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Investigating the Impacts of Temperature on the Electronic Conductivity of Si AND GaAs

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Abstract: This work explains the impacts of temperature on the electronic conductivity of silicon and gallium arsenide. Illustrations of how conductivity varies at different temperatures were depicted using equations and graphs. The effective use of semiconductor materials depends on the proper fabrication of the material about its temperature dependence. Also, the analysis of the variation of electronic conductivity in both silicon and that of gallium arsenide with a small band gap is performed towards analyzing the impacts of this on silicon and gallium arsenide.

Keywords: Temperature, Silicon, Gallium Arsenide, Conductivity, Variation.

I. INTRODUCTION

Before the invention of semiconductors, the electron tube was the basis of virtually all electronic devices. An electron tube is also known as a vacuum tube or valve is a glass or metal enclosure in which electrons move through the vacuum from one metal electrode to another. The vacuum tube is often used to amplify weak currents or act as a one-way valve (rectifier) for electric current. The simplest kind of electron tube is the diode, which was invented in 1904 by John A Fleming. The diode had two electrodes inside – the negative electrode or "Anode". A diode regulates the flow of electric current and acts like a one-way valve turning the current on and off. When a battery is connected to the metal cathode, it heats up and electrons "boil off" from its surface they fly around inside the glass tube and form an invisible cloud around the cathode (Oldfield *et al* 1960)

A. Silicon (Si)

Silicon is a chemical element with the symbol Si and atomic number 14. A hard and brittle crystalline solid with a blue-grey metallic luster, it is a tetravalent metalloid. It belongs to group 14 in the periodic table. It was first prepared in pure form only in 1823 by Jons Jakob Berzelius.

Silicon is the eighth most common element in the universe by mass, but very rarely occurs as the pure element in the earth's crust. It is most widely distributed in sands, planetoids, and planets as various forms of silicon dioxide (silica) or silicates. Over 90% of the earth's crust is composed of silicate materials, making silicon the second most abundant element in the earth's crust (28% by mass) after oxygen. (Meija *et al* 2016).

B. Gallium Arsenide (GaAs)

Gallium arsenide (GaAs) is a compound of the element's gallium and arsenic. It is an III-V direct bandgap semiconductor with a zinc blend structure. Gallium arsenide is often used as a substrate material for the epitaxial growth of other III-V semiconductors including indium gallium arsenide and others. (Moss and Ledwith 1987) GaAs have higher saturated electron velocity and higher electron mobility, allowing gallium arsenide transition to functioning at frequencies in the excess of 250GHz. GaAs devices are relatively insensitive to over-heating owing to their wider energy bandgap. (Smart, Lesley, Moore and Elanie 2005).

II. MATERIALS AND METHOD

A. Materials

This research aims to analyze the impacts of temperature on the electronic conductivity in both silicon and gallium arsenide at different temperatures. To achieve this aim, a mathematical expression that relates electronic conductivity with temperature is derived. This mathematical expression is used to see how temperature affects electronic conductivity in silicon and gallium arsenide semiconductors by the use of graphical analysis.

B. Method

In this research work, a method of graph analysis is used. This involves the use of graphs which would be plotted to show how the electronic conductivity of a semiconductor material is affected by temperature.

C. Conductivity Of A Semiconductor

The current flow in a semiconductor is using electron current I_n and hole current I_p. Hence the net current flowing in the system is given as;

$$I = I_n + I_p \qquad (1)$$

Recall that current $I = neVA$

This implies that $I_n = neV_nA$ $I_p = peV_pA$ and. Substituting the last two terms into Equation (1), we obtain:

$$I = neV_nA + peV_pA \qquad (2)$$

Also, there exists a relationship between drift velocity V and electric field E . We have that $V \alpha E$

$\Rightarrow V = \mu E$ where μ is the charge carrier mobility

$\therefore V_n = \mu_n E$ and $V_p = \mu_p E$. Substituting the last terms in Equation (2), we obtain

