HW – 4

Problem 5.2 An abrupt GaAs p-n diode has $N_a = 10^{17}$ cm^{-3} and $N_d = 10^{15}$ cm^{-3}.
(a) Calculate the Fermi level positions at 300K in the p and n regions.
(b)Draw the equilibrium band diagram and determine the contact potential V_{bi}.

Solution
We will use the Boltzmann approximation to solve this problem. The Fermi level in the p-side region is given by the equation,

$$E_{Fp} = E_v - k_B T \; \ell n \left(\frac{p}{N_v}\right)$$

where N_v is the valence band effective density. Using $N_v = 7.72 \times 10^{18}$ cm^{-3}, we get

$$E_{Fp} = E_v - (0.026) \; \ell n \left(\frac{10^{17}}{7.72 \times 10^{18}}\right) = E_v + 0.113 \text{ eV}$$

The Fermi level in the n-type region is given by

$$E_{Fn} = E_c + (k_B T) \; \ell n \left(\frac{n}{N_c}\right)$$

Using $N_c = 4.45 \times 10^{17}$ cm^{-3}, we get

$$E_{Fn} = E_c - 0.159 \text{ eV}$$

The built-in voltage can be obtained from these results by the simple equation

$$\begin{aligned} eV_{bi} &= (E_c - 0.159) - (E_v + 0.113) = E_g - 0.159 - 0.113 \\ &= 1.43 - 0.272 \text{ eV} = 1.158 \text{ eV} \end{aligned}$$

Thus $V_{bi} = 1.158$ volt.

Let us calculate V_{bi} using the relation,

$$V_{bi} = \frac{k_B T}{e} \; \ell n \left(\frac{n_n}{n_p}\right)$$

For GaAs the np product is 3.24×10^{12} cm^{-6} so that

$$\begin{aligned} n_p &= \frac{3.24 \times 10^{12}}{p_p} = \frac{3.24 \times 10^{12}}{10^{17}} = 3.24 \times 10^{-5} \text{ cm}^{-3} \\ V_{bi} &= (0.026 \text{ V}) \; \ell n \left(\frac{10^{15}}{3.24 \times 10^{-5}}\right) \\ &= 1.167 \text{ volt} \end{aligned}$$

The two results are quite close to each other and the differences arise from the round off errors made in obtaining the various quantities.

Problem 5.3 Consider an Si p-n diode doped at $N_a = 10^{17}$ cm^{-3}; $N_d = 5 \times 10^{17}$ cm^{-3} at 300 K. Plot the band profile in the neutral and depletion region. Also, plot the electron and hole concentration from the p- to the n-sides of equilibrium. How good is the depletion approximation?

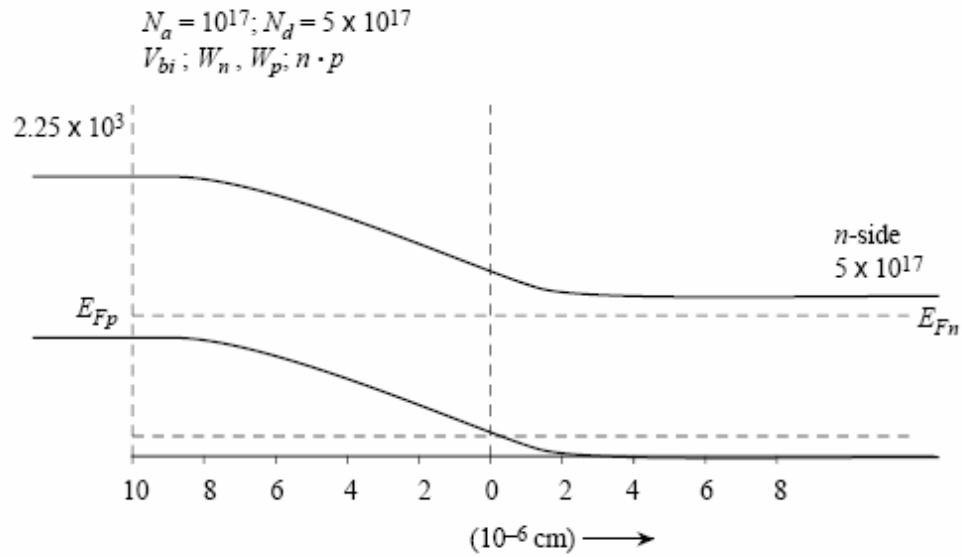

Figure 5.1:

