Semiconductors are one of the technologically most important class of materials. According to the band theory of solids, which is an outcome of quantum mechanics, semiconductors possess a band gap, i.e., there is a range of forbidden energy values for the electrons and holes. In this experiment, we will calculate the energy band gap in the intrinsic region and the temperature dependence of the majority carrier mobility in the extrinsic region.

**KEYWORDS**
Semiconductor · intrinsic conduction · extrinsic conduction · energy band gap · conduction band · valence band · conductivity · resistivity · mobility · unijunction transistor · temperature control · low temperature physics

**Approximate Performance Time** 2 weeks.

1 **Objectives**

In this experiment, we will,

1. understand how conductivity in semiconductors depends on carrier concentration and mobility, and how these depend on temperature,

2. distinguish between intrinsic and extrinsic temperature regimes and identify the applicable temperature range from an examination of measured data,

3. appreciate and utilize the advantages of the four-probe resistance measurement technique,

4. calculate the energy band gap for doped Si and pure Ge,
5. calculate the temperature dependent coefficient $\alpha$ of the majority carriers, 
6. through experimental realizations, appreciate a physical understanding of the band gap structure of semiconductors.

References


2 Theoretical introduction

2.1 Semiconductors

The available energies for electrons help us to differentiate between insulators, conductors and semiconductors. In free atoms, discrete energy levels are present, but in solid materials (such as insulators, semiconductors and conductors) the available energy states are so close to one another that they form bands. The band gap is an energy range where no electronic states are present. In insulators, the valence band is separated from the conduction band by a large gap while in good conductors such as metals the valence band overlaps the conduction band. Semiconductors have a small band gap between the valence and conduction bands that allows thermal excitation of electrons from the valence to conduction band. The overall picture is shown in Figure (1).
The Fermi level is an important consequence of band theory, the highest occupied quantum state of electrons at absolute zero temperature. The position of the Fermi level relative to the conduction band is an important parameter that contributes to determine the electrical properties of a particular material. The position of the Fermi level position is also indicated in Figure (1).

For a semiconductor, the electrical resistivity lies between a conductor and an insulator, i.e., in the range of $10^3$ Siemens/cm to $10^{-8}$ S/cm. An externally applied electrical field may change the semiconductor’s resistivity. In conductors, current is carried by electrons, whereas in semiconductors, current is carried by the flow of electrons or positively charged holes.

**Q 1.** Explain (or sketch) the temperature dependence of resistance for metals and semiconductors. Why does the resistance of a semiconductor decrease with increasing temperature?

### 2.2 Intrinsic and extrinsic semiconductors

An intrinsic semiconductor is a pure semiconductor having no impurities. In an intrinsic semiconductor, the numbers of excited electrons and holes are equal, i.e., $n = p$ as shown in Figure (2a). An extrinsic semiconductor on the other hand is the one in which doping has been introduced, thus changing the relative number and type of free charge carriers.

An extrinsic semiconductor, in which conduction electrons are the majority carriers is called an n-type semiconductor and its band diagram is illustrated in Figure (2b) and the one in which the holes are the majority charge carriers is called a p-type semiconductor and is indicated in Figure (2c). In extrinsic semiconductors, the dopant concentration $N_d$ is much larger than the thermally generated electron-hole pairs $n_i$ and is temperature independent at room temperature.

**Q 2.** Why is doping introduced in semiconductors? How does it effect the
Figure 2: Energy band diagrams for (a) intrinsic, (b) n-type, and (c) p-type semiconductors. \( E_f \) is the Fermi energy level, and the letters \( i, n, p \) indicate intrinsic, n and p-type materials. \( E_c \) and \( E_v \) are the edges of the conduction and valence bands.

... conductivity of a semiconductor?

### 2.3 The ubiquitous role of semiconductor devices

Semiconductor devices are the foundation of the electronic industry. Most of these devices can be constructed from a set of building blocks. The first building block is the metal-semiconductor interface as shown in Figure (3a). This interface can be used as a rectifying contact, i.e., the device allows current in one direction as in ohmic contact. By using the rectifying contact as a gate, we can form a MESFET (metal-semiconductor field-effect transistor), an important microwave device.

Figure 3: Basic device building blocks of (a) metal-semiconductor interface, (b) p-n junction, (c) heterojunction interface, (d) metal-oxide-semiconductor structure.

The second building block is the p-n junction, a junction of p-type and n-type materials indicated in Figure (3b). The p-n junction is the key compound for numerous semiconductor devices. By combining two p-n junctions, we can form the p-n-p bipolar transistor, and combining three p-n junctions to form a p-n-p-n structure, a switching device called a thyristor can be formed.
The third important building block is the heterojunction interface depicted in Figure (3c). It is formed between two dissimilar semiconductors, for example gallium arsenide (GaAs) and aluminium arsenide (AlAs) and is used in band gap engineering. Band gap engineering is a useful technique to design new semiconductor devices and materials. Heterojunctions and molecular beam epitaxy (MBE) are the most important techniques in which required band diagrams are devised by continuous band-gap variations. A new generation of devices, ranging from solid-state photomultipliers to resonant tunneling transistors and spin polarized electron sources, is the result of this technique.

