# DETERMINATION OF BANDGAP ENERGY OF SEMICONDUCTOR MATERIALS

**PROJECT REPORT**

Submitted by

**KRISHNAPRIYA M A - AB23PHY009**

Under the guidance of

**Dr. MARIYAM THOMAS**

**Assistant Professor,**

**Department of Physics and Centre for Research,**

**St. Teresa's College (Autonomous), Ernakulam.**

*In partial fulfilment of the requirement of award of*
*Bachelor Degree of science in Physics.*

**ST. TERESA'S COLLEGE (AUTONOMOUS)**
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## CERTIFICATE

This is to certify that the project report entitled "**DETERMINATION OF BANDGAP ENERGY OF SEMICONDUCTOR MATERIALS**" is an authentic work done by KRISHNAPRIYA M A, St Teresa's College(Autonomous), Ernakulam, under my supervision at Department of Physics and Centre for Research, St. Teresa's College(Autonomous), Ernakulam, for the partial requirements for the award of Degree of Bachelor of Science in Physics during the academic year 2025-26. The work presented in this dissertation has not been submitted for any other degree in this or university.

Supervising Guide
**Dr. MARIYAM THOMAS**
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Head of the Department
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Assistant professor

Department of Physics ★ St. Teresa's College (Autonomous) ★ Ernakulam

# ST. TERESA'S COLLEGE (AUTONOMOUS)
# ERNAKULAM

B.Sc. PHYSICS
PROJECT REPORT

NAME : KRISHNAPRIYA M A

REGISTER NUMBER : AB23PHY009

YEAR OF WORK : 2025-26

This is to certify that this project work entitled, "DETERMINATION OF BANDGAP ENERGY OF SEMICONDUCTOR MATERIALS" is an authentic work done by KRISHNAPRIYA M A .

Staff member in-charge
Dr. MARIYAM THOMAS

Head of the Department
Dr. MARY VINAYA

Submitted for the University examination held at St. Teresa's College(Autonomous), Ernakulam.

DATE: 16.04.26

EXAMINER:

1.

2.

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# DECLARATION

I, KRISHNAPRIYA M A , final B.Sc. Physics students, Department of Physics, St. Teresa's College (Autonomous), Ernakulam, do hereby declare that the project work entitled "**DETERMINATION OF BANDGAP ENERGY OF SEMICONDUCTOR MATERIALS**" has been originally carried out under the guidance and supervision of
**Dr. Mariyam Thomas**, Assistant Professor, Department of Physics and Centre for Research, St. Teresa's College (Autonomous), Ernakulam, in partial fulfilment for the award of the Degree of Bachelor of Physics. I further declare that this project is not partially or wholly submitted for any other purpose and the data included in the project is collected from various sources and is true to the best of my knowledge.

# ACKNOWLEDGEMENT

First and foremost, I thank God Almighty for His abundant blessings and guidance throughout the completion of this project.

I express my heartfelt gratitude to Dr. Mariyam Thomas, Department of Physics and Centre for Research, St. Teresa's College (Autonomous), for her invaluable guidance, constant encouragement, and insightful suggestions that greatly contributed to the successful completion of this work. Her timely support and constructive feedback have been truly inspiring.

I am also deeply thankful to the Department of Physics for providing the necessary facilities and a supportive academic environment. I extend my sincere appreciation to the Head of the Department and all the teaching and non-teaching staff for their cooperation and assistance throughout this endeavor.

Finally, I gratefully acknowledge everyone who directly or indirectly helped me in completing this project successfully.

# CONTENTS

# ABSTRACT

Semiconductors play a vital role in modern technology due to their versatile properties and wide range of applications. They are commonly used in the fabrication of solid-state electronic devices such as diodes and transistors. Materials like silicon and germanium are widely preferred because their electrical conductivity lies between that of conductors and insulators. In the energy band structure of a semiconductor, the valence band is nearly filled while the conduction band is almost empty, separated by a small forbidden energy gap of about 1 eV. The band gap is approximately 0.7 eV for germanium and 1.1 eV for silicon.

This project focuses on the experimental determination of the energy band gap of silicon and germanium diodes. The band gap was evaluated by studying the variation of current with temperature. From the observations and calculations, the obtained values of band gap energy were found to be in close agreement with the standard theoretical values.

# Chapter 1
# INTRODUCTION

## 1.1 Introduction

Materials are generally classified into conductors, insulators, and semiconductors according to their electrical conductivity. This classification is explained by the energy band theory, which describes the behavior of electrons in solids. In an isolated atom, electrons occupy discrete energy levels. When many atoms combine to form a solid, these discrete levels split and form continuous energy bands. The two most important bands are the valence band, which contains bound electrons, and the conduction band, where electrons are free to move and contribute to electric current. The region between these two bands, where no energy levels exist, is called the band gap.

In **conductors**, such as metals, the valence band is partially filled or overlaps with the conduction band. This allows electrons to move freely even under a small applied electric field, resulting in high electrical conductivity. In insulators, the valence band is completely filled and separated from the conduction band by a large band gap. Because electrons require significant energy to cross this gap, insulators exhibit very low conductivity under normal conditions.

**Semiconductors** have a band gap that is smaller than that of insulators but larger than that of conductors. At absolute zero temperature, a semiconductor behaves like an insulator because its valence band is full and the conduction band is empty. However, at room temperature, some electrons gain sufficient thermal energy to cross the band gap and enter the conduction band. This transition leaves behind vacancies in the valence band called holes. Both electrons and holes act as charge carriers and contribute to electrical conduction.

The electrical properties of semiconductors can be significantly modified by a process known as doping, in which small amounts of impurity atoms are introduced into a pure semiconductor. When pentavalent impurity atoms are added, extra electrons become available for conduction, forming an n-type semiconductor. When trivalent impurity atoms are added, they create holes in the valence band, forming a p-type semiconductor. The interface between p-type and n-type materials forms a p–n junction, which is the fundamental structure of many semiconductor devices.

One of the simplest semiconductor devices is the diode, which allows current to flow primarily in one direction. Diodes are widely used in rectification, voltage regulation, and signal detection. When exposed to light, certain semiconductor devices generate electron–hole pairs, increasing conductivity. This principle is utilized in photodiodes and light-emitting diodes (LEDs) for sensing, display, and communication applications.

Another important semiconductor device is the transistor, which functions either as an amplifier or as a switch. Transistors are the fundamental building blocks of modern electronic circuits. They are used in digital logic gates, microprocessors, and memory devices. Different types of transistors, such as bipolar junction transistors (BJTs) and field-effect transistors (FETs), operate by controlling the movement of charge carriers within semiconductor materials. Semiconductors also play a crucial role in energy conversion devices such as solar cells, which convert light energy directly into electrical energy through the photovoltaic effect. These devices are widely used in renewable energy systems, satellites, communication equipment, and portable electronics. The conductivity of semiconductors is strongly influenced by temperature. As temperature increases, more electrons acquire sufficient energy to move into the conduction band, thereby increasing the number of charge carriers. This behavior contrasts with that of metals, where resistance generally increases with temperature.

Due to their controllable electrical properties, compact size, reliability, and efficiency, semiconductors form the foundation of modern electronics. They are essential in communication systems, computing technologies, industrial automation, and renewable energy applications. Without semiconductors, the rapid advancement of electronic and information technologies would not have been possible.[1]

## 1.2 Conductors, Semiconductors, Insulators & Energy Bands

Based on the conduction of electricity, solids are classified into conductors, insulators and then there is also an intermediate class of semiconductors. This difference in the behaviour of solids based on their electrical conductivity can be explained in terms of their energy bands also.

**Insulators**: - Insulators are substances which do not allow the passage of electricity through them. In terms of energy band, the valance band is full while the conduction band is empty and the energy gap between the valance band and conduction band is very large (≈15 eV). That means, a very high electronic field is required for the valance electrons to cross over to the conduction band or else at room temperature the valance electrons of the insulators do not have enough energy to cross over to the conduction band. Therefore, the electrical conductivity of such materials is extremely small, and may be regarded as nil under normal conditions.

**Conductors**: - They are substances that easily allow the passage of electric current through them. A large number of free electrons are present in a conductor. As for energy bands, the valance and conduction bands overlap with each other. As a result, a slight potential difference across the conductor causes the free electrons to constitute electric current.

**Semiconductors**: - Semiconductors are substances whose electrical conductivity lies in between that of conductors and insulators. In terms of energy bands, the valance and conduction bands are separated by a very small energy gap. The valance band is almost filled, and the conduction band is almost empty. Therefore, comparatively smaller electric field is required to push the electrons from the valance band to the conduction band. Ge & Si are examples of two semiconductors. Like an insulator as temperature rises, electrons from the valence band cross over to the conduction band and conductivity increases. Semiconductors have negative temperature coefficient of resistance.

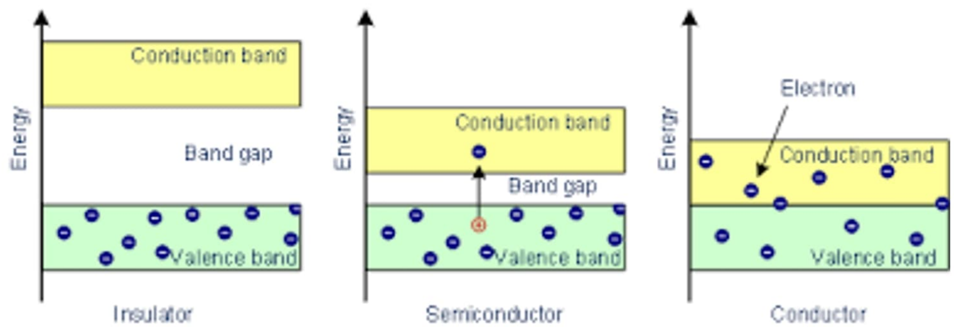


Fig 1.1 Bandgap of Insulator, Semiconductor & Conductor

### 1.3 Semiconductors

A semiconductor is a material whose electrical resistivity lies between that of a conductor and an insulator. Its resistivity typically ranges from about $10^{-4}$ to $10^{4}$ Ωm. Materials such as germanium (Ge) and silicon (Si) are common examples. The distinguishing feature of a semiconductor is not merely its resistivity value but its unique electrical behavior governed by energy band theory.
In a semiconductor, the valence band is completely filled and the conduction band is empty at absolute zero temperature. These two bands are separated by a small energy gap. At ordinary temperatures, some electrons gain sufficient thermal energy to cross this gap and move into the conduction band, leaving behind holes in the valence band. Both electrons and holes act as charge carriers and contribute to current flow.

