Semiconductor Optoelectronics

Lecture 6: Heterojunctions

Optical Devices

The pn Junction Solar Cell

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Basic Principles

Third Edition

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Chapter 9 & 14: Heterojunctions & Optical Devices

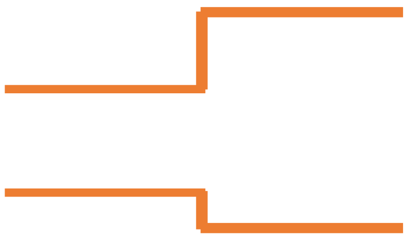
HETEROJUNCTIONS

- When the semiconductor material was homogeneous throughout the entire structure. This type of junction is called a homojunction.
- When two different semiconductor materials are used to form a junction, the junction is called a **heterojunction.**
- The energy diagram energy levels of the step heterojunction exhibit discontinuities at the junction interface.
- In order to have a useful heterojunction, the lattice constants of the two materials must be well matched.
- Nn, Np, nP and pP heterojunctions are used in practice. Here letters n and p denote a semiconductor with a relatively narrow forbidden band and capital letters N and P are related to a semiconductor with a wider forbidden band.
- The heights of the potential barriers are different for electrons and holes

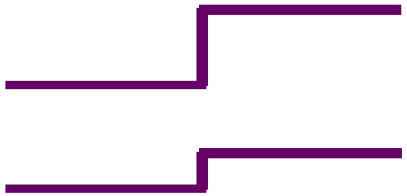
- Heterojunctions with the dopant type changes at the junction are called anisotype. We can form nP or Np junctions.
- Heterojunctions with the same dopant type on either side of the junction are called isotype. We can form nN and pP isotype heterojunctions.
- The ratio of electronic and hole currents is determined by the heights of the barriers for electrons and holes. (In a homojunction this ratio depends on doping of n and p regions.)

Energy-Band Diagrams

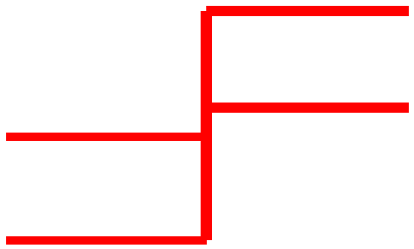
•Straddling
(Type I)
GaAs/$Al_xGa_{1-x}As$



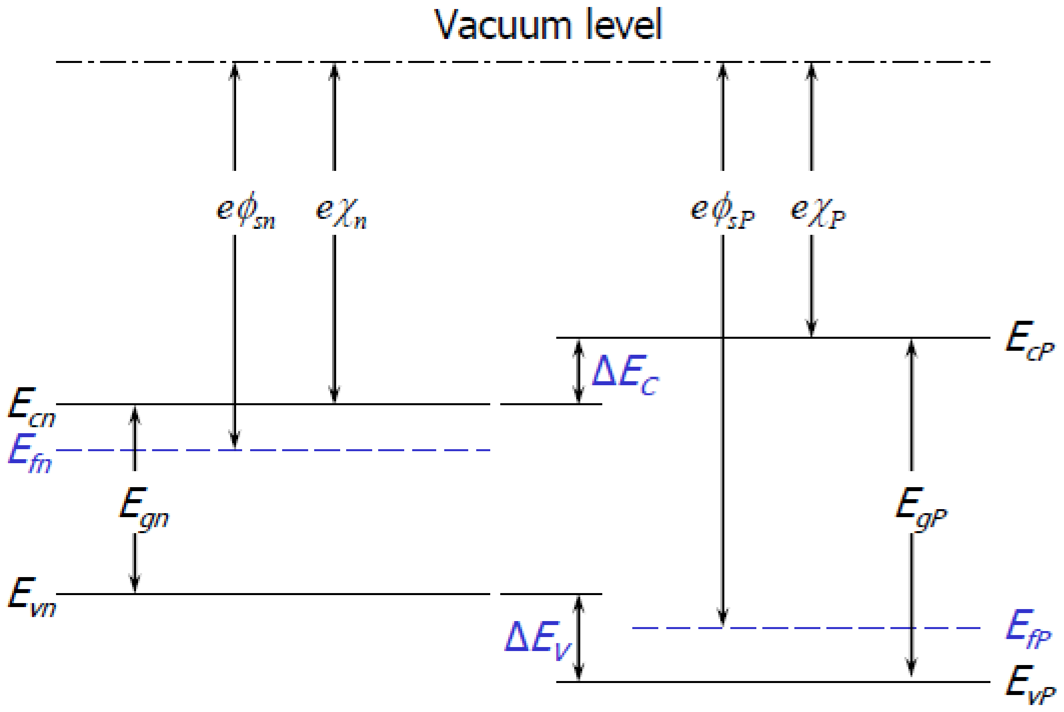
•Staggered
(Type II)
$Ga_xIn_{1-x}As/GaAs_xSb_{1-x}$



