1) The material is p-type silicon

- \( p = 1.5 \times 10^{16} \text{ cm}^{-3} \)
- \( N_t = 10^{12} \text{ cm}^{-3} \)
- \( E_i - E_F = 0.2 \text{ eV} \)
- \( \sigma_n = 6 \times 10^{-15} \text{ cm}^2 \)
- \( V_{thn} = 1.0 \text{ cm/s} \)
- \( V_{thp} = 6 \times 10^6 \text{ cm/s} \)
- \( T = 300 \text{ K} \)

a) Need to find the carrier conc. during irradiation, i.e., we need to know both the generated conc. and the "baseline" conc.

To find the "baseline", we can use the resistivity to look up the doping level. P.5 in notes: \( N_a = 1.5 \times 10^{16} \text{ cm}^{-3} \)

\( G_L = 10^{18} \text{ cm}^{-3} \text{ s}^{-1} \) can assume low level injection

\[
\tau_n = \frac{1}{V_{thp} \sigma_p N_t} = \frac{1}{(10^7 \text{ cm/s})(10^{-15} \text{ cm}^2)(10^{12} \text{ cm}^{-3})} = 100 \mu \text{s}
\]

\[
G_L = \frac{\Delta N}{\tau_n} \Rightarrow \Delta N = G_L \tau_n = 10^{18} \text{ cm}^{-3} \text{ s} \times 100 \mu \text{s} = 10^{17} \text{ cm}^{-3}
\]

\( \Delta p = \Delta n = 10^{14} \text{ cm}^{-3} \ll N_A \), so the LCI assumption was fine.

\[
\begin{align*}
\Delta n &= n_0 + \Delta n = 10^{14} \text{ cm}^{-3} \\
\Delta p &= p_0 + \Delta p = (1.5 \times 10^{16} + 10^{19}) \text{ cm}^{-3} \approx 1.5 \times 10^{16} \text{ cm}^{-3}
\end{align*}
\]
1. $G_L = 10^{24} \text{ cm}^{-3} \text{s}^{-1}$ → Cannot assume LTE.

Assuming high level injection $\Rightarrow \Delta N = \Delta P > \Delta N_0 \Delta P_0$.

\[
G_L = \frac{(P_0 + \Delta P)(N_0 + \Delta N)}{\tau_n (P_0 + \Delta P + P_1) + \tau_P (N_0 + \Delta N + n_1)}
\]

\[
n_1 = n_i \exp \left( \frac{E_i - E_f}{kT} \right) \quad P_1 = n_i \exp \left( \frac{E_i - E_f}{kT} \right)
\]

\[
\Rightarrow G_L \sim \frac{\Delta P_1^2}{\Delta P (\tau_n + \tau_P)} = \frac{\Delta P}{\tau_n + \tau_P}
\]

\[
\tau_P = \frac{1}{v_{thP} \sigma_P N_0} = 16.7 \mu s
\]

\[
\Rightarrow \Delta P = \Delta N = 0.1 G_L (\tau_n + \tau_P) = (10^{24} \text{ cm}^{-3} \text{s}^{-1})(100 + 16.7) \mu s
\]

\[
= 2.67 \times 10^{20} \text{ cm}^{-3}
\]

\[
\Rightarrow n_{up} \sim \Delta N \sim \Delta P = 2.67 \times 10^{20} \text{ cm}^{-3}
\]

And high level injection assumption was correct.
1 (c) Equation (28) from note becomes

\[ R = \frac{\rho n - n_i^2}{\tau_p (n + n_i) + \tau_n (P + P_i)} \]

\[ n_i = n_i \exp\left( \frac{E_i - E_T}{kT} \right) = (10^{10} \text{ cm}^{-3}) \left( \exp\left( \frac{-0.1}{25 \times 10^{-3}} \right) \right) = 1.8 \times 10^8 \text{ cm}^{-3} \]

\[ P_i = (10^{10} \text{ cm}^{-3}) \left( \exp\left( \frac{+0.1}{25 \times 10^{-3}} \right) \right) = 5.5 \times 10^{11} \text{ cm}^{-3} \]

\[ n \ll n_0 \]

\[ \Rightarrow R = \frac{-n_i^2}{\tau_p n_i + \tau_n (P + P_i)} \]

\[ = \frac{-10^{+20} \text{ cm}^{-6}}{(1.67 \mu s)(1.8 \times 10^8 \text{ cm}^{-3}) + (100 \mu s)(1.5 \times 10^6 \text{ cm}^{-3} + 5.5 \times 10^{11} \text{ cm}^{-3})} \]

\[ = 6.66 \times 10^7 \text{ cm}^{-3} \text{ s}^{-1} \]
2) P-type silicon \( N_d = 10^{17} \text{ cm}^{-3} \)

\[
600\mu \text{m} = 600 \times 10^{-4} \text{ cm} = 0.06 \text{ cm thick}
\]

\[ G_L = 10^{17} \text{ cm}^{-3} \text{ s}^{-1} (\text{uniform}) \]

\( S = \text{recombination velocity @ top and bottom surfaces} = 10^3 \text{ cm} \)

\( T_n = 10 \mu \text{s} \quad T_p = 16 \mu \text{s} \)

a) Given diffusion approximation is true \( \Rightarrow \) ignore minority drift current.

