Application of the thermionic field emission model in the study of a Schottky barrier of Ni on *p*-GaN from current–voltage measurements

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Barrier height values of Ni contacts to Mg-doped *p*-type GaN (*p*-GaN) were obtained from current–voltage measurements in this study. The induced deep level defect band through high Mg doping led to a reduction of the depletion layer width in the *p*-GaN near the interface and an increase in the probability of thermionic field emission. It also resulted in an increase in current flow under forward bias condition, which was not analyzed using the thermionic emission model. Further, the calculated barrier height value of Ni contacts to *p*-GaN using the thermionic field emission model is in good agreement with the value of 1.9 eV obtained from x-ray photoelectron spectroscopy measurements. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1890476]

GaN has a 3.4 eV direct gap at room temperature and has attracted a lot of interest because of its application to optical devices in the short-wavelength region. Other devices that have been demonstrated so far include ultraviolet Schottky barrier photodetectors, solar-blind Schottky photodiodes, metal–semiconductor field effect transistors, and high electron mobility transistors.[1–4] High-quality ohmic and Schottky contacts are required for the improvement of these devices. Since the sum of the barrier height of the *n* and *p* types equals the band gap 3.4 eV, a high barrier height is expected after the metals have been deposited on the *p*-GaN.[5] Recent reviews and studies of Schottky contact properties on *p*-GaN have been published.[6–11] Some reported values for barrier height for different metals are 0.49–0.50 eV for Pt,[6,8] 0.57 eV for Au,[6] 0.65 eV for Ti,[6] and 1.3 eV for Pd.[9] For Ni there is a fairly large discrepancy in reported values, ranging from 0.49 to 2.87 eV.[6,7,10,11] Consequently, the mechanism of current flow through the interface has not been established and the exact value of the barrier height has not yet been estimated using the current–voltage ($I-V$) measurement. The observed barrier height value from capacitance–voltage ($C-V$) measurements has been reported.[7] However, Yu *et al.*[7] did not obtain the barrier height value from the $I-V$ measurements. In this study, the barrier height value of the Ni/*p*-GaN samples was first successfully obtained from the $I-V$ measurements. Further, the calculated barrier height value of Ni contacts to *p*-GaN using the thermionic field emission (TFE) model is in good agreement with the value of 1.9 eV obtained from x-ray photoelectron spectroscopy (XPS) measurements.

The epitaxial layers used in the experiments were grown on *c*-plane sapphire substrates using a metalorganic chemical vapor deposition system. Trimethylgallium, ammonia, and bis-cyclopentadienylmagnesium were used as the Ga, N, and Mg sources, respectively. An undoped GaN buffer layer with a thickness of 650 nm was grown on the sapphire substrate at 520 °C, followed by the growth of a Mg-doped *p*-GaN layer (762 nm) at 1100 °C. Mg concentration ([Mg]) was $\sim 6 \times 10^{19}$ cm^{-3} for all samples. The grown samples were annealed for the purpose of generating holes at 750 °C for 30 min in N_2 ambient. According to the Van der Pauw-Hall measurements, we calculated the hole concentration to be 3.6×10^{17} cm^{-3}. The samples were cleaned in chemical clean solutions of trichloroethylene, acetone, and methanol. Planar-type Schottky contacts were formed by electron-beam evaporation. Using the lift-off technique, Ni/Au (5 nm/5 nm) ohmic contacts were deposited and annealed at 500 °C in air ambient for 10 min. The fabricated process of ohmic contacts combined with the low specific contact resistance has been previously reported.[12] Good ohmic contacts help to obtain the actual Schottky characteristics from $I-V$ measurements. Then, Ni (5 nm) Schottky contact with circular patterns (200 μm in diameter) was directly deposited. The Schottky diodes were measured by the $I-V$ method using a Keithley Model-4200-SCS/F semiconductor characterization system at 300, 350 and 400 K, respectively.

Figure 1 shows the typical semilog current density–voltage ($J-V$) characteristics of Ni/*p*-GaN Schottky diodes at 300 K. The fitting curve using the TFE model is also shown in Fig. 1. Yu *et al.*[7] indicated that the slope of ln $I-V$ curves could not be analyzed using the thermionic emission (TE) model, due to the carrier transport with a tunnel component. In addition, these reports[13,14] provide theoretical analysis of current tunneling through a Schottky barrier ($q\phi_B$). The $J-V$ characteristic in the presence of tunneling can be described by the relation[13,14]

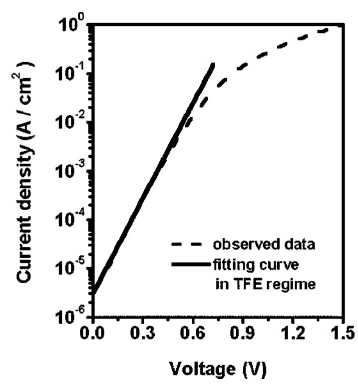

FIG. 1. $J-V$ curve of Ni/*p*-GaN Schottky diodes under forward bias condition at 300 K and the fitting curve to the $J-V$ characteristic in the TFE regime.