•Broken Gap
(*special* Type II)
InAs/GaSb



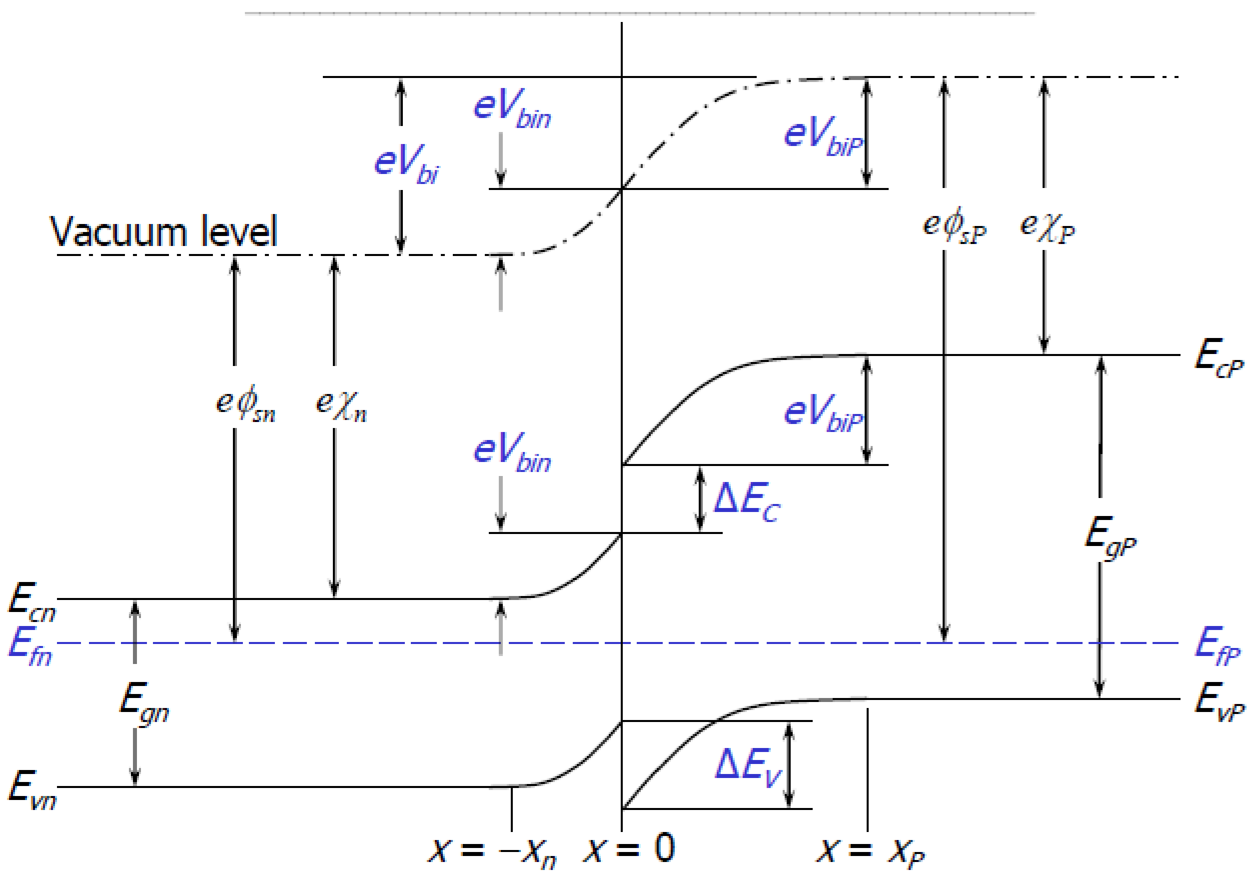
The energy-band diagrams of isolated n-type and P-type materials, with the vacuum level used as a reference. The difference between the two conduction band energies is denoted by ΔE_c and the difference between the two valence band energies is denoted by ΔE_v.



