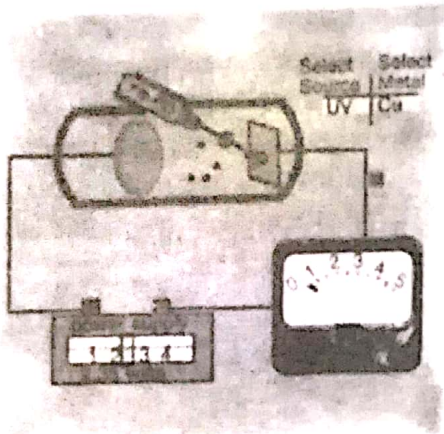
CHAPTER 16

Optoelectronic Devices



16.1. Introduction

Optoelectronic devices are the products of a technology that combines optics with electronics.

The present-day family tree of these devices is shown in Fig. 16.1.

Such devices fall into two broad categories :

1. Devices that convert electricity into light (visible or invisible). They are known as *emitters.*
2. Devices that convert light into electricity. It includes photoemissive (non-solid-state) devices and photodetectors (solid- state devices).

Since the characteristics of these devices depend on light, some fundamental facts about light would be discussed below.

What we call light is only a small portion of the vast electromagnetic spectrum shown in Fig. 16.2. This gives a graphical representation of the different radiations that exist at different frequencies and wavelengths.

Wavelength and Frequency

The wavelength (λ) and frequency (f) of light are related to the velocity of light by the relation

$$c = f\lambda$$

where $c = 3 \times 10^8$ m/s, f is in hertz (Hz) and λ in metres (m).

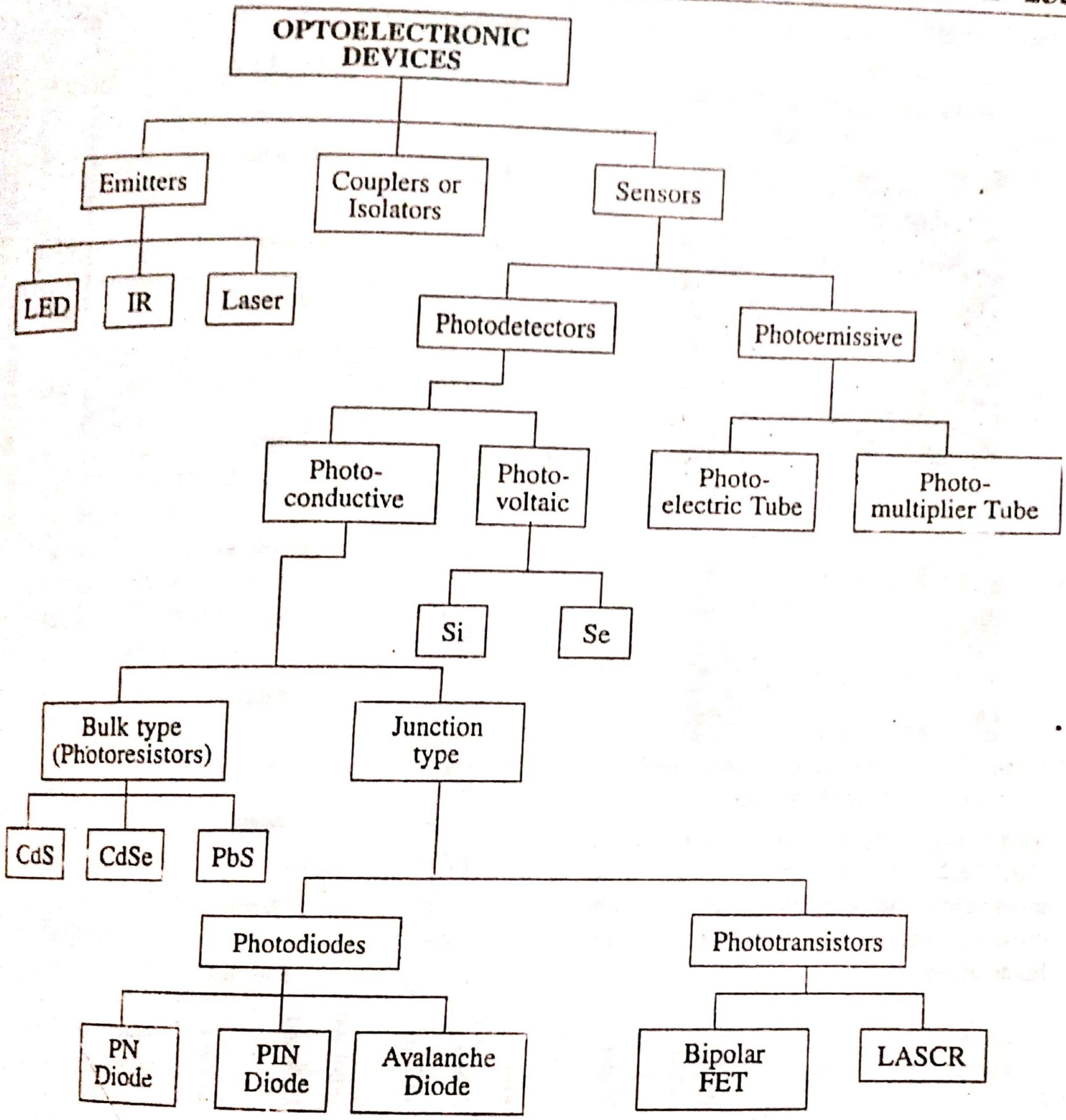


Fig. 16.1

The different units employed for measuring wavelength are

1 micrometre (μm) = 10^{-6} m

It is also known as micron (μ).

