Journal of Sciences, Islamic Republic of Iran 13(2): 173-179 (2002)
National Center For Scientific Research, ISSN 1016-1104

TEMPERATURE AND FIELD DEPENDENT ELECTRICAL CONDUCTIVITY OF $Al_XGa_{1-X}As$ TERNARY ALLOY

A.I. Mukolu

Department of Physics, University of Ado-Ekiti, Ado-Ekiti, Nigeria

Abstract

The variations of the electrical conductivity with temperature and electric field of the ternary alloy of gallium, aluminium and arsenic ($Al_{0.75}Ga_{0.25}As$) with atomic compositions of 99/1 and 98/2 have been investigated. The electrical conductivity of the alloy increases with temperature according to the relation, $\sigma = \sigma_0 \exp(-\epsilon/kT)$. The activation energy calculated from this empirical relation is 1.42±0.01 eV. The investigation of the variation of electrical conductivity with electric field of the samples reveals that in the low field region (< 1,400 V/m), the conduction is ohmic while in the high field region (> 1,400 V/m), the results are interpreted in terms of space charge limited currents.

Keywords: Electrical conductivity; Temperature; Electric field; Gallium; Aluminium; Arsenic

Introduction

Since the discovery of the Gunn effect [1], there has been considerable interest in the transport properties of materials like gallium arsenide which exhibit this effect [2-13]. Such interest led to the result that coherent microwave output is generated when a DC electric field is applied across a randomly oriented short, n-type sample of GaAs that exceeded a critical threshold value of several thousand volts per centimeter [1,14]. This principle is applied in solid state microwave sources used in radars, intrusion alarms and microwave test instruments [15].

Also, $Al_xGa_{1-x}As$ alloys are of considerable scientific interest because of their potential for device applications such as lasers, thermoelectric devices, local oscillators and power amplifiers [15-23]. The present work was therefore partly inspired by these applications and the need to search for more applications for the gallium aliminium arsenide ternary alloy.

The variation of electrical conductivity with electric field in semiconductors has been extensively studied in the past years by many investigators [24-30]. Their results demonstrate that for small values of electric field (< 10^3 V/m) ohmic conduction is obtained but for high fields (> 10^3 V/m) a non-linear dependence is obtained. Deviations from Ohm’s law for electronic conduction in metals and semiconductors are almost the rule rather than the exception. The drift velocity (V_d) of an electron or hole varies linearly with the electric field (E). This relationship given by Shockley [24] is

$$V_d = \mu_0 (E) \tag{1}$$

where the mobility (μ_0) is a function of the temperature of the specimen.

Mechanisms which might explain one or more of the observed characteristics are: space-charge limited flow with distributed traps [31,32], ionic flow, Poole-Frenkel effect [33], and Schottky emission [34]. The present investigation was undertaken in order to gain an understanding of the current flow processes in $Al_xGa_{1-x}As$ alloy, since a great deal of relevant information is still lacking.

Hava *et al.* [35] reported that rises in temperature at the junction of semiconductor lasers have undesirable effects on the laser performance. These effects reduce the efficiency and increase threshold current density emission line width and emitted wavelength [35]. Such changes limit the use of lasers in fibreoptical communication. It is with these in mind, that the present study was carried out in order to find the effect of varying temperatures on the electrical conductivity of $Al_xGa_{1-x}As$ samples, with a view to improving the efficiency and reliability of lasers fabricated from $Al_xGa_{1-x}As$ through the elimination of the risk of the upsurge of temperature.

Materials and Methods

Compounding of the Alloy ($Al_xGa_{1-x}As$)

Samples corresponding to atomic composition: 99/1, 98/2 and x = 0.5 were weighed Out and the composition by weight of the constituent elements is presented in Table 1. The alloy was treated as a unification of the alloys of $(GaAs)_{1-x}$ and $(AlAs)_x$. The value of x which was obtained from the phase diagram of Ga and Al was chosen such that the investigation could be carried out at the lowest possible temperature of about 300°C.

