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Optoelectronic Sources

After reading this chapter you will be able to understand the following:

- Fundamental aspects of semiconductor physics
 - The p - n junction
 - Injection efficiency
 - Injection luminescence and the light-emitting diode (LED)
 - Internal and external quantum efficiencies
 - LED designs
 - Modulation response of LEDs
 - Basics of lasers
 - Laser action in semiconductors
 - Modulation response of injection laser diodes (ILDs)
 - ILD designs
 - Source-fiber coupling
-

7.1 INTRODUCTION

In fiber-optic systems, electrical signals (current or voltage) at the transmitter end have to be converted into optical signals as efficiently as possible. This function is performed by an optoelectronic source. What should be the criterion for selecting such a source? Ideally, the size and shape of the source should be compatible with the size of an optical fiber so that it can couple maximum power into the fiber. The response of the source should be linear; i.e., the optical power generated by the source should be directly proportional to the electrical signal supplied to it. Further, it should provide sufficient optical power so that it overcomes the transmission losses down the link. It must emit monochromatic radiation at the wavelength at which the optical fiber exhibits low loss and/or low dispersion. Finally, it must be stable, reliable, and cheap as far as possible. There are two types of sources which, to a large extent, fulfil these requirements. These are (i) incoherent optoelectronic sources (e.g., light-emitting diodes, LEDs) and (ii) coherent optoelectronic sources (e.g., injection laser diodes, ILDs).

In order to understand the principle of operation, efficiency, and design of these devices, it is essential to be familiar with the properties of semiconductors, p - n homojunctions and heterojunctions, the light emission process, etc. This chapter, therefore, begins with the discussion of such fundamental aspects of semiconductor physics, followed by the efficiency and design aspects of light-emitting diodes. The basic principles of laser action and injection laser diodes are taken up next. We conclude with source-fiber coupling.

7.2 FUNDAMENTAL ASPECTS OF SEMICONDUCTOR PHYSICS

According to the band theory of solids, materials may be classified into three categories from the point of view of electrical conduction. These are (i) conductors, (ii) insulators, and (iii) semiconductors. This distinction may be understood with the aid of an energy band diagram. Within a material, the permitted electron energy levels fall into bands of allowed energy as shown in Fig. 7.1. Herein, the vacuum level E_o represents the energy of an electron at rest just outside the surface of the solid. The highest band of allowed energy levels inside the material, which extends from the vacuum level E_o down to energy E_c , is called the conduction band (CB). The energy width of this band, $\chi = E_o - E_c$, is called the electron affinity of the material. The next highest allowed band is known as the valence band (VB). The energy corresponding to the top of the VB is depicted as E_v . These two bands are separated by an energy gap (called the forbidden gap), or a band gap in which no energy levels exist. The energy gap $E_g = E_c - E_v$.

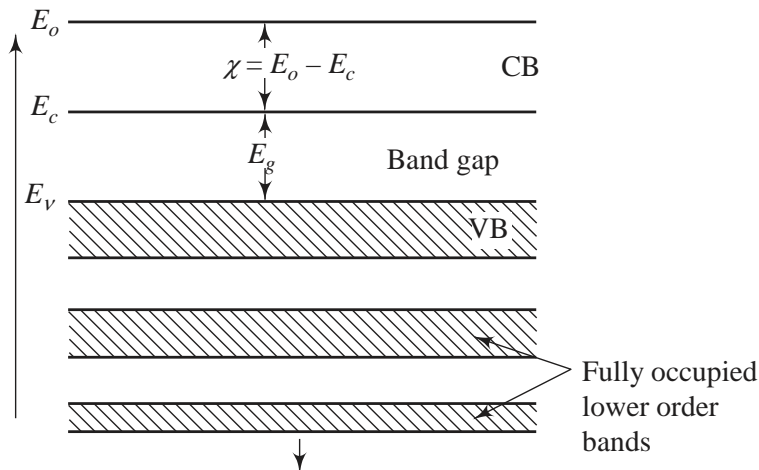


Fig. 7.1 Energy band diagram of a solid

A material with no energy gap between the conduction and valence bands or with overlapping bands is a good conductor. A material with a completely empty CB separated from a completely filled VB by a large band gap is an insulator. If this band gap is small, then the material is a semiconductor. The resistivity of these three classes of materials lies in the following range of values:

Conductor: 10^{-6} – $10^{-4} \Omega \text{ cm}$

Insulator: 10^{10} – $10^{20} \Omega \text{ cm}$

Semiconductor: 10^{-2} – $10^8 \Omega \text{ cm}$

7.2.1 Intrinsic and Extrinsic Semiconductors

In a pure semiconducting crystal, at absolute zero, the VB is completely filled and the CB is devoid of electrons. However, as the temperature is increased, some electrons from the top of the VB are thermally excited to the lower levels of the CB, thus giving rise to a concentration of n free electrons per unit volume in the CB. This process of electron excitation leaves behind an equal concentration per unit volume, p , of vacancies of electrons in the VB as shown schematically in Fig. 7.2. This vacancy of an electron is called a hole, and it carries a positive charge of magnitude equal to that of an electronic charge. Both the charge carriers, i.e., free electrons and holes are mobile within the material, so both contribute to electrical conductivity. Such semiconductors in which there are equal number of electrons and holes are called intrinsic semiconductors.

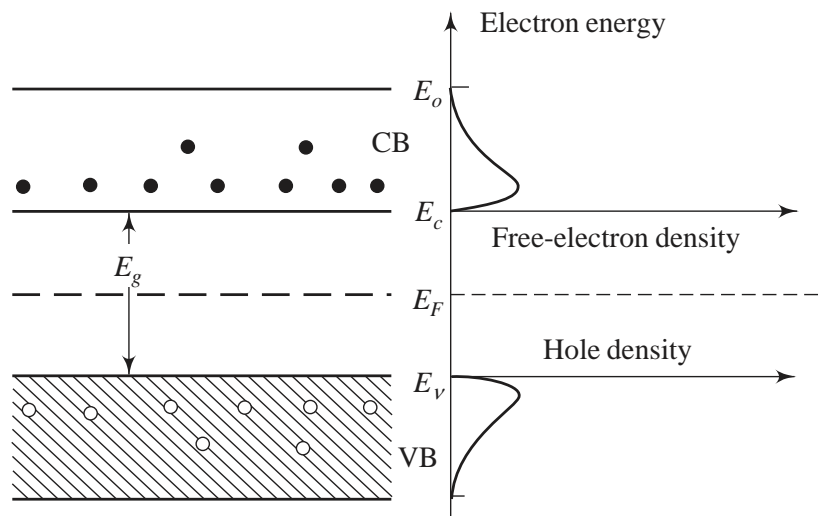


Fig. 7.2 Thermal excitation of electrons from the valence to the conduction band giving rise to concentration distributions of electrons and holes in the CB and VB, respectively. Solid circles represent electrons and hollow circles represent holes.

Let us calculate the density of charge carriers, namely, electrons and holes in an intrinsic semiconductor. For such a calculation, obviously, we need two parameters: (i) the density of states function $g(E)$ which may be defined as the number of energy states per unit energy, per unit volume and (ii) the probability function $f(E)$ that each of these energy states is occupied by an electron. The density of states function $g(E)$ is given by

$$g(E) = (4\pi/h^3)(2m_e)^{3/2} (E - E_c)^{1/2} \quad (7.1)$$

where h is Planck's constant, m_e is the effective mass of an electron, and E is the energy at which this density is sought.

The probability that a particular energy level at energy E is occupied at a temperature T (K) is given by the Fermi–Dirac distribution function $f(E)$ as follows:

$$f(E) = 1/[\exp\{(E - E_F)/kT\} + 1] \quad (7.2)$$

where E_F is called the Fermi energy and k is Boltzmann's constant. In Fig. 7.2, a reference energy level (dashed line) in the middle of the band gap has been shown. This is known as the Fermi level and the corresponding energy is E_F . An electron state at E_F , should one exist there, would have a 50% probability of being occupied. The difference of energy between a vacuum level and a Fermi level is called the work function ϕ . Thus $\phi = E_o - E_F$.

Coming to Eq. (7.2), if the lower edge of the CB is about $4kT$ above the Fermi level, i.e., if $E - E_F > 4kT$, we can neglect the unity term in the denominator. Thus Eq. (7.2) may be written as

$$f(E) = \exp[-(E - E_F)/kT] \quad (7.3)$$

This approximation is referred to as Boltzmann's approximation. The density of free electrons, i.e., the number of free electrons per unit volume, n , in the CB, will then be given by

$$n = \int_{E_c}^{E_o} n(E)dE = \int_{E_c}^{E_o} g(E)f(E)dE$$

or

$$n \approx \int_{E_c}^{\infty} g(E)f(E)dE \quad (7.4)$$

The CB extends only up to energy E_o , but the integration limit has been extended to ∞ in order to simplify calculations. However, not much error is introduced, as the Fermi function tapers to zero rapidly.

Substituting $g(E)$ and $f(E)$ from Eqs (7.1) and (7.3) in Eq. (7.4), we get

$$n \approx \int_{E_c}^{\infty} (4\pi/h^3) (2m_e)^{3/2} (E - E_c)^{1/2} \exp[-(E - E_F)/kT] dE$$

Solving this, we get

$$n = 2(2\pi m_e kT/h^2)^{3/2} \exp[(E_F - E_c)/kT] \quad (7.5a)$$

$$= N_c \exp[(E_F - E_c)/kT] \quad (7.5b)$$

where $N_c = 2(2\pi m_e kT/h^2)^{3/2}$ is known as the effective density of states in the CB.

Similarly, the density of holes, p , in the VB may be calculated using the integral

$$p = \int p(E)dE \approx \int_{-\infty}^{E_y} g(E)[1 - f(E)] dE \quad (7.6)$$

Here $[1 - f(E)]$ represents the probability of electron states being unoccupied in the VB. In other words, it is the probability of occupation of the states by holes. Now,

$$1 - f(E) = 1 - 1/[\exp\{(E - E_F)/kT\} + 1]$$

$$= \exp[(E - E_F)/kT]/[\exp\{(E - E_F)/kT\} + 1]$$

In the VB, E is lower than E_F and hence the term $\exp[(E - E_F)/kT]$ is much smaller compared to 1 in the denominator. Therefore

$$1 - f(E) \approx \exp[(E - E_F)/kT] \quad (7.7)$$

The density of states function for holes in the VB is given by

$$g(E) = (4\pi/h^3) (2m_h)^{3/2} (E_v - E)^{1/2} \quad (7.8)$$

where m_h is the effective mass of a hole. Substituting the values of $g(E)$ and $[1 - f(E)]$ from Eqs (7.8) and (7.7), respectively, in Eq. (7.6), we get

$$\begin{aligned} p &= (4\pi/h^3)(2m_h)^{3/2} \int_{-\infty}^{E_v} (E_v - E)^{1/2} \exp[(E - E_F)/kT] dE \\ &= 2(2\pi m_h kT/h^2)^{3/2} \exp[(E_v - E_F)/kT] \end{aligned} \quad (7.9a)$$

$$= N_v \exp[(E_v - E_F)/kT] \quad (7.9b)$$

where $N_v = 2(2\pi m_h kT/h^2)^{3/2}$ is known as the effective density of states in the VB.

On the assumption that, in an intrinsic semiconductor, all the electrons in the CB are obtained from the thermal excitation of the electrons from the VB, we can equate the electron and hole densities:

$$n = p = n_i \quad (7.10)$$

where n_i is called the intrinsic carrier density. Taking the product of n and p by substituting their values from Eqs (7.5) and (7.9), we get

$$\begin{aligned} n_i^2 &= np = N_c N_v \exp[(E_F - E_c - E_F + E_v)/kT] \\ &= N_c N_v \exp(-E_g/kT) \quad (\text{as } E_c - E_v = E_g) \end{aligned} \quad (7.11)$$

Therefore,
$$\begin{aligned} n_i &= n = p = (N_c N_v)^{1/2} \exp(-E_g/2kT) \\ &= 2(2\pi kT/h^2)^{3/2} (m_e m_h)^{3/4} \exp(-E_g/2kT) \end{aligned} \quad (7.12)$$

The conduction property of an intrinsic semiconductor may be modified by adding minute quantities of appropriate impurities. Let us take the case of silicon (Si) as an intrinsic semiconductor. Its band gap is 1.1 eV and it is tetravalent. If it is doped with a pentavalent impurity such as phosphorus, P (i.e., P substituting for Si in the crystal structure), then four electrons of P are used for covalent bonding with Si and the fifth loosely bound electron is available for conduction. This generates an occupied level just below the bottom of the CB called the *donor level*. Such dopant impurities which can donate electrons to the CB are called *donors*. This process of doping (Si with P) gives rise to an increase in the free-electron concentration in the CB as shown in Fig. 7.3. Now the majority of charge carriers in the semiconductor are (negative) electrons, and hence it is called an *n-type semiconductor*.

Taking the case of Si again, it is also possible to dope it with a trivalent impurity such as boron (B). In this case, the three electrons of B (substituting for Si) make covalent bonds, and a vacancy of one electron, i.e., a hole, is created. This produces an unoccupied *acceptor level* just above the top of the VB. This level is so called because it accepts electrons from the VB, thereby increasing the hole concentration

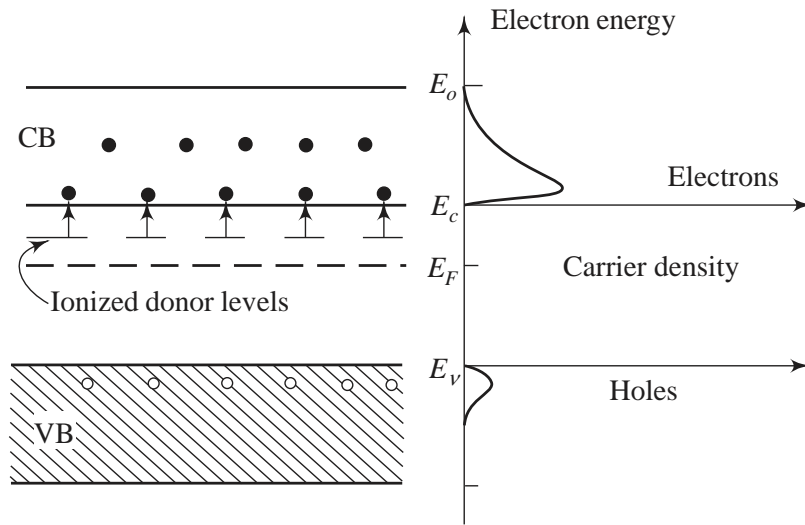


Fig. 7.3 Energy band diagram of an *n*-type semiconductor

in the VB, as shown in Fig. 7.4. The majority of charge carriers are now (positive) holes, and hence it is called a *p*-type semiconductor.

