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STIMULATION OF THE EFFECT OF TEMPERATURE ON THE ELECTRICAL CONDUCTIVITY AND CARRIER CONCENTRATION OF INTRINSIC AND EXTRINSIC SEMICONDUCTORS

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ABSTRACT

The impacts of temperature variations on the electrical conductivity and carrier concentration of some intrinsic and extrinsic semiconductors materials were studied. The response of the semiconductors materials for the doped and undoped species for ranges of temperature 0k to 1500k were considered. The ***MATLAB*** *Simulink simulation software was applied to the variables associated with electrical conductivity and carrier concentration of Silicon, Germanium and Gallium Arsenide. The results revealed a significant increase in carrier concentration and conductivity with increasing temperature for an undoped semiconductor material, whereas three regions were identified for doped materials: the ionization or freeze out region, where the rapid increase in carrier concentration is totally dependent on both temperature and dopant levels; the extrinsic region, where the increase in carrier concentration is totally dependent on dopant levels only; and the intrinsic region, where the increase in carrier concentration is totally dependent on temperature only.*

Keywords; Intrinsic and Extrinsic silicon (si),Intrinsic and Extrinsic Germanium (Ge), doperd ,undoped, and MatLab

1NTRODUCTION

Without doubt, semiconductors have definitely changed the world beyond anything that could have been imagined before them. Although people have always needed to communicate and process data, but thanks to the semiconductor revolution that these two important tasks have become easy and take up infinitely less time than, at the time of vacuum tubes. Semiconductor materials are the building blocks of the entire electronics and computer industry (Tukasiakand Andrzej,2010). Small, lightweight, high speed, and low power consumption devices would not be possible without integrated circuits (chips), which consist of semiconductor materials. There are certain substances that are neither good conductors (metals) nor insulators (glass).

Semiconductors have varied device applications, as result Computational Material Science involving the study of semiconductors is evolving because computer simulation is a tool to getting insight about the properties of materials at atomic or molecular level and their interactions to changes within a device which is used to predict and/or verify experiments. This is considered as a bridge between theory and experiment. The impurity modifies the electrical properties of the semiconductor and makes it more suitable for electronic devices such as diodes and transistors (Wienkes, Blackwell, Kakalios,2013). While adding impurities, a small amount of suitable impurity is added to pure material, increasing its conductivity by many times. Extrinsic semiconductors are also called *impurity semiconductors* or *doped semiconductors*. The process of adding impurities deliberately is termed as *doping* and the atoms that are used as an impurity are termed as *dopants*. The impurity modifies the electrical properties of the semiconductor and makes it more suitable for electronic devices such as diodes and transistors. It must be kept in mind that the addition of such impurities is really very minuscule and a typical dopant could have a concentration of the order of 1 part in a hundred million parts or it is equivalent to 0.01 ppm (Agrinskaya and Kozub,2009).

Xiaokuo, et al,(2019) investigated the thermal conductivity of intrinsic semiconductor at elevated temperature: role of four-phonon scattering and electronic heat conduction. They found out that while using first-principles-based Boltzmann transport equation approach to predict the thermal conductivity of crystalline semiconductor materials has been a routine, the validity of the approach is seldom tested for high-temperature conditions.

Danilyuk,et al, (2017) investigated the Low Temperature Conductivity in n-Type Non compensated Silicon below Insulator-Metal Transition. They investigate the transport properties of -type non compensated silicon below the insulator-metal transition by measuring the electrical and magneto resistances as a function of temperature for the interval 2–300 K.

Rahman, (2014) did a review on Semiconductors Including Applications and Temperature Effects in Semiconductors. He opined that semiconductor changed the world beyond anything that could have been imagined before them. Safa, et al,(2017) investigated the Electrical conductivity in semiconductors and metals. They found out that the Electrical transport through materials is a large and complex field, and in their work, they covered only a few aspects that are relevant to practical applications. They started with a review of the semi-classical approach that leads to the concepts of drift velocity, mobility and conductivity, from which Matthiessen’s Rule is derived. They made a more general approach based on the Boltzmann transport equation is also discussed. This present study is on the Stimulation of the effect of temperature on the electrical conductivity and carrier concentration of intrinsic and extrinsic semiconductors.

