Student Paper

Ultrathin MBE-Grown AlN/GaN HEMTs with Record High Current Densities

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III-V nitride-based HEMT technology has made rapid progress over the last decade. However, for traditional AlGaN/GaN heterostructures, the room-temperature (RT) 2DEG density and mobility limit the sheet resistance of the channel to ~250 Ω/sq, and maximum HEMT current is limited to around 1-1.5 A/mm. Recently, it was shown that by using AlInN/AlN/GaN heterojunctions, sheet resistances as low as 210 Ω/sq could be achieved, leading to DC current levels as high as 2.3 A/mm [1]. Ultrathin all-binary AlN/GaN heterojunctions on the other hand are ideally suited for very low sheet resistances and potentially offer the highest performance HEMTs in the III-V nitrides [2-3]. The theoretical limit of polarization-induced 2DEGs in AlN/GaN heterostructures is $\sim 6 \times 10^{13}/\mathrm{cm}^2$. We have recently demonstrated that it is possible to reach this limit with RFMBE-grown AlN/GaN heterojunctions. The 2DEG density was controllably tuned from $5 \times 10^{12}/\mathrm{cm}^2$ to $5 \times 10^{13}/\mathrm{cm}^2$ by changing the AlN barrier thickness [4]. We demonstrated a high-mobility window, and achieved the lowest RT sheet resistance (~170 Ω/sq) ever reported in the nitrides. Benefiting from the extremely high polarization charge, in this work, we demonstrate record high DC current density (2.9 A/mm) and very high extrinsic transconductance (~430 mS/mm) AlN/GaN HEMTs.

Ultrathin AlN/GaN heterojunctions were grown on semi-insulating GaN substrates on sapphire in a Veeco Gen 930 RF plasma MBE system under metal-rich conditions. As shown in Figure 1, a high RT mobility of $\sim 1600\ \mathrm{cm}^2/\mathrm{Vs}$ was achieved with the 2DEG density of $\sim 1.3 \times 10^{13}/\mathrm{cm}^2$ at an AlN thickness of ~2.5 nm. When the AlN barrier thickness was increased to ~4 nm, a RT mobility of $\sim 1370\ \mathrm{cm}^2/\mathrm{Vs}$ and a 2DEG density of $\sim 3.1 \times 10^{13}/\mathrm{cm}^2$ resulted in a new record-low RT sheet resistance of ~148 Ω/sq (Figure 2). Polar-optical phonon scattering sets the physical upper limit of electron RT mobility ($\sim 2000\ \mathrm{cm}^2/\mathrm{Vs}$), temperature-dependent Hall-effect studies confirm that interface roughness (IR) scattering plays a crucial role. The lowest sheet resistance achievable is limited by interface roughness scattering, which gets more severe as the 2DEG density increases, since the centroid of the 2DEG gets pushed closer to the AlN/GaN interface.

HEMTs were fabricated on the AlN/GaN heterojunctions (AlN thickness 3.5 nm, RT mobility $\sim 1370\ \mathrm{cm}^2/\mathrm{Vs}$, 2DEG density $\sim 2.7 \times 10^{13}/\mathrm{cm}^2$, sheet resistance ~165 Ω/sq) by E-beam lithography defined gates and annealed ohmic contacts. A 3 nm aluminum oxide gate dielectric was deposited to prevent tunneling gate leakage (Figure 3). Under DC conditions, a maximum current density of 2.9 A/mm was measured for a 10 μm gate width HEMT (Figure 4). This is the highest DC current density reported to date in nitride HEMTs. The extrinsic transconductance reached values as high as $g_m \sim 430$ mS/mm at $V_{ds}=6$ V, and was observed to be relatively constant for $-1\ \mathrm{V} < V_g < 2\ \mathrm{V}$ (Figure 5), and (f_T, $f_{max} =$ 52 GHz, 60 GHz) were measured for a 0.2 μm gate length HEMT. The relatively high ohmic contact resistances (~1.1 Ω.mm) and the low thermal conductivity of sapphire substrates currently limit the performance.

