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High-mobility AlGaN/GaN heterostructures grown by molecular-beam epitaxy on GaN templates prepared by hydride vapor phase epitaxy

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We report on the growth and transport properties of high-mobility two-dimensional electron gases (2DEGs) confined at the AlGaN/GaN interface grown by plasma-assisted molecular-beam epitaxy on GaN templates prepared by hydride vapor phase epitaxy. We have grown samples over a broad range of electron densities ranging from $n_s = 6.9\times10^{11}$ to 1.1×10^{13} cm^{-2}, and at $T=4.2$ K, observe a peak mobility of 53 300 cm^2/V s at a density of 2.8×10^{12} cm^{-2}. Magnetotransport studies on these samples display exceptionally clean signatures of the quantum Hall effect. Our investigation of the dependence of 2DEG mobility on carrier concentration suggests that the low-temperature mobility in our AlGaN/GaN heterostructures is currently limited by the interplay between charged dislocation scattering and interface roughness. © *2000 American Institute of Physics.* [S0003-6951(00)05343-2]

The combined effects of spontaneous and piezoelectric polarization make heterostructures formed from GaN and its Al and In alloys a unique semiconductor system. The large internal electric fields found in these highly polar materials have led to the discovery of a variety of new effects, including the spontaneous formation of a high-density (10^{13} cm^{-2}) two-dimensional electron gas (2DEG) at the AlGaN/GaN interface without modulation doping. Recently, significant progress in the growth of high mobility two-dimensional electron gases in the AlGaN/GaN system has been made.[1–4] Nevertheless, the experimentally achieved mobility values are still substantially less than theoretical studies would indicate is possible for GaN structures.[5–7] The highest reported mobility in the literature stands at 51 700 cm^2/V s at a density of 2.23×10^{12} cm^{-2} for a structure grown by molecular-beam epitaxy (MBE) on a GaN template prepared by metal organic chemical vapor deposition.[2] While the pace of progress has been swift, much still remains to be learned about the intrinsic transport scattering mechanisms that presently limit the low temperature mobility in state of the art AlGaN/GaN heterostructures.

In this study we report on the properties of high quality AlGaN/GaN heterostructures grown by plasma-assisted MBE on GaN templates prepared by hydride vapor phase epitaxy (HVPE) on sapphire [0001] substrates.[8] The reduced dislocation density and smooth surfaces of these HVPE GaN films make them ideal candidates for MBE overgrowth of quantum structures. The HVPE GaN templates discussed in this letter are ~20 μm thick and are residually n type with a carrier density of $\sim2\times10^{17}$ cm^{-3} and a bulk mobility $\mu \sim 400-500$ cm^2/V s at $T=300$ K. Our typical MBE overgrowth consists of a 0.5 μm undoped GaN buffer layer capped by approximately 30 nm of $Al_{0.09}Ga_{0.91}N$. Using the methods discussed in Ref. 2, we systematically varied the 2DEG density from 1.0×10^{12} to 6.1×10^{12} cm^{-2} by changing the thickness of the AlGaN barrier layer while keeping the Al concentration fixed. For carrier densities outside this range, the Al concentration was varied slightly. Our low temperature ($T=4.2$ K) Hall measurements were made in the van der Pauw configuration using indium for Ohmic contacts. Magnetoresistance measurements were performed at $T=0.3$ K in magnetic fields up to 14.5 T.

The existence and position of the two-dimensional electron gas has been verified using 100 kHz capacitance–voltage (CV) profiling using 250 μm diameter Pt Schottky contacts and In Ohmic contacts. Figure 1 displays the CV concentration profile as a function of distance from the top surface for an $Al_{0.09}Ga_{0.91}N$/GaN heterostructure. The high electron concentration observed at the AlGaN/GaN interface locates the position of the 2DEG. Away from the AlGaN/GaN interface, the net donor density ($N_D - N_A$) falls off sharply, reaching $\sim5\times10^{14}$ cm^{-3} in the MBE grown GaN.

