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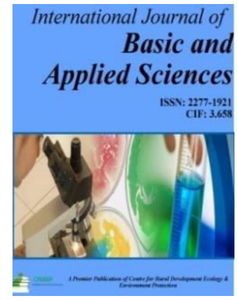

Full Length Research Paper

Thermal Noise Calculations in Insulators in SCDM regime at Low and High Injection Level of Currents

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ABSTRACT

Introduction about topic: The simple analysis is given for the single injection current flow in insulators operating under sublinear carrier density dependent mobility (CDDM) regime. The general equations are applied to obtain the current-voltage characteristic and thermal noise generated in the complete span of the current flow. The complete current-voltage characteristic of single injection current flow is evaluated for an insulator in the complete variation of applied voltage. Methodology adopted: It is shown that the current increases steeply from true Ohm's regime to space-charge-limited regime. The thermal noise calculations are done in the complete change of current flow and it is observed that the thermal noise is affected greatly for a slight charge in applied voltage.

Introduction

Single injection devices derived from insulator have within them a zone where the conductivity is modulated by the injected free current carriers when the current flows in the sample. It gives a nonlinear current-voltage characteristic [1-6]. It occurs in different carrier mobility regimes available in the literature [1-3, 9]. Now, it is possible to fabricate devices which approximately close to the current flow properties of the simple theoretical models given earlier to explain the single injection mode of the current flow. Therefore, it is necessary to observe the noise present in such devices. It will expand our knowledge of noise in nonlinear systems. Thermal noise is the main source of noise in such devices which is generated due to the scattering of the current carriers with the lattice [1-6, 10, 11].

The electrical behavior of single injection current flow in insulators depends greatly on the carrier density of free current carriers in solids [15]. The important and vital role of insulators in electronics is to fabricate the electrical devices derived from the insulator [16]. The important information is obtained due to the interaction of the current carriers with the presence of trapping states and thermal free carriers in the insulators [1, 12, 13].

The information of the electrical properties of insulators are expected to be obtained from scientific side under sublinear carrier density dependent mobility (SCDM) regime. The current injection in insulators is made in a planner structure to obtain the current flow in a complete current-voltage characteristic [14]. The modified structure seems to be different in the presence of different physical parameters. The emphasis in the present scientific investigation is to obtain the scientific information for the transition of current flow from ohmic to pure space-charge-limited current flow in low mobility insulators. The results will be used to investigate the complete thermal noise characteristics in the full span of the current-voltage characteristic of the insulator operating under SCDM regime. It is expected to obtain the new results from the current injection and thermal noise studies. The injection of the current carriers in an insulator is explained by the energy band theory [1,6]. This injection aspect is extended in this paper for non constant mobility regime [7]. The non-constant mobility is playing an important role because it affects greatly the current-voltage characteristic. The sensitivity and accuracy is affected by the thermal noise caused by the scattering process. It generates fluctuations in current and voltage.

Current flow and thermal noise at low injection level
Let us consider a low mobility insulator operating under sublinear carrier density dependent mobility (SCDM) regime [6]. Initially the injection level is low to give ohmic conduction. The general equations characterizing the current flow, Poisson's law and non constant mobility are given as [1,7]

$$J = e\mu n_o E \quad \text{.... (1)}$$

$$\frac{\epsilon}{e}\frac{dE}{dx} = 0 \quad \text{.... (2)}$$

$$\mu = H (n_o)^{1/2} \quad \text{.... (3)}$$

where; J is the current density, e is the electronic charge, μ is the sublinear carrier density dependent mobility of the charge carriers, n_o is the concentration of carriers under thermal - equilibrium condition, ϵ is the permittivity of the insulator, E(x) is the electric field at distance x and H is the proportionality constant.