$I = ne\mu_n EA + pe\mu_p EA$. Factorizing out common terms, we have

$$I = eA(n\mu_n + p\mu_p)E \qquad (3)$$

Remember that an applied electric field E is defined as the applied voltage per unit length i.e., $E = \frac{V}{l}$ Substituting E into Equation (3), we have

$$I = eA(n\mu_n + p\mu_p)\frac{V}{l} \qquad (4)$$

$V = IR$ from Ohm's law. Solving for resistance R , we have that

$$R = \frac{V}{I} \qquad (5)$$

Substituting I into Equation (5), we have;

$$R = \frac{V}{eA(n\mu_n + p\mu_p)\frac{V}{l}}$$

$$\therefore R = \frac{l}{eA(n\mu_n + p\mu_p)} = \frac{l}{A} \bullet \frac{1}{(n\mu_n + p\mu_p)e} \qquad (6)$$

In Equation (6), there exists a relationship between resistance and conductivity

$$R = \frac{l}{A} \bullet \rho \qquad (7)$$

Comparing Equations (6) and (7), we have: $\rho = \frac{1}{(n\mu_n + p\mu_p)e}$ where ρ is the resistivity of the material.

$\rho = \frac{1}{\sigma}$. This implies that $\sigma = (n\mu_n + p\mu_p)e$ (8)

Equation (8) represents the conductivity of a semiconductor. But then the electron concentration n is given as;

$$n = N_c \exp - \left[\frac{E_c - E_f}{KT}\right] \qquad (9)$$

Also, the electron conductivity of a semiconductor is given as;

$\sigma_n = q\mu_n n$

Substituting the relation in Equation (9), we have;

$$\sigma_n = q\mu_n N_c \exp - \frac{(E_c - E_f)}{KT} \qquad (10)$$

Taking the log of both sides of the last equation, we obtain;

$$\ln \sigma_n = inq + \ln \mu_n + \ln N_C - \frac{(E_C - E_F)}{KT} \qquad (11)$$

Also, for hole conductivity we have;

$$\sigma_n = q\mu_p p \qquad (12)$$

But the hole concentration P is given as:

$$P = N_V \exp - \frac{(E_f - E_v)}{KT} \qquad (13)$$

Using the last equation in (12) we obtain

$$\sigma_p = q\mu_p N_v \exp - \frac{(E_f - E_v)}{KT} \qquad (14)$$

$$\ln \sigma_p = \ln q + \ln \mu_p + \ln N_v - \frac{(E_f - E_v)}{KT} \qquad (15)$$

By definition the total conductivity is given by

$\sigma = \sigma_n + \sigma_p$

$$\therefore \sigma = \left[\ln q + \ln \mu_n + \ln N_c - \frac{(E_c - E_f)}{KT} \right] + \left[\ln q + \ln \mu_p + \ln N_v - \frac{(E_f - E_v)}{KT} \right] \qquad (16)$$

Equation (16) is the total conductivity of a semiconductor.

Where:

q = Charge

n = Electron

p = Hole

μ_n = Electron mobility

μ_p = Hole mobility

N_c = Effective density of state in the conduction band

N_v = Effective density of state in the valence band

E_c = Energy in conduction band

E_v = Energy in valence band

E_f = Fermi energy

K = Boltzmann's constant

T = Temperature

III. RESULTS

The mathematical expression explaining the total conductivity of a semiconductor is given in equation (16). From this equation, conductivity was plotted against temperature for both silicon and gallium arsenide.

