

Determination of the Band-Gap of a Semiconductor: *Germanium Chip Using Four Probe Set-Up*

Musa Abubakar Bilya¹, Mujahid Hassan Sani²

¹Physics Department, Jodhpur National University, 342001, Boranada, Rajasthan State of India

Abstract: This paper states the step by step experimental approach in determining the band gap of a semiconductor (Germanium crystal) using four probe set-up, which is a method that permits measurements of resistivity in samples (Germanium). Starting with an introduction, this paper further highlights about the Germanium crystal and continues to give a brief overview of the electronic conduction in solids. Experiment was conducted to determine the band gap of a germanium crystal. The apparatus used are mentioned, and the procedures taking in determining the required results are explicitly stated. Observations were made, and the readings observed are tabulated. Thus, it is observed that a plot of the log of resistivity in ohms-meter against the inverse of temperature in (kelvin)⁻¹ gives a curve whose slope was used to determine the band gap of the semiconductor material, (the germanium crystal). The calculation is shown in this paper, and the bandgap calculated is approximately 0.70 eV, which tallies with the standard experimental result.

Keywords: Germanium crystal, semiconductor, electronic conduction, Probe Set-up, Bandgap

1. Introduction

Semiconductors are materials whose electronic properties are intermediate between those of metals and insulators. These characteristics are determined by the structure of the crystal, bonding characteristics, electronic energy bands, and also by the fact that unlike metals, a semiconductor has both the positive (hole) and the negative (electron) carriers of electricity whose densities can be controlled by doping the pure semiconductor with chemical impurities during the crystal growth. In classifying the solids by their electrical properties, it should be understood that there are two types of materials; the metals and the semiconductors.

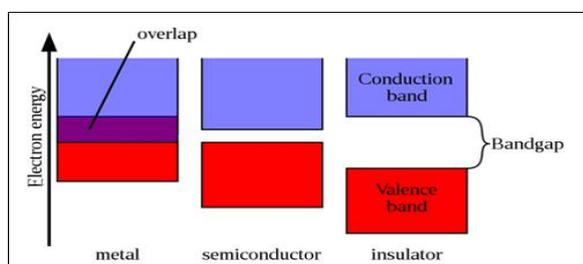


Figure 1: Shows the Band Gap in Semiconductors, Insulators, and the overlap in Metals.

Metals are said to have permanent electron gases permeating the whole of the solid and are confined within the solid. And the insulators are materials with virtually no free moving electrons; hence there is no electron gas as a result of which no electrical conductivity (S.O Pillai, 2010).

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.

2. Literature Review

Ms. NeelamSwarnkar and Dr. Purnima SwarupKhare (Jan-Feb, 2015), wrote on the “Analysis of Band Gap of Thermoelectric materials”. They opined that the thermoelectric properties are based on some parameters as the figure of merit, thermal conductivity, electrical conductivity and Seebeck coefficient. It is observed that the electric conductivity depends upon the energy Band Gap of the thermoelectric material. As soon as the Band Gap of the thermoelectric material reduces, it automatically increases the thermoelectric performance. It was concluded that the Band Gap of the semiconductor tends to decrease as the temperature increases. Hence, germanium is useful for doping or as a catalyst in any reaction involving the enhancement of the thermoelectric material.

Eunice S.M. Goh, T.P Chen, and Y.C Liu (January 22, 2010), wrote on the “Thickness Effect on the Band Gap and Optical properties of germanium thin film”. The band gap and optical properties of the dielectric functions, and optical constants of the Ge thin films with various thicknesses below 50nm, which were synthesized with electron beam evaporation technique, have been determined using spectroscopic ellipsometry and UV-visible spectrophotometry. These described the optical properties with the Forouhi-Bloomer model. They concluded that, for film thickness smaller than ~10nm, a band gap expansion is observed as compared to the bulk crystalline Ge, which is attributed to the one-dimensional quantum confinement effect. However, a bandgap reduction was observed for thickness larger than ~10nm, which was explained in terms of the amorphous effect in the Ge layers.

