VERTICAL TRANSPORT PROPERTIES OF GaN SCHOTTKY DIODES GROWN BY MOLECULAR BEAM EPITAXY

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ABSTRACT

Lateral and vertical electron transport parameters were investigated in lightly doped n-GaN films, grown by MBE. Diodes were fabricated by forming Schottky barriers on n^--GaN films using a mesa-etched vertical geometry. Doping concentrations and barrier heights were determined, from C-V measurements, to be 8-9x10^{16} cm^{-3} and 0.95-1.0 eV respectively. Reverse saturation current densities were measured to be in the 1-10x10^{-9} A/cm^2 range. Using the diffusion theory of Schottky barriers, vertical mobility values were determined to be 950 cm^2/V-s. Lateral mobility in films grown under similar conditions was determined by Hall effect measurements to be 150-200 cm^2/V-s. The significant increase in mobility for vertical transport is attributed to reduction in electron scattering by charged dislocations.

INTRODUCTION

Lateral transport in lightly doped n-GaN thin films has been extensively studied, most often by using Hall effect measurements. These studies indicate that electron transport in the lateral direction is dominated by scattering from charged dislocations, which serves to reduce the electron mobility.[1-2] Based on this model, transport in the vertical direction should be relatively unaffected by the presence of the threading dislocations and electron mobility should be significantly increased. Since a large number of GaN devices, including lasers, LEDs, detectors and bipolar junction transistors [3-5], have vertical geometry, it is important to investigate electron mobility in this direction to better understand and engineer device performance.

In this paper we have used Schottky barrier diodes, fabricated with a vertical geometry on lightly doped n-GaN films grown by ECR-MBE, to investigate electron mobility for vertical transport. The diodes were evaluated by I-V and C-V measurements to determine diode ideality, reverse saturation current, doping concentration and barrier height. Using the diffusion model for current transport in Schottky barriers, mobility for vertical transport was determined. The results are compared with lateral electron mobility determined by Hall Effect measurements.

EXPERIMENTAL METHODS

The GaN films were grown on c-plane sapphire, by plasma-assisted molecular beam epitaxy, following procedures described earlier.[5] In this paper we present only a brief description. Prior to introduction into the growth chamber, the substrates were subjected to solvent degreasing. The Al_2O_3 surface was converted to AlN by exposing the substrate, held at 800 °C, to nitrogen plasma using an electron cyclotron resonance (ECR) microwave plasma source. This step was followed by the deposition of 1000 Å

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AlN buffer. Two types of devices (Figure 1) were investigated. In the first, 2.25 µm thick n^+ GaN ($2x10^{18}$ cm^{-3}) was deposited first, followed by a n^- GaN ($1x10^{17}$ cm^{-3}) of about the same thickness.The second device consists of 4 µm thick n- GaN ($1x10^{17}$ cm^{-3}). All the layers were grown under Ga rich conditions. RHEED patterns, taken during growth of the n-GaN layers, showed 2x2 surface reconstruction, indicating that the films were grown with the Ga-polarity.[6]

Circular mesas, approximately 3 µm deep and 300 µm in diameter, were defined on both samples by reactive ion etching, using Cl_2 gas. Ohmic contacts were defined on the bottom of the mesa by electron beam deposition of 200/1000/200/2500Å Ti/Al/Ni/Au metal multilayers. The Ohmic contacts were rapid thermal annealed at 750°C for 60 seconds, prior to deposition of the Schottky contacts. Schottky contacts were formed at the top of the mesa by patterning 200 µm dots by photolithography and depositing a 200/1000/3000Å Ni/Pt/Au metal multilayer stack by electron beam evaporation. Some of the diodes were mounted on transistor headers and Au wires were bonded to the contacts by thermosonic bonding. Figure 1 shows a schematic illustration of the two types of samples reported in this paper.

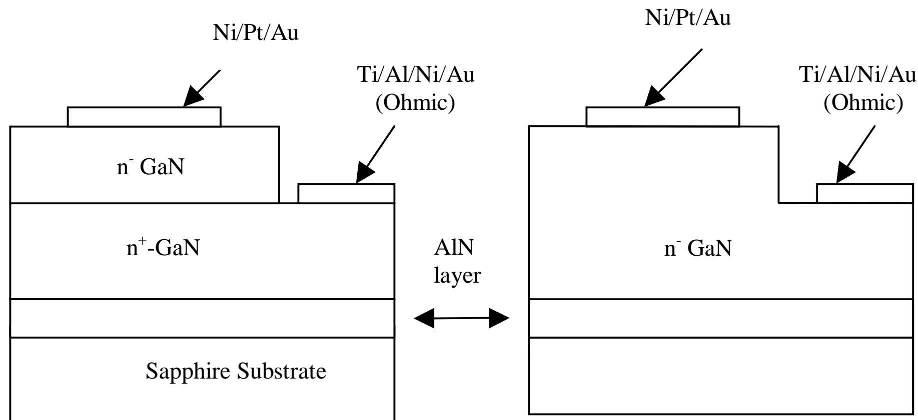

Figure 1: Schematic illustration of the two types of devices investigated.

