MOCVD AlGaN/GaN HFET's Material Optimization and Devices Characterization

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ABSTRACT

An optimization of growth parameters of $Al_xGa_{1-x}N$/AlN/GaN heterostructure field effect transistors (HFET) grown by low-pressure metalorganic chemical vapor deposition (LP-MOCVD) technique on SiC and sapphire substrates with relatively high Al mole fraction in the barrier layer ($0.3 < x < 0.5$) has been presented. The properties of the two-dimensional electron gas (2DEG) forming at the $Al_xGa_{1-x}N$/GaN heterojunction can be tuned by careful adjustments of $Al_xGa_{1-x}N$ barrier layer thickness and Al mole fraction, x. The 2DEG sheet conductivities (μn_s) as high as 2.6×10^{16} $V^{-1}s^{-1}$ at $\mu \sim 2200$ cm^2/Vs and $n_s \sim 1.2 \times 10^{13}$ cm^{-2} has been achieved on $Al_xGa_{1-x}N$/AlN/GaN HFET structures on SiC substrate at $x = 0.47$. HFET devices processed on these structures exhibited improved low field conductivities and DC and high frequency performance. Saturation currents above 1.2 A/mm at 0 V gate bias, transconductance as high as 340 mS/mm at $L_g = 0.25$ μm and $F_T \times L_g > 20$ GHz x μm were demonstrated on HFET structure grown on SiC substrates.

INTRODUCTION

Since their first demonstration some 11 years ago [1], AlGaN/GaN heterojunction field effect transistors (HFET) have attracted a great deal of interest due to their potential for high frequency power amplification and resistance to harsh environments. The inherent strong spontaneous polarization and piezo-electric effect at the AlGaN/GaN heterointerface produce 2DEG sheet density (n_s) in excess of 10^{13} cm^{-2}, mobilities (μ) of > 1500 cm^2/Vs and sheet conductivities (μn_s) above 2×10^{16} $V^{-1}s^{-1}$. In combination with high breakdown fields and large peak and saturated velocities the result can be state of the art power densities at microwave frequencies [2]. To obtain this level of performance it has been well documented that the planarity of the heterointerface is critical in minimizing the scattering of carriers in the channel of an HFET [3]. The electrical properties of the 2DEG also depend on the residual impurity concentration in the epitaxial layers as well as of the HFET structure design, Al mole fraction, x in $Al_xGa_{1-x}N$ barrier layer, presence of AlN spacer near channel region and cap layer [4, 5]. To increase both the breakdown field and the 2DEG conductivity, a high Al mole fraction in the $Al_xGa_{1-x}N$ barrier layer is highly desirable [2].

In these article, we report on the low-pressure metalorganic chemical vapor deposition (LP-MOCVD) growth optimization of $Al_xGa_{1-x}N$/AlN/GaN HFET structure on SiC and sapphire substrates with relatively high Al mole fraction in the barrier layer ($0.3 < x < 0.5$). The influence of Al mole fraction (x) and $Al_xGa_{1-x}N$ barrier layer thickness (d_{AlGaN}) on the electrical properties of the 2DEG was investigated. HFET devices processed on these structures exhibited improved low field conductivities and DC and high frequency performance making them very attractive for high frequency power applications.

GROWTH AND PROPERTIES OF LAYER STRUCTURE

The samples in this study were grown by LP-MOCVD on (0001) basal plane sapphire and 6H (0001) SiC 2-inch substrates in an inductively heated, custom built reactor using TEGa, TEAl, and NH_3. Details of the growth systems have been described previously [6]. The epitaxial designe imployed a low temperature nucleation AlN layer of 300 Å. This was followed by ~ 1.5 µm of undoped GaN. Then a 10 Å AlN spacer layer was grown followed by 100 - 300 Å of undpoped $Al_xGa_{1-x}N$ barrier layer with Al mole fraction x in $0.3 < x < 0.5$. No intentional doping was performed during growth. The estimate of the layer thickness was based on the growth rate determined using an optical reflection technique. This was confirmed by grazing incidence x-ray reflectivity (GIXRD) measurements [7]. Several techniques have been used to evaluate the material including high-resolution x-ray diffraction (HRXRD) and atomic force microscopy (AFM) [7]. The electrical properties of the 2DEG formed at the $Al_xGa_{1-x}N$/GaN heterojunction were evaluated by van der Pauw-Hall measurements, contactless resistivity and mobility maps.

