Chapter Three
PN-Junction (Diodes)

3.1: Introduction

Refreshment for the previous chapter

If you take a block of **silicon** and **dope part** of it with a **trivalent impurity** and the other part with a **pentavalent impurity**, a boundary called the $\boldsymbol{p-n}$ **junction** is formed between the resulting $\boldsymbol{p}$**-type** and $\boldsymbol{n}$**-type** portions and a basic **diode** is created. A **diode** is a device that usually conducts current in one direction. The $\boldsymbol{p-n}$ **junction** is the feature that allows diodes, certain transistors, and other devices to work.

After completing this chapter, you should be able to:

- *Describe a diode and how a $p-n$ junction is formed.*
- *Discuss diffusion across a $p-n$ junction.*
- *Explain the formation of the depletion region.*
- *Define barrier potential and discuss its significance.*
- *State the values of barrier potential in silicon and germanium.*

A $\boldsymbol{p}$**-type** material consists of silicon atoms and trivalent impurity atoms such as **boron**. The boron atom adds a hole when it bonds with the silicon atoms. However, since the number of protons and the number of electrons is equal throughout the material, there is no net charge in the material and so it is neutral.

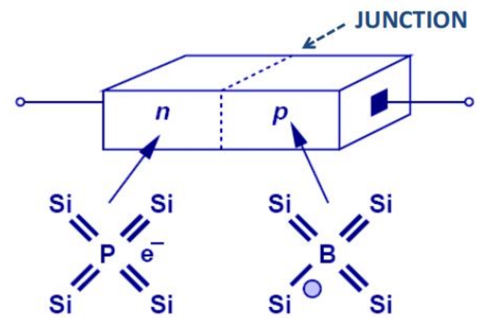
An $\boldsymbol{n}$**-type** silicon material consists of silicon atoms and pentavalent impurity atoms such as **antimony**. As you have seen an impurity atom release an electron when it bonds with four silicon atoms. Since there is still an equal number of protons and electrons (inducing the free electrons) throughout the material, there is no net charge in the material and so it is neutral.

If a piece of intrinsic silicon is doped so that part is $\boldsymbol{n}$**-type** and the other part is $\boldsymbol{p}$**-type**.
A $\boldsymbol{pn}$**-junction diode is formed by joining together $\boldsymbol{n}$-type and $\boldsymbol{p}$-type silicon**.

The $\boldsymbol{p}$ **region** has many **holes** (majority carriers) from the impurity atoms and only a few thermally generated **free electrons** (minority carriers).
The $\boldsymbol{n}$ **region** has many **free electrons** (majority carriers) from the impurity atoms and only a few thermally generated **holes** (minority carriers).

3.2: The Diode

A diode **is made from a small piece of semiconductor material, usually silicon**, in which half is doped as a ***p*** **region** and half is doped as an ***n*** **region** with a ***pn*** **junction** and **depletion region** in between.



The ***p*** **region** is called the **anode** and **is connected to a conductive terminal**. The ***n*** **region** is called the **cathode** and **is connected to a second conductive terminal**. The basic diode structure and schematic symbol are shown in Figure (1).

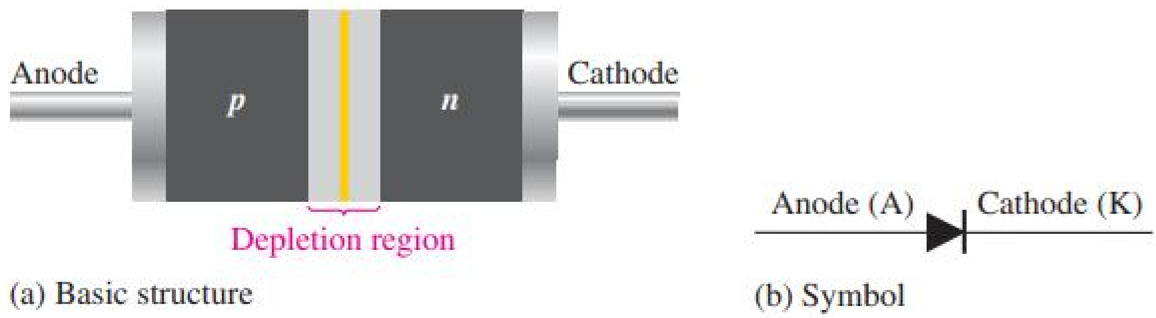


Figure (1): The diode.

NOTE:

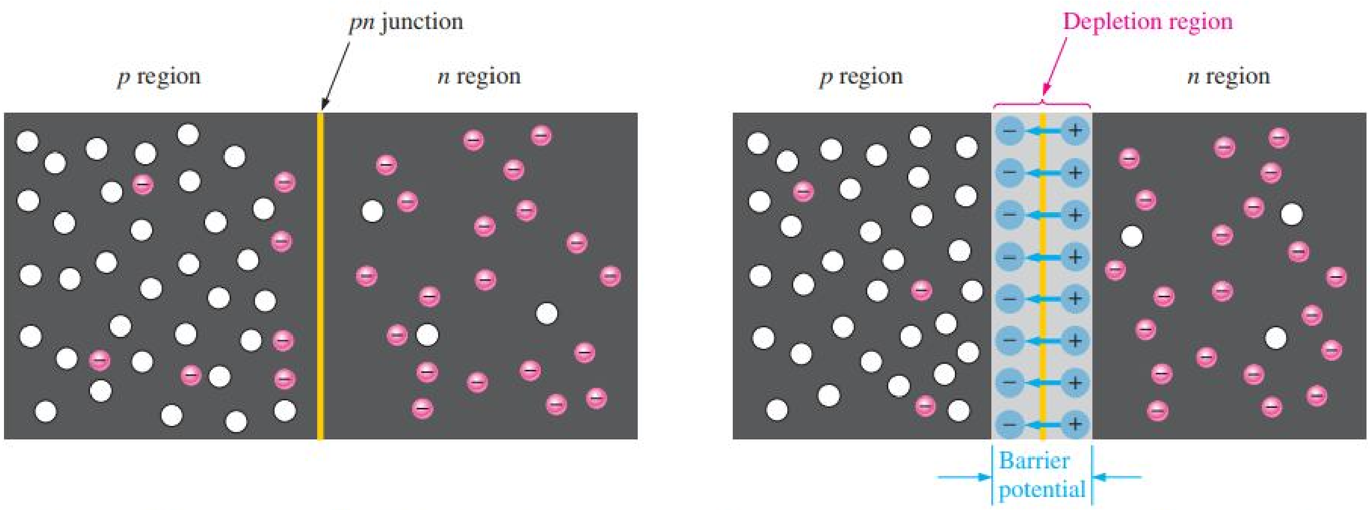
- A **diode** **is a 2-lead semiconductor that acts as a one-way gate to electron flow**. (**Normal Diodes** allow current to pass in only one direction (Some allows to pass current in reverse like **Zener diodes**).
- **In practice**, as the ***n* − *type*** Si crystal is being grown, the process is abruptly altered to grow ***p*-type** Si crystal.
- Finally, a **glass** or **plastic** coating is placed around the joined crystal.

When the **anode** and **cathode** of a ***pn*** **junction** diode are connected to **external voltage** such that the **potential at anode** is higher than the **potential at cathode**, the **diode** is said to be **forward biased**. In a **forward-biased diode** **current is allowed to flow through the device**.

When **potential at anode** is smaller than the **potential at cathode**, the **diode** is said to be **reverse biased**. In a **reverse-biased Some diode** **current is blocked**.

3.3: Formation of the Depletion Region

As you have seen, the **free electrons** in the ***n* region** are randomly drifting in all directions. At the instant of the ***pn* junction** formation. The **free electrons** near the junction in the ***n* region** begin to diffuse across the junction into the ***p* region** where they combine with **holes** near the junction, as shown in Figure (2a).



(a) The basic silicon structure at the instant of junction formation showing only the majority and minority carriers. Free electrons in the *n* region near the *pn* junction begin to diffuse across the junction and fall into holes near the junction in the *p* region.

(b) For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n* region and a negative charge is created in the *p* region, forming a barrier potential. This action continues until the voltage of the barrier repels further diffusion. The blue arrows between the positive and negative charges in the depletion region represent the electric field.

Figure (2): Formation of the depletion region. The width of the depletion region is exaggerated for illustration purposes.

Before the ***pn* junction** is formed, recall that there are as many electrons as protons in the ***n*-type** material, making the material neutral in terms of net charge. The same is true for the ***p*-type** material.

When the ***pn* junction** is formed, the ***n* region** loses **free electrons** as they diffuse across the junction. This creates a layer of **positive charges (pentavalent ions)** near the junction. As the electrons move across the junction.
The ***p* region** loses **holes** as the electrons and holes combine. This creates a layer of **negative charges (trivalent ions)** near the junction. These two layers of positive and negative charges form the **depletion region**, as shown in Figure (2b).

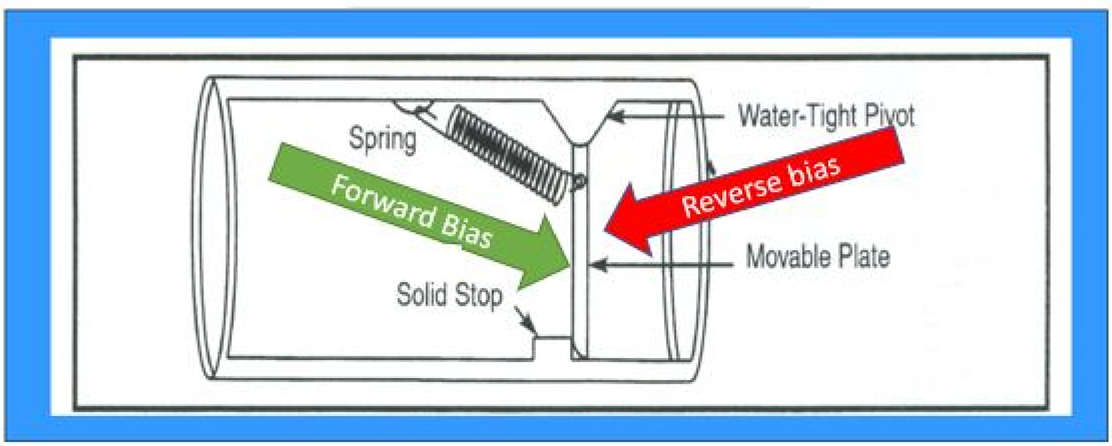
The term depletion refers to the fact that the region near the pn junction is depleted of charge carriers (electrons and holes) due to diffusion across the junction. Keep in mind that the **depletion region** is formed very quickly and is very thin compared to the n region and p region.

After the initial surge of free electrons across the $p-n$ junction. The **depletion region** has expanded to a point where equilibrium is established and there is **no further diffusion of electrons across the junction**.

