Semiconductor Optoelectronics

Lecture : LIGHT EMITTING DIODES LED

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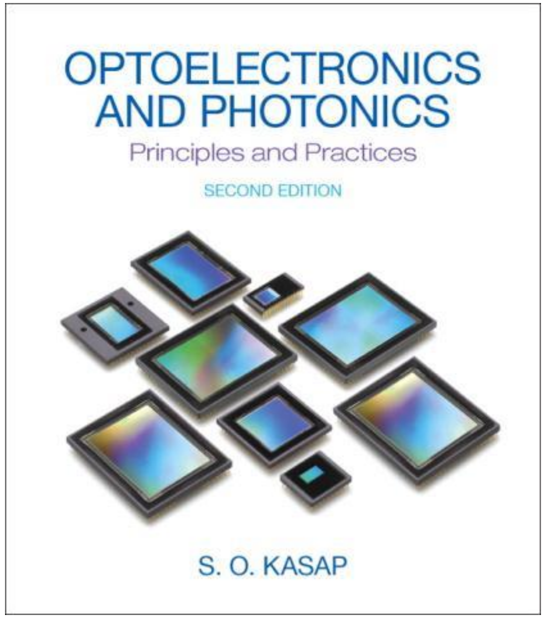
Chapter 5



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14.5 | LIGHT EMITTING DIODES

Photodetectors and solar cells convert optical energy into electrical energy—the photons generate excess electrons and holes, which produce an electric current. We might also apply a voltage across a pn junction resulting in a diode current, which in turn can produce photons and a light output. This inverse mechanism is called injection electroluminescence. This device is known as a **L**ight **E**mitting **D**iode (LED).

The spectral output of an LED may have a relatively wide wavelength bandwidth of between 30 and 40 nm.

14.5.1 Generation of Light

As we have discussed previously, photons may be emitted if an electron and hole recombine by a direct band-to-band recombination process in a direct bandgap material.

The emission wavelength, from Equation (14.1), is

$$\lambda = \frac{hc}{E_g} = \frac{1.24}{E_g} \ \mu\text{m} \tag{14.53}$$

When a voltage is applied across a pn junction, electrons and holes are injected across the space charge region where they become excess minority carriers. These excess minority carriers diffuse into the neutral semiconductor regions where they recombine with majority carriers. If this recombination process is a direct band-to band process, photons are emitted. The diode diffusion current is directly proportional to the recombination rate, so the output photon intensity will also be proportional to the ideal diode diffusion current. In gallium arsenide, electroluminescence originates primarily on the p side of the junction because the efficiency for electron injection is higher than that for hole injection.

14.5.2 Internal Quantum Efficiency

The *internal quantum efficiency* of an LED is the fraction of diode current that produces luminescence. The internal quantum efficiency is a function of the injection efficiency and a function of the percentage of radiative recombination events compared with the total number of recombination events.

The three current components in a forward-biased diode are the minority carrier electron diffusion current, the minority carrier hole diffusion current, and the space charge recombination current. These current densities can be written, respectively, as

$$J_n = \frac{eD_n n_{p0}}{L_n}\left[\exp\left(\frac{eV}{kT}\right) - 1\right] \quad (14.54a)$$

$$J_p = \frac{eD_p p_{n0}}{L_p}\left[\exp\left(\frac{eV}{kT}\right) - 1\right] \quad (14.54b)$$

The recombination of electrons and holes within the space charge region is, in general, through traps near midgap and is a nonradiative process.

$$J_R = \frac{en_i W}{2\tau_0}\left[\exp\left(\frac{eV}{2kT}\right) - 1\right] \quad (14.54c)$$

Since luminescence is due primarily to the recombination of minority carrier electrons in GaAs, we can define an injection efficiency as the fraction of electron current to total current. Then

$$\gamma = \frac{J_n}{J_n + J_p + J_R} \tag{14.55}$$

Once the electrons are injected into the p region, not all electrons will recombine radiatively. We can define the radiative and nonradiative recombination rates as

$$R_r = \frac{\delta n}{\tau_r} \tag{14.56a}$$

$$R_{nr} = \frac{\delta n}{\tau_{nr}} \tag{14.56b}$$

where τ_r and τ_{nr} are the radiative and nonradiative recombination lifetimes, respectively, and *n* is the excess carrier concentration.

The total recombination rate is

$$R = R_r + R_{nr} = \frac{\delta n}{\tau} = \frac{\delta n}{\tau_r} + \frac{\delta n}{\tau_{nr}} \tag{14.57}$$

where τ is the net excess carrier lifetime.

The radiative efficiency is defined as the fraction of recombinations that are radiative. We can write

$$\eta = \frac{R_r}{R_r + R_{nr}} = \frac{\frac{1}{\tau_r}}{\frac{1}{\tau_r} + \frac{1}{\tau_{nr}}} = \frac{\tau}{\tau_r} \tag{14.58}$$

where η is the radiative efficiency. The nonradiative recombination rate is proportional to N_t, which is the density of nonradiative trapping sites within the forbidden bandgap. Obviously, the radiative efficiency increases as N_t is reduced.

