Semiconductor Optoelectronics

Lecture 7: Optical Devices

PHOTODETECTORS

Asst. Prof. Dr. Ghusoon Mohsin Ali

4th year Electronics & Communication

Department of Electrical Engineering

College of Engineering

Mustansiriyah University

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Chapter 14: Optical Devices

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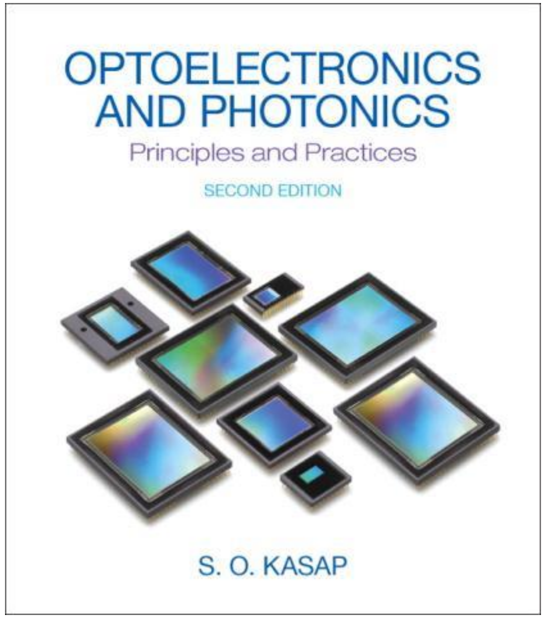
Chapter 5



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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 fi eld and a current will be produced.

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

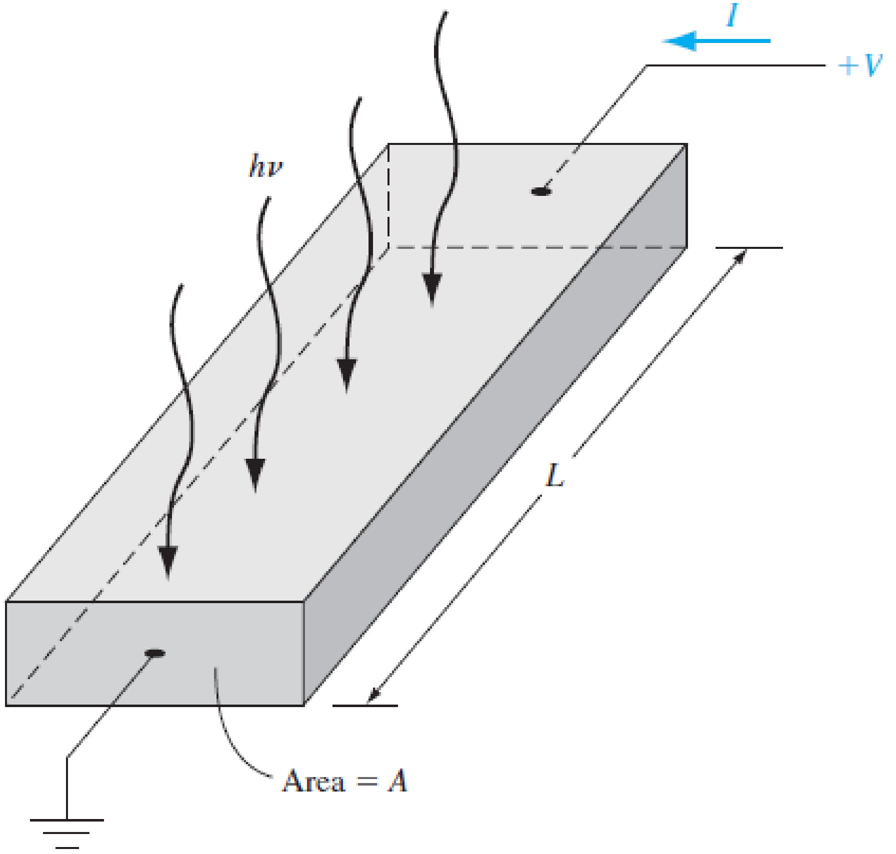


Figure 14.16 | A photoconductor.

$\delta n = \delta p \equiv \delta p$. 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.

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

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

which, using Equation (14.24), can be written

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

Objective: Calculate the photoconductor gain of a silicon photoconductor.

EXAMPLE 14.4

Consider an n-type silicon photoconductor with a length $L = 100\ \mu\text{m}$, cross-sectional area $A = 10^{-7}\ \text{cm}^2$, 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