**Properties of Semiconductors**

Semiconductors are materials whose electrical properties lie between those of conductors and insulators. This unique behavior arises from their atomic structure and energy band configuration, making them extremely important in modern electronic devices.

**1) Intermediate Resistivity:** Semiconductors exhibit electrical resistivity that is intermediate between that of conductors and insulators. In conductors, a large number of free electrons are available for conduction, resulting in very low resistivity, whereas insulators have tightly bound electrons and hence extremely high resistivity. In semiconductors, only a limited number of charge carriers are available at room temperature, leading to moderate resistivity. This resistivity is not fixed and can be significantly altered by changing temperature, applying an external electric field, or introducing impurities through doping. Because of this controllable resistivity, semiconductors are widely used in electronic components such as diodes, transistors, and integrated circuits.

**2) Negative Temperature Coefficient of Resistance:** One of the most important properties of semiconductors is their negative temperature coefficient of resistance. As the temperature of a semiconductor increases, thermal energy breaks some of the covalent bonds between atoms, generating additional charge carriers in the form of electrons and holes. The increase in the number of charge carriers enhances electrical conduction, thereby reducing the resistance of the material. This behavior is opposite to that of metals, where resistance increases with temperature due to increased lattice vibrations. The negative temperature coefficient makes semiconductors highly sensitive to temperature changes and forms the basis for temperature-dependent devices such as thermistors and temperature sensors.

**3) Crystalline Structure:** Semiconductors generally possess a well-defined crystalline structure, in which atoms are arranged in a regular and repeating pattern. Common semiconductor materials such as silicon and germanium have a diamond cubic crystal structure, where each atom is covalently bonded to four neighboring atoms. These covalent bonds result from the sharing of valence electrons between adjacent atoms, leading to a stable lattice at low temperatures. The crystalline nature of semiconductors plays a crucial role in determining their electrical properties, as the periodic arrangement of atoms gives rise to distinct energy bands, namely the valence band and the conduction band, separated by a small energy gap. Any imperfections or impurities in the crystal lattice can significantly influence the electrical behavior of semiconductors, which is exploited in the controlled doping process to enhance conductivity.

## 1.4 Types of Semiconductors

Semiconductors are classified into two main types based on their purity: intrinsic and extrinsic semiconductors. This classification depends on whether the material is in its pure form or contains added impurities to modify its electrical properties.

### Intrinsic Semiconductor

An intrinsic semiconductor is a semiconductor in its extremely pure and natural form, without any intentional impurities. Common examples are silicon and germanium. At absolute zero temperature, it behaves like an insulator because the valence band is completely filled and the conduction band is empty. As the temperature increases, thermal energy breaks some covalent bonds and frees electrons, which move into the conduction band and create holes in the valence band. In an intrinsic semiconductor, the number of electrons is equal to the number of holes, so the electron concentration is equal to the hole concentration.

**Extrinsic Semiconductor**

An extrinsic semiconductor is obtained by adding a small and controlled amount of impurity atoms to a pure intrinsic semiconductor. Since intrinsic semiconductors have low conductivity at room temperature, impurities are added to increase the number of charge carriers. This process is known as doping. Depending on the type of impurity, either trivalent or pentavalent atoms are introduced into the semiconductor crystal. The concentration and type of impurity must be carefully controlled during preparation. Typically, one impurity atom is added for about every hundred million atoms of the semiconductor to achieve the desired electrical properties.

**i) Germanium**

Germanium is one of the earliest and most important semiconductor materials used in electronic devices. It has an atomic number of 32 and an electronic configuration of 2, 8, 18, and 4, giving it four valence electrons. These electrons form covalent bonds with neighboring atoms, creating a crystalline structure. Germanium has a relatively small band gap of about 0.72 eV, which allows electrons to be easily excited into the conduction band at room temperature. Because of this property, it shows higher intrinsic conductivity compared to silicon. Germanium can be doped with suitable impurities to form n-type and p-type extrinsic semiconductors used in electronic devices.

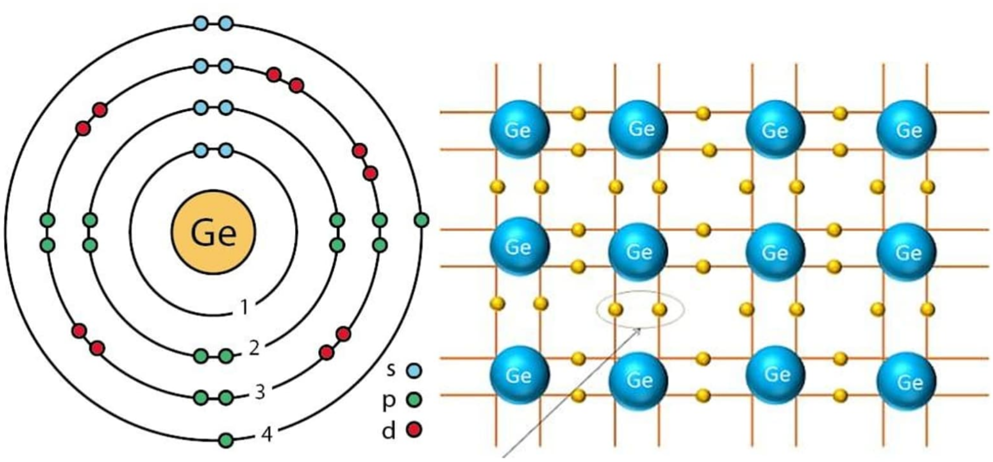


Fig 1.2 Electronic configuration and bonding of Ge atom

**ii) Silicon**

Silicon is the most widely used semiconductor material in modern electronics. It has an atomic number of 14 and an electronic configuration of 2, 8, and 4, giving it four valence electrons. These electrons form strong covalent bonds with neighboring silicon atoms, resulting in a stable crystalline lattice. Silicon has a band gap of about 1.1 eV, which makes it less sensitive to temperature compared to germanium and more suitable for practical applications. It is abundant in nature, easy to purify, and forms a stable oxide layer. By doping silicon with impurities, it can form n-type and p-type semiconductors for electronic devices.[2][3]

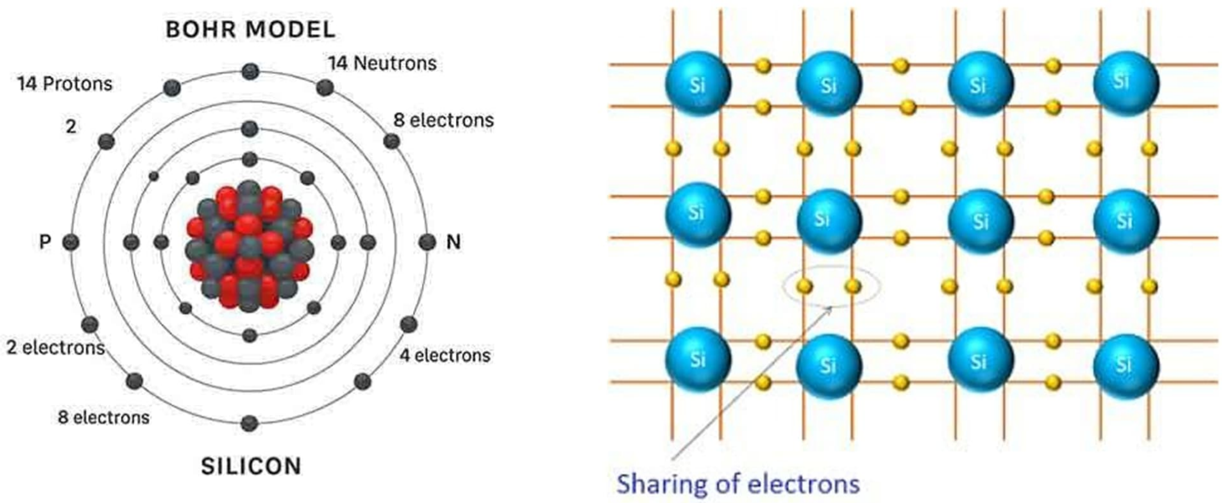


Fig 1.3 Electronic configuration and bonding of Si atom

## 1.5 n-type semiconductor and p-type semiconductor

### i) n-type semiconductor

An n-type semiconductor is formed when a small amount of pentavalent impurity is added to a pure semiconductor crystal. Such impurities include elements like arsenic, antimony, or phosphorus. Since these impurity atoms have five valence electrons, they are called donor impurities because they donate free electrons to the semiconductor.

To understand its formation, consider a pure germanium or silicon crystal, where each atom has four valence electrons and forms four covalent bonds with neighboring atoms. When a pentavalent impurity atom is introduced into the crystal, it replaces a semiconductor atom. Four of its valence electrons form covalent bonds with the surrounding atoms, while the fifth electron does not take part in bonding. This extra electron is loosely bound to the impurity atom and can easily become free.

The energy required to free this electron is very small and is supplied by thermal energy at room temperature. This electron then moves into the conduction band and becomes available for electrical conduction. The energy level of this electron lies just below the conduction band and is called the donor level. When the electron leaves, the impurity atom becomes a positively charged immobile ion.

Thus, in an n-type semiconductor, electrons are the majority charge carriers, while holes are the minority carriers. The presence of donor impurities greatly increases the electrical conductivity of the semiconductor.

