Determination of the band gap of a semiconductor by Four Probe Set-Up

Experiment No:

Date:

1 Aim

To deteremine the bandgap of given semiconductor material using four probe method.

2 Motivation

The properties of bulk materials used in the fabrication of transistors and other semiconductor devices are essential in determining the characteristics of the devices. Resistivity and lifetime (of minority carriers) measurement are generally made on germanium crystals to determine their suitability. The resistivity, in particular, must be measured accurately since its value is critical in many devices. The value of some transistor parameters, like the equivalent base resistance, is linearly related to the resistivity. The electrical properties of semiconductors involve the motion of charged particles within them. Therefore, we must have an understanding of the forces which control the motion of these particles. It is of course, the physical structure of the solid which exerts their control. This topic is very large, and you are expected to familiar atleast with the basics of electronic conduction in soilds.

3 Basics

For a brief idea, when the atoms are arranged in a crystal results the tremendous interaction between the atoms ($\sim 10^{22} \mathrm{per cm}^3$). So, the energy level found in isolated atoms will be split and form bands of allowed energies which contain almost continuum of levels. Accordingly, electrons are located in energy bands in crystalline solid. The band which contains the valence electrons is called the valence band. The unoccupied energy levels also split up and form another band called the conduction band. The interaction between the unused shells is very large and they spread widely. Therefore, while there is a bandgap, E_g (or forbidden region) between the valence and conduction bands, splitting of higher orbit is so wide that they usually overlap.

The bands below the energy gap E g are completely filled at absolute zero temperature and the conduction band is empty. This is a very important point and has direct consequences on the conduction properties, as we shall see soon. The fundamental theory is that current conduction is not possible in empty and filled bands. The reasons about the empty band is obvious since current is not possible without carriers. The reason about the filled band is as follows: though the valence electrons move about the crystal but they can not be accelerated because the acceleration means gain of energy and there are no higher energy levels available to which they could rise.

We can now readily see that the crystal band structure does not allow current conduction at T=0. If we increase the temperature, however, thermal agitation increases and some valence electron will gain energy greater than E_g and jump into the conduction band. The electron in the conduction band is called a free electron, and its former place in the valence band is called a hole. Electrons in conduction band can gain energy when a field is applied, because there are many higher energy states available. The fact that electrons left the valence band leaves some empty energy levels, this allows conduction in the valence band as well. Electrons can now gain energy in the valence band also, and we observe a motion of holes in the direction of the field. Because of this we begin to speak of a hole as a current carrying particles.

According to the proceeding theory, an insulator must have a large bandgap, so that at room temperature the conduction band is practically empty and the valence band is practically filled and a semiconductors must have a narrower band gaps so that appreciable number of carriers are present in the valence and conduction bands at room temperature.

In metals, however, the valence and conduction bands overlap and application of an electric field can, therefore, accelerate a great sea of electrons. The non-existance of a bandgap make conduction in metal almost independent of temperature, as compared to semiconductors.

3.1 Concentration of Intrinsic Carriers

The concentration of intrinsic carriers, that is the number of electrons in conduction band per unit volume is given by:

$$n = 2(\frac{m_e kT}{2\pi h^2})^{3/2} exp(\mu - E_g)/kT \tag{1}$$

where m_e is the effective mass of electron, K is the Boltzman constant, T is the temperature in °Kelvin, μ is the Fermi level and E_g is the bandgap energy. Now, the concentration of holes in valence band is given by the expression,

$$p = 2(\frac{m_h kT}{2\pi h^2})^{3/2} exp(\mu/kT) \tag{2}$$

where m_h is the effective mass of a hole. Then a equlibrium relaton is given by multiply the expressions 1 and 2,

$$np = 4(\frac{kT}{2\pi h^2})^{3/2} (m_e.m_h)^{3/2} exp(-E_g/kT) \tag{3}$$

Hence, equation 3 does not involve the fermi level μ, and is known as the expression for the law of mass action. In the case of intrinsic (highly purified) crystals, the number of electrons is equal to the number of holes, as the thermal excitation of an electron leaves behind a hole in the valence band. Thus, from equation 3 above letting i, for intrinsic, we have:

$$n_i = p_i = 2(\frac{kT}{2\pi h^2})^{3/2} (m_e.m_h)^{3/4} exp(-E_g/2kT) \tag{4}$$

Thus, we see that the concentration of intrinsic carriers depends exponentially on $E_g/2kT$.

