Ni Schottky diodes on cubic GaN

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Schottky diodes were fabricated by thermal evaporation of nickel on phase-pure cubic GaN (*c*-GaN) layers grown by plasma assisted molecular beam epitaxy on freestanding 3C-SiC. Detailed analysis of the *I-V* characteristics revealed the existence of a thin surface barrier at the Ni-semiconductor interface. Thermal annealing in air at 200 °C alters the composition of this thin surface barrier, reduces the leakage current by three orders of magnitude, and increases the breakdown voltage. The dependence of the breakdown voltage on the doping density of the *c*-GaN layers is in good agreement with calculated values. We obtain a critical electric-field strength of $E_{crit} \cong 2.5 \times 10^6$ V/cm for *c*-GaN. © *2006 American Institute of Physics*.
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Schottky diodes (SDs) are key elements for the realization of GaN-based electronic devices such as high-power high electron mobility transistors (HEMTs), high-power metal semiconductor field effect transistors (MESFETs), and UV photodetectors.[1] However, GaN-based Schottky contacts suffer from abnormal large leakage currents under reverse bias,[2] which strongly degrade gate control characteristics and increase power consumption. Different field emission (FE) models assuming a triangular Schottky potential,[3] trap-assisted tunneling,[4] spatial variations of barrier heights,[5] and the introduction of a thin surface barrier[6] (TSB) have been used to explain these leakage mechanisms.

It has been predicted by two-dimensional (2D) Monte Carlo device simulations of nitride-based FETs[7] that cubic GaN (*c*-GaN), although more difficult to grow than GaN with hexagonal crystal structure, yields a 50% gain in FET performance. When cubic group-III nitrides are grown in a (001) direction, spontaneous and piezoelectric polarization effects can be avoided at the interfaces and surfaces. Thus the density of the 2D electron gas (2-DEG) in cubic $Al_xGa_{1-x}N/GaN$ heterostructures does not depend on the thickness of the $Al_xGa_{1-x}N$ barrier layer and cubic AlGaN/GaN HEMTs can be realized with both normally on and normally off operation. Such devices are strongly required for logic devices.[8] In addition, the electronic structure of the *c*-GaN (001) surface is different than that of the *c* plane of the hexagonal GaN and therefore alters the electronic properties of Schottky diodes.[9]

In this letter, we report the fabrication of Ni-SDs on *c*-GaN. The *I-V* characteristics were measured at different temperatures and the influence of thermal annealing in the air was investigated. The dependence of the breakdown voltage on the doping density was measured and the critical field strength for electronic breakdown in *c*-GaN was determined.

Phase-pure *c*-GaN was grown by plasma assisted molecular beam epitaxy[10] (MBE) on 200 μm thick freestanding 3C-SiC (100) substrates. The thickness of the *c*-GaN layers was about 1000 nm. The quality of the layers was checked by high resolution x-ray diffractometry, atomic force microscopy, and photoluminescence spectroscopy. Details of the growth process are given elsewhere.[11] Ni/In (50 nm/150 nm) Schottky contacts with a diameter of 300 μm were produced by thermal evaporation. The contact geometry was defined by contact lithography. Prior to vacuum deposition, the GaN surfaces were cleaned by organic solvents and a buffered oxide etch (BOE). Indium contacts were used as an ohmic contact on *c*-GaN. The current voltage (*I-V*) characteristics, which were measured with the sample in the dark, revealed a rectifying behavior of our SDs. Capacitance-voltage (*C-V*) measurements and electrochemical *C-V* profiling[12] (ECV) were used to determine the net donor concentration in our *c*-GaN layers, which varied between 9×10^{16} to 2×10^{19} cm^{-3}.

Figure 1 shows the room temperature *I-V* curves of one of our SDs, which were measured before (open circles) and after annealing of the SD at 200 °C in ambient air (dots). The annealing was done on a hot plate located on a lab bench in open room air for 10 min. The net donor concentration of the as-grown *c*-GaN layer was $N_D - N_A = 1.8 \times 10^{17}$ cm^{-3}. The curve in Fig. 1 is calculated assuming that the current across the SD is dominated by thermionic emission (TE).