$$\Delta E_c = e(\chi_n - \chi_P)$$

$$\Delta E_c + \Delta E_v = E_{gP} - E_{gn} = \Delta E_g$$

Band diagram n--P junction



Example

To determine ΔE_c, ΔE_v and V_{bi} for an n-Ge to P-GaAs heterojunction using the electron affinity rule. Consider n-type Ge doped with $N_d = 10^{16}$ cm^{-3} and P-type GaAs doped with $N_a = 10^{16}$ cm^{-3} . Let T = 300 K so that $n_i = 2.4 \times 10^{13}$ cm^{-3} for Ge.

Solution

$$\Delta E_c = e(\chi_n - \chi_p) = e(4.13 - 4.07) = 0.06eV$$

$$\Delta E_v = \Delta E_g - \Delta E_c = (1.43 - 0.67) - 0.06 = 0.7eV$$

$$p_{no} = \frac{n_i^2}{N_d} = \frac{(2.4\times 10^{13})^2}{10^{16}} = 5.76\times 10^{10}\,cm^{-3}$$

$$eV_{bi} = \Delta E_v + kT\ln\left(\frac{N_{vn}}{N_{vP}}\cdot\frac{p_{po}}{p_{no}}\right)$$

$$eV_{bi} = 0.7 + 0.0259\ln\left(\frac{(10^{16})(10^{18})}{(5.76\times 10^{10})(7\times 10^{18})}\right)$$ then $$V_{bi} \approx 1V$$

Optical Devices

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*.

14.1 | OPTICAL ABSORPTION

$E = h\nu$ 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.

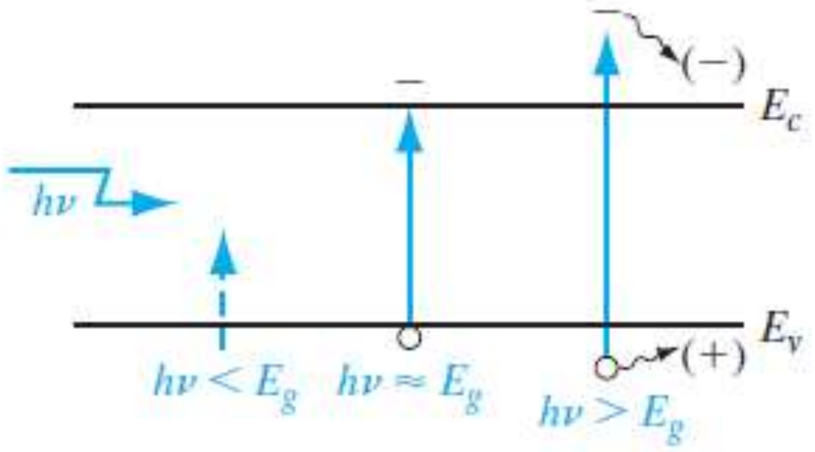


Figure 14.1 | Optically generated electron–hole pair formation in a semiconductor.

14.1.1 Photon Absorption Coefficient

The intensity of the photon flux is denoted by $I(x)$ 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

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

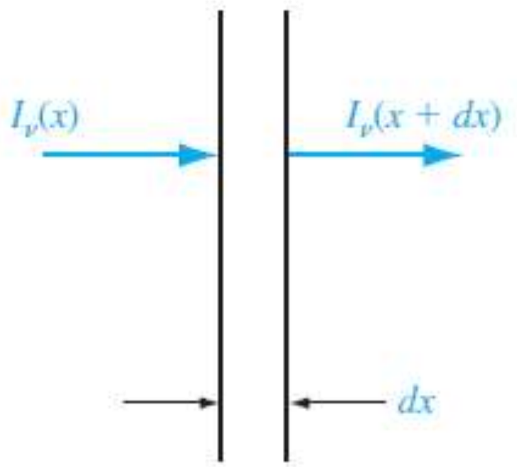


Figure 14.2 | Optical absorption in a differential length.

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.

