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Leakage mechanism in GaN and AlGaN Schottky interfaces

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Based on detailed temperature-dependent current–voltage ($I-V-T$) measurements the mechanism of leakage currents through GaN and AlGaN Schottky interfaces is discussed. The experiments were compared to calculations based on thin surface barrier model in which the effects of surface defects were taken into account. Our simulation method reproduced the experimental $I-V-T$ characteristics of the GaN and AlGaN Schottky diodes, and gave excellent fitting results to the reported Schottky $I-V$ curves in GaN for both forward and reverse biases at different temperatures. The present results indicate that the barrier thinning caused by unintentional surface-defect donors enhances the tunneling transport processes, leading to large leakage currents through GaN and AlGaN Schottky interfaces. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1762980]

Although significant progress has been achieved in GaN-based high-power/high-frequency electronic devices and ultraviolet photodetectors, surface-related problems still need an immediate solution. In particular, leakage currents through Schottky contacts not only impede device reliability but also degrade power efficiency and noise performance in such devices. In spite of the fact that Schottky diodes formed on GaN and AlGaN are suffering from excess reverse leakage currents that are many orders of magnitude larger than the prediction of the thermionic emission (TE) model,[1–6] only a few studies have focused on the reverse-current characteristics quantitatively.

Yu *et al.*[7] and Miller *et al.*[8] discussed the leakage mechanism in GaN and AlGaN Schottky interfaces on the basis of the field-emission (FE) tunneling transport assuming a triangular Schottky potential. However, unreasonably higher donor densities than the actual doping concentration were required in their calculation for reproduction of the experimental data. Thus, they expected some other processes such as defect-assisted tunneling to enhance leakage currents. Other groups also suggested the trap-assisted tunneling model to explain the leakage mechanism in the reverse bias region.[2,9] However, such model requires an unlikely multistep tunneling process or defect continuum with a wide energy band throughout a depletion region in semiconductor. Sawada *et al.*[10] proposed a surface patch model to explain forward current characteristics. Miller *et al.*[11] have recently suggested a leakage mechanism associated with a variable-range-hopping conduction through threading dislocations. However, little is known for the physical mechanism of excess leakage currents in GaN and AlGaN Schottky diodes.

This letter discusses the mechanism of leakage currents through GaN Schottky interfaces, investigating transport properties of Schottky diodes using temperature-dependent current–voltage ($I-V-T$) measurements for both forward and reverse biases. A simulation method for the calculation of currents based on the thin surface barrier (TSB) model[5] is discussed. The measured currents were compared to the calculated ones for different temperatures and voltages to ensure that the model described the entire data set.

The TSB model proposed by Hasegawa and Oyama[5] is shown in Fig. 1. This model assumes the unintentional introduction of high density of defect donors near GaN or AlGaN surfaces, reducing the width of the Schottky barrier in such a way that electrons can tunnel though this barrier in both forward and reverse directions by the thermionic field-emission (TFE) or the FE mechanism depending on the temperature. We have recently found that various kinds of device processings could cause serious nitrogen deficiency at GaN and AlGaN surfaces, resulting in the formation of a localized deep donor level related to N vacancy (V_N).[12,13] Thus, V_N or its complex was considered to be the most possible candidate for the surface defect donor.

The current, J, from semiconductor to metal through the Schottky barrier can be expressed by the following general expression:

$$J=\frac{4\pi q m^*}{h^3}\int_0^\infty T(E_x)\int_0^\infty [f_s(E_p+E_x) - f_m(E_p+E_x)]dE_p dE_x, \qquad (1)$$

where m^* is the effective mass, h is the Plank constant, $T(E_x)$ is the tunneling probability, E_x and E_p are the energy components normal and parallel to the Schottky barrier, respectively, and $f_s(E)$ and $f_m(E)$ are the Fermi-Dirac distribution functions for semiconductor and metal, respectively. Here, it is assumed that the wave numbers parallel to the barrier are conserved during tunneling. $T\ (E_x)$ was calculated using Wentzel–Kramers–Brillouin approximation:

$$T(E_x)=\exp\left[-2\frac{\sqrt{2m^*}}{\hbar}\int_{x_1}^{x_2}\sqrt{\phi(x)-E_x}dx\right], \qquad (2)$$

where $\phi(x)$ is the potential distribution and x_1 and x_2 are classical turning points. Since $T(E)$ is an exponentially increasing function and $f(E)$ is an exponentially decreasing function with E, the integrand in Eq. (1) forms a Gaussian peak for tunneling, E_m, at a certain energy whose energy position is temperature dependent, as shown in Fig. 1, lead-