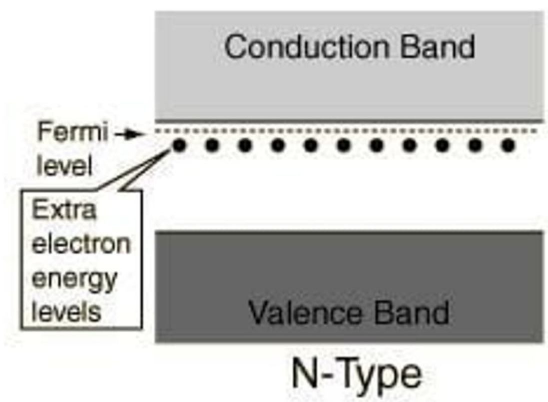


Fig 1.4 Valance band and conduction band of n-type semiconductor

**i) p-Type Semiconductor**

A p-type semiconductor is obtained by adding a small amount of trivalent impurity to a pure semiconductor crystal such as silicon or germanium. This process is called doping. Trivalent impurities such as boron, aluminium, or gallium have three valence electrons. When such an impurity atom is introduced into the crystal, it forms three covalent bonds with neighbouring semiconductor atoms. However, one bond remains incomplete due to the absence of the fourth valence electron.

This incomplete bond creates a vacancy called a hole. The hole behaves like a positive charge carrier. For each trivalent impurity atom added, one hole is produced in the crystal. Since holes are created in large numbers, they become the majority charge carriers, while electrons act as minority carriers.

In a p-type semiconductor, the impurity atoms are known as acceptor impurities because they accept an electron from neighbouring atoms to complete the covalent bond. The energy level corresponding to this missing electron lies just above the valence band and is called the acceptor level. Only a small amount of energy is needed for electrons from the valence band to move into this level, leaving behind holes.

Thus, the conduction in a p-type semiconductor mainly occurs due to the movement of holes under the influence of an electric field.

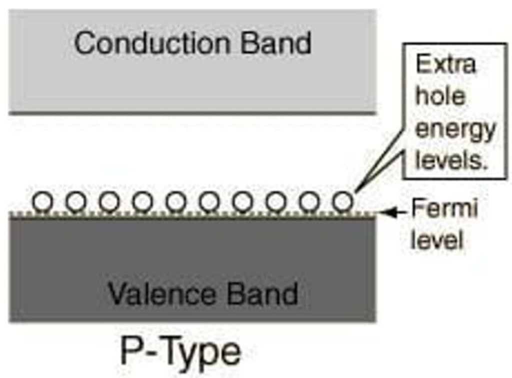


Fig 1.5 Valance band and conduction band of p-type semiconductor

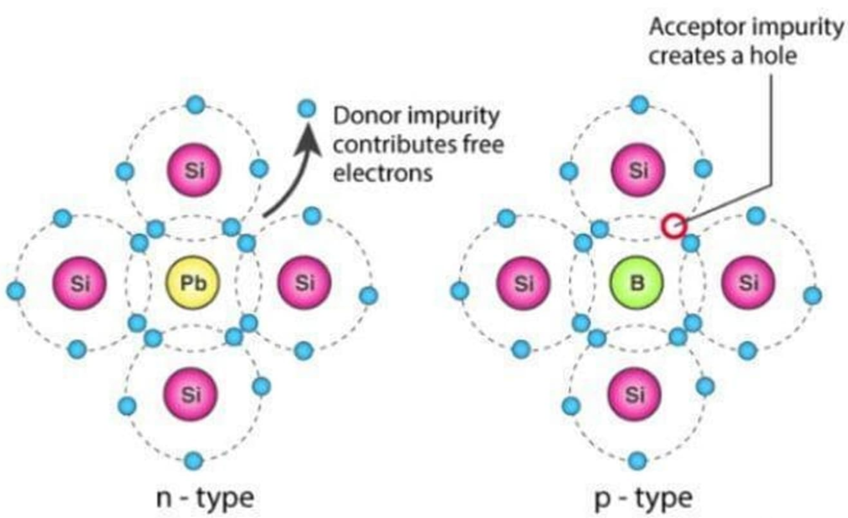


Fig 1.6 Difference between p type and n type semiconductors

### 1.6 PN Junction and its properties

A PN junction is the fundamental building block of most semiconductor devices and is formed when a p-type semiconductor is joined with an n-type semiconductor. In p-type material, holes are the majority charge carriers due to acceptor impurities, whereas in n-type material, electrons dominate because of donor impurities. When the two regions are brought into contact, carriers diffuse across the junction due to the concentration gradient: electrons move from the n-side to the p-side, and holes move from the p-side to the n-side.

This diffusion leads to recombination of electrons and holes near the junction, leaving behind uncovered ionized donor and acceptor atoms. As a result, a depletion region is formed around the junction, which is free of mobile charge carriers. The fixed ions create an internal electric field that opposes further diffusion. Equilibrium is reached when the diffusion current is exactly balanced by the drift current caused by this electric field. The potential difference established across the depletion region is called the built-in potential.

One of the key properties of a PN junction is its rectifying behavior. Under forward bias (p-side connected to positive terminal and n-side to negative terminal), the potential barrier is reduced, allowing charge carriers to cross the junction easily and resulting in a large current. Under reverse bias, the barrier height increases, widening the depletion region and permitting only a very small leakage current due to minority carriers.

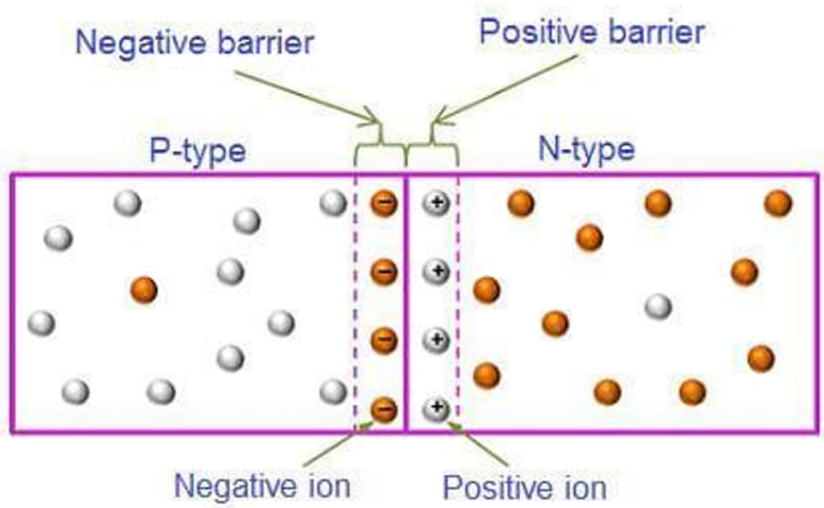


Fig 1.7 p-n junction

### 1.7 Forward Biasing and Reverse Biasing of a P–N Junction

Biasing refers to the application of an external DC voltage to a semiconductor device in order to establish suitable operating conditions. In a p–n junction diode, biasing is classified into two types: forward bias and reverse bias.

**Forward Bias**

A p–n junction is said to be forward biased when the p-type region is connected to the positive terminal of the battery and the n-type region is connected to the negative terminal. In this condition, the externally applied voltage opposes the built-in potential barrier of the junction. As a result, holes in the p-region are pushed towards the junction by the positive terminal, while electrons in the n-region are driven towards the junction by the negative terminal.

When the applied voltage becomes comparable to the barrier potential , the depletion layer becomes thinner. This reduction in barrier height allows majority charge carriers to cross the junction easily. Consequently, recombination occurs near the junction, leading to a significant increase in current. The forward current increases rapidly with applied voltage, and the diode exhibits low resistance under forward bias.

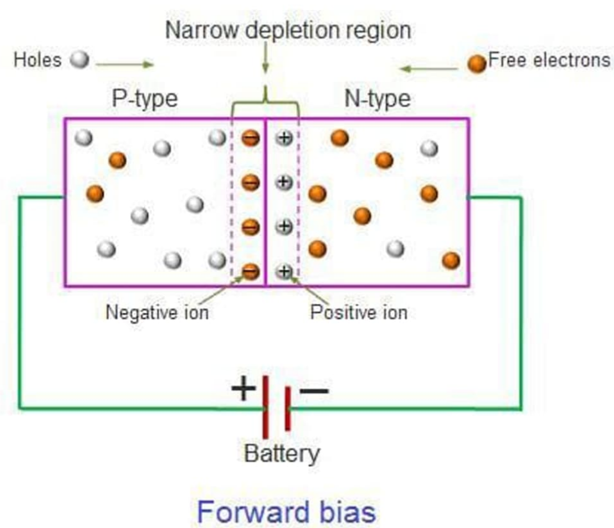


Fig 1.8 Forward biased p-n junction

The forward current–voltage characteristic shows that the current increases slowly until the applied voltage reaches a critical value known as the knee voltage. For germanium diodes, this value is approximately 0.3 V, while for silicon diodes it is about 0.7 V. Beyond this voltage, the current rises sharply even for a small increase in voltage.

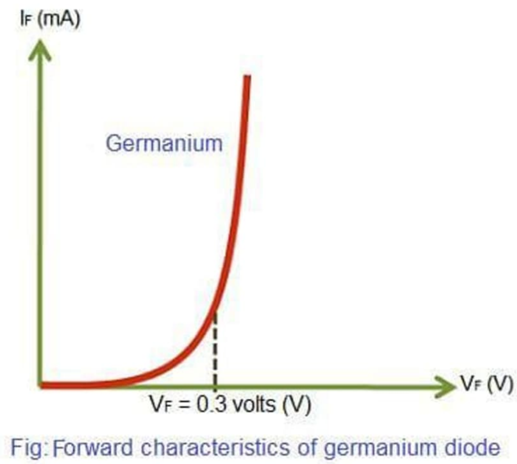


Fig 1.9 Forward characteristics of p-n junction diode

**Reverse Bias**

A p–n junction is said to be reverse biased when the p-region is connected to the negative terminal and the n-region to the positive terminal of the battery. In this configuration, holes in the p-region and electrons in the n-region are pulled away from the junction. The applied voltage reinforces the built-in electric field, thereby increasing the width of the depletion region and the potential barrier.

