High voltage (450 V) GaN Schottky rectifiers

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We fabricated high standoff voltage (450 V) Schottky rectifiers on hydride vapor phase epitaxy grown GaN on sapphire substrate. Several Schottky device geometries were investigated, including lateral geometry with rectangular and circular contacts, mesa devices, and Schottky metal field plate overlapping a SiO_2 layer. The best devices were characterized by an ON-state voltage of 4.2 V at a current density of 100 A/cm^2 and a saturation current density of 10^{-5} A/cm^2 at a reverse bias of 100 V. From the measured breakdown voltage we estimated the critical field for electric breakdown in GaN to be $(2.2\pm0.7)\times10^6$ V/cm. This value for the critical field is a lower limit since most of the devices exhibited abrupt and premature breakdown associated with corner and edge effects.
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Wide band gap materials, primarily SiC and GaN, have recently attracted a lot of interest for applications in high power and high temperature electronics. Although the processing technology for SiC is more mature, GaN offers several advantages. First, there are various device possibilities using GaN/AlGaN heterojunctions which are not available in the SiC system. Second, the availability of cheap and efficient hydride vapor phase epitaxy (HVPE) growth technology achieving growth rates in excess of 100 μm/h, have produced thick, high quality GaN layers on sapphire.[1] Third, by using AlGaN layers, one can take advantage of a larger band gap to achieve higher critical electric fields than in GaN alone.

In this study, we focus on the fabrication of high voltage, GaN based Schottky rectifiers and the measurement of the critical field for electric breakdown. The critical field for electric breakdown is one of the most significant parameters in the design and performance of high power devices. It directly influences the required thickness of the standoff region in the Schottky rectifier and bipolar devices, such as the thyristor. Since the thickness of the standoff region sets the resistivity of the device, it will determine power dissipation and maximum current density of the device.[2,3] In previous studies, Schottky diodes have been fabricated on GaN using a variety of elemental metals including Pd and Pt,[4,5], Au, Cr, and Ni,[6,7], and Mo and W.[8] More details on the metal-GaN contact technology can be found in Ref. 9.

In this work, Schottky rectifiers were fabricated on 8–10 μm thick GaN layers grown by HVPE on sapphire, where the electron concentration changes with the distance from the GaN/sapphire interface. We carried out conductivity and Hall measurements on a series of HVPE GaN films of varying thickness ranging from 0.07 to 9.2 μm, and fitted the data to a two layer model.[10–13] From the model, we concluded that the GaN films consisted of a low conductivity, low electron concentration, 8–10 μm thick top layer on a very thin (<100 nm), highly conductive, high electron concentration bottom layer. The electron concentrations and mobilities in the thin interface layer and thick upper layer were 2×10^{20} cm^{-3} and 35 cm^2/Vs, and 2×10^{16} cm^{-3} and 265 cm^2/Vs, respectively. These values correspond to conductivities of 1120 and 0.85 S cm^{-1} for the interface layer and upper layer, indicating that the interface layer is approximately three orders of magnitude more conductive. Capacitance–voltage ($C-V$) measurements performed on the 9.2 μm thick samples determined that the net donor concentration in the top few microns of the film was $(2\pm1)\times10^{16}$ cm^{-3}, consistent with the two layer model. A cross sectional transmission electron microscopy (XTEM) study on our HVPE samples (grown under similar conditions) was presented in Ref. 14, where it was concluded that the region adjoining the interface was highly disordered and included a large number of subgrain boundaries, stacking faults and prismatic plane faults. Previous XTEM studies on GaN samples grown by HVPE indicated the presence of a similar 100–200 nm thick, highly defective interface layer.[13,15] Secondary ion mass spectroscopy studies done on our samples revealed large oxygen impurity concentrations near the GaN/sapphire interface, which also can account for the observed high electron concentration. Therefore, we conclude that the high electron concentration and low electron mobility at the GaN/sapphire interface are a combination of both the observed high defect density and high concentration of impurities (oxygen).

We tested several device and contact geometries including lateral, mesa, and Schottky metal field plate devices as shown in Fig. 1. Prior to metal deposition, the GaN surfaces were cleaned with organic solvents, dipped in HF:H_2O (1:10), rinsed in de-ionized water, and blown dry with nitrogen gas. Following cleaning, gold (1500 Å) was sputtered in a chamber with a background pressure of 2×10^{-8} Torr and patterned to produce Schottky contacts. Ti/Al/Ni/Au (150 Å/1500 Å/100 Å/1000 Å) was then sputtered to produce ohmic contacts as deposited. On some devices, large area Au

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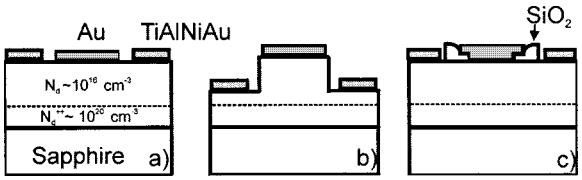

FIG. 1. Different device geometries for GaN Schottky rectifiers. The thicknesses of the layers of different electron concentration are not drawn to scale. (a) Lateral Schottky rectifier. (b) Mesa device offers lower resistivity since ohmic contacts are deposited closer to the high conductivity interface layer. (c) Lateral Schottky rectifier processed with Schottky metal field plate overlapping a SiO_2 layer.

metallization was used as a low resistivity contact instead. The mesa edge termination was produced by chemically assisted ion beam etching, using Xe ions accelerated with 1000 V, and 25 sccm of Cl_2 flow.[2,3] For the metal field plate devices, SiO_2 was sputtered using SiO_2 targets and 10 sccm of O_2 flow, and then patterned.

