Problem 5.2 An abrupt GaAs p-n diode has \( N_d = 10^{17} \text{ cm}^{-3} \) and \( N_d = 10^{15} \text{ cm}^{-3} \).

(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,

\[
E_{FP} = E_v - k_BT \ln \left( \frac{p}{N_v} \right)
\]

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

\[
E_{FP} = E_v - (0.026) \ln \left( \frac{10^{17}}{7.72 \times 10^{18}} \right) = E_v + 0.113 \text{ eV}
\]

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

\[
E_{FN} = E_c + (k_BT) \ln \left( \frac{n}{N_c} \right)
\]

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

\[
E_{FN} = E_c - 0.159 \text{ eV}
\]

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

\[
eV_{bi} = (E_c - 0.159) - (E_v + 0.113) = E_g - 0.159 - 0.113
\]

\[
= 1.43 - 0.272 \text{ eV} = 1.158 \text{ eV}
\]

Thus \( V_{bi} = 1.158 \text{ volt} \).

Let us calculate \( V_{bi} \) using the relation,

\[
V_{bi} = \frac{k_BT}{e} \ln \left( \frac{n_n}{n_p} \right)
\]

For GaAs the np product is \( 3.24 \times 10^{12} \text{ cm}^{-6} \) so that

\[
n_p = \frac{3.24 \times 10^{12}}{p_p} = \frac{3.24 \times 10^{12}}{10^{17}} = 3.24 \times 10^{-5} \text{ cm}^{-3}
\]

\[
V_{bi} = (0.026 \text{ V}) \ln \left( \frac{10^{15}}{3.24 \times 10^{-5}} \right)
\]

\[
= 1.167 \text{ volt}
\]

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?

\[
N_a = 10^{17}; N_d = 5 \times 10^{17}
\]

$V_{bi}$, $W_n$, $W_p$, $n \cdot p$

\[2.25 \times 10^3\]

$E_{Fn}$

$n$-side

$5 \times 10^{17}$

\[(10^{-6} \text{cm})\]

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

\[
V_{bi} = 0.026 \ln \left(\frac{10^{17}}{450}\right) = 0.86 \text{ V}
\]

\[
W_p(V_{bi}) = \left\{ \frac{2 \times (1.9 \times 8.85 \times 10^{-14} \text{ F/cm}) \times 0.86 \text{ V}}{(1.6 \times 10^{-19} \text{ C}) \times \left(\frac{5 \times 10^{17} \text{ cm}^{-3}}{(10^{17} \text{ cm}^{-3}) (6 \times 10^{17} \text{ cm}^{-3})}\right)} \right\}^{1/2} = 9.71 \times 10^{-6} \text{ cm}
\]

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

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 \(N_a = 10^{18} \text{ cm}^{-3}\), \(N_d = 10^{15} \text{ cm}^{-3}\). 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

\[
V_{bi} = \frac{k_B T}{e} \ln \frac{n_a}{n_p}
\]

\[
n_p = \frac{n_t^2}{p_p} = \frac{2.25 \times 10^{20} \text{ cm}^{-6}}{10^{18} \text{ cm}^{-3}} = 2.25 \times 10^2 \text{ cm}^{-3}
\]

\[
V_{bi} = (0.026 \text{ volt}) \ln \left( \frac{10^{15}}{2.25 \times 10^2} \right)
\]

\[
= 0.757 \text{ volt}
\]

The \(p\)-side depletion width is

\[
W_p(V_{bi}) = \left\{ \frac{2(11.9 \times 8.85 \times 10^{-14} \text{ F/cm})(0.757 \text{ V})}{(1.6 \times 10^{-19} \text{ C})} \right\}^{1/2}
\]

\[
= \frac{10^{15} \text{ cm}^{-3}}{(10^{18} \text{ cm}^{-3})(10^{18} + 10^{15} \text{ cm}^{-3})}
\]

\[
= 9.89 \times 10^{-8} \text{ cm} = 9.89 \text{ Å!}
\]

\[
W_n(V_{bi}) = W_p(V_{bi}) \times \frac{N_a}{N_d} = 9.89 \times 10^{-8} \text{ cm}
\]

\[
= 0.989 \mu\text{m}
\]

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) \(V_f = 0.1 \text{ V}\); (b) \(V_f = 0.5 \text{ V}\); (c) \(V_f = 1.0 \text{ V}\); (d) \(V_f = 5.0 \text{ V}\). Calculate the depletion widths and the maximum field \(E_m\) 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:

\[
V_f = 0.1 \text{ V}
\]

\[
W_p(V_{bi} - 0.1 \text{ V}) = \left\{ \frac{2 \times (13.18 \times 8.85 \times 10^{-14} \text{ F/cm})(1.058 \text{ V})}{(1.6 \times 10^{-19} \text{ C})} \right\}^{1/2}
\]

\[
= 123.3 \text{ Å}
\]

\[
W_n = 1.233 \times 10^{-4} \text{ cm}
\]

\[
F_m = \frac{(1.6 \times 10^{-19} \text{ C})(10^{15} \text{ cm}^{-3})(1.233 \times 10^{-4} \text{ cm})}{(13.18 \times 8.85 \times 10^{-14} \text{ F/cm})}
\]

\[
= 1.69 \times 10^4 \text{ V/cm}
\]

