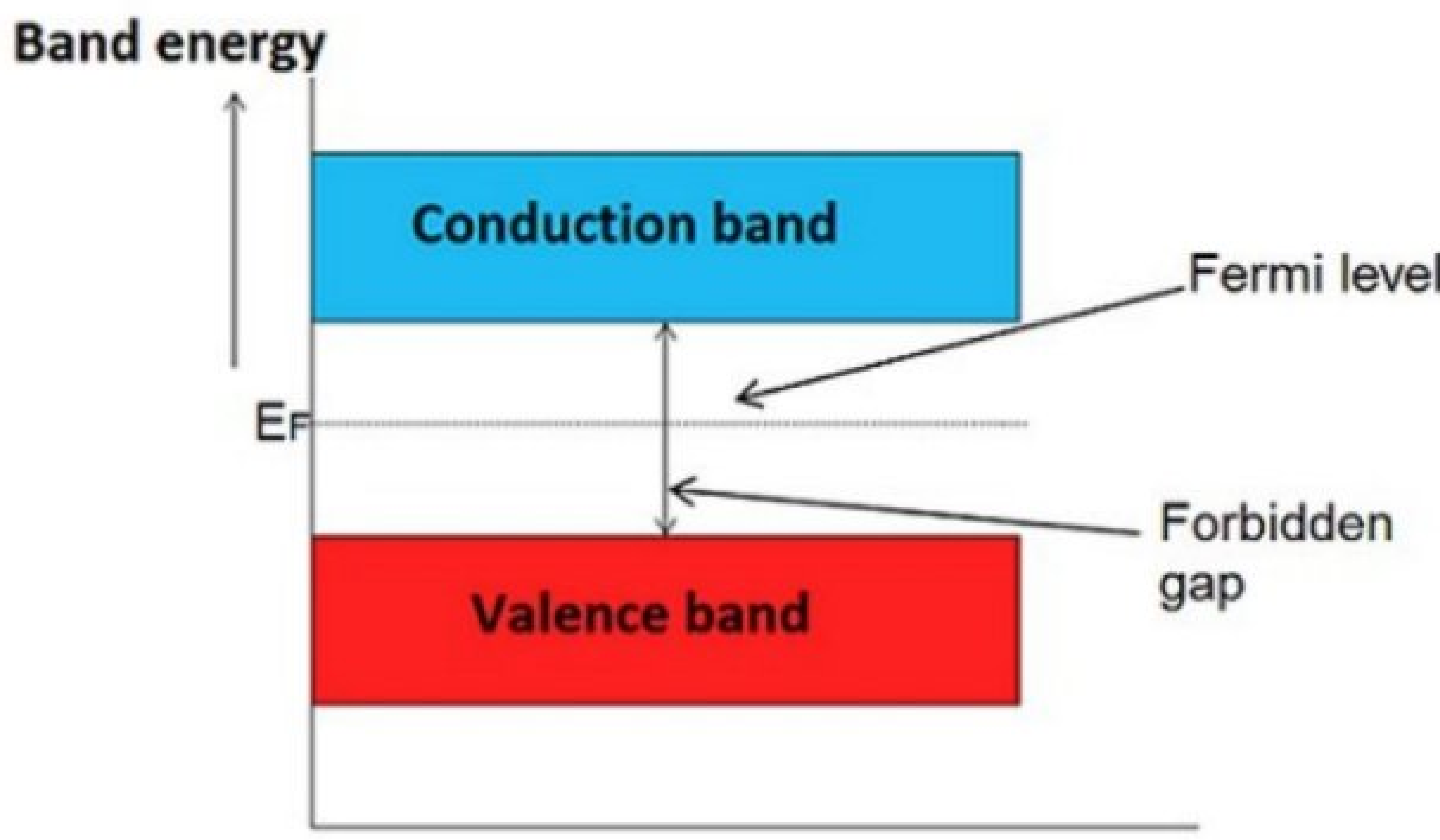
MODULE 5

SEMICONDUCTOR AND DEVICES

Fermi levels in intrinsic semiconductors

Fermi level is the highest occupied level in an atom and fermi level gets shifted depending on the doping concentration of semiconductor in extrinsic semiconductor. In intrinsic semiconductor fermi level lies exactly in between conduction band and valence band.



Expression for Electron Concentration (N_e)

$$N_e = \frac{4\sqrt{2}}{h^3}(\pi m_e^* kT)^{3/2} e^{\left(\frac{E_F - E_g}{kT}\right)}$$

where, m_e^* is the effective mass of electron
k is the Boltzmann constant
T is the temperature in absolute scale
E_F is the Fermi energy
E_g is the energy gap
h is the Planck's constant.

Scanned with OKEN Scanner

Expression for Hole Concentration (N_h)

$$N_h = \frac{4\sqrt{2}}{h^3}(\pi m_h^* kT)^{3/2} e^{\left(\frac{-E_F}{kT}\right)}$$

where, m_h^* is the effective mass of holes
k is the Boltzmann constant
T is the temperature in absolute scale
E_F is the Fermi energy
h is the Planck's constant.

