Space charge limited current in Schottky diode with single level traps

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The space charge limited current (SCLC) in a Schottky diode with a finite injection barrier at the injecting contact and single level traps in the energy space has been investigated by mathematical modelling. Solution of coupled Poisson's and continuity equations with non-zero Schottky barrier (ϕ) leaded us to calculate the electric field [$F(x)$] and the charge carrier $p(x)$ distribution in the sample. Considering the boundary conditions, the current density-voltage (*J-V*) characteristics have been calculated numerically. It is reported here that when Schottky barrier is not zero, *J-V* characteristics become Ohmic at infinitely large voltages. The expression of trap filled limit voltage (V_{TFL}) has also been derived. The effect of Schottky barrier on the SCLC current in semiconducting devices has been studied in the present paper.

Keywords: Space charge limited current, Single level traps, Trap filled limit, Charge carrier transport, Schottky diode

1 Introduction

In the past few decades, gallium nitride (GaN) has emerged as a vital material for electronic devices. It is largely used as Schottky barrier (ϕ) metal contacts[1,2]. It is extremely stable and hard semiconductor material. Traps in GaN are at single energy levels and it has a very wide band gap, which makes it suitable for blue optoelectronic devices. Despite its very high concentration of dislocations, it can be used to produce very high quality LEDs and lasers. Devices based on GaN are useful as engine monitoring, heat sensors, blue opto-electronics devices and satellite communications[3-5]. The epilayers of GaN and its alloys still have large dislocations densities and it results in the large dark currents in junction devices. Additionally, the carrier trapping causes additional difficulties. Dislocations and other defects give rise to localized states in the band gap. It is, therefore, important to study the electronic properties of these materials both experimentally and theoretically. The point defect includes chemical impurities, intrinsic vacancies and self-interstitials.

Lebedev *et al.*[4] have made extensive investigations of the *I-V* characteristics in the SCLC regime to elucidate the effect of defect states on the electrical and optical properties of GaN and its alloys. In a defect free insulator, the current depends on the square of the voltage, the dependence is known as Mott's V^2 law. Traps play a very important role in determining the charge transport through semiconductor devices. In GaN and other inorganic semiconductors, the traps are observed at discrete single energy levels.

There have been various models available in the literature for current in GaN diode with traps distributed at one or several discrete single energy levels[1]. All of these models are based on one key assumption that the charge injecting contact is Ohmic i.e. the injection Schottky barrier is zero. The *J-V* characteristics have been calculated, when Schottky barrier is not zero, it become Ohmic as the voltage tends to infinity. The expression of trap filled limit voltage (V_{TFL}) has also been derived. The effect of Schottky barrier on the charge transport through GaN diodes has been studied in the present paper.

2 Theory

There is no analytical *J-V* relation available in the literature for the entire range of the applied voltage for a sample with single energy level traps. If the Schottky barrier at the injecting contact is zero, the *J-V* relation for a semiconductor diode with traps at a single energy level of energy E_t at low voltages before the traps[6] are filled is given by:

$$J = \frac{9}{8}\mu\varepsilon\varepsilon_0\theta\frac{V^2}{d^3} \qquad \qquad \ldots(1)$$

where μ is charge carrier mobility, ε the dielectric constant of the semiconductor and ε_0 is the permittivity of free space, d is the sample thickness and $\theta = \dfrac{N_v}{H_b} \exp\left(\dfrac{-E_t}{kT}\right)$. In this case, once all the traps are filled the characteristics approaches asymptotically the Mott's V^2 law[7,8] which is given by:

$$J = \frac{9}{8}\mu\varepsilon\varepsilon_0 \frac{V^2}{d^3} \qquad \ldots(2)$$

For non-zero Schottky barrier, the injected charge carrier density at the contact is not infinitely large but a finite number $p(0)$. In this case also, no analytical relation is available for entire voltage range. The *J-V* characteristics for the case when injection Schottky barrier is not zero, have been calculated numerically. For this purpose, we eliminated $p(x)$ between the continuity and Poisson's equations and integrated for field $F(x)$ over the thickness d and solved the following equation:

$$\int_0^d dx = \frac{\varepsilon\varepsilon_0}{q} \int_{F(0)}^{F(d)} \frac{1}{\dfrac{J}{q\mu F} + \dfrac{H_b}{1 + \dfrac{q\mu F N_v \exp\left(\dfrac{-E_t}{kT}\right)}{J}}}. \qquad \ldots(3)$$

At the injecting contact, the current follows the condition of continuity and is given by:

$$J = q\mu p(0) F(0) \qquad \ldots(4)$$

where $p(0) = N_v \exp\left(-\dfrac{\phi}{kT}\right)$ and $F(0)$ are the charge carrier density and electric field, respectively at the injecting contact ($x = 0$) and ϕ is the injection barrier. Eqs (3 and 4) are solved for given currents J. The corresponding voltages are calculated using the boundary condition:

$$V = \int_0^d F(x)dx. \qquad \ldots(5)$$

The complete *J-V* characteristics are obtained by solving Eq. (3) along with Eqs (4 and 5), numerically.