The fourth building block is the metal-oxide-semiconductor (MOS) structure. It is a combination of a metal-oxide and an oxide-semiconductor interface indicated as in Figure (3d). The MOS structure is used as a gate and the two semiconductor-metal oxide junctions are the source and drain; the result is the MOSFET (MOS field-effect transistor). The MOSFET is the most important component of modern integrated circuits, enabling the integration of millions of devices per chip.

### 2.4 Conduction in intrinsic semiconductors

The process in which thermally or optically excited electrons contribute to the conduction is called intrinsic conduction. In the absence of photonic excitation, intrinsic conduction takes place at temperatures above 0 K as sufficient thermal agitation is required to transfer electrons from the valence band to the conduction band [3].

The total electrical conductivity is the sum of the conductivities of the valence and conduction band carriers, which are holes and electrons, respectively. It can be expressed as

$$\sigma = n_e q_e \mu_e + n_h q_h \mu_h;$$

(1)

where $n_e$, $q_e$, and $\mu_e$ are the electron’s concentration, charge and mobility, and $n_h$, $q_h$, and $\mu_h$ are the hole’s concentration, charge and mobility, respectively.

The mobility is a quantity that directly relates the drift velocity $v_d$ of electrons to the applied electric field $E$ across the material, i.e.,

$$v_d = \mu E.$$  

(2)

In the intrinsic region the number of electrons is equal to the number of holes, so Equation (1) implies that,

$$\sigma = n_e q_e (\mu_e + \mu_h).$$

(3)

The electron density (electrons/volume) in the conduction band is obtained by integrating $g(E)f(E)dE$ (density of states x probability of occupancy of states) from the bottom to top of the conduction band,

$$n_e = \int_{E_c}^{\infty} g(E)f(E)dE.$$ 

(4)
Figure 4: Band gap structure of an intrinsic semiconductor. (a) Schematic band diagram, (b) density of states $g(E)$, (c) Fermi distribution function $f(E)$, (d) carrier concentration $n_e(E)$ and $n_h(E)$. $E_c$, $E_v$ and $E_f$ represent the conduction band energy, valence band energy and Fermi energy level, respectively.

There are two important quantities introduced in the above expression: $g(E)$ is the number of states per unit energy per unit volume known as the density of states. The density of states in the conduction band can be derived from first principle and is given by,

$$ g(E) = \frac{(\sqrt{2})m^*}{\pi^2\hbar^3} \left( E - E_c \right)^{1/2}. \quad (5) $$

The function $f(E)$ is the probability of an electronic state of energy $E$ being occupied by an electron, and is given by the Fermi-Dirac distribution function,

$$ f(E) = \frac{1}{1 + \exp \left( \frac{(E - E_f)}{k_B T} \right)}. \quad (6) $$

The profiles of $g(E)$ and $f(E)$ are depicted in Figure (4). If we suppose that $E - E_f \gg k_B T$, then Equation (6) can be approximated as,

$$ f(E) \approx \exp \left( -\frac{E - E_f}{k_B T} \right). \quad (7) $$

Thus, we can replace the Fermi-Dirac distribution by the Boltzmann distribution under the assumption that the number of electrons in the conduction band is far less than the number of available states in this band ($E - E_f$ is large as compared to $k_B T$).
The number of mobile charge carriers (i.e., $n_e$ in the conduction band and $n_h$ in the valence band) can be obtained by performing the integration in Equation (4), and is given by,

$$n_e = N_c \exp \left( \frac{-(E_c - E_f)}{k_B T} \right), \quad (8)$$

and

$$n_h = N_v \exp \left( \frac{-(E_f - E_v)}{k_B T} \right), \quad (9)$$

where

$$N_c = 2 \left( \frac{m^*_e k_B T}{2 \pi \hbar^2} \right)^{3/2}, \quad (10)$$

$$N_v = 2 \left( \frac{m^*_h k_B T}{2 \pi \hbar^2} \right)^{3/2}. \quad (11)$$

$N_c$ and $N_v$ are the effective density of states for the edges of conduction and valence bands, respectively [1].

**Q 3.** Derive the expressions (10) and (11) for the effective density of states for the conduction band, $N_c$, and for the valence band, $N_v$.

The terms $m^*_e$ and $m^*_h$ are the effective masses of electrons and holes respectively, $k_B$ is Boltzmann’s constant, $T$ is the absolute temperature, and $\hbar$ is Plank’s constant.

