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EVALUATION OF IONIZATION RATE OF ELECTRONS IN WURTZITE-GAN VIA A GENERALIZED ANALYTICAL MODEL BASED ON MULTISTAGE SCATTERING PHENOMENA

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Abstract: A comprehensive analytical model based on multistage scattering phenomena has been used to evaluate the impact ionization rate of electrons in Wz-GaN within the field range of $4.0\times10^{7} – 2.0\times10^{8}$ V m^{-1}. The numerical results obtained from the proposed analytical model within the field range under consideration have been compared with the ionization rate values calculated by using the empirical relations fitted from the experimentally measured data. The calculated values of impact ionization rate of electrons in Wz-GaN are found to be in close agreement with the experimental results especially for the electron concentration of 10^{23} m^{-3} which is same as that taken into account in the experiment.

Keywords: Electron-electron interaction, impact ionization, multistage scattering, optical phonon scattering, Wurtzite-GaN.

I. INTRODUCTION

Avalanche multiplication by means of impact ionization of charge carriers within the active regions reversed biased *p-n* junctions plays a significant role in various microwave, millimeter-wave and optoelectronic semiconductor devices [1-4]. Several theoretical models to describe and formulate the impact ionization rates of charge carriers in a semiconductor material had been proposed by different researchers since last sixty years. Out of those, most acceptable analytical models were proposed by Wolff [5] in the year 1954 and Shockley [6] in the year 1961. In the year 1961, Mole and Meyer [7] modified the Shockley's theory by considering different possible ways through which electron can cause ionization by acquiring energy equal and greater than the ionization threshold energy. Two years later in 1963, Mole and Overstraeten [8] proved that the theories of Wolff [5] and Shockley [6] are applicable for low and high field conditions respectively. One year earlier of that, i.e. in the year 1962, Baraff [9] had plotted the impact ionization rates of charge carriers as function of electric field from the numerical simulation technique without any low or high field approximations. In the year 1975, Ghosh and Roy [10] shown that the higher carrier density in semiconductors enhance the energy loss due to electron-electron collisions which causes significant deterioration in ionization rate of charge carriers. They considered the energy loss occurred due to electron-electron interactions in addition to the usual scattering events like optical phonon scattering ionization collisions in their analysis. Ten years later in 1985, Singh and Pal [11] adopted the similar approach and evaluated the ionization rates of electrons and holes in <100> oriented in GaAs. The calculated results were in close agreement with the experimental results of Ito *et al.* [12] and Pearsall *et al.* [13]. In addition to that the theory proposed by Singh and Pal [11] was successful to explain the behavior of holes in GaAs as spin-orbit splitoff holes and heavy holes at lower and higher field ranges respectively.

Generation of electron hole pairs (EHP) by impact ionization process basically a multistage phenomena. Several combinations of optical phonon scattering as well as carrier-carrier collision events may take place prior to the generation of an EHP via impact ionization. This microscopic view of an EHP generation by means of impact ionization has been first taken into account by Acharyya *et al.* [14] in the year 2014. They considered the all possible combinations of optical phonon scattering and carrier-carrier collision events prior to the impact ionization and thereby generation of an EHP. Finally the probability of impact ionization has been obtained from a trinomial distribution function which describes the above mentioned multistage scattering phenomena. Using the probability of impact ionization, finally the analytical expression of ionization rate of charge carriers in a semiconductor material has been developed and using that the ionization rates of electrons and holes in 4H-SiC have been calculated as functions of electric field. The calculated results show better agreement with the experimental data [15] as compared to those calculated from the analytical expressions of Ghosh *et al*. [10] and Singh *et al*. [11].

In the present paper, similar approach (as in ref. [14]) has been taken into account to calculate impact ionization rate of electrons in Wurtzite-GaN (Wz-GaN). The calculated results have been compared with the values of electron ionization rates of Wz-GaN obtained from the empirical relation with the experimentally measured data of Kunihiro *et al*. [16] within the electrical field range under consideration. The calculated results are found to be in good agreement with the experimental results.

