Lecture 2
Diode Equivalent Circuit

Analog Electronics

By

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Outline and Aim

After completing this lecture, you should be able to:

- Describe the **characteristics and biasing of a semiconductor diode**
- Define **pn junction**
- Discuss the **depletion region** in a diode
- Define **barrier potential**
- Discuss **forward bias**
- Discuss **reverse bias**
- Define **reverse breakdown**

The Diode

If you take a block of silicon and dope half of it with a **trivalent** impurity and the other half with a **pentavalent** impurity, a boundary called the ***pn* junction** is formed between the resulting ***p*-type** and ***n*-type** portions of a semiconduction diode.

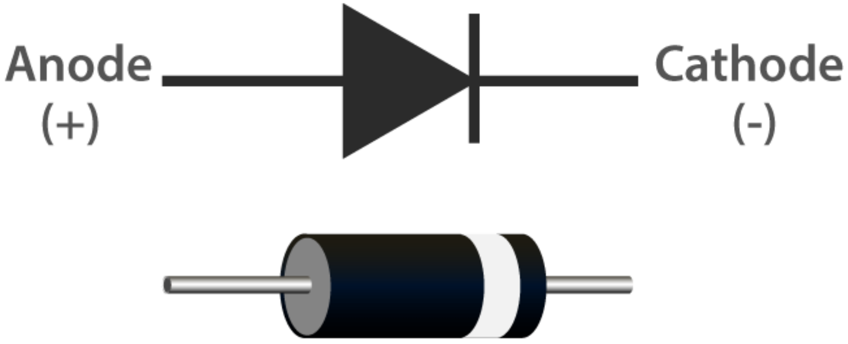


Fig. 1: Semiconductor diode symbol

The primary usefulness of the diode is its ability to allow current in only one direction and to prevent current in the other direction as determined by the bias. In electronics, **bias** refers to the use of a dc voltage to establish certain operating conditions for an electronic device. There are two practical bias conditions for a diode: **forward** and **reverse**.

N-Type and P-Type Semiconductors

Semiconductive materials do not conduct current well and are of little value in their intrinsic state. **This is because of the limited number of free electrons in the conduction band and holes in the valence band**. Intrinsic silicon must be modified by increasing the free electrons and holes to increase its conductivity and make it useful in electronic devices. This is done by adding impurities to the intrinsic material. Two types of extrinsic (impure) semiconductive materials, ***n*-type** and ***p*-type**, are the key building blocks for all types of electronic devices.

Doping The conductivities of silicon can be drastically increased and controlled by the addition of impurities to the intrinsic (pure) semiconductive material. This process, called **doping**, increases the number of current carriers (**electrons or holes**).

N-Type and P-Type Semiconductors

N-Type Semiconductor To increase the number of conduction-band electrons in intrinsic silicon, **pentavalent** impurity atoms are added. These are atoms with five valence electrons, such as **arsenic (As), phosphorus (P), and antimony (Sb)** and are known as **donor atoms** because they provide an extra electron to the semiconductor's crystal structure.

- **This extra electron** becomes a conduction electron because it is not attached to any atom.
- **The number of conduction electrons** can be controlled by the number of impurity atoms added to the silicon
- **Since most of the current carriers are electrons,** silicon doped in this way is an n-type semiconductor

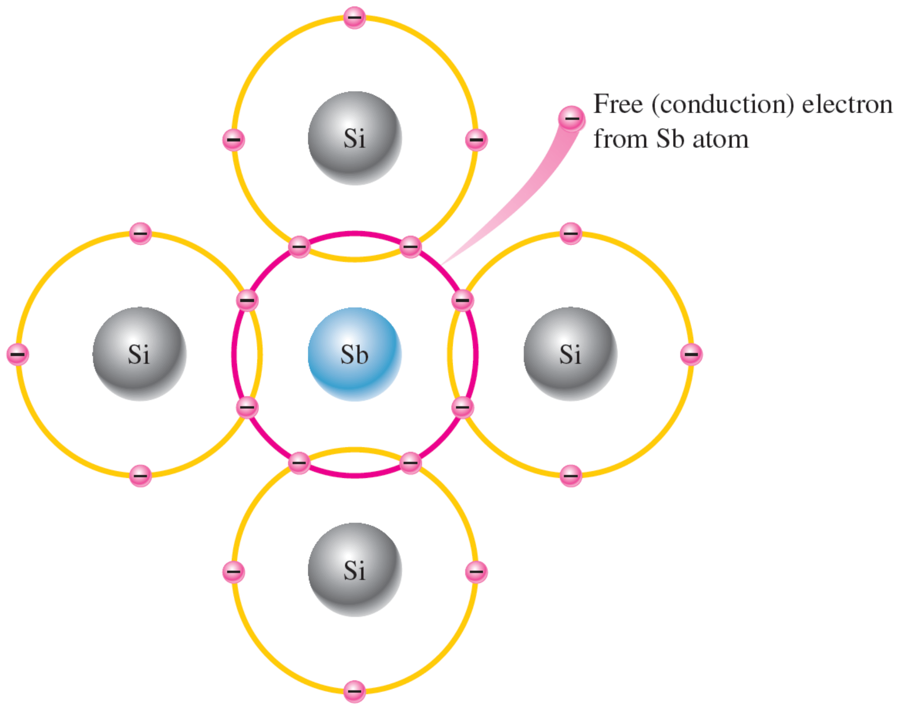


Fig. 2: **Pentavalent impurity** atom in a silicon crystal. An antimony (Sb) impurity atom is shown in the center. The extra electron from the Sb atom becomes a free electron.

N-Type and P-Type Semiconductors

P-Type Semiconductor To increase the number of holes in intrinsic silicon, **trivalent** impurity atoms are added. These are atoms with three valence electrons, such as **aluminum (Al), boron (B), and gallium (Ga)** and are known as **acceptor atoms** because they leave a hole in the semiconductor's crystal structure.

- **The number of holes** can be controlled by the amount of trivalent impurity added to the silicon.
- **Since most of the current carriers are holes,** silicon doped with trivalent atoms is a *p*-type semiconductor.

