The Cd composition is

\[ x = \frac{0.25 + 0.3}{1.9} = 0.29 \]
Problem 11.3  Calculate the absorption coefficient for GaAs for photons with energy 1.8 eV. Calculate the fraction of this light absorbed in a GaAs sample of thickness of 0.5 \( \mu \text{m} \).

Solution

According to Example 6.1, the absorption coefficient of GaAs is

\[
\alpha(h\omega) = 5.7 \times 10^4 \frac{(h\omega - E_g)^{1/2}}{h\omega} \text{ cm}^{-1}
\]

where the energies \( h\omega, E_g \) are expressed in eV. We get, for \( h\omega = 1.8 \text{ eV} \),

\[
\alpha(h\omega = 1.8 \text{ eV}) = \frac{(5.7 \times 10^4)(1.8 - 1.43)^{1/2}}{1.8} \text{ cm}^{-1} = 1.93 \times 10^4 \text{ cm}^{-1}
\]

The fraction of light absorbed in 0.5 \( \mu \text{m} \) is

\[
1 - \exp \left[ -(1.93 \times 10^4 \text{ cm}^{-1})(0.5 \times 10^{-4} \text{ cm}) \right] = 0.62
\]

Thus, 62\% of the incident light is absorbed.

6.4  An optical power density of 1W/cm\(^2\) is incident on a GaAs sample. The photon energy is 2.0 eV and there is no reflection from the surface. Calculate the excess electron-hole carrier densities at the surface and 0.5 \( \mu \text{m} \) from the surface. The \( e\cdot h \) recombination time is \( 10^{-8} \) s.

Solution

The optical absorption coefficient at \( h\omega = 2.0 \text{ eV} \) is

\[
\alpha(h\omega = 2.0 \text{ eV}) = \frac{5.7 \times 10^4(2.0 - 1.43)^{1/2}}{2.0} = 2.15 \times 10^4 \text{ cm}^{-1}
\]
The generation rate at the surface is

$$G_L = \frac{\alpha P_{op}(0)}{k \omega} = \frac{(2.15 \times 10^4 \text{ cm}^{-1})(1 \text{ W cm}^{-2})}{(2.0 \times 1.6 \times 10^{-19} \text{ J})}$$

$$= 6.72 \times 10^{22} \text{ cm}^{-3} \text{ s}^{-1}$$

The excess carrier density is

$$\delta n = \delta p = G_L \tau_n = G_L \tau_p = (6.72 \times 10^{22} \text{ cm}^{-3} \text{ s}^{-1})(10^{-8})$$

$$= 6.72 \times 10^{14} \text{ cm}^{-3}$$

The optical power density at a depth of 0.5 \( \mu \text{m} \) is

$$P_{op}(x = 0.5 \mu \text{m}) = P_{op}(0) \exp (-\alpha x)$$

$$= 0.34 \text{ W cm}^{-2}$$

The \( e \cdot h \) pair generation rate is now

$$G_L = 2.28 \times 10^{22} \text{ cm}^{-3} \text{ s}^{-1}$$

and the excess charge density is

$$\delta n = \delta p = 2.28 \times 10^{14} \text{ cm}^{-3}$$
Problem 11.7  Consider a long Si p-n junction solar cell with an area of 4 cm\(^2\) at 300 K. The solar cell has the following parameters:

- n-type doping, \(N_d = 10^{18} \text{ cm}^{-3}\)
- p-type doping, \(N_a = 3 \times 10^{17} \text{ cm}^{-3}\)
- Electron diffusion coefficient, \(D_n = 15 \text{ cm}^2/\text{s}\)
- Hole diffusion coefficient, \(D_p = 7.5 \text{ cm}^2/\text{s}\)
- Electron minority carrier lifetime, \(\tau_n = 10^{-7} \text{ s}\)
- Hole minority carrier lifetime, \(\tau_p = 10^{-7} \text{ s}\)
- Photocurrent, \(I_L = 1.0 \text{ A}\)
- Diode ideality factor, \(m = 1.25\)

Calculate the open circuit voltage of the diode. If the fill factor is 0.75, calculate the maximum power output.

Solution
The open circuit voltage is given by

\[ V_{oc} = \frac{m k_B T}{e} \ln \left( \frac{I_L}{I_o} \right) \]

The prefactor \(I_o\) is given by

\[ I_o = e A \left( \frac{D_{pn} n_p}{L_p} + \frac{D_n n_p}{L_n} \right) \]
\[ = (1.6 \times 10^{-19} \text{ C})(4 \text{ cm}^2) \]
\[ \left( \frac{7.5 \text{ cm}^2/\text{s}}{(2.73 \times 10^{-3} \text{ cm})} \right) + \frac{(15 \text{ cm}^2/\text{s})(7.5 \times 10^2 \text{ cm}^{-3})}{(1.22 \times 10^{-3} \text{ cm})} \]
\[ = 6.3 \times 10^{-12} \text{ A} \]

The open circuit voltage is now

\[ V_{oc} = (1.25)(0.026 V) \ln \left( \frac{1.0}{6.3 \times 10^{-12}} \right) \]
\[ = 0.84 \text{ V} \]

The maximum power output is

\[ P_{out} = I_L V_{oc} F = (1.0 \text{ A})(0.84 \text{ V})(0.75) \]
\[ = 0.63 \text{ W} \]
Problem 11.10 Consider a GaAs \( p-i-n \) detector with an intrinsic layer width of 1.0 \( \mu m \). Optical power density (photon energy 1.6 eV) of 0.1 watt/cm\(^2\) impinges upon the detector. The absorption coefficient for the active region is 10\(^4\) cm\(^{-1}\). Calculate the prompt photocurrent of the device. The device area is 10\(^{-4}\) cm\(^2\).