II. THEORY

Acharyya *et al.* [14] considered the multistage scattering phenomena by taking into account a *w*-stage process; where *w* = 1, 2, 3, 4,........., *N*, *N*+1. During the first *N* stages, all possible combinations of optical phonon scattering as well as carrier-carrier scattering events are assumed to be occurred. At the final $(N+1)^{th}$ stage, the impact ionization is assumed to be occurred. They have formulated the above mentioned *w*-stage process by means of a trinomial distribution function. And finally by considering all possible values of the number of stages, i.e. values of *w* varying from 1 to ∞, the total probability of multistage impact ionization initiated by electrons can be expressed as

$$P_{Te}(\xi)=\frac{p_{i(e,h)e}\exp\left(-\frac{E_{i(e,h)e}}{q\xi l_{re}}\right)}{\left[1-\left\{p_{re}\exp\left(-\frac{E_r}{q\xi l_{ie}}\right)+p_{ee}\exp\left(-\frac{E_{ee}}{q\xi l_{ire}}\right)\right\}\right]}, \qquad (1)$$

where $p_{i(e,h)e}$, p_{re}, p_{ee} are the probabilities of occurrence of impact ionization, optical phonon generation, electron-electron interaction after reaching the respective energies, E_r is the energy of optical phonons, E_{ee} is the average energy loss due to electron-electron interactions, $E_{i(e,h)e}$ is the ionization threshold energy of electrons, $l_{re}=\left(l_r^{-1}+l_{ee}^{-1}\right)^{-1}$, $l_{ie}=\left(l_{i(e,h)e}^{-1}+l_{ee}^{-1}\right)^{-1}$, $l_{ire}=\left(l_{i(e,h)e}^{-1}+l_r^{-1}\right)^{-1}$; where l_r, l_{ee} and $l_{i(e,h)e}$ are the mean free paths associated with optical phonon scattering, electron-electron collisions and impact ionization respectively, q is the electronics charge ($q = 1.62\times10^{-19}$ C) and ξ is the applied electric field.

Now considering the energy balance equation, i.e. applied energy per unit length equals to energy loss due to optical phonon collision, electron-electron interaction and impact ionization, along with the relative probabilities of impact ionization of electrons, impact ionization rates of charges carriers may be obtained as

$$\alpha_e(\xi)=\frac{P_{Te}(\xi)\left(1+\frac{l_r}{l_{ee}}\right)\left(q\xi-\left\langle\frac{dE_{ee}}{dx}\right\rangle\right)}{\left(1-P_{Te}(\xi)\right)E_r+P_{Te}(\xi)\left(1+\frac{l_r}{l_{ee}}\right)E_{i(e,h)e}}, \qquad (2)$$

where $\langle dE_{ee}/dx\rangle$ is the average energy loss per unit length due to electron-electron collision [14]. The effect of carrier density on $\alpha_e(\xi)$ has been incorporated by the dependence of l_{ee} on the electron concentration (i.e. n). That is taken to be $l_{ee}=(A_e)^c n^{-1/3}$ [11], where A_e and c are dimensionless fitting parameters which may be adjusted in numerical calculations for obtaining the best fit of the experimental data.

III. NUMERICAL RESULTS AND DISCUSSION

Numerical calculations have been carried out to obtain the ionization rate of electrons in Wz-GaN as functions of applied electric field within the field range $4.0\times10^7 - 2.0\times10^8$ V m^{-1} using the analytical expression given in equation (2) in which the multistage scattering phenomena have been taken into account for obtaining the total probability of impact ionization of the charge carriers. The calculated values of $\alpha_{e,h}$ are compared with the empirical relations fitted from the experimental data measured by Kunihiro *et al.* [16] given by

$$\alpha_e(\xi)=A_e\exp\left[-\left(\frac{B_e}{\xi}\right)^m\right], \qquad (3)$$

where the ionization coefficients A_e and B_e are 138.00×10^8 m^{-1} and 14.28×10^8 V m^{-1} respectively for $\xi \le 10^8$ V m^{-1} and 122.70×10^8 m^{-1} and 13.63×10^8 V m^{-1} respectively for $\xi > 10^8$ V m^{-1}, while m = 1 for the entire field range under consideration [16]. Other material parameters of Wz-GaN such as bandgap (E_g = 3.39 eV), ionization threshold energy of electrons ($E_{i(e,h)e}$ = 3.6612 eV) and corresponding mean free path ($l_{i(e,h)e}$ = 840 Å), optical phonon energy (E_r = 91.2 meV) and corresponding mean free path (l_r = 42 Å), permittivity (ε_r = 8.9), etc. are taken from the experimental reports [17].

