Temperature dependence of reverse-bias leakage current in GaN Schottky diodes as a consequence of phonon-assisted tunneling

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Temperature-dependent reverse-bias current-voltage data obtained by Miller *et al.* [Appl. Phys. Lett. **84**, 535 (2004)] for Schottky diodes fabricated on *n*-GaN are reinterpreted in terms of a phonon-assisted tunneling model. It is shown that the temperature dependence of the reverse-bias leakage current may be caused by the temperature dependence of the electron tunneling rate from traps in the metal-semiconductor interface to the conduction band of the semiconductor. A good fit of the experimental data with this theoretical model is obtained in the entire temperature range from 80 to 400 K, when an effective mass of $0.222m_e$ and a phonon energy of 70 meV are used for the calculation. The reverse current-voltage data for GaN diodes are also explained on the basis of this model. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2199980]

I. INTRODUCTION

Recently, a number of papers have been published on current mechanisms in GaN Schottky diodes.[1–7] In a very recent paper by Miller *et al.*,[1] temperature-dependent current-voltage (*I-V*) measurements of Schottky diodes fabricated on GaN grown by molecular beam epitaxy have been presented. Based on the analysis of these data, the authors of Ref. 1 suggested that two dominant leakage current mechanisms can be clearly identified: one associated with field-emission tunneling and another with an exponential temperature dependence, consistent with either trap-assisted tunneling or one-dimensional hopping conduction. The tunneling current model was found to fit the measured data for different voltages at temperatures from 125 K to approximately 250 K.[1] However, the comparison of the experimental data with this model was performed using the value of 9.8×10^{-3} for the effective mass, while the effective mass measured elsewhere[8] was found to be $0.222m_e$. In addition, the value $0.001\ \mathrm{A/cm^2\,K^2}$ for the effective Richardson's constant A^* used for fitting the tunneling current model to the measured data was significantly lower than the theoretically predicted value of $26\ \mathrm{A/cm^2\,K^2}$.

With reference to Ref. 9 we would point out that the observed temperature dependence of reverse-bias current can be explained by one dominant mechanism, namely, by phonon-assisted tunneling of electrons from electronic states/traps, located near the interface layer between electrode and semiconductor, to the conduction band of the semiconductor.

On the basis of this model we can explain not only temperature-dependent current measured at different bias voltages, as presented in Ref. 1, but also the *I-V* data obtained on GaN diodes extracted from Refs. 5 and 6.

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II. THEORY AND COMPARISON WITH EXPERIMENTAL DATA

If electrons emitted from local levels in the metal-semiconductor interface dominate the leakage current in the diode, then the current density J may be expressed as

$$J = eN_sW, \tag{1}$$

where e is the electronic charge, N_s is the occupied state density near the interface, and W is the rate of phonon-assisted tunneling of electrons from localized states into the conduction band. The rate of phonon-assisted tunneling W, as function of temperature T and field strength E, is[10]

$$W = \frac{eE}{(8m^*\varepsilon_T)}[(1+\gamma^2)^{1/2}-\gamma]^{1/2}[1+\gamma^2]^{-1/4} \times\exp\left\{-\frac{4}{3}\frac{(2m^*)^{1/2}}{eE\hbar}\varepsilon_T^{3/2}[(1+\gamma^2)^{1/2}-\gamma]^2 \times\left[(1+\gamma^2)^{1/2}+\frac{1}{2}\gamma\right]\right\}, \tag{2}$$

where

$$\gamma = \frac{(2m^*)^{1/2}\Gamma^2}{8e\hbar E\varepsilon_T^{1/2}}. \tag{3}$$

Here $\Gamma^2=\Gamma_0{}^2(2n+1)=8a(\hbar\omega)^2(2n+1)$ is the width of the center absorption band caused mainly by interaction with optical phonons, therefore $n=[\exp(\hbar\omega/(k_BT))-1]^{-1}$, where $\hbar\omega$ is the phonon energy, ε_T is the trap depth, and a is the electron-phonon interaction constant.