The percentages by weight were worked out from the following formulae connecting the weight percentages with atomic percentage equations:

$$Y = \frac{100XB}{XB + A(100 - X)} \tag{2}$$

$$X = \frac{100YA}{YA + B(100 - Y)} \tag{3}$$

where X is the percentage by weight and Y is the atomic percentage of the elements of atomic weight A in an alloy with another element which has atomic weight B. the combined atomic weight of $Ga_{1-x}Al_x$ is $(1-x)\ 69.72 + 26.98X = 69.72 - 42.74X$ while that of arsenic is 74.92. The borosilicate glass ampoules used in this investigation were cleaned by first boiling in chromic acid and then ultrasonically in distilled, deionized water, trichloroethylene, acetone and ethanol. The materials which were of 99.999% purity (Ventron Germany) were placed in the clean ampoules and heated over a range of temperatures from 300 to 900°C to from the molten alloy samples. They were homogenized at 800°C for 4 h. The samples were cut into flat circular tablets and polished with a fine grain sandpaper. Each sample had a diameter of 2 cm and a thickness of 0.5 cm. Two contacts were made on the samples with a fluxless solder. Copper wires were attached to the contacts using silver paste. The two contacts were to facilitate the measurement of conductivity using the two-point probe method. The samples were utilized to carry out subsequent measurements.

Annealing of the Samples

Some of the samples were placed in a glass ampoule which was evacuated to 1×10^{-5} torr. The ampoule was heat-treated in a furnace at 500°C for 5 min. After the heat treatment, the samples were cooled slowly to room temperature.

Variation of Electrical Conductivity with Temperature

Each sample with contacts was inserted in a thin walled test tube. The lower part of the test tube was immersed in a lagged heatable water bath. The water bath was maintained at the desired temperature with the aid of a temperature controller, while uniformity of temperature was ensured with the aid of a magnetic stirrer immersed in the bath. The insulated electrical leads from the contacts were taken out of the test tube via ports which were vacuum sealed with araldite. They were connected to a digital electrometer (Keithley 160B) and a digital millivoltmeter (Hewlett Packard 3465A) which measured the current and voltage respectively. The actual sample temperature and that of the water bath were determined with copper-constantan thermocouples whose cold junctions were maintained at 0°C. Effective temperature control was achieved by connecting both the sample thermocouple and the heater to the temperature controller. All the measurements were carried out at a number of temperatures between 300 and 363 K.

At any desired temperature, the currents were measured by varying the voltage from 0 to 70 V. from the current (l)-Voltage (V) data, the electrical conductivity of the sample was determined. This Process was repeated for the other sample.

Table 1. The composition by weight of the constituent elements in $Al_xGa_{1-x}As$ samples

Sample	Atomic composition	Percentage by weight (X)	Wt of ternary alloy for 50 g	Wt of As (g)	Wt of Al (g)	Wt of Ga (g)
A	99/1	99.10	49.50	4.60	9.90	35.50
B	98.2	98.25	49.45	4.00	10.00	36.00