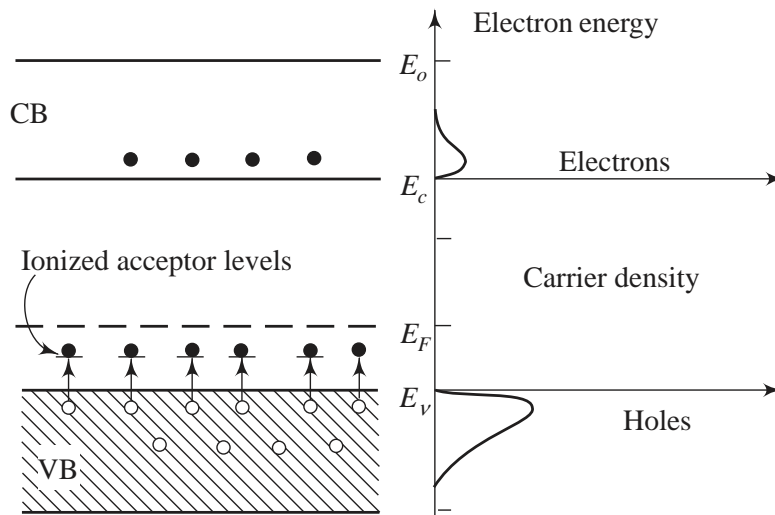


Fig. 7.4 Energy band diagram of a *p*-type semiconductor

The materials which become *n*- or *p*-type after doping are called *extrinsic semiconductors* because in this case, the doping concentration, rather than the temperature, is the main factor determining the number of free charge carriers available for conduction purposes.

As can be seen in Fig. 7.3, the increase in free-electron concentration in the *n*-type material causes the position of the Fermi level to be raised within the band gap. Conversely, the position of the Fermi level is lowered in the *p*-type material (see Fig. 7.4).

If the doping concentrations are not very high, the product of electron and hole densities remains almost independent of the doping concentration. That is,

$$np = n_i^2 = N_c N_v \exp(-E_g/kT) \quad (7.13)$$

This simply means that in an extrinsic semiconductor, there are *majority carriers* (either electrons in the *n*-type semiconductor or holes in the *p*-type material) and *minority carriers* (either holes in the *n*-type or electrons in the *p*-type material).

Example 7.1 Calculate the intrinsic carrier concentration in a semiconductor GaAs at room temperature ($RT = 300$ K) from the following data: $m_e = 0.07m$, $m_h = 0.56m$, $E_g = 1.43$ eV, where m is the mass of an electron in free space.

Solution

$$n_i = 2 \left(\frac{2\pi kT}{h^2} \right)^{3/2} (m_e m_h)^{3/4} \exp(-E_g/2kT).$$

$m = 9.11 \times 10^{-31}$ kg, $k = 1.38 \times 10^{-23}$ J K⁻¹, $h = 6.626 \times 10^{-34}$ J s, 1 eV = 1.6×10^{-19} J
Therefore,

$$\begin{aligned} n_i &= 2 \left[\frac{2\pi \times 1.38 \times 10^{-23} \times 300}{(6.626 \times 10^{-34})^2} \right]^{3/2} [0.07 \times 0.56 \times (9.11 \times 10^{-31})^2]^{3/4} \\ &\quad \times \exp \left[\frac{1.43 \times 1.6 \times 10^{-19}}{2 \times 1.38 \times 10^{-23} \times 300} \right] \\ &= 2.2 \times 10^{12} \text{ m}^{-3} \end{aligned}$$

7.3 THE *p-n* JUNCTION

7.3.1 The *p-n* Junction at Equilibrium

It is possible to fabricate an abrupt junction between a *p*-type region and an *n*-type region in the same single crystal of a semiconductor. Such a junction is called a *p-n junction*. We may assume (though it is not a practice) that this junction has been formed by cementing two isolated pieces of *p*-type and *n*-type materials. So when this contact is made, holes from the *p*-region will diffuse into the *n*-region, as their concentration is higher in the *p*-region as compared to the *n*-region. Similarly, the electrons from the *n*-region will diffuse into the *p*-region. The diffusion of holes from the *p*-region leaves behind ionized acceptors, thereby creating a negative space charge near the junction as shown in Fig. 7.5(a). The diffusion of electrons from the *n*-region creates a positive space charge near the junction.

This double space charge sets up an internal electric field (directed from the *n*- to the *p*-side) in a narrow region on either side of the junction. At equilibrium (that is, with no applied voltages or thermal gradients), it has the effect of obstructing the further diffusion of majority carriers. This induced field establishes a contact or diffusion potential V_D between the two sides and, as a consequence, the energy bands

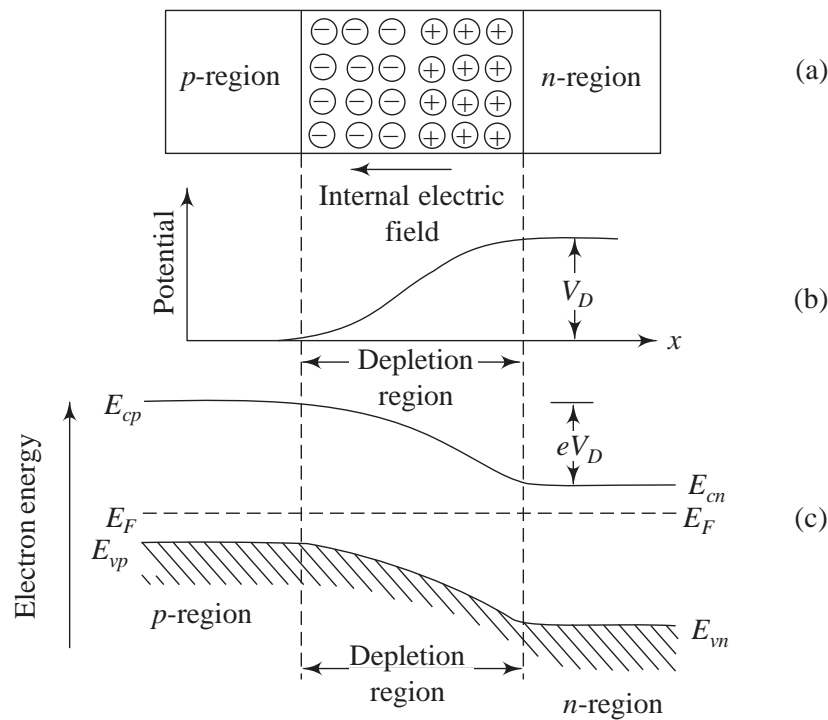


Fig. 7.5 Schematic illustration of (a) the formation of a p - n junction, (b) the potential gradient across the depletion region, and (c) the energy band diagram of a p - n junction

of the p -side are displaced relative to those of the n -side as shown in Fig. 7.5(c). The effect of the varying potential is that the region around the junction is almost depleted of its majority carriers. In fact, this region is normally referred to as the *depletion region*. The carrier densities on the two sides of a p - n junction, in equilibrium, are shown in Fig. 7.6. The following notation has been used: the equilibrium concentration of majority holes in the p -region $= p_{p0}$, minority electrons in the p -region $= n_{p0}$, majority electrons in the n -region $= n_{n0}$, minority holes in the n -region $= p_{n0}$.

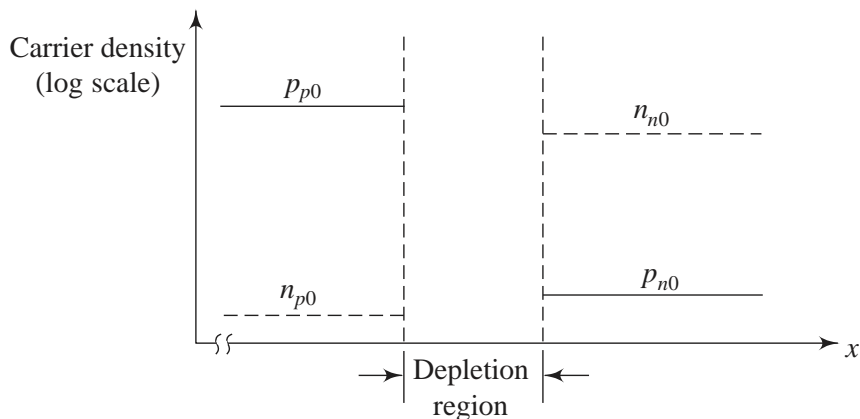


Fig. 7.6 Carrier densities on the two sides of a p - n junction, in equilibrium

Employing Eq. (7.5b), a relation between the diffusion potential and the doping concentration may be obtained. Thus, adopting the above notation, and that of Fig. 7.5, we may write the electron concentration in the CB of the p -region as

$$n_{p0} = N_c \exp[-(E_{cp} - E_{Fp})/kT] \quad (7.14)$$

Similarly, the electron concentration in the n -region will be given by

$$n_{n0} = N_c \exp[-(E_{cn} - E_{Fn})/kT] \quad (7.15)$$

Since the Fermi level is constant in both the regions, in equilibrium, we have $E_{Fp} = E_{Fn} = E_F$ (say).

Therefore, the elimination of N_c gives us

$$n_{p0}/n_{n0} = \exp[(E_{cn} - E_{cp})/kT] \quad (7.16)$$

or
$$E_{cp} - E_{cn} = kT \ln \left(\frac{n_{n0}}{n_{p0}} \right) = eV_D$$

or
$$V_D = (kT/e) \ln(n_{n0}/n_{p0}) \quad (7.17)$$

At normal operating temperature, the majority carrier concentrations are almost equal to the dopant concentrations. Thus, if the acceptor and donor concentrations per unit volume are N_a and N_d , respectively, then $p_{p0} = N_a$ and $n_{n0} = N_d$. From Eq. (7.13), we know that $np = n_i^2$, i.e.,

$$n_{n0}p_{n0} = n_{p0}p_{p0} = n_i^2 \quad (7.18)$$

Therefore we may write

$$n_{p0} = n_i^2 / p_{p0} = n_i^2 / N_a \quad (7.19)$$

and
$$p_{n0} = n_i^2 / n_{n0} = n_i^2 / N_d \quad (7.20)$$

Using Eqs (7.18)–(7.20), we may write Eq. (7.17) as

$$V_D = (kT/e) \ln(N_a N_d / n_i^2) \quad (7.21)$$

Equation (7.17) can also be used to express the relationship between the electron concentration on either side of the junction. Thus,

$$n_{p0} = n_{n0} \exp(-eV_D/kT) \quad (7.22)$$

Similarly, one may arrive at the following expression for the hole concentrations on the two sides of the p - n junction.

$$p_{n0} = p_{p0} \exp(-eV_D/kT) \quad (7.23)$$

Example 7.2 Consider a GaAs p - n junction in equilibrium at room temperature (RT = 300 K). Assume that the acceptor and donor impurity concentrations are $5 \times 10^{23} \text{ m}^{-3}$ and $5 \times 10^{21} \text{ m}^{-3}$, respectively. Calculate the diffusion potential V_D .

Solution

It is given that $N_a = 5 \times 10^{23} \text{ m}^{-3}$ and $N_d = 5 \times 10^{21} \text{ m}^{-3}$

$$\frac{kT}{e} = \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}} = 0.025875 \text{ V}$$

From Eq. (7.21), we have

$$V_D = \left(\frac{KT}{e} \right) \ln \left(\frac{N_a N_d}{n_i^2} \right)$$

We can take the value of n_i for GaAs from Example 7.1 to be $2.2 \times 10^{12} \text{ m}^{-3}$. Thus,

$$\begin{aligned} V_D &= (0.025875) \ln \left[\frac{5 \times 10^{23} \times 5 \times 10^{21}}{(2.2 \times 10^{12})^2} \right] \\ &= 1.234 \text{ V} \end{aligned}$$

7.3.2 The Forward-biased p - n Junction

When an external voltage source is connected across a p - n junction such that the p -side is connected to the positive terminal and the n -side is connected to the negative terminal of the voltage source as shown in Fig. 7.7(a), the junction is said to be forward-biased. As the depletion region is very resistive as compared to the bulk region on the two sides, almost all of the applied voltage V appears across this region. This lowers the height of the potential barrier to $V_D - V$ as shown in Fig. 7.7(b). Consequently, the majority carriers are injected into the bulk regions on the opposite sides of the depletion region to become minority carriers there. Thus the minority carrier densities adjacent to the depletion layer rise to new values n_p and p_n , and a concentration gradient of excess minority carriers is established as shown in Fig. 7.8.