Relation Between Fermi Energy and Energy Gap of an Intrinsic Semiconductor

The number of holes per unit volume in valence band is equal to number of electrons per unit volume in conduction band for intrinsic semiconductors,therefore $N_e = N_h$ Substituting for electron and hole concentration, we get

$$\frac{4\sqrt{2}}{h^3}(\pi m_e^* kT)^{3/2} e^{\left(\frac{E_F - E_g}{kT}\right)} = \frac{4\sqrt{2}}{h^3}(\pi m_h^* kT)^{3/2} e^{\left(\frac{-E_F}{kT}\right)}$$

$$e^{\frac{(2E_F - E_g)}{kT}} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

By taking natural log we get

$$\frac{2E_F - E_g}{kT} = \frac{3}{2} ln\left(\frac{m_h^*}{m_e^*}\right)$$

$$2E_F - E_G = \frac{3kT}{2} ln\left(\frac{m_h^*}{m_e^*}\right)$$

$$E_F = \frac{3}{4} kT\ ln\left(\frac{m_h^*}{m_e^*}\right) + \frac{E_g}{2}$$

under practical conditions, $m_e^* = m_h^*$, then equation (1) becomes

$$\boxed{E_F = \frac{1}{2}\,E_g} \qquad (since\ ln(1) = 0)$$

Scanned with OKEN Scanner

Law of Mass Action

The law of mass action states that the product of number of electrons in the conduction band and the number of holes in the valence band is constant at a fixed temperature and is independent of amount of donor and acceptor impurity added.
$N_e.N_h = a$ (*where 'a' is constant*)

Expression For Electrical Conductivity of a Semi-conductor

Consider a semi-conductor of area of cross section 'A' and 'v_d' be the drift velocity of the electrons whose flow constitutes the current 'I'. Then the current density 'J' of a semi-conductor is given by,

$$J = \frac{I}{A}$$
$$I = N_e e v_d A$$
$$\textit{substituting for 'I' in equation(1) we get}$$
$$J = \frac{N_e e v_d A}{A} \Longrightarrow J = N_e e v_d$$

The velocity of electrons in terms of mobility is given by,

$$\mu_e = \frac{v_d}{E} \Longrightarrow v_d = \mu_e E, \quad \textit{where } \mu_e \textit{ is the mobility of electrons}$$

$$\therefore J = (N_e e \mu_e)E$$
$$\textit{From Ohm's Law we have,} \quad J = \sigma E$$

If 'σ_e' is the conductivity due to electrons in the semiconductor material,then

$$J = \sigma_e E$$
$$\textit{comparing equation (2) and (3)}$$
$$\Longrightarrow \sigma_e E = N_e e \mu_e E$$
$$\therefore \boxed{\sigma_e = N_e e \mu_e}$$

Then the conductivity 'σ_h' due to the holes in semiconductor can be written as,

$$\boxed{\sigma_h = N_h e \mu_h}$$

Scanned with OKEN Scanner

∴ The total conductivity of a semiconductor is given by,

$$\sigma = \sigma_e + \sigma_h$$
$$\implies \sigma = N_e e \mu_e + N_h e \mu_h$$
$$\therefore \boxed{\sigma = e(N_e \mu_e + N_h \mu_h)}$$

Equation(4) represents the expression for electrical conductivity of a semiconductor.

For intrinsic semiconductors $\sigma_e = \sigma_h = \sigma_i$, ∴ $N_e = N_h = n_i$, then

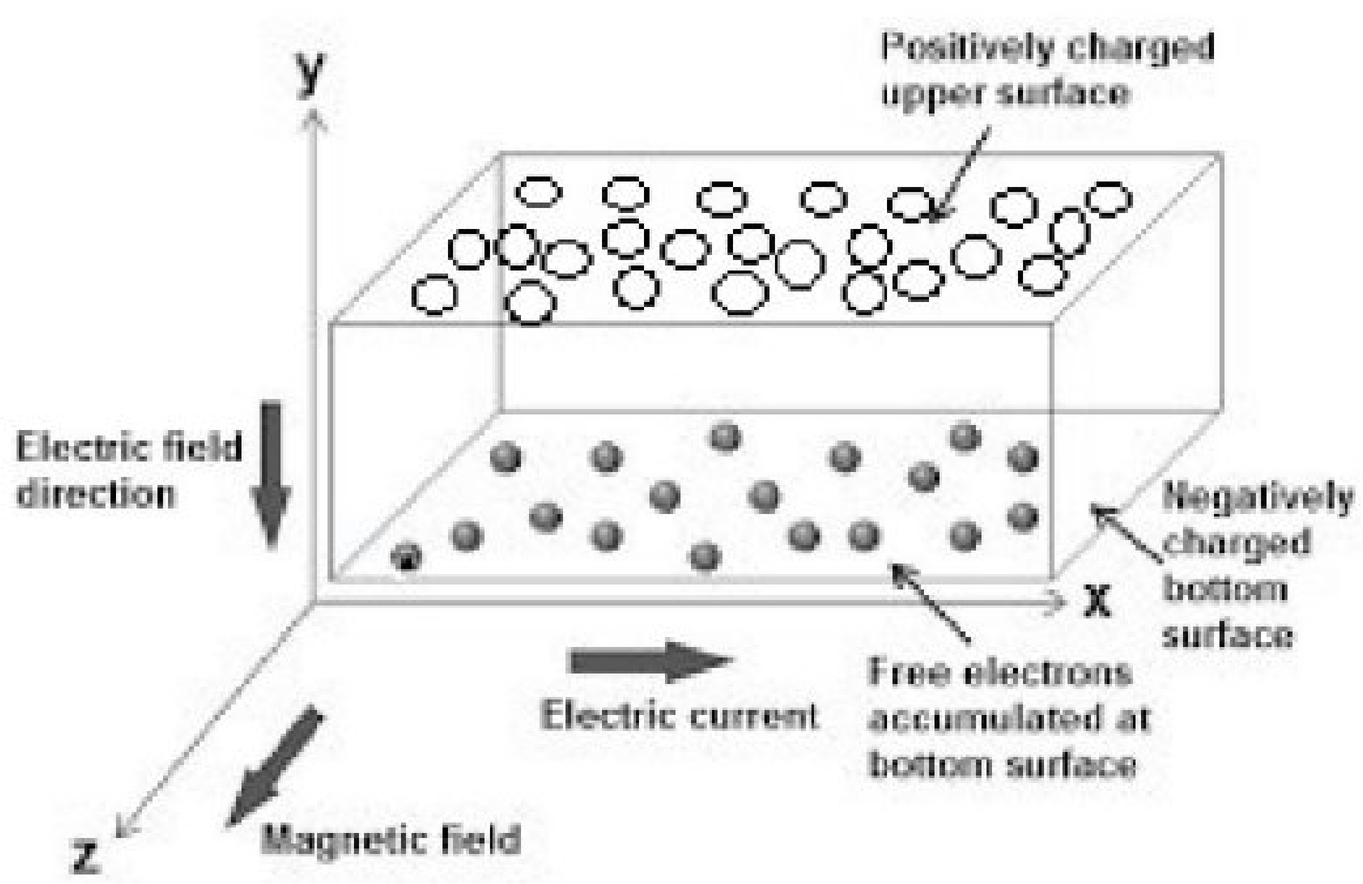
$$\boxed{\sigma_i = n_i e(\mu_e + \mu_h)}$$