Moustafa El Kurdi, Guy Fishman, SébastienSavage, and Philippe Boucaud (January 13, 2010), wrote on “Band structure and optical gain of tensile-strained germanium based on 30 band K.P formalism”. A transition from indirect to direct band gap has been predicted for tensile-strained

germanium since the energy position of the conduction valley versus strain decreases more rapidly than the band-edge L valley. A direct band gap is of particular importance for light emission and to achieve population inversion. Its occurrence would be very promising for the demonstration of a germanium laser and the development of germanium and silicon photonics. They calculate the energy band variation as a function of strain and inferred that the crossover from indirect to direct band gap occurs for a tensile in-plane strain of 1.9%. The effective masses of density of states are deduced from the calculated conduction and valence band density of states. Significant deviations are observed as compared to the effective masses of density of states values of unstrained bulk germanium. Finally, they calculated the optical gain that can be achieved with the tensile-strained bulk germanium.

V. N. Smelyanskiy (Sep 23, 2014) et. al, wrote on the donor spin qubits in Ge-based phononic crystals. It was highlighted that the spin orbit interaction for donor spins in germanium is in many orders of magnitude stronger than in silicon. In uniform bulk material, it leads to very short spin life time. They noted that as the life time increases dramatically when the donor is placed into a quasi 2D phononic crystal, and the energy of the Zeeman splitting turned to lie within a phonon bandgap. In this situation, single phonon process is suppressed by the energy conservation. The remaining two phonon decay channel is very slow. The Zeeman splitting within the gap can be finely tuned to induce a strong, long range coupling between the spins of remote donors via exchange by virtual phonons.

A.V. Sachenko et. al, (2000) wrote on the analysis of the attainable efficiency of a direct bandgap betavoltaic elements. They further stated that the conversion of energy of beta particles into electric energy in a p-n junction based on direct bandgap semiconductors, such as the GaAs, considering realistic semiconductor system parameters is analyzed. It was resolved or concluded that the attainable beta conversion efficiency, in the case of a $^3\text{H}/\text{GaAs}$ combination is found to exceed that of the $^{147}\text{pm}/\text{GaAs}$ combination.

G. Cassabois, P. Valvin, and B. Gil (December 10, 2015), wrote on the "Hexagonal boron nitride is an indirect bandgap semiconductor". Hexagonal boron nitride is a wide bandgap semiconductor with a very high thermal and chemical stability often used in devices operating under extreme conditions. The growth of high purity crystals has recently revealed the potential of this material for deep ultraviolet emission, with an intense emission around 215nm. Thus, it was disclosed that the existence of phonon-assisted optical transition was demonstrated, and the exciton binding energy was measured to about 130meV by two photon spectroscopy.

Chen Yong and Ravaioli Umberto (March, 2005), wrote on the "Band Structure Calculation of Si and Ge by Non-Local Empirical Pseudo-Potential Technique". The principle of spatial nonlocal empirical pseudo potential and its detailed calculation procedure is presented. Consequently, this technique is employed to calculate the band structures of Silicon and Germanium. By comparing the results with photo-emission experimental data, the validity and accuracy

of this calculation are fully conformed for valence or conductance band, respectively. Thus they concluded that the spin-orbit Hamiltonian will only affect the energy band gap and another conductance or valence band structure. Therefore, this nonlocal approach without spin-orbit part is adequate for the device simulation of only one carrier transport such as metal oxide semiconductor field effect transistors (MOSFETs), and it can significantly reduce the complication of the band structure calculation.

3. Apparatus Used

- 1) Probe arrangement
- 2) Sample: Ge Crystal chip
- 3) Oven
- 4) Four Probes Set-up (measuring Unit) Having Oven Controller, Multi-range Digital Voltmeter, and constant current generator.



Figure 1: Experimental Set-up

3.1 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.
- 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 385k.

3.2 Observation and Tabulation

S/N	TEMP, T(K)	Voltage (VOLTS)	p(Ωm)	T ⁻¹ × 10 ⁻³	Log p
1.	320.00	49.70	15.10	3.125	1.18
2.	325.00	43.80	13.31	3.076	1.12
3.	330.00	39.10	11.88	3.030	1.07
4.	335.00	35.00	10.64	2.985	1.02
5.	340.00	30.40	9.24	2.941	0.96
6.	345.00	26.20	7.96	2.898	0.90
7.	350.00	22.60	6.87	2.857	0.83
8.	355.00	19.20	5.83	2.816	0.76
9.	360.00	16.50	5.03	2.777	0.70
10.	365.00	14.20	4.31	2.739	0.63
11.	370.00	12.20	3.70	2.702	0.56
12.	375.00	10.60	3.22	2.666	0.50
13.	380.00	9.20	2.79	2.631	0.44
14.	385.00	7.90	2.40	2.597	0.38

