International Journal of Science and Research (IJSR)
ISSN: 2319-7064
SJIF (2019): 7.583

Dimensionless Current-Voltage Characteristics of Amorphous Semiconductor under Non-Constant Mobility Regime by Exact Method

Jyoti Dalal[1], Y. K. Sharma[2], N. K. Pandey[3]

Department of Physics, Rani Durgavati Vishwavidyalaya, Jabalpur – 482001, India

Physics Department, Seva Sadan College, Burhanpur, M.P., India

Abstract: ***The three dimensionless variables are used to obtain the exact analytical expressions for the complete current-voltage characteristics for the single injection current flow in amorphous semiconductors under non-constant mobility regime. The energy band model for linearly distributed states is considered for the dimensionless characteristics. It is shown that the complete current-voltage characteristics are obtained in a large change in current for a small change in applied voltage. The effect of space-charge-limited currents is understood in the complete span of current-voltage characteristics.***

1. Introduction

The electrical transport mechanism in amorphous materials is contributed by trap limited band transport in which the distribution of localized states plays an important role to obtain the proper explanation of currents [1, 2, 7-11,13,15, 16]

The important studies of an disordered solids may be done in the presence of both non-constant mobility regime and trapping states. The presence of trapping states is obtained in the forms of conduction and high temperature mobility measurements [3, 7]. Such results are surveyed by Mott & Davis [7] which shows that trapping states lie close to the band edge. The model is proposed by Mott, Cohen, Fristzsche & Ovshinsky [MCFO Model] [5,6,8].

According to the work of Mott [4,5] , the localized electronic states in the tails of amorphous semiconductor are linearly distributed in energy characterized by the following distribution as,

$$N_t(E) = \frac{N(E_v)}{\Delta}(E_B - E) \tag{1}$$

where $N_t(E)$ is the density of states in the valence band tail, $N(E_v)$ is the value of $N_t(E)$ at the mobility shoulders E_v, the energy range Δ and energy level E_B are shown in fig. (1) and E is energy value.

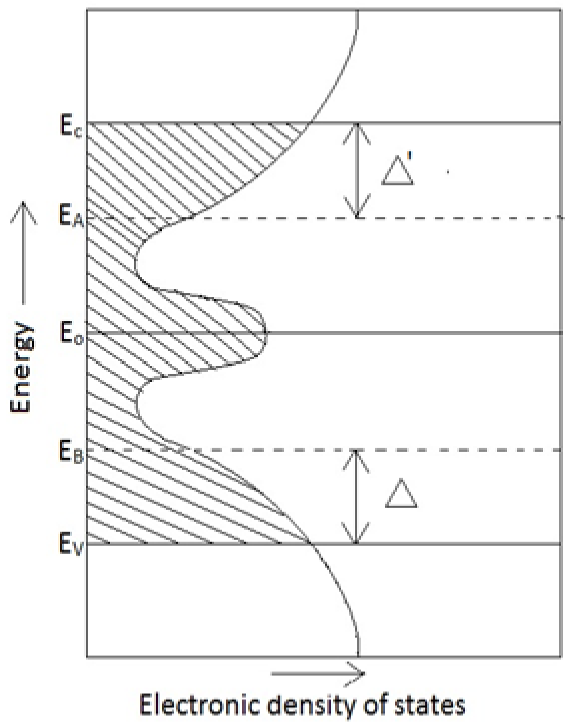

Figure 1

2. General Formulation of the Problem

Let us consider an amorphous sample with linearly distributed localized states characterized by the distribution function given by the eqn.(1). It is considered that holes are injected at the anode x = o and exit at the cathode x = L, where L is the device length. The one dimensional planner current flow eqn. is given by [1,2]

$$I = e\,\mu_p\,p(x)F(x) = \text{Constant.} \tag{2}$$

where I is the total current density independent of the position inside the amorphous material, e is the magnitude of electronic charge, μ_p is the nonconstant mobility of holes, p(x) is the total free hole concentration, F(x) is the electric field strength at position x inside the amorphous semiconductor from anode.