**Q 4.** What do you understand by the term ‘effective mass’ of an electron? How is it different from the conventional electron mass?

In an intrinsic semiconductor, the number of electrons is equal to the number of holes, so the charge carrier concentration is given by,

$$n_i = \sqrt{n_e n_h} = \left( N_c N_v \right)^{1/2} \exp \left( \frac{-E_g}{2k_B T} \right), \quad (12)$$

where, $E_g = E_c - E_v$ is the energy band gap. The term $(N_c N_v)^{1/2}$ in Equation (12) depends on the band structure of the semiconductor. It will be shown later that for intrinsic behavior, $n_i$ varies as some power of $T$, so Equation (12) can be written as,

$$n_i = C T^{3/2} \exp \left( \frac{-E_g}{2k_B T} \right), \quad (13)$$

where, $C$ is some constant. Substituting the expression (13) into (3) yield the following expression for the intrinsic conductivity,

$$\sigma = C T^{3/2} q \left( \mu_e + \mu_h \right) \exp \left( \frac{-E_g}{2k_B T} \right). \quad (14)$$
Equation (14) shows that the electrical conductivity of intrinsic semiconductors decreases exponentially with increasing temperature.

Q 5. Derive Equation (12).

Q 6. Using Equation (14), explain how the conductivity of a semiconductor changes at high temperatures.

Q 7. What is the difference between Fermi-Dirac and Boltzmann distributions? Which distribution is being followed by the majority carriers in semiconductors?

Q 8. Given that the effective masses of electrons and holes in Si are approximately 1.08 $m_e$ and 0.60 $m_e$, respectively, and the electron and hole drift mobilities at room temperature are 1350 and 450 cm$^2$V$^{-1}$s$^{-1}$, respectively, and the energy band gap value is 1.10 eV, calculate the intrinsic concentration and intrinsic resistivity of Si [2].

2.5 Conduction in extrinsic semiconductors

In doped semiconductors, the dopant concentrations ($n_e \simeq N_d$ for n-type and $n_h \simeq N_a$ for p-type doping) at room temperatures are greater than the thermally generated intrinsic carrier concentrations $n_i$. The conductivity depends on the carrier concentrations and the mobility. So to determine the temperature dependent conductivities, one has to consider, separately, how temperature affects both the carrier concentration and the mobility [2].

2.5.1 Temperature dependence of charge carrier concentration

Consider an n-type semiconductor with dopant carrier concentration ($N_d$) of arsenic atom (As). The As atoms introduce a donor energy level $E_d$, that is located at a gap $\Delta E$ below $E_c$. The ionization of As atoms leads to electrons jumping across $\Delta E$ into the conduction band. The scenario is depicted in Figure (5).

1. Low temperature regime  At very low temperatures, conductivity is almost zero because donor atoms are not ionized due to the small thermal vibrational energy. As temperature slightly increases, the donor atoms get ionized and move to the conduction band as shown in Figure (5a). The electron concentration at such low temperature is given by,

$$n_e = \left(\frac{1}{2}N_cN_d\right)^{1/2} \exp\left(-\frac{\Delta E}{2k_BT}\right), \quad (15)$$

where, $\Delta E = E_c - E_d$ is the energy difference from donor energy level to bottom of conduction band. The low temperature regime is also called the ionization regime.

Q 9. What are the similarities and differences between Equations (12) and (15)?
Figure 5: Electron concentration of an n-type semiconductor in (a) low temperature regime, (b) medium temperature regime, (c) high temperature regime. $E_f$ and $E_d$ are the Fermi and donor atom energy levels, respectively.

Figure 6: The temperature dependence of the electron concentration in an n-type semiconductor, showing the ionization, extrinsic and intrinsic regimes. Note that the horizontal axis is $1/T$ instead of $T$.

Q 10. Explore the origin of the extra factor of one half in Equation (15).

2. Medium temperature regime In this temperature range, the process of ionization has continued to the extreme that all donor atoms have been ionized as shown in Figure (5b). This temperature range is often called the extrinsic range and is also indicated in Figure (6). Since the electrical conductivity depends on carrier concentration $n$ and mobility $\mu$,

$$\sigma = qnm,$$  \hspace{1cm} (16)

and $n = N_d \simeq \text{constant}$ in the extrinsic region, the conductivity is solely determined by the temperature variation of the mobility. The mobility is proportional to some power $\alpha$ of the temperature,

$$\sigma = T^\alpha.$$  \hspace{1cm} (17)
A plot of $\log(\frac{1}{T})$ versus $\log(\frac{1}{T})$ will give the value of temperature dependent coefficient $\alpha$. Extrinsic semiconductors are almost always operated in this region.