The above equations are subjected to the boundary condition for ohmic contact as [1,4]

$$E(0) = 0 \quad \text{.... (4)}$$

The equations (1) - (4) are used to evaluate the current density and ohmic electric field inside the insulator as

$$J = e H (n_o)^{3/2} E \quad \text{.... (5)}$$

$$E_\Omega (x) = \frac{J}{eH\ (n_o)^{3/2}} \quad \text{.... (6)}$$

$$V = \int_0^L E(x)\, dx \quad \text{.... (7)}$$

Where; L is the device length.

The current-voltage characteristic of the insulator at low injection level is given by the equations (5) and (7) as below:

$$J = e H (n_o)^{3/2} \frac{V}{L} \quad \text{.... (8)}$$

This is called the pure Ohm's law ($J \propto V$) and the current carriers are uniformly distributed throughout the insulator.

Thermal noise calculations
At low injection level of current in insulator the carrier fluctuations in the individual section provide the mean square noise voltage $\overline{\Delta v^2}$. It gives the thermal noise across the insulator [2,5]

$$\overline{\Delta v^2} = 4\, k\, T\, R_\Omega\, \Delta f \quad \text{.... (9)}$$

where ; R_Ω is the ohmic resistance of the device, k is the Boltzmann's constant and T is lattice temperature.

The ohmic resistance across the insulator is given by [4,5]

$$R_\Omega = \sum \Delta R = \sum \frac{\Delta x}{e\mu n_o\, S} \quad \text{.... (10)}$$

Where; S is the area of cross-section of the insulator.

From equations (3), (9) and (10), the following noise expressions are obtained as

$$\frac{\overline{\Delta v^2}}{kT\Delta f} = \frac{4L}{e\, H\, (n_o)^{3/2}\, S} \quad , \quad g = \frac{\partial I}{\partial V} = \frac{JS}{V} = \frac{eH\ (n_o)^{3/2}\, S}{L} \quad \text{.... (11)}$$

The mean square ohmic noise current in the solid state diode is given by the relation [3-6].

$$\overline{i^2_\Omega} = g^2\ \Delta \overline{v^2} \quad \text{.... (12)}$$

The equations (11) and (12) give

$$\frac{\overline{i^2_\Omega}}{kT\Delta f} = \frac{4eH\ (n_o)^{3/2}\, S}{L} \quad \text{.... (13)}$$

General physical parameters of the insulator
At high injection level of current, the current, Poisson's equation and carrier mobility are given for the problem as [1, 7]

$$J = e\mu\, n(x)\, E(x) \quad \text{.... (14)}$$

$$\frac{\epsilon}{e}\frac{dE}{dx} = n(x) \quad \text{.... (15)}$$

$$\mu = H [n(x)]^{1/2} \quad \text{.... (16)}$$

The electric field inside the insulator becomes

$$E(x) = \left[\frac{125}{27}\ \frac{eJ^2}{\epsilon^3 H^2}\right]^{1/5} x^{3/5} \quad \text{.... (17)}$$

where the equations (14) - (16) are used.

The equations (7) and (17) give

$$J = \left[\frac{8}{5}\right]^{5/2} \left[\frac{27}{125}\ \frac{\epsilon^3 H^2}{e}\right]^{1/2} \frac{V^{5/2}}{L^4} \quad \text{.... (18)}$$

which is 5/2 - power law dependence of current on applied voltage.

The equation (18) gives the voltage across the insulator as

$$V(x) = \frac{5}{8}\left[\frac{125}{27}\ \frac{eJ^2}{\epsilon^3 H^2}\right]^{1/5} x^{8/5} \quad \text{.... (19)}$$

The equations (17) and (19) give the ratio as

$$\frac{E(x)}{V(x)} = \frac{8}{5}\ \frac{1}{x} \quad \text{.... (20)}$$

The value of ohmic electric field is given by[1]

$$E_\Omega = \frac{V}{L} \quad \text{.... (21)}$$

Now the ratio of electric field strength at position x and ohmic field is obtained as

$$\frac{E(x)}{E_\Omega} = \frac{8}{5}\left[\frac{x}{L}\right]^{3/5} \quad \text{.... (22)}$$

where x is the distance from cathode inside the insulator. The ohmic electric field is constant throughout the insulator.