1 nanometre (nm) = 10^{-9} m

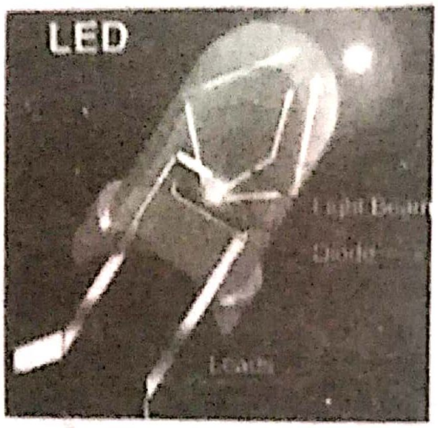
16.2. Spectral Response of Human Eye

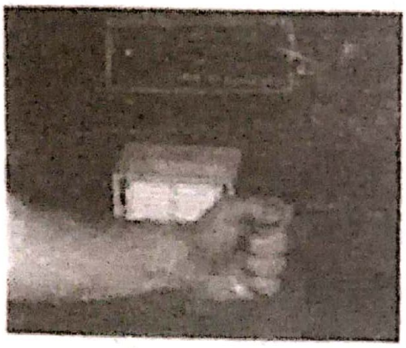
The human eye is somewhat like a filter with a response similar to that of a tuned circuit. Fig. 16.3 shows the response of an average human eye to the visible part of the spectrum extending from 400 nm to 760 nm. It is seen that peak sensitivity occurs at 550 nm and tapers off to zero at 400 nm and 760 nm. It drops to 50% of the peak sensitivity at 610 nm. Different colours corresponding to different wavelengths have also been shown in the figure. Speaking in terms of colours, the human eye is most sensitive to green-yellow and less sensitive to violet (shorter λ) and red (longer λ).

16.3. Light Emitting Diode (LED)

(*a*) Theory

As the name indicates, it is a forward-biased *P-N* junction which emits visible





Applying light-emitting diode (LED) technology to healing wounds.

light when energised. As discussed earlier (Art. 13.2), charge carrier recombination takes place when electrons from the *N*-side cross the junction and recombine with the holes on the *P*-side.

