SEMICONDUCTOR ELECTRONICS

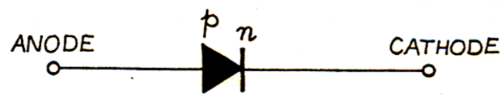
P-N JUNCTION AND SEMICONDUCTOR DIODE

JUNCTION DIODE

A junction diode serves as a fundamental semiconductor device, consisting of a semiconductor crystal divided into two distinct regions. In one region, the crystal is doped with acceptor impurities, forming a P-type crystal, while in the other region, it is doped with donor impurities, resulting in an N-type crystal. The interface or boundary between these two regions is termed the 'p–n junction.'

Circuit Symbol for a p-n Junction Diode:

In electronic circuit diagrams, semiconductor devices are denoted by their symbols. The symbol for the foundational device, the p-n junction diode, is depicted in the figure. An arrowhead is utilized to signify the p-region, while a bar denotes the n-region of the diode. The arrow direction, extending from p to n, signifies the direction of conventional current flow when the diode is subjected to forward bias. The 'anode' is attributed to the p-side, and the 'cathode' is attributed to the n-side.

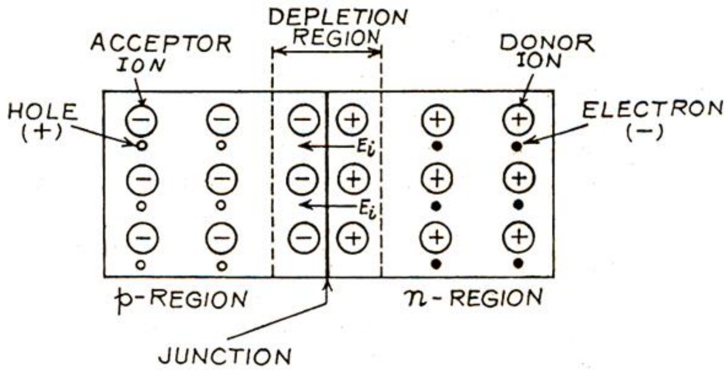


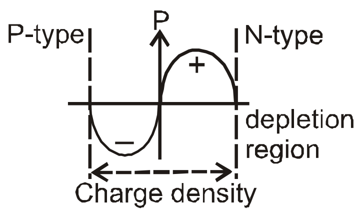
(a) Formation of p-n Junction:

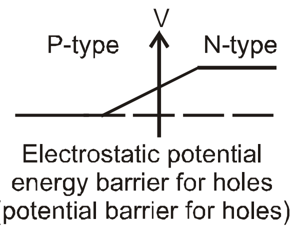
A p-n junction is not merely the junction formed by pressing together p-type and n-type semiconductor crystals. Rather, it is a unified piece of semiconductor crystal characterized by an abundance of acceptor impurities on one side and donor impurities on the other.

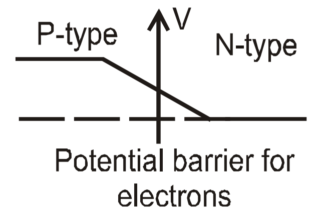
(b) Potential Barrier at the Junction: Formation of Depletion Region:

Illustrated in Figure, the p-type region of the p-n junction primarily consists of positively charged holes as the majority charge carriers, accompanied by an equivalent number of stationary negatively charged acceptor ions. It is crucial to note that the overall material maintains neutrality. Conversely, the n-type region comprises negatively charged electrons as the predominant charge carriers, alongside an equivalent number of stationary positively charged donor ions.









The portion of the junction that becomes void of mobile charge carriers is referred to as the 'depletion region,' depicted in Figure. The depletion region typically exhibits a width on the order of 10^{-6} meters. The potential difference arising across the depletion region is denoted as the 'potential barrier.' Specifically, for a germanium p-n junction, this potential barrier measures approximately 0.3 volts, while for a silicon p-n junction, it is around 0.7 volts. It's noteworthy that the actual value of the potential barrier is contingent upon the dopant concentration within the semiconductor.

The electric field strength associated with the barrier, denoted as E_i, can be approximated as Ei $\approx 7 \times \frac{10^5 \text{V}}{\text{m}}$ for a silicon junction.

Diffusion & Drift Current:

Due to a concentration difference, holes attempt to diffuse from the p-side to the n-side. However, the presence of the depletion layer allows only those holes with high kinetic energy to successfully diffuse from the p-side to the n-side. Similarly, electrons with high kinetic energy diffuse from the n-side to the p-side, resulting in a diffusion current flowing from the p-side to the n-side.

Furthermore, due to thermal collisions or an increase in temperature, some valence electrons transition into the conduction band. If this phenomenon occurs within the depletion region, holes move toward the p-side, and electrons move toward the n-side, generating a current from the n-side to the p-side. This phenomenon is referred to as drift current. In a steady state, both diffusion and drift currents are equal and opposite.

