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Determination of intrinsic barrier height in the Au/*n*-GaN contact system

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We have measured the intrinsic Schottky barrier height of Au/n-GaN metal–semiconductor diodes by performing current–voltage measurement on a series of diodes with varying in the range 10^{17}–$10^{19}\,\mathrm{cm}^{-3}$ in the GaN layer. The effective barrier height (Φ_B) monotonically decreases with increasing doping level. Taking account of the image-charge lowering ($\Delta\Phi$), the intrinsic barrier height $\Phi_{B0}=\Phi_B+\Delta\Phi$, is almost constant at (0.934 ± 0.015) V up to $\sim 5\times 10^{18}\,\mathrm{cm}^{-3}$, which is close to the Schottky limit of 0.94 V. *© 2001 American Institute of Physics.*
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The III–V mixed nitride semiconductors and their heterostructures have emerged as technologically important materials for application in visible to ultraviolet light emitters and high power/high frequency electronics.[1,2] Metal–semiconductor systems, serving as ohmic contacts or rectifying Schottky barriers form an intrinsic and vital part of these devices. A number of metals such as Au, Ni, Ti, Pd, Pt, PtSi, Ni/Au, Pt/Au, and indium tin oxide (ITO) have been deposited on nitride materials, and the rectifying characteristics of the resulting Schottky diodes have been investigated.[3–12] However, the results obtained from the measurements vary over a wide range. For example, in GaN-based Schottky diodes, the Richardson constant A^{**} is found to vary from 0.06 to 64.7 $\mathrm{A\,cm^{-2}\,K^{-2}}$, compared to a theoretically calculated value of 26.4 $\mathrm{A\,cm^{-2}\,K^{-2}}$.[11,12] Similarly, the barrier height for n-GaN based diodes is found to vary in the range of 0.8–1.4 V.[3–12] It is known that the Schottky barrier height ideally depends on the metal used and, under non-ideal conditions, on the morphology of the semiconductor, the processing used for Schottky diode formation and an interfacial states and defects.

In this letter, we report the results of a systematic experimental study of the characteristics of Au/n-GaN Schottky diodes. The doping in the GaN layers was varied in the range of 10^{17}–$10^{19}\,\mathrm{cm}^{-3}$ and the effects of image-charge lowering have been taken into account.

A series of n-GaN epitaxial layers were grown on c-plane sapphire (0001) by the low-pressure metalorganic chemical vapor deposition (LP–MOCVD) technique. All the layers were grown under the same conditions, except for the variation of flow rate of monosilane ($\mathrm{SiH_4}$) in order to vary the n-type doping level. The typical layer thickness is approximately 3.5 μm. The details of epitaxial growth have been described elsewhere.[13] Hall measurements were made on the n-type layers prior to Schottky diode formation. Circular Au Schottky diodes were formed on the n-GaN layers by thermal evaporation through a metal shadow mask. The thickness of the Au films is approximately 150 nm, and the diameter of the circular Au dots is 500 $\mu\mathrm{m}$($A=1.96\times 10^{-3}\,\mathrm{cm}^2$). Note that no special processing was done on the GaN layers before or after the evaporation of Au. The barrier height and the ideality factor of the diodes were determined from analysis of measured current–voltage (I–V) characteristics.

Figure 1 shows the measured current density–voltage (J–V) curve and the corresponding plot for the Norde function[14] for a representative Au/n-GaN diode under forward bias. For analyzing the data, we use the well-known diode equation based on thermionic emission theory,

$$J=J_s[\exp(qV/\eta k_BT)-1], \tag{1}$$

where J_s is the saturation current density given by

$$J_s=A^{**}T^2\exp[-q\Phi_B/k_BT]. \tag{2}$$

Here Φ_B and η are the effective barrier height and the diode ideality factor, respectively. Using a value of A^{**}

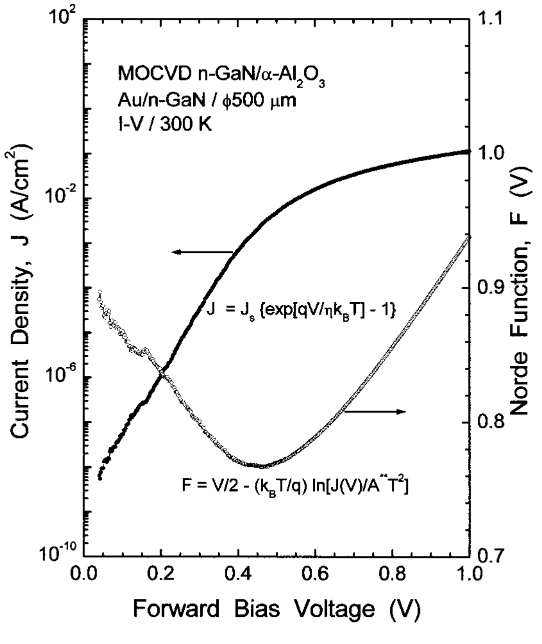

FIG. 1. Typical J–V and Norde analysis curves obtained from measurements on a representative Au/n-GaN Schottky contact ($n=1.0\times 10^{17}\,\mathrm{cm}^{-3}$).

