

Compensation Doping

Compensation doping describes the doping of a semiconductor with both donors and acceptors to control the properties.

Example: A *p*-type semiconductor doped with N_a acceptors can be converted to an *n*-type semiconductor by simply adding donors until the concentration N_d exceeds N_a .

The effect of donors compensates for the effect of acceptors.

The electron concentration $n = N_d - N_a > n_i$

When both acceptors and donors are present, electrons from donors recombine with the holes from the acceptors so that the mass action law $np = n_i^2$ is obeyed.

We cannot simultaneously increase the electron and hole concentrations because that leads to an increase in the recombination rate which returns the electron and hole concentrations to values that satisfy $np = n_i^2$.

$$N_d > N_a$$

$$n = N_d - N_a$$

$$p = n_i^2 / (N_d - N_a)$$



Example: Fermi levels in semiconductors

An *n*-type Si wafer has been doped uniformly with 10^{16} phosphorus (P) atoms cm^{-3} . Calculate the position of the Fermi energy with respect to the Fermi energy E_{Fi} in intrinsic Si. The above *n*-type Si sample is further doped with 2×10^{17} boron atoms cm^{-3} . Calculate position of the Fermi energy with respect to the Fermi energy E_{Fi} in intrinsic Si at room temperature (300 K), and hence with respect to the Fermi energy in the *n*-type case above.

Solution

P (Group V) gives *n*-type doping with $N_d = 10^{16} \text{ cm}^{-3}$, and since $N_d \gg n_i$ ($= 10^{10} \text{ cm}^{-3}$ from Table 3.1), we have $n = N_d = 10^{16} \text{ cm}^{-3}$. For intrinsic Si,

$$n_i = N_c \exp[-(E_c - E_{Fi})/k_B T]$$

whereas for doped Si,

$$n = N_c \exp[-(E_c - E_{Fn})/k_B T] = N_d$$

where E_{Fi} and E_{Fn} are the Fermi energies in the intrinsic and *n*-type Si. Dividing the two expressions

$$N_d/n_i = \exp[(E_{Fn} - E_{Fi})/k_B T]$$

so that

$$E_{Fn} - E_{Fi} = k_B T \ln(N_d/n_i) = (0.0259 \text{ eV}) \ln(10^{16}/10^{10}) = 0.358 \text{ eV}$$

Example: Fermi levels in semiconductors

Solution (Continued)

When the wafer is further doped with boron, the acceptor concentration, $N_a = 2 \times 10^{17} \text{ cm}^{-3} > N_d = 10^{16} \text{ cm}^{-3}$. The semiconductor is compensation doped and compensation converts the semiconductor to a *p*-type Si. Thus,

$$p = N_a - N_d = 2 \times 10^{17} - 10^{16} = 1.9 \times 10^{17} \text{ cm}^{-3}.$$

For intrinsic Si,

$$p = n_i = N_v \exp[-(E_{Fi} - E_v)/k_B T],$$

whereas for doped Si,

$$p = N_v \exp[-(E_{Fp} - E_v)/k_B T] = N_a - N_d$$

where E_{Fi} and E_{Fp} are the Fermi energies in the intrinsic and *p*-type Si respectively. Dividing the two expressions,

$$p/n_i = \exp[-(E_{Fp} - E_{Fi})/k_B T]$$

so that

$$\begin{aligned} E_{Fp} - E_{Fi} &= -k_B T \ln(p/n_i) \\ &= -(0.0259 \text{ eV}) \ln(1.9 \times 10^{17} / 1.0 \times 10^{10}) = -0.434 \text{ eV} \end{aligned}$$

EXAMPLE: LED brightness LED brightness

Consider two LEDs, one red, with an optical output power (radian flux) of 10 mW emitting at 650 nm, and the other, a weaker 5 mW green LED, emitting at 532 nm. Find the luminous flux emitted by each LED.

Solution

For the **red LED**, at $\lambda = 650 \text{ nm}$, Figure 3.41 gives $V \approx 0.10$ so that from Eq. (3.14.8)

$$\begin{aligned}\Phi_v &= P_o \times (633 \text{ lm W}^{-1}) \times V \\ &= (10 \times 10^{-3} \text{ W})(683 \text{ lm W}^{-1})(0.10) = \mathbf{0.68 \text{ lm}}\end{aligned}$$

For the **green LED**, $\lambda = 532 \text{ nm}$, Figure 3.41 gives $V \approx 0.87$ so that from Eq. (3.14.8)

$$\begin{aligned}\Phi_v &= P_o \times (633 \text{ lm W}^{-1}) \times V \\ &= (5 \times 10^{-3} \text{ W})(683 \text{ lm W}^{-1})(0.87) = \mathbf{3.0 \text{ lm}}\end{aligned}$$

Clearly the **green LED** at half the power is 4 times brighter than the **red LED**.

