DIMENSIONLESS CURRENT – VOLTAGE CHARACTERISTIC OF AMORPHOUS SEMICONDUCTOR AT HIGH FIELDS

Y.K. SHARMA

Department of Physics, Rani Durgavati Vishwavidyalaya, Jabalpur–482001 (M.P.), India

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Three dimensionless variables are used to obtain the complete dimensionless current-voltage characteristic of single injection current in amorphous semiconductors with the localised electronic states in the tails at high fields. It is shown that the time independent space-charge-limited conduction is observed at high injection level where the trapping states are no longer influence the current flow.

KEY WORDS : Amorphous semiconductors, High fields, Localised electronic states, Dimensionless variables, Effective density of states, High injection level.

Introduction

The present investigation is made to study the behaviour of the high field space-charge-limited current-voltage characteristics in amorphous semiconductors with a linear distribution of localised states in the band tail. At high electric field strength, the characteristic feature of all amorphous semiconductors is observed to be non-ohmic. The non-linear current-voltage characteristic of such materials fit a power law characteristic of the form $I \propto V^n$ or an exponential law lg $I \propto V^{1/2}$ where n is the exponent which characterises the current-voltage characteristic and the conduction mechanism. In the present analysis, the single injection space-charge-limited current shows a power law dependence for the current-voltage characteristic with exponent n exceeding 2.

Consider an amorphous sample containing the localised electronic states in the tails (Mott, 1970). The general equations characterizing the one dimensional planer current flow and Poisson's law at high fields are given by (Lampert and Mark 1970)

$$I = e\, \mu_p(F)\, p\,(x)\, F(x) = \text{Constant} \qquad \dots (1)$$

$$\frac{\in}{e}\frac{dF(x)}{dx} = [p(x) - p_0] + p_{it}(x) \qquad \dots (2)$$

where I is the total current density independent of the position, e is the magnitude of electronic charge, $\mu_p(F)$ is the field dependent mobility of holes, $p\,(x)$ is the total free hole concentration at position x, $F\,(x)$ is the electric field strength at position x, $\in$ is the static dielectric constant of the material, p_0 is the thermal-equilibrium value of $p\,(x)$ and $p_{it}\,(x)$ is the concentration of the trapped holes under injection conditions.

A power law dependence of hole mobility with the electric field strength is considered as [Hill (1974) and Sharma (1974)]

$$\mu_p(F) = \propto F^{1/2} \qquad \dots (3)$$

where $\propto$ is a parameter which depends on the high field conditions and the material. The localized electronic states in the problem are characterized by the following distribution as (Mott, 1970)

$$N_t(E) = \frac{N\,(E_v)}{\Delta}\,(E_B - E) \qquad \ldots (4)$$

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, Δ is the energy range, E_B is the energy level and E is the energy value. The above equations are subjected to an usual boundary condition for ohmic contact as

$$F(0) = 0 \quad \text{at} \quad x = 0 \qquad \ldots (5)$$

which is normally applied in single injection current theories [Gisoft and Zijlstra (1973) and Verma *et. al*., (1999)].

If the energy range Δ is larger than kT, the concentration of injected trapped holes is approximately equal to the total trap concentration $N_t\,[\varepsilon\,(x), \varepsilon_0]$ lying between the thermal-equilibrium position ε_0 of the Fermi level and the steady state position dependent quasi-Fermi level $\varepsilon\,(x)$ [Lampert and Mark, 1970]. Therefore, the expression for the localized distributed traps in the valence band tail is obtained as

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

$$= \int_{\Delta}^{\varepsilon(x)} N_t(E)\,dE = \frac{N(o)}{\Delta}\left[\Delta\varepsilon\,(x) - \frac{\left(\varepsilon(x)\right)^2}{2} - \frac{\Delta^2}{2}\right] \qquad \ldots (6)$$

where the equation (4) is used and the mobility shoulder E_v is considered as the origin of energy so that $N\,(E_v) = N\,(0)$ and $E_B = \Delta$.