This occurs as follows. As **electrons** continue to diffuse across the junction, more and more positive and negative charges are created near the junction as the **depletion region** is formed. A point is reached where the total negative charge in the depletion region repels any further diffusion of electrons (negatively charged particles) into the p region (like charges repel) and the diffusion stops. In other words, the **depletion region** acts as a **barrier** to the further movement of electrons across the junction.

NOTE:

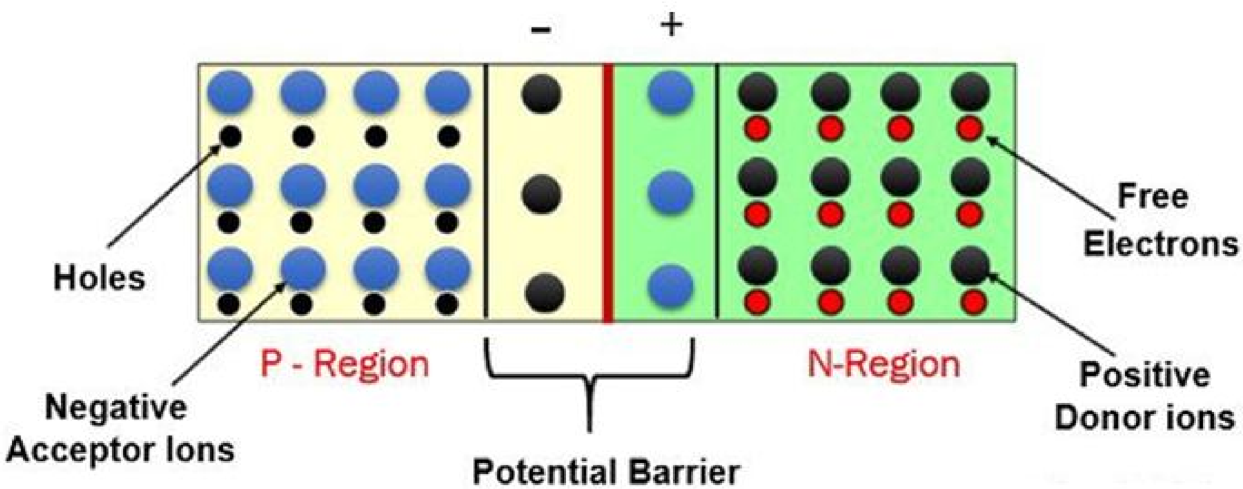
Water Analogy of Diodes



- When water pressure on left overcomes the restoring force of spring, the gate is **opened** and water is allowed to flow.
- When water pressure is from right to left, the gate is pressed against the solid **stop** and no water is allowed to flow.
- Spring restoring force is analogous to **0.6V** needed to **forward bias a Si diode**.

3.4: Barrier Potential

Any time there is a **positive charge** and a **negative charge** near each other, there is a **force** acting on the charges as described by **Coulomb's law**. In the depletion region there are many positive charges and many negative charges on opposite sides of the pn junction. The **forces** between the opposite charges form a "**field of forces**" called an **electric field**, as illustrated in Figure.

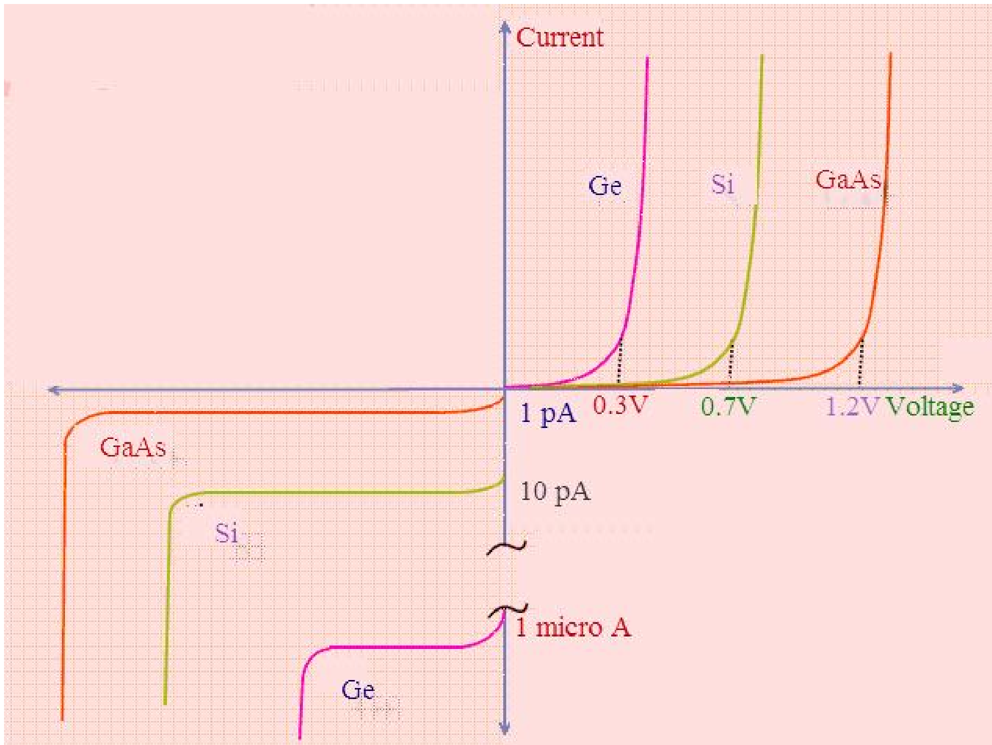


This electric field is a barrier to the free electrons in the n-region, and **energy** must be expended to move an **electron** through the **electric field**. That is external energy must be applied to get the electrons to move across the barrier of the electric field in the depletion region.

The potential difference of the electric field across the depletion region **is the amount of voltage required to move electrons through the electric field**. This potential difference is called the **barrier potential** and is expressed in **volts**.

Stated another way, a certain amount of voltage equal to the barrier potential and with the proper polarity must be applied across a $p-n$ junction before electrons will begin to flow across the junction.

The **barrier potential of a $p-n$ junction** depends on several factors including the **type of semi conductive material**, the **amount of doping**, and the **temperature**. The typical barrier potential is approximately **0.7 V for silicon**, **0.3 V for germanium**, and **1.2 V for Gallium arsenide** at 25°C as shown in curve.



3.5: Energy Diagrams of the PN Junction and Depletion Region

The **valence and conduction bands in an n-type** material is at slightly lower energy levels than the **conduction bands in a p-type material**. This is due to differences in the atomic characteristics of the pentavalent and the trivalent **impurity atoms**. An energy diagram for a $p-n$ junction at the instant of formation is shown in Figure.

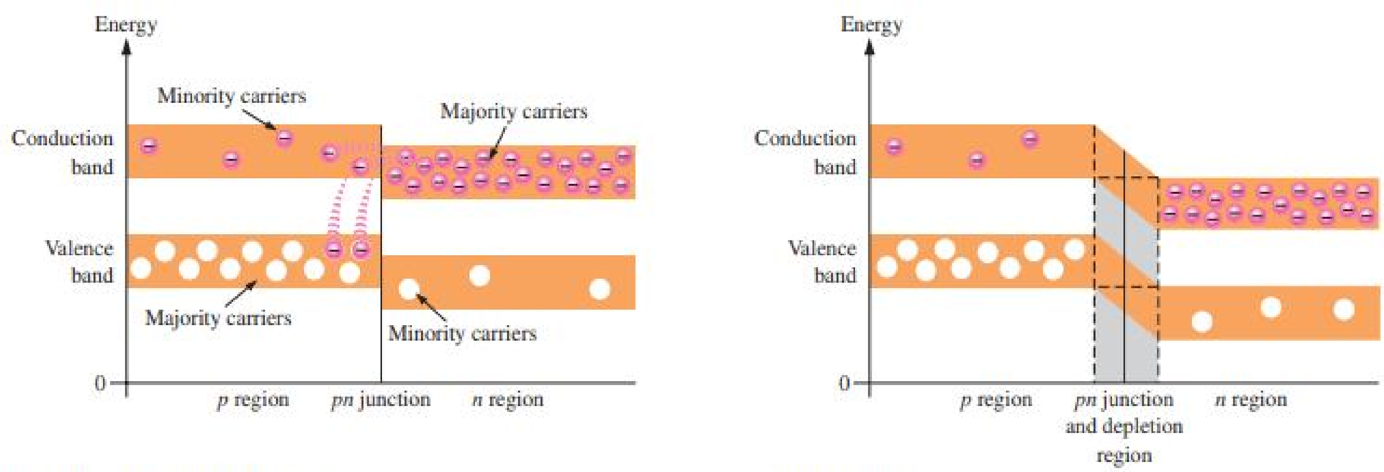


Figure (3): Energy diagrams illustrating the formation of the $p-n$ junction and depletion region.

As you can see, the valence and conduction bands in the n-region are at lower energy levels than those in the p-region, but there is a significant amount of **overlapping**.

The free electrons in the n-region that occupy the upper part of the conduction band in terms of their energy can easily diffuse across the junction (they do not have to gain additional energy) and temporarily become free electrons in the lower part of the p-region conduction band.

After crossing the junction, the **electrons** quickly lose energy and fall into the **holes** in the p-region valence band as indicated in the Figure (3).

As the diffusion continues, the **depletion region** begins to form and the **energy level** of the n-region conduction band decreases. The decrease in the energy level of the conduction band in the n-region is due to the loss of the higher-energy **electrons** that have diffused across the junction to the p-region.

Soon, there are no electrons left in the n-region conduction band with enough energy to get across the junction to the p-region conduction band.
As indicated by the alignment of the top of the n-region conduction band and the bottom of the p-region conduction band in Figure (3a).
At this point, the **junction is at equilibrium**; and the **depletion region is complete** because diffusion has ceased.
There is an energy gradient across the **depletion region** which acts as an "**energy hill**" that an ***n*-region electron** must climb to get to **the *p*-region**.

Notice that as the energy level of the n-region conduction band has shifted downward; the energy level of the valence band has also shifted downward. It **still takes the same amount of energy for a valence electron to become a free electron**. In other words, the **energy gap** between the valence band and the conduction band remains the same.

When **a junction** is formed between a p-type region and n-type region, the **Fermi levels** of both the regions attain a constant value under equilibrium conditions as shown in Figure (4).