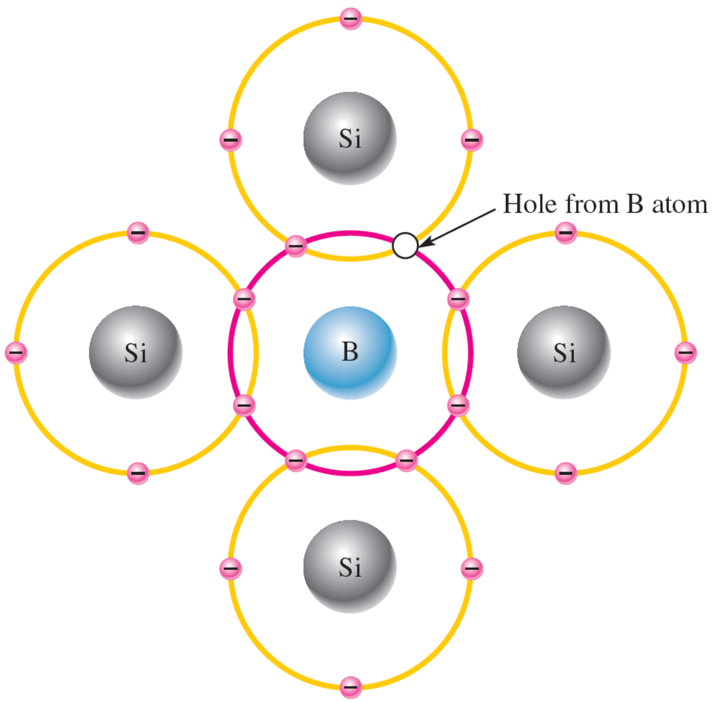


Fig. 3: **Trivalent impurity** atom in a silicon crystal. A boron (B) impurity atom is shown in the center.

Formation of the Depletion Region in a Diode

A **diode** consists of an ***n* region** and a ***p* region** separated by a ***pn* junction**, as illustrated in Fig. 4. The *n* region has many conduction electrons, and the *p* region has many holes. With no external voltage, the conduction electrons in the *n* region are randomly drifting in all directions.

a) 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.

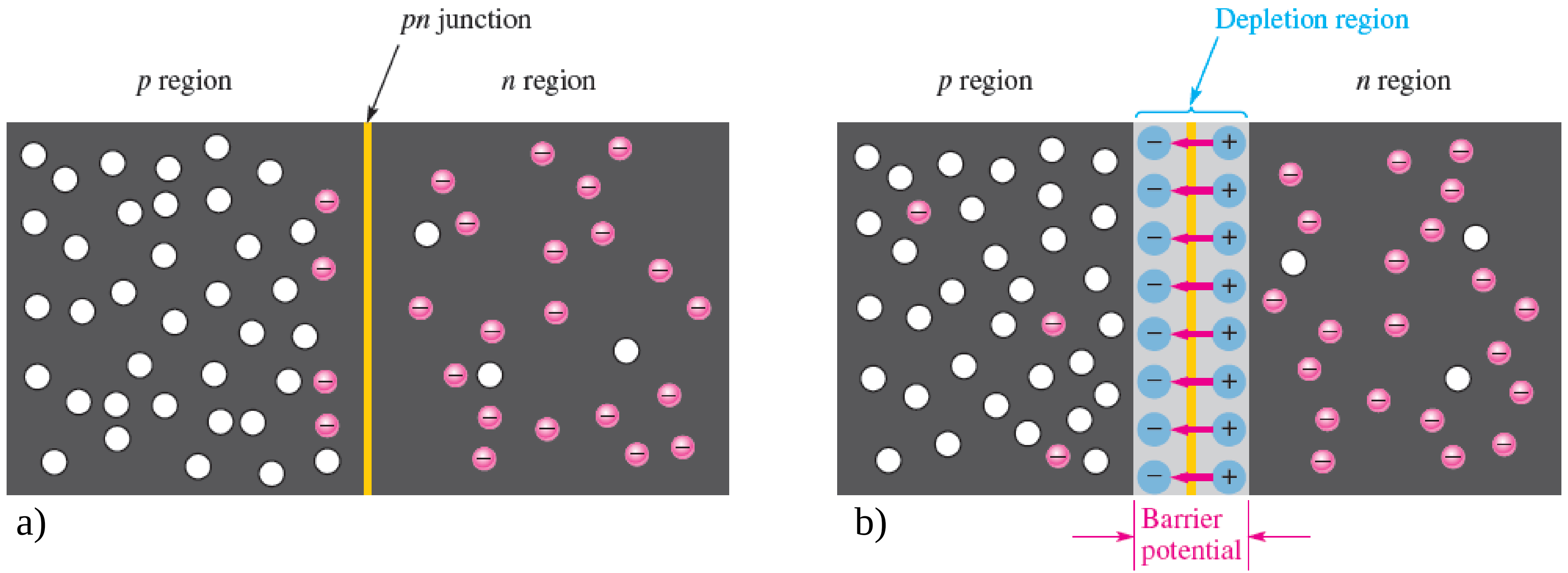


Fig. 4: Illustrate the formation of depletion region in a diode

Formation of the Depletion Region in a Diode

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.

