
Zener Diode

Objectives

After going through this module, the learners will be able to:

- Recognise that a Zener diode is a special type of p-n junction
- Understand the working of Zener diode in reverse bias
- Conceptualise Avalanche breakdown and Zener breakdown
- Plot $V-I$ characteristics of Zener diode both Forward and reverse characteristics
- Explain application of Zener diode as a voltage regulator

Content Outline

- Unit Syllabus
- Module Wise Distribution of Unit Syllabus
- Words You Must Know
- Introduction
- $p-n$ Junction Diode as a Zener Diode
- Zener Effect
- Avalanche Breakdown
- $V-I$ Characteristics of a Zener Diode
- Zener Diode as a Voltage Regulator
- Applications of Zener Diode
- Summary

Unit Syllabus

Unit -09: Electronic Devices

Chapter-14: Semiconductor Electronics, material, devices and simple circuits.

Energy bands in conductors, semiconductors and insulators (qualitative only)

Semiconductors: intrinsic and extrinsic

Semiconductor diode: I-V characteristics in forward and reverse bias, application of diode as a rectifier

Special purpose p-n diodes LED, photodiode, solar cell and Zener diode and their characteristics, Zener diode as a voltage regulator

Junction transistor, transistor action, characteristics of a transistor and transistor as amplifier-
common emitter configuration

Basic idea of Analog and digital signal, logic gates OR, AND, NOR, NOT, NAND

Keeping the needs of state boards in mind we have not changed the content

Module Wise Distribution of Unit Syllabus - 10 Modules

Module 1	<ul style="list-style-type: none">● Energy bands in solids● Forbidden gap● Fermi level● Energy bands in conductors, semiconductors and insulators
Module 2	<ul style="list-style-type: none">● Uniqueness of semiconductors● Charge carriers in semiconductors electrons and holes● Intrinsic semiconductors● Extrinsic semiconductors p and n type● Why are p and n type semiconductors neutral?
Module 3	<ul style="list-style-type: none">● p-n Junction diode● Potential barrier● Depletion layer● Characteristics of p-n junction diode● Forward and reverse bias, knee voltage, magnitude of bias voltages● To draw the I-V characteristics curve for a p-n junction in forward bias and reverse bias
Module 4	<ul style="list-style-type: none">● Application of diode● Rectifier meaning and need of such a device● Half wave and full wave rectifier● Rectifier in our homes● Special purpose diode<ul style="list-style-type: none">○ LED○ $Photodiode$○ $Solar cells$● Solar panels and future of energy
Module 5	<ul style="list-style-type: none">● To identify a diode, an LED, a resistor and a capacitor

	<ul style="list-style-type: none"> ● Use a multimeter to <ul style="list-style-type: none"> ○ <i>See the unidirectional flow of current in case of a diode and an LED</i> ○ <i>Check whether a given diode is in working order</i>
Module 6	<ul style="list-style-type: none"> ● Zener diode ● Characteristics of Zener diode ● To draw the characteristic curve of a Zener diode and to determine its reverse breakdown voltage ● How is a Zener diode different from other diodes? ● Zener diode as a voltage regulator ● Working of a Zener diode ● Zener diodes in our homes
Module 7	<ul style="list-style-type: none"> ● Junction transistor ● Design of the transistor ● <i>n-p-n</i> and <i>p-n-p</i> ● Use a multimeter to <ul style="list-style-type: none"> ○ <i>Identify base of transistor</i> ○ <i>Distinguish between n-p-n and p-n-p type transistor</i> ○ <i>Check whether a given electronic component (e.g. diode , transistor, or IC) is in working order</i> ● Transistor action ● Characteristics of a transistor, n-p-n -common emitter
Module 8	<ul style="list-style-type: none"> ● Understanding transistor characteristics and its applications ● To study the characteristics of a common emitter <i>n-p-n</i> and <i>p-n-p</i> transistor and to find the values of current and voltage gains. ● Transistor as switch ● Transistor as amplifier
Module 9	<ul style="list-style-type: none"> ● Transistor as an amplifier ● Circuit diagram and understanding bias ● Input and output waveforms ● Phase change
Module 10	<ul style="list-style-type: none"> ● Analog signals

	<ul style="list-style-type: none"> ● Logic gates ● Truth tables <ul style="list-style-type: none"> ○ OR gate ○ AND gate ○ NOT gate ○ NAND gate ○ NOR gate
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Module 6

Words You Must Know

- **Conductors:** These are the materials which conduct electricity easily. They have a very large number of free electrons.
- **Insulators:** These are the materials which do not conduct electricity because they do not have free electrons.
- **Semiconductors:** These are the materials for which electrical conductivity values are less than between conductors but more than that of insulators. The conductivities of semiconductors are highly temperature sensitive.
- **Energy Level:** As per Bohr's theory electrons revolve around the nucleus only in some specific orbits called stationary orbits. Energy of electrons in these orbits is constant, are termed as energy levels.
- **Valence Bands:** This band comprises energy of valence electrons. Electrons of this band do not contribute to conduction of electric current.
- **Conduction Band:** This band corresponds to energy of free electrons. Electrons of this band are responsible for conduction of electric current.
- **Forbidden Energy Gap (E_g):** It is the minimum energy required to take an electron from valence band to conduction band. Insulators have highest E_g and conductors have least E_g
- **Intrinsic Semiconductors:** These are pure semiconductors without any impurity. They show very small electrical conductivity at room temperature.
- **Doping:** It is the deliberate and controlled addition of impurities in intrinsic semiconductors to enhance their electrical conductivity in a controlled manner.