3. **High temperature regime** As temperature increases, the electron concentration $n_i$ due to thermal agitations across the band gap is much larger than the dopant concentrations $N_d$. In this regime, excitations from valence band to conduction band are also possible due to which hole concentration becomes equal to the electron concentration $n_h = n_e$ depicted in Figure (5c). This range is referred as the intrinsic range and is shown in Figure (6). This is the regime where the purpose of doping is defeated and the material behaves as an intrinsic semiconductor. In this temperature range, the slope of $\log(n)$ versus $1/T$ yields $(-E_g/2k_B)$.

**Q 11.** A silicon ignot is doped with $10^{16}$ As atoms/cm$^3$. Find the carrier concentrations and the Fermi level at room temperature (300 K). Also draw band diagram showing the Fermi level $E_f$ and intrinsic Fermi level $E_i$ [4].

**Q 12.** An n-type Si sample has been doped with $10^{15}$ phosphorus atoms cm$^{-3}$. The donor level for P in Si is 0.045 eV below the conduction band edge energy [2].

(a) What would be the temperature above which the sample behaves intrinsically?
(b) What is the lowest temperature above which most of the donors are ionized?

### 2.5.2 Temperature and impurity dependence of drift mobility

Now that we have established how temperature affects carrier concentration, we turn attention to the mobility. Drift mobility $\mu$ determines the average velocity $v_d$ in the presence of an applied external field. The variation with temperature follows two distinct regions.

1. **High temperature region** Let suppose an electron in the conduction ($C_B$) or valence band ($V_B$) suffers collisions from a scattering ion ($As^+$). These scattering events depend on how strongly the ions vibrate, the amplitude depends on the temperature $T$. The mean free time $\tau$ between scattering events, is given by,

$$\tau = \frac{1}{Sv_{th}N_s}. \quad (18)$$

According to the Drude model [2], the drift mobility is,

$$\mu = \frac{e\tau}{m^*_e}. \quad (19)$$

In Equation (18), $S$ is the cross-sectional area of the scatterer shown in Figure (7a), $v_{th}$ is the mean speed of the electrons, called the thermal velocity and $N_s$ is the number of scatterers per unit volume. Now both the scatterer
amplitude $a$ and the thermal velocity of the electron $v_{th}$ is temperature dependent. We unveil these dependences, one by one. The scatterer amplitude increases with temperature as $a^2 \propto T$. Now an electron in the conduction band has only kinetic energy and the mean kinetic energy per electron in the conduction band is $\frac{3}{2}k_BT$. Applying kinetic molecular theory to the gas of electrons in the conduction band, we obtain,

$$\frac{1}{2}m_e v_{th}^2 = \frac{3}{2}k_BT,$$

(20)

implying $v_{th} \propto T^{1/2}$. Using the above derived temperature dependences of $v_{th}$, the scatterer mean time $\tau_L$ due to lattice vibrations will become,

$$\tau_L = \frac{1}{Sv_{th}} \propto \frac{1}{T^{3/2}} = T^{-3/2},$$

(21)

resulting in lattice vibration scattering limited mobility, $\mu_L$,

$$\mu_L \propto T^{-3/2}.$$  

(22)

Clearly as the temperature goes up, $\mu_L$ decreases.

2. **Low temperature region** At low temperatures, the scattering of electrons by thermal lattice vibrations is not strong enough. The electron scattering is performed by the electrostatic interaction with the ionized donor impurities. Let us consider a case in which an electron passes by an ionized donor impurity $\text{As}^+$. The deflection from the rectilinear path depends on the following factors,

- If the $K.E$ of the electron is larger than the $P.E$ of the ionized donor impurity ($\text{As}^+$) at a distance $r$ ($K.E > |P.E|$), then the electron will not feel the $P.E$ and will continue its course unhindered, unswayed.
If the $K.E < |P.E|$, then the coulombic interaction energy is strong enough to deflect the electron. The two cases are depicted in Figure (8).

- $K.E \approx |P.E|$ at $r = r_c$, the critical radius at which the electron is just scattered, leading to,

$$\frac{3}{2} k_B T = \frac{e^2}{4\pi \varepsilon_0 \varepsilon_r r_c^2},$$

(23)

from which one can deduce the critical radius,

$$r_c = \frac{e^2}{6\pi \varepsilon_0 \varepsilon_r kT}.$$  

(24)

Thus, the critical scattering radius $r_c$ also possesses the inverse temperature dependence and decreases as temperature increases. By adding the value of $r_c$ into scattering cross section, $S = \pi r_c^2$, one may infer that
$S \propto T^{-2}$. Therefore, the ionized impurity scattering limited mobility, $\mu_I$ comes out as replacing the same argument given before Equation (22)

$$\mu_I \propto \frac{T^{3/2}}{N_I}, \quad (25)$$

where $N_I$ is the ionized impurity concentration. Thus in the low temperature regime, $\mu_I$ decreases with increasing ionized impurity concentration.