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

**Problem 5.10** Consider a p+n silicon diode with area \(10^{-4} \text{ cm}^2\). The doping is given by \(N_s = 10^{18} \text{ cm}^{-3}\) and \(N_d = 10^{17} \text{ cm}^{-3}\). 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 \(\tau_n = \tau_p = 1 \mu\text{s}\) and neglect recombination effects. \(D_n = 20 \text{ cm}^2/\text{s}\) and \(D_p = 10 \text{ cm}^2/\text{s}\).

**Solution**

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

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

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

\[
I_p(W_n) = \frac{(1.6 \times 10^{-19} \text{ C})(10^{-4} \text{ cm}^2)(0 \text{ cm}^2/\text{s})(2.25 \times 10^3 \text{ cm}^{-3})}{(3.16 \times 10^{-3} \text{ cm})} \left[ \exp \left( \frac{0.4}{0.626} \right) - 1 \right] \\
= 5.47 \times 10^{13} \text{ A}
\]
The electron current injected at the depletion edge into the p-side is,

\[ I_n(-W_p) = \frac{(1.6 \times 10^{-19} \text{ C})(10^{-4} \text{ cm}^2)(20 \text{ cm}^2/\text{s})(2.25 \times 10^3 \text{ cm}^{-3})}{(4.47 \times 10^{-3} \text{ cm})} \left[ \exp \left( \frac{0.4}{0.026} \right) - 1 \right] \]

\[ = 7.74 \times 10^{-11} \text{ A} \]

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

\[ V_{bi} = k_B T \ln \frac{n_n}{n_p} = (0.026) \ln \left( \frac{10^{17}}{2.25 \times 10^2} \right) \]

\[ = 0.877 V \]

\[ W_n(V_f = 0.4V) = \left\{ \left[ \frac{2 \times (11.9 \times 8.85 \times 10^{-4})(0.477)}{(1.6 \times 10^{-19})} \right] \left[ \frac{10^{18}}{10^{17}} \right] \right\}^{1/2} \]

\[ = 7.56 \times 10^{-6} \text{ cm} \]

\[ W_p(V_f = 0.4V) = 7.56 \times 10^{-7} \text{ cm} \]

Thus the electron injected current is \( 7.74 \times 10^{-11} \text{ A} \) at \( x = -7.56 \times 10^{-7} \text{ cm} \) and decays exponentially with a decay constant of \( L_n = 4.47 \times 10^{-3} \text{ cm} \). The hole current is \( 5.47 \times 10^{-10} \text{ A} \) at \( x = 7.56 \times 10^{-6} \text{ cm} \) and decays exponentially with a constant of \( L_o = 3.16 \times 10^{-3} \text{ cm} \).
Problem 5.14 Consider a p-n diode made from InAs at 300 K. The doping is \( N_d = 10^{16} \text{ cm}^{-3} = N_A \). Calculate the saturation current density if the electron and hole density of states masses are 0.02m_e and 0.4m_e, 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 \( \tau_n = \tau_p = 10^{-8} \text{s} \) for InAs. For the silicon diode use the values \( D_n = 30 \text{ cm}^2/\text{s}; D_p = 10 \text{ cm}^2/\text{s}; \tau_n = \tau_p = 10^{-7} \text{s} \).

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

\[
N_c = 7.26 \times 10^{16} \text{ cm}^{-3}; \quad N_v = 6.5 \times 10^{18} \text{ cm}^{-3}
\]

\[
n_i = (N_c N_v)^{1/2} \exp \left( \frac{-E_g}{2k_BT} \right) = 9.79 \times 10^{11} \text{ cm}^{-3}
\]

The diode parameters are

\[
n_p = \frac{n_i^2}{p_i} = \frac{(9.79 \times 10^{11})^2}{(10^{16})} = 9.58 \times 10^7 \text{ cm}^{-3}
\]

\[
p_n = \frac{n_i^2}{n_i} = 9.58 \times 10^7 \text{ cm}^{-3}
\]

\[
L_n = (D_n \tau_n)^{1/2} = (800 \times 10^{-8})^{1/2} = 2.8 \times 10^{-3} \text{ cm}
\]

\[
L_p = (30 \times 10^{-8})^{1/2} = 5.47 \times 10^{-4} \text{ cm}
\]

The saturation current density is

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

\[= 5.22 \times 10^{-6} \text{ A/cm}^2\]

