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Studies on Theoretical Electron Drift Mobility for Different Donor Concentrations in GaAs as a Function of Temperature

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Abstract

Electronic properties of semiconductors vary greatly with changes in temperature as well as with the changes in the donor and acceptor concentrations of the materials. The theoretical electron drift mobility μ_{Tnd} of GaAs roughly agrees with the experimental electron drift mobility μ_{nd} at very low and higher temperatures T. For different donor concentrations, the modeling results obtained for theoretical electron drift mobility μ_{Tnd} fairly agree with the predicted values at very low (5 – 10K) and very high (400 – 500K) temperatures, but at other temperatures they do not agree. Hence it is observed that the theoretical values of drift mobility of GaAs are the same with the experimental values at very low and very high temperatures. This might be due to a dominant effect called alloy scattering which limits the mobility of electrons and holes. The lower the donor concentration, the greater (more) the exponential curve of μ_{Tnd} and μ_{nd} versus T.

Keywords: Semiconductors, donor and acceptor concentrations, modeling results, dominant effect, alloy scattering, exponential curve

1.0 Introduction

Semiconductors form a group of materials having electrical conductivity intermediate between metals and insulators [1]. 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 [2].

The present study concentrates on Si and GaAs, from which majority of the present day electronic devices are being made. 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 [3]. The thermal variation of electronic properties of semiconducting materials is the subject of this study.

2.0 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.

2.1 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

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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 [4].
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 [2]. Phonons greatly influence the electronic properties of semiconductors.

2.2 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 [2]. 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 [5].

3.0 Conductivity and Mobility

The free charge carriers in a metal or semiconductor are in constant motion, even at thermal equilibrium. At room temperature, for example, the thermal motion of an electron may be visualized as random scattering from lattice atoms, impurities, other electrons, and defects [6]. Since the scattering is random, there is no net motion of the group of n electrons/cm^3 over any period of time. The probability of an electron returning to its starting point after sometime t is negligibly small. However, if a large number of electrons is considered there will be no preferred direction of motion for the group of electrons and no net current flow.
If an electric field E_x is applied in the x-direction, each electron experiences a net force
$-qE_x$ from the field. The effect of this force when averaged over all the electrons, however, is a net motion of the group in the x-direction. If P_x is the x-component of the total momentum of the group, the force of the field on the n electrons/cm^3 is

$$-nqE_x = \left.\frac{dP_x}{dt}\right|_{field} \qquad (1)$$

Let us consider a group of N_o electrons at time t = 0 and define N(t) as the number of electrons which have not undergone a collision by time t. The rate of decrease in N(t) at any time t is proportional to the number left unscattered at t,

$$-\frac{dN(t)}{dt} = \frac{N(t)}{\tau} \qquad \{2)$$

where τ^{-1} is a constant of proportionality. The solution to Eq.(2) is an exponential function

$$N(t) = N_0 e^{-t/\tau} \qquad (3)$$

τ represents the mean time between scattering events called the mean free time. The probability that any electron has a collision in the time interval dt is dt/τ. Thus the differential change in P_x due to collision in time dt is

$$dp_x = -p_x \frac{dt}{\tau} \qquad (4)$$

The rate of p_x due to the decelerating effect of collisions is

$$\left.\frac{dp_x}{dt}\right|_{collision} = -\frac{p_x}{\tau} \qquad (5)$$

The sum of acceleration and deceleration effect must be zero for steady state. Hence, combining Eqs. (1) and (5) gives

$$-\frac{p_x}{\tau} - nqE_x = 0 \qquad (6)$$

The average momentum per electron is

$$\langle p_x \rangle = \frac{p_x}{n} = -q\tau E_x \qquad (7)$$

Eq.(7) indicates that the electrons have on the average a constant net velocity in the negative x – direction:

$$\langle v_x \rangle = \frac{\langle p_x \rangle}{m_n^*} = -\frac{q\tau E_x}{m_n^*} \tag{8}$$

The drift speed described by Eq.(8) is usually much smaller than the random speed due to thermal motion.

The current density resulting from this net drift is just the number of electrons crossing a unit area per unit time ($n\langle v_x \rangle$) multiplied by the charge on the electron (–q):

$$J_x = -qn\langle v_x \rangle \tag{9}$$

Using Eq.(8) for the average velocity we obtain

$$J_x = \frac{nq^2\tau}{m_n^*} E_x \tag{10}$$

Thus, current density is proportional to the electric field, as we expect from Ohm's law:

$$J_x = \sigma E_x \tag{11}$$

where $\sigma = \frac{nq^2\tau}{m_n^*}$. The electronic conductivity σ (Ω-cm)$^{-1}$ can be written as

$$\sigma = qn\mu_n \tag{12}$$

where

$$\mu_n = \frac{q\tau}{m_n^*} \tag{13a}$$

The quantity μ_n, called the electron mobility, describes the ease with which electrons drift in the material, under applied electric field. For hole mobility, we have

$$\mu_p = \frac{q\tau}{m_p^*} \tag{13b}$$

Mobility is a very important quantity in characterizing semiconducting material and in device development. The mobility defined in Eqs.(13a) and (13b) can be expressed as the average particle drift velocity per unit electric field [6]. Comparing Eqs.(8) and (13a), we have

$$\mu_n = -\frac{\langle v_x \rangle}{E_x} \tag{14}$$

The minus sign in the definition results in a positive value of mobility, since electrons drift opposite to the field. The current density can thus be written in terms of mobility as

$$J_x = qn\mu_n E_x \tag{15}$$

This derivation has been based on the assumption that the current is carried primarily by electrons. For hole conduction, we change n to p, -q to +q, and μ_n to μ_p, where $\mu_p = +\frac{\langle v_x \rangle}{E_x}$ is the mobility of holes. If both electrons and holes participate, we must modify Eq. (15) to

$$J_x = q(n\mu_n + p\mu_p)E_x = \sigma E_x \tag{16}$$

where μ_n or μ_p is called the drift mobility [7].

