# Semiconductor Optoelectronics

## Lecture : LASER DIODES


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# Semiconductor Physics and Devices

## Basic Principles

**Third Edition**

***Donald A. Neamen***

# Chapter 14: Optical Devices

# Power Point for *Optoelectronics and Photonics: Principles and Practices* Second Edition

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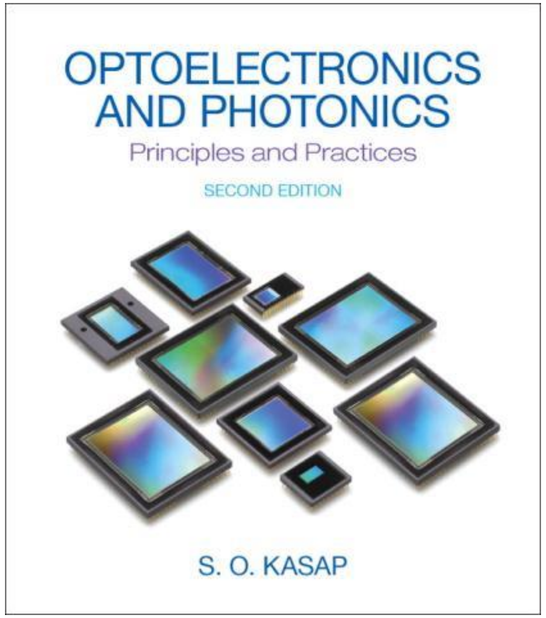
# Chapter 4

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# 14.6 | LASER DIODES

The LED photon emission is spontaneous in that each band-to-band transition is an independent event.
The spontaneous emission process yields a spectral output of the LED with a fairly wide bandwidth. If the structure and operating condition of the LED are modified, the device can operate in a new mode, producing a coherent spectral output with a bandwidth of wavelengths less than 0.1 nm.
This new device is a laser diode, where laser stands for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.

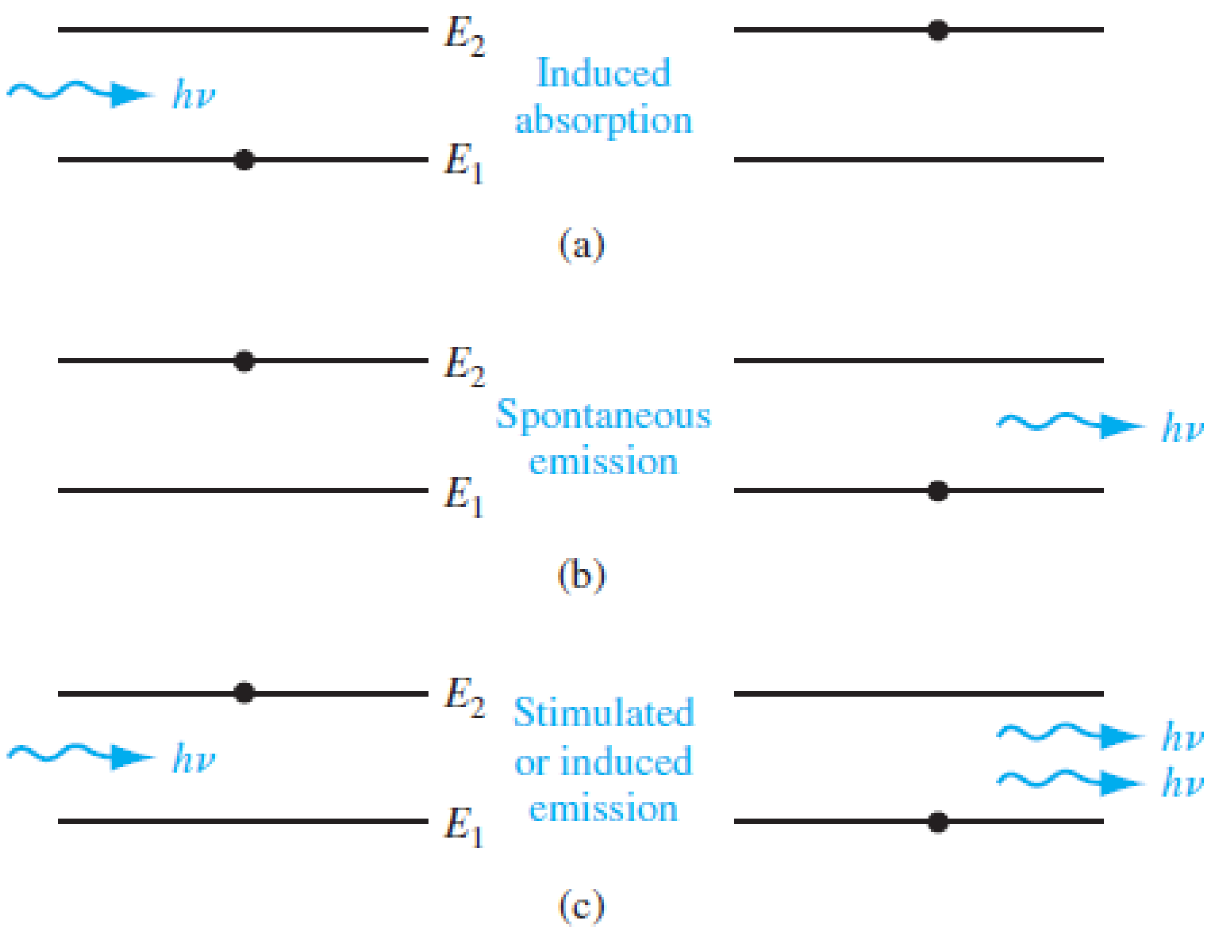



**Figure 14.31** | Schematic diagram showing (a) induced absorption, (b) spontaneous emission, and (c) stimulated emission processes.