Hall Effect measurements were performed on the n-GaN films by the Van der Pauw method, using indium contacts in the clover leaf configuration. Current–voltage characteristics were measured using the HP 4155A semiconductor parameter analyzer. Capacitance-voltage measurements were performed using the HP 4275A LCR measurement system. For some of the type II devices, Ohmic contacts were deposited at the top and bottom of the mesas, and their I-V characteristics were evaluated.

EXPERIMENTAL RESULTS

The current voltage characteristics for the structures with Ohmic contacts at both ends are shown in Figure 2. The resistance of the devices was measured to be in the 3-10 Ω range. In order to investigate the origin of this resistance, I-V measurements were performed as a function of temperature. The resistance was found to slightly increase

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with temperature, while our evidence from planar Hall effect measurements indicate that the resistance decreases with temperature. This suggests that the measured resistance in the vertical direction using two ohmic contacts is dominated by the contacts rather than the bulk GaN resistance. From the data of Fig. 2, the specific contact resistivity was estimated to be on the order of 10^{-3} Ω*cm^2. Such values of contact resistivity for lightly doped GaN layers are quite typical [7]. This observation has important implications for vertical devices with high-mobility layers because it indicates that in order to obtain the maximum current carrying capacity of the active layer, the Ohmic contact resistance must be brought down by several orders of magnitude.

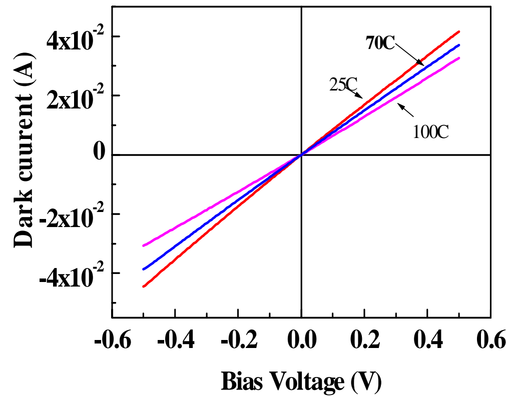

Figure 2: I-V characteristics of veritical GaN resistors measured as described in the text at different temperatures.

Typical current voltage characteristics of the two types of Schottky barrier diodes investigated are shown in Figure 3.

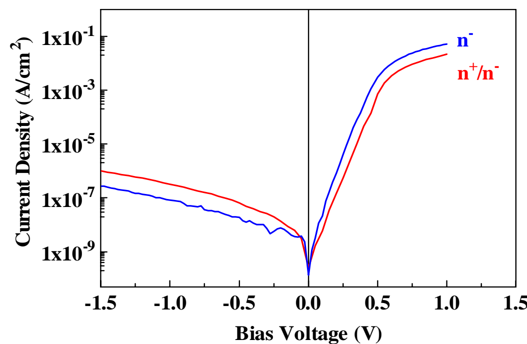

Figure 3: Typical I-V characteristics of the two types of Schottky barrier diodes

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In the forward direction the data can be fitted to Eq. 1. where J_o is the saturation current density and n is the ideality factor. Applying Eq. 1 to the data of Figure 3, we find that the diodes are practically ideal (n=1.15-1.2) and the value of the reverse saturation current densities for the n^+/n^- and n^--GaN samples are 1.08 x10^{-9} A/cm^2 and 1.0 x10^{-8} A/cm^2 respectively. A number of devices were probed on each wafer, and found to give very good uniformity over an area approximately equal to a quarter of a 2" wafer.

$$J = J_0 \exp(\frac{qV}{nkT}) \tag{1}$$

Results of the capacitance-voltage measurements are shown in Fig. 4. The doping concentration and barrier height were determined from the C-V measurements, using the following equation [8]:

$$\frac{1}{C^2} = \frac{2}{A_e^2}\left(\frac{(V_{bi} - V)}{q\varepsilon_s N_d}\right) \tag{2}$$

where C is the measured capacitance, V is the applied voltage, V_{bi} is the built-in voltage, ε_s is the dielectric constant, N_d is the doping concentration and A_e is the geometric area of the device. The barrier height is given by

$$\phi = \left(V_{bi} + \left(\frac{kT}{q}\right)\ln\left(\frac{N_c}{N_d}\right)\right) \tag{3}$$

where N_c is the effective density of states in the conduction band.

