Chapter 5

Optoelectronic Devices

CHAPTER HIGHLIGHTS

- *Photo Conductivity*
- *Photo Diode*
- *V – I Characteristics*
- *Avalanche Photo Diode*
- *PIN Photo Detectors*
- *Light Emitting Diodes (LED)*
- *Liquid Crystal Displays (LCD)*
- *Photo Voltaic or Solar Cells*
- *LASER*
- *Unique Characteristics of LASER Light*

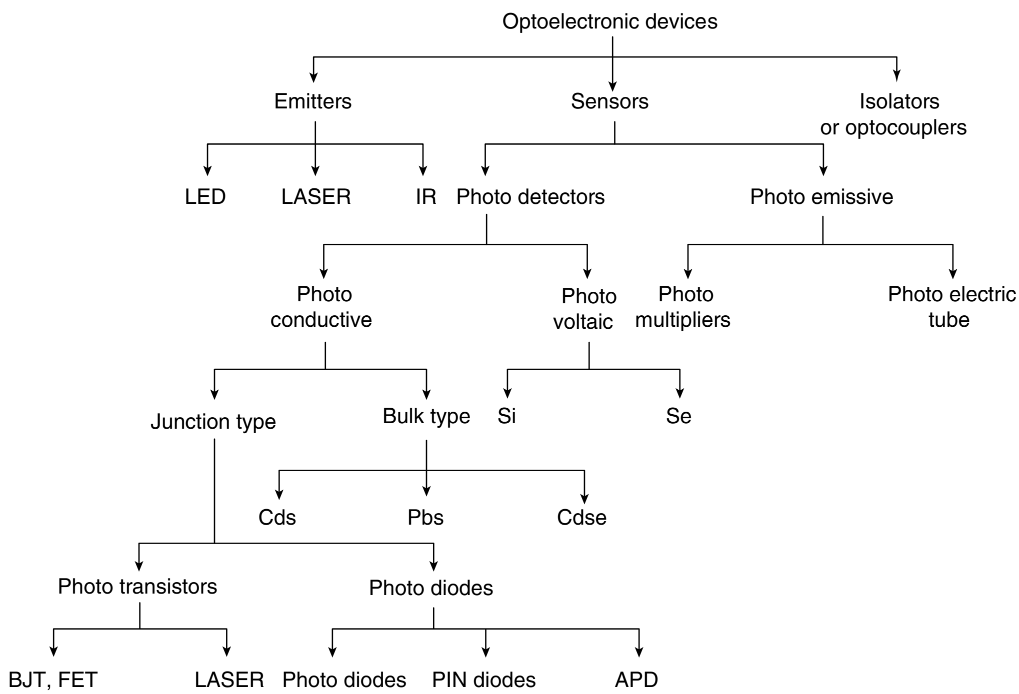
Introduction

Optoelectronics is the technology that combines optics and electronics, and the devices based on this technology are known as optoelectronic devices.

These devices are broadly classified as follows:

1. Devices that convert optical radiation into electrical energy such as photovoltaic device or solar cell.
2. Devices that detect optical signals through electronic processes such as photodetectors.
3. Devices that convert optical energy into optical radiation such as light-emitting diodes and the LASER diodes.
   - The devices that convert electrical energy into optical radiations are known as emitters.
   - Photo detectors are the semiconductor devices that can be used to detect the presence of photons and convert optical signals into electrical signals.

The photo conductors in which the photons-generates excess electron–hole pairs. It changes the conductivity of a semiconductor.



- According to the Quantum theory, light consists of discrete packets of energy called photons.

$$\therefore E = h\vartheta = \frac{hC}{\lambda} = hf$$

Where h is plank's constant
$h = 6.625 \times 10^{-34}$ J s
$\lambda \rightarrow$ wave length in meters
$C \rightarrow$ light velocity

$$\therefore E_G \leq \frac{1.24\text{eV}}{\lambda(\mu\text{m})}$$

In a forward bias p–n junction, electrons and holes both cross the junction. In this process, some electrons and holes recombine with the results that electrons lose energy; the amount of energy lost is equal to the energy band gap of semiconductor E_G.

At room temperature, the value of E_G is
For Si $\Rightarrow E_G = 1.1$ eV
Ge $\Rightarrow E_G = 0.72$ eV
GaAs $\Rightarrow E_G = 1.43$ eV
and INAS $\Rightarrow E_G = 0.36$ eV

Photo Conductivity

If radiation falls upon a semiconductor, its conductivity increases. This is called photoconductive effect. Radiant energy supplied to the semiconductor causes covalent bonds to be broken, and new electron–hole pairs in excess of those generated thermally are created. These increased current carriers decrease the resistance of the material, and hence, such a device is called a photoresistor or photoconductor.