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- **Extrinsic Semiconductors:** Semiconductors to which impurities are added to increase conductivity are known as extrinsic semiconductors or impurity semiconductors
 - **Dopant** two types of dopants used in doping the tetravalent Si or Ge element:
 - *Pentavalent dopants (valency 5); like Arsenic (As), Antimony (Sb), Phosphorous (P), etc.*
 - *Trivalent dopants (valency 3); like Indium (In), Boron (B), Aluminium (Al), etc.*
 - **p-type semiconductors**, these are formed by doping elements like Si and Ge with trivalent atoms.
 - **n-type semiconductors**, these are formed by doping elements like Si and Ge with pentavalent atoms.
 - **p-n Junction:** A p-n junction is a boundary, or interface, between the two types of semiconductors, (p-type and n-type), inside a single crystal
 - **Diffusion Current;** holes diffuse from p-side to n-side ($p \rightarrow n$) and electrons diffuse from n-side to p-side ($n \rightarrow p$).
 - **Potential Barrier** Initially both the sides were electrically neutral. Now, because of diffusion of electrons and the holes, there are immobilised additional ions on both the sides.

From the n side, electrons have diffused to p-side, so there are positive immobile ions on the n-side, from the p-side, holes have diffused to the n-side, so there are negative immobile ions on the p side. These immobile ions near the junction create a potential difference across the junction.
 - **Drift Current:** Due to the positive space-charge region on the n-side of the junction, and negative space charge region on the p-side of the junction, an electric field, directed from positive charge towards negative charge develops.
 - *Due to this field, an electron on the p-side of the junction moves to the n-side and a hole on the n-side of the junction moves to p-side.*
 - *The motion of charge carriers due to the electric field is called drift.*

A drift current, which is opposite in direction to the diffusion current, is set up.
 - **Forward Bias:** When an external voltage V is applied across a semiconductor diode such that p-side is connected to the positive terminal of the battery and n-side to the negative terminal it is said to be forward biased.
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- **Reverse Bias:** The positive terminal of the battery is connected to the n -side of the semiconductor and negative terminal is connected to the p -side. This way of connecting a diode with a battery is called Reverse Biasing.

- **Characteristics of a p - n Junction Diode**

When a bias is placed across a conductor, its characteristic curves show the dependence of current on voltage placed across the conductor.

- **Knee Voltage:** The special value of forward voltage beyond which the current increases with increase in the voltage is known as the knee Voltage.

- **Dynamic Resistance of a Junction Diode**

- The I - V characteristics of a p - n junction diode during forward /reverse biasing is not a straight line. We therefore cannot have a unique (constant) value for the resistance of the diode. We can, however use the basic definition of resistance

$$\text{resistance} = \frac{\text{change in potential difference}}{\text{corresponding change in current}}$$

We can use it to define

Dynamic resistance of a junction diode (for a particular value of the applied /current flowing) is defined as the ratio of small change in the applied potential across the diode to the corresponding small change in the junction current.

$$\text{dynamic resistance} = \frac{\Delta V}{\Delta I}$$

- **Rectifier** is a device which converts an alternating current (AC) into a direct current (DC).
- **Filter circuit** The ripples in the DC can be reduced by allowing the output to pass through a **filter circuit**.

Photodiodes used for detecting optical signals (photodetectors).

Light emitting diodes (LED) which convert electrical energy into light.

Photovoltaic devices which convert optical radiation into electricity (solar cells)

Introduction

A semiconductor device like diode finds multiple uses in modern electronic systems. Diode allows the current to flow through only in one direction, hence acts as a one-way switch.

A diode can be connected to an external source, in forward bias or in reverse bias. When connected in forward bias the diode conducts and in reverse bias it shows high resistance to current flow.

The application of a diode is in communication systems as modulators, logic gates or in power supply as rectifiers and inverters. They also find applications in solar cells, as photodiodes, as indicator LED etc.

We will now study the zener diode.

Zener Diode

It is a special purpose semiconductor diode, named after its inventor C. Zener.

Zener diodes are widely used in electronic equipment of all kinds and are one of the basic building blocks of modern electronic circuits.

- **They are used to convert input from a higher voltage and to constant desired voltages for circuits, such as stabilizers for air conditioners, refrigerators (stabilized power supplies).**
- **They are also used to protect circuits from sudden surge in voltage.**

A conventional p-n junction diode allows small but significant current if it is reverse biased. A large current suddenly flows at the **reverse breakdown voltage**.

When the reverse bias breakdown voltage is exceeded, a conventional diode is subject to high current, due to this; the diode gets heated and is damaged.

The special purpose is achieved by the fact that the Zener diode is designed to operate under reverse bias in the breakdown region and used as a voltage regulator.