4.0 Carrier Scattering Phenomena

We define a mean free time τ between successive collisions such that

$$\tau = \frac{l}{\overline{V}} \tag{17}$$

Where $\overline{V}$, is the mean velocity and l is the mean free path. Consider n electrons moving with velocity V in a given direction. The number of collisions dn in time dt is proportional to n and dt, so that

$$dn = -Cndt \tag{18}$$

where C is a constant of proportionality. We define

$$C = \frac{1}{\tau} \tag{19}$$

where τ is defined as the relaxation time. Combining Eqs.(18) and (19),

$$\frac{dn}{n} = -\frac{dt}{\tau} \tag{20}$$

which on integration, gives

$$n = n_0 \, e^{-t/\tau} \tag{21}$$

where $n = n_o$ at t=0. The probability that an electron has not made a collision is

$$\frac{n}{n_0} = e^{-t/\tau} \tag{22}$$

The mean time between collisions is

$$\bar{t} = \frac{1}{\tau}\int_0^{\infty} te^{-t/\tau} dt = \tau \tag{23}$$

The mean free path can also be defined as

$$\frac{1}{l} = N_{sc}\sigma_{st} \tag{24}$$

where N_{sc} is the density of scattering centers. Hence from Eq.(17)

$$\tau = \frac{1}{N_{sc}\sigma_{st}\mathrm{V}} \tag{25}$$

Consider now an electron under the influence of an electric field and suffering collisions. At time t = 0, its velocity is V_o and the velocity V at time t, when it suffers collision, is given by

$$\mathrm{V} = \mathrm{V}_0 - \frac{qEt}{m_n^*} \tag{26}$$

where E is the applied field. This equation must be averaged over all time knowing that $\frac{1}{\tau}e^{-t/\tau}$ is the probability that a collision will occur after t seconds [8]. Thus, the time-averaged velocity is given by

$$\overline{V} = \overline{V}_o - \frac{qE}{\tau m_n^*}\int_0^{\infty} t\, e^{-t/\tau} dt$$

$$= \overline{V}_o - \frac{qE\tau}{m_n^*} \tag{27}$$

If the collusions are truly random, $\overline{V} = 0$ and the mean drift velocity is given by

$$\overline{V} = \overline{V}_d - \frac{qE\tau}{m_n^*} \tag{28}$$

The magnitude of the mean drift velocity per unit field is defined as mobility, such that for electrons;

$$\mu_n = \frac{\overline{V_d}}{E} = -\frac{q\tau_n}{m_n^*} \tag{29}$$

and for holes

$$\mu_p = \frac{q\tau_p}{m_p^*} \tag{30}$$

In a very pure crystal, the mobility is limited at high temperatures by carrier-lattice or phonon scattering. The lattice vibrations depend on the temperature T. As a phonon moves through the crystal, the bandgap develops a periodic perturbation, which can be approximated by a periodic potential distribution. For such carrier-phonon scattering the mobility μ_L is approximately proportional to $T^{-3/2}$ at low T. That is

$$\mu_L \propto T^{-3/2} \tag{31}$$

and hence

$$\mu_L = \beta T^{-3/2} \tag{32}$$

As the temperature of the crystal is lowered, the rate of phonon scattering decreases and the mobility increases. As the temperature is lowered, the carriers move more slowly through the crystal and therefore the probability of collision with such charged or neutral (at very low temperatures) impurity centers increase [9]. To a first approximation, the mobility μ_I limited by ionized impurity scattering is proportional to $T^{3/2}$.
That is

$$\mu_I \propto T^{3/2} \tag{33}$$

and hence

$$\mu_I = \alpha T^{3/2} \tag{34}$$

and to N_i^{-1} where N_i is the density of impurity centers. α and β are constants of proportionality with units $cm^2/V.s.K^{3/2}$ and $cm^2.K^{3/2}/V.s$ respectively. The total mobility μ as a function of temperature, is then given by Mattheisen's rule as

$$\frac{1}{\mu} = \frac{1}{\mu_I} \div \frac{1}{\mu_L} \tag{35}$$

where μ_I is the mobility limited by impurity scattering and μ_L is the mobility limited by phonon scattering. The mobility is principally limited by impurity scattering and lattice or optical phonon scattering. Thus using Eqns.(32) and (34) in Eqn.(35) we have

$$\mu^{-1} = \alpha^{-1} T^{-3/2} + \beta^{-1} T^{3/2} \tag{36}$$

In addition to these two dominant carrier-scattering mechanisms, there are other sources of scattering in a real crystal. In alloy semiconductor, there is a dominant effect called alloy scattering, which limits the mobility. Alloy scattering arises from the random positioning of the substituting atom species in the relevant sub-lattice and the consequent perturbation of the crystal potential [10].

