Very Low Sheet Resistance AlN/GaN High Electron Mobility Transistors

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ABSTRACT

AlN/GaN high electron mobility transistor (HEMT) structures with a 3.5 nm AlN barrier were grown with a rf plasma-assisted molecular beam epitaxy (MBE) system on sapphire and SiC substrates, resulting in high electron mobility of >1800 cm^2/V s and 2DEG carrier density of 2.8×10^{13} cm^{-2}. A near record-low sheet resistance of ~167 ohm/sq was achieved using Ti/Al based Ohmic metallization annealed at 850 °C for 30s. The sheet resistance of AlN/GaN structure is about 57% lower than a AlGaN/GaN structure. UV ozone treatment was used to oxidize the AlN surface layer and this oxide layer served as the gate oxide layer and a protective layer during the device fabrication. AlN/GaN HEMTs exhibited a drain current density of 1.3 A/mm at gate voltage of +4 V and excellent pinch-off characteristics at gate voltage of -4 V. The current gain cut-off frequency, f_T, and maximum frequency of oscillation, f_{max}, were 19.6 GHz and 30.9 GHz, respectively for 0.4× 200 μm^2 gate HEMTs.

INTRODUCTION

Wide band gap AlGaN/GaN high electron mobility transistors (HEMTs) have emerged as excellent candidates for RF/microwave power amplifiers because of their high power and high speed handling capabilities [1-10]. The large band gap of AlN (6.2 eV) provides better carrier confinement and lowers gate leakage current, and the absence of alloy disorder (compared to AlGaN barriers) results in improvement of both low- and high-field carrier transport. The device output current is normally limited by the carrier sheet density and carrier injection velocity at the source end. Therefore, a high carrier density, along with high carrier mobility, is desired. AlN/GaN HEMTs grown on sapphire or SiC substrates are very promising for high power, high temperature applications in telecommunications, hybrid electric vehicles, power flow control and remote sensing.

A number of variations on AlN/GaN HEMTs have been explored with notable success [11-15]. However, AlN can be easily oxidized or etched by some of the chemicals used during device processing. A protective layer deposited on the surface is needed to protect the AlN, in addition to acting as a gate insulator. Recently, Zimmermann et al. [16] and Higashiwaki et al. [17] reported a f_T of 56 GHz and a f_T of 107 GHz for AlN-based devices utilizing insulated-gates grown by E-Beam deposition and catalytic chemical vapor deposition, respectively.

In this work, we report on high quality of AlN/GaN HEMT materials, and UV treatment to oxidize the AlN surface layer for protecting the AlN layer during the device fabrication and serving as the gate insulating layer.

EXPERIMENTAL

AlN/GaN HEMT structures were grown on c-plane sapphire by MBE system equipped with a RF nitrogen plasma source from SVT Associates (SVTA-RF45). During growth, reflection high-energy electron diffraction (RHEED) was used to monitor surface morphology. Other *in situ* measurements, including emissivity-corrected surface temperature, thin film growth rate, and III/V flux ratio were performed by a combination of pyrometry and a two-color reflectometry (SVTA-IS4000). The growth process started with surface nitridation at high temperatures using rf nitrogen plasma source, followed by the growth of a thin AlN nucleation layer. Then, a 2–3 µm low-defect GaN buffer was grown. Finally, the AlN/GaN active layer was formed by growing a thin (<5 nm) AlN layer at 700 °C. To protect the AlN layer, some of the samples had ~1 nm of undoped GaN cap layer grown. The thin film quality and interface roughness were studied by TEM.

In order to protect the device surface layer, the samples without GaN cap layer were treated by UV ozone for 1 min. Device fabrication began with mesa isolation by Cl_2/Ar inductively coupled plasma etching (150W source power, 40 W RF chuck power). Isolation currents were in the low µA at 40 V bias for a mesa depth of 1200Å. Ohmic contacts were formed by lift-off of e-beam deposited Ti/Al/Ni/Au based metallization, and subsequently annealed at 850 °C for 30 s under a N_2 ambient. A near record-low sheet resistance of ~167 ohm/sq was measured using transmission line method

(TLM). Finally, the submicron gate fingers with the dimension of 380 nm × 200 µm were defined by e-beam-lithography, followed by e-beam metal deposition of Ti/Au as the gate contact. The distance between source and drain was 2 µm. A schematic cross sectional view of the HEMT and a SEM image of the fabricated device are shown in Figure 1 and Figure 2, respectively. The DC characteristics of the HEMTs were measured with a Tektronix curve tracer 370A and an HP 4156 parameter analyzer. The RF performance of the HEMTs was characterized with an HP 8723C network analyzer.