## 14.6.1 Stimulated Emission and Population Inversion

Figure 14.31a shows the case when an incident photon is absorbed and an electron is elevated from an energy state $E_1$ to an energy state $E_2$. This process is known as induced absorption.

If the electron spontaneously makes the transition back to the lower energy level with a photon being emitted, we have a spontaneous emission process as indicated in Figure 14.31b.

On the other hand, if there is an incident photon at a time when an electron is in the higher energy state as shown in Figure 14.31c, the incident photon can interact with the electron, causing the electron to make a transition downward. The downward transition produces a photon. Since this process was initiated by the incident photon, the process is called *stimulated* or *induced emission*. Note that this stimulated emission process has produced two photons; thus, we can have optical gain or amplification. The two emitted photons are in phase so thatthe spectral output will be coherent.

In thermal equilibrium, the electron distribution in a semiconductor is determined by the Fermi–Dirac statistics. If the Boltzmann approximation applies, then we can write

$$\frac{N_2}{N_1} = \exp\left[\frac{-(E_2 - E_1)}{kT}\right] \quad (14.62)$$

where $N_1$ and $N_2$ are the electron concentrations in the energy levels $E_1$ and $E_2$, respectively, and where $E_2 > E_1$. In thermal equilibrium, $N_2 < N_1$. The probability of an induced absorption event is exactly the same as that of an induced emission event.

The number of photons absorbed is proportional to $N_1$ and the number of additional photons emitted is proportional to $N_2$. In order to achieve optical amplification or for lasing action to occur, we must have $N_2 > N_1$; this is called population inversion. We cannot achieve lasing action at thermal equilibrium.

Figure 14.32 shows the two energy levels with a light wave at an intensity *I* propagating in the *z* direction. The change in intensity as a function of *z* can be written as

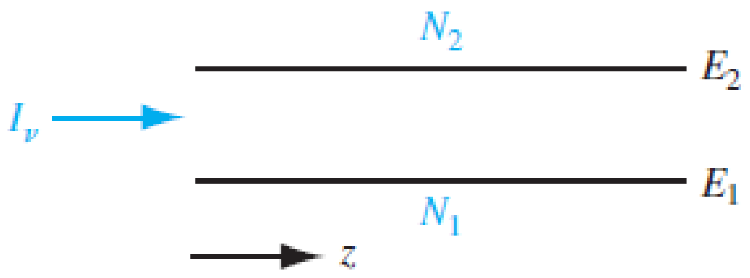



Figure 14.32 | Light propagating in *z* direction through a material with two energy levels.

$$\frac{dI_\nu}{dz} \propto \frac{\text{\# photons emitted}}{\text{cm}^3} - \frac{\text{\# photons absorbed}}{\text{cm}^3}$$

$$\frac{dI_\nu}{dz} = N_2 W_i \cdot h\nu - N_1 W_i \cdot h\nu \qquad (14.63)$$

where $W_i$ is the induced transition probability. Equation (14.63) assumes no loss mechanisms and neglects the spontaneous transitions.
Equation (14.63) can be written as

$$\frac{dI_\nu}{dz} = \gamma(\nu) I_\nu \qquad (14.64)$$

where $(\gamma) \alpha (N_2 - N_1)$ and is the amplification factor. From Equation (14.64), the intensity is

$$I_\nu = I_\nu(0) e^{\gamma(\nu) z} \qquad (14.65)$$

Amplification occurs when $\gamma(\nu) > 0$ and absorption occurs when $\gamma(\nu) < 0$.

We can achieve population inversion and lasing in a forward-biased pn homojunction diode, if both sides of the junction are degenerately doped. Figure 14.33a shows the energy-band diagram of a degenerately doped pn junction in thermal equilibrium.

The Fermi level is in the conduction band in the n-region and the Fermi level is in the valence band in the p region. Figure 14.33b shows the energy bands of the pn junction when a forward bias is applied. The gain factor in a pn homojunction diode is given by

$$\gamma(\nu) \propto \left\{1 - \exp\left[\frac{h\nu - (E_{Fn} - E_{Fp})}{kT}\right]\right\} \tag{14.66}$$

In order for $\gamma(\nu) > 1$, we must have $h\nu < (E_{Fn} - E_{Fp})$, which implies that the junction must be degenerately doped since we also have the requirement that $h\nu > E_g$.

In the vicinity of the junction, there is a region in which population inversion occurs. There are large numbers of electrons in the conduction band directly above a large number of empty states. If band-to-band recombination occurs, photons will be emitted with energies in the range $E_g < h\nu < (E_{Fn} - E_{Fp})$.