5.0 Theoretical Computation of Electron Drift Mobility at Different N_d as Functions of T

A mathematical expression relating μ_{nd} and T has been formulated in this work based on the fact that there is a mobility limited by carrier phonon scattering μ_L approximately proportional to $T^{-3/2}$ at low temperature and that limited by ionized impurity scattering μ_I proportional to $T^{3/2}$ as given in Eqn.(36). Then the unknown constants α and β are obtained by the least square fitting method of data for different temperatures using Eqn.(36). It shows that α and β depend on N_d. α and β values are then substituted into Eq.(36) to get different equations of μ_{Tnd}^{-1} for different N_d as functions of T. From these equations, theoretical drift mobility for electrons μ_{Tnd} values are computed and compared with the experimental drift mobility for electrons μ_{End} values for electrons.

6.0 Source of Data Collection

Mobility as a function of impurity concentration in GaAs is shown in Figure 1. Hall mobility measured as a function of temperature is also shown in Figure 2.

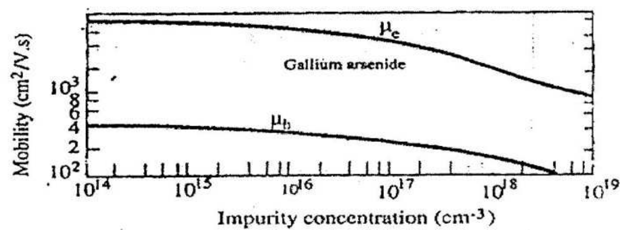

Fig. 1. Variation of electron and hole mobilities in GaAs as a function of doping level (from B.G. Streetman, Solid State Electronic Devices, 3rd Edition., © 1990. Reprinted by permission of Prentice Hall, Englewood Cliffs, N J).

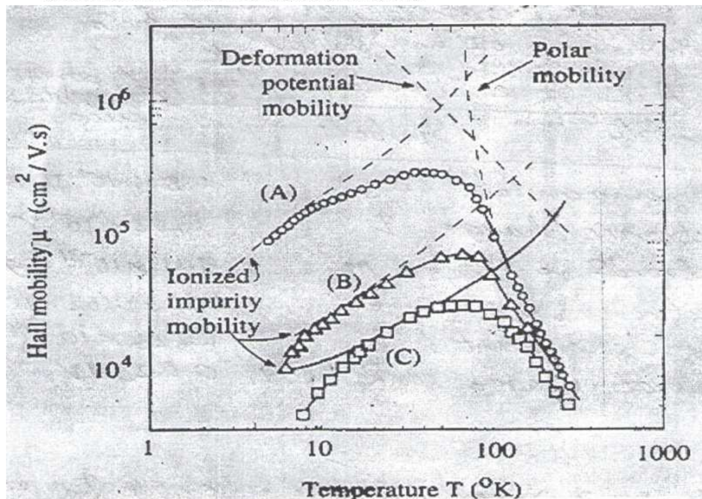

Fig. 2. Mobility measured as a function of temperature in a very pure sample GaAs grown by vapour phase epitaxy (from M. Shur, Physics of Semiconducting Devices,© 1990.Reprinted by permission of Prentice Hall, Englewood Cliffs, N J; the data are compiled from C.M. Wolf, et al., Journal of Applied Physics,41,3088,1970)

7.0 Drift Mobility for Electrons and Holes in GaAs as a Function of T.

Values for Hall mobility μ_H at different temperature T collected from published graph (Figure 2, curve A) of Hall mobility μ_H in a very pure GaAs measured at different temperatures T are given 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.

Table 1: 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 given in Table 1. From the published work of Figure 2 [11], electron drift mobility μ_{nd} and hole drift mobility μ_{pd} obtained are 8100 cm^2/V.s and 380 cm^2/V.s respectively for the lowest donor (impurity) concentration N_d of $10^{14}cm^{-3}$ for GaAs. 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 $r_n = \frac{\mu_{nd}}{\mu_H}$ and $r_p = \frac{\mu_{pd}}{\mu_H}$ 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. 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. Hence computed values of μ_H, μ_{nd} and μ_{pd} at different T are given in Table 2.

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

+ T(K)	+ μ_H(cm^2/V.s)	* μ_{nd}(cm^2/V.s)	* μ_{pd}(cm^2/V.s)
5	92000	101200	4600
6	120000	132000	6000
8	150000	165000	7500
10	170000	187000	8500
15	195000	214500	9750
20	220000	242000	11000
30	240000	264000	12000
40	245000	269500	12250
50	244000	268400	12200
60	235000	258500	11750
80	180000	198000	9000
100	98000	107800	4900
150	35000	38500	1750
200	15000	16500	750
250	10000	11000	500
300	7700	x 8470	x 385
350	5600	6160	280
400	4700	5170	235
450	4400	4840	220
500	3500	3850	175

+Values obtained from Figure 2 [11]. x values computed in this work which agrees very well with the experimental values at 300 K [1]. * Values obtained by computation in this work.