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TABLE I. The representative characteristics obtained from a series of Au/n-GaN Schottky contacts with different substrate concentration. The barrier heights determined by the Norde analysis are in parentheses for comparison with those by the linear fit of $J-V$ curve.

Carrier concentration n (cm^{-3})	Effective barrier height Φ_B (V)	Barrier lowering $\Delta\Phi$ (V)	Intrinsic barrier height $\Phi_{B0}=\Phi_B+\Delta\Phi$ (V)	Ideality factor η
1.0×10^{17}	0.895 (0.903)	0.054	0.949	1.20
3.7×10^{17}	0.839 (0.833)	0.075	0.914	1.32
1.4×10^{18}	0.815 (0.808)	0.104	0.919	1.86
5.0×10^{18}	0.787 (0.790)	0.144	0.931	2.33
7.1×10^{18}	0.709 (0.730)	0.157	0.866	3.97

$=26.4\ \mathrm{A\,cm^{-2}\,K^{-2}}$ and $m_e^*=0.22m_0$,[15] we have determined the barrier heights from a linear fit of the ($\ln J$–V) plots. The Norde function is given by[14]

$$F(V)=V/2-(k_BT/q)\ln[J(V)/A^{**}T^2]. \tag{3}$$

From a pair of values at a minimum point on the Norde curve, $[V_m, F(V_m)]$, the barrier height can be determined from

$$\Phi_B=F(V_m)+[(2/\eta)-1][(V_m/2)-(k_BT/q)]. \tag{4}$$

Five pairs of values for Φ_B, obtained by the two different methods are listed in Table I.

The variation of barrier height Φ_B, determined from a fit to the ($\ln J$–V) data, with doping concentration depicted in Fig. 2. The reduction of barrier height with increase in doping, $\Delta\Phi$, was analyzed by taking into account the image-force lowering effect.[16] Accordingly,

$$\Delta\Phi\cong[(q^3N_D/8\pi^2\varepsilon^3)(V_0-k_BT/q)]^{1/4}, \tag{5}$$

where the analysis is performed around zero bias. Values of $\Delta\Phi$ as a function of doping concentration are plotted in Fig. 2 and listed in Table I. The contact potential $V_0\cong1$ V, as obtained from the capacitance–voltage profile. It is evident that image-force lowering becomes more effective with increasing doping concentration. The intrinsic barrier height, $\Phi_{B0}=\Phi_B+\Delta\Phi$, can then be calculated, and the values of this parameter are also plotted in Fig. 2 as a function of doping concentration. A least square fit to the data, excluding the highest doping concentration, gives $\Phi_{B0}=(0.934\pm0.015)$ V. We believe that the additional lowering of the values of Φ_B and Φ_{B0} for $n=7.1\times10^{18}\ \mathrm{cm^{-3}}$ is caused by the onset of field emission. It therefore seems that for Au/n-GaN Schottky diodes, thermionic emission is the dominant transport mechanism for doping levels below $\sim5\times10^{18}\ \mathrm{cm^{-3}}$.