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

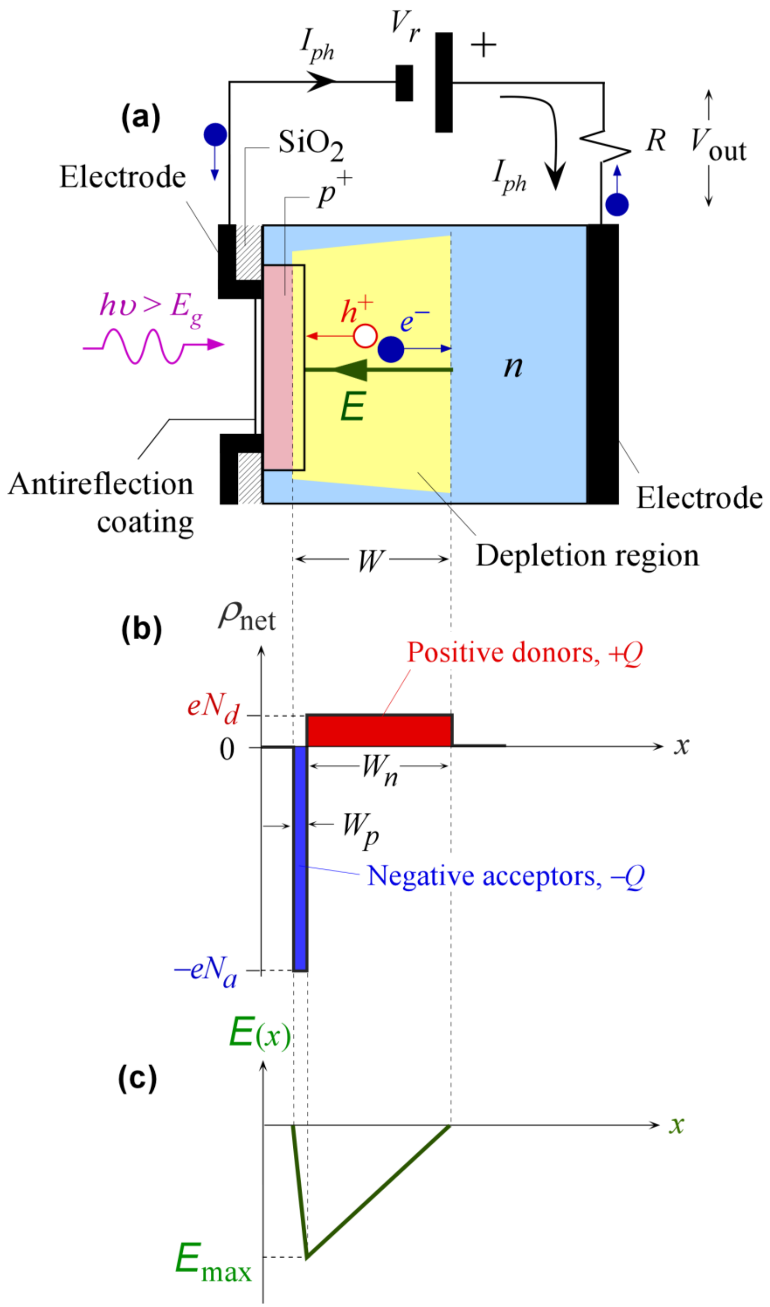
The photoconductor gain is then

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

■ Comment

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

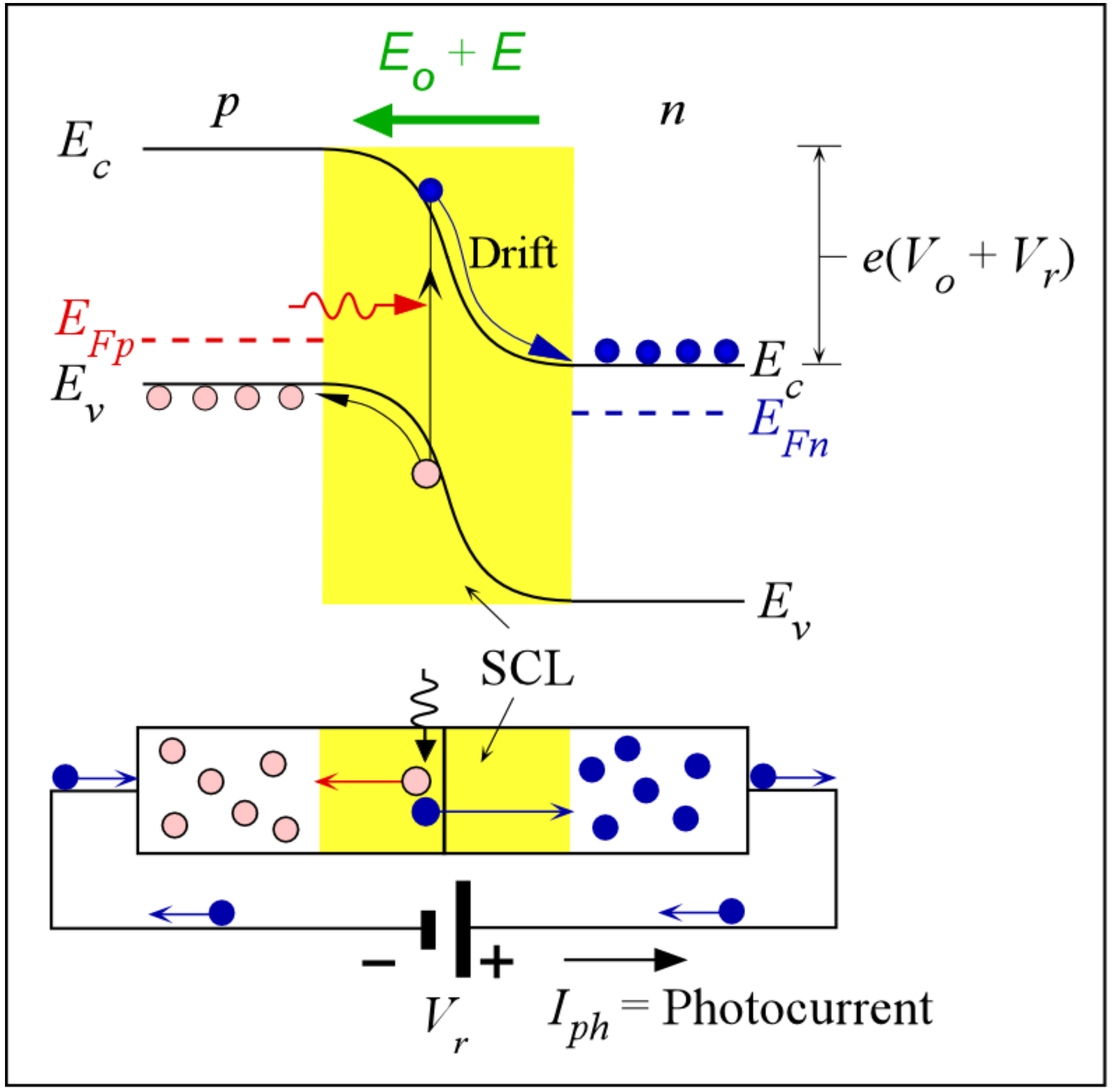
pn Junction Photodiode



(a) A schematic diagram of a reverse biased *pn* junction photodiode. (b) Net space charge across the diode in the depletion region. N_d and N_a are the donor and acceptor concentrations in the *p* and *n* sides. (c) The field in the depletion region.