8.0 Electron Drift Mobility μ_{nd}, for Different Donor Concentrations N_d in GaAs as a Function of Temperature T

μ_H at 300 K is 7700 cm^2/V.s given in Table 1. Thus the ratio r for electrons defined by $r = \mu_{nd}/\mu_H$ was found for different N_d. For example, for $N_{d1} = 10^{15}$ cm^{-3}, μ_{nd} = 7100 cm^2/V.s and the ratio r for electrons was found to the 0.92. Hence using values of μ_{nd} obtained from Figure 2 in the r ratio, we obtained different r values for different N_d which are given in Table 3 below.

Table 3: Values of μ_{nd} and r for different N_d in GaAs for which μ_H at 300 K is 7700 cm^2/V.s is used.

N_d (cm^{-3})	μ_{nd} (cm^2/V.s)	r
10^{15}	7100	0.92
10^{16}	6200	0.81
10^{17}	4800	0.62
10^{18}	2800	0.36
10^{19}	1300	0.17

Assuming that r remain fairly independent of T, multiplying μ_H values for different T (of Table 1) by r gives μ_{nd} values in GaAs at different T. Thus values of μ_{nd} for different N_d and r at different T were thus computed and are given in Table 4.

Table 4: Computed values of μ_{nd} in GaAs for different N_d at different temperature.

+ T(K)	+ μ_H(cm^2/V.s)	$N_{d1} = 10^{15} cm^3$ * μ_{nd}(cm^2/V.s)	$N_{d2} = 10^{16}$ cm^{-3} *μ_{nd}(cm^2/V.s)	$N_{d3} = 10^{17} cm^{-3}$ * μ_{nd}(cm^2/V.s)	$N_{d4} = 10^{18} cm^{-3}$ *μ_{nd}(cm^2/V.s)	$N_{d5} = 10^{19}$ cm^{-3} *μ_{nd}(cm^2/V.s)
5	92000	84640	74520	57040	33120	15640
6	120000	110400	97200	74400	43200	20400
8	150000	138000	121500	93000	54000	25500
10	170000	156400	137700	105400	61200	28900
15	195000	176640	157950	120900	70200	33150
20	220000	202400	178200	136400	79200	37400
30	240000	220800	194400	148800	86400	40800
40	245000	225400	198450	151900	88200	41650
50	244000	224480	197640	151280	87840	41480
60	235000	216200	190350	145700	84600	39950
80	180000	165600	145800	111600	64800	30600
100	98000	90160	79380	60760	35280	16660
150	35000	32200	28350	21700	12600	5950
200	15000	13800	12150	9300	5400	2550
250	10000	9200	8100	6200	3600	1700
300	7700	7084	6237	4774	2772	1309
350	5600	5152	4536	3472	2016	952
400	4700	4324	3807	2914	1692	799
450	4400	4048	3564	2728	1584	748
500	3500	3220	2835	2170	1260	595

+ Values obtained from Figure 2 [11]. * Values computed in this work.

The computed values of μ_{nd} in GaAs for different N_d at different T are represented graphically in Figure 3.

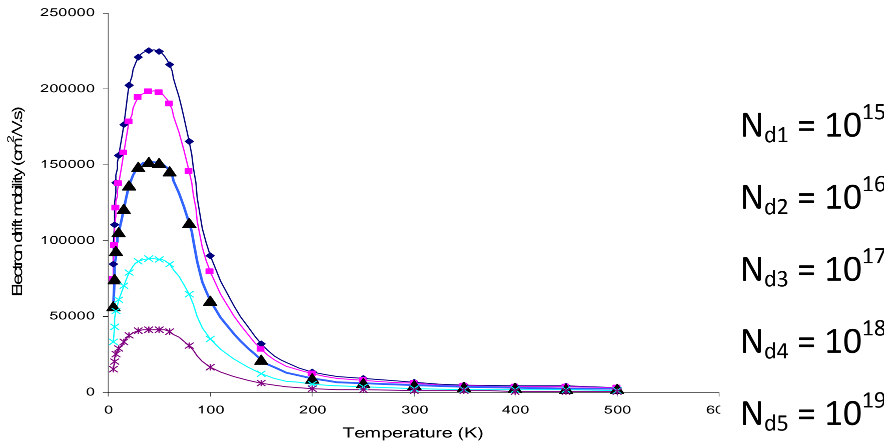

Fig.3. Electron drift mobility for different donor concentrations in pure GaAs versus temperature.

9.0 Theoretical Electron Drift Mobility μ_{Tnd} for Different Donor Concentrations N_d in GaAs as a Function of T

For the computation of μ_{Tnd} for different N_d as a function of T, Eq.(36) is restated as below.

$$\mu_{Tnd}^{-1} = \alpha^{-1} T^{-3/2} + \beta^{-1} T^{3/2} \quad (37)$$

From Eq.(37), the following equations were obtained

$$\mu_{Tnd}^{-1} T^{3/2} = \alpha^{-1} + \beta^{-1} T^{3} \quad (38)$$

And $\mu_{Tnd}^{-1} T^{-3/2} = \beta^{-1} + \alpha^{-1} T^{-3}$ (39)

Here Table 4 is used and the constants α and β computed for different donor concentrations by way of finding the intercepts and gradient of Eqs.(38) and (39) using linear regression method.