Solution

To solve this problem we need to calculate the built-in voltage and the depletion widths on the n-side and p-side.

$$n_p = \frac{n_i^2}{p_p} = \frac{(2.25 \times 10^{20}\ \text{cm}^{-6})}{10^{17}\ \text{cm}^{-3}} = 2.25 \times 10^3\ \text{cm}^{-3}$$

$$p_n = \frac{n_i^2}{n_n} = \frac{(2.25 \times 10^{20}\ \text{cm}^{-6})}{(5 \times 10^{17}\ \text{cm}^{-3})} = 450\ \text{cm}^{-3}$$

The built-in potential is

$$V_{bi} = 0.026\ \ell n \left(\frac{10^{17}}{450}\right) = 0.86\ \text{V}$$

$$W_p(V_{bi}) = \left\{ \frac{2\,(11.9 \times 8.85 \times 10^{-14}\ \text{F/cm})\,(0.86\ \text{V})}{(1.6 \times 10^{-19}\ \text{C})} \left[\frac{5 \times 10^{17}\ \text{cm}^{-3}}{(10^{17}\ \text{cm}^{-3})\,(6 \times 10^{17}\ \text{cm}^{-3})}\right] \right\}^{1/2} = 9.71 \times 10^{-6}\ \text{cm}$$

$$W_n(V_{bi}) = 1.94 \times 10^{-6}\ \text{cm}$$

The band profile is plotted in Figure 5.1.

Problem 5.5 An abrupt silicon p-n diode at 300 K has a doping of $N_a = 10^{18}$ cm^{-3}, $N_d = 10^{15}$ cm^{-3}. Calculate the built-in potential and the depletion widths in the n and p regions.

Solution

We assume that we can use the Boltzmann approximation on which the equations in the text are based. We have

$$\begin{aligned}
V_{bi} &= \frac{k_B T}{e}\, \ell n\, \frac{n_n}{n_p} \\
n_p &= \frac{n_i^2}{p_p} = \frac{(2.25 \times 10^{20}\ \text{cm}^{-6})}{(10^{18}\ \text{cm}^{-3})} = 2.25 \times 10^2\ \text{cm}^{-3} \\
V_{bi} &= (0.026\ \text{volt})\ \ell n\ \left(\frac{10^{15}}{2.25 \times 10^2}\right) \\
&= 0.757\ \text{volt}
\end{aligned}$$

The p-side depletion width is

$$\begin{aligned}
W_p(V_{bi}) &= \left\{\frac{2(11.9 \times 8.85 \times 10^{-14}\ \text{F/cm})(0.757\ V)}{(1.6 \times 10^{-19}\ \text{C})}\right. \\
&\qquad \left.\left[\frac{10^{15}\ \text{cm}^{-3}}{(10^{18}\ \text{cm}^{-3})(10^{18} + 10^{15}\ \text{cm}^{-3})}\right]\right\}^{1/2} \\
&= 9.89 \times 10^{-8}\ \text{cm} = 9.89\ \text{Å}! \\
W_n(V_{bi}) &= W_p(V_{bi}) \times \frac{N_a}{N_d} = 9.89 \times 10^{-5}\ \text{cm} \\
&\qquad = 0.989\ \mu\text{m}
\end{aligned}$$

Essentially all the depletion is on the lightly doped n-side.