The internal quantum efficiency is now written as

$$\eta_i = \gamma\eta \tag{14.59}$$

The radiative recombination rate is proportional to the p-type doping. As the p-type doping increases, the radiative recombination rate increases. However, the injection efficiency decreases as the p-type doping increases; therefore, there is an optimum doping that maximizes the internal quantum efficiency.

14.5.3 External Quantum Efficiency

One very important parameter of the LED is the *external quantum efficiency:* the fraction of generated photons that are actually emitted from the semiconductor. The external quantum efficiency is normally a much smaller number than the internal quantum efficiency. Once a photon has been produced in the semiconductor, there are three loss mechanisms the photon may encounter: photon absorption within the semiconductor, Fresnel loss, and critical angle loss.

Figure 14.25 shows a pn junction LED. Photons can be emitted in any direction. Since the emitted photon energy must be $h\upsilon > E_g$, these emitted photons can be reabsorbed within the semiconductor material. The majority of photons will actually be emitted away from the surface and reabsorbed in the semiconductor.

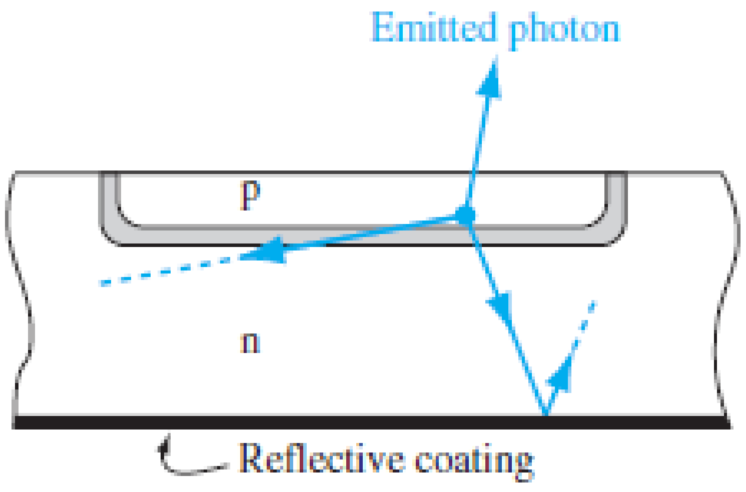


Figure 14.25 | Schematic of photon emission at the pn junction of an LED.

Photons must be emitted from the semiconductor into air; thus, the photons must be transmitted across a dielectric interface. Figure 14.26 shows the incident, reflected, and transmitted waves. The parameter n_2 is the index of refraction for the semiconductor and n_1 is the index of refraction for air. The reflection coefficient is

$$\Gamma = \left(\frac{\bar{n}_2 - \bar{n}_1}{\bar{n}_2 + \bar{n}_1} \right)^2 \qquad (14.60)$$

This effect is called Fresnel loss. The reflection coefficient Γ is the fraction of incident photons that are reflected back into the semiconductor.

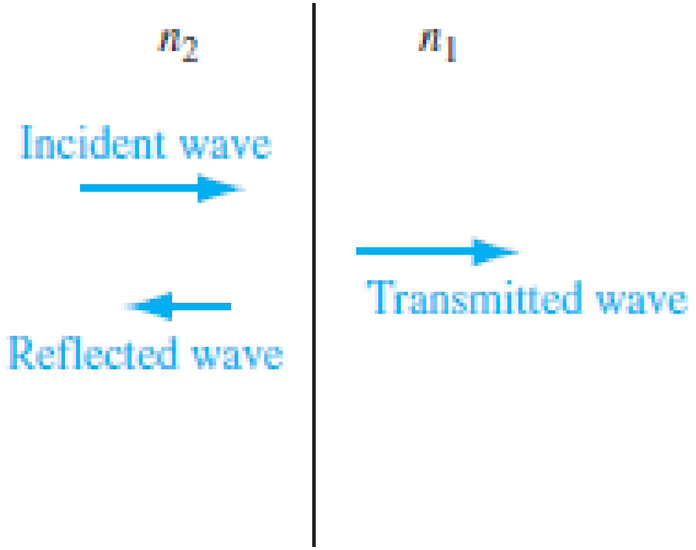


Figure 14.26 | Schematic of incident, reflected, and transmitted photons at a dielectric interface.

Objective: Calculate the reflection coefficient at a semiconductor–air interface. **EXAMPLE 14.8**

Consider the interface between a GaAs semiconductor and air.

Solution

The index of refraction for GaAs is $\bar{n}_2 = 3.8$ at a wavelength of $\lambda = 0.70\ \mu m$ and the index of refraction for air is $\bar{n}_1 = 1.0$. The reflection coefficient is

$$\Gamma = \left(\frac{\bar{n}_2 - \bar{n}_1}{\bar{n}_2 + \bar{n}_1}\right)^2 = \left(\frac{3.8 - 1.0}{3.8 + 1.0}\right)^2 = 0.34$$

Comment

A reflection coefficient of $\Gamma = 0.34$ means that 34 percent of the photons incident from the gallium arsenide onto the semiconductor–air interface are reflected back into the semiconductor.