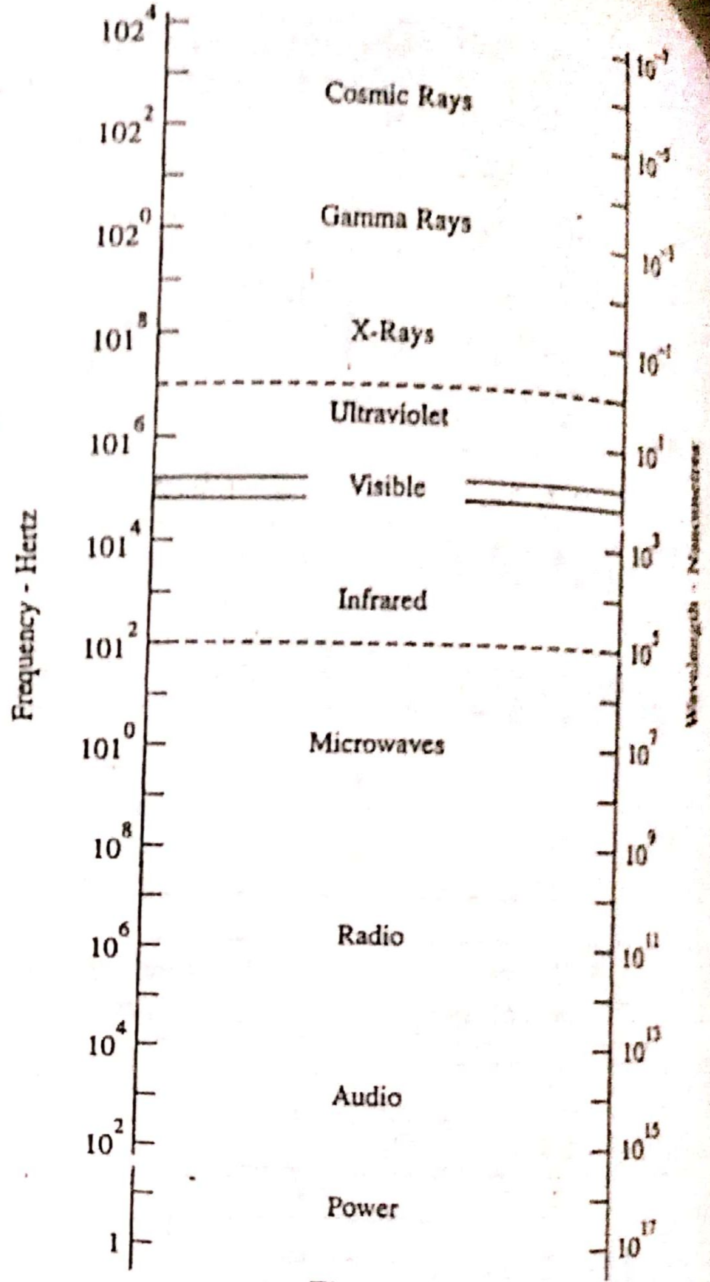


Fig. 16.2

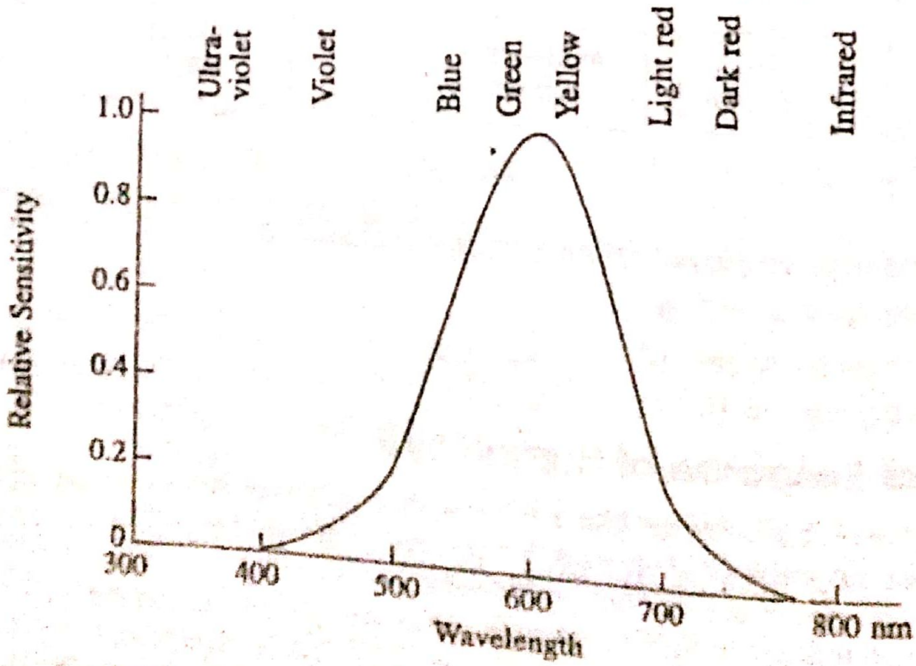


Fig. 16.3

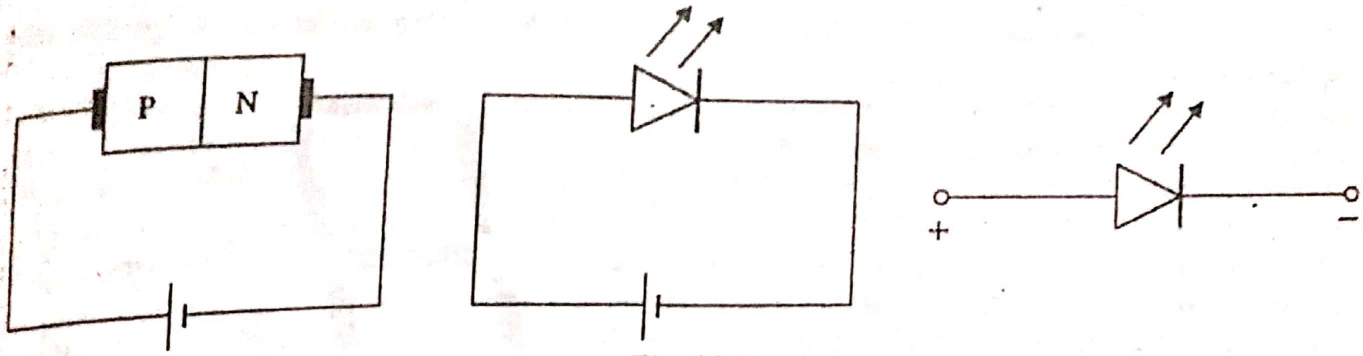


Fig. 16.4

Now, electrons are in the higher conduction band on the *N*-side whereas holes are in the lower valence band on the *P*-side. During recombination, some of this energy difference is given up in the form of heat and light (*i.e.*, photons). For Si and Ge junctions, greater percentage of this energy is given up in the form of heat so that the amount of emitted light is insignificant. But in the case of other semiconductor materials like gallium arsenide (GaAs), gallium phosphide (GaP) and gallium-arsenide-phosphide (GaAsP), a greater percentage of energy released during recombination is given out in the form of light. If the semiconductor material is transluscent, light is emitted and the junction becomes a light source *i.e.*, a light emitting diode (LED) as shown schematically in Fig. 16.5. The colour of the emitted light depends on the type of material used as given below :

1. GaAs — infrared radiation (invisible)
2. GaP — red or green light
3. GaAsP — red or yellow (amber) light

LEDs emit no light when reverse-biased. In fact, operating LEDs in reverse direction will quickly destroy them.

(*b*) Construction

An *N*-type layer is grown on a substrate and a *P*-type is deposited on it by diffusion. Since carrier recombination takes place in the *P*-layer *it is kept uppermost*. The metal anode connections are made at the outer edges of the *P*-layer so as to allow more central surface area for the light to escape. LEDs are manufactured with domed lenses in order to lessen the reabsorption problem.