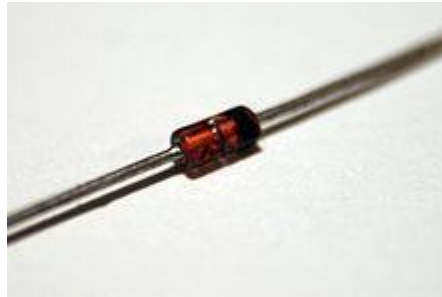
The voltage regulators used in computers, laptops, power supplies in TV, refrigerators etc.

How is a Zener diode different from a diode?

- **Zener diode is heavily doped, Zener diode is fabricated by heavily doping both *p*- and *n*- sides of the junction.**
- **Due to this, depletion region formed is very thin ($<10^{-6}$ m) and the electric field of the junction is extremely high ($\sim 5 \times 10^6$ V/m)**
- **Zener diodes exhibit almost the same properties as the *p-n* junction diode, except the device is specially designed so as to have a reduced breakdown voltage, the so-called Zener voltage.**
- **By contrast with the conventional *p-n* junction diode, a reverse-biased Zener diode exhibits a controlled breakdown and allows the current to keep the voltage across the Zener diode close to the Zener breakdown voltage.**

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- The Zener diode's operation depends on the heavy doping of its p - n junction.
 - The depletion region formed in the diode is very thin ($<1 \mu\text{m}$) and the electric field is consequently very high (about 500 kV/m) even for a small reverse bias voltage of about 5 V , allowing electrons to move from p side to n side

The symbol for Zener Diode is



https://upload.wikimedia.org/wikipedia/commons/thumb/2/24/Zener_Diode.JPG/440px-Zener_Diode.JPG

Zener Effect

- Zener effect takes place in the p - n junction reverse biased diodes which are heavily doped on both the sides as compared to rectifying p - n junction diodes.
- These operate in the breakdown region of the reverse voltage characteristics.
- This type of diode will have a narrow depletion region.
Zener diodes are fabricated by heavily doping both p -, and n - sides of the junction.
- Due to this, depletion region formed is very thin ($<10^{-6} \text{ m}$) and the electric field of the junction is extremely high ($\sim 5 \times 10^6 \text{ V/m}$)
- The width of the depletion region increases when a high reverse bias potential is applied across the junction.
- An electric field of the order of $3 \times 10^7 \text{ V/m}$ is generated across the depletion region with about 5 V .

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- Sufficiently strong field enables tunnelling of electrons across the depletion region of the semiconductor, leading to a large number of free charge carriers.
 - The electron tunnelling means that due to strong electric field in the direction from n type to p -type, the electrons move directly from the valence band of n type semiconductor to the conduction band of p type semiconductor.
 - The sudden increase in the reverse current takes place at a particular voltage, known as breakdown voltage or the Zener voltage.

Let us understand how reverse current suddenly increases at the breakdown voltage

- We know that reverse current is due to the flow of electrons (minority carriers) from p to n and holes from n to p .
- As the reverse bias voltage is increased, the electric field at the junction becomes significant.
- When the reverse bias voltage is say $V = V_z$, then the electric field strength is high enough to pull valence electrons from the host atoms on the p -side and take them to the n -side.
- These electrons account for high current observed at the breakdown.
- The emission of electrons from the host atoms due to the high electric field is known as **internal field emission or field ionisation**. This gives rise to a high reverse current or breakdown current. The large current at Zener voltage is called **Zener current**.
- The electric field required for field ionisation is of the order of 10^6 V/m.

Avalanche Effect

- With increasing reverse bias voltage, the electric field across the junction of p - n diodes increases. At a certain reverse bias, the electric field imparts a sufficiently high energy to a thermally generated carrier crossing the junction.
- This carrier, on colliding with a crystal ion on its way disrupts a covalent bond and produces an electron hole pair. These carriers on gaining sufficient energy from the applied field collide with other crystal ions and generate further electron hole pairs.
- This process is cumulative and results in a production of an avalanche of carriers in a very short time. This mechanism is known as avalanche multiplication, causes large reverse current and the diode is said to work in the region of avalanche breakdown.

Basis For Comparison	Avalanche Breakdown	Zener Breakdown
Definition	The avalanche breakdown is a phenomenon of increasing the free electrons or electric current in semiconductor and insulating material by applying the higher voltage.	The process in which the electrons are moving across the barrier from the valence band of the p-type material to the conduction band of the lightly filled n-material is known as the Zener breakdown.
Depletion Region	Thick	Thin
Junction	Destroy	Not Destroy
Electric Field	Weak	Strong
Produces	Pairs of electron and hole.	Electrons.
Doping	Low	Heavy
Reverse potential	High	Low
Temperature Coefficient	Positive	Negative
Ionization	Because of collision	Because of Electric Field
Breakdown Voltage	Directly proportional to temperature.	Inversely proportional to temperature.
https://circuitglobe.com/difference-between-avalanche-and-zener-breakdown.html		

Difference Between Zeenerfer and Avalanche Effect

One of the major differences between the **Avalanche** and the **Zener breakdown** is that the **Avalanche breakdown** occurs because of the collision of the electrons, whereas the **Zener breakdown** occurs because of the high electric field.

