STUDIES ON THERMAL VARIATION OF DRIFT MOBILITY AND MEAN FREE TIME FOR HOLES AND ELECTRONS IN GAAS.

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ABSTRACT

The electronic properties of semiconducting materials are significantly temperature dependent. To predict variation of electronic device functions with temperature, it is important to have knowledge of variation of fundamental electronic properties of semiconducting materials. These fundamental properties include bandgap energy E_g, electronic conductivity σ, intrinsic electronic conductivity σ_i, carrier mobility μ, intrinsic carrier mobility μ_i, diffusion coefficient D, diffusion length L, mean free time τ, intrinsic carrier concentration n_i, and Fermi energy level E_F. This research work however involved theoretical computations of drift mobility and mean free time for electrons and holes in GaAs at different temperatures in the range 0 – 500 K; using some experimental data deduced from a graph of Hall mobility, μ_H versus temperature, T available mostly at room temperature and some at low temperatures – and using the theoretical formulations developed in this work. The research work resulted in tables and graphs of variation with temperature of electron drift mobility μ_{nd}, hole drift mobility μ_{pd}, intrinsic carrier mobility μ_i, mean free time for electrons τ_n and mean free time for holes τ_p in GaAs. The results so obtained are expected to be useful for future prediction of variation of functions of electronic devices made of GaAs.

Keywords: electronic properties, intrinsic carrier mobility, semiconducting materials, theoretical formulations.

INTRODUCTION

Semiconductors form a group of materials having electrical conductivity intermediate between metals and insulators (Streetman, 1990). Semiconducting materials have their specific electrical conductivity somewhere between that of good conductors and that of good insulators; hence the name. Among these materials, silicon (Si) is by far the most important in engineering use, out of which semiconductor devices like diodes, rectifiers, transistors, Integrated Circuits (ICs) are made. Next to Si is germanium (Ge). These two elements belong to group IV of the periodic table. Also of importance are the compound semiconductors, usually compounded of two elements (but sometimes more) of group III and V or II and VI of the periodic table. From those gallium arsenide (GaAs) is most widely used in light emitting and gun diodes. Also in use for specific purposes are indium antimonide (InSb), lead-tin-telluride (PbSnTe), etc (James, 2006).

The present study concentrates on GaAs, from which majority of the present day electronic devices are being made (Streetman, 1990). The study is concerned with ascertaining the fact that environments with wide variation in temperatures, brings about the variation in the electronic properties of semiconducting materials and of course also variation in the efficiency of the electronic devices made from these semiconductors. Hence the need to get readily available data of electronic

properties dependent on temperature cannot be over emphasized.

It is significant to note that the conductivity of these materials varies over several orders of magnitude by changes in temperature, optical excitation and impurity content. This variability of electronic properties makes the semiconducting materials natural choices for electronic device investigations (Sah, 1994). The thermal variation of drift mobility and mean free time of a semiconducting material: GaAs is the subject of this study.

II. SEMICONDUCTING MATERIALS

There are two basic categories of semiconductors: elemental semiconductors and compound semiconductors. Si and Ge, the most common elemental seminconductors are used in many semiconductor components. GaAs and InP are examples of compound semiconductors that contain added materials or dopants (Chang and Francis, 1994; James et al., 2006). The semiconductor considered in this study is GaAs.

GaAs is a dark-gray crystalline compound used in transistors, solar cells, and semiconducting lasers. GaAs has some electronic properties, which are superior to silicon. It has a higher saturated electron velocity and higher electron mobility, allowing it to function at frequencies in excess of 250 GHz (Singleton, 2001). Also GaAs devices generate less noise than silicon devices when operated at high frequencies (Millman and Christos, 2000). They can also be operated at higher power levels than the equivalent silicon device because they have high breakdown voltages. These properties of GaAs make it useful in the circuits of mobile phones, satellite communications, microwave point-to-point links, and some radar systems (Bhattacharya, 2002). Another advantage of GaAs is that it has a direct bandgap, which means that it can be used to emit light. Silicon has an indirect band gap and so is very poor at emitting light. Nonetheless, recent advances may make silicon LEDS and lasers possible.