Figure 1 shows the variation of room temperature mobility (μ) as a function of 2DEG sheet density (n_s) in $Al_xGa_{1-x}N$/AlN/GaN structures with $0.3 < x < 0.5$ and 10 Å AlN spacer layer thickness (d_{AlN}) on SiC and sapphire substrates. Typically, sheet carrier density n_s increased with increasing Al mole fraction in the barrier layer. At the same time, the electron mobility dropped as shown in Fig. 1. The 2DEG sheet conductivity ($\mu\, n_s$) were as high as 2.6 x 10^{16} $V^{-1}s^{-1}$ (μ ~ 2200 cm^2/Vs at n_s ~ 1.2x10^{13} cm^{-2}) at film sheet resistance ~ 250 Ω/□ on HFET structure on SiC substrate.

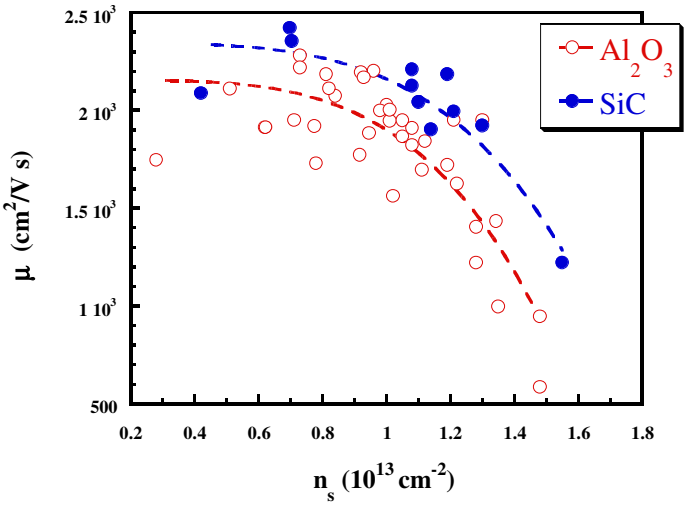
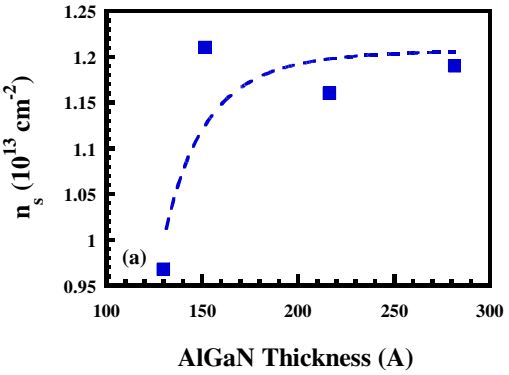
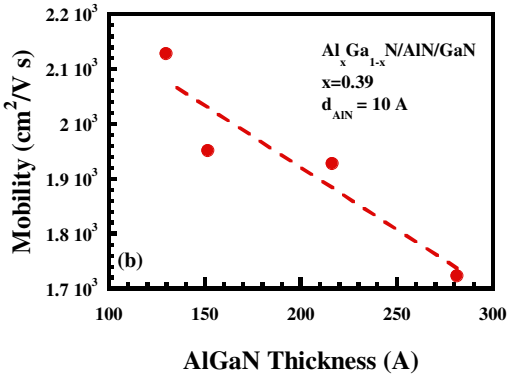


Figure 1. Room-temperature electron mobility as a function of 2DEG sheet density in $Al_xGa_{1-x}N$/AlN/GaN structures with $0.3 < x < 0.5$ and d_{AlN} = 10 Å grown on SiC and sapphire substrates.

