ELECTRONIC DEVICES
ASSIGNMENT 7

AAKASH JOG
ID : 989323563

Exercise 1.
Consider a silicon P$^+$N step junction diode, maintained at $T = 300\,\mathrm{K}$, with $N_D = 5 \times 10^{16}$. Assume that it is a long diode, with

$$\begin{aligned}\tau_n &= 100\mathrm{ns}\\ \tau_p &= 50\mathrm{ns}\\ D_n &= 50\mathrm{cm}^2\,\mathrm{s}^{-1}\\ D_p &= 20\mathrm{cm}^2\,\mathrm{s}^{-1}\end{aligned}$$

A forward bias of $0.6\,\mathrm{V}$ is applied to the diode.

(1) Calculate the hole diffusion current density 2µm away from the edge of the depletion region on the N-type side of the diode.
(2) If the doping on the P$^+$-type side is doubled, what effect will it have on the above?

Solution 1.
(1) As the diode is a P$^+$N step junction diode,

$$\begin{aligned}
J_{\text{diffusion}_p}(x = 2\mu\mathrm{m}) &= q\left(\frac{D_p}{L_p}p_{N0}\right)\left(e^{\frac{qV_a}{kT}} - 1\right)\left(e^{-\frac{x}{L_p}}\right)\\
&= q\left(\frac{D_p}{\sqrt{D_p\tau_p}}\frac{{n_i}^2}{N_D}\right)\left(e^{\frac{qV_a}{kT}} - 1\right)\left(e^{-\frac{x}{\sqrt{D_p\tau_p}}}\right)\\
&= q\left(\frac{\sqrt{D_p}}{\sqrt{\tau_p}}\frac{{n_i}^2}{N_D}\right)\left(e^{\frac{qV_a}{kT}} - 1\right)\left(e^{-\frac{x}{\sqrt{D_p\tau_p}}}\right)\\
&= \left(1.6 \times 10^{-19}\right)\left(\frac{\sqrt{20}}{\sqrt{50 \times 10^{-9}}}\frac{10^{20}}{10^{16}}\right)\left(e^{\frac{0.6}{0.026}}\right)\left(e^{-\frac{2\times 10^{-4}}{\sqrt{(20)\left(50\times 10^{-9}\right)}}}\right)\\
&= \left(1.6 \times 10^{-19}\right)\left(\frac{\sqrt{2}}{\sqrt{5}}10^{13}\right)\left(e^{23.076923077}\right)\left(e^{-0.2}\right)\\
&= \left(1.6 \times 10^{-19}\right)\left(0.632455532 \times 10^{13}\right)\left(e^{23.056923077}\right)\\
&= (1.0119288512)e^{23.056923077} \times 10^{-6}\mathrm{A\,cm}^{-2}
\end{aligned}$$

(2) As hole diffusion current density is independent of N_A, it is unchanged if the doping on the P$^+$-type side is doubled.

Date: Thursday 5$^{\text{th}}$ May, 2016.

Exercise 2.
Consider a silicon PN step junction diode, maintained at $T = 300\,\mathrm{K}$, with

$$
\begin{aligned}
N_A &= 5 \times 10^{16}\mathrm{cm}^{-3} \\
N_D &= 10^{16}\mathrm{cm}^{-3} \\
\tau_n &= 0.5\mathrm{\mu s} \\
\tau_p &= 0.2\mathrm{\mu s} \\
D_n &= 25\mathrm{cm}^2\,\mathrm{s}^{-1} \\
D_p &= 10\mathrm{cm}^2\,\mathrm{s}^{-1}
\end{aligned}
$$

and cross-sectional area of $10^{-3}\mathrm{cm}^2$.
A forward bias of $0.625\,\mathrm{V}$ is applied on the diode.