The charge carrier of the p-n junction diode absorbs heat from the environment at normal room temperature. When the reverse bias is applied across the junction, the kinetic energy of the electrons increases and they start moving at high drift velocity. While moving, they collide with the other atoms and create the number of free electrons which causes the **reverse saturation current**. Because of this saturation current, the avalanche breakdown mechanism occurs in the diode.

The Zener breakdown takes place in heavily doped diodes. When the high electric field is applied across the diode, the electrons start moving across the junction. This develops a small reversed bias current. When the activity of electrons increases beyond the rated capacity of the diode, then avalanche breakdown occurs which breaks the junction. Thus, as long as the current in the diode is limited the Zener diode will not destroy the junction. But avalanche breakdown destroys the junction.

Zener Diode Features

- An ideal p-n Junction diode does not conduct in reverse biased condition.
- A Zener diode conducts excellently even in reverse biased conditions.
- These diodes operate at a precise value of voltage called break down voltage.
- A Zener diode when forward biased behaves like an ordinary p-n junction diode.
- A Zener diode when reverse biased can either undergo avalanche breakdown or Zener break down.
- Avalanche breaks down: - If both p-side and n-side of the diode are lightly doped, the depletion region at the junction widens.
- Application of a very large electric field at the junction may rupture covalent bonding between electrons. Such rupture leads to the generation of a large number of charge carriers resulting in avalanche multiplication.

Zener Diode Characteristics

- To plot Volt-Ampere characteristics of Zener diode.
- To find Zener breakdown voltage in reverse biased condition.

Apparatus Required

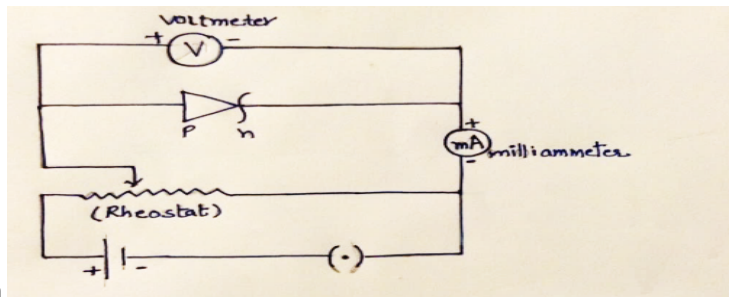
- Zener Diode -IZ 6.2 or any other
- Resistance 1k ohm
- Regulated power supply (0 – 30V)
- Ammeter mA (0-30) mA, (0-500) μ A
- Voltmeter mV (0 – 1) V, (0 – 30)V
- Connecting wires

Think About these Before you Start Work in the lab

- Explain the concept of Zener breakdown?
- How depletion region gets thin by increasing doping level in Zener diode?
- State the reason why an ordinary diode suffers avalanche breakdown rather than Zener breakdown?
- Give the reasons why the Zener diode acts as a reference element in the voltage regulator circuits.

Forward Bias

To obtain this characteristics plot we need to connect a Zener diode in the forward biasing, that is, positive terminal connected to p side and negative terminal connected to n side of the semiconductor. We would also need a voltmeter in parallel and a milli-ammeter, to be connected in series. The circuit diagram is shown:



use lab manual circuit diagram



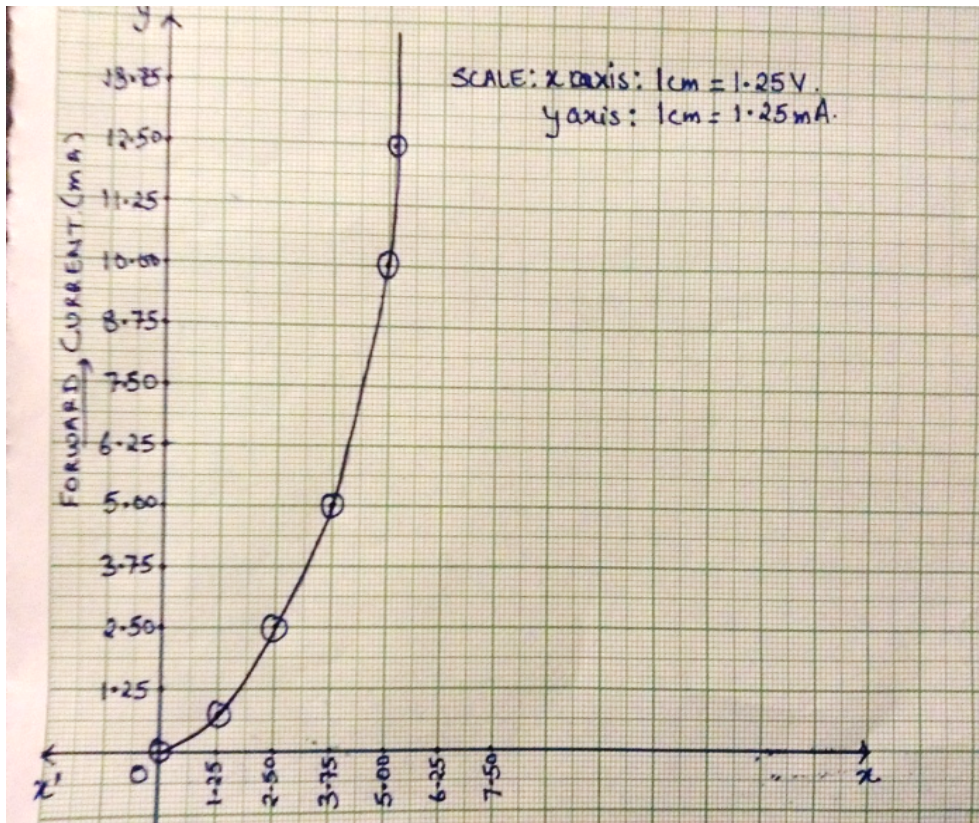
Many laboratories have a Zener diode “box”