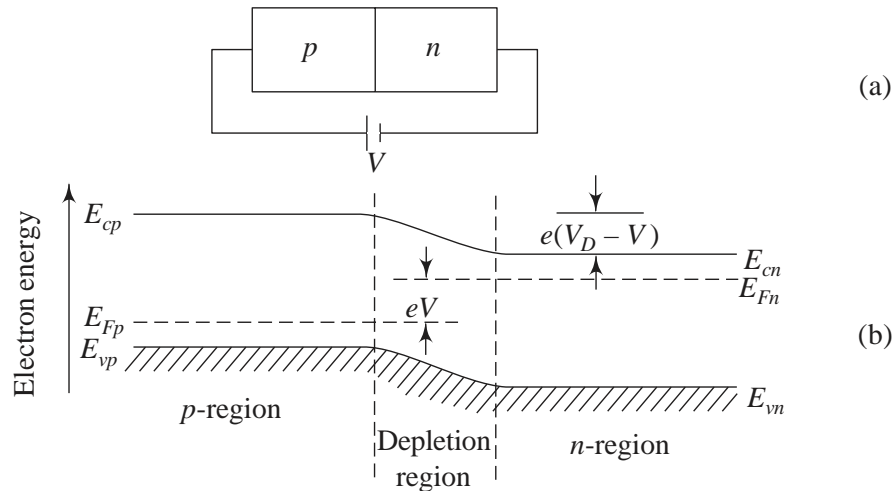


Fig. 7.7 (a) Forward-biased p - n junction and (b) energy-level diagram under forward bias (note the splitting of the Fermi level)

The appropriate expressions for the new densities of minority carriers (with forward bias) are given as follows:

$$n_p = n_{n0} \exp[-e(V_D - V)/kT] \quad (7.24)$$

and

$$p_n = p_{p0} \exp[-e(V_D - V)/kT] \quad (7.25)$$

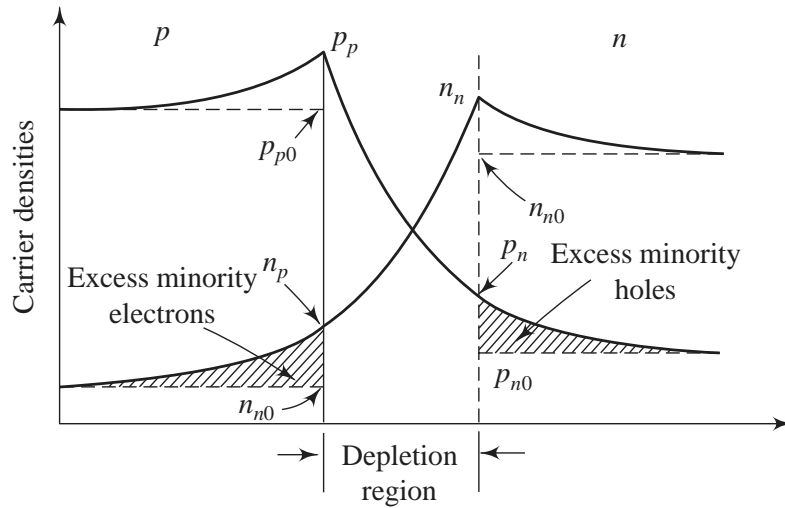


Fig. 7.8 Carrier densities in the p and n bulk regions of a forward-biased p - n junction

These equations may be modified with the aid of Eqs (7.22) and (7.23) to

$$n_p = n_{p0} \exp(eV/kT) \quad (7.26)$$

and

$$p_n = p_{n0} \exp(eV/kT) \quad (7.27)$$

In this non-equilibrium situation, let us denote the local instantaneous values of the densities of free electrons and holes by n and p , respectively (irrespective of the side). Thus, excess hole concentration on the n -side outside the depletion region may be written as

$$\Delta p = p - p_{n0} \quad (7.28)$$

As the bulk regions are supposed to be free of space charge, there will be equal excess concentration of majority electrons on the n -side. That is,

$$\Delta p = p - p_{n0} = n - n_{n0} \quad (7.29)$$

Similarly, the excess concentration of minority electrons on the p -side may be given by

$$\Delta n = n - n_{p0} = p - p_{p0} \quad (7.30)$$

What happens to the excess minority carriers that are injected by the forward bias? Let us consider the n -region. Here, injected holes diffuse away from the depletion layer and in the process recombine with the excess electrons. The electrons lost in this way are replaced by the external voltage source, so that a current flows in the external circuit. A similar process takes place in the p -region.

7.3.3 Minority Carrier Lifetime

In the bulk region of a forward-biased p - n junction, the net rate of recombination of carriers will be proportional to the local excess carrier concentration. Thus, in the

n -region, the net rate of recombination per unit volume of excess holes with electrons will be proportional to

$$\Delta p = p - p_{n0}$$

In the terms of an equality,

$$\text{The net rate of recombination per unit volume} = \Delta p / \tau_h$$

where τ_h is a proportionality constant, and it may be shown that it is the mean lifetime of holes in the n -region (that is, it is the average time for which a minority hole remains free before recombining). Since the net rate of recombination is equal to the rate of reduction of the carrier concentration, we may write

$$\text{The net rate of recombination per unit volume} = -d\Delta p(t)/dt = \Delta p / \tau_h \quad (7.31)$$

where $\Delta p(t)$ is the excess concentration of minority holes at time t . Solving Eq. (7.31), we get

$$\Delta p(t) = \Delta p(0) \exp(-t/\tau_h) \quad (7.32)$$

where $\Delta p(0)$ is the excess carrier concentration at $t = 0$. Then the mean lifetime of the excess minority holes will be given by

$$\langle t \rangle = \left(\int_0^\infty t \Delta p(0) \exp(-t/\tau_h) dt \right) / \left(\int_0^\infty \Delta p(0) \exp(-t/\tau_h) dt \right) = \tau_h \quad (7.33)$$

Similarly, in the p -region, we can write

$$\text{The net rate of recombination per unit volume} = \Delta n / \tau_e \quad (7.34)$$

where τ_e is the mean lifetime of minority electrons in the p -region.

7.3.4 Diffusion Length of Minority Carriers

Consider again a forward-biased p - n junction. The net rate of flow of minority holes per unit area due to diffusion in the n -region has been found to be proportional to the concentration gradient of holes, that is,

$$\text{The flux of minority holes} = -D_h d(\Delta p)/dx$$

Similarly,

$$\text{The flux of minority electrons in the } p\text{-region} = -D_e d(\Delta n)/dx$$

Here D_h and D_e are the hole and electron diffusion coefficients. These are related to the hole and electron mobilities μ_h and μ_e , respectively, by Einstein's relations:

$$D_e = \mu_e kT/e \quad (7.35)$$

$$D_h = \mu_h kT/e \quad (7.36)$$

Now let us concentrate on the flow of holes that are injected into the n -region. Consider an element of thickness Δx and cross-sectional area A at a distance x from the depletion layer edge (as shown in Fig. 7.9 by dashed lines). Then, the net rate at which holes accumulate in the elemental volume $\Delta x A$ is given by

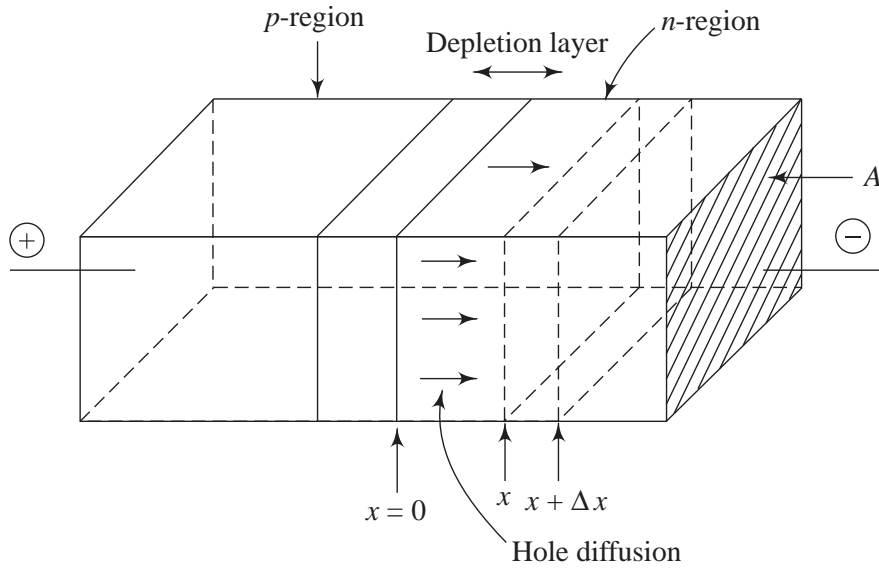


Fig. 7.9 Hole diffusion in the n -region of a forward-biased p - n junction

$$D_h(d\Delta p/dx)_x A - D_h(d\Delta p/dx)_{x+\Delta x} A = -D_h(d^2\Delta p/dx^2)\Delta x A$$

In the steady state, this rate will be equal to the rate of recombination of excess holes, within this volume. From Eq. (7.31), the rate of recombination in the elemental volume may be written as

$$(-\Delta p/\tau_h)\Delta x A$$

Equating the two rates, we obtain

$$\begin{aligned} -D_h(d^2\Delta p/dx^2)\Delta x A &= (-\Delta p/\tau_h)\Delta x A \\ d^2(\Delta p)/dx^2 - \Delta p/\tau_h D_h &= 0 \end{aligned} \quad (7.37)$$

Subject to the boundary conditions $\Delta p = \Delta p(0)$ at $x = 0$ and $\Delta p \rightarrow 0$ as $x \rightarrow \infty$, Eq. (7.37) may be integrated to give

$$\Delta p(x) = \Delta p(0)\exp(-x/\sqrt{D_h\tau_h}) \quad (7.38a)$$

$$\text{or} \quad \Delta p(x) = \Delta p(0)\exp(-x/L_h) \quad (7.38b)$$

where

$$L_h = \sqrt{D_h\tau_h} \quad (7.39)$$

is known as the *diffusion length* of minority holes in the n -region. If we put $x = L_h$ in Eq. (7.38b), we see that $\Delta p(L_h) = \Delta p(0)e^{-1}$. Thus, the hole diffusion length L_h may be defined as that distance inside the n -region at which the concentration of minority holes reduces to $1/e$ of its value at the depletion layer edge (i.e., $x = 0$).

Similarly, we can arrive at an expression for the diffusion of electrons in the p -region:

$$\Delta n(x') = \Delta n(0)\exp(-x'/L_e) \quad (7.40)$$

where

$$L_e = \sqrt{D_e\tau_e} \quad (7.41)$$

is the diffusion length of minority electrons in the p -region.

7.4 CURRENT DENSITIES AND INJECTION EFFICIENCY

We have discussed earlier that the electric fields in the bulk region are very small, and hence (referring to Fig. 7.9) in the n -region, particularly at $x = 0$, the total current density will be due to diffusion only. The current density due to hole diffusion in the n -region will be given by

$$\begin{aligned}
 J_h &= -eD_h[d\Delta p(x)/dx]_{x=0} \\
 &= -eD_h \frac{d}{dx} [\Delta p(0)\exp(-x/L_h)]_{x=0} \\
 &= -eD_h\Delta p(0)(-1/L_h)(e^{-x/L_h})_{x=0} \\
 &= e(D_h/L_h)\Delta p(0) \\
 &= e(D_h/L_h)[p_n - p_{n0}]
 \end{aligned}$$

Substituting p_n from Eq. (7.27), we get

$$\begin{aligned}
 J_h &= e(D_h/L_h)[p_{n0} \exp(eV/kT) - p_{n0}] \\
 &= e(D_h/L_h)p_{n0} [\exp(eV/kT) - 1]
 \end{aligned} \tag{7.42}$$

Similarly, we can obtain an expression for the current density J_e due to electron diffusion in the p -region.

$$J_e = e(D_e/L_e) n_{p0} [\exp(eV/kT) - 1] \tag{7.43}$$

The total current density crossing the junction would, therefore, be given by

$$\begin{aligned}
 J &= J_e + J_h \\
 &= e(D_e n_{p0}/L_e + D_h p_{n0}/L_h) [\exp(eV/kT) - 1] \\
 &= J_s [\exp(eV/kT) - 1]
 \end{aligned} \tag{7.44}$$

where

$$J_s = e(D_e n_{p0}/L_e + D_h p_{n0}/L_h) \tag{7.45}$$

is called the saturation current density. The total diffusion current I flowing across an ideal junction would then be given by

$$\begin{aligned}
 I &= JA = J_s A [\exp(eV/kT) - 1] \\
 &= I_s [\exp(eV/kT) - 1]
 \end{aligned} \tag{7.46}$$

where $I_s = J_s A$ is the saturation current.

An important case arises when one side is doped more heavily than the other side. This case is represented in Fig. 7.8. Here, the p -side is shown to possess a higher doping level. In such a case, the forward-biased current is mainly carried by the holes injected into the lightly doped n -region. These holes recombine with electrons to emit what is known as *recombination radiation* from the n -side. This device works as an optoelectronic source. Here, we can define the injection efficiency η_{inj} as the ratio of current density due to holes to the total current density. Thus,

$$\eta_{inj} = \frac{J_h}{(J_e + J_h)} = \frac{1}{1 + J_e/J_h} \tag{7.47}$$

Substituting the values of J_h and J_e from Eqs (7.42) and (7.43), respectively, we may write

$$\begin{aligned}\eta_{\text{inj}} &= 1/[1 + (D_e/D_h)(L_h/L_e)(n_{p0}/n_{n0})] \\ &= 1/[1 + (D_e/D_h)(L_h/L_e)(N_d/N_a)]\end{aligned}\quad (7.48)$$

It is clear from the above equation that, if η_{inj} is to approach unity, the ratio N_d/N_a has to be very small, that is, the acceptor concentration N_a should be much larger than N_d .

A similar expression for injection efficiency may be arrived at if the n -side is doped more heavily than the p -side. In this case,

$$\begin{aligned}\eta_{\text{inj}} &= \frac{J_e}{(J_e + J_h)} = \frac{1}{1 + J_h/J_e} \\ &= 1/[1 + (D_h/D_e)(L_e/L_h)(N_d/N_a)]\end{aligned}\quad (7.49)$$

Example 7.3 Calculate the injection efficiency of a GaAs diode in which $N_a = 10^{23} \text{ m}^{-3}$ and $N_d = 10^{21} \text{ m}^{-3}$. Assume that at RT = 300 K, $\mu_e = 0.85 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$, $\mu_h = 0.04 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$, and $L_e \approx L_h$.

Solution

It is given that $N_a = 10^{23} \text{ m}^{-3}$ and $N_d = 10^{21} \text{ m}^{-3}$. This means that the p -side is doped more heavily as compared to the n -side. Hence, in this case,

$$\eta_{\text{inj}} = \frac{1}{\left[1 + \frac{D_e}{D_h} \frac{L_h}{L_e} \frac{N_d}{N_a}\right]}$$

Now,
$$D_e = \mu_e \frac{kT}{e} = \frac{(0.85 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}) \times (1.38 \times 10^{-23} \text{ J K}^{-1}) \times (300 \text{ K})}{1.6 \times 10^{-19} \text{ C}}$$

$$= 0.02199 \text{ m}^2 \text{ J}^{-1}$$

and
$$D_h = \mu_h \frac{kT}{e} = \frac{(0.04 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}) \times (1.38 \times 10^{-23} \text{ J K}^{-1}) \times (300 \text{ K})}{1.6 \times 10^{-19} \text{ C}}$$

$$= 1.035 \times 10^{-3} \text{ m}^2 \text{ J}^{-1}$$

Therefore,
$$\eta_{\text{inj}} = \frac{1}{1 + \frac{0.02199}{1.035 \times 10^{-3}} \times \frac{1}{1} \times \frac{10^{21}}{10^{23}}} = 0.8247$$

7.5 INJECTION LUMINESCENCE AND THE LIGHT-EMITTING DIODE

In the previous section, we have discussed that if a p - n junction diode is forward-biased, the majority carriers from both sides cross the junction and enter the opposite

sides. This results in an increase in the minority carrier concentration on the two sides. The excess minority carrier concentration, of course, depends on the impurity levels on the two sides. This process is known as *minority carrier injection*. The injected carriers diffuse away from the junction, recombining with majority carriers as they do so. This recombination process of electrons with holes may be either non-radiative, in which the energy difference of the two carriers is released into the lattice as thermal energy, or radiative, in which a photon of energy equal to or less than the energy difference of the carriers is radiated. The phenomenon of emission of radiation by the recombination of injected carriers is called *injection luminescence*. A *p-n* junction diode exhibiting this phenomenon is referred to as a *light-emitting diode*.