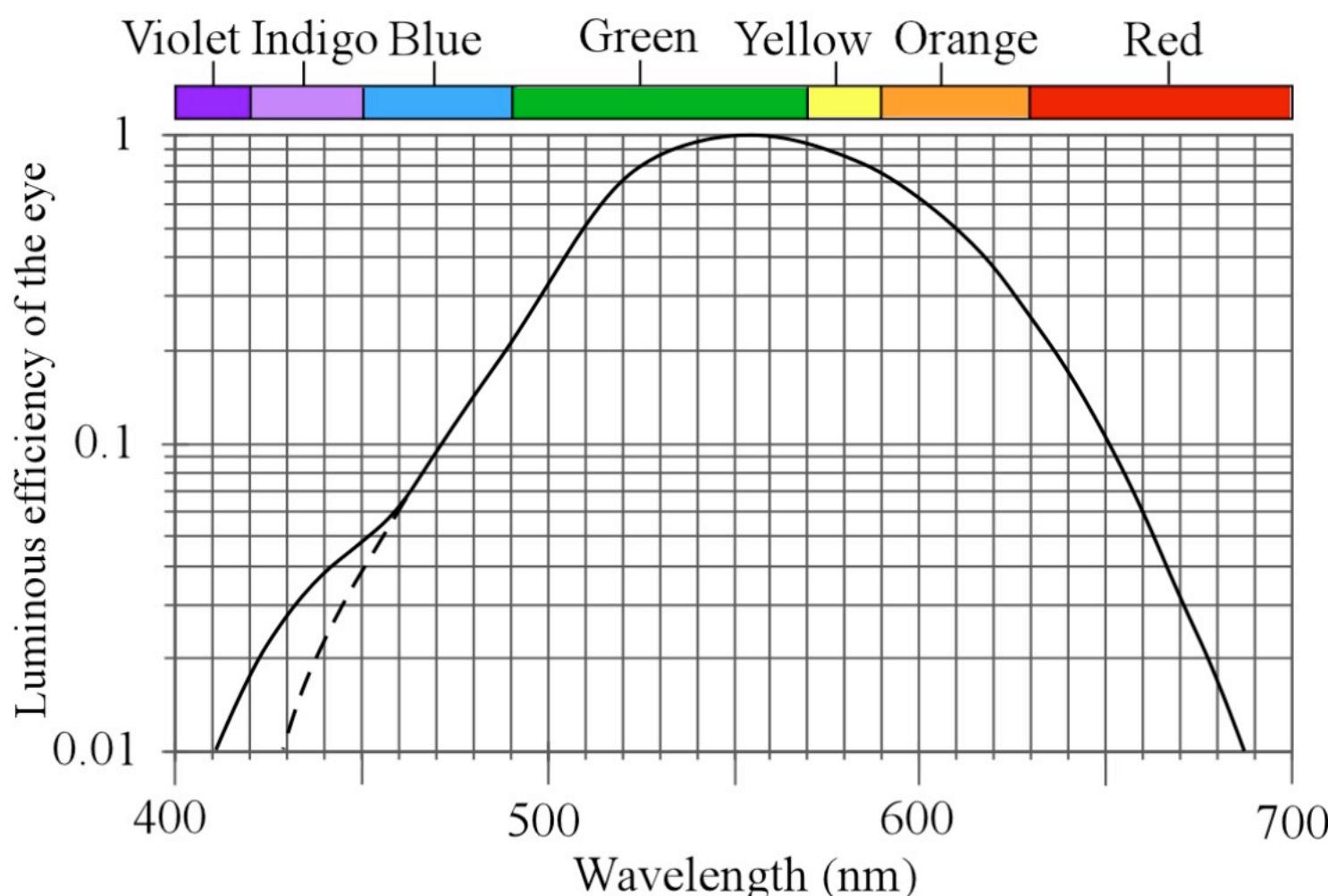


Figure 3.41

Solution

First note that $\theta_c = \arcsin(n_a/n_s) = \arcsin(1/3.4) = 17.1^\circ$. For T we will assume near-normal incidence (somewhat justified since the angle 17.1° is not too large) so that from Chapter 1,