The current–voltage ($I-V$) measurements were taken with a Keithley 237 high voltage source measure unit and with an HP 4156A precision semiconductor parameter analyzer. The Keithley 237 was used for high voltage measurements while the HP 4156A was used to determine the Schottky barrier height and for $I-V$ measurements up to 100 V. $I-V$ characteristics for the fabricated devices are shown in Figs. 2 and 3. The reverse breakdown voltages observed were in the range between 250 and 450 V and exceeded 450 V in several devices. We associate this variation in the device breakdown voltage with nonuniformities in the electron concentration. The Au Schottky barrier heights obtained from the $I-V$ measurements varied between 1.1 and 0.8 eV. The ideality factor of the diodes ranged between 1.6 and 4. In the case of the lateral diode, the ON-state voltage was 5 V for a current density of 100 A/cm^2. Large ON-state voltages are a consequence of both the large ohmic contact resistances and the low electron concentration of the upper layer. The series resistance of the device is significantly affected by the presence of the highly conductive interface layer. This layer ''shorts'' the conduction path, so that the series resistance consists mainly of the ohmic contact resistance, the resistance of the 8–10 μm thick layer between ohmic contact and the highly conductive layer, and the resistance of the 8–10 μm thick layer between the highly conductive layer and the Schottky contact. Without the highly conductive interface layer, the device series resistance would be determined by the distance between the ohmic and Schottky contact. To reduce the series resistance we etched 5 μm of the 8–10 μm top layer and deposited ohmic contacts closer to the more conductive interface layer [Fig. 1(b)]. This reduced the ON-state voltage from 5 to 4.2 V at a forward current density of 100 A/cm^2. However, as can be observed from Fig. 3, the reverse leakage current increased to approximately 10^{-2} A/cm^2, probably due to the etch damage of the mesa walls.

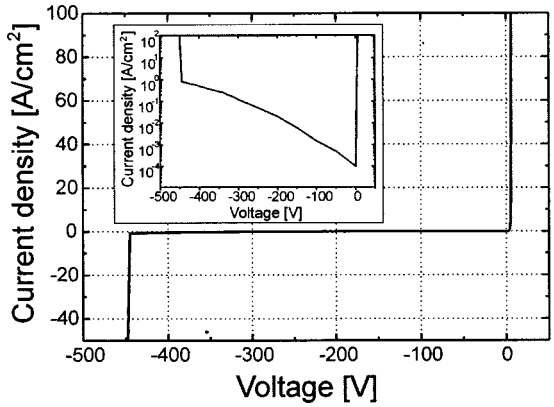

FIG. 2. $I-V$ curve taken with Keithley 237 high voltage source measure unit for the high voltage rectifier displaying large standoff voltage.

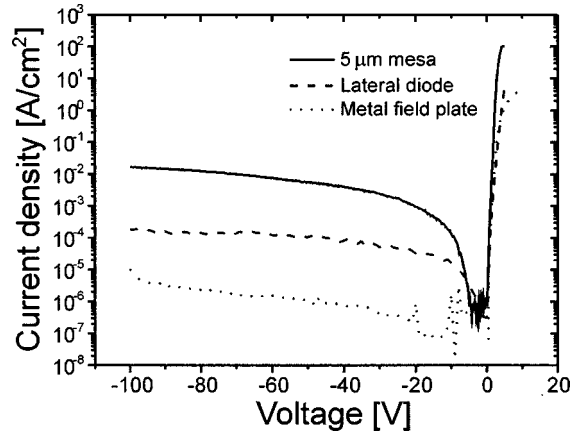

FIG. 3. $I-V$ curves obtained with the HP 4156A precision semiconductor parameter analyzer for the three device geometries discussed above. In all three data sets the Schottky contacts were squares with 100 μm sides.

The electric field crowding at the edges and corners of the Schottky contact will reduce the effective barrier height and increase the reverse leakage current. This can also lead to premature breakdown due to nonuniform current spreading and excessive heating of the device, as can be observed in Fig. 4. To improve the Schottky contacts, we fabricated metal field plate contacts using SiO_2 as an insulator.[16] The edge of the Schottky contact overlaps sputtered SiO_2, thereby reducing electric field crowding at edges and corners.[16] In this case, as can be observed from Fig. 3, measured saturation current at a reverse bias of 100 V was approximately 10^{-5} A/cm^2, an improvement of two orders of magnitude when compared to the saturation current density of diodes with lateral contacts.