Some probable radiative recombination processes are illustrated in Fig. 7.10. Radiation may be emitted via (i) the recombination of an electron in the CB with a hole in the VB (normally referred to as direct band-to-band transition), shown in Fig. 7.10(a), (ii) the downward transition of an electron in the CB to an empty acceptor level, shown in Fig. 7.10(b), and (iii) the transition of an electron from a filled donor level to a hole in the VB, shown in Fig. 7.10(c).

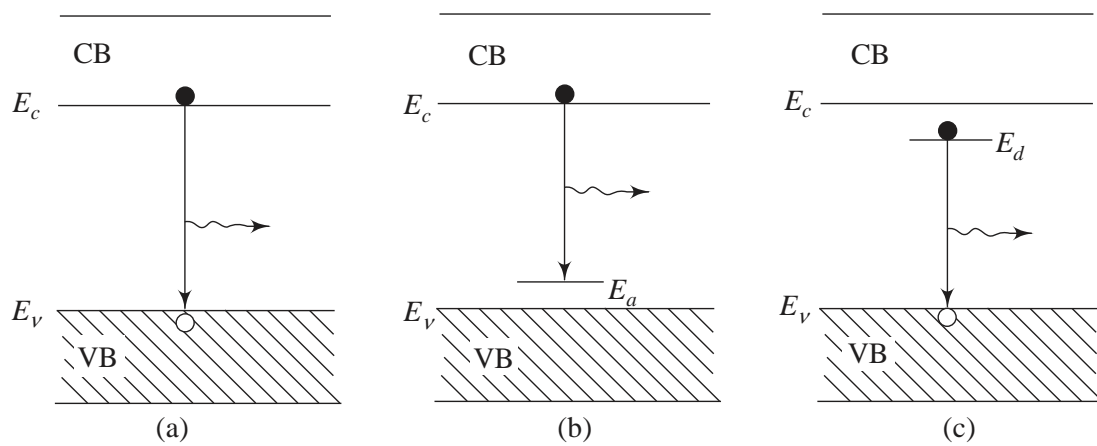


Fig. 7.10 Some probable radiative recombination mechanisms on either the *n*- or the *p*-side as the case may be

7.5.1 Spectrum of Injection Luminescence

What is the spectral distribution of the emitted radiation? In order to simplify things, we assume that radiation is primarily emitted via direct band-to-band transitions. If the transition takes place from the electron level at the bottom of the CB to the hole level at the top of the VB, the emitted photon will have energy

$$E_{\text{ph}} = hc/\lambda = E_c - E_v = E_g \quad (7.50)$$

where h is Planck's constant, c is the speed of light, and λ is the wavelength of emitted radiation. However, there is a distribution of electron energy levels in the CB and that of holes in the VB. Thus, depending on the energy levels involved, there will be a range of photon energies that are emitted by the LED.

A simplified calculation (see Review Question 7.4) shows that the spectral distribution of the radiated power P as a function of E_{ph} is given by the following expression:

$$P = \alpha(E_{\text{ph}} - E_g) \exp[-(E_{\text{ph}} - E_g)/kT] \quad (7.51)$$

where α is a constant. The theoretical plot of relative power versus E_{ph} is shown in Fig. 7.11(a). From this relation it is obvious that the peak power would be emitted at a photon energy $E_{\text{ph}} = E_g + kT$ and the full width at half maximum power would be $2.4kT$. However, the observed spectrum of real LEDs is much more symmetrical as shown in Fig. 7.11(b). The wavelength λ of the emitted radiation is given by

$$\lambda = hc/E_{\text{ph}} \quad (7.52)$$

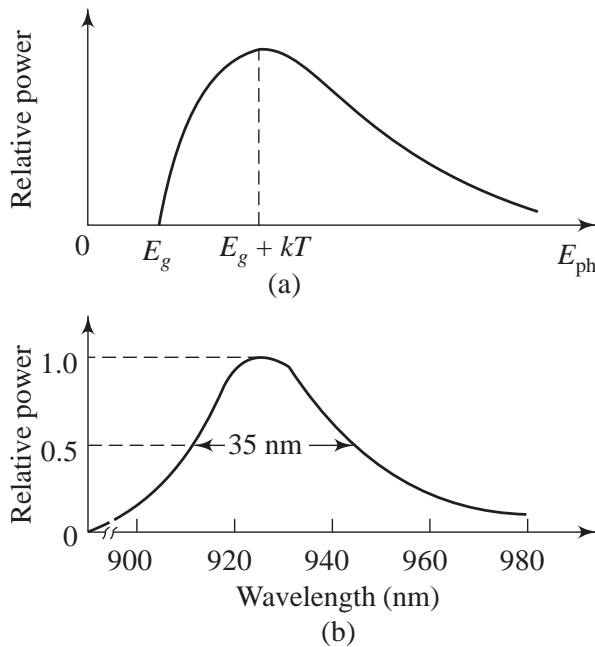


Fig. 7.11 (a) Theoretical spectral power distribution as a function of photon energy. (b) Actual power distribution for a typical GaAs LED.

The spread in wavelength $\Delta\lambda$ may be written as

$$\Delta\lambda = - (hc/E_{\text{ph}}^2) \Delta E_{\text{ph}} \quad (7.53)$$

and the relative spectral width of the source may be written as

$$\lambda = |\Delta\lambda/\lambda| = \Delta E_{\text{ph}}/E_{\text{ph}} = 2.4kT/E_{\text{ph}} \quad (7.54)$$

This expression leads us to roughly predict the values of γ and $\Delta\lambda$ for LEDs emitting at different wavelengths at room temperature. These are given in Table 7.1.

Table 7.1 Calculated spectral width values of LEDs

$\lambda_{\text{max}}(\mu\text{m})$	$E_{\text{ph}}(\text{eV})$	γ	Approx. $\Delta\lambda$ (nm)
0.85	1.455	0.0426	36
1.30	0.952	0.0652	85
1.55	0.798	0.0778	120

7.5.2 Selection of Materials for LEDs

In order to encourage the radiative recombination giving rise to injection luminescence, it is essential to select a proper semiconductor for making an LED. There are two types of semiconducting materials, namely, (i) direct band gap semiconductors and (ii) indirect band gap semiconductors. The energy–momentum diagrams for these two types of materials are shown in Fig. 7.12.

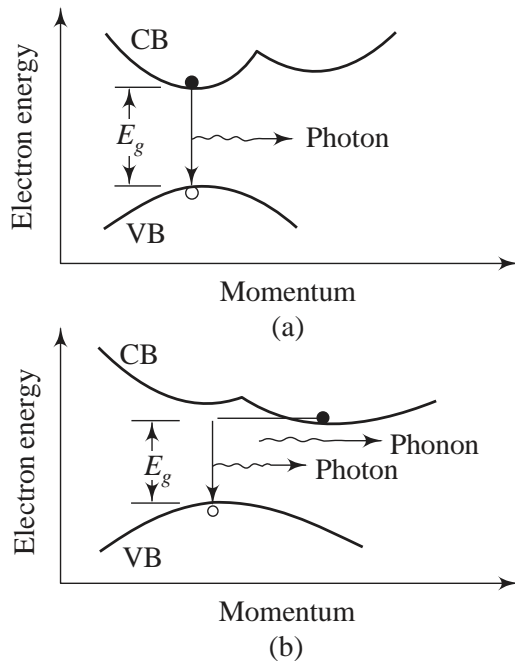


Fig. 7.12 Schematic energy–momentum diagram for (a) direct band gap and (b) indirect band gap semiconductors

In direct band gap materials, the energy corresponding to the bottom of the CB and that corresponding to the top of the VB have almost the same values of the crystal momentum. Thus there is a high probability of the direct recombination of electrons with holes, giving rise to the emission of photons. The materials in this category include GaAs, GaSb, InAs, etc. In indirect band gap materials, the energy corresponding to the bottom of the CB has excess crystal momentum as compared to that corresponding to the top of the VB. Here, the electron–hole recombination requires the simultaneous emission of a photon and a phonon (crystal lattice vibration) in order to conserve the momentum. The probability of such a transition is, therefore, low. The materials in this category include Si, Ge, GaP, etc. These materials are, therefore, not preferred for making LEDs. Among the direct band gap materials, GaAs is the most preferred semiconductor for fabricating LEDs. Its band gap $E_g = 1.43$ eV and it can be doped with *n*- as well as *p*-type impurities. It is also possible to make a heterojunction (to be discussed in the next section) of GaAs with AlAs to prepare a ternary alloy GaAlAs. The band gap of GaAlAs may be varied by varying the percentage of AlAs.

7.5.3 Internal Quantum Efficiency

The internal quantum efficiency η_{int} of an LED may be defined as the ratio of the rate of photons generated within the semiconductor to the rate of carriers crossing the junction. η_{int} will depend, among other things, on the relative probability of the radiative and non-radiative recombination processes. Thus, considering the n -side of a forward-biased p - n junction, the total rate of recombination of excess carriers per unit volume is given by Eq. (7.31); that is,

$$-dp/dt = -(dp/dt)_{\text{rr}} - (dp/dt)_{\text{nr}} = \Delta p/\tau_h \quad (7.55)$$

where

$$-(dp/dt)_{\text{rr}} = \Delta p/\tau_{\text{rr}} \quad (7.56)$$

represents the rate of radiative recombination per unit volume and

$$-(dp/dt)_{\text{nr}} = \Delta p/\tau_{\text{nr}} \quad (7.57)$$

represents the rate of non-radiative recombination per unit volume. τ_{rr} and τ_{nr} in the above relations are the minority carrier lifetimes for radiative and non-radiative recombinations, respectively. Employing Eqs (7.55)–(7.57), we get

$$1/\tau_h = 1/\tau_{\text{rr}} + 1/\tau_{\text{nr}} \quad (7.58)$$

Thus the internal quantum efficiency in the bulk n -region is given by

$$\begin{aligned} \eta_{\text{int}} &= -(dp/dt)_{\text{rr}}/[-(dp/dt)_{\text{rr}} - (dp/dt)_{\text{nr}}] = (1/\tau_{\text{rr}})/[1/\tau_{\text{rr}} + 1/\tau_{\text{nr}}] \\ &= \frac{1}{1 + \tau_{\text{rr}}/\tau_{\text{nr}}} \end{aligned} \quad (7.59)$$

Therefore, in order to increase η_{int} , the ratio $\tau_{\text{rr}}/\tau_{\text{nr}}$ should be as low as possible. Similar arguments hold for the p -region. Typically, the ratio $\tau_{\text{rr}}/\tau_{\text{nr}}$ for an indirect band gap material, e.g., Si, is of the order of 10^5 , whereas that for a direct band gap material, e.g., GaAs, is of the order of unity. Thus, η_{int} for the two cases is, respectively, of the order of 10^{-5} and 0.5.

7.5.4 External Quantum Efficiency

The external quantum efficiency η_{ext} of an LED may be defined as the ratio of the rate of photons emitted from the surface of the semiconductor to the rate of carriers crossing the junction.

In order to determine the order of magnitude of η_{ext} let us look at the configuration of an LED based on a p - n^+ homojunction. This is shown schematically in Fig. 7.13. Here, n^+ denotes that the n -region is more heavily doped as compared to the p -region so that the current is mainly carried by the electrons, and the injection efficiency is given by Eq. (7.49). On forward-biasing, the electrons cross the junction and reach the p -region, where within one or two diffusion lengths (L_e), they recombine with the holes to produce photons. The photons so generated in a thin layer, represented by

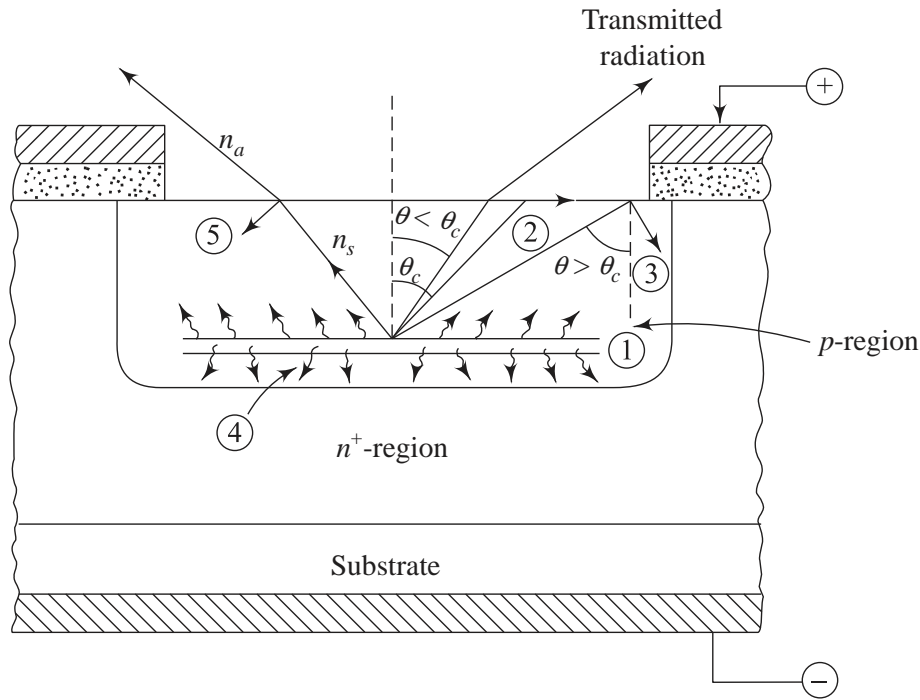


Fig. 7.13 Exploded view of a surface-emitting LED: (1) prime layer generating optical radiation, (2) critical ray, (3) total internal reflection, (4) backside emission, (5) Fresnel reflection