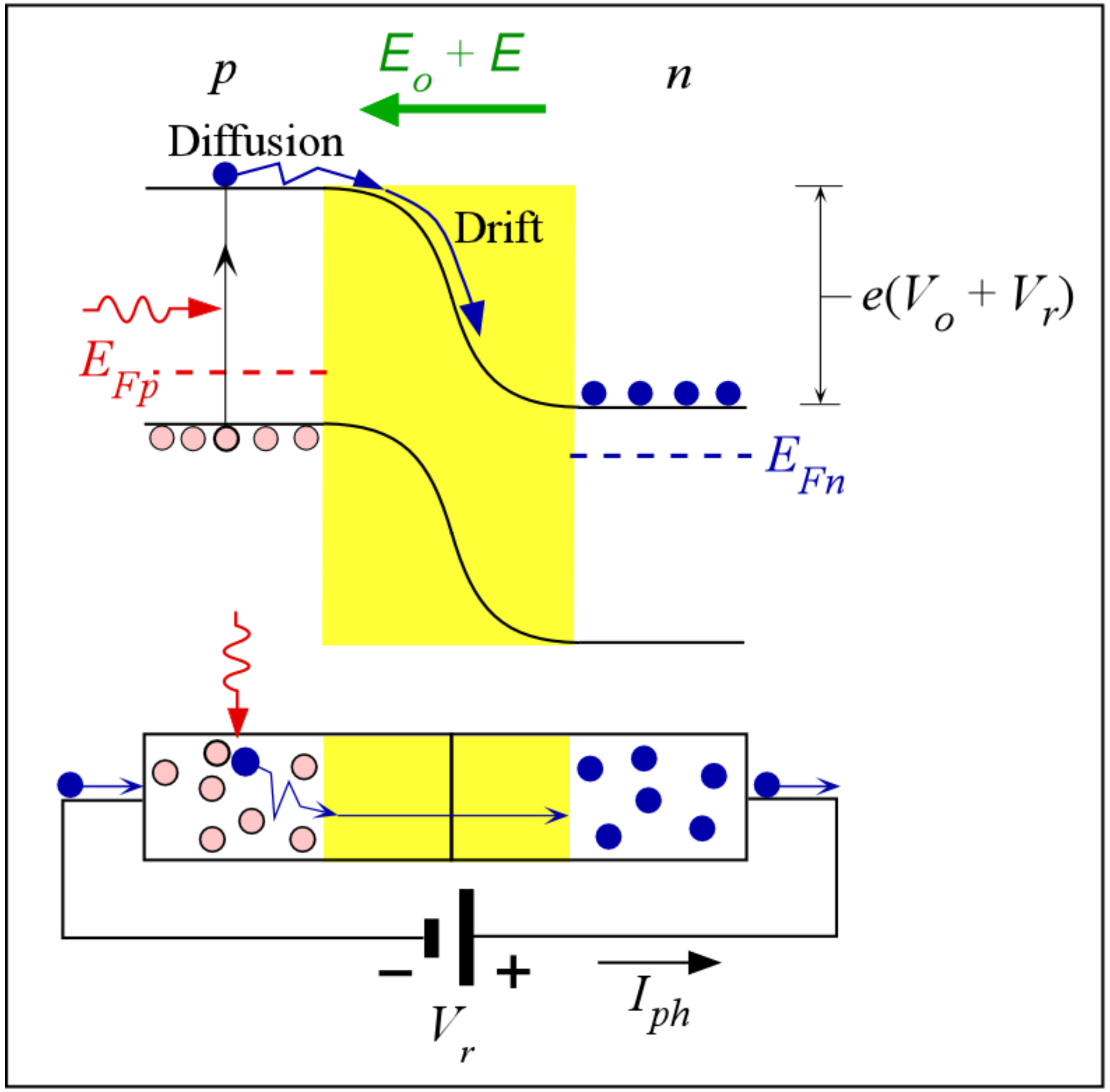
(Note: Depletion region shape in (a) is schematic only.)

pn Junction Photodiode



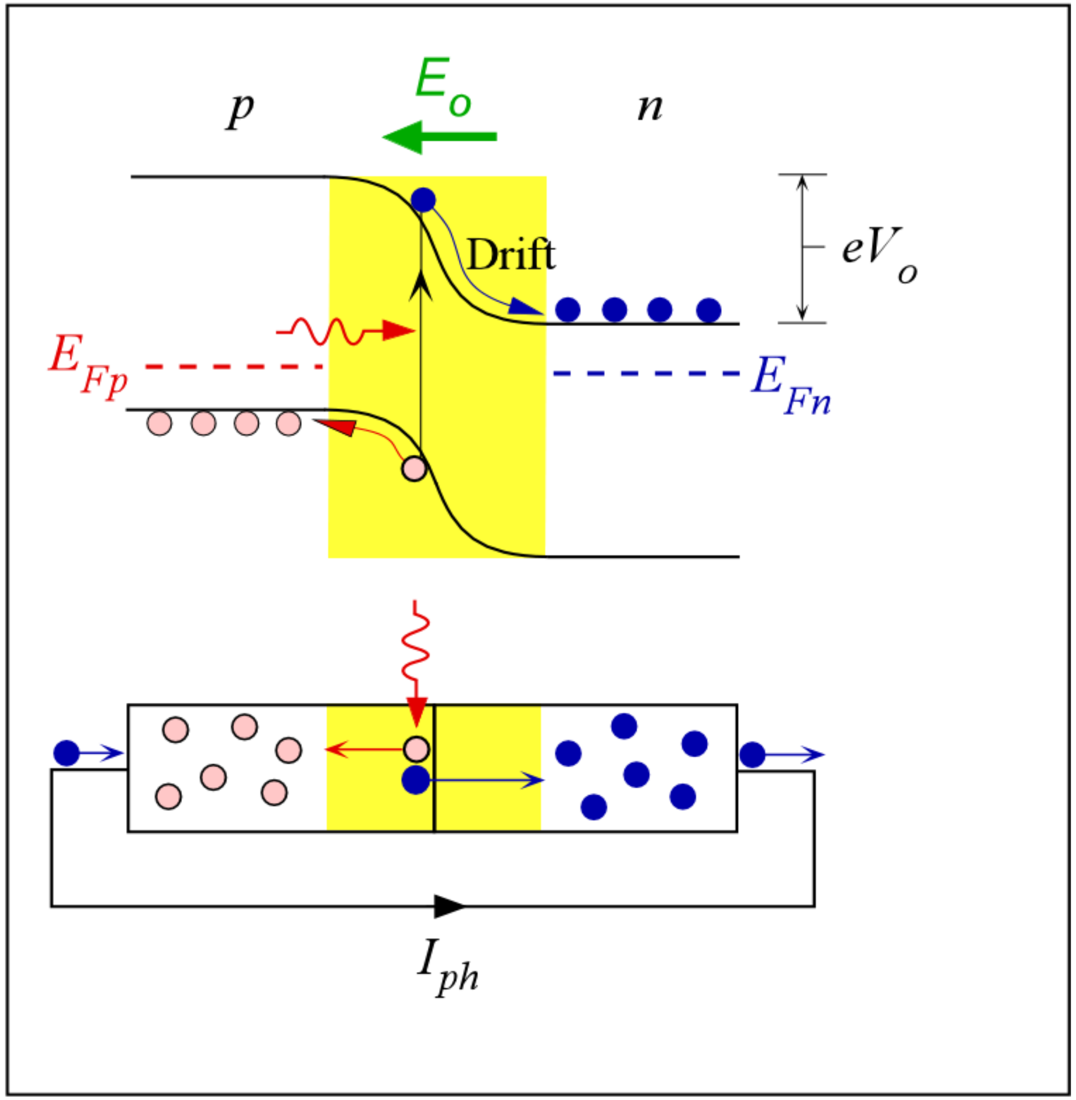
A reverse biased *pn* junction. Photogeneration inside the SCL generates an electron and a hole. Both fall their respective energy hills (electron along E_c and hole along E_v) *i.e.* they drift, and cause a photocurrent I_{ph} in the external circuit.

