CHAPTER 14

Optical Devices

In previous chapters, we have considered the basic physics of transistors that are used to amplify or switch electrical signals. Semiconductor devices can be designed to convert optical energy into electrical energy, and to convert electrical signals into optical signals. These devices are used in broadband communications and data transmission over optical fibers. The general classification of these devices is called *optoelectronics*.

In this chapter, we discuss the basic principles of solar cells, several photodetectors, light emitting diodes, and laser diodes. Solar cells and photodetectors convert optical energy into electrical energy; light emitting diodes and laser diodes convert electrical signals into optical signals. ■

14.0 | PREVIEW

In this chapter, we will:

- Discuss and analyze photon absorption in a semiconductor and present absorption coefficient data for several semiconductor materials.
- Consider the basic principles of solar cells, analyze their *I–V* characteristics, and discuss the conversion efficiency.
- Present various types of solar cells, including homojunction, heterojunction, and amorphous silicon solar cells.
- Discuss the basic principles of photodetectors, including photoconductors, photodiodes, and phototransistors.
- Derive the output current characteristics of the various photodectors.
- Present and analyze the basic operation of the **L**ight **E**mitting **D**iode (LED).
- Discuss the basic principles and operation of the laser diode.

14.1 | OPTICAL ABSORPTION

In Chapter 2, we discussed the wave–particle duality principle and indicated that light waves could be treated as particles, which are referred to as photons. The energy of a photon is $E = h\nu$ where h is Plank's constant and ν is the frequency. We can also relate the wavelength and energy by

$$\lambda = \frac{c}{\nu} = \frac{hc}{E} = \frac{1.24}{E} \ \mu\text{m} \tag{14.1}$$

where E is the photon energy in eV and c is the speed of light.

There are several possible photon–semiconductor interaction mechanisms. For example, photons can interact with the semiconductor lattice whereby the photon energy is converted into heat. Photons can also interact with impurity atoms, either donors or acceptors, or they can interact with defects within the semiconductor. However, the basic photon interaction process of greatest interest is the interaction with valence electrons. When a photon collides with a valence electron, enough energy may be imparted to elevate the electron into the conduction band. Such a process generates electron–hole pairs and creates excess carrier concentrations. The behavior of excess carriers in a semiconductor was considered in Chapter 6.

14.1.1 Photon Absorption Coefficient

When a semiconductor is illuminated with light, the photons may be absorbed or they may propagate through the semiconductor, depending on the photon energy and on the bandgap energy E_g. If the photon energy is less than E_g, the photons are not readily absorbed. In this case, the light is transmitted through the material and the semiconductor appears to be transparent.

If $E = h\nu > E_g$, the photon can interact with a valence electron and elevate the electron into the conduction band. The valence band contains many electrons and the conduction band contains many empty states, so the probability of this interaction is high when $h\nu > E_g$. This interaction creates an electron in the conduction band and a hole in the valence band—an electron–hole pair. The basic absorption processes for different values of $h\nu$ are shown in Figure 14.1. When $h\nu > E_g$, an electron–hole

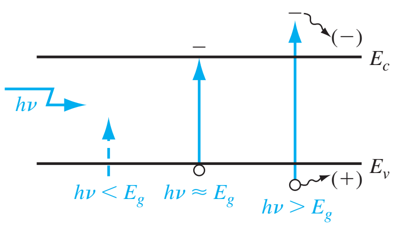

Figure 14.1 | Optically generated electron–hole pair formation in a semiconductor.

pair is created and the excess energy may give the electron or hole additional kinetic energy, which will be dissipated as heat in the semiconductor.

The intensity of the photon flux is denoted by $I_\nu(x)$ and is expressed in terms of energy/cm^2-s. Figure 14.2 shows an incident photon intensity at a position x and the photon flux emerging at a distance $x + dx$. The energy absorbed per unit time in the distance dx is given by

$$\alpha I_\nu(x)\,dx \tag{14.2}$$

where α is the absorption coefficient. The absorption coefficient is the relative number of photons absorbed per unit distance, given in units of cm^{-1}.

From Figure 14.2, we can write

$$I_\nu(x + dx) - I_\nu(x) = \frac{dI_\nu(x)}{dx} \cdot dx = -\alpha I_\nu(x)\,dx \tag{14.3}$$

or

$$\frac{dI_\nu(x)}{dx} = -\alpha I_\nu(x) \tag{14.4}$$

If the initial condition is given as $I_\nu(0) = I_{\nu 0}$, then the solution to the differential equation, Equation (14.4), is

$$I_\nu(x) = I_{\nu 0} e^{-\alpha x} \tag{14.5}$$

The intensity of the photon flux decreases exponentially with distance through the semiconductor material. The photon intensity as a function of x for two general values of absorption coefficient is shown in Figure 14.3. If the absorption coefficient is large, the photons are absorbed over a relatively short distance.

The absorption coefficient in the semiconductor is a very strong function of photon energy and bandgap energy. Figure 14.4 shows the absorption coefficient α plotted as a function of wavelength for several semiconductor materials. The absorption coefficient increases very rapidly for $h\nu > E_g$, or for $\lambda < 1.24/E_g$. The absorption

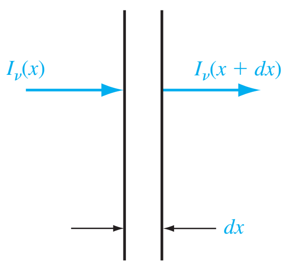

Figure 14.2 | Optical absorption in a differential length.

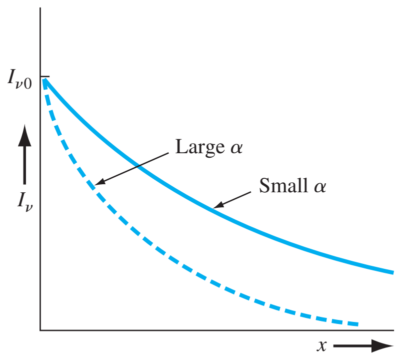

Figure 14.3 | Photon intensity versus distance for two absorption coefficients.