(\rightsquigarrow) in Fig. 7.13, are radiated in all directions. Therefore it behaves like a double-sided Lambertian emitter. (The radiation pattern of a Lambertian source is explained in Appendix A7.1.) Let us assume that the optical power radiated per unit solid angle from the entire emissive area along the normal to the emitting surface is P_0 . Then the total radiant power or the flux, ϕ_s , emitted within the semiconductor from both sides of this layer will be given by

$$\begin{aligned}\phi_s &= 2 \int_{\theta=0}^{\pi/2} P_0 \cos \theta (2\pi)(\sin \theta) d\theta \\ \phi_s &= 2\pi P_0\end{aligned}\quad (7.60)$$

This entire flux cannot be collected at the surface of the LED. The prime reason for this is that the rays striking the semiconductor–air interface at an angle greater than the critical angle θ_c (for this interface) will be total internally reflected. This is depicted by (2) and (3) in Fig. 7.13. Hence only those rays reaching the emitting surface at an angle of incidence $\theta < \theta_c$ will be transmitted. Further, the radiation emitted towards the backside, depicted by (4) in Fig. 7.13, cannot be collected. Therefore, the fraction F of the total optical power that can be collected at the semiconductor–air surface will be given by

$$F = (1/2\pi P_0) \int_0^{\theta_c} P_0 \cos \theta (2\pi)(\sin \theta) d\theta = \sin^2 \theta_c / 2$$

If n_s and n_a are the refractive indices of the semiconductor and the surrounding medium, respectively,

$$\sin\theta_c = n_a/n_s$$

Hence,
$$F = n_a^2/2n_s^2 \quad (7.61)$$

There are two more factors which will further reduce this fraction. First, a small fraction of the light is reflected at the semiconductor–air interface. This is known as Fresnel reflection and is represented by (5) in Fig. 7.13. For normal incidence, the fraction that is reflected is given by the Fresnel reflection coefficient

$$R = [(n_s - n_a)/(n_s + n_a)]^2 \quad (7.62)$$

Therefore, the transmission factor t will be given by

$$t = 1 - R = 4n_a n_s / (n_s + n_a)^2 \quad (7.63)$$

This factor varies with the angle of incidence. However, this variation is little. The second factor causing loss is the self-absorption of radiation within the semiconductor. This depends on the absorption coefficient of the semiconductor for the wavelength of emission, and the length of traversal inside the semiconductor. However, the effect of this loss mechanism is reduced by keeping the distance of the emitting layer from the surface as short as possible. If we assume that a_s is the fraction of light absorbed within the semiconductor while traversing from the generation layer to the emitting surface, the fraction that is transmitted may be given by

$$T = 1 - a_s \quad (7.64)$$

Thus, combining the factors F , t , and T , we get the external quantum efficiency of the LED:

$$\begin{aligned} \eta_{\text{ext}} &= \eta_{\text{int}} F t T \\ &= \eta_{\text{int}} (1 - a_s) 2n_a^3 / n_s (n_s + n_a)^2 \end{aligned} \quad (7.65)$$

Typically, if we take the case of a GaAs LED emitting in air, then $n_a = 1$ and $n_s = 3.7$, and assuming that $\eta_{\text{ext}} = 0.5$ and $a_s = 0.1$,

$$\eta_{\text{ext}} = 0.5(0.9)2/3.7(4.7)^2 = 0.011$$

This tells us about the low efficiencies that are observed from normal LEDs.

7.6 THE HETEROJUNCTION

In the previous section, our discussion has been centred on LED configuration, which is essentially based on a p - n homojunction (i.e., a junction formed by doping the same semiconductor, e.g., GaAs, with p - and n -type impurity atoms). The efficiency of such a configuration, from the point of view of its application in fiber-optic communication systems, is too low. LEDs with higher efficiencies may be fabricated using what are known as heterojunctions. Such junctions may be formed between two semiconductors which have the same lattice parameters (so that they may be grown together as a single crystal) but different band gaps. For example, a heterojunction may be formed between GaAs and its ternary alloy $\text{Ga}_{1-x}\text{Al}_x\text{As}$. The mole

fraction x of AlAs ($E_g = 2.16$ eV) with respect to GaAs_{1-x} ($E_g = 1.43$ eV) determines the band gap of the alloy and the corresponding wavelength of peak emission.

The heterojunction may be employed to sandwich a layer of narrow band gap material, e.g., n - or p -type GaAs, between layers of wider band gap materials, e.g., P - and N -type GaAlAs, to form a double-hetero structure (DH). This is shown schematically in Fig. 7.14. When forward-biased, the holes from P -GaAlAs are injected into n -GaAs, but are prevented from going into N -GaAlAs by a potential barrier at J_2 . Similarly, the electrons from N -GaAlAs are injected into n -GaAs but are prevented from going further by the potential barrier at J_1 . Thus, a large number of carriers are confined in the central layer of n -GaAs, where they recombine to produce optical radiation of wavelength corresponding to the band gap of n -GaAs.

As most of the activity takes place in the central layer, it is called an *active layer*.

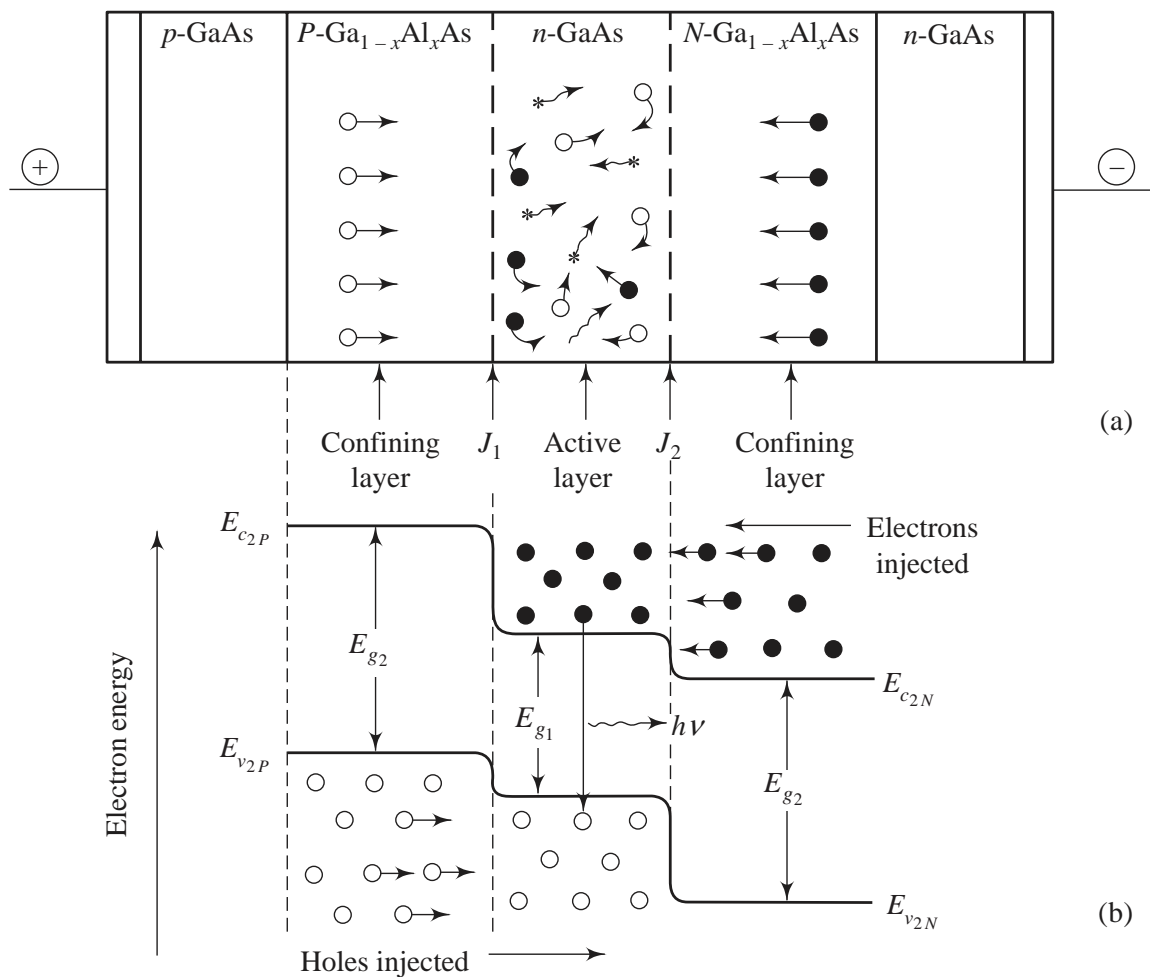


Fig. 7.14 (a) A schematic diagram of a DH LED under forward bias and (b) the corresponding energy-level diagram. Here, P - and N - denote acceptor and donor impurity doped wider band gap materials. J_1 and J_2 are heterojunctions between P - and n -type materials and n - and N -type materials, respectively. Solid circles (●) and hollow circles (○) represent electrons and holes, respectively, and the asterisks (*) denote radiative recombination. E_{g1} and E_{g2} are the band gaps of GaAs and Ga_{1-x}Al_xAs, respectively.

The radiation may be collected either through the edge or through one of the surfaces. The corresponding design will be discussed in the next section. An important point to be mentioned here is that such a structure gives rise to a higher rate of radiative recombination and, hence, a brighter LED. Further, the radiation generated by band-to-band transitions in the active layer cannot excite the carriers in the adjoining layers because E_{g1} is lower than E_{g2} . Thus, the confining layers of wider band gap material are transparent to this radiation. This effect may be used in designing surface-emitting LEDs. The limitation of GaAs/Ga_{1-x}Al_xAs based LEDs is that the range of wavelengths (0.80–0.90 μm) emitted by them is outside the wavelength limits of lowest attenuation and zero total dispersion of optical fibers. Therefore, such emitters cannot be used in long-haul communication systems. However, quaternary alloy indium-gallium-arsenide-phosphide/indium-phosphide (In_xGa_{1-x}As_yP_{1-y}/InP) based systems have emerged as better candidates for fiber-optic systems, in the sense that a wavelength range of 0.93–1.65 μm can easily be achieved from them. Thus, highly efficient DH LEDs emitting longer wavelengths may be fabricated employing such materials for the active region and InP or quaternary alloys of larger band gaps for the confining layers.

7.7 LED DESIGNS

Two basic structures of LED are in use. These are (i) surface-emitting LED (SLED) and (ii) edge-emitting LED (ELED). Configurations based on GaAs/GaAlAs have been used in short-haul applications, whereas those based on InGaAsP/InP have been employed in medium-range fiber links. Relatively recently, a third device known as a superluminescent diode (SLD) has also been increasingly used in communications. The description of these three types of LEDs, in brief, follows.

7.7.1 Surface-emitting LEDs

When optical radiation emitted in the active layer of a DH shown in Fig. 7.14(a) is taken out from one of the surfaces, the configuration becomes a SLED. A common configuration suitable for fiber-optic communications is shown in Fig. 7.15. It utilizes a P - n (or p)- N planar DH junction. A well is etched into the GaAs substrate layer to avoid reabsorption of light emitted from the substrate side and to accommodate the fiber. It is also called a Burrus-type structure after the scientist who pioneered this design for fiber-optic communications. To increase the carrier density and, hence, recombination rate inside the active region, the light-emitting area is restricted to a small region (typically, a circle of diameter 20–50 μm). This is achieved by confining the injection current to this region through the electrical isolation of the rest of the area by a dielectric (e.g., SiO₂) layer or some other means. The heat generated by the

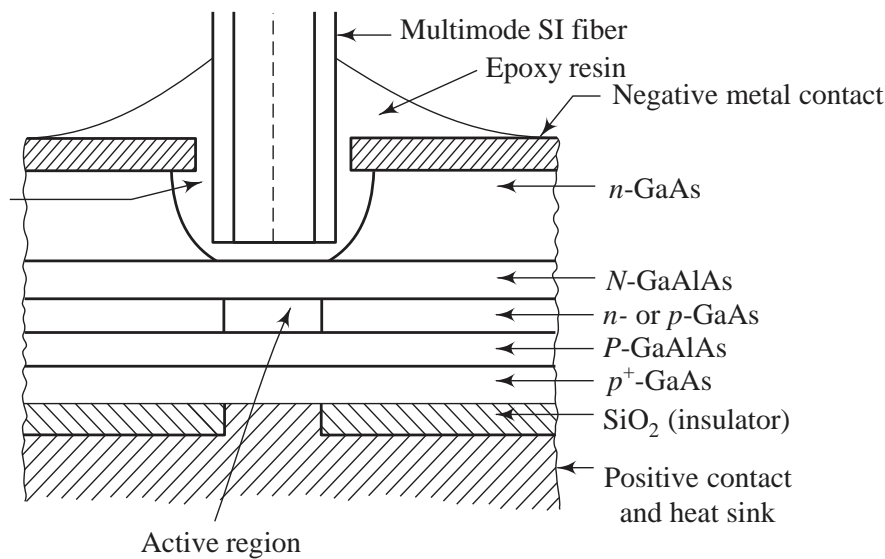


Fig. 7.15 A Burrus-type SLED

device is conducted away by mounting a heat sink near the hot region. A configuration based on GaAs/GaAlAs is shown in Fig. 7.15. A small fraction of AlAs is introduced into the GaAs active layer to tune the wavelength emitted by the device in the range 0.80–0.90 μm . A similar structure based on InP/InGaAsP may be fabricated to emit wavelengths in the range 0.93–1.65 μm . Epoxy resin is used to couple the optical fiber to the emitting surface of the LED. This also reduces the loss due to index mismatch at the semiconductor–air interface.