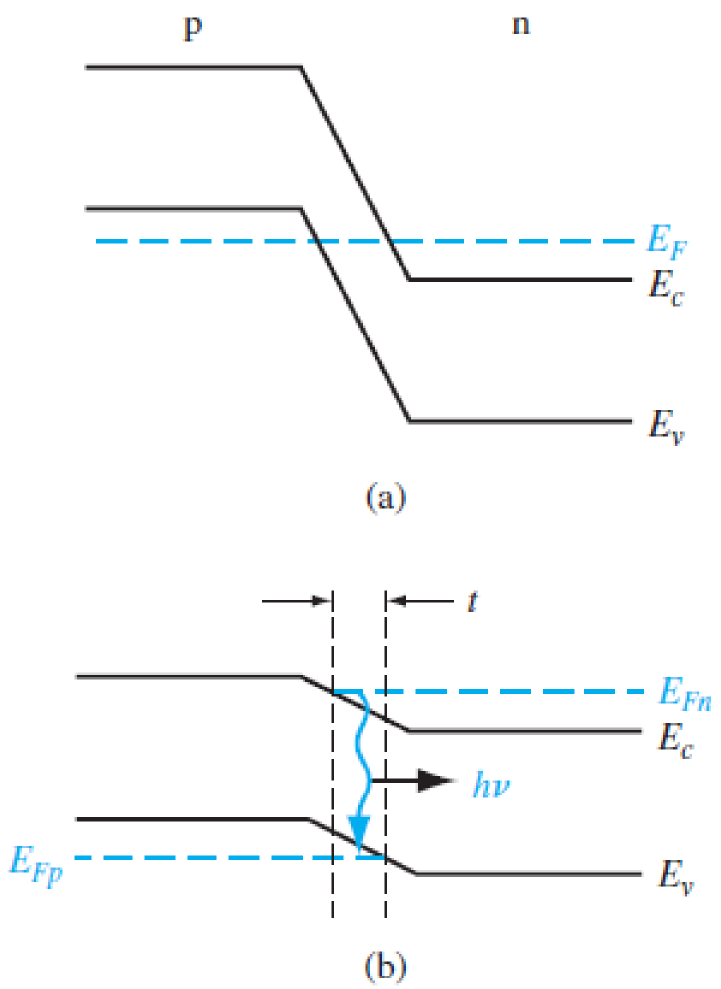



**Figure 14.33** | (a) Degenerately doped pn junction at zero bias. (b) Degenerately doped pn junction under forward bias with photon emission.

# 14.6.2 Optical Cavity

Population inversion is one requirement for lasing action to occur. Coherent emission output is achieved by using an optical cavity. The cavity will cause a buildup of the optical intensity from positive feedback. A resonant cavity consisting of two parallel mirrors is known as a Fabry–Perot resonator. The resonant cavity can be fabricated, for example, by cleaving a gallium arsenide crystal along the (110) planes as shown in Figure 14.34. The optical wave propagates through the junction in the *z* direction, bouncing back and forth between the end mirrors. The mirrors are actually only partially reflecting so that a portion of the optical wave will be transmitted out of the junction.

For resonance, the length of the cavity *L* must be an integral number of half wavelengths, or

$$N\left(\frac{\lambda}{2}\right) = L \qquad (14.67)$$

where *N* is an integer. Since  is small and *L* is relatively large, there can be many resonant modes in the cavity.

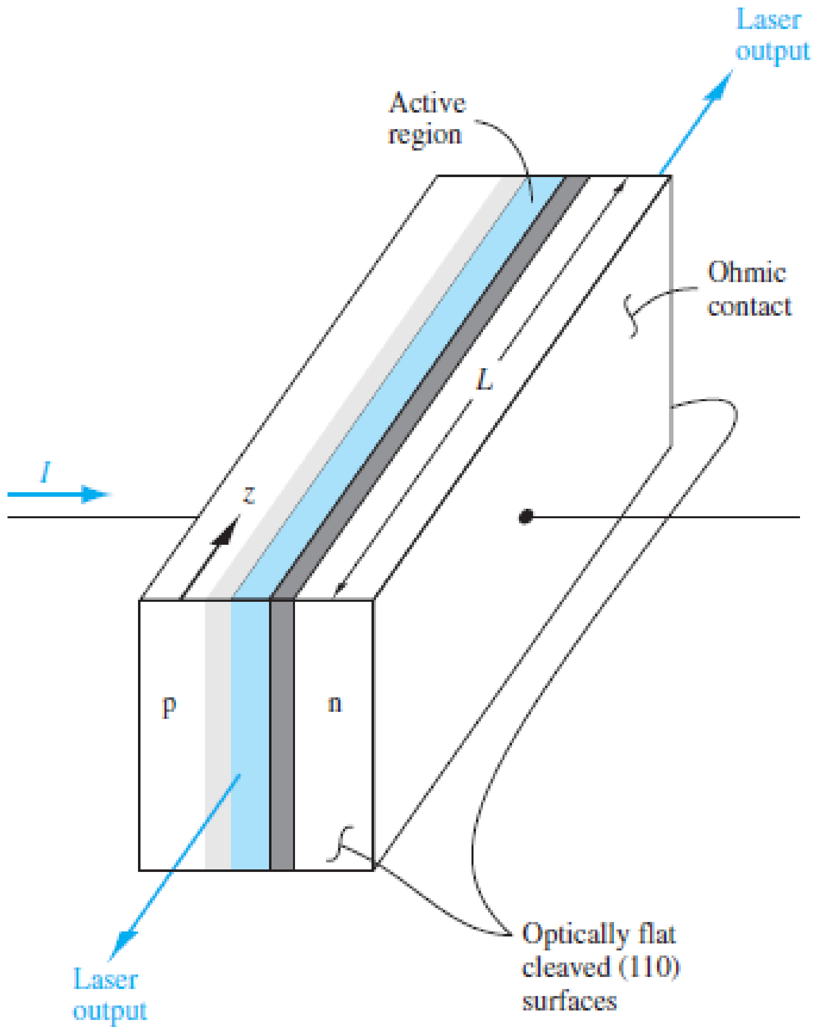



**Figure 14.34** | A pn junction laser diode with cleaved (110) planes forming the Fabry-Perot cavity. *(After Yang [22].)*

Figure 14.35a shows the resonant modes as a function of wavelength. When a forward-bias current is applied to the pn junction, spontaneous emission will initially occur. The spontaneous emission spectrum is relatively broadband and is superimposed on the possible lasing modes as shown in Figure 14.35b.

In order for lasing to be initiated, the spontaneous emission gain must be larger than the optical losses. By positive feedback in the cavity, lasing can occur at several specific wavelengths as indicated in Figure 14.35c.

