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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 4.5×10^{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[1] 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[8,9] 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_2O_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 $Al_xGa_{1-x}N$ barrier with $x=0.21\pm0.01$, 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_3N_4 layer was grown at 1020 °C using disilane and ammonia flows of 0.45 μmol/min and 90 mmol/min, respectively. The Si_3N_4 growth rate was determined from ~0.8-mm-thick Si_3N_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

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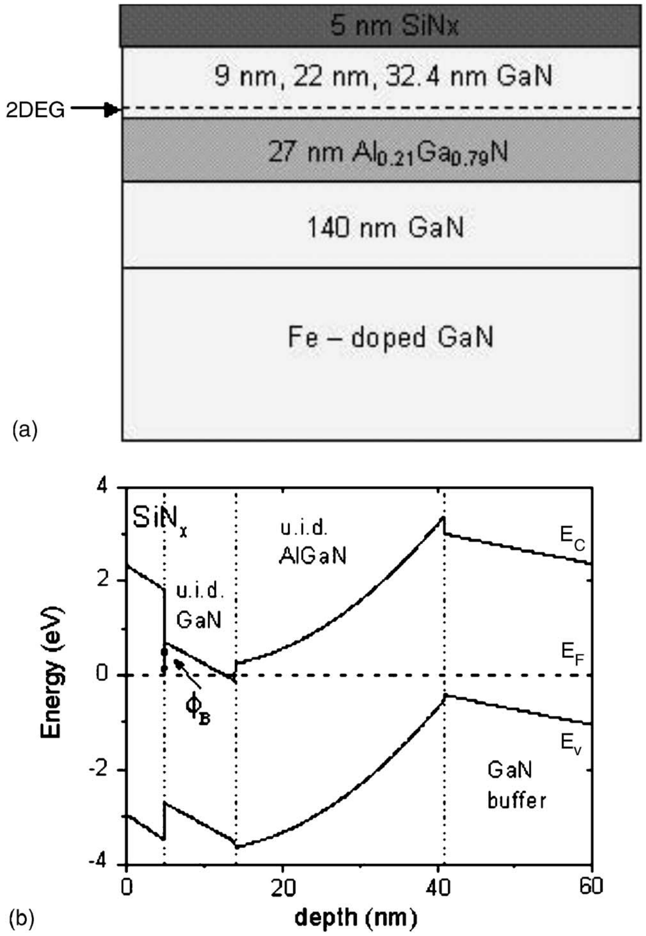

FIG. 1. (a) Schematic diagram of the epitaxial layer structure and (b) band diagram of a standard N-polar GaN/AlGaN/GaN HEMT used in this study.

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 (Gatan PIPS) 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.

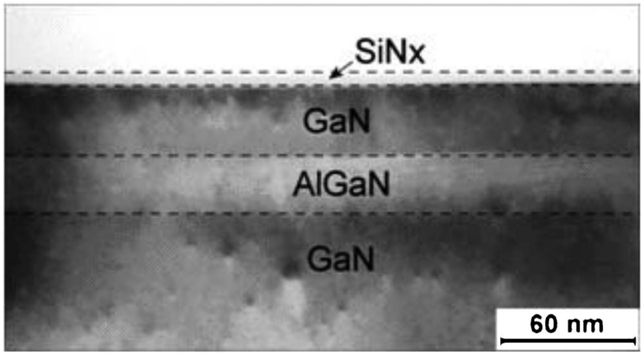

FIG. 2. TEM image of the N-polar GaN/AlGaN HEMT showing the layer structure. The thickness of the GaN cap was measured to be 32.4 nm.

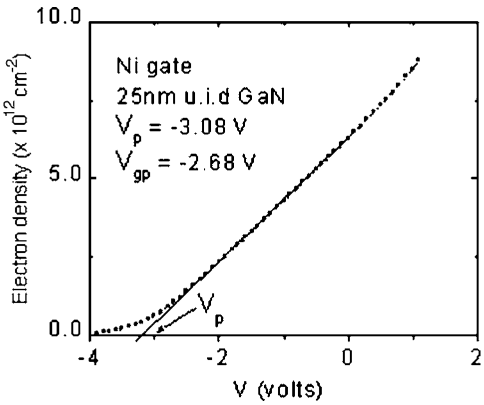

FIG. 3. Measured 2DEG density of the N-face HEMT with Ni gate as a function of voltage as determined from the *C*-*V* measurements.

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 N_2 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 SiN_X insulator and the GaN cap layer (see Fig. 3). The voltage drop in the GaN (V_{gp}) as a function of the applied gate voltage (V_p) at pinch off can be written as

$$V_{gp} = V_p \left. \frac{C_{\text{tot}}}{C_{\text{GaN}}} \right|_{V=V_p}, \tag{1}$$

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

It has been observed that there is significant impurity incorporation in N-face GaN and AlGaN grown by MOCVD.[18] Hence, the effect of unintentional doping (N_{D1} 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

