A piece of n-type silicon is doped with $N_D = 2 \times 10^{16} cm^{-3}$.

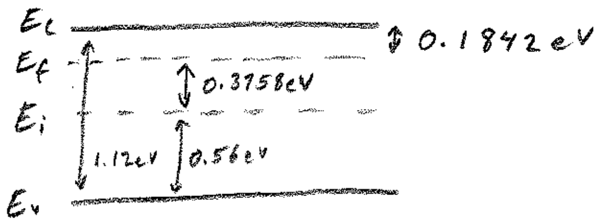
a. What is the probability of finding a hole in the valence band?
b. What is the probability of finding an electron in the valence band?
c. What is the probability of finding an electron 0.1meV above the conduction band?
d. What is the probability of finding a hole in the conduction band?

n-type material, so $n \approx N_D = 2 \times 10^{16} \text{ cm}^{-3}$

First, we must find the Fermi level

$$n = n_i e^{(E_f - E_i)/kT} \rightarrow E_f - E_i = kT \ln\left(\frac{n}{n_i}\right) = (0.0259 eV) \ln\left(\frac{2 \times 10^{16} \text{ cm}^{-3}}{10^{10} \text{ cm}^{-3}}\right) = 0.3758 eV$$

Band Diagram



$$a) \quad 1 - f(E_v) = 1 - \frac{1}{1 + e^{(E_v - E_f)/kT}} = \frac{e^{(E_v - E_f)/kT}}{1 + e^{(E_v - E_f)/kT}} = \frac{1}{e^{-(E_v - E_f)/kT} + 1}$$

$$\therefore 1 - f(E_v) = \frac{1}{1 + e^{(E_f - E_v)/kT}} = \frac{1}{1 + e^{(0.9358)/0.0259)}} = 2.0342 \times 10^{16}$$

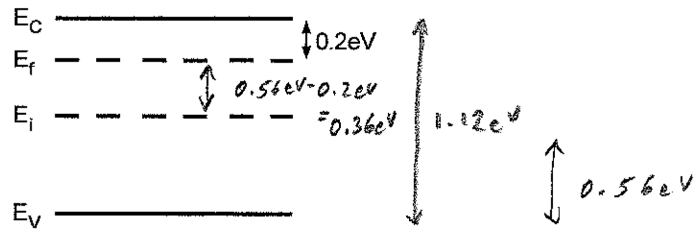
(not zero!)

$$b) \quad f(E_v) = \frac{1}{1 + e^{(E_v - E_f)/kT}} = \frac{1}{1 + e^{(-0.9358 eV)/0.0259 eV}} = 1$$

$$c) \quad f(E_c + 0.1 meV) = \frac{1}{1 + e^{(0.1843 eV)/0.0259 eV}} = 8.1149 \times 10^{-4}$$

$$d) \quad 1 - f(E_c) = \frac{1}{1 + e^{(E_f - E_c)/kT}} = \frac{1}{1 + e^{-0.1842 eV/0.0259 eV}} = 0.9992$$

Use the band diagram for silicon for the following parts of this problem.



a. Is this n-type or p-type material? Why?
b. What is the majority carrier and the majority carrier concentration?
c. What is the minority carrier and the minority carrier concentration?
d. What is the resistivity of this material?

a) n-type because the Fermi level is close to the conduction band (above E_i)

b) Majority carrier → electrons (n-type material)

$$n = n_i e^{(E_f - E_i)/kT}$$

$$n = (10^{10}\,cm^{-3})\, e^{(0.36eV)/(0.0259eV)} = 1.0877 \times 10^{16}\,cm^{-3}$$

c) Minority carrier → holes

$$p = \frac{n_i^2}{n} = \frac{(10^{10}\,cm^{-3})^2}{1.0877\times10^{16}\,cm^{-3}} = 9.1934\times10^{3}\,cm^{-3}$$

d) Resistivity

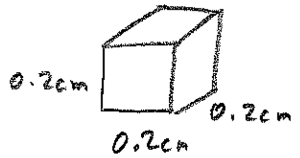
$$\rho = \frac{1}{q(\mu_n n + \mu_p p)} = \frac{1}{(1.602\times10^{-19}C)\left[(1360\,cm^2/Vs)(1.0877\times10^{16}\,cm^{-3}) + (460\,cm^2/Vs)(9.1934\times10^{3}\,cm^{-3})\right]}$$

$$= 0.4220\,\Omega\,cm$$

Also $\rho \approx \dfrac{1}{q\mu_n n} = 0.4220\,\Omega\,cm$

A silicon cube (2mm on each side) has been doped with $N_D = 1\times10^{16}cm^{-3}$ and $N_A = 5\times10^{16}cm^{-3}$.