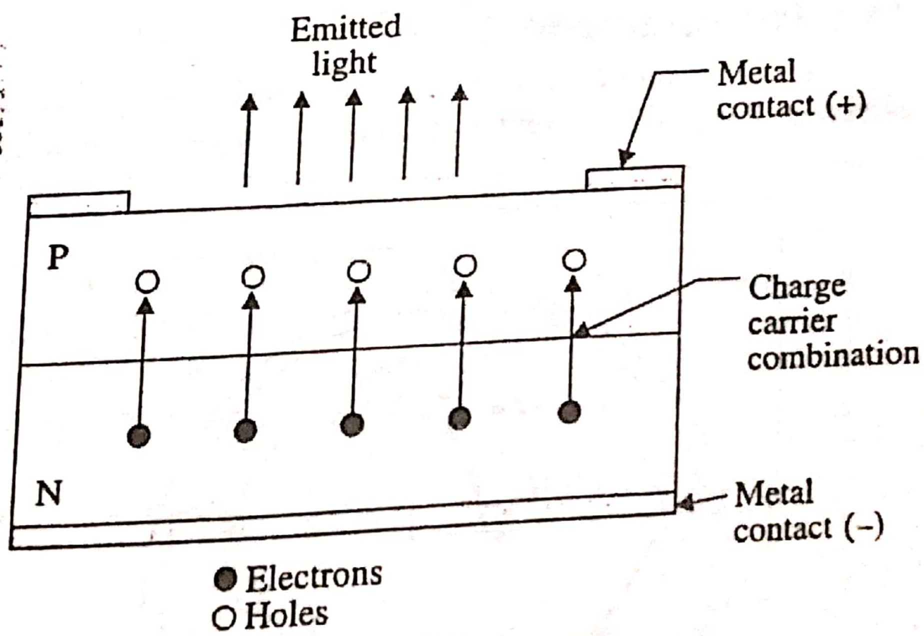


Fig. 16.5

A metal (gold) film is applied to the bottom of the substrate for reflecting as much light as possible to the surface of the device and also to provide cathode connection LEDs are always encased to protect their delicate wires.

Being made of semiconductor material, it is rugged and has a life of more than 10,000 hours.

(*c*) Applications

To choose emitting diodes for a particular application, one or more of the following points have to be considered: wavelength of light emitted, input power required, output power, efficiency, turn-on and turn-off time, mounting arrangement, light intensity and brightness etc.

Since LEDs operate at voltage levels from 1.5 V to 3.3 V, they are highly compatible with solid-state circuitry.

Their uses include the following :

1. *IR* LEDs are used in burglar-alarm systems,
2. for solid-state video displays which are rapidly replacing cathode-ray tubes (*CRT*),
3. in image sensing circuits used for 'picturephone',
4. in the field of optical communication where high-radiance GaAs diodes are matched into the silica-fibre optical cable,
5. in arrays of different types for displaying alphanumerics (letters and numbers) or supplying input power to lasers or for entering information into optical computer memories,
6. for numeric displays in hand-held or pocket calculators.

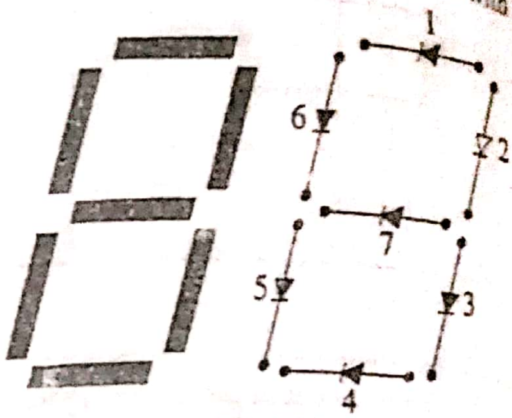


Fig. 16.6

A seven-segment array of LEDs is shown in Fig. 16.6 which can form the digits 0 to 9. Each segment contains a LED which can be turned ON or OFF to form the desired digit. For example, when all segments are ON, the digit formed is 8. If only the centre is OFF we get zero digit.

16.4. Photoemissive Devices

There are two devices in this category :

1. photoemissive cell or phototube, 2. photomultiplier tube.

The phototube will not be discussed becasue it has been almost displaced by its solid-state counterpart discussed later. Only photomultiplier tube will be considered because it is still being used.

16.5. Photomultiplier Tube

It is a phototube in which current is amplified by electron multiplication through secondary emission. It can give current amplification. Cross-section of one form of such a tube is shown in