Similarly the ratio of potentials is given from equations (19) - (21) as

$$\frac{V(x)}{V} = \left[\frac{x}{L}\right]^{8/5} \quad \text{.... (23)}$$

The expression for the carrier density at position x is obtained from equations (14) - (16) as

$$n(x) = \frac{\epsilon}{e}\left[\frac{125}{27}\ \frac{eJ^2}{\epsilon^3 H^2}\right]^{1/5} \frac{3}{5}\ x^{-2/5} \quad \text{.... (24)}$$

The equation (24) gives the average concentration of the free current carriers in insulator

$$\frac{n(x)}{\bar{n}} = \frac{3}{5}\left[\frac{L}{x}\right]^{2/5} \quad \text{.... (25)}$$

and

$$\bar{n} = \frac{1}{L}\int_0^L n(x)\,dx = \frac{8}{5}\ \frac{\epsilon}{e}\ \frac{V}{L^2} \quad \text{.... (26)}$$

The capacitance of the insulator is given by [1,5]

$$C = \frac{\epsilon E_a}{V} \quad \text{.... (27)}$$

where E_a is the electric field at anode derived from equation (17) as

$$E_a = \left[\frac{125}{27}\ \frac{eJ^2}{\epsilon^3 H^2}\right]^{1/5} L^{3/5} \quad \text{.... (28)}$$

The voltage at anode becomes

$$V = V(L) = \frac{5}{8}\left[\frac{125}{27}\ \frac{eJ^2}{\epsilon^3 H^2}\right]^{1/5} L^{8/5} \quad \text{.... (29)}$$

where the equation (19) is used.

The ohmic field and the geometric capacitance of the insulator are given by [1,7]

$$E_\Omega = \frac{V}{L}, \quad C_0 = \frac{\epsilon}{L} \quad \text{.... (30)}$$

The equations (29) and (30) give

$$C = \frac{8}{5} C_0 \quad \text{.... (31)}$$

The interval electrode transit time is obtained as[1,6]

$$t = \int_0^L \frac{dx}{\mu\, E(x)} = \frac{8}{5}\, t_o \qquad \text{.... (32)}$$

where $t_o = \frac{\epsilon V}{JL}$.

Thermal noise generated in the insulator

The mean square noise voltage developed across the insulator is caused by the interaction of the current carriers with the lattice. It is given in a frequency interval Δf as [4,5]

$$\overline{v^2} = 4\,k\,T\,R\,\Delta f \qquad \text{.... (33)}$$

where $$R = \sum \Delta x = \sum \frac{\Delta x}{\epsilon \mu n S} = \frac{\int E\,dx}{JS} \qquad \text{.... (34)}$$

here ΔR is the D.C. resistance of a small section Δx and the summation is carried over all sections of the insulator, R is the total noise resistance, k is Boltzmann's constant, T is the lattice temperature and S is the area of cross-section.

The equations (29) and (34) give the total resistance of the insulator

$$R = \frac{5}{8S}\left[\frac{125}{27}\,\frac{e}{J^4\,\epsilon^3\,H^2}\right]^{2/5} L^{8/5} = \frac{V}{JS} \qquad \text{.... (35)}$$

The differential conductance of the insulator is derived from equation (18) as

$$g = \frac{\partial I}{\partial V} = \frac{5}{2}\,\frac{JS}{V} \qquad \text{.... (36)}$$

where I = JS is the total current flow in the insulator.

The relation between mean square noise current and noise voltage for an insulator is given from the equations (33)-(36) as

$$\frac{\overline{i^2}}{k\,T\,\Delta f} = 25\,\left(\frac{I}{V}\right)^3 \quad ; \quad \frac{\overline{v^2}}{k\,T\,\Delta f} = \frac{4V}{I} \qquad \text{.... (37)}$$

It may be easily concluded from the expression (37) that the thermal noise is highly affected by the small change in applied voltage.

