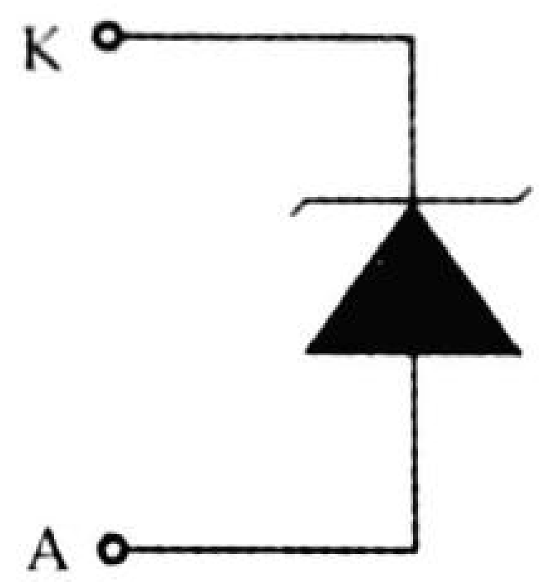
1.9 Zener Diode

Every diode has a specific reverse breakdown voltage. It is not advisable to operate a diode in its breakdown region. However, a special diode named as zener diode is made to operate in the reverse-biased mode. The zener diode is a p-n junction semiconductor device that operates by allowing the current to flow in the reverse breakdown region. In this diode doping is much higher in comparison to other p-n junction diodes. It is using on those voltages that could be exceeds the breakdown voltage. This breakdown voltage is called as the breakdown region or zener voltage (V_Z). It is the voltage at which the current across the zener diode rises sharply to a high value. The zener voltage varies from a few volts to a hundred volts.

Figure 46 shows a schematic symbol of a zener diode:



▲ **Figure 46: Displaying a Zener Diode Symbol**

The zener diode is a two-terminal device having point A as anode and point K as cathode. The arrowhead in the symbol indicates the direction of the current flowing through the zener diode in forward bias but it is always be using in reverse bias only.

In this section, you have learned about the characteristics, specifications, and applications of a zener diode.

■ V-I Characteristics of a Zener Diode

The V-I characteristics of a zener diode provides the graphical relationship between the current and voltage of the zener diode. It notifies the change in current flowing through the device when an applied voltage is varying across the zener diode. As the zener diode operates in both forward and reverse bias, it has the following two characteristics:

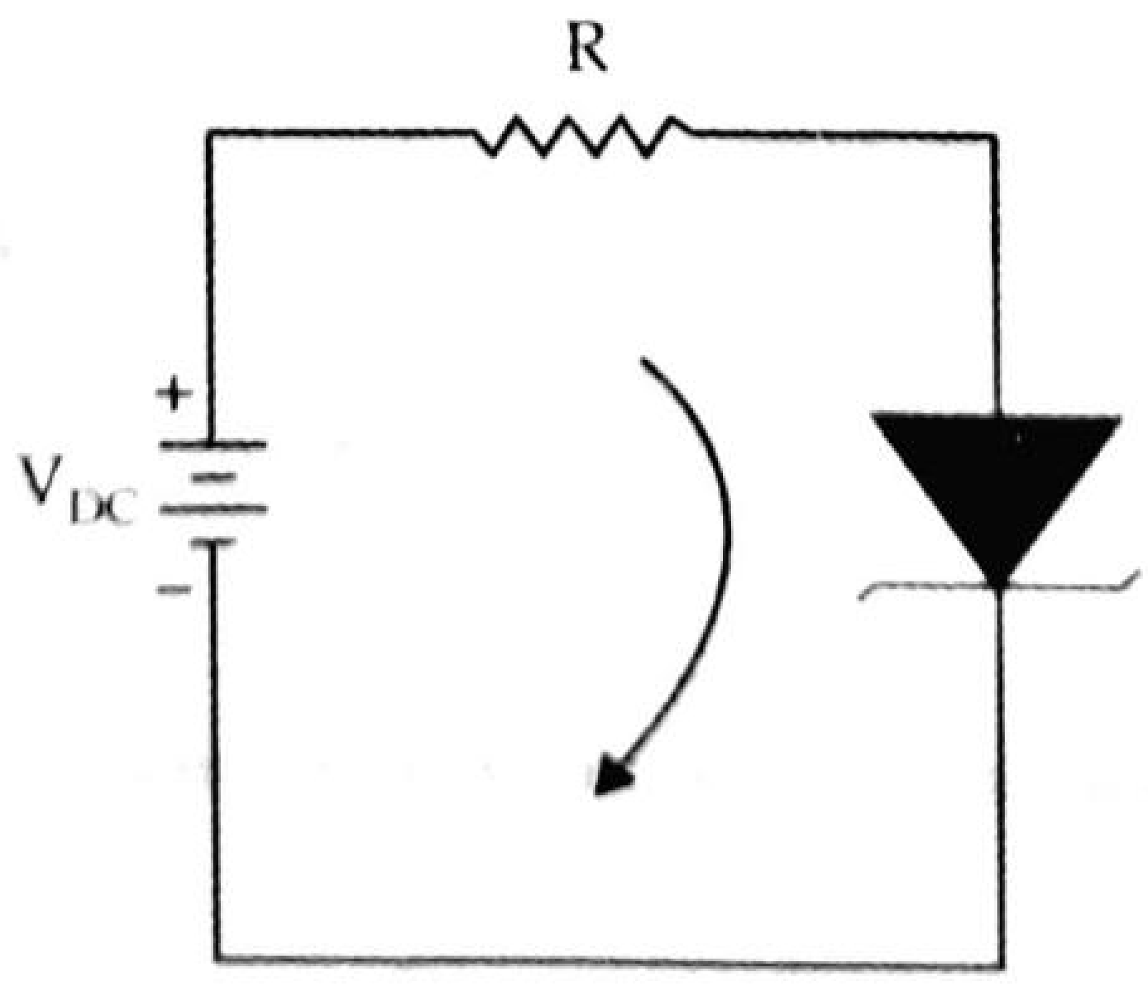
- ❐ Forward characteristics
- ❐ Reverse characteristics