Due to the increased barrier, the flow of majority carriers across the junction is prevented. However, a very small current flows due to minority carriers, which are generated thermally within the semiconductor. This reverse current is typically of the order of microamperes and remains nearly constant with increasing reverse voltage.[4]

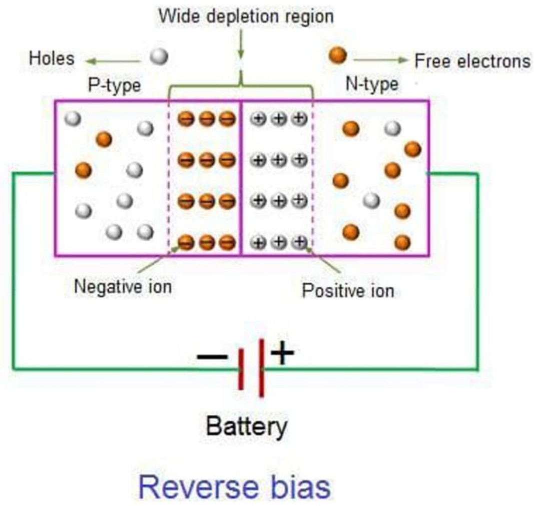


Fig 1.10 Reverse biased p-n junction

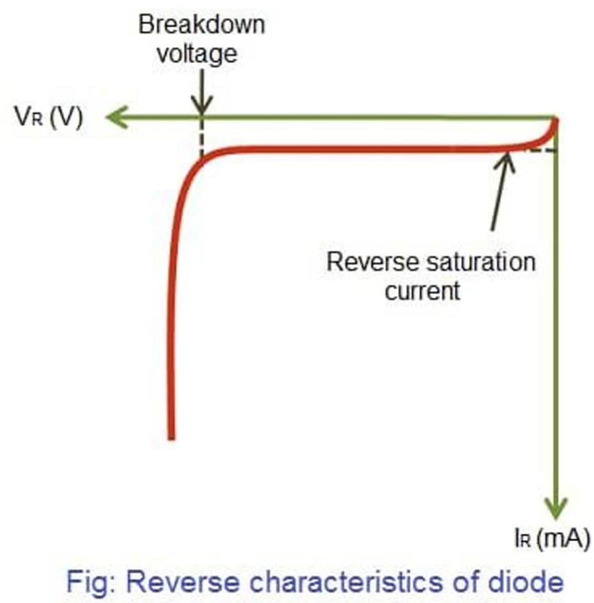


Fig 1.11 Reverse characteristics of p-n junction diode

### 1.8 Effect of Temperature on Semiconductors

Temperature has a significant influence on the electrical conductivity of semiconductors. Even small variations in temperature can cause noticeable changes in their electrical behavior.

**(i) At Absolute Zero (0 K):**

At absolute zero temperature, all electrons in a semiconductor are tightly bound to their respective atoms. The inner-shell electrons remain strongly attached to the nucleus, while the valence electrons are firmly held in covalent bonds. Under these conditions, no electrons possess sufficient energy to break free from the covalent bonds. As a result, there are no free charge carriers available for conduction, and the semiconductor behaves as an insulator.

From the energy band perspective, the valence band is completely filled, and a forbidden energy gap separates it from the conduction band. Since no electrons can cross this energy gap at absolute zero, the conduction band remains empty. The absence of free electrons prevents the flow of electric current, causing insulating behavior.

**(ii) Above Absolute Zero:**

When the temperature is increased above absolute zero, even up to room temperature, thermal energy is supplied to the semiconductor lattice. This energy causes some of the covalent bonds to break, thereby freeing a small number of electrons. These liberated electrons contribute to electrical conduction when an external electric field is applied, producing a weak current.

As the temperature continues to rise, more valence electrons acquire sufficient energy to move from the valence band into the conduction band. Each such transition results in the creation of a free electron in the conduction band and a corresponding hole in the valence band. Both electrons and holes act as charge carriers and participate in conduction.

Due to the increase in charge carrier concentration with temperature, the electrical resistance of a semiconductor decreases as temperature increases. Hence, semiconductors exhibit a negative temperature coefficient of resistance, distinguishing them from metallic conductors.

## 1.9 Fermi Level and Fermi Energy

The concepts of Fermi energy and Fermi level are essential for understanding the electrical behavior of conductors and semiconductors. In a solid, electrons occupy energy states according to the Fermi–Dirac distribution. The **Fermi energy** (EF)is defined as the highest occupied energy level by electrons at absolute zero temperature (0 K). At this temperature, all energy states below the Fermi energy are completely filled, while all states above it are empty. Thus, the Fermi energy represents the maximum energy possessed by electrons in a material at 0 K.

The **Fermi level** is a more general term used to describe the energy level at which the probability of finding an electron is one-half at a given temperature. In metals, the Fermi level lies within the conduction band, which accounts for their high electrical conductivity. In intrinsic semiconductors, the Fermi level is located approximately at the middle of the band gap between the valence and conduction bands.

When a semiconductor is doped, the Fermi level shifts according to the type of impurity. In n-type semiconductors, it moves closer to the conduction band due to the increased number of electrons. In p-type semiconductors, it shifts toward the valence band because holes become the majority carriers. The position of the Fermi level therefore determines the carrier concentration and electrical properties of the material.[5]

### 1.10 Energy Band Description of Semiconductors

In terms of electrical resistivity, a semiconductor is a material whose resistivity lies between that of conductors and insulators, typically ranging from about $10^{-4}$ to $10^{5}$ ohm-meter. On the basis of energy band theory, a semiconductor is defined as a substance having an almost completely filled valence band and a nearly empty conduction band separated by a small forbidden energy gap. This energy gap is of the order of 1 eV.

In silicon and germanium, the energy gap is relatively small, approximately 1.1 eV for silicon and 0.72 eV for germanium. Because of this small band gap, some valence electrons can acquire sufficient thermal energy at room temperature to jump from the valence band to the conduction band. However, the number of such free electrons is limited, and therefore these materials at room temperature behave neither as good conductors nor as perfect insulators. Hence, they are classified as semiconductors.

For electrical conduction to occur, electrons must be supplied with energy equal to or greater than the band gap so that they can move from the top of the valence band to the bottom of the conduction band. The band gap energy is thus the energy difference between these two bands. The energy gap of a semiconductor generally decreases slightly with increase in temperature.

The determination of band gap energy can be made by studying the temperature dependence of conductivity. In a PN junction under reverse bias, the current is mainly due to minority charge carriers and depends strongly on temperature. The reverse saturation current varies exponentially with temperature and is related to the band gap energy. Thus, the energy band model explains the electrical behavior and temperature dependence of semiconductor materials.[5]

Forward or reverse current of a diode depends upon temperature by relation,

$$I = I_0 \exp\left[\frac{eV}{\eta kT} - 1\right]$$

At ordinary temperature,

$$\exp\left[\frac{eV}{\eta kT} - 1\right] \gg 1$$

Hence, 1 is neglected.

$$I = I_0 \exp\left[\frac{eV}{\eta kT}\right]$$

Taking logarithm, we get

$$\ln(I) = \ln I_0 + \frac{eV}{\eta kT}$$

Differentiating with respect to $T$ for a given fixed current $I$,

$$0 = \frac{1}{I_0}\frac{dI_0}{dT} + \frac{1}{\eta kT}\frac{dV}{dT} - \frac{V}{\eta kT^2}$$

$$V - \eta V_T T \frac{1}{I_0}\frac{dI_0}{dT} = T\frac{dV}{dT}$$

The empirical relation connecting reverse saturation current and leakage current is given by,

$$I_0 = KT^m \exp\left(-\frac{eV_0}{\eta kT}\right)$$

Taking logarithm,

$$\ln I_0 = \ln K + m\ln T - \frac{eV_0}{\eta kT}$$

Where $V_0$ = Band gap energy

Differentiating with respect to $T$,

$$\frac{1}{I_0}\frac{dI_0}{dT} = \frac{m}{T} + \frac{eV_0}{\eta kT^2}$$

$$\frac{T}{I_0}\frac{dI_0}{dT} = m + \frac{eV_0}{\eta kT}$$

$$= m + \frac{V_0}{\eta V_T}$$

Substituting this in equation,

$$V - \eta V_T T \frac{1}{I_0}\frac{dI_0}{dT} = T\frac{dV}{dT}$$

We get,

$$T\frac{dV}{dT} = V - \eta V_T\left(m + \frac{V_0}{\eta V_T}\right)$$

$$= V - \eta m V_T - V_0$$

$$V_T = \frac{kT}{e} = \frac{T}{11600}$$

$$V_0 = V - \eta m V_T - T\frac{dV}{dT}$$

$$V_0 = V - \frac{\eta m k T}{e} - T\frac{dV}{dT}$$

$$V_0 = V - T\left[\frac{dV}{dT} + \frac{\eta m k}{e}\right]$$

# Chapter 2
# EXPERIMENTAL TECHNIQUES

## 2.1 Experimental setup

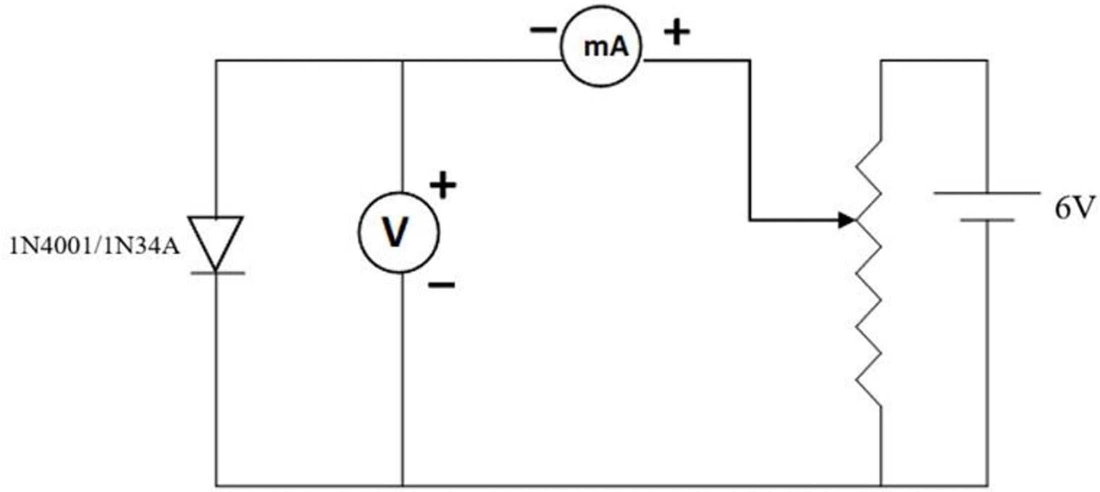


Fig 2.1 Circuit diagram of the experimental set up

The experimental set-up used to determine the band gap energy of germanium and silicon diodes consists of a regulated DC power supply, a semiconductor diode, a milliammeter, a voltmeter, and a rheostat arranged as shown in the circuit diagram. The diode is connected in forward bias, with the anode connected to the positive terminal of the power supply and the cathode connected to the negative terminal through a milliammeter. The milliammeter is connected in series with the diode to measure the forward current, while the voltmeter is connected in parallel across the diode to measure the forward voltage drop across the p–n junction. A rheostat is included in series with the circuit to regulate the forward current flowing through the diode, allowing a constant current to be maintained throughout the experiment. The regulated DC power supply ensures a stable and ripple-free voltage, thereby improving the accuracy of voltage measurements.

