Optical Devices

Semiconductor devices can be designed and fabricated to detect and generate optical signals (detect; solar cells and photodetectors convert optical power into electrical power): (generate; light emitting diodes and laser diodes convert electrical power into optical power).

The characteristics of solar cells and photodetectors are a function of optical energy, which is absorbed in a semiconductor and generates excess electron-hole pairs producing photocurrent. The excess carriers are separated very quickly by the electric field so that a photocurrent is generated.

The inverse mechanism of photodetector is electroluminescence. Excess carriers are generated and then recombine, which may result in the emission of photons in a forward biased pn junction, such as light emitting diode (LED) and Laser diode.

The energy of photon is given by

$$E_{(eV)} = \frac{12400}{\lambda_{(nm)}}$$

There are several possible photon-semiconductor interaction mechanisms. When photon collides with a valence electron, enough energy may be imparted to elevate the electron into the conduction band. Such a process generates electron-hole pairs and creates excess carrier concentration.

If the photon energy (hf) is equal E_g, the photon can interact with valence electron and elevate the electron into the conduction band. This interaction creates an electron in conduction band and hole in valence band an electron-hole pair. When $hf > E_g$ an electron-hole pair is created and the excess energy may give the electron or hole additional kinetic energy, which will be dissipated as heat in the semiconductor.

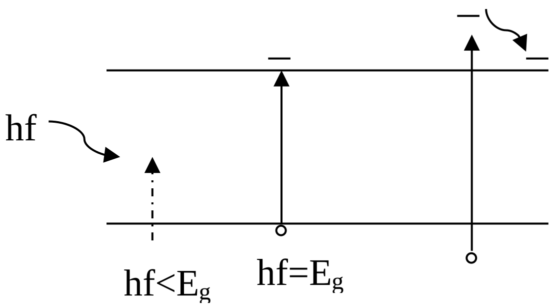

Fig. 15.1 Optically generated electron-hole formation in a semiconductor.

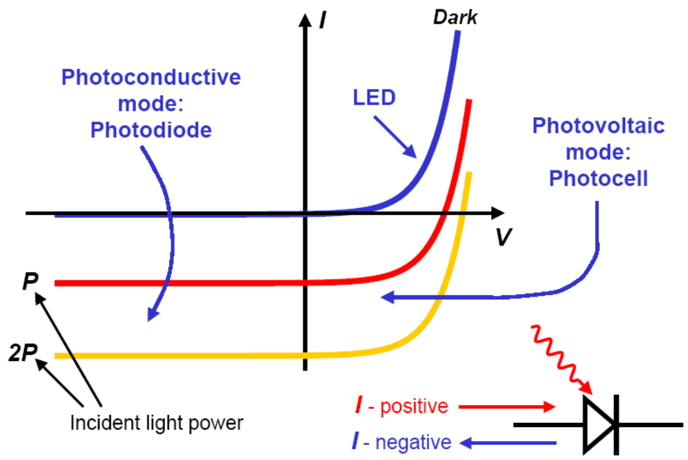

Fig. 15.2 Current-voltage characteristics of optoelectronic diodes

Solar Cells

Photovoltaics (PV) for short, is a solar power technology that uses solar cells or solar photovoltaic arrays to convert light from the sun directly into electricity. A solar cell is the smallest basic solar electric device, which generates electricity when exposed to light. The current-voltage (IV) characteristics are generally measured in the dark as well as under monochromatic and solar spectrum illuminations. In the dark, the cell displays regular diode-like characteristics with the curve passing through the origin. Under illumination, a non-zero photocurrent, called the short circuit current (I_{sc}), is observed for zero applied voltage. The value of the external bias at which the photocurrent is zero is called the open circuit voltage (V_{oc}) and when the biasing crosses this value, majority carriers take over and an exponentially increasing current in the forward bias direction.