Now, let's discuss about these characteristics one by one in the following sections.

➧ Forward Characteristics

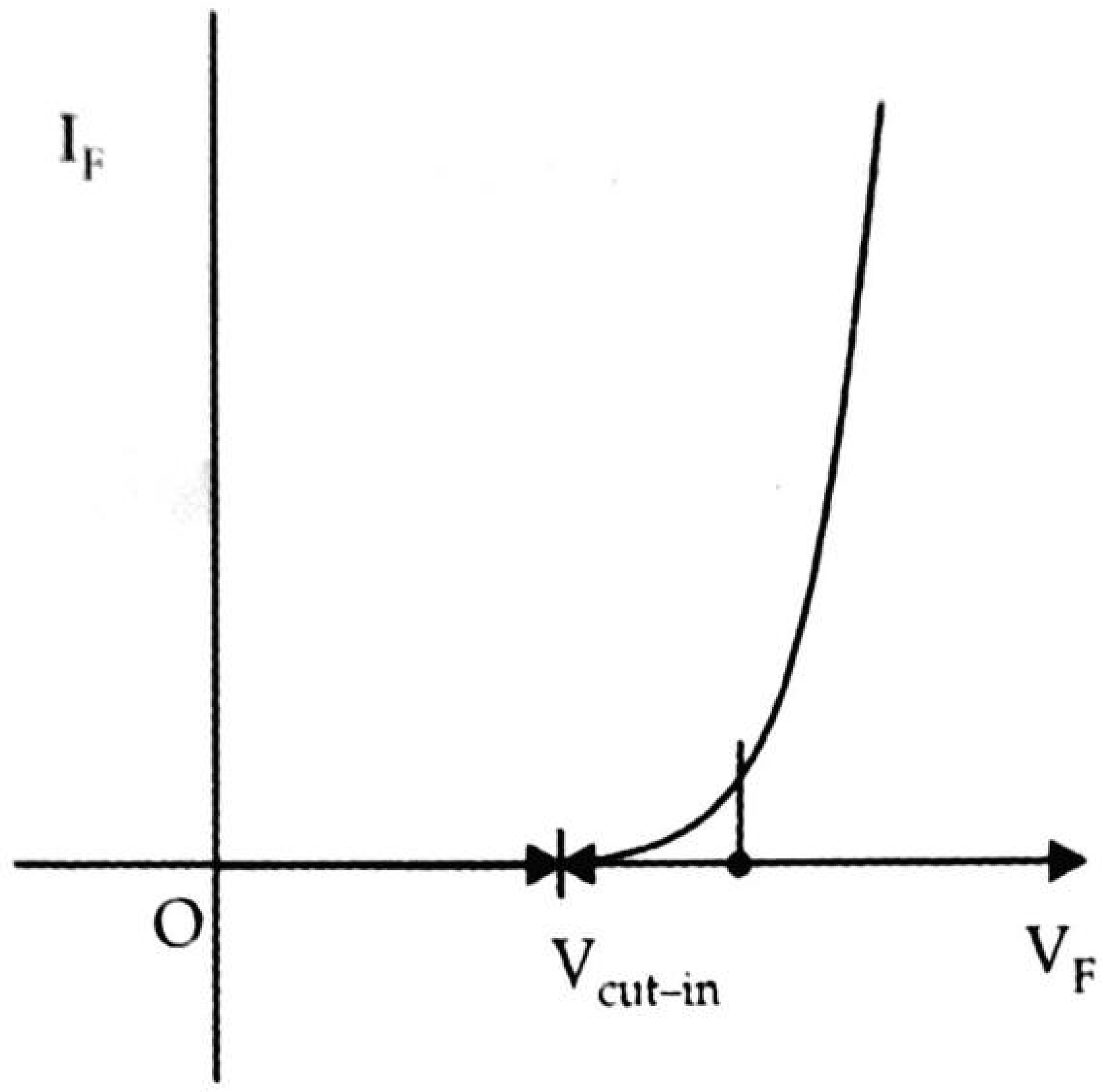
When the anode of the zener diode is connected to the positive terminal of the DC voltage and the cathode is connected to the negative terminal of the DC voltage, the zener diode is said to be operating in forward bias condition. In the forward-biased mode, the behavior of the zener diode is similar to a conventional p-n junction diode.