It is important to note, the properties of 2DEG are very sensitive to Al mole fraction (x) and $Al_xGa_{1-x}N$ barrier layer thickness (d_{AlGaN}). In Figure 2 the room temperature 2DEG sheet density (n_s) and the electron mobility (μ) as well as the 2DEG sheet conductivity ($\mu\, n_s$) are plotted versus of the $Al_xGa_{1-x}N$ barrier layer thickness (d_{AlGaN}) in $Al_xGa_{1-x}N$/AlN/GaN (x = 0.39, d_{AlN} = 10 Å) HFET structure grown on sapphire substrates. Typically, the 2DEG sheet density increased sharply and saturated at level ~ 1.2 x 10^{13} cm^{-2} with increase d_{AlGaN} in the range of 100 – 300 Å (Fig. 2 a). At the same time, mobility decreased from the value of ~ 2100 cm^2/Vs to ~ 1700 cm^2/Vs (Fig. 2 b). Importantly, the 2DEG sheet conductivity ($\mu\, n_s$) has pronounced maximum (~ 2.36 x 10^{16} $V^{-1}s^{-1}$) at d_{AlGaN} ~ 150 Å and with further increase of d_{AlGaN} the 2DEG sheet conductivity started decline following the mobility change (Fig 2 c).





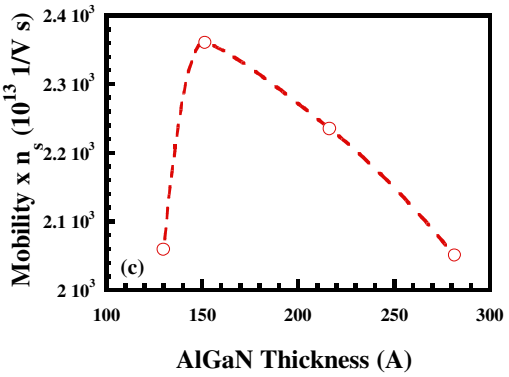
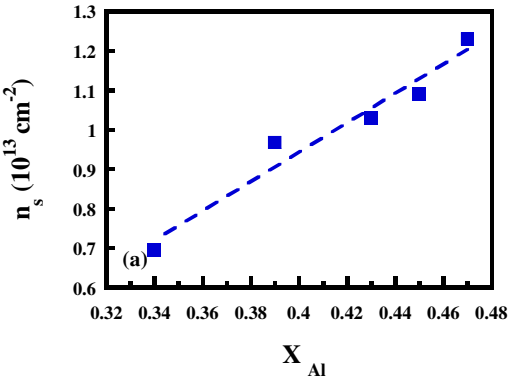
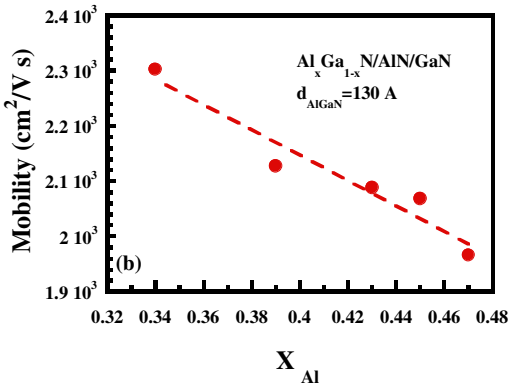


Figure 2. Room-temperature (a) 2DEG sheet density, (b) electron mobility and (c) 2DEG sheet conductivity ($\mu\, n_s$) in $Al_xGa_{1-x}N$/AlN/GaN (x = 0.39, d_{AlN} = 10 Å) HFET structure as a function of AlGaN film thickness.