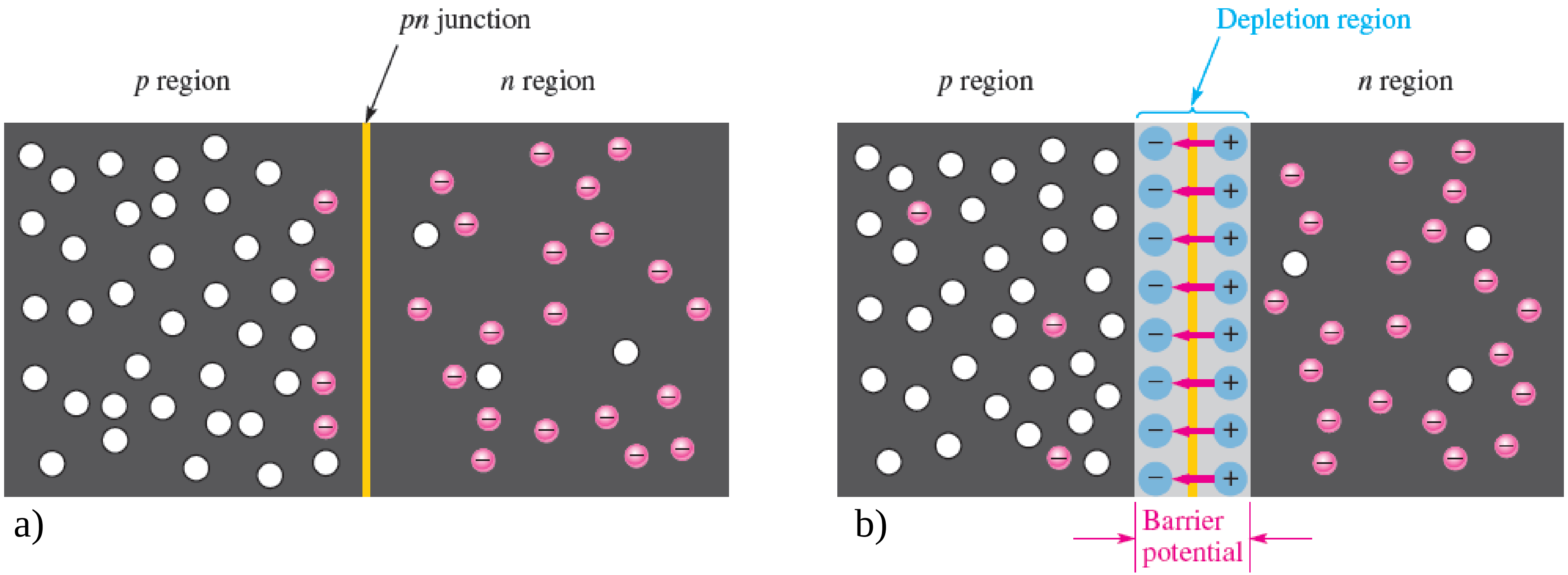


Fig. 4: Illustrate the formation of depletion region in a diode

Formation of the Depletion Region in a Diode

As this buildup occurs, the electrons in the *n* region must overcome both the attraction of the positive ions and the repulsion of the negative ions in order to migrate into the *p* region. Thus, as the ion layers build up, the area on both sides of the junction becomes essentially depleted of any conduction electrons or holes and is known as the **depletion region**.

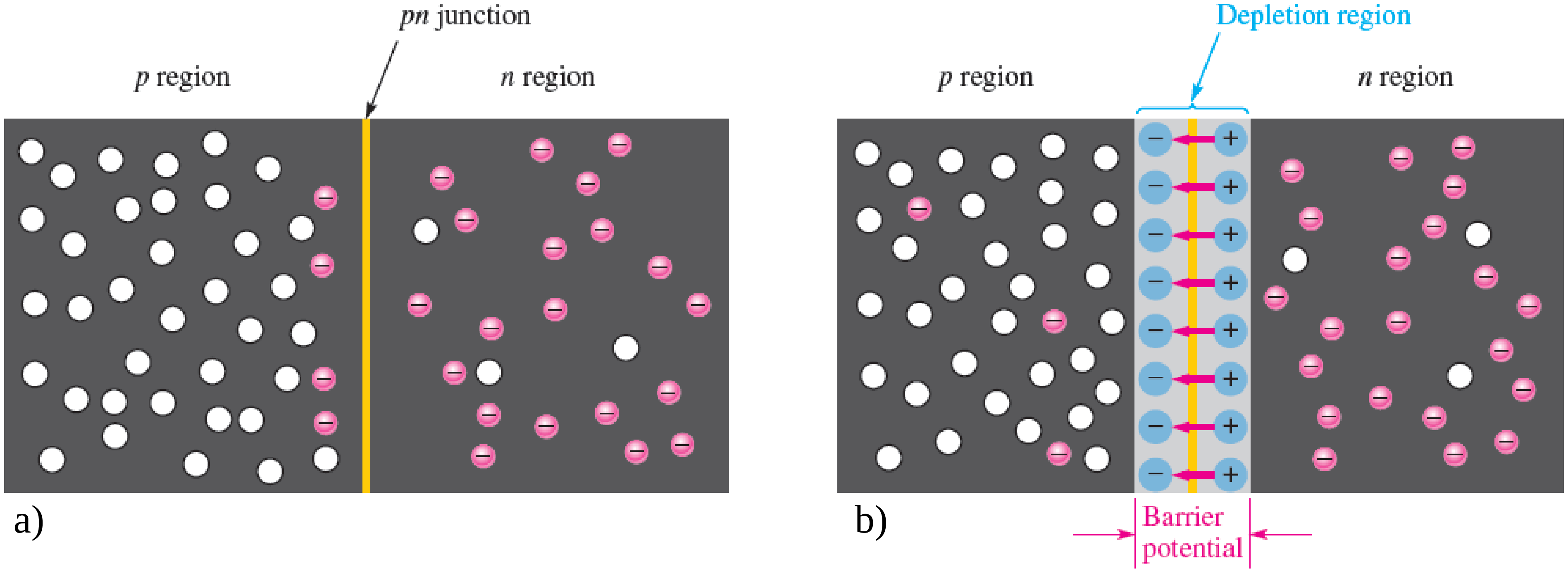


Fig. 4: Illustrate the formation of depletion region in a diode

Formation of the Depletion Region in a Diode

The existence of the positive and negative ions on opposite sides of the *pn* junction creates a barrier potential across the depletion region, as indicated in Fig. 4. The **barrier potential**, V_B is the amount of voltage required to move electrons through the depletion region. At 25°C it is approximately **0.7 V** for silicon and **0.3 V** for germanium. As the junction temperature increases, the barrier potential decreases, and vice versa.