Results

The comparison of the electrical properties of space-charge-limited current in insulators and vacuum diodes is given in table 1. It may be easily pointed out from the table 1 that the vacuum diode carries a much larger current with compared to the solid state diode of comparables dimensions under the same applied voltage, because, the mobility of the current carriers have lower values in solid state diodes. However, a large current in solid may be achieved by selecting a material with large mobility. In practice, the steady state space-charge-limited single injection current in solid state diodes is highly reduced to lower values to the presence of trapping states, which are generally present in significant concentration inside the forbidden gap of an insulator. The current-voltage characteristic is different at low and high injection levels which are observed under the effect of low and high voltage respectively. The Ohm's law is observed at low injection level and there is a significant departure from Ohm's law at high injection levels which is occurring in both constant and carrier density dependent mobility regimes.

Table 1: Comparison of the properties of space-charge-limited current in diodes.

S. No.	Current injection in vacuum diode	Current injection in solid with constant mobility	Current injection in solid with carrier density dependent mobility
1	$J = \frac{4\sqrt{2}}{9}\left(\frac{e}{m}\right)^{1/2} \epsilon_0 \frac{V^{3/2}}{L^2}$	$J = \frac{9}{8}\,\epsilon\,\mu\,\frac{V^2}{L^3}$	$J = \left[\frac{8}{5}\right]^{5/2}\left[\frac{27}{125}\,\frac{\epsilon^3 H^2}{e}\right]^{1/2}\frac{V^{5/2}}{L^4}$
2	$E(x) \propto x^{1/3}$	$E(x) \propto x^{1/3}$	$E(x) \propto x^{3/5}$
3	$\frac{E_a}{E_\Omega} = \frac{4}{3}$	$\frac{E_a}{E_\Omega} = \frac{3}{2}$	$\frac{E_a}{E_\Omega} = \frac{8}{5}$
4	$V(x) \propto x^{4/3}$	$V(x) \propto x^{3/2}$	$V(x) \propto x^{8/5}$
5	$n(x) \propto x^{-2/3}$	$n(x) \propto x^{-1/2}$	$n(x) \propto x^{-2/5}$
6	$t = 3L\,(\frac{m}{2eV})^{1/3}$	$t = \frac{4}{3}\,\frac{L^2}{\mu V}$	$t = \frac{4}{3}\,\frac{\epsilon V}{JL}$

In the advent of current injection technique in insulators, the investigations are progressed in the field of noise in nonlinear devices. The high resistivity materials have given the possibilities to fabricate the injection devices for which the simple theoretical models of single injection hold very closely.

The following facts are established due to accurate measurements on such devices. The thermal noise is the main source of noise in single injection and it follows Ohm's law at low injection level. This result extends the description of thermal noise in nonlinear devices, Johnson [10] showed experimentally and Nyquist [11] evaluated theoretically that the thermal fluctuation processes give a noise of amount as

$$S_v = 4kTR_n$$

which is also obtained in our analysis at low injection level. These same processes lead to an observable thermal noise in single injection space-charge-limited current flow in insulator operating under SCDM regime which follows 5/2 - power law. Thus, it is clearly a need for a careful distinction between the two cases. The "Nyquist noise" is called for the first case only in connection with thermal noise in linear systems. On the other hand, the "thermal noise" or "scattering noise" covers the noise of single injection space-charge-limited current flow in nonconstant mobility regime.

Conclusion

In this paper, the diffusion current is neglected with respect to drift current which is assumed generally in SCL single injection current theories [1,4,5,7], which are found to be correct to a certain extent by experimental studies.

The current-voltage characteristic of insulator operating under single injection and carrier density dependent mobility regime have evaluated at low and high injection level of currents. The current flow is started from a linear law ($J \propto V$) and finally it merges into 5/2 – power law ($J \propto V^{5/2}$). The comparison of the electric properties of space-charge-limited current in insulator and vacuum devices are shown in table 1.

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