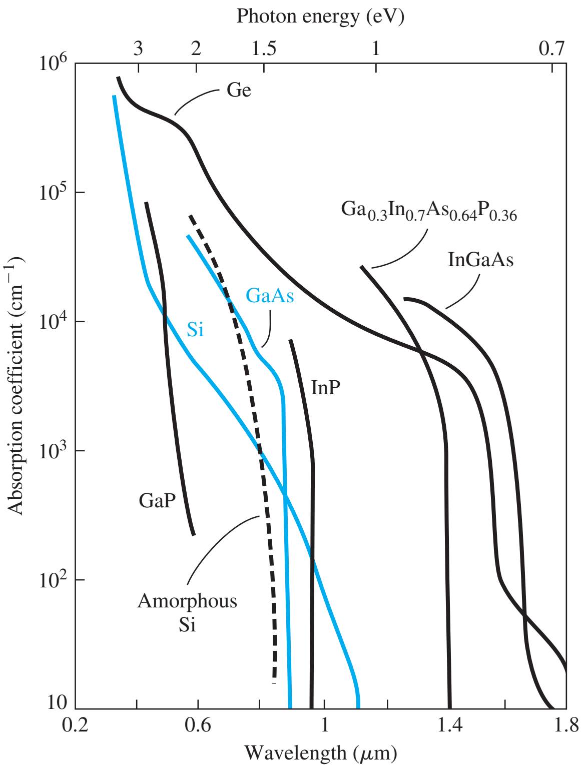

Figure 14.4 | Absorption coefficient as a function of wavelength for several semiconductors.
(From Shur [13].)

coefficients are very small for $h\nu < E_g$, so the semiconductor appears transparent to photons in this energy range.

EXAMPLE 14.1

Objective: Calculate the thickness of a semiconductor that will absorb 90 percent of the incident photon energy.

Consider silicon and assume that in the first case the incident wavelength is $\lambda = 1.0\ \mu$m and in the second case, the incident wavelength is $\lambda = 0.5\ \mu$m.

■ Solution

From Figure 14.4, the absorption coefficient is $\alpha \approx 10^2\ \text{cm}^{-1}$ for $\lambda = 1.0\ \mu$m. If 90 percent of the incident flux is to be absorbed in a distance d, then the flux emerging at $x = d$ will be 10 percent of the incident flux. We can write

$$\frac{I_\nu(d)}{I_{\nu 0}} = 0.1 = e^{-\alpha d}$$

Solving for the distance d, we have

$$d = \frac{1}{\alpha} \ln\left(\frac{1}{0.1}\right) = \frac{1}{10^2} \ln(10) = 0.0230 \text{ cm}$$

In the second case, the absorption coefficient is $\alpha \approx 10^4$ cm^{-1} for $\lambda = 0.5$ μm. The distance d, then, in which 90 percent of the incident flux is absorbed, is

$$d = \frac{1}{10^4} \ln\left(\frac{1}{0.1}\right) = 2.30 \times 10^{-4} \text{ cm} = 2.30 \ \mu\text{m}$$

Comment

As the incident photon energy increases, the absorption coefficient increases rapidly, so that the photon energy can be totally absorbed in a very narrow region at the surface of the semiconductor.

EXERCISE PROBLEM

Ex 14.1 Consider a slab of silicon 5 μm thick. Determine the percentage of photon energy that will pass through the slab if the photon wavelength is (*a*) $\lambda = 0.8$ μm and (*b*) $\lambda = 0.6$ μm.

[Ans. (*a*) 60.7%; (*b*) 10.5%]

The relation between the bandgap energies of some of the common semiconductor materials and the light spectrum is shown in Figure 14.5. We may note that silicon and gallium arsenide will absorb all of the visible spectrum, whereas gallium phosphide, for example, will be transparent to the red spectrum.

14.1.2 Electron–Hole Pair Generation Rate

We have shown that photons with energy greater than E_g can be absorbed in a semiconductor, thereby creating electron–hole pairs. The intensity $I_\nu(x)$ is in units of

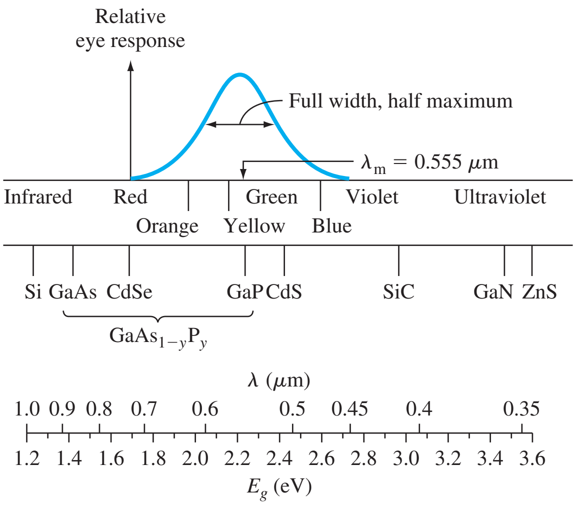

Figure 14.5 | Light spectrum versus wavelength and energy. Figure includes relative response of the human eye. *(From Sze [18].)*

energy/cm^2-s and $\alpha I_\nu(x)$ is the rate at which energy is absorbed per unit volume. If we assume that one absorbed photon at an energy $h\nu$ creates one electron–hole pair, then the generation rate of electron–hole pairs is

$$g' = \frac{\alpha I_\nu(x)}{h\nu} \tag{14.6}$$

which is in units of #/cm^3-s. We may note that the ratio $I_\nu(x)/h\nu$ is the photon flux. If, on the average, one absorbed photon produces less than one electron–hole pair, then Equation (14.6) must be multiplied by an efficiency factor.

EXAMPLE 14.2

Objective: Calculate the generation rate of electron–hole pairs given an incident intensity of photons.

Consider gallium arsenide at $T = 300$ K. Assume the photon intensity at a particular point is $I_\nu(x) = 0.05$ W/cm^2 at a wavelength of $\lambda = 0.75$ μm. This intensity is typical of sunlight, for example.

■ Solution

The absorption coefficient for gallium arsenide at this wavelength is $\alpha \approx 0.9 \times 10^4$ cm^{-1}. The photon energy, using Equation (14.1), is

$$E = h\nu = \frac{1.24}{0.75} = 1.65 \text{ eV}$$

Then, from Equation (14.6) and including the conversion factor between joules and eV, we have, for a unity efficiency factor,

$$g' = \frac{\alpha I_\nu(x)}{h\nu} = \frac{(0.9 \times 10^4)(0.05)}{(1.6 \times 10^{-19})(1.65)} = 1.70 \times 10^{21} \text{ cm}^{-3}\text{-s}^{-1}$$

If the incident photon intensity is a steady-state intensity, then, from Chapter 6, the steady-state excess carrier concentration is $\delta n = g'\tau$, where τ is the excess minority carrier lifetime. If $\tau = 10^{-7}$ s, for example, then

$$\delta n = (1.70 \times 10^{21})(10^{-7}) = 1.70 \times 10^{14} \text{ cm}^{-3}$$

■ Comment

This example gives an indication of the magnitude of the electron–hole generation rate and the magnitude of the excess carrier concentration. Obviously, as the photon intensity decreases with distance in the semiconductor, the generation rate also decreases.