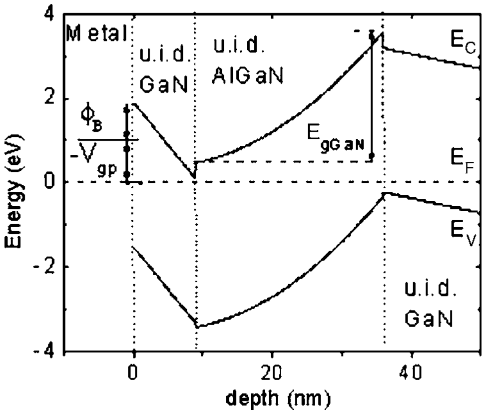

FIG. 4. Band diagram of a GaN/AlGaN/GaN HEMT without SiN_x at pinch off.

$$V_{gp} = \varphi_B + E_{g\mathrm{GaN}}\frac{d_{\mathrm{GaN}}}{d_{\mathrm{AlGaN}}} - \frac{qN_{D1}d_{\mathrm{GaN}}^2}{\varepsilon_{\mathrm{GaN}}} - \frac{Q_{\pi\mathrm{net}}}{\varepsilon}d_{\mathrm{GaN}} - \frac{qN_{D2}d_{\mathrm{AlGaN}}^2}{2\varepsilon_{\mathrm{GaN}}}\frac{d_{\mathrm{GaN}}}{d_{\mathrm{AlGaN}}}, \qquad (2)$$

where φ_B is the interface barrier height and d_{GaN} and d_{AlGaN} are thickness values for GaN and AlGaN layers. $Q_{\pi\mathrm{net}}$ is the net polarization charge at the GaN/AlGaN interface and is calculated from the Al composition by the expression obtained by Miller *et al.*[19] The secondary ion mass spectroscopy (SIMS) analysis of the device structure gave N_{D1} to be $\sim 1\times 10^{17}\ \mathrm{cm}^{-3}$ and N_{D2} to be $(2.8\pm 0.5)\times 10^{18}\ \mathrm{cm}^{-3}$. The AlGaN doping concentration cannot be accurately determined by SIMS due to its limited thickness. The values of φ_B and N_{D2} were also determined by fitting Eq. (2) with the measured values of V_{gp} and d_{GaN}, as shown in Fig. 5. The doping in AlGaN was found to be $3.5\times 10^{18}\ \mathrm{cm}^{-3}$, which is similar to the value obtained from SIMS measurements.

The interface barriers for Ni and Pt gates on SiN_x were calculated to be 0.97 and 1.18 eV, respectively. The difference 0.21 eV is less than the difference in the work function of the metals, which is 0.75 eV [Ni, 5.35 eV (Ref. 20), and Pt, 6.1 eV (Ref. 21)] calculated from photoelectric effect measurements.

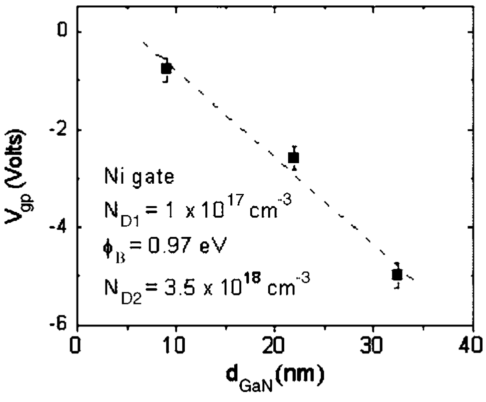

FIG. 5. Extraction of the interface barrier and the AlGaN doping from the V_{gp} vs d_{GaN} plot.

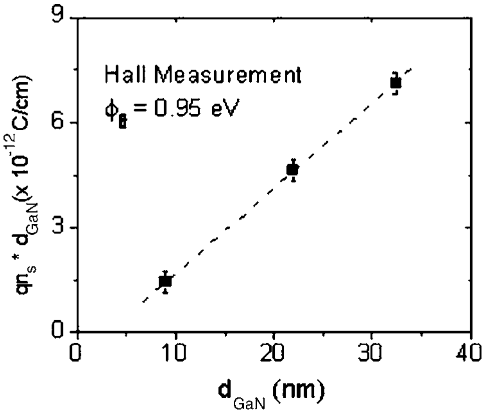

FIG. 6. Extraction of the interface barrier from the dependence of the 2DEG density determined from Hall measurements on the GaN cap thickness.

The interface barrier height φ_B 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

$$qn_s = -\frac{\varepsilon_{\mathrm{GaN}}\varphi_B}{d_{\mathrm{GaN}}} - \varepsilon_{\mathrm{GaN}}\frac{E_{g\mathrm{GaN}}}{d_{\mathrm{AlGaN}}} + qN_{D1}d_{\mathrm{GaN}} + Q_{\pi\mathrm{net}} + \frac{qN_{D2}d_{\mathrm{AlGaN}}}{2}. \qquad (3)$$

The 2DEG density was determined by room temperature Hall measurements. The value of the interface barrier height, φ_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 $\mathrm{GaN}/\mathrm{SiN}_x$ 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 1.08×10^6 V/cm. This change in electric field corresponds to an additional interface charge of $4.5\times 10^{12}\ \mathrm{cm}^{-2}$. 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 $\mathrm{SiN}_x/\mathrm{GaN}$ 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 $\mathrm{SiN}_x/\mathrm{GaN}$ interface pinning the Fermi level to around 1 eV. An approximate value for interface charge is calculated to be $4.5\times 10^{12}\ \mathrm{cm}^{-2}$. Further studies are needed to understand the nature of this trap and to analyze its effect on the 2DEG density.

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