Band structure and electrical conductivity in semiconductors

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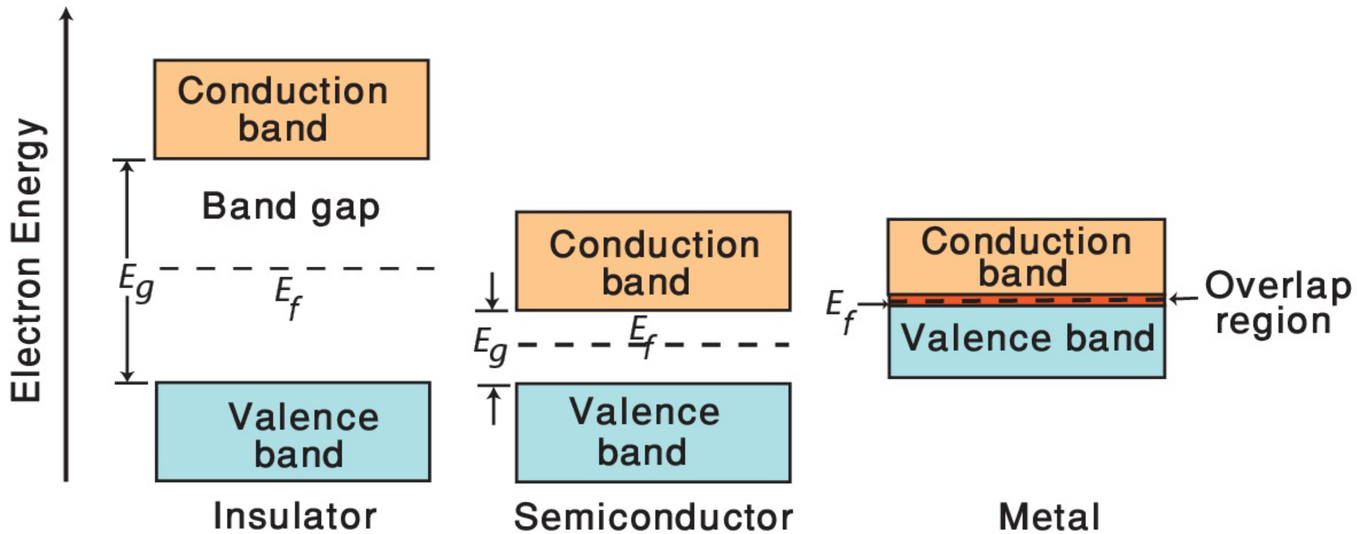
Outline

- Semiconductors and their types.
- Energy band gap.
- Conduction in intrinsic and extrinsic semiconductors.
- Experimental setup.
- Results.

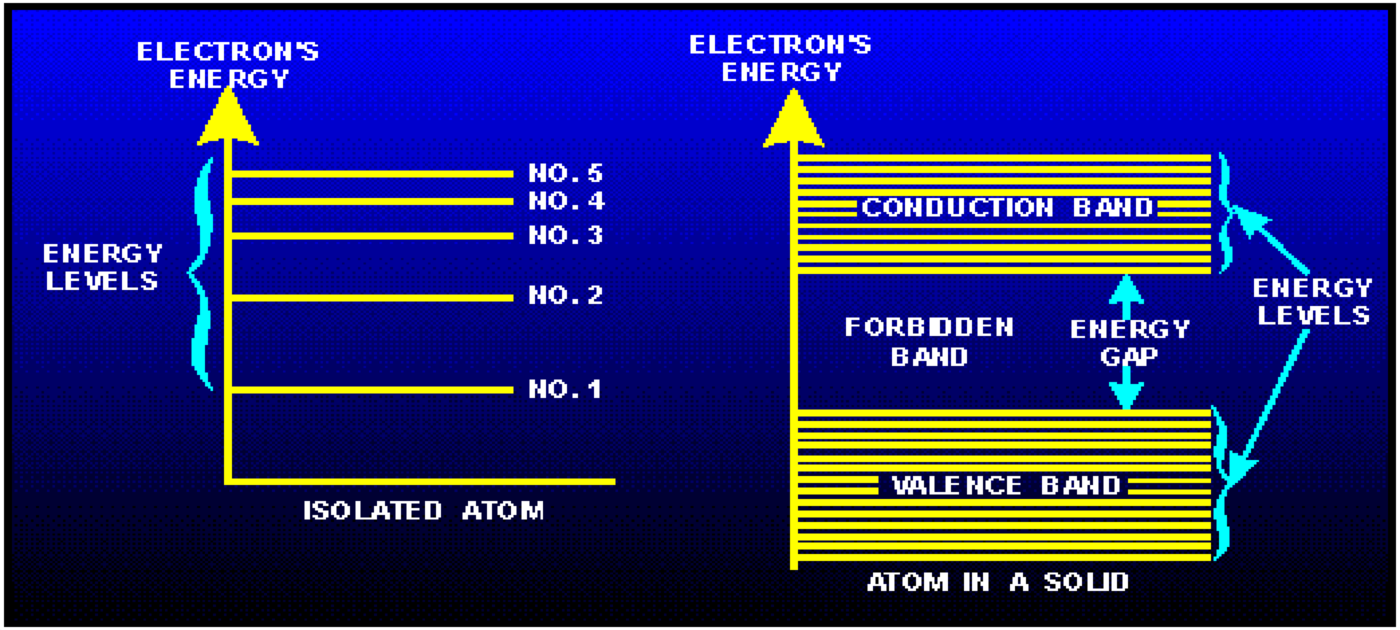
Semiconductors

- Semiconductors are materials in which both electrons and holes contribute to the conduction process. According to band theory of solids, semiconductors posses a band gap.



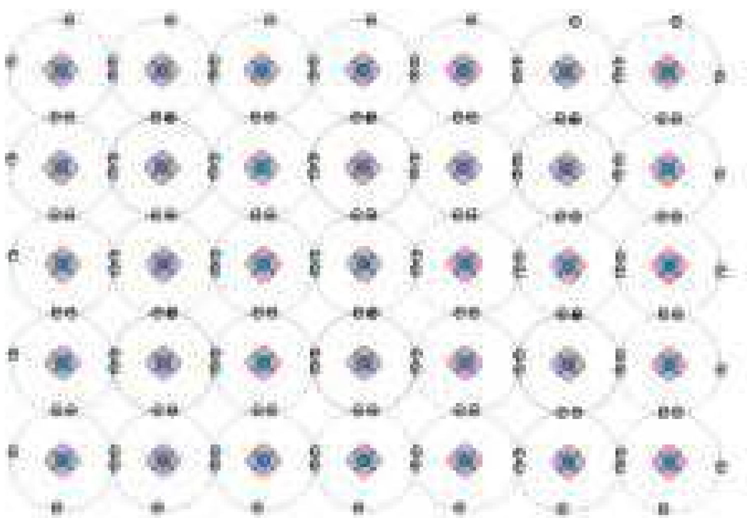
Energy band gap

- Energy band gap is a region in solids where no electron states can exist.
- Manifestation of the discrete character of basic atomic states.