3 Results and Discussion

Figure 1 shows the calculated *J-V* characteristics, using Eq. (3) for zero Schottky barrier (curve D) and Eq. (1) (curve B) along with the Mott's V^2 law (curve A). The values of the parameters used in the

calculations are given in the caption of Fig. 1. At low voltages when the traps are not filled completely the characteristic using Eq. (3) remains identical to Eq. (1) where current shows square dependence on the voltage (V^2) similar to Mott's V^2 law but the magnitude of current is reduced by a factor θ. As voltage increases further the current increases sharply and then goes to Mott's V^2 law at high voltages. This sharp increase in the current corresponds to the complete filling of the traps. The voltage corresponding to this sharp increase in the current[7] corresponds to the V_{TFL} and is given by:

$$V = V_{TFL} = 0.5 \frac{qH_b d^2}{\varepsilon\varepsilon_0}. \qquad \ldots(6)$$

Interestingly, the trap filled limit depends on the total traps density and thickness of the sample, not on the distribution of traps. The vertical line C in Fig. 1 corresponds to the V_{TFL} of the sample.

Figure 2 shows the calculated *J-V* characteristics using Eq. (3) for different Schottky barriers. Curves A, B and C are for the injection barrier (ϕ) = 0.13, 0.36 and 0.60 eV, respectively. The lines 1, 2 and 3 correspond to Ohm's law given by:

$$J = q\mu p(0) \frac{V}{d}$$

for respective injection barriers i.e. line 1 is for $\phi = 0.13$ eV, line 2 is for $\phi = 0.36$ eV and line 3 is for $\phi = 0.60$ eV. The dash dotted line in Fig. 2 corresponds to the Mott's V^2 law, whereas the vertical dotted line is for V_{TFL}. The values of rest of the parameters are the same as those for Fig. 1. For all cases, the characteristics overlap exactly before the
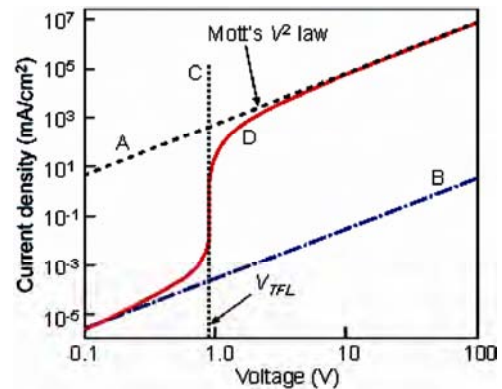

Fig. 1 — Calculated *J-V* characteristics using Eq. (1) (curve B), Eq. (2) (curve A) and Eq. (3) (curve D). The values of the parameters used in the calculations are; $\mu = 300$ cm^{2}V^{-1}s^{-1}, $\varepsilon = 10$, $\varepsilon_0 = 8.85\times10^{-14}$ F/cm, $d = 1$ μm, $T = 300$ K, $E_t = 0.6$ eV and $H_b = 10^{15}$ cm^{-3} and $N_v = 10^{19}$ cm^{-3}
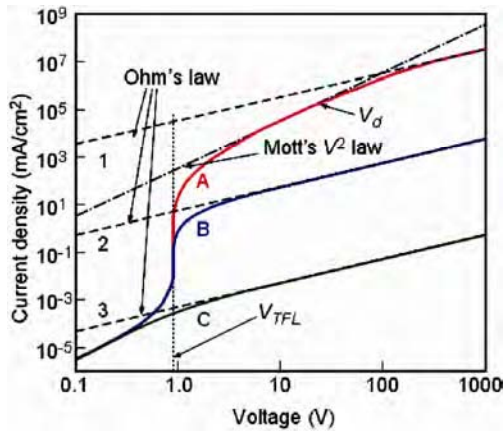
Fig. 2 — Calculated *J-V* plots using Eq. (3) (curves A, B and C) and Ohm's law (lines 1, 2 and 3) for different values of φ. The values of rest of the parameters used in these calculations are the same as those for curve A of Fig. 1
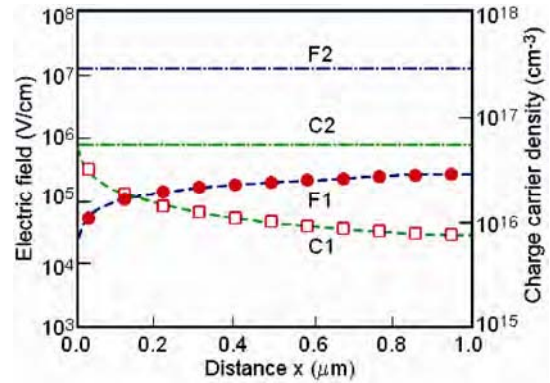