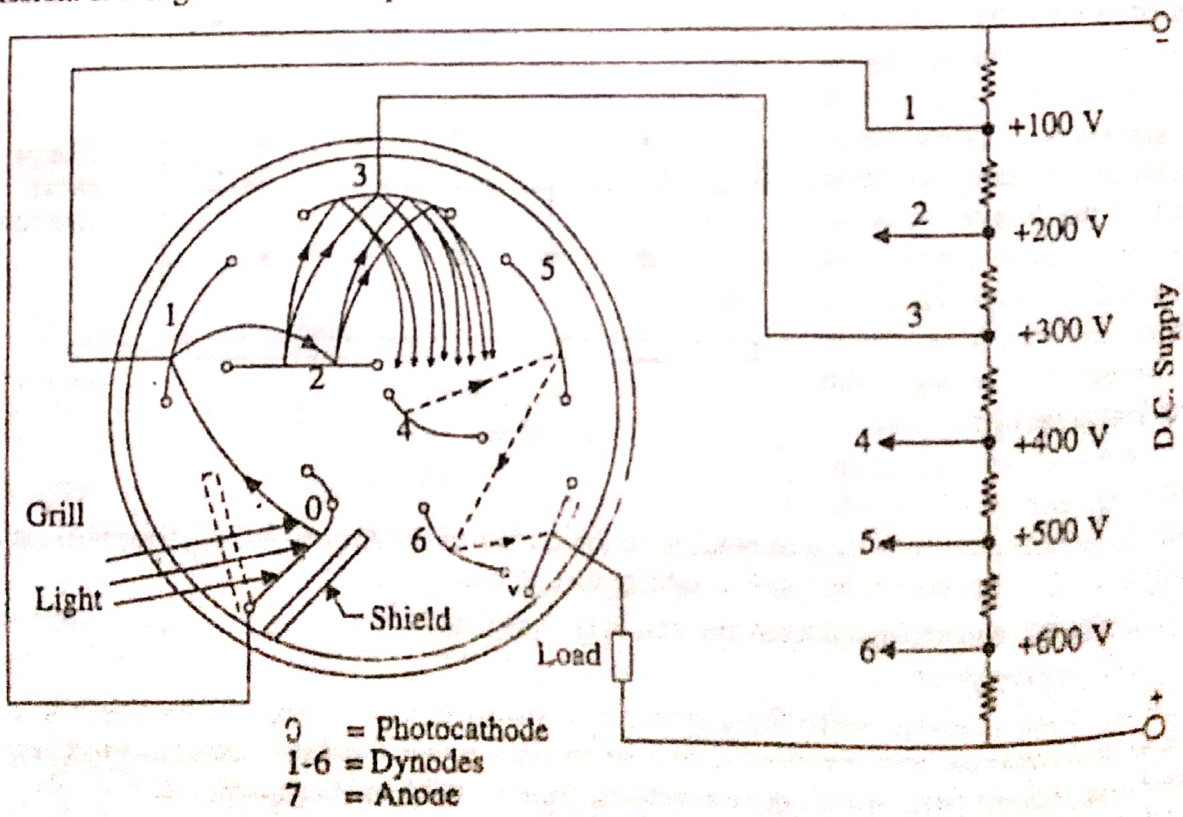


Fig. 16.7

Fig. 16.7. It consists of electrodes (called dynodes) which are maintained at increasing potentials in sequence from photocathode 0 to the anode marked 7 in the diagram. When light falls on the cathode, photoelectrons are emitted which are accelerated towards dynode 1, since it is at a higher potential. On colliding with this dynode, they liberate secondary electrons which are attracted by dynode No. 2, since it is at a relatively still higher potential. These electrons release further secondary electrons from it which are attracted by dynode 3. This process of secondary emission from different dynodes continues till the electrons are finally collected by the anode. It is obvious that at each dynode, the number of secondary keeps on multiplying. Photomultiplier tubes operate at voltages from 1 to 5 kV. Because of their ultrahigh sensitivity, low noise, extremely small dark current and very fast response time (less than 1 nanosecond), they are extensively employed in scintillators, radiation detectors and for space exploration.

16.6. Photovoltaic Devices

These are made of either silicon or selenium. We will discuss only the solid-state device that consists of a *P-N* junction which is used *without any bias*. It is worth making a distinction here regarding these devices. When a *P-N* junction is used without any bias, it is called a photovoltaic device (or solar cell already discussed in Art. 6.17) and when it is used with a reverse bias, it is called a photoconductive device *i.e.*, a photodiode (see chart of Fig. 16.1).

Photoconductive devices may be either of bulk type or junction type. The bulk type are made from a single layer of photosensitive material and have no *P-N* junction. The devices utilizing reverse biased junctions are called *photodiodes*.

16.7. Bulk Type Photoconductive Cells

It is also called a *photoresistive* device.

(a) Principle

It is based on the principle that the resistance of certain semiconductor materials *decreases when they are exposed to radiations* (both visible and invisible). In other words, such materials have high dark resistance and low irradiated resistance.

It is found that when radiations of sufficient energy fall on such photosensitive materials, they cause the electrons to break away from their covalent bonds thereby generating electron-hole pairs (Fig. 16.8). Since these charge carriers are created within the material, they reduce its resistance.

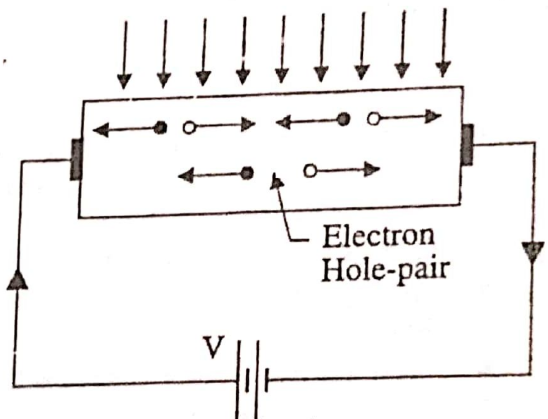


Fig. 16.8

(b) Construction

The four materials normally employed in photoconductive cells are : cadmium sulphide (CdS), cadmium selenide (CdSe), lead sulphide (PbS) and thalmium sulphide (TlS). The simplified two-dimensional model of the commonly-used CdS cell is shown in Fig. 16.9 (*a*) and its circuit symbol in Fig. 16.9 (*b*). As shown, the two electrodes are extended in an interdigital pattern in order to increase the contact area with the