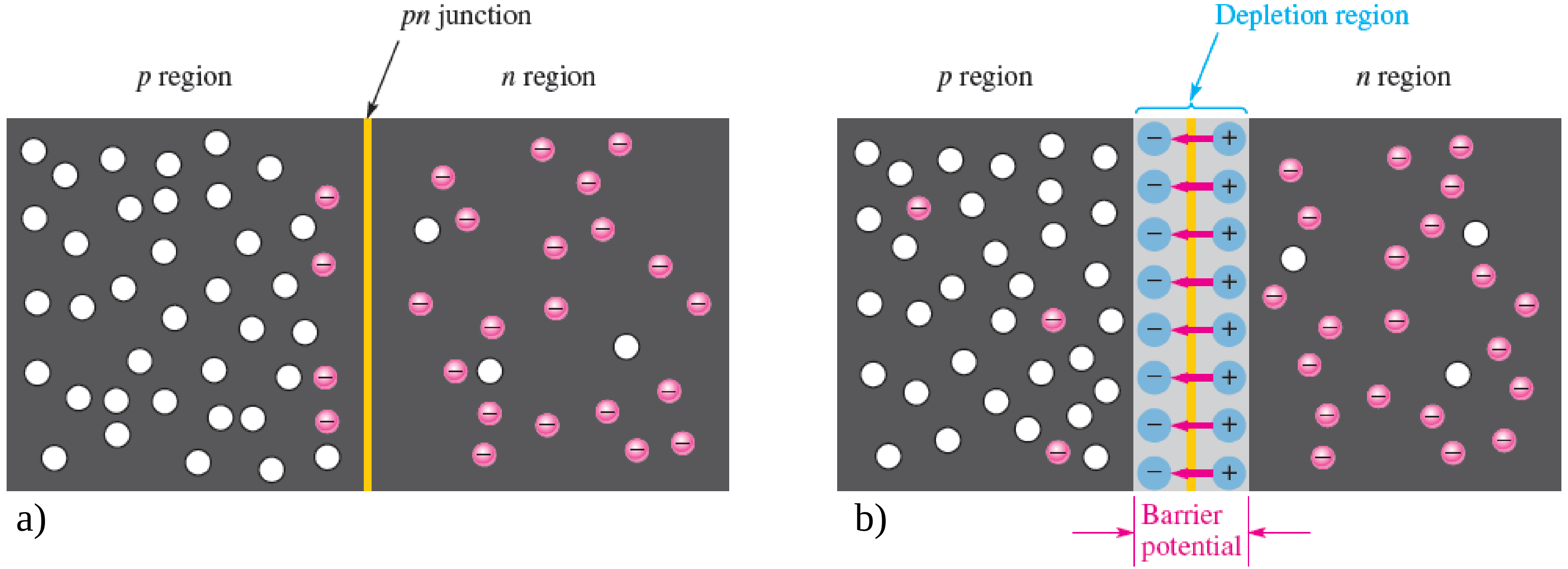


Fig. 4: Illustrate the formation of depletion region in a diode

Biasing a Diode (Forward bias)

Forward bias is the condition that permits current through a diode. Fig. 5 shows a dc voltage connected in a direction to forward-bias the *pn* junction. **Notice that** the negative terminal of the source is connected to the *n* region, and the positive terminal is connected to the *p* region.

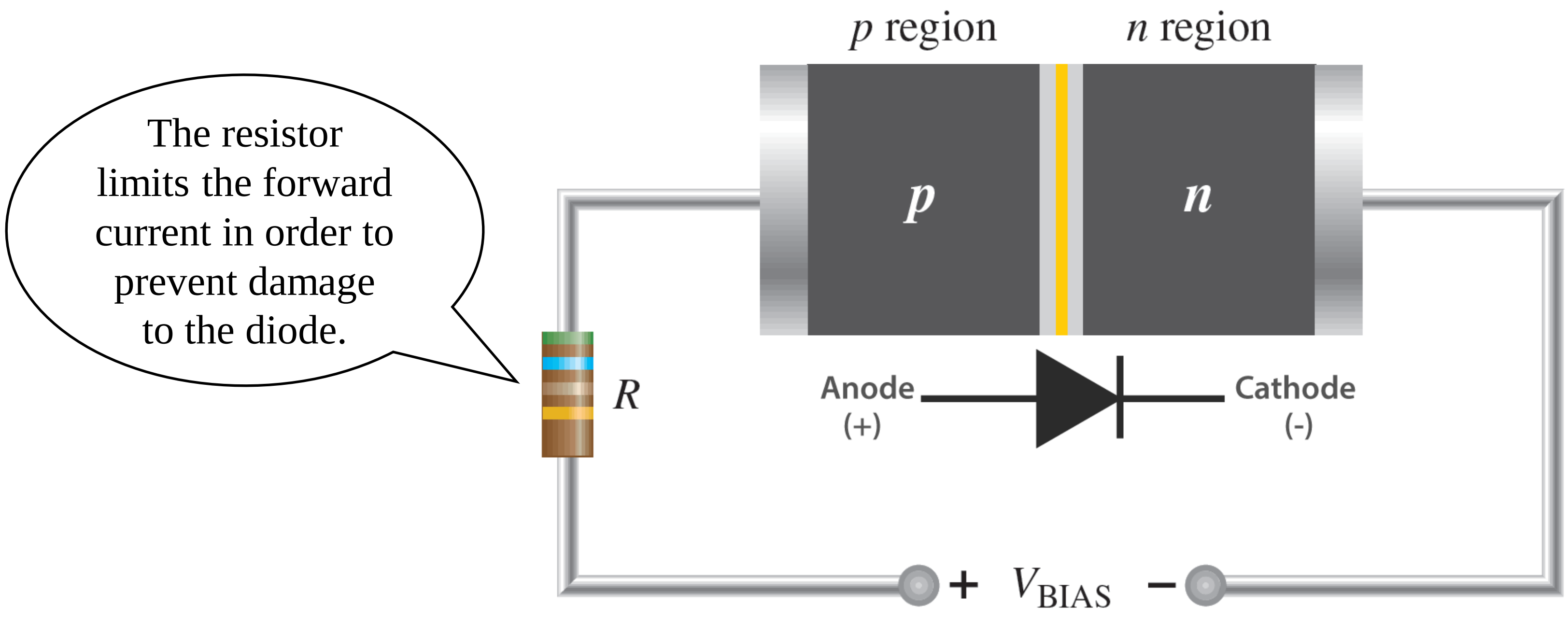


Fig. 5: Forward-bias connection.

Biasing a Diode (Forward bias)

The negative terminal of the bias-voltage source pushes the conduction-band electrons in the *n* region toward the *pn* junction, while the positive terminal pushes the holes in the *p* region also toward the *pn* junction. Recall that like charges repel each other.