7.7.2 Edge-emitting LEDs

The DH ELED, shown in Fig. 7.16, is another basic structure providing high radiance for fiber-optic communication. The structure consists of five epitaxial layers of GaAs/GaAlAs. The active layer consists of smaller band gap $\text{Ga}_{1-x}\text{Al}_x\text{As}$ (here, x is small, typically around 0.1 mole fraction). The positive contact is in the form of a stripe (the rest of the contact being isolated by the SiO_2 layer). The recombination radiation generated in the active region is guided by internal reflection at the heterojunctions and is brought out at the front-end facet of the diode. The rear-end facet is made reflecting while the front-end facet is coated with an antireflection coating, so that the laser action due to optical feedback is suppressed. The self-absorption of radiation in the active layer is reduced because its thickness is made very small. Much of the guided radiation propagates through the confining layers, which have a wider band gap. Therefore, they do not absorb this radiation. An important effect of the optical guidance of emitted radiation is that the output beam has low divergence (typically $\sim 30^\circ$) in the vertical direction. This increases the efficiency of coupling the LED with the optical fiber. Stripe geometry ELEDs based on InP/InGaAsP materials and with improved designs for coupling to single-mode fibers have also been made.

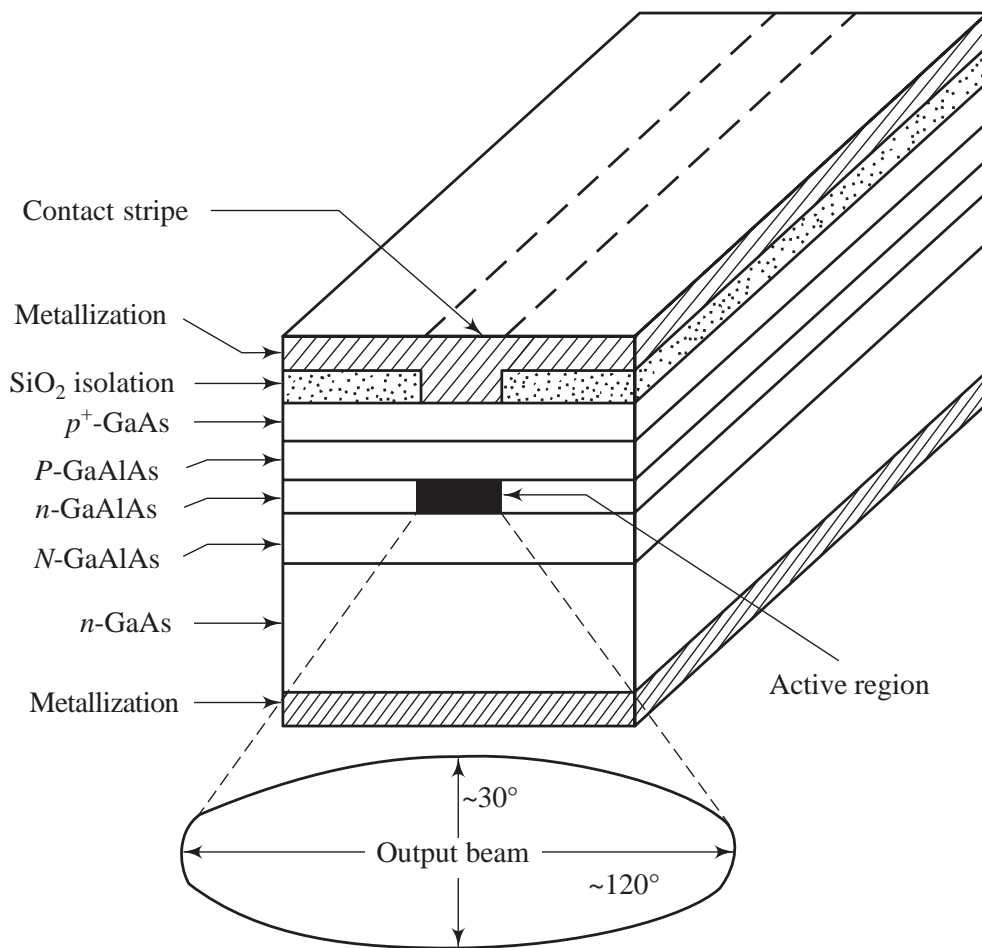


Fig. 7.16 Stripe geometry DH ELED based on GaAs/Ga AlAs

7.7.3 Superluminescent Diodes

The structural features of SLDs are similar to that of DH ELEDs. At low injection current, therefore, an SLD behaves as an ELED, but at high operating current, population inversion similar to that of an injection laser diode (ILD, to be discussed in the next section) is created. Hence this device is able to amplify light, but as it does not have positive feedback, it radiates spontaneous emission. Therefore, an SLD radiates a more powerful and narrower beam than a regular LED. However, its radiation is not coherent. The injection current versus output optical power characteristics for the three types of diodes are shown in Fig. 7.17.

Example 7.4 A Burrus-type p - n GaAs LED is coupled to a step-index fiber of core diameter larger than the emitting area of the LED, using transparent bonding cement. The refractive indices of the bonding cement and GaAs are, respectively, 1.5 and 3.7. (a) If the mean lifetimes corresponding to radiative and non-radiative recombinations are taken to be the same for GaAs and equal to 100 ns, calculate the internal quantum efficiency of the LED. (b) Calculate the external quantum efficiency, assuming negligible self-absorption within the semiconductor.

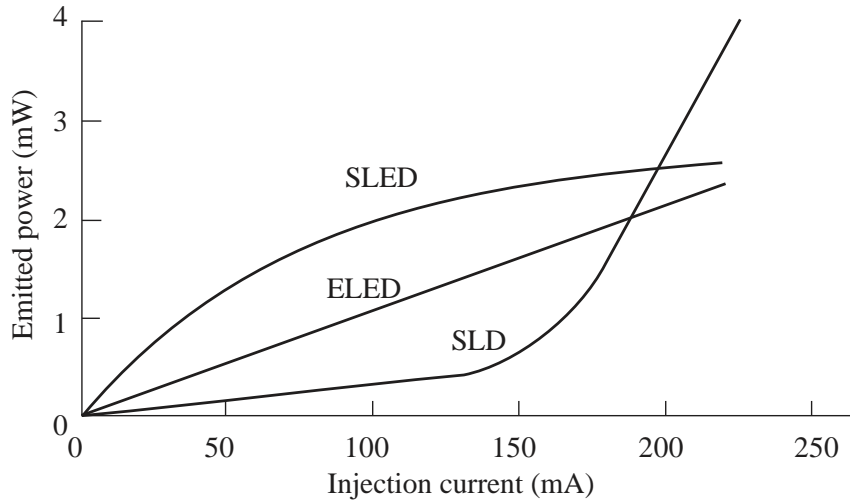


Fig. 7.17 Injection current vs emitted power curves for a typical SLED, ELED, and SLD

Solution

(a) Using Eq. (7.59), we have

$$\eta_{\text{int}} = \frac{1}{1 + \frac{\tau_{\text{rr}}}{\tau_{\text{nr}}}} = \frac{1}{1 + 1} = 0.5$$

(b) Using Eq. (7.65), we have

$$\begin{aligned} \eta_{\text{ext}} &= \eta_{\text{int}} (1 - a_s) \frac{2n_a^3}{n_s (n_s + n_a)^2} \\ &= 0.50(1) \frac{2 \times (1.5)^3}{3.7 (3.7 + 1.5)^2} \\ &= 0.0337 \end{aligned}$$

7.8 MODULATION RESPONSE OF AN LED

The modulation response of an LED is governed by the carrier lifetime τ , which represents the total recombination time of charge carriers. It can be defined by the relation

$$\tau = \frac{n}{R_{\text{rr}} + R_{\text{nr}}} \quad (7.66)$$

where n is the charge carrier density, R_{rr} is the rate of radiative recombination, and R_{nr} is the rate of non-radiative recombination. In general, $R_{\text{rr}} = R_{\text{sp}} + R_{\text{st}}$, where R_{sp} is

the rate of spontaneous recombination and R_{st} is the rate of stimulated recombination. In the case of an LED, there is no stimulated recombination, and hence $R_{tr} = R_{sp}$.

When the LED is forward-biased, electrons and holes are injected in pairs and they also recombine in pairs. Therefore, in order to study carrier dynamics, the rate equation for one type of charge carriers is enough. We take the case of electrons. The rate equation may be written as follows:

$$\frac{dn}{dt} = \frac{I}{eV} - \frac{n}{\tau} \quad (7.67)$$

where I is the total injected current and V is the volume of the active region.

Let us consider sinusoidal modulation of the LED; that is, the injected current $I(t)$ at time t is given by

$$I(t) = I_0 + I_m \exp(j\omega_m t) \quad (7.68)$$

where the first term, I_0 , is the bias current and the second term is the modulation current with I_m as the amplitude and ω_m as the frequency of modulation. Equation (7.67) is a linear differential equation, and hence its solution can be written as

$$n(t) = n_0 + n_m \exp(j\omega_m t) \quad (7.69)$$

where $n_0 = I_0 \tau / eV$ and n_m is given by

$$n_m(\omega_m) = \frac{I_m \tau / eV}{1 + j\omega_m \tau} \quad (7.70)$$

The corresponding power radiated by the source may be given by

$$P(t) = P_0 + P_m \exp(j\omega_m t) \quad (7.71)$$

The modulated power P_m is linearly related to $|n_m|$. The transfer function $H(\omega_m)$ of an LED may be defined as

$$H(\omega_m) = \frac{n_m(\omega_m)}{n_m(0)} = \frac{1}{1 + j\omega_m \tau} \quad (7.72)$$

The 3-dB (optical) modulation bandwidth of an LED is the modulation frequency at which $|H(\omega_m)|$ is reduced by a factor of 2; that is,

$$(\nu_{3\text{-dB}})_{\text{opt}} = \sqrt{3} \frac{1}{2\pi\tau} \quad (7.73)$$

Typical values of $\nu_{3\text{-dB}}$ are in the range of 50–140 MHz. The corresponding electrical bandwidth is given by

$$(\nu_{3\text{-dB}})_{\text{el}} = \frac{1}{2\pi\tau} \quad (7.74)$$

7.9 INJECTION LASER DIODES

Laser is an acronym for light amplification by stimulated emission of radiation. In order to understand the configuration of devices based on laser action, it is essential to know the basic processes governing the absorption and spontaneous and stimulated emission of radiation, first in the simplest atomic system and then in the very complex semiconducting materials.

To begin with, let us consider a hypothetical system consisting of atoms of only two energy levels with energies E_1 and E_2 . When a photon of energy $E_2 - E_1 = h\nu$, where h is Planck's constant and ν is the frequency, interacts with an atom of such a system, there exist two possibilities: (i) If the atom is in the ground state, with energy E_1 , the photon may be absorbed so that it is excited to the upper level of energy E_2 . Subsequent de-excitation may give rise to the emission of radiation in a random manner. This is called *spontaneous emission* and is shown in Fig. 7.18(a). (ii) If the atom is already in the excited state, then the incident photon may stimulate a downward transition with the emission of radiation. Photons emitted in such a manner have been found to be coherent with the stimulating photon; that is, both the stimulating and the stimulated photons have the same energy, same momentum, and same state of polarization. This phenomenon is called *stimulated emission* and is depicted in Fig. 7.18(b).

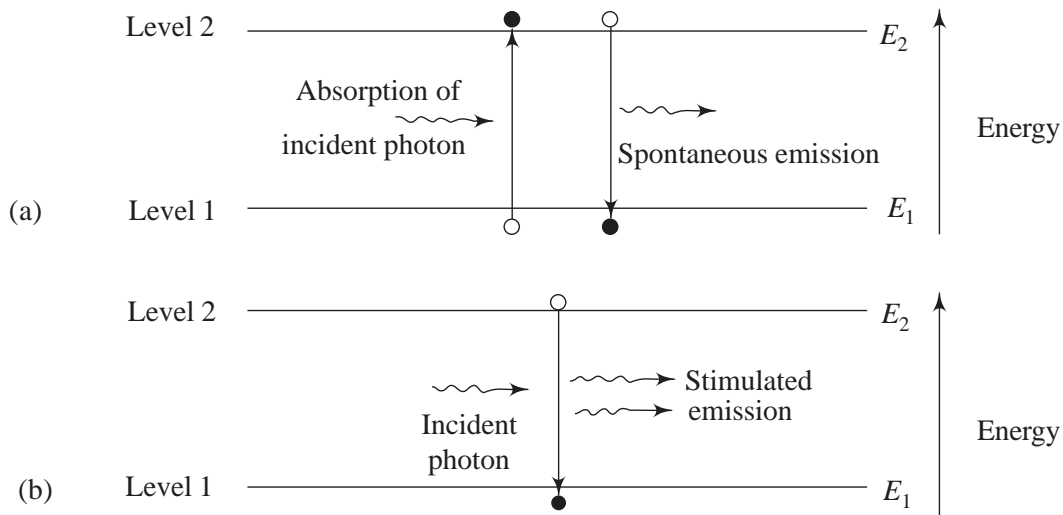


Fig. 7.18 (a) Absorption and spontaneous emission and (b) stimulated emission in a two-level atomic system. Hollow circles (O) and filled circles (●) depict the initial and final states of transitions.

Let us assume that the collection of atoms in a system is in thermodynamic equilibrium; then it must give rise to radiation identical to black-body radiation. The radiation density per unit range of spectral frequency about the frequency ν is then given by

$$\rho_\nu = (8\pi h\nu^3/c^3) [1/\{\exp(h\nu/kT) - 1\}] \quad (7.75)$$

where c is the speed of light, k is Boltzmann's constant, and T is the temperature (in kelvin).

Now if the population densities of atoms whose electrons at any instant are at energy levels E_1 and E_2 are N_1 and N_2 , respectively, then employing Boltzmann statistics one can show that

$$N_1/N_2 = (g_1/g_2) \exp[(E_2 - E_1)/kT] = (g_1/g_2) \exp(h\nu/kT) \quad (7.76)$$

where g_1 and g_2 are the degeneracies of levels 1 and 2, respectively, that is, g_1 and g_2 are the number of sublevels within the energy levels E_1 and E_2 , respectively. Since the atom can absorb a photon only when it is in level 1, the rate of absorption of a photon by such a system will be proportional to the population density N_1 at energy level E_1 and also to the radiation density ρ_ν . Then the rate of absorption (or the rate of upward transition) may be given by $B_{12} N_1 \rho_\nu$, where B_{12} is the proportionality constant. The downward transition may occur either via spontaneous emission or via stimulated emission. Spontaneous emission is a random process and hence its rate is proportional to the population density N_2 at energy level E_2 , whereas stimulated emission requires the presence of an external photon, and hence the rate of stimulated emission is proportional to N_2 as well as ρ_ν . The total rate of downward transition is the sum of the rates of spontaneous and stimulated emissions, which is given by $A_{21}N_2 + B_{21}N_2\rho_\nu$. The constants A_{21} , B_{21} , and B_{12} are called *Einstein's coefficients*. They denote, respectively, the probabilities of spontaneous emission, stimulated emission, and absorption. The relation among these constants may be established as follows.