Thus, we can compare the current dependence on field strength obtained at different temperatures with the transition rate $W(E,T)$. The electron tunneling rate $W(E,T)$ from the traps of ε_T depth to conduction band was computed using Eq. (2). The calculation was performed using a value of 0.8 eV for the trap depth. The effective mass of electrons m^* was set to $0.222m_e$ (Ref. 8) and for the phonon energy the value of 70 meV was selected. The value a was chosen so as to get the best fit of simulated $W(T,E)$ curves to a set of

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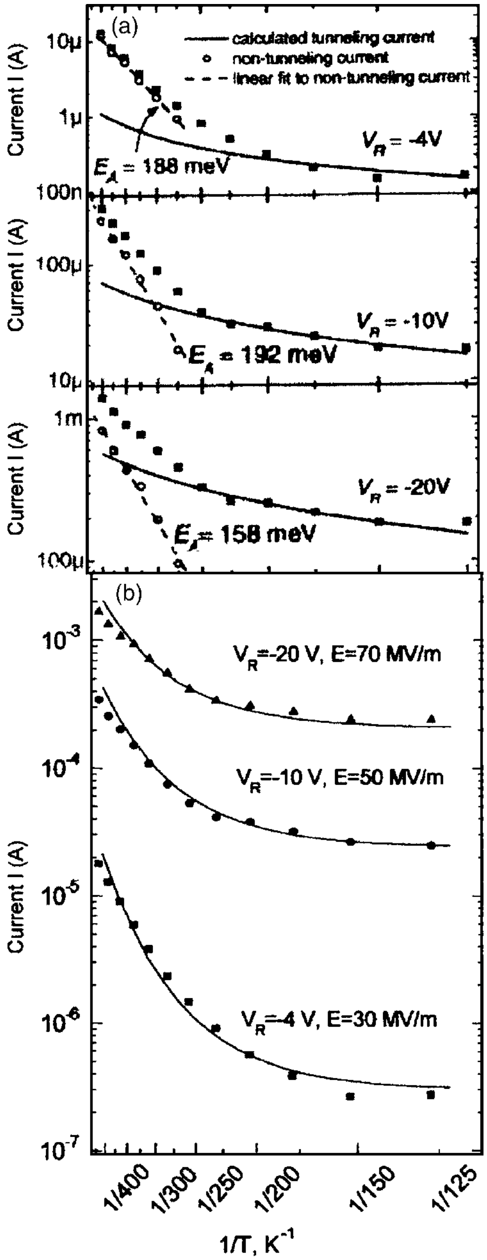

FIG. 1. Current-temperature characteristics for Schottky diode, measured at different reverse-bias voltages, extracted from Fig. 2 in Ref. 1. (a) Comparison of measured current (●) with theories performed by the authors of Ref. 1 ($m^*=9.8\times10^{-3}m_e$). (b) The fit of the experimental data (symbols) with the computed phonon-assisted tunneling rate dependencies on temperature at different field strengths (solid lines). The calculation of $W(E,T)$ was carried out using the following values of parameters: $a=2$, $\varepsilon_T=0.80$ eV, $m^*=0.222m_e$, and $\hbar\omega=70$ meV.

experimental data. The theoretical ln W vs $1/T$ dependencies fitted to the experimental data in Fig. 1 are depicted by solid lines. It is seen that at all temperatures the experimental data agree well with the computed dependencies.

The density of charge in local states estimated from the fit of the experimental data with the theory using relation (1) was found to be equal to $N_s=2.3\times10^{13}$ cm^{-2}.

We note that the current-voltage characteristics of reverse-biased diodes are explicable by this model as well. For example, in Fig. 2 we have used the data from Ref. 5 (symbols) to evaluate the current dependence of the reverse-

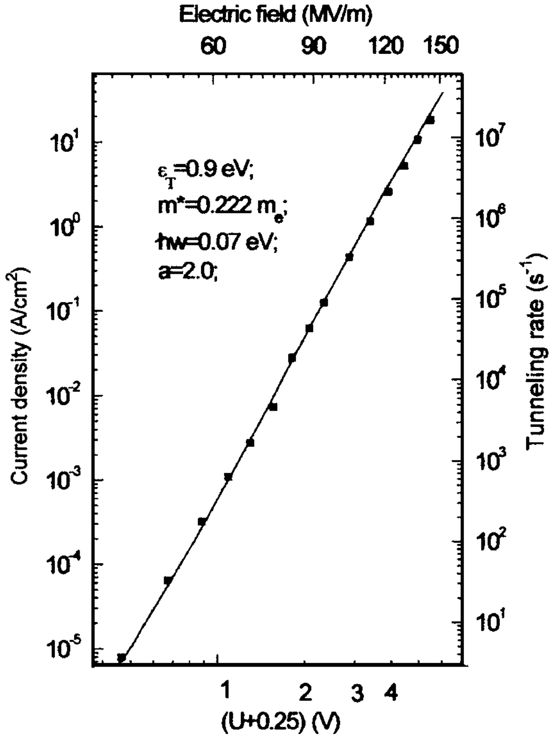

FIG. 2. I-V_R characteristic for GaN (as-grown) diode from Fig. 2(b) in Ref. 5 (squares), fitted to $W(E)$ dependence (solid line) computed for $a=1.7$, $\varepsilon_T=0.80$ eV, $T=290$ K. Other parameters are the same as in Fig. 1.

bias voltage for a GaN diode fitted to tunneling rate dependence on the field strength. The fit is performed under the assumption that the field strength is proportional to the square root of applied voltage, i.e., the tunneling occurs in the high field region. The theoretical W vs E dependence describes the leakage current on reverse-bias well. The estimated density of charged states for this diode is found to be equal to 1.2×10^{13} cm^{-2}.