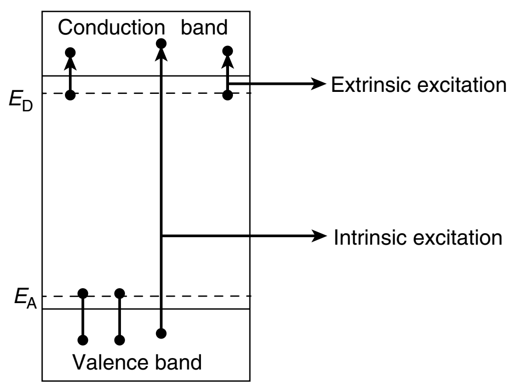


Figure 1 Photo excitation in a semiconductor

In the above figure, the energy band diagram of a semiconductor having both acceptor and donor impurities is shown. If photons of sufficient energies are illuminated on this specimen, then following transitions are possible:

1. An electron–hole pair can be created by a high-energy photon—what is called intrinsic excitation.
   i.e., the excitation takes place directly from valance band to conduction band. This is known as intrinsic excitation.
2. A photon may excite a donor electron into conduction band or a valance electron may go into an acceptor state. These transitions are known as impurity excitations.
   The minimum energy of a photon required for intrinsic excitation is the forbidden energy gap E_G of the semiconductor material.

$$\lambda = \frac{1.24}{E_G(\text{eV})}\mu\text{m}$$

For Si, $E_G = 1.1$ eV and $\lambda = 1.13$ µm
For Ge, $E_G = 0.72$ eV $\Rightarrow \lambda = 1.73$ µm at room temperature

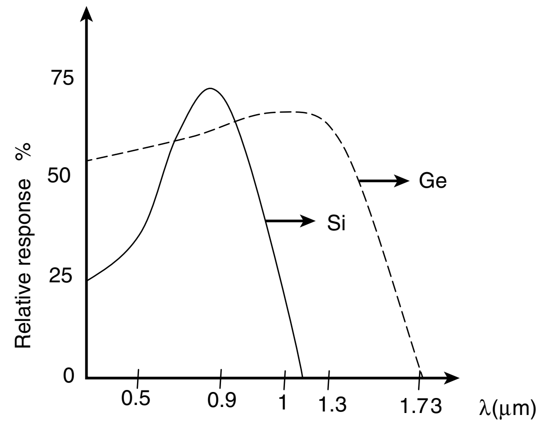


Figure 2 Relative response of Si and Ge

Solved Examples

Example 1

The longest wavelength that can be absorbed by Si, which has the band gap of 1.12 eV, is 1.1 µm. If the longest wave length that can be absorbed by another material is 0.87µm, then the band gap of this material is

(A) 1.425 eV (B) 0.85 eV
(C) 0.706 V (D) 1.23 eV

Solution

We know $E_G = \dfrac{1.24\text{eV}}{\lambda(\mu\text{m})}$

Given $\lambda = 0.87$ µm,

So $E_G = \dfrac{1.24\text{eV}}{0.87} = 1.425$ eV

Photodiode

If a junction diode is reverse biased, then conduction occurs due to the minority charge carriers only. The reverse, saturation current is practically of constant magnitude, which is irrespective of the applied reverse bias. If the temperature of the junction increases, then evidently the reverse saturation current also increases as new electron–hole pairs are created due to incident thermal energy; the same effect is caused with incident light also.

V – I Characteristics

Photodiode operates in the reverse bias mode, there is an arrangement by which light is allowed to fall on the particular surface across the junction through a window, the diode is kept enclosed within a plastic container. Except for the surface that receives the radiant energy, the other sides are painted black.

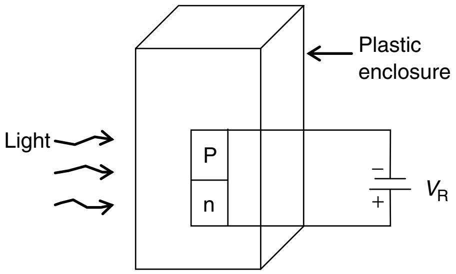
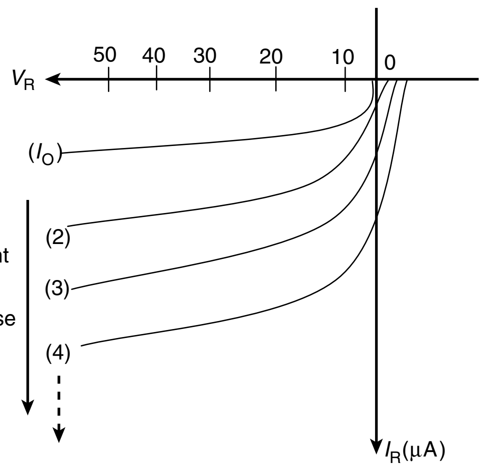
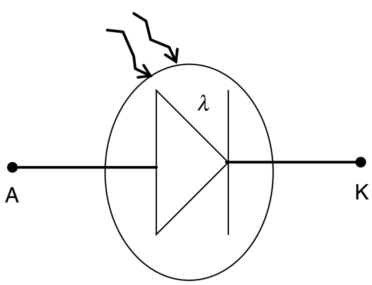


Figure 3 Structure of a photodiode

When light, which consists of photons, is incident on the junction surface, additional electron–hole pairs are created due to the fact that valance electrons acquire energy from the photons. This has the effect of increasing the reverse current. It depends on the incident photon energy at the junction. The $V-I$ characteristic of a photodiode is as shown below.



Where I_0 is the dark current, in the absence of incident light or photon energy.



Photodiode symbol.

Typical values of the parameter of a photodiode
Diode forward resistance $R_f = 100\ \Omega$
Reverse resistance $R_r = 50\ \text{n}\Omega$ and
$C_T = 10$ pF

Applications

1. Optoelectronic applications. They are used in light-operated switches, light detection systems, for reading of sound track on films, and for counting objects in a production line.
2. They are used in high-speed reading of computer punched cards and tapes.

Avalanche Photodiode

Avalanche photodiode is also a photodetector. A photodiode will produce less amount of current, which is not sufficient to drive some circuits. An avalanche photodiode (APD) gives more output current when compared to a photodiode. The 'impact ionization' takes place In APDs.