Figure 47 shows the circuit diagram of the zener diode in forward bias condition:



▲ **Figure 47: Displaying the Circuit Diagram of the Zener Diode in Forward Bias Condition**

Figure 48 shows the forward characteristics of the zener diode:



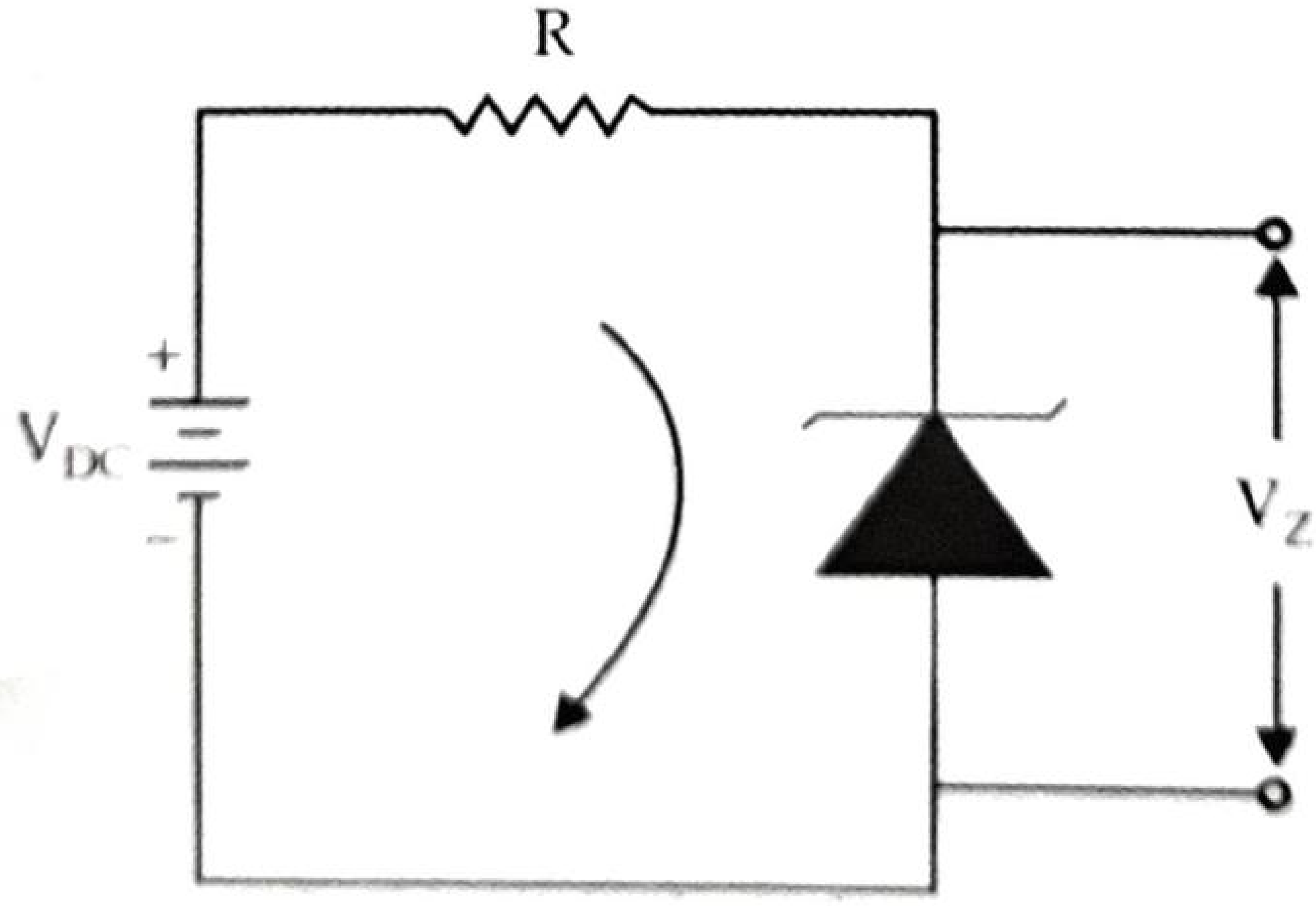
▲ **Figure 48: Displaying the Forward Characteristics of the Zener Diode**

When a forward bias voltage is applied to the zener diode, a part of the voltage is used to overcome the barrier potential developed across the junction. When the applied voltage exceeds the barrier potential of the diode, a sharp increase in current is observed. The voltage at which the current rises sharply is called the cut-in voltage or knee voltage, as shown in Figure 48.