■ EXERCISE PROBLEM

Ex 14.2 A photon flux with an intensity of $I_{\nu 0} = 0.10$W/cm^2 and at a wavelength of $\lambda = 1$ μm is incident on the surface of silicon. Neglecting any reflection from the surface, determine the generation rate of electron–hole pairs at a depth of (*a*) $x = 5$ μm and (*b*) $x = 20$ μm from the surface.

[Ans. (*a*) 4.79×10^{19} cm^{-3} s^{-1}; (*b*) 4.13×10^{19} cm^{-3} s^{-1}]

TEST YOUR UNDERSTANDING

TYU 14.1 (*a*) A photon flux with an intensity of $I_{\nu 0} = 0.10$ W/cm^2 is incident on the surface of silicon. The wavelength of the incident photon signal is $\lambda = 1$ μm. Neglecting any reflection from the surface, determine the photon flux intensity at a depth of (*i*) $x = 5$ μm and (*ii*) $x = 20$ μm from the surface. (*b*) Repeat part (*a*) for a wavelength of $\lambda = 0.60$ μm. [Ans. (*a*) (*i*) 0.0951 W/cm^2, (*ii*) 0.0819 W/cm^2; (*b*) (*i*) 0.0135 W/cm^2, (*ii*) 3.35×10^{-5} W/cm^2]

14.2 | SOLAR CELLS

A solar cell is a pn junction device with no voltage directly applied across the junction. The solar cell converts photon power into electrical power and delivers this power to a load. These devices have long been used for the power supply of satellites and space vehicles, and also as the power supply to some calculators. We will first consider the simple pn junction solar cell with uniform generation of excess carriers. We will also discuss briefly the heterojunction and amorphous silicon solar cells.

14.2.1 The pn Junction Solar Cell

Consider the pn junction shown in Figure 14.6 with a resistive load. Even with zero bias applied to the junction, an electric field exists in the space charge region as shown in the figure. Incident photon illumination can create electron–hole pairs in the space charge region that will be swept out producing the photocurrent I_L in the reverse-biased direction as shown.

The photocurrent I_L produces a voltage drop across the resistive load which forward biases the pn junction. The forward-bias voltage produces a forward-bias current I_F as indicated in the figure. The net pn junction current, in the reverse-biased direction, is

$$I = I_L - I_F = I_L - I_S\left[\exp\left(\frac{eV}{kT}\right) - 1\right] \tag{14.7}$$

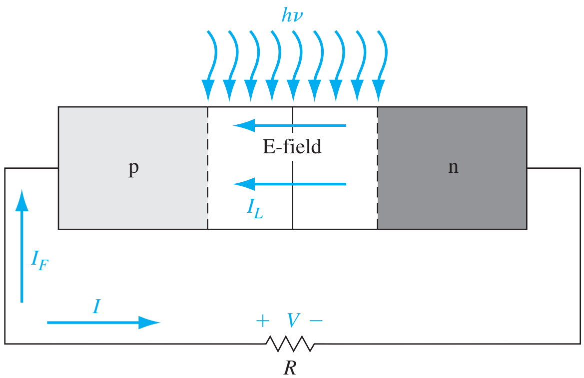

Figure 14.6 | A pn junction solar cell with resistive load.

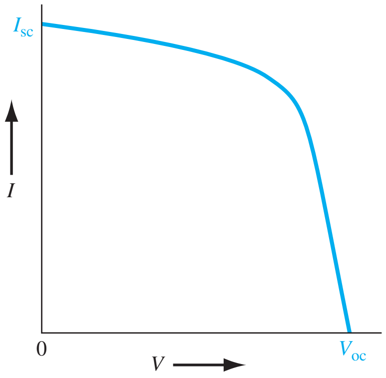

Figure 14.7 | I–V characteristics of a pn junction solar cell.

where the ideal diode equation has been used. As the diode becomes forward biased, the magnitude of the electric field in the space charge region decreases, but does not go to zero or change direction. The photocurrent is always in the reverse-biased direction and the net solar cell current is also always in the reverse-biased direction.

There are two limiting cases of interest. The short-circuit condition occurs when $R = 0$ so that $V = 0$. The current in this case is referred to as the *short-circuit current,* or

$$I = I_{sc} = I_L \tag{14.8}$$

The second limiting case is the open-circuit condition and occurs when $R \to \infty$. The net current is zero and the voltage produced is the *open-circuit voltage.* The photocurrent is just balanced by the forward-biased junction current, so we have

$$I = 0 = I_L - I_S\left[\exp\left(\frac{eV_{oc}}{kT}\right) - 1\right] \tag{14.9}$$

We can find the open circuit voltage V_{oc} as

$$V_{oc} = V_t \ln\left(1 + \frac{I_L}{I_S}\right) \tag{14.10}$$

A plot of the diode current I as a function of the diode voltage V from Equation (14.7) is shown in Figure 14.7. We may note the short-circuit current and open-circuit voltage points on the figure.

EXAMPLE 14.3

Objective: Calculate the open-circuit voltage of a silicon pn junction solar cell.

Consider a silicon pn junction at $T = 300$ K with the following parameters:

$N_a = 5 \times 10^{18}$ cm^{-3} $\quad$ $N_d = 10^{16}$ cm^{-3}
$D_n = 25$ cm^2/s $\quad$ $D_p = 10$ cm^2/s
$\tau_{n0} = 5 \times 10^{-7}$ s $\quad$ $\tau_{p0} = 10^{-7}$ s

Let the photocurrent density be $J_L = I_L/A = 15$ mA/cm^2.