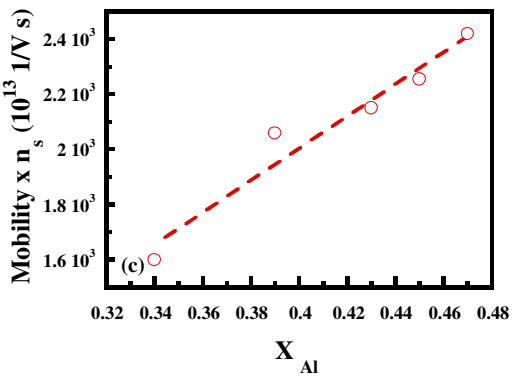


Figure 3. Room-temperature (a) 2DEG sheet density, (b) electron mobility and (c) 2DEG sheet conductivity ($\mu\, n_s$) in $Al_xGa_{1-x}N$/AlN/GaN (d_{AlGaN} = 130 Å) HFET structure as a function of Al mole fraction.

Figure 3 shows the variation of these parameters as a function of Al mole fraction in the $Al_xGa_{1-x}N$ barrier layer at fixed thickness in $Al_xGa_{1-x}N$/AlN/GaN (d_{AlGaN} = 130 Å, d_{AlN} = 10 Å) HFET structure on sapphire substrates. For $x > 0.3$, the electron mobility dropped with increasing Al mole fraction in the $Al_xGa_{1-x}N$ layer (Fig. 3 b). The 2DEG sheet density increased practically linearly with increasing x (Fig. 3 a). The 2DEG sheet conductivity increased steadily with increasing Al mole fraction reaching the value of 2.42 x 10^{16} $V^{-1}s^{-1}$ (Fig. 3 c).

Important to note, the 2DEG sheet conductivity reached the highest value in $Al_xGa_{1-x}N$/AlN/GaN HFET structure with higher Al mole fraction in the $Al_xGa_{1-x}N$ barrier layer. And the barrier layer thickness, corresponding the highest μn_s value (Fig. 2 c), becomes smaller with increasing Al mole fraction. Thus, for $x = 0.34$ the highest μn_s value of 2.28 x 10^{16} $V^{-1}s^{-1}$ have been achieved at d_{AlGaN} ~ 230 Å in HFET structure grown on sapphire substrate. At the same time, for $x = 0.47$ the highest μn_s value of 2.42 x 10^{16} $V^{-1}s^{-1}$ have been obtained at d_{AlGaN} ~ 130 Å. It is unclear at this point whether this result is related to the presence of parallel conduction in the $Al_xGa_{1-x}N$ barrier layer or other effects and more careful studies are necessary.

The root mean squared (RMS) surface roughness as low as 2.5 Å over 1 x 1 µm area have been measured by AFM in HFET structure even at highest Al mole fraction and typical atomic growth steps mode have been observed (Fig. 4 a). At the same time, the substrate related defects issues have been shown to cause film cracking (Fig. 4 b) making a significant effect on film resistivity.