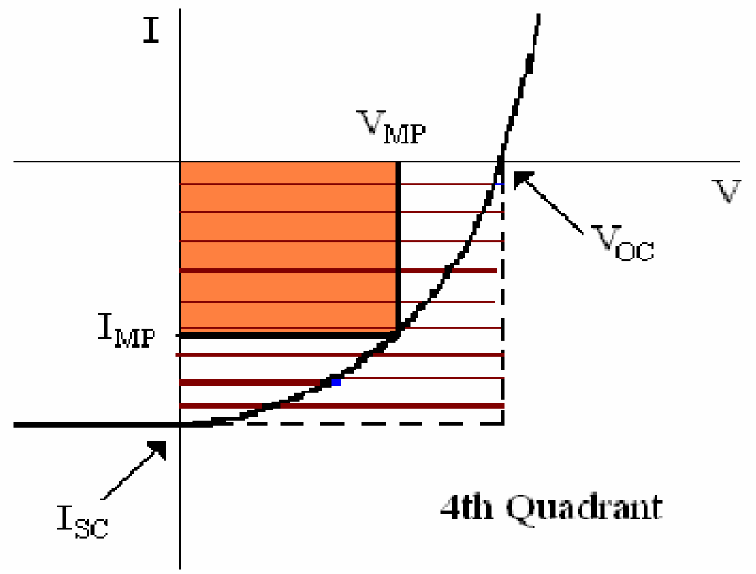

Fig. 15.3 The IV characteristics of Solar cell.

The fill factor (FF), which is the measure of the quality of the IV characteristics of a solar cell, is then given by:

$$FF = \frac{P_{\max}}{P_{ideal}} = \frac{V_{MP} I_{MP}}{V_{oc} I_{sc}}$$

The power conversion efficiency (η), which is the overall efficiency of a solar cell under illumination, is given by:

$$\eta = \frac{P_{\max}}{P_{source}} = \frac{V_{MP} I_{MP}}{P_{source}} = \frac{FF V_{oc} I_{sc}}{P_{source}}$$

Photodetector

Photodetectors are semiconductor devices that also convert optical power to electrical power.

In this type of device each photon absorbed in the photosensitive semiconductor creates electron-hole pair. The pn junction is the basis of several photodetector devices including photodiode and phototransistor. If electrons and holes are generated within the space charge region of pn junction, then they will separate by the electric field and a current will be produced.

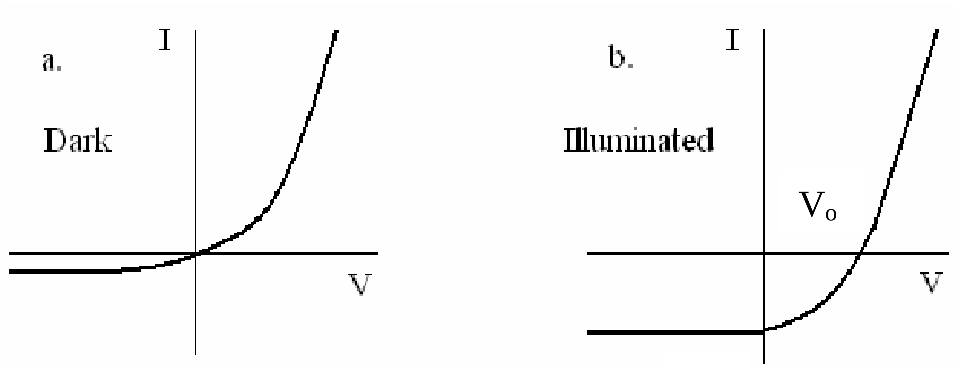

Fig. 15.4 The IV characteristics of photodiode.

Quantum efficiency, (**η**) of a photodetector is defined as the number of carriers (electron-hole pairs) collected to produce the photocurrent (I_{ph}) generated per the number of incident photons. The equation of quantum efficiency is given by

$$\eta = \frac{I_{ph}/e}{P_{inc}/hf} = \frac{I_{ph}}{e} \cdot \frac{hf}{P_{inc}}$$

where P_{inc} is the incident optical power.

Responsivity of the detector is the ratio of the photocurrent flowing in the detector to the incident optical power:

$$R = \frac{I_{ph}}{P_{inc}}$$

Then, responsivity can be rewritten as

$$R = \frac{\eta e}{hf} = \frac{\eta e \lambda}{hc} = \frac{\eta \lambda_{(\mu m)}}{1.24}$$

For a given value of quantum efficiency, the responsivity increases linearly with wavelength.

Luminescence

The figure shows the electromagnetic spectrum of the optical region. The detectable range of light by the human eye extends only from approximately 0.4μm to 0.7μm. The figure shows the major color band from violet to red in the expand scale.