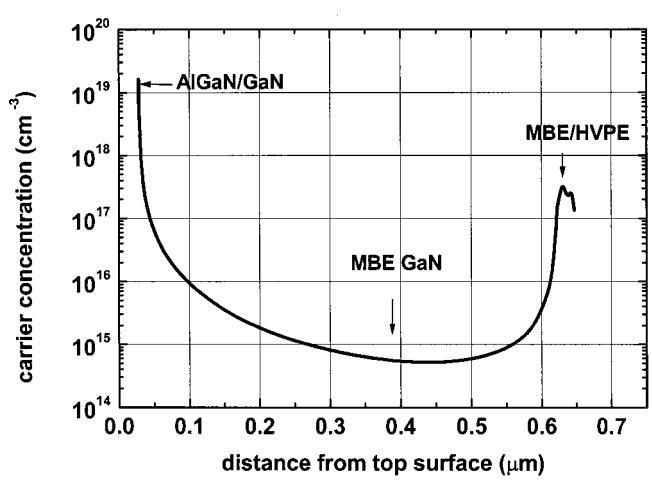

FIG. 1. Capacitance voltage profile of the 2DEG and net donor concentration of an $Al_{0.09}Ga_{0.91}N$/GaN heterostructure grown by MBE on a HVPE GaN template showing the low level of residual donors in the MBE material and the sharp interface between the MBE GaN and HVPE GaN.

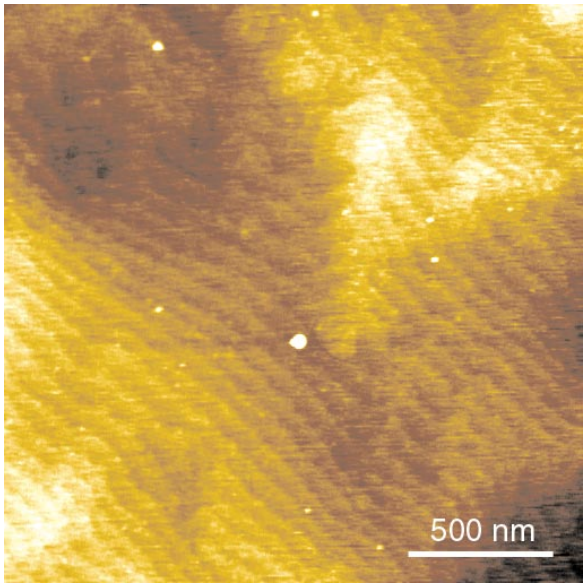

FIG. 2. (Color) AFM image of the surface of an $Al_{0.09}Ga_{0.91}N$/GaN heterostructure. The surface is dominated by monolayer steps and largely reproduces the morphology of the underlying HVPE layer. The full height range of this image is 5 nm.

This value is among the lowest residual donor concentrations reported for uncompensated GaN.[9] The low residual donor concentration in the MBE grown GaN implies that the incorporation of unintentional impurities during the MBE growth is minimal. At the MBE/HVPE interface a sharp rise in carrier concentration to the expected value of 2×10^{17} cm^{-3} is seen.

The surface morphology of our heterostructures was studied by atomic force microscopy (AFM). As seen in Fig. 2, the MBE growth produces extremely smooth AlGaN surfaces with the landscape dominated by monolayer steps. Comparison with the starting HVPE GaN substrates indicates that the MBE growth is largely reproducing the structure of the underlying HVPE GaN layer. AFM was also used to estimate the density of threading dislocations. Under less Ga-rich MBE growth conditions (not shown here), threading dislocations propagating through the heterostructure appear as pits on the AlGaN surface. The areal density of such features is measured to be $\sim(3-5)\times10^{8}$ cm^{-2}, a result consistent with transmission electron microscopy studies of our HVPE films of similar thickness.[8]

