Semiconductor Optoelectronics

Lecture 8: Optical Devices

PHOTODETECTORS

PHOTOLUMINESCENCE AND ELECTROLUMINESCENCE

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Basic Principles

Third Edition

Donald A. Neamen

Chapter 14: Optical Devices

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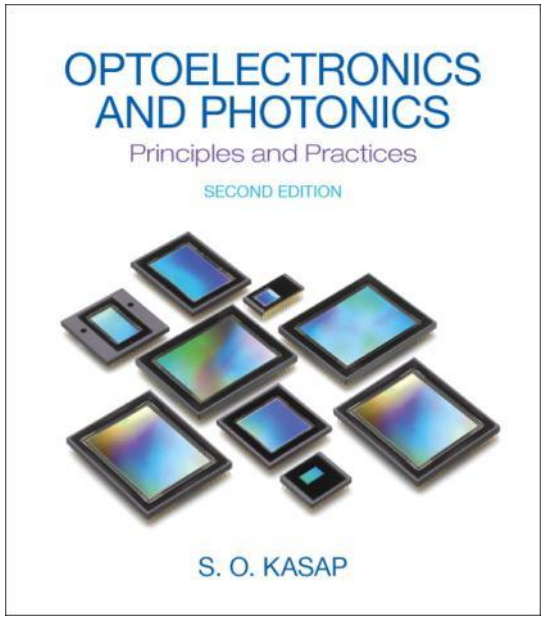
Chapter 5



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14.3.3 PIN Photodiode

The PIN diode consists of a p region and an n region separated by an intrinsic region. A sketch of a PIN diode is shown in Figure 14.19a. The intrinsic region width W is much larger than the space charge width of a normal pn junction. If a reverse bias is applied to the PIN diode, the space charge region extends completely through the intrinsic region.

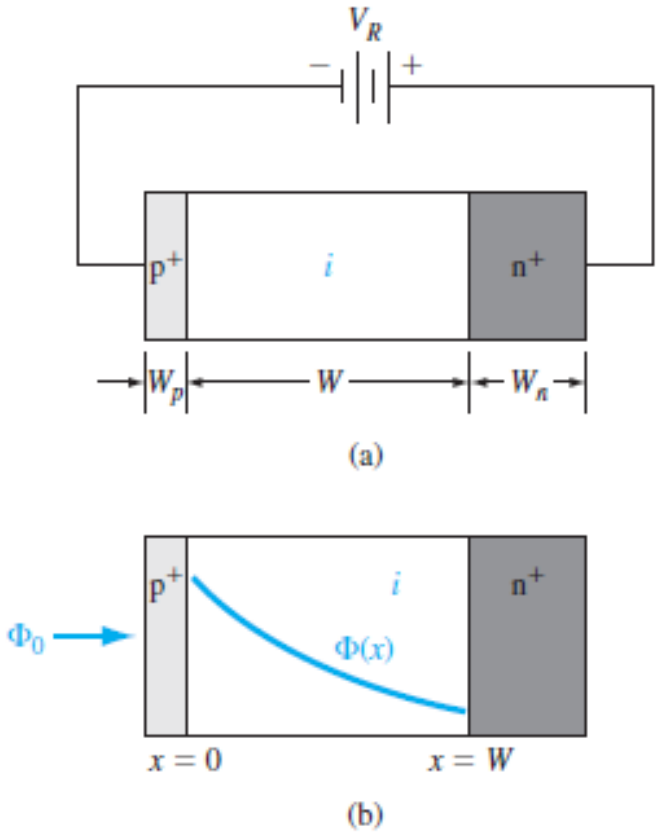
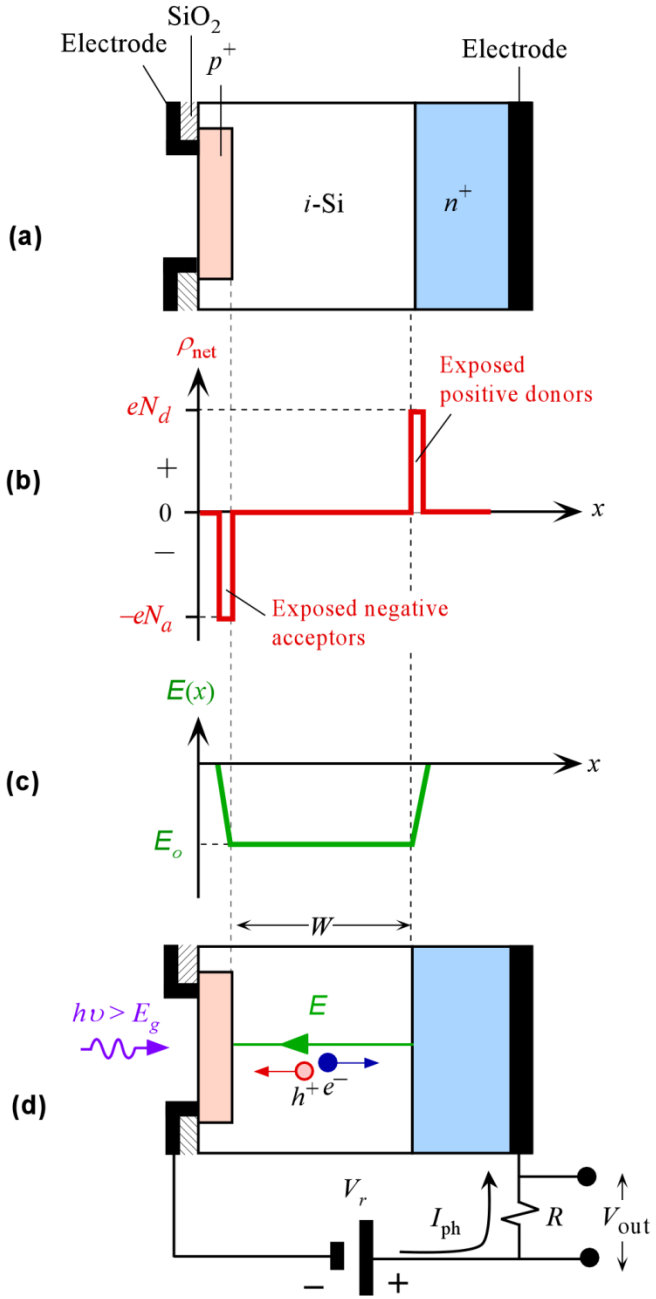
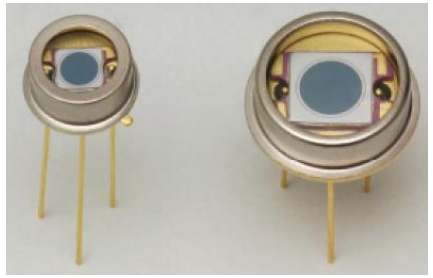


Figure 14.19 | (a) A reverse-biased PIN photodiode. (b) Geometry showing nonuniform photon absorption.

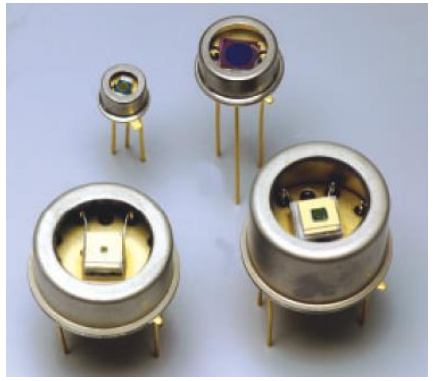
pin Photodiode



The schematic structure of an idealized pin photodiode (b) The net space charge density across the photodiode. (c) The built-in field across the diode. (d) The pin photodiode reverse biased for photodetection.