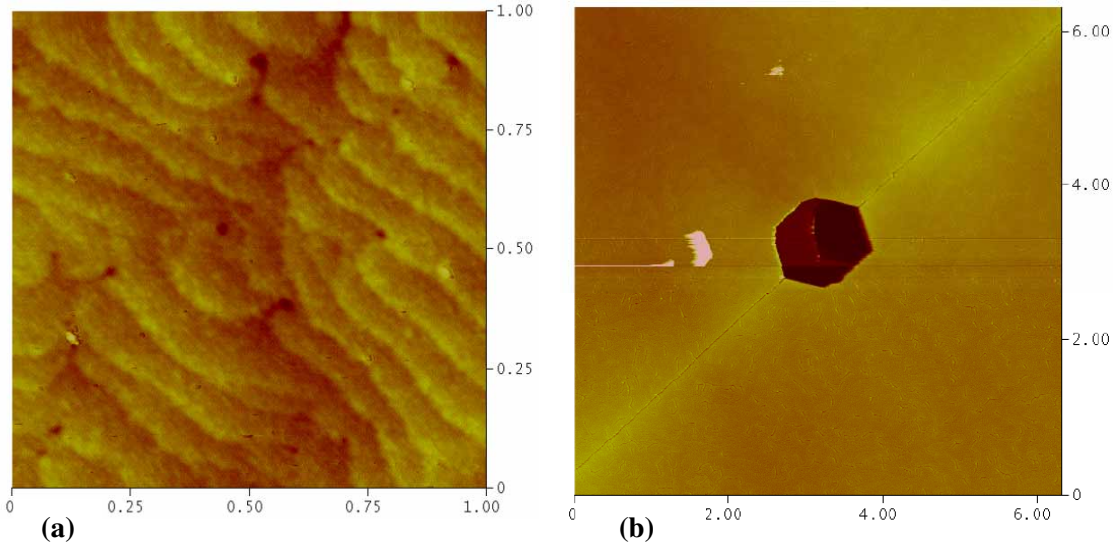


Figure 4. AFM images of the surface of (a) $Al_xGa_{1-x}N$/AlN/GaN HFET structure ($x = 0.47$) on SiC substrate showing atomic growth steps with RMS 2.5 Å (1 x 1 µm) and (b) typical hexagonal shape hole defect and film cracking in HFET structure grown on SiC substrate correlated to substrate defects.

Finally, some studies on the uniformity of the sheet resistance and mobility over 2-inch wafer have been carried out. The uniformity of the sheet resistance, measured with a Lehighton resistivity mapper (LEI 1510) is in the range of < 3% (Fig. 5 a). Non-contact mobility measurements with Lehighton (LEI 1600) system with a measurement spot of 0.823 inch (Fig. 5 b) show very closed mobility value obtained by van der Pauw-Hall technique.

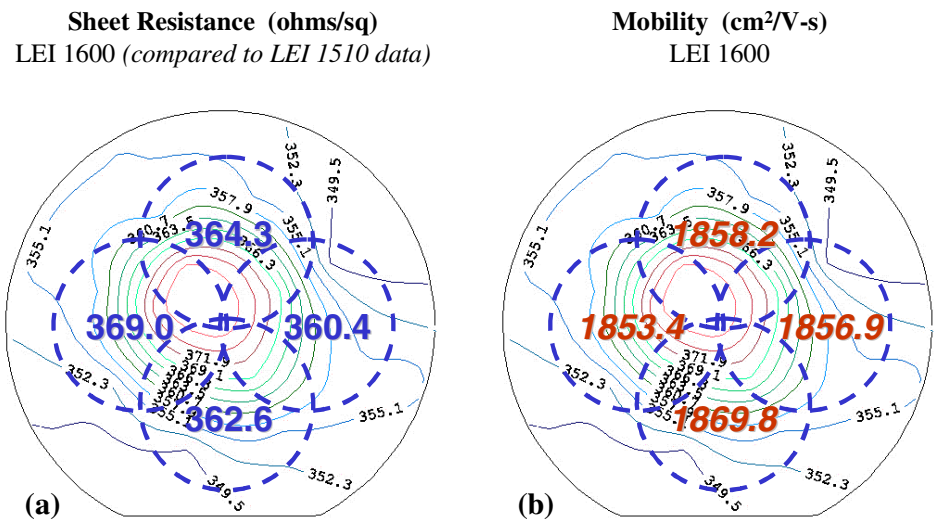


Figure 5. Typical (a) sheet resistance uniformity map and (b) 5 point mobility map (1877.2 cm^2/Vs in center) of 2-inch wafer $Al_xGa_{1-x}N$/AlN/GaN structure on sapphire substrates.

DEVICE STRUCTURE AND RESULTS

HFET devices have been made on some of these structures. Devices were He^+ implant isolated. A standard Ohmic Ti/Al/Ni/Au metallization for source and drain and Schottky Ti/Pt/Au gates metallization have been deposited were defined by optical and E-beam lithography (Fig. 6). Gate lengths ranged from approximately 0.25 to 5 µm with gate widths between 50 and 800 µm. The DC characteristics (Fig. 7) of the devices showed transconductances as high as 200 mS/mm for a gate length of greater than 2 µm and increase up to 340 mS/mm for a shorter gate length of 0.25 µm. The average gate length F_t product was consistently over 20 GHz x µm for 2 µm gate length. For shorter gate length as 0.25 µm this value was 15 GHz x µm. Unity current gain cutoff frequencies were measured at 8 GHz (>60 GHz, for 0.25 µm gate length). Measurement of F_{max} yielded a range of values from 14 GHz to 20 GHz (>100 GHz). Further study on how structure changes influence DC and RF measurements is underway.