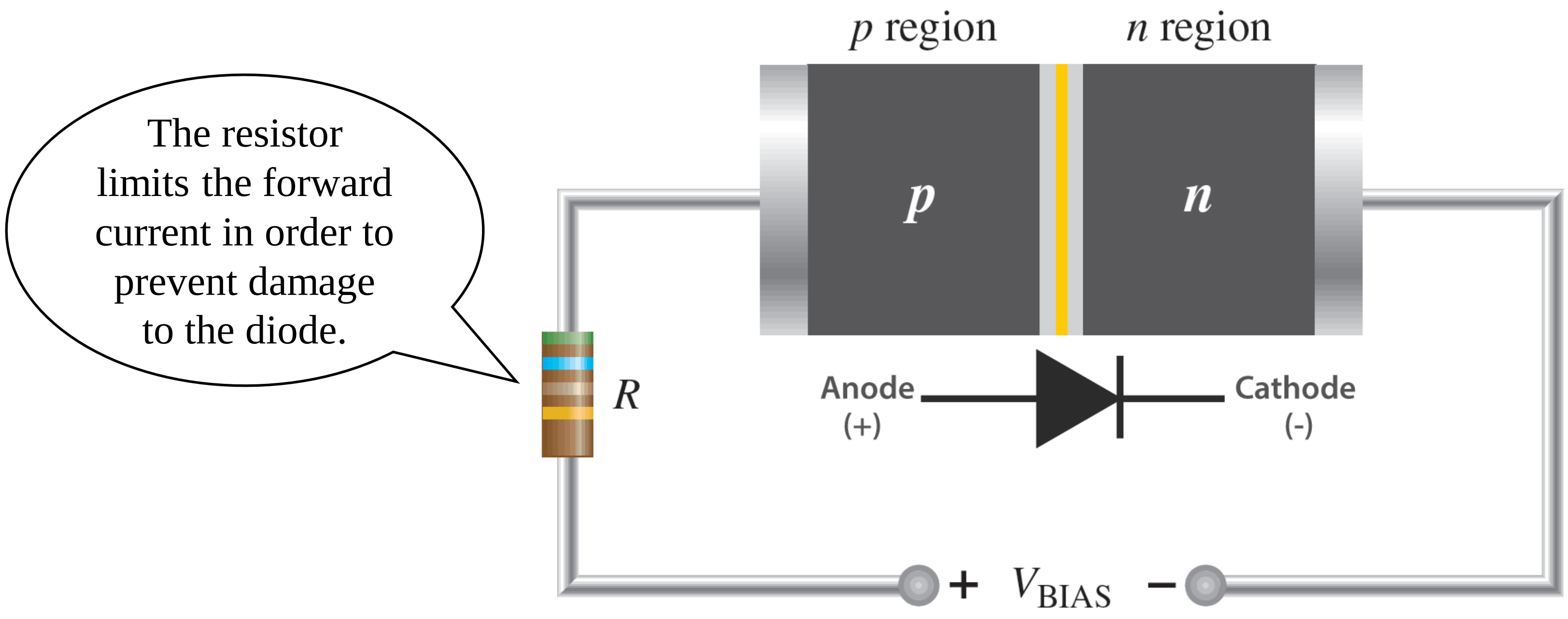


Fig. 5: Forward-bias connection.

Biasing a Diode (Forward bias)

When it overcomes the barrier potential V_B the external voltage source provides the *n*-region electrons with enough energy to penetrate the depletion region and move through the junction, where they combine with the *p*-region holes. As electrons leave the *n*-region, more flow in from the negative terminal of the bias-voltage source. Thus, current through the *n* region is formed by the movement of conduction electrons (majority carriers) toward the *pn* junction.

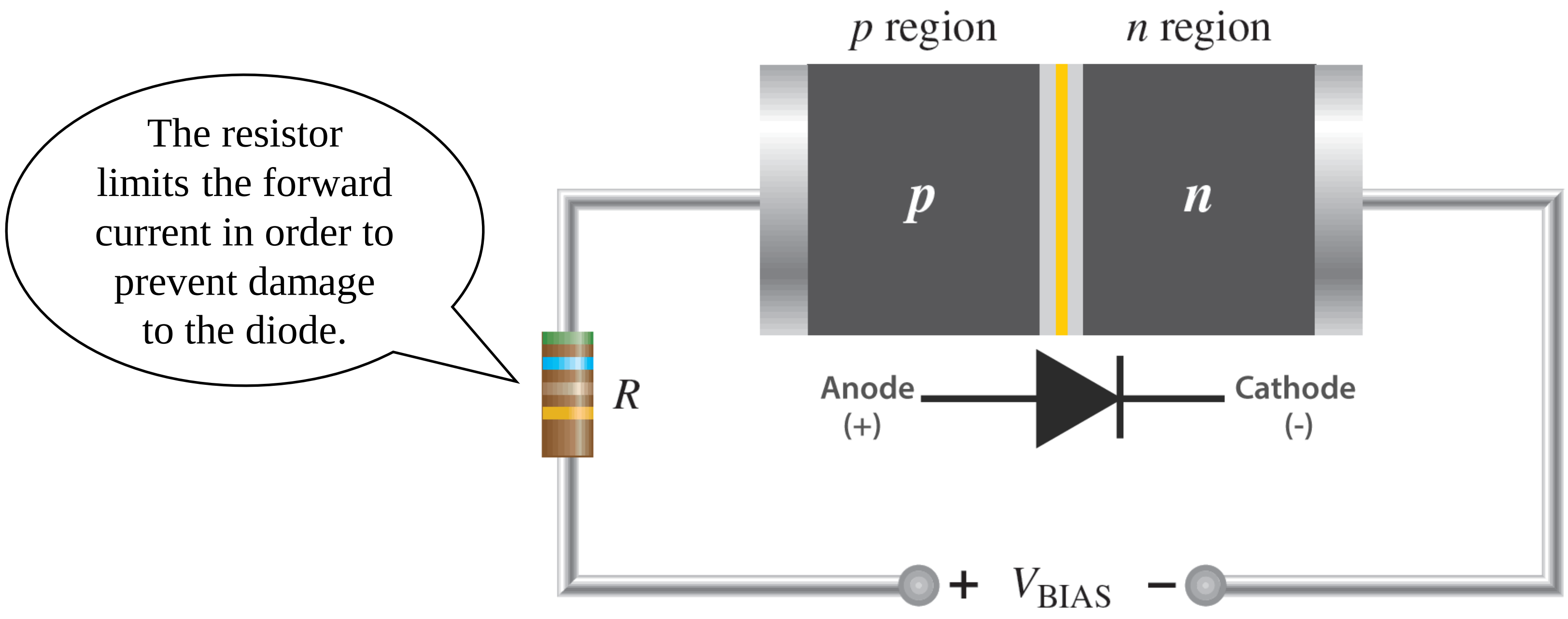


Fig. 5: Forward-bias connection.