pn Junction Photodiode



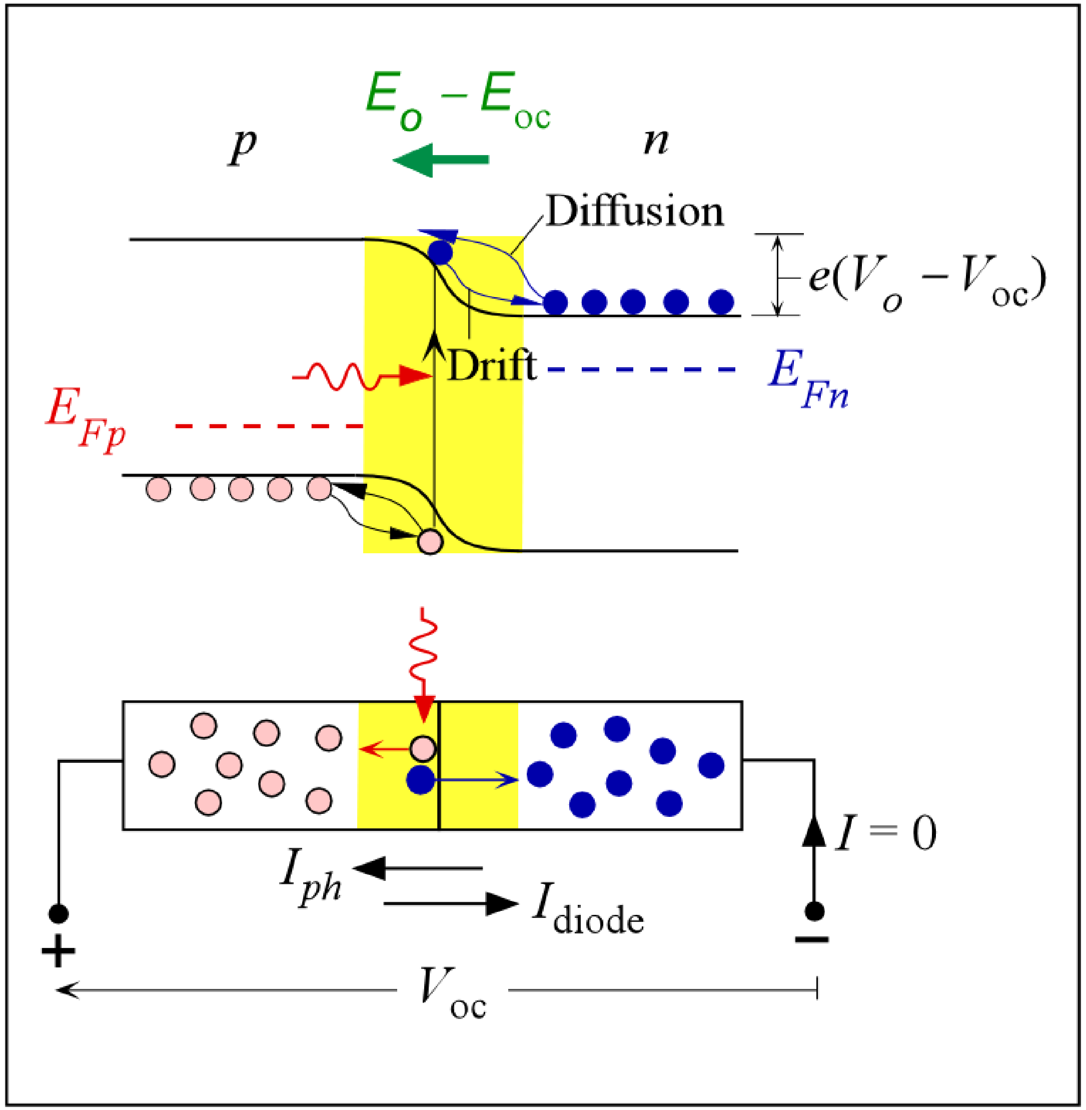
Photogeneration occurs in the neutral region. The electron has to diffuse to the depletion layer and then roll down the energy hill *i.e.* drift across the SCL.

