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Forward Current Transport Mechanism and Schottky Barrier Characteristics of a Ni/Au Contact on n-GaN *

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The forward current transport mechanism and Schottky barrier characteristics of a Ni/Au contact on n-GaN are studied by using temperature-dependent current-voltage (T–I–V) and capacitance-voltage (C–V) measurements. The low-forward-bias I–V curve of the Schottky junction is found to be dominated by trap-assisted tunneling below 400 K, and thus can not be used to deduce the Schottky barrier height (SBH) based on the thermionic emission (TE) model. On the other hand, TE transport mechanism dominates the high-forward-bias region and a modified I–V method is adopted to deduce the effective barrier height. It is found that the estimated SBH (∼0.95 eV at 300 K) by the I–V method is ∼0.20 eV lower than that obtained by the C–V method, which is explained by a barrier inhomogeneity model over the Schottky contact area.

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Ⅲ-nitride semiconductors outperform Si for fabrication of electronic devices capable of operating at high power density, in an elevated temperature environment, and at a high frequency range, due to their excellent physical properties such as wide bandgap, large critical breakdown electrical field, and high electron saturation velocity.[1] As intricate parts of many important Ⅲ-nitride opto-electronic devices, such as GaN-based light-emitting diodes, avalanche photodiodes, and high electron mobility transistors, the quality of the (Al)GaN Shottky contact is very critical for these devices' whole performance.[2–5] Unfortunately, there exist high-density defect states within the GaN epi-structure, resulted from heteroepitaxy growth. The GaN-based Schottky contact often suffers from relatively high leakage current than the theoretical predication based on the thermionic emission (TE) model, which severely degrades the reliability of the associated devices.[6,7] It should be noted that many past studies on leakage current of GaN Schottky contacts mainly dealt with leakage current at reverse bias conditions, while leakage current under forward bias was less studied, which is nevertheless equally important and should be considerably reduced. Actually in mass production process of semiconductor devices, low-forward-bias leakage current is an important parameter measured and evaluated when sorting. In this work, we investigate the forward current transport mechanism and Schottky barrier height (SBH) of Ni/n-GaN Schottky diodes grown on sapphire substrates by using temperature-dependent current-voltage (T–I–V) and capacitance-voltage (C–V) measurements. The low-forward-bias I–V curves show significant trap-assisted tunneling characteristics at temperatures below 400 K, making the traditional I–V method based on the TE model unsuitable for SBH extraction. On the other hand, based on TE dominant high-forward-bias region, the SBH is deduced by a modified I–V method, which is considerably lower than that obtained by the C–V method. This difference is explained by a barrier inhomogeneity model at the metal/semiconductor interface.

Figure 1(a) shows the cross-sectional schematic diagram of the fabricated Ni/Au/n-GaN Schottky diodes. The GaN epi-layers (∼3 μm) used were grown on c-plane sapphire substrates by the metal organic chemical vapor deposition (MOCVD) method. The dopant density N_d determined by C–V measurement is $\sim 2.5 \times 10^{17}\,\mathrm{cm}^{-3}$, consistent well with the epilayer design. The dislocation density measured by using the cathodoluminescence mapping technique is about $1 \times 10^{9}\,\mathrm{cm}^{-2}$ in average. Before fabrication of the Ohmic contact, the wafer surface was cleaned sequentially in trichloroethylene, acetone, and de-ionized water, followed by a dip in a HCl:H_2O solution for about 10 s. Optical lithography and lift-off technique were employed to pattern the electrode contact regions, where large area Ti/Al/Ti/Au (30/120/50/100 nm)

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and Ni/Au (50/300 nm) metal stacks with a series of sizes were deposited by e-beam deposition as Ohmic and Schottky contact electrodes, respectively. To form the Ohmic contact, the samples were immediately annealed using rapid thermal annealing in an N_2 environment at 800℃ for 1 min after deposition of Ti/Al/Ti/Au layers. The exposed GaN surface was finally covered by a 200 nm SiO_2 passivation layer deposited by plasma-enhanced chemical vapor deposition. Figure 1(b) shows the top view image of the fabricated sample, where the black dots are the SiO_2-uncovered Ohmic region retained for electrical probing. The devices studied in this work consist of 110 μm circular Schottky contact separated radially by 20 μm from the Ohmic contact.

