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# Low-resistance Ni-based Schottky diodes on freestanding *n*-GaN

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Schottky diodes formed on a low doped ($5 \times 10^{16}$ cm$^{-3}$) *n*-type GaN epilayer grown on a $n^+$ freestanding GaN substrate were studied. The temperature dependent electrical characteristics of Ni contacts on the as-grown material are compared with an aqueous, potassium hydroxide (KOH) treated surface. In both cases the diodes are dominated by thermionic emission in forward bias, with low idealities (1.04 at room temperature) which decrease with increasing temperature, reaching 1.03 at 413 K. The Schottky barrier height is $0.79 \pm 0.05$ eV for the as-grown surface compared with $0.85 \pm 0.05$ eV for the KOH treated surface at room temperature. This is consistent with an inhomogeneous barrier distribution. The specific on-state resistance of the diodes is 0.57 m$\Omega$ cm$^2$ The KOH treatment reduces the room temperature reverse leakage current density at −30 V to $1 \times 10^{-5}$ A cm$^{-2}$ compared to $6 \times 10^{-2}$ A cm$^{-2}$ for the as-grown samples. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2799739]

The formation of the basic metal to gallium nitride (GaN) interface remains of considerable interest both from a fundamental point of view[1,2] and as a means of forming robust Schottky diodes for use in power, transistor, and photodiode applications.[3,4] GaN layers grown on insulating sapphire substrates have a relatively high defect density which can be expected to compromise the ideality and reverse leakage current in Schottky diodes.[5,6] While the leakage current can be reduced by surface treatments,[7,8] the large reduction in the electron mobility for carrier transport in the lateral direction compared with vertical transport,[9] means that the resistance of such diodes can be large. Freestanding GaN substrates allow for vertical geometry devices and due to decreased dislocation density, the possibility of better performance. Recently such diodes have been investigated,[10–13] with high breakdown voltages being measured. These devices have relatively large on-state resistance due to the low doping level in the substrate. On the other hand Schottky diodes formed on highly doped layers have poor device idealities. We address this issue by forming Schottky diodes on a lowly doped epilayer grown on a highly doped substrate. We present the characteristics of nonannealed, Ni-based contacts to this material, which show near ideal thermionic emission behavior, low on-state resistance, and stable operation at high temperature. The addition of the epilayer adds little resistance to the device.

A 2.5 $\mu$m thick lowly doped *n*-GaN layer was grown on the Ga face of a 300 $\mu$m thick $n^+$ ($\sim 10^{18}$ cm$^{-3}$) doped freestanding GaN substrate. The doping level of the epilayer was determined by capacitance-voltage (*C*-*V*) measurements to be $5 \times 10^{16}$ cm$^{-3}$. The epilayer can be expected to contribute just 0.05 m$\Omega$ cm$^2$ to the specific resistance assuming a room temperature electron mobility of 600 V/cm$^2$ s.[14] Circular contacts with diameters ranging from 80 to 460 $\mu$m were formed by depositing Ni/Pt/Au (20/20/50 nm) by electron beam evaporation on the as-grown surface and on a surface treated for 90 s in a 45% KOH/H$_2$O mixture at 130 °C. It has been shown that the Ga plane remains inert in aqueous KOH treatment but that the surface chemistry is affected, leading to a potential change in the band bending.[15] KOH treatment also results in a smooth surface. A large area Ohmic contact was formed on the substrate (N face) by electron beam evaporated Ti/Al/Pt/Au (3/50/30/200 nm) to complete the fabrication of the vertical geometry diodes. The sample was not annealed.