Problem 5.8 The diode of Problem 5.3 is subjected to bias values of: (a) $V_f = 0.1$ V; (b) $V_f = 0.5$ V; (c) $V_r = 1.0$V; (d) $V_r = 5.0$ V. Calculate the depletion widths and the maximum field F_m under these biases.

Solution

The built-in voltage is given by (see the solution of Problem 5.3),

$$V_{bi} = 1.158\ \text{volt}$$

The depletion widths and the maximum electric field values are:

$$\begin{aligned}
V_f &= 0.1\ \text{V} \\
W_p(V_{bi} - 0.1\ \text{V}) &= \left\{\frac{2 \times (13.18 \times 8.85 \times 10^{-14}\ \text{F/cm})(1.058\ V)}{(1.6 \times 10^{-19}\ \text{C})}\right. \\
&\qquad \left.\left[\frac{10^{15}\ \text{cm}^{-3}}{10^{17}(10^{15} + 10^{17})\ \text{cm}^{-6}}\right]\right\}^{1/2} \\
&= 123.3\ \text{Å} \\
W_n &= 1.233 \times 10^{-4}\ \text{cm} \\
F_m &= \frac{(1.6 \times 10^{-19}\ \text{C})(10^{15}\ \text{cm}^{-3})(1.233 \times 10^{-4}\ \text{cm})}{(13.18 \times 8.85 \times 10^{-14}\ \text{F/cm})} \\
&= 1.69 \times 10^4\ \text{V/cm} \\
V_f &= 0.5\ \text{V}
\end{aligned}$$

$$
\begin{aligned}
W_p(V_{bi} - 0.5 \text{ V}) &= W_p(0.658\ V) = W_p(V_f = 0.1 \text{ V}) \left(\frac{0.658}{1.058}\right)^{1/2} \\
&= 97.2 \text{ Å} \\
W_n(V_{bi} - 0.5 \text{ V}) &= 0.972 \times 10^{-4} \text{ cm} \\
F_m(V_f - 0.5 \text{ V}) &= F_m(V_f = 0.1 \text{ V}) \left(\frac{97.2}{123.3}\right) \\
&= 1.33 \times 10^4 \text{ V/cm} \\
V_r &= 1.0 \text{ V} \\
W_P(V_{bi} + 1.0 \text{ V}) &= W_p(V_f = 0.1 \text{ V}) \left(\frac{2.158}{1.058}\right)^{1/2} \\
&= 176.09 \text{ Å} \\
W_n(V_{bi} + 1.0 \text{ V}) &= 1.76 \times 10^{-4} \text{ cm} \\
F_m(V_{bi} + 1.0 \text{ V}) &= F_m(V_f = 0.1 \text{ V}) \left(\frac{176.09}{123.3}\right) \\
&= 2.41 \times 10^4 V/cm \\
V_r &= 5.0 \text{ V} \\
W_p(V_{bi} + 50 \text{ V}) &= W_p(V_f = 0.1 \text{ V}) \left(\frac{6.158}{1.058}\right)^{1/2} \\
&= 297.5 \text{ Å} \\
W_n(V_{bi} + 5.0 \text{ V}) &= 2.975 \times 10^{-4} \text{ cm} \\
F_m(V_{bi} + 5.0 \text{ V}) &= F_m(V_f = 0.1 \text{ V}) \left(\frac{297.5}{123.3}\right) \\
&= 4.08 \times 10^4 \text{ V/cm}
\end{aligned}
$$

Problem 5.10 Consider a p^+n silicon diode with area 10^{-4} cm^2. The doping is given by $N_a = 10^{18}$ cm^{-3} and $N_d = 10^{17}$ cm^{-3}. Plot the 300 K values of the electron and hole currents I_n and I_p at a forward bias of 0.8 V. Assume $\tau_n = \tau_p = 1$ μs and neglect recombination effects. $D_n = 20$ cm^2/s and $D_p = 10$ cm^2/s.