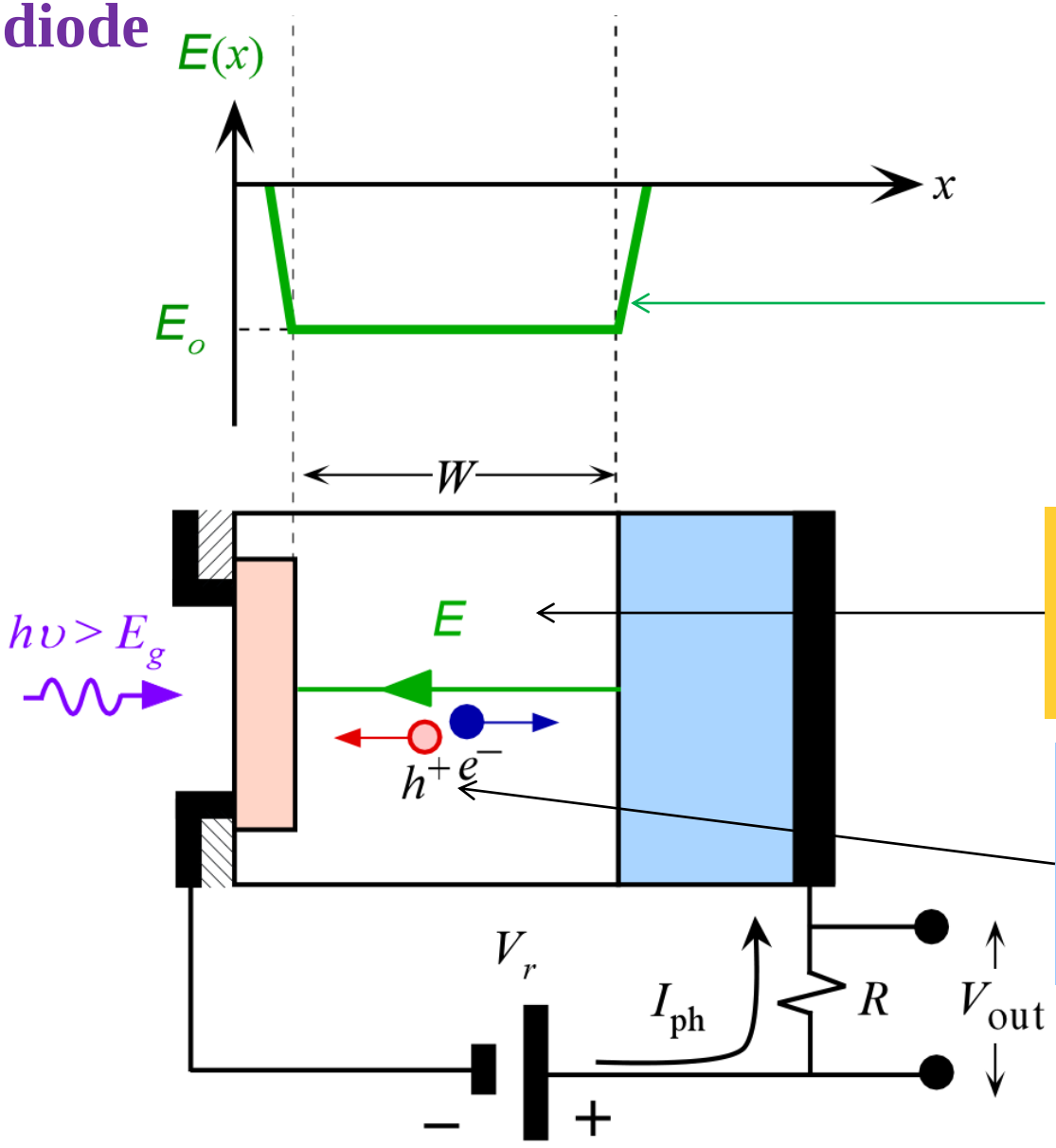
Si pin



InGaAs pin

Courtesy of Hamamatsu

pin Photodiode

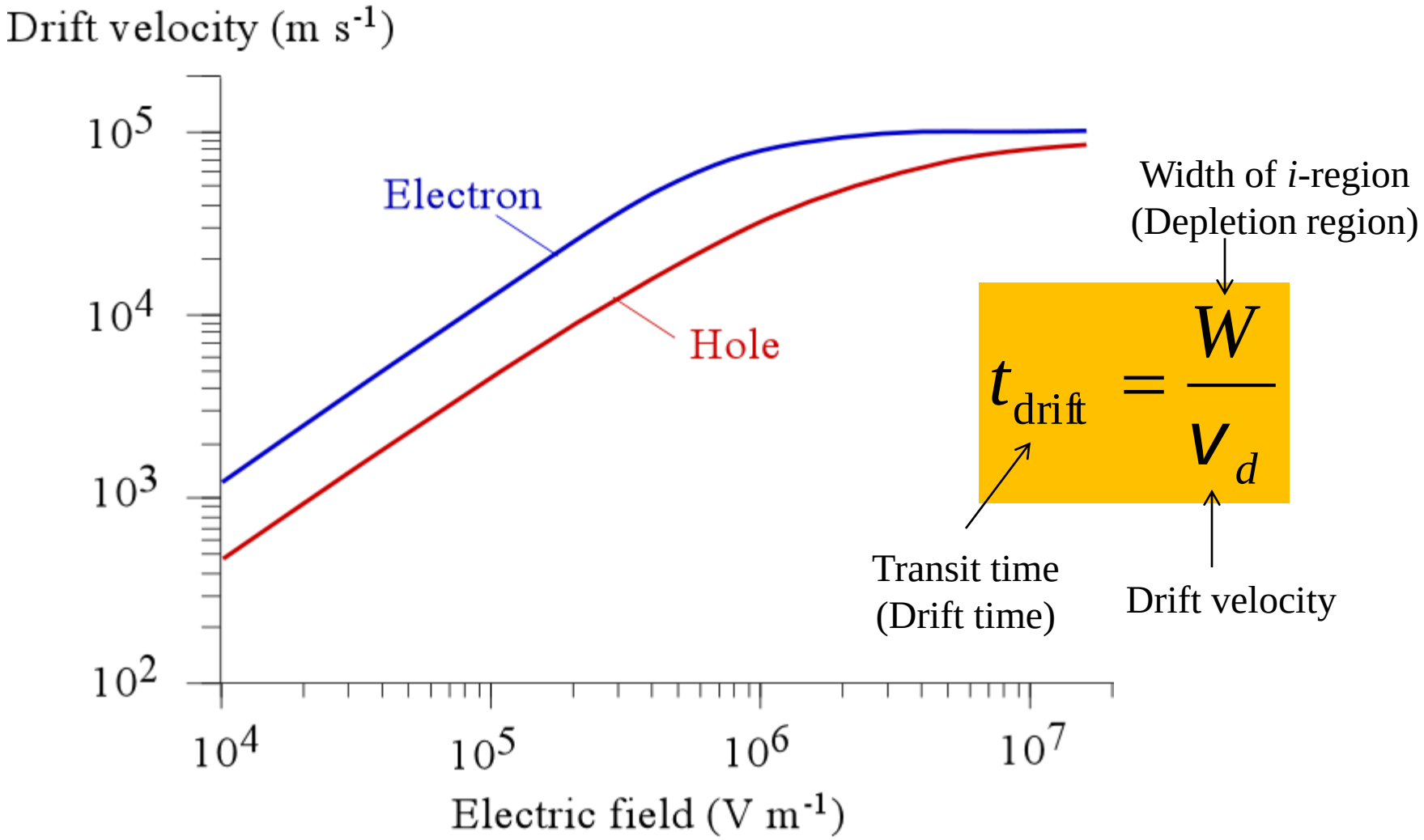


$$E \approx \frac{V_r}{W}$$

$$C_{\text{dep}} = \frac{\varepsilon_o \varepsilon_r A}{W}$$

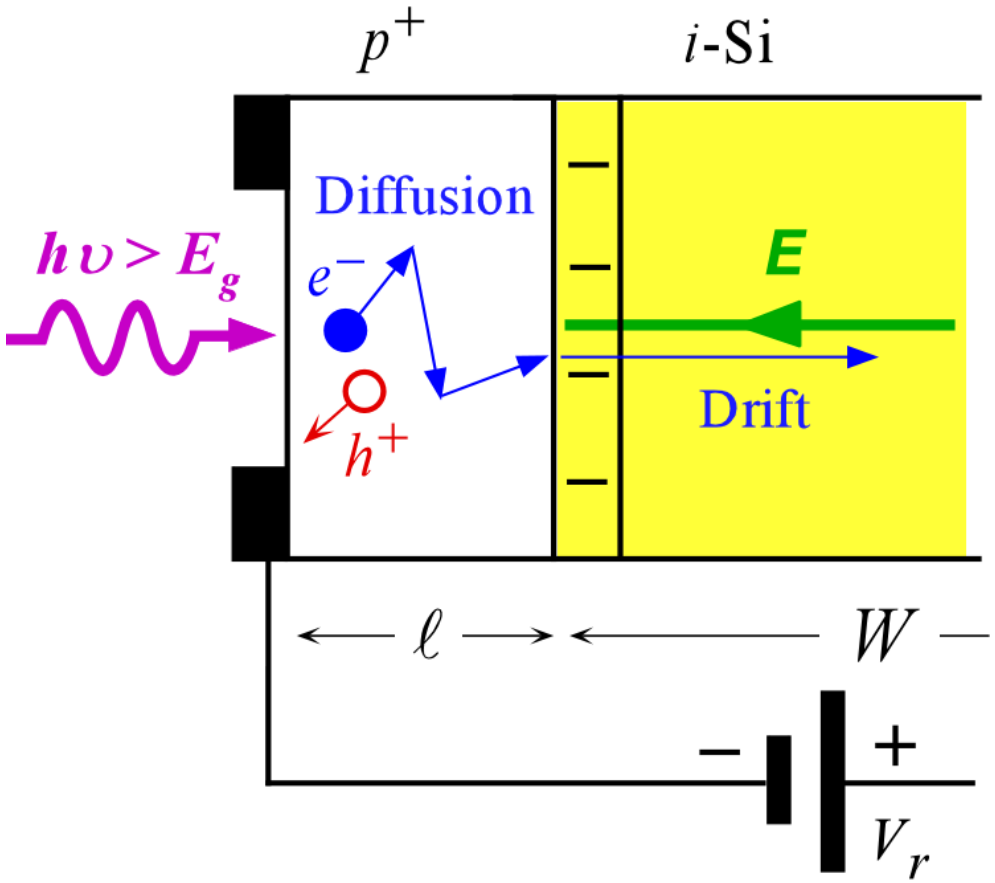
$$t_{\text{drift}} = \frac{W}{v_d}$$

pin Photodiode



