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Electron transport properties of low sheet-resistance two-dimensional electron gases in ultrathin AlN/GaN heterojunctions grown by MBE

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A study of the transport properties of polarization-induced 2DEGs at MBE-grown single AlN/GaN heterostructures with different growth rates is reported. It is observed that faster growth rates lead to high mobilities, approaching ∼ 1600 cm^2/Vs at 300 K and ∼ 6000 cm^2/Vs at low temperatures for ultrathin (2.3 nm AlN/GaN) heterojunctions. By using a theoretical model in conjunction with experimentally measured transport properties, it is concluded that the 300 K sheet resistances of very high density 2DEGs at AlN/GaN heterojunctions are currently limited (∼ 170 $\Omega/\square$) by interface roughness scattering, and can be further reduced by improving the growth conditions.

1 Introduction III-V nitride-based HEMT technology has made rapid progress over the last decade. However, for traditional AlGaN/GaN heterostructures, the room temperature (RT) two-dimensional electron gas (2DEG) density and mobility limit the sheet resistance of the channel to ∼250 $\Omega/\square$, and maximum HEMT current densities are 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 $\Omega/\square$ could be achieved, leading to DC current levels as high as 2.3 A/mm [1]. These heterostructures exploited the very high 2DEG density ($\sim 2.5 \times 10^{13}$ cm^{-2}) due to the large polarization discontinuity and conduction band offset at the heterojunction.

However, the maximum difference in polarization across the heterojunction, as well as the maximum band offset are obtained for an all-binary AlN/GaN heterojunction, where the AlN is pseudomorphically strained on the GaN layer. We recently presented a systematic study of the Molecular Beam Epitaxy (MBE) growth of such heterostructures. Building upon earlier efforts in this direction [3–6], we identified a AlN thickness window for obtaining sheet resistances as low as ∼170 $\Omega/\square$ [7], the lowest reported sheet density in nitride heterostructures to date. Ultrathin all-binary AlN/GaN heterojunctions have been shown to have a number of attractive properties for HEMTs [2]. In particular, the extreme proximity of the 2DEG to the gate can lead to very high transconductances, and the low sheet resistances can deliver high current densities, and at the same time reduce parasitic access resistances, leading to very high-speed operation. These structures also make it unnecessary to perform a gate-recess etch in the HEMT processing, simplifying the fabrication procedure. A good understanding of the electron transport properties of the 2DEGs in these heterostructures, and the effect of different growth conditions is a pre-requisite to realize their potential. In this work, we present the effect of different growth rates on the transport properties of the 2DEGs, and compare the temperature-dependent electron mobility of the 2DEGs as a function of the AlN thickness.

2 Growth The AlN/GaN heterojunctions studied here were grown by MBE in a Veeco Gen 930 system on Fe-doped semi-insulating 1×1 cm^2 GaN substrates on sapphire. Active N_2 was supplied through a Veeco RF plasma

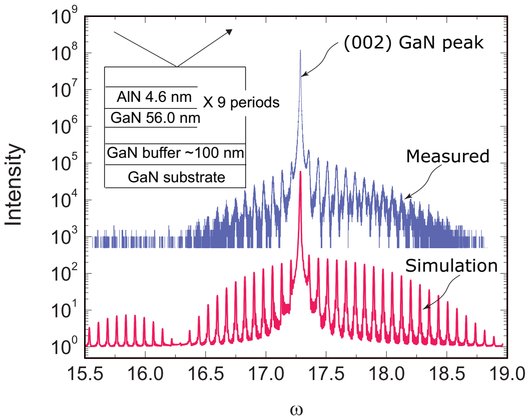

Figure 1 Comparison of measured X-ray diffraction pattern with a calculated spectrum for a 9-period AlN/GaN superlattice around the (002) GaN peak. The observation of a number of narrow peaks indicates the presence of very sharp heterointerfaces.

