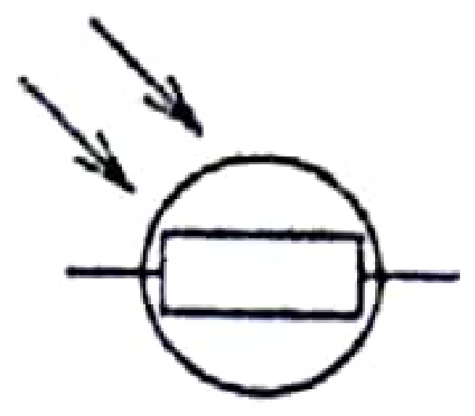
LDR

What is a Light Dependent Resistor or a Photo Resistor?

A **Light Dependent Resistor** (LDR) or a photo resistor is a device whose resistivity is a function of the incident electromagnetic radiation. Hence, they are light sensitive devices.
They are also called as photo conductors, photo conductive cells or simply photocells. They are made up of semiconductor materials having high resistance. There are many different symbols used to indicate a **LDR**, one of the most commonly used symbol is shown in the figure below. The arrow indicates light falling on it.



Working Principle of LDR

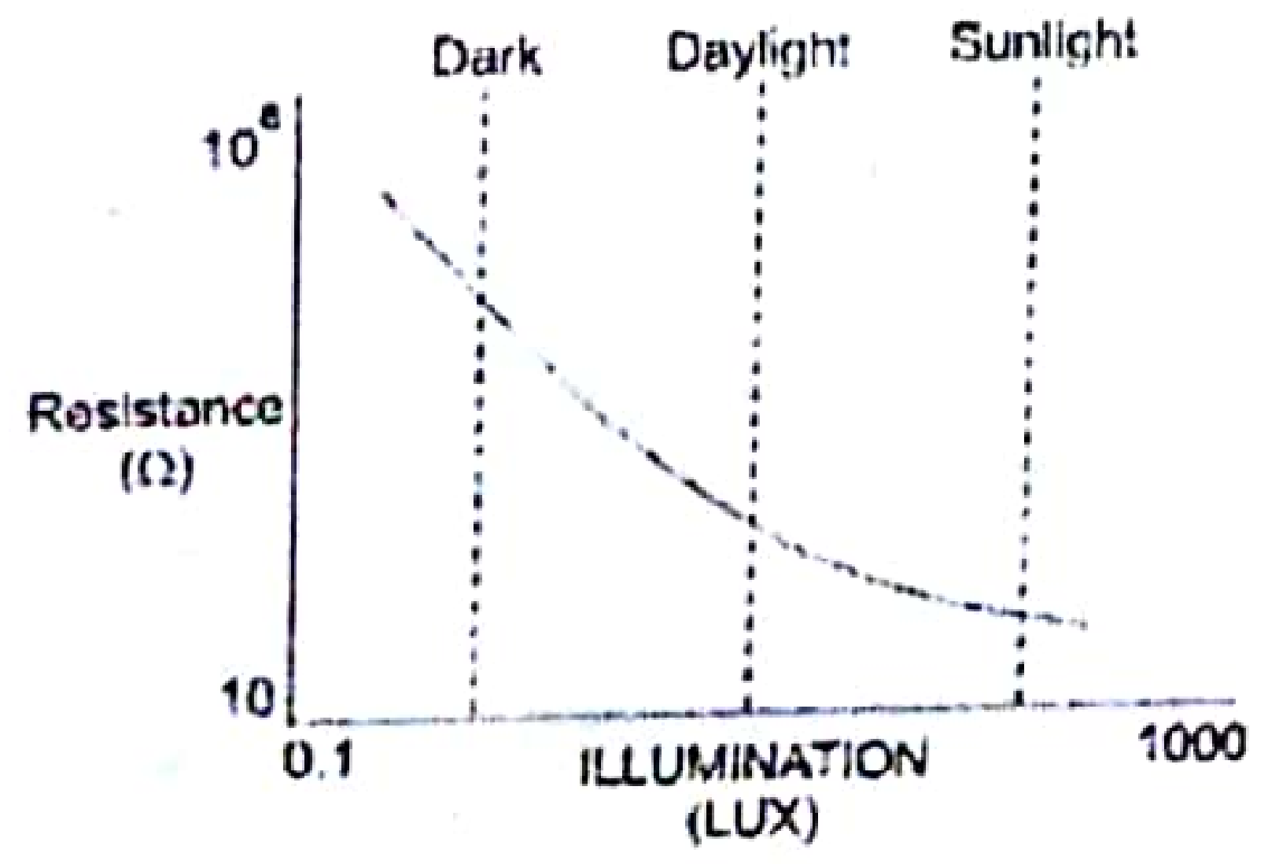
A **light dependent resistor** works on the principle of photo conductivity.

Photo conductivity is an optical phenomenon in which the materials conductivity is increased when light is absorbed by the material.

When light falls i.e. when the photons fall on the device, the electrons in the valence band of the semiconductor material are excited to the conduction band. These photons in the incident light should have energy greater than the band gap of the semiconductor material to make the electrons jump from the valence band to the conduction band. Hence when light having enough energy strikes on the device, more and more electrons are excited to the conduction band which results in large number of charge carriers. The result of this process is more and more current starts flowing throgh the device when the circuit is closed and hence it is said that the resistance of the device has been decreased. This is the most common **working principle of LDR**.

Characteristics of LDR

LDR's are light dependent devices whose resistance is decreased when light falls on them and that is increased in the dark. When a **light dependent resistor** is kept in dark, its resistance is very high. This resistance is called as dark resistance. It can be as high as 10^{12} Ω and if the device is allowed to absorb light its resistance will be decreased drastically. If a constant voltage is applied to it and intensity of light is increased the current starts increasing. Figure below shows resistance vs. illumination curve for a particular **LDR**.



Photocells or LDR's are non linear devices. There sensitivity varies with the wavelength of light incident on them. Some photocells might not at all response to a certain range of wavelengths. Based on the material used different cells have different spectral response curves.

When light is incident on a photocell it usually takes about 8 to 12 ms for the change in resistance to take place, while it takes one or more seconds for the resistance to rise back again to its initial value after removal of light. This phenomenon is called as resistance recovery rate. This property is used in audio compressors.

Also, **LDR's** are less sensitive than photo diodes and photo transistor. (A photo diode and a photocell (LDR) are not the same, a photo-diode is a p-n junction semiconductor device that converts light to electricity, whereas a photocell is a passive device, there is no p-n junction in this nor it "converts" light to electricity).

Types of Light Dependent Resistors:

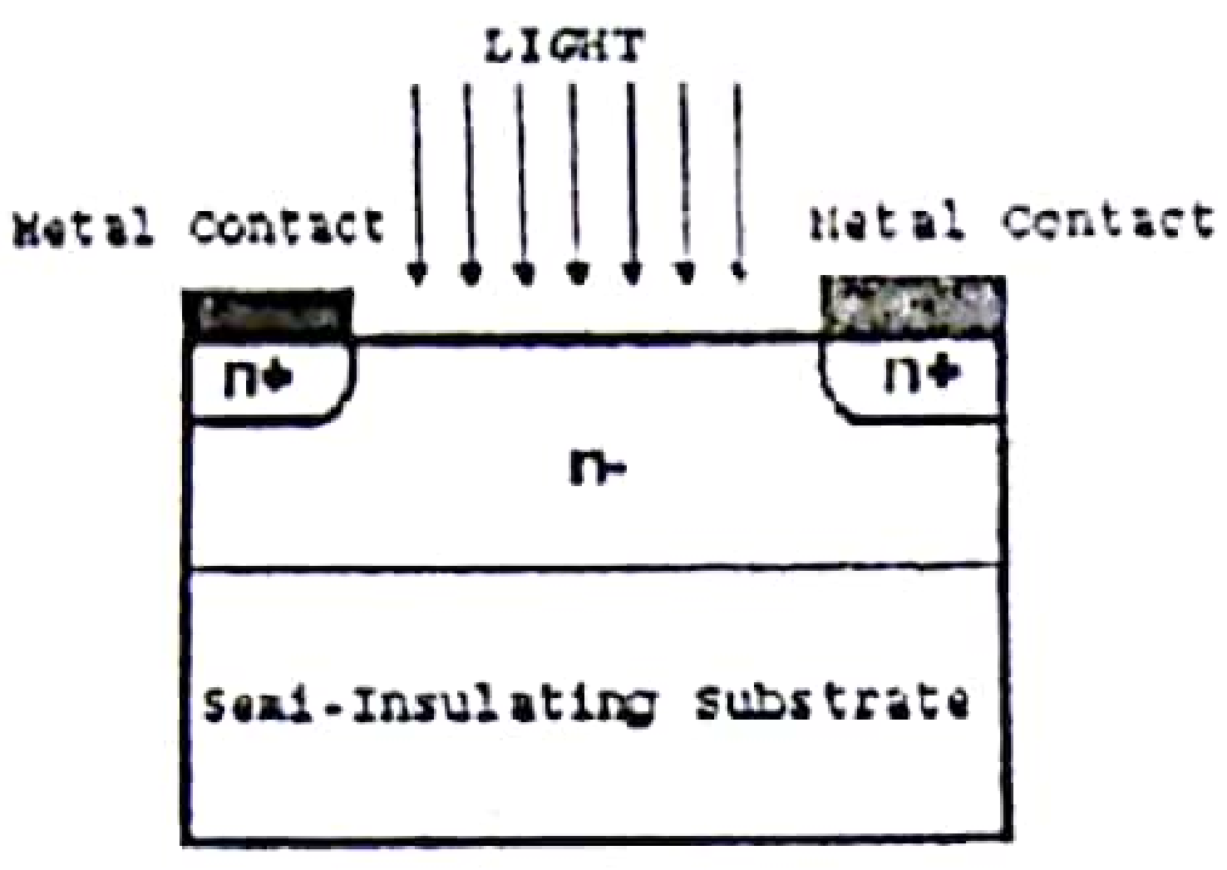
Based on the materials used they are classified as:

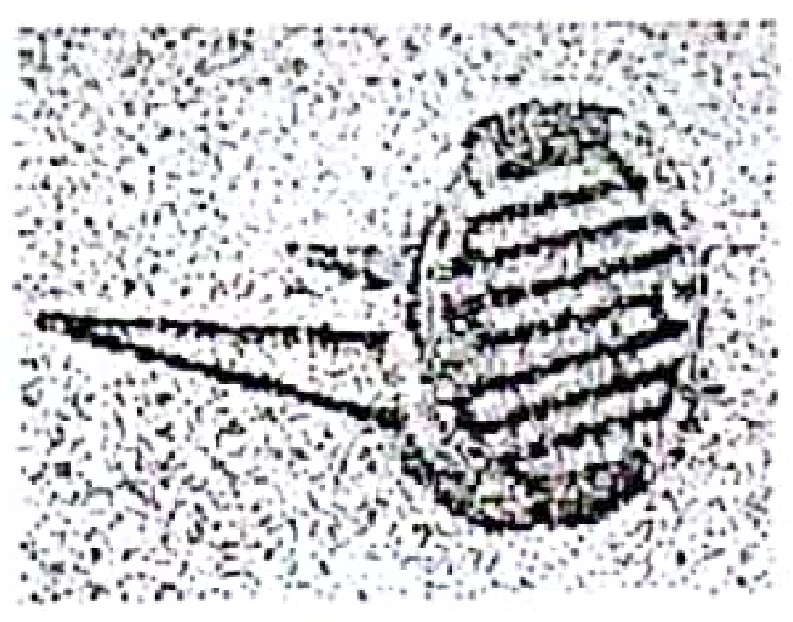
1. Intrinsic photo resistors (Un doped semiconductor): These are made of pure semiconductor materials such as silicon or germanium. Electrons get excited from valance band to conduction band when photons of enough energy fall on it and number charge carriers is increased.