Drift velocity vs. electric field for holes and electrons in Si.

pin Photodiode Speed



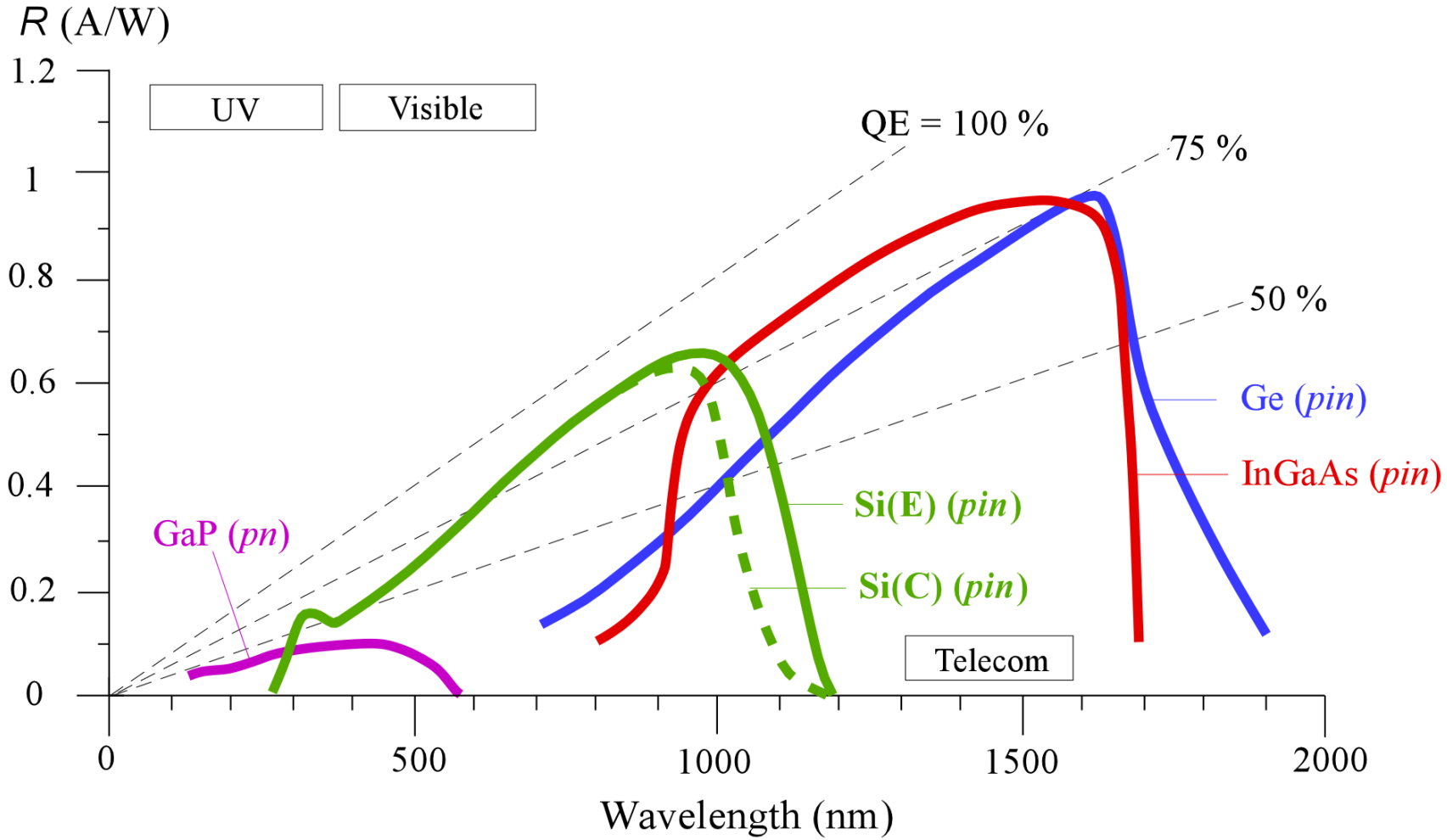
A reverse biased *pin* photodiode is illuminated with a short wavelength light pulse that is absorbed very near the surface. The photogenerated electron has to diffuse to the depletion region where it is swept into the *i*-layer and drifted across.