MATERIALS AND METHODS

Materials used for the study are Intrinsic and Extrinsic silicon (si), Intrinsic and Extrinsic Germanium (Ge) , and MatLab.

In determining the computer stimulation of the effect of temperature on the electrical conductivity and carrier concentration of intrinsic and extrinsic semiconductors, we made use of MATLAB computer programming language.

MATLAB is a proprietary multi-paradigm programming language and numeric computing environment developed by Math Works. MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages. Most importantly, it, together with its simulation package (SIMULINK), is one of the most recognized standard tools for running scientific programs and simulations.

Equations Used in Programming

MATLAB program was used to run the following equation

$$\sigma = Be - \frac{E_g}{2KT} \qquad 1$$

$$\sigma \sim \mathrm{n}e^{ue} \sim \mathrm{N_D}e^{ue} \qquad 2$$

$$\sigma \sim \mathrm{p}e^{u_h} \sim \mathrm{N_A}e^{uh} \qquad 3$$

$$\sigma = \mathrm{q}\ (\mathrm{N_e M_e} + \mathrm{N_h M_h})\ - \qquad 4$$

To determine the computer stimulation of the effect of temperature on the electrical conductivity and carrier concentration of intrinsic and extrinsic semiconductors, for the following semiconductors;

1. Intrinsic and Extrinsic Silicon
2. Intrinsic and Extrinsic Germanium
3. Gallium Arsenide

Determination of Conductivity

The relationship between the conductivity (sigma) of semiconductors and temperature is given by:

$$\sigma = \mathrm{Bexp}\ \frac{(-Eg)}{(2KT)} \qquad 5$$

Where

Sigma σ = conductivities of semiconductors,

B = effective densities of their states,
Eg = energy band gap, and is obtained from table x below (at room temperature)
K = the Boltzrnann's constant and
T = our varied temperature in Kelvin,

The variation in the conductivities of common intrinsic, extrinsic and compound semiconductors such as Silicon (Si), Germanium (Ge) and Gallium Arsenide (GaAs) was observed

Determination of Energy Band Gap of the Semi-conductors

In semiconductor, in certain temperature ranges the conductivity increases rapidly by increasing temperature. At low temperature, the charge carriers are frozen and the resistivity is extremely high, as the temperature raises, increasing fraction of carriers are ionized and the resistivity' decreases rapidly because of increase in the ionized charges. For a doped semiconductor, when temperature is sufficiently high, most of dopants are completely ionized. The conductivity begins to decrease and the resistivity is increased again just as in metals. At still higher temperature, there is further sharp decrease in resistivity due to appreciable excitation of all carriers and crossing the energy gap,

$$n_i^2 = N_c N_v \exp\left(\frac{Eg}{KT}\right) \approx T^3 \exp\left(-\frac{Eg}{KT}\right) \qquad 6$$

$$ni(T_2) = ni(Ti)\left(\frac{T_2}{T_1}\right) \exp\left(-\frac{EgT_2}{2kT_2} + \frac{EgT_1}{2kT_1}\right) \qquad 7$$

Where
N is the effective density of state in the conduction band
N_c is the effective density of state in the valency band
N_v is the intrinsic carrier concentration

Determination of Carrier Concentration

In intrinsic material n = p, and due to thermal excitation new hole - electron pairs are produced and others disappeared, $n\tau$ as a result of recombination after a time, $p\tau$,(mean lifetime). The mobility of a particle in a semiconductor is more it.