2. Extrinsic photo resistors: These are semiconductor materials doped with impurities which are called as dopants. Theses dopants create new energy bands above the valence band which are filled with electrons. Hence this reduces the band gap and less energy is required in exciting them. Extrinsic photo resistors are generally used for long wavelengths.

Construction of a Photocell

The structure of a light dependent resistor consists of a light sensitive material which is deposited on an insulating substrate such as ceramic. The material is deposited in zigzag pattern in order to obtain the desired resistance & power rating. This zigzag area separates the metal deposited areas into two regions. Then the ohmic contacts are made on the either sides of the area. The resistances of these contacts should be as less as possible to make sure that the resistance mainly changes due to the effect of light only. Materials normally used are cadmium sulphide, cadmium selenide, indium antimonide and cadmium sulphonide. The use of lead and cadmium is avoided as they are harmful to the environment.





Applications of LDR: LDR's have low cost and simple structure. They are often used as light sensors. They are used when there is a need to detect absences or presences of light like in a camera light meter. Used in street lamps, alarm clock, burglar alarm circuits, light intensity meters, for counting the packages moving on a conveyor belt, etc.

A Light Dependent Resistor (LDR) is also called a photoresistor or a cadmium sulfide (CdS) cell. It is also called a photoconductor. It is basically a photocell that works on the principle of photoconductivity. The passive component is basically a resistor whose resistance value decreases when the intensity of light decreases. This **optoelectronic device** is mostly used in light varying sensor circuit, and light and dark activated switching circuits. Some of its applications include camera light meters, street lights, clock radios, light beam alarms, reflective smoke alarms, and outdoor clocks.

Some projects with the application of LDR is listed below.

1. Automatic Street Light Circuit

2. Simple Fire Alarm Circuit

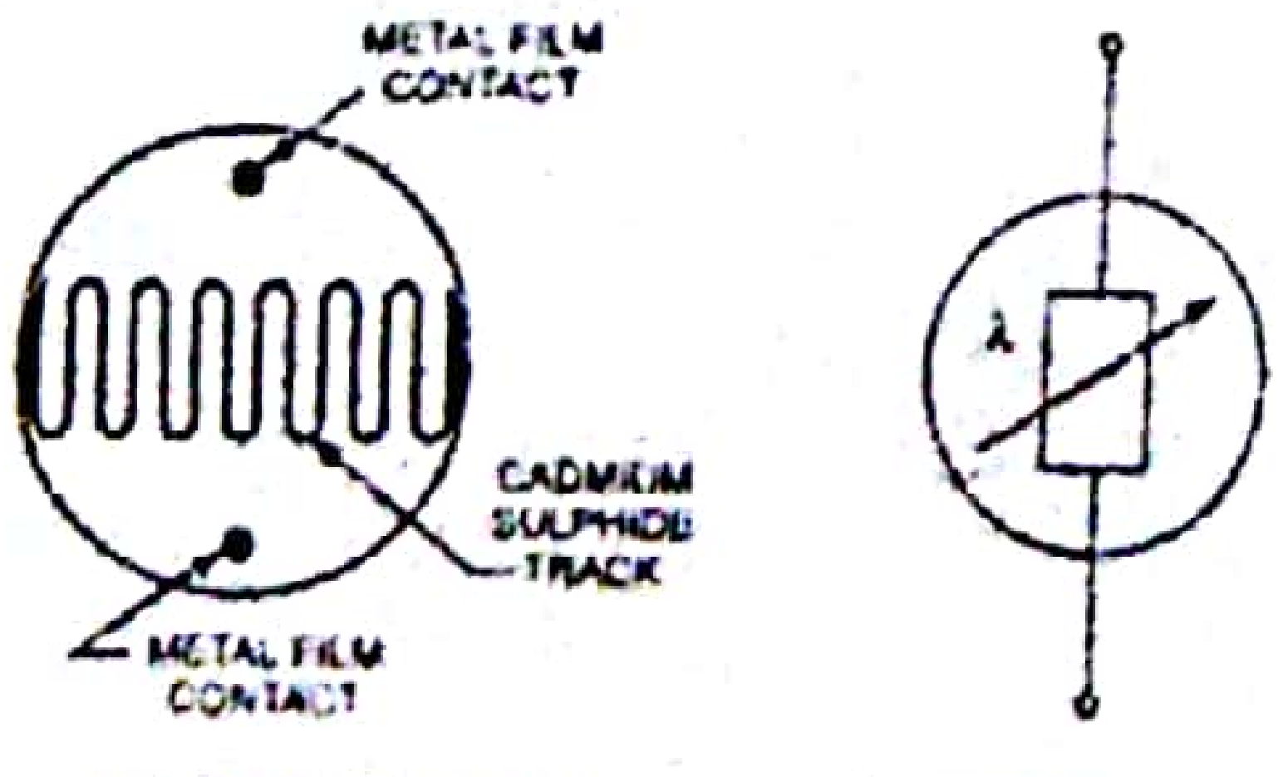
3. Light Activated Switch Circuit

4. Automatic LED Emergency Light

5. Night Security Light

LDR Structure and Working

The basic structure of an LDR is shown below.



(a) Basic Structure (b) Symbol

LDR

The snake like track shown below is the Cadmium Sulphide (CdS) film which also passes through the sides. On the top and bottom are metal films which are connected to the terminal leads. It is designed in such a way as to provide maximum possible contact area with the two metal films. The structure is housed in a clear plastic or resin case, to provide free access to external light. As explained above, the main component for the construction of LDR is cadmium sulphide (CdS), which is used as the photoconductor and contains no or very few electrons when not illuminated. In the absence of light it is designed to have a high resistance inthe range of megaohms. As soon as light falls on the sensor, the electrons are liberated and the conductivity of the material increases. When the light intensity exceeds a certain frequency, the photons absorbed by the semiconductor give band electrons the energy required to jump into the conduction band. This causes the free electrons or holes to conduct electricity and thus dropping the resistance dramatically (< 1 Kiloohm).

The equation to show the relation between resistance and illumination can be written as

R = A.E^a where E – Illumination (lux) R – Resistance (Ohms) A,a – constants

The value of 'a' depends on the CdS used and on the manufacturing process. Values usually range betwee 0.7 and 0[illegible].

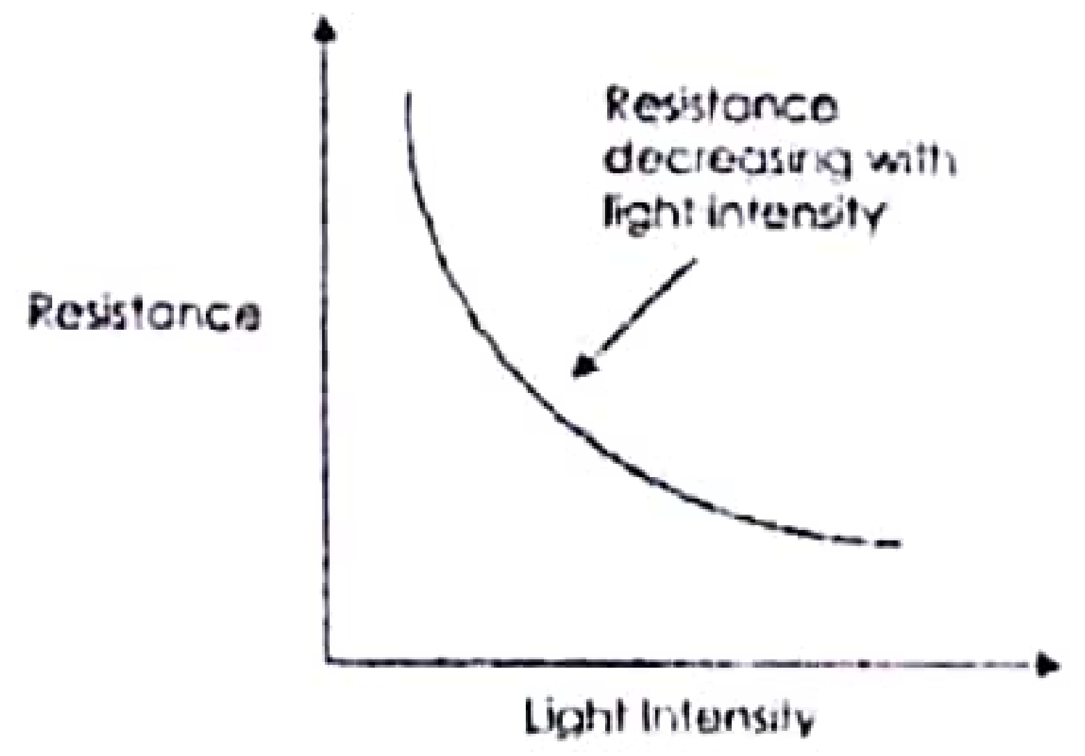
Advantages

LDR's are cheap and are readily available in many sizes and shapes. Practical LDRs are available in a variety of sizes and package styles, the most popular size having a face diameter of roughly 10 mm. They need very small power and voltage for its operation.

Disadvantages

Highly inaccurate with a response time of about tens or hundreds of milliseconds.

Variation in resistance with changing light intensity



Typical LDR resistance vs light intensity graph

The most common type of LDR has a resistance that falls with an increase in the light intensity falling upon the device (as shown in the image above). The resistance of an LDR may typically have the following resistances:

Daylight = 5000Ω Dark = 20000000Ω

You can therefore see that there is a large variation between these figures. If you plotted this variation on a graph you would get something similar to that shown by the graph shown above.

Types of light Dependent Resistors

Light dependent resistors are classified based on the materials used.

Intrinsic Photo Resistors

These resistors are pure semiconductor devices like silicon or germanium. When the light falls on the LDR, then the electrons get excited from the valence band to the conduction band and number of charge carriers increases.

Extrinsic Photo Resistors

These devices are doped with impurities and these impurities creates a new energy bands above the valence band. These bands are filled with electrons. Hence this decrease the band gap and small amount of energy is required in moving them. These resistors are mainly used for long wavelengths.

A **photoresistor** (or **light-dependent resistor, LDR,** or **photocell**) is a light-controlled variable resistor. The resistance of a photoresistor decreases with increasing incident light intensity; in other words, it exhibits photoconductivity. A photoresistor can be applied in light-sensitive detector circuits, and light- and dark-activated switching circuits.

A photoresistor is made of a high resistance semiconductor. In the dark, a photoresistor can have a resistance as high as several megohms (MΩ), while in the light, a photoresistor can have a resistance as low as a few hundred ohms. If incident light on a photoresistor exceeds a certain frequency, photons absorbed by the semiconductor give bound electrons enough energy to jump into the conduction band. The resulting free electrons (and their hole partners) conduct electricity, thereby lowering resistance. The resistance range and sensitivity of a photoresistor can substantially differ among dissimilar devices. Moreover, unique photoresistors may react substantially differently to photons within certain wavelength bands.

