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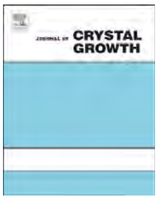

Thick homoepitaxial GaN with low carrier concentration for high blocking voltage

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High voltage GaN Schottky diodes require a thick blocking layer with an exceptionally low carrier concentration. To this aim, a metal organic chemical vapor deposition process was developed to create a (14 μm) thick stress-free homoepitaxial GaN film. Low temperature photoluminescence measurements are consistent with low donor background and low concentration of deep compensating centers. Capacitance–voltage measurements performed at 30 °C verified a low level of about 2×10^{15} cm^{-3} of n-type free carriers (unintentional doping), which enabled a breakdown voltage of about 500 V. A secondary ion mass spectrometry depth profile confirms the low concentration of background impurities and X-ray diffraction extracted a low dislocation density in the film. These results indicate that thick GaN films can be deposited with free carrier concentrations sufficiently low to enable high voltage rectifiers for power switching applications.

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1. Introduction

The combination of a wide bandgap and high thermal conductivity as well as a high electric field breakdown and electron saturation velocity establishes the clear advantages of GaN power diodes over conventional Si-based rectifiers. These advantages also extend over SiC rectifiers, considering GaN's lower on-state resistance for a given breakdown voltage [1,2].

Recently, it was demonstrated that GaN Schottky diodes fabricated on freestanding GaN substrates with simple metal overlap edge termination show reverse recovery time less than 50 ns, low on-state resistance, and low negative temperature coefficient of the breakdown voltage [3]. Such characteristics promote GaN as a promising material for the fabrication of fast switching devices to improve the efficiency of inductive motor controllers and power supplies [4]. However, the strong dependence of the reverse breakdown voltage on device contact diameter indicates that extended and point (impurity, vacancy, etc.) defect densities must be reduced. A theoretical calculation for the breakdown voltage of a GaN punch-through diode indicates that over 1000 V can be achieved with a 5 μm thick blocking layer and a donor concentration of 5×10^{15} cm^{-3} [3]. Experimental results reveal much lower breakdown voltages indicating that processing and growth induced defects are the major contributions for premature breakdown [3]. Zhang et al. [5] demonstrated that vertical devices fabricated with several microns thick homoepitaxial films reach a figure-of-merit (FOM) as high as 48 MW/cm^2, exceeding the 15.5 MW/cm^2 value achieved with optimized planar devices. The inability to deposit GaN films with n-type conductivity significantly lower than a typical value of 2×10^{16} has to date severely limited FOM and breakdown voltage values in unipolar GaN devices [5].

In this work, we report on the fabrication of vertical Schottky diodes using a 14 μm thick GaN drift layer. The GaN film directly deposited on a freestanding (FS) hydride vapor phase epitaxy (HVPE) substrate using low pressure metal organic chemical vapor (LP-MOCVD) displays a remarkably low intrinsic free carrier concentration in the drift layer, which enabled demonstration of a breakdown voltage of approximately 500 V, without any edge termination.

2. Growth and experimental techniques

The GaN film was deposited by LP-MOCVD on a commercial FS HVPE GaN substrate in a closed-spaced showerhead reactor. The GaN substrate was cleaned in trichloroethane, acetone, and methanol for 5 min each in an ultrasonic bath, and then blown dry in N_2. The wafers were then immediately loaded into the MOCVD reactor. Prior to ramping up to the growth temperature for MOCVD deposition of GaN, the flows of palladium-diffused high purity hydrogen and ammonia were initiated into the MOCVD growth chamber held at a total pressure of 50 Torr. The 14 μm thick GaN epitaxial film used in this work was deposited at 1025 °C and 50 Torr (6.7 kPa) with a V/III ratio of 20,000 and a growth rate of ~2 μm/h.

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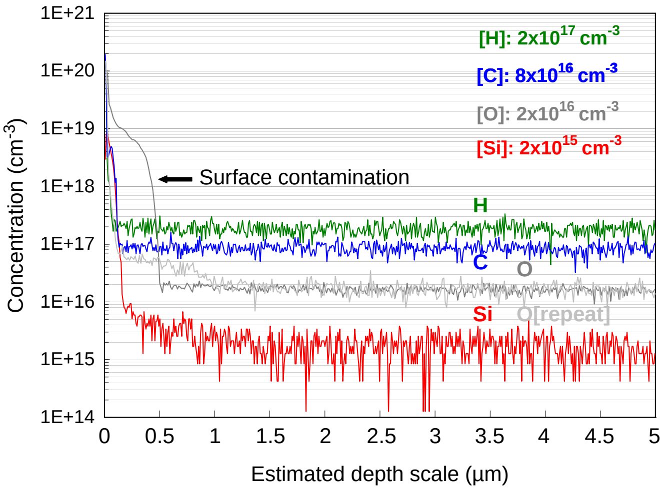

Fig. 1. SIMS impurities depth profile of the homoepitaxial film deposited on the freestanding HVPE GaN substrate.