pn Junction Photodiode



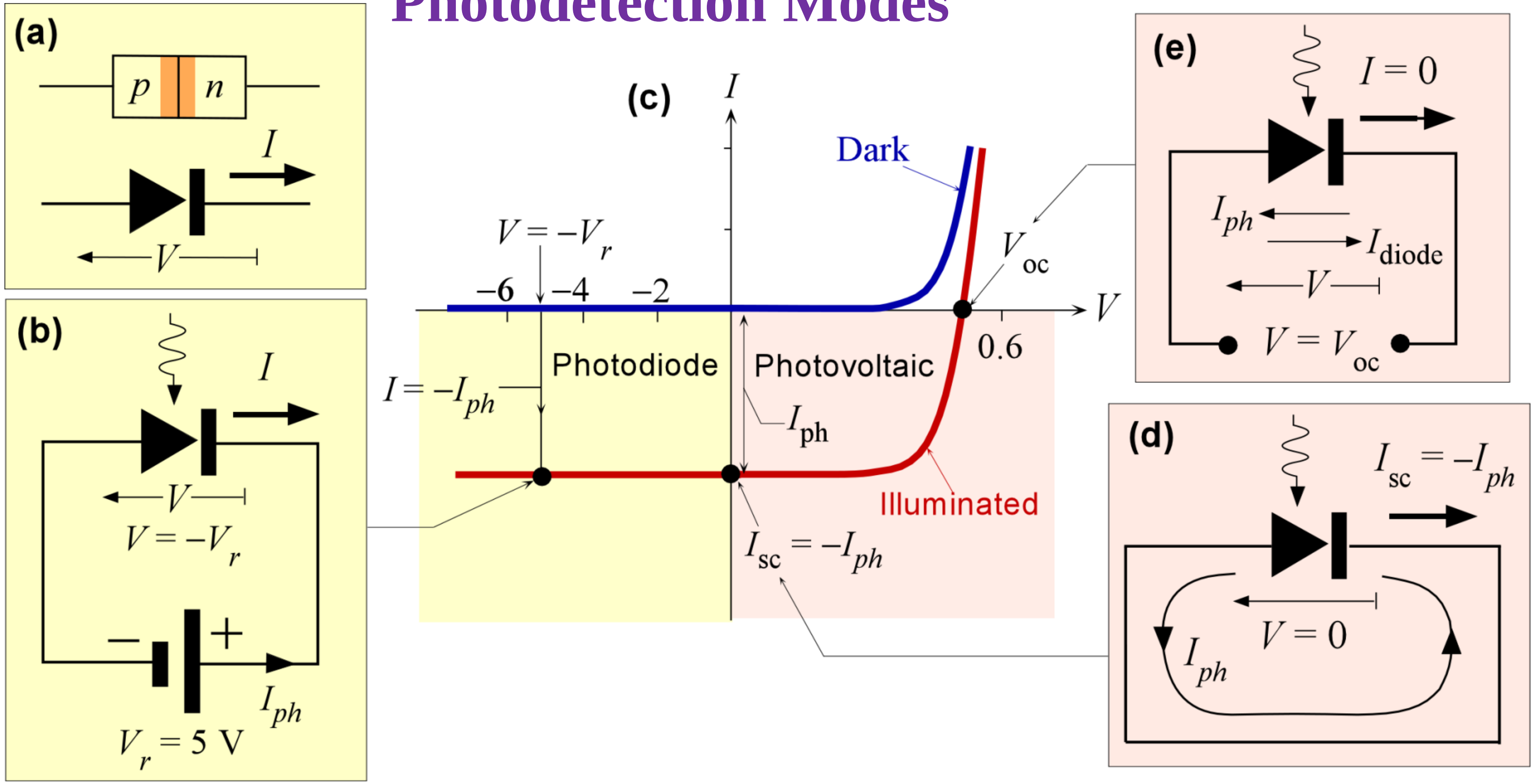
A shorted *pn* junction. The photogenerated electron and hole in the SCL roll down their energy hills, *i.e.* drift across the SCL, and cause a current I_{ph} in the external circuit.

pn Junction Photodiode



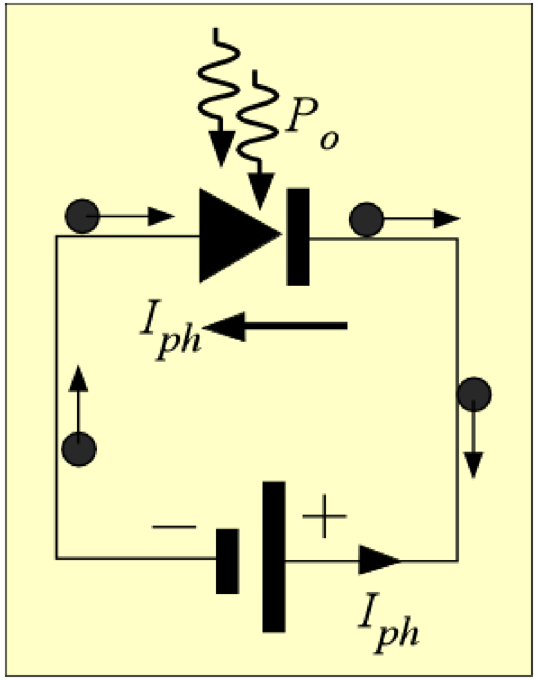
The *pn* junction in open circuit. The photogenerated electron and hole roll down their energy hills (drift) but there is a voltage V_{oc} across the diode that causes them the diffuse back so that the net current is zero.

Photodetection Modes



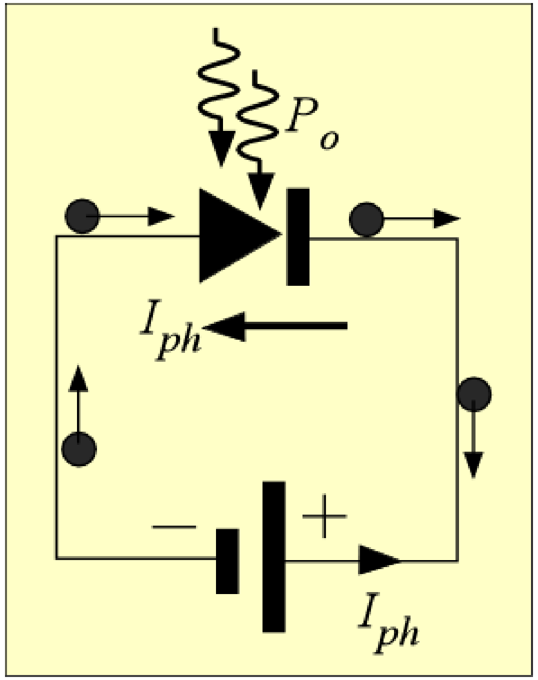
(a) The sign convention for the voltage V and current I for a pn junction. (b) If the pn junction is reverse biased by $V_r = 5$V, then $V = -V_r = -5$V. Under illumination, the pn junction current $I = -I_{ph}$ and is negative. (C) The I–V characteristics of a pn junction in the dark and under illumination. (d) A short circuit pn junction under illumination. The voltage $V = 0$ but there is a short circuit current so that $I = I_{sc} = -I_{ph}$. (e) An open circuit pn junction under illumination generates an open circuit voltage V_{oc}.