A photoelectric device can be either intrinsic or extrinsic. An intrinsic semiconductor has its own charge carriers and is not an efficient semiconductor, for example, silicon. In intrinsic devices the only available electrons are in the valence band, and hence the photon must have enough energy to excite the electron across the entire bandgap. Extrinsic devices have impurities, also called dopants, added whose ground state energy is closer to the conduction band; since the electrons do not have as far to jump, lower energy photons (that is, longer wavelengths and lower frequencies) are sufficient to trigger the device. If a sample of silicon has some of its atoms replaced by phosphorus atoms (impurities), there will be extra electrons available for conduction. This is an example of an extrinsic semiconductor.[1]

Three photoresistors with scale in mm

Photoresistors are less light-sensitive devices than photodiodes or phototransistors: the two latter components are true semiconductor devices, while a photoresistor is a passive component and does not have a PN-junction. The photoresistivity of any photoresistor may vary widely depending on ambient temperature, making them unsuitable for applications requiring precise measurement of or sensitivity to light.

Photoresistors also exhibit a certain degree of latency between exposure to light and the subsequent decrease in resistance, usually around 10 milliseconds. The lag time when going from lit to dark environments is even greater, often as long as one second. This property makes them unsuitable for sensing rapidly flashing lights, but is sometimes used to smooth the response of audio signal compression.[2]

Applications[edit]

The internal components of a photoelectric control for a typical American streetlight. The photoresistor is facing rightwards, and controls whether current flows through the heater which opens the main power contacts. At night, the heater cools, closing the power contacts, energizing the street light.

Photoresistors come in many types. Inexpensive cadmium sulphide cells can be found in many consumer items such as camera light meters, clock radios, alarm devices (as the detector for a light beam), nightlights, outdoor clocks, solar street lamps and solar road studs, etc.

Photoresistors can be placed in streetlights to control when the light is on. Ambient light falling on the photoresistor causes the streetlight to turn off. Thus energy is saved by ensuring the light is only on during hours of darkness.

They are also used in some dynamic compressors together with a small incandescent or neon lamp, or light-emitting diode to control gain reduction. A common usage of this application can be found in many guitar amplifiers that incorporate an onboard tremolo effect, as the oscillating light patterns control the level of signal running through the amp circuit..

The use of CdS and CdSe[3] photoresistors is severely restricted in Europe due to the RoHS ban on cadmium.

Lead sulphide (PbS) and indium antimonide (InSb) LDRs (light-dependent resistors) are used for the mid-infrared spectral region. Ge:Cu photoconductors are among the best far-infrared detectors available, and are used for infrared astronomy and infrared spectroscopy.

8.4.2 Photodiode and Phototransistor

A photodiode is a semiconductor diode which depends for its operation on the inner photoelectric effect. Let a p-n junction diode have its junction close to, and parallel with the surface (Fig. 8.26(b)). If the surface is irradiated by light of quantum energy $h\nu$ larger than the energy gap ε_g, hole-electron pairs will be generated. Under the influence of junction electric field, the holes will move to the p-region and the electrons to the n-region, resulting in a photocurrent I_{ph} (eqn. 8.4.4) flowing from n to p.

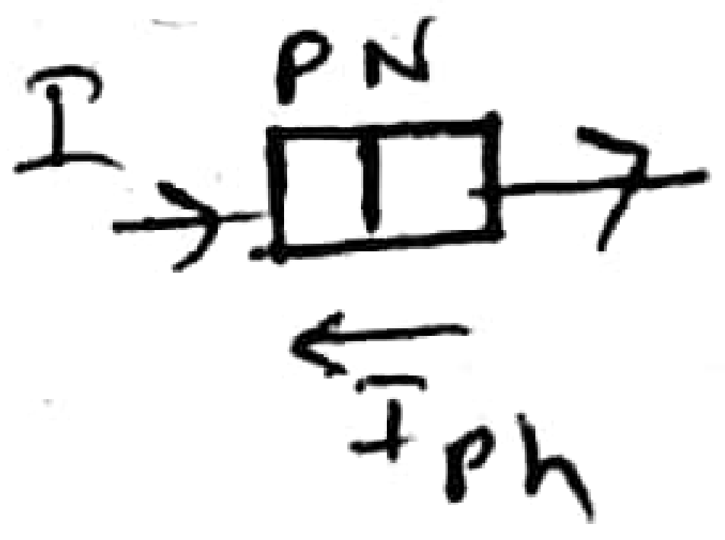
There are two ways of operating this diode :

1. The junction is biased in the reverse direction and the photocurrent is fully collected. The diode is then said to be operated in the *current mode* or *photoconductive mode.*
2. The junction electrodes are left open. The diode then biases itself in the forward direction, so that the net current is zero and an open-circuit voltage is developed (known as photovoltaic effect). The diode is then said to be operated in the *photovoltaic mode.*

Let the diode have a characteristics (Shockley eqn. (2.3.10))

$$I = I_0\left(\exp\frac{eV}{kT} - 1\right) \tag{8.4.5}$$

when kept in the dark, I_0 being the dark current. The characteristics for the illuminated diode will then be



$$I = I_0\left(\exp\frac{eV}{kT} - 1\right) - I_{ph} \tag{8.4.6}$$

If the diode is operated in the photoconductive mode (reversed-biased), then the device current is

$$I = -(I_0 + I_{ph}) \tag{8.4.7}$$

If the diode is operated in the photovoltaic mode (i.e., $I = 0$), the open-circuit voltage is

$$V_{oc} = \frac{kT}{e}\ln\left(1 + \frac{I_{ph}}{I_0}\right) \tag{8.4.8}$$

as can be seen by putting $I = 0$ in eqn. (8.4.6) and solving for V. For a good response one should keep the dark current I_0 of the diode small compared to photocurrent I_{ph}.

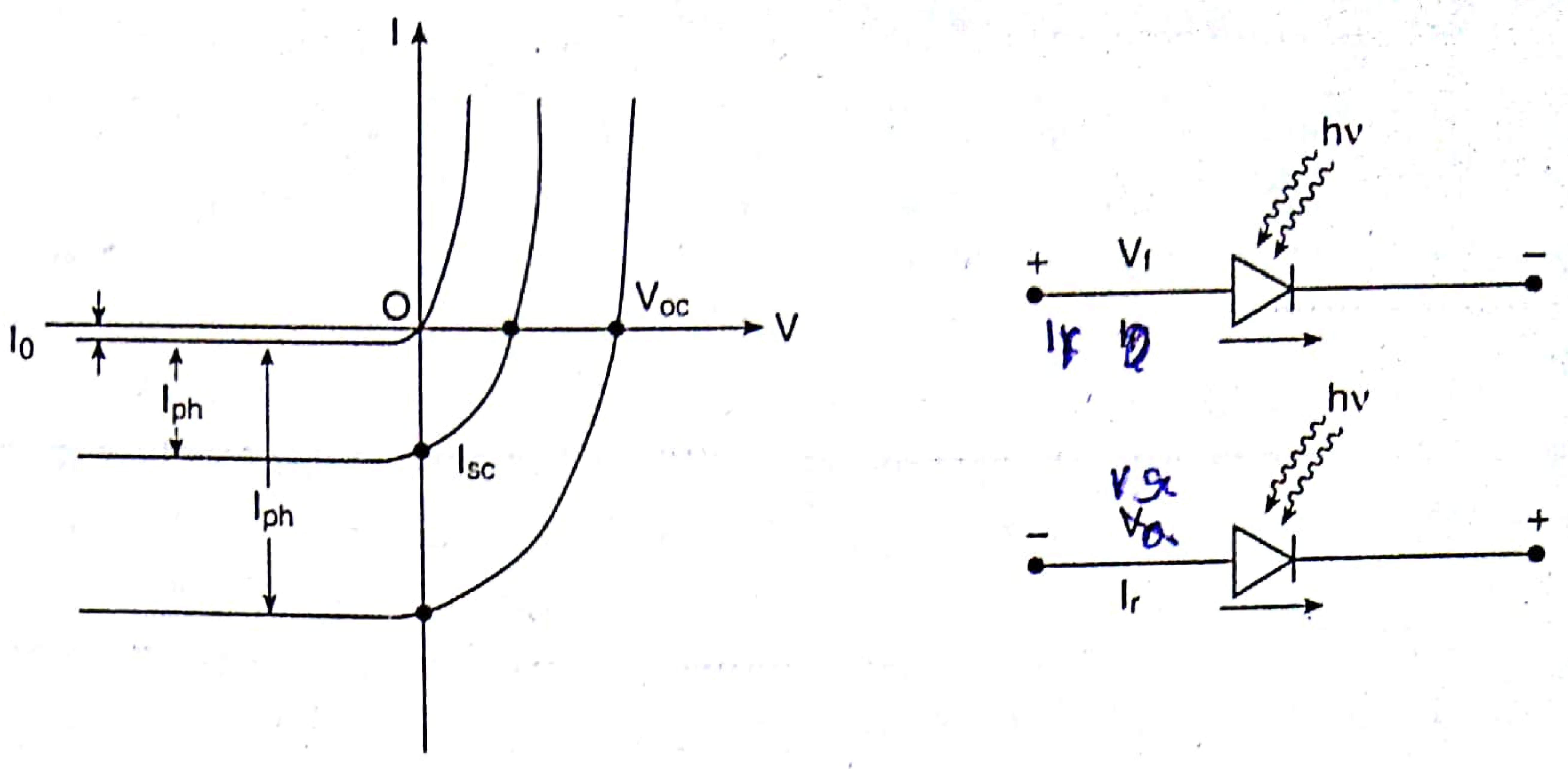
For very low light levels $I_{ph} \ll I_0$ and using $\log(1 + x) \approx x$ for small x,

$$V_{oc} \approx \frac{kT}{e}\frac{I_{ph}}{I_0} = I_{ph}R_0 \tag{8.4.9}$$

where $R_0 = kT/eI_0$ is the internal diode resistance for zero bias. The device then operates in the *linear* range. For higher light levels 1 may neglected in the parentheses of eqn. (8.4.8) and we get

