INTERFACE PROPERTIES AND ELECTRICAL CHARACTERISTICS OF III-V NITRIDE-BASED MISFETs

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Abstract — III-V Nitride Based MISFETs have been studied using AlN/GaN heterostructures grown by MOCVD at the University of Michigan. MIS structures fabricated on such materials showed very low interface state density D_{it} values of $\sim 1\times10^{11}cm^{-2}eV^{-1}$. The maximum drain current of AlN/GaN MISFETs made on these materials was greater than 700mA/mm, while drain-source breakdown was 30V and drain-gate breakdown was 40V. Devices with a gate length of 2µm exhibited a peak transconductance of 136mS/mm at V_{GS}=1V, which exceeds previously reported results.

I. INTRODUCTION

Most of the effort on GaN-based electronics is currently focused on HEMT development and more recently nitride-based Heterojunction Bipolar Transistor (HBT) studies have been initiated. GaN-based heterojunction FETs (HFETs) have demonstrated good high frequency and high power performance. AlGaN/GaN HEMTs grown on SiC were recently reported with a record power density of 7W/mm at 10GHz and a high output power of 9W from 3mm discrete devices at 7GHz [1]. The power capability can be further enhanced by means of increasing the Al fraction in the donor layer and a record power density of 3W/mm at 18GHz has been reported using $Al_{0.5}Ga_{0.5}N$/GaN HEMTs grown on sapphire [2].

Another promising candidate for high power, broadband operation is the Metal Insulator Semiconductor FET (MISFET). This device has not drawn adequate attention so far but offers unique features that are very attractive for power applications such as high ON-state breakdown, a predominant factor in determining nitride FET power performance and high frequency and thus broad bandwidth operation capability. First, very encouraging results on such devices were recently reported by the authors [3, 4].

The device explored in this paper is based on the use of AlN/GaN heterostructures. The use of Al-rich wide-bandgap semiconductors for the heterostructure allows higher electron mobility and increased surface density of the two-dimensional electron gas (2DEG) at the interface of AlGaN and GaN [5]. The $Al_xGa_{1-x}N$/GaN heterostructure properties are however, strongly influenced by piezoelectric effects that are very pronounced in III-Nitride devices [6].

The AlN/GaN approach explored in this work opens the possibility of utilizing devices with a very wide bandgap material under the gate and thus obtaining good microwave power performance. Approaches of this type with more traditional III-V semiconductors allowed demonstrating a large power density and high operation frequency up to the millimeter-wave range [7]. This paper reports for the first time good interface properties for AlN/GaN heterostructures and very promising electrical performance from devices built on such materials.

II. MATERIAL CONSIDERATIONS AND GROWTH OPTIMIZATION

Success of AlN/GaN HFET approaches critically depends on developing material with good structural properties and low density of interface states. AlN and GaN present lattice constant mismatch and thus the thickness of the AlN barrier should be kept below the critical thickness in order to minimize the number of dislocations. Moreover, results reported so far suggest mediocre interface roughness probably related to inter-diffusion between Al and Ga [8]. The studies reported here show that good interface properties can be obtained from AlN/GaN heterostructures and GaN-based MISFETS built on them demonstrate good current capability and charge control. The AlN/GaN layers were grown by low-pressure (60torr) MOVPE at the University of Michigan using TMGa, TMAl, and NH_3 as precursors.

The layers were, starting from the c-plane sapphire substrate, a thin low-temperature (515°C) grown GaN buffer layer, a 0.5µm-thick non-intentionally-doped GaN channel, and a thin AlN barrier layer. All layers except for the low-temperature buffer were grown at 1120°C. The layers had specular surface morphology and good structural and optical properties as evaluated by XRD and PL measurements.