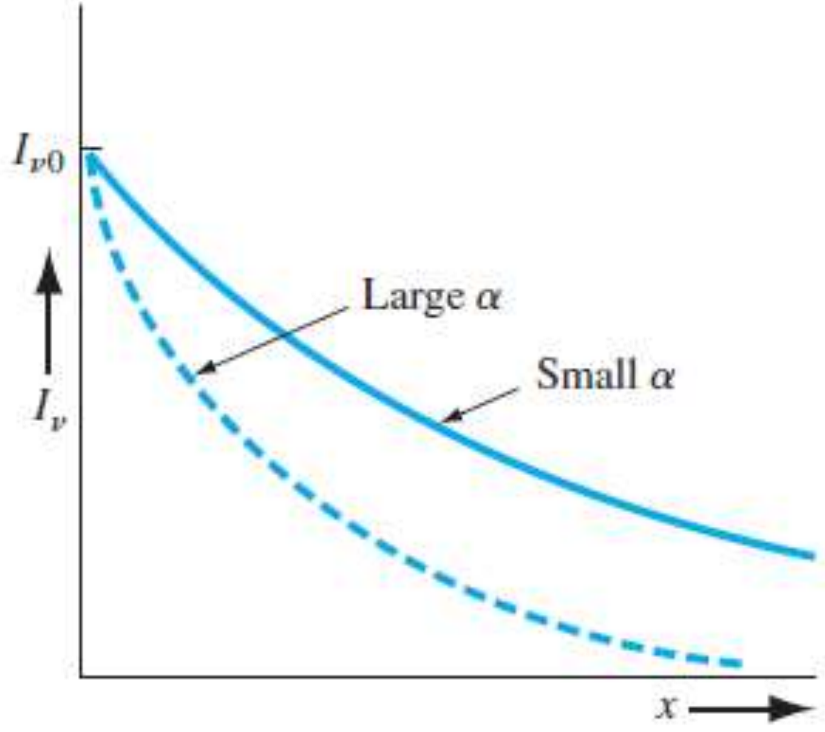
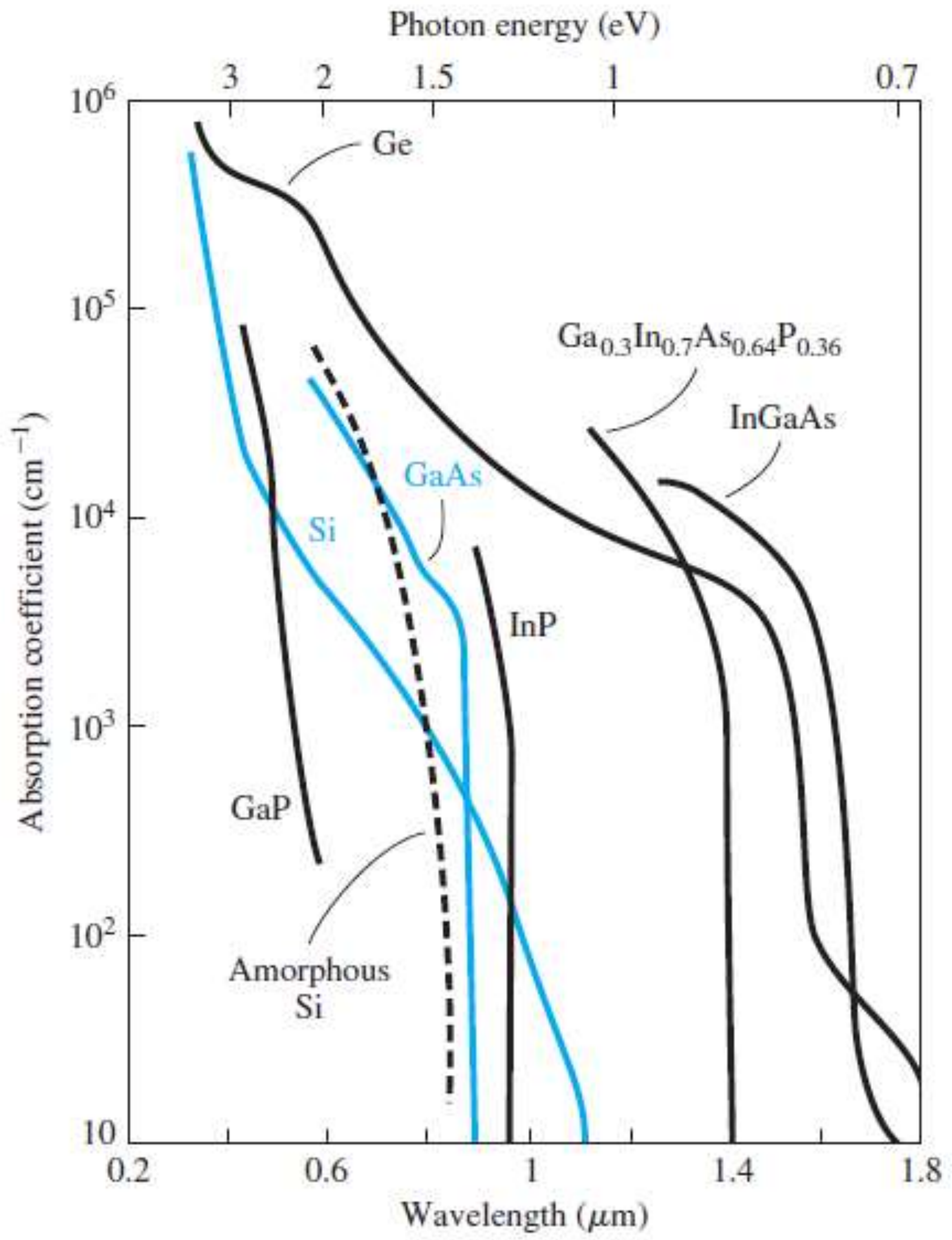