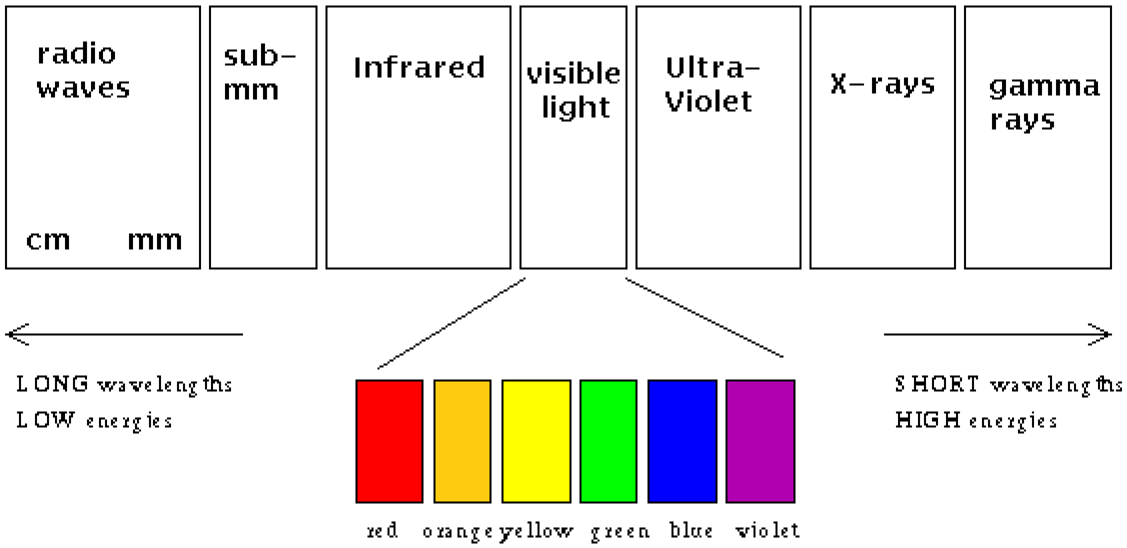

Fig. 15.5The Electromagnetic Spectrum. Notice how small the visible region of the spectrum is, compared to the entire range of wavelengths.

Luminescence Mechanism

There are three processes for the interaction between a photon and electron in a solid: absorption, spontaneous emission and stimulated emission. Consider two energy level E_1 and E_2 of an atom, where E_1 corresponds to ground state and E_2 corresponds to excited state. Any transition between these states involves the emission or absorption of a photon with frequency f is given by $hf=E_2-E_1$.

An atom in state E_1 absorbs the photon and thereby goes to the excited state E_2. The change in the energy state is the absorption process, as shown in the figure. The excited state of the atoms is unstable. After short time, without any external stimulus, it makes transition to the ground state, giving off a photon of energy *hf*. This process called spontaneous emission, which shown in the figure (b). When a photon of energy *hf* react with an atom while it is in the excited state, as shown in the figure (c), the atom can be a stimulated to make a transition to the ground state and gives off a photon of an energy *hf* which in phase with the incident radiation. This process called stimulated emission. The radiation from stimulated emission is monochromatic because each photon has the same energy *hf* and is coherent because all photons emitted are in phase.