3.2 Conductivity of Intrinsic Semiconductors

The electrical conductivity, σ will be the sum of the contributions of both the electrons and the holes. Thus, $\sigma = en_i(\mu_n + \mu_h)$, where μ_e and μ_h are the average velocities acquired by the electrons and holes in a unit electric field and known as mobilities. And since, $n_i = p_i$ Eqn. 4,

$$\sigma = (K)T^{3/2}(\mu_n + \mu_h).exp\frac{-E_g}{2kT} \tag{5}$$

where K is a constant. The factor $T^{3/2}$ and the mobilities μ_n and μ_h change relatively slow with temperature compared to the exponential term, and hence the logarithm of resistivity, $\rho = (1/\sigma)$ varies linearly with $1/T$. The width of the energy gap may be determined from the slope of the curve. Thus, we have,

$$Log_e\rho = \frac{E_g}{2kT} - log_e K \tag{6}$$

4 Apparatus

FIGURE 1

Experimental setup of four probe method to measure resitivity of the samples at different temperature

The basic model for all these measurements is indicated in Figure 1. Four sharp probes are placed on a flat surface of the material to be measured, current is passed through the two outer electrodes, and the floating potential is measured across the inner pair. The experimental circuit used for measurement is illustrated schematically in Figure 2. A nominal value of probe spacing which has been found satisfactory is an equal distance of 2.0 mm between adjacent probes. This permit measurement with reasonable current of n-type or p-type semiconductor from 0.001 to 50 ohm.cm. The following text breifly describe the experimental set up.

1. Probe arrangement: It has four individually spring loaded probes, coated with Zn at the tips. The probes are colinear and equally spaced. The Zn coating and individual spring ensure good electrical contacts with the sample. The probes are mounted in a teflon bush which ensure a good electrical insulation between the

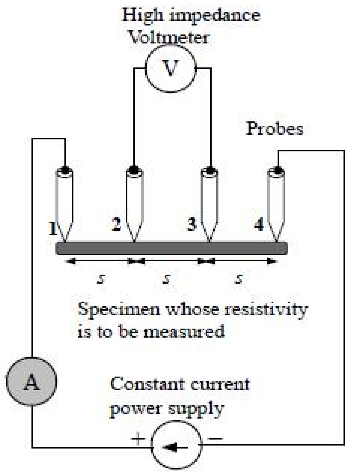

FIGURE 2

Schematic show the experimental circuit for the measurements

probe. A teflon spacer near the tips is also provided to keep the probes at equal distance. The whole arrangement is mounted on a suitable stand and leads are provided for current and voltage measurements.

2. Sample: Ge Crystal in the form of a chip/slice
3. Oven: It is a small oven for the variation of temperature of the crystal from room temperature to about 200 °C.
4. Four Probes Set-up (measuring Unit) includes, Oven Controller, Multi-range Digital Voltmeter, and constant current generator.

4.1 Resitivity Measurements

Figure 2, shows the geometry of this case. Four probes are spaced S_1, S_2 and S_3 apart. Current I is passed through the outer probes (1 and 4) and the floating potential V is measured across the inner pair of probes 2 and 3. The floating potential V_f at a distance r from an electrode carrying a current I in a material of resistivity ρ_0 is given by

$$V_f = \frac{\rho_0 . I}{2\pi r} \tag{7}$$

In the model shown in Figure 2 there are two current-carrying electrodes, numbered 1 and 4, and the floating potential V_f, at any Y point in the semiconductor is the difference between the potential induced by each of the electrodes, since they carry currents of equal magnitude but in opposite directions. Thus,

$$V_f = \frac{\rho_0 I}{2\pi}(\frac{1}{r_1} - \frac{1}{r_4}) \tag{8}$$

where r_1 is the distance from probe number 1 and r_4 is the distance from probe number 4. The floating potentials at probe 2, V_{f2} and at probe 3, V_{f3} can be calculated from Eqn. 8 by substituting the proper distance as follows:

$$V_{f2} = \frac{\rho_0 I}{2\pi}(\frac{1}{S_1} - \frac{1}{S_2 + S_3}) \tag{9}$$

$$V_{f3} = \frac{\rho_0 I}{2\pi}(\frac{1}{S_1 + S_2} - \frac{1}{S_3}) \tag{10}$$

The potential difference V between probes 2 and 3 is then,

$$V = V_{f2} - V_{f3} = \frac{\rho_0 I}{2\pi}(\frac{1}{S_1} + \frac{1}{S_3} - \frac{1}{S_2 + S_3} - \frac{1}{S_1 + S_2}) \tag{11}$$

and the resitivity ρ_0 is computable as

$$\rho_0 = \frac{V}{I} - \frac{2}{(\frac{1}{S_1} + \frac{1}{S_3} - \frac{1}{S_1+S_2} - \frac{1}{S_2+S_3})} \tag{12}$$

when the point spacing equal, that is, S_1=S_2=S_3=S the above equation simplifies as

$$\rho_0 = \frac{V}{I} \times 2\pi S \tag{13}$$

5 Procedure

1. Put the sample on the base plate of the four probe arrangement. Unscrew the pipe holding the four probes, and let the four probes rest in the middle of the sample. Apply very gentle pressure on the probes and tighten the pipe in this position. Check the continuity between the probes for proper electrical contacts. **Caution:** The Ge crystal is very brittle. Therefore, use only the minimum pressure required for proper electrical contacts.