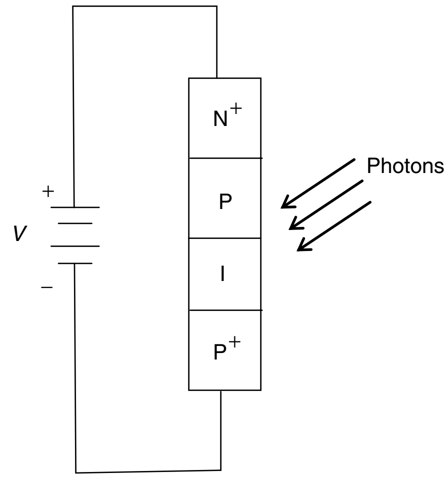
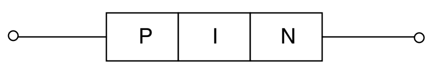


Figure 4 structure of an APD

PIN Photodetectors

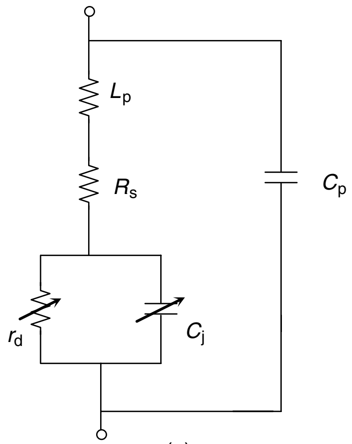
A PIN diode is composed of three sections. A high resistivity intrinsic layer is sandwiched between P- and N-regions. The high resistance of the intrinsic layer provides the possibility of larger electric field between the P- and N-regions, and therefore, electron–hole pair generation is enhanced by enabling PIN diode to process even very weak input signals. Because of more separation between P- and N-regions, the capacitance C_{pn} is reduced because the capacitance decreases with the increase in separation of P- and N-regions. It allows the diode a faster response time, thereby making it suitable for use as a microwave switch.



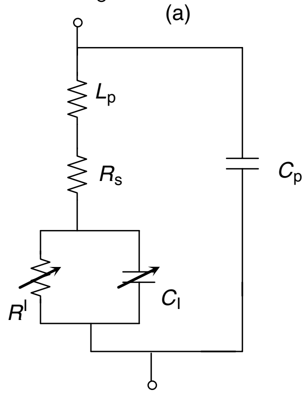
PIN diode

PIN diode in the forward bias mode offers a variable resistance—decreasing with the increase in forward current. For larger d.c. current, it will appear like a short. In reverse bias mode, it offers infinite resistance.

The equivalent circuit of a PIN diode at d.c. or low frequency operation is similar to a conventional P-N junction in Figure (a). Here L_p and C_p represent the package inductance and capacitance, respectively. C_j represents the junction diode capacitance. However, the effect of junction capacitance may be neglected for most of the applications of PIN diodes under forward bias operation. Since the dynamic resistance is very large and $C_j \approx C_T$ under reverse bias operation, the effect of dynamic resistance can be neglected, and therefore, the PIN diode behaves simply as a parallel plate capacitor of capacitance C_T in its reverse bias operation.



(a)



(b)

High frequency model

At high frequency, C_I represents the capacitance of the I region, which is approximately equal to C_T and depends on the geometry of the I region. R_I is the effective RF resistance of the I region and represents the value at the operating frequency of the RF signal.

When a light intensity of wavelength λ is incident on the photodiode, if energy $E_g < h\vartheta$ of PIN diode, then an output current 'I_p' in response to the incident light is produced.

$$\text{efficiency } \eta = \frac{\text{No.of } e^- - \text{hole pairs generated}}{\text{No.of photons incidented}}$$

$$\eta = \frac{(I_p/q)}{(P_0/hf)}$$

$$\text{Responsivity } R = \frac{I_p}{P_0} = \frac{\eta q}{hf} \text{ A/watt}$$

$$\text{Maximum wave light } \lambda_{max}(\mu\text{m}) = \frac{1.24}{E_G(ev)}$$

Where

$f \rightarrow$ frequency of incidence photon

$P_o \rightarrow$ incident optical power

$I_P \rightarrow$ photocurrent generated in PIN diode

$\therefore$ The main drawback of photodiode is the low output current.

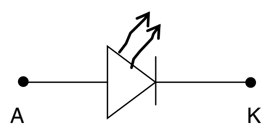
Light Emitting Diodes

The operation of light emitting diodes (LED) is based on the phenomenon of electro luminance, which is the emission of light from a semiconductor under the influence of an electric field. The recombination of charge carriers takes place in a forward P–N junction as the electron crosses from the N-region and recombines with the holes existing in P-region. Free electrons are in the conduction band, whereas holes are in the valence band. Therefore, the electrons are at high energy levels than holes. For the electrons to recombine with holes, they must give some of their energy. Typically, these electrons give up energy in the form of heat and light. In silicon and germanium diodes, most of the electrons give up their energy in the form of heat. However, with GaAsP and GaP semiconductors, the electrons give up their energy by emitting photons. If the semiconductor is translucent, then the light will be emitted and the junction becomes a source of light, that is, LED.

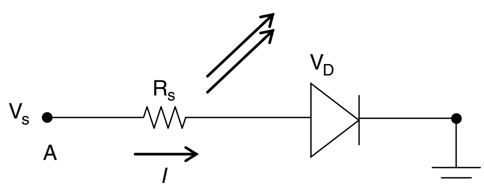
i.e. the electrons are at high energy levels than the holes. In the process of recombination of the electrons to holes, they must give energy in the form of heat and light but these are constructed by using direct band gap semiconductors. Hence, they are dissipated energy in the form of light.

