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The Effect of Temperature on Diffusion Co-Efficient of Electron and Hole in Gallium Asinide Semiconductor; Einstien's Relation

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ABSTRACT

Einstein diffusion coefficient was used to ascertain the relation how temperature affects diffusion of holes and electrons in gallium arsenide by considering various ranges of temperature. This was carried by first of all deriving the relation between diffusion and thermal voltage which was facilitated by combining the temperature dependence of VT andμ, the diffusion coefficient in conjunction with mobility which generally follows a power law with temperature. The computation were carried out for a range of temperatures starting from 273K to 450K for both hole and electron and the relationship plotted as shown in the graphs presented in section 3.00 which appears to have linear relation accept for few cases as in figures 3 and s4 where there were little distortion in the linear relationship of diffusion and mobility.

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1.0 INTRODUCTION

Current diffusion play a major role in operation of semiconductor devices and has invariably that temperature is found to play major role in operation of semiconductor devices It is not limited to that alone as the phenomenon in general affects the conductivity [1] of virtually all ls in all their states because since it moderates the electronic motion [2] and lattice vibration of crystal structure that play dominant role in electrical conduction in material. However, the real picture is that the conduction mechanism of some of the materials especially metals, semiconductor material, is different from the picture as presented in the classical concept. In a semiconductor both mobility and carrier concentration are temperature dependent[3] and this is the known reason why temperature alters the Fermi level of both n-type and p-type of pure and novel semiconductor material and thereby influencing the overall functionality of the materials, coupled with the fact that semiconductor is characterized by the activation current carriers either intrinsically or from impurity or both which is an exponential function of temperature, the result of which, lattice scattering becomes prominent and invariably leads to the reduction of the mobility of the charge carriers in semiconductor as the temperature increases thereby having explicitly overall effect on the functionality of semiconductor material in all forms.

Over years, the effect of temperature on the operation of all the semiconductor devices has been of concern and more pronounced when compared to other factors because it has been established right from the era of the vacuum devices like diode, triode withstand high temperature while in operation up to the recent dispensation when many of the electronics components today are now built from intrinsic and novel /extrinsic semiconductor materials such as (GaAs), zinc oxide (ZnO), copper-antimony sulphide ($Cu\text{-}Sb_2S_3$) etc that temperature stands to be influential factors to all electronic components [4;5;6] not only for vacuum tube devices that even now it has been replaced by semiconductor devices like p-n junction diodes, transistors etc. Accordingly, [7] expressed the fact that there is high influence of temperature on semiconductor while they in operation because it has been a proven fact that the Fermi level and impurity level of the devices are affected with increase in carrier concentration [8] [9]. Generally semiconductor material has a negative temperature co-efficient of resistance, which means that the resistance of a semiconductor material decreases with increase in temperature this is because the energy required to break their covalent bond is very small being 0.7 eV for Ge and 1.1 eV for Si [10] or that their band gap is small or may direct [11] [12] but contrary to metal conductor that has narrower bad gap compared to any of the semiconductors mentioned above, the resistivity increase [13] with increase in temperature[14;15] The study is based on the understanding that so many electronic equipment are made from some of these semiconductor materials and based on this we picked interest in theoretically examining the influence of temperature on charge carriers drift and diffusion behavior using Einstein's relation[16]. Here we consider the effect of temperature on the diffusion and minority carriers' mobility in GaAs semiconductors in order to ascertain how temperature affects diffusion of electron and hole carriers. Therefore different examination of the mobility and diffusion coefficients of electrons and holes at various temperatures are utilized in the Einstein relation equation to establish a comprehensive understanding of the effect.

2. MATERIALS AND METHOD

2.1; Derivation OF Einstein's relation:

In equilibrium, the density of particles having temperature T in an electric potential U is

$$N = N_o \exp\left[\frac{qU}{kT}\right],\ q = \pm e \qquad 1$$

Where k = Boltzmann's constant. The gradient of particles due to a gradient in potential is

$$\nabla N = \frac{q}{kT}\nabla U \bullet [N_o \exp(\frac{qU}{kT})] = \frac{q}{kT}\nabla U \bullet N \qquad 2$$

Where the Electric field is – ∇U. The total flux of particles at equilibrium is zero, and is

$$j = \pm \mu \nabla U \bullet N - D \nabla N = 0 \qquad 3$$

$$= \mu \nabla U \bullet N - D \frac{q}{kT} \nabla UN \qquad 4$$

$$= \pm \nabla U \bullet N [\mu - \frac{De}{kT}] = 0 \qquad 5$$

$$D = \frac{kT\mu}{e} \qquad 6$$

Where μ is the mobility of charge carrier (m^2/Vs)
D is the diffusion coefficient (m^2/s)
K is the Boltzmann's constant (k): 1.38×10^{-23} J/K
e is the Elementary charge: 1.6×10^{-19} C
T is the Temperature (K)

2.2 Computation of Diffusion Coefficient and Mobility of Holes and Electrons

In the computation temperature ranges were considered, we started from the 273k to a maximum of 420k in order to ascertain how electron and hole mobility relate to diffusion co-efficient in gallium arsenide semiconductor material bearing in mind the effect of temperature in operation of semiconductor materials.