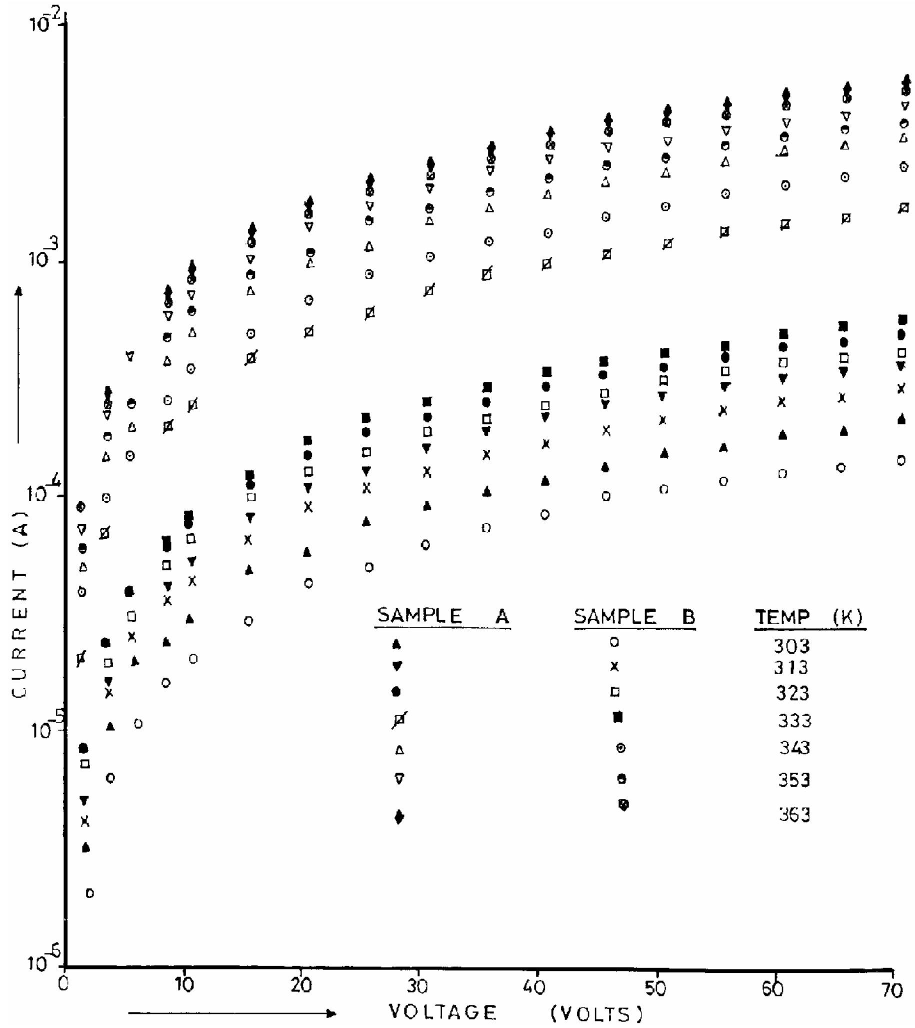

Figure 1. Current-Voltage characteristics of $Al_xGa_{1-x}As$ ternary alloy at various temperatures.

Determination of the Type of Conductivity of $Al_xGa_{1-x}As$ Alloy with the Hot Probe Technique

The hot probe measurement technique was used to determine the type of conductivity in the $Al_xGa_{1-x}As$ ternary alloy. For this measurement, two silver dots on the surface of the alloy were used as electrodes. The surface of each sample was touched by two identical metal probes between them a galvanometer was connected. One of the probes was heated while the ither was kept at room temperature. Thereafter, the galvanometer was observed for the direction of current flow which determined the type of conductivity of the sample.