It is assumed here that the junction is **abrupt** and the **field** exists only in the depletion region.
Apparently, the conduction band edge, E_{cp} in the p-region occupies high energy position as compared to the conduction band edge E_{cn} in the n-region; similarly, $E_{vp} > E_{vn}$.
The **barrier energy** is, therefore, given by:

$$E_B = E_{cp} - E_{cn} = E_{vp} - E_{vn} = eV_B$$

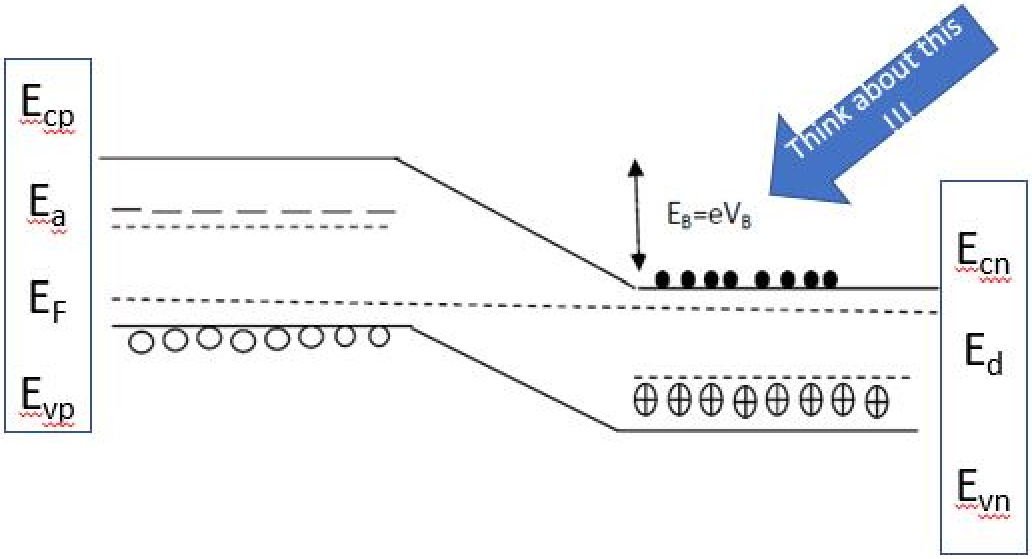


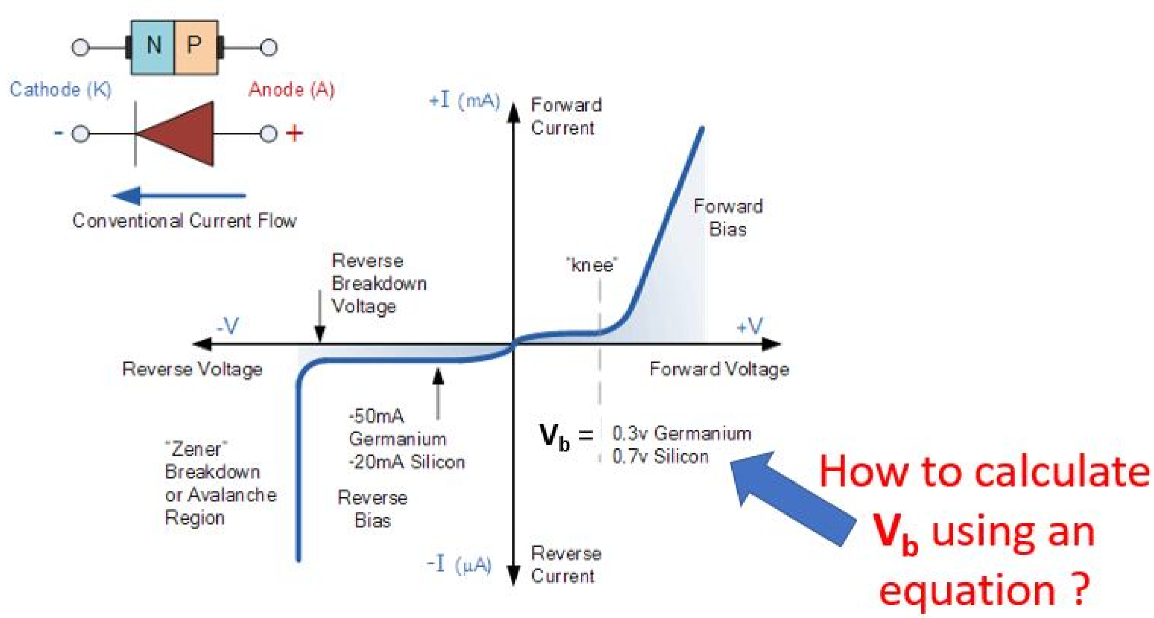
Figure (4): Energy levels in a $p-n$ junction.

The relative shifts in the conduction band and valence band edges in the p-region with respect to those in the n-region depend on the **difference in Fermi energies** of the two regions which further depends on the **carrier concentration** of these regions. This is explained next.

$$E_B = eV_B$$

The (V_B) Value will be derived and obtained with your help later in this chapter

Potential Barrier Calculation



The **concentration of electrons in the n-region** is given by equation:

$$n_n = 2\left[\frac{2\pi m_n^* KT}{h^2}\right]^{\frac{3}{2}} e^{-\left[\frac{E_{cn}-E_{fn}}{KT}\right]} \quad \dots (1)$$

Where E_c and E_f have been replaced by E_{cn} and E_{fn} respectively.

The **p-region** also contains some thermally generated **electrons of concentration**:

$$n_p = 2\left[\frac{2\pi m_p^* KT}{h^2}\right]^{\frac{3}{2}} e^{-\left[\frac{E_{cp}-E_{fp}}{KT}\right]} \quad \dots (2)$$

At $m_n^* = m_p^*$, from equation (1) and (2), we obtain:

$$\frac{n_n}{n_p} = \frac{e^{-\left[\frac{E_{cn}-E_{fn}}{KT}\right]}}{e^{-\left[\frac{E_{cp}-E_{fp}}{KT}\right]}} \quad \dots (3)$$

For the same semiconducting materials, the **positions** of the conduction and valence band edges do not change **with doping**, whereas the **position** of the **Fermi level** changes with both **concentration** and **type of doping**. Thus, for n and p regions, we must have:

$$E_{cn} = E_{cp} \ and \ \ E_{fn} \neq E_{fp}$$

The different energy values attained by E_{cp} and E_{cn} in figure (4) are indicative of the fact that the Fermi levels of the two regions have been brought to the same position. Thus, from equation (3), we get:

$$\frac{n_n}{n_p} = e^{\left[\frac{E_{fn}-E_{fp}}{KT}\right]} \quad \dots (4)$$

Similarly, for holes in the n and p regions, we obtain:

$$\frac{p_n}{p_p} = e^{-\left[\frac{E_{fn}-E_{fp}}{KT}\right]} \quad \dots (5)$$

Where p_n and p_p represent the **concentrations of holes** in the n and p regions respectively.
Since; $E_{fn} - E_{fp} = eV_B$

The equations (4) and (5) become:

$$\frac{n_n}{n_p} = e^{\left[\frac{eV_B}{KT}\right]} \quad \dots (6) \quad and \quad \frac{p_n}{p_p} = e^{-\left[\frac{eV_B}{KT}\right]} \quad \dots (7)$$

In an n-type material; $\boldsymbol{n_n \cong N_d}$

Also, in a p-type material; $\boldsymbol{n_p = \frac{n_i^2}{p_p} \cong \frac{n_i^2}{N_a}}$

Therefore equation (6) gives:

$$\frac{N_a N_d}{n_i^2} = e^{\left[\frac{eV_B}{KT}\right]} \quad or \quad \boldsymbol{V_B = \frac{KT}{e} ln\left[\frac{N_a N_d}{n_i^2}\right]} \quad \ldots (8)$$

3.6: Diffusion and Drift of Carriers: Einstein Relation

It has been described above that, for a $\boldsymbol{p-n}$ **junction** in equilibrium, the **drift current** is always equal and **opposite to the diffusion current**. The **drift electron current density** is given by equation:

$$\boldsymbol{J_n(drift) = en\mu_n E}$$

Where E denotes the **electric field**.

The **diffusion electron current density** is given by:

$$\boldsymbol{J_n(diff.) = eD_n \frac{d_n}{d_x}} \quad \ldots (9)$$

Where $\boldsymbol{\frac{d_n}{d_x}}$ represents the **electron concentration gradient** and $\boldsymbol{D_n}$ is called the **electron diffusion coefficient or electron diffusivity**.

The **total electron current density** is thus:

$$\boldsymbol{J_n = en\mu_n E + eD_n \frac{d_n}{d_x} = 0} \quad \ldots (10)$$

Similarly, the **total hole current density** is:

$$\boldsymbol{J_p = ep\mu_p E - eD_p \frac{d_p}{d_x} = 0} \quad \ldots (11)$$

Where $\boldsymbol{\frac{d_p}{d_x}}$ is the **hole concentration gradient** and $\boldsymbol{D_p}$ is the **hole diffusivity**.

It may be noted that equations (10) and (11) differ **by a negative sign**. This is due to the fact that **the diffusion electron current flows in a direction of increasing concentration gradient**.

Under non equilibrium conditions, the **total current density J** for pn-junction is always calculated as:

$$J = J_n + J_p \quad ..(12)$$

Now from equation (10), we obtain:

$$\frac{d_n}{n} = -\frac{\mu_n}{D_n} E d_x \quad ...(13)$$

Considering one dimensional motion of electrons and integrating from one depletion layer boundary to the other we get:

$$\int_{n_p}^{n_n} \frac{d_n}{n} = -\frac{\mu_n}{D_n} E \int_{x_p}^{x_n} d_x$$

Or

$$ln\frac{n_n}{n_p} = -\frac{\mu_n}{D_n} E(x_n - x_p) = \frac{\mu_n}{D_n} V_B \quad ...(14)$$

Where $V_B = -E(x_n - x_p)$.

$$\frac{n_n}{n_p} = e^{\left[\frac{\mu_n}{D_n} V_B\right]} \quad ...(15)$$

Similarly, **considering the hole current**, we obtain:

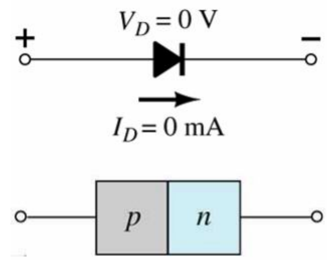
$$\frac{p_n}{p_p} = e^{-\left[\frac{\mu_p}{D_p} V_B\right]} \quad ...(16)$$

Comparing equations (15) and (16) with equations (6) and (7), we have:

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{KT}{e} \quad ...(17) \quad or\ simply \quad \frac{D}{\mu} = \frac{KT}{e} \quad ...(18)$$

This important relation is obtained irrespective of the type of the carrier and is called the **Einstein relation**. It allows one to calculate either D or μ from the measurement of the other.

3.7: Biasing a Diode



As you have learned, no electrons move through the $p-n$ junction at equilibrium.

∴ No Bias

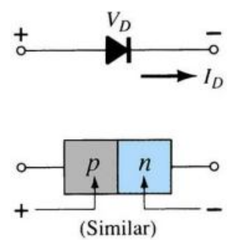
- No external voltage is applied: $V_D = 0$ V.
- No current is flowing: $I_D = 0$ A.
- Only a modest **depletion region** exists.

Generally, the term **bias** refers to the use of a ***dc* voltage** to establish certain operating conditions for an electronic device.

