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CARRIER DENSITY FLUCTUATIONS IN SINGLE-INJECTION SOLID-STATE DIODES WITH TRAPS LYING BELOW THE FERMI LEVEL

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ABSTRACT

The effects of space charge and trapping on low-frequency noise in single-injection solid-state diodes with traps lying below the Fermi level have been studied in the complete range of current–voltage characteristic. It is shown that the complete noise spectrum may be divided into four noise regimes and the low-frequency noise at high injection level of current is very much dependent on the injection level of current.

INTRODUCTION

In single-injection devices, current flow is dominated by the space charge, which gives nonlinear effects on current–voltage characteristics and noise spectrum[1-4]. Carrier density fluctuations in an insulator give low-frequency noise in injection diodes[1]. The presence of trapping states changes the current–voltage characteristic by the trapping effect and the noise spectrum is modulated under the influence of trapping.

CURRENT INJECTION

According to the current injection theory[2-4], an insulator containing traps lying below the Fermi level may be divided into three regions by two imaginary transition planes x_1 and x_2, which shift towards the anode with increasing injection level of current. The regional approximation scheme for the problem is shown in figure 1.

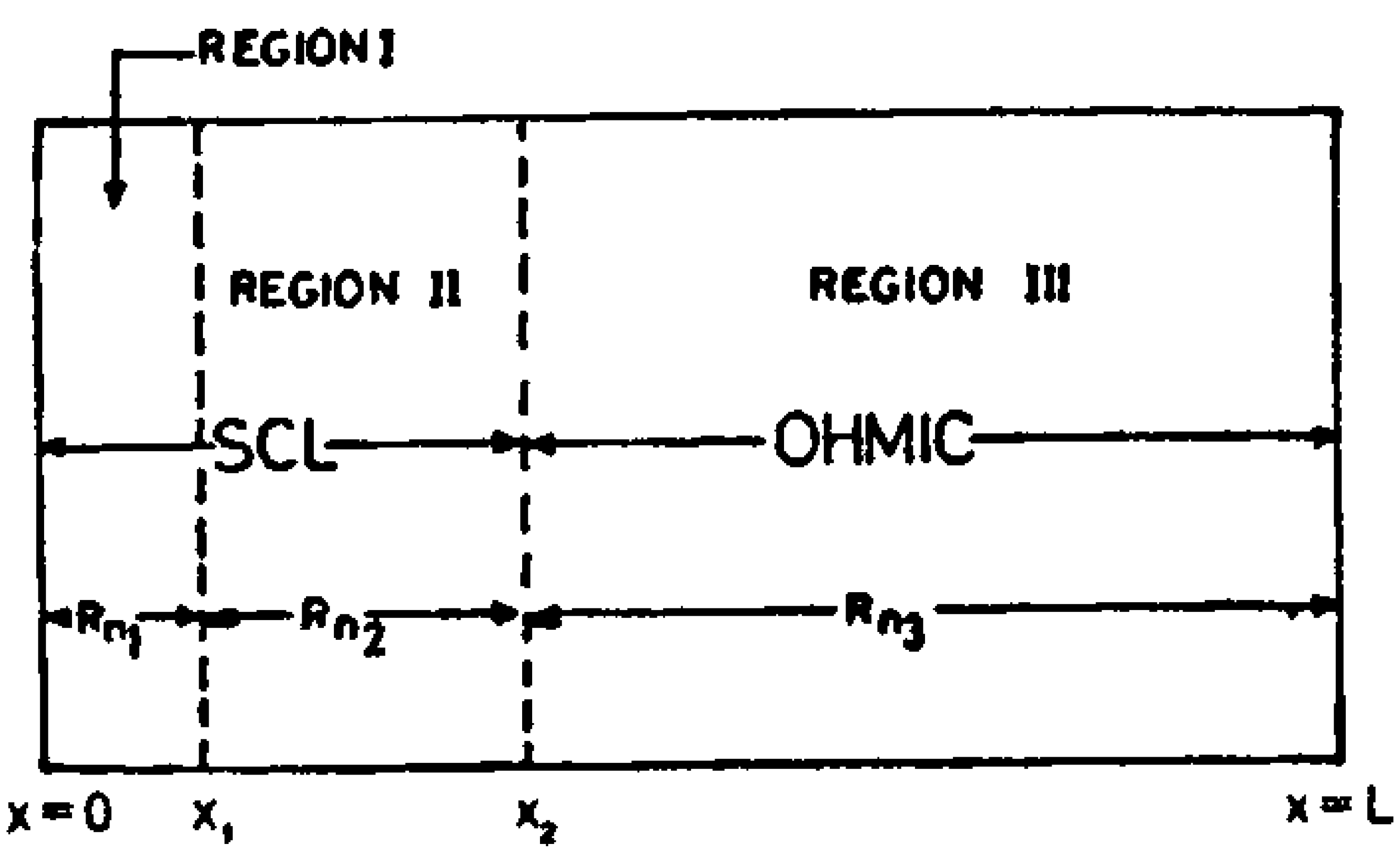

Figure 1. Schematic regional scheme for low-frequency noise resistance.