Solution

To calculate the electron and hole currents we first calculate the values of n_p, p_n and L_n and L_p.

$$
\begin{aligned}
n_p &= \frac{n_i^2}{p_p} = \frac{(2.25 \times 10^{20} \text{ cm}^{-6})}{(10^{18} \text{ cm}^{-3})} = 2.25 \times 10^2 \text{ cm}^{-3} \\
p_n &= \frac{n_i^2}{n_n} = \frac{(2.25 \times 10^{20} cm^{-6})}{(10^{17} \text{ cm}^{-3})} = 2.25 \times 10^3 \text{ cm}^{-3} \\
L_n &= (D_n \tau_n)^{1/2} = \left[(20 \text{ cm}^2/\text{ s})(10^{-6} \text{ s})\right]^{1/2} = 4.47 \times 10^{-3} \text{ cm} \\
L_p &= (D_p \tau_p)^{1/2} = \left[(10 \text{ cm}^2/\text{ s})(10^{-6} \text{ s})\right]^{1/2} = 3.16 \times 10^{-3} \text{ cm}
\end{aligned}
$$

The hole current injected at the depletion edge into the n-side is

$$
\begin{aligned}
I_p(W_n) &= \frac{(1.6 \times 10^{-19} \text{ C})(10^{-4} \text{ cm}^2)(10 \text{ cm}^2/\text{s})(2.25 \times 10^3 \text{ cm}^{-3})}{(3.16 \times 10^{-3} \text{ cm})} \left[\exp\left(\frac{0.4}{0.026}\right) - 1\right] \\
&= 5.47 \times 10^{10} \text{ A}
\end{aligned}
$$

The electron current injected at the depletion edge into the p-side is,

$$
\begin{aligned}
I_n(-W_p) &= \frac{(1.6\times10^{-19}\ \mathrm{C})(10^{-4}\ \mathrm{cm}^2)(20\ \mathrm{cm}^2/\mathrm{s})(2.25\times10^{2}\ \mathrm{cm}^{-3})}{(4.47\times10^{-3}\ \mathrm{cm})}\left[\exp\left(\frac{0.4}{0.026}\right)-1\right] \\
&= 7.74\times10^{-11}\ \mathrm{A}
\end{aligned}
$$

Both these currents decrease exponentially into the n-side and p-side region. To find their exact dependence in space, we need to calculate the depletion region edges W_n and W_p for the diode forward biased at 0.4 V. The built-in voltage is

$$
V_{bi} = k_B T\ \ell n\ \frac{n_n}{n_p} = (0.026)\ \ell n\ \left(\frac{10^{17}}{2.25\times10^{2}}\right)
$$

$$
\begin{aligned}
&= 0.877V \\
W_n(V_f = 0.4V) &= \left\{\frac{2\times(11.9\times8.85\times10^{-4}(0.477)}{(1.6\times10^{-19})}\left[\frac{10^{18}}{10^{17}(10^{18}+10^{17})}\right]\right\}^{1/2} \\
&= 7.56\times10^{-6}\ \mathrm{cm} \\
W_p(V_f = 0.4V) &= 7.56\times10^{-7}\ \mathrm{cm}
\end{aligned}
$$

Thus the electron injected current is 7.74×10^{-11} A at $x = -7.56\times10^{-7}$ cm and decays exponentially with a decay constant of $L_n = 4.47\times10^{-3}$ cm. The hole current is 5.47×10^{-10}A at $x = 7.56\times10^{-6}$ cm and decays exponentially with a constant of $L_p = 3.16\times10^{-3}$ cm.

Problem 5.14 Consider a p-n diode made from InAs at 300 K. The doping is $N_a = 10^{16}\ \text{cm}^{-3} = N_d$. Calculate the saturation current density if the electron and hole density of states masses are $0.02m_o$ and $0.4m_o$, respectively. Compare this value with that of a silicon p-n diode doped at the same levels. The diffusion coefficients are $D_n = 800\ \text{cm}^2/\text{s}$; $D_p = 30\ \text{cm}^2/\text{s}$. The carrier lifetimes are $\tau_n = \tau_p = 10^{-8}$s for InAs. For the silicon diode use the values $D_n = 30\ \text{cm}^2/\text{s}$; $D_p = 10\ \text{cm}^2/\text{s}$; $\tau_n = \tau_p = 10^{-7}$s.