Silicon has three major advantages over GaAs. First, silicon is abundant and cheap to process. Silicon's greater physical strength enables larger wafers (maximum of 300 mm compared to 150 mm diameter for GaAs). Si is highly abundant in the earth's crust, in the form of silicate minerals. The economy of scale available to the silicon industry has also reduced the adoption of GaAs. The second major advantage of Si is the existence of silicon dioxide – one of the best insulators. Silicon dioxide can easily be incorporated onto silicon circuits and such layers are adherent to the underlying Si. GaAs does not form a stable adherent insulating layer. The third, and perhaps most important advantage of Si is that it possesses a much higher hole mobility. This high hole mobility allows the fabrication of higher-speed P-channel field effect transistors, which are required for Complementry Metal Oxide Semiconductor (CMOS) logic. Because they lack a fast CMOS structure, GaAs logic circuits have much higher power-consumptions, which has made them unable to compete with Si logic circuits (Mayer and Lau, 1989).

III. EFFECTS OF TEMPERATURE AND DOPING ON MOBILITY

Charge carriers (electrons and holes) have the tendency of colliding with the lattice phonons and with the impurities in solid. This affects the ease with which the electrons and holes can flow through the crystal (that is the mobility μ of electrons and holes) in the solid. The collision and the consequent scattering processes that affect μ depend on temperature, which affects the thermal motion of the lattice atoms and the velocity of the carriers.

The two basic types of scattering mechanism, which influence electron and hole mobility are lattice scattering and impurity scattering.

(a) Lattice Scattering

In a perfectly periodic lattice an electron does not suffer any collision with lattice sites. Lattice scattering is caused by collision of the moving carrier with disturbances in the periodic internal potential inside the semiconductor crystal. Here, a carrier moving through the lattice encounters atoms, which are out of their normal lattice positions due to thermal variation. The frequency of such scattering events increases as the lattice temperature increases, since the thermal agitation of the lattice becomes greater. At a certain moment an electron can bump into a region where the crystal atoms are more densely packed than usual, yet a moment later it may find itself in a sparsely packed region. The dense and sparse regions form pressure waves inside the crystal (Narayanamurti, 1984).

These lattice thermal variation waves have also particulate or corpuscular properties, just as photons do. Their energy distribution also follows the same statistical law obeyed by photons. These vibrational wave-particle entities are called phonons. Phonons greatly influence the electronic properties of semiconductors.

(b) Impurity Scattering

It is caused by the presence of ionized impurity atoms in various positions in the crystal lattice. Due to their net charge, they exert a force on the free carrier passing nearby, causing it to change its direction (like a comet entering the gravity field of a star). This type of scattering is less severe if the free carrier is moving fast (i.e. at higher temperatures), and spends less time in the vicinity of the ionized impurity atom. However, it becomes the dominant mechanism at low temperatures. Since a slowly moving carrier is likely to be scattered more strongly by an interaction with a charged ion than is a carrier with a greater momentum, impurity scattering event causes a decrease in mobility with decreasing temperature. In contrast, phonons scattering causes an increase in mobility with decrease in temperature due to increase in collision time τ.

The study fits into the current trends of research in the areas of temperature variation data of electronic properties of semiconducting materials. Studies on the thermal properties of GaAs as carried out experimentally included bulk modulus, melting point, specific heat, thermal conductivity due to electron, thermal diffusivity, thermal expansion, etc (Boer et al., 2002). This work is specifically carried out on the mean free time and drift mobility of GaAs as a function of temperature which of course have not yet been attempted in the research trends. Besides measurement errors, some of the variation in the reported values results from the difficulty in preparing pure samples of these compound semiconductors and the fact that the measurement temperature is not always reported.