Biasing a Diode (Forward bias)

Once the conduction electrons enter the *p* region and combine with holes, **they become valence electrons**. Then they move as **valence electrons from hole to hole toward the positive connection of the bias-voltage source**. The movement of these valence electrons is the same as the movement of holes in the opposite direction. Thus, current in the *p* region is formed by the movement of holes (majority carriers) toward the *pn* junction. Fig. 6 illustrates current in a forward-biased diode.

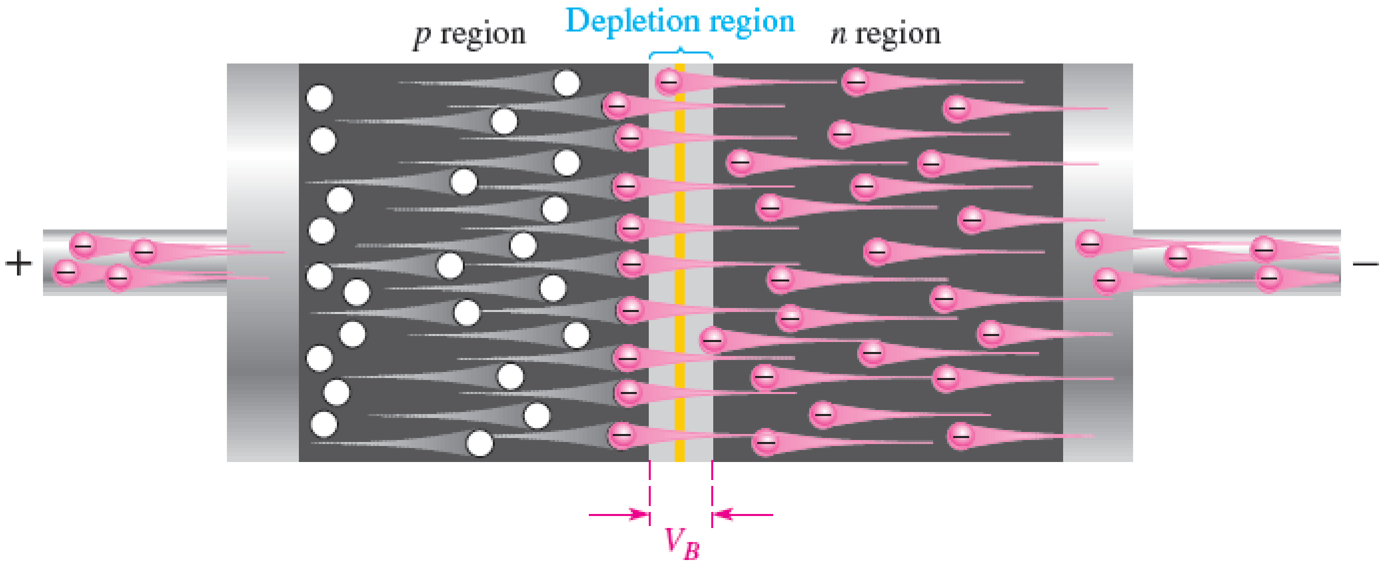
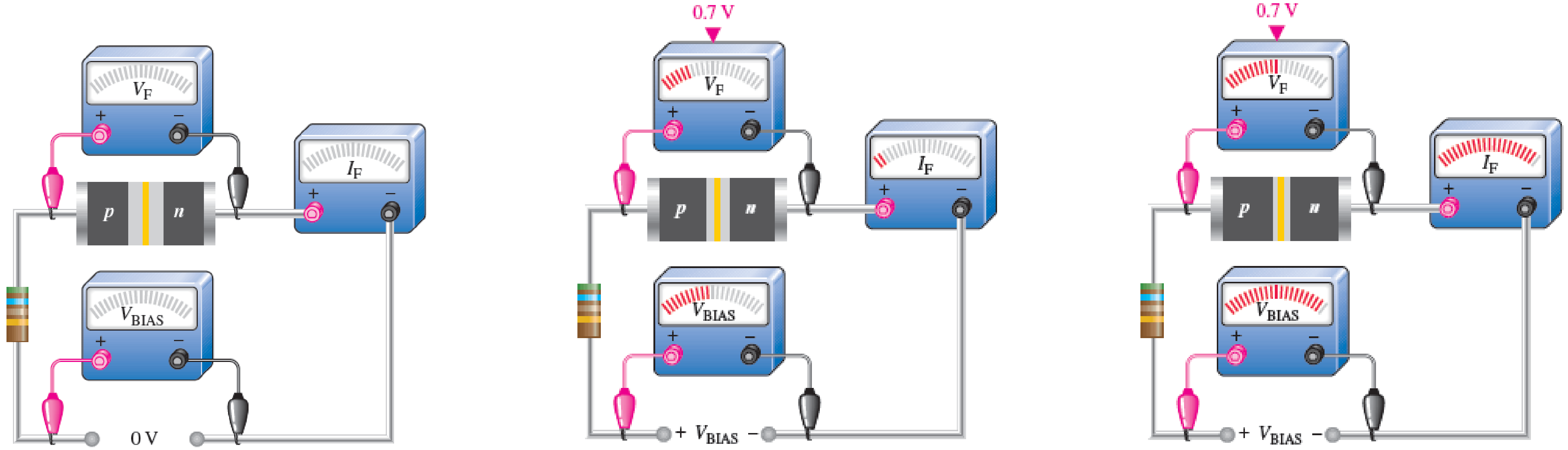


Fig. 6: Current in a forward-biased diode.

Biasing a Diode (Forward Bias)

The external bias voltage must overcome the effect of the barrier potential before the diode conducts, as illustrated in Figure 7. Conduction occurs at approximately 0.7 V for silicon. Once the diode is conducting in the forward direction, the voltage drop across it remains at approximately the barrier potential and changes very little with changes in forward current as illustrated in Fig. 7.



a) No bias voltage. The *pn* junction of the diode is at equilibrium.

b) Small forward-bias voltage (VF < 0.7 V), very small forward current.