■ Solution

We have that

$$J_S = \frac{I_S}{A} = \left(\frac{eD_n n_{p0}}{L_n} + \frac{eD_p p_{n0}}{L_p}\right) = en_i^2\left(\frac{D_n}{L_n N_a} + \frac{D_p}{L_p N_d}\right)$$

We may calculate

$$L_n = \sqrt{D_n \tau_{n0}} = \sqrt{(25)(5 \times 10^{-7})} = 35.4\ \mu\text{m}$$

and

$$L_p = \sqrt{D_p \tau_{p0}} = \sqrt{(10)(10^{-7})} = 10.0\ \mu\text{m}$$

Then

$$J_S = (1.6 \times 10^{-19})(1.5 \times 10^{10})^2 \times \left[\frac{25}{(35.4 \times 10^{-4})(5 \times 10^{18})} + \frac{10}{(10 \times 10^{-4})(10^{16})}\right]$$

$$= 3.6 \times 10^{-11}\ \text{A/cm}^2$$

Then from Equation (14.10), we can find

$$V_{\text{oc}} = V_t \ln\left(1 + \frac{I_L}{I_S}\right) = V_t \ln\left(1 + \frac{J_L}{J_S}\right) = (0.0259) \ln\left(1 + \frac{15 \times 10^{-3}}{3.6 \times 10^{-11}}\right) = 0.514\ \text{V}$$

■ Comment

We may determine the built-in potential barrier of this junction to be $V_{bi} = 0.8556$ V. Taking the ratio of the open-circuit voltage to the built-in potential barrier, we find that $V_{oc}/V_{bi} = 0.60$. The open-circuit voltage will always be less than the built-in potential barrier.

■ EXERCISE PROBLEM

Ex 14.3 Consider a GaAs pn junction solar cell with the following parameters: $N_a = 10^{17}\ \text{cm}^{-3}$, $N_d = 2 \times 10^{16}\ \text{cm}^{-3}$, $D_n = 190\ \text{cm}^2/\text{s}$, $D_p = 10\ \text{cm}^2/\text{s}$, $\tau_{n0} = 10^{-7}$ s, and $\tau_{p0} = 10^{-8}$ s. Assume a photocurrent density of $J_L = 20\ \text{mA/cm}^2$ is generated in the solar cell. (*a*) Calculate the open-circuit voltage and (*b*) determine the ratio of open-circuit voltage to built-in potential barrier.

[Ans. (*a*) $V_{oc} = 0.971$ V; (*b*) $V_{oc}/V_{bi} = 0.783$]

The power delivered to the load is

$$P = I \cdot V = I_L \cdot V - I_S\left[\exp\left(\frac{eV}{kT}\right) - 1\right] \cdot V \tag{14.11}$$

We may find the current and voltage which will deliver the maximum power to the load by setting the derivative equal to zero, or $dP/dV = 0$. Using Equation (14.11), we find

$$\frac{dP}{dV} = 0 = I_L - I_S\left[\exp\left(\frac{eV_m}{kT}\right) - 1\right] - I_S V_m\left(\frac{e}{kT}\right)\exp\left(\frac{eV_m}{kT}\right) \tag{14.12}$$

where V_m is the voltage that produces the maximum power. We may rewrite Equation (14.12) in the form

$$\left(1 + \frac{V_m}{V_t}\right)\exp\left(\frac{eV_m}{kT}\right) = 1 + \frac{I_L}{I_S} \tag{14.13}$$

The value of V_m may be determined by trial and error. Figure 14.8 shows the maximum power rectangle where I_m is the current when $V = V_m$.

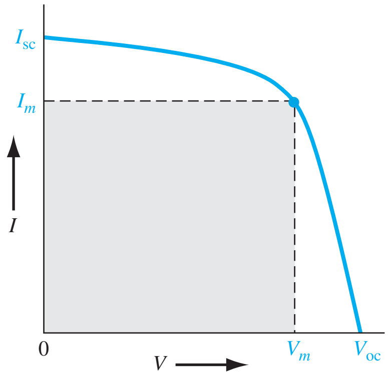

Figure 14.8 | Maximum power rectangle of the solar cell I–V characteristics.

14.2.2 Conversion Efficiency and Solar Concentration

The conversion efficiency of a solar cell is defined as the ratio of output electrical power to incident optical power. For the maximum power output, we can write

$$\eta = \frac{P_m}{P_{in}} \times 100\% = \frac{I_m V_m}{P_{in}} \times 100\% \tag{14.14}$$

The maximum possible current and the maximum possible voltage in the solar cell are I_{sc} and V_{oc}, respectively. The ratio $I_m V_m / I_{sc} V_{oc}$ is called the fill factor and is a measure of the realizable power from a solar cell. Typically, the fill factor is between 0.7 and 0.8.

The conventional pn junction solar cell has a single semiconductor bandgap energy. When the cell is exposed to the solar spectrum, a photon with energy less than E_g will have no effect on the electrical output power of the solar cell. A photon with energy greater than E_g will contribute to the solar cell output power, but the fraction of photon energy that is greater than E_g will eventually only be dissipated as heat. Figure 14.9 shows the solar spectral irradiance (power per unit area per unit wavelength) where air mass zero represents the solar spectrum outside the earth's atmosphere and air mass one is the solar spectrum at the earth's surface at noon. The maximum efficiency of a silicon pn junction solar cell is approximately 28 percent. Nonideal factors, such as series resistance and reflection from the semiconductor surface, will lower the conversion efficiency typically to the range of 10 to 15 percent.

A large optical lens can be used to concentrate sunlight onto a solar cell so that the light intensity can be increased up to several hundred times. The short-circuit current increases linearly with light concentration while the open-circuit voltage increases only slightly with concentration. Figure 14.10 shows the ideal solar cell efficiency at 300 K for two values of solar concentration. We can see that the conversion efficiency increases only slightly with optical concentration. The primary advantage of using concentration techniques is to reduce the overall system cost since an optical lens is less expensive than an equivalent area of solar cells.

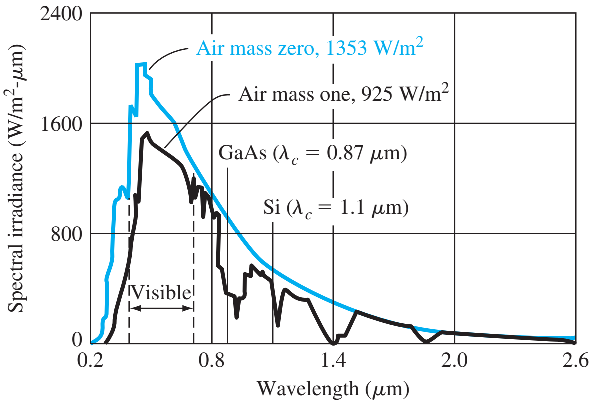

Figure 14.9 | Solar spectral irradiance.
(From Sze [18].)