Figure 3 displays low temperature (T=0.3 K) magnetotransport data from an $Al_{0.09}Ga_{0.91}N$/GaN structure with a Hall density $n_s=2.4\times10^{12}$ cm^{-2} and mobility $\mu=26\,000$ cm^2/V s. An especially clean spectrum of the integer quantum Hall effect is observed. The onset of Shubnikov–de Haas oscillations occurs at a magnetic field of 2 T. Spin splitting of the Landau levels is visible at filling factors as high as $\nu=19$, while full quantization ($R_{xx}\rightarrow0$, $R_{xy}\rightarrow h/e^2\nu$) starts at $\nu=10$. The observation of vanishing longitudinal resistance in the quantum Hall states attests to the absence of significant parallel conduction in these structures. By T=0.3 K the free carriers in the bulk have frozen onto their parent ions. Furthermore, we observe that the two-dimensional electron density extracted from the periodicity of the Shubnikov–de Haas oscillations agrees with the density extracted from the low-field Hall measurements to within 5%. We note that the data of Fig. 3 represents a substantial improvement in the quality of magnetotransport in the quantum Hall regime for the AlGaN/GaN system and is, in addition to low-field mobility, further indication of the high quality of 2DEGs now possible in GaN.

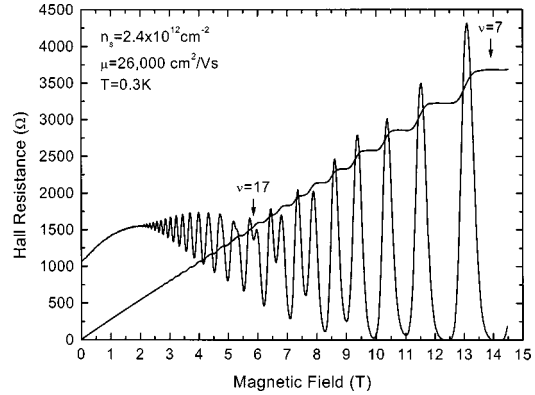

FIG. 3. Low temperature (T=0.3 K) magnetotransport data of an $Al_{0.09}Ga_{0.91}N$/GaN heterostructure with carrier density 2.4×10^{12} cm^{-2} and a mobility of 26 000 cm^2/V s. The data clearly show the quantum Hall effect with full quantization ($R_{xx}\rightarrow0$, $R_{xy}\rightarrow h/e^2\nu$) starting at $\nu=10$.

In Fig. 4 we plot our experimentally determined low temperature (T=4.2 K) mobility vs two-dimensional carrier concentration data. Each point represents the highest measured mobility *at a given electron density* for this series of growths. All samples in the density range of 1.0×10^{12} to 6.1×10^{12} cm^{-2} are nominally $Al_{0.09}Ga_{0.91}N$/GaN structures in which only the thickness of the barrier has been changed in order to vary the carrier density. At the low- and high-density limits, the Al fraction was changed slightly downward or upward to produce the required density. The most striking feature of this data is that mobility is clearly seen to be a nonmonotonic function of carrier density over the

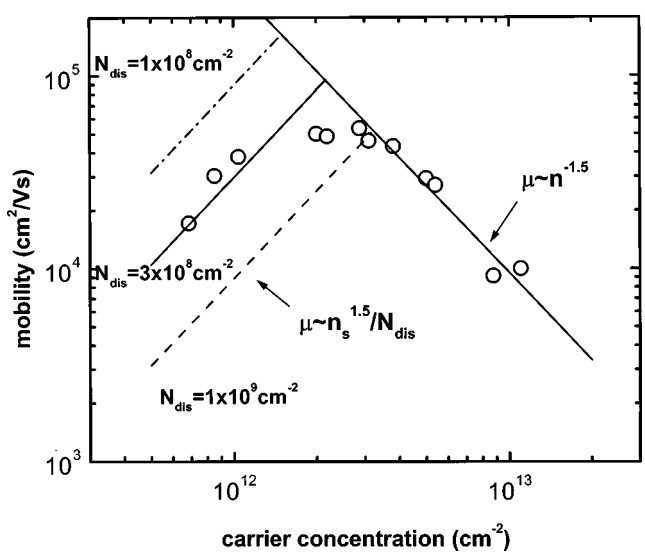

FIG. 4. Low temperature (T=4.2 K) mobility vs 2DEG carrier density. The mobility data represents the highest mobility *measured at each density* for this series of growths. Also plotted is the function $\mu\sim n_s^{1.5}/N_{dis}$ for various dislocation densities, representing the theoretical mobility limit due to dislocation scattering. The line drawn through the data at high density is a guide to the eye. The monotonic decrease of mobility with increasing carrier density above $n_s=3\times10^{12}$ cm^{-2} is consistent with a mobility limited by interface roughness and/or alloy scattering.

range of 6.9×10^{11} to 1.1×10^{13} cm^{-2}. Our mobility peaks at 53 300 cm^2/V s at a density of $n_s=2.8\times10^{12}$ cm^{-2}.