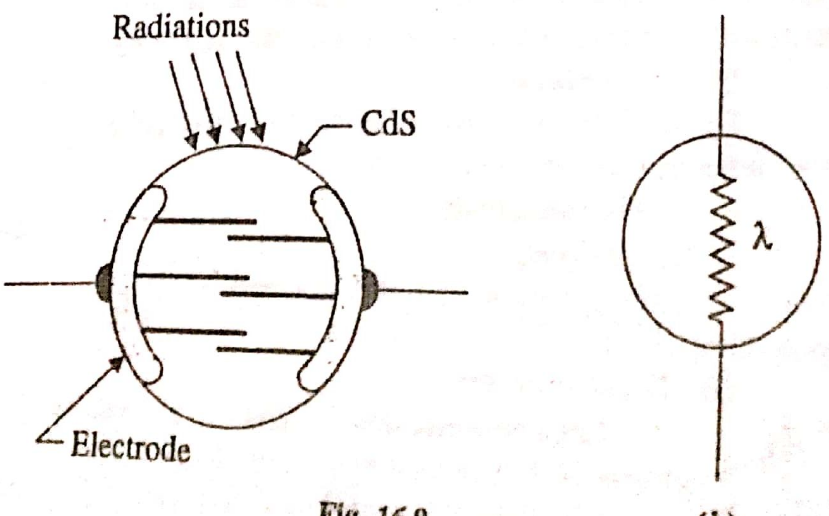


Fig. 16.9 (*b*)

sensitive material. In this way, it is possible to obtain a large ratio of 'dark-to-light' resistance.

An external power supply is necessary to generate a direction and provide a path for the current to flow. The value of applied voltage varies from a few volts to several hundred volts depending on photocell applications.

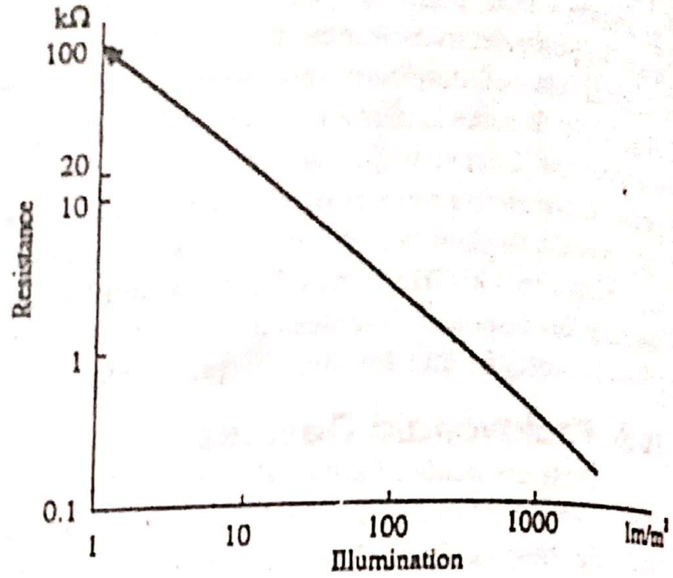


Fig. 16.10

(c) Working

The illumination characteristic of the cell is shown in Fig. 16.10 where logarithmic scales have been used. It is seen that when not illuminated, the cell has a resistance of more than 100 kΩ. It is known as its dark resistance. When illuminated, the resistance falls to only a few hundred ohms.

The spectral response of CdS cell is similar to that of the human eye *i.e.*, it is sensitive to visible light. The response of CdSe cell is at the longer wavelength of the visible spectrum and extends into the infrared region. Both materials respond rather slowly to *changes* in light intensity. CdSe has a response time of about 10 ms whereas CdS takes as long as 100 ms. Moreover, CdSe is much more sensitive to changes in ambient temperature than CdS.

(d) Applications

1. CdS cells are used in counting applications.
2. PbS and TlS cells have been used for detecting ships and aircraft by the radiations given out by their exhausts or funnels.
3. CdS cells are used as light meters.
4. As ON-OFF switch.
5. For relay control.
6. As a volume control that is itself controlled by light level.
7. As voltage regulator.

As shown in Fig. 16.11, if due to any reason, V_i decreases, the brightness of lamp will also decrease. This decrease in illumination would increase photocell resistance. Hence, V_0 would be maintained at its rated level as determined by the voltage divider rule (Art. 2.8).

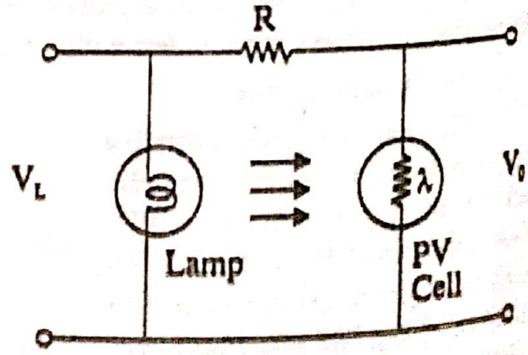


Fig. 16.11

(e) Advantages

Some of the advantages of photoconductive cells over other photodetectors are their

1. high sensitivity,
2. low cost,
3. high dark-to-light resistance ratio exceeding 100:1.

(f) Disadvantages

1. large response time and 2. relatively narrow spectral response.