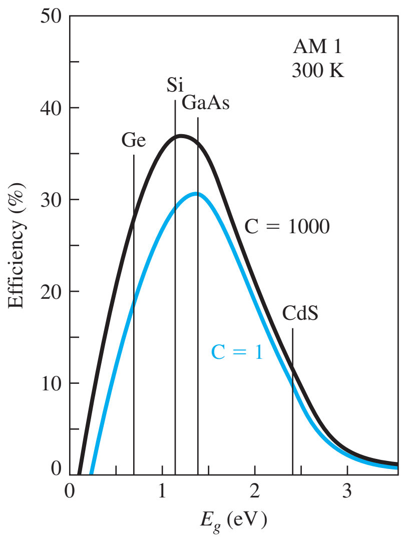

Figure 14.10 | Ideal solar cell efficiency at $T = 300$ K for C = 1 sun and for a C = 1000 sun concentrations as a function of bandgap energy.
(From Sze [18].)

14.2.3 Nonuniform Absorption Effects

We have seen from the previous section that the photon absorption coefficient in a semiconductor is a very strong function of the incident photon energy or wavelength. Figure 14.4 shows the absorption coefficient as a function of wavelength for several semiconductor materials. As the absorption coefficient increases, more photon energy will be absorbed near the surface than deeper into the semiconductor. In this case, then, we will not have uniform excess carrier generation in a solar cell.

The number of photons absorbed per cm^3 per second as a function of distance x from the surface can be written as

$$\alpha \Phi_0 e^{-\alpha x} \tag{14.15}$$

where Φ_0 is the incident photon flux ($\text{cm}^{-2}\ \text{s}^{-1}$) on the surface of the semiconductor. We can also take into account the reflection of photons from the surface. Let $R(\lambda)$ be the fraction of photons that are reflected. (For bare silicon, $R \approx 35$ percent.) If we assume that each photon absorbed creates one electron–hole pair, then the generation rate of electron–hole pairs as a function of distance x from the surface is

$$G_L = \alpha(\lambda)\Phi_0(\lambda)[1 - R(\lambda)]e^{-\alpha(\lambda)x} \tag{14.16}$$

where each parameter may be a function of the incident wavelength. Figure 14.11 shows the excess minority carrier concentrations in this pn solar cell for two values of wavelength and for the case when $s = 0$ at the surface.

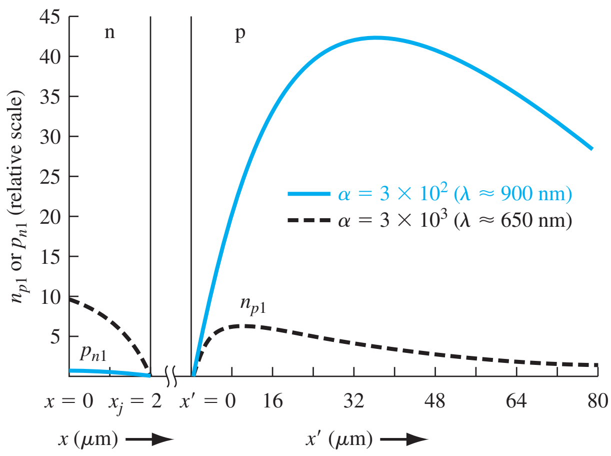

Figure 14.11 | Steady-state, photon-induced normalized minority carrier concentration in the pn junction solar cell for two values of incident photon wavelength ($x_j = 2\ \mu$m, $W = 1\ \mu$m, $L_p = L_n = 40\ \mu$m).

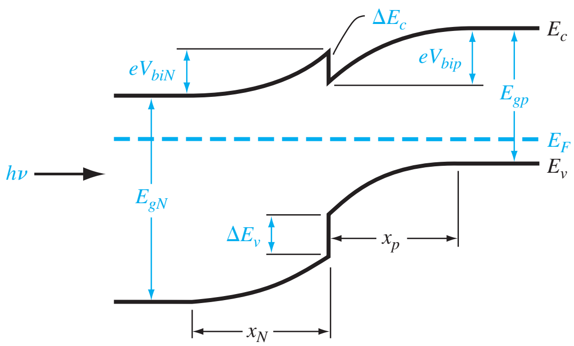

Figure 14.12 | The energy-band diagram of a pN heterojunction in thermal equilibrium.

14.2.4 The Heterojunction Solar Cell

As we have mentioned in previous chapters, a heterojunction is formed between two semiconductors with different bandgap energies. A typical pN heterojunction energy-band diagram in thermal equilibrium is shown in Figure 14.12. Assume that photons are incident on the wide-bandgap material. Photons with energy less than E_{gN} will pass through the wide-bandgap material, which acts as an optical window, and photons with energies greater than E_{gp} will be absorbed in the narrow bandgap material. On the average, excess carriers created in the depletion region and within a diffusion length of the junction will be collected and will contribute to the photocurrent. Photons with an energy greater than E_{gN} will be absorbed in the wide-bandgap

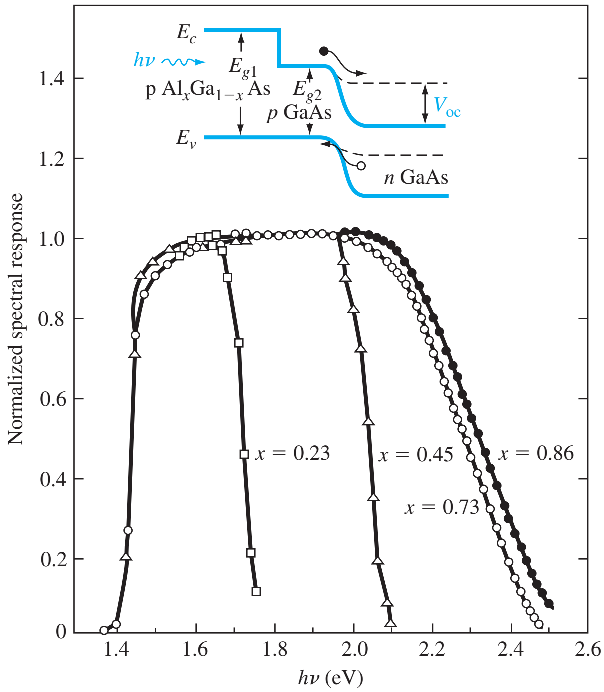

Figure 14.13 | The normalized spectral response of several AlGaAs/GaAs solar cells with different compositions.
(From Sze [17].)

material, and excess carriers generated within one diffusion length of the junction will be collected. If E_{gN} is large enough, then the high-energy photons will be absorbed in the space charge region of the narrow-bandgap material. This heterojunction solar cell should have better characteristics than a homojunction cell, especially at the shorter wavelengths.

