On the reverse leakage current of Schottky contacts on free-standing GaN at high reverse biases

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In this work, a dislocation-related tunneling leakage current model is developed to explain the temperature-dependent reverse current–voltage (I–V–T) characteristics of a Schottky barrier diode fabricated on free-standing GaN substrate for reverse-bias voltages up to −150 V. The model suggests that the reverse leakage current is dominated by the direct tunneling of electrons from Schottky contact metal into a continuum of states associated with conductive dislocations in GaN epilayer. A reverse leakage current ideality factor, which originates from the scattering effect at metal/GaN interface, is introduced into the model. Good agreement between the experimental data and the simulated I–V curves is obtained.

Keywords: homoepitaxial GaN, Schottky contact, leakage current, tunneling, dislocations, ideality factor

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1. Introduction

Schottky contact on GaN is widely used as a fundamental building block of III-nitride-based power and optoelectronic device. However, excessive reverse-bias leakage current through metal/GaN Schottky contact is many orders of magnitude larger than the prediction of the thermionic emission theory,[1–3] even for the device fabricated on high-quality homoepitaxial n-GaN.[4,5] An investigation of the reverse leakage current mechanism is necessary for developing more effective methods to minimize reverse leakage current, especially under high reverse voltages.

By using conductive atomic force microscopy or other relevant characterization techniques, several research groups suggested that dislocations, especially those with a screw component, are the primary leakage path in GaN grown by molecular beam epitaxy,[6] metal-organic chemical vapor deposition,[7,8] and hydride vapor phase epitaxy (HVPE).[9] One of the topics under debate is the electron emission mechanism, namely how electrons overcome metal/GaN Schottky barrier and are injected into the dislocations. Zhang *et al.*[10] propounded that the electron emission mechanism is dominated by tunneling emission at low temperatures and by Frenkel–Poole thermal emission at high temperatures at reverse voltages ranging from 0 V to −8 V. Yet, a fitting electron effective mass of $(3.4\pm0.3)\times10^{-3}m_e$ is derived from their fitting results at low temperatures while the well-accepted experimental electron effective mass is $0.222m_e$,[11] where m_e is the electron mass. In addition, as far as we know, most research has concentrated on the cases at low reverse biases. Obviously, for power devices, it is necessary to study the reverse leakage mechanism at high reverse bias voltages.

In our previous work,[5] we proposed a dislocation-related tunneling model to explain the reverse leakage mechanism at reverse bias voltages up to −20 V for a vertical Schottky barrier diode (SBD) on GaN homoepilayer. The model suggests that the leakage current through GaN Schottky contact is caused by electrons from the Schottky contact metal tunneling into a continuum of states associated with conductive dislocations in the Schottky barrier and then moving along the conductive dislocations.[5] In this work, the model is modified by introducing a reverse current ideality factor to explain the reverse leakage mechanism of Pt/n-GaN Schottky contact fabricated on free-standing GaN substrate for reverse-bias voltages up to −150 V at temperatures between 300 K and 450 K.

2. Experimental data and theoretical model

Figure 1 shows the semi-log plot of experimental reverse I–V–T characteristics of the vertical SBD with 300 μm in circular Pt Schottky contact diameter for reverse bias voltages up to −150 V published in Ref. [4]. The inset of Fig. 1 illustrates the schematic of the vertical SBD used in measurement. The vertical SBDs are fabricated on an n-GaN bulk substrate with a thickness of 447 μm synthesized by the HVPE technique. More details about material and device can be found in Ref. [4].

According to the dislocation-related tunneling model (as shown in Fig. 2), the total leakage current through a metal/n-GaN Schottky contact can be given by[5]

$$I_r = \frac{A_D A^* T}{k} \int_{-q(V_r - V_b)}^{q\Phi_D} \frac{1}{1+\exp\left(\frac{E}{kT}\right)}$$

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$$\times \exp\left[-\frac{4}{3}\frac{\sqrt{2m^*}}{q\hbar}\frac{(q\Phi_{\rm D}-E)^{3/2}}{\xi}\right] {\rm d}E, \qquad (1)$$

where the effective leakage area of dislocations $A_{\rm D} = AN_{\rm DD}\pi\lambda_{\rm D}^2$, the Debye length $\lambda_{\rm D}$ is defined as the effective radius of leakage area of each dislocation, A is the Schottky contact area, $N_{\rm DD}$ is the dislocation density, A^* is the effective Richardson constant, T is the temperature, k is the Boltzmann constant, $V_{\rm b}$ is the built-in potential at zero bias, $V_{\rm r}$ is the reverse bias voltage, q is fundamental electronic charge, $q\Phi_{\rm D}$ is the effective Schottky barrier height of dislocations, E is the energy of electron, m^* is the electron effective mass, $\hbar$ is the reduced Planck constant, and ξ is the uniform electric field over the triangular Schottky barrier.