$$V_{oc} \approx \frac{kT}{e}\ln\left(\frac{I_{ph}}{I_0}\right) \tag{8.4.10}$$

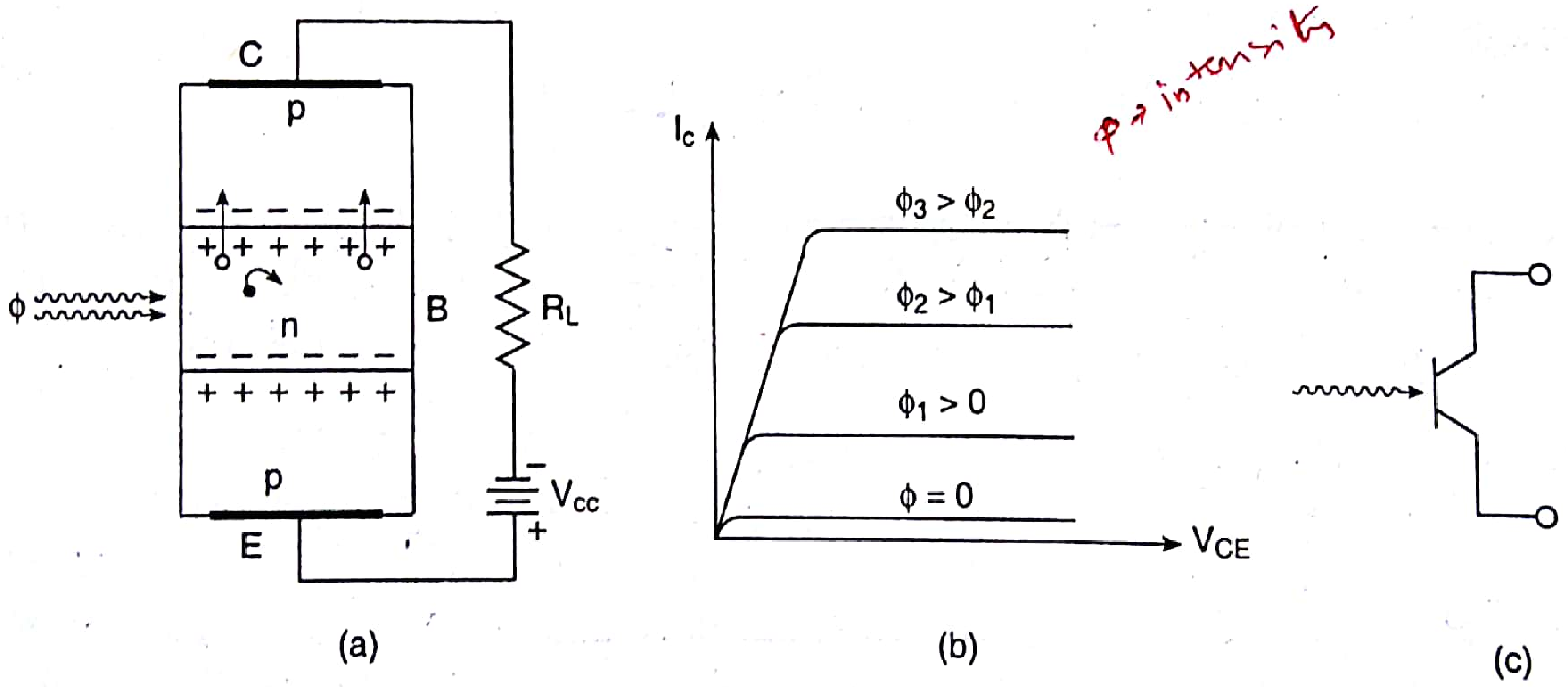
In this case the device response is said to be *logarithmic*. However, the relationship (8.4.8) between v_{oc} and I_{ph} is non-linear in general and hence V_{oc} is not used for light-intensity measurement. The characteristics and symbol of a photodiode for different illumination is shown in Fig. 8.27.



(a) (b)

Fig. 8.27 (a) Photodiode characteristics for different illumination, (b) Symbol

A bipolar *phototransistor* is similar in construction to a conventional bipolar transistor, except that the top surface has a window or lens so that its base region can be exposed to radiation. The photocurrent is now the base current, which is amplified by the normal transistor action to give a collector current h_{fe} times as large. For maximum sensitivity the phototransistor is operated with open base, as any base connection would divert some photocurrent and hence it acts as a two-terminal device (Fig. 8.28(a)). As usual, the emitter junction is forward-biased and the collector junction is reversed-biased.



(a) (b) (c)

Fig. 8.28 (a) Structure and connection of a floating-base phototransistor, (b) Output characteristics of a phototransistor, (c) Symbol

The output characteristics of a phototransistor are shown in Fig. 8.28(b). They are similar to those of a conventional transistor connected in a *CE*-circuit, but each curve corresponds to a particular level of irradiance (luminous flux) and not a particular value of base current. Photons incident on the base bring about the generation of electron-hole pairs which diffuse towards the collector junction where they are separated in much the same way as they are in a photo diode. The electric field at the collector urges the holes (open circles) to move from the base to the collector where they augment the base current. The electrons (solid circles), in contrast, remain in the base and raise the forward voltage across the emitter junction—a factor which stimulates the injection of holes in this junction, thereby building up the collector current.

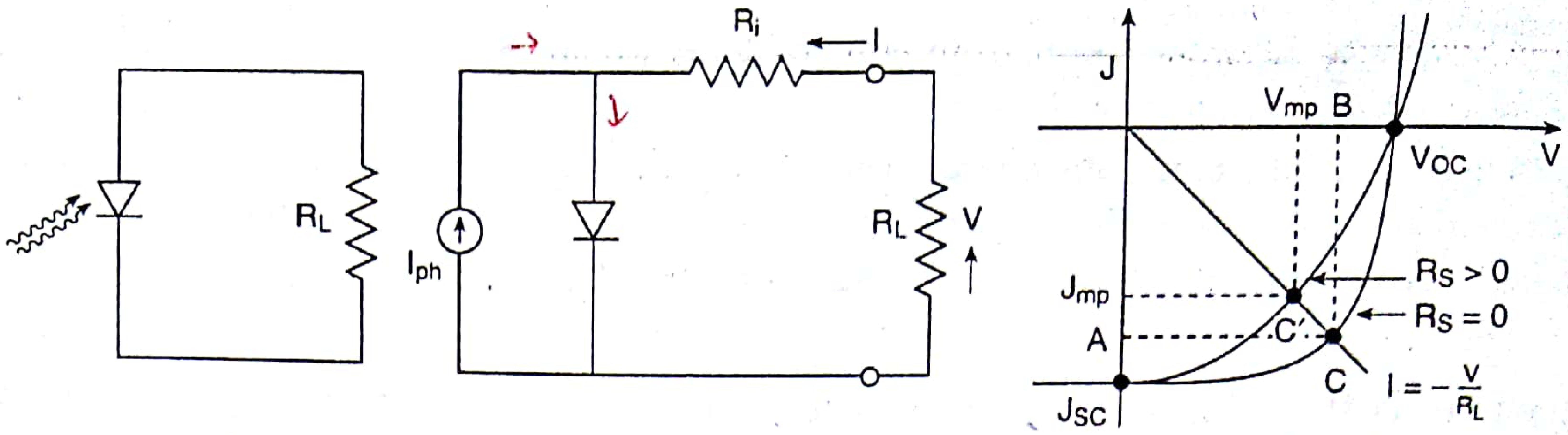
The bipolar design is not the only member of the phototransistor family. Another member is the *compound phototransistor*. This device is essentially a combination of a phototransistor and a conventional BJT in darlington mode (section 5.3.4) having a net current gain $\beta = \beta_1\beta_2$. As a result, the integral sensitivity of a compound phototransistor is tens of times the figure assured by a conventional device and thousands of times the figure obtained with photodiodes.

Photo FETs are also available and have advantages over ordinary phototransistors of greater gain and bandwidth and easily adjusted sensitivity. Normally, in a JFET the gate is reverse biased and no gate current flows. When illuminated, through a lens for focussing light onto the gate junction, a photocurrent flows in the reverse biased gate-channel diode, producing a voltage across a gate resistor R_G (see, for example, Fig. 4.17(d)). Variation of the gate resistor controls the sensitivity over a range of $\sim 10^6$. The gate current is delivered by a current generator, so the gate voltage will be proportional to the gate resistor. By using photo FET as a source follower the output will be a linear function of light intensity. The current gain can be several hundred times that of a phototransistor.

8.4.3 Solar Cell

The most important use of photovoltaic effect today is for direct conversion of solar energy to electricity. Diodes made for that specific purpose are called *solar cell* or *solar battery*. It is seen that in the fourth quadrant of the $I - V$ characteristics of a photodiode (Fig. 8.27(a)) the power is negative (positive voltage and negative current). This means that the device will deliver power from the junction instead of absorbing it from the power supply. Hence they are appropriately called cells. Only Si cells are available commercially today, though GaAs, because of its higher ε_g, yields higher voltage and efficiency. However, the high price and difficult technology of GaAs makes such cells still uneconomic today.

To be used as an energy source, the solar cell is connected to a load R_L as in Fig. 8.29(a) and (b). The load characteristic, or load line is $I = V/R_L$ (Fig. 8.29(c)). It is seen that to get maximum current the output voltage of the cell will be 0 (marked by A) and will deliver no power. Similarly, to get maximum voltage V_{oc} from the cell the output current will be zero (marked by B), again delivering no power. Hence to get maximum output power out of the solar cell the operating point should be somewhere at C which we shall now calculate.



(a) (b) (c)

Fig. 8.29 The solar cell, (a) circuit will load resistance R_L, (b) The equivalent circuit, (c) The fourth quadrant, in which the cell operates, and the load line

We shart with eqn. (8.4.6) but change over to current density, because it is important to know the power generated per sq. cm. of irradiated surface. Hence

$$J = J_0\left(\exp\frac{eV}{kT} - 1\right) - J_{ph} \tag{8.4.11}$$

The open-circuit voltage is (eqn. 8.4.8)

$$V_{oc} = \frac{kT}{e}\ln\left(1 + \frac{J_{ph}}{J_0}\right) \tag{8.4.12}$$

The power output of the device is

$$P = JV = \left[J_0\left(\exp\frac{eV}{kT} - 1\right) - J_{ph}\right]V \tag{8.4.13}$$

This power will be maximum when $dP/dV = 0$. This yields

$$J_0\left(\exp\frac{eV}{kT} - 1\right) - J_{ph} + V\,J_0\left(\frac{e}{kT}\right)\cdot\exp\frac{eV}{kT} = 0$$

$$\text{or}\quad \left(1 + \frac{eV}{kT}\right)\exp\left(\frac{eV}{kT}\right) = 1 + \frac{J_{ph}}{J_0} = \exp\left(\frac{eV_{oc}}{kT}\right) \tag{8.4.14}$$

with the help of eqn. (8.4.12). Eqn. (8.4.14) can not be solved analytically. The solution is normally obtained by successive approximation i.e., we choose a value of V between $0V$ and V_{oc} volt (which is known from eqn. (8.4.12). We now put this value of V in the left hand side of eqn. (8.4.14) and compare with the right hand side. If they are not equal, then we choose another value for V, slightly higher or lower than the earlier one, and compare again. Suppose that the implicit equation (8.4.14) has been solved in this way and the solution is found to be $V = V_{mp}$. We now substitute $V = V_{mp}$ into eqn. (8.4.11) and find the corresponding current for the maximum power transfer J_{mp} :

$$J_{mp} = J_0\exp\frac{eV_{mp}}{kT} - (J_0 + J_{ph}) \tag{8.4.15}$$

Using the value of $\exp\left(\frac{eV_{mp}}{kT}\right)$ from eqn. (8.4.14) we get

$$\begin{aligned} J_{mp} &= \frac{J_0 + J_{ph}}{1 + eV_{mp}/kT} - (J_0 + J_{ph}) \\ &= -\frac{(J_0 + J_{ph})\, eV_{mp}/kT}{1 + eV_{mp}/kT} \end{aligned}$$

Hence, the maximum obtainable power is

$$P_{\max} = J_{mp}V_{mp} = \frac{eV_{mp}/kT}{1 + eV_{mp}/kT} V_{mp}\,(J_0 + J_{ph}) \tag{8.4.16}$$

The area $J_{mp}V_{mp}$ in Fig. 8.29(c) is called the maximum power rectangle. Obviously, it is less than $J_{sc}V_{oc}$ product. The ratio

$$\text{Fill factor (FF)} \quad \xi = \frac{J_{mp}V_{mp}}{J_{sc}V_{oc}} \longrightarrow \text{figure of merit} \tag{8.4.17}$$

is called the *fill factor*, and is a figure of merit for solar cell design. The optimum load impedance is

$$R_{mp} = \frac{V_{mp}}{J_{mp}} = \frac{1 + eV_{mp}/kT}{e(J_0 + J_{ph})/kT} \tag{8.4.18}$$

Efficiency of a Solar Cell

Optimum efficiency of a solar energy converter is

$$\eta_{\max} = \frac{\text{Power output}}{\text{Power input}} \tag{8.4.19}$$

Since the power density output is given by eqn. (8.4.16) and the power density input is $N_{ph}\rho_{av}$, where N_{ph} is the total number of photons in the spectrum and ρ_{av} is the average density of photons, the optimum efficiency of the energy converter is

$$\eta_{\max} = \frac{eV_{mp}/kT}{1 + eV_{mp}/kT} \cdot \frac{V_{mp}(J_{ph} + J_0)}{N_{ph}\rho_{av}} \tag{8.4.20}$$

V_{mp} increases with increasing gap width of the semiconductor and J_{ph} decreases with increasing gap width. As a result, $\eta_{\max}$ first increases with increasing gap width, goes through a maximum at a gap width $\varepsilon_g \sim 1.5$ eV and decreases for higher gap widths as shown in Fig. 8.30. For the same reason, R_{mp} increases steadily with ε_g.