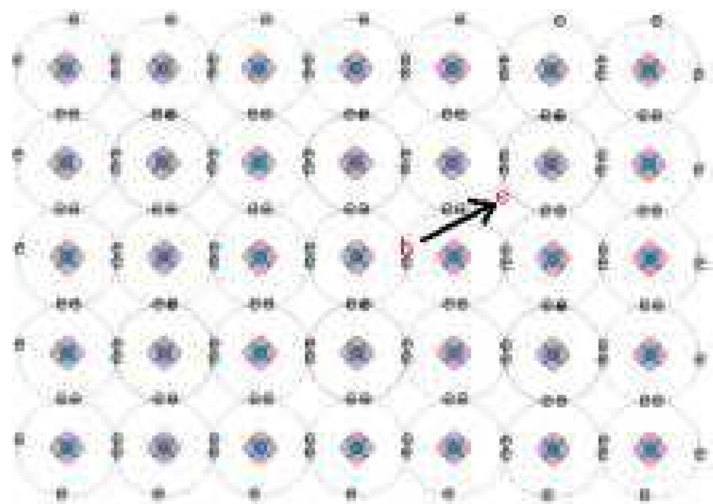


Energy band gap

- Ionization energy required to generate the electrons and holes.



Insulating crystal before ionizing event



Ionization event to give two mobile charge carriers

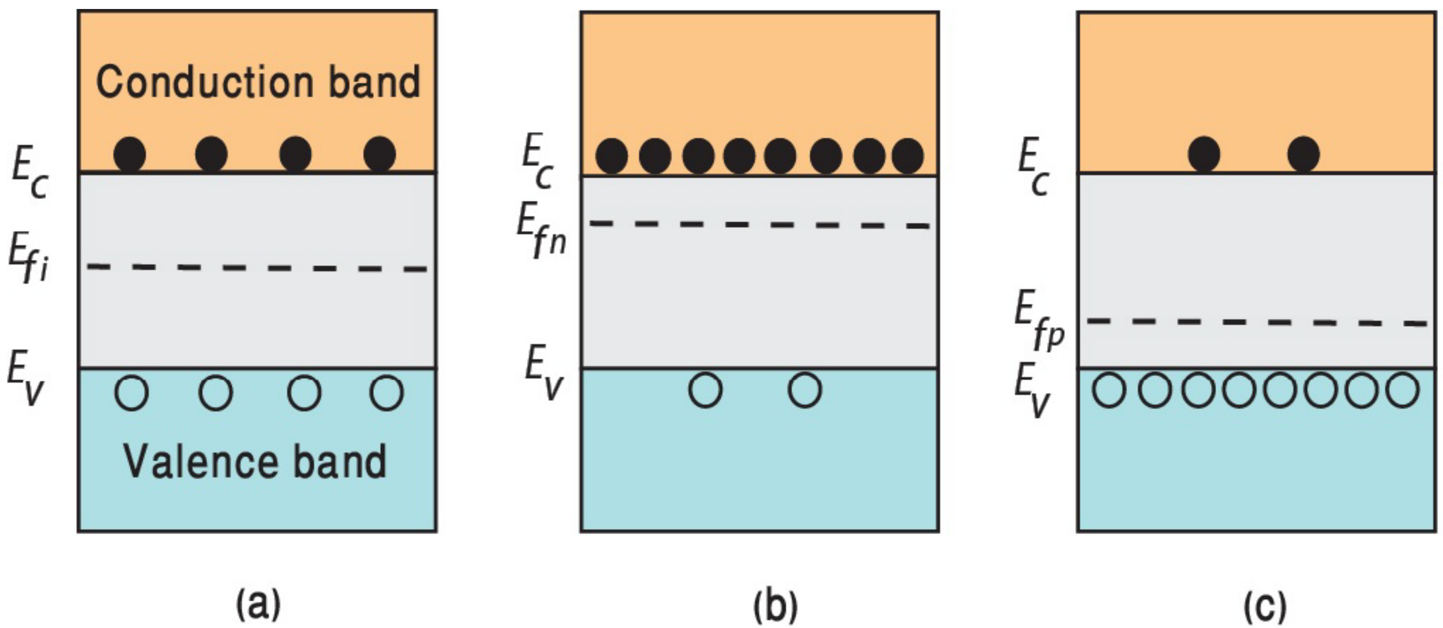
Semiconductor types

- An **intrinsic semiconductor** is a pure semiconductor having no impurities and equal numbers of excited electrons and holes, i.e., $n = p$.

- A semiconductor in which doping has been introduced, thus changing the relative number and type of free charge carriers, is called an **extrinsic semiconductor**.

Semiconductor types

- If the conduction electrons are the majority carriers that is an n-type semiconductor and the holes for the p-type semiconductor.



Intrinsic semiconduction

- Thermally or optically excited electron's contribution to the conduction is called intrinsic semi conduction.

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

- The electron density from bottom to the top of conduction band is

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

Intrinsic semiconduction

- Density of state is,

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

- Probability of an electronic state of energy E being occupied by an electron is,

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

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

Intrinsic semiconduction

- Electron and holes concentrations are,

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

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

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

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

Intrinsic semiconduction

- In intrinsic semiconductor, $n_e = n_h$, so charge carrier concentration is,

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

- Where, $E_g = E_c - E_v$ is the energy band gap, and intrinsic conductivity is,

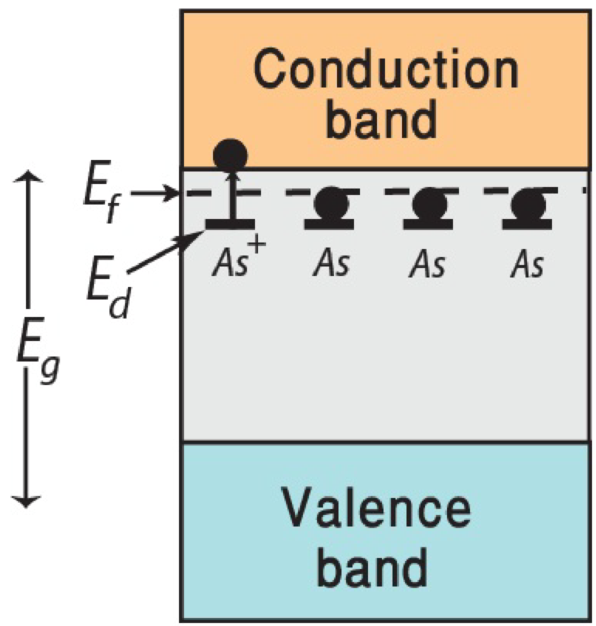
$$\sigma \;=\; C T^{3/2} q_e \left(\mu_e + \mu_h\right) \exp\left(\frac{-E_g}{2k_B T}\right).$$