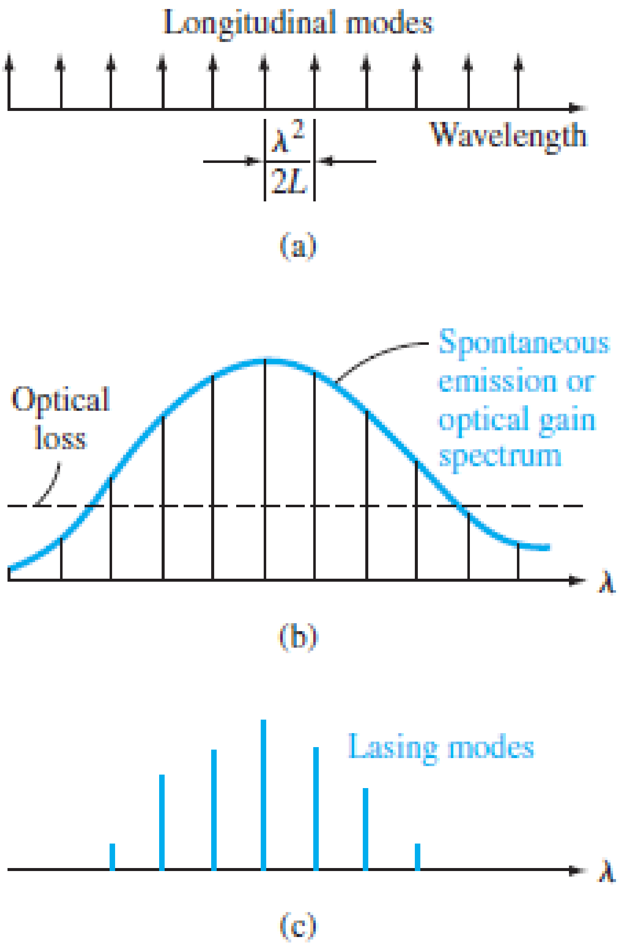



Figure 14.35 | Schematic diagram showing (a) resonant modes of a cavity with length $L$, (b) spontaneous emission curve, and (c) actual emission modes of a laser diode.
*(After Yang [22].)*

# 14.6.3 Threshold Current

The optical intensity in the device can be written from Equation (14.65) as $I_\nu \; \alpha \; e^{\gamma(\nu)z}$, where $\gamma(\nu)$ is the amplification factor. We have two basic loss mechanisms.
The first is the photon absorption in the semiconductor material. We can write

$$I_\nu \propto e^{-\alpha(\nu)z} \qquad (14.68)$$

where $\gamma(\nu)$ is the absorption coefficient. The second loss mechanism is due to the partial transmission of the optical signal through the ends, or through the partially reflecting mirrors.

At the onset of lasing, which is known as threshold, the optical loss of one round trip through the cavity is just offset by the optical gain. The threshold condition is then expressed as

$$\Gamma_1\Gamma_2 \exp[(2\gamma_t(\nu) - 2\alpha(\nu))L] = 1 \qquad (14.69)$$

Where $\Gamma_1$ and $\Gamma_2$ are the reflectivity coefficients of the two end mirrors. For the case when the optical mirrors are cleaved (110) surfaces of gallium arsenide, the reflectivity coefficients are given approximately by

$$\Gamma_1 = \Gamma_2 = \left(\frac{\bar{n}_2 - \bar{n}_1}{\bar{n}_2 + \bar{n}_1}\right)^2 \tag{14.70}$$

where $\bar{n}_2$ and $\bar{n}_1$ are the index of refraction parameters for the semiconductor and air, respectively. The parameter $\gamma_t(\nu)$ is the optical gain at threshold.

The optical gain at threshold, $\gamma_t(\nu)$, may be determined from Equation (14.69) as

$$\gamma_t(\nu) = \alpha + \frac{1}{2L}\ln\left(\frac{1}{\Gamma_1\Gamma_2}\right) \tag{14.71}$$

Since the optical gain is a function of the pn junction current, we can define a threshold current density as

$$J_{th} = \frac{1}{\beta}\left[\alpha + \frac{1}{2L}\ln\left(\frac{1}{\Gamma_1\Gamma_2}\right)\right] \tag{14.72}$$

where $\beta$ can be determined theoretically or experimentally. Figure 14.36 shows the threshold current density as a function of the mirror losses. We may note the relatively high threshold current density for a pn junction laser diode.

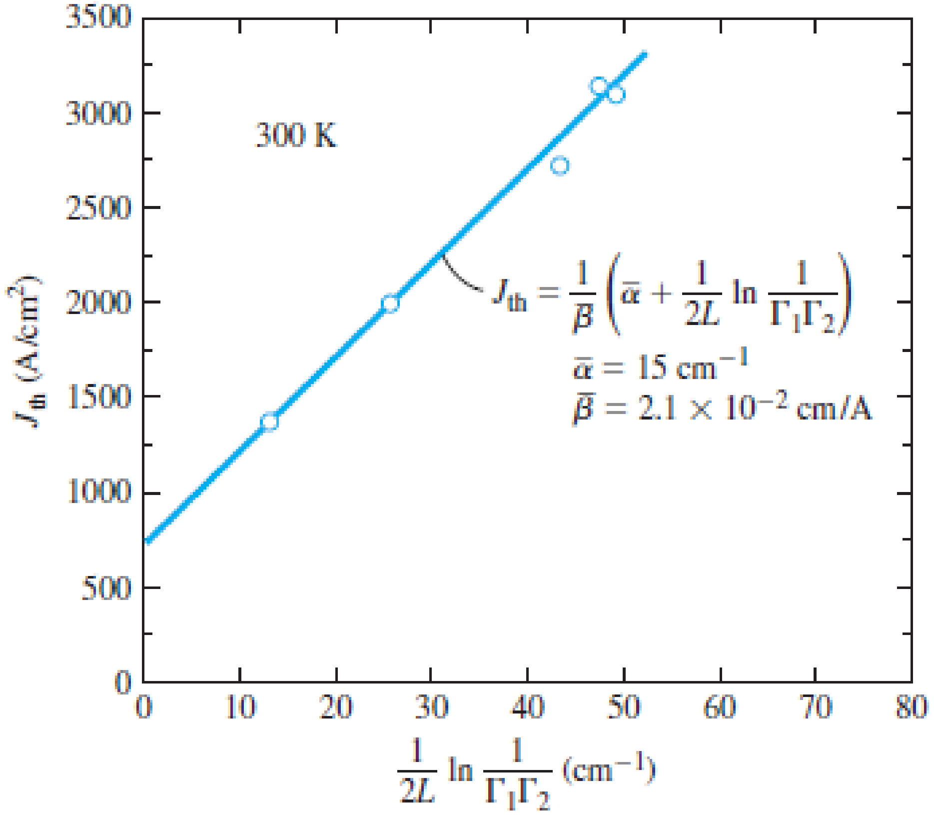



**Figure 14.36** | Threshold current density of a laser diode as a function of Fabry-Perot cavity end losses.
*(After Yang [22].)*