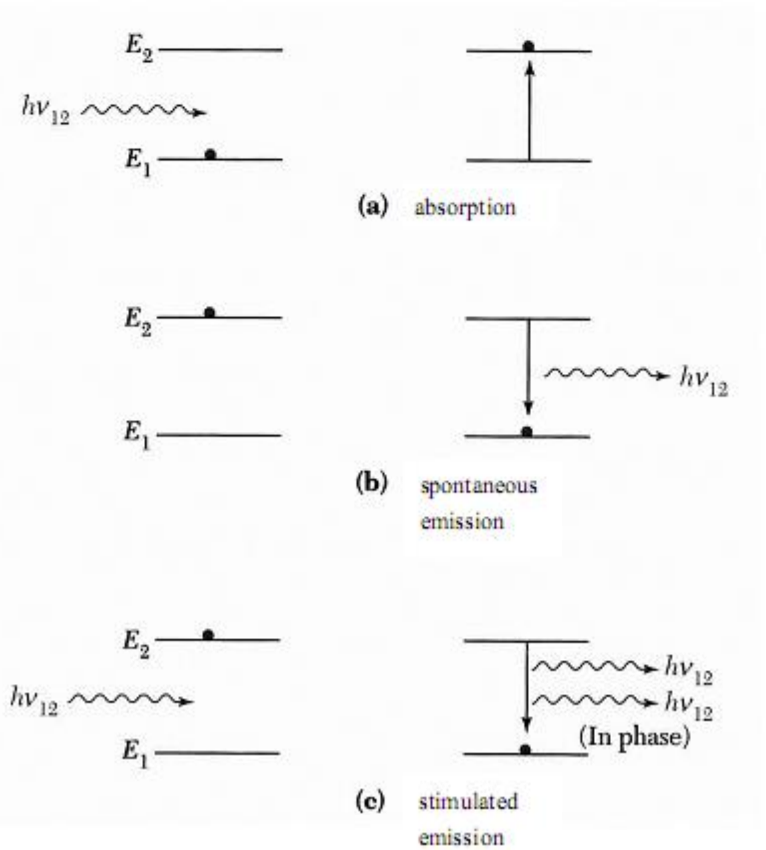

Fig. 15.6 Diagram showing (a) induced absorption, (b) spontaneous emission and (c) stimulated emission processes.

Light Emitting Diode (LED)

The LED converts input electrical energy into output optical radiation in the visible or infrared region of spectrum, depending on the semiconductor material. The wavelength of light emission required usually dictates the semiconductor materials required in terms of their bandgap energy. Lower bandgap materials are required for infrared applications, and larger bandgap materials are needed for a light source in the visible part of spectrum.

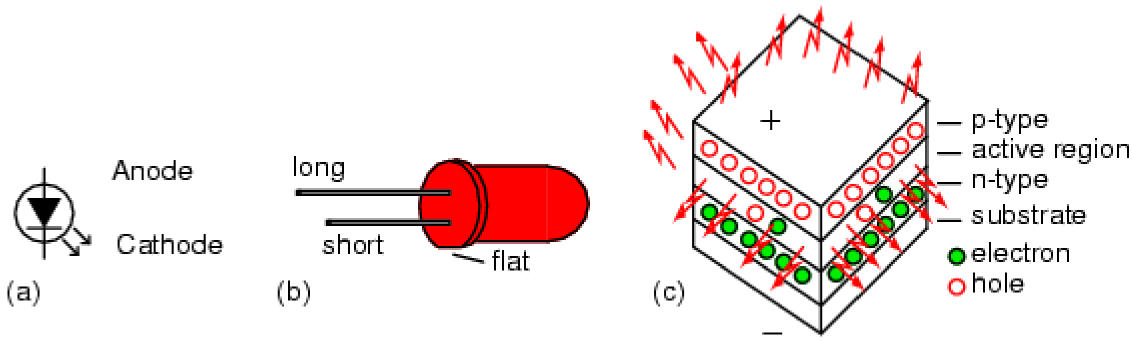

Fig. 15.7 Symbol of the LED, (b) typical LED, and (c) LED construction shown in the figures.

Laser diode

LASER is an acronym for Light Amplification by Stimulated Emission or Radiation. The laser, in principle, is an optical wave terminated by mirrors or reflecting facets to form a resonant cavity. In stimulated emission, if there is an incident photon at the time when an electron is in the higher energy as shown in the Fig. 15.6 (c), 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 called stimulated emission. Note that, this stimulated emission process has produced two photons; thus, we can have optical amplification. The two emitted photons are in phase so that the spectral output will be coherent.

The Tunnel Diode

Degenerate and Nondegenerate Semiconductors

In previous extrinsic semiconductors we assumed that the concentration of dopant atoms added is small when compared with the density of host semiconductor. There is no interaction between donor electrons in n-type semiconductor, so we have assumed that the impurities introduce discrete donor energy state in the n-type. Similarly, for p-type semiconductor. These types of semiconductors are referred to as nondegenerate semiconductor. If the impurity concentration increases, the distance between the impurity atoms decreases and will begin interacting with each other. When this occurs, the single discrete donor energy will split into a band of energies. As the donor concentration further increases, the band donor state widens and may overlap the bottom of the conduction band and the Fermi level lies within the conduction band. In similar way, in p-type the Fermi level will lie within the conduction band. These types of semiconductors are referred to as degenerate semiconductor.