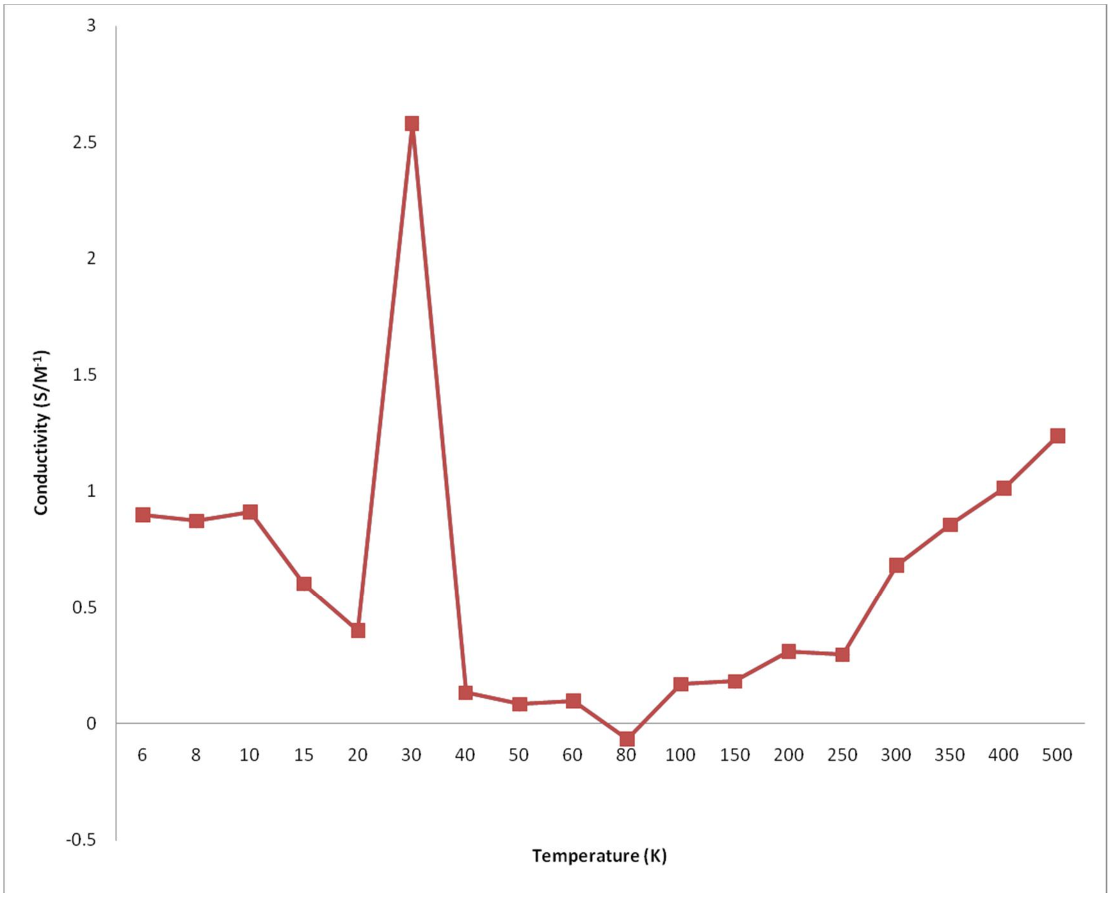

Fig. 1 Graph of conductivity against temperature for silicon at N_d 4 x 10^{13}

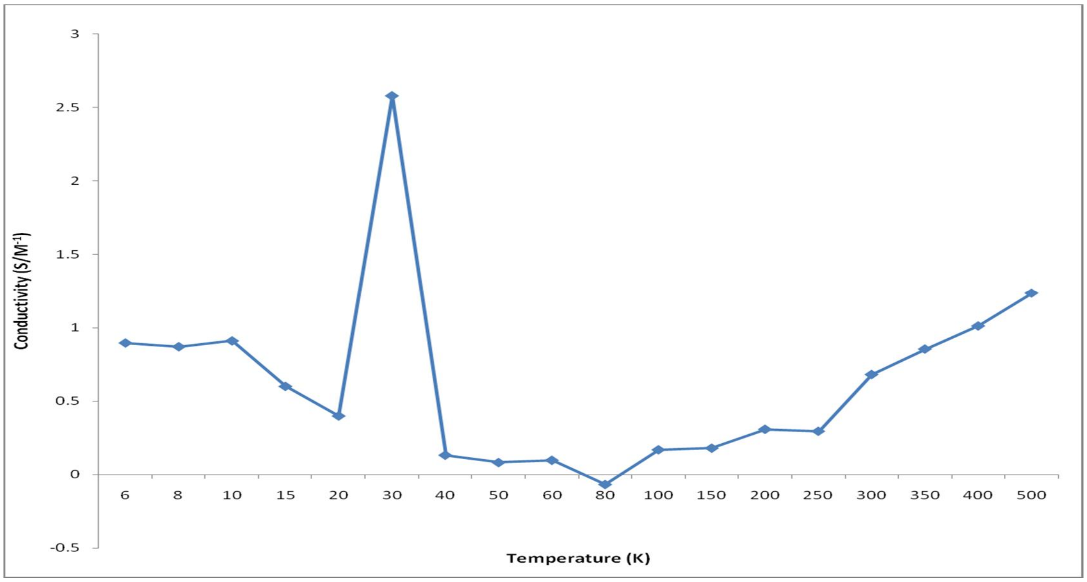

Fig. 2 Graph of conductivity against temperature for silicon at N_d 4 x 10^{14}