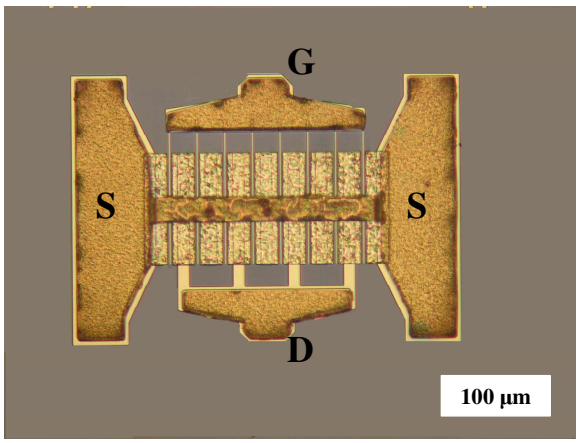


Figure 6. Micrograph of the multi-finger $Al_xGa_{1-x}N$/AlN/GaN HFET 8x100 µm.

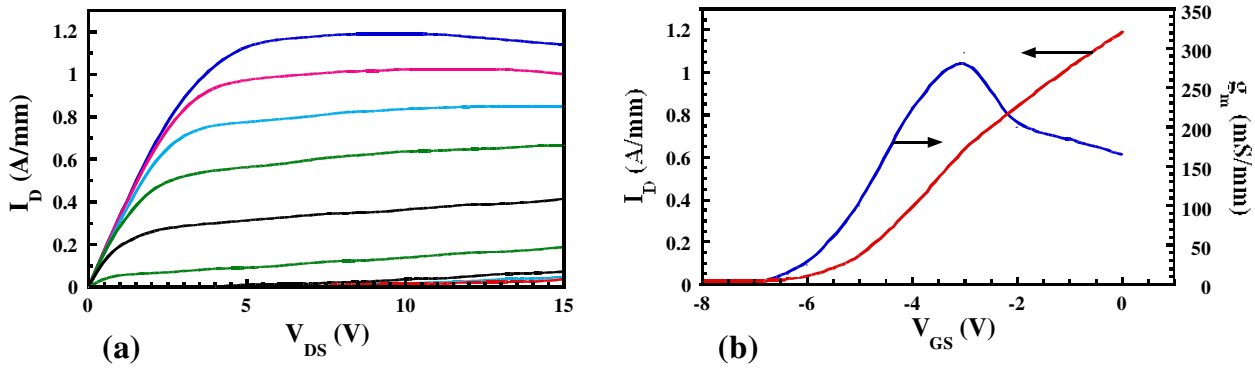


Figure 7. DC I-V (a) and transfer (b) characteristics for a 4 x 50 µm x 0.25 µm $Al_xGa_{1-x}N$/AlN/GaN HFET on SiC substrate. In (a) the gate was biased from 0 V to –8 V in increment of 1 V; in (b) the drain bias was 10 V.

CONCLUSIONS

The properties of the two-dimensional electron gas (2DEG) forming at the $Al_xGa_{1-x}N$/GaN heterojunction can be tuned by careful adjustments of $Al_xGa_{1-x}N$ barrier layer thickness and Al mole fraction, x. The 2DEG sheet conductivities (μn_s) as high as 2.6 x 10^{16} $V^{-1}s^{-1}$ at μ ~ 2200 cm^2/Vs and n_s ~ 1.2 x 10^{13} cm^{-2} has been achieved on $Al_xGa_{1-x}N$/AlN/GaN HFET structures on SiC substrate at x = 0.47. HFET devices proceed on these structures exhibited improved low field conductivities and DC and high frequency performance.

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