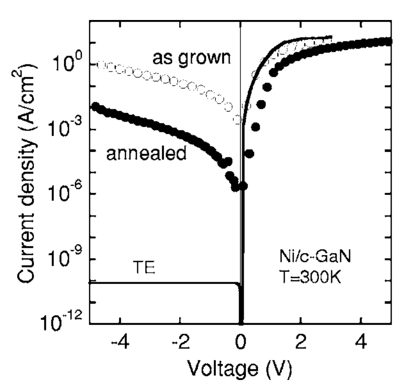

FIG. 1. Room temperature current voltage (*I-V*) characteristics of a Ni-SD on *c*-GaN before annealing (open circles) and after annealing in air at 200 °C (full circles). The full curve is calculated assuming TE across the Schottky barrier and a series resistance of 230 Ω.

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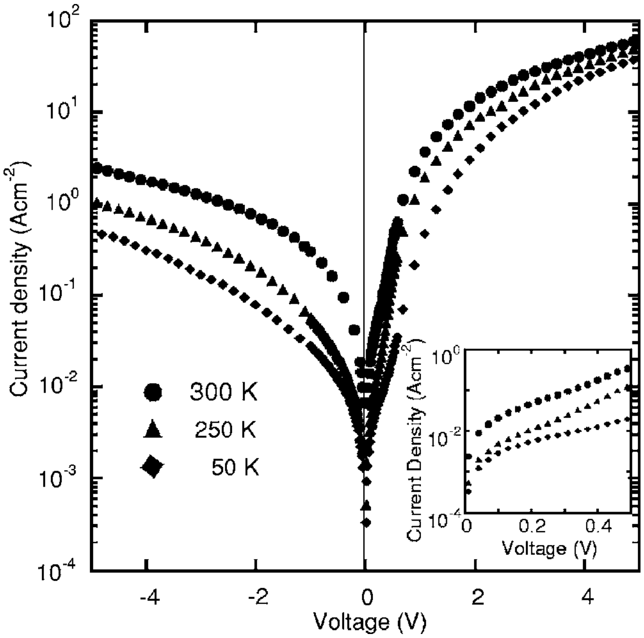

FIG. 2. Current voltage (*I-V*) characteristics of a Ni-SD on *c*-GaN at temperatures between 300 and 50 K. The inset emphasizes the formation of a current plateau in the low forward bias region.

Assuming a series resistance of 230 Ω, the forward characteristics can be fitted by, however, the reverse current shows strong deviations that are characterized by the following two salient features. First, the magnitude of the reverse current is generally larger than the reverse saturation current density given by the TE model, and second, a nearly exponential increase of the reverse current is observed with increasing reverse voltage. This behavior is found for as-grown and annealed SDs. Similar effects have also been measured with a SD on *h*-GaN. They were explained by a strong contribution of tunneling currents to the reverse current.[13]

To identify the mechanism responsible for the large leakage current, we measured the *I-V* curves of an annealed sample at temperatures between 300 and 50 K. Results are depicted in Fig. 2. The forward current has a plateau in the low bias region (see the inset of Fig. 2), which is a clear indication for tunneling transport.[14] A pronounced deviation from thermionic transport across the barrier is evident from the reverse bias characteristic. The magnitude of the reverse current density is nearly independent of the temperature and is more than eight orders of magnitude higher than that calculated by the TE model, especially at lower temperatures. Further, the reverse current density increases exponentially with reverse voltage.

Recently, Hasegawa *et al.*[15] observed similar features with Ni, Pt, and Au Schottky contacts in hexagonal GaN(*h*-GaN), which they explained by their TSB model. They proposed that due to the presence of donorlike defects at the interface between the metal and GaN a highly conducting layer is formed, which leads to a reduction of the thickness of the depletion layer resulting in severe tunneling of free carriers (FE). The relevant donorlike defects may be nitrogen vacancies (V_N).[16] Their density can be reduced by thermal annealing in air or a nitrogen atmosphere, which improves the *I-V* characteristic, also in good agreement with our experimental results. Other possible donorlike defects are oxygen impurities (O_N). Their density is expected to be high in $Al_xGa_{1-x}N$ layers due to the increased affinity of Al to O. We observed that the leakage current of SD on c-$Al_xGa_{1-x}N$ is higher than that of *c*-GaN SDs, indicating a high density of oxygen at the interface.