10.0 Theoretical Electron Drift Mobility μ_{Tnd} for Different Donor Concentrations, N_d in GaAs as Function of T.

Now considering μ_{nd} for different N_d in GaAs at different T, values of $\mu_{Tnd}^{-1} T^{3/2}$, $\mu_{Tnd}^{-1} T^{-3/2}$, T^3 and T^{-3} for different N_d in GaAs are computed for linear fittings with Eqs.(38) and (39) and given in Tables 5 to 9.

Table 5: Computed values of $\mu_{Tnd}^{-1} T^{3/2}$, $\mu_{Tnd}^{-1} T^{-3/2}$, T^3 and T^{-3} in GaAs ($N_{d1} = 10^{15}$ cm^{-3}) for linear fitting with Eqs.(38) and (39).

T(K)	μ_{nd} (cm^2/V.s)	$\mu_{Tnd}^{-1}T^{3/2}$($K^{3/2}$V.s/cm^2)	T^3(K^3)	$\mu_{Tnd}^{-1}T^{-3/2}$(V.s/$K^{3/2}$.cm^2)	T^{-3}(K^{-3})
5	84640	1.321	125	1.06E-02	8.00E-03
6	110400	1.331	216	6.16E-03	4.63E-03
8	138000	1.640	512	3.20E-03	1.95E-03
10	156400	2.022	1000	2.02E-03	1.00E-03
15	176640	3.289	3375	9.74E-04	2.96E-04
20	202400	4.419	8000	5.52E-04	1.25E-04
30	220800	7.442	27000	2.76E-04	3.70E-05
40	225400	11.224	64000	1.75E-04	1.56E-05
50	224480	15.750	125000	1.26E-04	8.00E-06
60	216200	21.497	216000	9.95E-05	4.63E-06
80	165600	43.209	512000	8.44E-05	1.95E-06
100	90160	110.914	1.00E+06	1.11E-04	1.00E-06
150	32200	570.533	3.38E+06	1.69E-04	2.96E-07
200	13800	2049.585	8.00E+06	2.56E-04	1.25E-07
250	9200	4296.573	1.56E+07	2.75E-04	6.40E-08
300	7084	7335.054	2.70E+07	2.72E-04	3.70E-08
350	5152	12709.434	4.29E+07	2.96E-04	2.33E-08
400	4324	18501.338	6.40E+07	2.89E-04	1.56E-08
450	4048	23581.871	9.11E+07	2.59E-04	1.10E-08
500	3220	34721.550	1.25E+08	2.78E-04	8.00E-09

Table 6: Computed values of $\mu_{Tnd}^{-1} T^{3/2}$, $\mu_{Tnd}^{-1} T^{-3/2}$, T^3 and T^{-3} in GaAs ($N_{d2} = 10^{16}$ cm^{-3}) for linear fitting with Eqs.(38) and (39).

T(K)	μ_{nd} (cm^2/V.s)	$\mu_{Tnd}^{-1}T^{3/2}$ ($K^{3/2}$V.s/cm^2)	T^3(K^3)	$\mu_{Tnd}^{-1}T^{-3/2}$(V.s/$K^{3/2}$.cm^2)	T^{-3}(K^{-3})
5	74520	1.50	125	1.20E-02	8.00E-03
6	97200	1.51	216	7.00E-03	4.63E-03
8	121500	1.86	512	3.64E-03	1.95E-03
10	137700	2.30	1000	2.30E-03	1.00E-03
15	157950	3.68	3375	1.09E-03	2.96E-04
20	178200	5.02	8000	6.27E-04	1.25E-04
30	194400	8.45	27000	3.13E-04	3.70E-05
40	198450	12.75	64000	1.99E-04	1.56E-05
50	197640	17.89	125000	1.43E-04	8.00E-06
60	190350	24.42	216000	1.13E-04	4.63E-06
80	145800	49.08	512000	9.59E-05	1.95E-06
100	79380	125.98	1.00E+06	1.26E-04	1.00E-06
150	28350	648.01	3.38E+06	1.92E-04	2.96E-07
200	12150	2327.92	8.00E+06	2.91E-04	1.25E-07
250	8100	4880.06	1.56E+07	3.12E-04	6.40E-08
300	6237	8331.17	2.70E+07	3.09E-04	3.70E-08
350	4536	14435.41	4.29E+07	3.37E-04	2.33E-08
400	3807	21013.92	6.40E+07	3.28E-04	1.56E-08
450	3564	26784.35	9.11E+07	2.94E-04	1.10E-08
500	2835	39436.83	1.25E+08	3.15E-04	8.00E-09

Table 7: Computed values of $\mu_{Tnd}^{-1} T^{3/2}$, $\mu_{Tnd}^{-1} T^{-3/2}$, T^3 and T^{-3} for GaAs ($N_{d3} = 10^{17}$ cm^{-3}) for linear fitting with Eqs.(38) and (39).

