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Study of interface barrier of SiN$_x$/GaN interface for nitrogen-polar GaN based high electron mobility transistors

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The SiN$_x$/GaN interface barrier height for N-polar GaN based metal-insulator-semiconductor high electron mobility transistors (MISHEMTs) was investigated. N-polar SiN$_x$/GaN/AlGaN/GaN MISHEMT structures with different GaN cap thicknesses were grown by metal-organic chemical vapor deposition. The properties of the SiN$_x$/GaN interface are of critical importance to device operation and modeling in these devices. An analytical expression for the pinch-off voltage of the HEMT was obtained, and capacitance-voltage (C-V) measurements with different Schottky metals were used to extract the barrier height. The Fermi level at the interface was found to be pinned at approximately 1 eV with respect to GaN conduction band edge, irrespective of the work function of the gate metal. Hall measurements of the two-dimensional electron gas density were found to corroborate the predicted interface barrier height. An approximate value for interface charge causing this pinning was calculated to be $4.5 \times 10^{12}$ cm$^{-2}$. © 2008 American Institute of Physics.

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I. INTRODUCTION

AlGaN/GaN based high electron mobility transistors (HEMTs) have been of interest to the semiconductor community because of their high breakdown voltage, high sheet carrier density, and the high saturation velocity of GaN.$^2$ Owing to these properties GaN based HEMTs are especially attractive for power devices$^3$ and for improved device structures$^4$ for millimeter-wave applications.

Epitaxial growth of wurtzite GaN can be done in (0001) or (000\bar{1}) direction giving rise to Ga- or N-polarity, respectively.$^5$ In the past, most device researches focused on Ga-polar devices, while N-polar device structures received little attention due to several growth related issues. However, there are several advantages associated with N-polar GaN based devices as compared to Ga-polar, such as lower contact resistance,$^6$ better electron confinement,$^7$ low gate leakage, low dispersion devices, and enhancement mode operation. Progress has been made toward improving the growth techniques for N-face GaN by both molecular-beam epitaxy$^8$ and metal-organic chemical vapor deposition (MOCVD),$^{10}$ including several experiments to understand its chemical nature, electrical properties, and the demonstration of first AlGaN/GaN transistor devices.$^{11,12}$

The pinning of the Fermi level at the surface of N-polar GaN is an important parameter for device design and simulations. Due to opposite polarity and surface termination, surface properties of N-polar GaN are expected to be different from Ga-polar GaN. Several groups have calculated for surface pinning for N-face GaN,$^{13-16}$ but there is significant scatter in the data, possibly due to the variation of the surface properties. To address this issue we have stabilized the N-polar GaN surface with a SiN$_x$ layer grown in situ by MOCVD and systematically studied the interface barrier height at the SiN$_x$/GaN interface for application in a GaN/AlGaN/GaN metal insulator semiconductor HEMT structure [Fig. 1(a)]. The thin MOCVD SiN$_x$ under the gate also reduced the gate leakage. In these devices the charge and device operation is dependent on the SiN$_x$/GaN interface barrier, as shown in Fig. 1(b). Following the methodology developed for Ga-polar GaN,$^{17}$ we studied the surface pinning for the N-polar GaN in a HEMT structure and its dependence on the Schottky metal. By analyzing the electrostatics of the structure, an analytical expression for the pinch-off voltage was obtained. The interface barrier was then extracted by comparing the analytical expression to the experimental pinch-off voltage of the device extracted from capacitance-voltage (C-V) measurements.

II. EXPERIMENT

The HEMTs used in this letter were grown by MOCVD on Al$_2$O$_3$ substrates with a misorientation of 4° toward the a-sapphire plane, enabling the growth of smooth (Al,Ga)N films by MOCVD.$^{10}$ The samples consisted of a 1.4-μm-thick semi-insulating Fe-doped GaN base layer, followed by 140 nm of unintentionally doped GaN, a 27-nm-thick Al$_x$Ga$_{1-x}$N barrier with $x=0.21 \pm 0.01$, and unintentionally doped GaN cap layers with varying thicknesses (9, 22, and 32 nm for three different samples). After the deposition of the GaN cap layer, a 5-nm-thick Si$_3$N$_4$ layer was grown at 1020 °C using disilane and ammonia flows of 0.45 μmol/min and 90 mmol/min, respectively. The Si$_3$N$_4$ growth rate was determined from ~0.8-mm-thick Si$_3$N$_4$ calibration samples. Details related to the growth of the N-polar GaN and GaN/AlGaN/GaN heterostructures were reported in Refs. 10 and 12. The Al mole fraction and thickness of the
AlGaN layer were determined by high resolution x-ray diffraction. The microstructure of the samples was evaluated by transmission electron microscopy (TEM) with a FEI Tecnai 20 operated at 200 kV. Cross-sectional TEM samples were prepared by mechanical polishing followed by Ar+ ion milling to confirm the thickness of the GaN and AlGaN layers for the sample with a 32.4-nm-thick GaN cap (Fig. 2). The GaN cap layer thickness of the other two samples was scaled according to the GaN growth time. An accurate measurement of the layer thickness is crucial for the electrostatic calculations.