Example 16.1. *A relay is to be controlled by a photoconductive cell having a dark resistance of 100 kΩ of 1 kΩ when illuminated mith 400 lm/m². The relay is to be supplied with 8 mA from a 24-V battery (Fig. 16.12) when the cell is illuminated with 400 lm/m² and is required to be de-energised when the cell is dark. Calculate the required series resistance and the dark current.*

Solution. The relay circuit is shown in Fig. 16.12 where R is included to limit circuit current. As seen

$$I = \frac{24}{R + \text{cell resistance}}$$

$$\therefore \quad 8 \times 10^{-3} = \frac{24}{R + 1000}$$

$$\therefore \quad R = 2000\ \Omega = 2\text{ K}$$

Dark current is

$$= \frac{24}{2\text{K} + 100\text{K}} \cong 0.24\text{ mA}$$

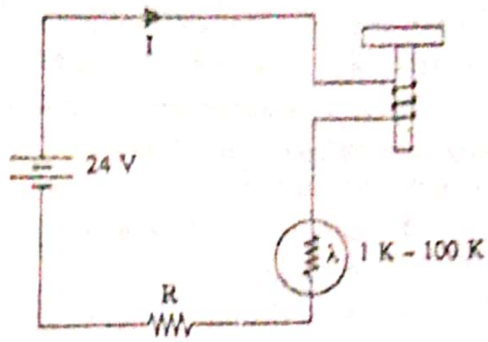


Fig. 16.12

16.8. Photodiodes

They are junction-type photoconductive devices and consists of

1. *PN* diode 2. *PIN* diode and 3. avalanche diode

We will take them up one by one in the pages to follow.

16.9. P-N Junction Photodiode

It is a two-terminal junction device which is operated by first reverse-biasing the junction and then illuminating it. A reverse-biased *P-N* junction has a small amount of reverse saturation current I_s (or I_0) due to thermally-generated electron-hole pairs. In silicon, I_s is in the range of nanoamperes. The number of these minority carriers depends on the intensity of light incident on the junction. When the diode is in a glass package, light can reach the junction and thus change the reverse current.

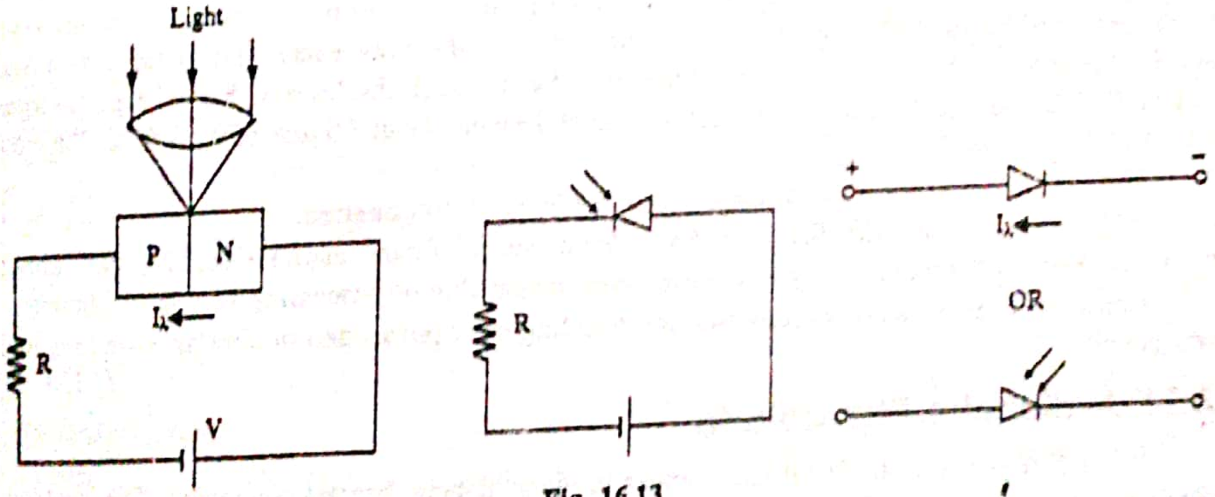
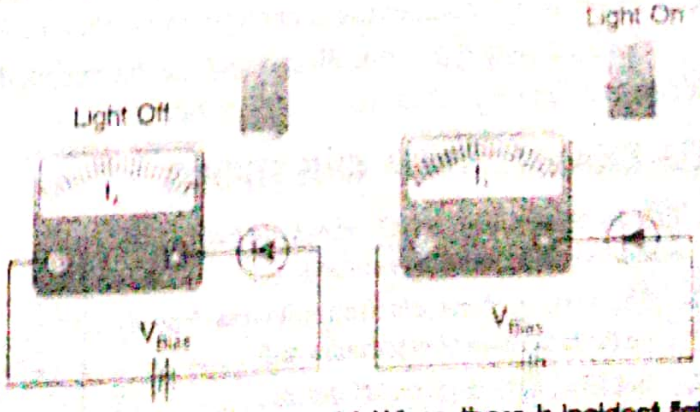


Fig. 16.13

The basic biasing arrangement, construction and symbol of a photodiode are shown in Fig. 16.13. As seen, a lens has been used in the cap of the unit to focus maximum light on the reverse-biased junction. The active diameter of these devices is about 2.5 mm but they are mounted in standard TO-5 packages with a window to allow maximum incident light.



(a) No light, no current, except a negligible dark current.

(b) When there is incident light, resistence decreases and reverse (light) current flows.

The characteristics of Fig. 16.14 show that for given reverse voltage, I_λ (or I_r) increases with increase in the level of illumination. The dark current refers to the current that flows *when no light is incident*. By changing the illumination level, reverse current can be changed. In this way, reverse resistance of the diode can be changed by a factor nearly 20.