T(K)	**μ_{nd} (cm^2/V.s)**	**$\mu_{Tnd}^{-1}T^{3/2}$ (K$^{3/2}$V.s/cm^2)**	T^3(K^3)	**$\mu_{Tnd}^{-1}T^{-3/2}$ (V.s/K$^{3/2}$.cm^2)**	T^{-3}(K^{-3})
5	57040	1.96	125	1.57E-02	8.00E-03
6	74400	1.98	216	9.15E-03	4.63E-03
8	93000	2.43	512	4.75E-03	1.95E-03
10	105400	3.00	1000	3.00E-03	1.00E-03
15	120900	4.81	3375	1.42E-03	2.96E-04
20	136400	6.56	8000	8.20E-04	1.25E-04
30	148800	11.04	27000	4.09E-04	3.70E-05
40	151900	16.65	64000	2.60E-04	1.56E-05
50	151280	23.37	125000	1.87E-04	8.00E-06
60	145700	31.90	216000	1.48E-04	4.63E-06
80	111600	64.12	512000	1.25E-04	1.95E-06
100	60760	164.58	1.00E+06	1.65E-04	1.00E-06
150	21700	846.60	3.38E+06	2.51E-04	2.96E-07
200	9300	3041.32	8.00E+06	3.80E-04	1.25E-07
250	6200	6375.56	1.56E+07	4.08E-04	6.40E-08
300	4774	10884.27	2.70E+07	4.03E-04	3.70E-08
350	3472	18859.16	4.29E+07	4.40E-04	2.33E-08
400	2914	27453.67	6.40E+07	4.29E-04	1.56E-08
450	2728	34992.45	9.11E+07	3.84E-04	1.10E-08
500	2170	51522.30	1.25E+08	4.12E-04	8.00E-09

Table 8: Computed values of $\mu_{Tnd}^{-1} T^{3/2}$, $\mu_{Tnd}^{-1} T^{-3/2}$, T^3 and T^{-3} for GaAs ($N_{d4} = 10^{18}$ cm^{-3}) for linear fitting with Eqs.(38) and (39).

T(K)	**μ_{nd} (cm^2/V.s)**	**$\mu_{Tnd}^{-1}T^{3/2}$ (K$^{3/2}$V.s/cm^2)**	T^3(K^3)	**$\mu_{Tnd}^{-1}T^{-3/2}$ (V.s/K$^{3/2}$.cm^2)**	T^{-3}(K^{-3})
5	33120	3.36	125	2.70E-02	8.00E-03
6	43200	3.40	216	1.58E-02	4.63E-03
8	54000	4.19	512	8.18E-03	1.95E-03
10	61200	5.17	1000	5.17E-03	1.00E-03
15	70200	8.28	3375	2.45E-03	2.96E-04
20	79200	11.29	8000	1.41E-03	1.25E-04
30	86400	19.02	27000	7.04E-04	3.70E-05
40	88200	28.68	64000	4.48E-04	1.56E-05
50	87840	40.25	125000	3.22E-04	8.00E-06
60	84600	54.94	216000	3.34E-04	4.63E-06
80	64800	110.42	512000	2.16E-04	1.95E-06
100	35280	283.45	1.00E+06	2.83E-04	1.00E-06
150	12600	1458.03	3.38E+06	4.32E-04	2.96E-07
200	5400	5237.83	8.00E+06	6.55E-04	1.25E-07
250	3600	10980.13	1.56E+07	7.03E-04	6.40E-08
300	2772	18745.14	2.70E+07	6.94E-04	3.70E-08
350	2016	3247.97	4.29E+07	7.58E-04	2.33E-08
400	1692	47281.32	6.40E+07	7.39E-04	1.56E-08
450	1584	60264.78	9.11E+07	6.61E-04	1.10E-08
500	1260	88732.86	1.25E+08	7.10E-04	8.00E-09

Table 9: Computed values of $\mu_{Tnd}^{-1} T^{3/2}$, $\mu_{Tnd}^{-1} T^{-3/2}$, T^3 and T^{-3} for GaAs ($N_{d5} = 10^{19}$ cm^{-3}) for linear fitting with Eqs. (38) and (39).

T(K)	μ_{nd} (cm^2/V.s)	$\mu_{Tnd}^{-1}T^{3/2}$ ($K^{3/2}$V.s/cm^2)	T^3(K^3)	$\mu_{Tnd}^{-1}T^{-3/2}$ (V.s/$K^{3/2}$.cm^2)	T^{-3}(K^{-3})
5	15640	7.15	125	5.72E-02	8.00E-03
6	20400	7.20	216	3.34E-02	4.63E-03
8	25500	8.87	512	1.73E-02	1.95E-03
10	28900	10.94	1000	1.09E-02	1.00E-03
15	33150	17.52	3375	5.19E-03	2.96E-04
20	37400	23.92	8000	2.99E-03	1.25E-04
30	40800	40.27	27000	1.49E-03	3.70E-05
40	41650	60.74	64000	9.49E-04	1.56E-05
50	41480	85.23	125000	6.82E-04	8.00E-06
60	39950	116.33	216000	5.39E-04	4.63E-06
80	30600	233.84	512000	4.57E-04	1.95E-06
100	16660	600.24	1.00E+06	6.00E-04	1.00E-06
150	5950	3087.59	3.38E+06	9.15E-04	2.96E-07
200	2550	11091.87	8.00E+06	1.37E-03	1.25E-07
250	1700	23252.04	1.56E+07	1.49E-03	6.40E-08
300	1309	39695.59	2.70E+07	1.47E-03	3.70E-08
350	952	68780.47	4.29E+07	1.60E-03	2.33E-08
400	799	100125.16	6.40E+07	1.56E-03	1.56E-08
450	748	127619.54	9.11E+07	1.40E-03	1.10E-08
500	595	187904.87	1.25E+08	1.50E-03	8.00E-09

Now considering Tables 5 to 9, linear fittings for different N_d for Eqs.(38) and (39) give the average values of α^{-1} and β^{-1} for different N_d in GaAs which are therefore given in Table 10.

