mass Action" into account $n_c p_v = n_i^2$ with n_i the intrinsic carrier concentration. For simplicity it is suggested that one uses the effective donor density in the following $\Delta n = N_d - N_a$. Hint: assume that both the donor and acceptor atoms are all fully ionized.

   (a) Derive the general expressions for n_c and p_v as a function of n_i and Δn. (1P)

   (b) Approximate n_c and p_v in terms of n_i and Δ_n in the limit of weak doping i.e. $\Delta n \ll n_i$.(1P)

   (c) Approximate n_c and p_v in terms of n_i and Δ_n in the limit of strong doping i.e. $\Delta n \gg n_i$.(1P)

3. **p-n-Diode** 14P

   A p-n-diode is fabricated with the following doping profile:

$$N_d(x) = \begin{cases} N_d, & x > 0 \\ 0, & x < 0 \end{cases}, \qquad N_a(x) = \begin{cases} 0, & x > 0 \\ N_a, & x < 0 \end{cases}. \tag{1}$$

   Far away from the junction at $x = 0$ we may assume the validity of the relevant chemical potentials $\mu_n = \mu_e(x \to \infty)$ and $\mu_p = \mu_e(x \to -\infty)$. In these regions (I and IV) we expect the concentrations of the local majority carriers to be given by the dopant concentrations. Assume that only in a narrow region in the immediate vicinity of the junction a depletion region arises where there is no significant concentration of carriers. Hence the following (approximate) charge density distribution is expected to arise:

$$\rho(x) = \begin{cases} 0, & x < -d_p \text{ (region I)} \\ -eN_a, & -d_p < x < 0 \text{ (region II)} \\ +eN_d, & 0 < x < d_n \text{ (region III)} \\ 0, & x > d_n \text{ (region IV)} \end{cases}. \tag{2}$$

   The 1D Poisson equation may be written as:

$$\frac{d^2\phi}{dx^2} = -\frac{\rho(x)}{\epsilon_r \epsilon_o}. \tag{3}$$

(a) By directly integrating the Poisson equation (3) once, derive the explicit expression for $\phi'(x) = -E(x)$. Assuming that the total voltage across the junction is finite, determine the integration constants in region I and region IV. Further, use the appropriate boundary condition (continuity) for $E(x)$ at $x = -d_p$ and $x = d_n$ to determine the other two integration constants. Finally, use the boundary condition (continuity) for $E(x)$ at $x = 0$ to show that $N_d d_n = N_a d_p$. What is the physical interpretation of the last result? (2P)

(b) Integrate the obtained expression for $\phi'(x)$ the second time to obtain $\phi(x)$. Use the appropriate boundary conditions (continuity) for $\phi(x)$ at $x = -d_p$ and $x = d_n$ to determine two integration constants. (2P)

(c) Use the boundary condition (continuity) for $\phi(x)$ at $x = 0$ to show that the potential difference between the two doped regions I and IV far from the junction $\Delta\phi = \phi(\infty) - \phi(-\infty)$ is given by (1P) :

$$\Delta\phi = \frac{e}{2\epsilon_r\epsilon_o}\left(N_d d_n^2 + N_a d_p^2\right). \tag{4}$$

(d) Derive an expression for the lateral extent of the depletion regions d_n and d_p and their dependence on $\Delta\phi$. (2P)

(e) In the absence of an applied voltage U the potential difference is given by: $e(\Delta\phi)_o = \mu_n - \mu_p$. How does $\Delta\phi$ change when a positive voltage U is applied to the p-side of the diode (the n-side remains at ground potential). How are the depletion regions expected to change as a result? Express your result as $d_n(U) = d_n(0)\cdot f(U)$, where $f(U)$ is a function that explicitely shows the U-dependence of the size of the depletion region. (2P)

(f) Qualitatively the resistance of such a diode may be considered as arising from the series resistance of three resistive components: two highly-doped contact regions and the depletion region located between the two contacts. Describe qualitatively how the resulting current-voltage characteristic is expected to look. (1P)

(g) From which processes do the recombination and generation current arise at a pn-junction? Which condition must they fulfill if there is no external voltage? (1P)

(h) Now consider a pn-junction made of p- and n-doped Si ($\epsilon_r = 11.9$) with the doping levels $N_a = 10^{15}\,\mathrm{cm}^{-3}$ and $N_d = 2\cdot 10^{17}\,\mathrm{cm}^{-3}$. For $\Delta\phi = 0.717\,\mathrm{V}$ calculate the width of the space charge region at room temperature for the case of externally applied voltages $U = 0\,\mathrm{V}$ and for $U = -10\,\mathrm{V}$. (2P)

(i) Calculate how the size of the space charge region changes, if $N_a = 1\cdot 10^{17}\,\mathrm{cm}^{-3}$ and $N_d = 5\cdot 10^{17}\,\mathrm{cm}^{-3}$ ($U_{\mathrm{pn}} = -10\,\mathrm{V}$).(1P)