In relation to a diode, there are **two bias** conditions: **forward** and **reverse**.

Either of these bias conditions is established by connecting a sufficient dc voltage of the proper polarity across the $p-n$ junction.

3.7.1: Forward Bias



To **bias** a diode, you apply a ***dc* voltage** across it.

Forward bias is the condition that allows current through the $p-n$ junction.

Figure (5) shows a ***dc* voltage** source connected by conductive material (contacts and wire) across a diode in the direction to produce **forward bias**. This external bias voltage is designated as $\boldsymbol{V_{BIAS}}$. The **resistor *R***, limits the **current** to a value that will not damage the diode.

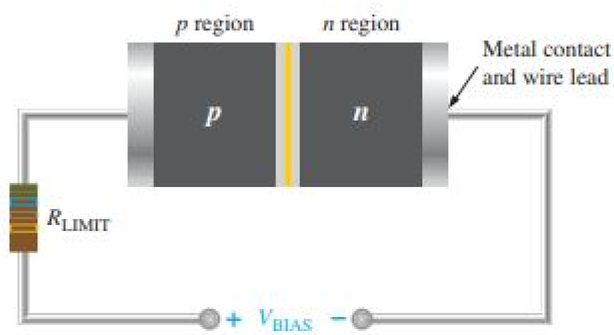


Figure (5): A diode connected for forward bias.

Notice that the negative side of V_{BIAS} is connected to the n region of the diode and the positive side is connected to the p region. This is one requirement for **forward bias**. A second requirement is that the bias voltage $\boldsymbol{V_{BIAS}}$ must be greater than the **barrier potential**.

A fundamental picture of what happens when a diode is **Forward biased** is shown in Figure (6). Because as (like) charges repel, the **negative side** of the bias voltage source pushes the free electrons, which are the **majority carriers** in the n region toward the $p-n$ junction. This **flow of free electrons** is called **electron current**.
The negative side of the source also provides a continuous flow of electrons through the external connection (conductor) and into the n region as shown.

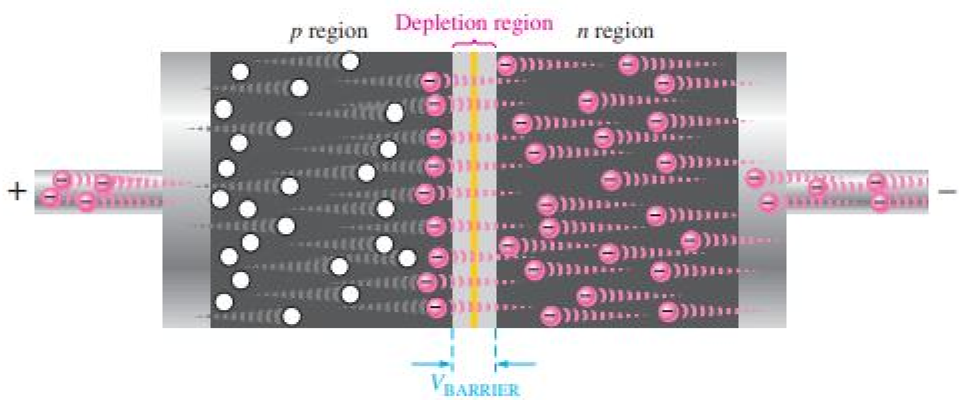


Figure (6): A forward-biased diode showing the flow of majority carriers and the voltage due to the barrier potential across the depletion region.

The bias-voltage source imparts sufficient energy to the free electrons for them to overcome the barrier potential of the depletion region and move on through into the p region.
Once in the p region, these **conduction electrons** have lost enough energy to immediately combine with holes in the valence band.

Now, the electrons are in the valence band in the p region, simply because they have lost too much energy overcoming the barrier potential to remain in the conduction band. Since unlike charges attract, the positive side of the bias-voltage source attracts the **valence electrons** toward the left end of the p region.
The **holes** in the p region provide the **medium** or "**pathway**" for these valence electrons to move through the p region. The electrons move from one hole to the next toward the left.
The **holes**, which are the majority carriers in the p region, effectively (not actually) move to the right toward the junction, as you can see in Figure (6).

This **effective flow of holes** is called the **hole current**.
You can also view the **hole current** as being created by the flow of valence electrons through the p region, with the holes providing the only means for these electrons to flow.

As the electrons flow out of the p region through the external connection (conductor) and to the positive side of the bias-voltage source, they leave **holes** behind in the p region; at the same time, these electrons become conduction electrons in the metal conductor.
Recall that the conduction band in a conductor overlaps the valence band so that it takes much less energy for an electron to be a free electron in a conductor than in a semiconductor.
So, there is continuous availability of holes effectively moving toward the $p-n$ junction to combine with the continuous stream of electrons as they come across the junction into the p region.

3.7.1.1: The Effect of Forward Bias on the Depletion Region

As more **electrons** flow into the depletion region, the **number of positive ions** is reduced.
As more **holes** effectively flow into the depletion region on the other side of the $p-n$ junction, the **number of negative ions** is reduced.
This reduction in positive and negative ions during forwarding bias causes the **depletion region to narrow**, as indicated in Figure (7).

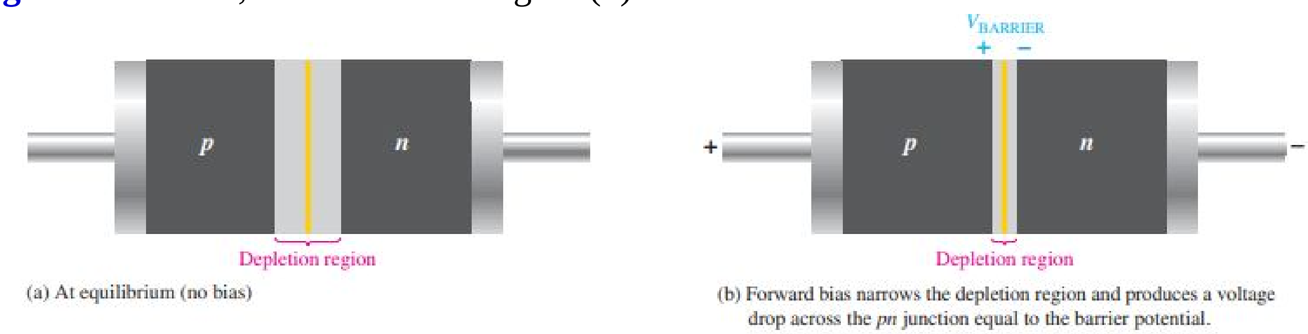


Figure (7): The depletion region narrows and a voltage drop is produced across the $p-n$ junction when the diode is forward-biased.

3.7.1.2: The Effect of the Barrier Potential During Forward Bias

Recall that the **electric field** between the positive and negative ions in the depletion region on either side of the junction creates an "**energy hill**" that prevents free electrons from diffusing across the junction at equilibrium (see Figure 3b). This is known as the **barrier potential**.

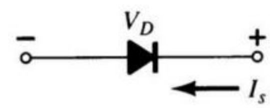
When a forward bias is applied, the free electrons are **provided with enough energy** from the bias-voltage source to overcome the **barrier potential** and effectively "climb the energy hill" and cross the depletion region. *The energy that the electrons require in order to pass through the depletion region **is equal** to the barrier potential*.

In other words, the electrons give up an amount of energy equivalent to the barrier potential when they cross the depletion region. This energy loss results in a **voltage drop across the $p - n$ junction equal to the barrier potential (0.7 V)**, as indicated in Figure (7b).

An additional small voltage drop occurs across the p and n regions due to the **internal resistance of the material**.

For doped semiconductive material, this resistance, called **dynamic resistance**, *is very small and can usually be neglected*.

3.7.2: Reverse Bias



Reverse bias is the condition that essentially prevents (no allows) current through the diode.

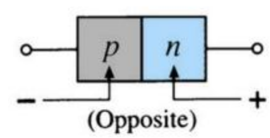


Figure (8) shows a ***dc* voltage** source connected across a diode in the direction to produce **reverse bias**. This external bias voltage is designated as $\boldsymbol{V_{BIAS}}$ just as it was for forward bias.

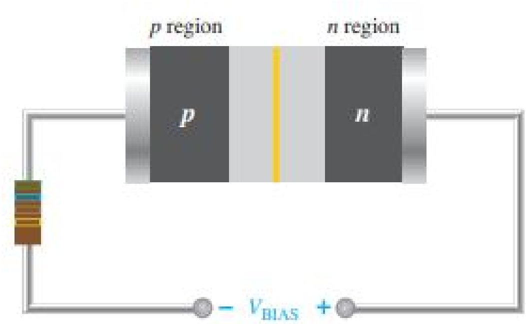


Figure (8): A diode connected for reverse bias.

Notice that the positive side of V_{BIAS} is connected to the n region of the diode and the negative side is connected to the p region.

Also note that the **depletion region** is shown much wider than in forward bias or equilibrium.

A limiting **resistor** is shown although it is not important in reverse bias because there is essentially **no current**.

An illustration of what happens when a diode is reverse-biased is shown in Figure (9).

Because unlike charges attract, the **positive side** of the bias-voltage source "pulls" the free electrons, which are the **majority carriers** in the n region, away from the $p - n$ junction.
As the electrons flow toward the positive side of the voltage source, **additional positive ions are created**. This results in a **widening of the depletion region** and a depletion of majority carriers.

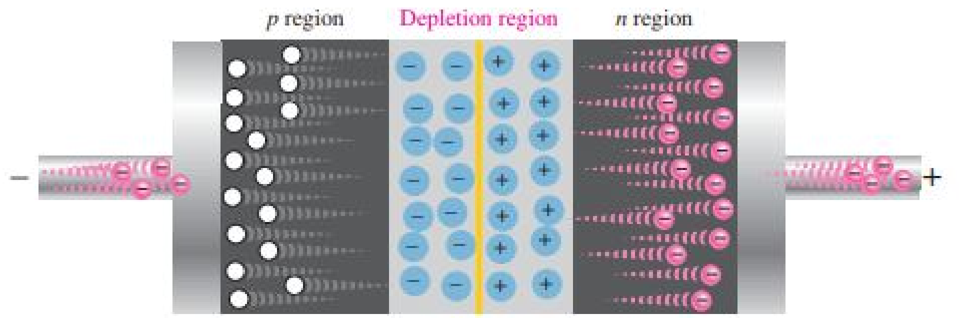


Figure (9): The diode during the short transition time immediately after reverse-bias voltage is applied.

In the p region, **electrons** from the negative side of the voltage source enter as valence electrons and *move from hole to hole* toward the depletion region where they create **additional negative ions**. This results in a **widening of the depletion region** and a depletion of majority carriers. The flow of **valence electrons** can be viewed as **holes** being "pulled" toward the positive side.

The initial flow of charge carriers is transitional and lasts for only a very short time after the reverse-bias voltage is applied.