Photons incident on the semiconductor–air interface at an angle are refracted as shown in Figure 14.27. If the photons are incident on the interface at an angle greater than the critical angle θ_c, the photons experience total internal reflection. The **critical angle** is determined from Snell's law and is given by

$$\theta_c = \sin^{-1}\left(\frac{\bar{n}_1}{\bar{n}_2}\right) \qquad (14.61)$$

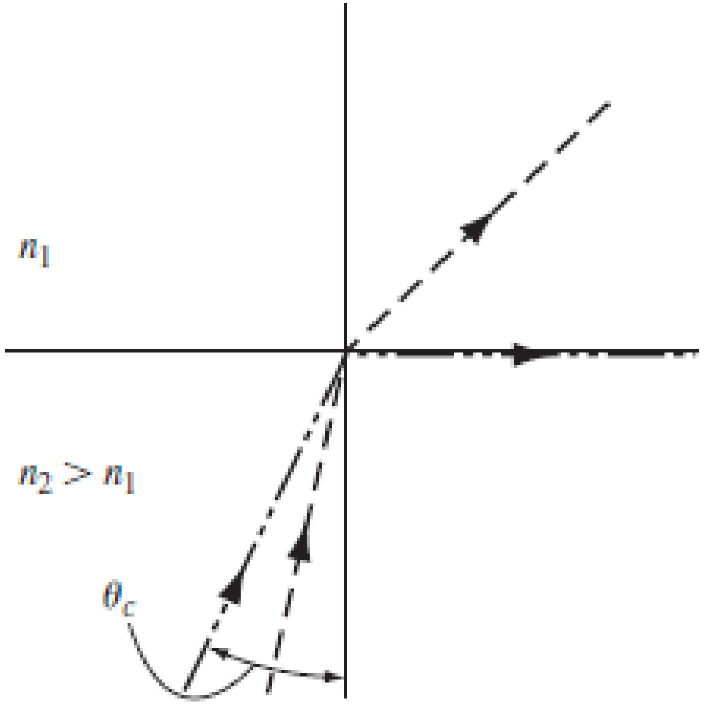


Figure 14.27 | Schematic showing refraction and total internal reflection at the critical angle at a dielectric interface.

EXAMPLE 14.9

Objective: Calculate the critical angle at a semiconductor–air interface.

Consider the interface between GaAs and air.

■ Solution

For GaAs, $\bar{n}_2 = 3.8$ at a wavelength of $\lambda = 0.70\ \mu\text{m}$ and for air, $\bar{n}_1 = 1.0$. The critical angle is

$$\theta_c = \sin^{-1}\left(\frac{\bar{n}_1}{\bar{n}_2}\right) = \sin^{-1}\left(\frac{1.0}{3.8}\right) = 15.3^\circ$$

■ Comment

Any photon that is incident at an angle greater than 15.3° will be reflected back into the semiconductor.

■ EXERCISE PROBLEM

Ex 14.9 Repeat Example 14.9 for $GaAs_{0.6}P_{0.4}$. See Exercise Problem Ex 14.8 for a discussion of the dielectric constant.

(Ans. $\theta_c = 16.3^\circ$)

14.5.4 LED Devices

GaAs1*x*P*x* is a direct bandgap material for 0 *x* 0.45, as shown in Figure 14.24. At *x* 0.40, the bandgap energy is approximately *Eg* 1.9 eV, which would produce an optical output in the red range. Figure 14.29 shows the brightness of GaAs1*x*P*x* diodes for different values of *x*. The peak also occurs in the red range. By using planar technology, GaAs0.6P0.4 monolithic arrays have been fabricated for numeric and alphanumeric displays. When the mole fraction *x* is greater than 0.45, the material changes to an indirect bandgap semiconductor so that the quantum effi ciency is greatly reduced.

$GaAl_xAs_{1x}$ can be used in a heterojunction structure to form an LED. A device structure is shown in Figure 14.30. Electrons are injected from the wide-bandgap *N*-$GaAl_{0.7}As_{0.3}$ into the narrow-bandgap *p*-$GaAl_{0.6}As_{0.4}$. The minority carrier electrons in the p material can recombine radiatively. Since *Egp* *EgN*, the photons are emitted through the wide-bandgap N material with essentially no absorption. The wide bandgap N material acts as an optical window and the external quantum efficiency increases.