Extrinsic semiconduction

- In extrinsic semiconductor $\mathbf{N_d>n_i}$, so the conductivity depends on carrier cocentration and mobility
- **Temperature dependence of carrier concentration**

- **Ionization regime**: The electron concentration is given as,

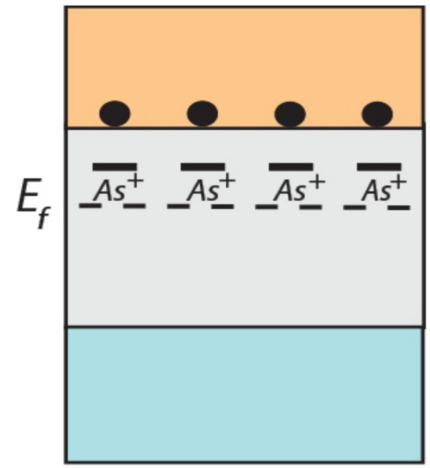
$$n_e = \left(\frac{1}{2}N_c N_d\right)^{1/2} \exp\left(-\frac{\Delta E}{2k_B T}\right),$$



Temperature dependence of carrier concentrations

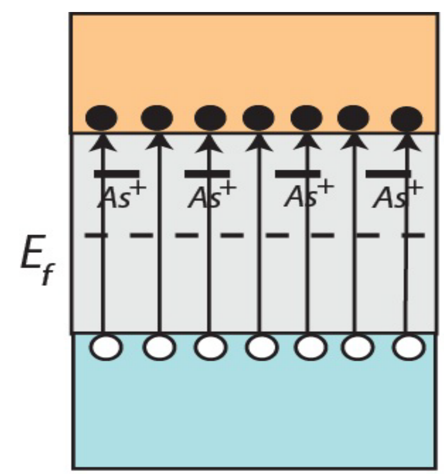
- **Extrinsic regime:** The electrical conductivity is,

$$\sigma = qn\mu,$$
$$n = N_d \simeq \text{constant}$$
$$\sigma = T^{\alpha}.$$



- **Intrinsic regime:** Doping importance is lost here and material behaves as an intrinsic semiconductor with,

$$n_i = CT^{3/2}\exp\left(\frac{-E_g}{2k_BT}\right),$$



Temperature dependence of mobility

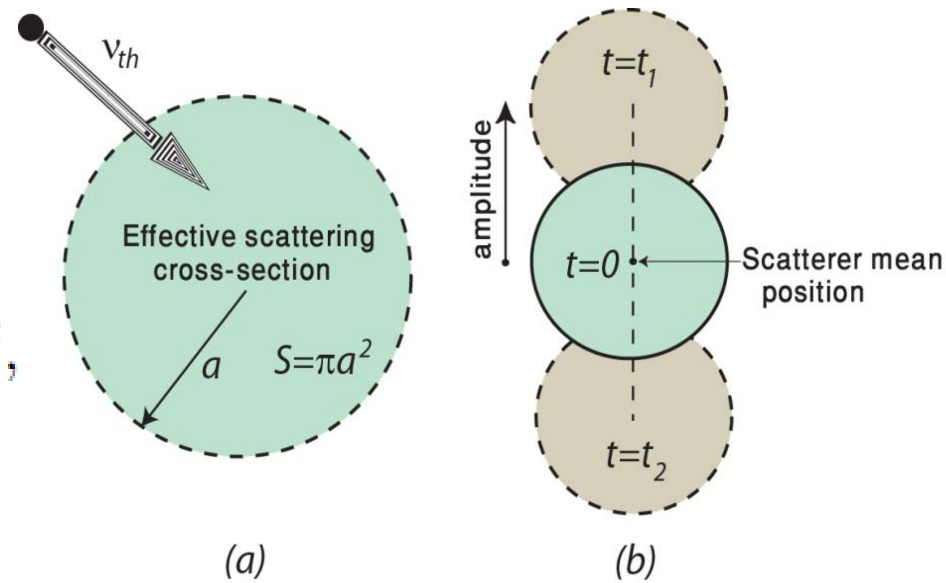
- **High temperature:** Electrons in C_B or C_V suffer collision with the impurity ion. The mean free time between scattering event and mobility is,

$$\tau = \frac{1}{S v_{th} N_s}.$$

$$\mu = \frac{e\tau}{m_e^*}.$$

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

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



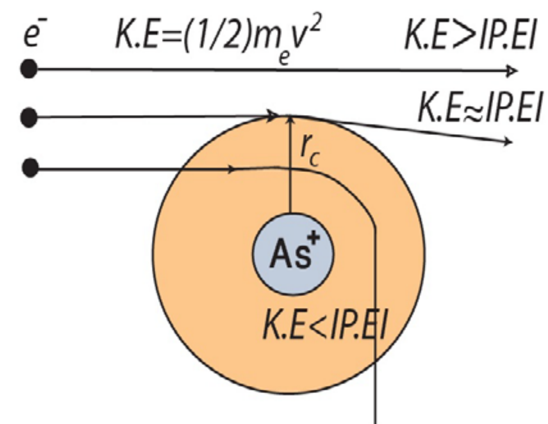
Temperature dependence of mobility

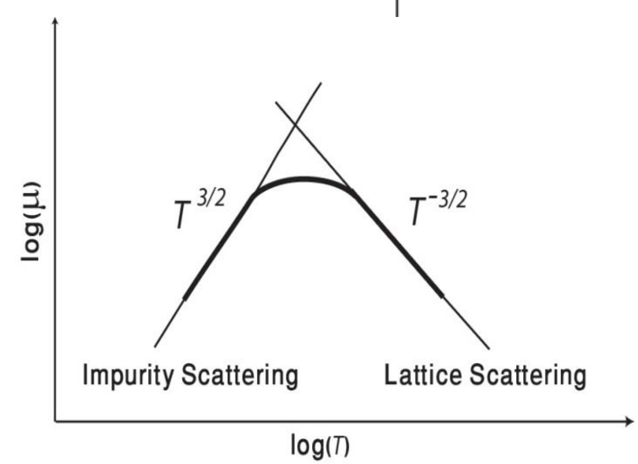
- **Low temperature**: Electron scattering is done by interaction with the ionized impurity.
- **K.E>|P.E|**, electron moves straight.
- **K.E<|P.E|**, electron is deflected.
- **K.E≈|P.E|**,