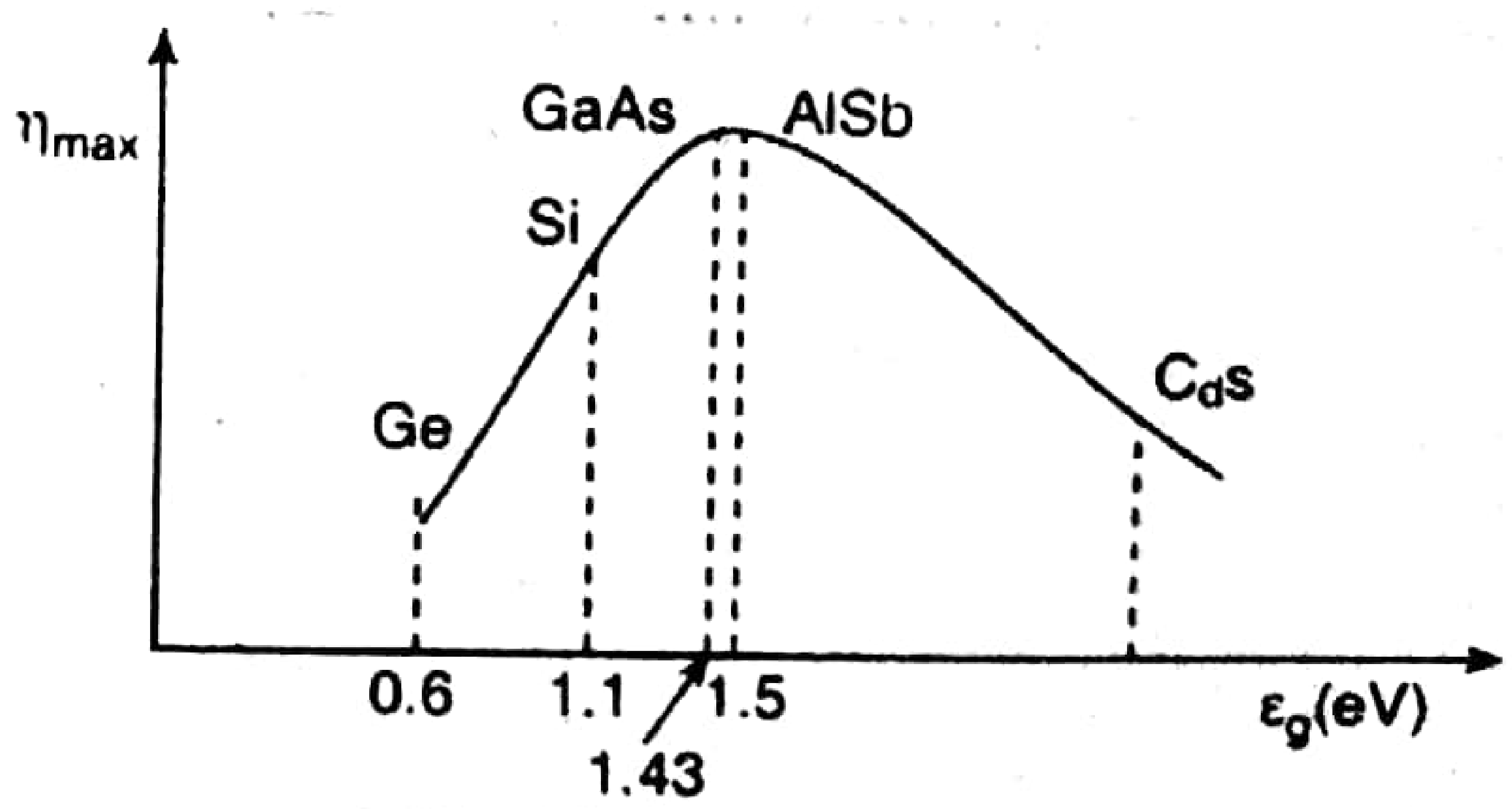


Fig. 8.30 Efficiency versus energy gap

If the series resistance R_s (Fig. 8.29(b)) is taken into account, J_{ph} and V_{oc} do not change. but the $(J - V)$ characteristic for $R_s > 0$ will lie below the characteristic for

$R_s = 0$. Consequently, the maximum power rectangle decreases in area. The series resistance thus reduces the efficiency of the device and should be kept as small as possible.

The available sea-level solar energy at noon of a cloudless day is about 70–80 mW cm^{-2}. The best commercially available cells today are made in single crystal Si, have efficiencies around 15%, $V_{oc} \sim 0.6$ V and areas upto 40 cm^2. They are arranged in large area arrays and connected in series (to increase voltage) and parallel (to increase current) to obtain useful load voltages and currents. This makes solar cells a comparatively expensive energy source, limited by economic considerations to special uses for which no other source is available, such as in space, or in inaccessible places on earth. The cell arrays (also called modules) are used for continuous battery recharge as long as the sun shines and using the battery during night or cloudy days.

Present day energy research aims at reducing the cost of a cell by shifting from single to polycrystalline Si (with relatively large crystallites) or by using cheap plastic lenses to concentrate sunlight on a small-area high quality cell.

Polycrystalline (also called amorphous Si, written as a–Si) silicon films are produced by the glow discharge decomposition of silane gas (SiH_4). The a–Si material produced by this process is, in fact, an amorphous silicon-hydrogen alloy with fairly large concentration of hydrogen. The properties of a–Si : H are quite different from those of crystalline material. The energy gap ε_g is close to 1.7 eV for a–Si : H. It is a direct gap semiconductor and has a much larger absorption coefficient of light compared to crystalline Si. This is especially important in photovoltaic and optoelectronic applications.

Very high efficiencies have already been achieved for a a–Si solar cells, including large area ($\sim 60 \times 120$ cm^2), mass-produced cells ($\sim$ 10% for one-square-foot cells). The obtained values of the short-circuit current are $\sim$ 15 mA/cm^2, and typical $V_{oc} \sim 900$ to 950 mV, with fill factors $\xi \sim 0.7$ to 0.75. Maximum efficiencies reach 13% to 14%. Further improvement in this technology may be expected if high-quality a–Si : Ge : H alloys with narrower energy gaps are developed. However, intensive research work is under way globally to reduce the cost of solar-cell modules per peak watt of produced electricity.

If may be remarked that Nature (plants) is somehow more intelligent than man in the sense that they can convert solar energy with an efficiency of 40% which human brains cannot even dream of even today.

8.4.4 Light-Emitting Diode (LED)

In solar cells and photodetectors illumination by light causes an electric current flow in a device. An opposite effect, light emission caused by electric current flowing through the sample, is called *electroluminiscence*, and is known for hundred years. Electroluminiscence may be caused by various methods. We shall concentrate only on the most widely used electroluminiscence excitation technique, known as *injection* *electroluminiscence*, which provides an important application of junction diodes as generators of light. Light emission results from the radiative recombination (i.e., direct electron-hole recombination with photon emission) of electrons injected into the p-region and holes injected into the n-region of a $p-n$ junction under a forward bias. Such diodes are called *light-emitting diodes* (LED).

In a semiconductor with indirect band gap, such as Si or Ge, the vast majority of the recombination events occur via *recombination levels* within the band gap, and the resulting energy loss by recombining electrons is usually given up to the lattice as heat rather than by the emission of light. On the other hand, radiative recombination is much more probable in direct-gap semiconductors such as GaAs, InP, GaAs$_{1-x}P_x$ (for x less than 0.45), etc.

GaAs LEDs cannot be used for displays since the wavelength is beyond the visible range ($\lambda = 8,800\text{Å}$). But the compound semiconductor GaAs$_x$ P$_{1-x}$ (gallium arsenide phosphide) has a band gap which depends on x, the arsenic percentage. ε_g varies from 1.43 eV for GaAs ($x = 1$) to 2.26 eV for pure GaP ($x = 0$) as is shown in Fig. 8.31. The band gap of GaAs$_{1-x}$ P$_x$ varies almost linearly with x until $x = 0.45$ is reached, and electron-hole recombination is direct over this range. For this composition the band gap is direct, since the Γ minimum (at $\vec{k} = 0$) is the lowest part of the conduction band. This results in efficient radiative recombination, and the emitted photons ($\sim 1.9\,\text{eV}$) are in the red portion (eqn. 8.4.2) of the spectrum. This composition is used for red LEDs, widely used in calculators and other displays.

For GaAs$_{1-x}$ P$_x$ with P concentrations above $x = 0.45$, the band gap is due to the indrect X minimum (called the first Brillouin Zone). Radiative recombination in such indirect materials is generally unlikely, because electrons in the conduction band have different momentum from holes in the valence band. Interestingly, however, indirect GaAs$_{1-x}$ P$_x$ (including $x = 1$) doped with nitrogen can be used in LEDs with light emission in the yellow to green portions of the spectrum. The output light intensity is determined by the current level and maintains almost a linear relation.