IV. ELECTRONIC PROPERTIES OF SEMICONDUCTING MATERIALS

These include basic parameters such as breakdown fields, mobility of electrons and holes, electron and hole thermal velocity, mobility and Hall effects, impact ionization, and recombination parameters such as in pure n-type and p-type materials (Mckelvey, 1993). Temperature variation of the concentrations of carriers (electrons and holes) and of their mobilities is determined from resistivity and Hall data for different samples. In intrinsic range at high temperatures, conductivity results when an electron is thermally excited from the filled

valence band to the conduction band. In saturation range, which occurs just below intrinsic range, concentrations are independent of temperature. All donors (or acceptors) are ionized and the concentration of carriers equals the net concentration of significant impurities (Bastard *et al.*, 1991). At high temperatures, mobility is limited by carrier – lattice or phonon scattering and is independent of impurity concentration in very pure crystals (Kasap, 1989). At lower temperatures, scattering by both ionized and neutral impurity centres contribute, and the mobility is largest in pure samples. Impurity scattering increases rapidly with decrease in temperature and the mobility passes through a maximum, which depends on impurity concentration.

V. METHODS/THEORETICAL DEVELOPMENT

From a published graph (Fig.1) of Hall mobility μ_H measured as a function of temperature T in a very pure sample GaAs grown by Vapour Phase Epitaxy (VPE) (Bhattacharya, 2002), deduced and interpolated values of μ_H at different T obtained from curve A are recorded in Table 1. The curves A, B and C are obtained for GaAs at different doping (impurity) concentrations; 10^{14}, 10^{16} and 10^{18} cm^{-3} respectively.

Hall mobility μ_H of GaAs at 300 K temperature is obtained from Table1. The ratio r given by

$$r_n = \frac{\mu_{nd}}{\mu_H} \quad (1)$$

and

$$r_p = \frac{\mu_{pd}}{\mu_H} \quad (2)$$

for electrons and holes respectively are obtained and μ_H values in Table1 are then multiplied by r_n and r_p to get electron drift mobility μ_{nd} and hole drift mobility μ_{pd} respectively of the sample GaAs at different T as shown in equs 3 and 4 below.

$$\mu_{nd} = \mu_H r_n \quad (3)$$

$$\mu_{pd} = \mu_H r_p \quad (4)$$

The mean free time (τ_n and τ_p) for electrons and holes respectively are computed using Esq. (5) and (6) below.

$$\tau_n = \frac{m_n^* \mu_{nd}}{q} \quad (5)$$

$$\tau_p = \frac{m_p^* \mu_{pd}}{q} \quad (6)$$

where $m_n^* = 0.067\ m_o$ and $m_p^* = 0.082\ m_o$ are the effective masses in kilograms for electrons and holes respectively in GaAs, $m_o = 9.11 \times 10^{-31}$ kg is the electronic rest mass and

$q = 1.602 \times 10^{-19}$ C is the electronic charge.

The intrinsic drift mobility μ_i for an intrinsic semiconductor is given by

$$\mu_i = \mu_{nd} + \mu_{pd} \quad (7)$$

VI. SOURCE OF DATA COLLECTION

Hall mobility μ_H measure as function of temperature in a very pure GaAs grown by Vapour Phase Epitaxy (V.P.E) given in Fig. 1below.