Example.

In a P-N junction, where a potential barrier of 0.50 V is present and the depletion region has a width of 5.0 × 10^−7 m, determine the intensity of the electric field within this region from the following options:

(1) 1.0×10^6 V/m (2) 1.0×10^5 V/m

(3) 2.0×10^5 V/m (4) 2.0×10^6 V/m

Solution.

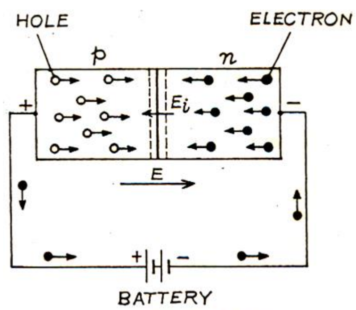
(1) $E = \frac{V}{d} = \frac{0.5}{5 \times 10^{-7}} = 10^6$ V/m

(c) Forward and Reverse Biasing of Junction Diode

The junction diode can be linked to an external battery through two distinct methods known as 'forward biasing' and 'reverse biasing' of the diode. These terms refer to the specific manner in which an electromotive force (EMF) source is connected to the P-N junction diode. The two types are as follows:

(i) Forward Biasing:

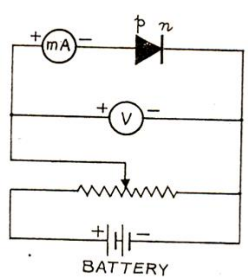
A junction diode is said to be forward-biased when the positive terminal of the External battery is connected to the p -region and the negative terminal to the n-region of the diode.



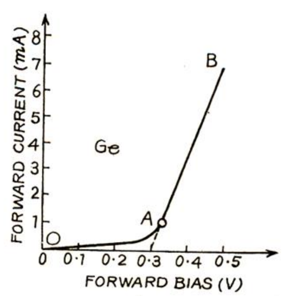
(FORWARD BIASED)

Forward-Biased Characteristics:

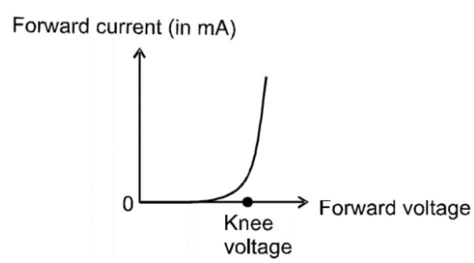
The circuit connections, as illustrated in Fig, depict the positive terminal of the battery linked to the p-region and the negative terminal to the n-region of the junction diode through a potential-divider arrangement. This arrangement facilitates the adjustment of the applied voltage. A voltmeter V and a millimeter mA measure the voltage and current, respectively. The forward bias voltage starts with a low value and is increased incrementally, with the corresponding forward current being noted at each step. A graph is then constructed, depicting the relationship between voltage and current. The resulting curve, OAB (as shown in Fig. b), represents the forward characteristic of the diode.



(a)



(b)



Initially, when the applied voltage is low, the current through the junction diode is nearly zero. This is due to the presence of the potential barrier (approximately 0.3 V for Ge p-n junction and about 0.7 V for Si junction), which opposes the applied voltage. As the applied voltage increases, the current rises slowly and non-linearly until it surpasses the potential barrier. This phase is represented by the segment OA of the characteristic curve. With further increments in applied voltage, the current undergoes a rapid and nearly linear increase.

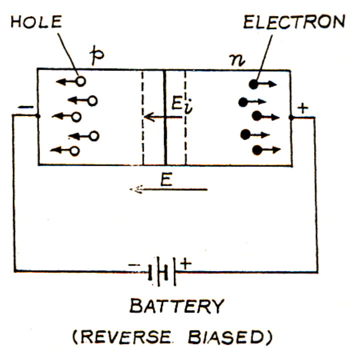
At this point, the diode behaves as an ordinary conductor, as depicted by the straight-line segment AB of the characteristic curve. If this straight line is extended backward, it intersects the voltage-axis at the barrier potential voltage.

Note:

- In the forward biasing condition, the width of the depletion layer decreases.
- The resistance offered in forward biasing, RForward, is approximately in the range of 10 ohms to 25 ohms.
- Forward bias opposes the potential barrier, and for applied voltages greater than the barrier potential ($V > VB$), a forward current is established across the junction.
- Cut-in (Knee) voltage: This is the voltage at which the current begins to increase rapidly. For Ge, it is 0.3 V, and for Si, it is 0.7 V.