Equation(5) represents the expression for electrical conductivity of a intrinsic semiconductor.

Hall Effect

If a current carrying material is subjected to the magnetic field acting at right angles to direction of flow of current, then the electric field is induced across the material in a direction perpendicular to both the direction of magnetic field and current flow. This phenomenon is called as Hall effect.

Expression for the Hall co-efficient and Hall voltage of Semiconductor.



Hall Effect in N-type semiconductor

Consider an n-type semiconductor carrying current 'I' and a magnetic field

Scanned with OKEN Scanner

'B' is applied along Z-direction, then the Lorentz force experienced by the electrons under the influence of magnetic field is given by,

$$F_L = Bev_d$$

where v_d is the drift velocity Then according to Fleming's left hand rule the electric current is induced along negative Y-direction which is perpendicular to current 'I' and magnetic field 'B' which establishes electric field 'E_H' and is called as Hall field.
$\therefore$ The upward force exerted on electrons due to Hall field is given by,

$$F_H = eE_H$$

At equilibrium the Lorentz force and the force due to Hall field are equal, then equating (1) and (2), we get

$$Bev_d = eE_H$$

$$\implies v_d = \frac{E_H}{B}$$
$$\textit{we know that}$$
$$J = nev_d$$
$$\implies v_d = \frac{J}{ne}$$
$$\textit{equating (3) and (4) we get}$$
$$\frac{E_H}{B} = \frac{J}{ne}$$
$$\therefore \frac{E_H}{BJ} = \frac{1}{ne}$$
$$or\ \frac{E_H}{BJ} = R_H$$

where $R_H = \frac{1}{ne}$ and is called as Hall co-efficient.

$$\boxed{\therefore R_H = \frac{E_H}{BJ}}$$

Scanned with OKEN Scanner

Hall Voltage:

If the semiconductor slab is of thickness 'd' and width 'w', then the current density of that slab is given by:

$$J = \frac{I}{wd}$$

The Hall voltage V_H can be measured by placing two probes at the top and bottom faces of the slab, If E_H is the Hall field then,

$$E_H = \frac{V_H}{w}$$

$$\implies V_H = wE_H$$

$$where \;\; E_H = BjR_H$$

substituting for E_H from equation(8) in equation (7)

$$\implies V_H = wBjR_H$$

$$But \; j = \frac{I}{wd}$$

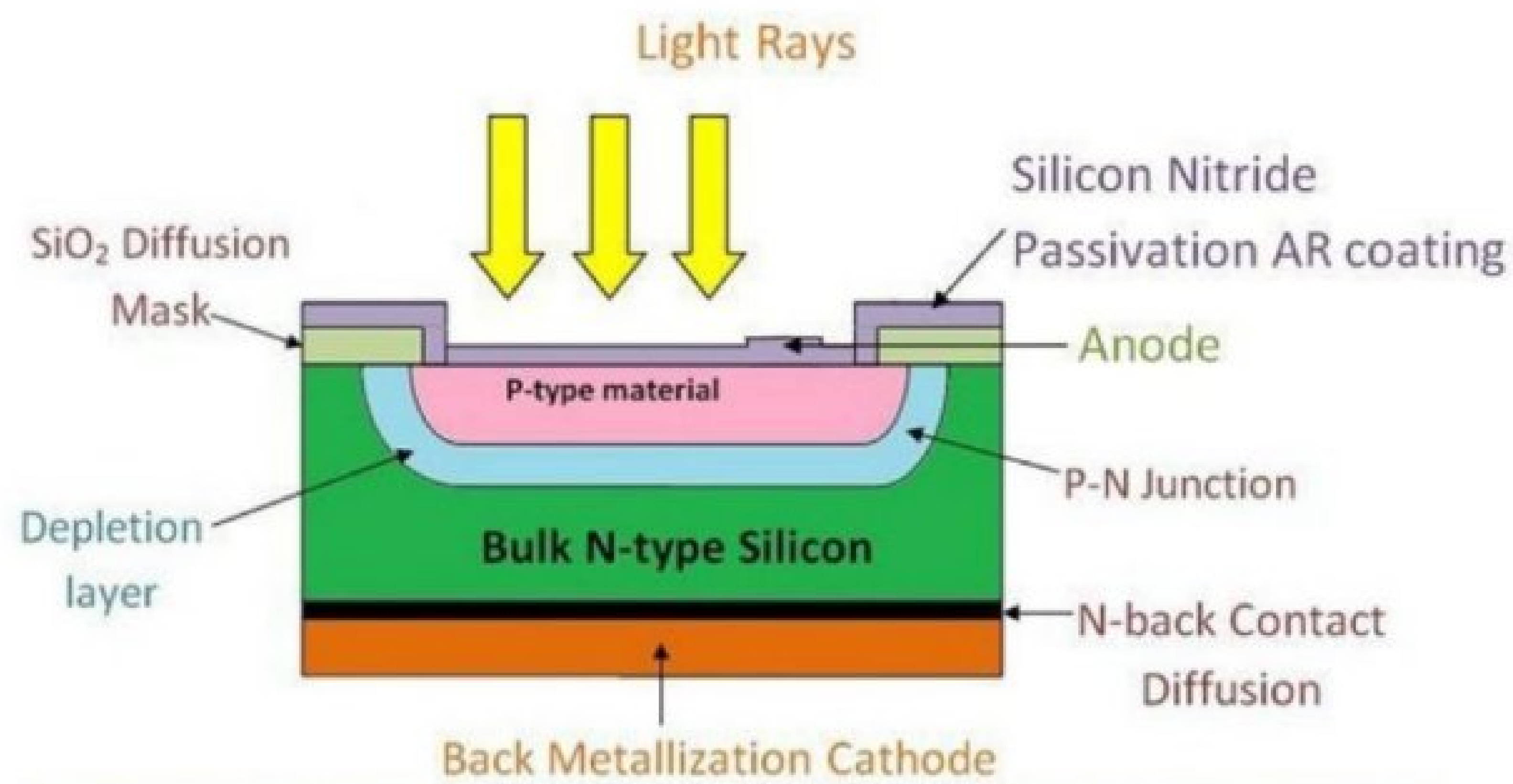
$$\therefore \; V_H = \frac{wBIR_H}{wd}$$