The AlN/GaN layer design was optimized by evaluating the mobility dependence on AlN layer thickness as obtained by Hall measurements and the results are shown in Fig. 1. When the growth time of AlN was 450sec corresponding to a thickness of ~110Å for the AlN layer, the combined bulk-2DEG electron mobility was $320cm^2/Vs$ and the associated 2DEG density was $2\times10^{13}cm^{-2}$, respectively. This growth time was used for growing the device layers employed in the study as it represents the best conditions for good interface properties and the best carrier-density conditions in the channel.

III. MIS INTERFACE CHARACTERISTICS

Large test diodes with an area of $300\mu m^2$ were fabricated for interface characterization as described in the next section. The C-V characteristics of

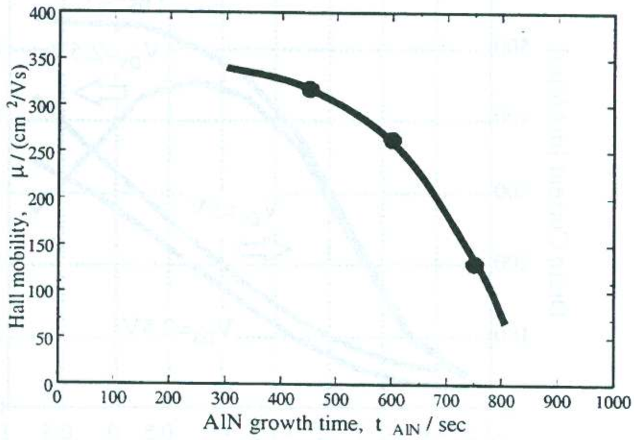

Fig. 1. Dependence of electron mobility on the growth time of the AlN barrier layer.

AlN/GaN diodes were measured using an LCR meter and a voltage signal with 200KHz frequency and 25mV amplitude.

The C-V characterization of AlN/GaN diodes revealed MIS-like behavior as shown by the results of Fig. 2. The minimum capacitance C_{MIN} evaluated from these characteristics was only an 8% of the maximum capacitance C_I corresponding to the capacitance of the AlN insulator. This indicated that excellent charge modulation was possible in the AlN/GaN MIS structure.

The C-V characteristics of AlN/GaN MIS structures were also calculated using the treatment described in [9] and assuming an electron affinity of 4.1eV and a metal work function of 4.5eV. The theoretical C-V characteristics are shown in Fig. 2 together with the experimental data. A voltage shift of ~0.4V was observed between the calculated and the measured data. This difference can be attributed to the uncertainty in the values of electron affinity and work function, as well as the presence of fixed charge at the interface.

By matching experimental and theoretical C-V data, it was possible to obtain information about the AlN/GaN layers. Thus, based on the slope of $1/C^2$-V characteristics, the doping of the GaN channel was found to be $N_D=1\times10^{17}cm^{-3}$. The thickness ($t$) of the AlN barrier was estimated from the values of C_{MIN} and C_I to be 110Å. This value is close to the expected critical thickness of AlN on GaN.

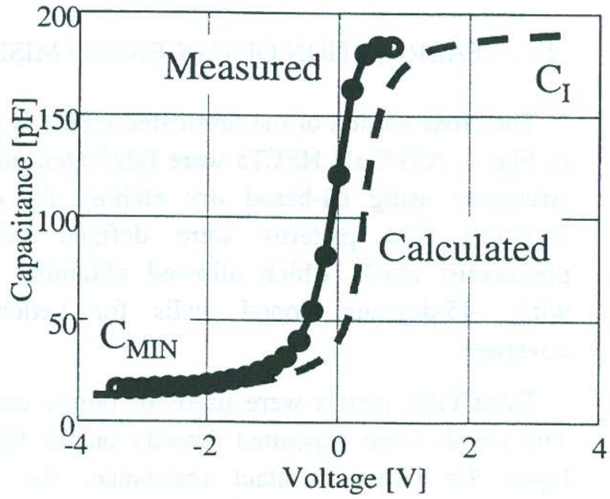

Fig. 2. C-V characteristics of UofM AlN/GaN MIS used to evaluate the density of interface states of AlN/GaN heterojunction.