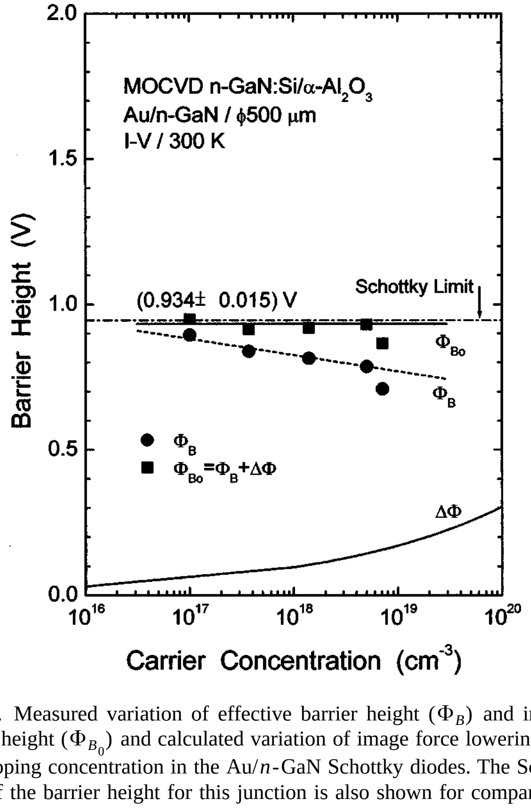

FIG. 2. Measured variation of effective barrier height (Φ_B) and intrinsic barrier height (Φ_{B_0}) and calculated variation of image force lowering ($\Delta\Phi$) with doping concentration in the Au/n-GaN Schottky diodes. The Schottky limit of the barrier height for this junction is also shown for comparison.

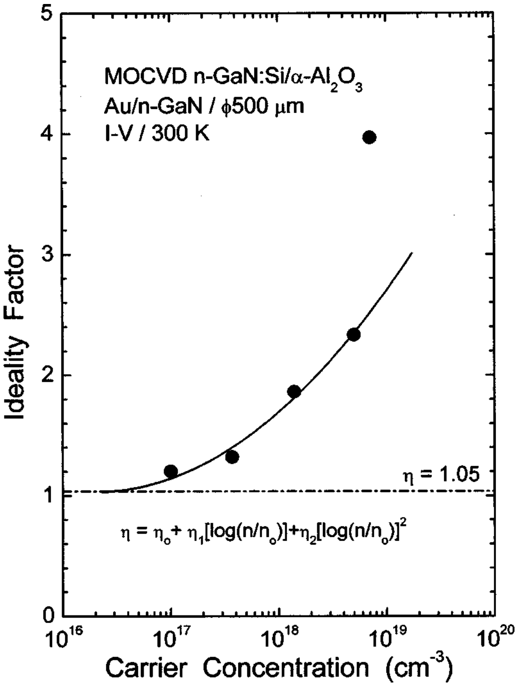

FIG. 3. Measured Au/n-GaN ideality factors as a function of carrier concentration. The data show a superlinear increase with a quadratic $\log(n/n_0)$ dependence (solid line), except for the value at the highest concentration ($7.1\times10^{18}\ \mathrm{cm^{-3}}$), and has a limiting value of 1.05.

The barrier height of most metal–semiconductor junctions usually lies between two limiting values; the Schottky limit defined by the work function of the metal (W) and the electron affinity of the semiconductor (χ), and the Bardeen limit defined by the band gap of the semiconductor and the neutral level at the interface resulting from localized surface states. It is interesting to note that the value of the intrinsic barrier height $\Phi_{B0}=(0.934\pm0.015)$ V, determined in this study, is very close to the Schottky limit of 0.94 V ($W=5.1$ V; $\chi=4.16$ V). This indicates that there is no significant Fermi-level pinning at the metal–semiconductor interface in Au/n-GaN junctions, unlike the case of Au/GaAs Schottky contacts. The very small discrepancy may arise from residual impurities and defects at the interface.

The measured diode ideality factors, η, are plotted in Fig. 3 as a function of doping level. The value of η superlinearly increases from 1.2 to 2.3 as the doping level increases from 1×10^{17} to $5\times10^{18}\ \mathrm{cm^{-3}}$, which is in the thermionic emission regime. The variation can be fitted by the empirical quadratic relation:

$$\eta = \eta_0 + \eta_1[\log(n/n_0)] + \eta_2[\log(n/n_0)]^2 \tag{6}$$

with values of $\eta_0 = 1.05$, $\eta_1 = -0.14$, $\eta_2 = 0.23$, and $n_0 = 10^{16}\,\mathrm{cm}^{-3}$. Therefore the ideality factor approaches the value of 1.05 for a carrier concentration of $n = 10^{16}\,\mathrm{cm}^{-3}$ in the semiconductor, which is generally true in most metal–semiconductor junctions. The large deviation of the measured η for $n = 7.1\times 10^{18}\,\mathrm{cm}^{-3}$ is most probably due to field-assisted tunneling, as discussed earlier.

In conclusion, we have measured the intrinsic Schottky barrier height $\Phi_{B0} = (0.934 \pm 0.015)$ V in Au/n-GaN Schottky diodes. We have taken the effects of image–force lowering into account in diodes with increasing doping in the semiconductor. The value of Φ_{B0} is very close to the Schottky limit and suggests that there is no severe Fermi level pinning by interface states in this system.

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