Secondary ion mass spectrometry (SIMS) depth profiled the top 5 μm of the film. Fig. 1 shows that the hydrogen and the oxygen concentrations are at the detection limit (2×10^{17} cm^{-3} and 1–2×10^{16} cm^{-3}, respectively), while the uniform concentration of carbon and silicon are 8×10^{16} cm^{-3} and 2×10^{15} cm^{-3}, respectively (the detection limit of carbon and silicon in this experiment are 1–2×10^{16} cm^{-3} and 6×10^{14} cm^{-3}, respectively). This impurity trace analysis indicates that a low background impurity level in homoepitaxial films, a requirement for high breakdown blocking layers of fast switches, can be achieved by a MOCVD system.

X-ray diffraction (XRD) and Raman scattering (RS) techniques were employed to evaluate the structural properties of the homoepitaxial film. A PANalytical X'Pert X-ray diffraction (XRD) system with a Cu Kα source was used to measure a series of symmetry and skew-symmetric rocking curves to extract the density of screw and edge threading dislocations [7]. The effective sampling depth from Cu Kα at a typical incident angle is approximately 2 μm.

The micron-Raman spectra was acquired with a 0.5 m single spectrometer equipped with a 1800 groves/mm grating and a liquid nitrogen cool back-thinned/deep-depleted CCD sensitive in the visible–near IR spectral range. The sample was illuminated with the 532 nm line of a solid-state laser and typically spot size of 1 μm and laser intensity of about 5 mW were employed for this experiment. Polarizers were used to control the laser polarization and select the scattering geometry.

The 5 K low- and high-resolution photoluminescence (PL) measurements were carried out to verify the dominant recombination processes to obtain insights on the optical and electronic properties of the epitaxial film. The luminescence was excited with the 325 nm line of a He–Cd laser, and the laser excitation intensity was kept between 1 and 2 mW, using calibrated neutral density filters. The collected luminescence was dispersed by a double grating spectrometer fitted with 1800 groves/mm. The spectra were acquired with a UV-sensitive GaAs photomultiplier tube coupled with a computer controlled photon counter.

The higher conductivity of the FS HVPE GaN substrate compared to the MOCVD film prevented useful extraction of mobility and carrier density information via a Hall measurement technique. Rather, carrier concentration data was obtained using high frequency capacitance–voltage measurements, which relied on AC modulation of a depletion region accessed through a reverse-biased Schottky contact. The Schottky contacts were deposited on the top side of the epitaxial layer by e-beam evaporation of 20 nm thick Ni layer, followed by 200 nm thick Au layer. No post-evaporation annealing was performed. The diameters of the circular contacts were 100, 300, 1000, and 3000 μm and no termination scheme was employed. Contact to the backside was achieved with a gold metal gasket. Capacitance–voltage measurements were performed at 100 kHz and 1 MHz, respectively, using a Keithley 590 LCR meter. A sweep of the gate voltage from accumulation to depletion and vice versa did not reveal the presence of any capacitance hysteresis, which indicated that no Ga-rich oxide was formed during MOCVD growth. Breakdown voltage measurements were performed by supplying a linear voltage ramp and recording the device current using a Keithley 237 source-measurement unit.

3. Characterization results and discussions

It has been shown that extended defects increase reverse-bias leakage current and reduce blocking voltage [6]. Therefore, it is important to find out the concentration of these defects in the device blocking layer. The two most common defects in GaN are threading edge and threading screw dislocations. The density of threading edge dislocations tends to be more order of magnitude greater than threading screw dislocations and the screw component is often integrated with an edge dislocation as a mixed dislocation.