The lattice limited and impurity limited regimes of the mobility are shown in Figure (9). It is observed from Equations (22), (25) and Figure (9) that the mobility has a divergent behavior with respect to temperature. At low temperature, mobility increases with increasing temperature, and starts decreasing as temperature increases in the high temperature regime.

**Q 13.** Calculate the temperature dependence of the mean free time $\tau$ between impurities and derive Equation (25).

### 2.6 Temperature dependence of conductivity

We have determined the temperature dependence of the carrier concentration and mobility for a doped semiconductor. Hence, the electrical conductivity in extrinsic semiconductors can be determined by combining the results of Figures (6) and (9), as shown in Figure (10).

![Figure 10: Combined effects of mobility and carrier concentration.](image)
3 The experiment

3.1 Overview of the experiment

In this experiment we will investigate the conductivity temperature variation of a semiconductor sample (the base region in the unijunction transistor UJT(2N2646) and pure germanium Ge). The conductivity is derived from the measured resistance while temperature is controlled by a controller and measured using a thermocouple.

The semiconductor sample is placed inside a sample cell. The sample cell is placed inside a flow cryostat which can be filled by liquid nitrogen. The cell is cooled by the cool vapor of N2. Alternatively, the cell can be heated to elevated temperatures by passing current through a heater wire wound around it. The flow cryostat is sketched in Figure (11a) highlighting the various components.

The resistance of the semiconductor sample is measured by the four-probe technique [5], [6]. A constant current is passed through the sample. The current is generated by a constant current source. The voltage drop across the sample is acquired by a four-probe circuit and facilitated by a Labview programme. To measure the temperature of the sample, a K-type thermocouple is placed inside the sample cell and the temperature control is achieved by a multi-zone controller.

The measured resistance at different temperatures yields the conductivity versus temperature behaviour of the semiconductor sample, from which the energy band gap $E_g$ and the temperature dependent coefficient of mobility $\alpha$ can be calculated.

3.2 Apparatus

The experiment involves the following major components.

1. cryostat
2. sample cell containing the sample and wound with heater wire
3. temperature controller
4. thermocouple
5. voltmeter with high input resistance
6. constant current source
7. power supply for the constant current source
8. solid state relay (SSR)
9. data acquisition system (DAQ)
Figure 11: Experimental setup: (a) cryostat with the sample cell, (b) circuitry of the temperature control setup, and (c) assembled view. \( I \) is the input constant current and \( V \) is the measured voltage.

10. supply of liquid nitrogen \( N_2 \).

Following some brief description of the above listed components.

### 3.2.1 Samples

The samples used for band gap measurements are pure Ge (donated by Dr. S. A. Siddiqi (Punjab University) and extremely expensive!) and the base of a unijunction transistor UJT (a lightly doped n-type material).

Pure Ge was powdered and pressed into a pellet of diameter \( d = 1.3 \) cm and thickness \( t = 0.65 \) cm. When used in Four probe technique, the distance between voltage wires was kept \( s = 0.25 \) cm. The sample was treated as a bulk material since the sample thickness is significantly larger than the spacing between voltage wires. The resistivity is measured from the following expression [5],

\[
\rho = 2\pi s \frac{V}{I},
\]

where \( I \) is the current applied to the sample from the constant current source and \( V \) is the voltage drop across the sample.
3.2.2 Cryostat

The cryostat, shown in Figure (12a) is a copper cylinder (4 inch in diameter, 12 inch long with one end closed), used to maintain cryogenic temperatures, and also able to withstand high temperatures. An insulating sheet is wrapped around the cylinder for reducing heat losses.

![Cryostat and Sample Cell](image)

Figure 12: (a) Cryostat. (b) Sample cell with heat sink.

3.2.3 Sample cell

For high temperature measurements, the semiconductor sample is slowly heated inside the sample cell wound with nichrome heater wire (Nichrom 37). It is essentially a copper pipe (20 mm diameter with one end closed). For low temperature measurement, a copper braid is attached to the bottom of the sample cell that serves as a heat sink, and is shown in Figure (12b). The heat sink ensures good thermal contact with liquid nitrogen. The sample cell is lowered into the cryostat for the measurements.

3.2.4 Thermocouple

A thermocouple is a temperature sensor used to measure the sample temperature. It is made up of two different metals with the metals at one end joined together. Whenever the junction of two metals is heated or cooled, voltage is produced that can be correlated with temperature through a calibration procedure. In this experiment, we use a K-type thermocouple, for which some details are given in Table (1). The thermocouple reading is fed into a multi-zone controller.
### Table 1: Some characteristics of the K-type thermocouple.