- This is also a hint to use minority carriers to solve for this.

- \( \Delta n = \Delta p \) \( \Rightarrow \) so solving \( \Delta n \) would give \( \Delta p \), assuming this is low level injection, at steady state, using equation (36)

\[
D_n \frac{\partial^2 \Delta n}{\partial x^2} - \frac{\Delta n}{T_n} + G_L = 0
\]

\( \Delta x \) Diffusion \( \Delta n \) Recomb. \( G_L \) Generation (No drift term)

\[
\Rightarrow \frac{\partial^2 \Delta n}{\partial x^2} - \frac{\Delta n}{D_n T_n} + \frac{G_L}{D_n} = 0
\]
Let \( \Delta n = Ae^{\frac{x}{\ln}} + Be^{-\frac{x}{\ln}} \) (General Solution)

where \( \ln = \sqrt{Dn \tau_n} \) \( \Rightarrow \frac{d\Delta n}{dx} = \frac{A}{\ln} e^{\frac{x}{\ln}} - \frac{B}{\ln} e^{-\frac{x}{\ln}} \)

we need some boundary conditions for \( A \) and \( B \).

using flux at \( x=0 \) (or also the flux at \( x=L/2 \) which is zero)

\[
Dn \frac{d\Delta n}{dx} \bigg|_{x=0} = \frac{Dn}{\ln} (A-B) = S \left( G_n \ln + \frac{S}{\ln} \right)
\]
(Diffusion current)

\( (\text{General Solution}) \Rightarrow \left. \frac{d\Delta n}{dx} \right|_{x=0} = S \left( G_n \ln + A + B \right) \tag{1}
\)

using flux at \( x=L/2 \)

\[
-Dn \frac{d\Delta n}{dx} \bigg|_{x=L/2} = -\frac{Dn}{\ln} \left( A e^{\frac{L/2}{\ln}} - B e^{-\frac{L}{\ln}} \right) = S \left( G_n \ln + Ae^{\frac{L/2}{\ln}} + B e^{-\frac{L}{\ln}} \right) \tag{2}
\]

we have two equations and two unknowns.

\[
\begin{align*}
A &= -5.7 \times 10^{10} \text{ cm}^{-3} \\
B &= -4.1 \times 10^{12} \text{ cm}^{-3}
\end{align*}
\]

\[
Na = 10^{17} \text{ cm}^{-3} \Rightarrow \\
\left( \text{Area} = 800 \text{ cm}^2 \Rightarrow D = 20 \text{ cm}^2 \right) \\
\Rightarrow \ln = 0.041 \text{ cm}.
\]

Particular Solution: \( \Delta n = C \) and Substituting gives:

\[
C = G_n \ln = 10^{13} \text{ cm}^{-3}
\]
So, overall:

\[ \Delta n(x) = \left[10^{18} - 5.7 \times 10^6 \times e^{10} \left( \frac{x}{\ln} \right)^{-4.1} \times 10^{-2} e^{\frac{12}{2} \left( \frac{-x}{\ln} \right)} \right] \text{cm}^{-3} \]

\[ \Delta n = \Delta p \]

2-b) \( \Delta n(0) = 5.9 \times 10^{12} \text{ cm}^{-3} \)

For electrons:

\[ n = n_0 + \Delta n = \frac{n_i^2}{n_0} + \Delta n = (0 + 5.9 \times 10^{12}) \text{ cm}^{-3} \]

\[ \Rightarrow n = 5.9 \times 10^{12} \text{ cm}^{-3} \]

For holes:

\( P_0 = 10^{17} \text{ cm}^{-3} \)

Top surface recomb. carriers

\[ \times 100\% = \frac{\frac{3}{(10^8 \text{ cm}^{-3})(600 \text{um})}}{\frac{5.9 \times 10^9 \text{ cm}^{-2}}{5}} \times 100 = 9.8\% \]

(And because of symmetry this ratio is the same at the bottom)
2. c) \( J_n = J_p \Rightarrow J_n(\text{drift}) + J_n(\text{diff}) = J_p(\text{drift}) + J_p(\text{diff}) \)

\[ J_n(\text{diff}) = q D_n \frac{\partial n}{\partial x} = q \frac{D_n}{L_n} \left( \frac{x}{L_n} - \frac{1}{e} \right) \]