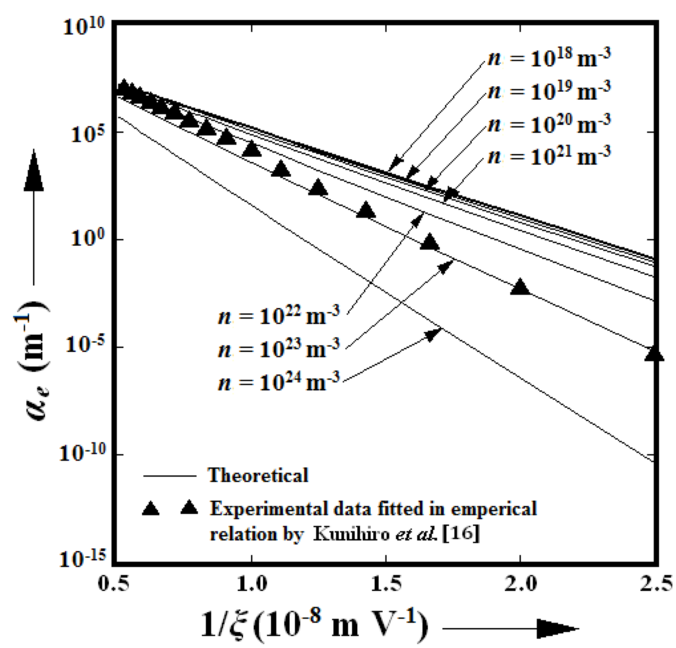

Figure 1: Ionization rate of electrons in Wz-GaN versus inverse of applied electric field. Points (▲) represent the plot of empirical relation given by equation (4) fitted from experimental data of Kunihiro *et al.* [16] (electron concentration in [16] is $n = 10^{23}$ m^{-3}).

Variation of ionization rate of electrons and holes in Wz-GaN obtained from the analytical model presented in this paper with inverse of the electric field for different electron concentrations respectively are shown in Figure 1. The same variation obtained from the empirical relation given in equation (3) [16] is also shown in Figure 1. The parameters A_e and c associated with the mean free path of electron-electron collisions (l_{ee}) are adjusted in numerical calculations for the best fit of the experimental data. In the present analytical model the best fittings for electron and hole ionization rates described by equations (2) with the empirical relation describing the field variation of the same parameters, i.e. equations (3) are obtained from l_{ee} = $(0.75)^{3.12}$ $n^{-1/3}$ m. It can be observed from Figure 1 that the analytical expression of ionization rate of electrons considering the multistage scattering phenomena presented in this paper are in close agreement with respect to the experimental data [16] at any electric field especially for the electron concentration of 10^{23} m^{-3} which is same that taken for the experiment [16].

It is also noteworthy from Figure 1 that the impact ionization rate of electrons decreased significantly when the carrier concentrations are increased. This decrement of impact ionization rates are more pronounced for the carrier concentrations of 10^{21} m^{-3} and above of it. Degradation of impact ionization probabilities for electrons as a consequent of increase of energy loss per unit length due to increased amount of electro-electron collisions is responsible for decrement of impact ionization rate of charge carriers at higher carrier concentrations. Moreover the degradations impact ionization rate of electrons is found to be more severe at lower electric field values especially below 1.0×10^{8} V m^{-1} for all carrier densities. At lower electric fields the supplied energy per unit length ($q\xi$) is smaller and comparable to the energy loss per unit length due to the carrier-carrier interactions which leads to more degradation in impact ionization probabilities at those electric fields as compared to at higher fields. Thus the values of ionization rates are more affected by energy loss due to carrier-carrier collisions at lower electric fields.

IV. CONCLUSION

In this paper, a comprehensive analytical model based on multistage scattering phenomena has been used to evaluate the impact ionization rate of electrons in Wz-GaN within the field range of 4.0×10^{7} – 2.0×10^{8} V m^{-1}. The numerical results obtained from the proposed analytical model within the field range under consideration have been compared with the ionization rate values calculated by using the empirical relations fitted from the experimentally measured data. The calculated values of impact ionization rate of electrons in Wz-GaN are found to be in close agreement with the experimental results especially for the electron concentration of 10^{23} m^{-3} which is same as that taken into account in the experiment.

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