<table>
<thead>
<tr>
<th>characteristic</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>temperature range</td>
<td>−200 °C to 1250 °C</td>
</tr>
<tr>
<td>composition</td>
<td>Chromium-Aluminium</td>
</tr>
<tr>
<td>sensitivity</td>
<td>∼41 μV/°C</td>
</tr>
</tbody>
</table>

#### 3.2.5 Temperature controller

Our aim is to attain a stable temperature for the sample, for which a multi-zone controller (CN1504-TC from Omega Engineering) is used. It is a compact unit comprising four PID controllers, and is shown in Figure (13). Additionally, it is also equipped with an ON/OFF control [8]. A temperature profile is programmed into the controller to achieve a particular temperature for a certain duration of time. To obtain an understanding of the programming modes and a guide to constructing the profiles, refer to Appendix A or the datasheet of the controller [8].

![Temperature controller](image)

**Figure 13:** Temperature controller, (a) front view, (b) rear view.

The advantage of the temperature controller is that it possesses a “Proportional, Integrator, Derivative” (PID) controller. The PID controller calculates an error value as the difference between a measured process variable and a desired set point. For more details see Appendix B.

**Q 14.** Read Appendix A. Programme a profile in the temperature controller. Your starting point will be the room temperature, achieve 40°C in 1 min and keep the temperature fixed at 40°C for 10 minutes. Subsequently, migrate to 50°C in 1 min and keep the temperature fixed at 50°C for 10 minutes.

The purpose of the previous step is to familiarize you with the programming of the temperature controller. **This step must be completed and practised before the start of the experiment.**
3.2.6 Four-probe versus two-probe method

Resistance measurements are often taken by a two-probe method, that is depicted in the self-explanatory Figure (14a). The disadvantage of this method is that some voltage drop occurs across the lead resistance, hence the voltage measured by the meter \( V_m \) will be different from the actual voltage \( V_r \) across the test resistance. So when applied to low test resistances \( R_x < 100 \Omega \), the voltage drop due to current \( I_{lead} \) flowing through the lead resistance can no longer be neglected, leading to significant error in the results.

In order to remove the error of contact resistances, a four-probe method is preferred, specially when \( R_x \) is small. In this method, current is passed through the test resistance using one set of leads and voltage drop is measured through another set, as depicted in Figure (14b). Although small current may flow through the voltage measuring leads but that would be much smaller, owing to the extremely large input resistance of the voltmeter, and can generally be neglected for all practical purposes [6].

3.2.7 Constant current source and voltmeter

The resistance of the semiconductor sample is measured by passing constant current through the sample and measuring the voltage drop generated across it. In order to provide stable current to the sample, a constant current generator is required and is shown in Figure (14c). **You are required to construct this constant current source.** The sample resistance \( R_x \) is calculated from the output voltage as,

\[
R_x = \frac{V_o}{I},
\]

\[
= R \left( \frac{V_o}{V_z} \right),
\]

where \( V_z \) is the Zener voltage and \( V_o \) is the output voltage that will ultimately provide the sample resistance given in Table (2). Figure (14c) shows a circuit that generates 1 mA current. The operational parameters for the various samples that will be used in this experiment are given in Table (2).

<table>
<thead>
<tr>
<th>Semiconductor sample</th>
<th>( R_x )</th>
<th>( I )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unijunction transistor (UJT)</td>
<td>up to 10 kΩ</td>
<td>100 µA</td>
</tr>
<tr>
<td>Germanium (Ge)</td>
<td>&lt;1 kΩ</td>
<td>10 mA</td>
</tr>
</tbody>
</table>

Table 2: Current (\( I \)) required for semiconductor samples.

The overall four-probe circuit including a current source and a voltmeter, based on a differential amplifier [10], is drawn in Figure (14d). Two separate contact pairs are made on both ends, (AB) for passing current and (CD) for voltage detection, as indicated in Figure (14d). The output from the voltmeter is fed into the data acquisition system (DAQ).
Figure 14: The Electronic circuitry. (a) 2-probe method, (b) 4-probe method, (c) current source, (d) overall circuit showing the current source and differential amplifier, (e) DC power supply.

Q 15. Make circuits capable of providing stable currents of 100 μA and 10 mA.

Q 16. What is the gain of the differential amplifier circuit given in Figure (14d)?
What is the advantage of a differential amplifier as compared to an ordinary amplifier.

### 3.2.8 Power supply

In order to supply DC voltage to the constant current source and volt-meter, a bipolar power supply is used in which AC voltage is converted to a selectable DC voltage. The home built power supply is already provided to you. For interested students, the circuit description of the supply is presented in Figure (14e). The assembled circuit is photographed in Figure (15a) and enclosed in an aluminium box depicted in Figure (15b). The BNC connectors provide $+12 \text{ V}$, $-12 \text{ V}$ and ground points.