➡ Reverse Characteristics

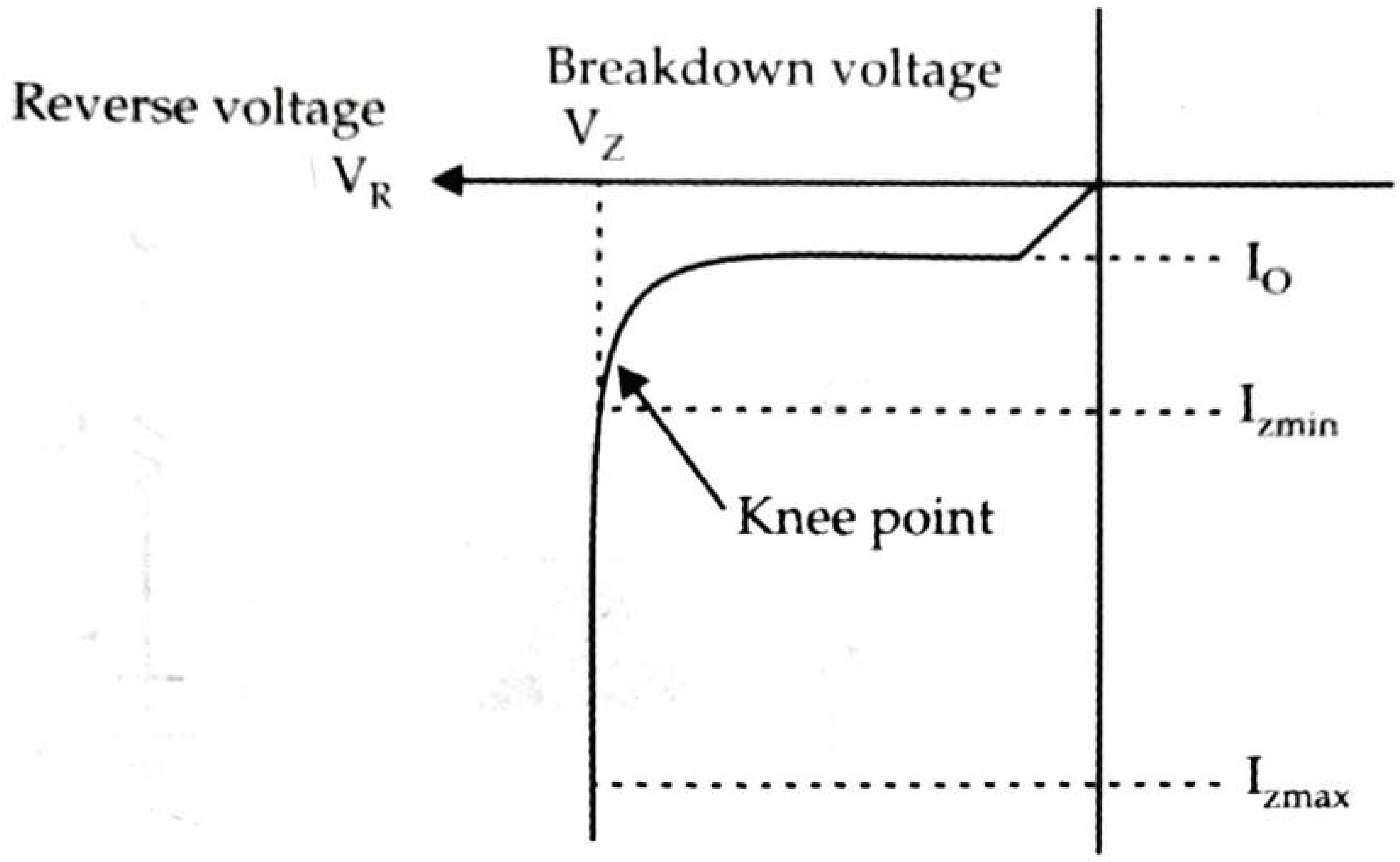
When the cathode is connected to the positive terminal of the DC voltage source and the anode is connected to the negative terminal of the DC voltage source, the zener diode operates in reverse bias condition. During this mode, the operation of zener diode is totally different from the conventional p-n junction diode.

Figure 49 shows the circuit diagram of the zener diode in reverse bias condition:



▲ **Figure 49: Displaying the Circuit Diagram of the Zener Diode in Reverse Bias Condition**

The reverse V–I characteristic of the zener diode is shown in Figure 50:



▲ **Figure 50: Displaying the Reverse Characteristics of the Zener Diode**

Figure 50 shows that when a reverse bias voltage is applied to a zener diode then a leakage current (I_0) flows through it. This leakage current is caused due to the thermally generated minority charge carriers present in the zener diode. This current is of the order of a few microamperes. Leakage current is flows when the applied reverse voltage is less than the reverse breakdown voltage (V_Z).