A non-constant mobility of the free carriers is considered as [11,12]

$$\mu_p = \text{H p(x)}, \quad (3)$$

where μ_p is the nonconstant mobility of holes and H is a proportionality constant which depends on the electrical properties of the material.

The eqns (2) and (3) are combined to give the modified current equation of the free carriers inside the amorphous material operating under nonconstant mobility regime as :

$$I = eH\,[p(x)]^2\,F(x) = \text{Constant} \quad (4)$$

The Poisson's equation of the problem is given by [1,2,9-11]

$$\frac{\in}{e}\frac{dF(x)}{dx} = [p(x) - p_o] + p_{it}(x) \quad (5)$$

where ∈ is the static dielectric constant of the material, p_o is the thermal – equilibrium position dependent hole concentration, p(x) is the total free hole concentration and p_{it}(x) is the concentration of the trapped carriers under the hole injection condition.

The localized distributed traps present in the valence band tail is given by [1, 2]

$$p_{it}(x) \approx N_t\,[\xi_o(x), \xi_o] = N_t\,[\xi_o(x, \Delta)]$$

$$= \int_{\Delta}^{\xi(x)} N_t(E)\ dE$$

$$= \frac{N(0)}{\Delta}\,[\Delta\xi_0(x) - \frac{[\xi_0(x)]^2}{2} - \frac{\Delta^2}{2}] \quad (6)$$

where the eqn. (1) is used, and $N_t[\xi_0(x), \xi_0]$is the total trap concentration lies between the thermal – equilibrium position of the Fermi level and the mobility shoulder E_v is considered as the origin of the energy, so that $N(E_v) = N(o)$ and $E_B = \Delta$.

The concentration of free holes in a material is given by,

$$p(x) = N_v \exp.(-\xi(x)/kT) \quad (7)$$

where N_v is the effective density of states in the valence band. The eqns. (6) and (7) give the following expression

$$p_{it}(x) = \frac{N(o)}{2\Delta}\,[\Delta + kT\log\frac{p(x)}{N_v}]^2 \quad (8)$$

The equations (4), (5) and (8) are the general equations for the three unknowns p(x), $p_{it}(x)$ and F(x) for the given current density I. These equations are considered to obtain the final results.

The above equations are subjected to as usual boundary condition for ohmic contact as,

$$F(o) = 0 \text{ at } x = 0, \quad (9)$$

which is generally employed in single injection current theories [2,9-11,13,14]. The other boundary conditions for ohmic contact are given by,

$$p(x) \rightarrow p_o \text{ as } x \rightarrow \infty \quad (10)$$

The amorphous sample is of small thickness, therefore the concentration p_o appears inside the sample at low injection level of current.

In this condition, the Poission's eq. (5) becomes,

$$\frac{\varepsilon}{e}\frac{dF(x)}{dx} \approx p_{it}(x) \quad (11)$$

3. Solutions of the Problem and Three Dimensionless Variables

The solutions of the complicated problem is obtained conveniently by assuming the following three dimensionless variables as [2,9-11,13,14]

$$M(X) = p_o\sqrt{\frac{eHF(x)}{I}}\ , \quad (12)$$

$$X = \frac{eP_0^2 x}{\varepsilon}\sqrt{\frac{eH}{IF(x)}}\ , \quad (13)$$

$$\mathcal{V}(X) = \frac{e^2 P_0^3 HV(x)}{\varepsilon IF(x)}, \quad (14)$$

where M(X) is the value for dimensionless concentration, X is the dimensionless distance and $\mathcal{V}$(X) is the dimensionless potential of the problem. The injection level of current is considered to be sufficiently high so that

$$p_{it}(x) > (p(x) - p_o) >> p_o\ . \quad (15)$$

The dimensionless variables (12) – (14) give the following relation

$$\frac{1}{M_c X_c} = \left[\frac{\varepsilon I}{e^2 p_0^3 HL}\right] \quad (16)$$