At higher densities ($n_s>2.8\times10^{12}$ cm^{-2}) the measured mobility is found to be a decreasing function of carrier concentration. Similar behavior has been reported in Refs. 2 and 10 in which only the density range $n_s>2.0\times10^{12}$ cm^{-2} was explored and a single monotonic decrease in mobility with increasing carrier density was observed. Loss of mobility with increasing carrier density is consistent with scattering dominated by interface roughness and/or alloy scattering.[11] Both effects are expected to diminish mobility at increased densities as the electron wave function is pressed tightly against the heterointerface. In Fig. 4 we plot the function $\mu\sim n_s^{-1.5}$ over the experimentally explored range of carrier density. In the high-density region ($n_s>2.8\times10^{12}$ cm^{-2}), our experimentally determined mobility displays a similar functional dependence on carrier density. We note that the function $\mu\sim n_s^{-1.5}$ was not generated by any theoretical model, but is simply meant to be a guide to the eye. Interestingly, a simple theoretical treatment of interface roughness scattering explored in Ref. 10 yielded essentially the same functional dependence. It seems apparent that interface roughness and/or alloy scattering is reducing the 2DEG mobility in the high-density regime.

At low carrier densities ($n_s<2.0\times10^{12}$ cm^{-2}), the measured mobility is found to be an increasing function of carrier density. This behavior is well known and is typical of AlGaAs/GaAs heterostructures in which the 2DEG mobility is known to be limited by Coulomb scattering due to ionized impurities.[11] In this regime, mobility increases with density as $\mu\sim n_s^{\alpha}$ where α typically varies from 0.7 to 1.5. In addition to the contribution of residual ionized impurities residing near the heterointerface, in the AlGaN/GaN system we must also consider the contribution from the high density of charged threading dislocations originating in the HVPE GaN and piercing the 2DEG. The importance of charged dislocations can be appreciated by the following simple argument. At a dislocation density of 5×10^8 cm^{-2} the average distance between dislocations is $\sim$0.5 μm. The electronic mean free path (l) is given by $l=v_F*\tau$ where v_F is the Fermi velocity and τ is the momentum relaxation time. For an AlGaN/GaN heterostructure with a carrier density of 2.0×10^{12} cm^{-2} and a mobility of 50 000 cm^2/V s, the mean free path is approximately 1 μm. The mean free path is comparable to the dislocation spacing and thus dislocation scattering is expected to be a factor influencing the transport. Very recent theoretical work[7] has shown the mobility limit due to charged dislocation scattering should have a $\mu\sim n_s^{1.5}/N_{\rm dis}$ dependence where $N_{\rm dis}$ is the areal density of dislocations. In Fig. 4 we plot the theoretically predicted mobility for three dislocation densities of 1×10^8, 3×10^8, and 1×10^9 cm^{-2}. The correspondence between the experimentally measured mobility on substrates known to have a dislocation density of $\sim(3-5)\times10^8$ cm^{-2} and the theoretical model for $N_{\rm dis}=3\times10^8$ cm^{-2} clearly highlights the importance of dislocation scattering for high mobility AlGaN/GaN heterostructures in the low-density regime.

In conclusion, we have demonstrated that our HVPE GaN templates are an exceptionally good substrate for the MBE growth of high quality AlGaN/GaN heterostructures. We measure a peak 2DEG mobility of 53 300 cm^2/V s at a carrier density of 2.8×10^{12} cm^{-2}. We observe extremely high quality magnetotransport in the quantum Hall regime. The dependence of mobility on carrier density suggests that the interplay between AlGaN/GaN interface roughness scattering and charged dislocation scattering presently limits the low temperature mobility in state of the art AlGaN/GaN heterostructures.

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