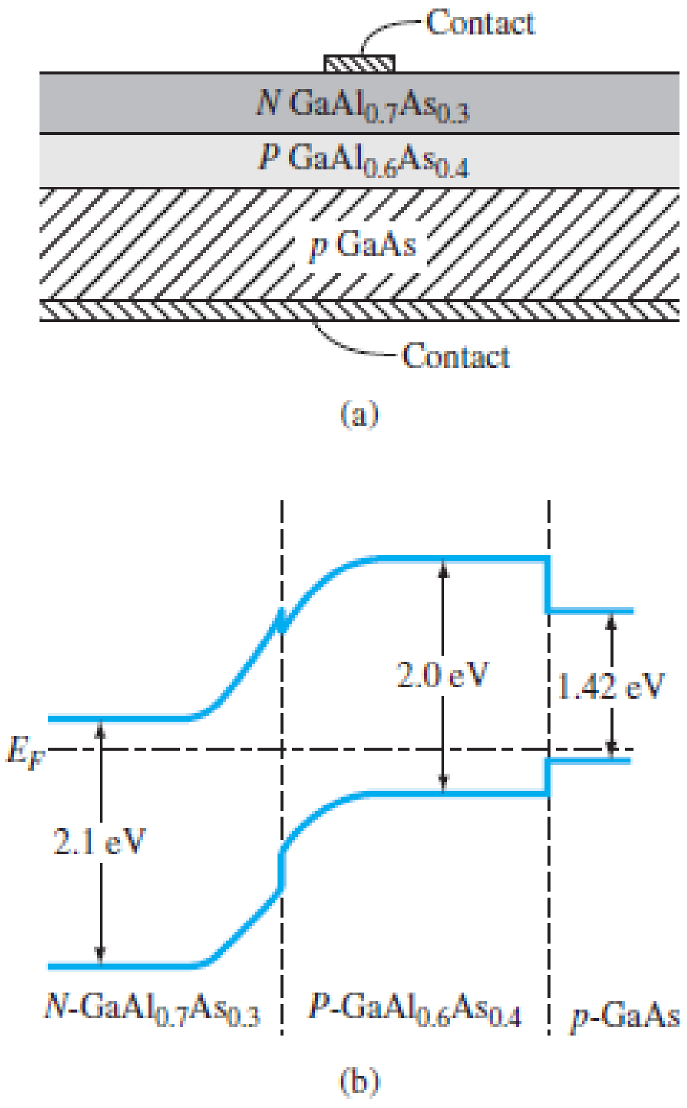
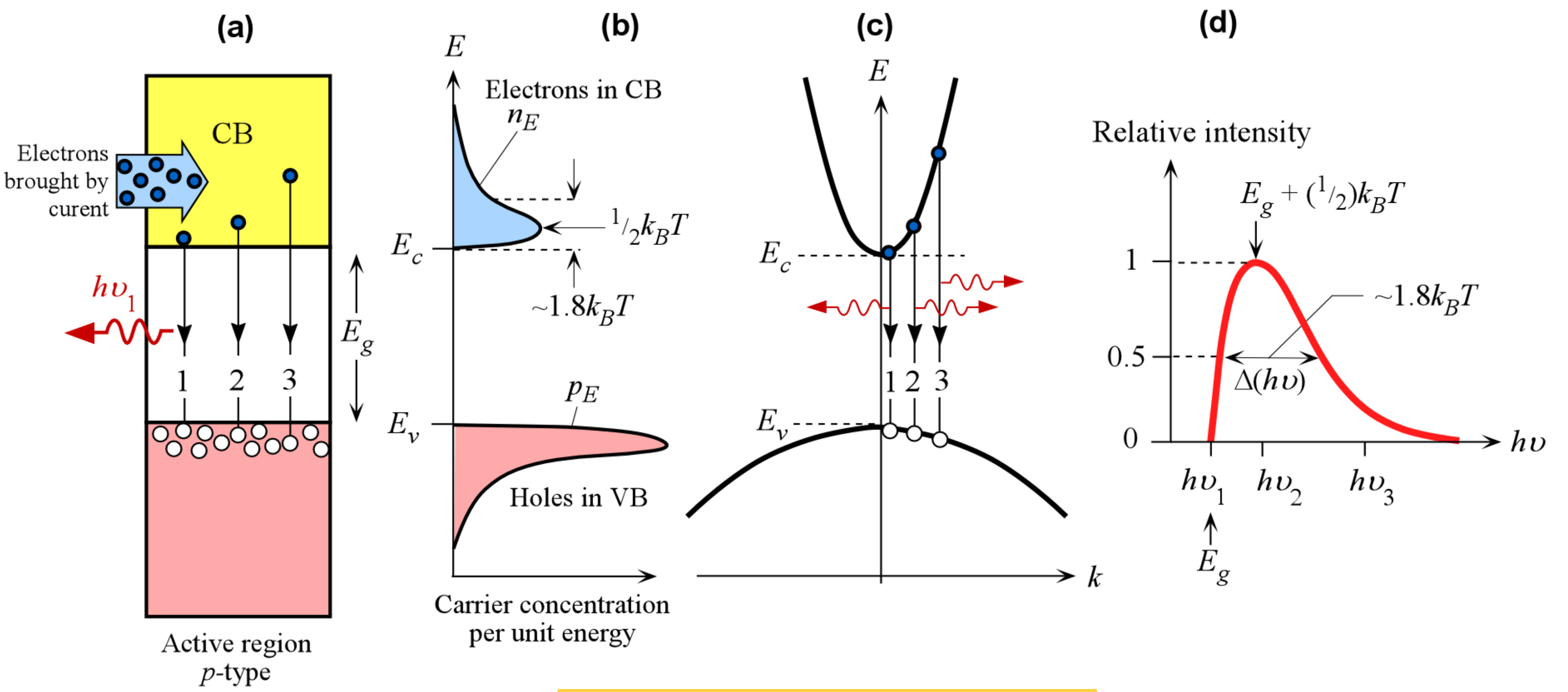