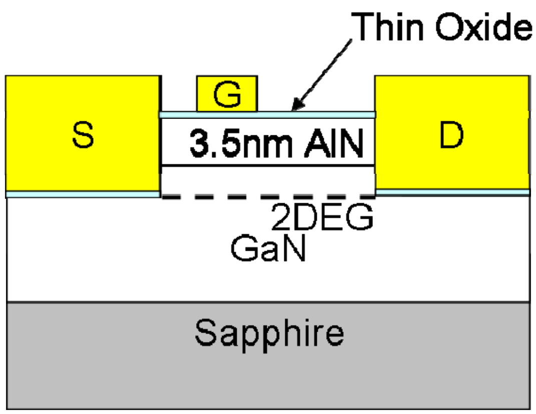

Figure 1. Schematic cross-sectional view of the AlN/GaN HEMT structure with thin oxide gate.

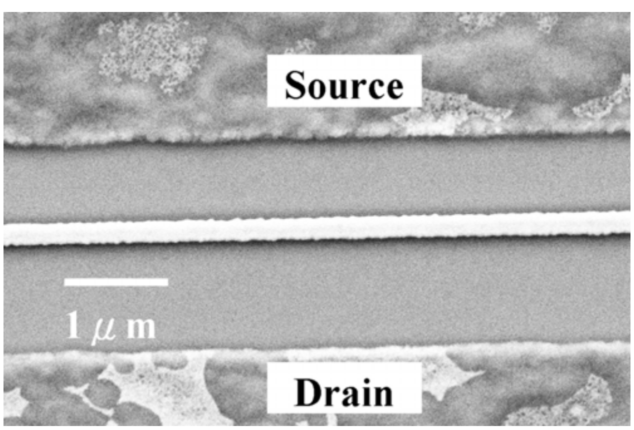

Figure 2. SEM top view of an AlN/GaN HEMT with a 380 nm Ti/Au gate.

RESULTS AND DISCUSSION

In order to reduce alloy scattering effects and improve channel conductivity in III-nitride HEMTs, structures with very thin AlN barrier layers have been studied recently. However, these efforts have been hindered by the large mismatch in lattice constant and thermal expansion coefficient of AlN and GaN, which usually results in the formation of defects and/or cracks in the AlN layer. SVTA has recently developed RF plasma-assisted MBE growth of high-quality thin AlN layers on low-defect GaN buffers at relatively lower growth temperatures on both sapphire and SiC substrates, showing both very high sheet carrier density and electron mobility values as shown in Figure 3 [15]. The corresponding room-temperature sheet resistivities are shown in Figure 4.

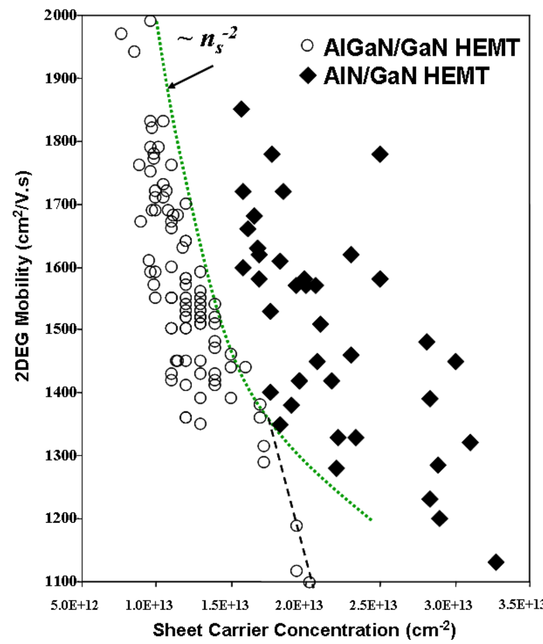

Figure 3. 2DEG Hall mobility for AlGaN/GaN (circles) and AlN/GaN (diamonds) HEMTs grown on sapphire and SiC by PA-MBE.