The Tunnel Diode

The tunnel diode is a pn junction in which both the n and p regions are degenerately doped, the figure shows the energy band diagram of a pn junction in thermal equilibrium and the typical IV characteristics. The depletion region width decreases as the doping increase.

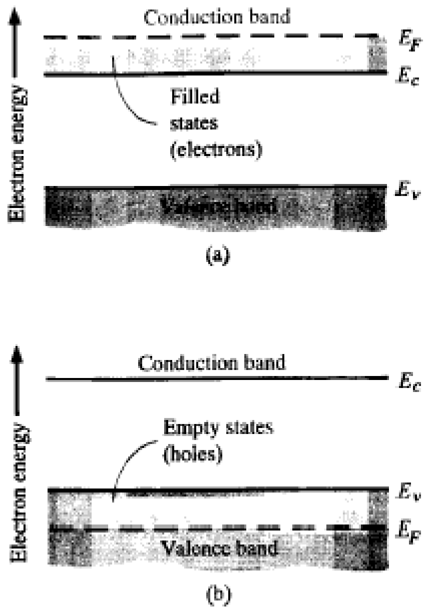

Fig. 15.8 Simplified energy band diagram for degenerate doped (a) n- type semi-conductor (b) p- type semi-conductor

$$W = \left\{ \frac{2\varepsilon_s V_{\text{bi}}}{e} \left[\frac{N_a + N_d}{N_a N_d} \right] \right\}^{1/2}$$

The barrier width is small and the electric field in the space charge region is quite large: the electrons may tunnel through the forbidden band from one side of junction to the other. The IV characteristics of this device has a negative resistance. From IV characteristics we see that the tunnel diode is an excellent conductor in the reverse condition. Also, for small forward voltages, the resistance remains small. At peak point I_p corresponding to the voltage V_p. If the V is increased beyond V_p, then the current decreases. As consequences the device exhibit a negative resistance between the peak current I_p and minimum value I_v called a valley current. At larger voltages the current increases.

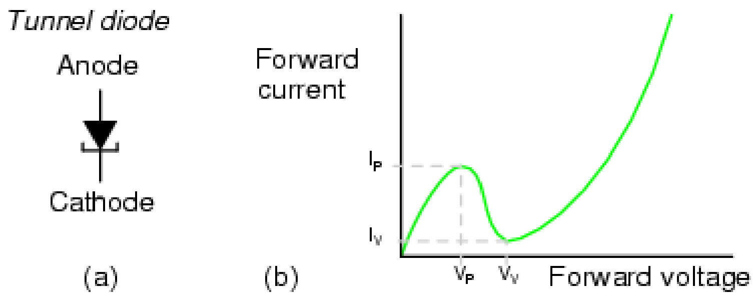

Fig. 15.9 (a) Symbol and (b) IV characteristics of the tunnel diode,

Varactor Diode

We observe from the equation of junction capacitance is not a constant but varies with applied voltage. The larger the reverse voltage, the larger is the space charge width W, and hence smaller capacitor. The voltage variable capacitance of pn junction biased in the reverse direction is useful in several circuits. Diodes made for such applications which are based on the voltage variable capacitance are called varactor or varicap diode.

$$C' = \left\{ \frac{e\varepsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)} \right\}^{1/2} = \frac{\varepsilon_s}{W}$$

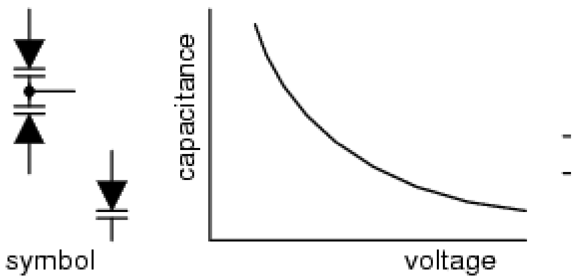

Fig. 15.10 (a) Symbol and (b) CV characteristics of the varactor diode,

Problems

Q1: Identify the photodetector enrich your explanation with related equations and diagrams

Q2: Identify the solar cell with related equations and diagrams.

Q3: Identify the following with related equations and diagrams

1) The process for the interaction between a photon and electron in a solid.
2) Degenerate semiconductors give an example of a device use such type of the semiconductors.