- Effective mass of particles is lesser
- Time between scattering events is more for intrinsic silicon at 300 K, the mobility of electrons is 1500 $\text{cm}^2 (\text{V·s})^{-1}$ and the mobility of holes is 475 $\text{cm}^2 (\text{V·s})^{-1}$

The electrical conductivity is the sum of' the electron and holes contributions:
$\sigma = q(N_e M_e + N_h M_h)$
where n and p are the concentrations of electrons and holes.
where;
$\mu_e - e\tau_e / m_{e;} and$

$\mu_h - e\tau_h / m_h$

Where τ is the relaxation time
μ_e is the election mobility
μ_h is the hole mobility

The hole-concentration in the valence band is given as;

$$p = N_v e \frac{-(E_f - E_v)}{KBT} \qquad 9$$

The electron- concentration in the conduction band is given as;
$n = N_c \exp -(E_c - Ef)/KBT$ 10
where K_B is the Boltzmann constant

T is the absolute temperature of the intrinsic semiconductor
N_c is the effective density of states in the conduction band
N_v is the effective density of states in the valence band
The number of electrons in the conduction band depends on effective density of states in the conduction band and the distance of Fermi level from the conduction band. The number of holes in the valence band depends on effective density of states in the valence band and the distance of Fermi level from the valence band. For an intrinsic semiconductor, the electron-carrier concentration is equal to the hole-carrier concentration.
It can be written as;
p = n = ni
Where P = hole-carrier concentration
n = electron-carrier concentration
and n_i = intrinsic carrier concentration
The fermi level for intrinsic semiconductor is given as,

$$E_f = \frac{E_c + E_v}{2} \qquad 11$$

Where;
E_f is the fermi level
E_c is the conduction band
E_v is the valence band
Therefore, the Fermi level in an intrinsic semiconductor lies in the middle of the forbidden gap.

Fermi level in Extrinsic Semiconductor

In extrinsic semiconductor, the number of electrons in the conduction band and the number of holes in the valence band are not equal. Hence, the probability of' occupation of energy levels in conduction band and valence band are not equal. Therefore, the Fermi level for the extrinsic semiconductor lies close to the conduction or valence band.

Fermi Level in n-type Semiconductor

In n-type semiconductor pentavalent impurity is added. Each pentavalent impurity donates a free electron. The addition of pentavalent impurity creates large number of free electrons in the conduction band. At room temperature, the number of electrons in the conduction band is greater than the number of holes in the valence band. Hence, the probability of' occupation of energy levels by the electrons in the conduction band is greater than the probability ofoccupation of energy levels by the holes in the valence band. This probability of occupation of energy levels is represented in terms of Fermi level. Therefore, the Fermi level in the n-type semiconductor lies close to the conduction band.
The Fermi level for n-type semiconductor is given as;

$$n = N_c \exp\left[-\frac{EC - EFn}{K_B T}\right] \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 12$$

Where E_f: is the fermi level.
E_c is the conduction band.
K_B is the Boltzmann constant.
T is the absolute temperature.
$N_C$is the effective density of stales in the conduction band.
N_D is the concentration of donar atoms.

Fermi Level in p-type Semiconductor

In p-type semiconductor trivalent impurity is added. Each trivalent impurity creates a hole in the valence band and ready to accept an electron. The addition of trivalent impurity creates large number of holes in the valence band. At room temperature, the number of holes in the valence band is greater than the number of electrons in the conduction band. Hence, the probability of occupation of energy levels by the holes in the valence band is greater than the probability of occupation of' energy levels by the electrons in the conduction band. This probability of' occupation of energy levels is represented in terms of Fermi level. Therefore, the Fermi level in the p-type semiconductor lies close to the valence band.

The Fermi level for p-type semiconductor is given as;

$$E_F = E_v + K_B T \log \frac{N_V}{N_A} \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad 13$$

Where:

N_v = the effective density of states in the valence band.

N_A = the concentration of acceptor atoms.

Values of Temperature Used

The values (column vector) of temperature used are:

1. T = 273:10:373 which gives 273K to 373K at 10K intervals.
2. T = 273:10:873 which gives 273K to 873K at 10K intervals.
3. T = 0:1 0: 1200 which gives OK to 1200K at 10K intervals.
4. T = 300: 10: 1500 which gives 300K to 1 500K at 10K intervals.

We obtained a result similar to that from existing materials, which shows that as temperature increases, the concentration of carriers for all investigated semiconductors also increase, as confirmed by our graphs in the result section of this paper.

RESULT AND DISCUSSION

Below are the graphs plotted, tables used in plotting the graphs are obtained from our stimulation program.