For comparison, both Figures 3 and 4 also include results for AlGaN/GaN HEMTs with varying Al composition. As indicated in Figure 3, with similar mobility values, the sheet carrier density of AlN/GaN HEMTs are much higher than that of AlGaN/GaN HEMTs due to higher strain and better carrier confinement at the AlN/GaN interface.

As illustrated in Figure 4, the product of both very high carrier sheet density and mobility, measured by room – temperature van der Pauw Hall method, resulted in record low values of sheet resistivity, ρ_{sheet} of < 140 Ω/ , in these AlN/GaN HEMTs. Figure 5 shows a TEM image of the top AlN/GaN layer in a HEMT sample with an atomically abrupt interface.. Both very high quality AlN/GaN interface and low-defect GaN buffer layers were found to be critical for achieving very low sheet resistivity values.

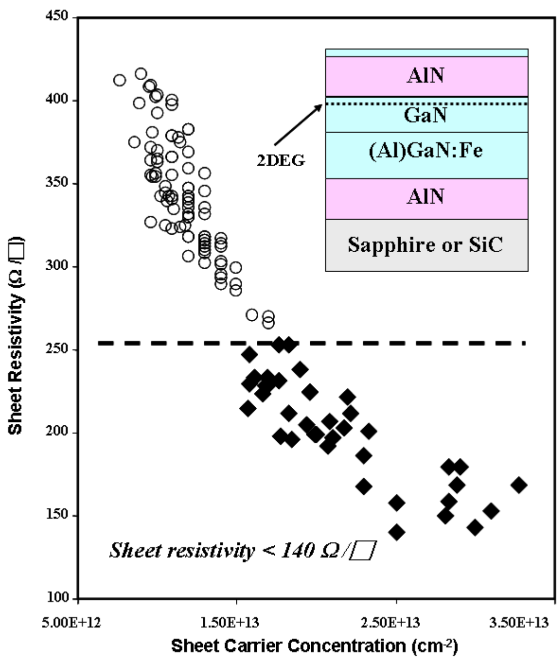

Figure 4. 2DEG sheet resistivity for AlGaN/GaN (circles) and AlN/GaN (diamonds) HEMTs grown on sapphire and SiC by PA-MBE.

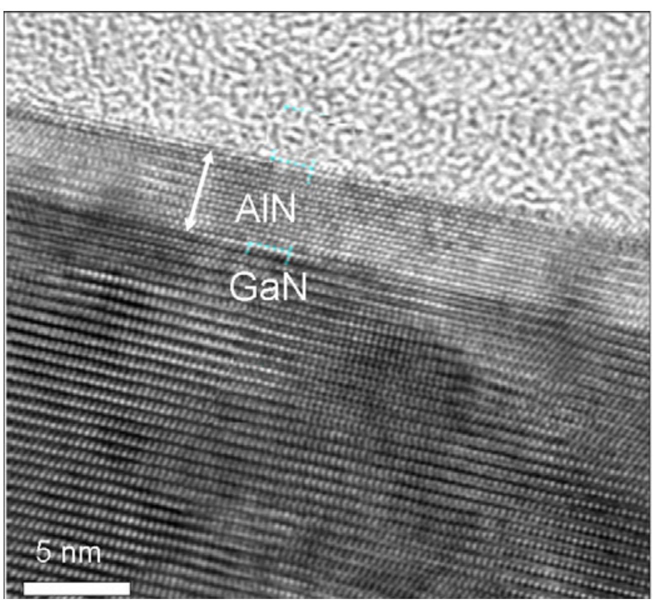

Figure 5. TEM image of AlN/GaN HFET structure grown by MBE on sapphire show high-quality AlN/GaN structure

As mentioned previously, AlN can be easily attacked by wafer processing chemicals such as photoresist developer solutions, buffered oxide etch (BOE), and HF acid, and hence a protective layer is needed during the device fabrication. Silicon nitride (SiN) has been widely used for surface passivation of AlGaN/GaN HEMTs. Plasma enhanced vapor deposition or electron beam deposition was used to deposit the SiN. Since the HF and BOE would attack the SiN, after the ohmic contact pattern definition, the SiN cannot be removed by the HF solution or BOE. CF_4 plasma exposure has shown a passivation effect on the 2DEG of the AlGaN/GaN HEMT. Therefore, the CF_4 plasma can not be used to remove the SiN prior the ohmic metal deposition. Here, the Ohmic metal was directly deposited on the protective SiN and the metal was alloyed through the SiN.