- Connect the Zener diode in forward bias i.e. p is connected to positive of the power supply and n is connected to negative of the power supply as in circuit.

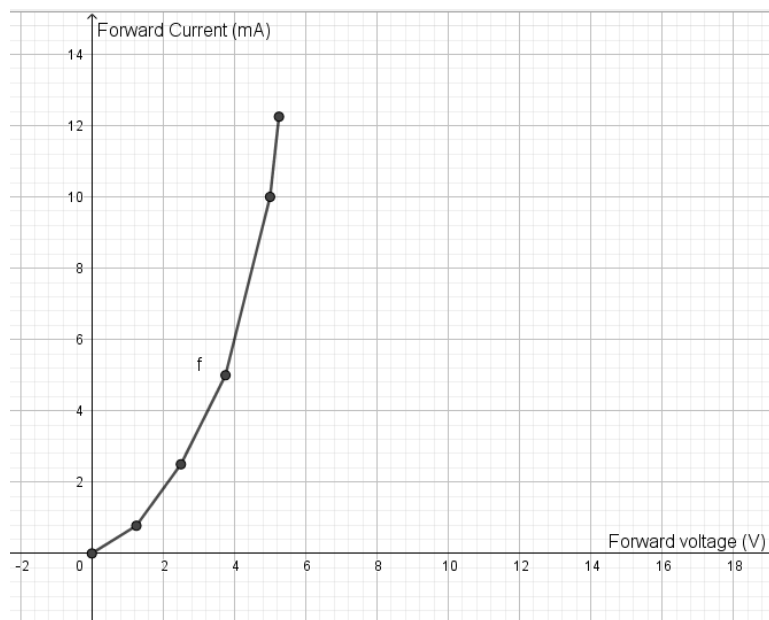
- Use a Regulated power supply of range (0-30) V and a series resistance of $1k\Omega$.
- For various values of forward voltage (V) note down the corresponding values of forward current (I).
- By simply changing the rheostat, we can vary the forward voltage applied and measure the forward current.
- Suppose taking the readings by changing the rheostat we get the following observations:
 - Least count of voltmeter: 0.25V
 - Least count of ammeter: 0.25mA

S.N.	Voltmeter reading(V)	Milliammeter reading(mA)
1	0.0	0.00
2	1.25	0.75
3	2.50	2.50
4	3.75	5.00
5	5.00	10.00
6	5.25	12.50

Now plot a graph with these readings using suitable scale or use GeoGebra



GeoGebra graph

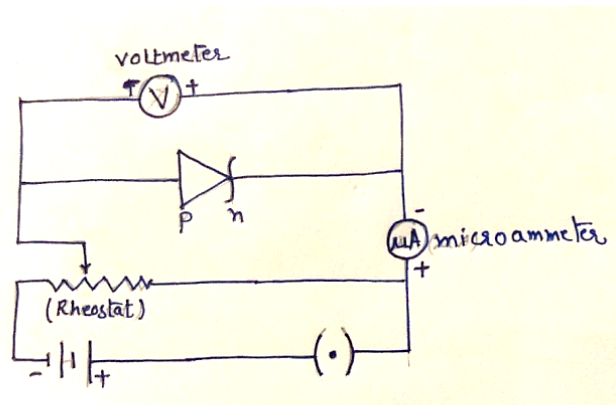


Reverse Bias

To obtain this characteristic plot we need to connect a Zener diode in the reverse biasing, that is, positive terminal connected to n side and negative terminal connected to p side of the semiconductor. We would also need a voltmeter in parallel and a micro-ammeter, to be

connected in series. The circuit diagram is shown:

use lab manual circuit diagram

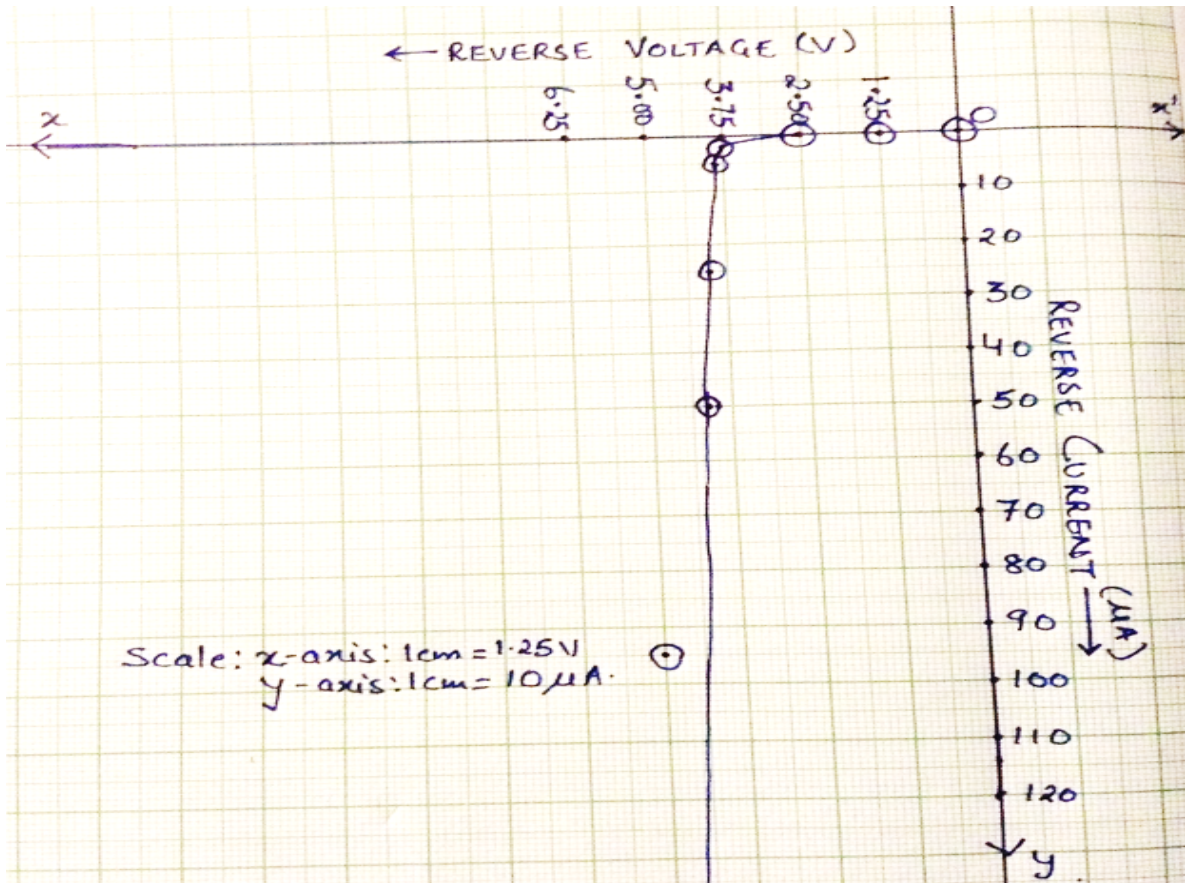


Now taking the readings by changing the rheostat we get the following observations:

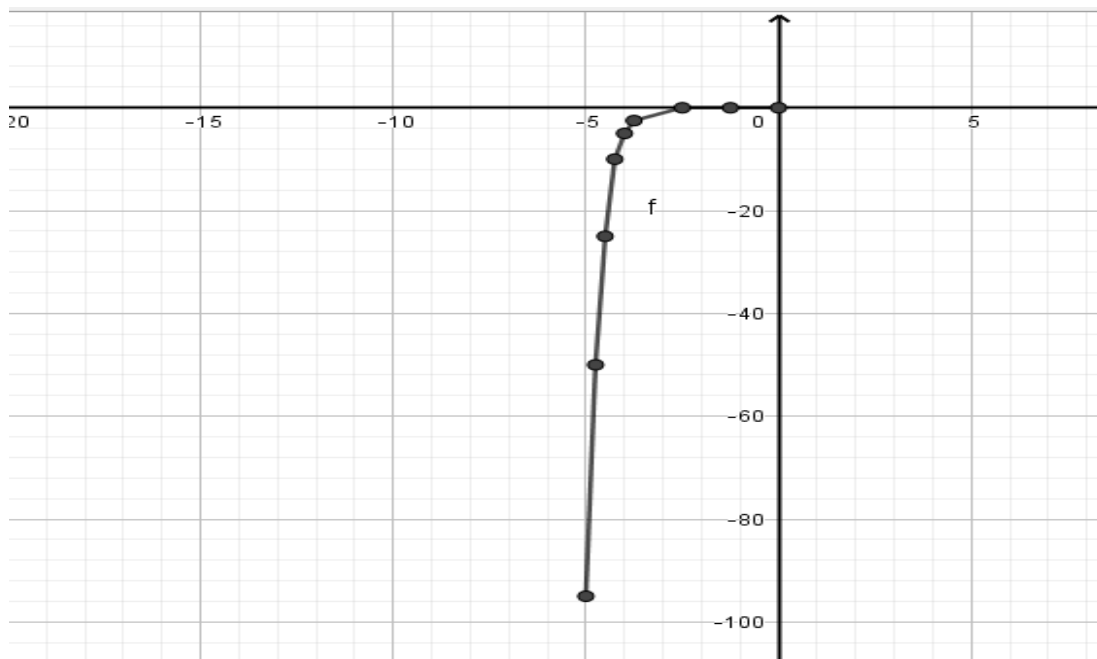
- **Least count of voltmeter: 0.25V**
- **Least count of ammeter: 2.5 μ A**