Temperature and carrier Concentration to increase in Conductivity

The tables shows the result of how temperature increase and concentration affects the conductivity of the semiconductors, its responses to temperature increase and their electrical conductivity.

Table 1: Effect of carrier Concentration and Temperature Increase to increase in Conductivity

Semiconductor	Temperature Range (K)	Frozen Region (K)	Electrical conductivity Region (K)
Silicon	273-373	273-300	300-373
Silicon	273-873	273-550	550-873
Silicon	0-1200	0-650	650-1200
Silicon	300-1500	300-800	800-1500
Germanium	273-373	273-310	310-373
Germanium	273-873	273-560	560-873
Germanium	0-1200	0-650	650-1200
Germanium	300-1500	300-800	800-1500
Gallium Arsenide	273-373	273-310	310-373
Gallium Arsenide	273-873	373-600	600-873
GalliumArsenide	0-1200	0-750	750-1200
Gallium Arsenide	300-500	300-880	880-1500

Graphs of Carrier Concentration Against Temperature

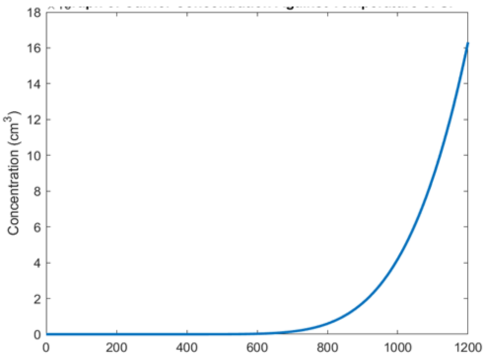


Figure 1: Graph of Carrier Concentration against Temperature for Silicon

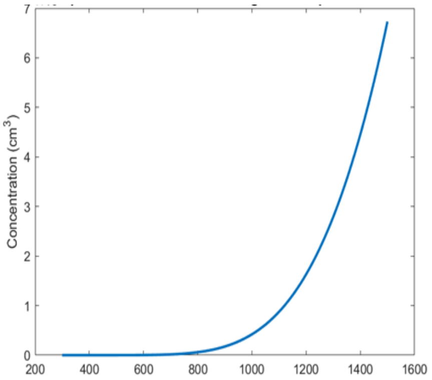


Figure 2: Graph of Carrier Concentration against Temperature for Silicon

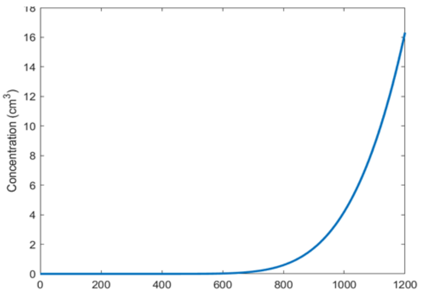


Figure 3: Graph of Carrier Concentration against Temperature for Germanium (Temp. Range: 0-1200K)

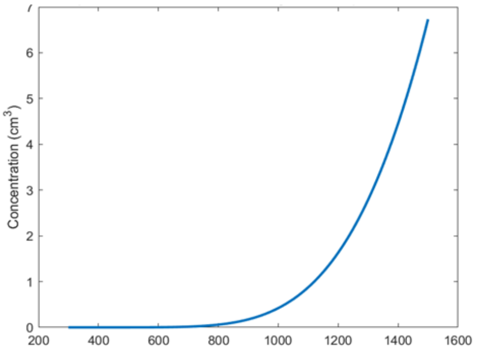


Figure 4: Graph of Carrier Concentration against Temperature for Germanium (Temp. Range: 300-1500K)

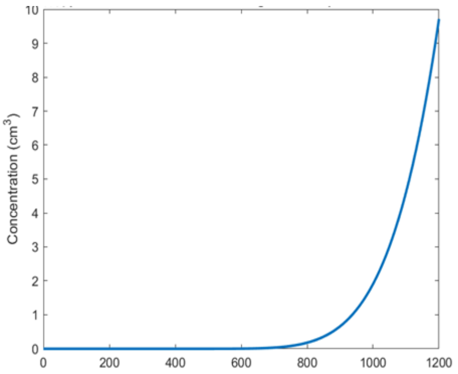


Figure 5: Graph of Carrier Concentration against Temperature for Gallium Arsenide (Temp. Range: 0-1200K)