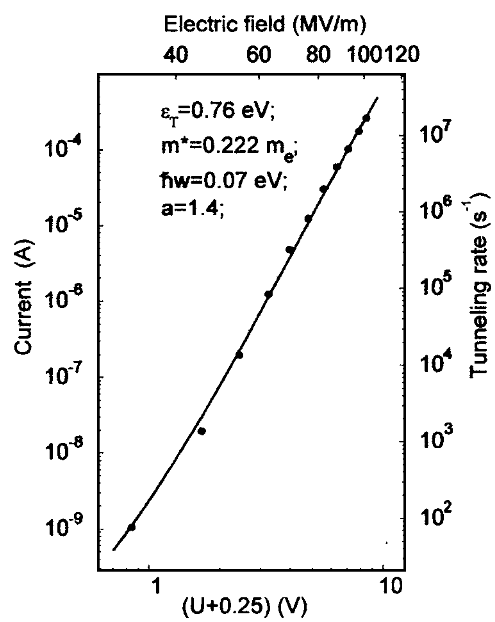

FIG. 3. Reverse I-V_R characteristics of Ni n-GaN Schottky contacts after being annealed at temperature of 700 °C for 5 min from Fig. 2 of Ref. 6 (symbols) fitted to $W(E)$ vs E dependence computed for $a=1.6$, $\varepsilon_T=0.76$ eV, and $T=290$ K.

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In Fig. 3 the reverse-current data for GaN–Ni diode from Ref. 6 fitted to the theoretical $W(E)$ dependence is shown. The fit of I-V data with the theory was performed using for barrier height the value of 0.76 eV extracted from Ref. 6. As can be seen, the theoretical W vs E dependence describes the experimental data also well.

III. CONCLUSION

In conclusion, we have shown that the phonon-assisted tunneling model describes well the peculiarities of reverse-bias current temperature dependence observed in Schottky diodes fabricated on GaN. The comparison of the experimental data with the computed phonon-assisted tunneling rate, performed using basic characteristics of the material, allows us to estimate the field strength at which the free charge carriers are generated, the density of charged states near the interface between metal and semiconductor. In the terms of this model the ambiguity in the value of effective mass, which emerged in Ref. 1, falls away as well. Thus, phonon-assisted tunneling mechanism must be taken into account in explaining the reverse leakage current characteristics for diodes with Schottky barriers.

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[1]E. J. Miller, E. T. Yu, P. Waltereit, and J. S. Speck, Appl. Phys. Lett. **84**, 535 (2004).
[2]E. J. Miller, D. M. Schaadt, E. T. Yu, P. Waltereit, C. Poblenz, and J. S. Speck, Appl. Phys. Lett. **82**, 1293 (2003).
[3]E. J. Miller, D. M. Schaadt, E. T. Yu, X. L. Sun, L. J. Brillson, P. Waltereit, and J. S. Speck, J. Appl. Phys. **94**, 7611 (2003).
[4]E. J. Miller, D. M. Schaadt, E. T. Yu, C. Poblenz, Z. Elsass, and J. S. Speck, J. Appl. Phys. **91**, 9821 (2003).
[5]J. Spradlin, S. Dogan, M. Mikkelson, D. Huang, L. He, D. Johnostone, H. Morkoç, and R. J. Molnar, Appl. Phys. Lett. **82**, 3556 (2003).
[6]G. L. Chen *et al.*, Appl. Phys. Lett. **80**, 595 (2002).
[7]J. W. P. Hsu, M. J. Manfra, R. J. Molnar, B. Heying, and J. S. Speck, Appl. Phys. Lett. **81**, 79 (2002).
[8]A. M. Witowski, K. Pakula, J. M. Baranowski, M. L. Sadowski, and P. Wyder, Appl. Phys. Lett. **75**, 4154 (1999).
[9]P. Pipinys, A. Pipiniene, and A. Rimeika, J. Appl. Phys. **86**, 6875 (1999).
[10]A. Kiveris, Š. Kudžmauskas, and P. Pipinys, Phys. Status Solidi A **37**, 321 (1976).

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