(1) Calculate the minority electron diffusion current at the edge of the depletion region.
(2) Calculate the minority hole diffusion current at the edge of the depletion region.
(3) Calculate the electron and hole currents at
  (a) $x = x_n$
  (b) $x = x_n + L_p$
  (c) $x = x_n + 10L_p$

Solution 2.
(1)

$$
\begin{aligned}
J_{\mathrm{diffusion}_n}(x=0) &= q\left(\frac{D_n}{L_n}n_{P0}\right)\left(e^{\frac{qV_a}{kT}}-1\right) \\
&= q\left(\frac{D_n}{\sqrt{D_n\tau_n}}n_{P0}\right)\left(e^{\frac{qV_a}{kT}}-1\right) \\
&= q\left(\frac{\sqrt{D_n}}{\sqrt{\tau_n}}\frac{{n_i}^2}{N_A}\right)\left(e^{\frac{qV_a}{kT}}-1\right) \\
&= \left(1.6\times10^{-19}\right)\left(\frac{\sqrt{25}}{\sqrt{0.5\times10^{-6}}}\frac{10^{20}}{5\times10^{16}}\right)\left(e^{\frac{0.625}{0.026}}\right) \\
&= \left(1.6\times10^{-19}\right)\left(1.4142135623\times10^{7}\right)e^{24.038461538} \\
&= 2.2627416997e^{24.038461538}\times10^{-12}\mathrm{A\,cm^{-2}}
\end{aligned}
$$

Therefore,

$$
\begin{aligned}
I_{\mathrm{diffusion}_n}(x=0) &= J_{\mathrm{diffusion}_n}\times10^{-3} \\
&= 2.2627416997e^{24.038461538}\times10^{-15}\mathrm{A}
\end{aligned}
$$

(2)

$$
\begin{aligned}
J_{\text{diffusion}_p}(x=0) &= q\left(\frac{D_p}{L_p}p_{N0}\right)\left(e^{\frac{qV_a}{kT}}-1\right) \\
&= q\left(\frac{D_p}{\sqrt{D_p\tau_p}}p_{N0}\right)\left(e^{\frac{qV_a}{kT}}-1\right) \\
&= q\left(\frac{\sqrt{D_p}}{\sqrt{\tau_p}}\frac{{n_i}^2}{N_D}\right)\left(e^{\frac{qV_a}{kT}}-1\right) \\
&= \left(1.6\times10^{-19}\right)\left(\frac{\sqrt{10}}{\sqrt{0.2\times10^{-6}}}\frac{10^{20}}{10^{16}}\right)\left(e^{\frac{0.625}{0.026}}\right) \\
&= \left(1.6\times10^{-19}\right)\left(\sqrt{50}\times10^{7}\right)e^{24.038461538} \\
&= \left(1.6\times10^{-19}\right)\left(7.071067812\times10^{7}\right)e^{24.038461538} \\
&= 11.313708499e^{24.038461538}\times10^{-12}\,\mathrm{A\,cm^{-2}}
\end{aligned}
$$

Therefore,

$$
\begin{aligned}
I_{\text{diffusion}_p}(x=0) &= J_{\text{diffusion}_n}\times10^{-3} \\
&= 11.313708499e^{24.038461538}\times10^{-15}\,\mathrm{A}
\end{aligned}
$$

(3) (a)

$$
\begin{aligned}
I_p(x=x_n) &= I_{\text{diffusion}_p}(x=0) \\
&= 11.313708499e^{24.038461538}\times10^{-15}\,\mathrm{A}
\end{aligned}
$$

Therefore,

$$
\begin{aligned}
I_n(x=x_n) &= I_{\text{total}} - I_p(x=x_n) \\
&= I_{\text{total}} - I_{\text{diffusion}_p}(x=0) \\
&= I_{\text{diffusion}_n}(x=0) + I_{\text{diffusion}_p}(x=0) - I_{\text{diffusion}_p}(x=0) \\
&= I_{\text{diffusion}_p}(x=0) \\
&= 2.2627416997e^{24.038461538}\times10^{-15}\,\mathrm{A}
\end{aligned}
$$