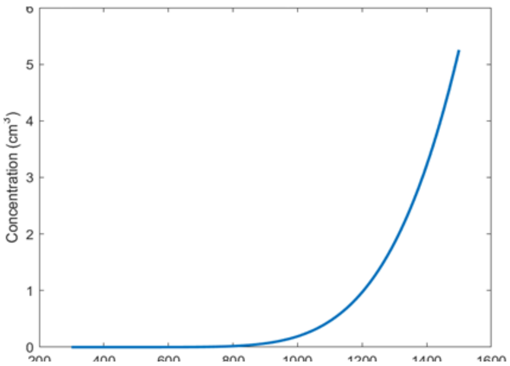


Figure 6: Graph of Carrier Concentration against Temperature for Gallium Arsenide (Temp. Range: 300-1500K)

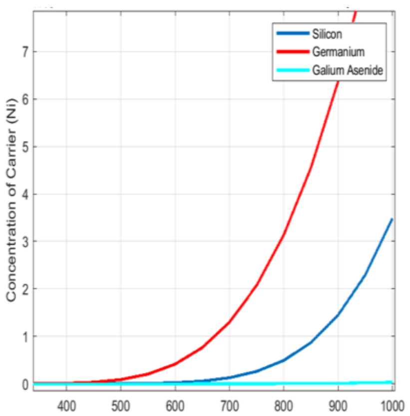


Figure 7: Graph of Carrier Concentration for Silicon, Germanium, Gallium Arsenide against Temperature

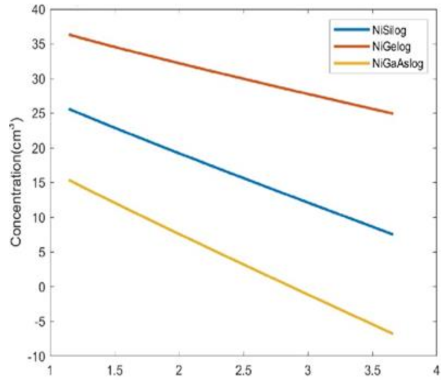


Figure 8: Graph of Carriers Concentration against Temperature for Silicon Germanium and Gallium Arsenide

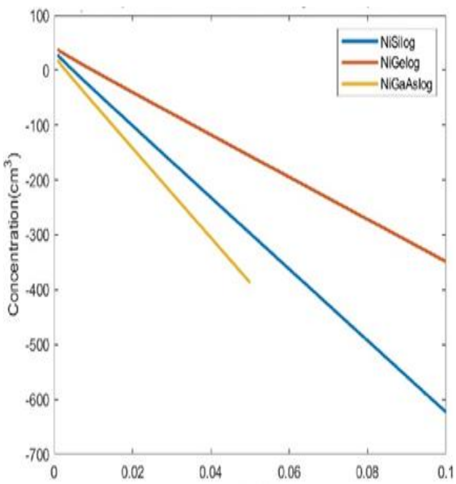


Figure 9: Graph of Carriers Concentration against Temperature for Silicon Germanium and Gallium Arsenide (Temp. Range: 0-1200K)

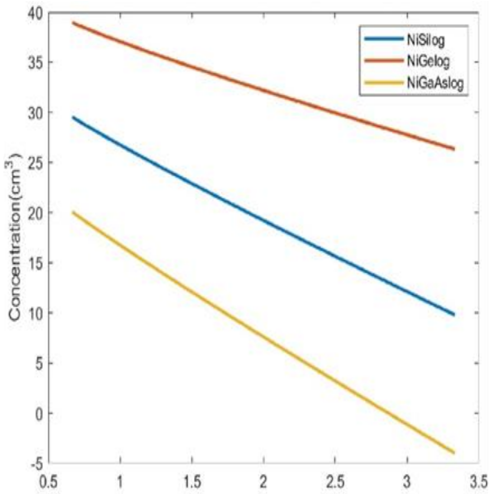


Figure 10: Graphs of Carriers Concentration against Temperature for Silicon Germanium and Gallium Arsenide(Temp. Range: 300-1500K)