A photodiode can turn its current ON and OFF in nanoseconds. Hence, it is one of the fastest photodetectors. It is used where it is required to switch light ON and OFF at maximum rate. Applications of photodiode include

1. detection, — both visible and invisible
2. demodulation,
3. switching,
4. logic circuits that require stability and high speed,
5. character recognition,
6. optical communication equipment,
7. encoders etc.

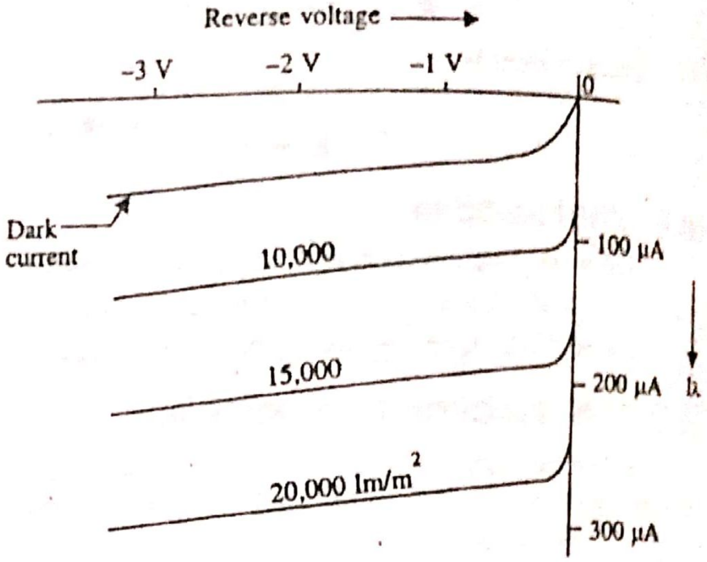


Fig. 16.14

16.10. PIN Photodiode

It is a three-region reverse-biased junction diode as shown in Fig. 16.9. A layer of intrinsic silicon is sandwiched between two heavily-doped *P*- and *N*-type silicon materials. This has the effect of reducing the transit time of photo-induced electron-hole pairs. It is so because carriers generated by light photons incident on the middle of the *I*-layer have less distance to travel than if generated at one or the other side of the layer. Hence, such diodes have faster response than even the *P-N* photodiode. Moreover, the relatively thick *I*-layer (about 2.5 μm) ensures the absorption of most of the incident light.

The reverse current increases linearly with the level of illumination.

PIN photodiodes are *ultrafast* having a switching speed of nanosecond or so. They have broad spectral response and generate very low noise. They are capable of processing very weak signals.

Hence, such devices are widely used for detecting laser pulses and in ultrafast switching and logic circuits.

16.11. Avalanche Photodiode

It is a *P-N* junction diode which operates in the avalanche breakdown region. The electron-hole pairs that are generated by the incident light are accelerated by the electric field to produce more such carriers thereby achieving a photomultiplication of 50 or so.

It is ultrafast (like PIN diode) and can be operated at a modulation frequency of a few GHz with an excellent signal-to-noise (*S/N*) ratio.

SELF EXAMINATION QUESTIONS

A. Fill in the blanks with most appropriate word (s) or numerical value(s).

1. The working of optoelectronic devices depends on the basic laws of electronics and ....
2. In LEDs, light is given off due to .... of electrons and holes.
3. LEDs emit light only when .... biased.
4. LED alphanumeric displays can indicate both .... and numbers.
5. A seven-segment LED array can display digits ....to 9.

6. Photovoltaic cells do not need an external _____ supply.
7. A photodiode is essentially a .... biased P-N junction which is illuminated with radiations.
8. Incident radiations in a photodiode increase its _____ current.

B. Answer True or False

1. A LED emits light when forward-biased.
2. Light emission by LED is due to recombination of electrons and holes.
3. A LED using GaAs material gives out infrared radiations.
4. LED emits no light when reverse-biased.
5. Photovoltaics are self-generating devices.
6. A photodiode is a junction device needing forward bias.
7. Bulk type photoconductive cells are also called photoresistors.
8. Higher its dark-to-light resistance ratio, better the photoconductive cell.
9. P-N photodiode has faster response than a PIN photodiode.
10. Higher the illumination level, greater the reverse current of a photodiode.

C. Multiple Choice Items

1. The colour of light emitted by a LED depends on
   (a) its forward bias
   (b) its reverse bias
   (c) the amount of forward current
   (d) the type of semiconductor material used
2. Bulk type photoconductive cells have
   (a) wide spectral response
   (b) small response time
   (c) high cost
   (d) high dark-to-light resistance ratio
3. A P-N junction photodiode is
   (a) operated in forward direction
   (b) encased in an opaque package
   (c) a very fast photodetector
   (d) dependent on thermally-generated minority carriers
4. Silicon is invariably used in the manufacture of junction photodiodes because
   (a) more electron-hole pairs are generated in it
   (b) its thermally-generated minority current is extremely small
   (c) it is more rugged than Ge
   (d) it needs less reverse bias
5. A PIN photodiode has ultrafast response primarily due to
   (a) the presence of middle I-layer
   (b) heavy doping of P and N-regions
   (c) higher electrical conductivity of Si
   (d) its wide spectral response

ANSWERS

A. Fill in the blanks

1. optics 2. recombination 3. forward 4. letters 5. 0
6. voltage 7. reverse 8. reverse

B. True or False

1. T 2. T 3. T 4. T 5. T 6. F 7. T 8. T 9. F 10. T

C. Multiple Choice Items

1. d 2. d 3. c 4. b 5. a