S.N.	Voltmeter reading(V)	Micro-ammeter reading(μ A)
1	0.00	0.00
2	1.25	0.00
3	2.50	0.00
4	3.75	2.50
5	4.00	5.00
6	4.25	10.0
7	4.50	25
8	4.75	50
9	5.00	95
10	5.25	Out of scale

The following is the plot of the above readings:



GeoGebra graph

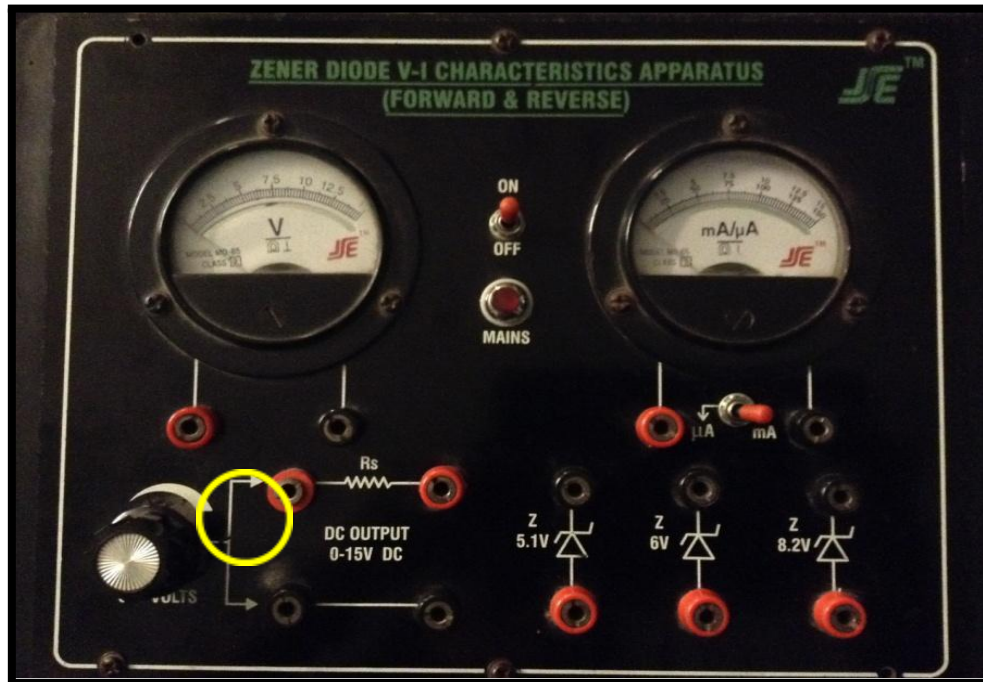


In the above graph the Zener voltage is nearly 5.00V. So the diode exhibits a potential drop of 5.00V across a wide range of reverse current.

Why do we use a high resistance termed protective resistance in practical circuits? the box shows a resistance of R_S ?

There is a relation between protective resistance(R_S) and Zener breakdown voltage(V_Z)
The supplied voltage across the Zener diode and the resistance is shared

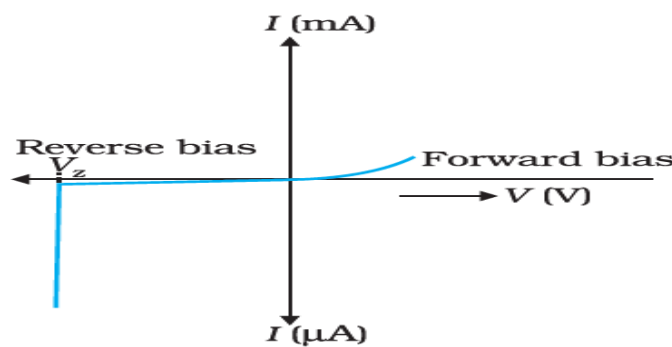
$$V = V_Z + I_Z R_S$$



Depending upon the maximum allowed I_Z the value of R_S is calculated. It may be in the range from 100 ohms to 1000 ohms.

Example

Match the experimental graphs to the following the graph



Explain why the experimental graph for current at V_Z is not parallel to the y axis?

Solution

The avalanche effect and Zener effect depend on the reverse bias and temperature.

Example

Explain the shape of the graph, why does reverse current suddenly increases at the breakdown voltage

Solution

We know that reverse current is due to the flow of electrons (minority carriers) from $p \rightarrow n$ and holes from $n \rightarrow p$.

As the reverse bias voltage is increased, the electric field at the junction becomes significant.