$$\frac{\mathcal{V}_c}{X_c^2} = \frac{\varepsilon V(L)}{e p_0 L^2} \quad (17)$$

The equations (16) and (17) give the following proportionalities for dimensionless current-voltage characteristics as :

$$\left.\begin{aligned} I &\propto \frac{1}{M_c X_c} \text{ and} \\ V &\propto \frac{\mathcal{V}_c}{X_c^2} \end{aligned}\right\} \quad (18)$$

which shows that the current-voltage characteristics [I ∝ V] may be considered as : $\frac{1}{M_c X_c} \propto \frac{\mathcal{V}_c}{X_c^2}$

which is known as the dimensionless current-voltage characteristics .

The equations (8), (11) and (13) give the variation of dimensionless variable as

$$\frac{MdM}{d[MX]} = \frac{\Gamma}{2}[A + lg\frac{1}{M}]^2 \quad (19)$$

$$\text{where } \Gamma = \frac{N(o)(kT)^2}{2\Delta p_o} \text{ and} \quad (20)$$

$$A = \frac{\Delta}{kT} + lg\frac{p_o}{N_v} \quad (21)$$

The eqn. (19) is solved under the boundary condition given at anode as

F(o) = 0, M(X) = M(o) at X = 0 .

The eqn. (19) is integrated as,

$$\int_{M(o)}^{M_c}\frac{MdM}{[A + lg\frac{1}{M}]^2} = \Gamma M_c X_c \quad (23)$$

which directly gives the solution in terms of exponential integral Ei as,

$$\frac{1}{[M_c X_c]^{\frac{1}{2}}} = \frac{\Gamma^{\frac{1}{2}}}{(2)^{\frac{1}{2}}}\left[\frac{M_c^2}{A + lg\frac{1}{M_c}} + 2e^{2A}Ei\{-2(A + lg\frac{1}{M_c})\}\right]^{-\frac{1}{2}} \quad (24)$$

which satisfies the boundary condition M=o at X=o, and for M → 1 , the value of variable X → ∞. It shows that for all values of variable M less than unity, X is finite.

The voltage applied across the sample is given by,

$$V(x) = \int_o^x F(x)dx \quad (25)$$

From eqns. (11), (14) and (25), the dimensionless potential is obtained as

Paper ID: SR201214214026 DOI: 10.21275/SR201214214026

$$v(X) = \frac{1}{M^2}\int_o^{MX} M^2\{d[MX]\}$$
$$= \frac{2}{M^2}\int_o^{M_c} \frac{M^3 dm}{\Gamma[A+lg\frac{1}{M}]^2} \quad (26)$$

where the equation (19) is used. At cathode, the eqn (26) becomes,

$$v_c = \frac{2}{M_c}\int_o^{M_c} \frac{M^3 dm}{\Gamma[A+lg\frac{1}{M}]^2}$$
$$= \frac{2}{\Gamma M_c^2}\left[\frac{M_c^4}{A+lg\frac{1}{M_c}} + 4e^{4A}Ei\{-4\,(A+lg\frac{1}{M_c})\}\right] \quad (27)$$

where Ei is the exponential integral function.

The eqn. (24) gives the following dimensionless variable X_c as,

$$\frac{1}{X_c} = \frac{M_c}{2}\,\Gamma\left[\frac{M_c^2}{A+lg\frac{1}{M_c}} + 2e^{2A}Ei\{-2\,(A+lg\frac{1}{M_c})\}\right]^{-1} \quad (28)$$

The equations (27) and (28) yield the dimensionless value at cathode as,

$$\frac{v_c}{X_c^2} = \frac{\Gamma}{2}\,\frac{\left[\frac{M_c^4}{A+lg\frac{1}{M_c}} + 4e^{4A}Ei\{-4\,(A+lg\frac{1}{M_c})\}\right]}{\left[\frac{M_c^2}{A+lg\frac{1}{M_c}} + 2e^{2A}Ei\{-2\left(A+lg\frac{1}{M_c}\right)\}\right]^2} \quad (29)$$

Let us consider the new dimensionless variable y given by,

$$y = A + lg\,\frac{1}{M_c} \quad (30)$$

where y is the value of variable at cathode.