Under thermodynamic equilibrium, the rate of upward transitions (from level 1 to 2) must equal the rate of downward transitions (from level 2 to 1) (Einstein 1917). Thus, we must have

$$B_{12}N_1\rho_\nu = A_{21}N_2 + B_{21}N_2\rho_\nu \quad (7.77)$$

or

$$\rho_\nu[B_{12}N_1 - B_{21}N_2] = A_{21}N_2$$

or

$$\rho_\nu[(B_{12}/B_{21})(N_1/N_2) - 1] = A_{21}/B_{21}$$

or

$$\rho_\nu = (A_{21}/B_{21}) / [(B_{12}/B_{21})(N_1/N_2) - 1]$$

Substituting the value of N_1/N_2 from Eq. (7.76) in the above expression, we get

$$\rho_\nu = (A_{21}/B_{21}) / [(g_1 B_{12}/g_2 B_{21}) \exp(h\nu/kT) - 1] \quad (7.78)$$

Comparing Eqs (7.75) and (7.78), we see that for the two equations to be valid we must have

$$B_{12} = (g_2/g_1)B_{21} \quad (7.79)$$

and

$$A_{21}/B_{21} = 8\pi h\nu^3/c^3 \quad (7.80)$$

Equations (7.79) and (7.80) are called *Einstein's relations*.

If the degeneracies of the two levels are equal, i.e., $g_1 = g_2$, then $B_{12} = B_{21}$, which means that the probabilities of absorption and stimulated emission are equal.

Now let us find the ratio of the rate of stimulated emission to that of spontaneous emission for our simplified two-level system. Equation (7.80) enables us to show that

$$\begin{aligned} \text{Rate of stimulated emission/rate of spontaneous emission} &= B_{21}\rho\nu/A_{21} \\ &= 1/[\exp(h\nu/kT) - 1] \end{aligned} \quad (7.81)$$

An incandescent lamp operating at a temperature of 2000 K would emit a peak wavelength $\lambda = 1.449 \mu\text{m}$ and a corresponding frequency $\nu = c/\lambda = 3 \times 10^8/1.449 \times 10^{-6} = 2.07 \times 10^{14}$ Hz. The ratio of the rate of stimulated emission to that of spontaneous emission for this frequency would be equal to

$$1/[\exp(6.626 \times 10^{-34} \times 2.07 \times 10^{14}/1.381 \times 10^{-23} \times 2000) - 1] = 7.02 \times 10^{-3}$$

This result simply shows that in an atomic system under thermodynamic equilibrium, spontaneous emission is a dominant mechanism.

In order to produce stimulated emission, it is essential to create a non-equilibrium situation in which the population of atoms in the upper energy level is greater than that in the lower energy level, that is, $N_2 > N_1$. This non-equilibrium condition is called *population inversion*. Now, to achieve this condition we need to excite atoms from the lower to the upper level by some external means. This process of excitation is known as *pumping*. Normally an external source of intense radiation is employed for pumping. However, in semiconductor lasers, electrical excitation is used.

7.9.1 Condition for Laser Action

In a two-level atomic system that is pumped externally, stimulated emission cannot become a dominant process because it has to compete with stimulated absorption. Therefore, either three-level or four-level atomic systems are used for achieving laser action. These are shown in Figs 7.19(a) and 7.19(b).

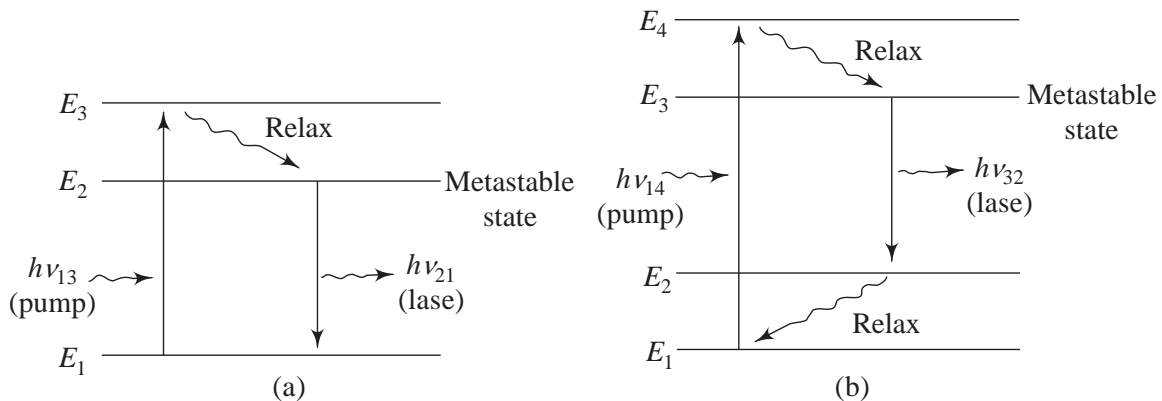


Fig. 7.19 Laser action in a (a) three-level and (b) four-level atomic system

Let us first consider the three-level system shown in Fig. 7.19(a). Assume that this system is pumped with light of photon energy $h\nu_{13}$, so that a large number of atoms in the ground state absorb this radiation and are raised to the excited state E_3 . Let us

choose this atomic system such that the transition from E_3 to E_2 is faster and preferably non-radiative and that from E_2 to E_1 is much slower. The result of this will be that once the system is pumped, atoms will accumulate in level E_2 , which is called the metastable level. Hence, unlike the two-level system, atoms in level E_2 are immune to getting stimulated by photons of energy $h\nu_{13}$. Thus we can increase the number of atoms in level E_2 at the expense of those in level E_1 by increasing the intensity of the exciting radiation at $h\nu_{13}$. This means that we can make $N_2 > N_1$, i.e., achieve population inversion by pumping at frequency ν_{13} .

After population inversion has been achieved, if photons of energy $h\nu_{21}$ corresponding to the energy difference $E_2 - E_1$ (such as those produced by the spontaneous transition from E_2 to E_1) are released into this system, they will stimulate the downward transition from E_2 to E_1 , producing more photons at energy $h\nu_{21}$ in the process. Thus the system acts as an optical amplifier.

It is obvious that in order to achieve population inversion, more than half the atoms from the heavily populated ground state must be excited by the pump. It is indeed a hard work for the pump to excite all these atoms. Let us now consider the four-level system shown in Fig. 7.19(b). Here, the system is pumped by photons of energy $h\nu_{14}$ corresponding to the energy difference between levels E_1 and E_4 . The absorption of such photons excites atoms to E_4 , from where they quickly relax (through non-radiative decay) to level E_3 (metastable or lasing state). The transition from E_3 to E_2 is radiative but slow and the transition from E_2 to E_1 is again fast and non-radiative. In this scheme, it is relatively easy to provide level E_3 with an inverted population over level E_2 because (i) E_2 is not well populated in the first place (by virtue of being above the ground state) and (ii) atoms do not accumulate there, as they quickly relax to the ground state. Hence it is quite easy to ensure that the population in level E_3 exceeds that in level E_2 . The amplification at $h\nu_{32}$ is much more efficient, and hence a four-level system is a better amplifier.

Now let us assume that this assembly of atoms (two-level, three-level, or four-level atomic system) exists in a medium which we now call an active medium. Further, assume that this medium is in the form of a cylinder of length L whose axis is along the z -axis. Also assume that this system is appropriately (depending on the atomic system in the active medium) pumped so that population inversion has been achieved. Under this condition, if a beam of light corresponding to the difference of energy between the lasing levels ($E_2 - E_1$ for the two- and three-level systems and $E_3 - E_2$ for the four-level system) is allowed to pass through the medium in the z -direction, the power P in the beam will grow as it passes through the medium according to the relation

$$P_z = P_0 \exp(g_{21}z) \quad (7.82)$$

where P_0 is the incident power and P_z is the power at a distance of z along the axis. g_{21} is the gain coefficient (for the two- and three-level system). For a four-level system it can be represented as g_{32} .

This is laser action. In fact, the laser is more analogous to an oscillator than an amplifier, and hence it is necessary to provide some positive feedback to turn this optical amplifier into an optical oscillator. This is done by placing the active medium between a pair of mirrors, which reflect the amplified light back and forth to form an optical cavity as shown in Fig. 7.20. This is also called a Fabry–Perot resonator. It has a set of characteristic resonant frequencies. Therefore, the radiation is characteristic of these frequencies rather than the normal emission spectrum of the atomic system. Under equilibrium, the optical power loss (which includes the transmission loss at the mirrors) during one round trip through the active medium just balances the gain. Thus the self-oscillation will start only after the gain exceeds the losses.

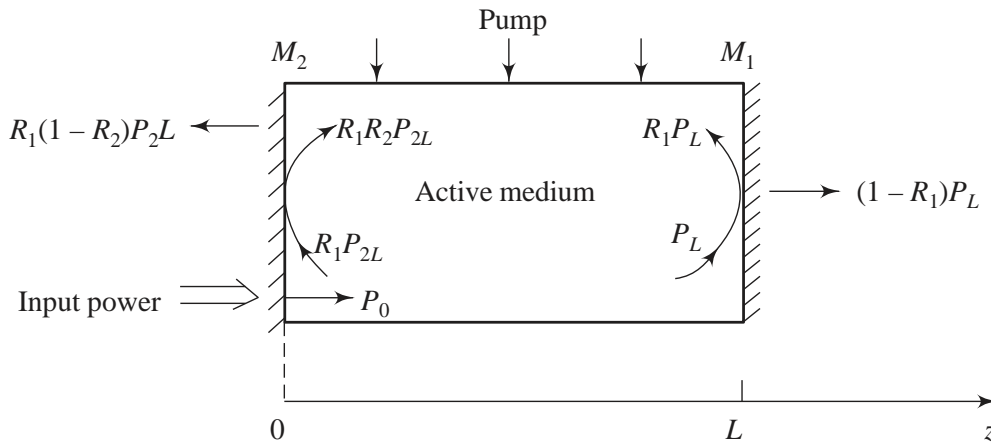


Fig. 7.20 An optical cavity

The total loss of optical power is due to a number of different processes, one of which is the transmission at the mirrors and forms the output beam of the laser. To simplify things, let us represent all the losses except the transmission losses at the mirrors by a single effective loss coefficient α_{eff} . This reduces the effective gain coefficient to $g_{21} - \alpha_{\text{eff}}$. We assume that the active medium fills the space between the mirrors M_1 and M_2 , which have reflectivities R_1 and R_2 and a separation L . Then the optical power in the beam will vary with distance according to the following expression:

$$P_z = P_0 \exp[(g_{21} - \alpha_{\text{eff}})z] \quad (7.83)$$

Then, in travelling from M_2 (at $z = 0$) to M_1 (at $z = L$), the power in the beam will increase to

$$P_L = P_0 \exp[(g_{21} - \alpha_{\text{eff}})L] \quad (7.84)$$

At the mirror M_1 , a fraction R_1 of the incident power is reflected, and hence the power in the reflected beam will be $R_1 P_L$, and after a complete round trip (i.e., after traversing back to M_2 and suffering a reflection there), the power will be

$$R_1 R_2 P_{2L} = R_1 R_2 P_0 \exp[(g_{21} - \alpha_{\text{eff}})2L] \quad (7.85)$$

Therefore, the gain in power G in one round trip of the active medium will be

$$G = \frac{R_1 R_2 P_0 \exp[(g_{21} - \alpha_{\text{eff}}) 2L]}{P_0} = R_1 R_2 \exp[2(g_{21} - \alpha_{\text{eff}})L] \quad (7.86)$$

For sustained oscillations, G must be greater than unity. We may, therefore, write the threshold condition for laser action as

$$G = R_1 R_2 \exp[2(g_{\text{th}} - \alpha_{\text{eff}})L] = 1 \quad (7.87)$$

where g_{th} is the threshold gain coefficient. From this equation, we may arrive at an expression for the threshold gain coefficient as follows

$$g_{\text{th}} = \alpha_{\text{eff}} + (1/2L) \ln(1/R_1 R_2) \quad (7.88)$$

Here, the first term represents the losses in the volume of the cavity and the second term gives the loss in the form of a useful output.

7.9.2 Laser Modes

The oscillations are sustained in the optical cavity over a narrow range of frequencies for which the gain is sufficient to overcome the net loss. Thus, the output of the cavity is not perfectly monochromatic (i.e., consisting of a single frequency) but is a narrow band of frequencies centred around that corresponding to the energy difference between the levels involved in stimulated emission as shown in Fig. 7.21(a). The

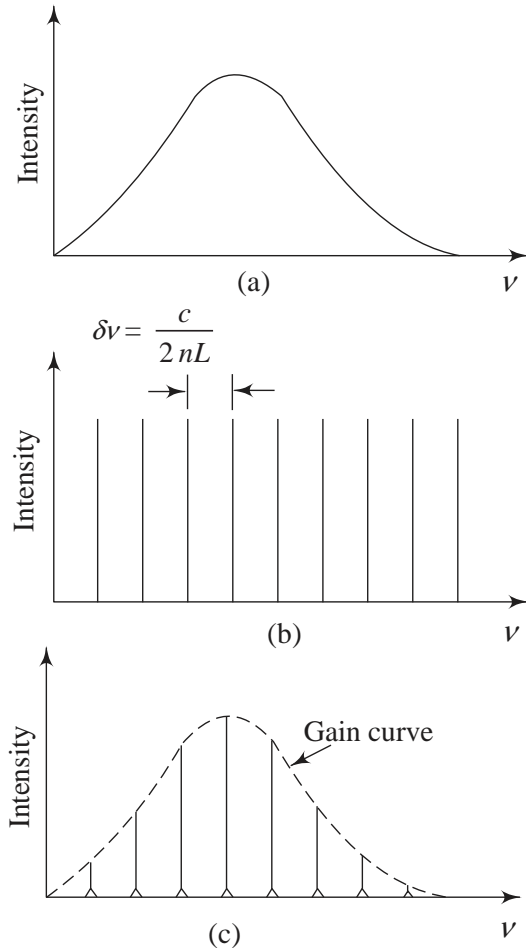


Fig. 7.21 (a) The gain curve or the broadened laser transition line, (b) possible axial modes, and (c) axial modes in the laser output

radiation in the form of electromagnetic waves emitted along the axis of the cavity forms a standing-wave pattern between the two mirrors. The condition for reinforcement of the waves, or resonance, is that the optical path length L between the mirrors must be an integral multiple of the half-wavelength of the waves in the active medium. Hence all the waves which satisfy the condition given below will form standing-wave patterns:

$$L = m\lambda/2n = mc/2n\nu \quad (7.89)$$

where λ is the wavelength in vacuum, n is the refractive index of the active medium, m is an integer, c is the speed of light, and ν is the frequency of the wave. Thus the resonant frequencies may be given by the expression

$$\nu = mc/2nL \quad (7.90)$$

These frequencies corresponding to different integer values of m and are also known as axial or longitudinal modes of the cavity.