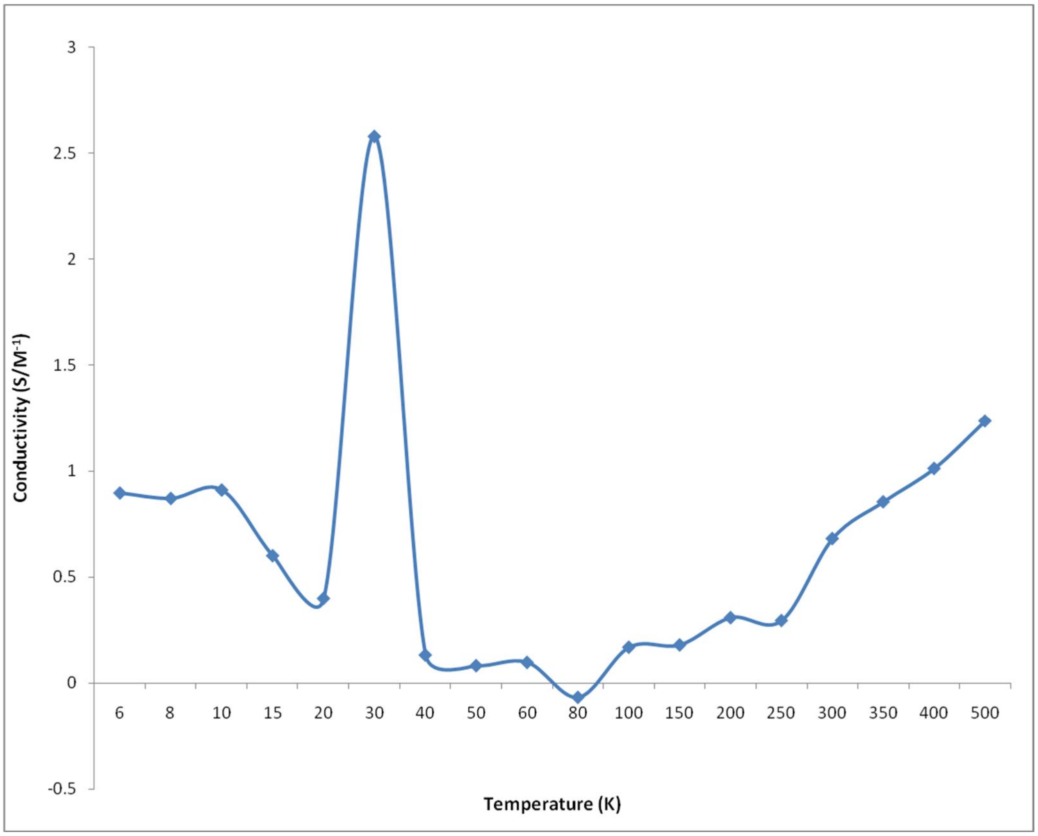

Fig. 3 Graph of conductivity against temperature for silicon at N_d 4 x 10^{15}

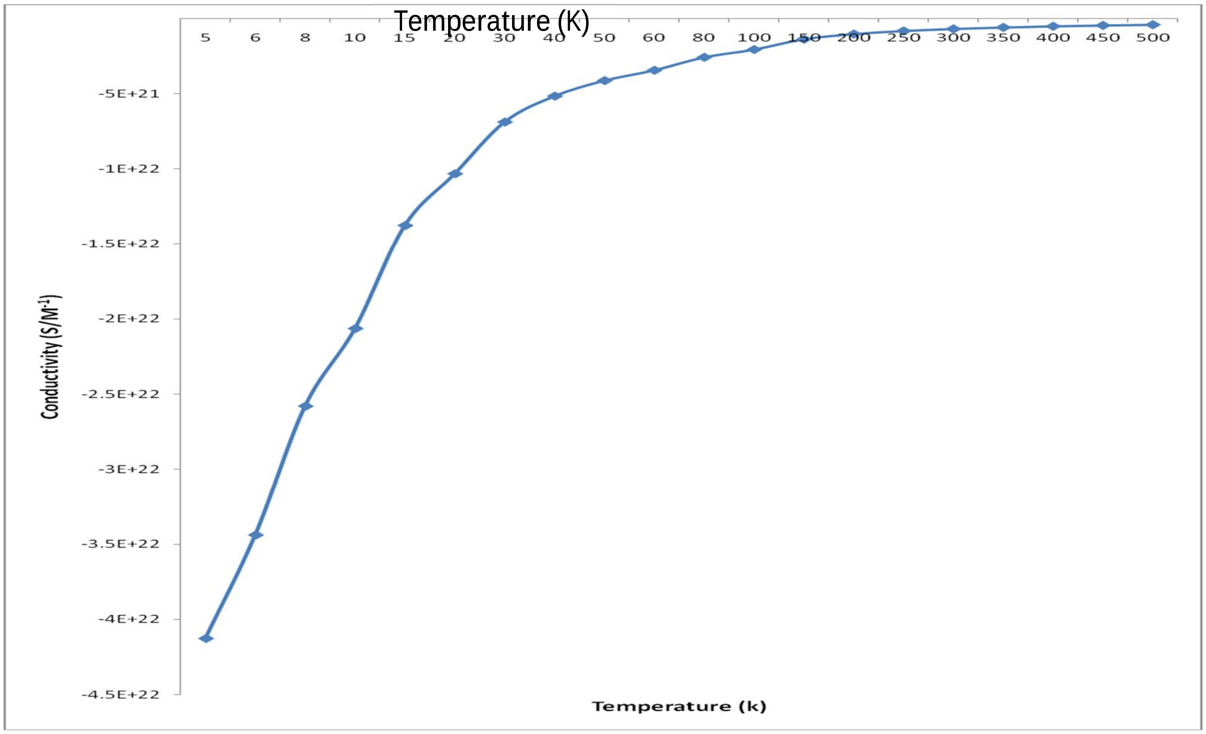