Table 10. Average values of α^{-1} and β^{-1} for different N_d in GaAs

N_d (cm^{-3})	Equation number	Slope	Intercept	Average of α^{-1} and β^{-1}
10^{15}	(38) (39)	$\beta^{-1} = 2.75 \times 10^{-4}$ $\alpha^{-1} = 1.297$	$\alpha^{-1} = 1.286$ $\beta^{-1} = 2.80 \times 10^{-4}$	$\alpha_{av}^{-1} = 1.292$ $\beta_{av}^{-1} = 2.78 \times 10^{-4}$
10^{16}	(38) (39)	$\beta^{-1} = 3.17 \times 10^{-4}$ $\alpha^{-1} = 1.461$	$\alpha^{-1} = 1.474$ $\beta^{-1} = 3.13 \times 10^{-4}$	$\alpha_{av}^{-1} = 1.467$ $\beta_{av}^{-1} = 3.15 \times 10^{-4}$
10^{17}	(38) (39)	$\beta^{-1} = 4.08 \times 10^{-4}$ $\alpha^{-1} = 1.925$	$\alpha^{-1} = 1.908$ $\beta^{-1} = 4.14 \times 10^{-4}$	$\alpha_{av}^{-1} = 1.917$ $\beta_{av}^{-1} = 4.11 \times 10^{-4}$
10^{18}	(38) (39)	$\beta^{-1} = 6.74 \times 10^{-4}$ $\alpha^{-1} = 3.315$	$\alpha^{-1} = 3.271$ $\beta^{-1} = 7.18 \times 10^{-4}$	$\alpha_{av}^{-1} = 3.293$ $\beta_{av}^{-1} = 6.96 \times 10^{-4}$
10^{19}	(38) (39)	$\beta^{-1} = 1.49 \times 10^{-3}$ $\alpha^{-1} = 7.022$	$\alpha^{-1} = 6.962$ $\beta^{-1} = 1.51 \times 10^{-4}$	$\alpha_{av}^{-1} = 6.992$ $\beta_{av}^{-1} = 1.50 \times 10^{-3}$

Units of α^{-1} and β^{-1} are V.s.$K^{3/2}$/cm^2 and V.s/cm^2.$K^{3/2}$ respectively.

Hence substituting for α_{av}^{-1} and β_{av}^{-1} for different N_d of Table 10 into Eq.(37) gives the following μ_{Tnd}^{-1} equations for different N_d in GaAs recorded in Table 11.

Table 11: Equations of μ_{Tnd}^{-1} for different N_d in GaAs as a function of T.

Nd (cm^{-3})	Equation	Equation number
10^{15}	$\mu_{Tnd}^{-1} = 1.292\ T^{-3/2} + 2.78 \times 10^{-4}\ T^{3/2}$	(40)
10^{16}	$\mu_{Tnd}^{-1} = 1.467\ T^{-3/2} + 3.15 \times 10^{-4}\ T^{3/2}$	(41)
10^{17}	$\mu_{Tnd}^{-1} = 1.917\ T^{-3/2} + 4.11 \times 10^{-4}\ T^{3/2}$	(42)
10^{18}	$\mu_{Tnd}^{-1} = 3.293\ T^{-3/2} + 6.96 \times 10^{-4}\ T^{3/2}$	(43)
10^{19}	$\mu_{Tnd}^{-1} = 6.992\ T^{-3/2} + 1.50 \times 10^{-4}\ T^{3/2}$	(44)

Using Eqs.(40) to (44) of Table 11, values of μ_{Tnd} for different donor concentrations in GaAs for different T are computed and given in Table 12.

Table 12: Computed values of μ_{Tnd} in GaAs for different N_d at different T.

T(K)	$N_d(cm^{-3})$ $N_{d1} = 10^{15}$ $\mu_{Tnd}(cm^2/V.s)$	$N_{d2} = 10^{16}$ $\mu_{Tnd}(cm^2/V.s)$	$N_{d3} = 10^{17}$ $\mu_{Tnd}(cm^2/V.s)$	$N_{d4} = 10^{18}$ $\mu_{Tnd}(cm^2/V.s)$	$N_{d5} = 10^{19}$ $\mu_{Tnd}(cm^2/V.s)$
5	84273	74220	56800	33049	15573
6	108710	95743	74057	42645	20089
8	157784	138965	106360	61953	29159
10	201483	177457	135837	79215	37238
15	260683	229612	175825	102914	48193
20	254677	224336	171840	100906	47095
30	187053	164778	126262	74392	34599
40	132785	116975	89643	52881	24563
50	98265	86566	66343	39155	18178
60	75901	66865	51245	30251	14041
80	49908	43967	33696	19896	9233
100	35869	31599	24218	14300	6636
150	19589	17257	13226	7810	3624
200	12733	11217	8597	5077	2356
250	9114	8029	6153	3634	1686
300	6934	6108	4682	2765	1283
350	5503	4848	3715	2194	1018
400	4504	3968	3041	1796	833
450	3775	3325	2549	1505	698
500	3223	2839	2176	1285	596

The computed values of μ_{Tnd} in GaAs for different N_d at different T are represented graphically in Figure 4.