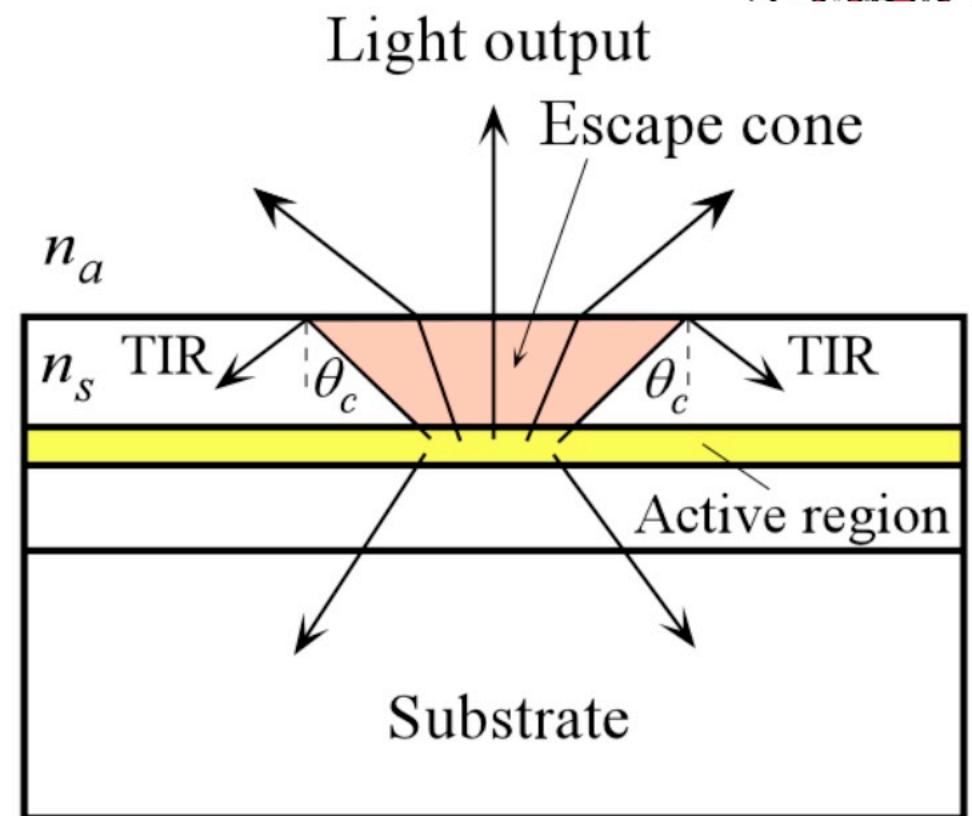
$$T = 4n_s n_a / (n_s + n_a)^2 = 4(3.4)(1)/(3.4 + 1)^2 = 0.702$$

Using Eq.(1),

Light extraction ratio

$$\begin{aligned} &\approx (1/2)[1 - \cos \theta_c] \times T = (1/2)[1 - \cos(17.1^\circ)] \times 0.702 \\ &\approx \mathbf{0.0155 \text{ or } 1.6\%} \end{aligned}$$

It is clear that only 1.6% of the generated light power is extracted from a bare chip, which is disappointingly small. The technological drive is therefore to improve light extraction as much as possible. If we now repeat the calculation for $n_a = 1.8$, we would find, $\theta_c = 32^\circ$, and 6.9% light extraction.



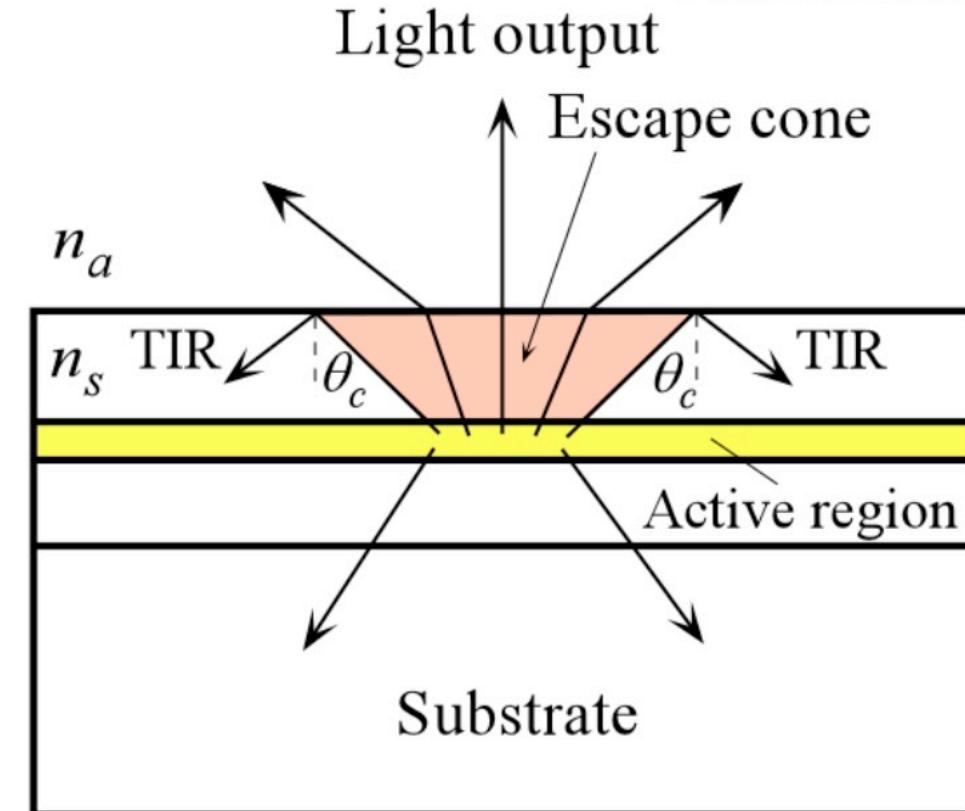
EXAMPLE: Light extraction from a bare LED chip

As shown in (a), due to total internal reflection (TIR) at the semiconductor-air surface, only a fraction of the emitted light can escape from the chip. The critical angle θ_c is determined by $\sin \theta_c = n_a / n_s$ where n_a and n_s are the refractive indices of the ambient (e.g. for air, $n_a = 1$) and the semiconductor respectively. The light within the **escape cone** defined by θ_c can escape into the ambient without TIR as indicated in (a). To find the fraction of light within the escape cone we need to consider solid angles, which leads to $(1/2)[1 - \cos \theta_c]$.