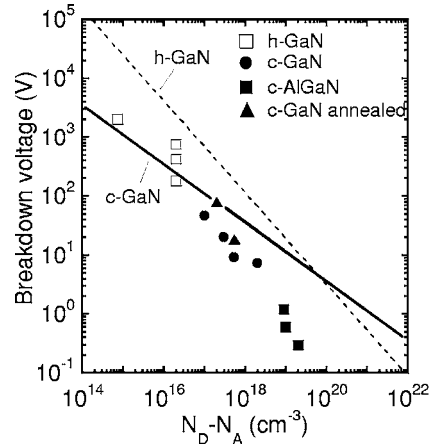

FIG. 3. Breakdown voltage vs N_D-N_A of SDs on *c*-GaN and c-$Al_{0.3}Ga_{0.7}N$ (full symbols) and hexagonal GaN (open symbols). Lines are calculated using a model by Matocha *et al.* (Ref. 20).

During annealing at temperatures above 200 °C, Ga_4Ni_3, Ni_3N, and Ni_4N are formed at the Ni-GaN interface.[17] These clusters may compensate the donorlike defects responsible for the formation of the TSB.

Figure 3 shows the breakdown voltages V_{br} of SDs on *c*-GaN and *c*-AlGaN plotted versus the net donor concentration of the semiconductor (full symbols). V_{br} was determined from the reverse breakdown voltage of our SD. The donor density (N_D-N_A) was measured either by *C-V* or ECV. Also included in Fig. 3 are experimental data obtained from *h*-GaN.[18,19]

The lines in Fig. 3 are calculated using a model for the relation between V_{br} and the net donor concentration by Matocha *et al.*[20] Our experimental data clearly follow the trend of increasing V_{br} with decreasing donor concentration. However, all experimental values of V_{br} are about one-third smaller than the calculated values. We suggest that the TSB leads to premature breakdown. The effect of the TSB is reduced by annealing of *c*-GaN SDs at 200 °C in air, which yields an increase of the breakdown voltage by a factor of 3 (full triangles in Fig. 3). Our interpretation is supported by experimental data obtained with SDs on c-$Al_{0.3}Ga_{0.7}N$ (full squares in Fig. 3), where an even larger difference between experimental and calculated data is observed. We suppose that this difference is due to a high O_N concentration in the TSB.

One of the most significant parameters for the design and performance of high power devices is the electric field at breakdown E_{crit}, which can be obtained from the measured breakdown voltage V_{br} of SDs. E_{crit} is given by

$$E_{crit} = \sqrt{\frac{2qN_D V_{br}}{\varepsilon_s \varepsilon_0}}, \qquad (1)$$

where q is the electron charge and ε_0 the dielectric constant of the vacuum. Inserting the data of an annealed SD, $V_{br} = 80$ V and $N_D = 2 \times 10^{17}$ cm^{-3}, and the dielectric constant of *c*-GaN $\varepsilon_s = 8.9$, we get $E_{crit} \cong 2.5 \times 10^6$ V/cm.

In conclusion, SDs were fabricated by thermal evaporation of Ni on *c*-GaN. Analysis of the *I-V* characteristic of these SDs at 300 K and at low temperature revealed that a TSB is formed at the Ni-GaN interface, which leads to premature breakdown of the SDs. Thermal annealing in air at 200 °C reduces the leakage current by three orders of magnitude and avoids premature breakdown most likely due to a reduction of the TSB. The measured dependence of V_{br} on the doping level of *c*-GaN is in good agreement with calculated values. From our experiments we obtain a critical electric field in SD on *c*-GaN of about $E_{crit} \cong 2.5 \times 10^6$ V/cm.

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