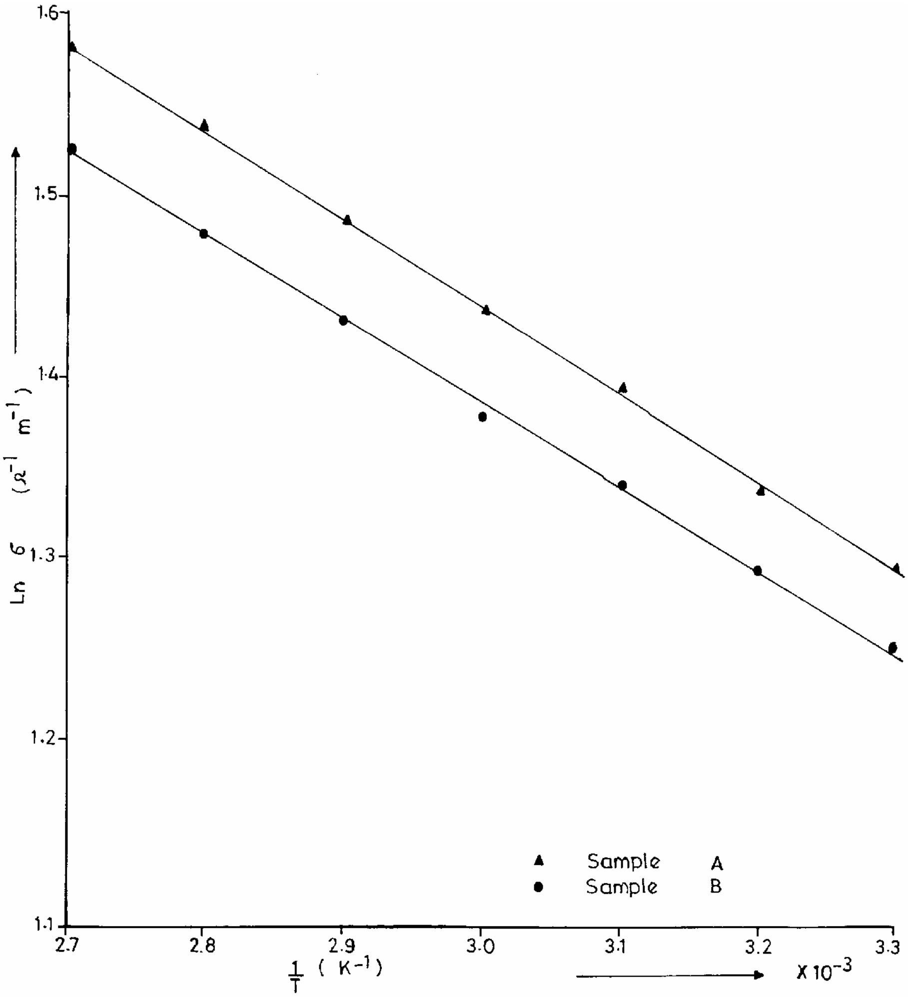

Figure 2. lnσ *vs.* 1/T for $Al_xGa_{1-x}As$ samples.

Results and Discussion

The results of measurements, of the current-voltage characteristics of $Al_xGa_{1-x}As$ samples at various temperatures are summarized in Figure 1. The graph shows that current increases with temperature. At higher temperatures, there is sufficient thermal activation for some electrons to be excited from the valence band to the conduction band. An external electric field can now influence the electron states in both bands and current flow is thereby enhanced.

Figure 2 shows the variation of log of conductivity (lnσ) of the ternary alloy with inverse of temperature (1/T). This plot displays a linear variation between in σ and 1/T, indicating that the different curves obey the Arrhenius relation

$$\sigma = \sigma_0 \exp(-\epsilon/kT) \qquad (4)$$

where ϵ is the activation energy, k, the Boltzmann constant, σ_0 is a constant and T, the temperature. It is known that this type of variation could result in case of semiconductors or ionic solids [36]. The activation energy (ϵ) was determined from the slopes of these curves using Equation (4) and found to be about 1.42±0.01 eV. The nearly constancy of ϵ at the temperature regime under investigation is indicative of intrinsic semiconductivity so that it is reasonable to assume that the $Al_xGa_{1-x}As$ alloy behaves like an intrinsic semiconductor. The empirically determined values of σ_0 are 0.34 and 0.41 $\Omega^{-1}m^{-1}$ for samples B and A respectively.