Further, suppose that T is the average light transmittance of the n_s - n_a interface for those rays within the escape cone, then for a simple bare chip,

$$\text{Light extraction ratio} \approx (1/2)[1 - \cos \theta_c] \times T \quad (1)$$

Estimate the extraction ratio for a GaAs chip with $n_s = 3.4$ and air as ambient ($n_a = 1$) and then with epoxy dome with $n_a = 1.8$.



EXAMPLE: Energy levels in the quantum well

Consider a GaAs QW sandwiched between two $\text{Al}_{0.40}\text{Ga}_{0.60}\text{As}$ layers. Suppose that the barrier height ΔE_c is 0.30 eV, the electron effective mass in the well is $0.067m_e$ and the width of the QW (d) is 12 nm. Calculate the energy levels E_1 and E_2 from the bottom of the well (E_c) assuming an infinite PE well as in Eq. (1). Compare these with the calculations for a finite PE well that give 0.022 eV, 0.088 and 0.186 for $n = 1, 2$ and 3.

Solution

We use Eq. (1) with $m_e^* = 0.067m_e$, $d = 12 \times 10^{-9} \text{ nm}$, so that for $n = 1$,

$$\Delta E_n = E_n - E_c = \frac{\hbar^2 n^2}{8m_e^* d^2} = \frac{(6.624 \times 10^{-34} \text{ Js})^2 (1)^2 / (1.602 \times 10^{-19} \text{ J eV}^{-1})}{8(0.067 \times 9.1 \times 10^{-31} \text{ kg})(12 \times 10^{-9} \text{ m})^2} = 0.039 \text{ eV}$$

We can repeat the above calculation for $n = 2$ and 3 to find $\Delta E_2 = 0.156 \text{ eV}$ and $\Delta E_3 = 0.351 \text{ eV}$. The third level will be above the well depth ($\Delta E_c = 0.3 \text{ eV}$). Clearly, the infinite QW predicts higher energy levels, by a factor of 1.8, and puts the third level inside the well not outside. The finite QW calculation is not simple, and involves a numerical solution.

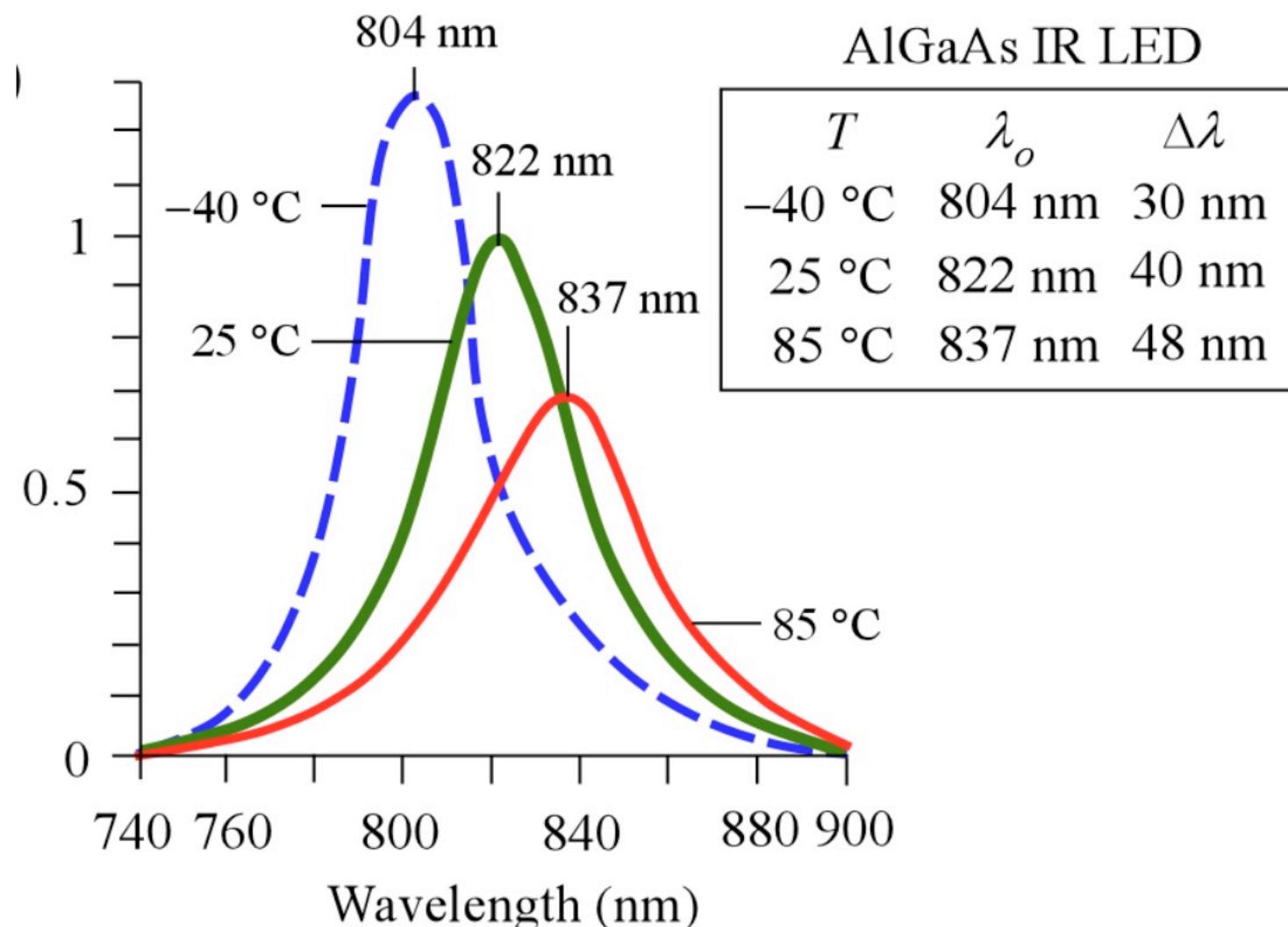
EXAMPLE: Dependence on the emission peak and linewidth on temperature

