Birla Institute of Technology & Science, Pilani

Pilani Campus

PHY F244 : Modern Physics Laboratory

Measurement of Boltzmann Constant

1. **Aim and Objectives** : This experiment aims to determine the Boltzmann constant using ideal diode equation.

2. **Keywords** : Boltzmann Constant, Diode Equation.

3. **Theory** :

   (a) **Semiconductors:**

   A *semiconductor* is a material whose electrical conductivity lies between that of a conductor and an insulator. The conductivity of semiconductors can be controlled and manipulated by introducing impurities, known as *doping*, or by applying external influences like electric fields, temperature, and light. Common semiconductor materials include *silicon (Si)* and *germanium (Ge)*.

   Band Structure: In semiconductors, the energy bands are divided into two regions: the *valence band* (where electrons are present) and the *conduction band* (where electrons are free to move). The gap between these two bands is called the *band gap*. For semiconductors, this band gap is small enough to allow electrons to jump from the valence band to the conduction band under certain conditions, like applying energy via heat or voltage.

   Intrinsic Semiconductors: Pure semiconductors without any added impurities. In intrinsic semiconductors, at absolute zero temperature, no electrons are in the conduction band. At higher temperatures, some electrons gain enough energy to jump into the conduction band, leaving behind holes in the valence band.

   Extrinsic Semiconductors: Semiconductors that have been doped with impurities to enhance their conductivity. There are two types:

   - *n-type (negative):* Doping with elements that have more valence electrons (e.g., phosphorus in silicon), creating free electrons in the conduction band.
   - *p-type (positive):* Doping with elements that have fewer valence electrons (e.g., boron in silicon), creating "holes" in the valence band, which act as positive charge carriers.

   The control of charge carriers (electrons and holes) is what makes semiconductors extremely useful for electronic devices like transistors, diodes, and integrated circuits.

   (b) $p-n$ **junction diode:**

   A *p-n junction diode* is one of the most fundamental semiconductor devices. It consists of two regions of semiconductor material: one is *p-type* (positive) and the other is *n-type* (negative). When these two types of semiconductors are brought together, a junction is formed, which gives the diode its unique electrical properties.

   - **P-Type Region:** In this region, doping with an element like boron creates "holes" (missing electrons) that act as positive charge carriers.
   - **N-Type Region:** Doping with an element like phosphorus introduces extra electrons, which are free to move in the conduction band.

   When the p-type and n-type materials are brought into contact, electrons from the n-region will diffuse into the p-region, where they will recombine with the holes. This creates a *depletion region* around the junction, which is devoid of free charge carriers. This depletion region acts as an insulating barrier that prevents current from flowing freely under normal conditions.

   (c) **Characteristics of the** $p-n$ **junction diode:**

   - **Forward Bias:** When a voltage is applied such that the p-type region is connected to the positive terminal and the n-type region is connected to the negative terminal (forward bias), the electric field reduces the width of the depletion region. This allows current to flow through the diode as electrons move from the n-region to the p-region and holes from the p-region to the n-region. Once the voltage exceeds a certain threshold (the *cut-in voltage* or *forward voltage*), current flows more easily.

- **Reverse Bias:** When the polarity of the applied voltage is reversed (the p-type region is connected to the negative terminal and the n-type region to the positive terminal), the depletion region widens, and current is blocked. This is the normal behavior of a diode, where it acts as a *one-way switch* for current.
- **Breakdown Region:** If the reverse voltage exceeds a certain limit (called the *reverse breakdown voltage*), the diode may break down and conduct a large reverse current. This behavior is typically unwanted but is used in special devices like *Zener diodes*.

(d) **Diode I-V Characteristics**

The current-voltage (I-V) characteristics of a diode show how the current through the diode varies with the applied voltage: In forward bias, the current increases exponentially with voltage once the threshold is crossed. In reverse bias, the current remains very small (except in breakdown).

(e) **Derivation of the Diode Equation** The diode equation describes the current-voltage (I-V) characteristics of a p-n junction diode. This derivation incorporates the ideality factor (η) and demonstrates its use in determining the Boltzmann constant (k) using simple diode measurements.

A p-n junction diode exhibits:

i. **Diffusion Current**: Due to charge carriers moving from regions of high concentration to low concentration.

ii. **Drift Current**: Due to charge carriers moving under the influence of the electric field in the depletion region.

In equilibrium, the diffusion and drift currents balance each other. When an external voltage V is applied, this balance is disrupted, leading to net current flow.

Under non-equilibrium conditions, the carrier concentrations at the edges of the depletion region follow the Boltzmann distribution. The electron concentration on the p-side is given by:

$$n_p = n_{p0} e^{qV/\eta kT}$$

Similarly, the hole concentration on the n-side is:

$$p_n = p_{n0} e^{qV/\eta kT}$$

where:

- η: Ideality factor ($\eta = 1$ for ideal diodes, higher for non-ideal diodes).
- V: Applied voltage.
- k: Boltzmann constant.
- T: Temperature in Kelvin.
- q: Electron charge.

The total current across the diode is the sum of the drift and diffusion components. In forward bias, the majority carrier injection dominates the current:

$$I = I_0 \left(e^{qV/\eta kT} - 1 \right)$$

where:

- I_0: Reverse saturation current, dependent on material properties and temperature.
- The term $e^{qV/\eta kT}$ accounts for the exponential increase in current due to applied forward voltage.

Thus, the diode equation is expressed as:

$$I = I_0 \left(e^{qV/\eta kT} - 1 \right)$$

- For forward bias ($V > 0$), the exponential term dominates ($e^{qV/\eta kT} \gg 1$).
- For reverse bias ($V < 0$), the current approximately equals $-I_0$ (reverse saturation current).

(f) **Determination of the Boltzmann Constant:**
When $V \gg kT/q$, the diode equation simplifies to:

$$I \approx I_0 e^{qV/\eta kT}$$

Taking the natural logarithm on both sides:

$$\ln I = \ln I_0 + \frac{qV}{\eta kT}$$

The slope of the straight-line graph of $\ln I$ vs. V is:

$$\frac{\Delta \ln I}{\Delta V} = \frac{q}{\eta kT}$$

Rearranging for k:

$$\boxed{k = \frac{q}{\eta T} \left(\frac{\Delta \ln I}{\Delta V} \right)}$$

In the above equation use $q = e$ charge of electron and $\eta = 1$ for Ge and $\eta = 2$ for Si.

(g) This derivation incorporates the ideality factor η in the diode equation and shows how to use the slope of $\ln I$ vs. V to determine the Boltzmann constant. This method is straightforward and utilizes simple diode measurements for accurate results.

4. **Tasks** :
   (a) Create an appropriate observation table to take your observations.
   (b) Vary the voltage and measure the current.
   (c) Plot the graph and obtain the appropriate slope to determine k_B.
   (d) Calculate the percentage error of the value obtained.
   (e) Comment on the Reverse Saturation Current I_0 from the graph.
   (f) What can cause these errors in the measurement?

5. **Observations and Results** :

S.N.	V (volts)	I (mA)	$\ln I$
1			
2			
3			