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1. (a) The breakdown voltage is

$$V_B = \frac{\varepsilon_s E_{crit}^2}{2eN_B}$$

so the semiconductor doping in the low-doped region of the one-sided junction

$$N_B = \frac{\varepsilon_s E_{crit}^2}{2eV_B}$$

$$N_B = \frac{11.7\varepsilon_0 \times (4\times10^5)^2 \times 10^{-2}}{2e \times 40} = 1.293 \times 10^{16}\ cm^{-3}$$

(b) The maximum p-type doping concentration such that the breakdown voltage is 20V is

$$N_B = \frac{11.7\varepsilon_0 \times 0.01 \times (4\times10^5)^2}{2e \times 20} = 2.586\times10^{16}\ cm^{-3}$$

2. (a) $V_{bi} = \frac{kT}{e}\ln\left(\frac{N_aN_d}{n_i^2}\right) = V_t \ln\left(\frac{N_aN_d}{n_i^2}\right)$

$$= \frac{300k}{e}\ln\frac{2\times10^{17}\times2\times10^{15}}{(1.5\times10^{10})^2}$$

$$= 0.7292V$$

(b) (i) The cross-sectional area $A = 10^{-5}\ cm^2$

$$C = C'A = A\sqrt{\frac{e\varepsilon_s N_aN_d}{2(V_{bi}+V_R)(N_a+N_d)}}$$

$$C = 10^{-5}\sqrt{\frac{11.7e\times100\,\varepsilon_0\times2\times10^{17}\times2\times10^{15}}{2(0.7292+1)(2\times10^{17}+2\times10^{15})}} = 9.749\times10^{-14}F$$

(ii) The junction capacitance

$$C = 10^{-5}\sqrt{\frac{11.7e\times100\,\varepsilon_0\times2\times10^{17}\times2\times10^{15}}{2(0.7292+3)(2\times10^{17}+2\times10^{15})}} = 6.638\times10^{-14}F$$

(iii) $C = 10^{-5}\sqrt{\frac{11.7e\times100\,\varepsilon_0\times2\times10^{17}\times2\times10^{15}}{2(0.7292+5)(2\times10^{17}+2\times10^{15})}} = 5.356\times10^{-14}F$

(c) The graph see attached pages.

From the graph we can find that as $N_a \gg N_d$, the junction capacitance of the pn junction can be reduced to $C' \simeq \sqrt{\frac{e\varepsilon_s N_d}{2(V_{bi}+V_R)}}$ or $\left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi}+V_R)}{e\varepsilon_s N_d}$, so the slope of $1/C'^2 - V_R$ curve is $\frac{2}{e\varepsilon_s N_d}$ is related to N_d and the intercept at the voltage axis is $-V_{bi}$ that is related to V_{bi} (absolute value is V_{bi})

3. (a) The ideal reverse-saturation current density is given by

$$J_s = \frac{eD_p p_{no}}{L_p} + \frac{eD_n n_{po}}{L_n} = en_i^2\left(\frac{1}{N_a}\sqrt{\frac{D_n}{\tau_{no}}} + \frac{1}{N_d}\sqrt{\frac{D_p}{\tau_{po}}}\right)$$

$$J_s = (1.5\times10^{10})^2 e\left(\frac{1}{8\times10^{15}}\sqrt{\frac{10}{8\times10^{-8}}} + \frac{1}{5\times10^{17}}\sqrt{\frac{25}{10^{-7}}}\right)$$

$$= 5.152\times10^{-11}\ A/cm^2$$

The reverse-biased saturation current

$$I_s = J_s A = 1.030\times10^{-14}\ A$$

(b) (i) The forward-biased current at $V_a = 0.45V$

$$I = I_s \exp\left(\frac{eV_a}{kT}\right)$$

$$= I_s \exp\left(\frac{0.45e}{300k}\right)$$

$$= 3.738\times10^{-7} A$$

(ii) $I = I_s \exp\left(\frac{0.55e}{300k}\right) = 1.789\times10^{-5} A$

(iii) $I = I_s \exp\left(\frac{0.65e}{300k}\right) = 8.561\times10^{-4} A$

4. (a) Denote the current in the depletion region due to the flow of electrons as I_n and the corresponding current density as J_n. Denote the current in the depletion region due to the flow of holes as I_p and the corresponding current density as J_p.

then we have $\frac{I_n}{I_n+I_p} = 90\% = 0.9 = \frac{J_n}{J_n+J_p}$

$$J_n = en_i^2 \frac{1}{N_a}\sqrt{\frac{D_n}{\tau_{no}}} \qquad J_p = en_i^2\frac{1}{N_d}\sqrt{\frac{D_p}{\tau_{po}}}$$

so

$$\frac{1}{1+\frac{N_d}{N_a}\sqrt{\frac{D_p \tau_{no}}{D_n \tau_{po}}}} = 0.9$$

The ratio of $\frac{N_d}{N_a} = \frac{\frac{1}{0.9}-1}{\sqrt{\frac{D_p \tau_{no}}{D_n \tau_{po}}}} = \frac{\frac{1}{0.9}-1}{\sqrt{\frac{10\times5\times10^{-7}}{25\times10^{-7}}}} = 0.0785\overline{7}$

(b) The ratio of $\frac{N_d}{N_a} = \frac{\frac{1}{0.2}-1}{\sqrt{\frac{10\times5\times10^{-7}}{25\times10^{-7}}}} = 2.828$