## 14.6.4 Device Structures and Characteristics

We have seen that in a homojunction LED, the photons may be emitted in any direction, which lowers the external quantum efficiency.

Significant improvement in device characteristics can be made if the emitted photons are confined to a region near the junction. This confinement can be achieved by using an optical waveguide.

The basic device is a three-layered, double heterojunction structure known as a double heterojunction laser. A requirement for a waveguide is that the index of refraction of the center material be larger than that of the other two materials.

Figure 14.37 shows the index of refraction for the AlGaAs system. We may note that GaAs has the highest index of refraction.

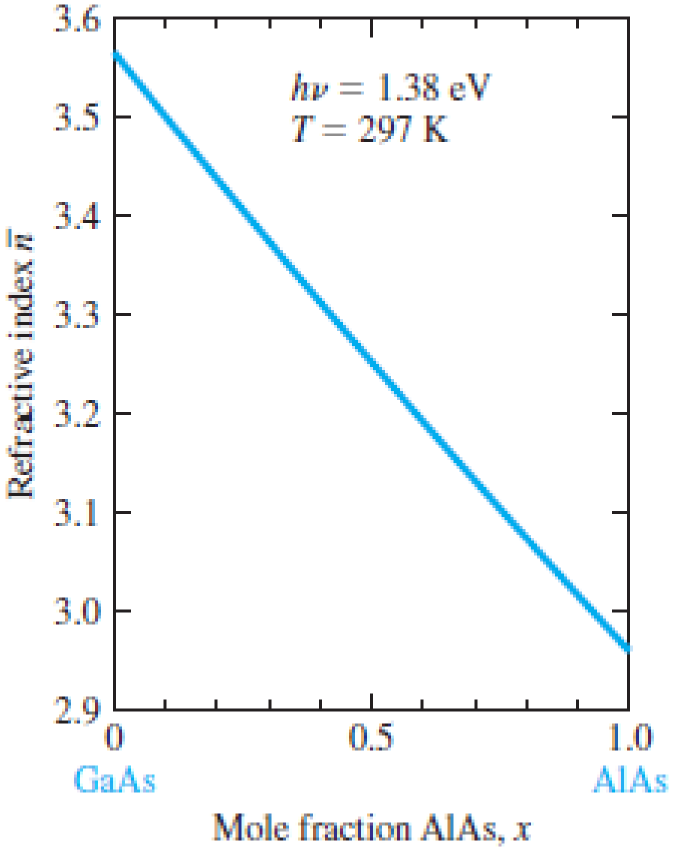



**Figure 14.37** | Index of refraction of $Al_xGa_{1-x}As$ as a function of mole fraction $x$.
*(From Sze [18].)*

An example of a double heterojunction laser is shown in Figure 14.38a. A thin p-GaAs layer is between P-AlGaAs and N-AlGaAs layers.

A simplified energy-band diagram is shown in Figure 14.38b for the forward-biased diode. Electrons are injected from the N-AlGaAs into the p-GaAs.

Population inversion is easily obtained since the conduction band potential barrier prevents the electrons from diffusing into the P-AlGaAs region.

Radiative recombination is then confined to the p-GaAs region. Since the index of refraction of GaAs is larger than that of AlGaAs, the light wave is also confined to the GaAs region. An optical cavity can be formed by cleaving the semiconductor perpendicular to the N-AlGaAs–p-GaAs junction.

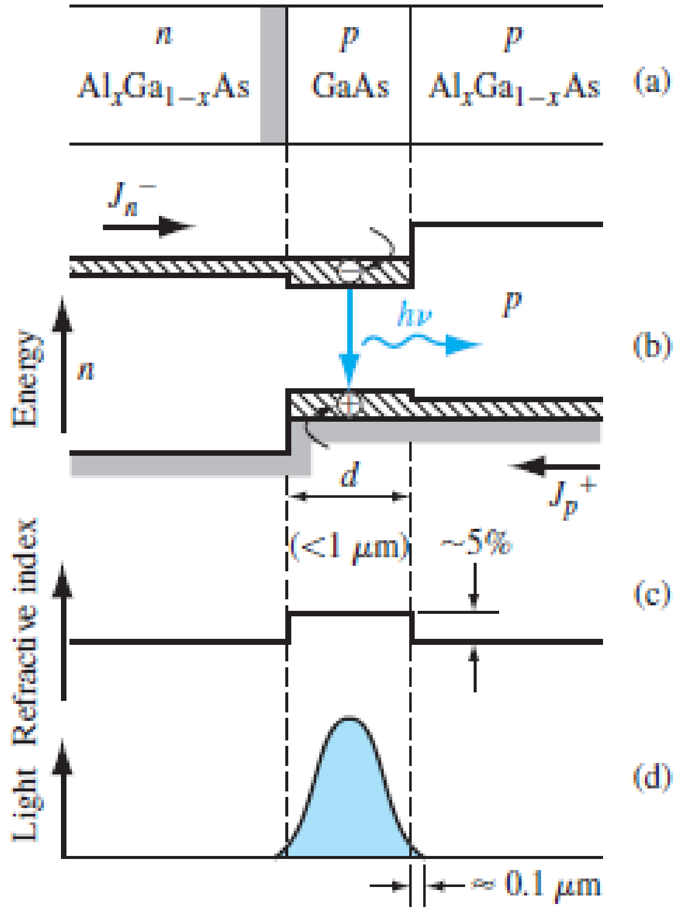



**Figure 14.38** | (a) Basic double hetero-junction structure. (b) Energy-band diagram under forward bias. (c) Refractive index change through the structure. (d) Confinement of light in the dielectric waveguide. *(From Yang [22].)*