### 3.3 Experimental procedure

1. Make circuits for constant current sources of $100 \mu \text{A}$, $10 \text{ mA}$ and the volt-meter on bread board according to the circuit diagrams in Figures (14c), (14d).

2. You are provided with one unijunction transistor (UJT) and a pellet of pure germanium (Ge). Current and voltage wires have already been connected using silver paint with these samples, shown in Figure (16).

3. Pass the insulated wires, enshrouded in a ceramic rod through the steel pipe. Connect current and voltage leads with constant current source and volt-meter. You will acquire voltage through the data acquisition system (DAQ).

4. Before making any electrical connection, set the output voltage of the variac to $100 \text{ V}$. Measure it with a voltmeter.

5. Layout the experiment as suggested in Figure (11). Do not switch on power at this stage.

6. Connect the solid state relay (SSR) with the sample cell as well as with the temperature controller, in a way that its positive terminal is connected
to the positive output channel of the temperature controller, and negative terminal is connected with the negative output channel of the controller. The remaining terminals are connected to the sample cell and variac, as sketched in Figure (11b).

7. Open the Labview file titled `energyband.vi`. Make a folder, and enter your file name (e.g D:\amrozia\test.lvm). Your data will automatically be saved in that file. You will use the DAQ system together with the Labview code to measure the output voltage of the four-probe circuit.

8. First set the variac at 100 V. Switch on the variac, the temperature controller will turn on. Leave the setup for 10 minutes to warm up the temperature controller.

9. Turn on the DC power supply that is connected to the current source and voltmeter. Check the output of the voltmeter.

10. **UJT sample, low temperature measurement:**

    - It is not required to programme the temperature controller in this phase of the experiment as the temperature is naturally increasing.
    - Add liquid nitrogen to the cryostat through the funnel.
    - The temperature controller will start showing the corresponding temperature. Pour liquid $N_2$ until you reach the temperature $\sim (-150^\circ C)$.
    - Leave the setup to warm up to room temperature. As it warms, do the following.
    - Take voltage measurement after every $10^\circ C$ rise in temperature using the Labview file `energyband.vi`.
    - Suppose the temperature controller shows $-150^\circ C$. In the front panel, enter the value $-150^\circ C$ in the temperature box. Press the run button to start acquiring data and the stop button to stop running the acquisition, while the temperature is still $-150^\circ C$. 

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Figure 16: (a) Pure germanium Ge. (b) Unijunction transistor UJT.
• Open Matlab, and add the appropriate folder to the Matlab path.
• Take the mean of the voltage value at the different temperatures.

11. **UJT sample, high temperature measurement:**

• When you have reached room temperature, you will start taking your readings for higher temperatures. For this purpose, you will require the heater and the PID controller.
• Suppose you want to take readings in steps of $10^\circ$C, ranging from $40^\circ$C, $50^\circ$C, up to $250^\circ$C.
• Suppose the room temperature is $32^\circ$C. At this point we need to enter a profile so that the temperature negotiates $40^\circ$C, $50^\circ$C and $60^\circ$C, as it is only possible to programme for these three points at one time. Now enter this temperature profile according to the instructions in Appendix A.
• Acquire the voltage for $40^\circ$C, $50^\circ$C and $60^\circ$C using Labview as discussed earlier.
• For the next set of points (e.g. $70^\circ$C, $80^\circ$C, $90^\circ$C), you will have to repeat the above steps.
• Complete your measurements up to $\sim 250^\circ$C.
• Find resistance from the acquired voltage.
• Tabulate temperature versus resistance, as indicated in Table (3).

<table>
<thead>
<tr>
<th>Temperature ($^\circ$C)</th>
<th>Resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>–150</td>
<td></td>
</tr>
<tr>
<td>–140</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Relationship between temperature and sample resistance.

12. **Ge sample, high temperature measurement:**

• You are provided with a pure Ge sample, an intrinsic semiconductor. Set up the complete experiment being guided by your experience with the UJT sample. The constant current for the Ge sample is $I = 10$ mA.
• Again enter the temperature profile in the temperature controller. You will require measurements up to $150^\circ$C.
• Complete acquiring the data.
• Tabulate temperature versus resistance.

Q 18. Plot a graph of $\log\left(\frac{1}{R}\right)$ versus $T$ in Kelvins, and distinguish the intrinsic and extrinsic regions for the UJT.
Q 19. Calculate the energy band gap from the intrinsic region data for UJT and Ge. As conductivity depends on both the charge carrier concentration and mobility, so in calculating band gap take both of these factors into account. The published energy band gap values for silicon (Si) and germanium (Ge) are provided in Table (4).

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Band gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon (Si)</td>
<td>1.12 eV</td>
</tr>
<tr>
<td>germanium (Ge)</td>
<td>0.67 eV</td>
</tr>
</tbody>
</table>

Table 4: Energy band gap ($E_g$) for Si and Ge.