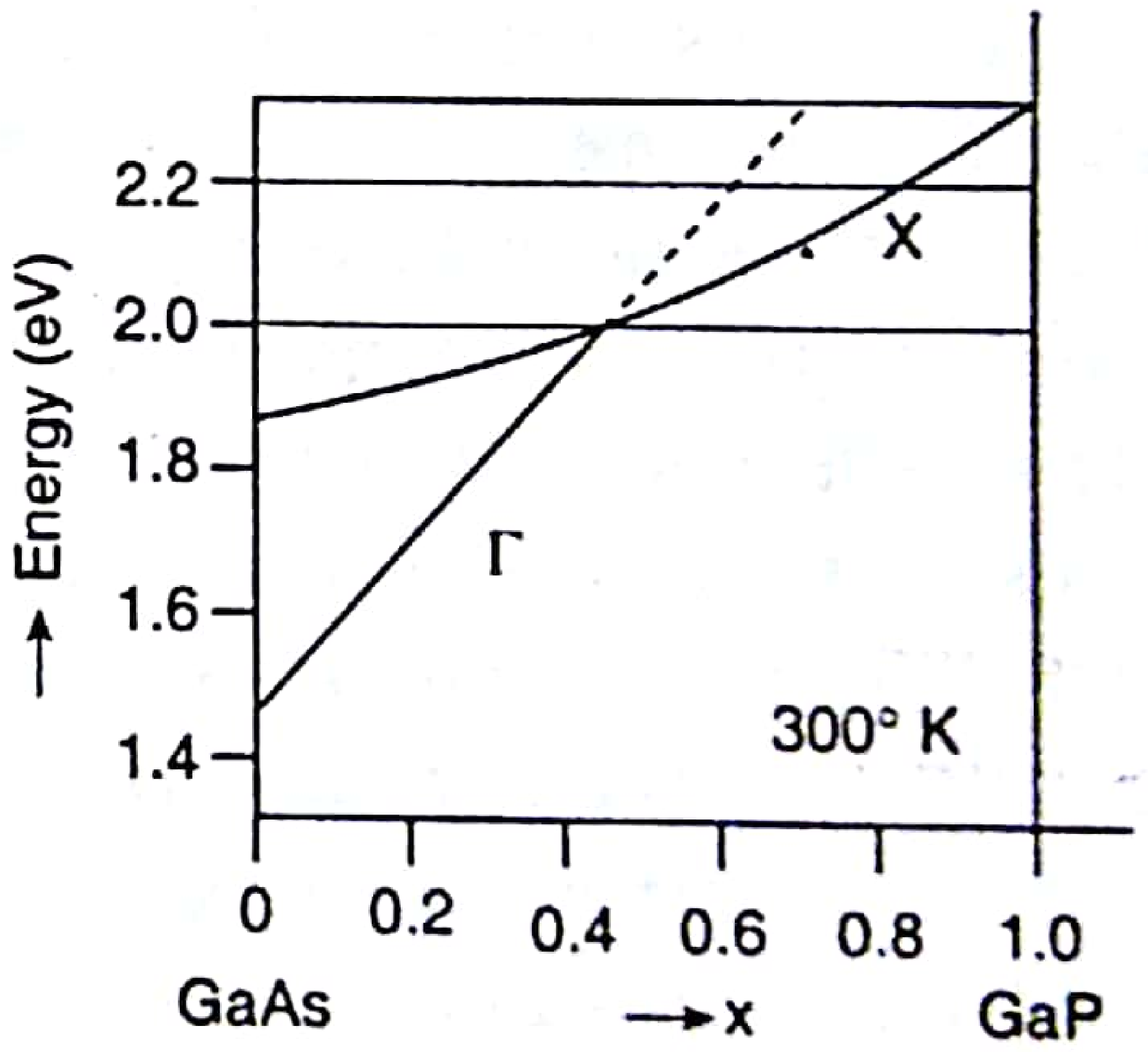


Fig. 8.31 Energy gap as a function of alloy composition for GaAs$_{1-x}$ P$_x$

LEDs are used widely in electronic and optoelectronic circuits. Parallel connection of many LEDs of small area may be used to display numbers and letters, as is done in modern pocket calculators, digital watches, etc. Infrared LEDs are useful in opto-isolators and is a potential source for fibre optic communication.

In many applications light from a LED need not be visible to the eye. Infrared emitters such as GaAs (0.9μm), I_nP, and mixed alloys are particularly well suited to optical communication systems. It is possible to encapsule a GaAs LED and Si $p-i-n$ detector diode (which is very sensitive at 0.9μm) in close proximity on the same header, forming an *optical coupler*, also called an *optoelectronic coupler* (abbreviated as opto coupler), a photon coupled isolator, and opto-isolater.

8.4.5 Optoelectronic Coupler

One of the most useful developments in the optoelectronic field is the photon coupled isolator. This consists basically of a LED (or laser) emitter and a photo dectector, usually a phototransistor, with close optical coupling but electrical isolation, as shown in Fig. 8.32. This integrated device is used to replace relays in situations where electrical isolation between the input and output circuits is required.

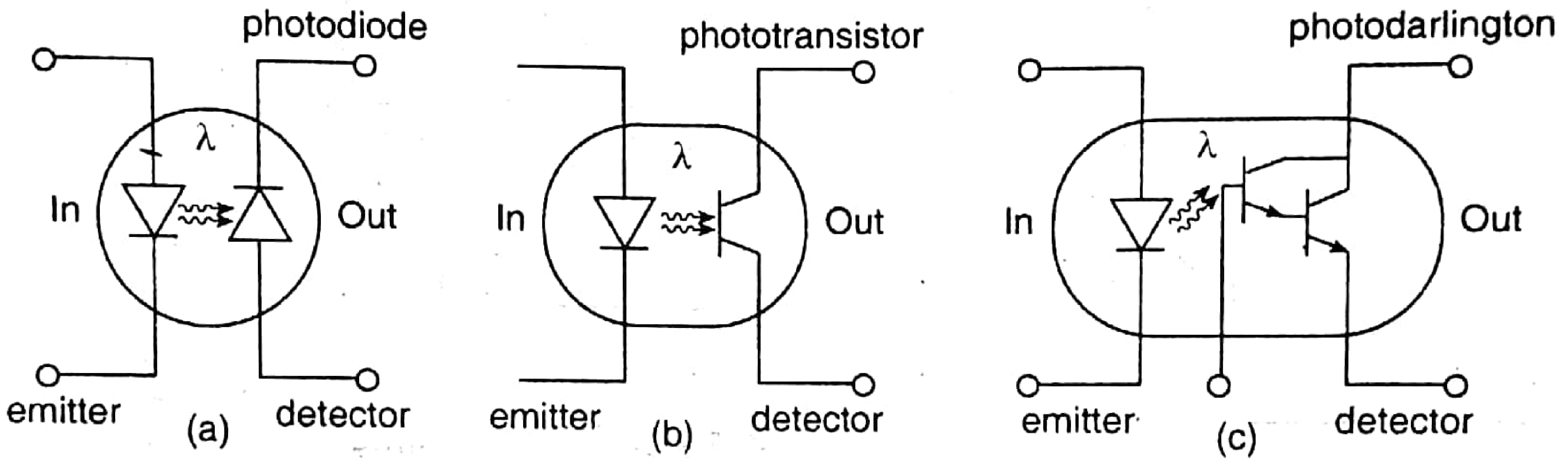


Fig. 8.32 Basic optocouplers, (a) with photodiode, (b) with phototransistor, (c) wioth photodarlington

Opto-coupler has two outstanding properties : (i) electrical isolation upto very high voltages, and (ii) the unilateral nature of the signal transfer. In case (i), its property is similar to a transformer, but it has the advantage of operating down to zero frequency. In case (ii), the unilateral signal transfer arises since the photodetector does not emit, so there can be no return signal. Strictly speaking, there will be a small capacity between emitter and receiver (usually < 1pF in practical devices) which does provide a return path, but in critical applications this can be eliminated by a grounded screen. Reduction by physical separation reduces the transfer efficiency, unless an efficient light-pipe (or optical guide) is used. The current transfer efficiency is the ratio of the photocurrent in the detector to the input current supplied to the light emitter. This ratio depends on the type of the detector, being $\sim 10^{-3}$ for a photodiode, 0.2 to 1 for a phototransistor, and 5 or more for a photodarlington.

Optocouplers find a wide range of applications, such as :

(i) Transfer of signals between circuits at widely different potentials.

(ii) Elimination of common ground bus (i.e., electrically conducting wire or a group of wires) between circuits, to remove ground loops and common-mode effects.

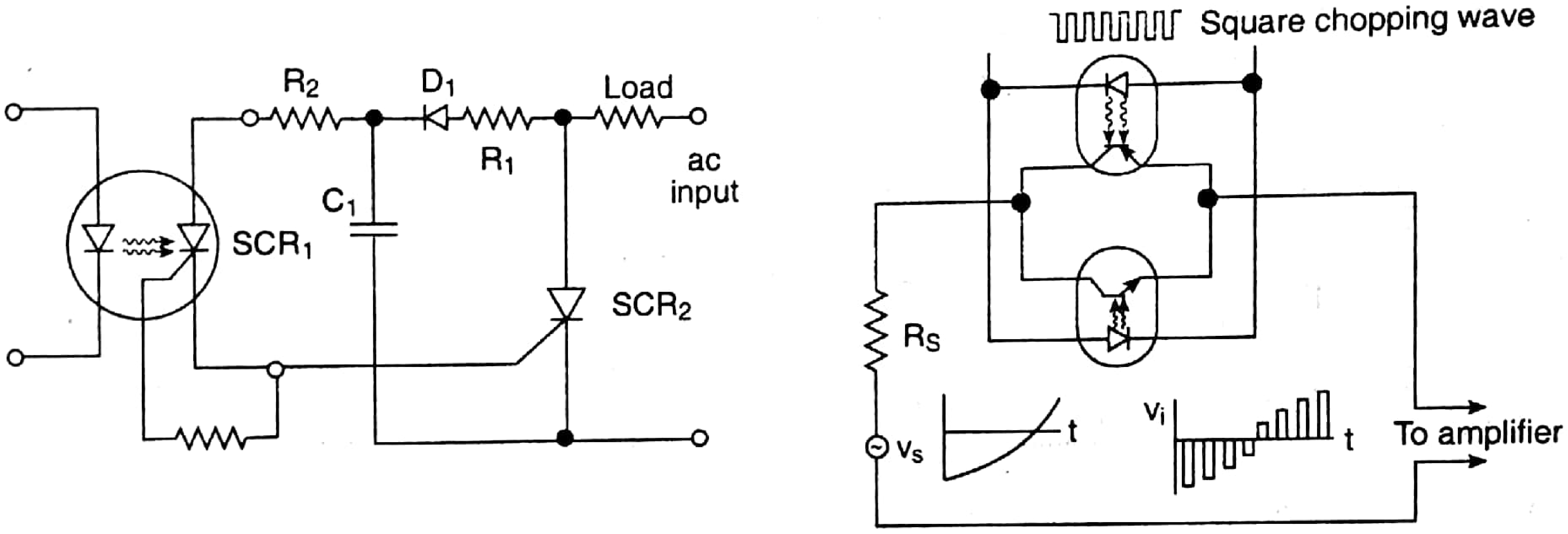
(iii) Unilateral transfer of signals to avoid reaction, as in coupling an oscillator to a variable load.

(iv) Driving multiple circuits from one source with no interaction between them.

(v) Provision of isolated current source using reverse biased receiver (detector).

The attractions of optical coupling has led to the development of many variations on the basic coupler. These include receivers with SCR, triac, Schmitt trigger, and logic gate output. Let us illustrate with two applications.

Fig. 8.33(a) shows a photo-SCR coupler used to trigger a higher rating SCR. Here C_1 is charged from ac input via R_1 and D_1, to provide a dc supply for SCR_1. When SCR_1 is triggered via the photon coupling, C_1 discharges into the gate of SCR_2 to fire it (Section 8.2.2). R_2 limits the current through SCR_1, and C_1 limits the dv/dt on SCR_1.