Figure 14.3 | Photon intensity versus distance for two absorption coefficients.

The absorption coefficient in the semiconductor is a very strong function of photon energy and bandgap energy. Figure 14.4 shows the absorption coefficient 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 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 $\alpha \approx 10^2\ cm^{-1}$ 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 $\lambda = 0.5\ \mu m$. 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.

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.

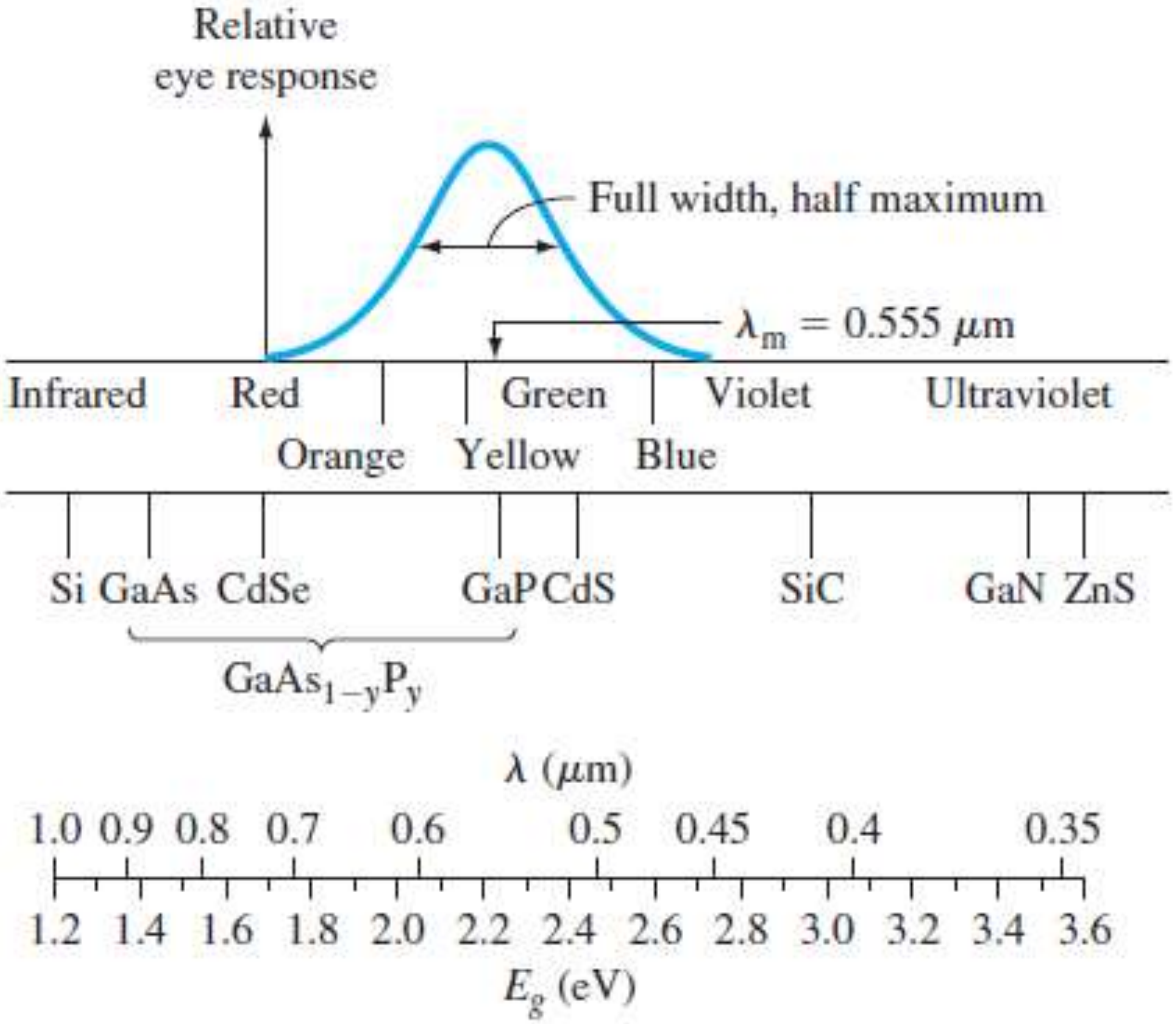


Figure 14.5 | Light spectrum versus wavelength and energy. Figure includes relative response of the human eye. *(From Sze [18].)*

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 $I(x)$ is in units of

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.

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

EXAMPLE 14.2

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.

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.