When the applied reverse bias voltage across the zener diode crosses the specified limit of breakdown voltage (V_Z) then suddenly the reverse current increases to higher level but the voltage across the diode remains constant. The reverse voltage at which the current flowing through the zener diode increases massively is called as the zener breakdown voltage. This point is referred to as the knee point. In the breakdown region, the voltage across the zener diode remains constant, and if the applied DC voltage is increased, the current flowing through the device increases, again. The safe limit of operation of a zener diode is in the range of I_{ZMIN} to I_{ZMAX}. The breakdown voltage V_z can be precisely controlled by controlling the doping levels of p- and n-regions while manufacturing a zener diode. After breakdown, the voltage across the diode remains constant. If the source voltage (V_{DC}) increases further, V_Z remains constant, whereas the reverse current flowing through the zener diode increases. To control the current flowing through the diode after reverse breakdown, a current limiting resistor (R), as shown in Figure 49, must be connected in series with the zener diode. This resistor R protects the device from damage due to excessive heat developed across it.

The zener diode can widely use as a voltage regulator in the electronic circuits and named as a voltage regulator, as the voltage remains constant in zener or breakdown region even after the breakdown occurs. The value of the current limiting resistor R is given as:

$$R = \frac{V_{DC} - V_Z}{I}$$

where:

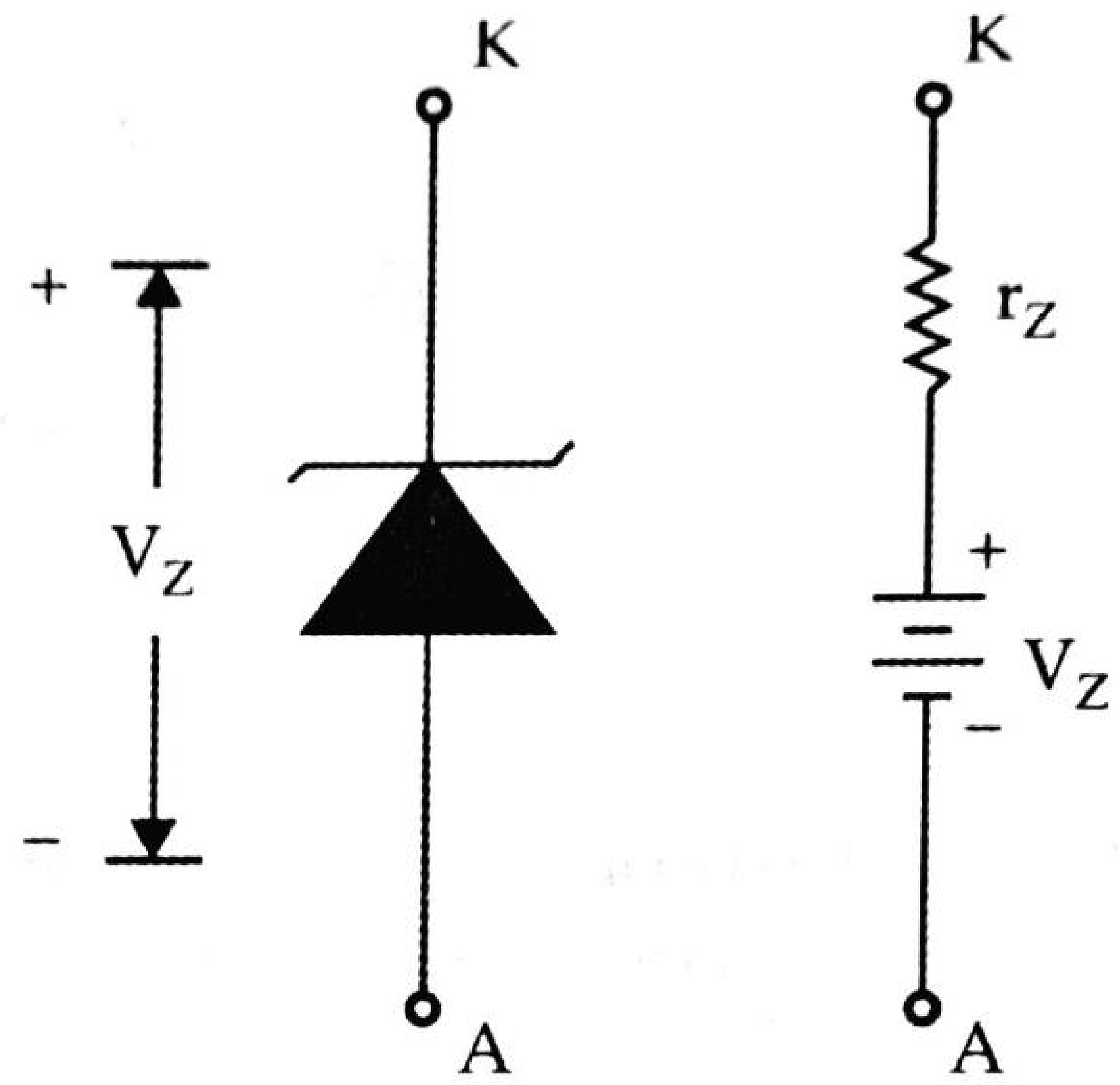
V_{DC} = external applied voltage in volts

V_Z = zener breakdown voltage in volts

I = current flowing through the zener diode in amperes.