Solution (continued)

and the new peak emission wavelength λ'_0 is

$$\lambda'_0 = \frac{(3 \times 10^8 \text{ ms}^{-1})(6.626 \times 10^{-34} \text{ Js}) / (1.602 \times 10^{-19} \text{ eV J}^{-1})}{(1.445 \text{ eV} + 0.01069 \text{ eV})} = 852.4 \text{ nm}$$

The change $\Delta\lambda = \lambda_o - \lambda'_0 = 864.2 - 852.4 = 11.8 \text{ nm}$ over $50 \text{ }^\circ\text{C}$, or $0.24 \text{ nm} / \text{ }^\circ\text{C}$.



The examination of the Figure 3.32(b) shows that the change in the peak wavelength per unit temperature in the range $-40 \text{ }^\circ\text{C}$ to $85 \text{ }^\circ\text{C}$ is roughly the same. Because of the small change, we kept four significant figures in E_g and λ_o calculations.

EXAMPLE: Dependence of the emission peak and linewidth on temperature

Using the Varshni equation, Eq. (3.11.2), $E_g = E_{go} - AT^2/(B + T)$, find the shift in the peak wavelength (λ_o) emitted from a GaAs LED when it is cooled from 25 °C to -25 °C. The *Varshni constants* for GaAs are, $E_{go} = 1.519 \text{ eV}$, $A = 5.41 \times 10^{-4} \text{ eV K}^{-1}$, $B = 204 \text{ K}$.

Solution

At $T = 298 \text{ K}$, using the Varshni equation

$$E_g = E_{go} - AT^2/(B + T) \\ = 1.519 \text{ eV} - (5.41 \times 10^{-4} \text{ eV K}^{-1})(298 \text{ K})^2/(204 \text{ K} + 298 \text{ K}) = 1.423 \text{ eV}.$$

At 298 K, $(1/2)k_B T = 0.0128 \text{ eV}$. The peak emission is at $h\nu_o \approx E_g + (1/2)k_B T$. Using $\nu_o = c/\lambda_o$, we get