To study the variation of forward voltage with temperature, the diode is placed inside a thin glass test tube and immersed in a water bath. The water bath provides uniform heating of the diode junction and minimizes temperature gradients that could otherwise lead to inaccurate measurements. A thermometer or temperature sensor is positioned close to the diode to measure the temperature of the water bath, which is assumed to be approximately equal to the junction temperature of the diode after thermal equilibrium is achieved. This arrangement allows the diode temperature to be increased gradually and uniformly during the experiment.

After making the circuit connections, the power supply is switched on and the rheostat is adjusted to set a small, constant forward current through the diode. The forward voltage across the diode is first measured and recorded at room temperature. The water bath is then heated slowly, and the temperature is increased in small steps. For each rise in temperature, the rheostat is adjusted carefully, if necessary, to maintain the forward current at the same constant value. Once thermal equilibrium is reached at each temperature, the corresponding forward voltage is measured using the voltmeter and recorded. This procedure is repeated over a suitable range of temperatures to obtain sufficient data for analysis.

The recorded values of temperature and forward voltage are used to plot a graph with temperature on the X-axis and forward voltage on the Y-axis. The graph shows an approximately linear decrease in forward voltage with increase in temperature at constant current. From this graph, the slope dV/dT is determined. Using the calculated slope along with the observed values of voltage and temperature, the band gap energy of the semiconductor diode is evaluated using the appropriate theoretical relation. This method provides a reliable experimental determination of the band gap energy of germanium and silicon diodes.

A semiconductor diode obeys the relation

$$I = I_0 \exp\left(\frac{eV}{\eta kT}\right)$$

where $I$ is the diode current, $I_0$ is the reverse saturation current, $V$ is the forward voltage, $e$ is the electronic charge, $k$ is Boltzmann constant, $T$ is the absolute temperature and $\eta$ is the ideality factor.

When the diode current is kept constant, the forward voltage decreases with increase in temperature. The reverse saturation current varies with temperature as

$$I_0 = KT^m \exp\left(-\frac{eV_0}{\eta kT}\right)$$

where $V_0$ represents the band gap energy of the semiconductor and $K, m$ are constants.

After mathematical simplification, the band gap energy is obtained as

$$V_0 = V - T\left[\frac{dV}{dT} + \frac{\eta mk}{e}\right]$$

Thus, by plotting a graph between temperature and forward voltage and calculating the slope $\frac{dV}{dT}$, the band gap energy of the semiconductor material can be determined.

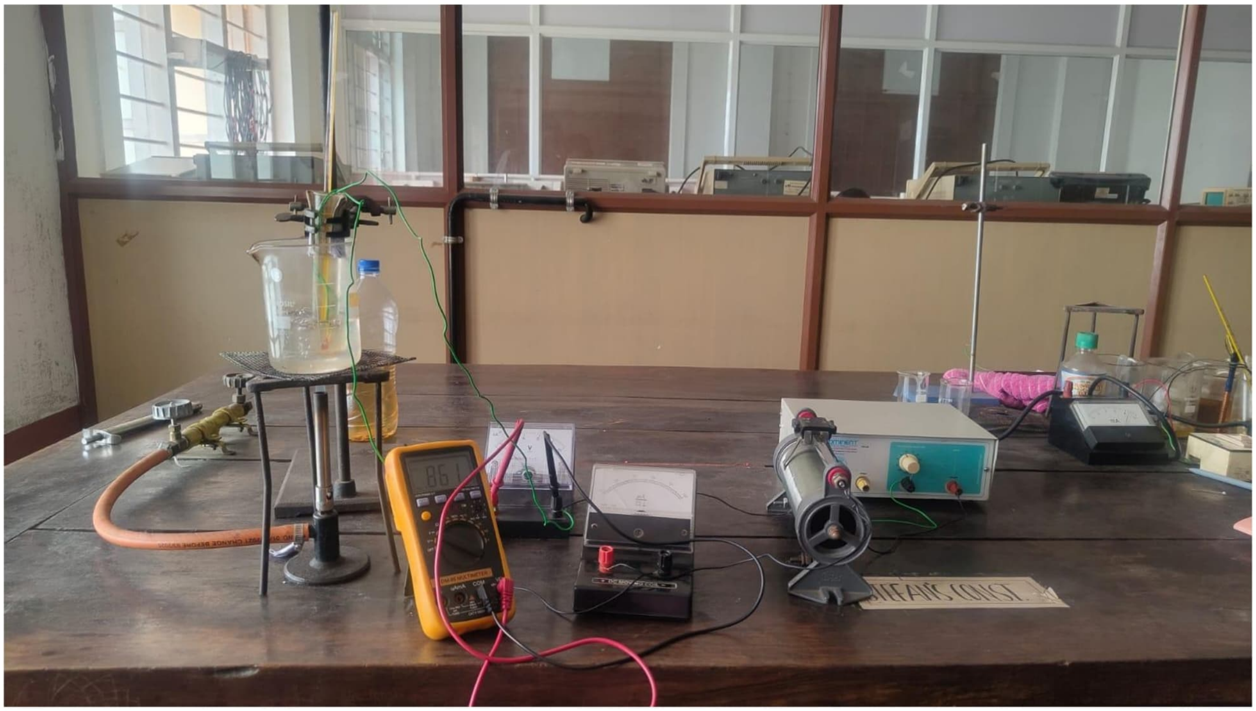

Fig 2.2 Experimental setup

## 2.2 OBSERVATION

**a) Silicone Diode**

Voltage of the cell = 6V

| Temperature(K) | Voltage(V) | | | |
|---|---|---|---|---|
| | I = 10mA | I = 30mA | I = 50mA | I = 70mA |
| 313 | 0.692 | 0.744 | 0.772 | 0.795 |
| 318 | 0.685 | 0.736 | 0.763 | 0.783 |
| 323 | 0.678 | 0.729 | 0.756 | 0.776 |
| 328 | 0.672 | 0.722 | 0.748 | 0.769 |
| 333 | 0.667 | 0.715 | 0.742 | 0.763 |
| 338 | 0.66 | 0.709 | 0.735 | 0.755 |
| 343 | 0.654 | 0.702 | 0.728 | 0.749 |
| 348 | 0.643 | 0.695 | 0.721 | 0.742 |
| 353 | 0.636 | 0.687 | 0.715 | 0.736 |
| 358 | 0.629 | 0.68 | 0.708 | 0.729 |
| 363 | 0.627 | 0.675 | 0.702 | 0.724 |
| 368 | 0.619 | 0.67 | 0.698 | 0.72 |