The concentration of free holes in an amorphous material is given by

$$p\,(x) = N_v \exp\,[-\varepsilon\,(x)/kT] \qquad \ldots (7)$$

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

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

Dimensionless variables and solutions

The solutions of the complicated problem is obtained with the help of following three dimensionless variables as

$$M(X) = \frac{P_o}{P\,(x)} = \frac{\propto e P_o F^{1/2}}{I} \qquad \ldots (9)$$

$$X = \frac{\propto e^2 P_o^2}{\in I\, F^{1/2}} X \qquad \ldots (10)$$

$$V(x) = \frac{\propto^2 e^3 p_o^3\, V\,(\mathrm{x})}{\in\, I^2 F} \qquad \ldots (11)$$

From equations (9) – (11), the dimensionless relations are evaluated as

$$\frac{1}{[M_c X_c]^{\frac{1}{2}}} = \left[\frac{\in}{\propto^2 e^3 p_o^3 L}\right]^{1/2} I \qquad \ldots (12)$$

$$\frac{\nu_c}{X_c^2} = \frac{\in}{e p_o L^2} V \qquad \dots (13)$$

where '*c*' represents the value of three variables at cathode and the current-voltage characteristic $(I \propto V)$ may be considered as

$$\frac{1}{(M_c X_c)^{1/2}} \propto \frac{\nu_c}{X_c^2} \qquad \dots (14)$$

For $p_{it}(x) > p(x) - p_o >> p_o$, the equations (2)-(11) are used to evaluate the dimensionless Poisson's equations as

$$\frac{M dM}{d[MX]} = \frac{\Gamma}{2}\left[A + lg\frac{1}{M}\right]^2 \qquad \dots (15)$$

where $$\Gamma = \frac{N(0)\,(kT)^2}{2\,\Delta p_o} \quad \text{and} \quad A = \frac{\Delta}{kT} + lg\,\frac{p_o}{N_v} \qquad \dots (16)$$

The equation (15) is integrated to give directly the solution in terms of exponential integral *Ei* as

$$\frac{1}{(M_c X_c)^{1/2}} = \frac{\Gamma^{1/2}}{(2)^{1/2}}\left[\frac{M_c^2}{A + lg\dfrac{1}{M_c}} + 2e^{2A}\,Ei\left\{-2\left(A + lg\frac{1}{M_c}\right)\right\}\right]^{-1/2} \qquad \dots (17)$$

where $$Ei\,(-y) \simeq -\frac{e^{-y}}{y} + \frac{e^{-y}}{y^2} \simeq \frac{e^{-y}}{y} \text{ for } y > 1.$$

The equation (17) satisfy the boundary condition $M = 0$ at $X = 0$. For $M \to 1$, the value of variable $X \to \infty$. It shows that X is finite for all values of variable M less than unity.

The voltage applied across the sample is given by

$$V(x) = \int_0^x F(x)\,dx \qquad \dots (18)$$

From equations (9) – (11) and (18), the dimensionless potential at cathode is obtained as

$$V_c = \frac{2}{M_c^2}\int_o^{M_c}\frac{M^3 dM}{\Gamma\left[A + lg\dfrac{1}{M}\right]^2} = \frac{2}{\Gamma\,M_c^2}\left[\frac{M_c^4}{A + lg\dfrac{1}{M_c}} + 4e^{4A}\,Ei\left\{-4\left(A + lg\frac{1}{M_c}\right)\right\}\right] \qquad \dots (19)$$

where *Ei* is the exponential integral function. The equations (17) and (19) yield the dimensionless value at cathode as

$$\frac{\nu_c}{X_c^2} = \frac{y\Gamma}{2}\left[\frac{e^{4(A-y)} + 4\,y e^{4A}\,Ei\,(-4y)}{\{e^{2(A-y)} + 2y e^{2A}\,Ei\,(-2y)\}^2}\right] \qquad \dots (20)$$

where y is a new dimensionless variables given by

$$y = A + lg\frac{1}{M_c} \qquad \dots (21)$$

Complete dimensionless current-voltage characteristic

The complete dimensionless characteristic is started from low injection level of current at which the injected current carriers are negligibly small and the current flow is obtained from thermally generated free carriers. The characteristic is evaluated for this injection level from equations (9) – (11), (17) and (20) with $M_c = 1$ as