a. Is this n-type or p-type material? Why?
b. What is the majority carrier and the majority carrier concentration?
c. What is the minority carrier and the minority carrier concentration?
d. Now, assume that a voltage of 5V is placed across two opposing sides if this material. What are the values of the hole current and the electron current?
e. Instead of a voltage across this material, this silicon cube is exposed to light and undergoes photogeneration. Determine the diffusion length of the minority carrier in this material, assuming low-level injection.



a) $N_A > N_D,\ n_i \quad \therefore$ p-type material

b) majority carriers → holes (p-type material)

$$p = \frac{N_A N_D}{2} + \left[\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2\right]^{1/2} =$$

$$= \frac{4\times10^{16}cm^{-3}}{2} + \left[\left(\frac{4\times10^{16}cm^{-3}}{2}\right)^2 + \left(1\times10^{10}cm^{-3}\right)^2\right]^{1/2} = 4\times10^{16}cm^{-3}$$

c) minority carriers → electrons

$$n = \frac{n_i^2}{p} = \frac{(1\times10^{10}cm^{-3})^2}{4\times10^{16}cm^{-3}} = 2500\ cm^{-3}$$

d) 5V place across the silicon

$\therefore$ Electric field → $E = \frac{V}{x} = \frac{5V}{0.2cm} = 25\ V/cm$

no diffusion current because no concentration gradient

$\therefore$ all current is drift current

cross-sectional area = 0.2cm × 0.2cm

$$I_p = J_p A = \mu_p q p E A = (460\ cm^2/Vs)(1.602\times10^{-19}C)(4\times10^{16}cm^{-3})(25\ V/cm)(0.04cm^2)$$

$$= \boxed{2.9477\ A}$$ hole current

$$I_n = J_n A = \mu_n q n E A = (1360\ cm^2/Vs)(1.602\times10^{-19}C)(2500cm^{-3})(25\ V/cm)(0.04\ cm^2) =$$

$$= \boxed{5.4468\times10^{-13}\ A}$$ Electron current

e) $L_n = \sqrt{D_n \tau_n} \longrightarrow L_n = \sqrt{\frac{\mu_n kT}{q}\tau_n} = \sqrt{(1360cm/Vs)(0.0259V)(1\times10^{-4}s)}$

$\frac{D_n}{\mu_n} = \frac{kT}{q} \rightarrow D_n = \frac{\mu_n kT}{q}$

$= 5.9350\times10^{-2}cm$

A silicon p-n junction with a cross sectional area of $10^{-4}cm^2$ has been doped on the p-type side with $N_A = 10^{17}cm^{-3}$ and on the n-type side with $N_D = 3x10^{17}cm^{-3}$.

a. Determine the built-in potential.
b. Determine the equilibrium width of the depletion region.
c. Determine the maximum electric field in the p-n junction in equilibrium.
d. Determine the zero-bias junction capacitance.
e. Determine the junction capacitance if the junction is reverse biased with 3V.

For Parts f-h, a forward bias of 0.1V has been applied to the p-n junction diode.

f. Determine the width of the depletion region under bias.
g. Determine the maximum electric field under bias.
h. Determine the total current that flows under bias.

a) $V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.0259V \ln\left(\frac{(10^{17}cm^{-3})(3\times10^{17}cm^{-3})}{(10^{10}cm^{-3})^2}\right) = 0.8634 V$

b) $W = \left[\frac{2K_s\varepsilon_0}{q} \frac{N_A+N_D}{N_A N_D}\left(V_{bi} - \cancel{V_A}^{0}\right)\right]^{1/2} =$ $\qquad \frac{N_A+N_D}{N_A N_D} = \frac{1}{N_A} + \frac{1}{N_D}$

in cm

$= \left[\frac{(2)(11.8)(8.854\times10^{-14}\,F/cm)}{(1.602\times10^{-19}C)}\left(\frac{1}{10^{17}cm^{-3}} + \frac{1}{3\times10^{17}cm^{-3}}\right)(0.8634V)\right]^{1/2} =$

$= 1.2254\times10^{-5}\,cm = 0.1225\,\mu m$

c) $E_{max} = -\frac{qN_A}{K_s\varepsilon_0}x_p$

$x_p = \left[\frac{2K_s\varepsilon_0}{q}\frac{N_D}{N_A(N_A+N_D)}\left(V_{bi} - \cancel{V_A}^{0}\right)\right]^{1/2} = 9.1903\times10^{-6}\,cm = 0.091903\,\mu m$