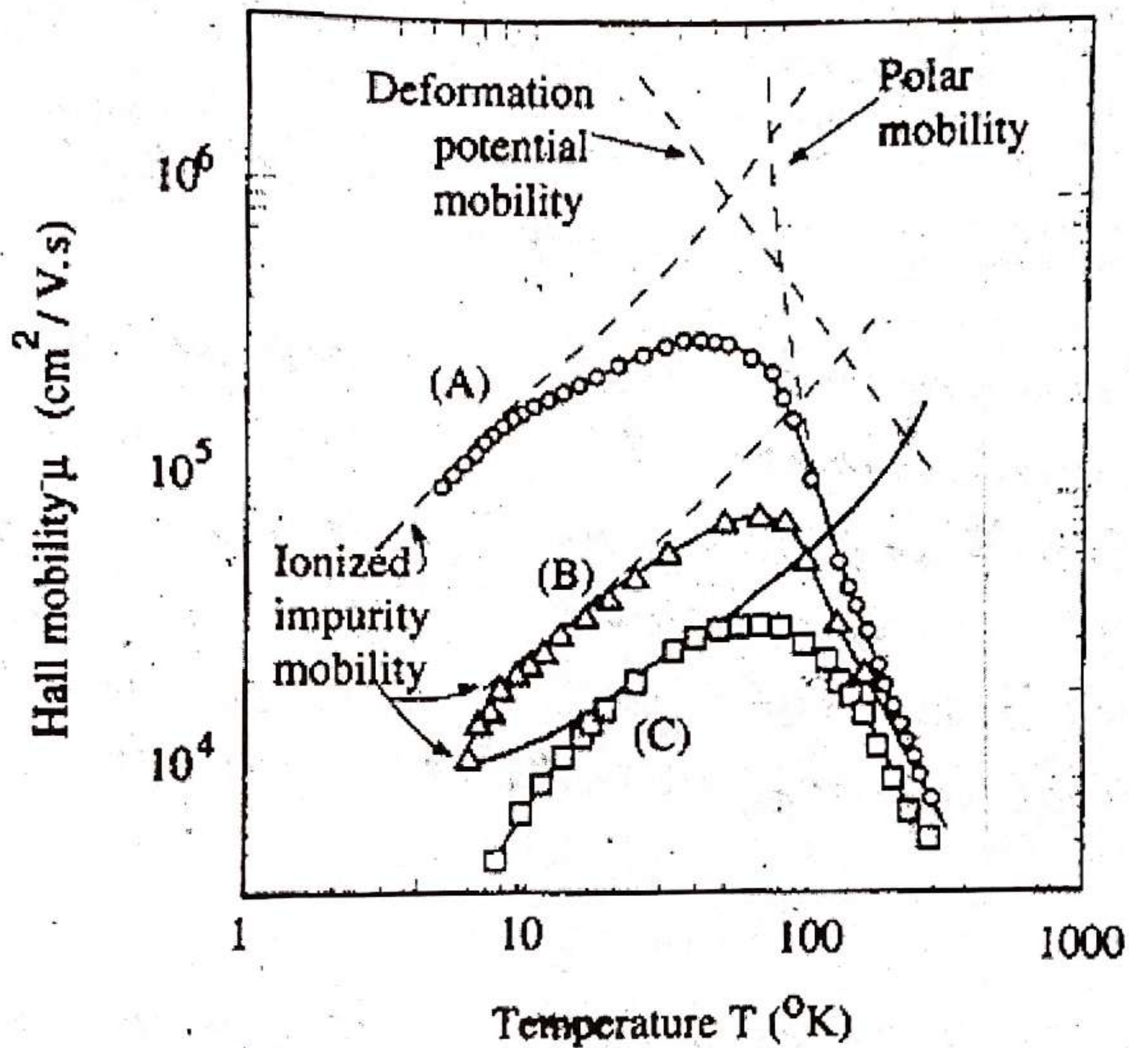

Fig.1. Mobility measured as a function of temperature in a very pure sample GaAs grown by vapour phase epitaxy (from M. Shur, Physics of Semiconducting Devices,© 1990.Reprinted by permission of Prentice Hall, Englewood Cliffs, N J; the data are compiled from C.M. Wolf, et al., Journal of Applied Physics,41,3088,1970)

VII. DATA COLLECTION, COMPUTATION AND RESULTS

Values for Hall mobility μ_H at different temperature T deduced and interpolated from published graph (Fig.1) of Hall mobility μ_H in a very pure GaAs measured at different temperatures T (Bhattacharya, 2002) are given in Table 1.

Table1. Experimental values of Hall mobility μ_H in a very pure GaAs measured at different temperatures T

T(K)	μ_H(cm^2/V.s)
5	92000
6	120000
8	150000
10	170000
15	195000
20	220000
30	240000
40	245000
50	244000
60	235000
80	180000
100	98000
150	35000
200	15000
250	10000
300	7700
350	5600
400	4700
450	4400
500	3500

The Hall mobility at a temperature of 300 K is 7700 cm^2/V.s as seen in Table 1. In order to compute μ_{nd} and μ_{pd} at different T in GaAs, the ratios r_n and r_p for electrons and holes respectively defined by eqns (1) and (2) are computed and found to be 1.1 and 0.05 respectively at 300 K.