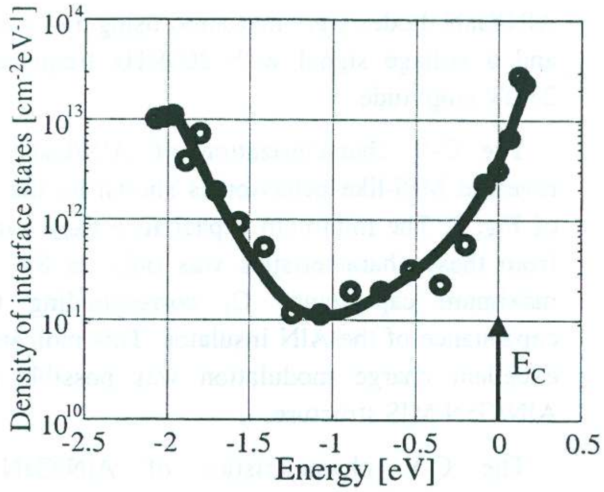

Fig. 3. Density of interface states vs. surface potential in AlN/GaN MISFETs.

Terman's method was used to evaluate the density of interface states in the MIS structures by calculating the difference in the slope between the experimental and theoretical surface potential-voltage dependencies. The analysis showed a low minimal interface state density D_{it} of $1\times10^{11}cm^{-2}\,eV^{-1}$ in the AlN/GaN MIS structure as shown in Fig. 3. The interface state density was found to decrease when the surface potential varies from E_C to 1eV below the conduction band edge. The increase of the interface state density for energies below E_C-1eV is attributed to measurement errors due to increased MIS leakage.

The reported studies show that good interface properties are obtained from AlN/GaN heterostructures.

IV. FABRICATION OF GaN-BASED MISFETs

The cross section of the fabricated HFET is shown in Fig. 4. AlN/GaN HFETs were fabricated on these structures using Cl-based dry etching for device isolation. The patterns were defined using a photoresist mask, which allowed obtaining mesas with ~45-degrees sloped walls for better step coverage.

Ti/Al/Ti/Pt metals were used for ohmic contacts. The metals were deposited directly on the top AlN layer. To reduce contact resistance, the ohmic contacts were annealed for 30sec at 800°C in nitrogen. A sheet resistance R_{SH} of 860Ω/sq and a specific contact resistivity ρ_C of $4\times10^{-7}\Omega cm^2$ were obtained by TLM analysis.

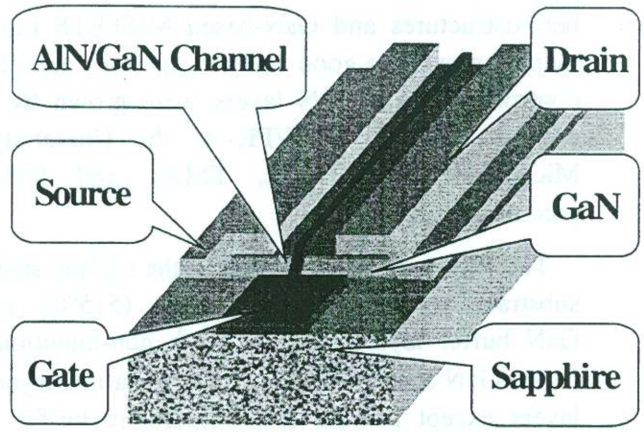

Fig. 4. Schematic representation of the AlN/GaN MISFET.

Gate contacts were made using Pt/Ti/Au metals. Optical lithography was used to define 2μm-long gate patterns. The development time in NaOH-based optical photoresist developer was optimized in order to minimize damage to the AlN barrier layer. 30sec-long oxide etching was performed immediately prior to gate and ohmic deposition using hot (80°C) HCl-H_20 solution (1:10).