The equations (29) and (30) give,

$$\frac{v_c}{X_c^2} = \frac{y\Gamma}{2}\left[\frac{e^{4(A-y)} + 4ye^{4A}Ei(-4y)}{[e^{2(A-y)} + 2ye^{2A}Ei(-2y)]^2}\right] \quad (31)$$

For the variable values y>1, the exponential integral in eqn. (31) may be expanded as,

$$Ei(-y) \simeq -\frac{e^{-y}}{y} + \frac{e^{-y}}{y^2} \simeq \frac{e^{-y}}{y} \quad (32)$$
$$Ei(-2y) \simeq \frac{(1-2y)e^{-2y}}{4y^2} \quad (33)$$
$$Ei(-4y) \simeq \frac{(1-4y)e^{-4y}}{16y^2} \quad (34)$$

Substituting the exponential integral values from equations (33) and (34) into equation (31), the following equation is obtained as

$$\frac{v_c}{X_c^2} = \frac{\Gamma}{4}e^{2(A-y)} = \frac{\Gamma}{4}M_c^2 \quad (35)$$

Similarly, the equations (28), (30) and (33) give the dimensionless value as,

$$\frac{1}{[M_c X_c]^{\frac{1}{2}}} = \frac{y\Gamma^{\frac{1}{2}}}{e^{(A-y)}} = \frac{\Gamma^{\frac{1}{2}}[A + lg\,\frac{1}{M_c}]}{M_c} \quad (36)$$

It is difficult to obtain a direct relationship between the current and applied voltage to get the current-voltage characteristics for the current injection in an amorphous semiconductor with linearly distributed localised states operating under nonconstant mobility regime. However, the dimensionless current – voltage characteristics is represented by $\frac{1}{[M_c X_c]^{\frac{1}{2}}}$ versus v_c / x_c^2 with the help of equations (35) and (36), respectively. These dimensionless values for the dimensionless characteristics may be evaluated by the tabulation of variables X_c and v_c from equations (27) and (28), when the variable M_c varies from 0 to 1.

4. Complete Dimensionless Current-Voltage Characteristics

The complete characteristics is divided into three current-voltage regimes as given below:
Ohmic Regime ($M_c \simeq 1$) :

The complete dimensionless characteristics is started from the low injection level of current at which the injected current carriers are negligibly small. It gives ohmic regime where the current is carried by the free carriers distributed uniformly throughout the amorphous sample before the current injection for ohmic regime where $M_c = 1$.

The equations (35) and (36) becomes,

$$\frac{v_c}{X_c^2} = \frac{\Gamma}{4} \text{ and} \quad (37)$$
$$\frac{1}{[M_c X_c]^{\frac{1}{2}}} = A\Gamma^{\frac{1}{2}} \quad (38)$$

which directly gives the dimensionless current-voltage characteristics for ohmic regime as,

$$\frac{v_c}{X_c^2} = \frac{1}{4A^2[M_c X_c]} \quad (39)$$

Substituting the values of M_c, X_c and v_c from equations (12) – (14) into (39), the current-voltage characteristic of amorphous semiconductor under Ohmic regime is obtained as

$$I = 4eHp_0^2A^2(\frac{V}{L}) \quad (40)$$

which is the linear power law for amorphous semiconductor operating under non-constant mobility regime. The ohmic region is terminated from the amorphous material when the injected space charge is sufficiently large. The change in the situation occurs rapidly because the amorphous sample is working under non-constant mobility regime.