External quantum efficiency (QE) η_e of the detector



$$\eta_e = \frac{\text{Number of free EHP generated and collected}}{\text{Number of incident photons}}$$

$$\eta_e = \frac{I_{ph}/e}{P_o/h\upsilon}$$

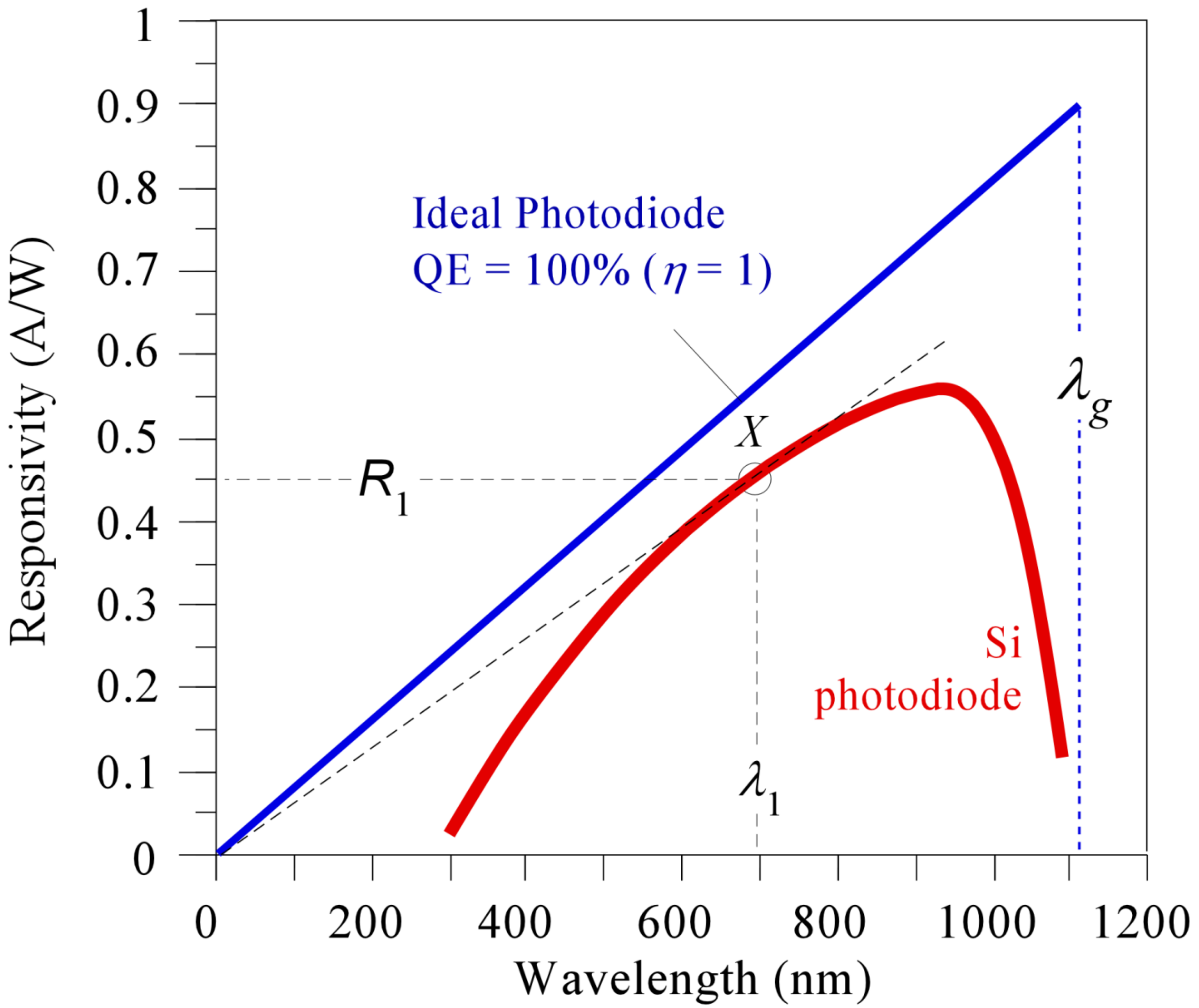


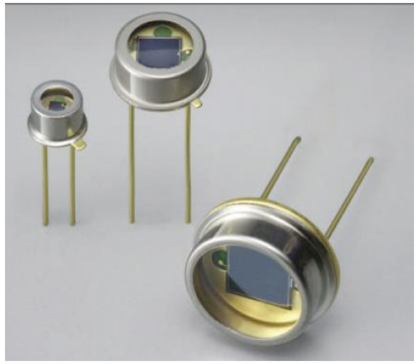
Responsivity *R*

$$R = \frac{\text{Photocurrent (A)}}{\text{Incident Optical Power (W)}} = \frac{I_{ph}}{P_o}$$