Fig. 4 graph of conductivity against temperature for gallium arsenide at N_d 10^{17}

Temperature (K)

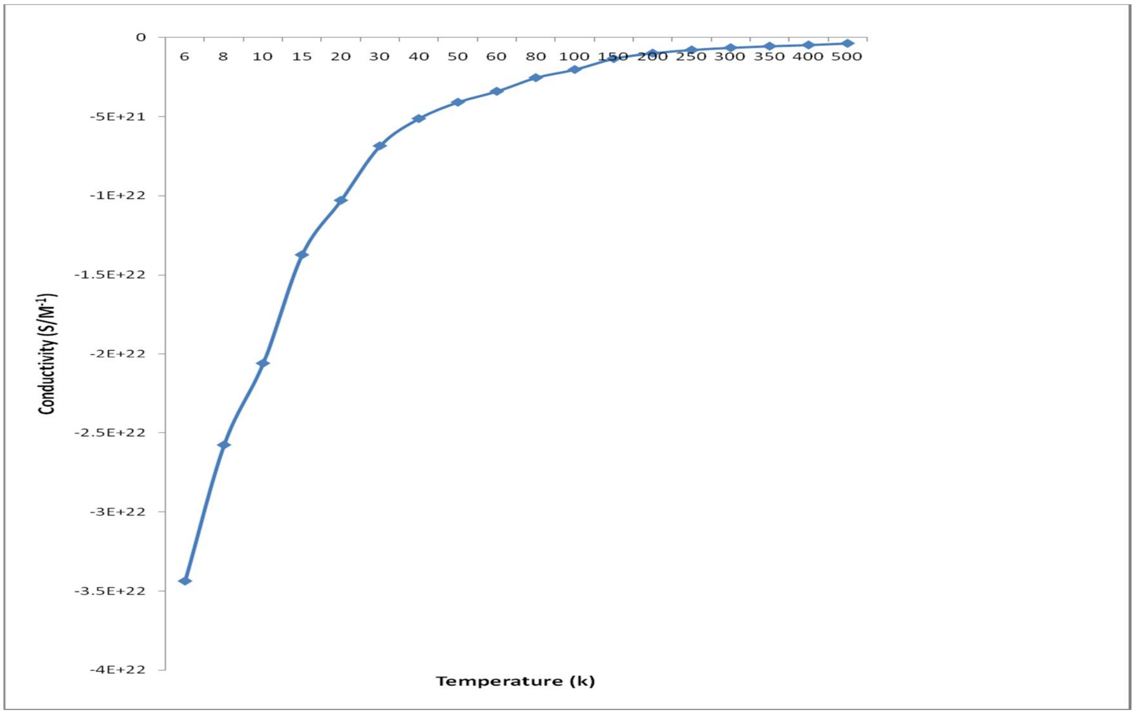

Fig. 5 graph of conductivity against temperature for gallium arsenide at N_d 10^{18}