These results indicate that ultrathin AlN/GaN HEMTs promise to push the performance of GaN HEMTs into current, power, and speed levels currently unachievable in AlGaN/GaN, and even AlInN/AlN/GaN technology. However, minimization of the contact resistance, further scaling of the gate length, and reduction of gate and buffer leakage must be achieved to realize the unique potential of these novel heterostructures in high-speed high-power RF technologies of the future.

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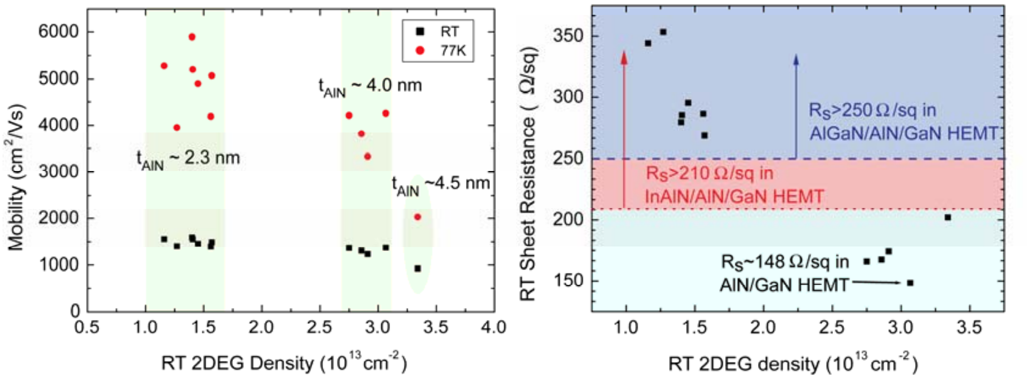


Figure 1 (Left) and 2 (Right): (1) Plot of mobilities at RT (black) and 77K (red) as a function of 2DEG density for AlN/GaN heterojunctions with different AlN layer thickness. (2) Measured sheet resistance with respect to 2DEG density at room temperature. The lowest RT sheet resistance from AlGaN and InAlN HEMTs are marked for comparison with AlN HEMT.

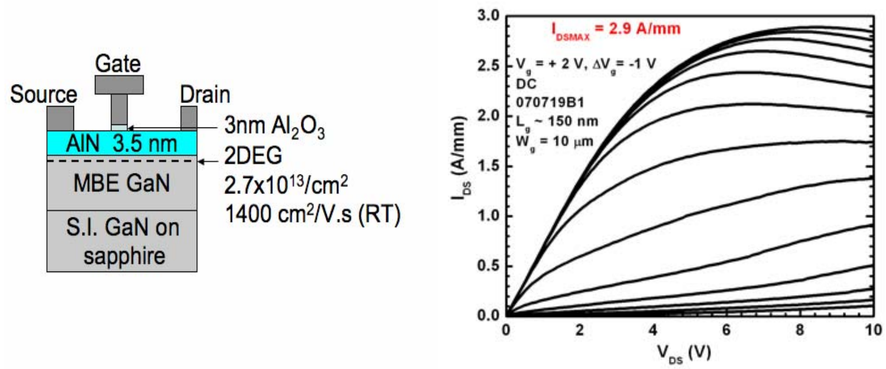
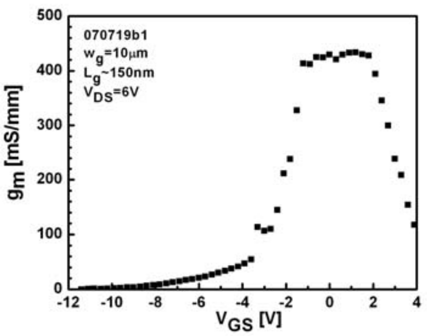


Figure 3 (Left) and 4 (Right): (3) The HEMT structure. (4) DC I-V curves showing a record high maximum drain-source current of 2.9 A/mm.



Figures 5: The extrinsic transconductance of the HEMT reaches values of ~430 mS/mm.