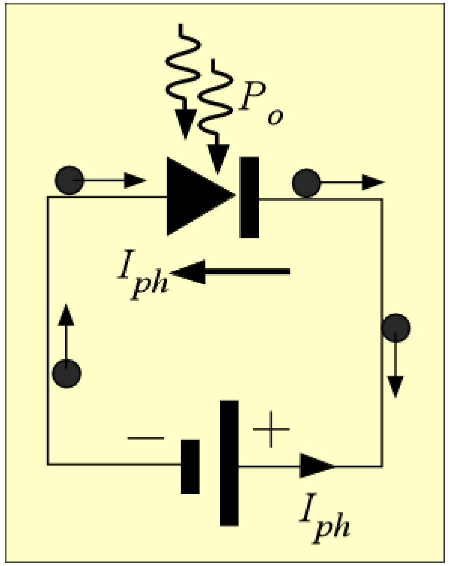
$$R = \eta_e \frac{e}{h\upsilon} = \eta_e \frac{e\lambda}{hc}$$

Responsivity *R*

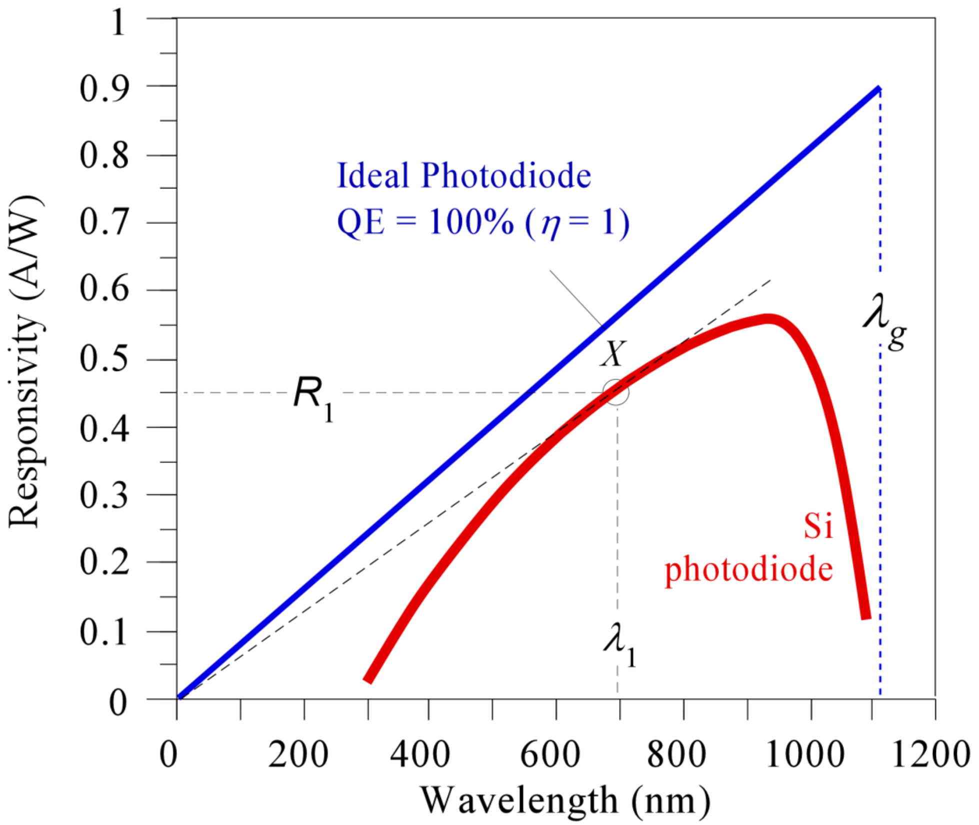




Si photodiodes of various sizes (S1336 series). (Courtesy of Hamamatsu)



Responsivity *R*



Responsivity (R) vs. wavelength (λ) for an ideal photodiode with QE = 100% (η_e = 1) and for a typical inexpensive commercial Si photodiode. The exact shape of the responsivity curve depends on the device structure.

The line through the origin that is a tangent to the responsivity curve at *X*, identifies operation at λ_1 with maximum QE

EXAMPLE: Quantum efficiency and responsivity

Consider the photodiode shown in Figure 5.7. What is the QE at peak responsivity? What is the QE at 450 nm (blue)? If the photosensitive device area is 1 mm^2, what would be the light intensity corresponding to a photocurrent of 10 nA at the peak responsivity?

Solution

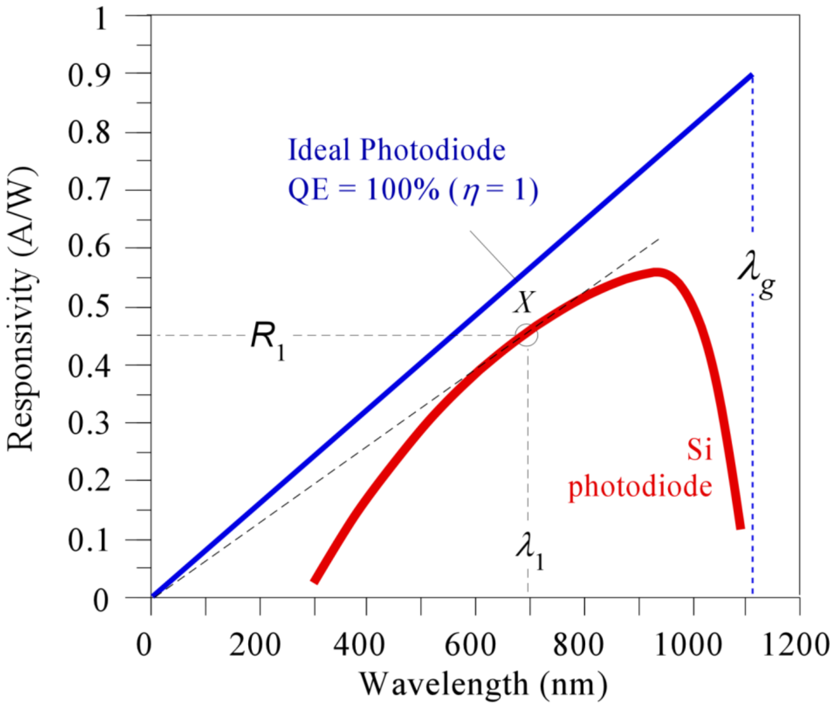
The peak responsibility in Figure 5.7 occurs at about $\lambda \approx 940$ nm where $R \approx 0.56$ A W^{-1}. Thus, from Eq. (5.4.4), that is $R = \eta_e e\lambda / hc$, we have

$$0.56\text{AW}^{-1} = \eta_e \frac{(1.6\times10^{-19}\ \text{C})(940\times10^{-9}\ \text{m})}{(6.63\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})}$$

i.e. $\eta_e = 0.74$ or **74%**

We can repeat the calculation for $\lambda = 450$ nm, where $R \approx 0.24$ AW^{-1}, which gives $\eta_e = 0.66$ or 66%.