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

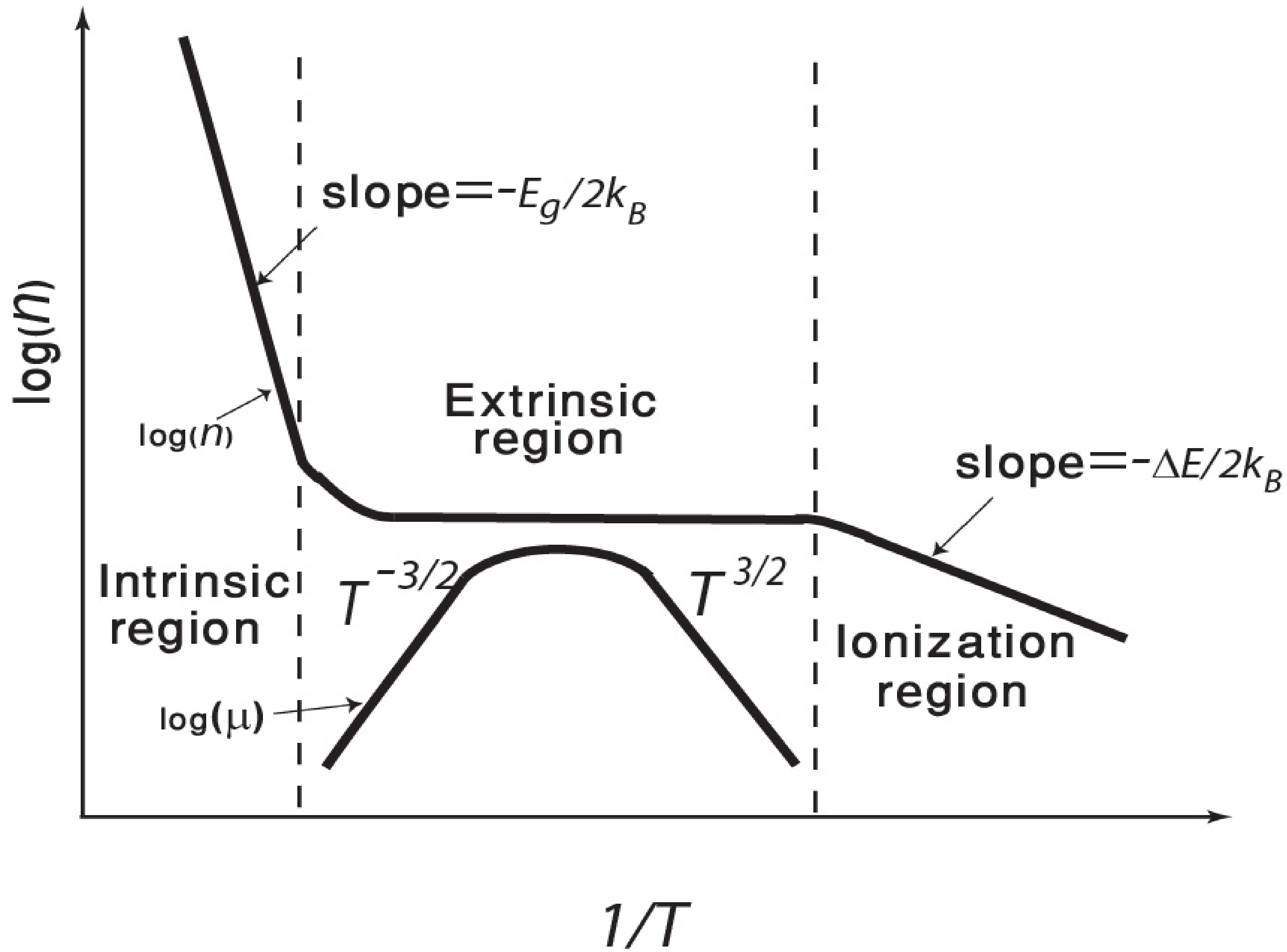
$$S = \pi r_c^2.$$

$$\mu_I \propto \frac{T^{3/2}}{N_I}$$





Temperature dependence of conductivity

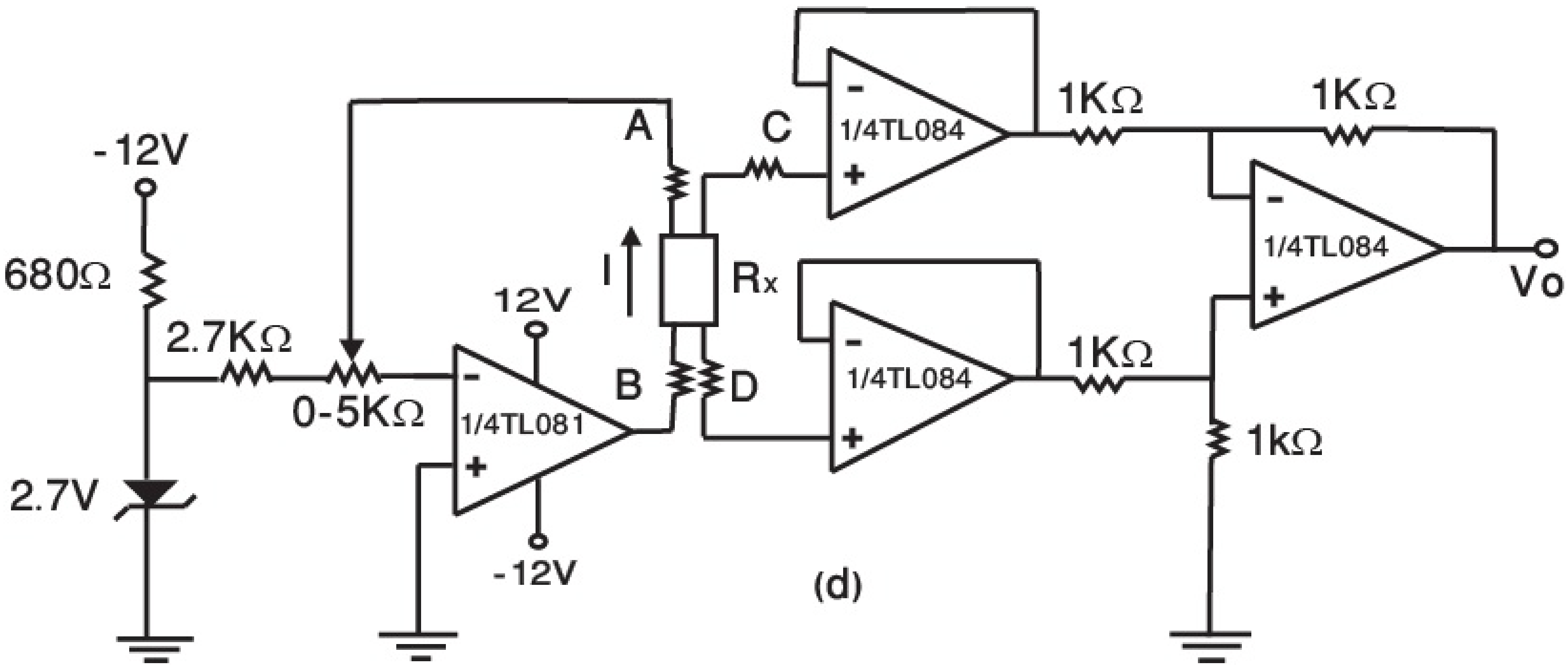


Experiment

- **Purpose**
- Calculate the energy band gap for doped Si and pure Ge.
- Calculate the temperature dependent coefficient of the majority carriers.
- **Important parameters**
- Resistance measurement.
- Achieving high and low temperature regimes.
- Temperature control.