The forward and reverse current-voltage (*I*-*V*) characteristics were measured using a Cascade Microtech probe station and an HP4156 parameter analyzer as a function of temperature between 243 and 413 K. We can expect the forward characteristics to follow the thermionic emission (TE) model,

$$I = AA^*T^2 e^{-q\phi_B/kT} e^{(qV - IR_s)/nkT}, \tag{1}$$

where $A$ is the contact area, $A^*$ the Richardson constant (taken to be 26.4 A cm$^{-2}$ K$^{-2}$),[16] $T$ the temperature, $\phi_B$ the barrier height, $n$ the diode ideality, and $R_s$ the series resistance of the diode. The forward current density–voltage *J*-*V* characteristics between 243 and 413 K for a 100 $\mu$m diameter diode on the as-grown sample are shown in Fig. 1. The inset shows the room temperature *J*-*V* characteristics for the different diameter diodes. Similar characteristics are obtained for the KOH treated sample.

To analyze the different current transport processes we calculated an effective diode ideality, $\eta_{\text{eff}} = q/kT\,(dV/dI)I$, as a function of voltage and temperature. Figure 2 shows $\eta_{\text{eff}}$

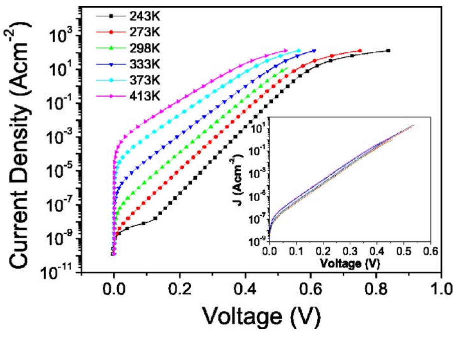

FIG. 1. (Color online) The *J*-*V* characteristics for a 100 $\mu$m diameter contact between 243 and 413 K. The inset is the room temperature forward *J*-*V* characteristics of diodes with diameters between 80 and 460 $\mu$m.

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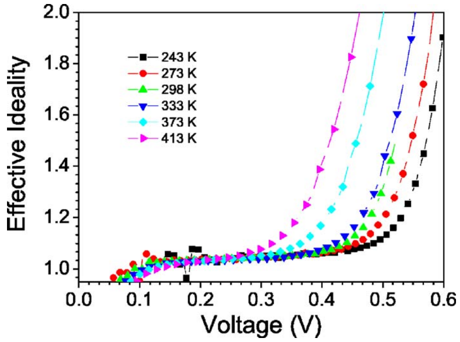

FIG. 2. (Color online) The voltage-dependent effective ideality $[\eta_{\text{eff}} = q/kT(dV/dI)I]$ of a 100 $\mu$m diameter device on the as-grown samples as measured over the temperature range.

for a 100 $\mu$m diameter diode. At low bias $(V<0.15\text{ V})$ a tunneling current with $\eta_{\text{eff}}<1$ is present. At low temperature (243 K) an additional current component is observed. At higher bias the current transport becomes dominated by the TE component, with an ideality factor for TE of 1.04±0.01 at room temperature. The voltage range for dominant TE behavior is dependent on temperature and it becomes difficult to define for temperatures above 140 °C in our diodes. This is because $\eta_{\text{eff}}$ becomes dominated by the effect of series resistance, the effect of which is larger at higher temperatures because of the larger TE current. The idealities for the TE component of both sample sets show a slight decrease with increasing temperature reaching 1.03±0.02 at 413 K. Inhomogeneity in the barrier heights has been shown to lead to a temperature dependent ideality of the form $\eta=1+T_0/T$, where $T_0$ is a constant related to the distribution of barrier heights.[17] For our devices a $T_0$ of ~13 K is estimated.

The barrier heights $\phi_B$ of the diodes were extracted by fitting the *I-V* data to Eq. (1). $\phi_B$ for diodes of different contact diameters from both sample sets are shown in Fig. 3. A variation in $\phi_B$ is measured which has no systematic dependence on contact diameter. $\phi_B$ is 0.79±0.05 eV for diodes on the as-grown surface compared with 0.85±0.05 eV for those on the KOH treated surface. $\phi_B$ on the KOH treated surface are temperature independent while $\phi_B$ on the as-grown surface increases with temperature, though remaining less than that of the KOH treated surface. The variation in $\phi_B$ is consistent with inhomogenity in the barrier heights[17,18] and the measured decrease in $n$ with temperature via $T_0$. An estimate of the standard deviation in barrier heights can be calculated using $T_0$. For $T=13$ K, $\sigma_B$ is calculated to be 0.06 eV in reasonable agreement with the observed spread. The larger $\phi_B$ for the KOH treated samples could be due to increased band bending at the surface. A plot of $n$ against $\phi_B$ (not shown) for each set shows a trend of reducing $n$ for higher $\phi_B$.