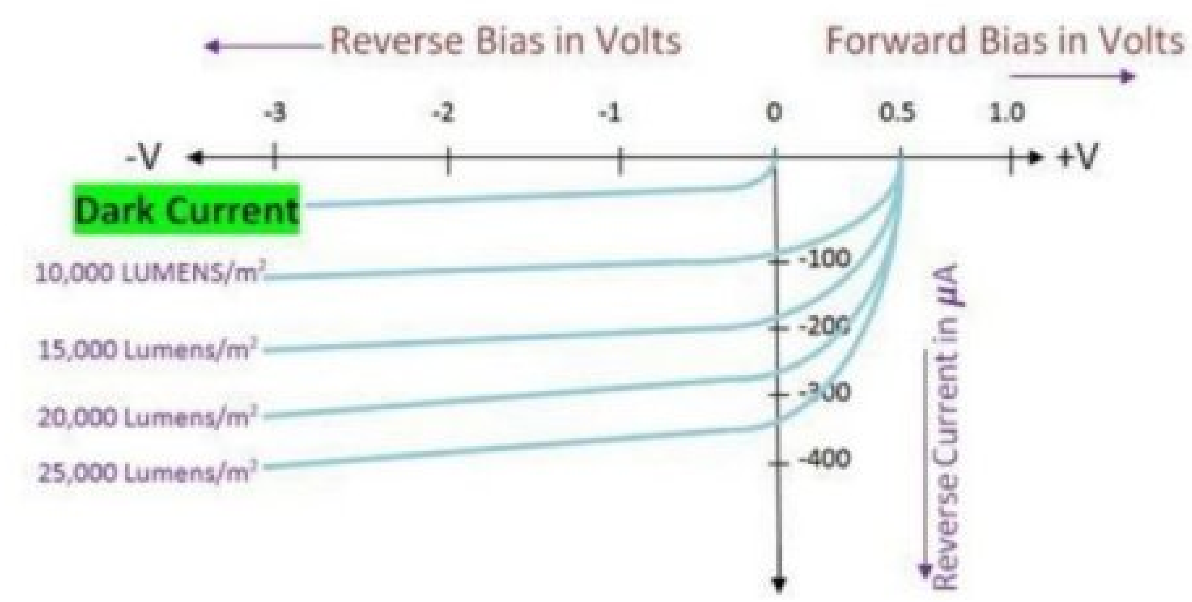
$$\boxed{V_H = \frac{BIR_H}{d}}$$

Equation (10) represents the expression for Hall voltage of a semiconductor.

Scanned with OKEN Scanner

Photodiode: Construction and Working





Construction: The photodiode is made up of two layers of P-type and N-type semiconductor. In this, the P-type material is formed from diffusion of the lightly doped P-type substrate. The P+ diffusion layer is developed on N-type heavily doped epitaxial layer. The contacts are made up of metals to form two terminal cathode and anode.

The non-active surface is made up of SiO2 and the active surface is coated with anti-reflection material so as to convert the maximum light energy to current. The entire unit has dimensions of the order of 2.5 mm.

Working: When the conventional diode is reverse biased, the depletion region starts expanding and the current starts flowing due to minority charge carriers. With the increase of reverse voltage, the reverse current also starts increasing. The same condition can be obtained in Photodiode without applying reverse voltage.

The junction of Photodiode is illuminated by the light source, the photons strike the junction surface and impart their energy in the form of light to the junction due to which electrons from valence band get the energy to jump into the conduction band and contribute to current. In this way, the photodiode converts light energy into electrical energy.