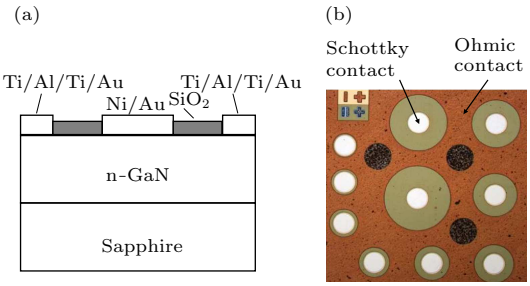


Fig. 1. (a) Schematic diagram of the Ni/Au/n-GaN Schottky diode; (b) top view of the fabricated diodes.

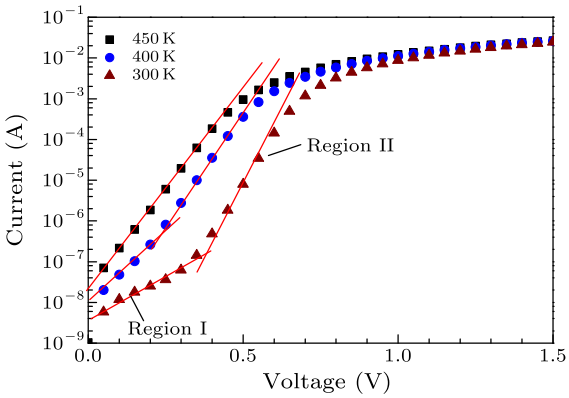


Fig. 2. The temperature dependence of the I–V characteristics of the diode under forward bias conditions. For 300 K, the ideality factor n_1(region I) = 4.56, n_2(region II) = 1.20. For 400 K, $n_1 = 1.769$, $n_2 = 1.16$. For 450 K, $n_1 = 1.12$, $n_2 = 1.12$.

Figure 2 shows the experimental forward I–V curves of the Ni/n-GaN Schottky barrier diodes measured at different temperatures and plotted in a semi-log scale. Depending on bias levels, two successive linearly dependent segments with different slopes can be observed from the I–V curves measured at 300 K and 400 K, which are defined as the low-bias (I) and medium-bias (II) regions, respectively. Conventionally, the I–V characteristics of a Schottky diode can be described by[8]

$$I = AA^*T^2 \exp\Big(-\frac{\phi_b}{kT}\Big) \exp\Big(\frac{q(V-IR)}{nkT}\Big), \qquad (1)$$

where A^* ($\sim$32 A·cm^{-2}K^{-2}) is the Richardson constant,[9] k is the Boltzmann constant, R is the series resistance, A is the area of diode, ϕ_b is the Schottky barrier height, and $n \equiv (q/k)\partial V/\partial \ln(J)$ is the ideality factor. According to the value of factor n, the current transport mechanism can be judged as follows: if $n = 1$, the current flow is mainly the TE current; while if $n > 1$, the tunneling or recombination current component should be involved. Figure 2 gives the deduced values of factor n at various temperatures, where the subscripts 1 and 2 refer to the low-bias and medium-bias regions, respectively. As can be seen, when the temperature decreases from 450 K to 300 K, n_1 increases from 1.12 to 4.56 while n_2 ($\sim$1) is almost unchanged. The recombination current component can be negligible due to the small injection of minority carrier into barrier region and the light doping density $\sim 2.5 \times 10^{17}$ cm^{-3} in the GaN layer.[10] Thus, below 400 K, the current component in region I should be dominated by tunneling current flow, and the current in region II should be TE current flow. At higher temperatures, the current slopes at low- and medium-bias regions become equal due to enhanced thermionic current component. At higher current level above 0.1 mA, the I–V behaviors of the diodes are influenced by the increasing voltage drop on the series resistance of the diode.

According to the classic theory, tunneling becomes significant only in the heavily doped semiconductor case for an "ideal" trap-free Schottky diode, and its contribution with respect to TE can be judged by comparing the thermal energy kT to E_{00}: If $E_{00} \gg kT$, the current flow is mainly tunneling current; while if $E_{00} \ll kT$, TE regime dominates. The expression of E_{00} can be written as[8]

$$E_{00} = \frac{q\hbar}{2}\sqrt{\frac{N_D}{m^*\varepsilon_r\varepsilon_0}}, \qquad (2)$$

where m^* is the effective mass of carrier ($\sim 0.2m_0$ for electron in GaN), ε_r is the relative permittivity ($\sim$9.5 for GaN) and ε_0 is the vacuum permittivity. It is found that the E_{00} value of the sample is $\sim$6.75 meV, much smaller than the room temperature thermal energy $\sim$26.5 meV, indicating that the TE mechanism should be mainly responsible for the forward current flow in high-quality diodes. This conclusion disagrees with our previous deduction that tunneling dominates the current flow below 400 K in region I. The most possible reason is that the tunneling possibility has been significantly enhanced due to the presence of high-density defect states in GaN even with a light doping concentration of $\sim 2.5 \times 10^{17}$ cm^{-3}. It has been pointed out that if the concentration of intermediate levels is sufficiently high in the band gap of space-charge region of GaN, carriers can go though the barrier by trap-assisted tunneling.[11] We think that the above men-

tioned trap-assisted tunneling model should be applicable as well for the GaN-based Schottky diodes. Figure 3 illustrates the transport processes of the forward current, in which most electrons could tunnel from the conduction band of n-GaN to the metal side via the high-density defect states in the space depletion region of semiconductor below 400 K; while at higher temperatures many electrons can be thermally excited over the barrier, the TE process will gradually dominate.