A variation of the heterojunction is shown in Figure 14.13. A pn homojunction is formed and then a wide-bandgap material is grown on top. Again, the wide-bandgap material acts as an optical window for photon energies $h\nu < E_{g1}$. Photons with energies $E_{g2} < h\nu < E_{g1}$ will create excess carriers in the homojunction and photons with energies $h\nu > E_{g1}$ will create excess carriers in the window type material. If the absorption coefficient in the narrow bandgap material is high, then essentially all of the excess carriers will be generated within a diffusion length of the junction, so the collection efficiency will be very high. Figure 14.13 also shows the normalized spectral response for various mole fractions x in the $Al_xGa_{1-x}As$.

14.2.5 Amorphous Silicon Solar Cells

Single-crystal silicon solar cells tend to be expensive and are limited to approximately 6 inches in diameter. A system powered by solar cells requires, in general, a very large area solar cell array to generate the required power. Amorphous silicon solar cells provide the possibility of fabricating large area and relatively inexpensive solar cell systems.

When silicon is deposited by CVD techniques at temperatures below 600°C, an amorphous film is formed regardless of the type of substrate. In amorphous silicon, there is only very short range order, and no crystalline regions are observed. Hydrogen may be incorporated in the silicon to reduce the number of dangling bonds, creating a material called hydrogenated amorphous silicon.

The density of states versus energy for amorphous silicon is shown in Figure 14.14. Amorphous silicon contains large numbers of electronic energy states within the normal bandgap of single-crystal silicon. However, because of the short-range order, the effective mobility is quite small, typically in the range between 10^{-6} and 10^{-3} cm^2/V-s. The mobilities in the states above E_c and below E_v are between 1 and 10 cm^2/V-s. Consequently, conduction through the energy states between E_c and E_v is negligible because of the low mobility. Because of the difference in mobility values, E_c and E_v are referred to as the mobility edges and the energy between E_c and E_v is referred to as the mobility gap. The mobility gap can be modified by adding specific types of impurities. Typically, the mobility gap is on the order of 1.7 eV.

Amorphous silicon has a very high optical absorption coefficient, so most sunlight is absorbed within approximately 1 μm of the surface. Consequently, only a

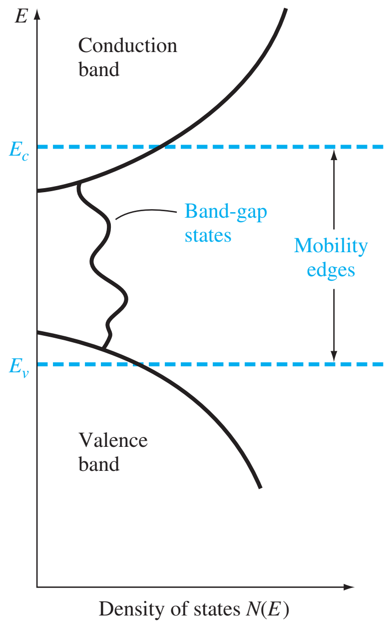

Figure 14.14 | Density of states versus energy of amorphous silicon.
(From Yang [22].)

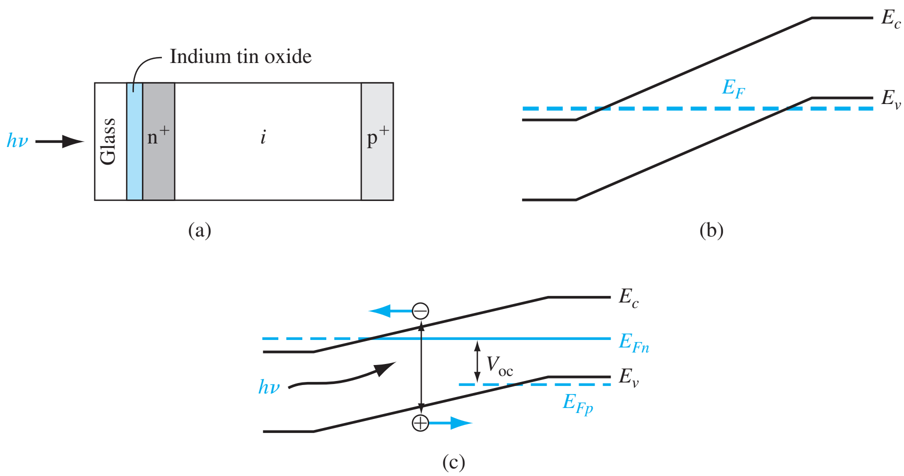

Figure 14.15 | The (a) cross section, (b) energy-band diagram at thermal equilibrium, and (c) energy-band diagram under photon illumination of an amorphous silicon PIN solar cell. *(From Yang [22].)*

very thin layer of amorphous silicon is required for a solar cell. A typical amorphous silicon solar cell is a PIN device shown in Figure 14.15. The amorphous silicon is deposited on an optically transparent indium tin oxide–coated glass substrate. If aluminum is used as the back contact, it will reflect any transmitted photons back through the PIN device. The n^+ and p^+ regions can be quite thin while the intrinsic region may be in the range of 0.5 to 1.0 μm thick. The energy-band diagram for the thermal equilibrium case is shown in the figure. Excess carriers generated in the intrinsic region are separated by the electric field and produce the photocurrent, as we have discussed. Conversion efficiencies are smaller than in single-crystal silicon, but the reduced cost makes this technology attractive. Amorphous silicon solar cells approximately 40 cm wide and many meters long have been fabricated.