- In Si and Ge diodes (indirect band gap S.C), most of the electrons give up their energy in the form of heat.
- In GaAsP, GaAs, GaP, and InP semiconductors, the electrons give up their energy by emitting photons (direct band gap S.C).
- LEDs operate the forward biasing with a current of 20 mA.

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



(a) LED symbol



(b) LED circuit

$$I = \frac{V_S - V_D}{R_s}$$

- LEDs are forward biased P–N junctions, which emit 'Spontaneous radiation'.
- The colour of the emitted light depends on the type of material used, which is given below.

Colour	Construction	Typical forward voltage V_f (volts)
Amber	Al Gap	2.1
Blue	GaN	5
Red	GaAsP	1.8
Green	GaP	2.2
Yellow	AlGaP	2.1
White	GaN	4.1

The visible wavelength ranges from 0.45 μm to 0.7 μm (energy 2.8 eV to 1.8 eV)

Applications

LEDs are used in remote controls, as display devices in designing optocouplers.

The LED emits light of a particular colour because the band gap of the semiconductor material used in the fabrication of the diodes is equal to energy $h\vartheta$ of the light photon.

Liquid Crystal Displays

1. LCDs operate on the principle of dynamic scattering of light.
2. Power dissipation is in the order of μW.
3. Response time is in m sec.
4. Its operating life time is 50,000 + hours
5. These are used as display devices.

Example 2

Photons of energy 1.5×10^{-18} Joules are incident on photodiode that has a responsivity of 0.7 A/W. If the optical power level is 10μW, then the photocurrent generated is

(A) 70 ηA (B) 7 μA
(C) 6.5 μA (D) 6.5 ηA

Solution

We know that responsivity $R = \frac{I_p}{I_0}$

$$\therefore I_P = R.I_0 = 0.7 \times 10\ \mu\ \frac{A}{W}$$

$$= 7\ \mu A$$

Photovoltaic or Solar Cells

These cells are semiconductor junction devices used for converting radiation energy into electrical energy. These cells generate a voltage proportional to electromagnetic radiation intensity and are called the photovoltaic cells. Selenium and Si are the most widely used materials for solar cells.

- The working principle of solar cell is 'photovoltaic effect'.
- Popularly used solar cells are se cells, Ni–cd cells, and pbs cells.
- Ni–cd cells are rechargeable cells used in satellites.
- These are used in automatic traffic signal lighting.
- These are generally operated under open circuit condition. It can be operated in forward biased condition and has cut in voltage equal to zero.

Laser

Laser is the short form of 'Light Amplification by Stimulated Emission of Radiation'. A laser emits radiation of essentially one wavelength or a very narrowband of wave lengths. This means that the light has a single colour, that is, mono chromatic.

In a laser, the atoms are struck by photons (or packets of energy) that are exactly similar to the photons of energy emitted when recombination occurs. This triggers energy emission and the result is two identical photons for each recombination: the incident photon and the emitted photon. The photons produce further emission of similar photons, which in turn generate more similar photons. The result is emission of energy in the form of a beam of coherent light.

- LASER light is referred to as coherent light as opposed to light made up of a wide band of wavelengths, which is termed as incoherent.
- LASERs are fabricated with direct band gap materials having larger carrier life time.
- Emission in LASER is both spontaneous and stimulated.
- Population inversion occurs in LASER. These are highly directional.
  The primary requirement is the population inversion, that is, the higher energy level is more populated than the lower energy level.

Unique Characteristics of LASER Light

The beam of LASER light produced by the diode has the following unique characteristics:

1. It is coherent, that is, there is no path difference between the waves comprising the beam.
2. It is monochromatic, that is, it consists of one wavelength and hence one colour only.
3. It is collimated, that is, light waves travel parallel to each other.

NOTE

	Diode	Operating bias
1.	Photodiode, APD	Reverse bias
2.	LED, LASER, and solar cells	Forward bias

Example 3

A PIN diode is frequently used as a

(A) Peak clipper (B) voltage regulator
(C) harmonic generator (D) fast switching diode

Solution: (D)

Example 4

Match List-I with List-II.

	List-I		List-II
P.	LED	1.	Coherent radiation
Q.	LASER	2.	Spontaneous emission
R.	APD	3.	Current controlled attenuator
S.	PIN diode	4.	Current gain

(A) P – 2, Q – 1, R – 4, S – 3
(B) P – 1, Q – 2, R – 4, S – 3
(C) P – 2, Q – 1, R – 3, S – 4
(D) P – 1, Q – 2, R – 3, S – 4

Solution: (C)

Example 5

Match Group-I with Group-II.

	Group-I		Group-II
P.	JFET	1.	Population inversion
Q.	MOS capacitor	2.	Pinch-off voltage
R	LASER diode	3.	Early effect
S.	BJT	4.	Flat-band voltage

(A) P – 2, Q – 4, R – 3, S – 1
(B) P – 2, Q – 3, R – 1, S - 4
(C) P – 2, Q – 1, R – 4, S – 3
(D) P – 2, Q – 4, R – 1, S – 3

Solution: (D)

Exercises

Practice Problems I

Direction for questions 1 to 12: Select the correct alternative from the given choices.