The relation in terms of voltage and the charge carriers mobility μ is based on voltage which is designated as thermal voltage V_T based on which the relationship from equation (6) can now be written as

$$D = \mu V_T \qquad 7$$

V_T is the thermal voltage, which is given by:

$$V_T = \frac{kT}{e} \qquad 8$$

Where

K is the Boltzmann's constant (1.38 ×10^{-23} J/K)
T is the absolute temperature in kelvin
e is the elementary charge (1.6 ×10^{-19} C)
Temperature effect on diffusion coefficient D:

The thermal voltage V_T is directly proportional to temperature increases, V_T increases, causing the diffusion coefficient D to increase.

Carrier Mobility μ of carriers in a semiconductor typically decreases with increasing temperature due to enhanced phonon scattering. Mobility generally follows a power law with temperature:

$$\mu(T) \propto T^{-\gamma} \qquad 9$$

Where γ is a material dependent exponent, often around 1.5 to 2.0 for GaAs.
Diffusion coefficient D: combining the temperature dependence of V_T and μ, the diffusion coefficient can be written as:

$$D(T) \propto \frac{T}{T^{\gamma}} = T^{1-\gamma} \qquad 10$$

This shows that the diffusion coefficient depends on temperature, with the exact relationship influenced by the mobility's temperature dependence.

For Gallium Arsenide GaAs the electron and hole mobility have difference values and the temperature dependence for each varies slightly:

i. Electron mobility: typically, high in GaAs and has a strong dependence on the temperature. At room temperature (300K), the electron mobility in GaAs is about 8500cm^2/Vs, and it decreases with increasing temperature.
ii. Hole mobility: much lower than electron mobility in GaAs, around 400cm^2/Vs at room temperature, and also decreases with temperature.

To determine the temperature effects on the minority carrier diffusion coefficient in GaAs semiconductor, the following constants were used in the computation.

1. Boltzmann's constant (k): 1.38 ×10^{-23} J/K
2. Elementary charge (e): 1.6 ×10^{-19} C
3. Temperature range: 273 K, 300 K and 330 K
4. Reference electron mobility μ_e: 0.85 m^2/Vs
5. Reference hole mobility μ_p: 0.04 m^2/Vs

Temperature dependence of mobility: mobility decreases with the temperature due to the phonon scattering, following the power law from eq. (9);

$$\mu(T) = \mu_{273}\left(\frac{T}{300}\right)^{-\gamma} \qquad 11$$

Where

μ_{273} is the reference mobility at 273 K
T is the temperature in kelvin
γ is a material specific exponent (for GaAs, γ ≈ 1.5

(i). Computation of electron mobility using the equation (9):
The electron mobility at different temperature:

$$\mu_e(273) = 0.85\left(\frac{273}{300}\right)^{-1.5} = 0.979\ m^2/Vs$$

$$\mu_e(300) = 0.85\ m^2/Vs$$

$$\mu_e(330) = 0.737\ m^2/Vs$$

For hole mobility at different temperature:

$$\mu_p(273) = 0.04\left(\frac{273}{300}\right)^{-1.5} = 0.0461\ m^2/Vs$$

$$\mu_p(300) = 0.04\ m^2/Vs$$

$$\mu_p(330) = 0.0347\ m^2/Vs$$

The thermal voltage calculation:

The thermal voltage V_T at each temperature as given by equation (8);

At 273 K
$$V_T = \frac{1.38\ \times 10^{-23} \times 273}{1.6 \times 10^{-19}} \approx 0.0235\ V$$

At 300 K
$$V_T = \frac{1.38\ \times 10^{-23} \times 300}{1.6 \times 10^{-19}} \approx 0.0259\ V$$

At 330 K
$$V_T = \frac{1.38\ \times 10^{-23} \times 330}{1.6 \times 10^{-19}} \approx 0.0284\ V$$

(ii) Computation of diffusion coefficient of electron using the Einstein Relation (equation 7)

At 273 K
$$D_e = 0.979 \times 0.0235 \approx 0.0231\ m^2/s$$

At 300 K
$$D_e = 0.979 \times 0.0259 \approx 0.02199\ m^2/s$$

At 330 K
$$D_e = 0.979 \times 0.0284 \approx 0.02097\ m^2/s$$

(Iii) Computation of diffusion coefficient of hole coefficient: using the same equation 7