Resistance measurement

- The resistance of the semiconductor sample is measured by the four-probe technique.

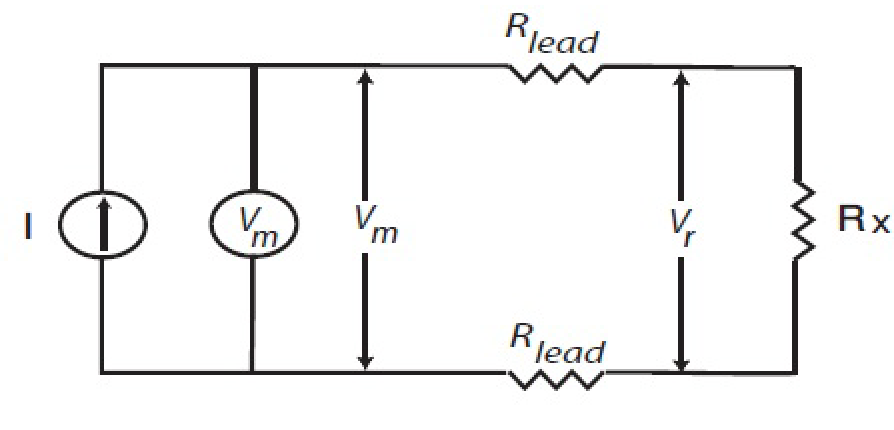


Resistance measurement

- Two-probe method

Measured resistance= $\frac{V_m}{I}$

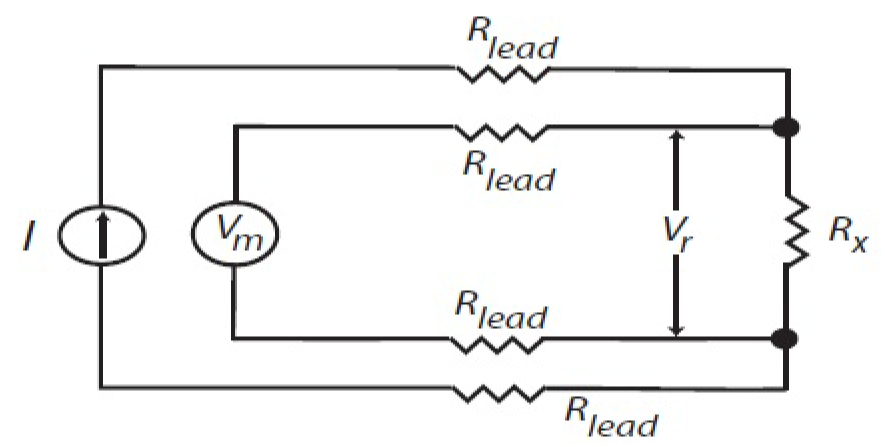
$= R+(2^* R_{lead})$



- Four-probe method

Measured resistance= $\frac{V_m}{I}$

$= \frac{V_r}{I}$



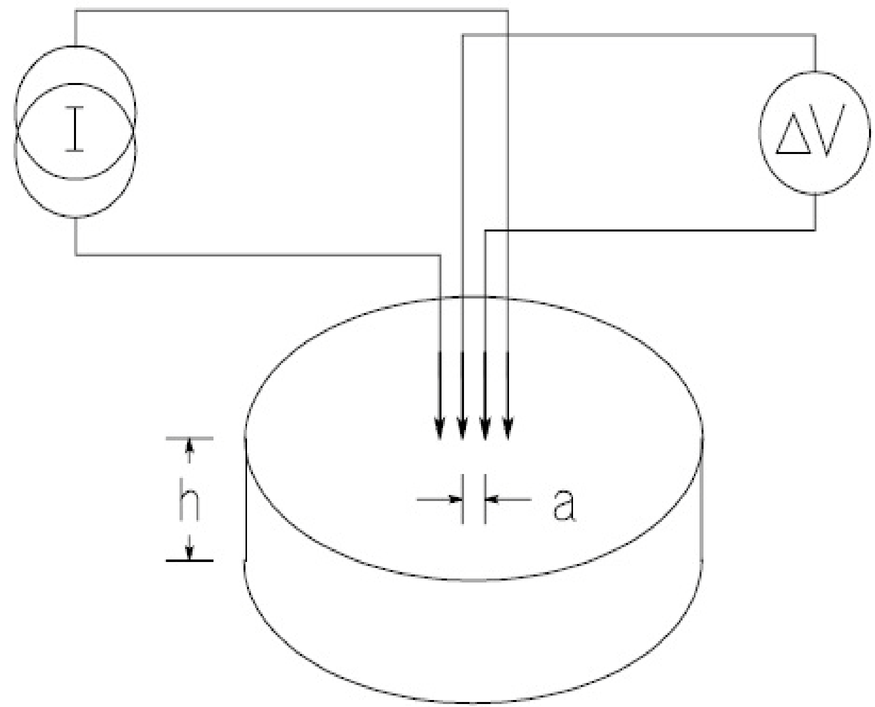
Resistance measurement

- The resistivity of a bulk sample in which h>>a is,

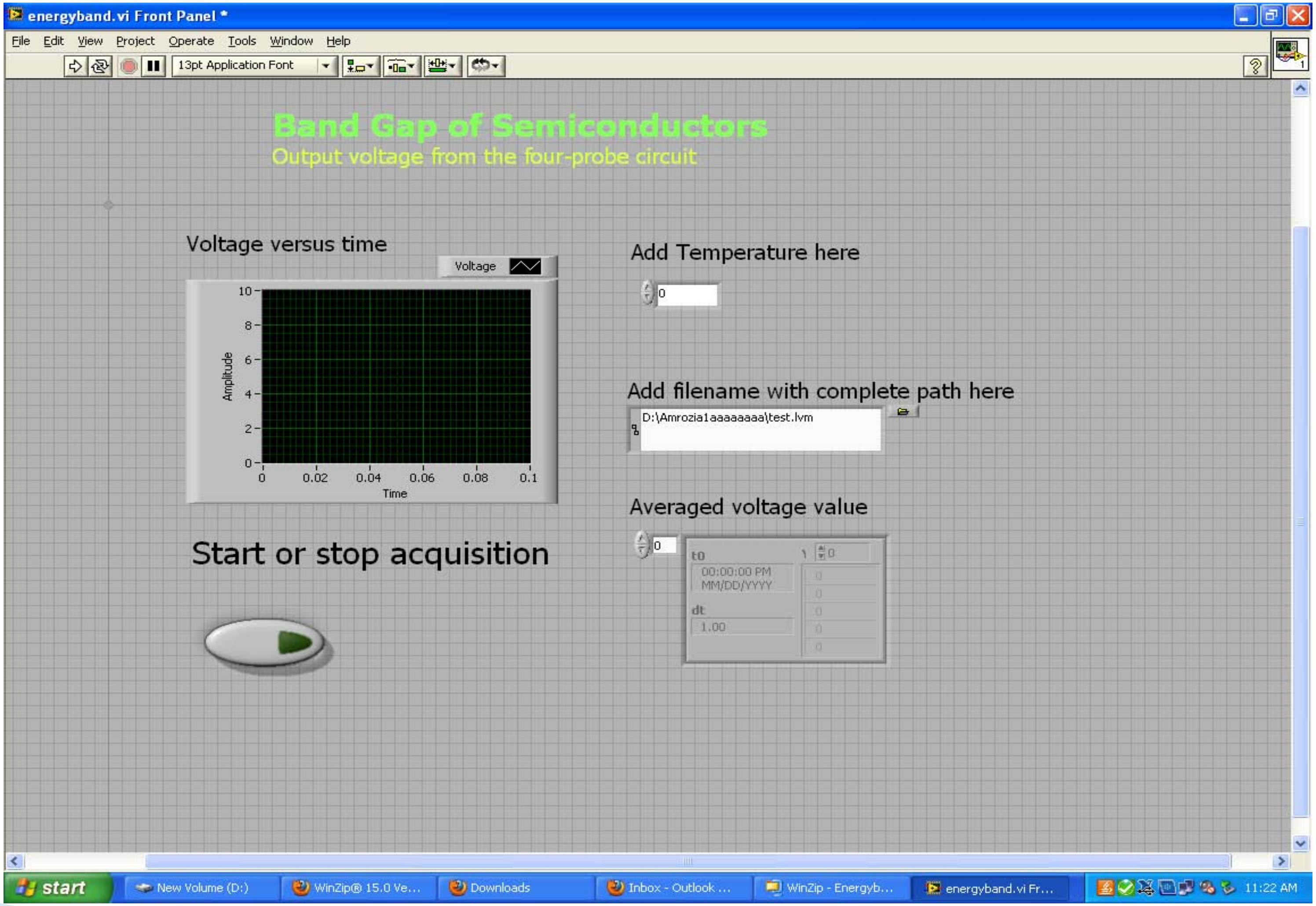
$$\rho = 2\pi a\left(\frac{\Delta V}{I}\right)$$

- For thin sheets having h<<a, resistivity is,