For the said computation, we assume that these ratios r_n and r_p remain fairly independent of T as they are obtained at constant temperature of 300 K. Then μ_H values at different T of Table 1 when multiplied by the ratios r_n and r_p should give μ_{nd} and μ_{pd} respectively in GaAs at different T. Similarly using Eqs. (5) and (6), τ_n and τ_p at different T are also computed. Hence computed values of μ_H, μ_{nd}, μ_{pd}, μ_i (i.e. sum of μ_{nd} and μ_{pd}), τ_n and τ_p at different T are given in Table 2.

Table 2. Computed drift mobilities and mean free time of electrons and holes from the experimental values of Hall mobility in very pure GaAs measured at different T.

+ T(K)	+ $\mu_H (cm^2/V.s)$	* $\mu_{nd} (cm^2/V.s)$	* $\mu_{pd} (cm^2/V.s)$	* μ_i $(cm^2/V.s)$	* $\tau_n (s)$	* $\tau_p (s)$
5	92000	101200	4600	105800	3.86E-12	2.15E-13
6	120000	132000	6000	138000	5.03E-12	2.80E-13
8	150000	165000	7500	172500	6.29E-12	3.50E-13
10	170000	187000	8500	195500	7.12E-12	3.96E-13
15	195000	214500	9750	224250	8.11E-12	4.55E-13
20	220000	242000	11000	253000	9.22E-12	5.13E-13
30	240000	264000	12000	276000	1.01E-11	5.60E-13
40	245000	269500	12250	281750	1.03E-11	5.71E-13
50	244000	268400	12200	280600	1.02E-11	5.69E-13
60	235000	258500	11750	270250	9.85E-12	5.48E-13
80	180000	198000	9000	207000	7.54E-12	4.20E-13
100	98000	107800	4900	112700	4.11E-12	2.28E-13
150	35000	38500	1750	40250	1.47E-12	8.16E-14
200	15000	16500	750	17250	6.29E-13	3.50E-14
250	10000	11000	500	11500	4.20E-13	2.33E-14
300	7700	x 8470	x 385	x 8855	3.23E-13	1.80E-14
350	5600	6160	280	6440	2.35E-13	1.31E-14
400	4700	5170	235	5405	1.97E-13	1.10E-14
450	4400	4840	220	5060	1.84E-13	1.03E-14
500	3500	3850	175	4025	1.47E-13	8.16E-15

+Values obtained from the graph i.e. Fig.1 x values computed in this work which agrees very well with the experimental values at 300 K. * Values obtained by computation in this work.

τ_p values are smaller than τ_n and both τ_p and τ_p generally decrease with increase in temperature.μ_i in column five of Table 2 is tenable only to intrinsic semiconductors. The computed values of τ_p, τ_n, μ_{nd}, μ_i and μ_{pd} in GaAs at different T are represented graphically in Fig.1-5.