Fig. 3 — Electric field (curves F1 and F2) and charge carrier (curves C1 and C2) profiles in a sample with specification similar to curve A in Fig. 2. The filled and open symbols are for the electric field and charge carrier profiles in a sample, respectively, when current follows the Mott's V^2 law. The values of rest of the parameters used in these calculations are the same as those for curve A of Fig. 1

V_{TFL}. The characteristics show different nature for different Schotky barriers. For low Schottky barriers (curve A), the characteristics beyond V_{TFL}, first follow the Mott's V^2 law and then deviates at high voltages (say V_d) and go to Ohm's law.

Therefore, for non-zero Schottky barriers the characteristics may follow first the Mott's V^2 law but finally they approach the Ohm's law at high voltages. The value of V_d decreases with increment in the injection barrier and for somewhat larger value of Schottky barrier (curve B), the characteristic beyond V_{TFL} does not follow the V^2 law and goes directly the Ohm's law at high voltages. This is an interesting observation. From the calculations, we found more interesting results that if the injection Schottky barrier is quite large, all the traps in the sample will never be filled. The number of traps that are filled in a particular case[6] is given by:

$$p_t(x) = \frac{H_b}{1 + \dfrac{N_v \exp\left(\dfrac{-E_t}{kT}\right)}{p(x)}} . \qquad \qquad …(7)$$

Therefore, in the present case the maximum number of traps that will be filled in the sample (H_b') will be given by:

$$H_b' = \frac{H_b}{1 + \dfrac{N_v \exp\left(\dfrac{-E_t}{kT}\right)}{p(0)}} . \qquad \qquad …(8)$$

The voltage corresponding to filling of this maximum number of traps will be given by:

$$V = V_{TFL} = 0.5 \frac{q H_b' d^2}{\varepsilon \varepsilon_0}. \qquad \qquad …(9)$$

In this case, first the characteristics follow Eq. (1) at low voltages, the H_b' traps are filled and then current go to Ohm's law at high voltages (curve C).

The above observations are also well supported by the electric field and charge carrier profiles in the sample. Fig. 3 shows the electric field (F1, F2) and charge carrier (C1, C2) profiles calculated numerically for the current 10^5 and 10^8 mA/cm^2, respectively for the sample with specification similar to that for curve A in Fig. 2. F1 and C1 are for current 10^5 mA/cm^2 while F2 and C2 are for 10^8 mA/cm^2. Open and filled symbols are for the profiles of charge carriers and electric field, respectively in the V^2 law at a current 10^5 mA/cm^2. Note that when current follows the V^2 law, charge carrier density varies as $1/\sqrt{x}$, while electric field as $\sqrt{x}$. At this current, the charge carrier (C1) and field (F1) profiles agree perfectly with the open and filled symbols, respectively. It is clear evidence that at 10^5 mA/cm^2, current follows the V^2 law. As the current increases further, say to 10^8 mA/cm^2, the charge carrier (C2) and electric filed (F2) profiles become uniform, which represents the Ohmic conduction in the sample.

Though the case of traps existing in a single energy level has been discussed, the obtained results will also be applied to the samples containing traps at different discrete energy levels. A case of trap distribution in

several discrete single energy levels with zero Schottky barrier has been discussed by Jain *et al*[7]. For such a sample with a sufficiently high barrier, only deeper traps are filled. The results presented here are for a given set of parameters for GaN diode and the characteristics can also be obtained easily for a sample with different specifications.

It has been difficult to compare our theoretical results for GaN diodes with non-zero Schottky barrier, with experimental *J-V* characteristics, as we have not come across the reliable *J-V* characteristics of GaN with non-zero Schottky barrier. Results of Shen *et al*[9]. and that of Jain *et al*[7]. are reliable but they are for zero Schottky barriers i.e. Ohmic contacts.

4 Conclusions

The following important results have been derived from the calculations made in this paper; (i) Before V_{TFL} all the characteristics with zero on non-zero Schottky barrier overlap; (ii) For small barriers once all the traps are filled, current follows the Mott's V^2 law and deviate from it at a high voltage V_d and approaches to Ohm's law; (iii) The value of V_d depends on the magnitude of Schottky barrier; (iv) The voltage at which Ohm's law occurs depends on the thickness of the sample and Schottky barrier;

(v) For large Schottky barriers once all the traps are filled, current directly goes to the Ohm's law; (vi) For quite large injection barriers all the traps are not filled and current goes to Ohm's law at high voltages.

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