Ohmic Regime :
$$\frac{\nu_c}{X_c^2} = \left[\frac{\Gamma^{1/2}}{4A}\right]\frac{1}{[M_c X_c]^{1/2}} \qquad \dots(22)$$

which directly yields the following relationship as

$$I = 2A \propto e\, p_o \left[\frac{V}{L}\right]^{1/2} \qquad \dots(23)$$

which is the sublinear power law $[I \propto V^{1/2}]$ for amorphous semiconductors at high field.

At medium injection level of current, the concentration of injected current carriers is sufficient to compensate the sublinear current-voltage characteristic and the trap limited space charge regime is observed through the amorphous sample. A direct relationship for the current dependence on voltage is difficult to derive for the transition regime from equations (17) and (20).

The injection level of current is sufficiently high to overcome the ohmic and trap controlled currents in amorphous materials. The approximate expression for the dimensionless current-voltage characteristic of the space charge regime (M_c << 1) may be obtained from the equations (17) and (20) with neglecting the parameter A as

Space Charge Regime

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

$$\frac{\nu_c}{X_c^2} = \frac{\Gamma}{2}\, \frac{\left[\frac{M_c^4}{lg\frac{1}{M_c}} + e^{4A}\, Ei\left(-4\ lg\frac{1}{M_c}\right)\right]}{\left[\frac{M_c^2}{lg\frac{1}{M_c}} + 2e^{2A}\, Ei\left(-2\ lg\frac{1}{M_c}\right)\right]^2} \qquad \dots(25)$$

Discussion and conclusions

The single injection current flow is considered in amorphous semiconductors containing localised linearly distributed states where the diffusion current is negligibly small. The complexities in the problem are obtained due to the presence of localised states distributed in the band tail of amorphous sample. The electrical properties are controlled by the bulk of the specimen [Sharma (1974) and (2015)].

The complete dimensionless current-voltage characteristic is divided into three separate current-voltage regimes : (a) Ohmic regime ($M_c \approx 1$), (b) trapped charge regime ($M_c < 1$) and (c) space charge regime (M_c << 1). The mathematical procedure for the dimensionless current-voltage characteristic of disordered material is sufficiently complex to such an extent that no explicit analytical expression is not possible to represent the relationship between the current and voltage. Therefore, the approximation of the dimensionless variable M_c has been considered in the complete range of variation from the value 0 to 1. The three different ranges of dimensionless variable M_c give the three dimensionless current-voltage regimes.

References

1. Mott, N.F., *Phil. Mag*., **22**, 7 (1970).
2. Mott, N.F., *Phil. Mag*., **22**, 903(1970).
3. Lampert, M.A. and Mark, P., "*Current Injection in Solids*", Academic Press, New York (1970).
4. Gisolf, A. and Zijlstra, R.J.J., *Solid State Electron*, **16**, 571 (1973).
5. Hill, R.M., *Phys. Stat. Sol.*, **(a) 24**, 433 (1974).
6. Sharma, Y.K., *Phys Rev.*, **B 10**, 3273 (1974).
7. Verma, A.S., Sharma, Y.K. and Singh, L.R., *Bull of Pure & Appl. Sci*., **18D**, 171 (1999).
8. Kumar, M., Vashishtha, G.K. and Sharma, Y.K., *Eur. Phy. J. Appl. Phys*., **40**, 125 (2007).
9. Sharma, Y.K., *Acta Ciencia Indica*, Vol. **XLI P**, No.**1**, 69 (2015).

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