In time *t,* an electron, on average, diffuses a distance ℓ given by

$$\ell = (D_e t)^{1/2}$$

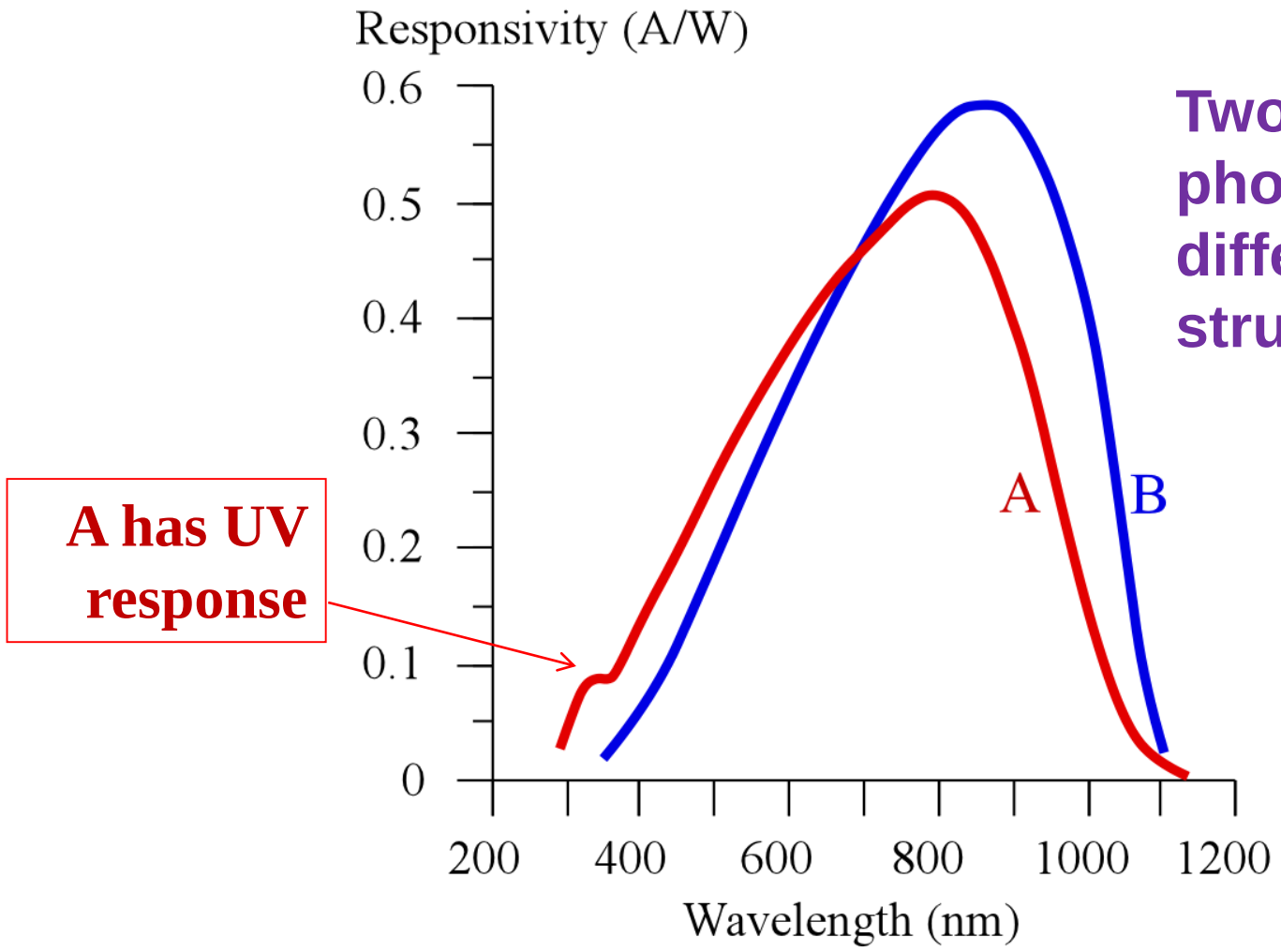
Electron diffusion coefficient

pin Photodiode



The responsivity of Si, InGaAs and Ge *pin* type photodiodes. The *pn* junction GaP detector is used for UV detection. GaP (Thorlabs, FGAP71), Si(E), IR enhanced Si (Hamamatsu S11499), Si(C), conventional Si with UV enhancement, InGaAs (Hamamatsu, G8376), and Ge (Thorlabs, FDG03). The dashed lines represent the responsivity due to QE = 100 %, 75% and 50 %.

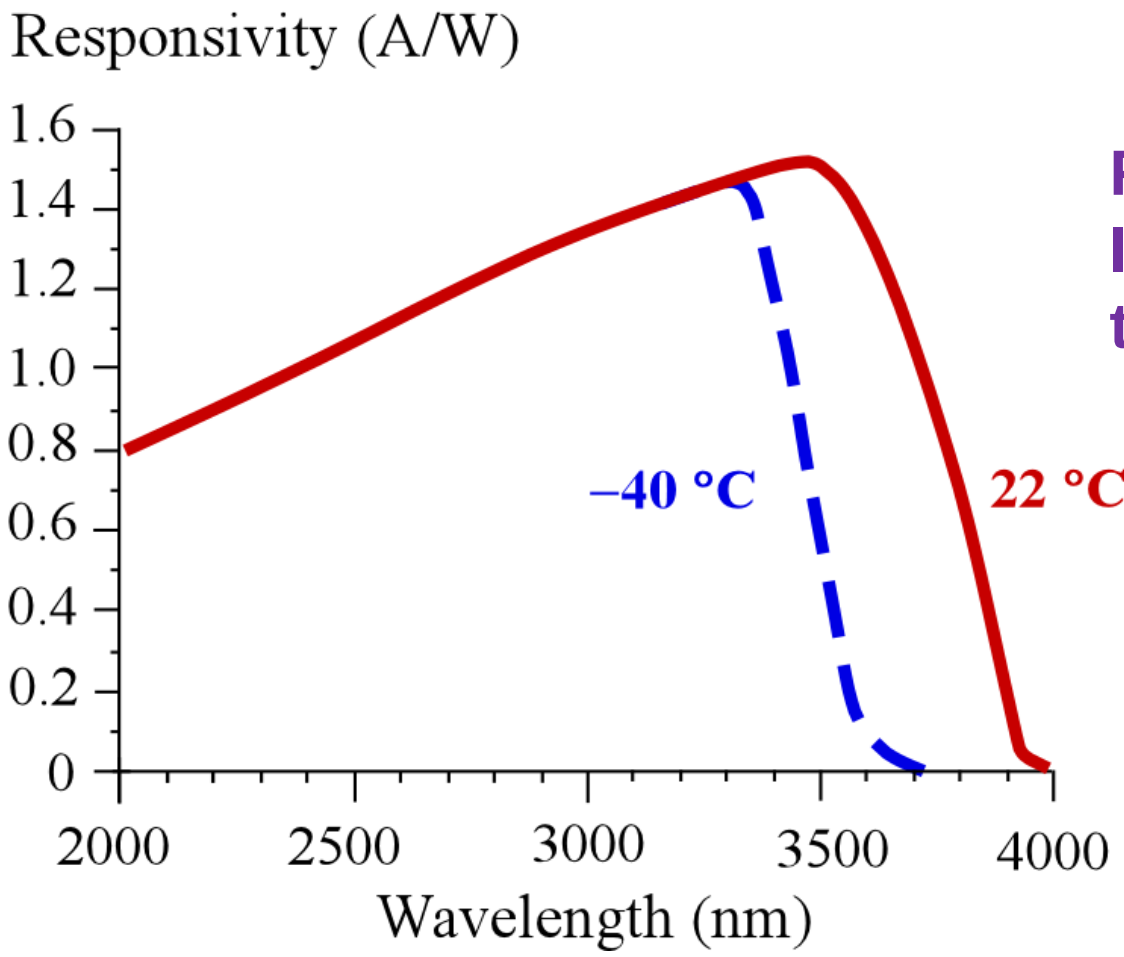
Responsivity *R* depends on the device structure



A has UV response

Two Si *pin* photodiodes with different device structures.

Responsivity *R* depends on the temperature



Responsivity of an InAs photodiode at two temperatures

EXAMPLE: Responsivity of a *pin* photodiode

A Si *pin* photodiode has an active light receiving area of diameter 0.4 mm. When radiation of wavelength 700 nm (red light) and intensity 0.1 mW cm^{-2} is incident, it generates a photocurrent of 56.6 nA. What is the responsivity and external QE of the photodiode at 700 nm?