Figures 3 and 4 show the variation of electrical conductivity (σ) with electric field (E) at different temperatures for samples A and B of $Al_xGa_{1-x}As$. The plotted graphs are similar but vary in values. From these plots, it is evident that at low fields (< 1400 V/m), σ

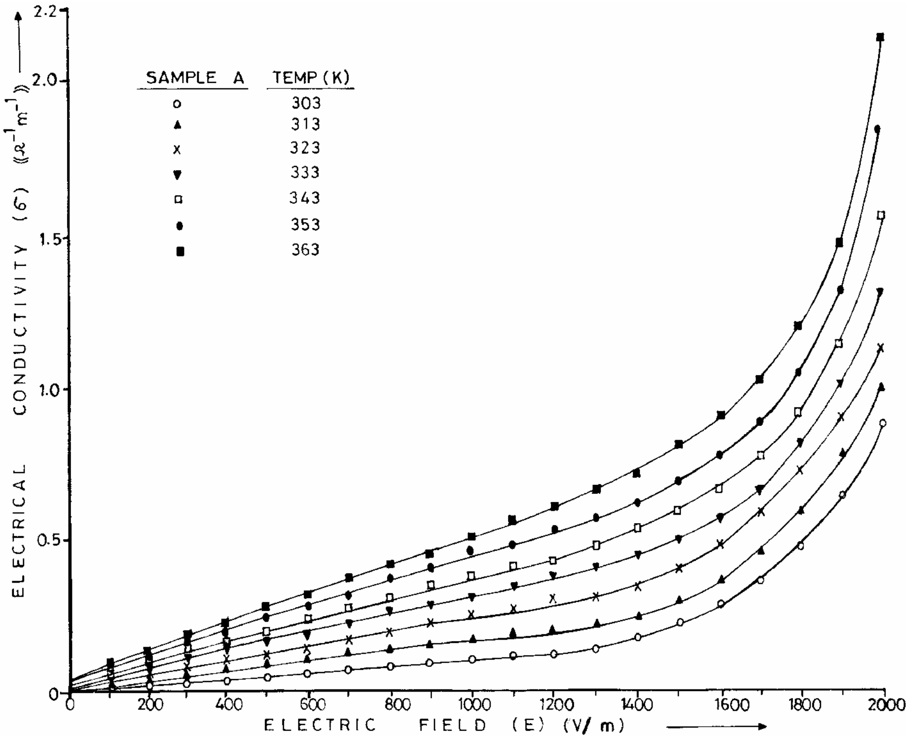

Figure 3. Variation of electrical conductivity (σ) with electric field (E) at different temperatures for samples A of $Al_xGa_{1-x}As$.