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

Fig.7: Illustration of diode operation under forward-bias conditions.

Diode Equivalent Circuit (Forward bias)

The effect of the **barrier potential in the depletion region is to oppose forward bias**. This is because the negative ions near the junction in the *p* region tend to prevent electrons from moving through the junction into the *p* region. The barrier potential effect as a small battery connected in a direction to oppose the forward-bias voltage, as shown in Fig.8. The resistances R_p and R_n represent the **dynamic resistances** of the *p* and *n* **materials**.

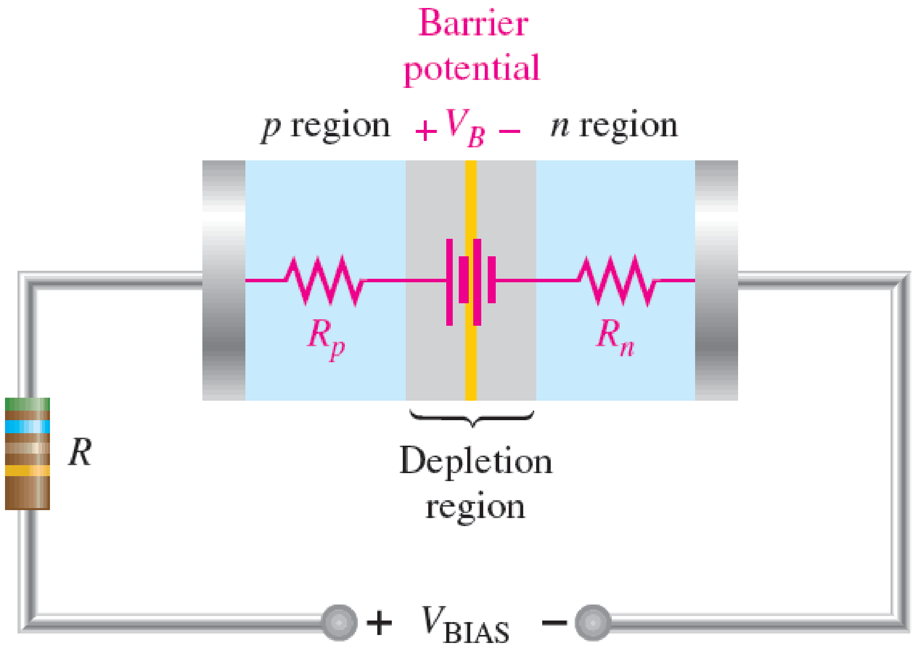


Fig. 8: Barrier potential and dynamic resistance equivalent for a diode.

Biasing a Diode (Reverse Bias)

Reverse bias is the condition that prevents current flow through the diode. Fig. 9 shows a dc voltage source connected to reverse-bias the diode. **Notice that** the negative terminal of the source is connected to the *p* region and the positive terminal is connected to the *n* region.

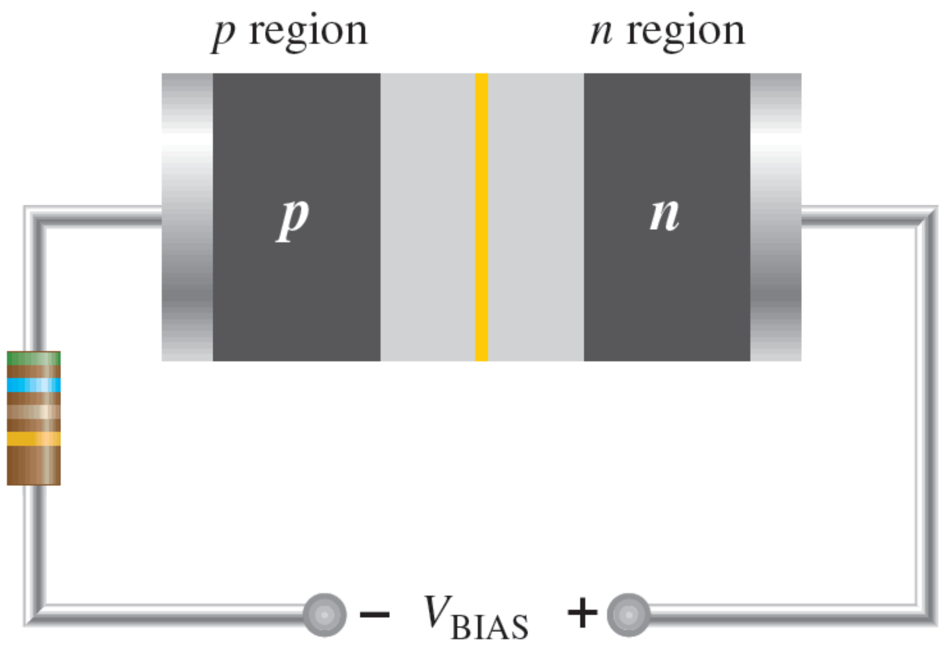


Fig. 9: Reverse-bias connection.

Biasing a Diode (Reverse Bias)

The negative terminal of the bias-voltage source attracts holes in the *p* region away from the *pn* junction, while the positive terminal also attracts electrons away from the *pn* junction. As electrons and holes move away from the *pn* junction, the depletion region widens; more positive ions are created in the *n* region, and more negative ions are created in the *p* region, as shown in Fig. 10 . The initial flow of majority carriers away from the *pn* junction is called **transient current** and lasts only for a very short time upon application of reverse bias.