Q 20. Calculate the temperature coefficient $\alpha$ of the carriers mobility from the extrinsic region data of the UJT. The published value of $\alpha$ is 2.3, given in [10].

Q 21. What is your uncertainty in the energy band gap measurement?

Q 22. In the low temperature measurements, the sample is continuously thawing (warming) as data is being acquired. What kind of uncertainty does this cause in your measurements?

A How to construct a temperature profile in temperature controller

Suppose we want to make the temperature profile, sketched in Figure (17). For this you have to do the following steps.

Figure 17: An example of temperature profile. Setpt#1, 2 is 40°C, setpt#3, 4 is 50°C, and setpt#5, 6 is 60°C.

1. The very first and the most important step is to power up the temperature controller. Power connections should be made to L1, L2.
L1 is connected to the positive terminal of the AC power supply and L2 with the negative one. Our AC power supply is the variac, and it should be set at 100 V. Be careful in applying voltage to the temperature controller as it can be damaged, if you operate it over 120 V AC.

2. To enter into the programming mode, hold the CTR.SEL key until the unit displays EntEr PASSCOde. At this point, enter the pass code which is 3254 for our device.

3. Select programme system PrG SYS mode, the controller will enter into the system configuring mode. Push PROG key, the display will show DSP OPt, select Process-Setpoint. You have to push PROG key to go to the next mode. The display will show dSPLy t, enter time in seconds using ▲▼ and < □ □ □ □ □ keys are used to assign values. Select Strt SP mode. Assign a value of 10 to rAtE tb mode. Enter COLd JN value that would be the room temperature. Enter a value of 10 to the V rAnGE mode and next to it, assign value to the C RAnGE that would be 20.

4. Move to the programme control PrG Ctr mode. Push PROG key, the display shows CntrL x (where x=controller no.), select controller 1. Then go to Ct tYPE mode and select PID option. Select Cr.Al (for the K-type thermocouple) for SIGnAL mode. Then select dEGrE C and finally, select engineering unit mode Cx UNIt that would be C if input signal is a thermocouple.

5. Next select the tuning mode. Push PROG key until the unit displays tUn-ing. Select the PID mode. Enter the following values as,

- proportional band = 0.5,
- reset = 1,
- rate = 1.

6. Push PROG key to enter into profile mode. When the unit displays the PROFILE, select the required controller (controller 1) using PROG key. When the display will briefly read Strt SP, enter the value of starting set point that would be room temperature, for example 32°C as indicated in Figure (profile). Use ▲▼ and < □ □ □ □ □ keys to enter the desired value. Next press SETUP to go to the next function. At this point the display will briefly read SetPt 1 enter the value of setpoint 1, for example 40°C. Push PROG key to go on to the next step. The display will show EntEr t, enter the time value like 1 min. Move to setpoints 2 by pressing PROG key. Enter setpoint 2 value which is 40°C and time=10 min. Repeat the above steps to program up to setpoint 6 as shown in Figure (17).

7. Push EXT key. Again push EXT key for saving programme. Select the desired controller using PROG key and run it by pressing RUN/STOP key.
The PID controller manipulates the process inputs based on the history and rate of change of the signal [9]. The basic idea is that the controller reads the system by a sensor as shown in Figure (18a). Then it subtracts the measurement from the desired reference to generate the error value. The error will be managed in three ways: to handle the present through the proportional term; recover from the past using the integral term; and to anticipate the future through the derivative term.

![Block diagram of a PID controller](image)

**Figure 18:** (a) Block diagram of a PID controller. (b) Response of a PID closed loop system.

### B.1 Proportional term

The proportional term (sometimes called gain) changes the output in proportion to the present error value. The proportional response can be adjusted by multiplying the error by a constant $K_P$ called the proportional gain. A high proportional gain results in a large change in the output. If the proportional gain is too high, the system can become unstable. In contrast, a small gain results in a small output response, and a less responsive controller.
B.2 Integral term

The integral term (sometimes called reset) is proportional to both the magnitude and duration of the error. This term sums up the previous errors to the system control input. The summing of the error will continue until the system process value equals the desired value, and this results in no stationary error. The magnitude of the contribution of the integral term correction is determined by the integral gain $K_i$.

B.3 Derivative term

The derivative term (also called the rate) calculates the rate of change of the process error by determining the slope of the error over time. The magnitude of the contribution of the derivative term to the overall system is determined by the term $K_d$. The derivative term slows the rate of change of the controller output. However, derivative control is used to reduce the magnitude of the overshoot produced by the integral term and improve the controller-process stability. If the derivative term is too large, it can cause the process to become unstable as this term is highly sensitive to noise in the error.