Figure 14.30 | The (a) cross section and (b) thermal equilibrium energy-band diagram of a GaAlAs heterojunction LED. *(From Yang [22].)*

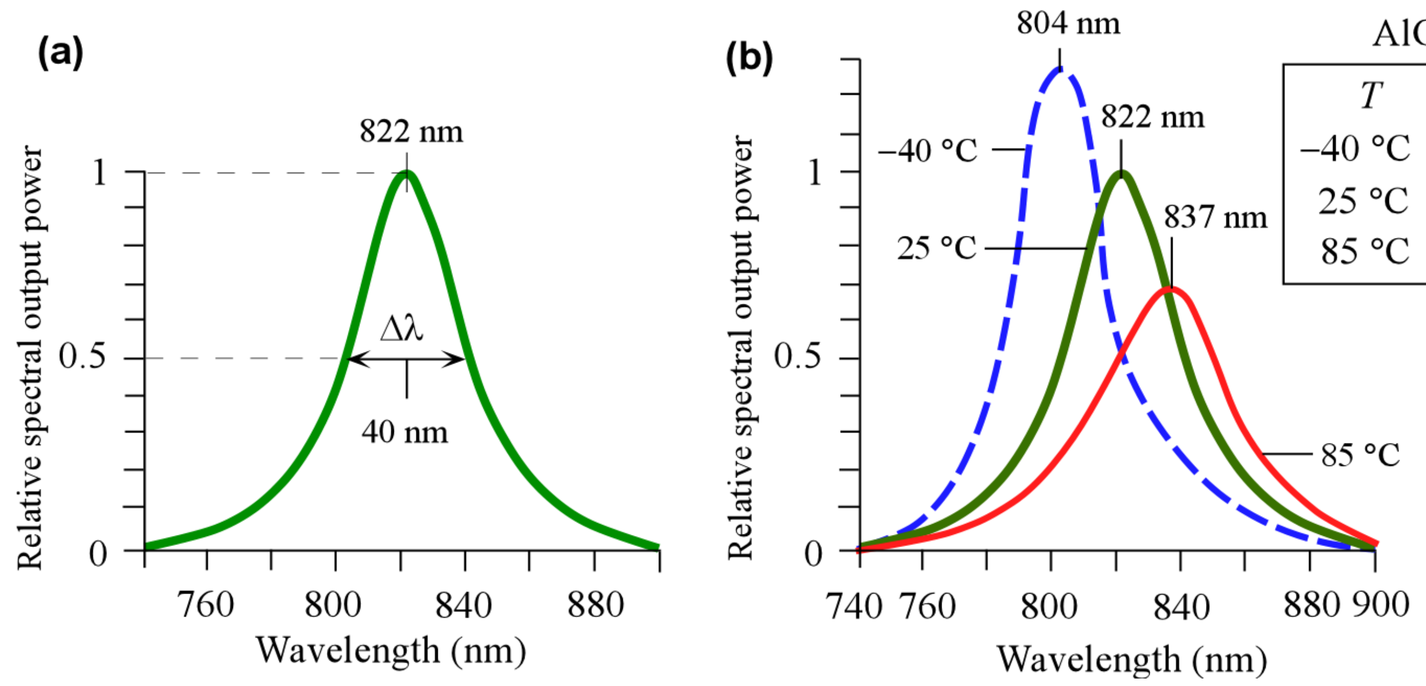
Emission Spectrum



$$h\upsilon_o \approx E_g + \frac{1}{2}k_BT$$

$$h\Delta\upsilon = mk_BT$$

Emission Spectrum



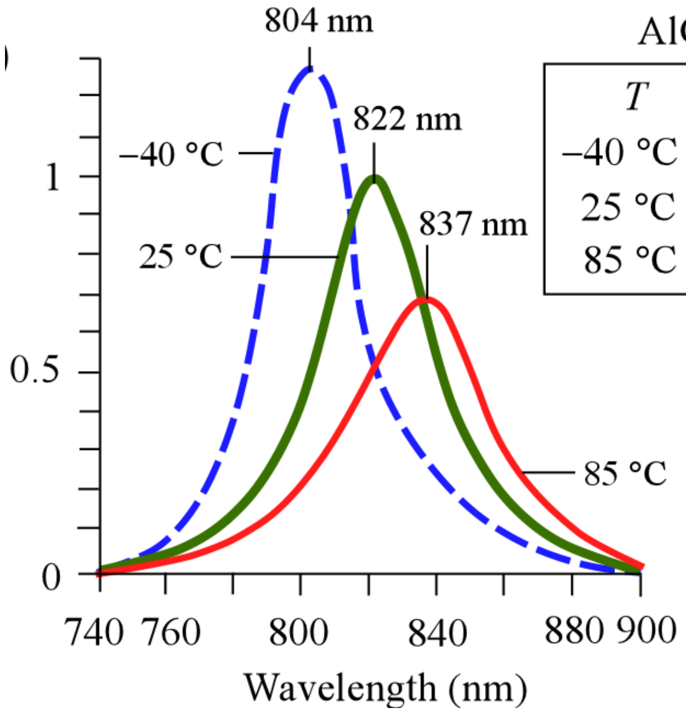
T	λ_o	$\Delta\lambda$
−40 °C	804 nm	30 nm
25 °C	822 nm	40 nm
85 °C	837 nm	48 nm

(a) A typical output spectrum (relative intensity vs. wavelength) from an IR (infrared) AlGaAs LED. (b) The output spectrum of the LED in (a) at 3 temperatures: 25 °C, –40 °C and 85 °C. Values normalized to peak emission at 25 °C. The spectral widths are FWHM.

$$h\upsilon_o \approx E_g + \frac{1}{2}k_B T$$

$$h\Delta\upsilon = mk_B T$$

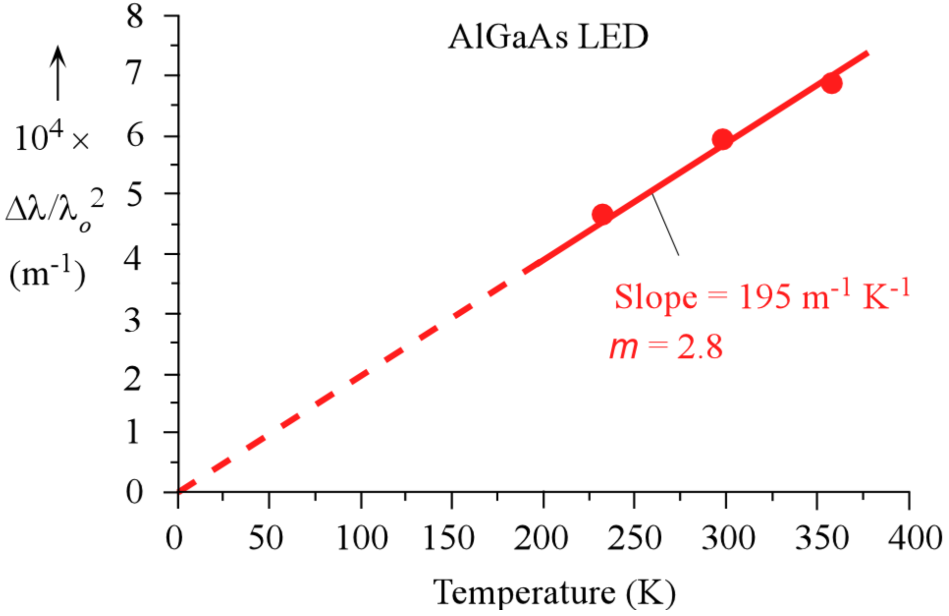
Emission Spectrum



AlGaAs IR LED

T	λ_o	$\Delta\lambda$
–40 °C	804 nm	30 nm
25 °C	822 nm	40 nm
85 °C	837 nm	48 nm

The output spectrum at 3 temperatures: 25 °C, –40 °C and 85 °C. Values normalized to peak emission at 25 °C. The spectral widths are FWHM



The plot of plot $\Delta\lambda/\lambda_o^2$ vs. T for an AlGaAs infrared LED, using the peak wavelength λ_o and spectral width $\Delta\lambda$ at three different temperatures