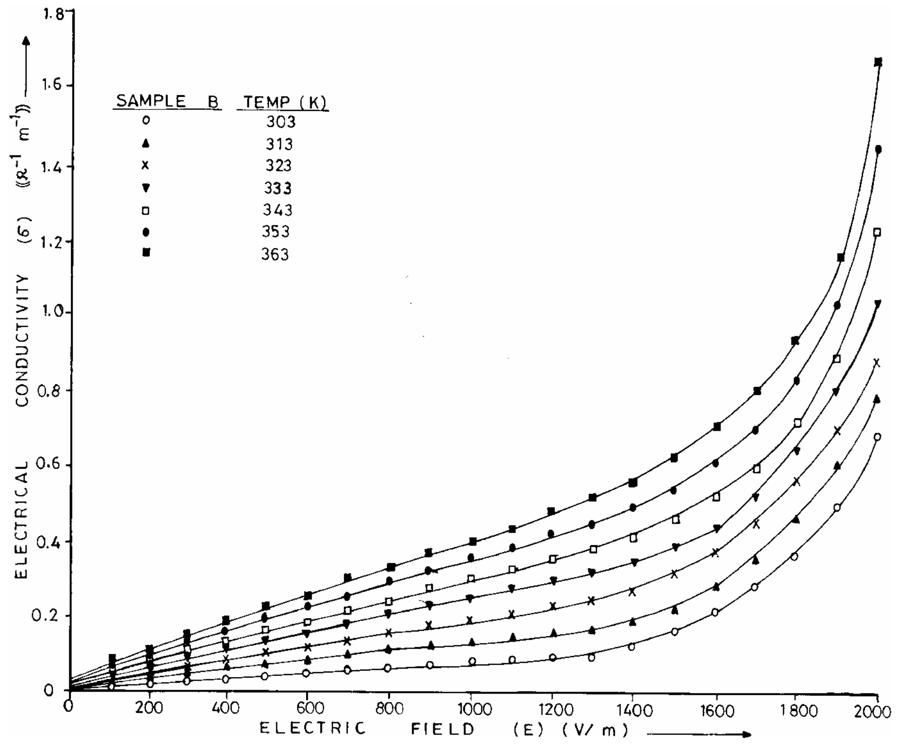

Figure 4. Variation of electrical conductivity (σ) with electric field (E) at different temperatures for samples B of $Al_xGa_{1-x}As$.

Table 2. The electrical conductivity of annealed and unannealed $Al_xGa_{1-x}As$ samples

Nature of sample	**Electrical Conductivity ($\Omega^{-1}m^{-1}$)**	
	Sample A	Sample B
Unannealed	0.30	0.15
Annealed	0.20	0.10

increases linearly with E obeying Ohm's law. However, there is a non-ohmic variation of σ with E at high fields (>1400 V/m). The ohmic behavior at low fields can be explained by the fact that there is negligible injection of carriers from the aluminium layer to the GaAs layer and the initial current is governed by the intrinsic free carriers in the material. At high fields, the non-ohmic behavior can be explained with the model of space charge limited currents. Condition of thermodynamic equilibrium the conduction levels of the GaAs layer are essentially empty and the valence levels are filled. With Al source contact, however, electrons can be injected into the conduction levels. The injected charge is a space charge and the charge carriers are electrons. At sufficiently high field, the injected space-charge density is sufficient to saturate the trapping centres and current increases. Consequently, the electrical conductivity of the samples is enhanced. Also, the onset of non-linearity is caused by heating which increases the mean energy of the electrons. As the mean electron energy increases, the mobility increases thereby increasing the current. This concomitantly increases the electrical conductivity of the ternary alloy.

In the course of the determination of the type of conductivity of $Al_xGa_{1-x}As$ structures by the hot probe method, the hot probe heats the samples immediately under it, with a consequent rise in the kinetic energy of the free carriers there.

These then move with higher velocities than their cooler neighbors. Therefore, the majority carries at the hot probe diffuse out to the cold probe. This results in the hot region becoming slightly depleted of majority carriers and acquiring the potential of the ionized impurities there while the vicinity of the cold probe remains neutral; current flows in the galvanometer. The direction of the current depends on the sing of the charge of the ionized impurity. Since the hot probe was more negative with respect to the cold probe, it shows that the sample investigated behaves like a p-type semiconductor.

From the present measurement, it was observeb that the electrical conductivity of unannealed $Al_xGa_{1-x}As$ sample is higher than that of heat-treated sample (see Table 2). Annealing is known to eliminate defects due to coagulation of voids [37]. The elimination of defects decreases the dangling bond density with a corresponding decrease in carrier concentration. As a result the electrical conductivity of $Al_xGa_{1-x}As$ structure decreases on annealing.

Conclusions

The results obtained from this investigation show that:

1) The electrical conductivity of the $Al_xGa_{1-x}As$ ternary alloy increases with temperature and obeys the relation $\sigma = \sigma_0 \exp(-\epsilon/kT)$, which is characteristic of semiconductors.

2) Variation of electrical conductivity whit electric field follows Ohm's law at low field (< 1400 V/m), but deviates from Ohm's law at high fields (< 1400 V/m).

3) The activation energy of about 1.42 eV for $Al_xGa_{1-x}As$ sample which may be equal to the energy gap of the sample makes the sample a promising material for the fabrication of lasers.

Acknowledgements

I am indebted to the international Science programs of the Uppsala, University Uppsala, Sweden for providing the experimental used for this investigation.