5. The ratio of hole current to the total current crossing the space charge region

$$\frac{I_p}{I} = \frac{J_p}{J_n + J_p} = \frac{1}{1 + \frac{N_d}{N_a}\sqrt{\frac{D_n \tau_{p0}}{D_p \tau_{n0}}}} \quad \text{(using result from 4)}$$

$$\frac{D_n}{D_p} = \frac{25}{10} = \frac{5}{2}$$

$$\frac{I_p}{I} = \frac{1}{1 + \frac{10^{16}}{N_a}\sqrt{\frac{5}{2} \times \frac{10^{-7}}{10^{-6}}}} = \frac{1}{1 + \frac{5 \times 10^{16}}{N_a}}$$

The graph plotted by Mathematica LogLinear plot function is attached at last

6. (a) The ideal reverse-saturation current density

$$J_s = e n_i^2 \left(\frac{1}{N_a}\sqrt{\frac{D_n}{\tau_{n0}}} + \frac{1}{N_d}\sqrt{\frac{D_p}{\tau_{p0}}} \right)$$

The ideal reverse-saturation current

$$I_s = J_s A = A e n_i^2 \left(\frac{1}{N_a}\sqrt{\frac{D_n}{\tau_{n0}}} + \frac{1}{N_d}\sqrt{\frac{D_p}{\tau_{p0}}} \right)$$

$$= 10^{-4} e \times (1.5 \times 10^{10})^2 \times \frac{1}{4 \times 10^{16}} \left(\sqrt{\frac{25}{10^{-7}}} + \sqrt{\frac{10}{10^{-7}}} \right)$$

$$= 2.326 \times 10^{-15} A$$

(b) The built-in potential across the semiconductor device

$$V_{bi} = \frac{kT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right) = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) = 0.7650 V$$

The depletion width when applied a reverse-biased voltage

$$W = \sqrt{\frac{2\varepsilon_s (V_{bi} + V_R)}{e} \frac{N_a + N_d}{N_a N_d}}$$

The reverse-biased generation current

$$I_{gen} = J_{gen} A = \frac{e n_i W A}{2\tau_0} = \frac{A n_i}{\tau_0}\sqrt{\frac{e\varepsilon_s (V_{bi} + V_R)(N_a + N_d)}{2 N_a N_d}} = 7.336 \times 10^{-11} A$$

(c) The ratio of the generation current to ideal saturation current

$$\frac{I_{gen}}{I_s} = 3.154 \times 10^4$$

7. (i) Since the question description gives the data of mobility μ_n and μ_p, calculate D_n and D_p on our own with the given data

$$D_n = \frac{kT}{e}\mu_n = \mu_n V_t = 142.2 \ cm^2/s$$

$$D_p = \frac{kT}{e}\mu_p = \mu_p V_t = 5.687 \ cm^2/s$$

The ideal reverse-saturation current

$$I_s = J_s A = A e n_i^2 \left(\frac{1}{N_a}\sqrt{\frac{D_n}{\tau_{n0}}} + \frac{1}{N_d}\sqrt{\frac{D_p}{\tau_{p0}}} \right) = 1.501 \times 10^{-22} A$$

The ideal diode current

$$I_D = -I_S\left(\exp\left(\frac{eV_a}{kT}\right) - 1\right) = 1.501\times10^{-22}\,A$$

(ii) $I_D = I_S\left(\exp\left(\frac{eV_a}{kT}\right) - 1\right) = 1.802\times10^{-12}\,A$

(iii) $I_D = I_S\left(\exp\left(\frac{eV_a}{kT}\right) - 1\right) = 4.128\times10^{-9}\,A$

(iv) $I_D = I_S\left(\exp\left(\frac{eV_a}{kT}\right) - 1\right) = 9.452\times10^{-6}\,A$

If we use $D_n = 205\,cm^2/s$, $D_p = 9.8\,cm^2/s$ compare with our previous results.

$I_S = 1.830\times10^{-22}\,A$.

(i) $I_D = 1.830\times10^{-22}\,A$ (ii) $I_D = 2.198\times10^{-12}\,A$

(iii) $I_D = 5.033\times10^{-9}\,A$ (iv) $I_D = 1.153\times10^{-5}\,A$

8. Using Einstein relation, $D_n = \frac{kT}{e}\mu_n = 90.48\ cm^2/s$

$D_p = \frac{kT}{e}\mu_p = 5.687\ cm^2/s$

$$I_S = A e n_i^2\left(\frac{1}{N_a}\sqrt{\frac{D_p}{\tau_{p0}}} + \frac{1}{N_d}\sqrt{\frac{D_n}{\tau_{n0}}}\right) = 3.088\times10^{-21}\,A$$

$$I = I_S\left(\exp\left(\frac{eV_D}{kT}\right) - 1\right)$$

$$I_{rec} = \frac{e n_i W A}{2\tau_0} e^{\frac{V_a}{2V_t}} = \frac{e n_i A}{2\tau_0} e^{\frac{V_a}{2V_t}}\sqrt{\frac{2\varepsilon_s(V_{bi}-V_a)}{e}\frac{N_a+N_d}{N_a N_d}}$$ where $V_{bi} = \frac{kT}{e}\ln\frac{N_a N_d}{n_i^2} = 1.279\,V$

$I_{net} = I + I_{rec}$

$= 3.088\times10^{-21}(\exp(38.68V_D) - 1) + 1.228\times10^{-12}\exp(19.34V_D)\sqrt{1.279 - V_D}$

for an ideal diode $I = 3.088\times10^{-21}(e^{38.68V_D} - 1)$

Graphs see <u>attached pages</u>.