$E_{max} = -\frac{qN_A}{K_s\varepsilon_0}x_p = -\frac{(1.602\times10^{-19}C)(10^{17}cm^{-3})}{(11.8)(8.854\times10^{-14}\,F/cm)}(9.1903\times10^{-6}cm) =$

$= -1.4092\times10^{5}\,V/cm$

Alternatively,

$E_{max} = -\frac{2(V_{bi} - \cancel{V_A}^{0})}{W} = \frac{-2V_{bi}}{W} = \frac{(-2)(0.8634V)}{1.2254\times10^{-5}cm} = -1.409\times10^{5}\,V/cm$

d) $$C_{jo} = \sqrt{\frac{q K_s \varepsilon_0 N_A N_D}{2V_{bi}(N_A+N_D)}} =$$

$$= \sqrt{\frac{(1.602\times10^{-19}\,C)(11.8)(8.854\times10^{-14}\,F/cm)(10^{17}\,cm^{-3})(3\times10^{17}\,cm^{-3})}{(2)(0.8634V)(4\times10^{17}\,cm^{-3})}} =$$

$$= 8.5261\times10^{-8}\ F/cm$$

e) $$C_j = \frac{C_{jo}}{\sqrt{1+\frac{V_A}{V_{bi}}}} = \frac{8.5261\ F/cm^2}{\sqrt{1+\frac{3V}{0.8634V}}} = 4.0306\times10^{8}\ F/cm$$

f) Under bias ($V_A = 0.1V$ forward bias)

$$W = \left[\frac{2K_s\varepsilon_0}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_{bi}-V_A)\right]^{1/2} = 1.1522\times10^{-5}\ cm = 0.011522\times10^{-5}\ m$$
$$= 0.11522\ \mu m$$

g) $$E_{max} = \frac{-2(V_{bi}-V_A)}{W} = \frac{(-2)(0.8634V-0.1V)}{1.1522\times10^{-5}\,cm} = -1.3251\times10^{5}\ V/cm$$

h) $$I = qA\left[\underbrace{\frac{D_n}{L_n}\frac{n_i^2}{N_A}}_{\text{min. carriers in p-type side}} + \underbrace{\frac{D_p}{L_p}\frac{n_i^2}{N_D}}_{\text{min. carriers in n-type side}}\right]\left[e^{V_A/nV_T}-1\right]$$

$$\tau_n = \tau_p = 100\mu s\ ,\quad L_n = \sqrt{D_n\tau_n} = \sqrt{\mu_n\frac{kT}{q}\tau_n} = \sqrt{(1360\,cm^2/Vs)(0.0259V)(100\times10^{-6}s)} =$$
$$= 5.9350\times10^{-2}\ cm$$

$$L_p = \sqrt{D_p\tau_p} = \sqrt{\mu_p\frac{kT}{q}\tau_n} = 3.4517\times10^{-2}\ cm$$

$$D_n = \mu_n\frac{kT}{q} = (1360\ cm^2/Vs)(0.0259V) = 35.2240\ cm^2/s$$

$$D_p = \mu_p\frac{kT}{q} = (460\ cm^2/Vs)(0.0259V) = 11.9140\ cm^2/s$$

$$I = (1.602\times10^{-19}C)(10^{-4}\,cm^2)\left[\frac{35.2240\ cm^2/s}{5.9350\times10^{-2}\,cm}\ \frac{(10^{10}\,cm^{-3})^2}{10^{17}\,cm^{-3}} + \frac{11.9140\ cm^2/s}{3.4517\times10^{-2}\,cm}\ \frac{(10^{10}\,cm^{-3})^2}{3\times10^{17}\,cm^{-3}}\right]\times$$

$$\times\left[e^{0.1V/(1)(0.0259V)} - 1\right] = 5.2797\times10^{-16}\ A$$

A silicon p-n junction has been doped on the p-type side with $N_A = 10^{17}cm^{-3}$ and on the n-type side with $N_D = 10^{18}cm^{-3}$. Draw the following to scale. Be sure to label all important points and intercepts (exact values are not needed, but expressions are required).

a. Band diagram in equilibrium.
b. Charge density in equilibrium verses position along the p-n junction.
c. Electric field in equilibrium verses position along the p-n junction.
d. Repeat Parts a-c for a forward biased p-n junction. Emphasize the differences from the equilibrium conditions.
e. Repeat Parts a-c for a reverse biased p-n junction. Emphasize the differences from the equilibrium conditions.

$N_D = 10\, N_A$ $\therefore$ E_f will be very close to E_c on the n-type side

$$|E_f - E_c|\Big|_{\text{n-type side}} < |E_f - E_v|\Big|_{\text{p-type side}}$$

Draw the band diagrams for each side, and then line up the Fermi levels for equilibrium conditions