(a) (b)

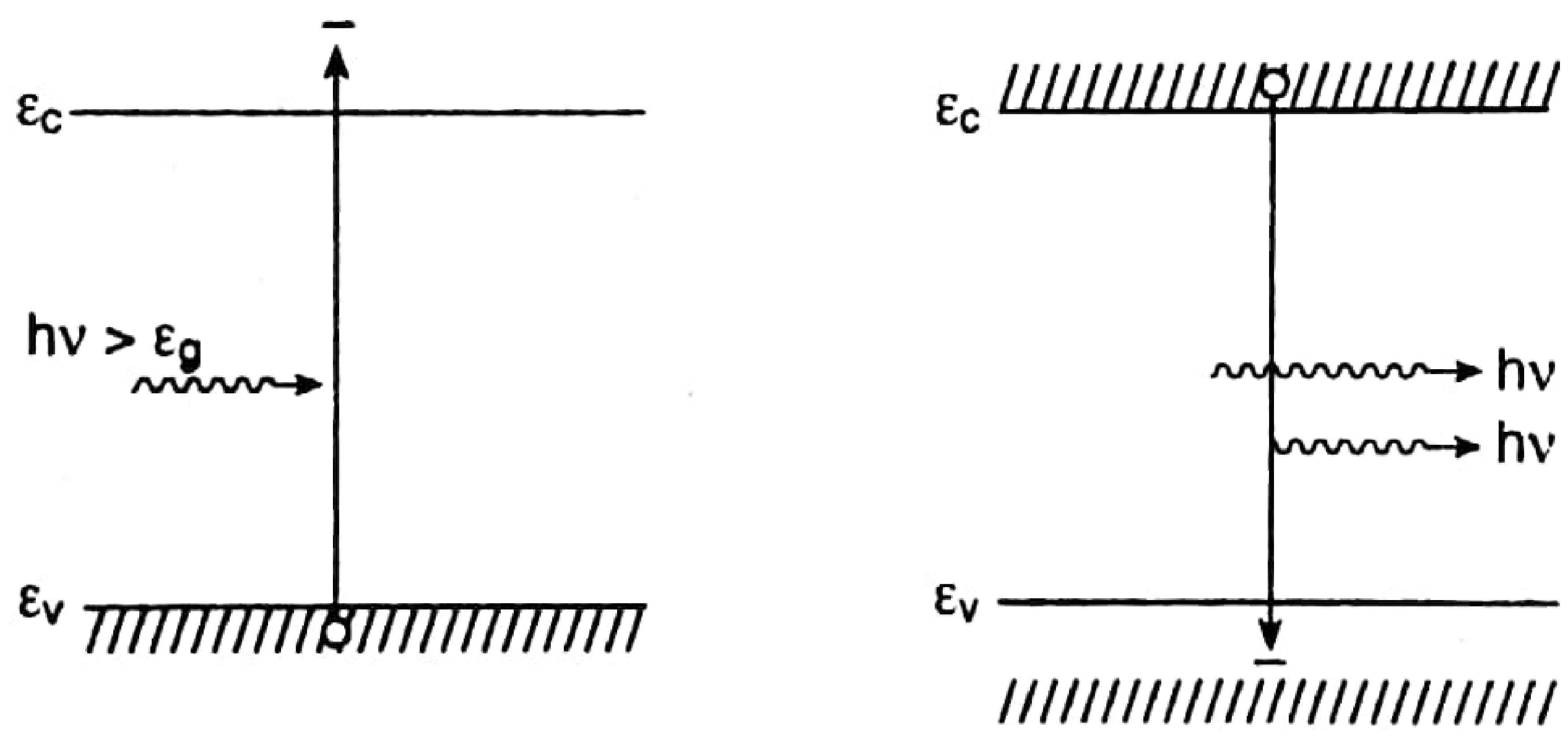
Fig. 8.33 (a) Photo–SCR trigger circuit, (b) Two optoisolators to obtain signal-chopping circuit

Fig. 8.33(b) is a chopper circuit, whose purpose is to chop a slowly varying positive or negative input signal provided by the signal source and turn it into an ac signal (which can be amplified more easily than the dc by the following amplifier). A square chopping wave is applied to both the LEDs of the two optocouplers causing them to emit corresponding light pulses. The phototransistors are consequently switched into a high-conduction state, connecting the input signal to the output in turns. Two opto-couplers have been used to chop both positive and negative input signals. Such chopping, if done by relays, severely restricts the frequency of operation and introduces noise into the output due to jitter of the relay contacts. If chopping is done by convensional transistors the capacitive coupling inside the transistor causes spikes, originated by the square chopping wave, to appear in the output as unwanted noise. In opto isolators the coupling capacitance is insignificant (~ 0.02pF).

8.4.6 The Junction Laser

Light-emitting diodes (LEDs) emits *spontaneous* or noncoherent radiation generated by the spontaneous recombination of electrons and holes injected across the junction. With no special geometrical structure and operating conditions intented to prevent optical losses such radiation will tend to have a relatively wide spectral range of a few hundred angstroms around the value corresponding to ε_g and it will not be really monochromatic. Also the phase of the emitted photons will be random, i.e., with no relations between the phases of the electromagnetic waves constituting each photon.

LASER (an abbreviation for Light Amplification by Stimulated Emission of Radiation) is a device which produces coherent radiation (all the waves having the same phase relationship). The possibility of lasing comes from the quantum–mechanical principle, (originally conceived by Einstein) proved by Dirac, which states that when a photon interacts with an electron, it is equally probable that (i) the photon will be absorbed and the electron will become excited, or (ii) if the electron is already excited, the emission of a second photon will be *stimulated* with the electron dropping from its excited state to a low-energy one, as shown in Fig. 8.34. This second photon has the same frequency ν, phase, polarization, and direction of propagation as the first. Thus, the original photon can be *amplified.*

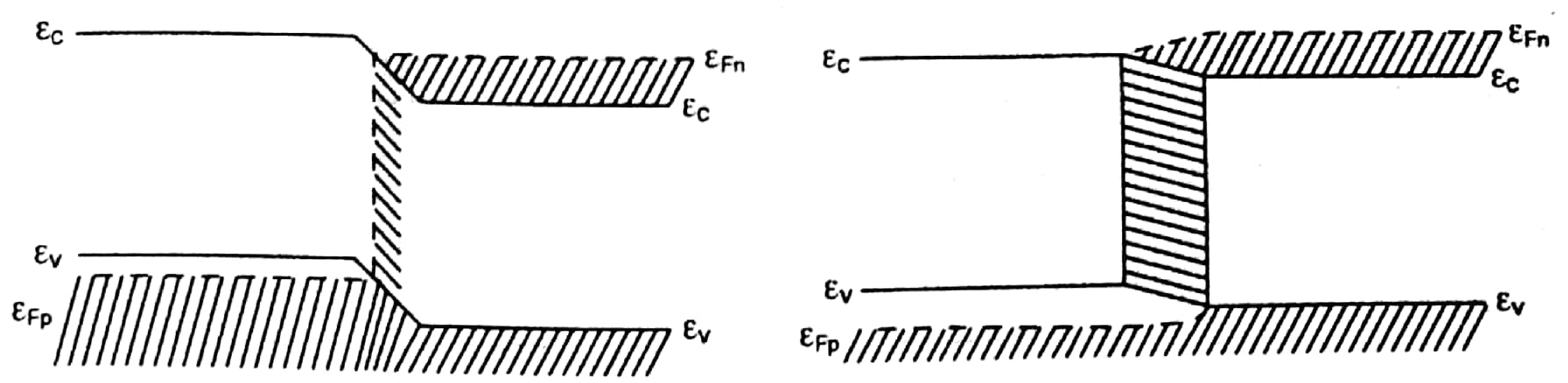


(a) (b)

Fig. 8.34 Interaction between a photon and a semiconductor (shaded portions represent states occupied by electrons). (a) Photon is absorbed and an electron is created—no population inversion existed, (b) Population inversion exists — the original photon stimulates the emission of a second one

The question as to whether the original photon will be amplified or absorbed in a semiconductor (or for that matter in any lasing material) depends on whether most of the electrons are in excited states or in low-energy states. The first situation is called *population inversion* and cannot normally occur unless special means are used to *pump* (or raise) the electrons to their excited states before lasing starts.

Population inversion is achieved near a *pn* junction by the use of high doping densities (so that they become degenerate) and forward current. It a bias (and thus the current) is large enough, the electrons and holes are injected into and across the transition region in considerable concentrations. This situation is similar to that of a tunnel diode (Section 8.1.2). As a result, the region around the junction is far from depleted of carriers. This region contains a large concentration of electrons within the conduction band and a large concentration of holes within the valence band. If these population densities are high enough, a condition of population inversion results, and the region around the junction over which it occurs is known as *inversion region.* The width of the inversion region depends on the forward bias (or current) as can be seen from Fig. 8.35. It should be kept in mind that the meaning of the term "inversion region" has a different meaning than that used in reference to MOS transistors (Ch. 4).

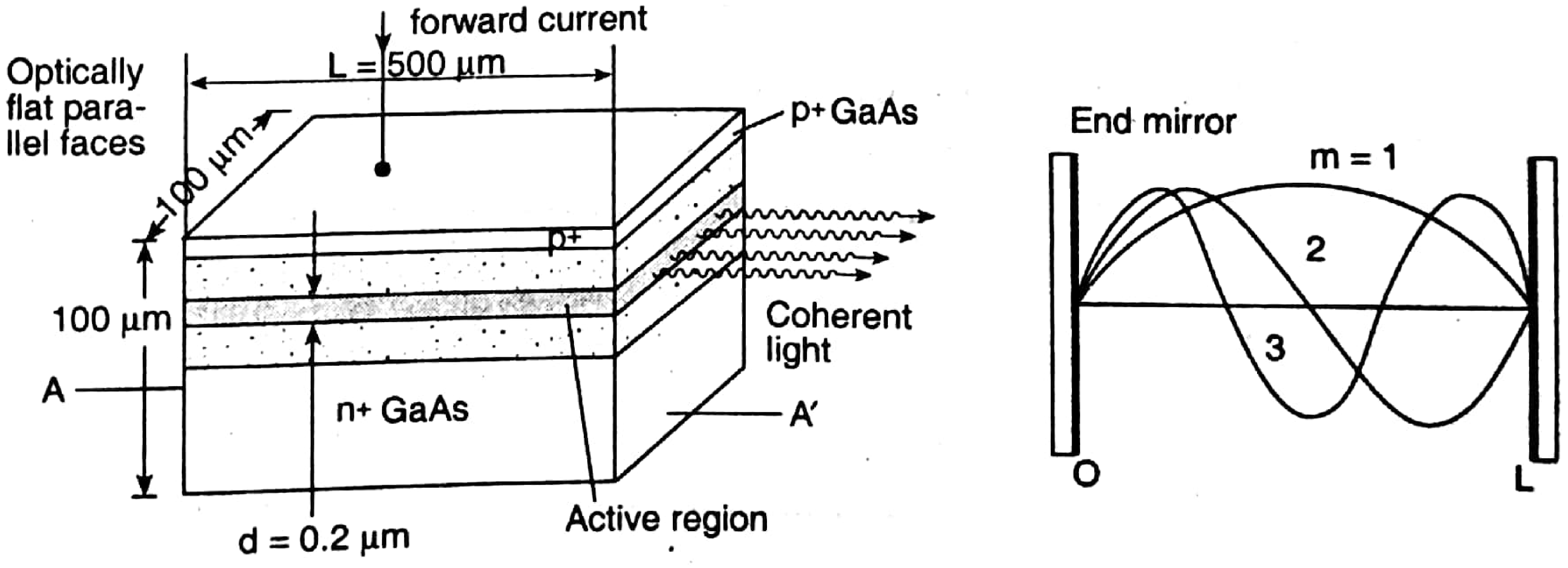


(a) (b)

Fig. 8.35 Band diagram of a pn-junction laser under forward bias. The cross-hatched portions indicate the inversion regions at the junction, (a) Moderate forward bias, (b) Heavy forward bias

A schematic diagram of a junction laser (it is also often called an injection laser due to the fact that the population inversion is achieved electrically, and not optically as in a ruby laser, by the injection of carriers in a forward-biased diode) is shown in Fig. 8.36. Initially, at the onset of a forward bias, some of the injected electrons will start to recombine spontaneously. This is alsolutely necessary to start the lasing action. These sponteneously emited photons will then stimulate the emission of more photons, reach the device wall, and then are reflected back internally into the junction plane by its mirror-like crystal surface. They now pass again through the region of population inversion stimulating more photons, all coherent with them, and reach the opposite wall. Some of them are again reflected and, in turn, stimulate a stronger and stronger coherent light emission.