$$\rho = \frac{\pi}{\ln(2)} h\left(\frac{\Delta V}{I}\right)$$



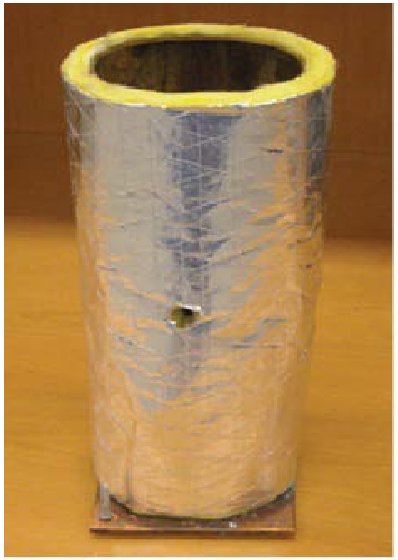
Resistance measurement



Low and high temperatures

- **Low temperature** is achieved using Liquid nitrogen that is poured into the flow cryostat.

- **High temperature** is attained by passing current through a heater wire wound around the sample cell.



Low and high temperatures

- **Heater calculations**

  Nicrome wire (36)

  Resistance=42.7Ω/m.

  Resistance of the used wire=42.7*3=128.1Ω.

  Applied voltage=100 V AC.

  Power=78.1.

- **Cryostat dimensions**

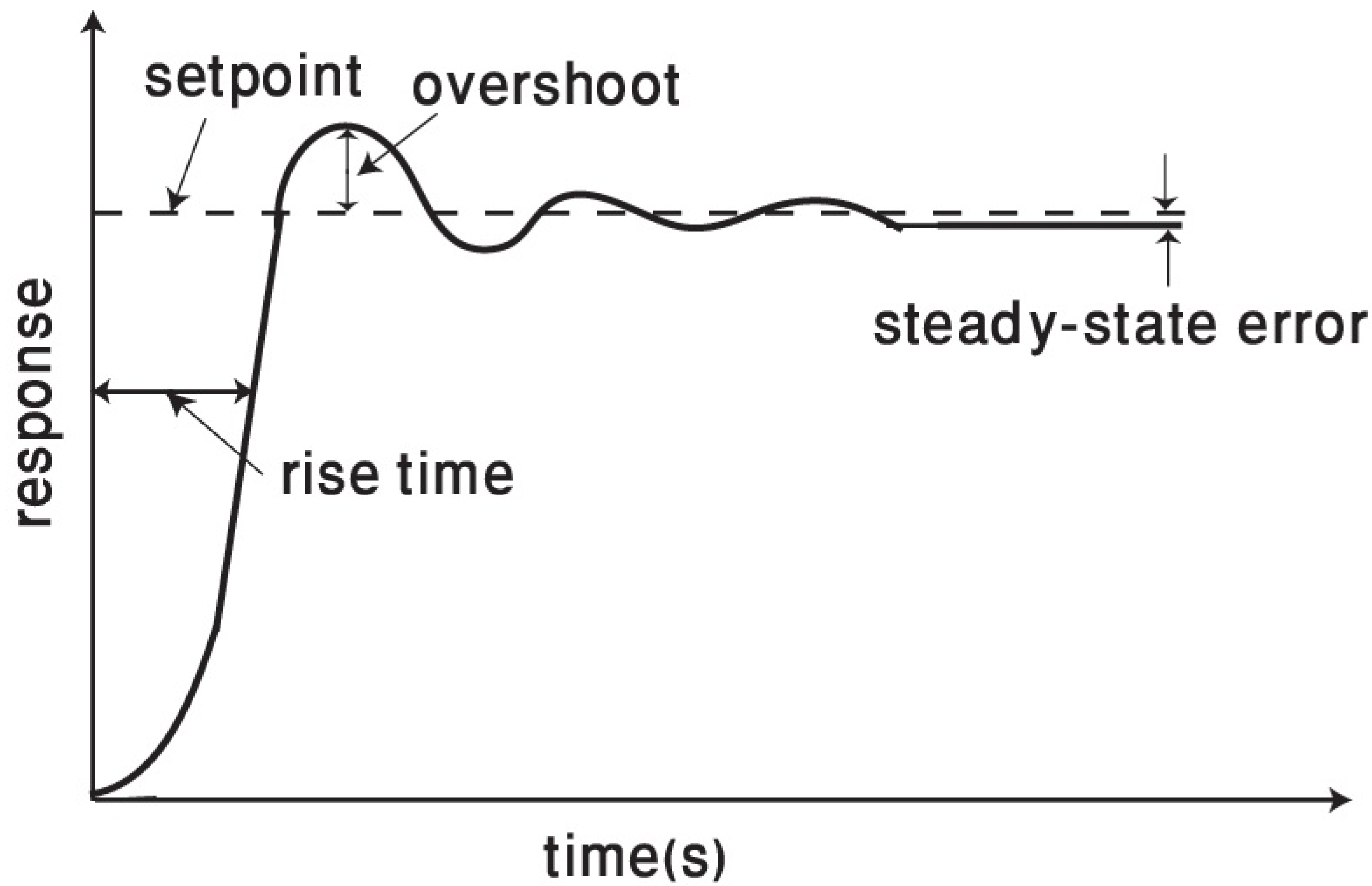
  Length=12 inches.