TEST YOUR UNDERSTANDING

TYU 14.2 Consider a silicon pn junction solar cell with the parameters given in Example 14.3. Determine the required photocurrent density to produce an open-circuit voltage of $V_{oc} = 0.60$ V.
(Ans. $J_L = 0.414$ A/cm^2)

TYU 14.3 Consider the silicon pn junction solar cell described in Example 14.3. Let the solar intensity increase by a factor of 10. Calculate the open-circuit voltage.
(Ans. $V_{oc} = 0.574$ V)

TYU 14.4 The silicon pn junction solar cell described in TYU 14.2 has a cross-sectional area of 1 cm^2. Determine the maximum power that can be delivered to a load.
(Ans. 0.205 W)

14.3 | PHOTODETECTORS

There are several semiconductor devices that can be used to detect the presence of photons. These devices are known as photodetectors; they convert optical signals into electrical signals. When excess electrons and holes are generated in a semiconductor, there is an increase in the conductivity of the material. This change in conductivity is the basis of the photoconductor, perhaps the simplest type of photodetector. If electrons and holes are generated within the space charge region of a pn junction, then they will be separated by the electric field and a current will be produced. The pn junction is the basis of several photodetector devices including the photodiode and the phototransistor.

14.3.1 Photoconductor

Figure 14.16 shows a bar of semiconductor material with ohmic contacts at each end and a voltage applied between the terminals. The initial thermal-equilibrium conductivity is

$$\sigma_0 = e(\mu_n n_0 + \mu_p p_0) \tag{14.17}$$

If excess carriers are generated in the semiconductor, the conductivity becomes

$$\sigma = e[\mu_n(n_0 + \delta n) + \mu_p(p_0 + \delta p)] \tag{14.18}$$

where δn and δp are the excess electron and hole concentrations, respectively. If we consider an n-type semiconductor, then, from charge neutrality, we can assume that

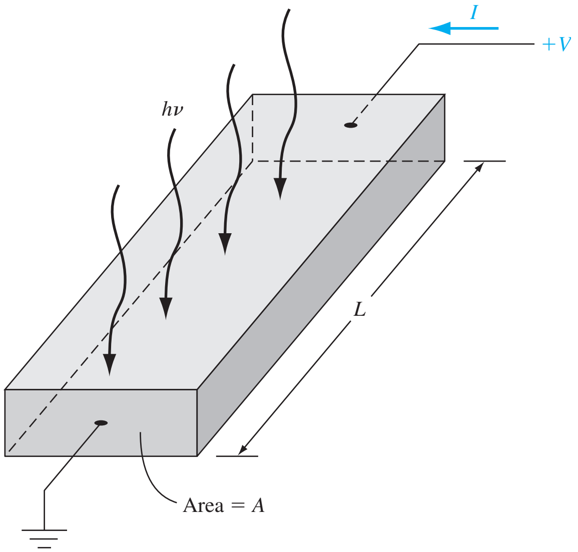

Figure 14.16 | A photoconductor.

$\delta n = \delta p \equiv \delta p$. We will use δp as the concentration of excess carriers. In steady state, the excess carrier concentration is given by $\delta p = G_L \tau_p$, where G_L is the generation rate of excess carriers (cm^{-3}-s^{-1}) and τ_p is the excess minority carrier lifetime.

The conductivity from Equation (14.18) can be rewritten as

$$\sigma = e(\mu_n n_0 + \mu_p p_0) + e(\delta p)(\mu_n + \mu_p) \tag{14.19}$$

The change in conductivity due to the optical excitation, known as the *photoconductivity,* is then

$$\Delta\sigma = e(\delta p)(\mu_n + \mu_p) \tag{14.20}$$

An electric field is induced in the semiconductor by the applied voltage, which produces a current. The current density can be written as

$$J = (J_0 + J_L) = (\sigma_0 + \Delta\sigma)\mathrm{E} \tag{14.21}$$

where J_0 is the current density in the semiconductor prior to optical excitation and J_L is the photocurrent density. The photocurrent density is $J_L = \Delta\sigma \cdot \mathrm{E}$. If the excess electrons and holes are generated uniformly throughout the semiconductor, then the photocurrent is given by

$$I_L = J_L \cdot A = \Delta\sigma \cdot A\mathrm{E} = eG_L\tau_p(\mu_n + \mu_p)A\mathrm{E} \tag{14.22}$$

where A is the cross-sectional area of the device. The photocurrent is directly proportional to the excess carrier generation rate, which in turn is proportional to the incident photon flux.

If excess electrons and holes are not generated uniformly throughout the semiconductor material, then the total photocurrent is found by integrating the photoconductivity over the cross-sectional area.

Since $\mu_n \mathrm{E}$ is the electron drift velocity, the electron transit time, that is, the time required for an electron to flow through the photoconductor, is

$$t_n = \frac{L}{\mu_n \mathrm{E}} \tag{14.23}$$

The photocurrent, from Equation (14.22), can be rewritten as

$$I_L = eG_L\left(\frac{\tau_p}{t_n}\right)\left(1 + \frac{\mu_p}{\mu_n}\right)AL \tag{14.24}$$

We may define a photoconductor gain, Γ_{ph}, as the ratio of the rate at which charge is collected by the contacts to the rate at which charge is generated within the photoconductor. We can write the gain as

$$\Gamma_{\mathrm{ph}} = \frac{I_L}{eG_LAL} \tag{14.25}$$

which, using Equation (14.24), can be written

$$\Gamma_{\mathrm{ph}} = \frac{\tau_p}{t_n}\left(1 + \frac{\mu_p}{\mu_n}\right) \tag{14.26}$$

EXAMPLE 14.4

Objective: Calculate the photoconductor gain of a silicon photoconductor.

Consider an n-type silicon photoconductor with a length $L = 100\ \mu$m, cross-sectional area $A = 10^{-7}$ cm^2, and minority carrier lifetime $\tau_p = 10^{-6}$ s. Let the applied voltage be $V = 10$ volts.

■ Solution

The electron transit time is determined as

$$t_n = \frac{L}{\mu_n \mathrm{E}} = \frac{L^2}{\mu_n V} = \frac{(100 \times 10^{-4})^2}{(1350)(10)} = 7.41 \times 10^{-9}\ \mathrm{s}$$

The photoconductor gain is then

$$\Gamma_{\mathrm{ph}} = \frac{\tau_p}{t_n}\left(1 + \frac{\mu_p}{\mu_n}\right) = \frac{10^{-6}}{7.41 \times 10^{-9}}\left(1 + \frac{480}{1350}\right) = 1.83 \times 10^2$$

■ Comment

The fact that a photoconductor—a bar of semiconductor material—has a gain may be surprising.

■ EXERCISE PROBLEM

Ex 14.4 Consider the photoconductor described in Example 14.4. Determine the photocurrent if $G_L = 10^{21}$ cm^{-3} s^{-1} and $\mathrm{E} = 10$ V/cm. Also assume that $\mu_n = 1000$ cm^2/V-s and $\mu_p = 400$ cm^2/V-s.