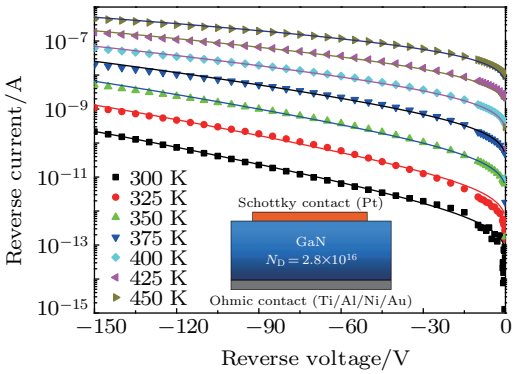


Fig. 1. (color online) Simulated reverse I–V curves (solid line) along with the experimental curves (symbol line) at temperatures ranging from 300 K to 450 K. The inset shows the schematic diagram of the Schottky barrier diode fabricated on n-bulk GaN substrate.

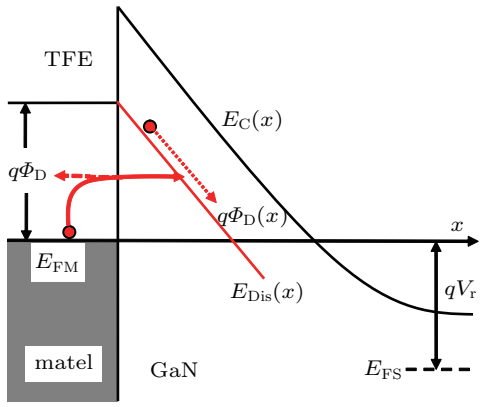


Fig. 2. (color online) Energy band diagram showing the suggested dislocation-related tunneling model.

However, the model mentioned above cannot fit the experimental reverse I–V–T curves shown in Fig. 1, especially at high bias voltages (not shown here). After trials, we find that in order to reproduce the experimental curves, the model should be modified by introducing a parameter α into formula (1). Then the total leakage current can be expressed as

$$I_{\rm r} = \frac{A_{\rm D}A^*T}{k}\int_{-q(V_{\rm r}-V_{\rm b})}^{q\Phi_{\rm D}} \frac{1}{1+\exp\left(\dfrac{E}{kT}\right)}$$

$$\times \exp\left\{\alpha\left[-\frac{4}{3}\frac{\sqrt{2m^*}}{q\hbar}\frac{(q\Phi_{\rm D}-E)^{3/2}}{\xi}\right]\right\} {\rm d}E. \qquad (2)$$

The role of α is similar to the ideality factor for forward current. Thus, α is named the reverse current ideality factor. In the following, we will fit the experimental I–V–T curves by using Eq. (2) and discuss the physics meaning of α.

3. Results and discussion

The vertical SBD measured has a Schottky barrier height of 1.1 eV, and an n-type unintentional doping concentration $N_{\rm D}$ of 2.8×10^{16} cm^{-3}.[4] The effective Richardson's constant A^* extracted from the saturation current is 6.18 A·cm^{-2}·K^{-2}.[4] The dislocation density $N_{\rm DD}$ was not reported in Ref. [4]. By referring to Refs. [5] and [12], a value of $\sim 5\times10^6$ cm^{-2} is assigned to $N_{\rm DD}$ in our simulations. According to Eq. (2), the effective leakage area of dislocations $A_{\rm D}$ is unrelated to the shape of the simulation curves, so a certain deviation of $A_{\rm D}$ from the actual value would not invalidate the simulation results. Thus, the value of $N_{\rm DD}$ assumed in the simulations is reasonable and acceptable.