References

1. Gunn J.B. *Solid State Commun*. **1**: 83 (1963).
2. Kroemer H. *Proc. IEEE*, **52**, 1936 (1964).
3. Allen J.W., Shyam M., Chen Y.S. and Pearson G.L. *Appl. Phys. Lett.*, **7**: 78 (1965).
4. Butcher P.N. and Fawcett W. *Phys. Lett.*, **21:** 489 (1966).
5. Fukui H. *Proc. IEEE*, **54:** 792 (1966).
6. Ruch J.G. and Kino G.S. *Appl. Phys. Lett.*, **10:** 40 (1967).
7. Ostrovskii I.V. and Saiko S.V. *Semiconductors*, **30**(9): 857 (1996).
8. Karpovich I.A. and Stepikhova M.V. *Ibid*, **30**(10): 934 (1996).
9. Gongjio J. and Jones B.K. *J. Appl. Phys.*, **80**(11): 6340 (1996).
10. Guo T. *Thin Solid Films*, **281**: 379 (1996).
11. Cao J.C. and Lei X.L. *Solid State Eletronics*, **41**: 1181 (1997).
12. Herfort J., Austing D.G. and Hirayama Y. *Ibid*, **42**: 1135 (1998).
13. Kumakura K., Motohisa J. and Fukui T. *Ibid*, **42**: 1227 (1998).
14. Gunn J.B. *IBM J. Res. Dev.*, **8**: 141 (1964).
15. Sze S.M. *Physics of Semiconductor Devices*. John Wiley and Sons, Inc., New Jersey, p. 637 (1985).
16. Parker S.P. *McGraw Hill Dictionary of Physics*. McGraw Hill Book Company, New York, p. 227 (1986).
17. Austing D.G., Honda T. and Tarucha S. *Solid State Electronics*, **40**: 237 (1996).

18. Inarea J. and Platero G. *Ibid*, **40**: 295 (1996).
19. Shimomura S., Shinohara K., Kasahara K., Motokawa T., Adachi A., Okamoto Y., Sano N. and Hiyamizu S. *Ibid*, **40**: 417 (1996).
20. He L. *Ibid*, **41**: 1881 (1997).
21. Ashby C., Sullivan J., Choquette K., Geib K. and Hou H. *J. Appl. Phys.*, **82**: 3134 (1997).
22. Reyna R., Mati A. and Maroto J. *Solid State Electronics*, **42**: 567 (1998).
23. Chia C.K., David J.P., Rees G.J., Plimmer S.A., Grey R. and Robson P.N., *J. Appl. Phys.*, **84**: 4363 (1998).
24. Shockley W. *Bell Syst. Tech. J.*, **30**: 990 (1951).
25. Ryder E.J. *Phys. Rev.*, **90**: 766 (1953).
26. Hartke J.L., *Ibid*, **125**: 1177 (1962).
27. Lanyon H.P.D. *Ibid*, **130**: 134 (1963).
28. Baynham A.C., Butcher P.N., Fawcett W. and Loveluck J.W. *Proc. Phys. Soc.*, **92**: 783 (1967).
29. Das A.R., Kar R.K. and Mukherjee M.N. *Indian J. Phys.*, **48**: 1124 (1974).
30. Jain D.K. and Garg J.C. *Indian J. Pure Appl. Phys.*, **18**: 842 (1980).
31. Rose A. *Phys. Rev.*, **97**: 1538 (1955).
32. Smith R.W. and Rose A. *Ibid*, **97**: 1531 (1955).
33. Frenkel J. *Ibid*, **54**: 657 (1938).
34. Schottky W. *Z. Phys.*, **15**: 872 (1914).
35. Hava S. and Hunsperger R. *J. Appl. Phys.*, **57**(12): 5330 (1985).
36. Prasad J.N., Sinha S.K. and Prasad R.S. *Indian J. Pure Appl. Phys.*, **17**: 462 (1979).
37. Mott N.F. and Davis E.A. *Electronic Processes in Non-Crystalline Materials*. Clarendon Press, Oxford, pp. 1-70 (1979).