Distance between Probes = 0.200 cm
 Thickness of the Crystal (w) = 0.050 cm

3.3 Graph of Logp against T⁻¹ × 10⁻³

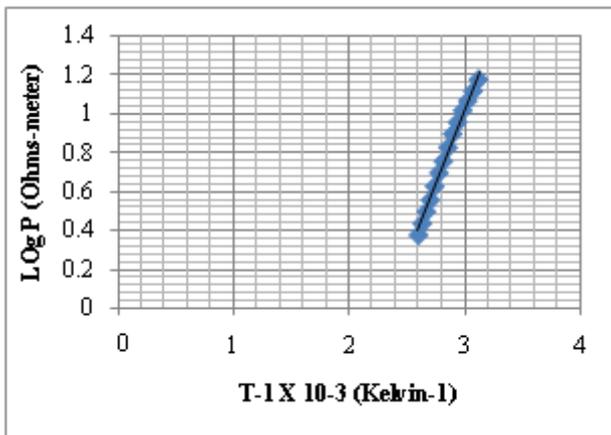


Figure 3: Graph of the resistivity, Log P of a germanium crystal as a function of the inverse of temperature, T⁻¹ × 10⁻³. For T < 363°K, conduction is due to the electrons transferred to the conduction Band (and the corresponding holes created in the valence band), called the intrinsic region.

4. Concentration of Intrinsic Carriers

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

$$n = 2 \left(\frac{MeKT}{2\pi h^2} \right)^{3/2} \exp(-Eg/kT) \quad (1)$$

Where Me— effective mass of electron

And the concentration of holes in valence band is given by the expression

$$p = 2 \left(\frac{MhKT}{2\pi h^2} \right)^{3/2} \exp(-\mu/kT) \quad (2)$$

Where Mh ---- effective mass of hole

If we multiply the expression for n and p together, we obtain an equilibrium relation given by;

$$np = 4 \left(\frac{KT}{2\pi h^2} \right)^{3/2} (Me.Mh)^{3/2} \exp(-Eg/kT) \quad (3)$$

Hence, equation (3) does not involve the fermi level μ, and is known as the expression for the law of mass action. Thus, in the above equation, K-is the Boltzmann's constant, μ- Fermi level, Eg- the Bandgap energy, and T- Temperature in °K.

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:

$$n_i = p_i = 2 \left(\frac{KT}{2\pi h^2} \right)^{3/2} (Me.Mh)^{3/2} \exp(-Eg/2kT) \quad (4)$$

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

4.1 Conductivity of Intrinsic Semiconductors

The electrical conductivity, δ will be the sum of the contributions of both the electrons and the holes. Thus;

$$\delta = en_i(\mu_n + \mu_h); \quad \text{Since } n_i = p_i$$

$$\delta = (K)T^{3/2}(\mu_n + \mu_h). \exp\left(\frac{-Eg}{2kT}\right) \quad (5)$$

Using the equation (4) above, and taking k as 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, P (=1/ δ) varies linearly with 1/T. The width of the energy gap may be determined from the slope of the curve. Thus, we have,

$$\text{Log}_e P = \frac{Eg}{2kT} - \text{log}_e K \quad (6)$$

5. Calculations

Given that;

$$p_o = \frac{v}{l} \times 2\pi s \quad (1)$$

Since the thickness of the crystal is very small compared to the probe distance S, a correction factor for it has to be applied. In this case, the bottom surface is non-conducting, so that the correction factor would be, from the graph,

$$P = \frac{p_o}{G_7} (w/s) \quad (2)$$

Where G₇ is the correction factor, and we know that;

$$p_o = \frac{V}{l} 2\pi S. \quad (3)$$

Where S=0.200cm, is the distance between the probes. Now, substituting the proper values into (3) we have;

$$p_o = \frac{V}{l} \times 2.0 \times 3.14 \times 0.20$$

$$= \frac{V}{l} \times 1.256 \quad (6)$$

Thus, the correction factor corresponding to G₇(0.50/0.20) or G₇(0.350) is 5.89.