Solution

The incident light intensity I = 0.1 mW cm^{-2} means that the incident power for conversion is

$$P_o = AI = [\pi(0.02\ \text{cm})^2](0.1\times10^{-3}\ \text{W cm}^{-2}) = 1.26\times10^{-7}\ \text{W or } \mathbf{0.126\ \mu W}.$$

The responsivity is

$$R = I_{ph}/P_o = (56.6\times10^{-9}\ \text{A})/(1.26\times10^{-7}\ \text{W}) = \mathbf{0.45\ A\ W^{-1}}$$

The QE can be found from

$$\eta = R\frac{hc}{e\lambda} = (0.45\ \text{A W}^{-1})\frac{(6.62\times10^{-34}\ \text{J s})(3\times10^{8}\ \text{m s}^{-1})}{(1.6\times10^{-19}\ \text{C})(700\times10^{-9}\ \text{m})} = 0.80 = \mathbf{80\ \%}$$

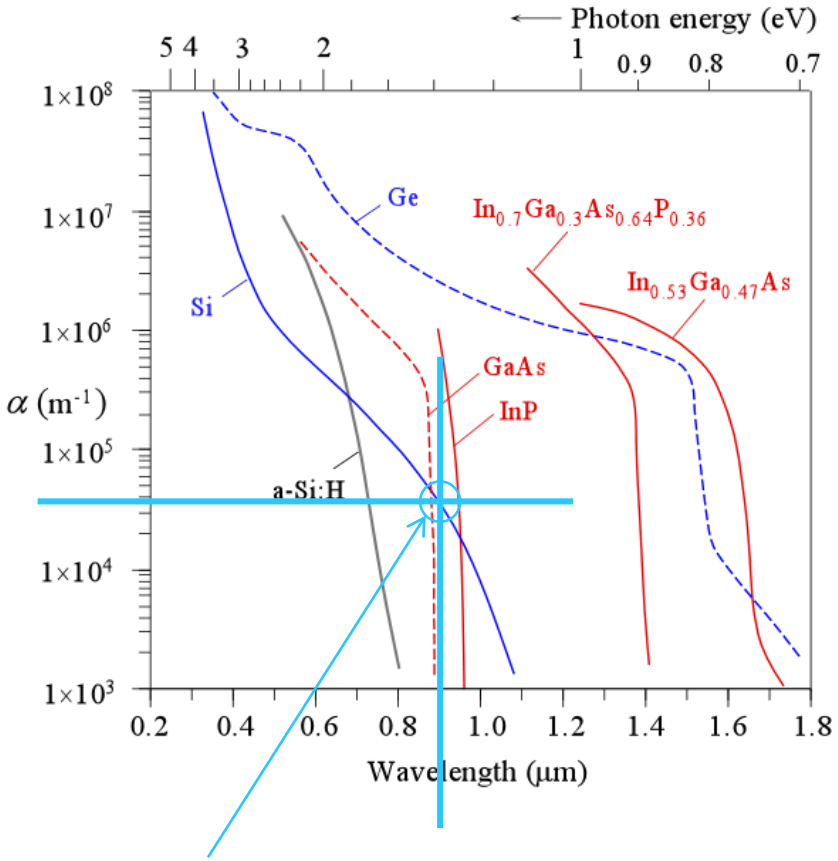
EXAMPLE: Operation and speed of a *pin* photodiode

A Si *pin* photodiode has an *i*-Si layer of width 20 μm. The p^+-layer on the illumination side is very thin (0.1 μm). The *pin* is reverse biased by a voltage of 100 V and then illuminated with a very short optical pulse of wavelength 900 nm. What is the absorption depth, the field in the *i*-Si and the response time of the *pin*?

Solution

From Figure 5.5 , the absorption coefficient at 900 nm is ~ 3×10^4 m^{-1} so that the absorption depth is ~33 μm. We can assume that absorption and hence photogeneration occurs over the entire width *W* of the *i*-Si layer. The field in the *i*-Si layer is

$$E \approx V_r / W$$
$$= (100\ V)/(20\times10^{-6}\ m)$$
$$= 5\times10^6\ V\ m^{-1}$$



Note: The absorption coefficient is between 3×10^4 m^{-1} and 4×10^4 m^{-1}

EXAMPLE: Operation and speed of a *pin* photodiode
Solution (continued)

At this field the electron drift velocity v_e is very near its saturation at 10^5 m s^{-1}, whereas the hole drift velocity $v_h \approx 7\times10^4$ m s^{-1} as shown in Figure 5.10. Holes are slightly slower than the electrons. The transit time t_h of holes across the *i*-Si layer is

$$t_h = W/v_h = (20\times10^{-6}\text{ m})/(7\times10^4\text{ m s}^{-1})$$
$$= 2.86\times10^{-10}\text{ s or } \mathbf{0.29\text{ ns}}$$

This is the response time of the *pin* as determined by the transit time of the slowest carriers, holes, across the *i*-Si layer. To improve the response time, the width of the *i*-Si layer has to be narrowed but this decreases the quantity of photons absorbed and hence reduces the responsivity. There is therefore a trade off between speed and responsivity.

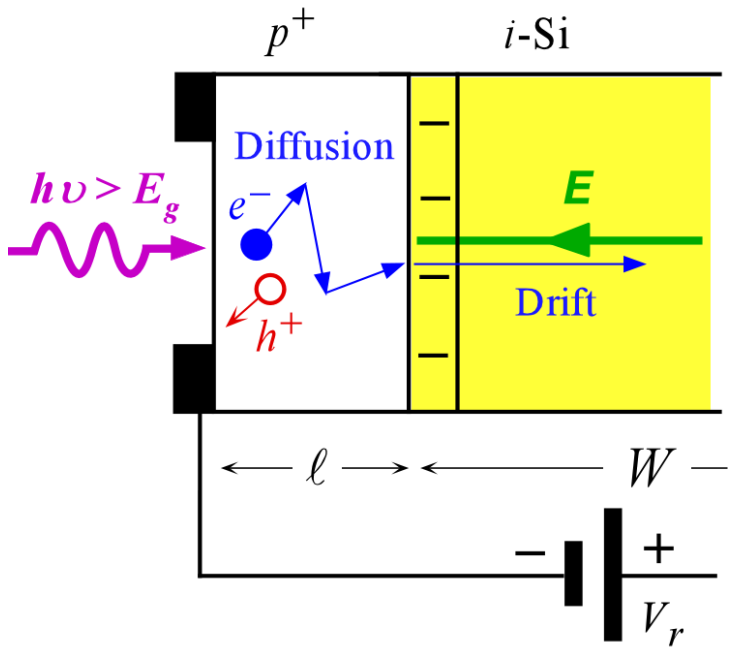
EXAMPLE : Photocarrier Diffusion in a *pin* photodiode

A reverse biased *pin* photodiode is illuminated with a short wavelength light pulse that is absorbed very near the surface. The photogenerated electron has to diffuse to the depletion region where it is swept into the *i*-layer and drifted across by the field in this region. What is the speed of response of this photodiode if the *i*-Si layer is 20 μm and the p^+-layer is 1 μm and the applied voltage is 60 V? The diffusion coefficient (D_e) of electrons in the heavily doped p^+-region is approximately 3×10^{-4} m^2 s^{-1}.

Solution

There is no electric field in the p^+-side outside the depletion region as shown in Figure 5.12 . The photogenerated electrons have to make it across to the n^+-side to give rise to a photocurrent. In the p^+-side, the electrons move by diffusion. In time *t,* an electron, on average, diffuses a distance ℓ given by

$$\ell = [D_e t]^{1/2}$$



The *diffusion time* t_{diff} is the time it takes for an electron to diffuse across the p^+-side (of length ℓ) to reach the depletion layer and is given by

EXAMPLE: Photocarrier Diffusion in a *pin* photodiode
Solution (continued)

$t_{diff} = \ell^{\,2}/(D_e) = (1\times10^{-6}\ \text{m})^2 / [\ (3\times10^{-4}\ \text{m}^2\ \text{s}^{-1})] = 3.34\times10^{-9}$ s or **3.34 ns**.