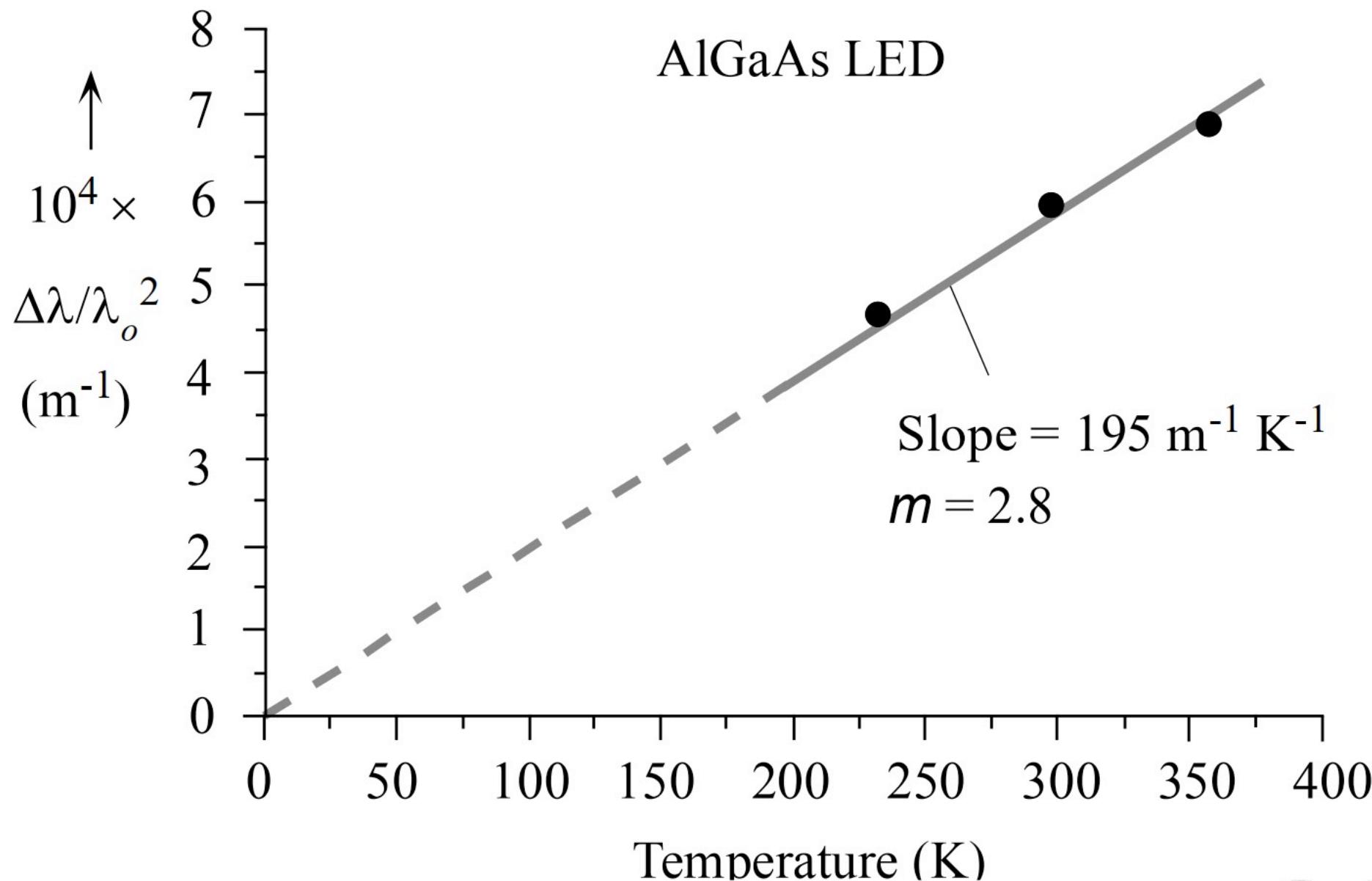
$$\lambda_o = \frac{ch}{(E_g + \frac{1}{2}k_B T)} = \frac{(3 \times 10^8 \text{ m s}^{-1})(6.626 \times 10^{-34} \text{ Js}) / 1.602 \times 10^{-19} \text{ eV J}^{-1}}{(1.4223 \text{ eV} + 0.0128 \text{ eV})} = 864.2 \text{ nm}$$

At -25 °C or , 248 K, $(1/2)k_B T = 0.0107 \text{ eV}$, repeating the above calculation,

$$E_g = 1.519 \text{ eV} - (5.41 \times 10^{-4} \text{ eV K}^{-1})(248 \text{ K})^2/(204 \text{ K} + 248 \text{ K}) = 1.445 \text{ eV}$$

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 $\Delta\lambda/\lambda_o^2$ 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.



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

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

Solution

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

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

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 $1.95 \times 10^{-7} \text{ nm}^{-1} \text{ K}^{-1}$ or $195 \text{ m}^{-1} \text{ K}^{-1}$. Thus,

$$\text{slope} = 195 \text{ m K}^{-1} = \frac{m(1.38 \times 10^{-23} \text{ J K}^{-1})}{(6.626 \times 10^{-34} \text{ Js})(3 \times 10^8 \text{ ms}^{-1})}$$

so that

$$m = 2.81$$

EXAMPLE : LED spectral linewidth

Solution (continued)

$$\Delta\lambda = \frac{\lambda_o^2}{hc} \Delta(h\nu) = \lambda_o^2 \frac{3k_B T}{hc}$$

where we used $\Delta(h\nu) = 3k_B T$. We can substitute $\lambda = 1310 \text{ nm}$, and $T = 300 \text{ K}$ to calculate the linewidth of the 1310 nm LED

$$\Delta\lambda = \lambda^2 \frac{3k_B T}{hc} = (1310 \times 10^{-9})^2 \frac{3(1.38 \times 10^{-23})(300)}{(6.626 \times 10^{-34})(3 \times 10^8)}$$

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

The spectral linewidth of an LED output is due to the spread in the photon energies, which is fundamentally about $3k_B T$. The only option for decreasing $\Delta\lambda$ at a given wavelength is to reduce the temperature. The output spectrum of a laser, on the other hand, has a much narrower linewidth.



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 $h\nu = hc/\lambda$. Assume that the spread in the photon energies $\Delta(h\nu) \approx 3k_B T$ between the half intensity points. Show that the corresponding linewidth $\Delta\lambda$ between the *half intensity points* in the output spectrum is

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

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

First consider the relationship between the photon frequency ν and λ ,

$$\lambda = \frac{c}{\nu} = \frac{hc}{h\nu}$$

in which $h\nu$ is the photon energy. We can differentiate this

$$\frac{d\lambda}{d(h\nu)} = -\frac{hc}{(h\nu)^2} = -\frac{\lambda^2}{hc} \quad (3.11.4)$$

The negative indicates that increasing the photon energy decreases the wavelength. We are only interested in changes, thus $\Delta\lambda/\Delta(h\nu) \approx |d\lambda/d(h\nu)|$, and this spread should be around $\lambda = \lambda_o$, so that Eq. (3.11.4) gives,

EXAMPLE : The built-in voltage from the band diagram

Derive the expression for the built-in voltage V_o using the energy band diagram.