$$\text{Hence; } P = \frac{p_o}{5.89} = \frac{V}{l} \left(\frac{1.256}{5.89} \right) = \frac{V}{l} \times 0.213$$

Now, putting I = 7.00 mA (constant for whole sets of readings).

$$P = \frac{0.213XV}{7.00 \times 10^{-3}} = 30.40 \times V \quad (7)$$

To calculate the energy bandgap, we proceed as follows;

Log p = 0.56 (obtained from the plotted graph)

$$\frac{1}{T} = 0.32 \times 10^{-3}$$

$$\text{Hence, } \frac{\text{Log}_e P}{\frac{1}{T}} = \frac{2.3026 \times \text{Log } p}{\frac{1}{T}}$$

$$= \frac{2.3026 \times 0.56}{0.32 \times 10^{-3}} = 4029 \quad (2)$$

Thus,

$$E_g = \frac{2 \times k \times \text{Loge}P}{T^{-1}} = 2.0 \times 8.60 \times 10^{-5} \times 4029$$
$$= 0.693 \approx 0.70 \text{ eV} \quad (3)$$

Where E_g is the band gap, and is approximately equal to $E_g = 0.70 \text{ eV}$

6. Precautions Taking while Carrying Out the Experiment

- 1) The Ge crystal is very brittle; as such only minimum pressure was applied on it for proper electrical contact.
- 2) I ensured that the oven was turned off after every reading, to avoid overheating.
- 3) The current through the sample was adjusted to the most bearable minimum, because if large, it will amount to overheating.

7. Conclusion

The experiment was concluded and proven that the band gap energy between the conduction band and the valence band is approximately equal to; $E_g \approx 0.70 \text{ eV}$.

References

- [1] C. Kittel, Introduction to Solid State Physics, John Wiley & Sons Inc., New York, 1996.
- [2] N.Swarnkar, P.S Khare (2015), "Analysis of Bandgap of Thermoelectric Materials", IOSR Journals of Applied Physics, Volume 7, issue 1 ver III, pp 26.
- [3] Eunice S.M. Goh, T.P Chen, C.Q Sun and Y.C Liu (2010), "Thickness Effect on the Band Gap and Optical Properties of Germanium Thin Films", Journal of Applied physics 107, 024305.
- [4] M. El kurdi, G. Fishman, S. Sauvage, and P. Boucaud (2010), "Band Structure and Optical Gain of Tensile-Strained Germanium Based on a 30 Band **K.P** Formalism", Journal of Applied Physics 107, 013710.
- [5] V. N Smelyanskiy (2014), "Donor Spin Qubits in Ge-Based Phononic Crystals", Quantum Artificial Intelligencelaboratory, NASA Ames research center, mail stop 269-3, moffet field CA 94035.
- [6] A.V Sachencoet. Al (2010), "Analysis of The Attainable Efficiency of A Direct Band Gap Betavoltaic Element.
- [7] G. Cassabois, P. Valvin, and B.Gil (2015), "Hexagonal Boron Nitride is An Indirect Bandgap Semiconductor", Laboratoire Charles Coulomb (L2C), UMR 5221 CNRS-Universite de Montpellier, F-34095, Montpellier, France.
- [8] C. yong, R. Umberto (2005), "Band Structure Calculation of Si and Ge by Non-Local Empirical Pseudo-Potential Technique", *Journal of Electronic Science and Technology of China*, Vol. 3 No 1, pp 52-56.
- [9] S.O Pillai (2010), "Solid State Physics", *New Age International Publishers Revised 6th edition, Chapter 10, pp 521.*
- [10] SES Instrument Pvt. Ltd (2015), "Four Probe Set-up Manual", Model DFP-03, #686.ISO 9001:2008 certified company.

Author Profile



Musa Abubakar Bilya M.Sc. Student of the Jodhpur National University, Faculty of Applied Sciences, Department of Physics, 342001 Boranada, Jodhpur, Rajasthan State of India.



Mujahid Hassan Sani, M.Sc. student of the Jodhpur National University, Faculty of Applied Sciences, Department of Physics, 342001 Boranada, Jodhpur, Rajasthan State of India.