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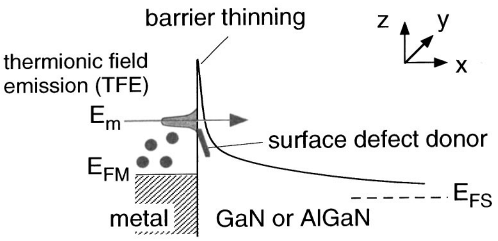

FIG. 1. Thin surface barrier (TSB) model.

ing to the TFE process. Equation (1) also contains the TE transport component. We first calculated the potential profile of the Schottky interface by solving the Poisson equation self-consistently, taking into account the surface defect donor with an arbitrary spatial distribution in density. Then the currents through the Schottky interface were calculated using Eqs. (1) and (2) for both forward and reverse bias voltages at different temperatures. Thus the present method is applicable to any Schottky interface with arbitrary potential shapes.

A typical example of the measured $I-V-T$ characteristics for the Ni/n-GaN Schottky diodes is shown in Fig. 2. We used the Si-doped n-GaN layers (2 μm) grown on sapphire substrates by metalorganic vapor phase epitaxy. The doping concentration of the epitaxial layer was 1.0×10^{17} cm^{-3}. A typical value of electron mobility at room temperature was 500 $\mathrm{cm}^2/\mathrm{V\,s}$. A ring shaped ohmic contact was formed by standard photolithography on the GaN surface, using a Ti/Al/Ti/Au alloy which was annealed at 600 °C for 2 min. Schottky contact dots with a diameter of 200–600 μm were formed at the center of the ohmic ring by a conventional electron-beam deposition.

If we pay attention only to the forward current at room temperature (RT), as shown in Fig. 2, the $I-V$ behavior apparently follows the simple TE or TFE transport model. In the reverse bias region, however, an excess leakage current flows even at RT. Moreover, less temperature dependence of $I-V$ curves was observed even at the forward bias voltages. These characteristics showed a large deviation from the prediction by a simple TFE model[14] using the actual doping density, as indicated by the broken lines in Fig. 2.

We have applied the numerical simulation method presented here to fit the experimental data. We found that the distribution shape and the energy depth of surface donors change theoretical $I-V$ characteristics very sensitively. After many trials, we obtained the best fitting result for the Ni/GaN Schottky diode, as indicated by the solid lines in Fig. 2. It is noted that series resistances were considered in the calculation.

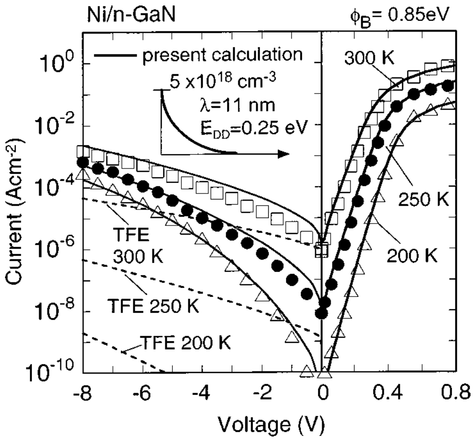

FIG. 2. $I-V-T$ characteristics of the Ni/n-GaN diode. The solid and the broken lines represent the calculated results by the present method and TFE model, respectively.

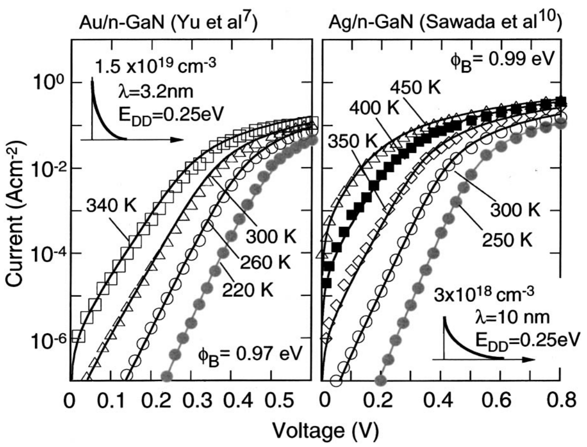

FIG. 3. Forward $I-V-T$ curves reported by Yu *et al.* and Sawada *et al.* The solid lines indicate our calculation results.