2. Connect the outer pair of the probes (red/black) leads to the constant current power supply and the inner pair (yellow/green) to the probe's voltage terminals.

3. Place the four-probe arrangement in the oven and connect the sensor lead to the RTD connector on the panel.

4. Switch on the mains supply of the four-probe set-up and put the digital panel meter in the current measuring inside. In this position, the LED facing `mV` will glow and the meter would read the voltage between the probes.

5. Now, put the panel of the digital meter inside in voltage. In this position, the `mV` would glow and the meter would read the voltage between the probes.

6. Switch on the temperature controller and adjust the set-temperature. The green LED would light up indicating that the oven is 'ON' and the temperature would start rising. Temperature of the oven in Kelvin is indicated by the DPM.

7. Now, take the voltage reading corresponding to the temperature and tabulate the data starting from 320k to 400k.

6 Observations

Distance between the probes (s) = 2 mm, Thickness of the crystal (w) = 0.5 mm

Current (I) = 5 mA, Correction parameter G_7(W/S)=5.89

S. No	**Temperature (K)**	**Voltage (V)**	ρ **(ohm.cm)**	T^{-1} $\times 10^{-3}$	**Log P**
1.	310				
2.	320				
3.	330				
4.	340				
5.	350				
6.	360				
7.	370				
8.	380				
9.	390				
10.	400				

7 Calculations

From Eqn 13,

$$\rho_0 = \frac{V}{I} \times 2\pi S \tag{14}$$

Since the thickness of the crystal is small compared to the probe distance a correction factor for it has to be applied. Further the bottom surface is non-conducting in the present case, resitivity can be determined from,

$$\rho = \frac{\rho_0}{G_7(W/S)} \tag{15}$$

Thus ρ may be calculated for various temperatures. Plot a graph for $Log_{10}\rho$ vs. $T^{-1} \times 10^{-3}$ and by using Eqn. 6,

$$Log_e\rho = \frac{E_g}{2kT} - log_e K \tag{16}$$

the slope of the curve is given by, $\frac{log_e\rho}{\frac{1}{T}} = \frac{E_g}{2k}$. Thus E_g can be obtained from the slope of the graph. Note that log_e=2.3026 log_10 and the Eqn. 6 is applicable only in the intrinsic region of the semiconductor. A typical graph is shown in Figure 3.

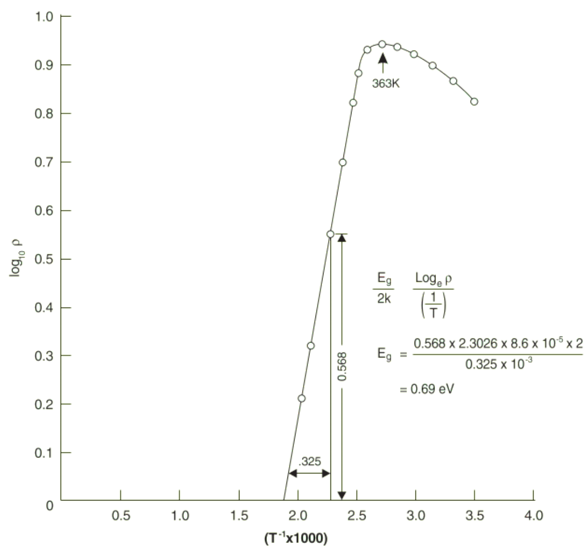

FIGURE 3

Resitivity of Ge crystal as a function of temperature

8 Results

The bandgap of the semiconductor (Ge) by four probe method is calculated as, E_g=______________ eV.

Instructor comments:

Signature

9 Assignments

1. What is the advantage of Four Probe method over the other conventional methods.
2. Why a semiconductor behaves as an insulator at zero degree kelvin.
3. Does the geometry of the sample plays a role in measurements?
4. Explain the behaviour of the $log_{10}\rho$ vs. $1/T$ curve.

10 References

10.1 Basics

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10.2 Experiment

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