(Ans. $I_L = 0.224\ \mu$A)

Let's consider physically what happens to a photon-generated electron, for example. After the excess electron is generated, it drifts very quickly out of the photoconductor at the anode terminal. In order to maintain charge neutrality throughout the photoconductor, another electron immediately enters the photoconductor at the cathode and drifts toward the anode. This process will continue during a time period equal to the mean carrier lifetime. At the end of this period, on the average, the photoelectron will recombine with a hole.

The electron transit time, using the parameters from Example 14.4, is $t_n = 7.41 \times 10^{-9}$ s. In a simplistic sense, the photoelectron will circulate around the photoconductor circuit 135 times during the 10^{-6} s time duration, which is the mean carrier lifetime. If we take into account the photon-generated hole, the total number of charges collected at the photoconductor contacts for every electron generated is 183.

When the optical signal ends, the photocurrent will decay exponentially with a time constant equal to the minority carrier lifetime. From the photoconductor gain expression, we would like a large minority carrier lifetime, but the switching speed is enhanced by a small minority carrier lifetime. There is obviously a trade-off between gain and speed. In general, the performance of a photodiode, which we will discuss next, is superior to that of a photoconductor.

14.3.2 Photodiode

A photodiode is a pn junction diode operated with an applied reverse-biased voltage. We will initially consider a long diode in which excess carriers are generated

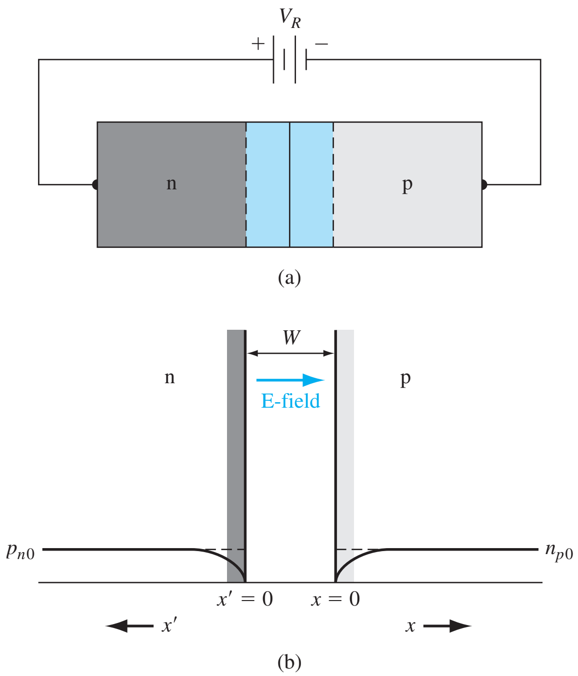

Figure 14.17 | (a) A reverse-biased pn junction. (b) Minority carrier concentration in the reverse-biased pn junction.

uniformly throughout the semiconductor device. Figure 14.17a shows the reverse-biased diode and Figure 14.17b shows the minority carrier distribution in the reverse-biased junction prior to photon illumination.

Let G_L be the generation rate of excess carriers. The excess carriers generated within the space charge region are swept out of the depletion region very quickly by the electric field; the electrons are swept into the n region and the holes into the p region. The photon-generated current density from the space charge region is given by

$$J_{L1} = e \int G_L \, dx \tag{14.27}$$

where the integral is over the space charge region width. If G_L is constant throughout the space charge volume, then

$$J_{L1} = eG_L W \tag{14.28}$$

where W is the space charge width. We may note that J_{L1} is in the reverse-biased direction through the pn junction. This component of photocurrent responds very quickly to the photon illumination and is known as the prompt photocurrent.

We may note, by comparing Equations (14.28) and (14.25), that the photodiode gain is unity. The speed of the photodiode is limited by the carrier transport through the space charge region. If we assume that the saturation drift velocity is 10^7 cm/s and the depletion width is 2 μm, the transit time is $\tau_t = 20$ ps. The ideal modulating frequency has a period of $2\tau_t$, so the frequency is $f = 25$ GHz. This frequency response is substantially higher than that of photoconductors.

Excess carriers are also generated within the neutral n and p regions of the diode. The excess minority carrier electron distribution in the p region is found from the ambipolar transport equation, which is

$$D_n \frac{\partial^2(\delta n_p)}{\partial x^2} + G_L - \frac{\delta n_p}{\tau_{n0}} = \frac{\partial(\delta n_p)}{\partial t} \tag{14.29}$$

We will assume that the E-field is zero in the neutral regions. In steady state, $\partial(\delta n_p)/\partial t = 0$, so that Equation (14.29) can be written as

$$\frac{d^2(\delta n_p)}{dx^2} - \frac{\delta n_p}{L_n^2} = -\frac{G_L}{D_n} \tag{14.30}$$

where $L_n^2 = D_n \tau_{n0}$.

The solution to Equation (14.30) can be found as the sum of the homogeneous and particular solutions. The homogeneous solution is found from the equation

$$\frac{d^2(\delta n_{\mathrm{ph}})}{dx^2} - \frac{\delta n_{\mathrm{ph}}}{L_n^2} = 0 \tag{14.31}$$

where δn_{ph} is the homogeneous solution and is given by

$$\delta n_{\mathrm{ph}} = Ae^{-x/Ln} + Be^{+x/L_n} \qquad (x \geq 0) \tag{14.32}$$

One boundary condition is that δn_{ph} must remain finite, which implies that $B \equiv 0$ for the "long" diode.

The particular solution is found from

$$-\frac{\delta n_{pp}}{L_n^2} = -\frac{G_L}{D_n} \tag{14.33}$$

which yields

$$\delta n_{pp} = \frac{G_L L_n^2}{D_n} = \frac{G_L(D_n \tau_{n0})}{D_n} = G_L \tau_{n0} \tag{14.34}$$

The total steady-state solution for the excess minority carrier electron concentration in the p region is then

$$\delta n_p = Ae^{-x/L_n} + G_L \tau_{n0} \tag{14.35}$$

The total electron concentration is zero at $x = 0$ for the reverse-biased junction. The excess electron concentration $x = 0$ is then

$$\delta n_p(x = 0) = -n_{p0} \tag{14.36}$$

Using the boundary condition from Equation (14.36), the electron concentration given by Equation (14.35) becomes

$$\delta n_p = G_L \tau_{n0} - (G_L \tau_{n0} + n_{p0})e^{-x/L_n} \tag{14.37}$$