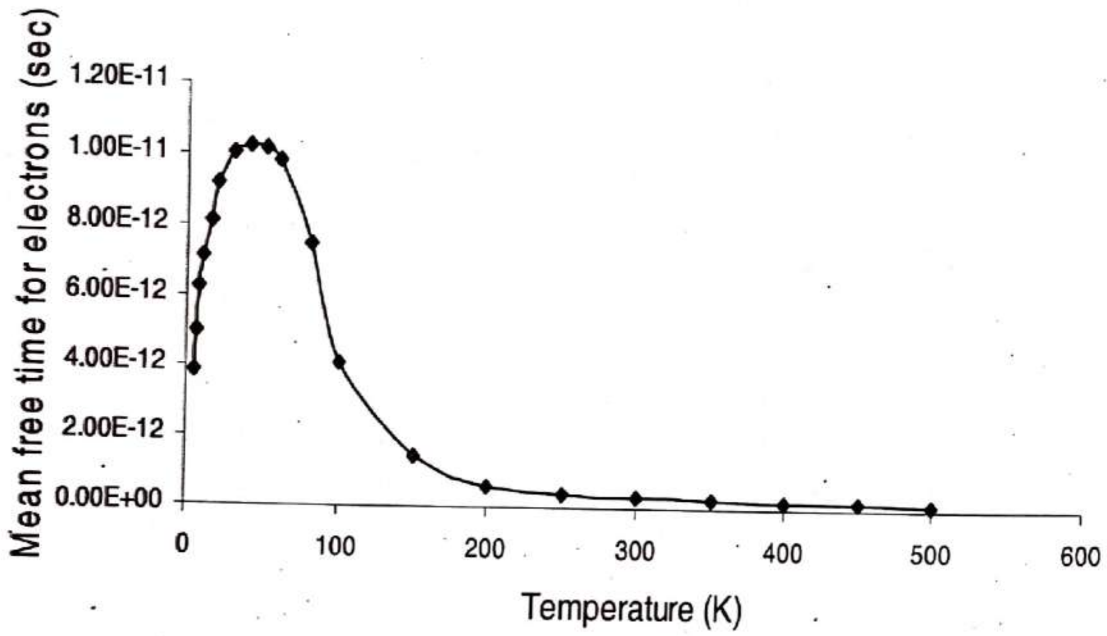

Fig.2. Mean free time for electrons versus temperature in very pure GaAs.

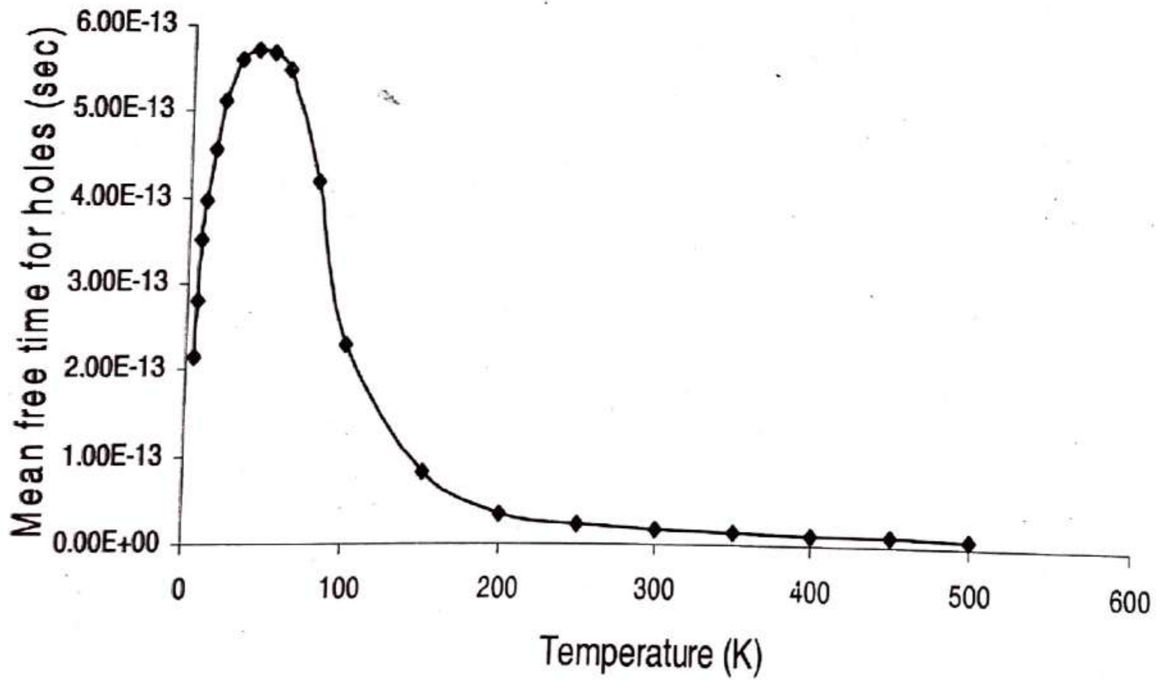

Fig.3. Mean free time for holes versus temperature in very pure GaAs.