1. Photodiode output electrical power is maximum under
   (A) large reverse bias across it
   (B) small forward bias exists across it
   (C) small reverse bias exists across it
   (D) small forward current flows through it, irrespective of bias

2. The efficiency of light generation in LED depends on __________
   (A) increase with injected current
   (B) decrease in temperature results increase in efficiency
   (C) independent of injected current and temperature
   (D) Both (A) and (B)

3. A Schottky junction is formed between the gold and silicon with cross-sectional area $A = 4 \times 10^{-4}$ cm^2. Assume that electron affinity of silicon is 4.01 eV and work function of the gold is 5.1 eV. Then Schottky barrier at the junction is __________
   (A) 1.09 eV (B) 1.09 volts
   (C) 1.74 volts (D) None of the above

4. A silicon APD has a quantum efficiency of 70% at the radiation wavelength of 700 nm. Then the photon current is __________ (Given output power = 0.5 µw)
   (A) 0.225 µA (B) 0.1125 µA
   (C) 0.098 µA (D) 0.196 µA

5. For the APD, $\eta = 60\%$ and $\lambda = 700$ nm and $P_0 = 0.6$ µ W, then the responsivity of the detector is __________
   (A) 0.338 A/W (B) 0.338 µA/W
   (C) 0.338 mA/W (D) 0.338 nA/W

6. For the silicon APD of efficiency 60% at the radiation wave length of 700 nm and $P_0 = 0.6$ µw produces an output current of 10 µA, then the gain is __________
   (A) 49.30 (B) 98.60 (C) 147.90 (D) 221.89

7. If a negative potential of 2 eV is applied between the collector and the emitting surface of a metal, then the maximum velocity of emitted electrons is __________
   (A) 3×10^8 m/s (B) 2.09×10^{18} m/s
   (C) 2.09×10^{14} m/s (D) 8.386×10^5 m/s

8. A tungsten surface having a work function of 4.52 eV is irradiated with a mercury line 2,500 A°. Then the maximum speed of emitted electrons is __________
   (A) 1.9667×10^5 m/s (B) 6.603×10^5 m/s
   (C) 13.206×10^5 m/s (D) 3.93351×10^5 m/s

9. The advantage of Schottky barrier diode over normal P–N junction is __________
   (A) higher cut is voltage
   (B) high reverse saturation current density
   (C) low reverse saturation current density
   (D) low cut in voltage

10. Dielectric relaxation frequency of P–I–N diode is __________ given $\sigma_i = 3 \times 10^5 \dfrac{\text{mho}}{\text{m}}$, $\varepsilon_{rs} = 2$.
    Where σ_i and ε_{rs} represent conductivity and relative permittivity of the intrinsic region, respectively
    (A) 27×10^{14} Hz (B) 27×10^{13} Hz
    (C) 2.7×10^{16} Hz (D) 0.27×10^{18} Hz

11. The ratio of $\dfrac{I_p}{I_v}$ is larger in the case of
    (A) Ge tunnel diode (B) Ga As diode
    (C) Si diode (D) None of the above

12. In a forward biased photodiode, an increase in incident light Intensity causes the diode current to

(A) increase
(B) remain constant
(C) decrease
(D) remain constant, whereas the voltage drop across the diode increases

Practice Problems 2

Direction for questions 1 to 14: Select the correct alternative from the given choices.

1. Photovoltaic potential is the voltage at which the current is ___________
(A) zero
(B) maximum
(C) minimum typically 100 mA
(D) independent of current

2. The intensity of light in a LED is maximum when ___________
(A) near to conduction band
(B) near to Fermi level
(C) near to junction
(D) near to valency band

3. A avalanche photodiode is operated under ___________
(A) small forward bias (B) small reverse bias
(C) independent of bias (D) large reverse bias

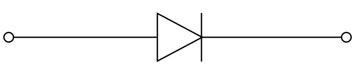
4. The breakdown voltage of APD for the following specifications is ___________; η = 70%, P_0 = 0.5 µm, I_m = 10 µA, and λ = 80 nm. Assume n = 3 and reverse voltage is 5.6 V.
(A) 7.52 volts (B) 6.26 volts
(C) 5.99 volts (D) 5.6434 volts

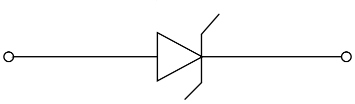
5. Which of the following statements is not true regarding LASER Diode?
(A) Non-coherent
(B) Monochromatic
(C) Collimated
(D) Consists of only one wave length

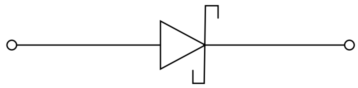
6. Schottky barrier diode is used for ___________
(A) high speed switching applications
(B) high voltage application
(C) low current application
(D) None of the above

7. Diffusion capacitance of Schottky barrier diode is ___________
(A) zero (B) ∞
(C) large value (D) None of the above

8. Symbolic representation of Schottky barrier diode is ___________

(A) 

(B) 

(C) 

(D) None of the above

9. Larger diffusion capacitance is ___________
(A) reverse bias condition
(B) forward bias condition
(C) independent of the bias
(D) near the junction

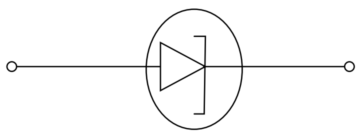
10. Space charge or transition capacitance is ___________
(A) forward bias capacitance
(B) reverse bias capacitance
(C) independent of bias
(D) None of the above