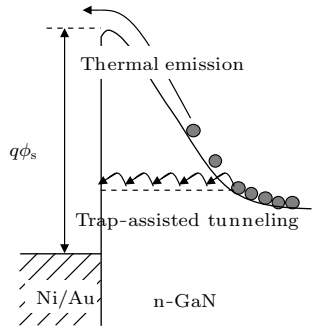


Fig. 3. Schematic illustration of the trap-assisted tunneling and thermal emission processes in the Ni/Au/n-GaN Schottky didoes, where the gray solid dots represent electrons.

For a Schottky barrier diode, the barrier height is responsible for controlling the current conduction as well as the capacitance behavior. Thus, it is very important to deduce the effective barrier height of the Schottky contact reliably. However, due to the complicated mechanisms of the carrier transport across such diodes, the conventional I–V method can not be used to extract the barrier height based on the TE model, otherwise a lower value will be deduced. Here an alternative I–V method proposed by Cheung will be used to deduce the barrier height, the advantage of this method is that the derivation only depends on the TE dominated high-forward-bias region of I–V curve.[12] Rewrite Eq. (1) as

$$V = RAJ + n\phi_{\rm b} + \frac{nkT}{q}\ln\left(\frac{J}{A^*T^2}\right). \tag{3}$$

Differentiating Eq. (3) with respect to J yields

$$\frac{dV}{d\ln(J)} = RAJ + \frac{nkT}{q}. \tag{4}$$

This equation predicts a linearly dependent $dV/d\ln(J)$ vs J plot with a slope of RA and a y-axis intercept of nkT/q. In good agreement with the prediction, the derived data from the I–V curve at 300 K can be nicely linearly fitted (see Fig. 4(a)), which gives a value of factor n to be about 1.01, representing almost pure TE mechanism in the corresponding bias region. Equation (3) can also be transformed into the following linear dependence

$$V - \frac{nkT}{q}\ln\left(\frac{J}{A^*T^2}\right) = RAJ + n\phi_{\rm b}. \tag{5}$$

This equation allows us to determine the effective barrier height from the extrapolated y-axis intercept of the linear relationship with a known n value. As shown in Fig. 4(b), the derived data agree reasonably well with the characteristics of Eq. (5), and from its intercept the barrier value is determined to be about 0.95 eV with n∼1.01.

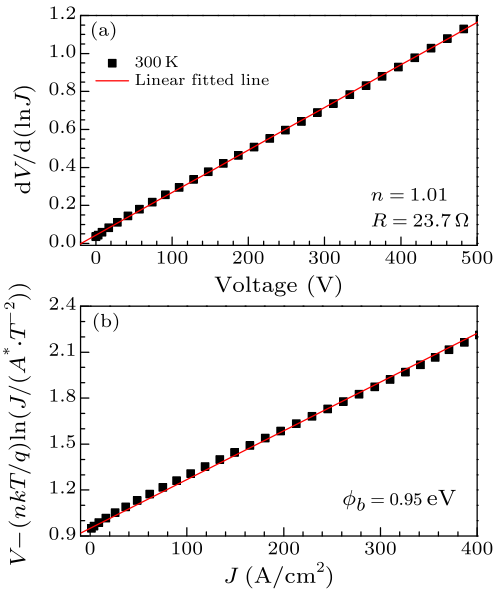


Fig. 4. (a) Plot of $\mathrm{d}(V)/\mathrm{dln}(J)$ of the Schottky diodes vs J. The ideality factor and the series resistance deduced are 1.01 and 23.7 Ω, respectively. (b) Plot of $V-(nkT/q)\ln(J/A*T^2)$ of the diode vs J. The deduced Schottky barrier height is about 0.95 eV with $n = 1.01$. The measurement temperature is 300 K.