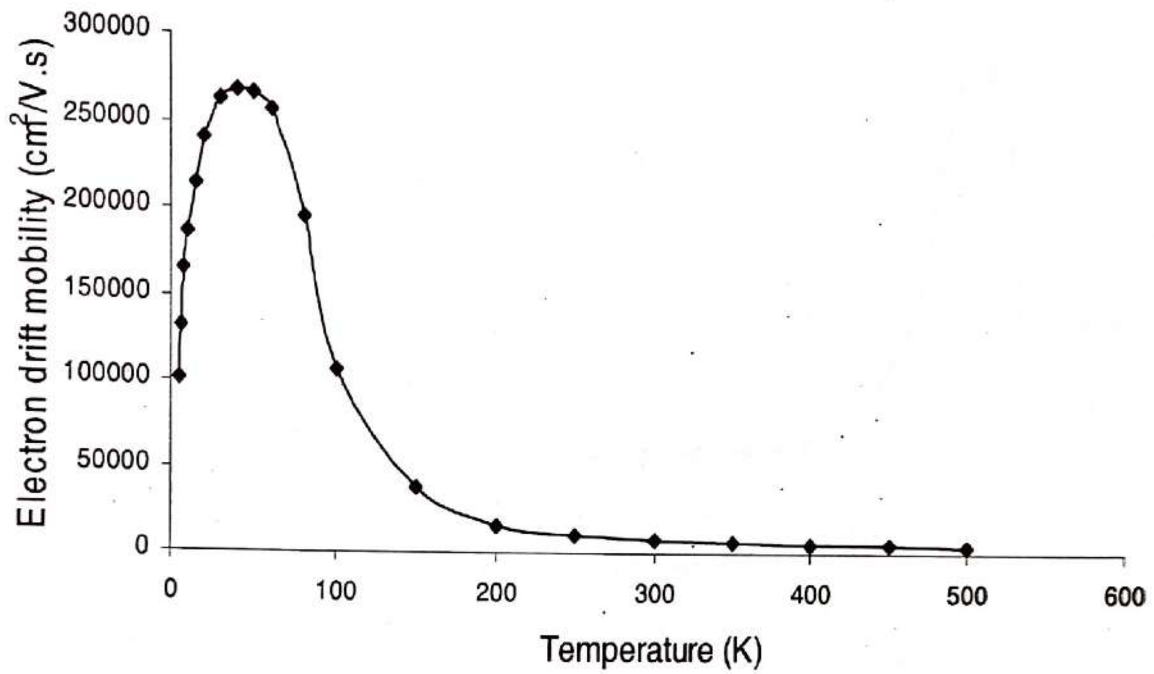

Fig.4. Electron drift mobility in very pure GaAs versus temperature.