V. ELECTRICAL PERFORMANCE OF AlN/GaN MISFETs

Typical transfer characteristics of the AlN/GaN MISFET are shown in Fig. 5. Devices with a gate length of 2μm exhibited a peak transconductance of 136mS/mm at V_{GS}=1V, which exceeds previously reported results [10].

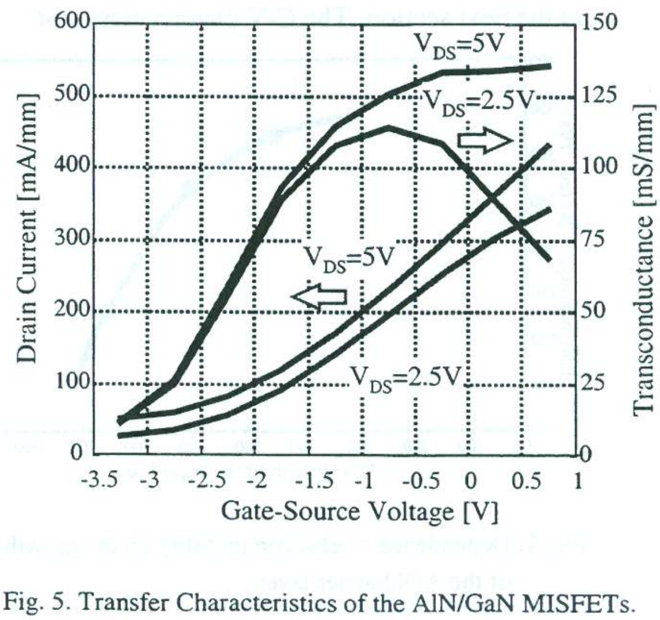

Fig. 5. Transfer Characteristics of the AlN/GaN MISFETs.

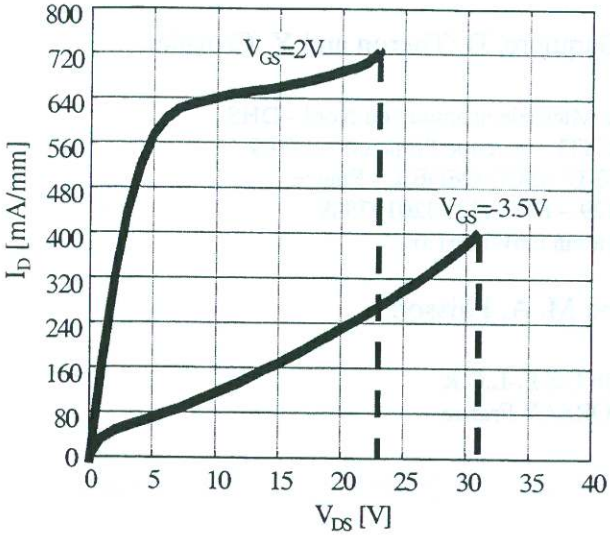

Fig. 6. I_{DS}-V_{DS} characteristics showing the device breakdown features.

The threshold voltage of the devices was -3.5V and the absence of full pinch-off at large drain bias was due to parasitic conductance in the N.I.D.-GaN layer.

The I_D-V_{DS} characteristics of the AlN/GaN MISFET shown in Fig. 6 demonstrate its maximum current- and voltage-handling capability. A drain-source breakdown at 30V and drain-gate breakdown at 40V was evidenced by "flashing" of the contact pads. The maximum drain current was greater than 700mA/mm.

VI. CONCLUSIONS

AlN/GaN heterostructures using thin epitaxially grown AlN barrier layers have been investigated for the purpose of developing III-N-based MISFETs. C-V characterization and Terman's method were used to demonstrate low values of interface state density of AlN/GaN interface. The high quality of the interface is confirmed by very high values of transconductance and current density obtained from HFETs fabricated on the AlN/GaN layers. These results indicate a high potential of AlN/GaN MISFETs for microwave power applications.

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