The fabrication of the diodes started with the definition of the source and drain contacts using optical lithography. An e-beam evaporator was used to deposit a Ti/Al/Ni/Au multilayer stack for Ohmic contacts. The contacts were annealed at 870 °C for 30 s in N2 ambient using a rapid thermal annealer. The isolation of the transistors was obtained by reactive ion etching using chlorine-based chemistry. Schottky diodes of 100 μm diameter were defined by optical lithography, and a M/Au/Ni metal stack was used as the Schottky contact where different Schottky metals (M), Ni, and Pt, were deposited on different dies on each sample. C-V measurements were performed using a Keithley 590 CV analyzer. The sheet carrier density as a function of voltage was determined from the area under the C-V curve (Fig. 3). The pinch-off voltages for both Ni and Pt gates for each sample were calculated by extrapolating the linear part of the electron density curve.

III. ANALYSIS AND RESULTS

The gate voltage applied on the capacitor is divided between the SiNx insulator and the GaN cap layer (see Fig. 3). The voltage drop in the GaN (Vgp) as a function of the applied gate voltage (Vp) at pinch off can be written as

$$V_{gp} = V_p \left. \frac{C_{tot}}{C_{GaN}} \right|_{V=v_p},$$

where $C_{tot}$ is the measured capacitance of the structure and $C_{GaN}$ is extracted from $C_{tot}$ by eliminating the capacitance of SiNx.

It has been observed that there is significant impurity incorporation in N-face GaN and AlGaN grown by MOCVD. Hence, the effect of unintentional doping ($N_D$) in GaN and $N_{D2}$ in AlGaN) must be taken into account while calculating the pinch-off voltage. Including these values, the expression for the pinch-off voltage for the device shown in Fig. 4 is given as

![Figure 1](image1.png)

**FIG. 1.** (a) Schematic diagram of the epitaxial layer structure and (b) band diagram of a standard N-polar GaN/AlGaN/GaN HEMT used in this study.

![Figure 2](image2.png)

**FIG. 2.** TEM image of the N-polar GaN/AlGaN HEMT showing the layer structure. The thickness of the GaN cap was measured to be 32.4 nm.

![Figure 3](image3.png)

**FIG. 3.** Measured 2DEG density of the N-face HEMT with Ni gate as a function of voltage as determined from the C-V measurements.

![Figure 4](image4.png)
The interface barrier height $V_{gp}$ can also be calculated from the dependence of the two-dimensional electron gas (2DEG) density $n_s$ on the GaN cap thickness. The expression for the 2DEG density $n_s$ at zero gate voltage is given as

$$q n_s = -\frac{\varepsilon_{GaN} \varphi_B}{d_{GaN}} - \frac{\varepsilon_{AlGaN} E_{GaN}}{d_{AlGaN}} + q N_{D1} d_{GaN} + Q_{net} + \frac{q N_{D2} d_{AlGaN}}{2}.$$  

The 2DEG density was determined by room temperature Hall measurements. The value of the interface barrier height, $\varphi_B$, was calculated by fitting the measured $n_s$ values for different GaN cap thicknesses using Eq. (3), as shown in Fig. 6. The resulting barrier height was 0.95 eV, similar to the previously calculated value.

These results may be explained by the presence of interface states at the GaN/SiN$_x$ junction that pins the electron Fermi level close to 1 eV. An approximate value for the interface charge causing the Fermi level pinning can also be calculated from the results of this experiment. The difference in electric field in SiN$_x$ for Ni and Pt Schottky contacts can be calculated to be $1.08 \times 10^6$ V/cm. This change in electric field corresponds to an additional interface charge of $4.5 \times 10^{12}$ cm$^{-2}$. This calculated interface charge is due to interface states in the GaN band gap, which are contained in an energy range of 0.21 eV around the measured Fermi level pinning of 1 eV from the GaN conduction band edge.

IV. CONCLUSION

In this letter, C-V measurements have been used to directly measure the interface barrier at the SiN$_x$/GaN interface for N-polar HEMTs. The unintentional doping in the GaN and AlGaN layers was taken into account in the analysis. The interface barriers were found to be 0.97 and 1.18 eV for Ni and Pt metals, respectively. The barrier height calculated from Hall measurements was 0.95 eV. These results indicate the presence of interface states at the SiN$_x$/GaN interface pinning the Fermi level to around 1 eV. An approximate value for interface charge is calculated to be $4.5 \times 10^{12}$ cm$^{-2}$. Further studies are needed to understand the nature of this trap and to analyze its effect on the 2DEG density.
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