On the other hand, once the electron reaches the depletion region, it becomes drifted across the width W of the *i*-Si layer at the saturation drift velocity since the electric field here is $E = V_r / W = 60\ \text{V} / 20\ \mu\text{m} = 3\times10^6\ \text{Vm}^{-1}$; and at this field the electron drift velocity v_e saturates at $10^5\ \text{m s}^{-1}$. The drift time across the *i*-Si layer is

$$t_{drift} = W / v_e = (20\times10^{-6}\ \text{m}) / (1\times10^5\ \text{m s}^{-1}) = 2.0\times10^{-10}\ \text{s or}\ \mathbf{0.2\ ns}.$$

Thus, the response time of the *pin to* a pulse of short wavelength radiation that is absorbed near the surface is very roughly $t_{diff} + t_{drift}$ or 3.54 ns. Notice that the diffusion of the electron is much slower than its drift. In a proper analysis, we have to consider the **diffusion and drift of many carriers, and we have to average ($t_{diff} + t_{drift}$) for all the electrons**.

Assume that a photon flux Φ_0 is incident on the p^+ region. If we assume that the p^+ region width W_p is very thin, then the photon flux, as a function of distance, in the intrinsic region is $\Phi(x) = \Phi_0 e^{-\alpha x}$, where α is the photon absorption coefficient. This nonlinear photon absorption is shown in Figure 14.19b. The photocurrent density generated in the intrinsic region can be found as

$$J_L = e\int_0^W G_L\,dx = e\int_0^W \Phi_0\alpha e^{-\alpha x}\,dx = e\Phi_0(1-e^{-\alpha W}) \tag{14.43}$$

This equation assumes that there is no electron–hole recombination within the space charge region and also that each photon absorbed creates one electron–hole pair.

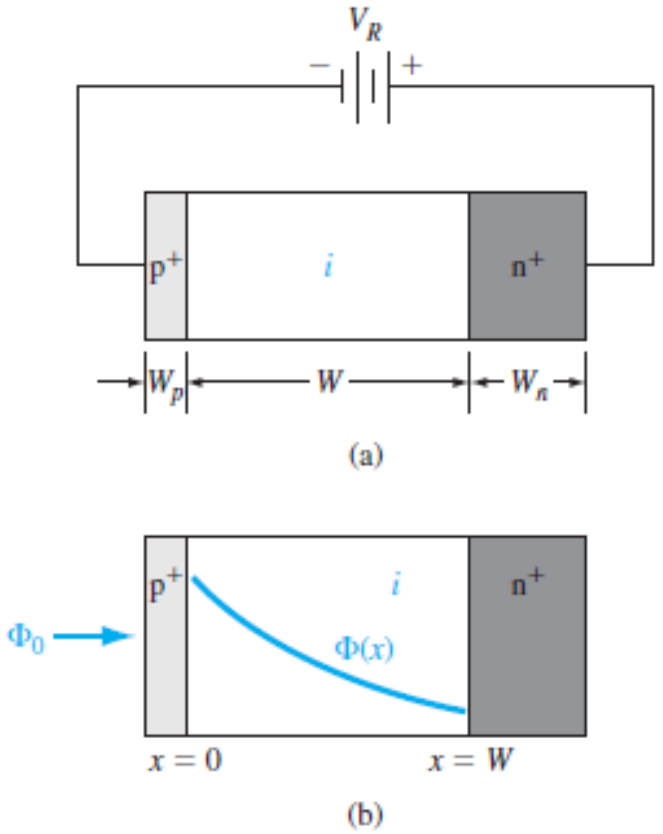


Figure 14.19 | (a) A reverse-biased PIN photodiode. (b) Geometry showing nonuniform photon absorption.

EXAMPLE 14.6

Objective: Calculate the photocurrent density in a PIN photodiode.

Consider a silicon PIN diode with an intrinsic region width of $W = 20\ \mu$m. Assume that the photon flux is 10^{17} cm^{-2}-s^{-1} and the absorption coefficient is $\alpha = 10^3$ cm^{-1}.

■ Solution

The generation rate of electron–hole pairs at the front edge of the intrinsic region is

$$G_{L1} = \alpha\Phi_0 = (10^3)(10^{17}) = 10^{20}\ \text{cm}^{-3}\text{-s}^{-1}$$

and the generation rate at the back edge of the intrinsic region is

$$G_{L2} = \alpha\Phi_0 e^{-\alpha W} = (10^3)(10^{17})\exp\left[-(10^3)(20\times 10^{-4})\right]$$

$$= 0.135\times 10^{20}\ \text{cm}^{-3}\text{-s}^{-1}$$

The generation rate is obviously not uniform throughout the intrinsic region. The photocurrent density is then

$$J_L = e\Phi_0(1-e^{-\alpha W})$$

$$= (1.6\times 10^{-19})(10^{17})\{1-\exp\left[-(10^3)(20\times 10^{-4})\right]\}$$

$$= 13.8\ \text{mA/cm}^2$$

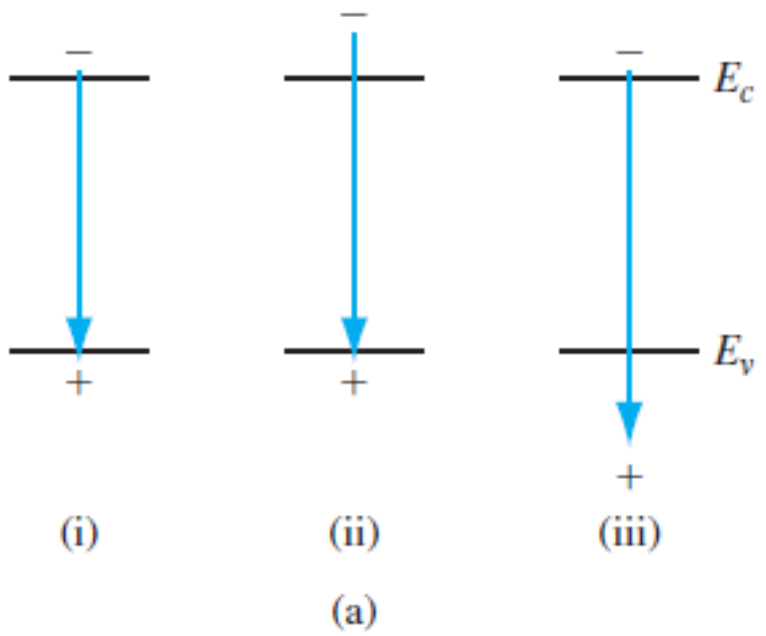
■ Comment

The prompt photocurrent density of a PIN photodiode will be larger than that of a regular photodiode since the space charge region is larger in a PIN photodiode.

14.4 | PHOTOLUMINESCENCE AND ELECTROLUMINESCENCE

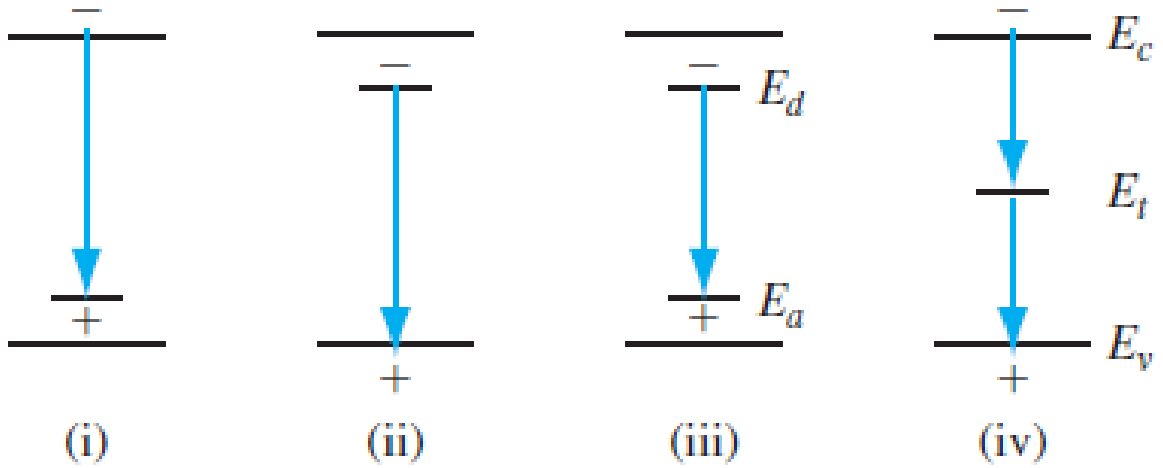
14.4.1 Basic Transitions

Figure 14.21a shows the basic interband transitions. Curve (i) corresponds to an intrinsic emission very close to the bandgap energy of the material. Curves (ii) and (iii) correspond to energetic electrons or holes. If either of these recombinations result in the emission of a photon, the energy of the emitted photon will be slightly larger than the bandgap energy. There will then be an emission spectrum and a bandwidth associated with the emission.