Solution

To find the saturation current, we need to first calculate the intrinsic carrier concentration is InAs which has a bandgap of 0.35 eV at 300 K. Using the expressions for intrinsic carrier concentration, we find that

$$\begin{aligned} N_c &= 7.26 \times 10^{16}\ \text{cm}^{-3}; N_v = 6.5 \times 10^{18}\ \text{cm}^{-3} \\ n_i &= (N_c N_v)^{1/2}\ \exp\left(\frac{-E_g}{2k_B T}\right) = 9.79 \times 10^{11}\ \text{cm}^{-3} \end{aligned}$$

The diode parameters are

$$\begin{aligned} n_p &= \frac{n_i^2}{p_p} = \frac{(9.79 \times 10^{11})^2}{(10^{16})} = 9.58 \times 10^7\ \text{cm}^{-3} \\ p_n &= \frac{n_i^2}{n_n} = 9.58 \times 10^7\ \text{cm}^{-3} \\ L_n &= (D_n \tau_n)^{1/2} = (800 \times 10^{-8})^{1/2} = 2.8 \times 10^{-3} \\ L_p &= (30 \times 10^{-8})^{1/2} = 5.47 \times 10^{-4}\ \text{cm} \end{aligned}$$

The saturation current density is

$$\begin{aligned} J_o &= (1.6 \times 10^{-19}\ \text{C}) \left[\frac{(30\ \text{cm}^2/\text{s})(9.58 \times 10^7\ \text{cm}^{-3})}{(5.47 \times 10^{-4}\ \text{cm})} + \frac{(800\ \text{cm}^2/\text{s})(9.58 \times 10^7\ \text{cm}^{-3})}{(2.8 \times 10^{-3}\ \text{cm})}\right] \\ &= 5.22 \times 10^{-6}\ \text{A/cm}^2 \end{aligned}$$

For a comparable silicon p-n diode, we have the following parameters:

$$\begin{aligned} n_p &= \frac{n_i^2}{p_p} = \frac{2.25 \times 10^{20}}{10^{16}} = 2.25 \times 10^4\ \text{cm}^{-3} = p_n \\ L_n &= (30 \times 10^{-7})^{1/2} = 1.73 \times 10^{-3}\ \text{cm} \\ L_p &= (10 \times 10^{-7})^{1/2} = 1.0 \times 10^{-3}\ \text{cm} \\ J_o &= (1.6 \times 10^{-19}) \left[\frac{30 \times 2.25 \times 10^4}{1.73 \times 10^{-3}} + \frac{10 \times 2.25 \times 10^4}{1.0 \times 10^{-3}}\right] \\ &= 9.84 \times 10^{-11}\ \text{A/cm}^2 \end{aligned}$$

We see that the saturation current values are extremely high in the InAs diode when compared to the silicon diode.

Problem 5.18 Consider a Si p-n diode at 300 K. Plot the I-V characteristics of the diode between a forward bias of 1.0 V and a reverse bias of 5.0 V. Consider the following cases for the impurity-assisted *electron-hole recombination time in the depletion region*: (a) 1.0 μs; (b) 10.0 ns; and (c) 1.0 ns. Use the following parameters:

$$\begin{aligned} A &= 10^{-3}\ \text{cm}^2 \\ N_a &= N_d = 10^{18}\ \text{cm}^{-3} \\ \tau_n &= \tau_p = 10^{-7}\ \text{s} \\ D_n &= 25\ \text{cm}^2/\text{s} \\ D_p &= 6\ \text{cm}^2/\text{s} \end{aligned}$$