As the depletion region widens, the availability of majority carriers decreases.

As more of the n and p regions become depleted of majority carriers, the **electric field** between the positive and negative ions **increases** in strength until the ***potential*** *across the depletion region equals the* ***bias voltage*** V_{BIAS} at this point.

The **transition current** essentially ceases (stands) except for a *very small* ***reverse current*** *that can usually be neglected*.

3.7.2.1: Reverse Current

The extremely **small current** that exists in reverse bias after the **transition current** dies out is caused by the **minority carriers** in the n and p regions that are produced by **thermally** generated electron-hole pairs.
The **small number of free minority electrons** in the p region is "pushed" toward the pn junction by the negative bias voltage.

When these **electrons** reach the **wide depletion region**, they "**fall down the energy hill**" and combine with the **minority holes** in the n region as valence electrons and flow toward the positive bias voltage, creating a small hole current.
The **conduction band in the *p* region** is at a higher energy level than the **conduction band in the *n* region**. Therefore, the **minority electrons** easily pass through the depletion region because **they require no additional energy**. Reverse current is illustrated in Figure (10).

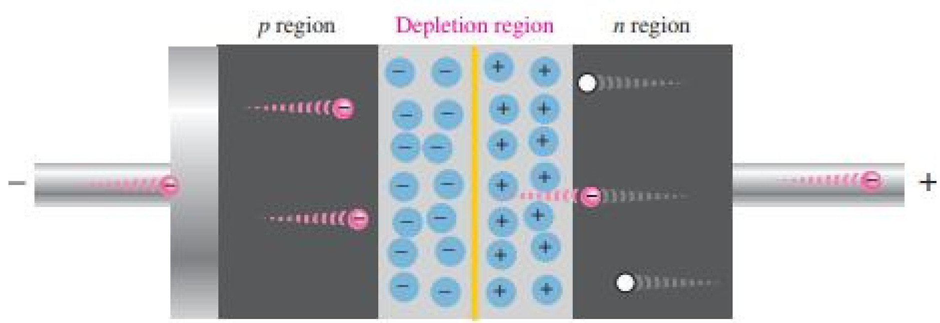


Figure (10): The extremely small reverse current in a reverse-biased diode is due to the minority carriers from thermally generated electron-hole pairs.

3.7.2.2: Reverse Breakdown

Normally, the **reverse current** is so small that it can be neglected.

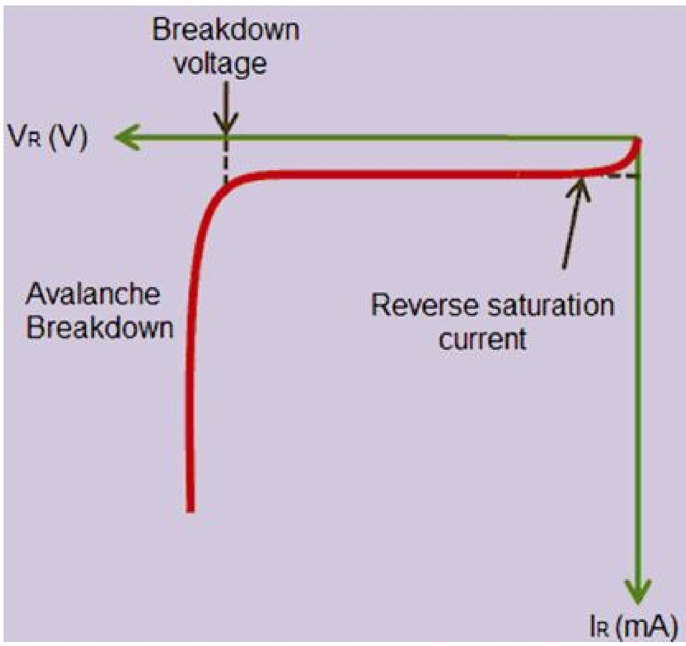
However, if the external **reverse-bias voltage** is increased to a value called the **breakdown voltage**, the **reverse current** will drastically increase.

This is what happens.
The high reverse-bias voltage imparts energy to the free minority **electrons** so that as they speed through the p-region, they collide with atoms with enough energy to knock valence electrons out of orbit and into the conduction band.

The **newly created conduction electrons** are also high in energy and repeat the process.
If one electron knocks only two others out of their valence orbit during its travel through the *p*-region, the *numbers quickly multiply*.

As these high-energy **electrons** go through the depletion region, they have enough energy to go through the *n*-region as conduction electrons, *rather than combining with holes*.

The **multiplication of conduction electrons** just discussed is known as an **avalanche** and results in a **very high reverse current** that can damage the diode **because of excessive heat dissipation**.



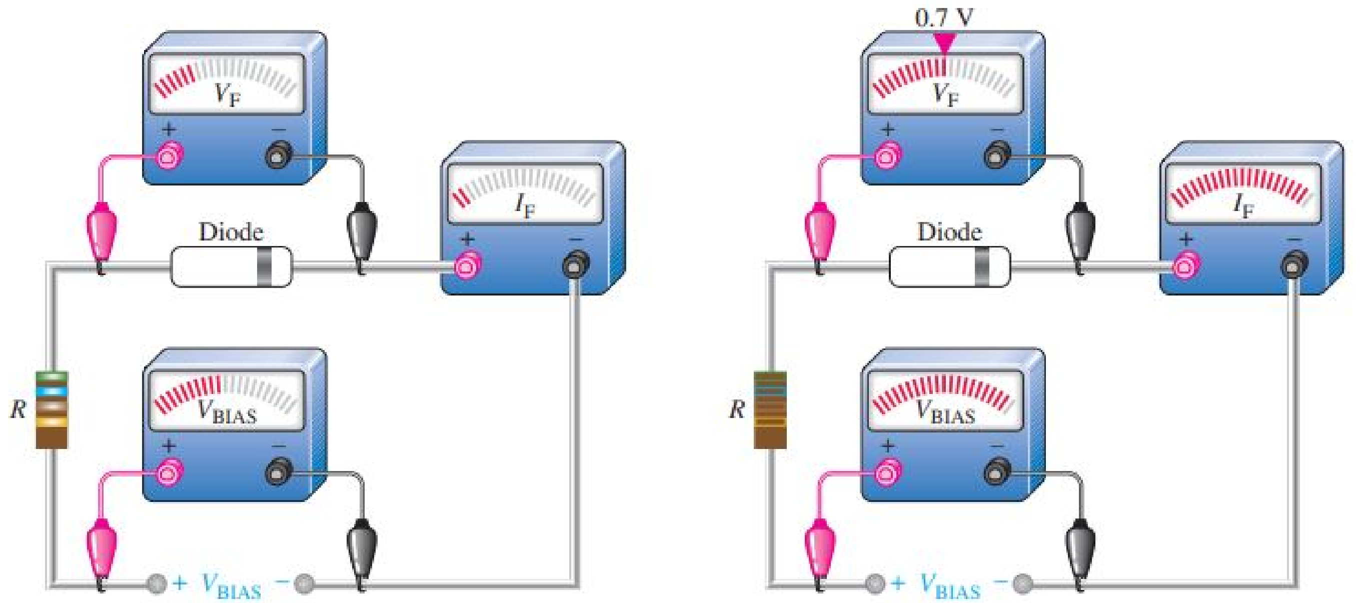
3.8: Voltage-Current Characteristic of a Diode

As you have learned, **forward bias produces current through a diode** and **reverse bias essentially prevents current**, except for a negligible reverse current. Reverse bias prevents current as long as the reverse-bias voltage does not equal or exceed the breakdown voltage of the junction.

In this section we will examine more closely the relationship between the **voltage** and the **current** in a diode on a graphical basis.

3.8.1: V-I Characteristic for Forward Bias

When a **forward-bias voltage** is applied across a diode, there is **current**. This current is called the **forward current** and is designated I_F. Figure (11) illustrates what happens as the **forward-bias voltage** is increased positively from 0 V. The **resistor** is used to limit the **forward current** to a value that *will not overheat the diode and cause damage*.



(a) Small forward-bias voltage ($V_F < 0.7$ V), very small forward current.

(b) Forward voltage reaches and remains nearly constant at approximately 0.7 V. Forward current continues to increase as the bias voltage is increased.

Figure (11): Forward-bias measurements show general changes in V_F and I_F as V_{BIAS} is increased.

With 0 V across the diode, there is **no** **forward current**. As gradually increase the **forward-bias voltage**, the **forward current** and the **voltage across** the diode gradually increase, as shown in Figure (11a). A portion of the forward-bias voltage is dropped across the limiting resistor. When the **forward-bias voltage** is increased to a value where the **voltage across the diode** reaches approximately **0.7 V** (**barrier potential**), the **forward current** begins to increase rapidly, as illustrated in Figure (11b).

As you continue to increase the **forward-bias voltage**, the **current continues** to increase very rapidly, *but the voltage across the diode increases only gradually above* ***0.7 V***. This small increase in the diode voltage above the barrier potential is due to the voltage drop across the internal dynamic resistance of the semiconductive material.

3.8.2: V-I Characteristic for Reverse Bias

When a **reverse-bias voltage** is applied across a diode, there is only an extremely small **reverse current (I_R)** through the $p-n$ junction. With **0V** across the diode, there is no reverse current. As you gradually increase the **reverse-bias voltage**, there is a very small **reverse current** and the **voltage across** the diode increases. When the applied **bias voltage** is increased to a value where the **reverse voltage** across the diode (V_R) reaches the **breakdown value (V_{BR})** the **reverse current** begins to increase rapidly.

As you continue to increase the **bias voltage**, the **current continues** to increase very rapidly, *but the voltage across the diode increases very little above* V_{BR}.
Breakdown, with exceptions, is not a normal mode of operation for most $p-n$ junction devices.

The balance between the **diffusion** and **drift currents** is disturbed during forward or reverse bias and a net current flow through the junction. We now determine the **current-voltage relationship for the biased $p-n$ junction**.