By a situable choice of the directions of the crystal axes, the two opposing walls ($A-A'$) in Fig. 8.36(a) can be cleaved (cut and polished) so that the ends are extremely flat and parallel. When the light strikes those walls from the inside, about 30% of it is reflected back because of the change in the refractive index. This is normally enough to overcome the internal losses due mainly to (i) absorption, (ii) transmission, and (iii) diffraction. If necessary, the ends may be coated with a highly reflecting material, such as Al or Ag, producing a *resonant cavity*, in which light intensity can build up by



(a) (b)

Fig. 8.36 (a) Junction laser structure. The dotted portion is included for double heterostructure $Al_x\,Ga_{1-x}\,As/GaAs$ laser; for basic GaAs junction laser these portions may be omitted, (b) Resonant modes within a laser cavity multiple reflection (Fig. 8.36(b)). One of the end mirrors is inadvarently made partially transmitting so that a fraction of the light will "leak out" of the resonant system. This transmitted light is the output of the laser. The arrangement of parallel plates providing multiple internal reflections is similar to that used in the Fabry-Perot interferometer and the resonant cavity is called Fabry-Perot cavity. As Fig. 8.36(b) indicates, light of a particular frequency can be reflected back and forth within the resonant cavity in a coherent manner if the length of the cavity (for stimulated emission) is

$$L = \frac{m\lambda}{2\mu} \tag{8.4.21}$$

where m is an integer and μ is the refractive index of the active region.

The main difficulty of this basic laser structure is the high current densities needed to pump it up to lasing threshold (40 to 100 kA/cm^2 at room temperature but only 5 kA/cm^2 at 77°K). Since the area of cross-section of lasing material is typically $\sim 10^{-6}$ cm^2, the forward current needed for lasing action is $\sim$ 100 mA. However, this is supposed to be very high current for laser diodes.

New technologies have been developed now a days, most popular among them are heterojunction diodes, such as $\mathrm{Al}_x\,\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ and $\mathrm{In}_x\mathrm{Ga}_{1-x}\,\mathrm{As}_y\cdot\mathrm{P}_{1-y}/\mathrm{In\,P}$, so that much less current is needed for the laser emission.

Lasers are widely used in many fields, such as high accuracy distance measurements, 3-D lensless photography (holo-graphy), bio-engineering for sophisticated surgery, for cutting metals and drilling extremely small holes, and of course in optical communications. It should be mentioned that war-mongers may utilize lasers in an extremely bad way.

We have earlier mentioned that the population inversion in junction laser is achieved by carrier injection. To understand how this can be accomplished, consider a $p-n$ junction of a direct band gap material having degenerate p and n regions (Fig. 8.35). Let ε_c be the energy of the electrons in the conduction band and ε_v the energy of holes in the valence band. The probabilities fc and fv that the energy states ε_c and ε_v are occupied are

$$f_c = \left[1 + \exp\left(\frac{\varepsilon_c - \varepsilon_{Fn}}{kT}\right)\right]^{-1} \tag{8.4.22}$$

$$f_v = \left[1 + \exp\left(\frac{\varepsilon_v - \varepsilon_{Fp}}{kT}\right)\right]^{-1} \tag{8.4.23}$$

respectively, where ε_{Fn} and ε_{Fp} are the quasi-Fermi levels of electrons and holes. Let $\rho(\nu)$ be the radiation density of light of frequency ν; then the number of photon absorbed per unit time is

$$\frac{dNa}{dt} = C\,M_{cv} f_v(1 - f_c)\rho(\nu) \tag{8.4.24}$$

where C is a constant of proportionality, M_{cv} is the transistion probability that an electron from the valence band may go to an empty state in the conduction band (Fig. 8.34(a)) by absorbing a photon of frequency ν; $(1 - f_c)$ is the probability that the energy level in the conduction is empty.

In the same way, the rate of stimulated emission of photons, due to the transistion of an electron in the conduction band (inverted population) to an empty state $(1 - f_v)$ in the valence band (Fig. 8.34(b)), is

$$\frac{dNe}{dt} = C\,M_{vc} f_c (1 - f_v) \rho(\nu) \tag{8.4.25}$$

The constants are assumed to be the same for the sake of simplicity. Then there will be lasing action if $dNe/dt > dNa/dt$. That is, if, from eqns. (8.4.24) and (8.4.25)

$$\begin{aligned} & f_c(1 - f_v) > f_v(1 - f_c) \\ \text{or,} \quad & f_c > f_v \\ \text{or,} \quad & (\varepsilon_{Fn} - \varepsilon_{Fp}) > (\varepsilon_c - \varepsilon_v) = \varepsilon_g \end{aligned} \tag{8.4.26}$$

Since $\varepsilon_{Fn} - \varepsilon_{Fp} = \text{eV}$, where V is the forward voltage applied across the laser diode, and $h\nu = (\varepsilon_c - \varepsilon_v) = \varepsilon_g$, the energy of the emitted photon, we see that for a population inversion the applied voltage V must be chosen so that

$$\text{eV} > \varepsilon_g = h\nu \tag{8.4.27}$$

In other words, the voltage applied to the junction must be greater than the energy gap (in eV). For GaAs, this is ≈ 1.5 volts, for GaP ≈ 2.7 volts. Thus operation of junction lasers can be made with just one or two pencil torch batteries.

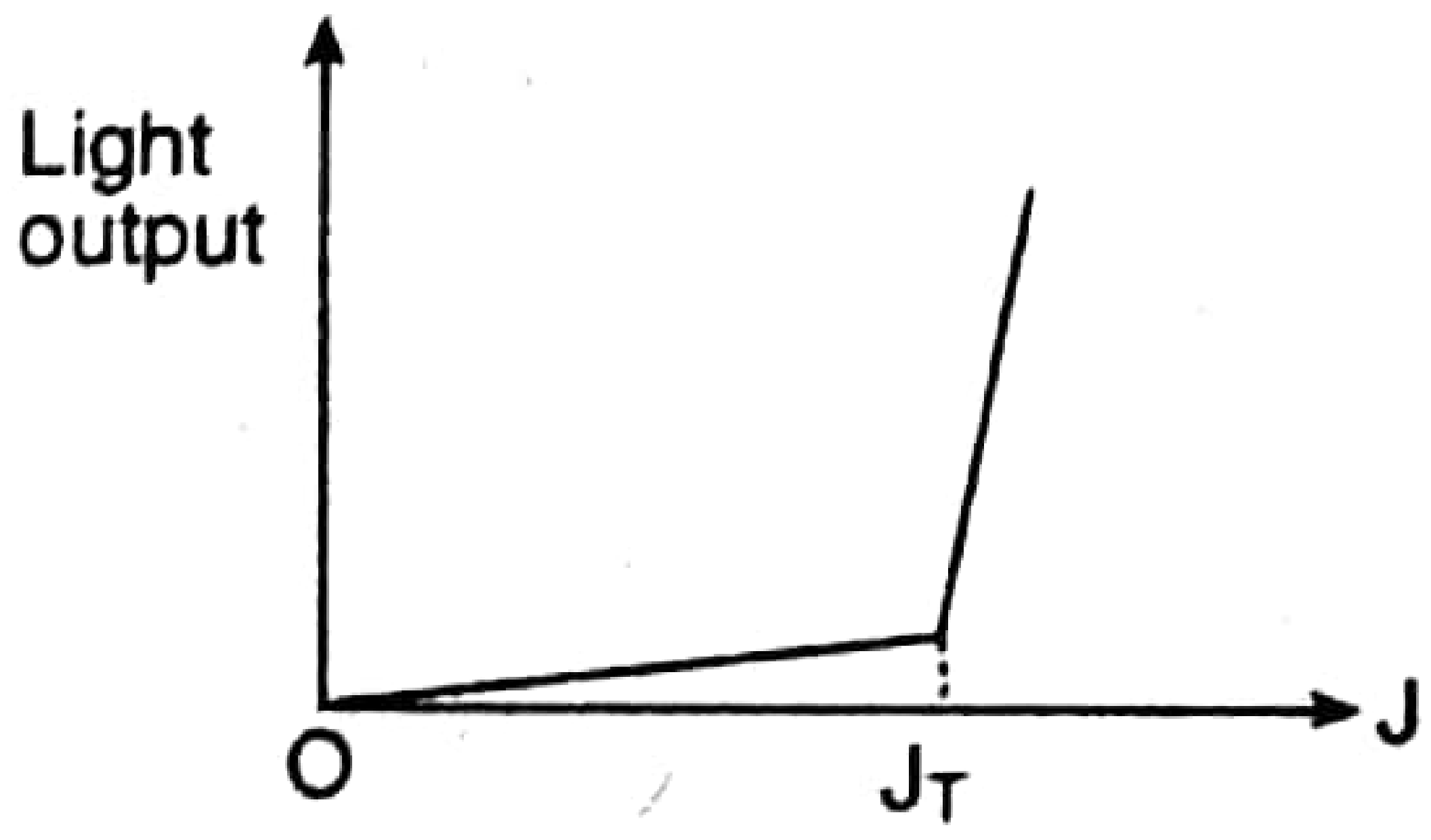


Fig. 8.37 Light output as a function of current density in a laser diode

To achieve population inversion, a threshold current density J_T is required. This parameter is very important in the operation of a diode laser. The light output versus current density is shown in Fig. 8.37.

Diode lasers can operate both in the pulse mode when driven by a step current and in the continuous mode using a dc or more commonly a sinusoidal current source.

For effective laser action to occur, it is necessary to confine the area of the light output to a narrow interfacial layer near the junction region. *Light confinement* poses an additional requirement of beam confinement, which can be achieved by increasing the dopant density near the edges of the *pn* junction. Heavily doped (highly degenerate) semiconductors are known to give a lower refractive index, which increases the light confinement within the junction region. A graded structure built, using a heterostructure (see section 8.5.1) of $\text{Ga}_x\text{Al}_{1-x}$ As around a GaAs diode laser, can also generate similar effects. The epitaxial layer of $\text{Ga}_x\ \text{Al}_{1-x}$ AS has a wider energy gap and hence has a lower refractive index. Such a sandwich structure is called a double heterostructure and is shown in Fig. 8.35(a) with dotted portion as heterostructure.