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

\[
n_p = \frac{n_i^2}{p_i} = \frac{2.25 \times 10^{20}}{10^{16}} = 2.25 \times 10^4 \text{ cm}^{-3} = p_n
\]

\[
L_n = (30 \times 10^{-7})^{1/2} = 1.73 \times 10^{-3} \text{ cm}
\]

\[
L_p = (10 \times 10^{-7})^{1/2} = 1.0 \times 10^{-3} \text{ cm}
\]

\[
J_o = (1.6 \times 10^{-19}) \left[ \frac{30 \times 2.25 \times 10^4}{1.73 \times 10^{-3}} + \frac{10 \times 2.25 \times 10^4}{1.0 \times 10^{-3}} \right]
\]

\[= 9.84 \times 10^{-11} \text{ A/cm}^2\]

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:

\[ A = 10^{-3} \text{ cm}^2 \]
\[ N_a = N_d = 10^{16} \text{ cm}^{-3} \]
\[ \tau_n = \tau_p = 10^{-7} \text{ s} \]
\[ D_n = 25 \text{ cm}^2/\text{s} \]
\[ D_p = 6 \text{ cm}^2/\text{s} \]

Solution

We start by calculating the built-in voltage,

\[ n_p = \frac{n_i^2}{N_a} = 225 \text{ cm}^{-3} = p_n \]
\[ V_{bi} = \frac{k_B T}{e} \left( \frac{\tau_p}{\tau_n} \right)^{1/2} = 0.94 \text{ V} \]

The prefactor for the ideal current is

\[ I_0 = (1.6 \times 10^{-19}) (10^{-3}) \left( \frac{6 \times 225}{1.75 \times 10^{-4}} + \frac{25 \times 225}{1.58 \times 10^{-3}} \right) \]
\[ = 8.5 \times 10^{-16} \text{ A} \]

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

\[ I_{GR}^p = \frac{(1.6 \times 10^{-19}) (10^{-3}) (5.13 \times 10^{-6}) (1.5 \times 10^{10}) \sqrt{V_{bi} - V}}{2\tau} \]

Case (a): \( \tau = 1.0 \mu s; \ I_{GR}^p = 6.16 \times 10^{-12} \sqrt{V_{bi} - V} \text{ A} \)
Case (b): \( \tau = 10 \text{ ns}; \ I_{GR}^p = 6.16 \times 10^{-10} \sqrt{V_{bi} - V} \text{ A} \)
Case (c): \( \tau = 1 \text{ ns}; \ I_{GR}^p = 6.16 \times 10^{-8} \sqrt{V_{bi} - V} \text{ A} \)

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

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

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)

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

where $C$ is in units of $\mu F$ 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

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

This slope gives us

$$\frac{N_aN_d}{N_a + N_d} = \frac{2}{A^2 \varepsilon e} \frac{dV}{d(1/C^2)} = \frac{2}{(10^{-2} \text{ cm}^2)^2 (1.6 \times 10^{-19} \mu F/cm)(11.9 \times 8.85 \times 10^{-14} F/cm)(2 \times 10^{21} F^{-2} V^{-1})} = 5.93 \times 10^{15} \text{ cm}^{-3}$$

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

$$V_{bi} = \frac{kT}{e} \ln \frac{N_aN_d}{n_i^2}$$

which gives for $N_aN_d$ the value,

$$N_aN_d = \exp \left( \frac{0.625}{0.026} \right) \times (2.25 \times 10^{23} \text{ cm}^{-5}) = 6.19 \times 10^{30} \text{ cm}^{-6}$$
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),

\[
N_a = 1.04 \times 10^{17} \text{ cm}^{-3} \\
N_d = 5.95 \times 10^{13} \text{ cm}^{-3}
\]

The zero bias depletion width is given by,

\[
W = \left[ \frac{2eV_{bi}}{c} \left( \frac{N_a + N_d}{N_a N_d} \right) \right]^{1/2} \\
= \left[ \frac{2(11.9 \times 8.85 \times 10^{-14} \text{ F/cm})(0.625)}{(1.6 \times 10^{-19} \text{C})(5.93 \times 10^{13} \text{ cm}^{-3})} \right]^{1/2} \\
= 3.72 \times 10^{-4} \text{ cm}
\]

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

\[
N_d = N_a = 10^{17} \text{ cm}^{-3} \\
D_n = 20 \text{ cm}^2/\text{s} \\
D_p = 12 \text{ cm}^2/\text{s} \\
\tau_n = \tau_p = 10^{-7} \text{ s}
\]

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 \( \mu \text{m} \). The thickness of the \( p \)-side region is also 1.0 \( \mu \text{m} \). 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

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

The storage delay time depends upon the details of the switching condition, but is approximately equal to \( \tau_n \) or \( \tau_p \), 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

$$J_o = (1.6 \times 10^{-19}) \left( \frac{12 \times 2250}{8.6 \times 10^{-5}} + \frac{26 \times 2250}{8.6 \times 10^{-5}} \right)$$

$$= 1.34 \times 10^{-10} \text{ A cm}^{-2}$$

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