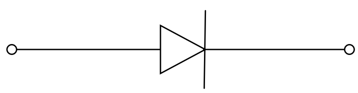
11. The dynamic resistance of a Ge diode for a forward current of 2.6 mA is ___________
(A) 10 Ω (B) 1 Ω (C) 100 Ω (D) 1 kΩ

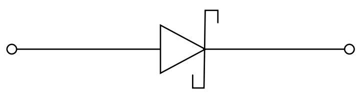
12. Zener breakdown occurs for ___________
(A) $V_z < 6$ V
(B) $V_z > 6$ V
(C) V_z = Volts
(D) independent of V_z

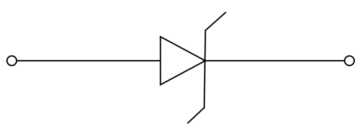
13. Which of the following is not an advantage of tunnel diode?
(A) Low output swing
(B) High speed
(C) Low power
(D) Environmental immunity

14. Circuit symbol of tunnel diode is ___________

(A) 

(B) 

(C) 

(D) 

Previous Years' Questions

1. The longest wavelength that can be absorbed by silicon, which has the band gap of 1.12 eV, is 1.1 μm. If the longest wavelength that can be absorbed by another material is 0.87μm, then the band gap of this material is **[2004]**

(A) 1.416 eV (B) 0.886 eV
(C) 0.854 eV (D) 0.706 eV

2. Group I lists four types of P–N junction diodes. Match each device in Group I with one of the option in Group II to indicate the bias condition of that device in its normal mode of operation. **[2007]**

Group I	Group II
(P) Zener Diode	(1) Forward bias
(Q) Solar cell	(2) Reverse bias
(R) LASER diode	
(S) Avalanche photodiode	

(A) P – 1, Q – 2, R – 1, S – 2
(B) P – 2, Q – 1, R – 1, S – 2
(C) P – 2, Q – 2, R – 1, S – 1
(D) P – 2, Q – 1, R – 2, S – 2

3. Group I lists four different semiconductor devices. Match each device in Group I with its characteristic property in Group II. **[2007]**

Group I	Group II
(P) BJT	(1) Population inversion
(Q) MOS capacitor	(2) Pinch-off voltage
(R) LASER diode	(3) Early effect
(S) JFET	(4) Flat-band voltage

(A) P – 3, Q – 1, R – 4, S – 2
(B) P – 1, Q – 4, R – 3, S – 2
(C) P – 3, Q – 4, R – 1, S – 2
(D) P – 3, Q – 2, R – 1, S – 4

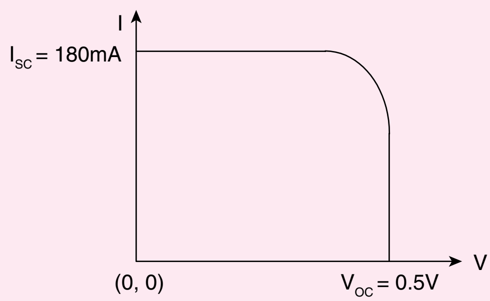
4. When the optical power incident on a photodiode is 10 μW and the responsivity is 0.8 A/W, the photocurrent generated (in μA) is __________. **[2014]**

5. At T = 300 K, the band gap and the intrinsic carrier concentration of GaAs are 1.42 eV and 10^6 cm^{-3}, respectively. In order to generate electron–hole pairs in GaAs, which one of the wavelength (λ_C) ranges of incident radiation is most suitable? (Given that: Plank's constant is 6.62×10^{-34} J-s, velocity of light is 3×10^{10} cm/s and charge of electron is 1.6×10^{-19} C) **[2014]**

(A) 0.42 μm < λ_C < 0.87 μm
(B) 0.87 μm < λ_C < 1.42 μm
(C) 1.42 μm < λ_C < 1.62 μm
(D) 1.62 μm < λ_C < 6.62 μm

6. The cut-off wavelength (in μm) of light that can be used for intrinsic excitation of a semiconductor material of band gap E_g = 1.1 eV is __________. **[2014]**

7. The figure shows the I – V characteristics of a solar cell illuminated uniformly with solar light of power 100 m W/cm^2. The solar cell has an area of 3 cm^2 and a fill factor of 0.7. The maximum efficiency (in %) of the device is __________ . **[2016]**



Answer Keys

Exercises

Practice Problems 1

1. B **2.** D **3.** B **4.** D **5.** A **6.** A **7.** D **8.** D **9.** B **10.** A
11. B **12.** B

Practice Problems 2

1. A **2.** C **3.** D **4.** D **5.** A **6.** A **7.** A **8.** C **9.** B **10.** B
11. A **12.** A **13.** A **14.** A

Previous Years' Questions

1. A **2.** B **3.** C **4.** 7.99 to 8.01 **5.** A **6.** 1.127 **7.** 21%

Test

Electronic Devices and Circuits

Time: 60 Minutes

Direction for questions 1 to 30: Select the correct alternative from the given choices.