14.2.1 The pn Junction Solar Cell

The photocurrent I_L produces a voltage drop across the resistive load which forward biases the pn junction

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

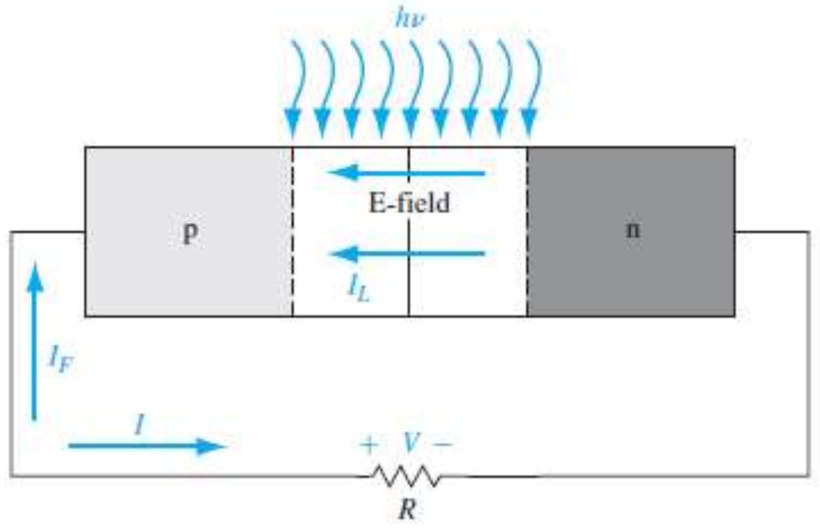


Figure 14.6 | A pn junction solar cell with resistive load.

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.

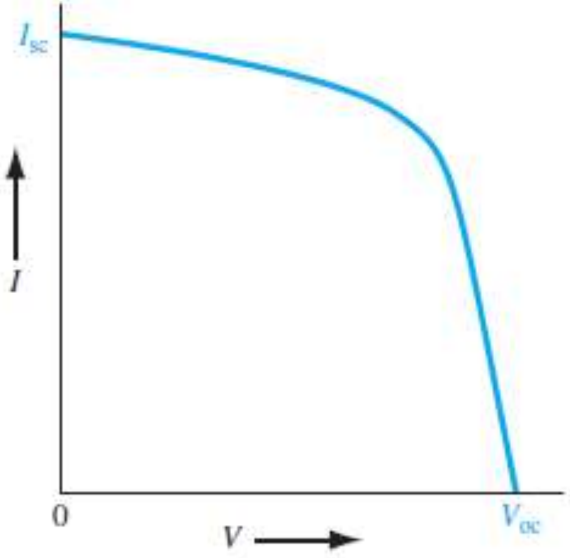


Figure 14.7 | I–V characteristics of a pn junction solar cell.

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

EXAMPLE 14.3

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

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

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

■ 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

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

■ 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.

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

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

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.