From Eq. (7.90) we can obtain the frequency separation between the adjacent modes ($\delta m = 1$) as follows:

$$\delta\nu = c/2nL \quad (7.91)$$

Since $\delta\nu$ is independent of m , the mode separation is the same, irrespective of the actual mode frequencies.

Equation (7.90) indicates that a very large number of axial modes (corresponding to all values of m) may be generated within the cavity. However, oscillations are sustained only for those modes which lie within the gain curve or the laser transition line. These two situations are illustrated in Figs 7.21(b) and 7.21(c), respectively.

As the laser output consists of several modes, the device is called a multimode laser. All these axial modes contribute to a single 'spot' of light in the output. The resonant modes may be formed in a direction transverse to the axis of the cavity. These are called transverse electromagnetic (TEM) modes and are characterized by two integers l and m ; e.g., TEM_{lm} . Here, l and m give the number of minima as the output beam is scanned horizontally and vertically, respectively (say, in the x - and y -direction, assuming the direction of propagation to be the z -axis). Thus, these modes may give rise to a pattern of spots in the output as shown in Fig. 7.22. The TEM_{00} mode is called a uniphase mode because all the points of the propagating wavefront are in phase. However, this is not so with higher order modes. As a consequence, a laser operating in the TEM_{00} mode has the greatest degree of coherence and the highest spectral purity. Oscillations of higher order TEM modes require the aperture of the cavity to be large enough. Therefore, in order to eliminate them, the aperture of the cavity is suitably narrowed down for single-mode operation.

Example 7.5 A typical gas laser is emitting a spectral line centred at 632.8 nm, whose gain curve has a half-width of 3.003×10^{-3} nm. If the cavity length of the laser

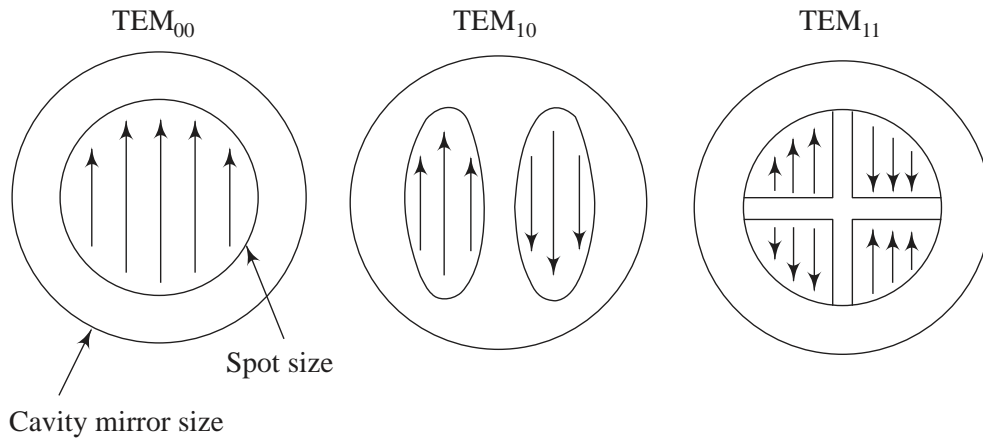


Fig. 7.22 Lower order TEM_{lm} modes of a laser. Arrows represent the direction of the electric-field vectors within the light spot in the output beam

is 20 cm, calculate the number of longitudinal modes excited. Take the refractive index inside the gas medium to be 1.

Solution

Using Eq. (7.89), we have

$$m = \frac{2nL}{\lambda}$$

Therefore the separation $\Delta\lambda$ of the spectral lines between adjacent longitudinal modes can be calculated as follows:

$$\Delta m = 1 = \frac{1}{\lambda^2} 2nL\Delta\lambda$$

or
$$\Delta\lambda = \frac{\lambda^2}{2nL}$$

Here, $\lambda = 632.8 \times 10^{-9}$ m, $n = 1$, and $L = 20 \times 10^{-2}$ m. Therefore,

$$\begin{aligned} \Delta\lambda &= \frac{(632.8 \times 10^{-9})^2}{2 \times 1 \times 20 \times 10^{-2}} \\ &= 1.001 \times 10^{-12} \text{ m} \\ &= 1.001 \times 10^{-3} \text{ nm} \end{aligned}$$

The separation $\Delta\lambda$ of the spectral lines is one-third of the half-width of the gain curve, and hence three longitudinal modes can be excited.

7.9.3 Laser Action in Semiconductors

Laser action in semiconductors may be achieved by forming an optical cavity in the active region of a DH, shown in Fig. 7.23(a). The configuration is analogous to a broad-area DH LED, with the difference that the end faces of the crystal forming the

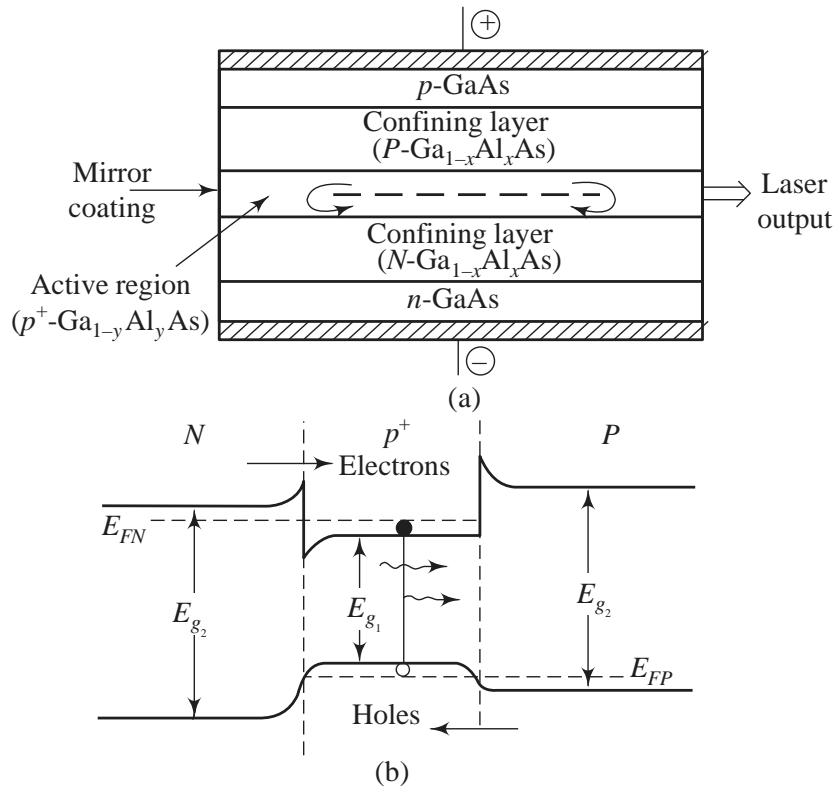


Fig. 7.23 (a) A DH laser diode. (b) Energy-level diagram of confining and active layers under heavy forward bias. p^+ denotes that the active region is a heavily doped p -type material.

active region along the longitudinal direction are cleaved so that they act as mirrors. In some cases, a mirror coating is deposited on one side to make the reflectivity nearly unity. When the device is strongly forward-biased, the energy levels of the different regions of the N - p^+ - P DH typically take the form shown in Fig. 7.23(b). The electrons are injected from the N -region into the CB of the p -region and the holes are injected from the P -region into the VB of the p -region. As a result, population inversion occurs corresponding to the transition between those levels for which the photon energy is greater than the band gap E_{g1} of the active region, but is less than the energy difference between the quasi-Fermi levels E_{FN} and E_{FP} . The refractive index of the active region is greater than that of the confining layer, and hence optical confinement is provided in the transverse direction, but optical feedback is provided in the longitudinal direction. Thus the laser action takes place along the longitudinal direction as in Fig. 7.23(a).

The gain coefficient g_{th} given by Eq. (7.88) for a two-level system will be modified in this case because only a fraction Γ of the optical power that lies within the active region can participate in stimulated emission. This parameter Γ is called the *confinement factor* and it causes the condition for the lasing threshold (i.e., when the gain just exceeds the total loss) to be given by

$$\Gamma g_{th} = \alpha_{eff} + (1/2L) \ln(1/R_1 R_2) \quad (7.92)$$

where L is the length of the active region.

The external quantum efficiency of the laser diode is measured in terms of the differential quantum efficiency η_D , which is defined as the number of photons emitted per radiative electron–hole pair recombination above the lasing threshold. If the gain coefficient is assumed to be constant above the threshold, then η_D may be given by (Kressel & Butler 1977)

$$\eta_D = \eta_{\text{int}}(g_{\text{th}} - \alpha_{\text{eff}})/g_{\text{th}} \quad (7.93)$$

where η_{int} is the internal quantum efficiency of stimulated emission.

Experimentally, η_D is calculated from the slope of the curve for emitted optical power or the flux ϕ as a function of drive current I above the threshold current I_{th} . This is also sometimes called the *slope efficiency*. The curve is shown in Fig. 7.24.

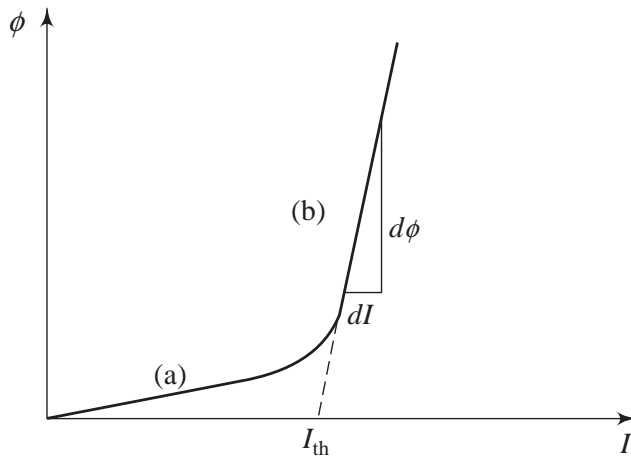


Fig. 7.24 Curve illustrating output optical power as a function of ILD drive current. (a) At low current, the optical output is a spontaneous LED-type emission, (b) above threshold, I_{th} , the output radiation is dominated by stimulated emission.

Thus,

$$\eta_D = (e/E_{g_1}) (d\phi/dI) \quad (7.94)$$

where e is the electronic charge and E_{g_1} is the band gap of the semiconductor used in the active region. η_D of the order of 15–20 % is common in standard ILDs. Higher efficiencies are possible with improvement in designs.

Example 7.6 A DH GaAs/GaAlAs ILD has a cavity length of 0.5 mm, an effective loss coefficient α_{eff} of 1.5 mm^{-1} , a confinement factor Γ of 0.8, and uncoated facet reflectivities of 0.35. (a) Calculate the reduction that occurs in the threshold gain coefficient when the reflectivity of one of the facets is increased to 1. (b) In the latter case, if the internal quantum efficiency of stimulated emission is 0.80, calculate the differential quantum efficiency of the device.

Solution

(a) Using Eq. (7.92), we have

$$g_{\text{th}} = \frac{1}{\Gamma} \left[\alpha_{\text{eff}} + \frac{1}{2L} \ln \left(\frac{1}{R_1 R_2} \right) \right]$$

Thus, with $R_1 = R_2 = 0.35$,

$$(g_{\text{th}})_1 = \frac{1}{0.80} \left[1.5 + \frac{1}{2 \times 0.5} \ln \left(\frac{1}{0.35 \times 0.35} \right) \right]$$

$$= 4.50 \text{ mm}^{-1}$$

and with $R_1 = 0.35$ and $R_2 = 1.0$

$$(g_{\text{th}})_2 = \frac{1}{0.80} \left[1.5 + \frac{1}{2 \times 0.5} \ln \left(\frac{1}{0.35 \times 1} \right) \right]$$

$$= 3.18 \text{ mm}^{-1}$$

Therefore, $\Delta g_{\text{th}} = (g_{\text{th}})_1 - (g_{\text{th}})_2 = 1.32 \text{ mm}^{-1}$

(b) Using Eq. (7.93), we get

$$\eta_D = \frac{0.80(3.18 - 1.5)}{3.18} = 0.42$$

7.9.4 Modulation Response of ILDs

ILDs are increasingly finding applications in fiber-optic communication. Therefore, the study of high-speed modulation of their output is of great technological importance. They can be modulated either externally (using optoelectronic modulators, discussed in Chapter 9) or directly by modulating the excitation current. In this section, we discuss direct current modulation. The treatment given below follows that of Yariv (1997a) closely.

As discussed earlier, stimulated emission will dominate spontaneous emission only when population inversion has occurred. For semiconductor lasers, this condition is satisfied by doping p -type and n -type confining layers so heavily that the Fermi level separation exceeds the band gap of the active region under forward bias [see Fig. 7.23(b)]. When the injected carrier density in the active region exceeds a certain value (n_{tr}) called the *transparency value*, population inversion is achieved and the active region starts exhibiting optical gain. An input signal propagating through the active region would then amplify as $\exp(gz)$, where g is the gain coefficient. At transparency, $g = 0$. For semiconductors, g is normally calculated numerically. In general, the value of the peak gain coefficient g_p is approximated by the relation

$$g_p = B(n - n_{\text{tr}}) \quad (7.95)$$

where B is the gain constant. Typically, B is about $1.5 \times 10^{-16} \text{ cm}^2$ for GaAs/GaAlAs lasers at 300 K. However, it increases with decrease in temperature. n_{tr} is typically around $1.55 \times 10^{18} \text{ cm}^{-3}$.