The general equations are obtained as[3]

region I: $(0 \leqslant x \leqslant x_1)$: $n_0 \ll n(x)$, $p_{t,0} \ll n(x)$

$$J = e\,\mu\, n(x)\, E(x), \ \frac{\varepsilon}{e}\frac{\mathrm{d}E}{\mathrm{d}x} = n(x), \qquad (1)$$

region II: $(x_1 \leqslant x \leqslant x_2)$: $n_0 \leqslant n(x) \leqslant p_{t,0}$,

$$J = e\,\mu\, n(x)\, E(x), \ \frac{\varepsilon}{e}\frac{\mathrm{d}E}{\mathrm{d}x} = p_{t,0}, \qquad (2)$$

region III: $(x_2 \leqslant x \leqslant L)$: $n(x) - n_0 \ll n_0$,

$$J = e\,\mu\, n_0 E, \ \frac{\varepsilon}{e}\frac{\mathrm{d}E}{\mathrm{d}x} = 0, \qquad (3)$$

where J is the current density, μ the mobility of current carriers, ε the permittivity of the insulator, n_0 the thermally generated free carriers, $n(x)$ the concentration of carriers at distance x, L the device length, and $p_{t,0}$ the thermal equilibrium value of the concentration of traps not occupied by electrons.

The transition planes connecting the separate regions are defined as[3]

$$n(x_1) = p_{t,0},\ n(x_2) = n_0, \qquad (4)$$

where

$$x_1 = \frac{\varepsilon J}{2A^2 e^2 \mu n_0^2},\ x_2 = \frac{\varepsilon J}{A e^2 \mu n_0^2},\ A = \frac{p_{t,0}}{n_0}. \qquad (5)$$

The detailed theory of current injection in insulator diodes with traps lying below the Fermi level is described elsewhere[2-4].

LOW-FREQUENCY NOISE

The low-frequency noise characteristic starts from the pure Ohm's regime and the last regime is obtained by space charge conduction[2-4]. Adopting usual procedures[1,2], equations (1)–(5) are used to derive the expression for noise resistances in three regions as given below:

$$\text{region I:}\quad R_{n_1}=\frac{\varepsilon^2 J^2 S}{288\,k\,T\,A^8\,e^7\,\mu^4\,n_0^8}, \tag{6}$$

$$\text{region II:}\quad R_{n_2}=\frac{\varepsilon^2 J^5 S}{32\,k\,T\,A^4\,e^7\,\mu^4\,n_0^8}\left[1+\frac{1}{16\,A^4}-\frac{1}{2\,A^2}\right], \tag{7}$$

$$\text{region III:}\quad R_{n_3}=\frac{J^2}{2\,kT\,e^2\,\mu^2\,n_0^3}\left[L-\frac{\varepsilon J}{A\,e^2\,\mu\,n_0^2}\right]^2, \tag{8}$$

where S is cross-sectional area, k Boltzmann's constant, T the lattice temperature, and A is as given in (5). The total noise resistance of the diode is given by

$$R_n=R_{n_1}+R_{n_2}+R_{n_3}. \tag{9}$$

At very low injection level of current, only region III contributes to the low-frequency noise of the diode. This is the true Ohm's regime of low-frequency noise characteristic, whose noise resistance is obtained from (8) as

$$R_t=\frac{J^2 L^2}{2\,k\,T\,e^2\,\mu^2\,n_0^3}, \tag{10}$$

where region III extends from cathode to anode and the transition plane x_2 is close to the cathode.

The expression for low-frequency noise in the ohmic regime is considered for the injection level at which all three regions are present in the insulator. The noise resistance for this regime is derived from equations (6)–(8):

$$R_0=\frac{J^2}{2\,k\,T\,e^2\,\mu^2\,n_0^3}\left[\frac{\varepsilon^2 J^3 S}{144\,A^8\,e^5\,\mu^2\,n_0^5}+\frac{\varepsilon^2 J^3 S}{16\,A^4\,e^5\,\mu^2\,n_0^5}\times\left(1+\frac{1}{16\,A^4}-\frac{1}{2\,A^2}\right)+\left(L-\frac{\varepsilon J}{A\,e^2\,n_0^2}\right)^2\right], \tag{11}$$

which is a complex relation depending on the injection level and physical parameters of the diode.

Regions I and II are considered to obtain the noise resistance of the diode at medium injection level of current because the injected current carriers are distributed over all parts of the diode and region III is not present in the insulator. Equations (6) and (7) give

$$R_m=R_{n_1}+R_{n_2}=\frac{\varepsilon^2 J^5 S}{32\,k\,T\,A^4\,e^7\,\mu^4\,n_0^8}\left[1-\frac{1}{2\,A^2}+\frac{25}{144\,A^4}\right], \tag{12}$$

where the different sets of noise resistances are obtained for different values of the parameter A.

At high injection level of current, the low-frequency noise is generated in only region I. The noise resistance of the diode in this regime is derived from equation (6):

$$R_h=\frac{\varepsilon^2 J^5 S}{288\,k\,T\,A^8\,e^7\,\mu^4\,n_0^8}, \tag{13}$$

which is strongly dependent on the injection level of current. The space charge conduction mechanism is dominant at high injection level.

DISCUSSION

The complete low-frequency noise characteristic is divided into four noise regimes. The characteristic starts from very low injection level of current, at which the noise resistance is obtained only by the ohmic contributions. All the three regions are present in the insulator in the ohmic regime; therefore the noise characteristic is obtained by the space charge, trapping and ohmic contributions. The trapping effect is dominant in the low-frequency noise characteristic at medium injection level of current. The parameter A gives different sets of noise resistances for different insulating materials. The low-frequency noise of the diode at high injection level of current is controlled by space charge and the trapping and ohmic effects are negligibly small.

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