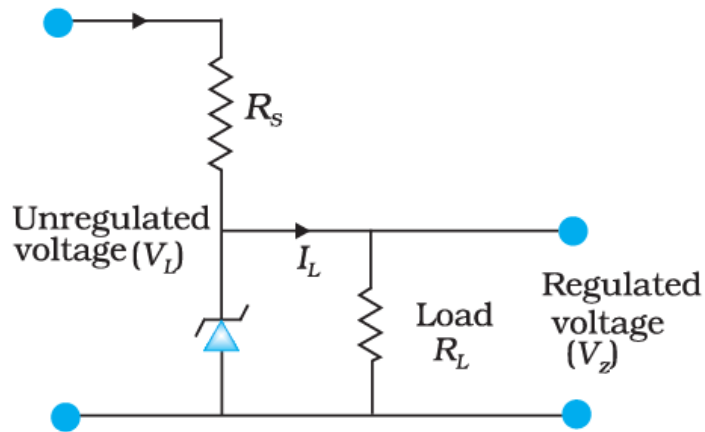
When the reverse bias voltage $V = V_Z$, then the electric field strength is high enough to pull valence electrons from the host atoms on the p-side which are accelerated to n-side.

These electrons account for high current observed at the breakdown.

The emission of electrons from the host atoms due to the high electric field is known as **internal field emission or field ionisation**. The electric field required for field ionisation is of the order of 10^6 V/m.

Zener Diode as a Voltage Regulator

- We know that when the ac input voltage of a rectifier fluctuates, its rectified output also fluctuates. **To get a constant dc voltage from the dc unregulated output of a rectifier, we use a Zener diode.**
- It is seen that when the applied reverse bias voltage (V) reaches the breakdown voltage (V_Z) of the Zener diode, there is a large change in the current. Note that after the breakdown voltage V_Z , a large change in the current can be produced by almost insignificant change in the reverse bias voltage.
- In other words, Zener voltage remains constant, even though current through the Zener diode varies over a wide range.
- This property of the Zener diode is used for regulating supply voltages so that they are constant



The circuit diagram of a voltage regulator using a Zener diode

- The unregulated dc voltage (filtered output of a rectifier) is connected to the Zener diode through a series resistance R_s such that the Zener diode is reverse biased.
- If the input voltage increases, the current through R_s and Zener diode also increases.
- This increases the voltage drop across R_s without any change in the voltage across the Zener diode.
- This is because in the breakdown region, Zener voltage remains constant even though the current through the Zener diode changes.
- Similarly, if the input voltage decreases, the current through R_s and Zener diode also decreases. The voltage drop across R_s decreases without any change in the voltage across the Zener diode.

Thus any increase or decrease in the input voltage results in, increase or decrease of the voltage drop across R_s without any change in voltage across the Zener diode.

Thus the Zener diode acts as a voltage regulator. We have to select the Zener diode according to the required output voltage and accordingly the series resistance R_s .

Example

In a Zener regulated power supply a Zener diode with $V_Z = 6.0$ V is used for regulation.

The load current is to be 4.0 mA and the unregulated input is 10.0 V.

What should be the value of a series resistor R_s ?

Solution

The value of R_S should be such that the current through the Zener diode is much larger than the load current. This is to have good load regulation.

Choose Zener current as five times the load current, i.e.,

$$I_Z = 20 \text{ mA.}$$

The total current through R_S is, therefore, 24 mA.

The voltage drop across R_S is $10.0 - 6.0 = 4.0 \text{ V}$.

This gives

$$R_S = \frac{4.0\text{V}}{24 \times 10^{-3}\text{A}} = 167 \text{ ohms}$$

The nearest value of the carbon resistor is 150 ohms.

So, a series resistor of 150 ohms is appropriate. Note that slight variation in the value of the resistor does not matter, what is important is that the current I_Z should be sufficiently larger than I_L .

Application of Zener Diode

- **A Zener diode can be used as a voltage regulator.**
- **A Zener diode can be used as a waveform clipper, two Zener diodes facing each other clips both the halves of an input signal. This can help prevent voltage spikes from affecting circuits that are connected to the power supply.**
- **Zener diodes are used in surge suppression circuitry for device protection.**
- **Zener diodes are used in over voltage protection circuits.**
- **They are also used in switching applications as in an automated lighting control system.**
- **Zener diodes are also used as voltage reference in power supplies etc. All Bluetooth devices use Zener as a reference for their 3V requirements.**

Summary

In this module we have learnt

- Zener diode is a $p-n$ junction diode which is heavily doped.
- The charge carrier of the $p-n$ junction diode absorbs heat from the environment at normal room temperature. When the reverse bias is applied across the junction, the kinetic energy of the electrons increases and they start moving at high velocity. While moving, they collide with the other atoms and create the number of free electrons which causes the

reverse saturation current. Because of this saturation current, the **avalanche breakdown** mechanism occurs in the diode.

- The **Zener breakdown** takes place in heavily doped diodes. When the high electric field is applied across the diode, the electrons start moving across the junction. Thus, develop the small reversed bias current. When the jumping of electrons increases beyond the rated capacity of the diode, then avalanche breakdown occurs which breaks the junction.
- Zener diode characteristics can be checked using suitable circuits and by plotting graphs for forward and reverse bias.
- When the applied reverse bias voltage (V) reaches the breakdown voltage (V_z) of the Zener diode, there is a large change in the current. After the breakdown voltage V_z , a large change in the current can be produced by an almost insignificant change in the reverse bias voltage.
- Zener voltage remains constant, even though current through the Zener diode varies over a wide range. This property of the Zener diode is used for regulating supply voltages so that they are constant