**Solution**

The photocurrent is simply given by

\[
I_L = eA J_{ph}(0)[1 - \exp(-\alpha W)]
\]

where \( W \) is the intrinsic region width. The photon flux density is

\[
J_{ph}(0) = \frac{P_{op}}{h\omega} = \frac{(0.1 \text{ W cm}^{-2})}{(1.6 \times 1.6 \times 10^{-19} \text{ J})} = 3.9 \times 10^{17} \text{ s}^{-1} \text{ cm}^{-2}
\]

\[
I_L = (1.6 \times 10^{-19} \text{ C})(10^{-4} \text{ cm}^2)(3.9 \times 10^{17} \text{ cm}^{-2}\text{s}^{-1})[1 - 0.368] = 3.94 \times 10^{-6} \text{ A}
\]

Problem 11.14 Consider a GaAs \( p-n^+ \) junction LED with the following parameters at 300 K:

- Electron diffusion coefficient, \( D_n = 25 \text{ cm}^2/\text{s} \)
- Hole diffusion coefficient, \( D_p = 12 \text{ cm}^2/\text{s} \)
- \( n \)-side doping, \( N_d = 5 \times 10^{17} \text{ cm}^{-3} \)
- \( p \)-side doping, \( N_a = 10^{16} \text{ cm}^{-3} \)
- Electron minority carrier lifetime, \( \tau_n = 10 \text{ ns} \)
- Hole minority carrier lifetime, \( \tau_p = 10 \text{ ns} \)

Calculate the injection efficiency of the LED assuming no trap-related recombination.

**Solution**

The injection efficiency for the GaAs \( pn^+ \) LED is given by

\[
\gamma_{inj} = \frac{D_n n_{po}}{L_n} = \frac{D_p p_{po}}{L_p}
\]

The diffusion lengths are

\[
L_n = \sqrt{D_n \tau_n} = 1.12 \times 10^{-3} \text{ cm}
\]

\[
L_p = \sqrt{D_p \tau_p} = 1.1 \times 10^{-3} \text{ cm}
\]

Also

\[
n_{po} = \frac{n_i^2}{N_a} = \frac{(1.84 \times 10^6 \text{ cm}^{-3})^2}{(10^{16} \text{ cm}^{-3})} = 3.39 \times 10^{-4} \text{ cm}^{-3}
\]

\[
p_{po} = \frac{n_i^2}{N_d} = \frac{(1.84 \times 10^6 \text{ cm}^{-3})^2}{(5 \times 10^{17} \text{ cm}^{-3})} = 6.77 \times 10^{-6}
\]

\[
\gamma_{inj} = 0.9903
\]
Section 11.6

**Problem 11.17** Consider the semiconductor alloy InGaAsP with a bandgap of 0.8 eV. The electron and hole masses are 0.04 m and 0.35 m, respectively. Calculate the injected electron and hole densities needed at 300 K to cause inversion for the electrons and holes at the bandedge energies. How does the injected density change if the temperature is 77 K? Use the Joyce-Dixon approximation.

**Solution**

The condition for inversion is that at the bandedges

\[ f^e + f^h \geq 1 \]

The effective density of states for the system are

\[ N_c = (4.45 \times 10^{17} \text{ cm}^{-3}) \left( \frac{m^*(\text{InGaAsP})}{m^*(\text{GaAs})} \right)^{3/2} \]
\[ = 2.05 \times 10^{17} \text{ cm}^{-3} \]
\[ N_v = 5.31 \times 10^{18} \text{ cm}^{-3} \]

The procedure for finding the conditions for inversion involves choosing an injection density \( n \), calculating \( E_{Fn} \) and \( E_{Fp} \) and finding \( f^e \) and \( f^h \) at the bandedges. This procedure is repeated until the inversion condition is satisfied at the bandedges. For example, we find the following for 300 K (in eV):

\[ n = 5 \times 10^{17} \text{ cm}^{-3} \Rightarrow E_{Fn} = E_c + 4.68 \times 10^{-2}; f^e(E_c) = 0.86 \]
\[ E_{Fp} = E_v + 6.06 \times 10^{-2}; f^h(E_v) = 0.09 \]
\[ n = 6 \times 10^{17} \text{ cm}^{-3} \Rightarrow E_{Fn} = E_c + 5.61 \times 10^{-2}; f^e(E_c) = 0.896 \]
\[ E_{Fp} = E_v + 5.67 \times 10^{-2}; f^h(E_v) = 0.102 \]

Thus the inversion condition is satisfied when \( n = p \approx 6 \times 10^{17} \text{ cm}^{-3} \). When the temperature changes to 77 K, the effective density of states are

\[ N_c = 2.67 \times 10^{16} \text{ cm}^{-3} \]
\[ N_v = 6.9 \times 10^{17} \text{ cm}^{-3} \]

The density at which inversion occurs is \( \sim 1.0 \times 10^{17} \text{ cm}^{-3} \).