Applications of Photodiode:

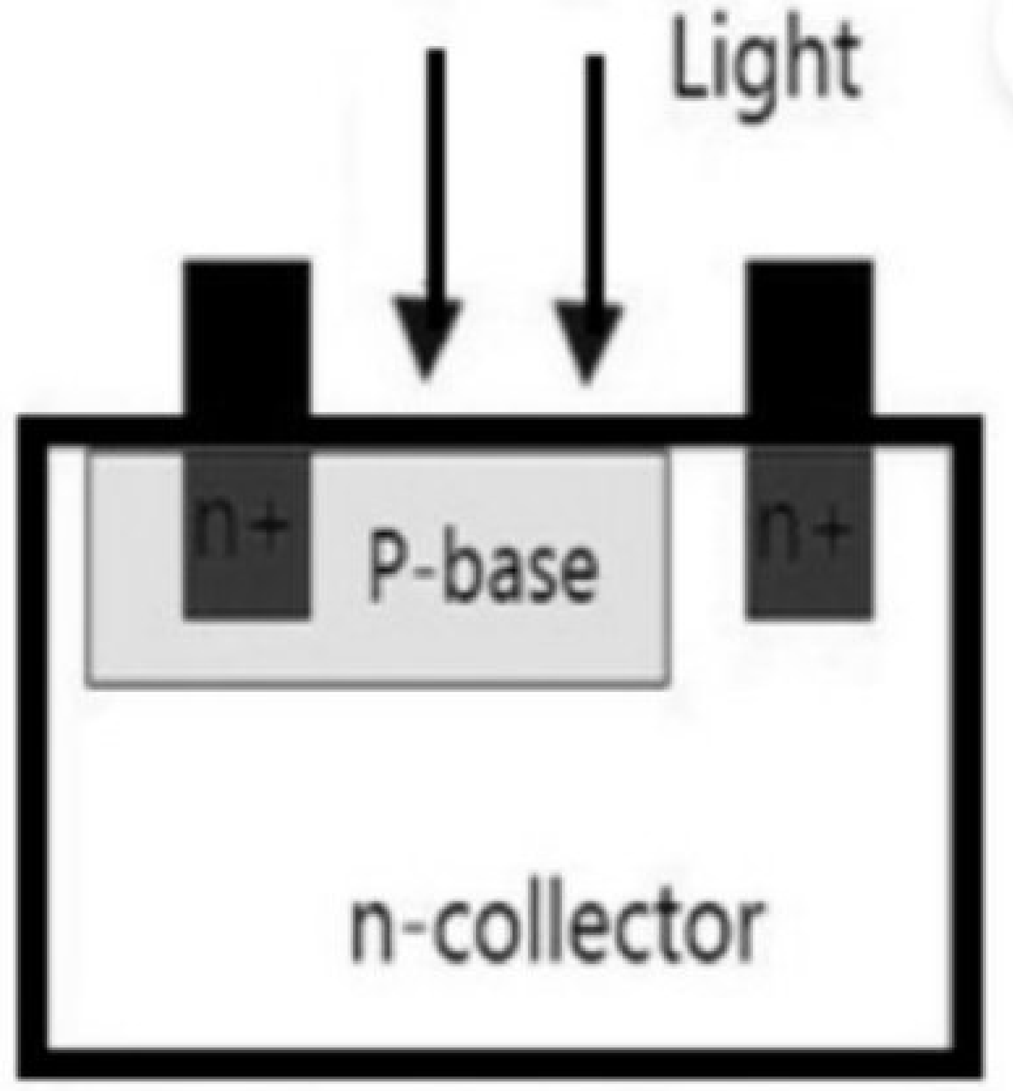
1. It is used for detection of both visible as well as invisible light rays. Photodiodes are used for the communication system for encoding and demodulation purpose.