Screw dislocations in *c*-axis GaN create a tilt of the lattice planes parallel to the surface and can be easily examined with symmetric (0 0 1) XRD rocking curves. Edge dislocations create a twist that can only be directly isolated in XRD with a grazing incidence beam, which is an experimentally challenging technique. Skew-symmetric XRD reflections taken at interplanar angles approaching grazing incidence can approximate this technique; however these rocking curves, e.g., the (3 0 2) reflection at 70.45° interplanar angle, also have contributions from the screw dislocations. Additionally, the peak broadening of the skew-symmetric XRD reflections is further complicated by interactions between the screw and edge dislocations as well as the limited correlation lengths common for GaN films grown on sapphire substrates. Recently, several models have been developed to extrapolate the contribution of tilt, twist, and correlation length in GaN films for a series of XRD symmetric and skew-symmetric ω-scans [7]. Lee et al. [8] employs a peak fitting parameter, n, to assess the contribution from Lorentzian ($n=1$) to Gaussian ($n=2$) curve shape in the rocking curves. A fit to the rocking curves as well as an extrapolation to 90° can be made with $\beta_{hkl}^{n}=(\beta_{\text{tilt}}\cos X)^{n}+(\beta_{\text{twist}}\sin X)^{n}+(1/L)^{n}/|K_{hkl}|^{n}$, where X is the interplanar angle, and $|K_{hkl}|^{n}$ is the magnitude of the reciprocal scattering vector. Similar to the analysis of Lee et al. [8] we found that the GaN thick films in the present work had negligible correlation length and could be optimally fitted with a Gaussian curve shape. Overall the diffraction peaks were sharp indicating a low dislocation density. This low dislocation density combined with the apparent lack of distinct grains justified the use of the Dunn and Koch model for random distribution in a crystal, $D_{\text{B}}=\beta^{2}/4.35b^{2}$, where b is the length of the Burgers vector [9]. This analysis, visualized in Fig. 2. extracted a screw and edge dislocation densities of 7.1×10^{6} and 3.1×10^{7} cm^{-2}, respectively, which indicates a reduced concentration of dislocation densities in the homoepitaxial layer compared to the typical HVPE substrates used in this experiment.

The first order Raman scattering spectra measured in cross-sectional geometry for both the homoepitaxial film and the HVPE substrate, which separates the contribution from each region, are represented in Fig. 3. Note that the perfect overlap of all the phonon lines indicates a stress-free epitaxial film. Raman

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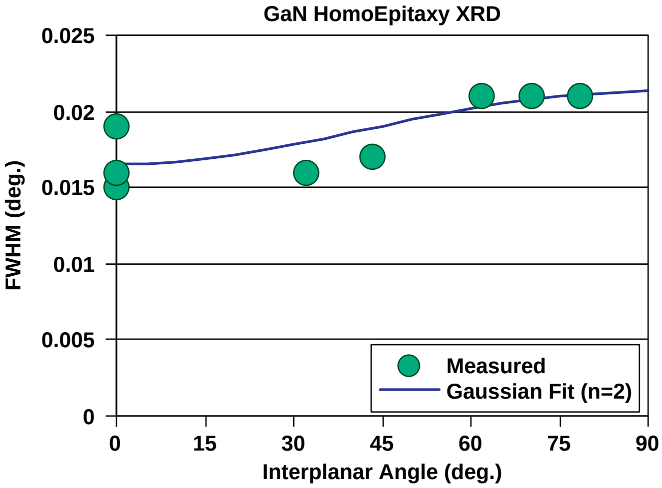

Fig. 2. Graphical representation of the fitting of XRD rocking curve line width measured at different interplanar angles, employed to extract screw and edge dislocation densities.

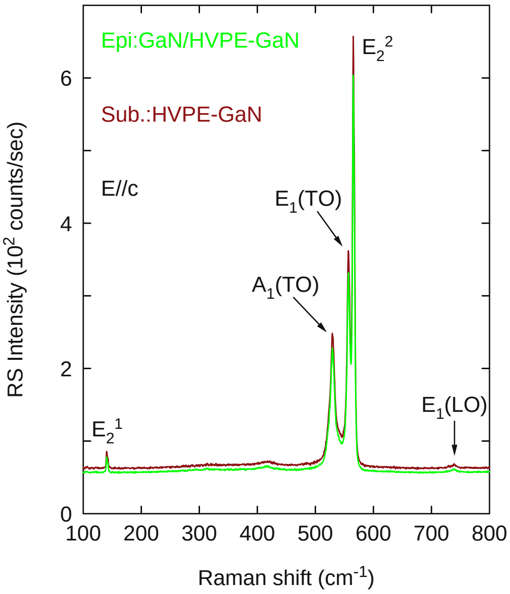

Fig. 3. Room temperature Raman spectra of the MOCVD epitaxial film (green) and the HVPE substrate (red) measured in cross-sectional geometry. The perfect alignment of the phonon in both spectra confirms the absence of biaxial stress. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

scattering with the $z(xy,xy)\bar{z}$ geometry (not represented) shows a sharp A_1(LO) phonon with symmetric lines shape, which is consistent with residual free-carrier concentration below the detection limit of 10^{16} cm^{-3} of this technique [10].