@ \( x = 0 \)

\[ J_n(\text{diff}) = q \frac{D_n}{L_n} (A - B) = q \frac{D_n}{L_n} \times 4.44 \times 10^{12} \]

\[ J_p(\text{diff}) = -q \frac{D_p}{L_n} (A - B) = -q \frac{D_p}{L_n} \times 4.1 \times 10^{12} \]

\[ J_p(\text{drift}) = q \mu_p \varepsilon = q \times 10^{-17} \text{ cm}^{-3} \times 250 \text{ cm}^2 V s^{-1} x \varepsilon \]

\[ \frac{Q \cdot D_n}{L_n} \times 4.1 \times 10^{12} = 25 \times 10^{-18} \varepsilon \]

\[ \frac{26.25 \times 4.1 \times 10^{12}}{0.014} = 25 \times 10^{-18} \varepsilon \]

\[ \varepsilon = 3.1 \times 10^{-4} \text{ V/cm} \]

\[ \Rightarrow J_n(\text{drift}) = q \mu_n \varepsilon = q \times 800 \text{ cm}^2 V s^{-1} \times 8.1 \times 10^{-12} \text{ cm}^3 \]

\[ = q \times 2.46 \times 10^{-11} \text{ cm}^{-2} S \ll J_n(\text{diffusion}) \Rightarrow \text{Diffusion Approx. is Valid} \]
3. $N_d = 10^{17} \text{cm}^{-3}$, $k_{Sl}/\varepsilon_{Si} = 11.7$, metal: Al: $\Phi_{p_m} = 4.1 \text{eV}$
$Si_s$, $\Phi_{p_s} = 4.05 \text{eV}$

a) Ignoring Surface States, need to find $\Phi_s$:

$E_0$ ↓ $\Phi_{p_m}$ $\Phi_{p_s}$
$E_f$ $\Phi_{x_s}$ $E_c$ (n-type, close to $E_v$)

We only need to consider majority carriers in metal-

-Semiconductor contacts.

$\Phi_s \Rightarrow$ need to find $E_f$ location:

$E_f = E_C - kT \ln \left( \frac{N_C}{N_d} \right) = E_C - 0.05 \text{meV} \ln \left( \frac{2.8 \times 10^{19}}{10^{17}} \right)$

$= E_C - 0.191 \text{eV}$

From the diagram, we can see that

$\Phi_{p_s} = \Phi_{x_s} + E_C - E_f = 4.05 \text{eV} + 0.191 \text{eV} = 4.241 \text{eV}$

Once in contact,

$E_0$ ↓ $\Phi_{p_m}$ $\Phi_{p_B}$ $\Phi_{p_s}$
$E_f$ $\Phi_{x_s}$ $E_C$ $E_f$ $E_v$
\( \eta^\text{m} = \eta^\text{m} - \eta^\text{S} = 0.05 \text{eV} \) defined as the barrier for majority carriers from metal to semiconductor.

\( \eta^\text{fi} = \eta^\text{m} - (E_C - E_F) = 0.05 \text{eV} - 0.191 \text{eV} = -0.091 \text{eV} \) barrier for majority carriers from semiconductor to metal.

The contact is OHMIC. The barrier is small @ 0.05eV.

Given that \( n \propto \exp \left( -\frac{\eta^\text{fi}}{kT} \right) \Rightarrow \)

we have charge accumulation.

Metal has a large amount of carriers and the surface is accumulated \( \Rightarrow \) lots of them would easily go through.

3.6) This time, very large number of surface states @ 0.4eV above Fermi. Surface states are effectively "trap level". In large number, they "pin" the Fermi level to the trap level.
The band diagram is modified.

\[ E_G - 0.4 \text{ eV} = (1.12 - 0.4) \text{ eV} = 0.72 \text{ eV} \]

\[ \varphi_i = E_G - (E_C - E_F) = (0.12 - 0.141) \text{ eV} = 0.579 \text{ eV} \]

It is rectifying because there is a barrier for electrons in metal to get in the semiconductor.

We can also check if tunneling can happen:

Metal - Semiconductor

Junction

\[ \varphi_i = \frac{1}{2} x_d \left| E_{max} \right| = \frac{q N_d}{2} x_d \frac{q N_d}{k T} \]

\[ x_d = \sqrt{\frac{2 k T \varphi_i}{q N_d}} = 86.6 \text{ nm} \]

\[ x_d \gg 50 \text{ Å} \Rightarrow \text{tunneling would not happen.} \]

\[ \Rightarrow \text{The contact is rectifying} \]
3-c) 0.2V bias applied to both cases (on the semiconductor relative to metal).

(i) case 1 → no depletion region → voltage dropped across semiconductor → bias on semiconductor is higher \( \varepsilon \) potential.

(ii) case 2, barrier height increases voltage drop across \( X_d \).