Graph of Conductivity against Temperature

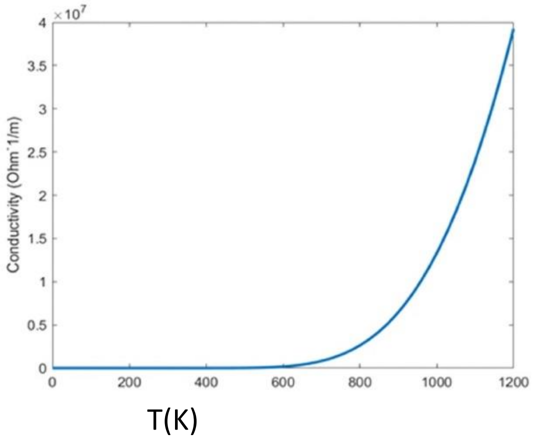


Figure 11: Graph of Conductivity against Temperature for Silicon (Temp Range: 0-1200K)

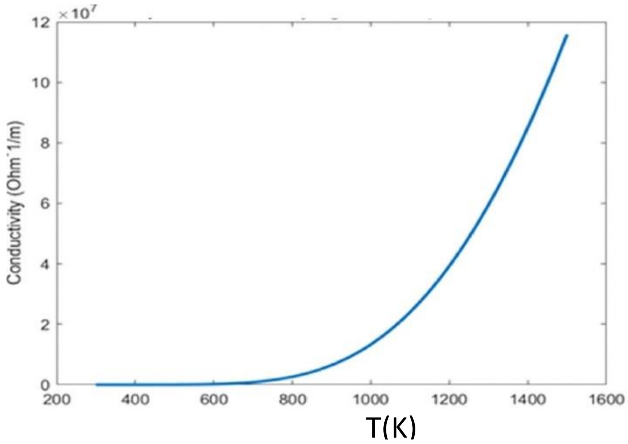
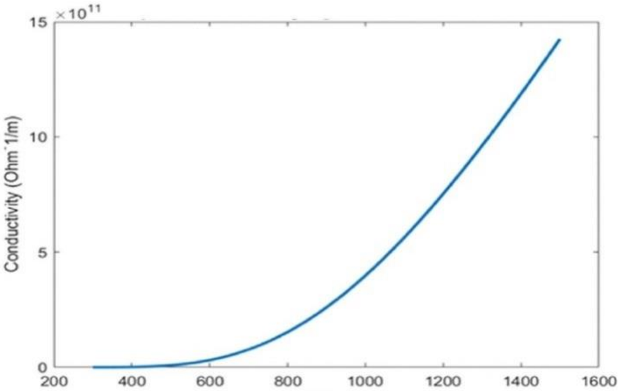
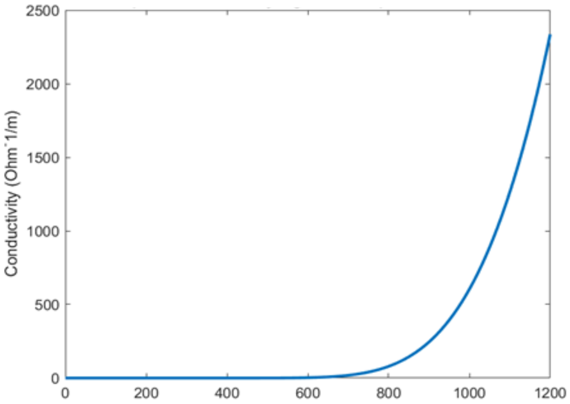


Figure 12: Graph of Conductivity against Temperature for Silicon (Temp Range: 300-1500K)