$E_{ph} = h\upsilon$

$d(E_{ph}) / d\lambda = d(h\upsilon) / d\lambda$

$d(h\upsilon) / d\lambda = d(hc\lambda^{-1}) / d\lambda$

$d(h\upsilon) / d\lambda = -hc\lambda^{-2}$

The negative indicates that increasing the photon energy decreases the wavelength.

$|d(h\upsilon) / d\lambda| \approx \Delta(h\upsilon) / \Delta\lambda$

$\Delta(h\upsilon) / \Delta\lambda = hc\lambda^{-2}$

$\Delta(h\upsilon)\lambda^2/hc = \Delta\lambda$

$\Delta(h\upsilon) = mk_BT$

Then

$\Delta\lambda = mk_BT\lambda^2/hc$

EXAMPLE: LED spectral linewidth

We know that a spread in the output wavelengths is related to a spread in the emitted photon energies. The emitted photon energy $h\upsilon = hc/\lambda$. Assume that the spread in the photon energies $\Delta(h\upsilon) \approx 3k_BT$ between the half intensity points. Show that the corresponding linewidth $\Delta\lambda$ between the *half intensity points* in the output spectrum is

$$\Delta\lambda = \lambda_o^2 \frac{3k_BT}{hc} \qquad \textit{LED spectral linewidth} \qquad (3.11.3)$$

where λ_o is the peak wavelength. What is the spectral linewidth of an optical communications LED operating at 1310 nm and at 300 K?