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$$J = J_0 \exp(qV/E_0), \tag{1}$$

$$E_0 = E_{00} \coth(E_{00}/kT), \tag{2}$$

$$J_0 = \frac{A^* T[\pi E_{00} q(\phi_B - V - \xi)]^{0.5}}{k \cosh(E_{00}/kT)} \exp\left[- \frac{q\xi}{kT} - \frac{q}{E_0}(\phi_B - \xi) \right], \tag{3}$$

$$E_{00} = (qh/4\pi)(N/m^* \varepsilon)^{0.5}, \tag{4}$$

where J is the observed current density of Schottky diodes under forward bias condition, m^* ($m^* = 0.6 m_0$, m_0 is the mass of hole at rest)[15] is the hole effective mass, ε ($\varepsilon = 9.5\varepsilon_0$, ε_0 is the permittivity in vacuum)[16] is the dielectric constant of GaN, A^* ($A^* = 103.8$ A/cm^2 K^2)[17] is the effective Richardson constant of p-GaN, h is Planck's constant, V is voltage, q is the electron charge, N is the doping concentration, and ξ is equal to $(E_F - E_V)/q$. E_V is the valence band maximum and E_F is the position of the Fermi level. ξ was assumed to be equal to 0.1 V in this study. According to the fitting J versus V curve of samples using Eqs. (1)–(3), the value of E_0, E_{00}, and $q\phi_B$ can be calculated to be 66 meV, 65 meV, and 1.8 eV, respectively. Then, the calculated value ($\sim 7 \times 10^{19}$ cm^{-3}) of N using Eq. (4) is similar to [Mg], which indicated that the tunneling current under forward bias conditions took place because of the high Mg doping [or the deep level defect (DLD) band induced by high Mg doping].[18,19] Kwak *et al.*[18] have suggested that the current transport at the metal/high Mg doped p-GaN interface was dominated by a DLD band which was induced by high Mg doping. Kwak *et al.*[19] have also suggested that the DLD band had a large density defect, over 10^{19} cm^{-3} size, existing in the p-GaN films and that the density of the DLDs increased as [Mg] increased. In addition, Shiojima *et al.*[20] have found carrier capture and emission from acceptor-like DLDs for Ni/p-GaN Schottky diodes. Further, it is worth noting that the calculated value of E_{00}/kT is slightly larger than 1, which implies the current transport processes a tunnel component.[14] On the other hand, the observed current is too small to obtain the fitting parameters for the J–V characteristic in the field emission (FE) regime for Ni/p-GaN. This suggests that the FE model cannot be used to study the $q\phi_B$ of Ni/p-GaN in this case. In addition, the E_{00} of 65 meV is not much greater than kT ($kT = 26$ meV, at 300 K), so the FE will not take place.[13] The effective resistance of the Schottky barrier in the FE regime is quite low, so the FE model is often used for ohmic contact.[13]

Figure 2 shows the typical semilog J–V characteristics of Ni/p-GaN Schottky diodes at 350 and 400 K, respectively. The fitting curves using the TFE model are also shown in Fig. 2. We find that the barrier heights can readily be obtained by fitting the J–V curves using Eqs. (1)–(3). From the TFE theory, a linear fit to the data for the J–V measurements at 350 K yields $E_0 = 67$ meV and $q\phi_B = 1.8$ eV, whereas a linear fit to the data for the J–V measurements at 400 K yields $E_0 = 68$ meV and $q\phi_B = 1.8$ eV. Both values for the Schottky barrier height are in good agreement with the value calculated for J–V measurements at 300 K. These results indicate that a TFE model can quantitatively explain the observed large forward leakage currents due to the existence of the induced high density of the acceptor-type DLDs by high Mg doping. We conclude that the creation of a large number of DLDs in p-GaN leads to the reduction of the depletion layer width in the p-GaN near the interface, an increase in the probability of the TFE, and gives rise to large forward leakage. Consequently, the forward current transport with a tunnel component is not analyzed using the TE model.

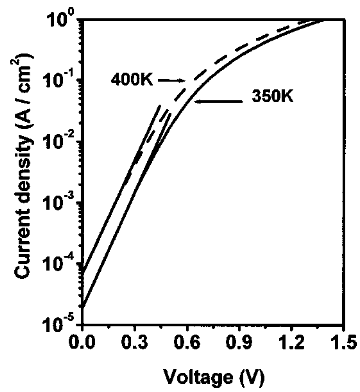

FIG. 2. Forward J–V characteristic of Ni/p-GaN Schottky diodes as a function of temperature.