Solution
We start by calculating the built-in voltage.

$$\begin{aligned} n_p &= \frac{n_i^2}{N_a} = 225\ \text{cm}^{-3} = p_n \\ V_{bi} &= \frac{k_B T}{e}\ \ell n \frac{n_n}{n_p} = 0.94\ \text{V} \end{aligned}$$

The prefactor for the ideal current is

$$\begin{aligned} I_o &= \left(1.6 \times 10^{-19}\right)\left(10^{-3}\right)\left(\frac{6 \times 225}{7.75 \times 10^{-4}} + \frac{25 \times 225}{1.58 \times 10^{-3}}\right) \\ &= 8.5 \times 10^{-16}\ \text{A} \end{aligned}$$

To get the prefactor for the nonideal case we need to calculate the depletion width as a function of bias. The depletion width for this diode turns out to be

$$W(V) = 5.13 \times 10^{-6}\sqrt{V_{bi} - V}\ \text{cm}$$

where V_{bi}, V are in volts. The prefactor for the recombination-generation current is

$$I_{GR}^o = \frac{\left(1.6 \times 10^{-19}\right)\left(10^{-3}\right)\left(5.13 \times 10^{-6}\right)\left(1.5 \times 10^{10}\right)\sqrt{V_{bi} - V}}{2\tau}$$

Case (a): $\tau = 1.0\ \mu$s; $I_{GR}^o = 6.16 \times 10^{-12}\sqrt{V_{bi} - V}$ A
Case (b): $\tau = 10$ ns; $I_{GR}^o = 6.16 \times 10^{-10}\sqrt{V_{bi} - V}$ A
Case (c): $\tau = 1$ ns; $I_{GR}^o = 6.16 \times 10^{-9}\sqrt{V_{bi} - V}$ A
The I-V relation for the diode is (the value of V_{bi}, V in the second term square root is in units of volts)
Case (a):

$$I = 8.5 \times 10^{-16}\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right) + 6.16 \times 10^{-12}\sqrt{V_{bi} - V}\left(\exp\left(\frac{eV}{2k_B T}\right) - 1\right)\ \text{A}$$

Problem 5.23 The critical field for breakdown of silicon is 4 $\times 10^5$ V/cm. Calculate the n-side doping of an abrupt p^+n diode that allows one to have a breakdown voltage of 30 V.

Solution

The critical field for the silicon is

$$F_{crit} = 3 \times 10^5 V/cm$$

The doping concentration needed to allow a breakdown voltage of 30 volts is

$$\begin{aligned} N_d &= \frac{eF_{crit}^2}{2eV_{BD}} = \frac{(11.9 \times 8.85 \times 10^{-14} \text{ F/cm})(3 \times 10^5 V/cm)^2}{2 \times (1.6 \times 10^{-19} \text{ C})(30V)} \\ &= 9.87 \times 10^{15} \text{ cm}^{-3} \end{aligned}$$

Problem 5.28 A p^+-n silicon diode has an area of 10^{-2} cm^2. The measured junction capacitance is given by (at 300 K)

$$\frac{1}{C^2} = 5 \times 10^8 (2.5 - 4 \text{ V})$$

where C is in units of μF and V is in volts. Calculate the built-in voltage and the depletion width at zero bias. What are the dopant concentrations of the diode?

Solution

The intercept of the $\frac{1}{C^2}$ vs. V relation occurs at

$$V = \frac{2.5}{4} \text{volt} = 0.625 \text{ volt} = V_{bi}$$

The slope of the $\frac{1}{C^2}$ vs. V relation gives the value

$$\frac{d(1/C^2)}{dV} = 2 \times 10^9 (\mu\text{F})^{-2} \text{ V}^{-1} = 2 \times 10^{21} \text{ F}^{-2} \text{ V}^{-1}$$