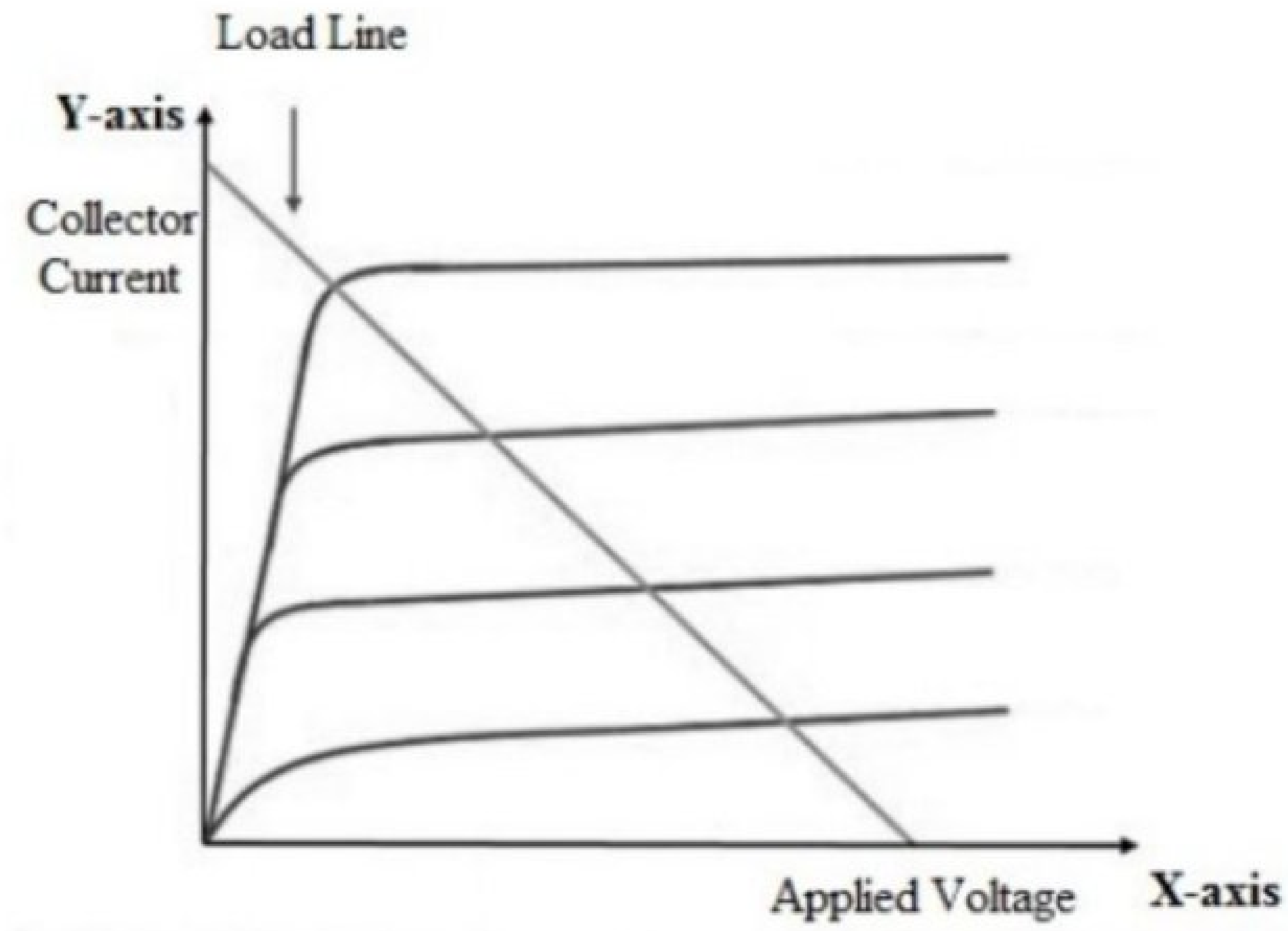
2. It is also used for digital and logic circuits which require fast switching and high-speed operation.

3. These diodes also find application in character recognition techniques and IR remote control circuits.

Scanned with OKEN Scanner

Phototransistor: Construction and Working





Construction: The phototransistor construction can be done like an ordinary transistor apart from the base region. In this type of transistor, the flow of current to the base region is not provided, but the light energy can be used as the input. In this type of transistor, the base to collector junction size is higher because it is a light-sensitive area of the sensor. Since the size of the junction is higher, it results in a significantly better junction capacitance. Consequently, these transistors have less frequency response as compared to photodiode despite the high gain.

Working: The light falls on the base terminal of a phototransistor then it induces a little current then the current is amplified through the action of a normal transistor, which results in an extensively large current. The phototransistor is fabricated with a semiconductor material. Once the light falls on the material the charge carriers like holes or electrons of the semiconductor material can cause the current to supply within the base area. The base region of this can be used for transistor biasing.

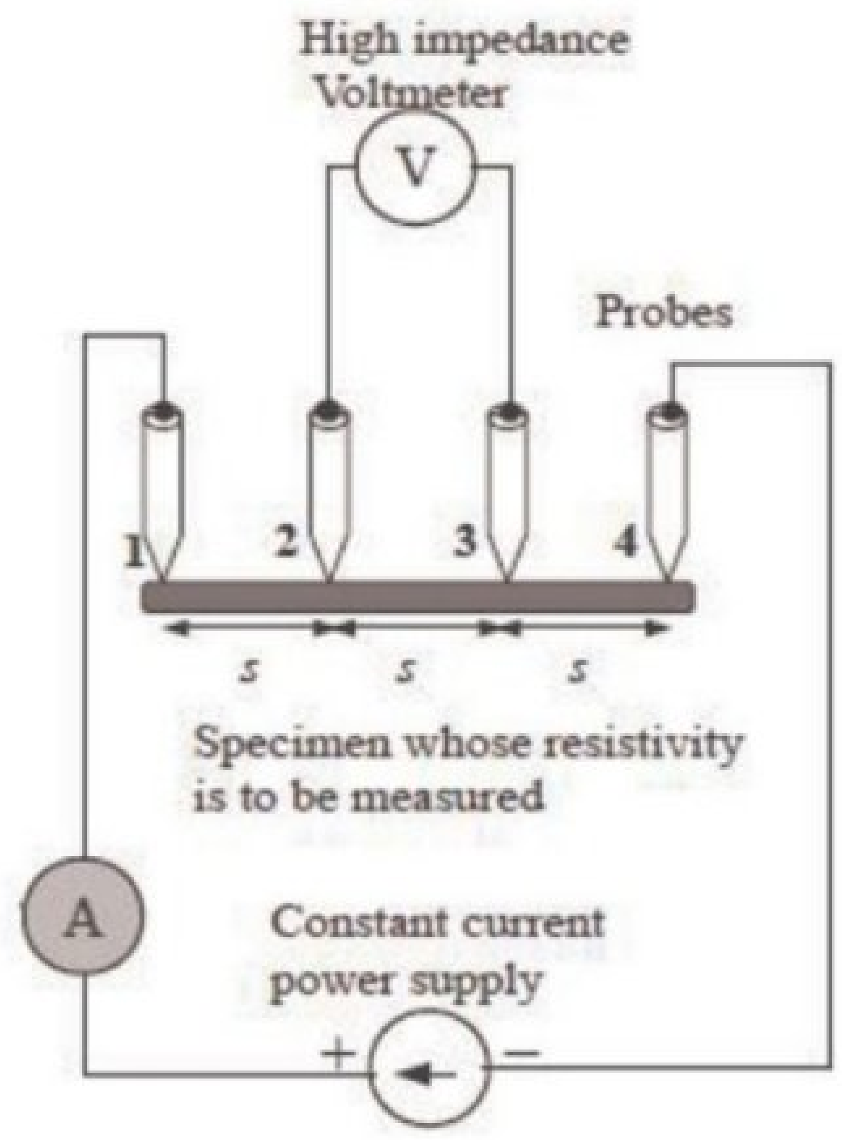
The light penetrates the base terminal of the transistor to produce the pairs of electron-hole in the reverse biasing. The flow of electrons in the pressure of the electric field can cause the current within the base region. This current can be injected with the electrons within the emitter area.