1. A hole in semiconductor is
   (S1) absence of electron in covalent bond
   (S2) positive charge carrier
   (A) S1 and S2 are true
   (B) S1 true and S2 false
   (C) S1 assumed and S2 true
   (D) S1 true and S2 assumed

2. The intrinsic carrier concentration of silicon sample at 300 K is $1.5 \times 10^{16}/m^3$. If donor atom concentration of doped silicon is $5 \times 10^{20}/m^3$, then p-type and n-type carrier concentrations are:
   (A) $4.5 \times 10^{11}/m^3$ and $5 \times 10^{20}/m^3$
   (B) $5 \times 10^{20}/m^3$ and $4.5 \times 10^{11}/m^3$
   (C) $5.5 \times 10^{11}/m^3$ and $4.0 \times 10^{20}/m^3$
   (D) $4.5 \times 10^{20}/m^3$ and $5 \times 10^{11}/m^3$

3. An n-type Silicon bar 0.15 cm long and 150 cm^2 in cross-sectional area has a majority carrier concentration of $15 \times 10^{20}/m^3$. If the carrier mobility is 0.13 m^2/v–s at 300 k, then the resistance of the bar is
   (A) .32 mΩ (B) 3.2 mΩ
   (C) 2.3 mΩ (D) 0.23 mΩ

4. Resistivity of a uniformly doped p-type silicon sample is 0.5 Ω–cm. If the electron mobility is 1,250 cm^2/v and holes mobility is 450 cm^2/v, then the acceptor impurity concentration is
   (A) $2.78 \times 10^{16}/cm^3$ (B) $7.35 \times 10^{15}/cm^3$
   (C) $4.55 \times 10^{16}/cm^3$ (D) $3.24 \times 10^{16}/cm^3$

5. A silicon sample 'A' is doped with 10^{18} atoms/cm^3 of Boron, another sample of same dimensions 'B' is doped with 10^{18} atom/cm^3 of phosphorus. The ratio of electron to hole mobility is 3. The ratio of conductivity of the sample A to B is
   (A) 3 (B) 1/3 (C) 2/3 (D) 3/2

6. A heavily doped n-type semiconductor has the following data:
   Hole electron mobility ratio = 0.33
   Doping concentration = $3.6 \times 10^8/m^3$
   Intrinsic concentration = $1.5 \times 10^4/m^3$
   The ratio of conductance of n-type semiconductor to that of the intrinsic semiconductor of same material and at the same temperature will be
   (A) 0.00018 (B) 1,800
   (C) 18,000 (D) 5.55×10^{-1}

7. The concentration of atoms in germanium is 4.41×10^{22} atoms/cm^3. Donor impurity is added to the extent of 1 part in 10^8 germanium atoms. Intrinsic concentration is $2.5 \times 10^{13}/cm^3$. Minority carrier concentration will be
   (A) 1.42×10^{12} /cm^3 (B) $1.42 \times 10^4/cm^3$
   (C) $1.42 \times 10^8/cm^3$ (D) None of the above

8. Match the following and select correct answers:

List-I		List-II	
1.	Intrinsic semiconductor	a.	Impure semiconductor
2.	P-type semiconductor	b.	Pentavalent impurity added semiconductor
3.	N-type semiconductor	c.	Donor impurities added
4.	Extrinsic semiconductor	d.	Acceptor impurities added
		e.	Trivalent impurities added
		f.	Pure semiconductor

   (A) 1 – f, 2 – e, 3 – c, 4 – a
   (B) 1 – d, 2 – b, 3 – c, 4 – f
   (C) 1 – b, 2 – f, 3 – c, 4 – d
   (D) 1 – e, 2 – d, 3 – a, 4 – b

9. Calculate the resistance of piece of silicon doped with Boron ($N_A = 10^{18}$ cm^{-3}), 1 mm long, 10 μm wide, 1 mm thick. μ_n = 1,250 cm^2/v–c-sec, μ_p = 450 cm^2/v-sec.
   (A) 13.9 kΩ (B) 13.9 Ω
   (C) 139.9 Ω (D) 1.39 kΩ

10. The hole density is an n-type silicon wafer ($N_d = 10^{17}$ cm^{-3}), which decreases linearly from 10^{14} cm^{-3} to 10^{12} cm^{-3} between $x = 0$ and $x = 10$ μm. Calculate hole diffusion current density, given μ_p = 450 cm^2/v.sec
    (A) 0.185 A/cm^2 (B) 1.85 A/cm^2
    (C) 18.5 A/cm^2 (D) 0.0185 A/cm^2

11. A diode has reverse saturation current of 10^{-18} A and non-ideality factor of 1.05. If the diode current is 60 μA, then the diode voltage is
    (A) 6.3 V (B) 0.86 V (C) 0.54 V (D) 0.42 V

12. A P–N junction diode operates in reverse bias region. The applied reverse bias at which the ideal reverse current reaches 70% of its reverse saturation value is
    (A) 13.8 mV (B) 41.5 mV
    (C) 51.7 mV (D) 23.5 mV

Direction for questions 13 and 14:
An abrupt P–N junction at zero bias and at room temperature has impurity concentration of $N_a = 10^{18}$ cm^{-3} and $N_d = 6 \times 10^{17}$ cm^{-3}, $n_i = 1.5 \times 10^{10}/cm^3$

13. The Fermi level on n-side is
    (A) 0.9 eV (B) 0.45 eV
    (C) 0 eV (D) 0.1 eV

14. The Fermi level on p-side
    (A) 0.95 eV (B) 1.1 eV
    (C) 0.468 eV (D) 0.72 eV

15. The forward dynamic resistance of a junction diode varies with forward current

(A) inversely (B) directly
(C) square (D) independent

16. In a junction diode

(a) The depletion capacitance increases with reverse bias.
(b) The depletion capacitance decreases with reverse bias.
(c) The diffusion capacitance increases with increase in the forward bias.
(d) The diffusion capacitance is much higher than the depletion capacitance when it is reverse biased