Typical optical output versus diode current characteristics are shown in Figure 14.39. The threshold current is defined to be the current at the breakpoint. At low currents, the output spectrum is very wide and is the result of the spontaneous transitions. When the diode current is slightly above the threshold value, the various resonant frequencies are observed. When the diode current becomes large, a single dominant mode with a narrow bandwidth is produced.

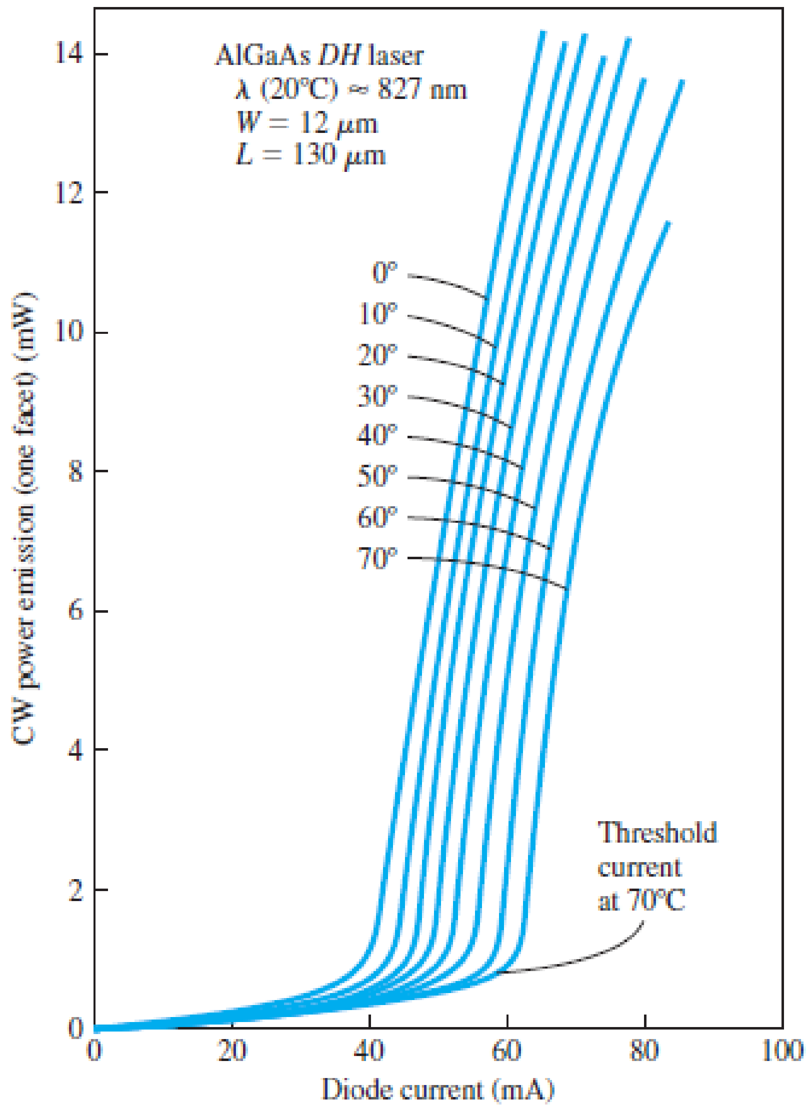
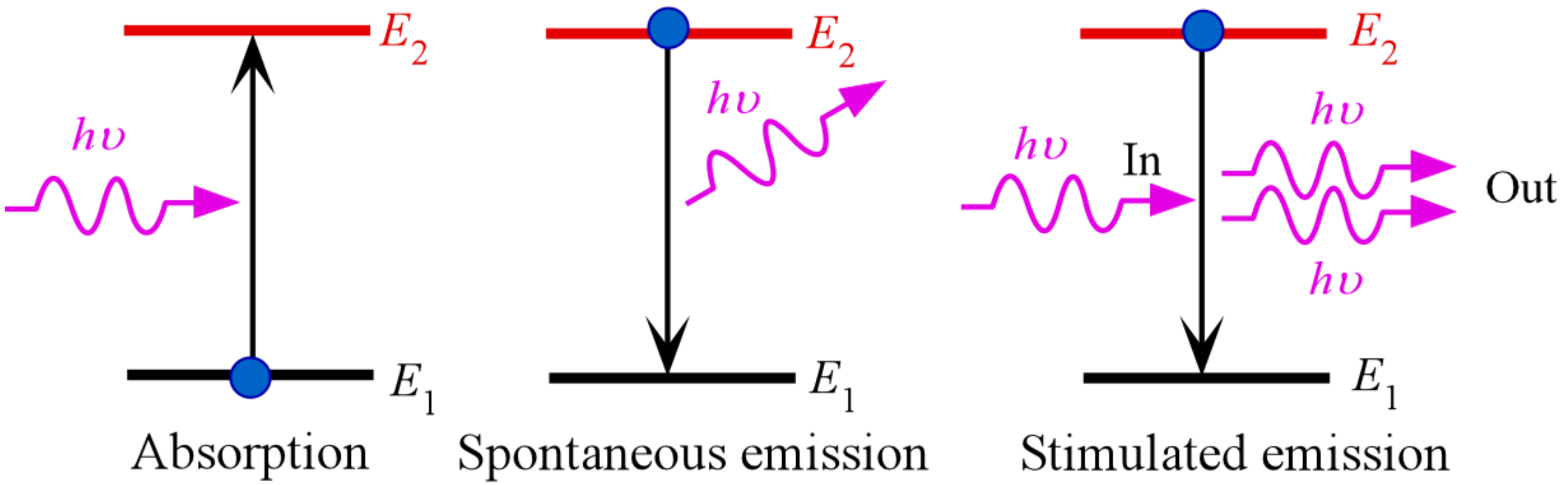