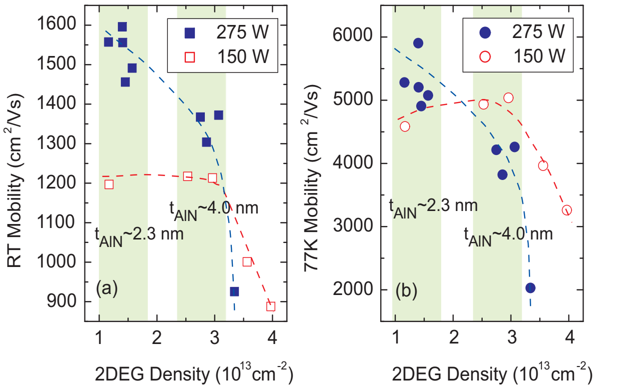

Figure 2 Mobility of 2DEGs measured at (a) room temperature and (b) 77 K for samples grown at 275 W (blue) and 150 W (red). The dashed lines are guides to the eye.

source. All growths were performed in metal-rich regime. The N_2 flux at the substrate position was kept constant at $\sim 2{\times}10^{-5}$ Torr. Since the growth is limited by the active N_2 flux, two RF plasma powers were used for this study: 150 W for a slow growth rate, and 275 W for higher growth rate. For growth at 150 W, a Ga flux of $\sim 10^{-7}$ Torr (for the entire growth) and an Al flux of $\sim 4{\times}10^{-8}$ Torr was used (for the AlN layer). Ga atoms served as surfactants during the growth of AlN layer to enhance the diffusivity of Al adatoms on the surface. Both GaN buffer layers and AlN layers were grown at a substrate temperature of $\sim$ 800°C. The structures comprised of a 143-nm-thick undoped GaN buffer layer, followed by an ultrathin pseudomorphic AlN cap, the thickness of which was varied between 1.0 and 8.0 nm. A 9-period 4.6 nm/56.0 nm AlN/GaN multiple quantum well (MQW) calibration structure was grown with a RF power of 150 W. The growth rate was measured to be 86.4 nm/hr by fitting experimentally measured high-resolution X-ray diffraction (XRD) spectra with a theoretically simulated one, as shown in Fig 1. The XRD spectra for this MQW sample shows well-defined and sharp peaks, indicating sharp interfaces, which is necessary for achieving high mobility 2DEGs.

By a similar XRD-based calibration, the growth rate for samples grown at a RF plasma power of 275 W was found to be $\sim$210 nm/hr. The thickness of the AlN cap for the faster growth rate samples were varied from $\sim$2.3 nm to $\sim$4.5 nm. Due to the faster growth rate, a Ga flux of $\sim 1.6{\times}\,10^{-7}$ Torr and an Al flux of $\sim 1.55{\times}10^{-7}$ Torr was used, and the substrate temperature was maintained at $\sim$ 800°C. The growth recipe was first optimized using the samples with 2.3 nm AlN cap layer for both slow and fast growth rates to obtain the highest mobility. Thicker AlN layers were thereafter grown to achieve higher 2DEG densities.

3 Results and discussion To investigate the transport properties of 2DEGs at single AlN/GaN heterojunctions, Hall-effect measurements were performed at room temperature and 77 K. The measured mobilities are plotted against the 2DEG densities for the series of growths in Fig 2. The dashed lines are guides to the eye, to highlight the effect of the growth rate on the transport properties. As seen in Fig 2 (a), 2DEGs grown at a faster growth rate show higher mobilities than those grown at a slower rate for 2DEG densities less than $\sim 3 \times 10^{13}$ cm^{-2} at RT. The highest mobility achieved with a plasma power of 150 W is $\sim$1200 cm^2/Vs at RT and 4578 cm^2/Vs at 77 K, compared to $\sim$1600 cm^2/Vs at RT and $\sim$6000 cm^2/Vs at 77 K for growth at 275 W for the same AlN thickness of 2.3 nm. However, the RT mobility of the faster growth rate 2DEGs degrades faster with the increase of the 2DEG density.

From our earlier work, the RT mobility of the 2DEGs in these samples is determined by the combination of polar optical phonon (POP) scattering, acoustic phonon (AP) scattering, and interface roughness (IR) scattering [7]. At RT, though POP scattering is the dominant mechanism, IR scattering and AP scattering have a measurable effect. At 77 K, the POP and AP scattering are negligible, and the effect of IR scattering can be clearly identified. The measured 77 K mobilities for various 2DEG densities are shown in Fig 2 (b). A slower growth rate is expected to lead to smooth interfaces, and IR scattering is most severe at high 2DEG densites; the higher 77 K mobilities for the 150 W grown structure for carrier densities $\geq 3 \times 10^{13}$ cm^{-2} are attributed to this fact. However, for lower 2DEG densities, the sample grown at a slow growth rate exhibits lower mobilities both at 77 K and at RT. This leads us to conjecture the presence of ionized impurity scattering in samples grown at slower growth rates. It is well known that high Al fluxes in Al(Ga)N growth lead to the incorporation of oxygen dopants in MBE growth, and the incorporation is enhanced at slow growth rates. Though ionized impurity scattering is screened at very high 2DEG densities, at lower densities, ionized impurity scattering can have a perceivable effect. However, more modeling and characterization is necessary to prove this conjecture. For the rest of this work, owing to its importance for HEMT technology, we concentrate on characterizing the transport properties of the highest mobility sample grown at 275 W, in which we expect ionizied impurity scattering to be negligible.