Fig 2.3

**Graphs**

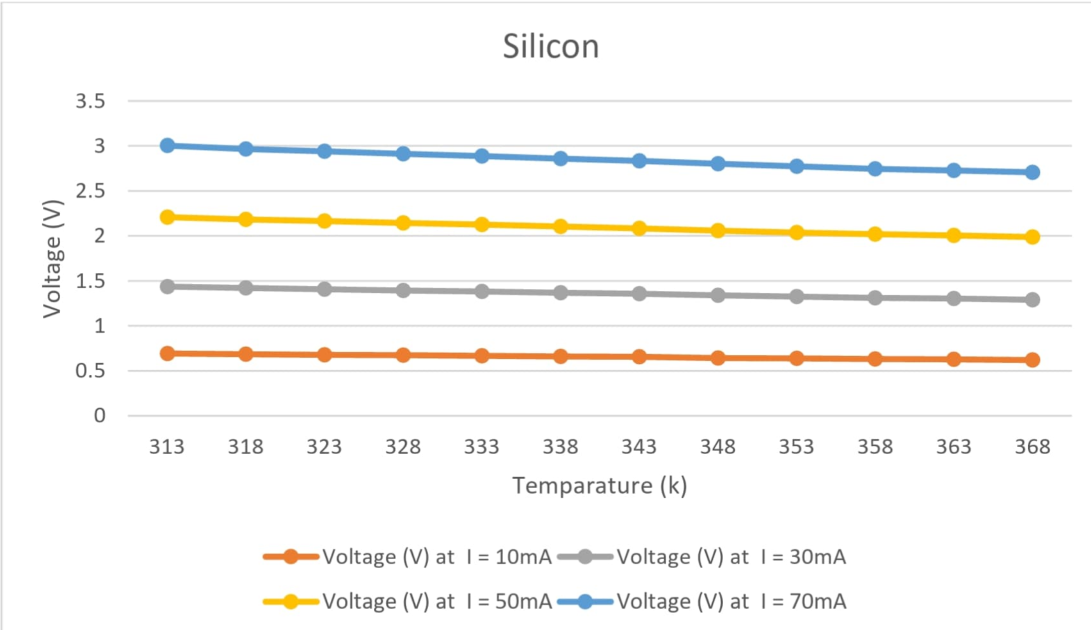


Fig 2.4 Temperature vs Voltage graph of Silicon diode

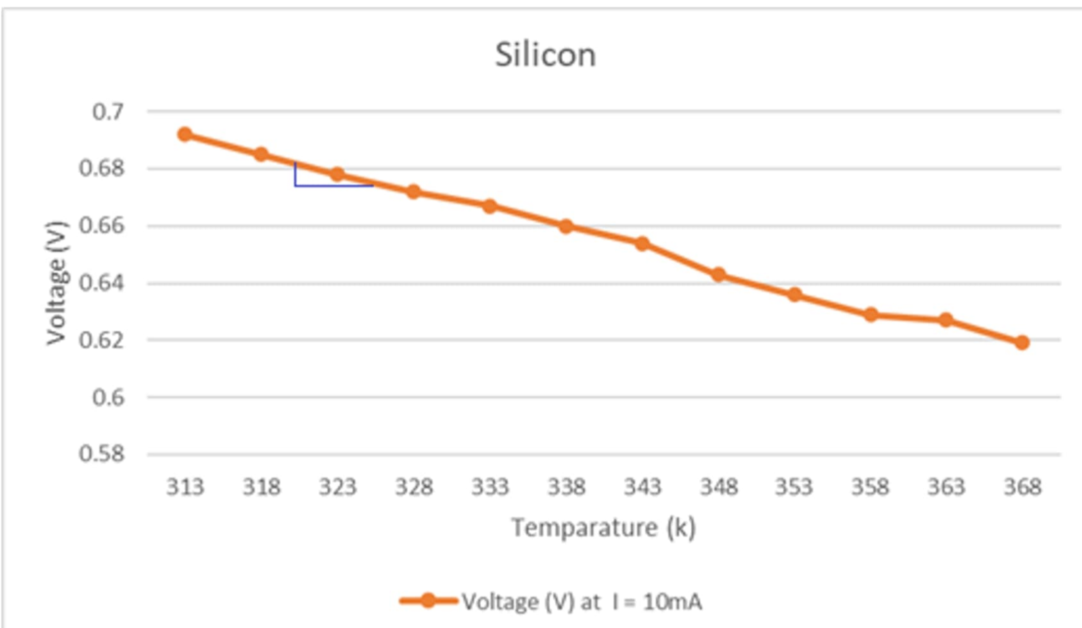


Fig 2.6 Slope of Temperature vs Voltage graph of Silicon for 10mA

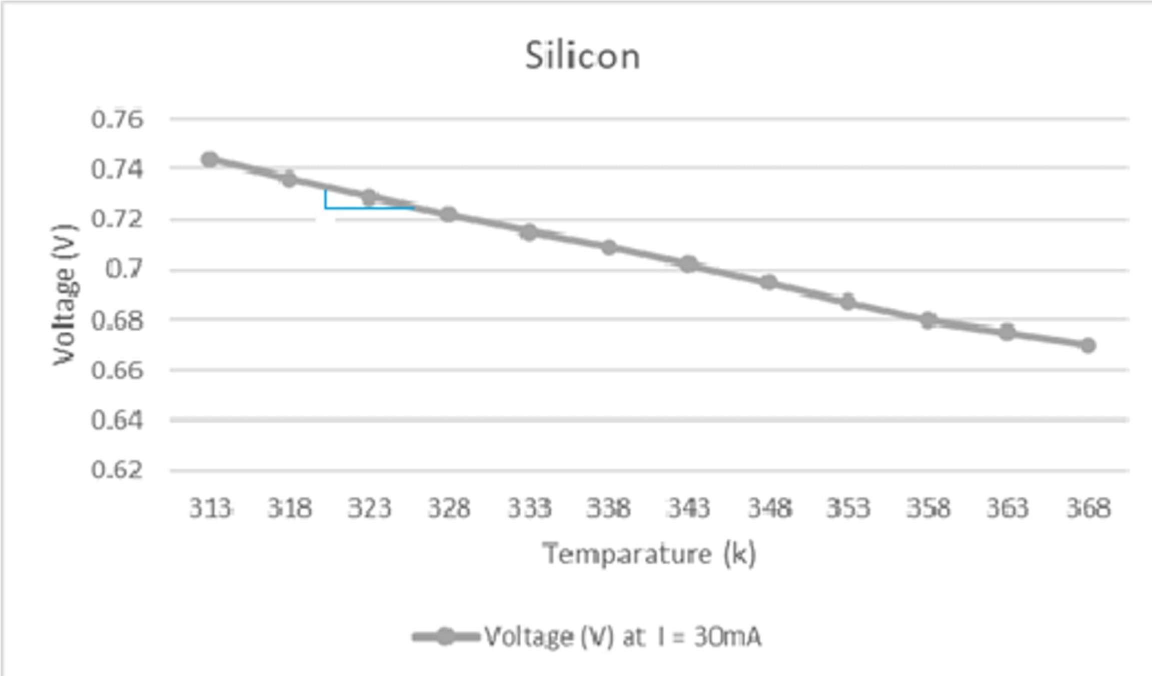


Fig 2.5 Slope of Temperature vs Voltage graph of Silicon for 30mA

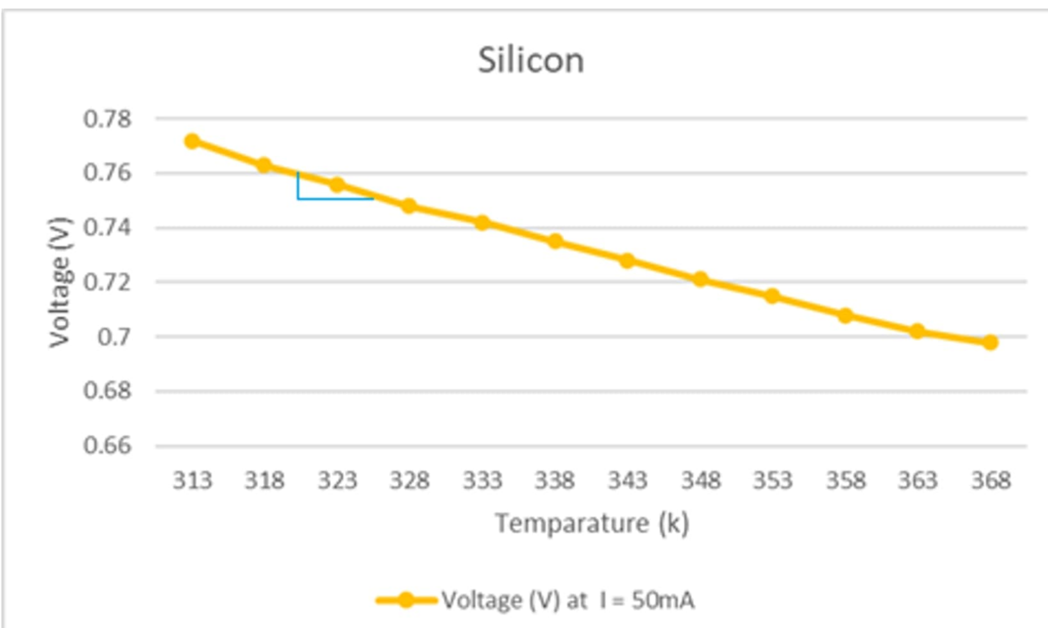


Fig 2.7 Slope of Temperature vs Voltage graph of Silicon for 50mA

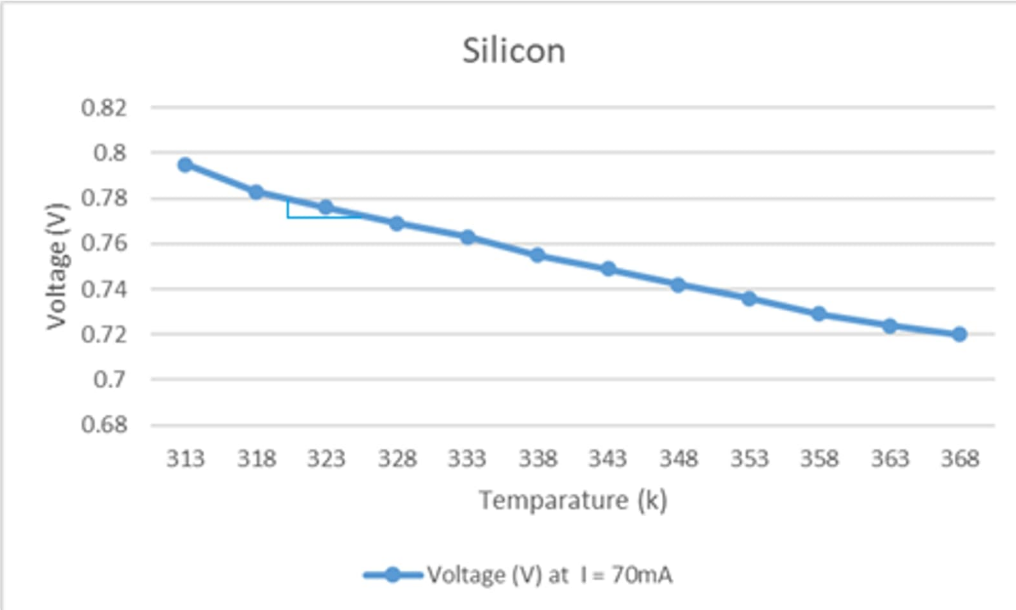


Fig 2.8 Slope of Temperature vs Voltage graph of Silicon for 70mA

**From graph**

| Current (mA) | Voltage (V) | Temperature (kelvin) | $dV$ (V) | $dT$ (K) | $-\frac{dV}{dT}$ (V/K) | Band Gap Energy, $V_{g0}$ (eV) |
|---|---|---|---|---|---|---|
| 70 | 0.776 | 323 | -6 $\times 10^{-3}$ | 5 | -1.2 $\times 10^{-3}$ | 1.0802 |
| 50 | 0.756 | 323 | -7 $\times 10^{-3}$ | 5 | -1.4 $\times 10^{-3}$ | 1.1248 |
| 30 | 0.729 | 323 | -8 $\times 10^{-3}$ | 5 | -1.6 $\times 10^{-3}$ | 1.1624 |
| 10 | 0.678 | 323 | -7 $\times 10^{-3}$ | 5 | -1.4 $\times 10^{-3}$ | 1.0468 |