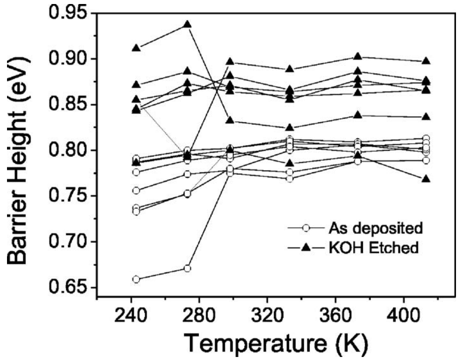

FIG. 3. The temperature dependent barrier heights of the diodes formed on the as-grown and KOH treated samples.

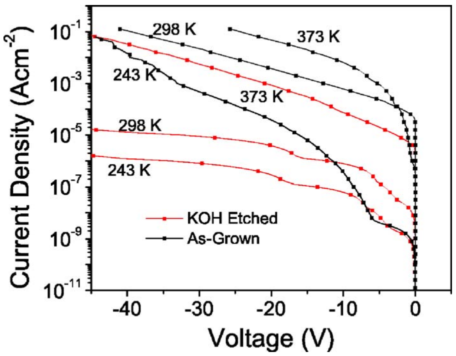

FIG. 4. (Color online) The reverse current characteristics of the 100 $\mu$m diodes on the as-grown and KOH treated samples at 243, 298, and 373 K.

The series resistance of a 100 $\mu$m diameter as-grown diode was measured using a four-point method to be 7 $\Omega$ at a current density of 500 A cm$^{-2}$ corresponding to a specific on resistance of 0.57 m$\Omega$ cm$^2$. Calculating the on resistance from the resistances of the epilayer, the bulk, and the Ohmic contact yields a value of 8 $\Omega$. This resistance is dominated by the substrate and can be reduced by thinning. The forward on voltage at 100 A cm$^{-2}$ (Ref. 13) was 0.57 V. The diode resistance increases with temperature due to decreasing electron mobility. However, the voltage required to deliver 100 A cm$^{-2}$ decreases with temperature due to the dominance of TE component at this current density.

The reverse *J-V* characteristics for 100 $\mu$m diameter as-grown and KOH treated diodes at two different temperatures are shown in Fig. 4. The leakage current density is dependent on the diode diameter with reduced leakage for smaller diameters. The leakage current is reduced for the KOH treated diodes as previously reported[7,8] and is exponentially dependent on voltage and heavily dependent on temperature. A possible explanation for this characteristic is phonon-assisted tunneling associated with traps at the metal to semiconductor interface.[19] This current could also explain the tunneling characteristic measured at low forward bias for these diodes. The leakage current is less than other reports for Schottky diodes on sapphire substrates[20] but is larger than that reported on freestanding substrates due to the larger electric field across the 2.5 $\mu$m thick, low doped epilayer in this case.

In summary, vertical Schottky diodes with low turn-on voltage, low on resistance, near ideal thermionic emission characteristics, and low reverse leakage have been realized through the use of Ni contacts on a lowly doped epilayer, grown on a freestanding GaN substrate. The temperature dependent electrical characteristics are consistent with phonon-assisted tunneling associated with traps in the metal-semiconductor interface, thermionic emission through a distribution of Schottky barrier heights, and a low series resistance. KOH treatment of the surface is shown to increase the Schottky barrier height and to reduce the reverse leakage current.

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