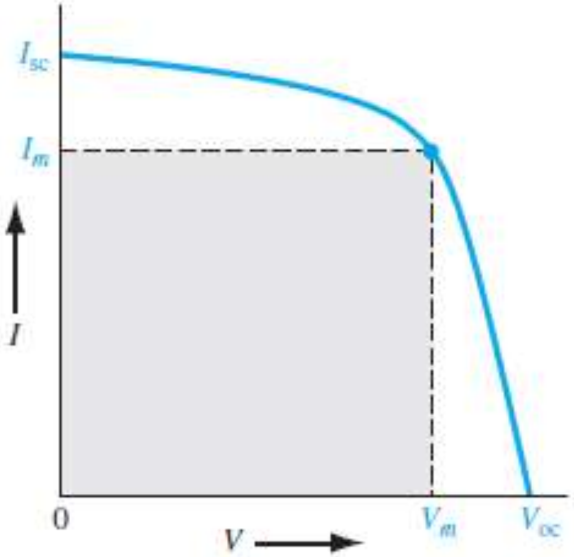


Figure 14.8 | Maximum power rectangle of the solar cell I–V characteristics.

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.

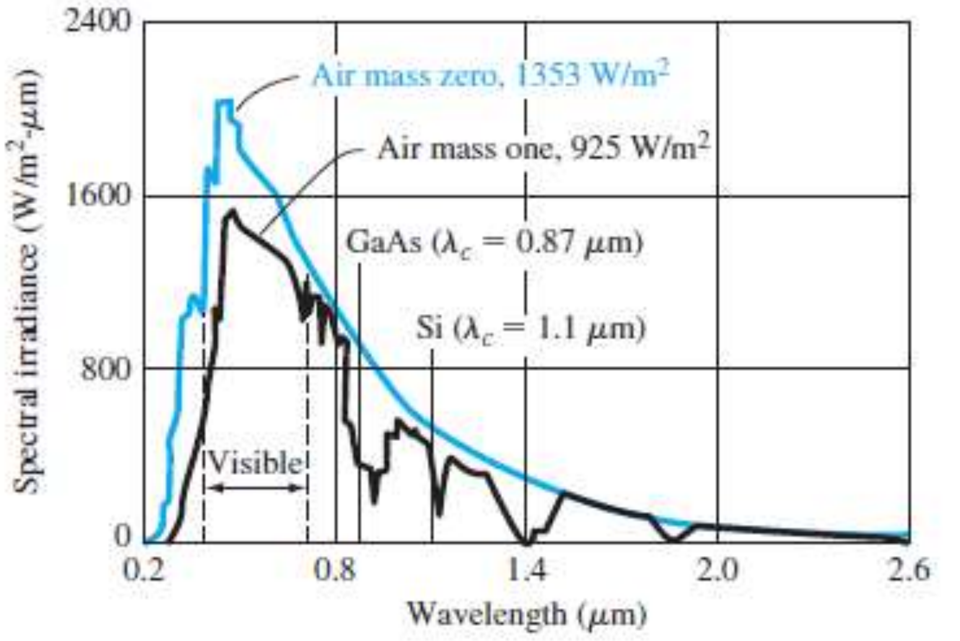


Figure 14.9 | Solar spectral irradiance.
(From Sze [18].)

14.2.4 The Heterojunction Solar Cell

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

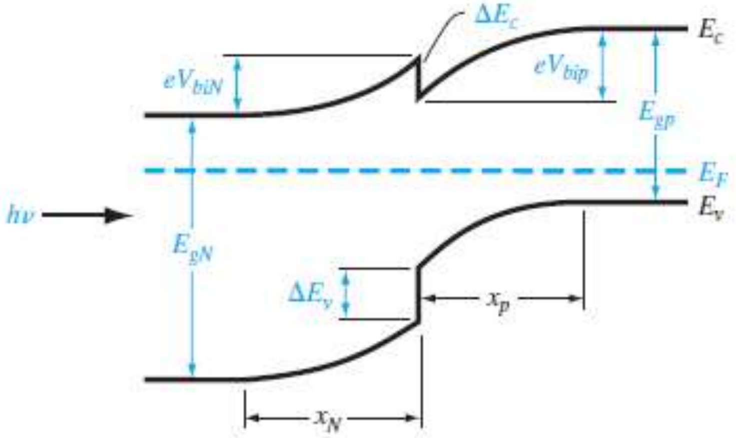


Figure 14.12 | The energy-band diagram of a pN heterojunction in thermal equilibrium.