Solution

The extent of band bending from gives the PE barrier eV_o , thus

$$eV_o = \Phi_p - \Phi_n = E_{Fn} - E_{Fp} \text{ (before contact)}$$

Before the contact, on the n -side we have

$$n = N_c \exp[-(E_c - E_{Fn})/k_B T] = N_d$$

so that

$$E_c - E_{Fn} = -k_B T \ln(N_d / N_c) \quad (3.9.1)$$

On the p -side

$$n = N_c \exp[-(E_c - E_{Fp})/k_B T] = n_i^2 / N_a$$

so that

$$E_c - E_{Fp} = -k_B T \ln[n_i^2 / (N_a N_c)] \quad (3.9.2)$$

Subtracting Eq. (3.9.2) from (3.9.1) gives

$$eV_o = E_{Fn} - E_{Fp} = k_B T \ln[(N_a N_d) / n_i^2]$$



Solution (continued)

$$= \frac{(10^{-6})(1.6 \times 10^{-19})(2.1 \times 10^{12})}{2} \left(\frac{1.16 \times 10^{-7}}{5.00 \times 10^{-8}} \right) \approx 3.9 \times 10^{-13} \text{ A}$$

so that at $V = 0.8 \text{ V}$,

$$\begin{aligned} I_{\text{recom}} &\approx I_{ro} \exp\left(\frac{eV}{2k_B T}\right) \\ &\approx (3.9 \times 10^{-13} \text{ A}) \exp\left[\frac{0.8 \text{ V}}{2(0.02585 \text{ V})}\right] = 2.0 \times 10^{-6} \text{ A or } 2.1 \mu\text{A} \end{aligned}$$

The recombination current is more than an order of magnitude greater than the diffusion current. If we repeat the calculation for a voltage of 1.05 V across the device, then we would find $I_{\text{diff}} = 1.9 \text{ mA}$ and $I_{\text{recom}} = 0.18 \text{ mA}$, where I_{diff} dominates the current. Thus, as the voltage increases across a GaAs pn junction, the ideality factor η is initially 2 but then becomes 1 as shown in Figure 3.20.

The EHP recombination that occurs in the SCL and the neutral regions in this GaAs pn junction case would result in photon emission, with a photon energy that is approximately E_g . This direct recombination of injected minority carriers and the resulting emission of photons represent the principle of operation of the Light Emitting Diode (LED).



Solution (continued)

Depletion layer width W is

$$\begin{aligned} W &= \left[\frac{2\epsilon(N_a + N_d)(V_o - V)}{eN_a N_d} \right]^{1/2} \\ &= \left[\frac{2(13)(8.85 \times 10^{-12} \text{ F m}^{-1})(10^{23} + 10^{23} \text{ m}^{-3})(1.27 - 0.80 \text{ V})}{(1.6 \times 10^{-19} \text{ C})(10^{23} \text{ m}^{-3})(10^{23} \text{ m}^{-3})} \right]^{1/2} \\ &= 1.16 \times 10^{-7} \text{ m, or } 0.116 \text{ } \mu\text{m.} \end{aligned}$$

As this is a symmetric diode, $W_p = W_n = W/2$. The pre-exponential I_{ro} is

$$\begin{aligned} I_{ro} &= \frac{Aen_i}{2} \left[\frac{W_p}{\tau_e} + \frac{W_n}{\tau_h} \right] = \frac{Aen_i}{2} \left(\frac{W}{\tau_e} \right) \\ &= \frac{(10^{-6})(1.6 \times 10^{-19})(2.1 \times 10^{12})}{2} \left(\frac{1.16 \times 10^{-7}}{5.00 \times 10^{-8}} \right) \approx 3.9 \times 10^{-13} \text{ A} \end{aligned}$$



Solution (continued)

Recombination component of the current is quite difficult to calculate because we need to know the mean electron and hole recombination times in the SCL.

Direct recombination time within the SCL is actually very long (carrier concentrations are small) and the main recombination mechanism is due to indirect recombination, which depends on defects and impurities. As a worst case assumption, we can take τ_e and τ_h due to indirect recombination in the SCL to be roughly the same as direct recombination lifetimes in the neutral regions above, though they are likely to be longer in practice.

First, we need the width W of the depletion region and hence V_o .

The built-in voltage V_o

$$V_o = \frac{k_B T}{e} \ln \left(\frac{N_a N_d}{n_i^2} \right) = (0.02585) \ln \left[\frac{10^{23} 10^{23}}{(2.1 \times 10^{12})^2} \right] = 1.27 \text{ V}$$



Solution (continued)

where $k_B T/e$ was taken as 0.02585 V. The diffusion lengths are easily calculated as

$$L_h = (D_h \tau_h)^{1/2} = [(6.46 \times 10^{-4} \text{ m}^2 \text{ s}^{-1})(50.0 \times 10^{-9} \text{ s})]^{1/2} = 5.69 \times 10^{-6} \text{ m},$$

$$L_e = (D_e \tau_e)^{1/2} = [(1.29 \times 10^{-2} \text{ m}^2 \text{ s}^{-1})(50.0 \times 10^{-9} \text{ s})]^{1/2} = 2.54 \times 10^{-5} \text{ m}.$$