(a)

The possible recombination processes involving impurity or defect states are shown in Figure 14.21b. Curve (i) is the conduction band to acceptor transition, curve (ii) is the donor to valence-band transition, curve (iii) is the donor to acceptor transition, and curve (iv) is the recombination due to a deep trap. Curve (iv) is a non radiative process corresponding to the Shockley–Read–Hall recombination process discussed in Chapter 6. The other recombination processes may or may not result in the emission of a photon.



(b)

Figure 14.21c shows the Auger recombination process, which can become important in direct bandgap materials with high doping concentrations. The Auger recombination process is a nonradiative process. The Auger recombination, in one case, shown in curve (i), is a recombination between an electron and hole, accompanied by the transfer of energy to another free hole. Similarly, in the second case, the recombination between an electron and hole can result in the transfer of energy to a free electron as shown in curve (ii). The third particle involved in this process will eventually lose its energy to the lattice in the form of heat. The process involving two holes and an electron would occur predominantly in heavily doped p-type materials, and the process involving two electrons and a hole would occur primarily in a heavily doped n-type material.

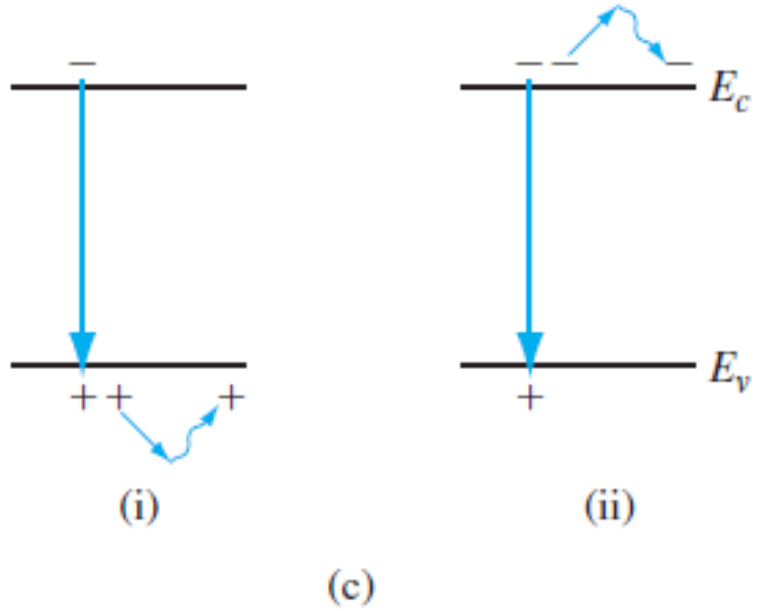


Figure 14.21 | Basic transitions in a semiconductor.

The recombination processes shown in Figure 14.21a indicate that the emission of a photon is not necessarily at a single, discrete energy, but can occur over a range of energies. The spontaneous emission rate generally has the form

$$I(v) \propto v^2 (hv - E_g)^{1/2} \exp\left[\frac{-(hv - E_g)}{kT}\right] \qquad (14.48)$$

where *Eg* is the bandgap energy. Figure 14.22 shows the emission spectra from gallium arsenide. The peak photon energy decreases with temperature because the bandgap energy decreases with temperature.

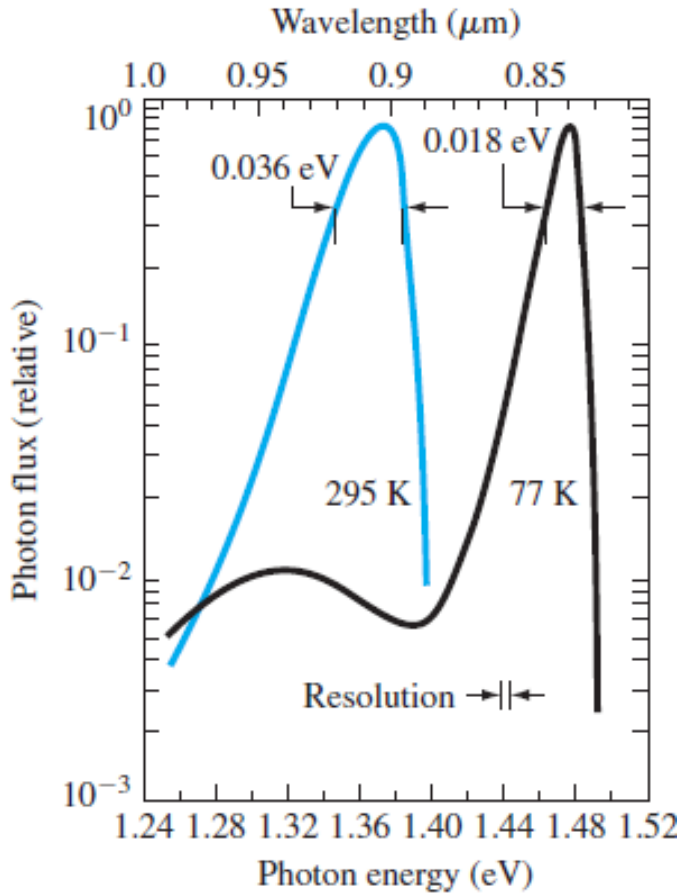


Figure 14.22 | GaAs diode emission spectra at $T = 300$ K and $T = 77$ K. *(From Sze and Ng [17].)*

14.4.2 Luminescent Efficiency

We have shown that not all recombination processes are radiative. The quantum efficiency is defined as the ratio of the radiative recombination rate to the total recombination rate for all processes. We can write

$$\eta_q = \frac{R_r}{R} \tag{14.49}$$

where η_q is the quantum efficiency, R_r is the radiative recombination rate, and R is the total recombination rate of the excess carriers.

Since the recombination rate is inversely proportional to lifetime, we can write the quantum efficiency in terms of lifetimes as

$$\eta_q = \frac{\tau_{nr}}{\tau_{nr} + \tau_r} \tag{14.50}$$

where τ_{nr} is the nonradiative lifetime and τ_r is the radiative lifetime.

For a high luminescent efficiency, the nonradiative lifetimes must be large; thus, the probability of a nonradiative recombination is small compared to the radiative recombination.

The interband recombination rate of electrons and holes will be directly proportional to the number of electrons available and directly proportional to the number of available empty states (holes). We can write

$$R_r = Bnp \tag{14.51}$$

where R_r is the band-to-band radiative recombination rate and B is the constant of proportionality. The values of B for direct-bandgap materials are on the order of10^6 larger than for indirect bandgap materials.