Fig 2.9

**Substitution & Calculations**

Band gap energy,

$$V_{g0} = V - T\left[\frac{dV}{dT} + \frac{nmk}{e}\right]$$

Where,

n = 2

m = 1.5 (for silicon diode)

$$\frac{nmk}{e} = \frac{2 \times 1.5 \times 1.38 \times 10^{-23}}{1.6 \times 10^{-19}} = 2.58 \times 10^{-4}$$

Now,

$$V_{g0} = V - T\left[\frac{dV}{dT} + \frac{nmk}{e}\right]$$

$$= 0.776 - 323[(-1.2 \times 10^{-3}) + (2.58 \times 10^{-4})]$$

$$= 1.0802 \text{ eV}$$

Mean Bandgap energy = **1.10355 eV** $(V_{g0})$

Theoretical energy gap = **1.1 eV** $(V_g)$

$$\% \text{ of error} = \left|\frac{1.1 - 1.10355}{1.1}\right| \times 100$$

$$= 0.32\%$$

## 2.3 OBSERVATION

**b) Germanium Diode**

Voltage of the cell = 6V

| Temperature(K) | Voltage (V) | | | |
|---|---|---|---|---|
| | I = 1mA | I = 3mA | I = 5mA | I = 7mA |
| 313 | 0.153 | 0.196 | 0.218 | 0.234 |
| 318 | 0.141 | 0.19 | 0.206 | 0.226 |
| 323 | 0.135 | 0.179 | 0.195 | 0.217 |
| 328 | 0.126 | 0.168 | 0.186 | 0.206 |
| 333 | 0.12 | 0.157 | 0.177 | 0.195 |
| 338 | 0.108 | 0.148 | 0.17 | 0.183 |
| 343 | 0.1 | 0.14 | 0.155 | 0.173 |
| 348 | 0.094 | 0.126 | 0.146 | 0.167 |
| 353 | 0.084 | 0.12 | 0.138 | 0.156 |
| 358 | 0.072 | 0.108 | 0.127 | 0.145 |
| 363 | 0.064 | 0.105 | 0.123 | 0.135 |
| 368 | 0.052 | 0.091 | 0.113 | 0.125 |