  Diameter=20mm.

Temperature measurement

- The temperature of the sample is measured by using a K-type thermocouple and controlled temperature is attained by a multi-zone controller (CN1504-TC).

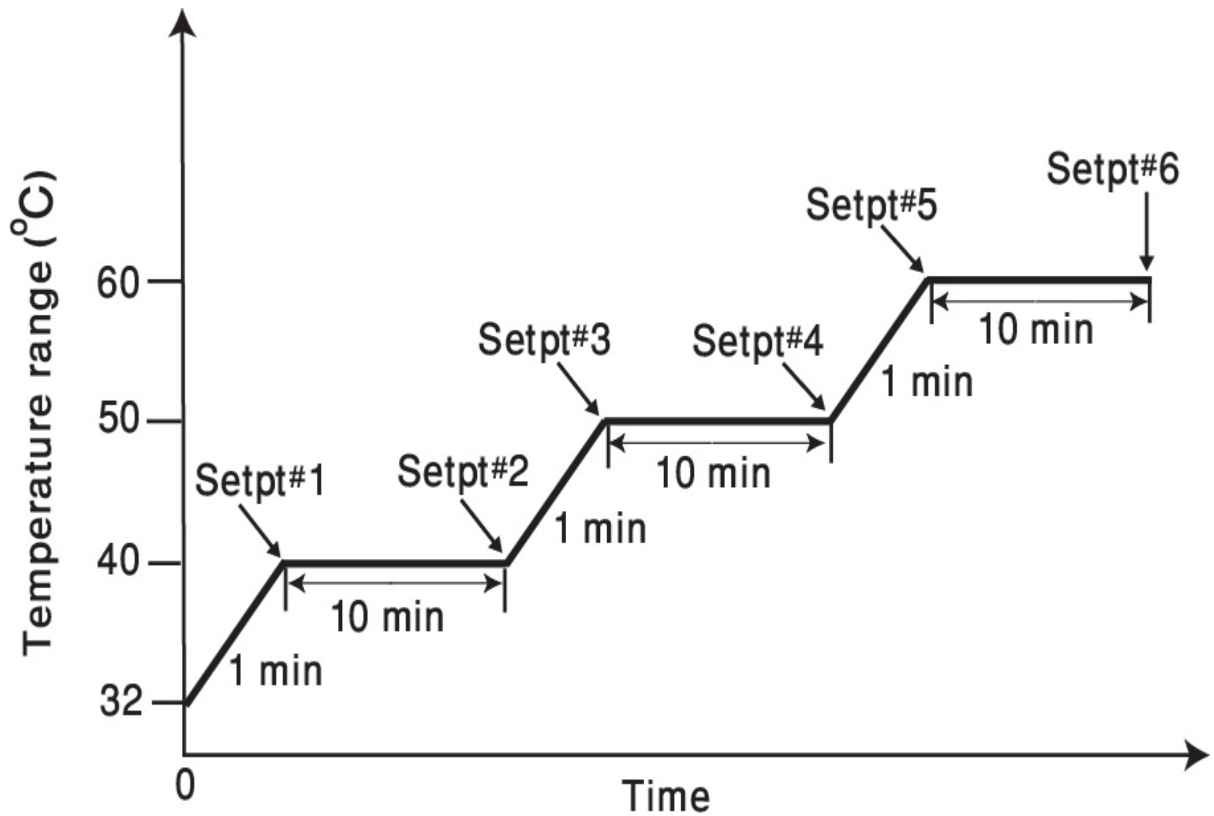
Temperature measurement



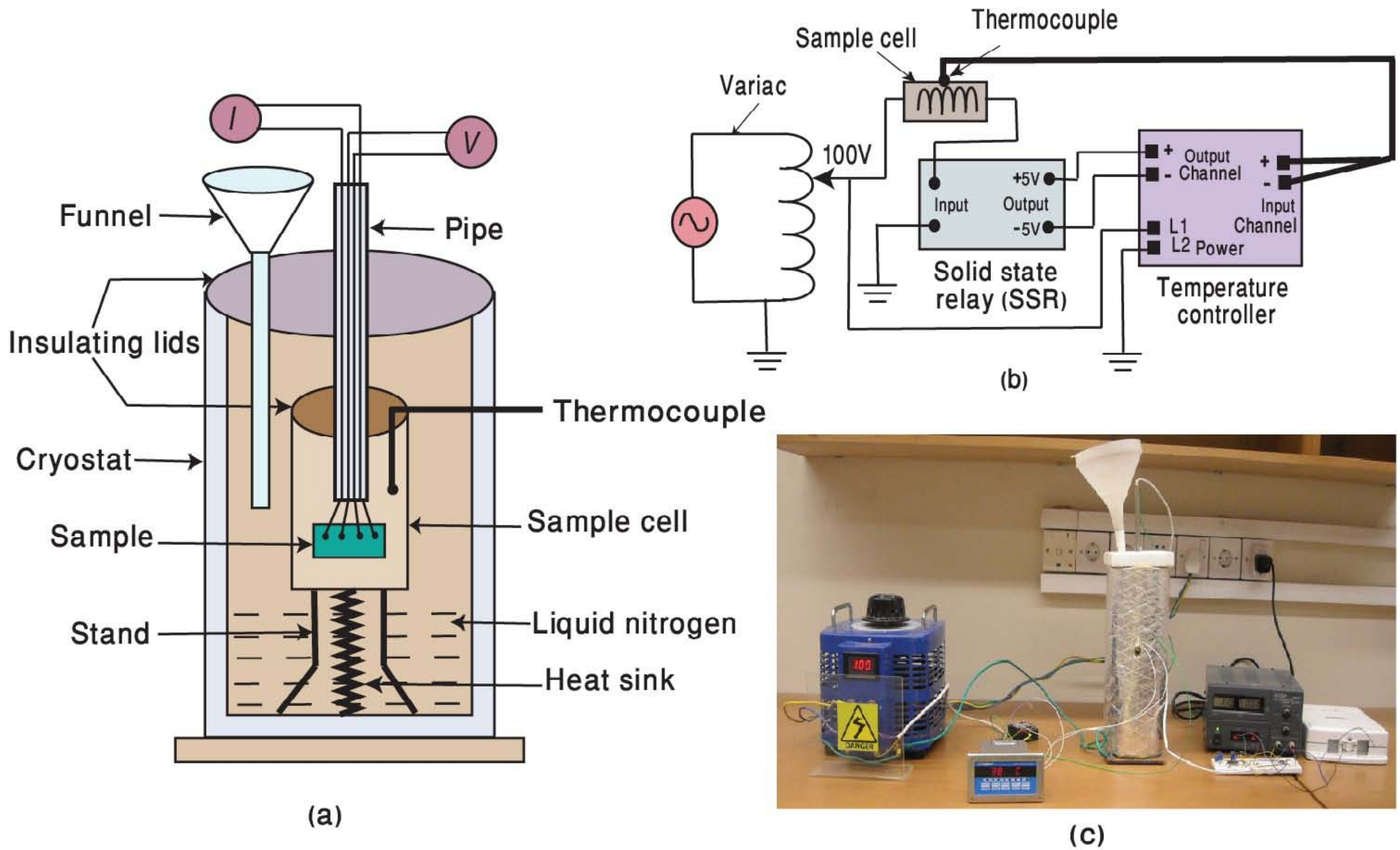
Temperature measurement

- **PID constants**

- P=0.5,
- I=1,
- D=1.

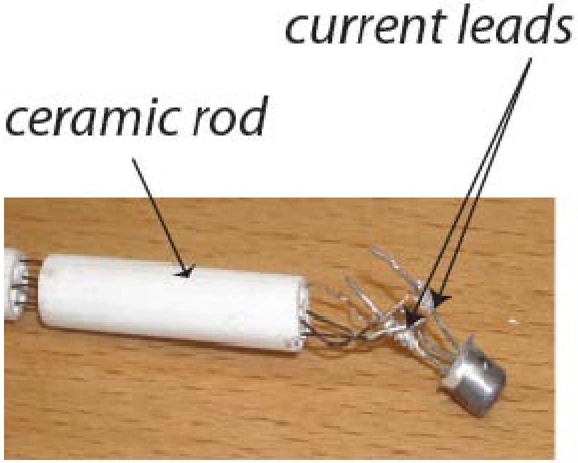


Experimental setup



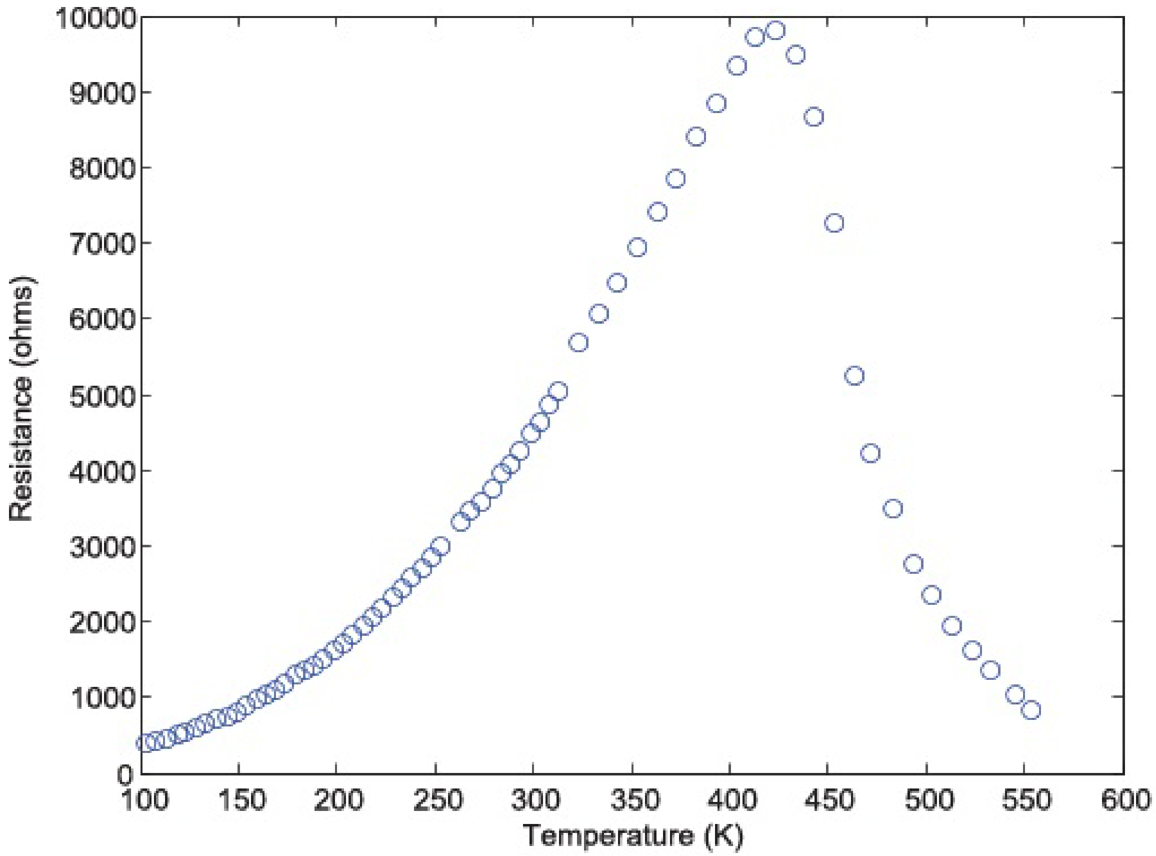
UJT sample (doped silicon)

- Constant current of 100 μA