Excellent dc and rf characteristics were also obtained for processed AlN/GaN HEMTs. As shown in Figure 6, a maximum drain current density of 1.3A/mm was measured for 200-μm-gate-width device at a gate bias voltage of +4V. The device pinch-off voltage was -4 V. The corresponding transfer characteristic of this device is shown in Figure 7. The maximum transconductance of 330 mS/mm was obtained.

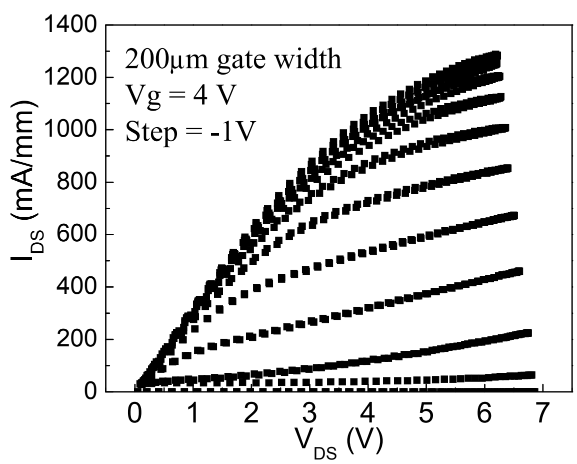

Figure 6. Drain I_{DS}-V_{DS} characteristics of an AlN/GaN HEMT with a gate dimension of 0.38 × 200 μm^2.

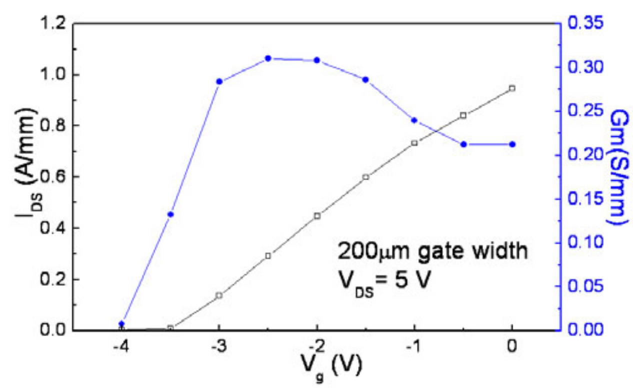

Figure 7. Ids and extrinsic transconductance of an AlN/GaN HEMT with a gate dimension of 0.38 × 200 μm^2.

The small signal rf performance of the AlN/GaN HEMTs are shown in Figure 8. The device was biased at V_{ds} = 3V and V_g = -2V during the measurements. A unity current gain cutoff frequency, f_T, and power gain cutoff frequency, f_{max}, of 19.6 and 30.9 GHz were obtained, respectively.

CONCLUSIONS

AlN/GaN HEMTs with a thin aluminum oxide gate barrier using UV ozone treatment have been demonstrated. Excellent dc and rf performance of these devices show the potential of this approach to enhance the performance of GaN-based power amplifiers.

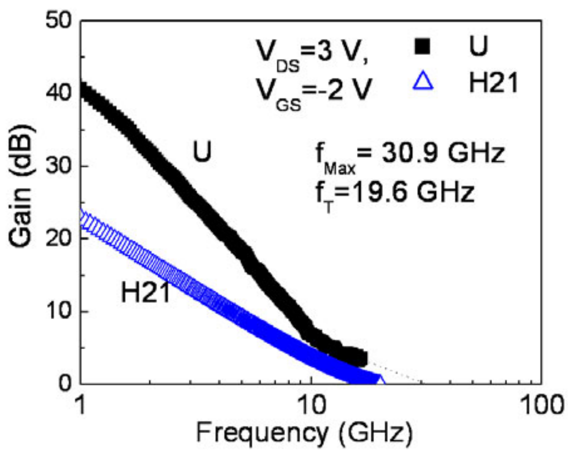

Figure 8. RF performance of a 0.38 × 200 µm^2 gate length HEMT on sapphire at a fixed gate voltage of -2 V.

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ACRONYMS

HEMT: High Electron Mobility Transistor
MBE: molecular beam epitaxy
RHEED: reflection high-energy electron diffraction
TLM: transmission line model
Cat-CVD: Catalytic chemical vapor deposition
SEM: scanning electron microscope
TEM: transmission electron microscope