The low temperature PL study is summarized in Fig. 4. The low-resolution spectrum covering the spectral range from 1.82 to 3.65 eV is dominated by an intense sharp line around 3.47 eV, represented by near bandedge emission (NBE), associated with the recombination processes involving the annihilation of free excitons and excitons bound to neutral donors [11]. Also observed two relatively weak bands at 2.25 eV and at 3.1 eV represented in the figure by “yellow band” and “violet band”, respectively. The former is a weak well-known yellow band and the latter has been assigned to carbon acceptor impurity in GaN [12]. Similar spectra have been often observed in unintentionally doped (UID) GaN

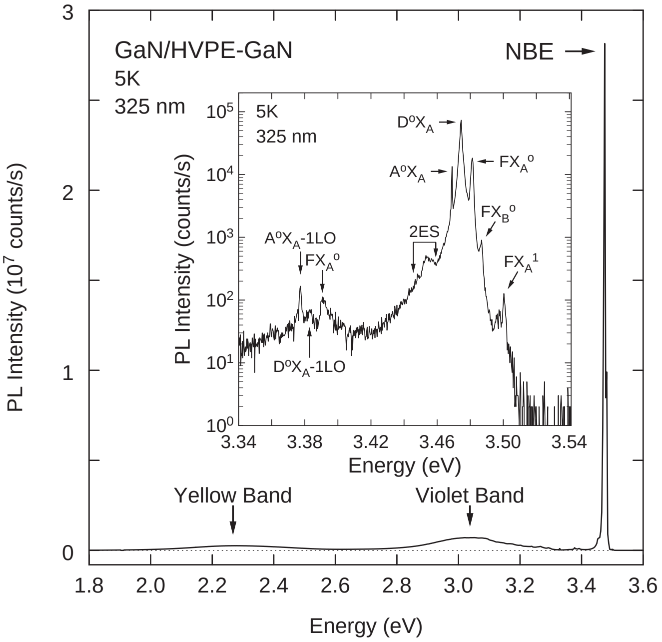

Fig. 4. Low temperature and low resolution PL spectrum of the homoepitaxial film measured at the film surface. The inset depicts the low temperature and high resolution spectrum of the NBE.

films characterized by high resistivity and large breakdown voltage [13]. Therefore, it is expected that these defects partially compensate the free carrier associated with the unintentional oxygen and silicon shallow donors in GaN. The high-resolution spectrum of the near bandedge emission is highlighted in the inset of Fig. 4, which depicts the PL spectrum between 3.34 and 3.54 eV. This spectrum shows emission lines related to the ground state of the free-exciton B (FX_B), the ground state and the first excited state of the free-exciton A (FX_A and FX_A^1, respectively), the dominant exciton bound to neutral donors ($S_i^0X_A$ and O^0X_A), and the exciton bound to a shallow unknown neutral acceptor A^0X_A. The line assigned to Si donor ($S_i^0X_A$) is only a shoulder at the higher energy side on the exciton bound to the shallow donors (D^0X_A), which is consistent with low incorporation of Si and/or compensation by the deep compensating centers, since Si is the shallower donor. Around 3.45 eV we detect the so-called two-electron satellite (2ES) spectrum resulting from the recombination processes that leave neutral donors in an excited state after the exciton annihilation. Spectral separations between D^0X_A and 2ES lines yield the intra-center transition energies of the impurities. Note that for energies below 3.42 eV, we observe one-phonon replicas of all features listed above, represented as (FX_A^0, D^0X_A, A^0X_A) 1LO. The presence of a number of sharp lines in such a small spectral range confirms the high quality and low background concentration of neutral shallow donor impurities, which are responsible for the room temperature free carrier concentration of the epitaxial film. These observations are consistent with the SIMS and Raman scattering results.