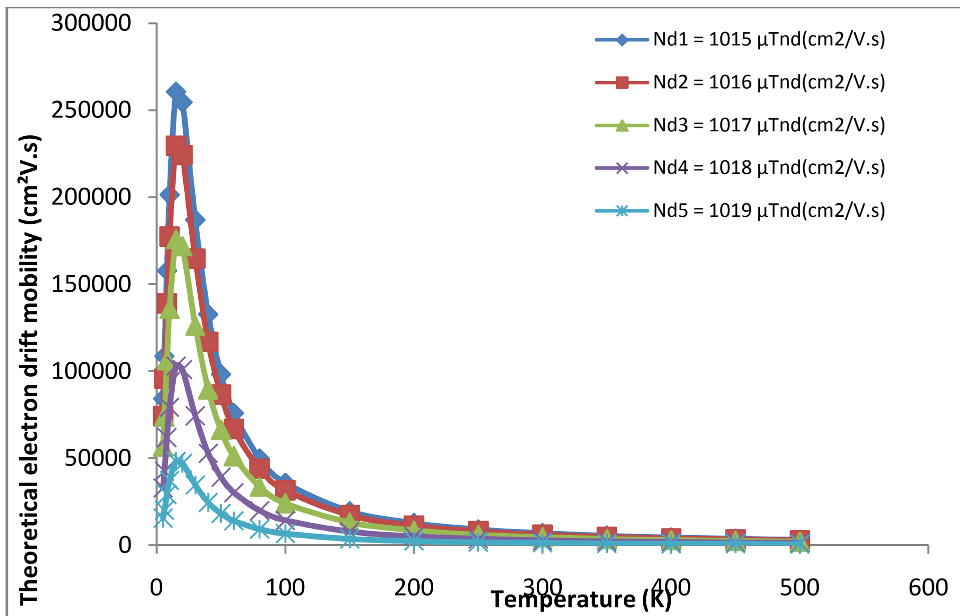

Fig. 4: Theoretical electron drift mobility for different donor concentrations in pure GaAs versus temperature

Computed values of α and β for different N_d in GaAs are thus given in Table 13.

Table 13: Computed values of α and β for different N_d in GaAs

Semiconductor	N_d (cm^{-3})	α^{-1} ($V.s.K^{3/2}/cm^2$)	β^{-1} ($V.s/cm^2.K^{3/2}$)	α ($cm^2/V.s.K^{3/2}$)	β ($cm^2.K^{3/2}/V.s$)
GaAs	10^{15}	1.292	2.78×10^{-4}	0.7740	3603.6
	10^{16}	1.467	3.15×10^{-4}	0.6817	3174.6
	10^{17}	1.917	4.11×10^{-4}	0.5216	2433.1
	10^{18}	3.293	6.96×10^{-4}	0.3037	1436.8
	10^{19}	6.992	1.50×10^{-3}	0.1430	666.7

11.0 Discussion

It is observed from Table 4 that experimental electron drift mobility μ_{nd} in GaAs increases rapidly with increasing temperature for different N_d and is maximum at 40K after which it decreases rapidly with increasing temperature for different N_d. That is, (from Figure 3) after 40K from 80K, the curve assumes an exponential shape. The lower the N_d, the steeper or the more exponential the cure becomes (as shown in Figure 3) and vice versa.

In general (comparing Table 4 with Table 12), for different N_d, μ_{nd} and μ_{Tnd} are almost the same at lower and higher temperatures. The theoretical electron drift mobility μ_{Tnd} increases with increasing temperature and reaching at a particular T, decreases with increasing temperature just like experimental electron drift mobility μ_{nd}. For example in GaAs (for $N_d = 10^{16}$ cm^{-3}), μ_{Tnd} values are 74220 $cm^2/V.s$, 95743 $cm^2/V.s$, 3968 $cm^2/V.s$ and 2839 $cm^2/V.s$ at 5 K, 6 K, 400 K and 500 K respectively while μ_{nd} values are 74520 $cm^2/V.s$, 97200 $cm^2/V.s$, 4536 $cm^2/V.s$ and 2835 $cm^2/V.s$ at 5 K, 6 K, 400 K and 500 K respectively [5]. From Table 13, α and β values varies inversely with Nd.

12.0 Conclusion

It is seen that generally the theoretical electron drift mobility μ_{Tnd} roughly agrees with the experimental electron drift mobility μ_{nd} at very low and higher temperatures. Moreover, it is seen that just like in the case of experimental electron drift mobility μ_{nd}, for theoretical electron drift mobility μ_{Tnd}, the lower the N_d, the steeper or the more exponential the curve becomes and vice versa.

13.0 Reference

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