- Resistance values in the temperature range of −150 °C to 250 °C .
- Calculate band gap from the intrinsic region data.
- Calculate the temperature coefficient of the carriers mobility from the extrinsic region data.



UJT sample (doped silicon)

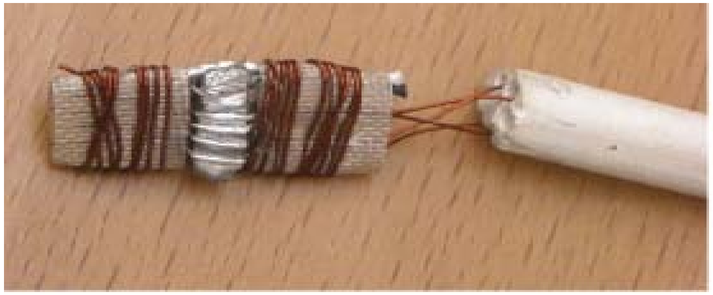
- $E_g = 1.03$ eV
- $\alpha = 2.5$



Resistance versus temperature plot of UJT

Germanium sample

- Constant current of 10 mA.
- Resistance values from room temperature to 150°C .
- Resistance is calculated through 4-probe method.
- Calculate band gap from the intrinsic region data.



Germanium sample

- Eg=0.77eV