Trapped Charge Regime ($M_C < 1$)

At medium injection level of current, the concentration of injected current carriers is sufficient to compensate the linear current-voltage characteristic. Therefore, the trap-limited space-charge regime is observed through the amorphous sample. The non-constant mobility is present in the sample. The current-voltage characteristics is dominated by the trapping effect. Therefore, it is a complex current-voltage regime which is contributed by the ohmic, trapping and space charge regimes. The states are gradually filled with the current carriers and the value of dimensionless variable v_c lies in the middle span. The exact form of dimensionless values is given by equations (24) and (29), and has to be used to obtain the exact dimensionless current-voltage characteristics of this regime.

Space Charge Regime ($M_c << 1$)

The injection level of current is sufficiently high to overcome the ohmic and trap controlled current flow in amorphous semiconductor. The approximate expressions for the dimensionless current-voltage characteristics may be derived from the eqns. (24) and (29) by neglecting the parameter A as

$$\frac{\mathcal{V}_c}{X_c^2} = \frac{\frac{\Gamma}{2}[\frac{M_c^4}{lg\frac{1}{M_c}} + 4e^{4A}Ei\,(-4\,lg\frac{1}{M_c})]}{[\frac{M_c^2}{lg\frac{1}{M_c}} + 2e^{2A}Ei\,(-2\,lg\frac{1}{M_c})]^2} \quad (41)$$

$$\frac{1}{(M_c X_c)^{\frac{1}{2}}} = (\frac{\Gamma}{2})^{\frac{1}{2}}\ [\frac{M_c^2}{lg\frac{1}{M_c}} + \ 2e^{2A}Ei\,(-2\,lg\frac{1}{M_c})] \quad (42)$$

It is difficult to remove M_c from eqns. (41) and (42) to obtain the final current-voltage characteristics of a disordered solid due to complexity in these expressions. However, the different dimensionless values $\frac{1}{(M_c X_c)^{\frac{1}{2}}}$ versus $\frac{\mathcal{V}_c}{X_c^2}$ may be estimated for different values of M_c.

5. Conclusions

The complete dimensionless current-voltage characteristics is divided into three current-voltage regimes on the basis of the dimensionless variable M_c as described earlier. The complete mathematical procedure for the dimensionless current-voltage characteristics of disordered materials is sufficiently complicated to such an extent that no explicit expression is not possible to show the relation between the current and voltage. Therefore, the approximation of the dimensionless variable M_c has been considered in its complete range of variation from 0 to 1. Thus, the three dimensionless current-voltage regimes are obtained for the sample for three different values of the dimensionless variable M_c.

References

[1] Hill, R.M., Phys Stat. Sol. (a) 24, 433 (1974).
[2] Lampert, M.A. and Mark, P., “Current Injection in Solids”. Academic Press, New York (1970).
[3] Lecomber, P.G. and Mort, J., Electronic and Structural Properties of Amorphous Semiconductors, Academic Press, New York (1973).
[4] Mott, N.F., Phil. Mag. 22, 7 (1970).
[5] Mott, N.F., Phil. Mag. 22, 903 (1970).
[6] Mott, N.F., Phil. Mag. 24, 911 (1971).
[7] Mott, N.F. and Davis, E.A., “Electronic Processes in Non-Crystalline Materials”. (Oxford : Claredan) 1st edn. (1971).
[8] Mott., N.F. and Davis, E.A., “Electronic Process in Non-Cryst. Materials”. (Oxford : Claredon) 2nd edn. (1979).
[9] Sharma, Y.K., Phys. Rev. B10, 3273 (1974).
[10] Sharma, Y.K., J. Appl. Phys. 53, 1241 (1982).
[11] Sharma, Y.K., Sharma. R.N. and Raghav, V.S., J. Appl. Phys. 54, 4213 (1983).
[12] Wintle, H.J., J. Appl. Phys. 43, 2927 (1972).
[13] Kumar, M., Vashistha, G.K. and Sharma, Y.K., The European Physical Journal : Applied Physics, 40, 125 (2007).
[14] Sharma, Y.K., Acta Ciencia India XLIP, No.3, 119 (2015).
[15] Orton, J.W., Philo. Mag B.49, No.1, L1 (1984).
[16] Orton, J.W., Philo. Mag B.50, No.1, 11 (1984).