Solution

We are only interested in changes, thus $\boldsymbol{\Delta\lambda/\Delta(h\upsilon) \approx |d\lambda/d(h\upsilon)|}$, and this spread should be around $\lambda = \lambda_o$, so

$$\Delta\lambda = \frac{\lambda_o^2}{hc}\Delta(h\upsilon) = \lambda_o^2 \frac{3k_BT}{hc}$$

where we used $\Delta(h\upsilon) = 3k_BT$. We can substitute $\lambda = 1310$ nm, *and* $T = 300$ K to calculate the linewidth of the 1310 nm LED

$$\Delta\lambda = \lambda^2 \frac{3k_BT}{hc} = (1310\times10^{-9})^2 \frac{3(1.38\times10^{-23})(300)}{(6.626\times10^{-34})(3\times10^{8})}$$

$= \mathbf{1.07 \times 10^{-7}}$ **m or 107 nm**

EXAMPLE: LED spectral width

Consider the three experimental points in Figure 3.32 (b) as a function of temperature. By a suitable plot find m and verify

$$\Delta\lambda = \lambda_o^2 \frac{3k_B T}{hc}$$ *LED spectral linewidth* (3.11.3)

Solution

From Example,3.11.1, we can use the Eq. (3.11.3). with m instead of 3 as follows

$$\frac{\Delta\lambda}{\lambda_o^2} = \left(\frac{mk_B}{hc}\right)T$$ ***LED linewidth and temperature*** (3.11.5)

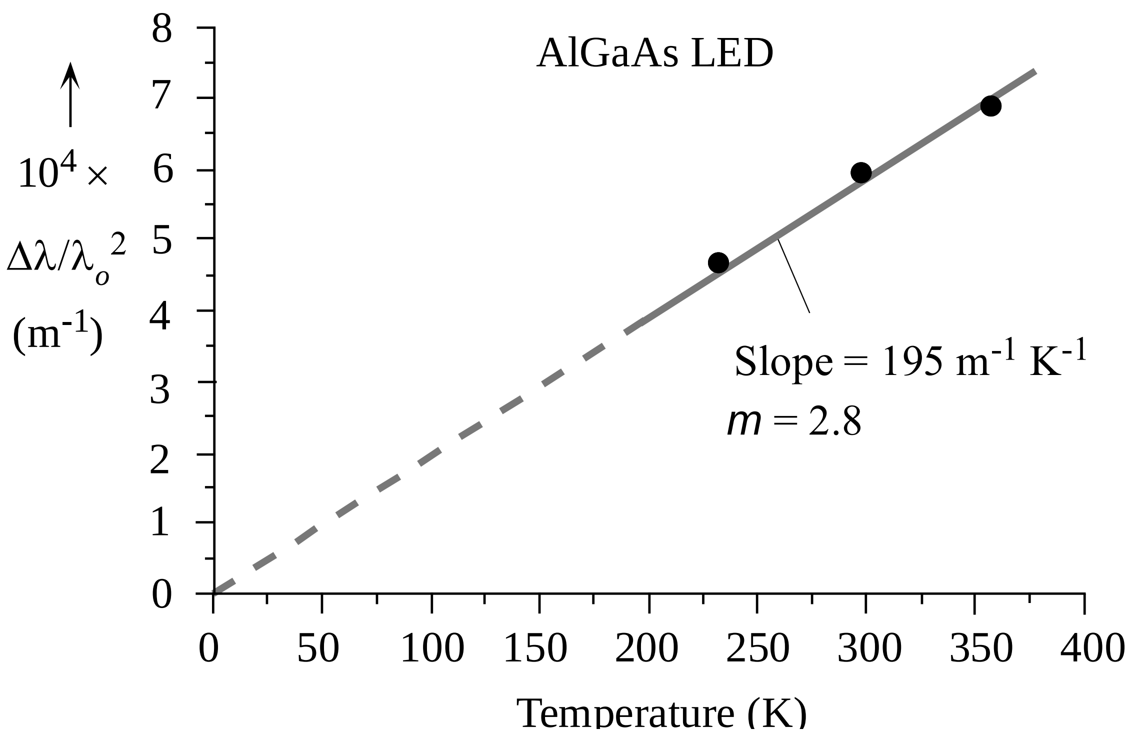
and plot $\Delta\lambda/\lambda_o^2$ *vs.* T. The slope of the best line forced through zero should give mk/hc and hence m. Using the three λ_o and $\Delta\lambda$ values in the inset of Figure 3.32(b), we obtain the graph in Figure 3.34. The best line is forced through zero to follow *Eq.* (3.11.5), and gives a slope of 1.95×10^{-7} nm^{-1} K^{-1} or 195 m^{-1} K^{-1}. Thus,

$$\text{slope} = 195\,\text{m K}^{-1} = \frac{m(1.38\times10^{-23}\,\text{J K}^{-1})}{(6.626\times10^{-34}\,\text{J s})(3\times10^{8}\,\text{m s}^{-1})}$$

so that $\boldsymbol{m = 2.81}$

EXAMPLE: LED spectral width

Solution (continued)