Temperature-dependent Hall-effect measurements were performed on the highest mobility 2.3 nm AlN/GaN heterojunction grown at 275 W. The sample was loaded into a closed-cycle He cryostat, and the temperature was varied between 10 and 300 K. The measured temperature-dependent mobilities are shown in Fig 3, along with a theoretical model. The effect of Coulombic scattering (due to charged dislocations $N_{disl} \sim 10^9$ cm^{-2} and ionized impurities) was found to be negligible compared to POP, IR, and AP scattering. The theoretical model assumed a Fang-Howard variational wavefunction for the 2DEG, and the penetration of the wavefunction into the AlN barrier was neglected. The individual energy-dependent scattering mechanisms were obtained from Fermi's Golden Rule, and taking advantage of the strongly degenerate nature of the high-density 2DEG ($E_F - E_C \sim 0.7$ eV $>> 3k_BT$ at all temperatures of interest here and E_C is the conduction band edge), the scattering rates were evaluated at the Fermi energy (E_F). The total electron mobility was then calculated by applying Matheissen's rule to the individual scattering mechanisms; the results are shown in Fig 3. The IR was modeled using a roughness of =0.5 nm in the growth direction with a correlation length L=2.5 nm at the AlN/GaN interface, as depicted in the inset of the figure. Since phonon scattering is intrinsic at room temperature, and IR scattering depends on growth conditions and the quality of the heterointerface, a maximum mobility in the range of $\mu_{max} \sim (\mu_{POP}^{-1} + \mu_{AP}^{-1})^{-1}$ is achievable with very sharp interfaces. Within limits of the theoretical model, this evaluates to a RT mobility of ~ 1800 cm^2/Vs for an AlN/GaN heterojunction with the measured 2DEG density. This indicates that if the interface is further improved in the growth, it is possible to achieve higher 2DEG mobilities, and hence even lower sheet resistances for high-density 2DEGs.

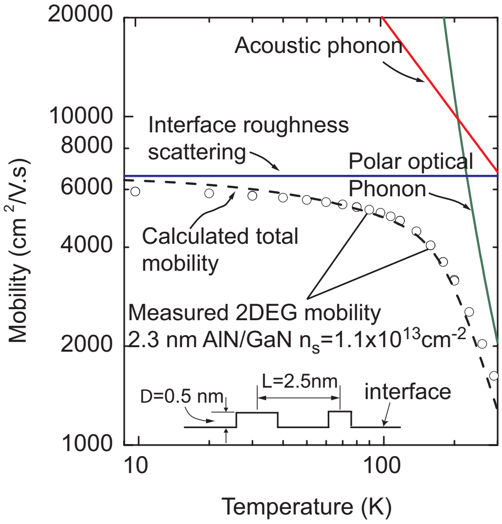

Figure 3 Temperature-dependent Hall data of single AlN/GaN heterojunction with the thickness of 2.3 nm (circles), with a theoretical model (dashed and solid lines).

4 Conclusion

The effect of growth rate on electron transport in 2DEGs in MBE-grown AlN/GaN heterojunctions was studied. The RT transport properties of 2DEGs in single AlN/GaN heterostructures was observed to improve at higher growth rates. A theoretical model was used to understand the experimental observations. Interface roughness scattering was identified as the primary scattering mechanism limiting the conductivity at low temperature, and the combination of polar optical phonon, interface roughness, and acoustic phonon scattering was found to limit the room temperature electron mobility. The very low sheet resistances observed in AlN/GaN heterojunctions indicate that it is possible to push the performance of GaN HEMTs into current, power, and speed levels currently unachievable in AlGaN/GaN, and even AlInN/AlN/GaN heterostructures. However, various hurdles remain - minimization of the contact resistance, 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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