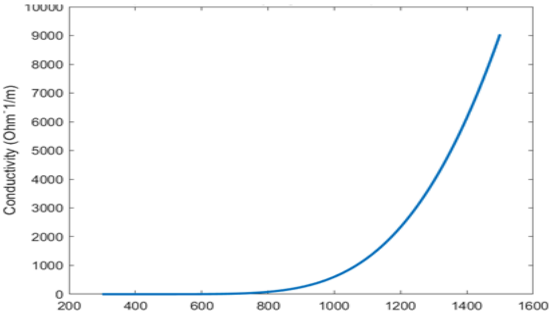
T(K)

Figure 13: Graph of Conductivity against Temperature for Germanium (Temp. Range 300-1500)



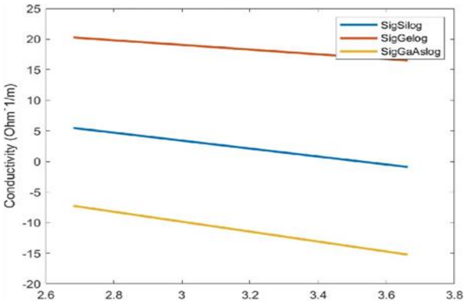
T(K)

Figure 14: Graph of Conductivity against Temperature for Gallium Arsenide(Temp. Range 0-1200)



T(K)

Figure 15: Graph of Conductivity against Temperature for Gallium Arsenide (Temp. Range 300-1500k)



T(K)

Figure 16: Graph of Conductivity against Temperature for Gallium Arsenide (Temp. Range 300-1500)

Effect of Temperature Increase to Conductivity

Semiconductor	Temperature Range (K)	Frozen Region (K)	Electrical conductivity Region (K)
Silicon	273-373	273-293	293-373
Silicon	273-873	273-550	550-873
Silicon	0-1200	0-650	650-1200
Silicon	300-1500	300-800	800-1500
Germanium	273-373	273-305	305-373
Germanium	273-373	273-420	420-873
Germanium	0-1200	0-500	500-1200
Germanium	300-1500	300-520	520-1200
Gallium Arsenide	273-373	273-280	280-373
Gallium Arsenide	273-873	273-580	580-873
GalliumArsenide	0-1200	0-700	700-1200
Gallium Arsenide	300-150	0-800	800-1500

Graph of Electron Density against Temperature for Doped Semiconductors

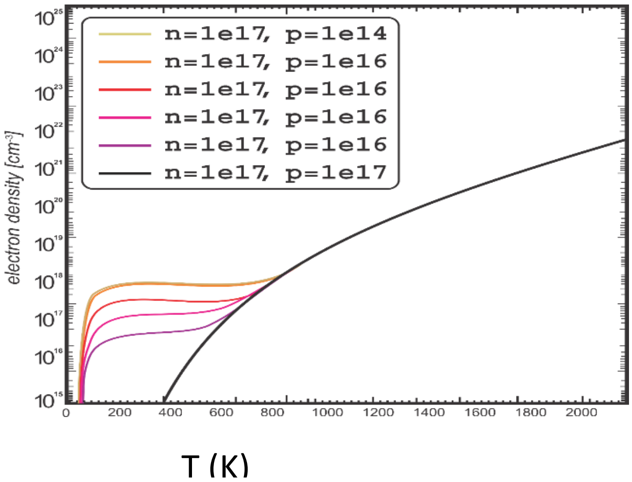


Figure 17. A Graph of Electron Density against Temperature.

CONCLUSION

The carrier concentration and conductivity of semiconductors are dependent on rise in temperature and the concentration of dopant (N_i) or N_A). The relationship between conductivity and temperature is given by equation I and equation 5 which reveals a significant rise in conductivity with temperature increase as shown in graphs of conductivity against temperature. Also, the relationship between temperature and carrier concentration and/or the concentration/density of dopants is given in equation 9 and equation 10 and it shows that the increase in carrier concentration of a semiconductor rises with temperature increase. Three regions were revealed which includes:

- The ionization or freeze out region where the rapid increase in carrier concentration is totally dependent on both temperature and dopant levels;
- The extrinsic region where the increase in carrier concentration is totally dependent on the level of dopants only
- And the intrinsic region where the rise in carrier concentration of semiconductors are totally dependent on temperature.

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