From the definition of responsivity, $R = I_{ph}/P_o$, we have 0.56 AW^{-1} = (10×10^{-9} A)/P_o, *i.e.* P_o = 1.8×10^{-8} W or 18 nW. Since the area is 1 mm^2 the intensity must be 18 nW mm^{-2}.



Total steady state photodiode current

Let G_L be the generation rate of excess carriers. The photon-generated current density from the space charge region is given by

$$J_L = eG_LW + eG_LL_n + eG_LL_p = e(W + L_n + L_p)G_L \qquad (14.42)$$

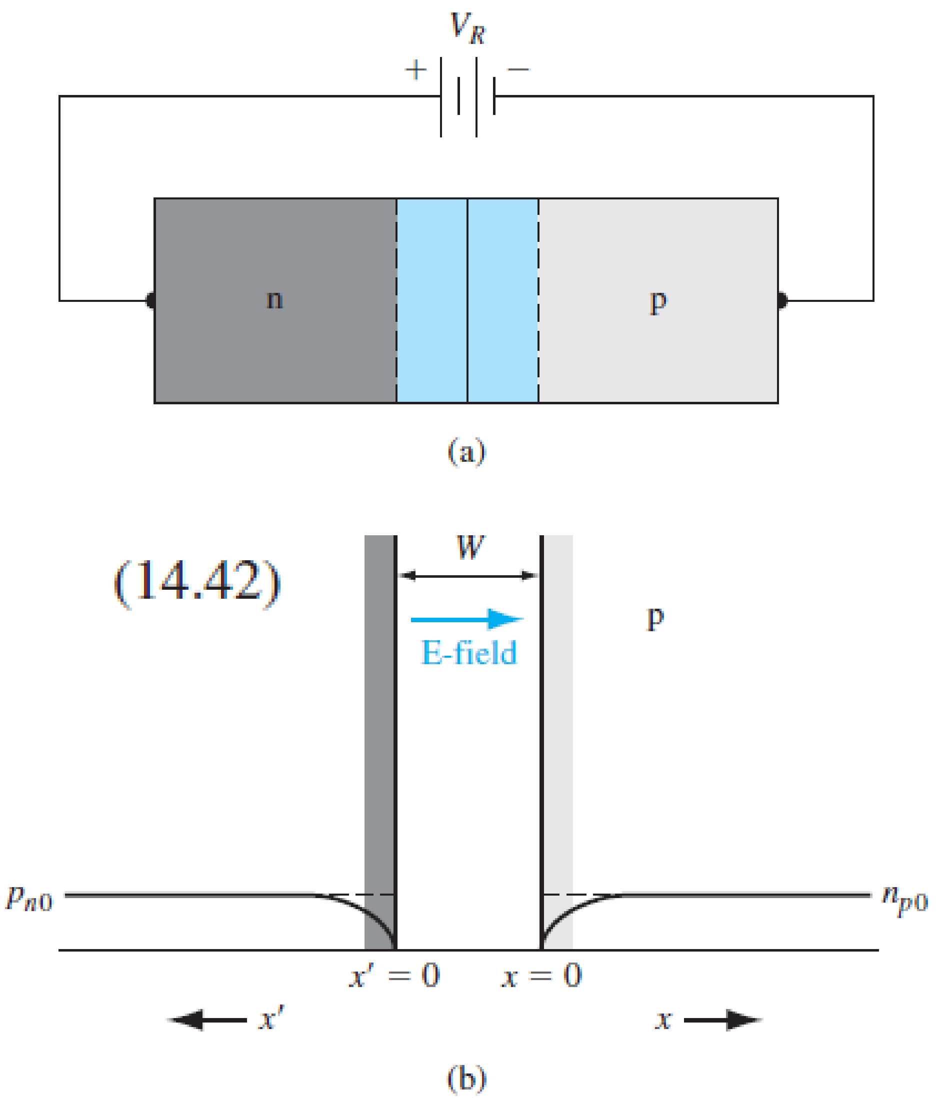


Figure 14.17 | (a) A reverse-biased pn junction. (b) Minority carrier concentration in the reverse-biased pn junction.

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 τ = 20 ps. The ideal modulating frequency has a period of 2τ, so the frequency is f = 25 GHz. This frequency response is substantially higher than that of photoconductors.

EXAMPLE 14.5

Objective: Calculate the steady-state photocurrent density in a reverse-biased, long pn diode.

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

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

Assume that a reverse-biased voltage of $V_R = 5$ volts is applied and let $G_L = 10^{21}$ cm^{-3}-s^{-1}.

■ Solution

We may calculate various parameters as follows:

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

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

$$V_{bi} = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right) = (0.0259) \ln\left[\frac{(10^{16})(10^{16})}{(1.5 \times 10^{10})^2}\right] = 0.695\ \text{V}$$

$$W = \left\{\frac{2\epsilon_s}{e}\left(\frac{N_a + N_d}{N_a N_d}\right)(V_{bi} + V_R)\right\}^{1/2}$$

$$= \left\{\frac{2(11.7)(8.85 \times 10^{-14})}{1.6 \times 10^{-19}} \cdot \frac{(2 \times 10^{16})}{(10^{16})(10^{16})} \cdot (0.695 + 5)\right\}^{1/2} = 1.21\ \mu\text{m}$$

Finally, the steady-state photocurrent density is

$$J_L = e(W + L_n + L_p)G_L$$
$$= (1.6 \times 10^{-19})(1.21 + 35.4 + 10.0) \times 10^{-4}(10^{21}) = 0.75\ \text{A/cm}^2$$

■ Comment

Again, keep in mind that this photocurrent is in the reverse-biased direction through the diode and is many orders of magnitude larger than the reverse-biased saturation current density in the pn junction diode.