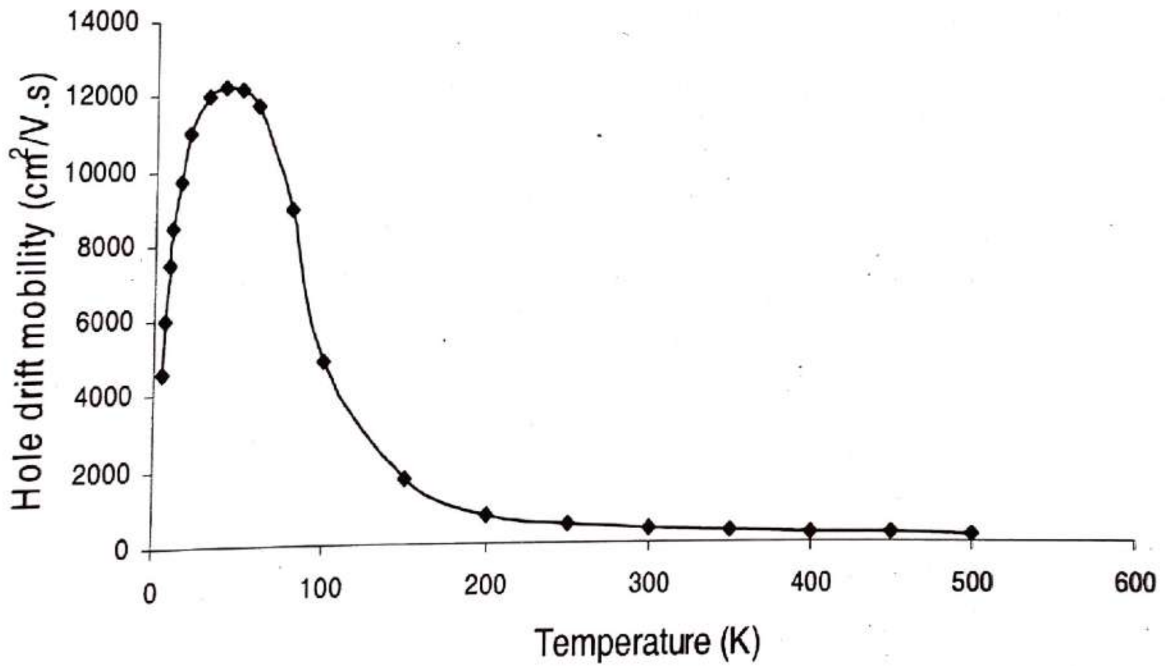

Fig.5. Hole drift mobility in very pure GaAs versus temperature.

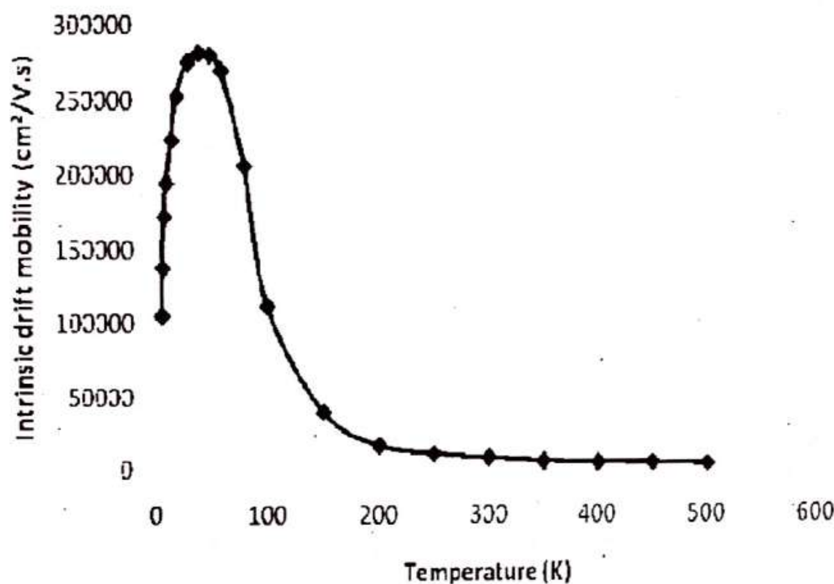

Fig.6. Intrinsic drift mobility in very pure GaAs versus temperature.

In the above graphs generally the mean free time and drift mobility start increasing steadily with temperature T until at 40 K where they begin to vary exponentially. It may be mentioned that in literature, experimental values of those electronic properties are not seen at other temperatures for which the values are computed in this work. The computed values of Table 2 may be used as a guide to the expected values of the electronic properties at other temperatures. It is also worthwhile mentioning that from Table 2; μ_i, μ_{nd}, μ_{Pd}, τ_p and τ_n increase rapidly with T reaching a maximum at 40 K and fall gradually with increase in T beyond $T > 40$ K. This trend is also represented in Figs. 2, 3, 4 and 5.

The theoretical equations (1), (2), (3) and (4) developed for the study has been based mostly on the existing theories in literatures. Experimental data on temperature variation of such properties do not exist in the literature at all temperatures which are computed in this work and can be used as data bank by electronic industries.

CONCLUSION

The theoretical model developed in this study is thus proven authentic and correct as values of μ_{nd}, μ_{Pd} and μ_i computed at 300 K corresponds with those available in highly recognized worldwide published 'Solid State Physics' and 'Semiconductor Optoelectronic Devices' text books.

Temperature changes greatly affect the electronic properties of semiconductors. μ_i, μ_{nd}, μ_{Pd}, τ_p and τ_n increase rapidly with T reaching a maximum at 40 K and fall gradually with increase in T beyond $T > 40$ K. The performance of electronic components made from these semiconductors is also expected to vary greatly with temperature.

Electronic industries need a thorough knowledge or data bank of variation of electronic properties of semiconductors as functions of temperatures and this is worked out in this study. This will enable them to predict the functional variation of the electronic device functions with

temperature and be able to take necessary measures for any undesirable effects arising from temperature variation.

Such predictions will be highly desirable for environment with wide variation of temperature such as in space or geographical (underground) exploration.

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