Equivalent Circuit of a Zener Diode

The equivalent circuit of a zener diode consists of an internal resistance called as a dynamic resistance r_Z and a DC battery equal to the zener potential V_Z, as shown in Figure 51:



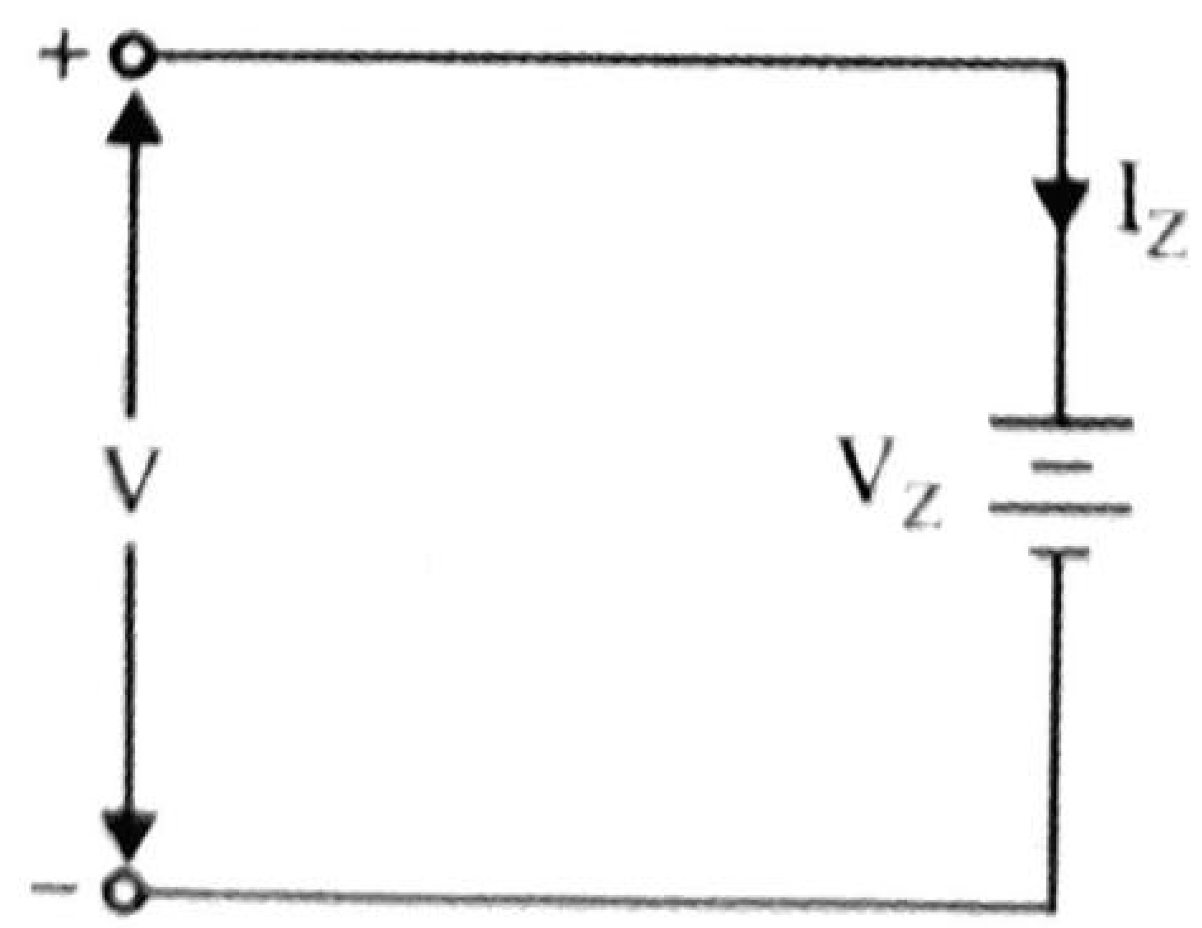
▲ **Figure 51: Displaying the Equivalent Circuit of a Zener Diode**

The dynamic resistance of the zener diode can be obtained by taking the reciprocal of the slope of V-I characteristics in the zener region. The dynamic resistance (r_Z) of zener diode is in the range of few tens of ohm, and is given as:

$$r_Z = \frac{\Delta V_Z}{\Delta I_Z}$$

The zener diode operates in two states namely: ON and OFF states. When the reverse voltage across a zener diode is equal to or greater than the breakdown voltage (V_Z), the current increases very sharply to a higher value. The curve in this region of operation is linear (see Figure 50). This implies that the breakdown voltage in this region is constant and irrespective of the variations in the current. Therefore, in the breakdown region, an ideal zener diode operates in an ON state.