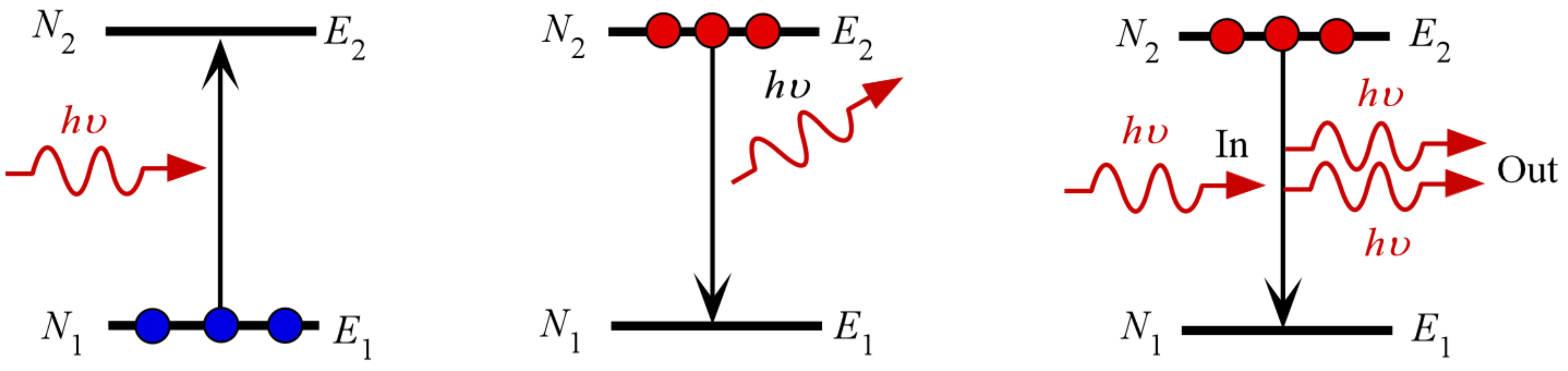

**Figure 14.39** | Typical output power versus laser diode current at various temperatures.
*(From Yang [22].)*

# Einstein Coefficients




In order to study all the three phenomena above, certain coefficients have been assigned to these phenomena which are actually defined by the transition probabilities and are called as Einstein coefficients. The phenomenon that occurs in the absence of external stimulus (spontaneous emission) is assigned the coefficient, A21. The phenomena that occur in presence of external stimuli are denoted by „B"; the absorption phenomenon is assigned B12 and the stimulated emission is assigned B21. Note that the subscripts in the coefficients indicate the direction of transition from the initial level to the final level. Using these coefficients, the three processes can now be expressed in mathematically.

# Einstein Coefficients



(a) Absorption (b) Spontaneous emission (c) Stimulated emission

$$R_{12} = B_{12} N_1 \rho(\upsilon)$$

$-dN_1/dt$ → $R_{12}$; $B_{12} N_1 \rho(\upsilon)$ → **Absorption**

$$R_{21} = A_{21} N_2 + B_{21} N_2 \rho(\upsilon)$$

$-dN_2/dt$ → $R_{21}$; $A_{21} N_2$ → **Spontaneous emission**; $B_{21} N_2 \rho(\upsilon)$ → **Stimulated emission**

$R_{12}$ = rate at upward transition
$R_{21}$ = rate at which $N_2$ is decreasing by spontaneous and stimulated emission
we assume an input photon flux which can be denoted by a flux density function „ρ(ν)"

We need $A_{21}$, $B_{12}$ and $B_{21}$

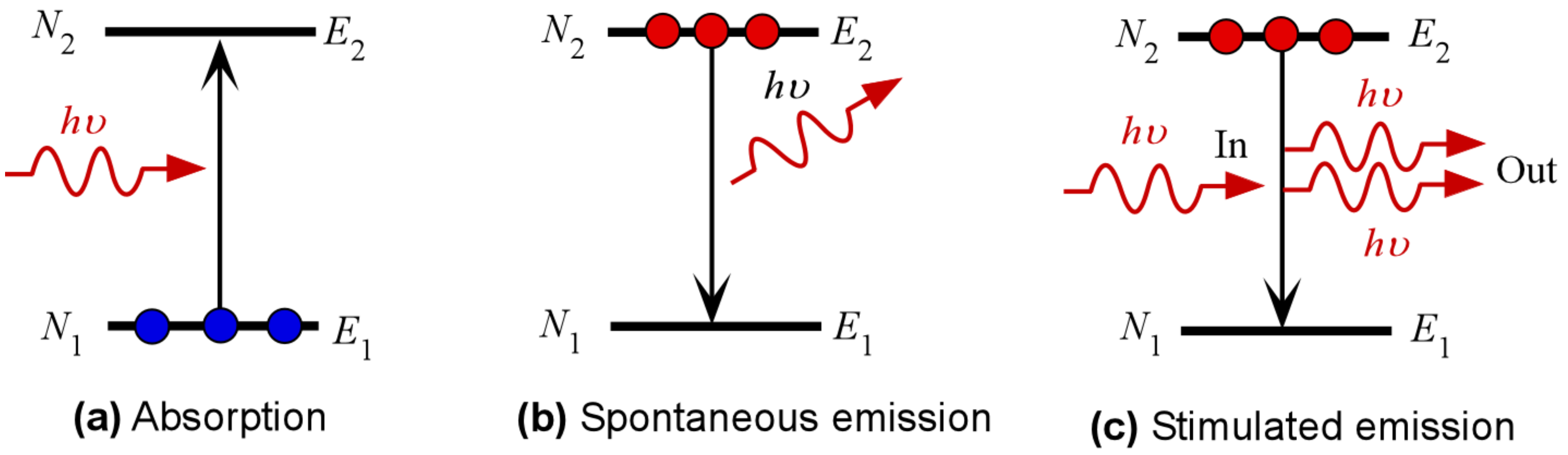
Thus we have three phenomena that may simultaneously occur inside a material; two processes cause electron transition from excited state to the ground state and the third causes electron transition from ground state to the excited state. At thermal equilibrium and without the injection of external electrons, the electron densities in the two states have to be maintained and so the total number of emissive transitions must be equal to the total number of absorptive transitions. Mathematically,