At 273 K
$$D_p = 0.0461 \times 0.0235 \approx 0.0108\ m^2/s$$

At 300 K
$$D_p = 0.04 \times 0.0259 \approx 0.0104\ m^2/s$$

At 330 K
$$D_p = 0.0347 \times 0.0284 \approx 0.00987\ m^2/s$$

4. RESULT AND DISCUSSION

The result is presented as shown in the graphs show the diffusion relation with electron and hole mobility at various ranges of temperature respectively as computed from above using the relation as derived as in the equation.

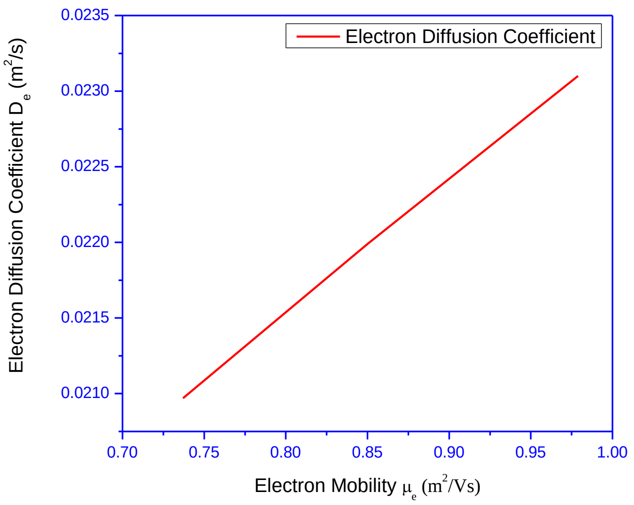

Figure 1; Graph Showing Electron diffusion coefficient electron as a function of mobility at the range of 273-330 K

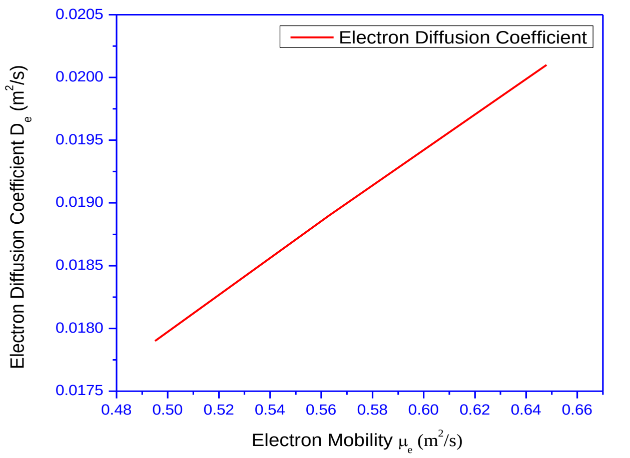

Figure 2 Graph Showing Electron Diffusion Coefficient vs Electron Mobility within the range of 360-420 K

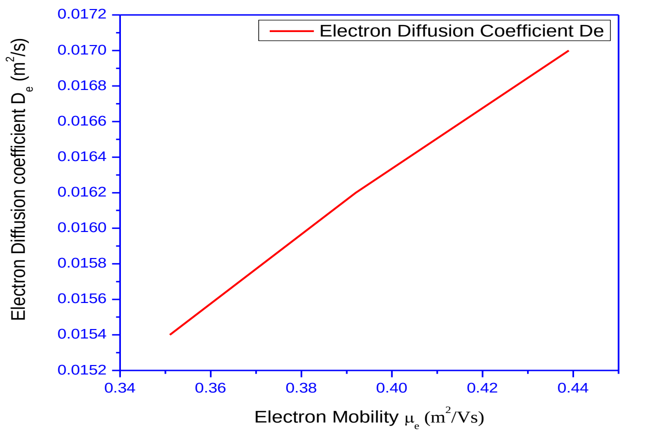

Figure 3; Graph Showing Electron Diffusion Coefficient vs. Electron Mobility at the range 450-510 K

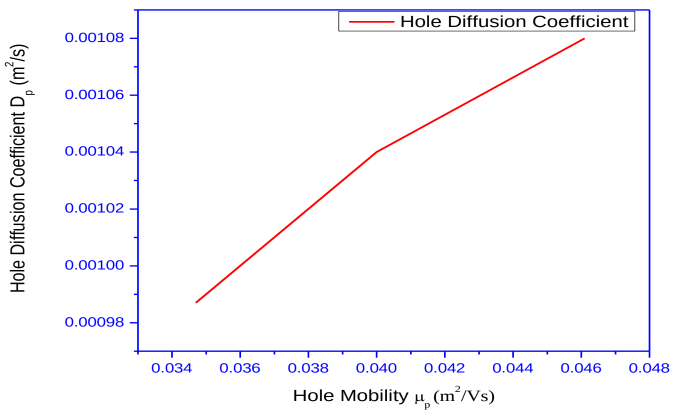

Fig.4; Graph showing Hole Diffusion Coefficient vs Hole Mobility at the range 273-330 K