In order to further confirm whether the barrier-height value of Ni/p-GaN Schottky diodes is 1.8 eV or not, XPS is used to study the surface Fermi level position within the band gap for Ni overlayer on p-GaN. XPS measurements were performed using a monochromatic Al K_α x-ray source. The barrier height was determined from the XPS data using the following relation.[21,22] This equation was previously employed by Tracy *et al.*[23] for the calculation of the barrier heights ($q\phi_n$) of metals on n-GaN:

$$q\phi_n = E_G - E^i v + (E^i_{\text{core}} - E^m_{\text{core}}) = E_G - (E^m_{\text{core}} - E_{VC}) \tag{5}$$

E_G is the band gap of the semiconductor, E^m_{core} is the binding energy of the semiconductor core-level peak following metal deposition, E^i_{core} is the initial binding energy of the core-level peak, E^i_V is the initial binding energy of the E_V of the semiconductor, and E_{VC} is equal to $(E^i_{\text{core}} - E^i_V)$. All binding energies are measured relative to the E_F. For the calculation of the barrier heights ($q\phi_p$) of Ni/p-GaN, the equation is expressed as

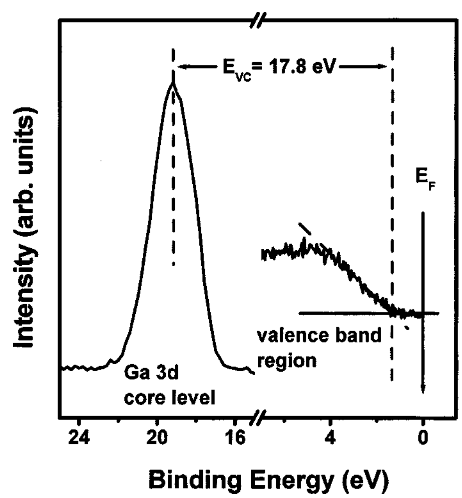

FIG. 3. The left-hand spectrum shows the Ga 3d core-level peak on p-GaN without a Ni overlayer. The right-hand panel presents the spectrum of the valence-band region. A linear fit is used to determine the energy of the valence-band edge.

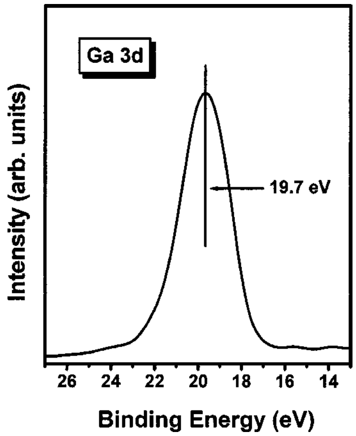

FIG. 4. Ga 3*d* core level at the Ni/*p*-GaN interface. The binding energy is referenced to the Fermi level.

$$q\phi_p = E_{\mathrm{core}}^{\mathrm{Ni}} - E_{VC} \qquad (6)$$

where $E_{\mathrm{core}}^{\mathrm{Ni}}$ is the binding energy of the *p*-GaN core-level peak following Ni deposition.

Figure 3 shows an example of the Ga 3*d* core level and the valence-band spectrum collected on a *p*-GaN sample without a Ni overlayer. The E_{VC} is calculated to be 17.8 eV. This value is in good agreement with the value of 17.8 eV reported by Hashizume *et al.*,[24] Bermudez,[25] Waldrop and Grant,[26] and Wu and Kahn.[27] Figure 4 shows the Ga 3*d* core level at the Ni/*p*-GaN interface. The spectra determine the Ga 3*d* binding energy $E_{\mathrm{core}}^{\mathrm{Ni}}$ relative to the E_F. In Fig. 4, we can see that the $E_{\mathrm{core}}^{\mathrm{Ni}}$ is equal to 19.7 eV. Therefore, the $q\phi_p$ was calculated to be 1.9 eV, according to Eq. (6). This value is similar to the value of 1.8 eV obtained from *J*–*V* measurements. In addition, Rickert *et al.*[28] suggested that the barrier height value of the Ni/*p*-GaN sample is approximately 1.9 eV, which supported our observed results from the XPS and *J*–*V* measurements.

In summary, the barrier height value of Ni/*p*-GaN Schottky diodes was obtained from *J*–*V* measurements in this study. For Ni/*p*-GaN Schottky diodes, the calculated barrier height value using the TFE model is in good agreement with the value of 1.9 eV obtained from x-ray photoelectron spectroscopy measurements. The induced DLD band through high Mg doping would lead to the reduction of the depletion layer width in the *p*-GaN near the interface, an increase in the probability of the TFE, and an increase in current flow under forward bias conditions, which was not analyzed using the TE model.

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