$$B_{12}\rho(\upsilon)N_1 = A_{21}N_2 + B_{21}\rho(\upsilon)N_2$$

Rearranging the equation, we may obtain the expression for the photon flux density function as:

$$\rho(\upsilon) = \frac{\dfrac{A_{21}}{B_{12}}}{\dfrac{B_{12}}{B_{21}}\dfrac{N_1}{N_2} - 1}$$

# Einstein Coefficients




Consider equilibrium $R_{12} = R_{21}$

Boltzmann statistics

$$N_2 / N_1 = \exp[-(E_2 - E_1)/k_B T]$$

$$N_2 / N_1 = \exp[-(h\upsilon)/k_B T]$$

$$N_1 / N_2 = \exp[(h\upsilon)/k_B T]$$

$E_1$ and $E_2$ have the same degeneracy

Planck's black body radiation law

$$\rho_{eq}(\upsilon) = \frac{8\pi h \upsilon^3}{c^3\left[\exp\left(\frac{h\upsilon}{k_B T}\right) - 1\right]}$$

# Einstein Coefficients

$$\rho(\upsilon) = \frac{\frac{A_{21}}{B_{12}}}{\frac{B_{12}}{B_{21}}\frac{N_1}{N_2} - 1}$$

$$\rho_{\text{eq}}(\upsilon) = \frac{8\pi h\upsilon^3}{c^3\left[\exp\left(\frac{h\upsilon}{k_B T}\right) - 1\right]}$$

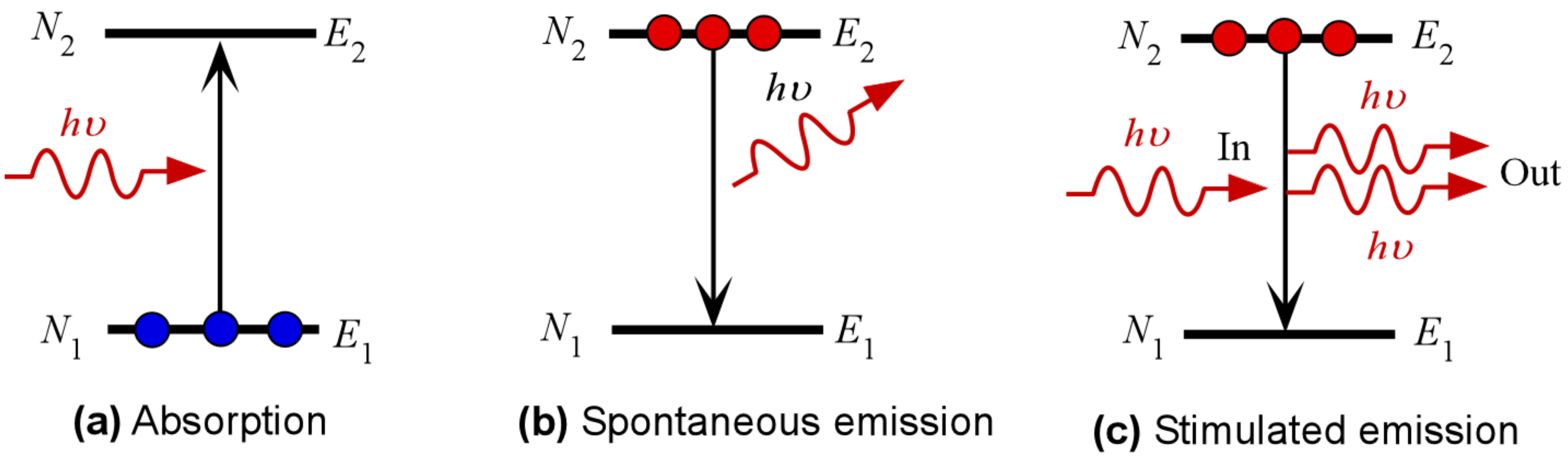
$$\mathbf{B_{12} = B_{21}}$$

$$\mathbf{A_{21}/B_{21} = 8\pi h\upsilon^3/c^3}$$

$$\frac{R_{21}(\text{stim})}{R_{21}(\text{spon})} = \frac{B_{21}N_2\rho(\upsilon)}{A_{21}N_2} = \frac{B_{21}\rho(\upsilon)}{A_{21}} = \frac{c^3}{8\pi h\upsilon^3}\rho(\upsilon)$$

$$\frac{R_{21}(\text{stim})}{R_{12}(\text{absorp})} = \frac{N_2}{N_1}$$

# LASER Requirements




$$\frac{R_{21}(\text{stim})}{R_{12}(\text{absorp})} = \frac{N_2}{N_1}$$

**Population inversion**

$$\frac{R_{21}(\text{stim})}{R_{21}(\text{spon})} \propto \rho(\upsilon)$$

**Optical cavity**