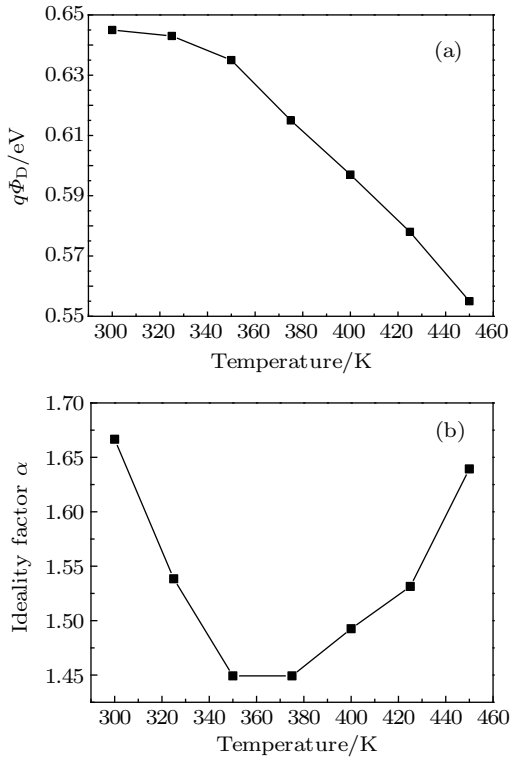


Fig. 3. Fitted dislocation-related effective local barrier height $q\Phi_{\rm D}$ (a) and the reverse current ideality factor α (b) as a function of temperature.

By taking $q\Phi_{\rm D}$ and α as fitting parameters, we use Eq. (2) to fit the experimental reverse I–V–T curves shown in Fig. 1. Good agreement between the measured and simulated curves indicates the applicability of the modified leakage current model. The fitting values of $q\Phi_{\rm D}$ and α are shown in Fig. 3. At temperatures above approximately 360 K, $q\Phi_{\rm D}$ decreases linearly with a bandgap-shrinkage-induced average negative temperature coefficient of -8.0×10^{-4} eV/K which agrees well

with that of -8.9×10^{-4} eV/K obtained in Ref. [5] as shown in Fig. 3(a). At temperatures below approximately 360 K, the nonlinear decrease in $q\Phi_{\rm D}$ below 360 K (It should be noted that this phenomenon was not observed in Ref. [4].) may indicate the presence of additional tunneling mechanism, such as trap-assisted tunneling,[3,13] for the devices used for measurement.

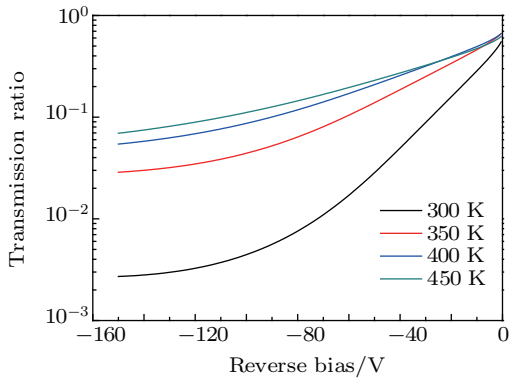


Fig. 4. (color online) Ratios of $I_{\rm r}$ simulated using Eq. (1) to that simulated using Eq. (2) at 300 K, 350 K, 400 K, 450 K for reverse bias voltages up to −150 V.

As shown in Fig. 3(b), all the values of α at temperatures between 300 K and 450 K are larger than 1. Figure 4 shows the ratios of $I_{\rm r}$ simulated by using Eq. (1) to that simulated by using Eq. (2) at 300 K, 350 K, 400 K, 450 K for reverse bias voltages up to −150 V. The results mean that only part of the tunneling electrons predicted by Eq. (1) can transmit into GaN. The transmission ratio is dependent on the temperature and reverse bias. As is well known, the leakage current is highly interface-sensitive because the leakage current can be significantly suppressed by surface treatment[14] and annealing[15,16] processes. So transmission ratio should be related to the property of Metal/GaN interface. Theoretically, the interruption of lattice periodicity at the interface will lead to carrier scattering. Many research studies also show that there are strong carrier scatterings at the heterojunction interface in carrier transport.[17] Thus, we think that most of the electrons are scattered back to the metal at the interface of metal/GaN before they tunnel into GaN epilayer as shown in Fig. 2. The interface scattering mechanisms are complex and not clear for M/GaN. Furthermore, the scattering effect cannot be modeled into the one-dimensional band energy model shown in Fig. 2. Thus, it can only be modeled phenomenologically as the reverse current ideality factor α in Eq. (2).

4. Conclusions

We developed a modified dislocation-related tunneling model by introducing a reverse leakage current ideality factor to explain the reverse leakage current mechanism in Schottky contact fabricated on the bulk GaN substrate up to −150 V. The ideality factor originates from the carrier scattering effect at metal/GaN interface. Good agreement between the experimental data and the simulated *I*–*V* curves is obtained.

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