Temperature (K)

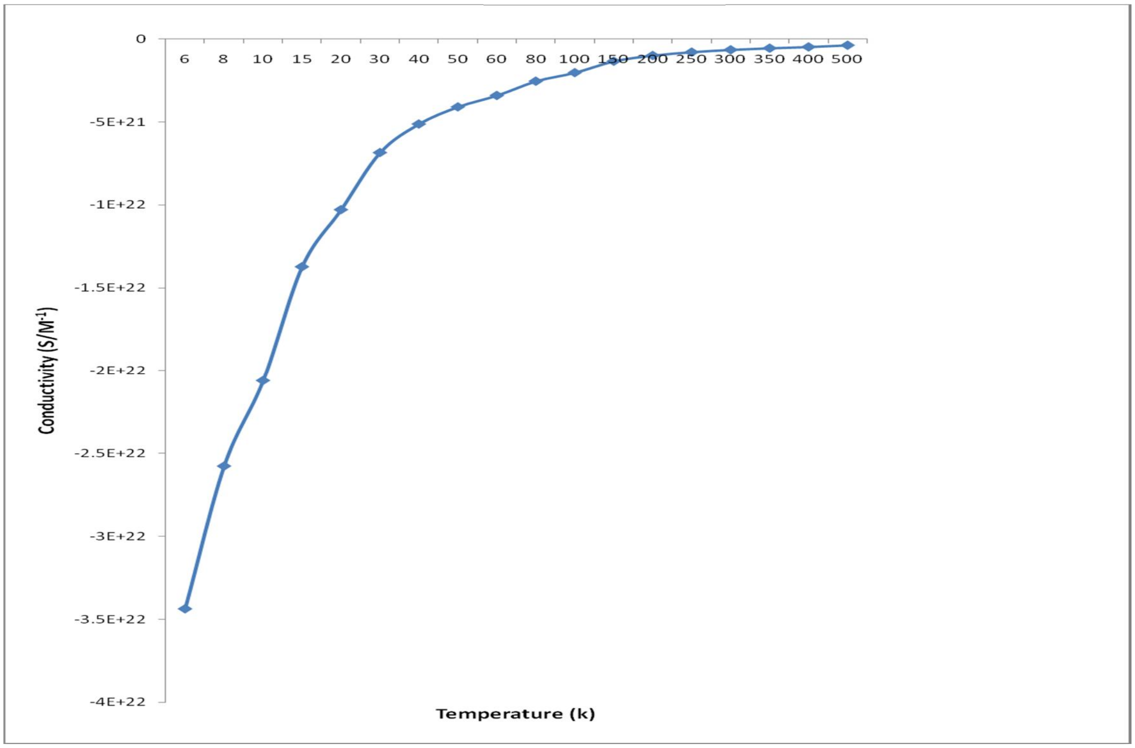

Fig. 6 graph of conductivity against temperature for gallium arsenide at N_d 10^{19}

IV. DISCUSSION

The graphs which are shown in fig 1, fig 2, fig 3, fig 4, fig 5, and fig 6 were plotted from a computed data in the appendix using equation (16) shows the effect of temperature on the electronic conductivity for both silicon and gallium arsenide at a temperature range from 5k to 500k. conductivity depends on both carrier concentration and mobility, so there is a variety of possible temperature dependencies for conductivity. For instance, at a fairly how temperature (less than 200k), the dominant scattering mechanism might be impurity scattering ($\mu \alpha T^{\frac{3}{2}}$) while the carrier concentration is determined by extrinsic doping. Therefore, conductivity would be seen to increase with temperature $\left(5 \alpha T\right)$. Other possibilities, depending on the material, doping and temperature will show the different temperature dependence of conductivity. The current flow in semiconductors is using electrons and holes. The covalent bond that exists in semiconductors must be broken and the charge carriers (electrons and holes) are produced in pairs and their movement in opposite direction brings about conduction. When the temperature of a semiconductor is increased, electrons move from the valence band into the conduction band. An increase in the temperature of a semiconductor brings about an increase in its conductivity and a decrease in its receptivity.

The sum of the electron conductivity and hole conductivity as shown in equation (16) gives the total conductivity that has been used to plot the graphs as shown in the result of this research work. It can be seen that an increase in temperature leads to an increase in the conductivity of silicon at (N_d $4x10^{13}$, $4x10^{14}$, $4x10^{15}$) respectively while in GaAs its wide band gap has a negative conductivity coefficient at (N_d 10^{17}, 10^{18}, 10^{19}) respectively.