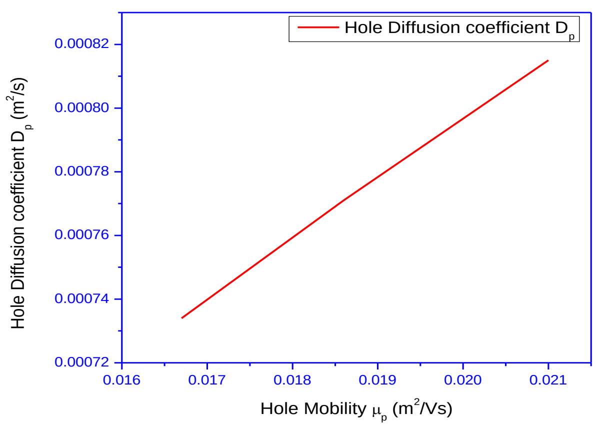

Fig.5; Graph Showing Hole Diffusion Coefficient vs Hole Mobility at the range 360-420 K

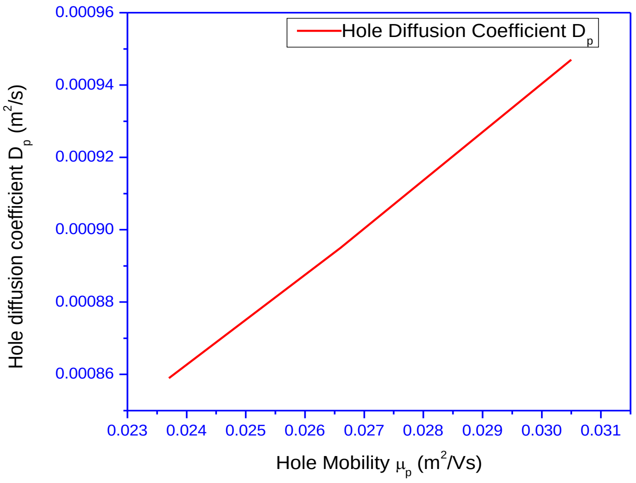

Fig.6; Graph Showing Hole Diffusion Coefficient vs Hole Mobility at the range 450-510 K.

Whereby the from the graphs of diffusion coefficient for both electrons and holes it is observed that there is linear relationship between diffusion and the mobility of electron s and holes respectively increases which is in agreement with the Einstein relation as in equation 6. where the expression shows that diffusion coefficient, D relate to mobility μ directly for given thermal voltage, V_T at any fixed temperature, any change in mobility is found to generate proportionally effect on the diffusion coefficient. The electron diffusion coefficient and mobility and that of holes with electrons' diffusion coefficient being stepper than that of holes' This indicates that the gradient of electrons' diffusion coefficient in GaAs in relation mobility is higher when compared to that of holes. This behavior is typical in GaAs, where electrons are the major carriers. In view of this also it is also observed that as temperature changes (from 273K to 330K), the mobility of both electrons and holes act in linear with the temperature confirming generalized linear relationship between the duo as shown in the Einstein's relation

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3.0 SUMMARY

From our study of the effect of temperature on the minority carrier diffusion coefficient in Gallium Arsenide (GaAs), using the Einstein relationship. It was observed that Einstein relation gave a well-defined relation between the diffusion coefficient D of charge carriers in a semiconductor and the mobility μ of the carrier through the thermal voltage V_T which on the other hands that diffusion coefficient is influenced by both mobility and temperature based thermal voltage V_T relation with the temperature as temperature increases with the thermal voltage which invariably affects the diffusion of the carriers, D. Both electron and hole diffusion coefficients showed a linear relation with rising temperature even at higher temperature value aligning the device with the theoretical expectations as in Einstein's formula. Therefore this why semiconductor that is made from GaAs offers better performance at higher temperatures. Though it is still expected that like others it may still require cooling mechanisms during operation to keep temperatures at the optimal value in order to enhance good performance. Therefore, this study reveals that the knowledge and understanding of the effect of temperature on semiconducting devices is very vital in order to be able to manage the equipment for optimum efficiency which is crucial for all semiconductor based devices in order minimized thermal generated noise that is normally experienced while semiconducting devices are in operation.

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