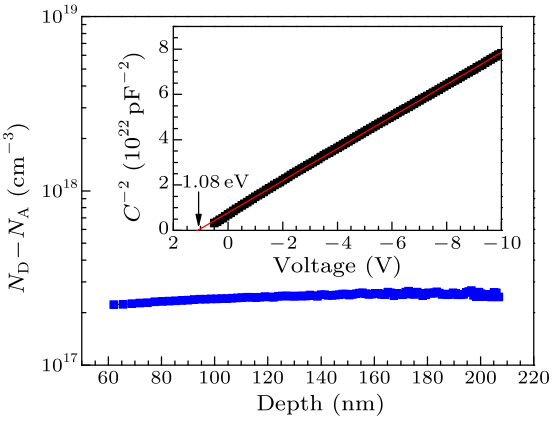


Fig. 5. The dopant concentration as a function of the junction depth calculated from the C–V measurement. The inset shows a plot of $1/C^2$ vs V: its intercept on the x axis gives the built-in potential $V_{\rm bi}$.

It was found that the barrier height estimated from the I–V method is ∼0.20 eV lower than that obtained by the C–V method. The capacitance per unit area of a Schottky diode can be expressed as[13]

$$\frac{C}{A} = \sqrt{\frac{q\varepsilon_r\varepsilon_0(N_{\rm D}-N_{\rm A})}{2(V_{\rm bi}-V-kT/q)}}, \tag{6}$$

where $V_{\rm bi}$ is the built-in potential, the kT/q term in the denominator accounts for the majority of carrier tail in space-charge region, and $N_{\rm D} - N_{\rm A}$ is the net doping concentration, which is almost constant as a function of junction depth, as shown in Fig. 5. In accordance with Eq. (6), by plotting $1/C^2$ vs V the extrapolated intercept on the x axis gives $V_i = V_{bi} - kT/q \sim 1.08$ eV (shown in the inset of Fig. 5). Thus, the $\phi_{\rm b}$ value can be calculated $\sim$1.14 eV by

$$\phi_{\rm b}(C - V) = V_{\rm bi} + (E_{\rm C} - E_{\rm F}), \qquad (7)$$

where $E_{\rm C} - E_{\rm F} = (kT/q)\ln(N_{\rm C}/N_{\rm D}) \sim 58.8$ meV at 300 K, and $N_C \sim 2.3 \times 10^{18}$ cm^{-3} is the effective density of states in the conduction band, close to the reported typical high value for Ni Schottky metal contact on n-GaN.[14]

In many past relevant studies, the significant tunneling current component at low bias has been regarded as one of the major factors for a decreased barrier height of GaN-based Schottky diodes. Since our barrier height was extracted based on the TE dominant high-forward-bias region, the influence of tunneling can be ruled out. Although reported values of A^* are scattered in the literature,[15,16] its influence can also be negligible because it appears in the the logarithm term and an error of two in A^* gives rise to an error of only $0.7kT/q$ in $\phi_{\rm b}$. Thus we think that the barrier inhomogeneity over the Schottky contact area might be mainly responsible for the differing effective barriers discrepancy: when two Schottky diodes of different barrier heights are connected in parallel, the lower barrier height dominates the I–V behavior, but the barrier height with the largest contact area dominates the C–V behavior.[17] In this parallel model, contacts with different local barrier heights are assumed to be electrical independent, and their individual current components contribute to the total current flow. Experimental observations revealed that the negatively charged threading dislocations, running through the devices and surrounded by accumulated acceptor-like states, can cause a decreased surface potential, inducing barrier inhomogeneity at the metal/semiconductor interface.[18] For n-type GaN grown by the MOCVD method on sapphire substrates, the surface potential variations around the dislocations can be $\sim$0.3–0.5 V with the full width at half maximums of $\sim$20–50 nm, in good agreement with our result.[19] One of the strong evidence for the model is an increasing effective barrier height with temperature estimated by the I–V method, because the electrons in semiconductor layer can overcome higher barrier due to enhanced thermal excitation at a certain forward bias. Experimentally, the effective barrier height of the diodes increases from 0.95 eV to 1.05 eV in the temperature range from 300 K to 450 K, confirming the validity of the barrier inhomogeneity model.

In summary, the forward current transport regime and interface Schottky barrier characteristics of Ni/Au/n-GaN Schottky barrier diodes have been analyzed by using I–V and C–V measurements. The low-bias I–V curve of the diodes below 400 K shows significant trap-assisted tunneling characteristics, meaning that the conventional I–V method cannot be used for effective barrier extraction based on the TE model. A modified high-forward-bias I–V method is used to deduce the reliable barrier height. It is found that the derived result can be 0.20 eV lower than that determined by the C–V method. This difference is attributed to the barrier inhomogeneity over the Schottky contact area.

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