(ii) Reverse Biasing:

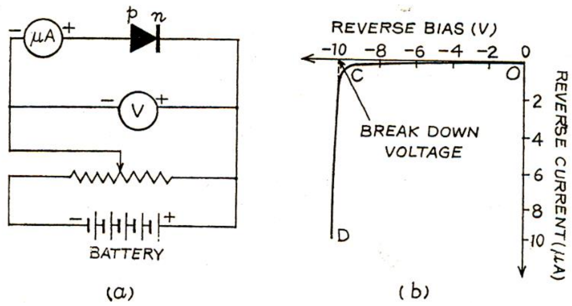
When the positive terminal of an external battery is connected to the n -region, and the negative terminal is connected to the p -region of a junction diode, the diode is said to be in a reverse-biased state (as depicted in the figure). In this configuration, the external electric field E is directed from the n -region toward the p -region, reinforcing the internal barrier field Ei. Consequently, both holes in the p -region and electrons in the n -region are pushed away from the junction, preventing their combination at the junction. As a result, there is minimal current flow due to the movement of majority carriers.



Reverse-Biased Characteristic:

The circuit connections, as illustrated in Fig. (a), involve connecting the positive terminal of the battery to the n -region and the negative terminal to the p -region of the junction diode, resulting in a reverse-biased diode. In this state, a minute current, typically of the order of microamperes (A), flows across the junction. This current arises from the movement of thermally-generated minority carriers—electrons in the p -region and holes in the n -region—whose motion is facilitated by the applied voltage.

The small reverse current remains nearly constant across a sufficiently broad range of reverse bias (applied voltage), exhibiting minimal increase even as the bias is raised. This behavior is depicted by the segment OC of the reverse characteristic curve (Fig. b).



Note:

- In reverse biasing, the width of the depletion layer increases..
- The resistance offered in reverse biasing, denoted as RReverse, is approximately 10^5 ohms.
- Reverse bias reinforces the potential barrier, preventing the flow of current across the junction due to the diffusion of majority carriers.
- Although a very small reverse current may exist in the circuit owing to the drifting of minority carriers across the junction.
- Breakdown voltage is the reverse voltage at which the breakdown of the semiconductor occurs. It is 25V for Ge and 35V for Si.

(d) Avalanche Breakdown:

Avalanche breakdown occurs in a lightly doped junction. When the reverse bias is increased significantly, minority carriers gain enough kinetic energy to break the covalent bonds near the junction, resulting in the liberation of electron-hole pairs. These charge carriers, in turn, accelerate and generate additional electron-hole pairs through a cumulative process. This avalanche effect leads to a sudden increase in the reverse current, reaching a relatively high value (depicted by part CD of the characteristic curve). This phenomenon is termed 'avalanche breakdown' and has the potential to damage the junction due to the excessive heat generated. The reverse bias voltage at which the reverse current sharply increases is referred to as the 'breakdown voltage.'

Zener Breakdown:

Zener breakdown occurs in heavily doped junctions, particularly in Zener diodes. When subjected to a high reverse-bias voltage, the depletion region of the p-n junction expands, creating a strong electric field across the junction. This potent electric field has the capability to break the covalent bonds of the semiconductor atoms, leading to the liberation of a significant number of free minority

carriers. The sudden surge in carrier generation results in a rapid increase in the reverse current, causing the Zener diode to exhibit a high slope resistance.
The reverse bias voltage at which the reverse current experiences a sudden and substantial increase is termed the 'Zener breakdown voltage' or simply 'Zener voltage.' The numerical value of the breakdown voltage varies, ranging from tens of volts to several hundred volts, contingent upon the number density of impurity atoms doped into the diode.

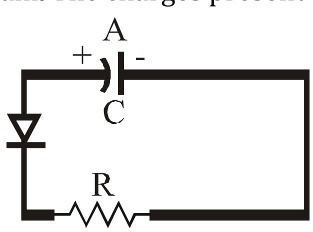
(e) Dynamic Resistance of a Junction Diode

The current-voltage curve of a junction diode reveals a nonlinear relationship between current and voltage, indicating a deviation from Ohm's law. To characterize this behavior, the concept of 'Dynamic resistance' (or a.c. resistance) is introduced.

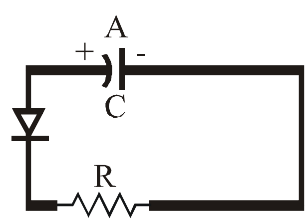
Dynamic resistance of a junction diode is defined as the ratio of a small change in applied voltage (ΔV) to the corresponding small change in current (Δi), expressed as $Rd = \frac{\Delta V}{\Delta i}$. In the forward characteristic of a p-n junction diode, particularly beyond the turning point (knee), the current exhibits nearly linear variation with voltage. In this specific region, dynamic resistance (Rd) becomes nearly independent of voltage (V), and Ohm's law is observed to be applicable.

Example.

Two identical capacitors, denoted as A and B, are initially charged to the same potential V. They are subsequently incorporated into two separate circuits at time t = 0, as illustrated in the diagram. The charges present on the capacitors at a given time t = CR are as follows:



(A)



(B)

(1) VC, VC

(2) VC/e, VC

(3) VC, VC/e

(4) VC/e, VC/e

Solution.

Option 2 is correct VC/e, VC