To achieve such good fitting for both forward and reverse directions simultaneously, we found that defect donors should have specific features. Namely, the experimental data could be reproduced only by assuming that the defect donor is a deep donor with an exponentially decaying spatial distribution shown in the inset of Fig. 2. The energy depth from the bottom of the conduction band, E_{DD}, should be between 0.2 and 0.3 eV. We have recently reported that various kinds of device processings could cause the formation of a localized deep donor level related to V_{N} at GaN and AlGaN surfaces.[12,13] Neugebauer and Van de Walle[15] have calculated energy levels of native point defects in GaN, and concluded that the simple V_{N} defect acts as a shallow donor. On the other hand, the calculation by Yamaguchi and Junnarkar[16] predicted that the V_{N} defect can form an s-like deep donor. Thus, these suggest a possibility that V_{N}-related defects may act as donor-type deep levels.

The $I-V-T$ characteristics of the Ni/n-$\mathrm{Al_{0.26}Ga_{0.74}N}$ diode[12] were similarly analyzed by applying the present simulation method. We found that the temperature dependence of $I-V$ curves was surprisingly small and that reverse leakage currents were anomalously large, as compared to the GaN Schottky diodes. Our calculation could reproduce such experimental forward and reverse $I-V-T$ behavior almost completely. The result indicated the existence of the defect donor at the AlGaN surface with a density of 1×10^{13} cm^{-2} or higher, causing seriously excess gate leakage in AlGaN/GaN heterostructure field effect transistors (HFETs).[6] The energy depth was found to be 0.37 eV, which was deeper than GaN. This value is consistent with that obtained from the current transient measurement in AlGaN/GaN HFETs.[12]

We also attempted to fit the experimental $I-V$ data of GaN Schottky diodes from other groups. Figure 3 shows forward $I-V-T$ curves of Ni/n-GaN and Ag/n-GaN diodes reported by Yu *et al.*[7] and Sawada *et al.*,[10] respectively. Also shown are the calculation results by the present simulation.

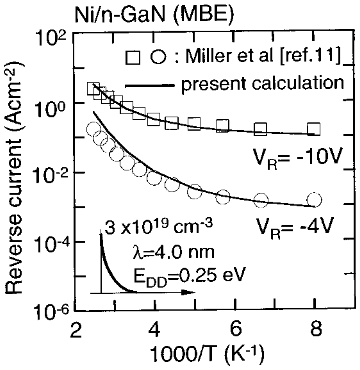

FIG. 4. The temperature-dependent reverse leakage currents of the Ni/n-GaN diodes (Ref. 11) and our fitting results.

Again, our simulation completely reproduced the corresponding forward $I-V-T$ curves, using the exponentially decaying density distribution and the same energy depth of 0.25 eV for the surface defect donor. This indicated that both samples included large amounts of surface defect donors at GaN surfaces. In fact, Yu *et al.*[7] expected the enhancement of tunneling components due to the large amount of defects in GaN.

Very recently, Miller *et al.*[11] have reported temperature dependence of the reverse-bias current for the Ni Schottky contact fabricated on n-GaN grown by molecular beam epitaxy. From the deviation between the experimental data and the calculation based on the simple FE tunneling at temperatures above 250 K, they proposed two possible transport processes: a trap-assisted tunneling transport or a variable-range-hopping conduction through threading dislocations. Without assuming such complicated processes, however, the present simulation method can quantitatively explain the reverse-leakage behavior for entire temperatures, as shown in Fig. 4. In this case, a high density of the defect donors with a decaying depth of 4 nm could be introduced at the GaN surface. The calculation of tunneling electron distributions at different temperatures showed that the peak position of Gaussian beam (E_m) shifted to higher energies with temperatures, due to a broadening of the Fermi–Dirac distribution. This leads to a high tunneling probability at relatively higher energies, and enhances the TFE transport. Thus, our calculation clearly showed that the TFE transport through the thin surface barrier is dominant in the current-leakage mechanism at temperatures above 250 K, showing the temperature dependence of leakage current.

In summary, the experimental $I-V-T$ characteristics of the GaN and AlGaN Schottky diodes were compared to the calculations based on the TSB model in which the effects of surface defects were taken into account. The present simulation method reproduced our experimental $I-V-T$ characteristics as well as the reported $I-V$ curves in GaN for both forward and reverse biases at different temperatures. The enhancement of tunneling transport processes by the barrier thinning due to the processing-induced surface-defect donors seems to be the dominant mechanism associated with large leakage currents through GaN and AlGaN Schottky interfaces.

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