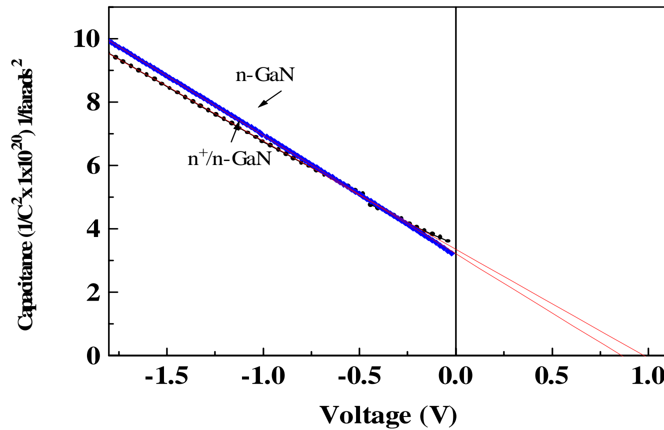

Figure 4: C-V plots for the two types of Schottky barrier diode structures investigated.

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The doping concentration and barrier height obtained by fitting the data of Fig. 4 to Eqs. (2) and (3), were determined to be $9x10^{16}$ cm^{-3} and 1.0 V for the n^+/n^--GaN diode, $8.4x10^{16}$ cm^{-3} and 0.95 V for the n^--GaN diode. These results are in general agreement with those reported earlier. [9-10] A number of devices, fabricated on the same wafer were tested and were found to give similar values of barrier heights, doping concentration and reverse saturation current densities.

DISCUSSION

The carrier concentration in the two types of samples was determined by measuring the Hall effect on the n^--GaN films as well as by measuring the capacitance voltage characteristics of both types of Schottky barrier diodes.

From the Hall effect measurements, the carrier concentration of the n^--GaN film was determined to be 1.4 $x10^{17}$ cm^{-3} and the lateral mobility (μ_l) was 160 cm^2/V-s. Although the dislocation densities in these particular samples have not been measured, from measurements on samples grown under similar conditions, the threading dislocation density is estimated to be in the range of 5-$10x10^9$$cm^{-2}$. As discussed previously, the lateral electron mobility in our samples attains its highest value at 300-400 cm^2/V-s at carrier concentrations of 3-$5x10^{17}$ cm^{-3} and then it reduces at lower carrier concentrations. This result was accounted for by scattering from negatively charged dislocations [1,2].

In order to investigate the electron mobility for vertical transport, the diffusion theory of Schottky barriers, which expresses the relation between the reverse saturation current as a function of barrier height and the diffusion coefficient of electrons in the space charge region was employed. According to this model, the reverse saturation current density is given by the relation [11]

$$J_0 = \left\{ qN_c \mu_v \left[\frac{2qV_{bi} N_d}{\varepsilon_s} \right]^{1/2} \right\} \exp\left(\frac{-q\phi}{kT} \right) \quad (4)$$

where μ_v is the electron mobility in the vertical direction. Using the values of J_0, N_d, ϕ and V_{bi} in Eq. (4), we obtain a vertical mobility of μ_v=932 cm^2/V-s for the n^+/n^-GaN and μ_v =949 cm^2/V-s for the n^--GaN film.

In the calculation of the vertical mobility, we have assumed that the active area is equal to the geometric area of the device. A reduction of the active area (up to one-third for dislocation density of $5x10^9$ cm^{-2} and doping concentrations of $1x10^{17}$$cm^{-3}$) is expected due to depletion around each charged dislocation. Specifically, considering the active area to be two- thirds the geometric area, increases the doping concentration and reverse saturation current density to be $1.9x10^{17}$ cm^{-3}, $1.62x10^{-9}$ A/cm^2 respectively for the n^+/n^- device. This leads to a vertical mobility of 1070 cm^2/V-s for the same device. These results are in good agreement with Monte-Carlo calculations for electron mobility in GaN thin films.[2]

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CONCLUSIONS

Investigation of lateral and vertical transport in n^--GaN films indicates that for samples doped at the level of $1x10^{17}$ cm^{-3}, the vertical mobility is more than six times higher than the lateral mobility. This result is attributed to the reduction of electron scattering by charged dislocations during vertical transport.

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