14.4.3 Materials

An important direct bandgap semiconductor material for optical devices is gallium arsenide. Another compound material that is of great interest is $Al_xGa_{1-x}As$. This material is a compound semiconductor in which the ratio of aluminium atoms to gallium atoms can be varied to achieve specific characteristics. Figure 14.23 shows the bandgap energy as a function of the mole fraction between aluminium and gallium.
We can note from the figure that for $0 < x < 0.45$, the alloy material is a direct bandgap material. For $x > 0.45$, the material becomes an indirect bandgap material, not suitable for optical devices. For $0 < x < 0.35$, the bandgap energy can be ex pressed as

$$E_g = 1.424 + 1.247x \text{ eV} \qquad (14.52)$$

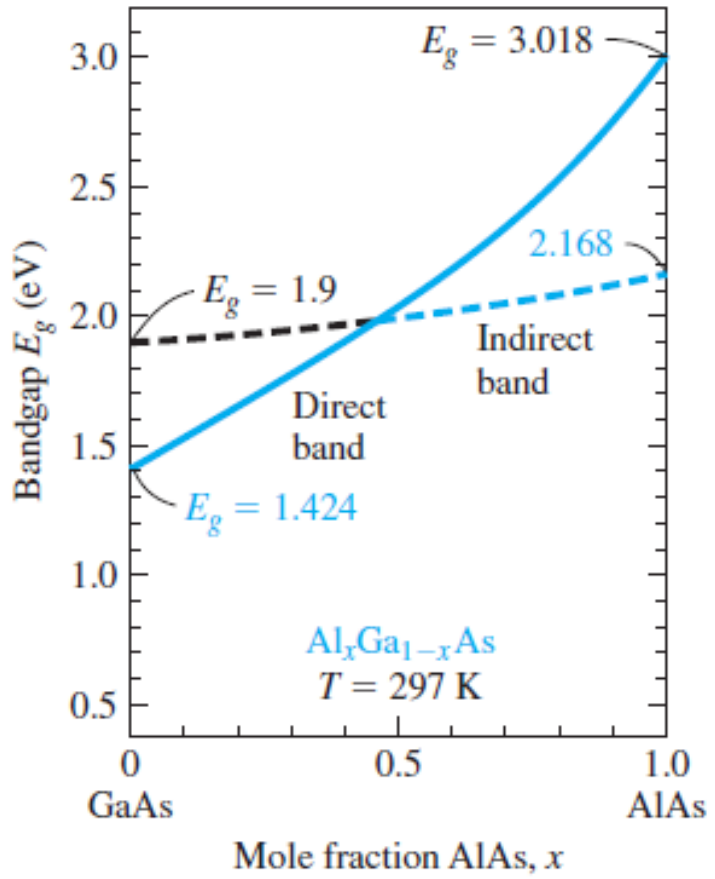


Figure 14.23 | Bandgap energy of $Al_xGa_{1-x}As$ as a function of the mole fraction x.
(From Sze [18].)

Another compound semiconductor used for optical devices is the $GaAs_{1-x}P_x$ system. Figure 14.24a shows the bandgap energy as a function of the mole fraction x. For $0 < x < 0.45$, this material is also a direct bandgap material, and for $x > 0.45$, the bandgap becomes indirect. Figure 14.24b is the E versus k diagram, showing how the bandgap changes from direct to indirect as the mole fraction changes.

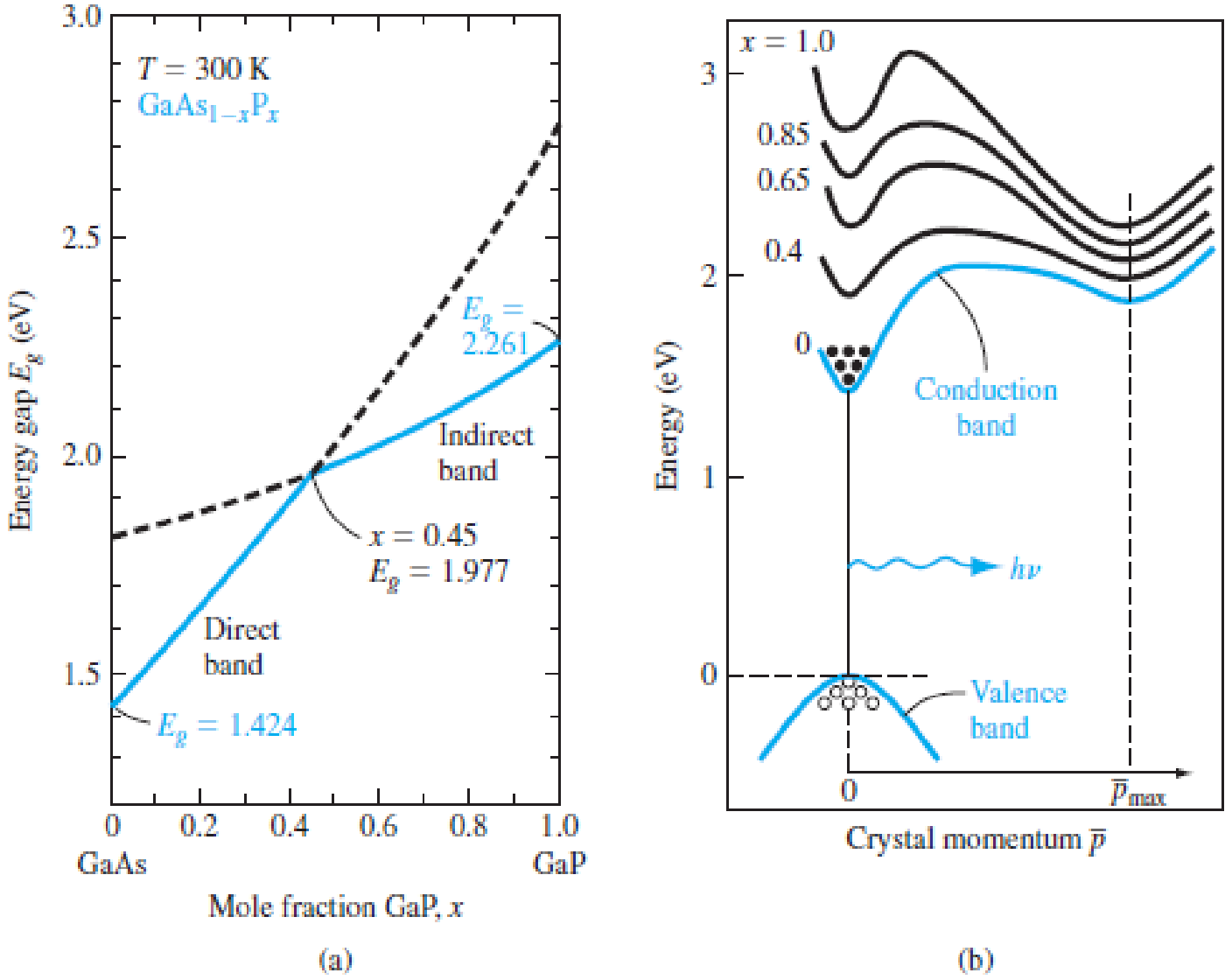


Figure 14.24 | (a) Bandgap energy of $GaAs_{1-x}P_x$ as a function of mole fraction x. (b) E versus k diagram of $GaAs_{1-x}P_x$ for various values of x. *(From Sze [18].)*

EXAMPLE 14.7

Objective: Determine the output wavelength of a $GaAs_{1-x}P_x$ material for two different mole fractions.

Consider first GaAs and then $GaAs_{1-x}P_x$.

Solution

GaAs has a bandgap energy of $E_g = 1.42$ eV. This material would produce a photon output at a wavelength of

$$\lambda = \frac{1.24}{E} = \frac{1.24}{1.42} = 0.873\ \mu\text{m}$$

This wavelength is in the infrared range and not in the visible range. If we desire a visible output with a wavelength of $\lambda = 0.653\ \mu$m, for example, the bandgap energy would have to be

$$E = \frac{1.24}{\lambda} = \frac{1.24}{0.653} = 1.90\ \text{eV}$$

This bandgap energy would correspond to a mole fraction of approximately $x = 0.4$.

Comment

By changing the mole fraction in the $GaAs_{1-x}P_x$ system, the output can change from the infrared to the red spectrum.