V. CONCLUSION

The results obtained in this research work agree strongly with the theory that the electronic properties of a semiconductor are completely determined by the comparatively small number of electrons excited into the conduction band and holes left in the valence band. The band gap of any semiconductor material depends on temperature reason, because of the thermal expansion which the electrons experience.

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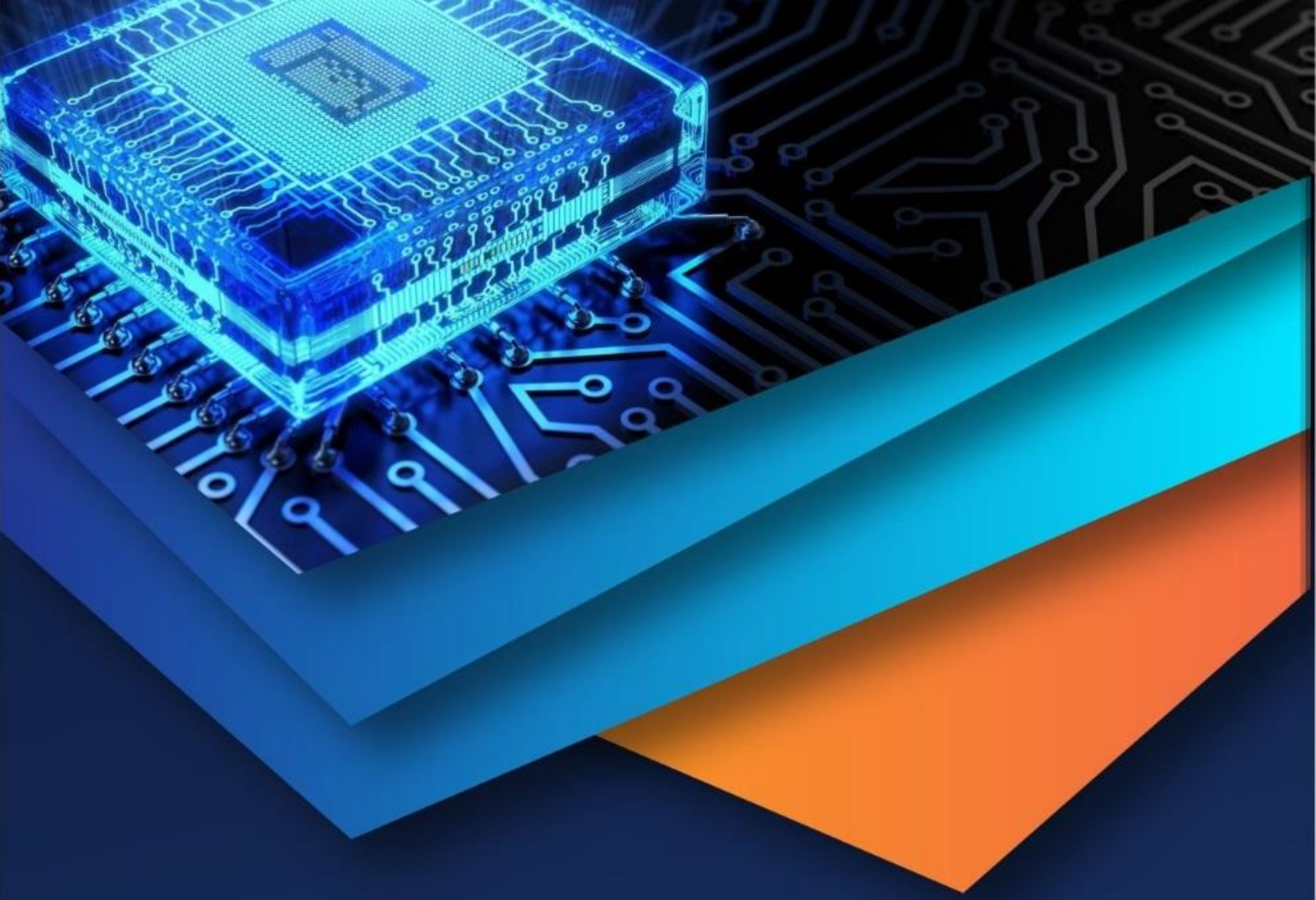

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