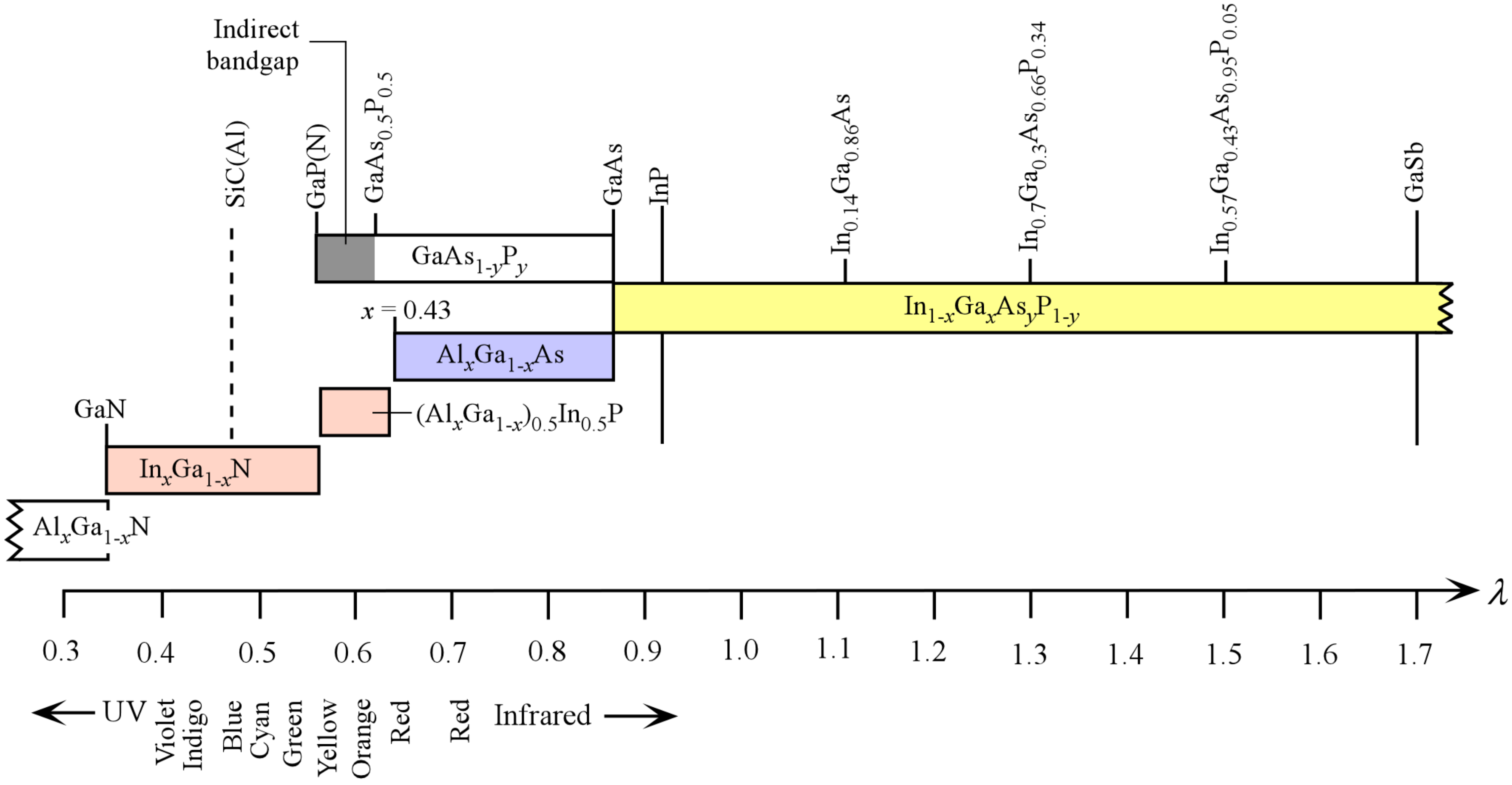


AlGaAs IR LED

T	λ_o	$\Delta\lambda$
–40°C	804 nm	30 nm
25°C	822 nm	40 nm
85°C	837 nm	48 nm

The plot of plot $\Delta\lambda/\lambda_o^2$ *vs.* T for an AlGaAs infrared LED, using the peak wavelength λ_o and spectral width $\Delta\lambda$ at three different temperatures, using the data shown in the table.

LED Materials



Free space wavelength coverage by different LED materials from the visible spectrum to the infrared including wavelengths used in optical communications. Hatched region and dashed lines are indirect E_g materials. Only material compositions of importance have been shown.