(b)

$$
\begin{aligned}
I_p(x=x_n+L_p) &= I_{\text{diffusion}_p}(x=L_p) \\
&= 11.313708499e^{24.038461538}e^{-\frac{x}{L_p}}\times10^{-15} \\
&= 11.313708499e^{24.038461538}e^{-\frac{L_p}{L_p}}\times10^{-15} \\
&= 11.313708499e^{23.038461538}\times10^{-15}\,\mathrm{A}
\end{aligned}
$$

Therefore,

$$
\begin{aligned}
I_n(x=x_n+L_p) &= I_{\text{total}} - I_p(x=x_n+L_p) \\
&= I_{\text{total}} - I_{\text{diffusion}_p}(x=L_p) \\
&= I_{\text{diffusion}_n}(x=0) + I_{\text{diffusion}_p}(x=0) - I_{\text{diffusion}_p}(x=L_p) \quad = I_{\text{diffusion}_n}(x=0) + I_{\text{di}}
\end{aligned}
$$

(c)

$$\begin{aligned}
I_p(x = x_n + 10L_p) &= I_{\text{diffusion}_p}(x = 10L_p) \\
&= 11.313708499e^{24.038461538}e^{-\frac{x}{L_p}} \times 10^{-15} \\
&= 11.313708499e^{24.038461538}e^{-\frac{10L_p}{L_p}} \times 10^{-15} \\
&= 11.313708499e^{14.038461538} \times 10^{-15}\text{A}
\end{aligned}$$

Therefore,

$$\begin{aligned}
I_n(x = x_n + 10L_p) &= I_{\text{total}} - I_p(x = x_n + 10L_p) \\
&= I_{\text{total}} - I_{\text{diffusion}_p}(x = 10L_p) \\
&= I_{\text{diffusion}_n}(x = 0) + I_{\text{diffusion}_p}(x = 0) - I_{\text{diffusion}_p}(x = 10L_p) \\
&= I_{\text{diffusion}_n}(x = 0) + I_{\text{diffusion}_p}(x = 0) - 11.313708499e^{14.038461538} \times 10^{-15}\text{A}
\end{aligned}$$

Exercise 3.
Consider a silicon PN step junction diode with a cross-sectional area of 100µm^2 with

$$\begin{aligned}
N_A &= 10^{17}\text{cm}^{-3} \\
N_D &= 10^{17}\text{cm}^{-3} \\
\tau_n &= 10^{-6}\,\text{s} \\
\tau_p &= 10^{-7}\,\text{s} \\
T &= 300\,\text{K} \\
\mu_n &= 1350\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1} \\
\mu_n &= 480\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}
\end{aligned}$$

(1) For an applied voltage of 0.5 V, sketch the minority and majority carrier concentrations as a function of x.
(2) Calculate the minority carrier diffusion lengths L_n and L_p.
(3) What are the excess minority carrier charge stored within the quasi-neutral regions? Set up the integral and calculate.
(4) Calculate the diode current using the charge control model. Is it dominated by hole injection into the N-type side or by electron injection into the P-type side?

Solution 3.
(1)

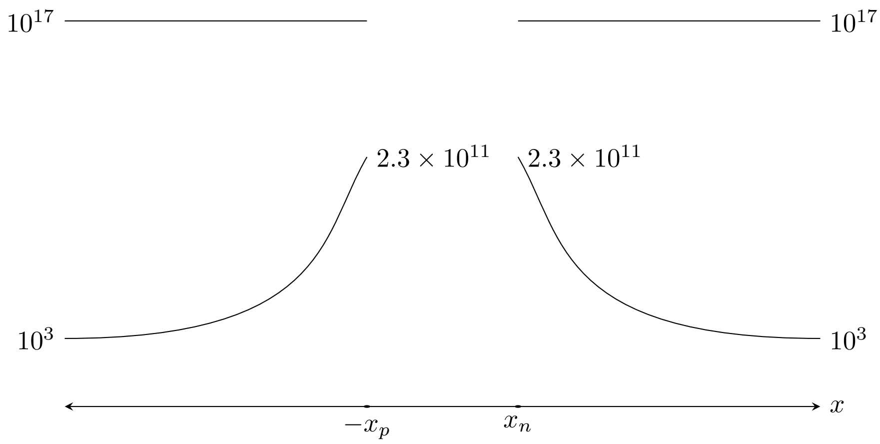
$$\begin{aligned}
p_{N0} &= \frac{{n_i}^2}{N_D} \\
&= \frac{10^{20}}{10^{17}} \\
&= 10^3\text{cm}^{-3}
\end{aligned}$$