At equilibrium, the **minority carrier electron concentration in the p region (n_p)** is related to the **majority carrier electron concentration in the n region (n_n)** by equation (6) as

$$n_n = n_p e^{-\left[\frac{eV_B}{KT}\right]} \quad \dots (19)$$

When a small **forward voltage V** is applied, the effective **barrier potential V_B** decrease to $V_B - V$. This results in diffusion of some of the majority carriers across the junction, i.e., holes to n side and electron to p side.
Thus, the **minority carrier electron concentration** at the edge of the transition region on the **p side**, **$n(-x_p)$,** becomes greater than its **equilibrium value** by a small amount **Δn_p**. such an increase in the **minority carrier concentration** with **forward bias** is referred to as the **minority carrier injection**. The **minority carrier electron concentration** in the n region, however, changes only slightly with bias compared to its equilibrium value and hence can be taken as nearly constant, particularly for low level injection. Thus, for applied forward bias, **equation (19) can be written as**:

$$n(-x_p) = n_p + \Delta n_p = n_n e^{-\left[\frac{e(V_B-V)}{KT}\right]} = n_p e^{\left(\frac{eV_B}{KT}\right)} e^{-\left[\frac{e(V_B-V)}{KT}\right]} \quad \dots (20)$$

OR: $n_p + \Delta n_p = n_p e^{\left(\frac{eV}{KT}\right)} \quad \dots (20)$

OR:

$$\Delta n_p = n_p\left(e^{\left(\frac{eV}{KT}\right)} - 1\right) \quad \dots (21)$$

This gives the excess electron concentration at the edge of the transition region, i.e., for $x = -x_p$, in terms of the equilibrium electron concentration in the? region and the applied forward bias. Similarly, **for excess holes on the n side**, we have:

$$\Delta p_n = p_n\left(e^{\left(\frac{eV}{KT}\right)} - 1\right) \quad \dots (22)$$

The injected minority carriers diffuse into their respective regions up to certain distances and then recombine with the opposite type of carrier.
The **diffusion currents** produced by these **charges** can be determined by using the **diffusion equations** and the **Ficks first law**.

The **electron diffusion current injected** into the p type material at the junction is given by:

$$I_n = \frac{eAD_n}{L_n}\Delta n_p = \frac{eAD_n}{L_n} n_p\left(e^{\left(\frac{eV}{KT}\right)} - 1\right) \quad \dots (23)$$

When D_n is the **diffusion coefficient of electrons** in m^2/s, A is the **area of cross section of the junction** and $L_n = \sqrt{D_n \tau_n}$ ... (24) is the **electron diffusion length** which represents the average distance an electron diffuses before recombining, and τ_n is **the recombination lifetime of the electron carriers**.

Similarly, the **hole diffusion current injected** into the n type material at the junction is:

$$I_p = \frac{eAD_p}{L_p}\Delta p_n = \frac{eAD_p}{L_p} p_n\left(e^{\left(\frac{eV}{KT}\right)} - 1\right) \quad \dots (25)$$

Where D_p and L_p represent the **diffusion coefficient** and **diffusion length** for **holes** respectively.

The direction of both the currents is the same. The **total diffusion current I**, is thus given by:

$$I = I_n + I_p = eA\left(\frac{D_n}{L_n} n_p + \frac{D_p}{L_p} p_n\right)\left(e^{\left(\frac{eV}{KT}\right)} - 1\right) \rightarrow I = I_s\left(e^{\left(\frac{eV}{KT}\right)} - 1\right) \quad \dots (26)$$

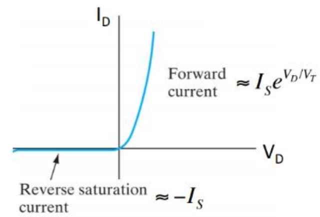
Where $I_s = eA\left(\frac{D_n}{L_n} n_p + \frac{D_p}{L_p} p_n\right)$ ... (27)

The current I_s is called the **reverse saturation current**. It is the same as the equilibrium diffusion current or drift current, both being equal at equilibrium. Equation (26) is called **Diode equation**.

When the **forward bias** V is grater then a few $\frac{KT}{e} \cong 0.026\ V$ at 300k, the exponential term is much larger than unity and equation (26) gives the forward current as:

$$I_F = I_s e^{\left(\frac{eV}{KT}\right)} \quad \ldots (28)$$

i.e., the current increases exponentially with forward bias, the equation (26) also holds for reverse bias case. Putting $V = -V_r$ in equation (26), the **current during reverse bias** is given by:



$$I_R = I_s\left(e^{-\left(\frac{eV_r}{KT}\right)} - 1\right) \quad \ldots (29)$$

For V_r greater than a few $\frac{KT}{e}$, the exponential term is negligible and we obtain:

$$I_R = -I_s \quad \ldots (30)$$

Thus, the **current I_R is** numerically equal to I_s and flows in a direction opposite to I_F (i.e., from n to p side). Hence I_s is termed the **reverse saturation current**.

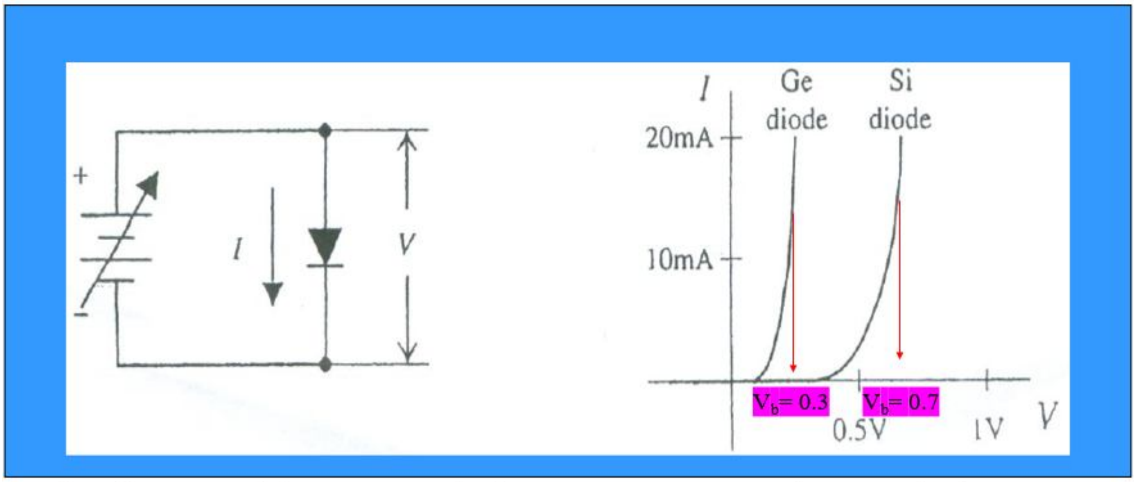
At a given temperature, the **reverse current** is very small and is almost constant. The reverse current has a magnitude less than or the order of **1μA** and is quite small as compared to the forward current which generally lies in the milli-ampere range. The empirical form of equation (26) is:

$$I = I_s\left(e^{\left(\frac{eV}{\eta KT}\right)} - 1\right) \quad \ldots (31)$$

Where η is a **numerical constant (Diode Ideality Factor)** which depends on the **material of the diode**. It is value is **1 for Ge** and **2 for Si**. This equation is called the $p-n$ diode equation.

The typical I-V characteristic of a $p-n$ junction is shown in figure (12). Unlike an ordinary resistor, a $p-n$ junction exhibits highly nonlinear characteristic. The **current** flows **relatively freely** in the forward direction. Whereas a **negligible current** flows in the reverse direction. It is due these salient features of the I-V characteristic that a $p-n$ junction is considered to be a very useful device.

It is relevant to point out that besides the reverse saturation current produced by minority carriers, there also exist a small ohmic current which leaks along the surface edges of the junction during reverse bias. for small value of forward bias (region 0 A), the diode current is very small and increases rapidly with further increase in voltage. This is because a small part of the applied voltage is used up in overcoming the barrier potential at the junction. The voltage at which the current begins to increase rapidly is known as the cut in, offset, or **threshold voltage** and is about **0.7V for Si** and **0.3V for Ge**.



Circuit Assemble (Forward Bias) IV characteristics

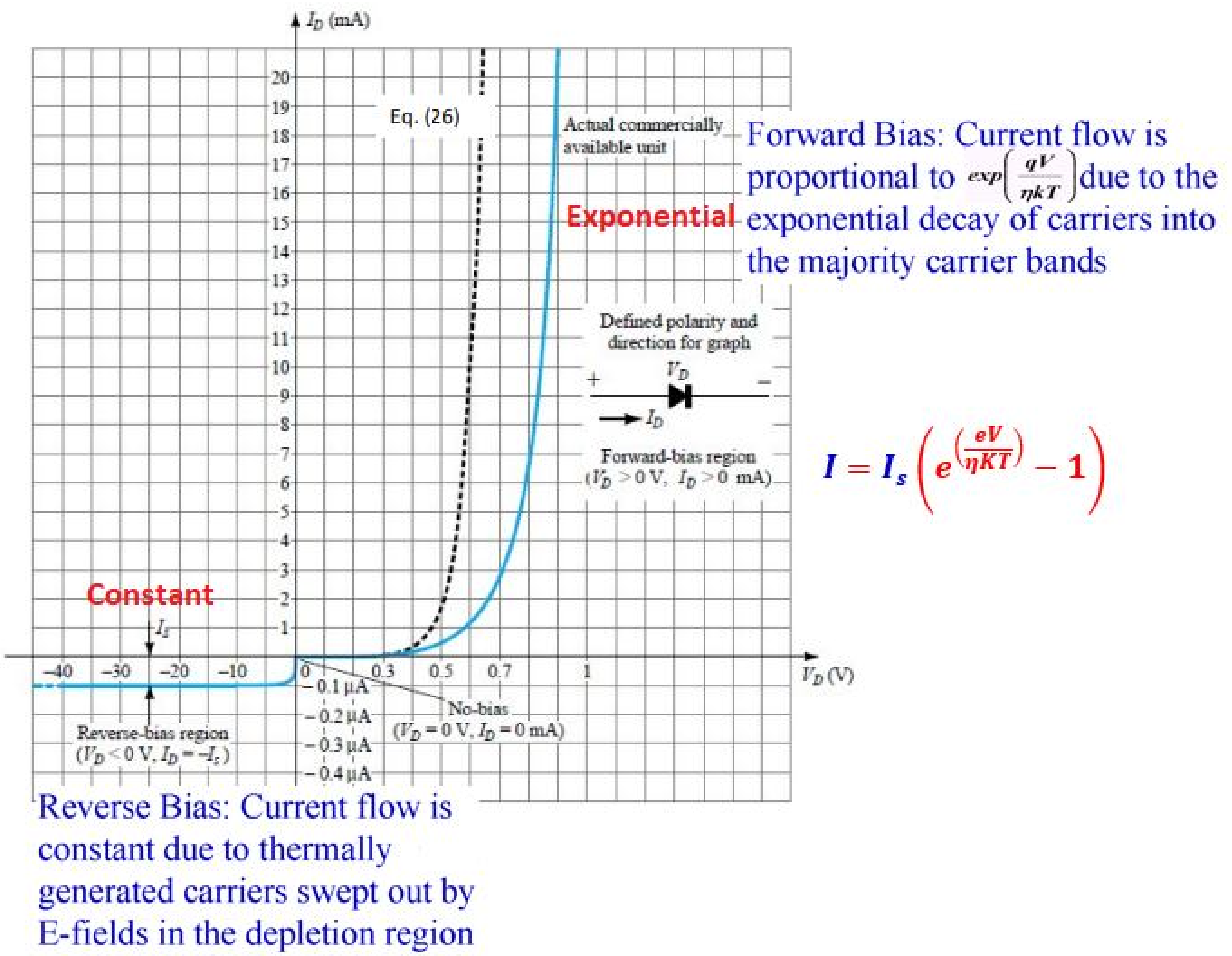
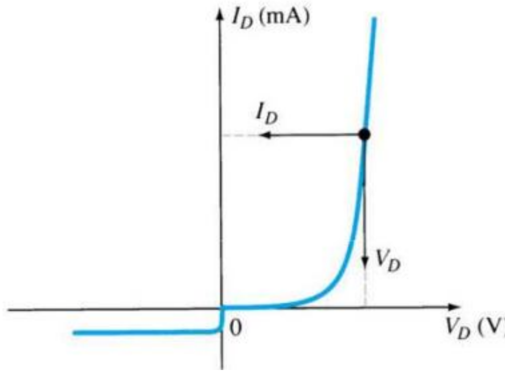


Figure (12): I-V: Characteristic of a $p-n$ junction.