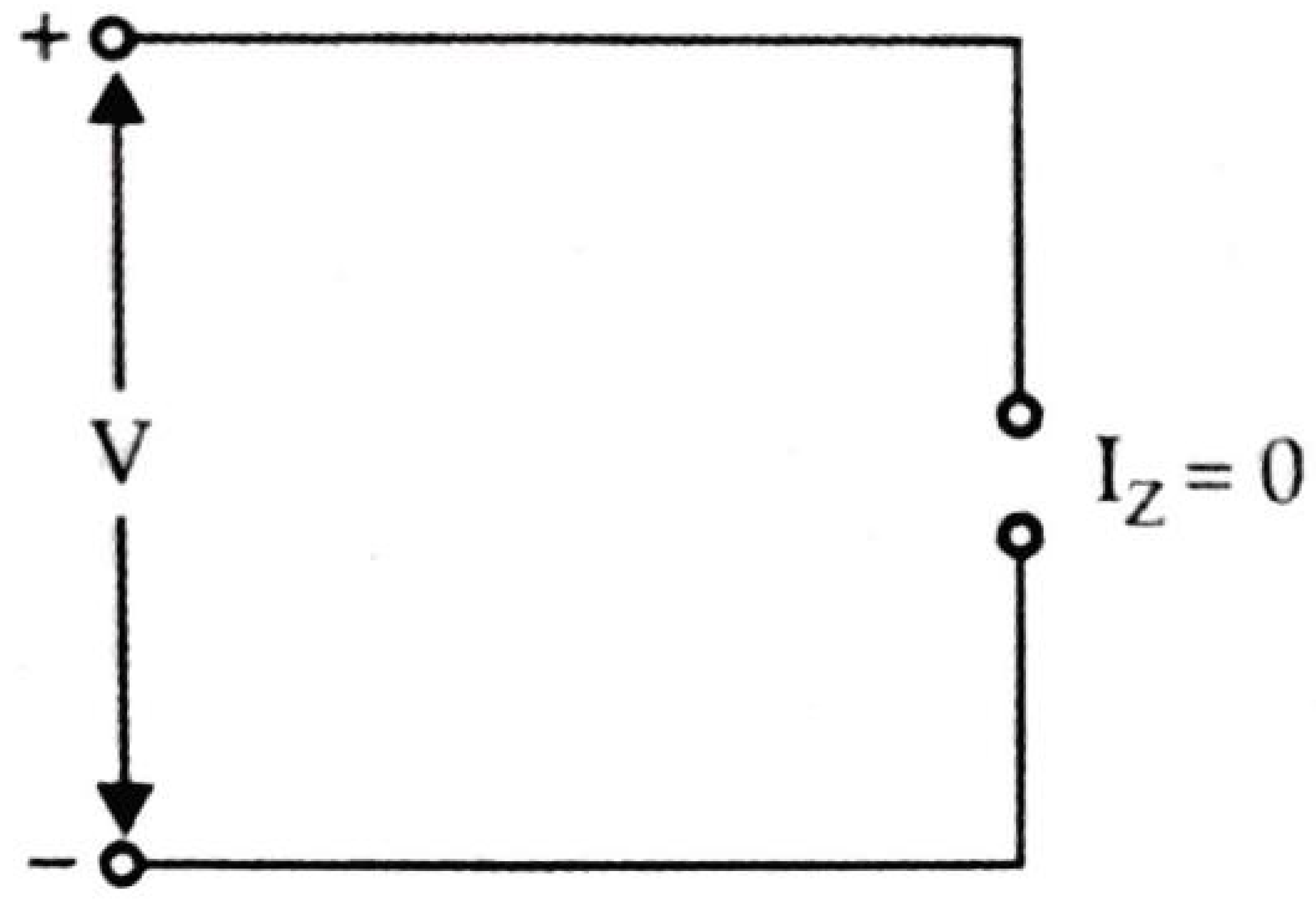
Figure 52 shows the equivalent circuit of the zener diode in the ON state:



▲ **Figure 52: Displaying the Equivalent Circuit of the Zener Diode in the ON State**

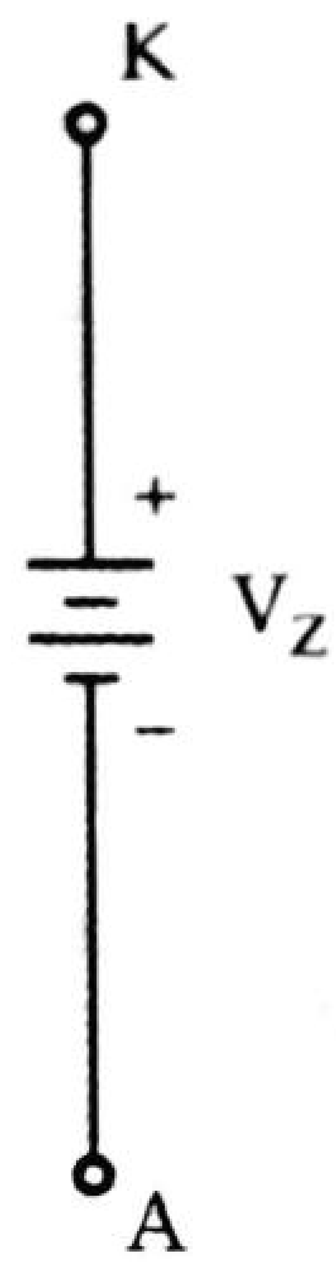
When the voltage applied across the zener diode is less than the reverse breakdown voltage but greater than 0 V, the diode operates in the OFF state.