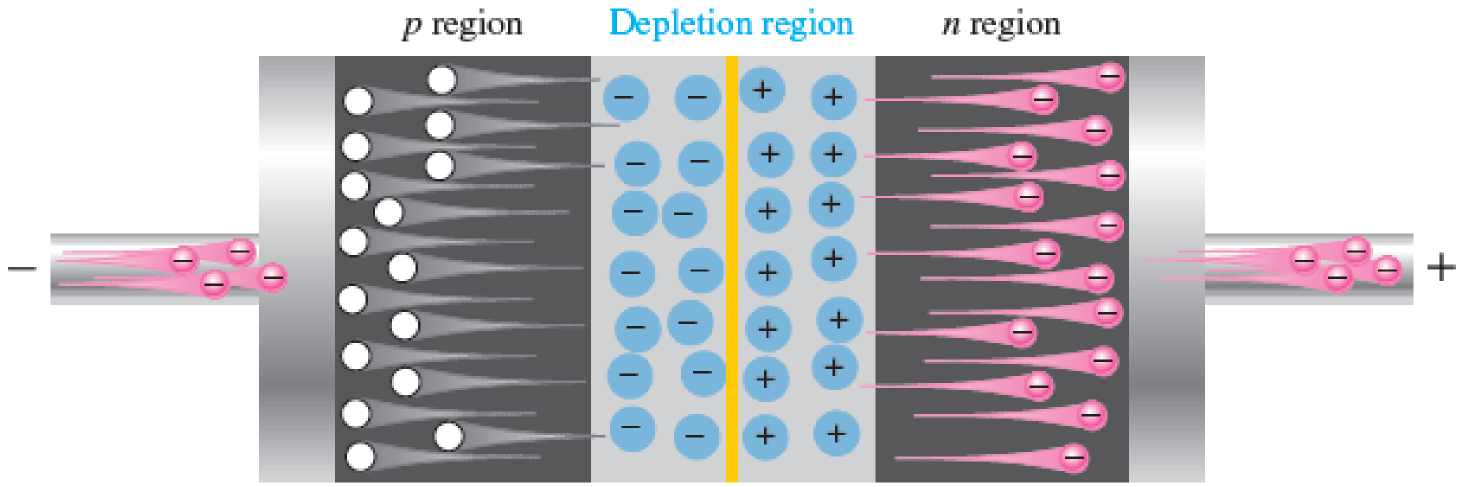


Fig. 10: There is **transient current** as depletion region widens

Biasing a Diode (Reverse Bias)

The depletion region widens until the potential difference across it equals the external bias voltage. At this point, the holes and electrons stop moving away from the *pn* junction, and majority current ceases, as indicated in Fig. 11.

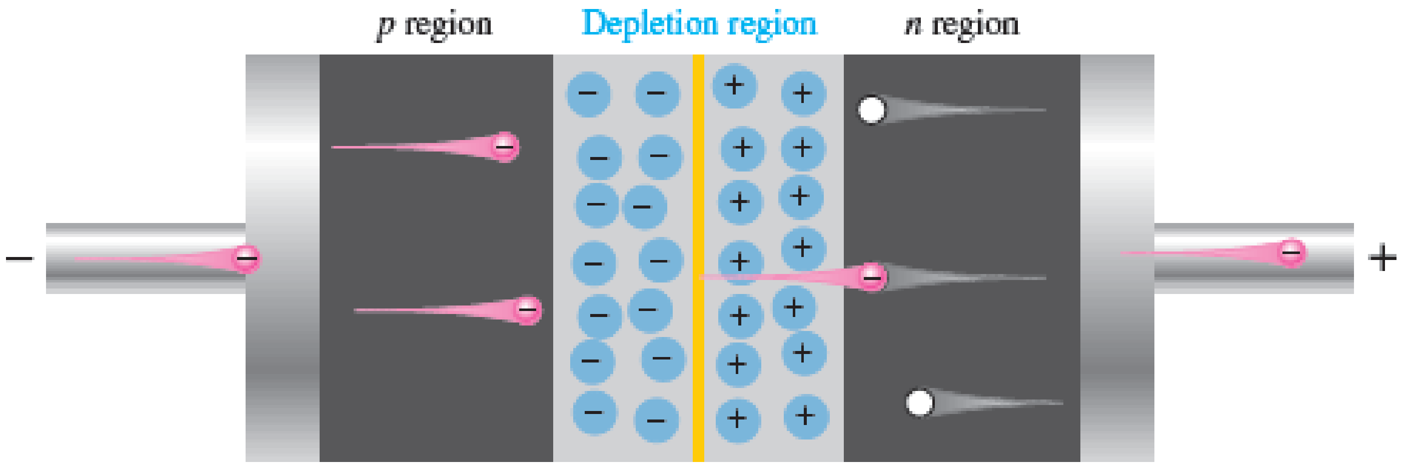


Fig. 11: Majority current ceases when barrier potential equals bias voltage. There is an extremely small reverse current due to minority carriers.

Biasing a Diode (Reverse Breakdown)

If the external reverse-bias voltage is increased to a large enough value, **reverse breakdown** occurs.

Assume that one minority conduction-band electron acquires enough energy from the external source to accelerate it toward the positive end of the diode. During its travel, it collides with an atom and imparts enough energy to knock a valence electron into the conduction band. There are now two conduction-band electrons. Each will collide with an atom, knocking two more valence electrons into the conduction band. There are now four conduction band electrons which, in turn, knock four more into the conduction band.

This rapid multiplication of conduction-band electrons, known as an **avalanche effect**, results in a rapid buildup of reverse current.

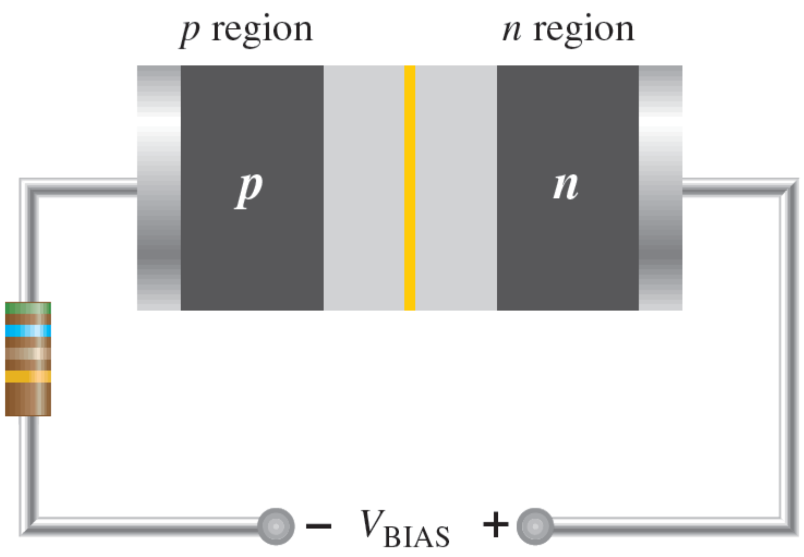


Fig. 12: Reverse-bias connection.