To obtain reliable information of the concentration and type of free carriers in the epitaxial film capacitance–voltage measurements were carried out at room temperature. The n-type free carrier concentration up to 2×10^{15} cm^{-3}, represented in Fig. 5 inset, was extracted from the 100 kHz curves using standard carrier concentration profiling methods [14]. The low level of unintentional doping, attributed to shallow silicon and oxygen donors, was consistent with the SIMS depth profile and the PL analyses (note that the SIMS concentration of carbon is larger

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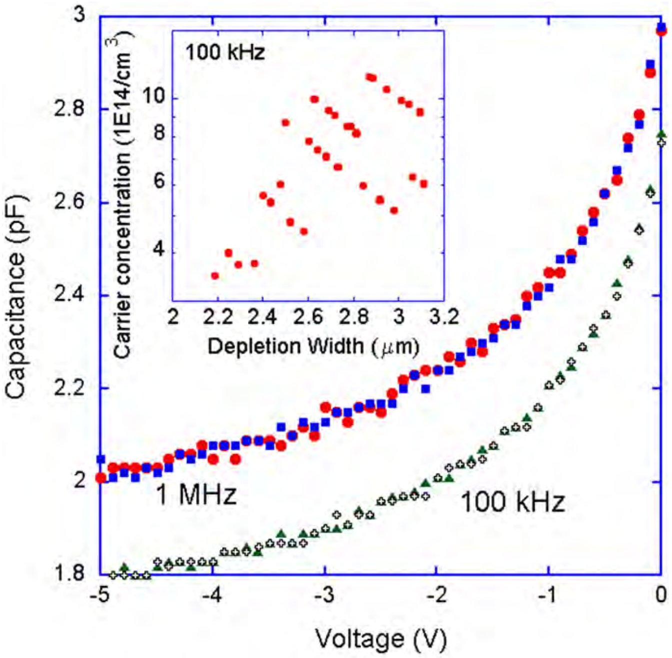

Fig. 5. Capacitance–voltage measurements acquired with 300 μm diameter contacts at 100 kHz and 1 MHz. Circle (red) and triangle (green) symbols indicate gate voltage sweep direction from accumulation to depletion. Square (blue) and cross (black) indicate sweep direction from depletion to accumulation. The room temperature free carrier concentration is represented in the inset. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

than the measured free carrier concentration, indicating that not all the carbon are electrically active), and resulted in measured breakdown voltage V_{BR} of 500 V at 30 °C in 100 μm Schottky devices fabricated from this material. Here, we defined V_{BR} as the voltage at which the reverse current level of the diode reached the instrument compliance limit of 1 μA. The breakdown voltage for larger diameters Schottky contacts was approximately inversely proprotional to the area, indicating that the breakdown is dominated by threading defects rather than edge effects.

This preliminary result establishes that thick GaN drift layer can be fabricated with low carrier and dislocation densities to enable high V_{BR} vertical conduction devices. The vertical device discussed in this manuscript used Schottky contacts and it is reasonable to expect that proper edge termination would significantly increase the blocking voltage of the device. Nevertheless, for GaN Schottky diodes to operate above 10 kV would require a decrease in the carrier concentration below 10^{15} cm^{-3} and an increase in the thickness for the blocking layer to 50 μm. It has been reported that due to the crystalline morphology of heteroepitaxial GaN films, vertical geometry GaN-based Schottky barrier diodes have better performance than the ones with lateral configuration. This results directly from the reduction of electron scattering by charged dislocations during vertical electrical transport [2].

4. Conclusion

A thick GaN drift layer has been synthesized with low carrier and dislocation densities suitable for high V_{BR} vertical power devices. XRD study of the homoepitaxial film indicated a low density of edge and screw dislocations, which are source of leakage current in vertical devices. Comparison of the first order Raman spectra of the epitaxial film to the substrate, measured in cross-sectional geometry, is consistent with stress-free film deposition. The smaller relative intensity of the photoluminescence lines associated with recombination process involving the annihilation of excitons bound to neutral shallow donors to that associated with the annihilation of free excitons and the small intensity of the deep emission bands related to compensation centers strongly indicates a low intrinsic background of shallow donor in this homoepitaxial film. This observation supports the C–V experimental results, which measured a RT concentration of 2×10^{15} cm^{-3} of n-type free carriers.

This work demonstrates that a thick epitaxial GaN film deposited on freestanding HVPE GaN is a potential platform for the fabrication of high voltage unipolar power devices.

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