Figure 53 shows the equivalent circuit of the zener diode in the OFF state:



▲ **Figure 53: Displaying the Equivalent Circuit of the Zener Diode in the OFF State**

In the breakdown region, the zener current (I_Z) increased from I_{ZMIN} to I_{ZMAX}, but the voltage remains constant. This implies that the internal resistance (r_Z) of the zener diode decreases as the zener current increases. Figure 54 shows the equivalent circuit of an ideal zener diode:



▲ **Figure 54: Representing the Equivalent Circuit of an Ideal Zener Diode**

Since the internal resistance is very small, it can be neglected while considering the case of an ideal zener diode.

Breakdown Mechanisms in a Zener Diode

The following two different breakdown mechanisms may occur in a zener diode:

- Zener breakdown
- Avalanche breakdown

Let us discuss each of these mechanisms in detail.

Zener Breakdown

Normally, zener breakdown is observed when a reverse breakdown voltage of less than 6 V is applied to a zener diode. Since the zener diode is heavily doped so the depletion region formed is narrower, and therefore, the reverse breakdown occurs at a low voltage. When a reverse bias voltage within a range of 3—6 V is applied to a zener diode, the electrons travel from the VB of p-type material to the CB of n-type material through the narrow depletion region. This leads to an electric field of the order of 2×10^7 V/m to appear across the junction. Such a high electric field exerts a strong force on the bound electrons and pullout them from their covalent bonds. This creation of new electron-hole pair increases the reverse current. This overall process is called as zener breakdown.

Zener diodes have negative temperature coefficients because breakdown voltage decreases with the increase in temperature. This happens because increase in temperature increases the energies of the valence electrons, due to which these electrons can easily free from their respective covalent bonds. As a result, less amount of applied voltage is required to pull these valence electrons from the atom and converting them into the conduction electrons. Therefore, the zener breakdown voltage decreases with the increase in temperature.

The following are the terms related with zener breakdown:

- **Temperature coefficient (TC):** Refers to the rate of change in breakdown voltage per degree change in temperature, and is given as:

$$TC = \frac{\Delta V_Z}{\Delta T}$$

- **Temperature stability (S):** Refers to the ratio of the temperature coefficient (TC) to the breakdown voltage. It is generally expressed in percentage and is given as:

$$S\,(\%) = \frac{TC}{V_Z} \times 100\%$$

In order to have a highly stable voltage reference using zener diode, appropriate steps must be taken to compensate the temperature of the diode.

Avalanche Breakdown

Avalanche effect is dominant in the zener diode when the breakdown voltage exceeds 6 V. When reverse voltage is applied to a zener diode, a small current I_0 flows through the device. This current is generated due to the minority charge carriers. With the increase in the reverse voltage, these charge carriers gain kinetic energy and hence accelerate. They collide with the atoms and ionize their valence band electrons by giving up their kinetic energy. Thus, more electron-hole pairs are generated which further, collides with another atoms to generate more electron-hole pairs. This leads to high increase in the reverse current. This process of carrier multiplication is called as avalanche breakdown. Since the process includes ionization of valence electrons on being impacted by accelerated charge carriers, it is also termed as impact ionization. The current flowing through the zener diode can be limited by connecting a current limiting resistor in series with it.

The breakdown voltage in the avalanche breakdown increases with the increase in temperature i.e. the diodes experiencing avalanche breakdown exhibit positive temperature coefficient.

Comparison between Zener Breakdown and Avalanche Breakdown

Table 5 lists the comparison between zener breakdown and avalanche breakdown:

Table 5: Comparison between Zener Breakdown and Avalanche Breakdown

Zener Breakdown	Avalanche Breakdown
1. Zener breakdown is observed in zener diodes with V_Z between 3 to 6 V	1. Avalanche breakdown is observed in zener diodes with V_Z greater than 6 V.
2. Valence electrons are pulled into the CB due to an intense electric field appearing across the narrow depletion region	2. Valence electrons are pushed into the CB due to high kinetic energy
3. V-I characteristic of zener diode is very sharp in the breakdown region.	3. V-I characteristic of the avalanche breakdown in the breakdown region is smooth.
4. The breakdown voltage decreases with the increase in junction temperature	4. The breakdown voltage increases with the increase in junction temperature
5. The Temperature Coefficient of zener breakdown is negative (NTC)	5. The Temperature Coefficient of avalanche breakdown is positive (PTC)

Specifications of a Zener Diode