$$\begin{aligned}
n_{P0} &= \frac{{n_i}^2}{N_A} \\
&= \frac{10^{20}}{10^{17}} \\
&= 10^3\text{cm}^{-3}
\end{aligned}$$

Therefore,

$$
\begin{aligned}
p_N &= p_{N0} e^{\frac{qV_a}{kT}} \\
&= 10^3 e^{\frac{0.5}{0.026}} \\
&= \left(10^3\right)\left(2.3 \times 10^8\right) \\
&= 2.3 \times 10^{11} \text{cm}^{-3} \\
n_P &= n_{P0} e^{\frac{qV_a}{kT}} \\
&= 10^3 e^{\frac{0.5}{0.026}} \\
&= \left(10^3\right)\left(2.3 \times 10^8\right) \\
&= 2.3 \times 10^{11} \text{cm}^{-3}
\end{aligned}
$$

Therefore, the carrier concentrations are



(2)

$$
\begin{aligned}
L_n &= \sqrt{D_n \tau_n} \\
&= \sqrt{\mu_n \frac{kT}{q} \tau_n} \\
&= \sqrt{(1350)(0.026)\left(10^{-6}\right)} \\
&= \sqrt{3.51 \times 10^{-5}} \\
&= 5.924525297 \times 10^{-3} \text{cm} \\
L_p &= \sqrt{D_p \tau_p} \\
&= \sqrt{\mu_p \frac{kT}{q} \tau_p} \\
&= \sqrt{(480)(0.026)\left(10^{-7}\right)} \\
&= \sqrt{1.248 \times 10^{-6}} \\
&= 1.117139204 \times 10^{-3} \text{cm}
\end{aligned}
$$

(3)

$$
\begin{aligned}
Q_p &= qA \int_0^\infty \hat{p}\, \mathrm{d}x \\
&= qA \int_0^\infty p_{N0} \left(e^{\frac{qV_a}{kT}} - 1\right) e^{-\frac{x}{L_p}}\, \mathrm{d}x \\
&= \left(1.6 \times 10^{-19}\right) \left(100 \times 10^{-8}\right) \int_0^\infty \left(2.3 \times 10^{11}\right) e^{-\frac{x}{L_p}}\, \mathrm{d}x \\
&= 3.96 \times 10^{-17}\mathrm{C} \\
Q_n &= qA \int_0^\infty \hat{n}\, \mathrm{d}x \\
&= qA \int_0^\infty n_{P0} \left(e^{\frac{qV_a}{kT}} - 1\right) e^{-\frac{x}{L_p}}\, \mathrm{d}x \\
&= 21.33 \times 10^{-17}\mathrm{C}
\end{aligned}
$$

(4) As the junction is in steady state,

$$
\begin{aligned}
I_{\text{total}} &= \frac{Q_p}{\tau_p} + \frac{Q_n}{\tau_n} \\
&= \frac{3.96 \times 10^{-17}}{10^{-7}} + \frac{21.33 \times 10^{-17}}{10^{-6}} \\
&= 3.96 \times 10^{-10} + 2.133 \times 10^{-10} \\
&= 6.093 \times 10^{-10}\mathrm{A}
\end{aligned}
$$

The diode current is dominated by hole injection into the N-type side.