(A) (a) and (d) are true
(b) and (c) are false
(B) (a) and (b) are true
(c) and (d) are false
(C) (a) and (d) are false
(b) and (c) are true
(D) (a) and (c) are true
(b) and (d) are false

17. Silicon P–N junction diode under reverse bias has depletion region of width 20 μm. The relative permitivity $\varepsilon_r = 12$. Depletion capacitance per square metre is

(A) 10.35 μF (B) 5.31 μF
(C) 53.1 μF (D) 6.39 μF

18. In a uniformly doped abrupt P–N junction, the doping level of n-side is 5 times the doping level of the p-side. The ratio of the depletion layer width for n-side to p-side is

(A) 0.25 (B) 0.5 (C) 0.2 (D) 5

19. Fermi function is expressed as

(A) $\dfrac{1}{1 + \exp(E - E_F)/KT}$

(B) $\dfrac{1}{1+\exp^{-(E-E_F)/KT}}$

(C) $\exp(E - E_F)/KT$

(D) $\dfrac{1}{1-e^{(E-E_F)/KT}}$

20. Diffusion constant, mobility of electron and hole are related as

(A) $\dfrac{D_n}{\mu_n} = \dfrac{kT}{q} = \dfrac{D_p}{\mu_p}$ (B) $\dfrac{D_n}{\mu_n} = \dfrac{q}{kT} = \dfrac{\mu_p}{D_p}$

(C) $D_n/\mu_n = qkT = \dfrac{D_p}{\mu_p}$ (D) $\dfrac{D_n}{\mu_n} = \dfrac{1}{qKT} = \dfrac{\mu_p}{D_p}$

21. A sample of silicon at room temperature is doped with boron with a concentration of 2×10^{13}/cm^3 and with phosphorus at a concentration of 1×10^{13}/cm^3. The material is (p_o, n_o – free carrier concentration)

(A) p-type with $p_o = 1.5 \times 10^7$ cm^{-3}
(B) n type with $n_o = 1.5 \times 10^7$ cm^{-3}
(C) p-type with $p_o = 1.0 \times 10^{13}$ cm^{-3}
(D) n-type with $n_o = 1.0 \times 10^{13}$ cm^{-3}

22. Find the diffusion constant D_n if the mobility of electron is 1,200 cm^2/v–s at room temperature.

(A) 40.85 cm^2/s (B) 38.85 cm^2/s
(C) 31.2 cm^2/s (D) None of the above

23. An abrupt Si, P–N junction has impurities $N_a = 10^{12}$cm^{-3} on one side and $N_d = 3 \times 10^{15}$ cm^{-3} on the other side. Calculate built in potential.
($n_i = 1.5 \times 10^{10}$ cm^{-3})

(A) 0.796 V (B) 0.426 V
(C) 3.37 V (D) 2.6 V

24. Probability that an electron in a metal occupies the Fermi level at any temperature greater than 0 Kelvin is

(A) 0 (B) 1 (C) 0.5 (D) 0.99

25. Pure silicon is experimentally determined to exhibit a carrier (electron or hole) density of 1.2×10^{10}/cm^3 at room temperature.
The resistivity of that intrinsic Si specimen was found 2.89×10^5 Ωm, if the mobility of electron and holes are in the ratio 3:1. Find the individual mobilities of carriers (cm^2/v-s)

(A) $\mu_e = 1{,}350$, $\mu_h = 450$ (B) $\mu_e = 450$, $\mu_h = 1{,}350$
(C) $\mu_e = 1{,}200$, $\mu_h = 400$ (D) $\mu_e = 1{,}500$, $\mu_h = 500$

Direction for questions 26 to 29:

For a semiconductor at room temperature, the intrinsic carrier concentration is 2.5×10^{15}/m^3 and resistivity is 4×10^3 Ωm. It was doped (donor type) with concentration of 10^{20}/m^3. For the extrinsic semiconductor, calculate the following:

26. Minority carrier concentration is

(A) 2.25×10^{12} atom/m^3 (B) 2.65×10^{10} atom/m^3
(C) 6.25×10^{12} atom/m^3 (D) 6.25×10^{10} atom/m^3

27. If the mobilities are in the ratio 1:2, then calculate the mobility of electrons.

(A) 0.208 m^2/volt-s (B) 0.416 m^2/volt-s
(C) 0.624 m^2/volt-s (D) 0.832 m^2/volt-s

28. Calculate the resistivity of extrinsic semiconductor.

(A) 0.5998 Ω-m (B) 0.1502 Ω-m
(C) 0.1609 Ω-m (D) 6.656 Ω-m

29. Determine the shift in Fermi level due to doping

(A) 0.275 eV (B) 0.026 eV
(C) 0.59 eV (D) 0.1042 eV

30. Contact potential in an abrupt P–N junction (silicon) when resistivity of two sides are 2 Ω/cm (p-side) and 1 Ω/cm (n-side). $\mu_n = 1350$ cm^2/VS, $\mu_p = 450$ cm^2/VS, and $n_i = 1.5 \times 10^{13}$ cm^{-3}

(A) 0.318 eV (B) 0.456 eV
(C) 0.556 eV (D) 0.656 eV

Answer Keys

1. D	**2.** A	**3.** B	**4.** A	**5.** B	**6.** C	**7.** A	**8.** A	**9.** B	**10.** A
11. B	12. A	13. B	14. C	15. A	16. C	17. B	18. C	19. A	20. A
21. C	22. C	23. B	24. B	25. A	26. D	27. B	28. B	29. A	30. A