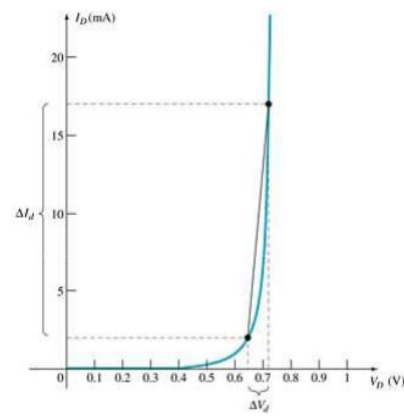
3.9: DC and AC Resistance of $p-n$ junction



The **static or Dc resistance, R_{dc}**, of a $p-n$ junction diode is defined as **the ratio of the total applied voltage to the total diode current**, i.e.,

$$R_{dc} = \frac{V}{I} = \frac{V}{I_s\left(e^{\left(\frac{eV}{\eta KT}\right)} - 1\right)} \quad \ldots (32)$$

Since the I-V characteristic of the junction is nonlinear R_{dc} has different values at different point on the curve. The **forward resistance** of a typical $p-n$ diode is about a few ohms only, whereas its **reverse resistance** may be of the order of several mega ohms.



The **dynamic or AC resistance, r_{ac}**, of a diode is defined as **the ratio of the small change in voltage to the small change in current**, i.e.,

$$r_{ac} = \frac{dV}{dI} \quad \ldots (33)$$

It is thus reciprocal of the **slope** of I-V characteristic curve. Like r_{dc} , r_{ac} also depends on the operating point. It is an important parameter particularly for small values of the ac input signal. From equation (31) and (33), we obtain:

$$\frac{1}{r_{ac}} = \frac{dI}{dV} = \frac{d}{dV}\left(I_s e^{\left(\frac{eV}{\eta KT}\right)} - I_s\right) = \frac{e}{\eta KT} I_s e^{\left(\frac{eV}{\eta KT}\right)} = \frac{e}{\eta KT}(I + I_s)$$

$$r_{ac} = \frac{\eta KT}{e(I + I_s)} \quad \ldots (34)$$

For **Si** at 300k, $\frac{KT}{e} \cong 0.026$ and $\eta = 2$; $r_{ac} = \frac{\eta KT}{e(I+I_s)} = \frac{0.052}{(I+I_s)} \cong \frac{0.052}{I}\,\Omega$

Where I is forward current in amperes. Thus r_{ac} decreases with increase in current however, for small applied signals, it remains practically constant.

Example 3.1: An alloyed junction is formed by melting a pellet of indium on to an n-type Si of conductivity 200 $(\Omega.m)^{-1}$. If the conductivity of the alloyed regrown region is 3.6×10^4 $(\Omega.m)^{-1}$ and intrinsic carrier concentration of Si is 1.5×10^{16} m^{-3}, determine the built-in voltage (V_B) at 27^0 C. The mobilities of electrons and holes are 0.135 and 0.048 m^2/Vs respectively.

Solution: For the n-type, we have: $\sigma_n = en\mu_n \cong eN_d\mu_n$

Donor concentration;

$$N_d = \frac{\sigma_n}{e\mu_n} = \frac{200}{1.6 \times 10^{-19} \times 0.135} = 9.26 * 10^{21} m^{-3}$$

Similarly, the acceptor concentration in the p-region is:

$$N_a = \frac{\sigma_p}{e\mu_p} = \frac{3.6 \times 10^4}{1.6 \times 10^{-19} \times 0.048} = 4.69 * 10^{24} m^{-3}$$

Built-in voltage V_B;

$$V_B = \frac{KT}{e} ln\left[\frac{N_a N_d}{n_i^2}\right] = 0.026\, ln\left[\frac{9.26 \times 10^{21} \times 4.69 \times 10^{24}}{(1.5 \times 10^{16})^2}\right] = 0.86V$$

Example 3.2: A $p - n$ junction silicon diode is given a forward bias of 0.5V. Determine the static (R_{dc}) and dynamic (r_{ac}) resistances of the diode at 27^0 C, if the reverse saturation current is 1μA.

Solution: The current through the diode is; $I = I_s\left[e^{\left(\frac{eV}{\eta kT}\right)} - 1\right]$

For **Si** at 300k, $\frac{KT}{e} \cong \mathbf{0.026}$ and $\boldsymbol{\eta = 2}$;

$$I = 10^{-6}\left[e^{\left(\frac{0.5}{2*0.026}\right)} - 1\right] = 15\, mA$$

Static resistance;

$$R_{dc} = \frac{V}{I} = \frac{0.5}{15 \times 10^{-3}} = 33.3\,\Omega$$

Dynamic resistance;

$$r_{ac} = \frac{\eta KT}{e(I + I_s)} = \frac{2 \times 0.026}{(I + I_s)} \cong \frac{0.052}{I} = \frac{0.052}{15 \times 10^{-3}} = 3.47\,\Omega\,,\, since\ I + I_s \cong I$$

Example 3.3: Using approximate Boltzmann's diode equation, find the change in forward bias (ΔV) for doubling the forward current of a germanium semiconductors at 290ºK.

Solution:

$$\frac{\eta KT}{e} \cong 2 \times 0.026 = 0.05 \rightarrow \frac{e}{\eta KT} = 20$$

$$I_1 = I_s\left(e^{\left(\frac{eV_1}{\eta KT}\right)} - 1\right) = I_s e^{(20V_1)} \text{ and } I_2 = I_s\left(e^{\left(\frac{eV_2}{\eta KT}\right)} - 1\right) = I_s e^{(20V_2)}$$

$$\frac{I_2}{I_1} = \frac{I_s e^{(20V_2)}}{I_s e^{(20V_1)}} = e^{20V_2 - 20V_1} \rightarrow \Delta V = 0.05\, ln\left(\frac{I_2}{I_1}\right) = 0.05\, ln(2) = 34.66\, mV$$

Example 3.4: A certain $p-n$ junction diode has a leakage current of 10^{-14} A at room temperature of 27ºC and 10^{-9} A at 125ºC. The diode is forward-biased with a constant-current source of 1 mA at room temperature. If current is assumed to remain constant, calculate the junction barrier voltage at room temperature and at 125ºC.

Solution:

$$I = I_0 \exp(eV/kT - 1) \quad \text{or} \quad (I/I_0) + 1 = \exp(eV/kT)$$

Taking logarithm of both sides and solving for V, we get

$$V = \frac{kT}{e} \ln\left(\frac{I}{I_0} + 1\right)$$

Now, at 27°C or (273 + 27) = 300ºK

$$\therefore \quad kT/e = 1.38 \times 10^{-23} \times 300 / 1.6 \times 10^{-19} = 26 \text{ mV}$$

At $(273 + 125) = 398$ºK,

$$kT/e = 1.38 \times 10^{-23} \times 398 \times (1.6 \times 10^{-19}) = 36 \text{ mV}$$

Hence, at 27ºC, $V_B = 26 \ln\left(\frac{10^{-3}}{10^{-14}} + 1\right) = 660 \text{ mV} = \mathbf{0.66\ V}$

At 125ºC, $V_B = 36 \ln\left(\frac{10^{-3}}{10^{-9}} + 1\right) = 500 \text{ mV} = \mathbf{0.5\ V}$

Example 3.5: A silicon diode has a forward voltage drop of 1.2 V for a forward dc current of 100 mA. It has a reverse current of 1 μA for a reverse voltage of 10 V. Calculate:

(a) bulk and reverse resistance of the diode

(b) ac resistance at forward dc current of **(i)** 2.5 mA and **(ii)** 25 mA.

Solution:

Bulk resistance (r_B)

It is the sum of the resistance values of the P-and N-type semiconductor materials of which the diode is made of.

$$\therefore \quad r_B = r_P + r_N$$

Usually, it is very small. It is given by

$$r_B = (V_F - V_B)/I_F$$

Its value for forward-biased junction depends on the magnitude of forward *dc* current.

$$r_j = 25\ \text{mV}/I_F(\text{mA}) \quad \text{– for Ge}$$
$$= 50\ \text{mV}/I_F(\text{mA}) \quad \text{– for Si}$$

For large values of forward current, r_j is negligible. Hence, $r_{ac} = r_B$. For small values of *IF*, r_B *is* negligible as compared to r_j. Hence *rac = rj*.

It is the resistance offered by the diode well above the barrier voltage *i.e.*, when current is large. Obviously, this resistance is offered in the forward direction.

$$(a) \quad r_B = \frac{V_F - V_B}{I_F} = \frac{1.2\ \text{V} - 0.7\ \text{V}}{100\ \text{mA}} = 5\ \Omega$$

$$R_R = V_R / I_R = 10\ \text{V}/1\ \mu\text{A} = \mathbf{10\ M}$$

$$(b)\ (i) \quad r_j = 25\ \text{mV}/2.5\ \text{mA} = 10\ \Omega \qquad r_{ac} = r_B + r_j = 5 + 10 = \mathbf{15\ \Omega}$$

$$(ii) \quad r_j = 25\ \text{mV}/25\ \text{mA} = 1\ \Omega \qquad \therefore\ r_{ac} = 5 + 1 = \mathbf{6\ \Omega}$$

Example 3.6: Using analytical expression for diode current, calculate the dynamic slope resistance of a germanium diode at 290 K when forward biased at current of **(i)** 10 μA and **(ii)** 5 mA.