Fig 2.10

**Graphs**

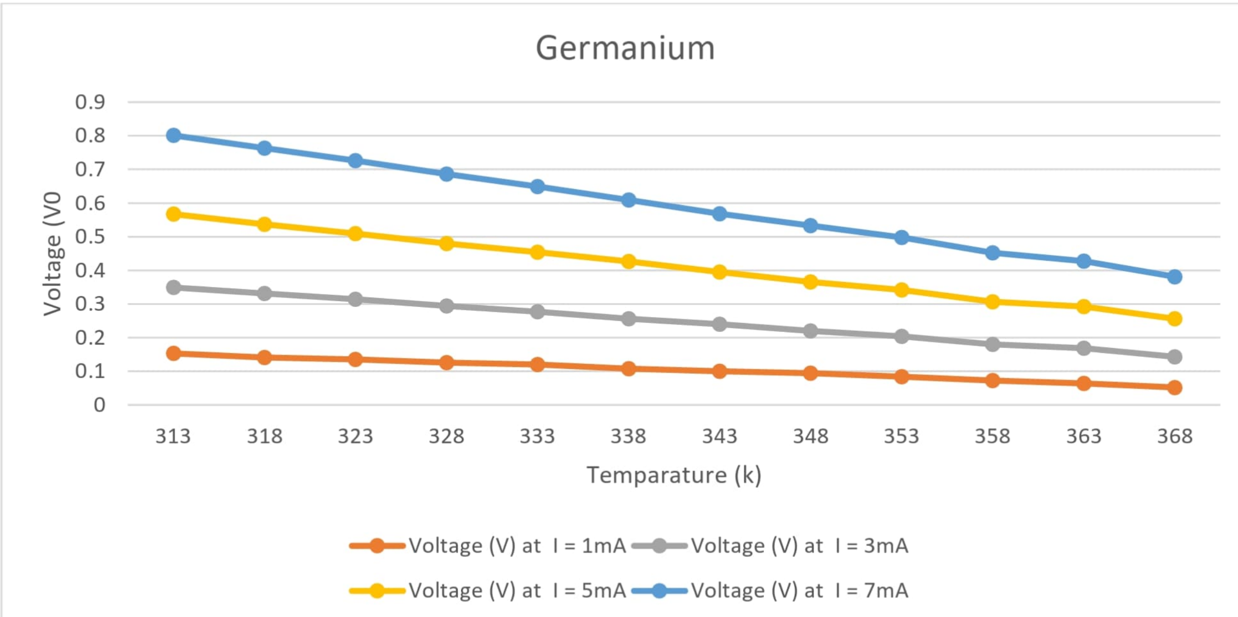


Fig 2.11 Temperature vs Voltage graph of Germanium diode

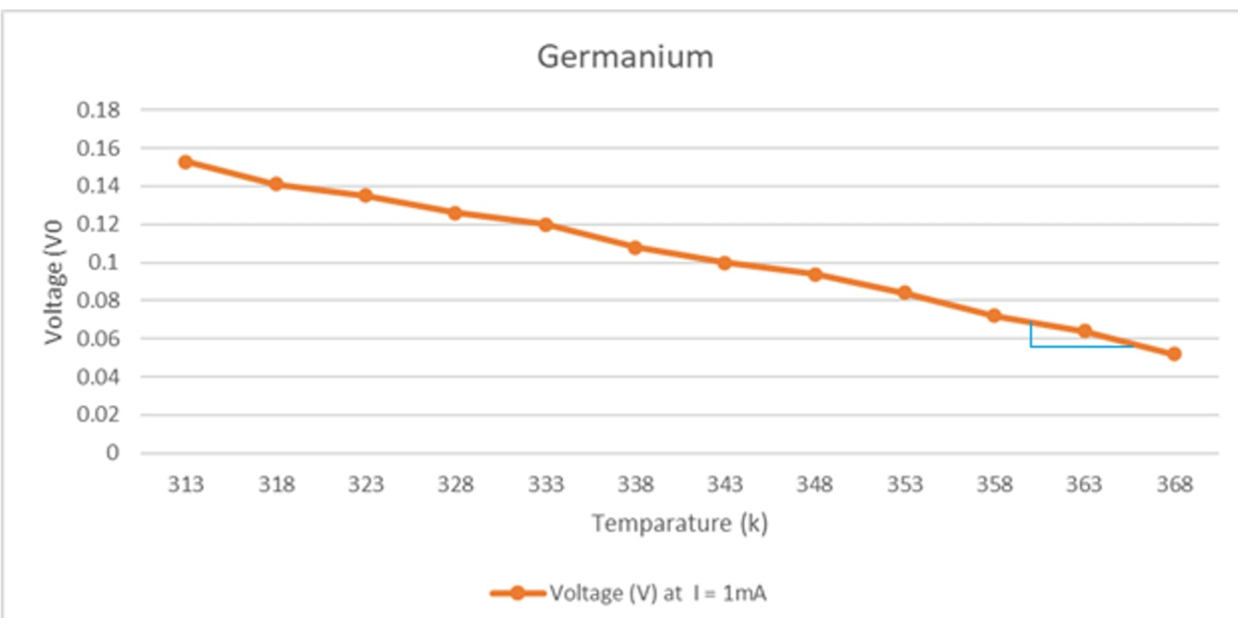


Fig 2.12 Slope of Temperature vs Voltage graph of Germanium for 1mA

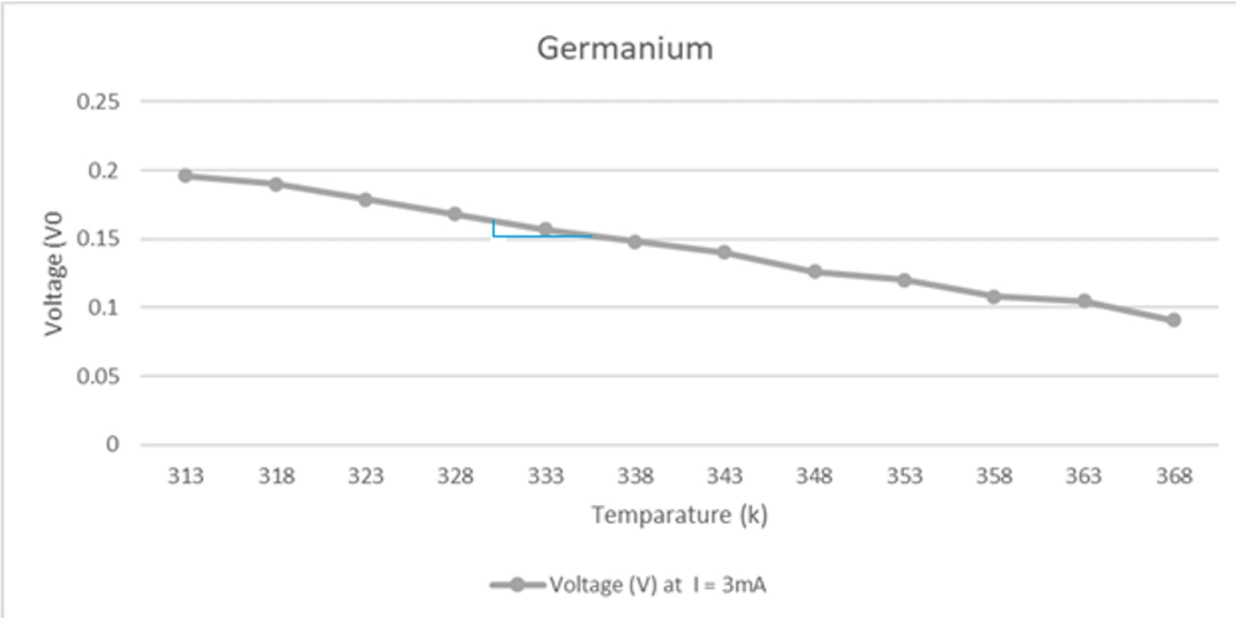


Fig 2.13 Slope of Temperature vs Voltage graph of Germanium for 3mA

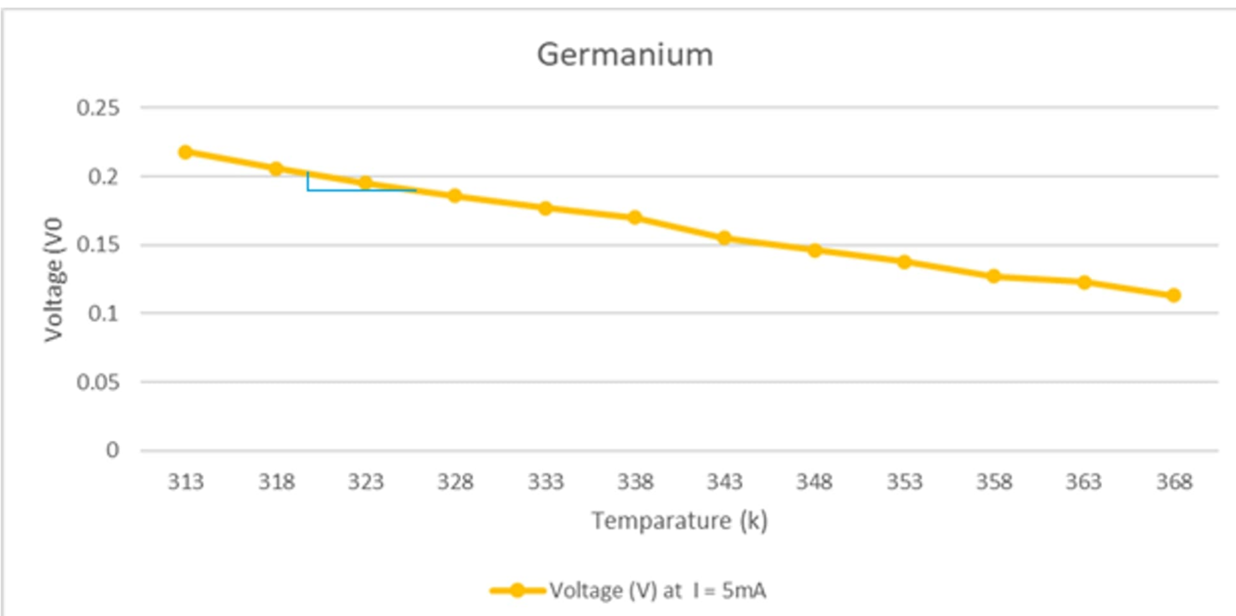


Fig 2.14 Slope of Temperature vs Voltage graph of Germanium for 5mA

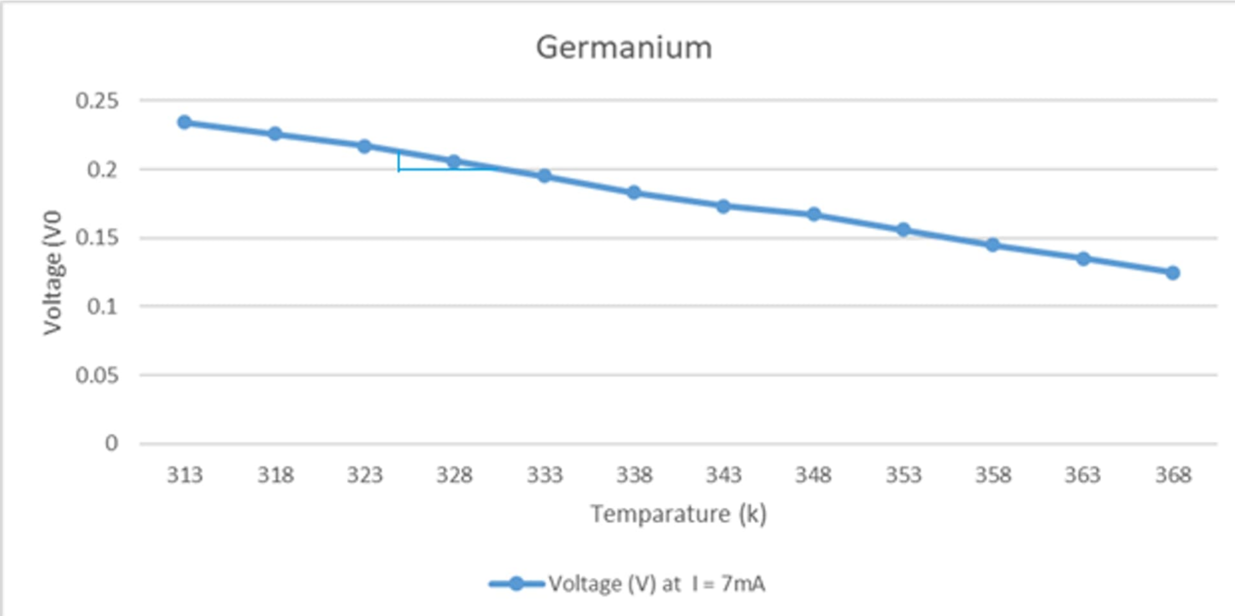


Fig 2.15 Slope of Temperature vs Voltage graph of Germanium for 7mA

**From graph**

| Current (mA) | Voltage (V) | Temperature (kelvin) | $dV$ (V) | $dT$ (K) | $-\frac{dV}{dT}$ (V/K) | Band Gap Energy, $V_{g0}$ (eV) |
|---|---|---|---|---|---|---|
| 7 | 0.206 | 328 | -0.0116 | 5 | -2.32$\times 10^{-3}$ | 0.718 |
| 5 | 0.195 | 323 | -0.012 | 5 | -2.4 $\times 10^{-3}$ | 0.733 |
| 3 | 0.157 | 333 | -0.0117 | 5 | -2.34 $\times 10^{-3}$ | 0.7357 |
| 1 | 0.064 | 363 | -0.01167 | 5 | -2.334$\times 10^{-3}$ | 0.7985 |

Fig 2.16

**Substitution & Calculations**

Band gap energy,

$$V_{g0} = V - T\left[\frac{dV}{dT} + \frac{nmk}{e}\right]$$

Where,

n = 1

m = 1.5 (for germanium diode)

$$\frac{nmk}{e} = \frac{1 \times 1.5 \times 1.38 \times 10^{-23}}{1.6 \times 10^{-19}} = 1.29375 \times 10^{-4}$$

Now,

$$V_{g0} = V - T\left[\frac{dV}{dT} + \frac{nmk}{e}\right]$$

$$= 0.206 - 328[(-2.32 \times 10^{-3}) + (1.29375 \times 10^{-4})]$$

$$= 0.718 \text{ eV}$$

Mean Bandgap energy = **0.7463 eV** $(V_{g0})$

Theoretical energy gap = **0.72 eV** $(V_g)$

$$\% \text{ of error} = \left|\frac{0.12 - 0.7463}{0.72}\right| \times 100$$

$$= 3.65\%$$

The experiment to determine the band energy gap of silicon and germanium diodes was conducted successfully.

Band energy gap of silicon = 1.10355eV
Band energy gap of germanium = 0.7463eV

**The results were found to be nearer to the standard values which are 0.72 eV and 1.14 eV for silicon and germanium respectively**.

# Chapter 3
# CONCLUSION

In this experiment, the band gap energy of germanium and silicon diodes was successfully determined by studying the temperature dependence of the forward voltage under constant current conditions. As the temperature of the diode increased, a systematic decrease in the forward voltage was observed, which is consistent with the theoretical behavior of p–n junction diodes. The use of a regulated DC power supply and a rheostat ensured that the forward current remained constant throughout the experiment, thereby improving the accuracy and reliability of the measurements.

The water bath arrangement provided uniform and gradual heating of the diode, allowing the junction temperature to closely follow the measured bath temperature. By plotting the forward voltage as a function of temperature and determining the slope of the resulting graph, the band gap energy of the semiconductor material was calculated using the appropriate relation. The experimentally obtained values of band gap energy were found to be in good agreement with standard reported values for germanium and silicon, within the limits of experimental error.

Thus, the experiment demonstrates a simple and effective method for determining the band gap energy of semiconductor diodes and highlights the strong dependence of the electrical properties of semiconductors on temperature. The results confirm the fundamental concepts of semiconductor physics and validate the theoretical relationship between temperature, forward voltage, and band gap energy.

## 3.1 Applications of Ge and Si diodes

Both germanium (Ge) and silicon (Si) diodes have a wide range of applications in modern electronics and photonic systems due to their distinct electrical and optical properties.

Germanium diodes are extensively used in photonic applications, particularly in optical communication systems. Most long-distance data transmission, including internet communication, is carried out through optical fibres made of transparent glass. Light in the near-infrared region is preferred for such transmission because it experiences minimal loss while propagating through glass.[9]

The band gap energy of germanium closely matches the energy of near-infrared photons. When near-infrared light is incident on a germanium diode, electrons are excited across the band gap, resulting in the generation of an electric current. Hence, germanium diodes are widely used as photodetectors in telecommunication applications.[8]

In addition, the operating principles of light-emitting and light-detecting devices are closely related. Therefore, germanium diodes can also be employed in the fabrication of lasers that emit near-infrared radiation, which is suitable for transmitting data over long distances.

Germanium diodes also play an important role in solar cell technology. Solar cells are efficient only over limited wavelength ranges. To improve efficiency, multiple solar cells with different band gaps are stacked together to absorb ultraviolet, visible, and infrared radiation. In such multi-junction solar cells, germanium diodes are used to absorb infrared radiation and convert it into electrical energy.[10]

Silicon diodes, especially silicon rectifier diodes, are widely used in electronic circuits. They are commonly employed in radios, computers, alternating current to direct current (AC/DC) power supplies, and also function as temperature and radiation sensors, along with many other practical applications.

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