Applications of Phototransistor:

For light detecting and controlling, in counting systems and punch card readers, in relays, alarm systems, level indicators, proximity detectors, encoders.

Scanned with OKEN Scanner

Four Probe Method:



Explanation:

Temperature dependence of resistivity of semiconductor using Four Probe:

This method is employed when the sample is in the form of a thin wafer, such as a thin semiconductor material deposited on a substrate. The sample is millimeter in size and having a thickness w. It consists of four probe arranged linearly in a straight line at equal distance S from each other. A constant current is passed through the two probes and the potential drop V across the middle two probes is measured. An oven is provided with a heater to heat the sample so that behavior of the sample is studied with increase in temperature.

Total electrical conductivity of a semiconductor is the sum of the conductivities of the valence band and conduction band carriers. Resistivity is the reciprocal of conductivity and its temperature dependence is given by,

$\rho = Aexp(\frac{E_g}{2KT})$

Where Eg – band gap of the material

T – Temperature in kelvin

K – Boltzmann constant

i.e., The resistivity of a semiconductor rises exponentially on decreasing the temperature.

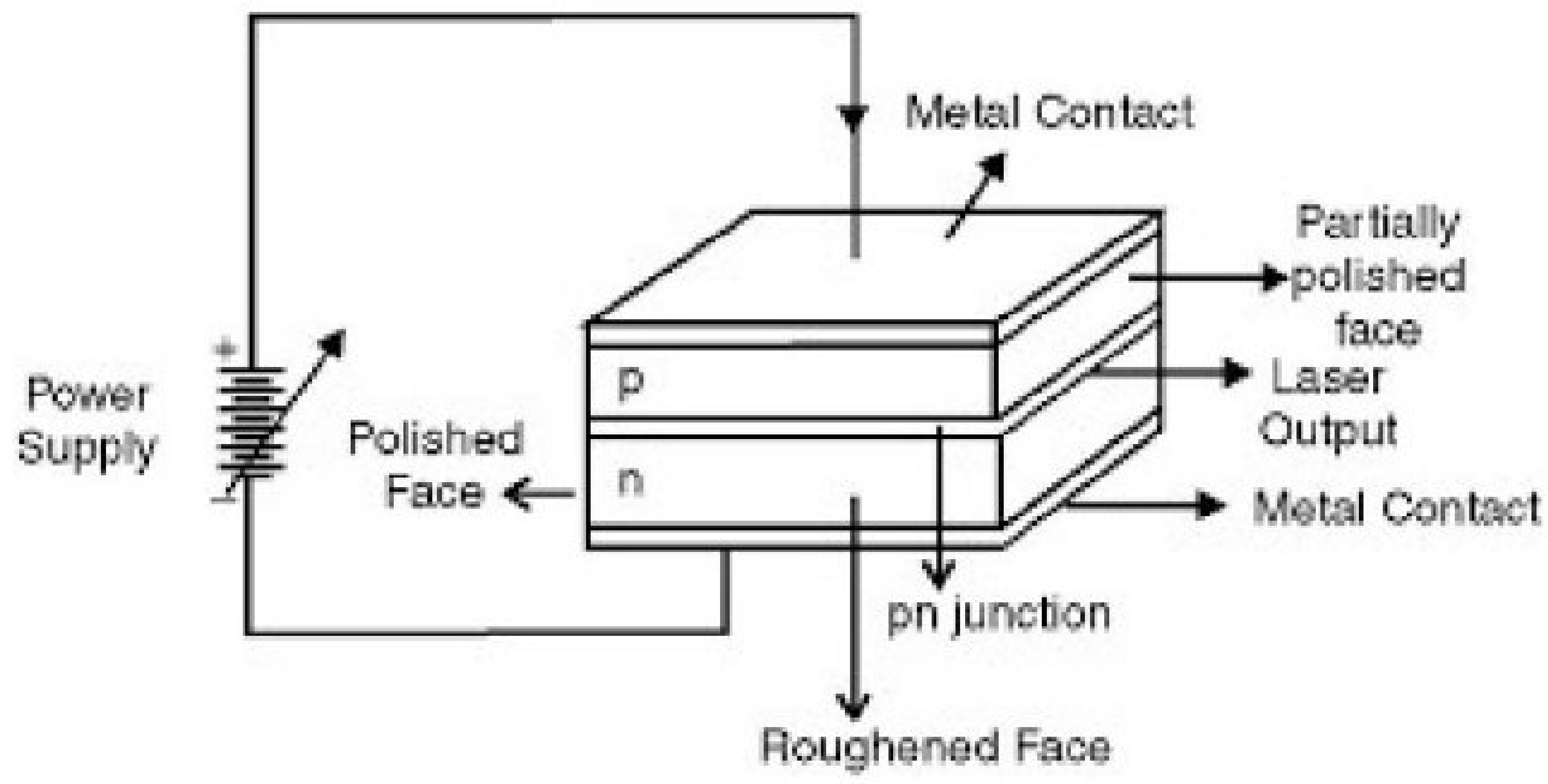
Applications:

1. Remote sensing areas

Scanned with OKEN Scanner

2. Resistance thermometers
3. Induction hardening process
4. Accurate geometry factor estimation
5. Characterization of fuel cells bipolar plates

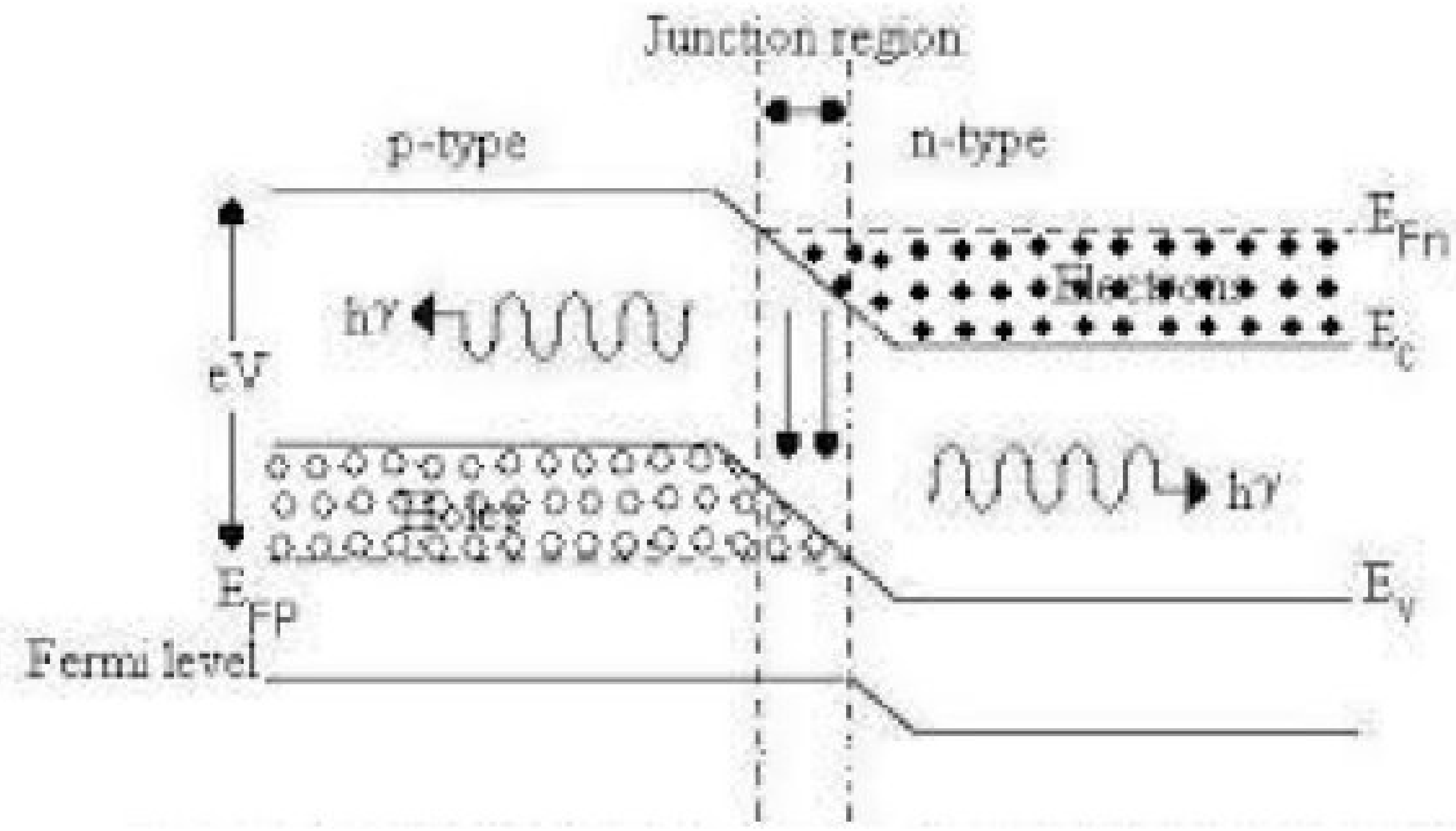
Semi-conductor Laser



- In semiconductor laser the active medium is formulated by semiconducting materials.
- The direct band gap semiconductor materials are used for fabrication since they consume less energy.
- The n and p sections of a diode laser belong to a type of doped semiconductors called as degenerate semiconductors.
- n-type is doped with tellurium and p-type is doped with zinc.
- Doping concentration varies around $10^{17} - 10^{19}$ atoms $/cm^3$.
- The overall size of the diode is 1mm and the junction layer width varies from 1μm to 100μm .

Scanned with OKEN Scanner

Working: Energy level diagram



- When a diode is forward biased with a voltage nearly equal to the energy gap voltage, electrons from the n-region and holes from the p-region flow across the junction.
- As the density of holes and electrons increases across junction region the population inversion is achieved in active region.
- Since Gallium and arsenide has a direct band gap, high concentration of electron-hole recombination takes place in the region which causes spontaneous emission of photons initially.
- The photons emitted due to spontaneous emission may either interact with valence band electrons and be absorbed or interact with conduction band electrons thereby stimulating radiative recombination *i.e,* stimulated emission.
- The GaAs laser emits light at $900nm$ (IR) while GaAsP emits the laser of wavelength $650nm$.
- The wavelength of laser light emitted through semiconductor laser can be calculated by using the formula $\lambda = \frac{hc}{E_g}$.

Scanned with OKEN Scanner