Solution:

$$I = I_0(e^{eV/kT} - 1) \approx I_0 e^{eV/kT}$$

$$\therefore \quad dI = \frac{e}{kT} I_0 [e^{eV/kT}]\, dV = \frac{e}{kT} I\, dV$$

$$\therefore \quad r_d = \frac{dV}{dI} = \frac{kT}{eI} = \frac{25 \times 10^{-3}}{I} \quad \text{– } I \text{ in ampere}$$

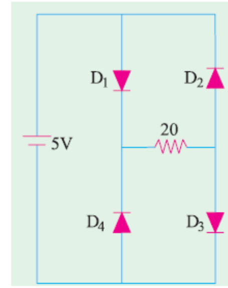
$$(i)\ \text{Now,} \quad I = 10\ \mu\text{A} = 10 \times 10^{-6} = 10^{-5}\ \text{A}$$

$$r_d = 25 \times 10^{-3} / 10^{-5} = \mathbf{2500\ \Omega}$$

$$(ii)\ \text{Now,} \quad I = 5\ \text{mA} = 5 \times 10^{-3}\ \text{A}$$

$$\therefore \quad r_d = 25 \times 10^{-3}/5 \times 10^{-3} = \mathbf{5\ \Omega}$$

Example 3.6:



Find the current through the 20Ω resistor shown in this Figure. Each silicon diode has a barrier potential of 0.7 V and a dynamic resistance of 2 Ω. Use the diode equivalent circuit technique.

Solution. In Fig. (*b*) each diode has been replaced by its equivalent circuit. It is seen that diodes D_1 and D_3 are forward-biased by 5 V battery whereas D_2 and D_4 are reverse-biased. Hence, the current will flow from point *A* to *B*, then to *C* via 20 Ω resistance and then back to the negative terminal of the 5 V battery.

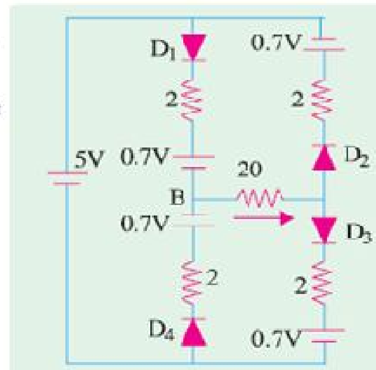
The net voltage in the equivalent circuit is

$$V_{net} = 5 - 0.7 - 0.7 = 3.6 \text{ V}$$

Total resistance seen by this net voltage is

$$R_T = 2 + 20 + 2 = 24 \ \Omega$$

The circuit current $\quad I = V_{net}/R_T = 3.6/24 = \mathbf{0.15 \ A}$



(*b*)

H.W: Q29: Calculate the barrier potential for Si junction at (a) 100ºC and (b) 0ºC if its value at 25ºC is 0.7 V.

H.W: Q30: A germanium diode draws 40 mA with a forward bias of 0.25 V. The junction is at room temperature of 293ºK. Calculate the reverse saturation current of the diode.

H.W: Q31: Calculate forward current in Ge diode at 20ºC when forward voltage is 0.3 V. Compare this value with that after a temperature rise of 50ºC. Assume that reverse saturation current doubles for every 10ºC rise in temperature.

REVIEW Yourself!!!

Q1: What is a $p-n$ junction?
A $p-n$ junction is **an interface or a boundary between two semiconductor material types, namely the p-type and the n-type, inside a semiconductor**.

Q2: Explain what does the arrow head represent in the schematic symbol of a $p-n$ junction?
The arrow head in the schematic symbol of a $p-n$ junction indicates the direction of conventional current flow when the diode is forward biased.

Q3: Explain what is an ideal diode?
An ideal diode is a two terminal polarity sensitive device that has zero resistance when it is forward biased and infinite resistance when reverse biased.

Q4: What is depletion region in pn junction?
Depletion region or depletion layer is **a region in a $p-n$ junction diode where no mobile charge carriers are present**.

Q5: Give the other names of depletion region?
i. Space charge region ii. Transition region

Q6: What is barrier potential?
The potential difference required to move the electrons through the electric field is called the barrier potential.

Q7: What is the typical value of the barrier potential for a silicon diode?
0.7V

Q8: What is the typical value of the barrier potential for a germanium diode?
approximately 0.3 V

Q9: What is forward bias and reverse bias in a pn junction?
When positive terminal of the external supply is connected to p region and negative terminal to n region, the $p-n$ junction is said to be forward biased. under forward biased condition the $p-n$ region offers a very low resistance and a large amount of current flows through it.

Q10: What are the types of biasing a pn junction?
1. Forward bias 2. Reverse bias.

Q11: Which bias condition produces majority carrier current?

Forward bias condition.

Q12: Compare the depletion regions in forward bias and reverse bias.

The depletion layer of a diode is much thicker while in reverse bias and substantially thinner while in forward bias.

Q13: Is reverse saturation current of a diode is independent of reverse bias voltage?

Yes.

Q14: How is reverse current in a diode produced?

The reverse current in reverse bias condition is **due to the minority carriers in the p and n regions**.

Q15: What is Reverse saturation current?

The current due to the minority carriers in reverse bias is said to be reverse saturation current. This current is independent of the value of the reverse bias voltage.

Q16: What is break down? What are its types?

When the reverse voltage across the $p-n$ junction is increased rapidly at a voltage the junction breaks down leading to a current flow across the device. This phenomenon is called as break down and the voltage is break down voltage. The types of break down are:

i) Zener break down ii) Avalanche breakdown

Q17: When does reverse breakdown occur in a diode?

When a pn junction is reverse biased, meaning the p-side of the diode is connected to the negative terminal of the battery and n-side is connected to the positive terminal of the battery, a small current flow through the circuit.

Q18: Explain what are the two mechanisms of breakdown in a $p-n$ junction?

Avalanche and Zener breakdown.

Q19: Name the breakdown mechanism in a lightly doped $p-n$ junction under reverse biased condition.

Avalanche breakdown.

Q20: Name the breakdown mechanism in a highly doped $p-n$ junction under reverse biased condition.

Zener breakdown.

Q21: What is meant by biasing a pn junction?
Connecting a pn junction to an external voltage source is biasing a pn junction.

Q22: Define avalanche as applied to diodes.
Description. Avalanche occurs in diodes **when the voltage across a diode exceeds a specified value**. An avalanche diode is a diode that is designed to break down and conduct at a specified reverse bias voltage. This is somewhat similar, but not identical to Zener breakdown.

Q23: Define dynamic resistance.
Dynamic resistance of a diode can be defined as the ratio of change in voltage across the diode to the change in current through the diode.

Q24: What is the static resistance of a diode?
Static resistance R of a diode can be defined as the ratio of voltage V across the diode to the current flowing through the diode. R = V/ I Where R - Static resistance of a diode V - Voltage across the diode I - current across the diode

Q25: What are break down diodes or Zener diodes?
Diodes which are designed with adequate power dissipation capabilities to operate in the break down region are called as break down or Zener diodes.

Q26: Why is silicon preferred over germanium in the manufacture of semiconductor devices?
The silicon semiconductor devices have, in general, higher PIV and current ratings and wider temperature range than germanium semiconductor devices, that's why silicon is preferred over germanium in the manufacture of semiconductor devices.

Q27: Why is germanium more temperature dependent than silicon?
Because the reserve saturation current in case of a germanium diode is approximately 1,000 times larger.
JUNCTION DIODES Interview Questions and Answers::

H.W: Q28: **Answers can be found at www.pearsonhighered.com/floyd.**

1. A $p-n$ junction is formed by
   (a) the recombination of electrons and holes
   (b) ionization
   (c) the boundary of a p-type and an n-type material
   (d) the collision of a proton and a neutron
2. The depletion region is created by
   (a) ionization (b) diffusion (c) recombination (d) answers (a), (b), and (c)
3. The depletion region consists of
   (a) nothing but minority carriers (b) positive and negative ions
   (c) no majority carriers (d) answers (b) and (c)
4. Which of the following is present in the depletion region of a $-n$ junction diode.
   (a) positive ions only (b) free electrons only
   (c) both positive and negative ions (d) none of the above
5. When a diode is forward-biased and the bias voltage is increased, the forward current will
   (a) increase (b) decrease (c) not change
6. When a diode is forward-biased and the bias voltage is increased, the voltage across the diode (assuming the practical model) will
   (a) increase (b) decrease (c) not change
7. When a diode is reverse-biased and the bias voltage is increased, the reverse current (assuming the practical model) will
   (a) increase (b) decrease (c) not change
8. When a diode is forward-biased and the bias voltage is increased, the voltage across the diode (assuming the complete model) will
   (a) increase (b) decrease (c) not change
9. If the forward current in a diode is increased, the diode voltage (assuming the practical model) will
   (a) increase (b) decrease (c) not change
10. If the forward current in a diode is decreased, the diode voltage (assuming the complete model) will
    (a) increase (b) decrease (c) not change
11. If the barrier potential of a diode is exceeded, the forward current will
    (a) increase (b) decrease (c) not change

12. The term bias means
    (a) the ratio of majority carriers to minority carriers
    (b) the amount of current across a diode
    (c) a dc voltage is applied to control the operation of a device
    (d) neither (a), (b), nor (c)
13. To forward-bias a diode,
    (a) an external voltage is applied that is positive at the anode and negative at the cathode
    (b) an external voltage is applied that is negative at the anode and positive at the cathode
    (c) an external voltage is applied that is positive at the p region and negative at the n region
    (d) answers (a) and (c)
14. When a diode is forward-biased,
    (a) the only current is hole current
    (b) the only current is electron current
    (c) the only current is produced by majority carriers
    (d) the current is produced by both holes and electrons
15. Although current is blocked in reverse bias,
    (a) there is some current due to majority carriers
    (b) there is a very small current due to minority carriers
    (c) there is an avalanche current
16. For a silicon diode, the value of the forward-bias voltage typically
    (a) must be greater than 0.3 V
    (b) must be greater than 0.7 V
    (c) depends on the width of the depletion region
    (d) depends on the concentration of majority carriers
17. When forward-biased, a diode
    (a) blocks current (b) conducts current (c) has a high resistance (d) drops a large voltage
18. A diode is normally operated in
    (a) reverse breakdown (b) the forward-bias region
    (c) the reverse-bias region (d) either (b) or (c)
19. The dynamic resistance can be important when a diode is
    (a) reverse-biased (b) forward-biased (c) in reverse breakdown (d) unbiased
20. The V-I curve for a diode shows
    (a) the voltage across the diode for a given current (c) the power dissipation
    (b) the amount of current for a given bias voltage (d) none of these

21. A p-type semiconductor is ……
    (a) positively charged (b) negatively charged
    (c) electrically neutral (d) not used in semiconductor devices
22. An example of trivalent impurity is:
    (a) Aluminum (b) Germanium
    (c) Barium (d) Chlorine
23. Ideally, a diode can be represented by a
    (a) voltage source (b) resistance (c) switch (d) all of these
24. An ideal diode can be considered as an:
    (a) Amplifier (b) Bi-stable switch (c) Oscillator (d) Fuse
25. In the practical diode model,
    (a) the barrier potential is taken into account (c) none of these
    (b) the forward dynamic resistance is taken into account (d) both (a) and (b)
26. In the complete diode model,
    (a) the barrier potential is taken into account
    (b) the forward dynamic resistance is taken into account
    (c) the reverse resistance is taken into account
    (d) all of these