This slope gives us

$$\begin{aligned} \frac{N_a N_d}{N_a + N_d} &= \frac{2}{A^2 e\epsilon} \frac{dV}{d(1/C^2)} \\ &= \frac{2}{(10^{-2} \text{ cm}^2)^2 (1.6 \times 10^{-19})(11.9 \times 8.85 \times 10^{-14} \text{ F/cm})(2 \times 10^{21} F^{-2} V^{-1})} \\ &= 5.93 \times 10^{13} \text{ cm}^{-3} \end{aligned}$$

We know that the built-in voltage is given by,

$$V_{bi} = \frac{k_B T}{e} \ell n \frac{N_a N_d}{n_i^2}$$

which gives for $N_a N_d$ the value,

$$\begin{aligned} N_a N_d &= \exp\left(\frac{0.625}{0.026}\right) \times (2.25 \times 10^{20} \text{ cm}^{-6}) \\ &= 6.19 \times 10^{30} \text{ cm}^{-6} \end{aligned}$$

Using these two values (i.e. for $N_a N_d$ and $N_a N_d/(N_a + N_d)$ we get (N_a is larger than N_d in the p^+n diode),

$$\begin{aligned} N_a &= 1.04 \times 10^{17} \text{ cm}^{-3} \\ N_d &= 5.95 \times 10^{13} \text{ cm}^{-3} \end{aligned}$$

The zero bias depletion width is given by,

$$\begin{aligned} W &= \left[\frac{2\epsilon V_{bi}}{e}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2} \\ &= \left[\frac{2(11.9 \times 8.85 \times 10^{-14} \text{ F/cm})(0.625)}{(1.6 \times 10^{-19} C)(5.93 \times 10^{13} \text{ cm}^{-3})}\right]^{1/2} \\ &= 3.72 \times 10^{-4} \text{ cm} \end{aligned}$$

Problem 5.32 Consider a Si p-n diode at room temperature with following parameters:

$$\begin{aligned} N_d &= N_a = 10^{17} \text{ cm}^{-3} \\ D_n &= 20 \text{ cm}^2/\text{s} \\ D_p &= 12 \text{ cm}^2/\text{s} \\ \tau_n &= \tau_p = 10^{-7} \text{ s} \end{aligned}$$

Calculate the reverse saturation current for a long ideal diode. Also estimate the storage delay time for the long diode.

Now consider a narrow diode made from the structure given above. The thickness of the n-side region is 1.0 μm. The thickness of the p-side region is also 1.0 μm. Calculate the reverse saturation current in the narrow diode at a reverse bias of 2.0 volt. Also estimate the storage delay time for this diode.

Solution

The built-in voltage for the diode is

$$V_{bi} = 0.817 \text{ V}$$

The depletion width for the diode is (V_{bi}, V are in volts)

$$W_n = W_p = 8.13 \times 10^{-6}\sqrt{V_{bi} - V}$$

For the long diode the reverse saturation current density is

$$\begin{aligned} J_o &= (1.6 \times 10^{-19})\left(\frac{12 \times 2250}{1.09 \times 10^{-3}} + \frac{20 \times 2250}{1.41 \times 10^{-3}}\right) \\ &= 9.05 \times 10^{-12} \text{ A cm}^{-2} \end{aligned}$$

The storage delay time depends upon the details of the switching condition, but is approximately equal to τ_n or τ_p, i.e., 10^{-7} s. For the short diode the reverse current is bias dependent even for the ideal diode case. The depletion width changes the neutral

region width of the n and p diodes by about 10%. The reverse saturation current at a reverse bias of 2.0 V is

$$\begin{aligned} J_o &= (1.6 \times 10^{-19}) \left(\frac{12 \times 2250}{8.6 \times 10^{-5}} + \frac{20 \times 2250}{8.6 \times 10^{-5}} \right) \\ &= 1.34 \times 10^{-10} \text{ A cm}^{-2} \end{aligned}$$

The storage delay time is approximately the transit time across the neutral n or p regions. For the p-side the transit time is 4.2×10^{-10} s. This is a very short time.