Notice that the electrons diffuse much further in the *p*-side. The reverse saturation current due to diffusion in the neutral regions is

$$\begin{aligned} I_{so} &= A \left(\frac{D_h}{L_h N_d} + \frac{D_e}{L_e N_a} \right) e n_i^2 \\ &= (10^{-6}) \left[\frac{6.46 \times 10^{-4}}{(5.69 \times 10^{-6})(10^{23})} + \frac{1.29 \times 10^{-2}}{(2.54 \times 10^{-5})(10^{23})} \right] (1.6 \times 10^{-19})(2.1 \times 10^{12})^2 \\ &\approx 4.4 \times 10^{-21} \text{ A} \end{aligned}$$

Thus, the forward diffusion current at $V = 0.80 \text{ V}$ is

$$\begin{aligned} I_{\text{diff}} &= I_{so} \exp\left(\frac{eV}{k_B T}\right) \\ &= (4.4 \times 10^{-21} \text{ A}) \exp\left[\frac{0.80 \text{ V}}{0.02585 \text{ V}}\right] = 1.2 \times 10^{-7} \text{ A or } 0.12 \mu\text{A} \end{aligned}$$



EXAMPLE : A direct bandgap *pn* junction

Solution

Assuming weak injection, we can calculate the recombination times τ_e and τ_h for electrons and holes recombining in the neutral p and n-regions respectively. Using S.I. units throughout, and taking $k_B T/e = 0.02585 \text{ V}$, and since this is a symmetric device,

$$\tau_h = \tau_e \approx \frac{1}{BN_a} = \frac{1}{(2.0 \times 10^{-16} \text{ m}^3 \text{s}^{-1})(1 \times 10^{23} \text{ m}^{-3})} = 5.00 \times 10^{-8} \text{ s}$$

To find the Shockley current we need the diffusion coefficients and lengths. The Einstein relation gives the diffusion coefficients as

$$D_h = \mu_h k_B T/e = (250 \times 10^{-4}) (0.02585) = 6.46 \times 10^{-4} \text{ m}^2 \text{ s}^{-1},$$

$$D_e = \mu_e k_B T/e = (5000 \times 10^{-4}) (0.02585) = 1.29 \times 10^{-2} \text{ m}^2 \text{ s}^{-1}.$$



EXAMPLE : A direct bandgap *pn* junction

Consider a symmetrical GaAs *pn* junction which has the following properties. N_a (*p*-side doping) = N_d (*n*-side doping) = 10^{17} cm^{-3} (or 10^{23} m^{-3}), direct recombination coefficient $B \approx 2 \times 10^{-16} \text{ m}^3 \text{ s}^{-1}$, cross sectional area $A = 1 \text{ mm}^2$. Suppose that the forward voltage across the diode $V = 0.80 \text{ V}$. What is the diode current due to minority carrier diffusion at 27°C (300 K) assuming direct recombination. If the mean minority carrier lifetime in the depletion region were to be the same as this lifetime, what would be the recombination component of the diode current? What are the two contributions at $V = 1.05 \text{ V}$?

What is your conclusion? Note that at 300 K, GaAs has an intrinsic concentration (n_i) of $2.1 \times 10^6 \text{ cm}^{-3}$ and a relative permittivity (ϵ_r) of 13.0. The hole drift mobility (μ_h) in the *n*-side is $250 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and electron drift mobility (μ_e) in the *p*-side is $5000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ (these are at the doping levels given).



Example: Conductivity of *n*-Si

Consider a pure intrinsic Si crystal. What would be its intrinsic conductivity at 300K? What is the electron and hole concentrations in an *n*-type Si crystal that has been doped with 10^{16} cm^{-3} phosphorus (P) donors. What is the conductivity if the drift mobility of electrons is about $1200 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at this concentration of dopants.

Solution

The intrinsic concentration $n_i = 1 \times 10^{10} \text{ cm}^{-3}$, so that the intrinsic conductivity is

$$\begin{aligned}\sigma &= en_i(\mu_e + \mu_h) = (1.6 \times 10^{-19} \text{ C})(1 \times 10^{10} \text{ cm}^{-3})(1450 + 490 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}) \\ &= 3.1 \times 10^{-6} \Omega^{-1} \text{ cm}^{-1} \text{ or } 3.1 \times 10^{-4} \Omega^{-1} \text{ m}^{-1}\end{aligned}$$

Consider *n*-type Si. $N_d = 10^{16} \text{ cm}^{-3} > n_i (= 10^{10} \text{ cm}^{-3})$, the electron concentration $n = N_d = 10^{16} \text{ cm}^{-3}$ and

$$p = n_i^2/N_d = (10^{10} \text{ cm}^{-3})^2/(10^{16} \text{ cm}^{-3}) = 10^4 \text{ cm}^{-3}$$

and negligible compared to n .

The conductivity is

$$\sigma = eN_d\mu_e = (1.6 \times 10^{-19} \text{ C})(1 \times 10^{16} \text{ cm}^{-3})(1200 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}) = 1.92 \Omega^{-1} \text{ cm}^{-1}$$