From the experimental results, we find the critical field for electric breakdown to be $(2.2\pm0.7)\times10^6$ V/cm by using the formula for the punch-through diode,[16] $V_{PT}=E_{CR}W-qN_dW^2/2\epsilon_0\epsilon_r$, and substituting measured values. This is

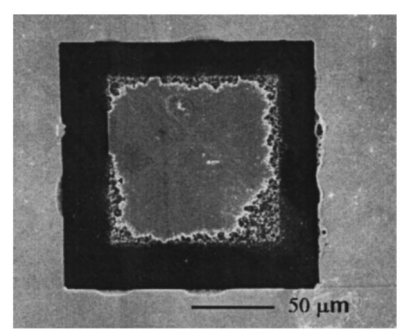

FIG. 4. Scanning electron microscope (SEM) photo of the Schottky contact of a diode after breakdown. The melted Au at its edges and corners indicates premature corner and edge breakdown.

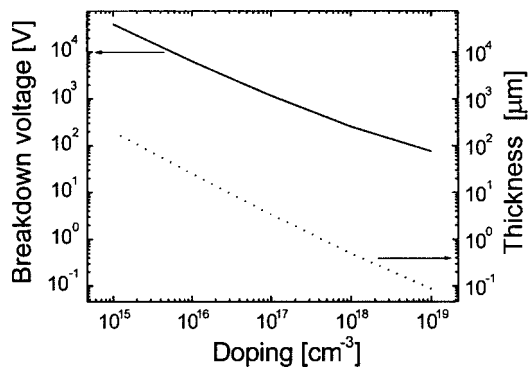

FIG. 5. The calculation of the reverse breakdown voltage of uniformly doped GaN Schottky rectifier based on Ref. 18. For a chosen breakdown voltage one can find corresponding doping concentration (solid line), which further gives required thickness (dotted line). For example, 5 kV Schottky rectifiers can be fabricated using 18 μm thick GaN layers with a doping concentration of approximately $1.5\times10^{16}\,\mathrm{cm}^{-3}$.

in agreement with recent experimental and theoretical predictions[17,18] Since our devices suffered from premature corner and edge breakdown (Fig. 4), and since device geometries were not fully optimized, we conclude that this value of critical field is only a lower limit.

It is of considerable interest to theoretically estimate and optimize the required thickness and doping of the GaN standoff layer in the Schottky rectifier. Smaller required thickness and larger doping will both contribute to smaller resistance and power dissipation. We calculated the reverse breakdown voltage of a uniformly doped GaN Schottky rectifier, by solving: $\int_0^{x_{sc}}\alpha[E(x)]dx=1$, where x_{sc} is the width of the space-charged layer. Ionization coefficients α for electrons (n) and holes (p) in GaN were obtained from Ref. 18 by fitting calculated values of α at large values of electric field, and are: $\alpha=\alpha_n=\alpha_p=2.9\times10^8\exp[-32.7(\mathrm{MV/cm})/E]$. The results of the calculation are shown in Fig. 5. For example, 5 kV Schottky rectifiers can be fabricated using 18 μm thick GaN layers with a doping concentration of approximately $1.5\times10^{16}\,\mathrm{cm}^{-3}$. At the point of reverse breakdown, the electric field is 5×10^6 V/cm, which we can accept as the theoretical maximum value of the critical field. However, the particular device geometry will affect the value of the critical field for electric breakdown.

One of the most important consequences of this study is the experimental demonstration of a high critical field for electric breakdown in GaN. A high critical field indicates feasability of GaN as a material for a variety of unipolar and bipolar devices.[2,3] Furthermore, assuming that the critical field for electric breakdown approximately scales as the square of the band gap, even higher critical fields can be expected for AlGaN. The lack of a suitable conductive GaN substrate which can provide large area back ohmic contact and therefore uniform current spreading, can be circumvented by using highly doped layers underneath the active standoff layer. Although ON-state voltages demonstrated in this work are rather high, our estimates based on the Richardson equation show that the ON-state voltage for a current density of $100\,\mathrm{A/cm}^2$ can be as low as 1–2 V. However, it is necessary to improve Schottky contact edge terminations, reduce ohmic contact resistances and achieve more precise control over doping.

In conclusion, we have fabricated Schottky rectifiers on HVPE-grown GaN which had a standoff voltage of 450 V, a minimum saturation current density of $10^{-5}\,\mathrm{A/cm}^2$ at reverse bias of 100 V, and 4.2 V ON-state voltage at a forward current density of $100\,\mathrm{A/cm}^2$. We have also demonstrated a critical field for electric breakdown in GaN of $(2.2\pm0.7)\times10^6$ V/cm which approaches the theoretical estimate. This value is only a lower limit since the reverse breakdown voltage was limited by premature edge breakdown. Theoretical calculations indicated the possibility of 18 μm thick nitride devices with a 5 kV standoff voltage.

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