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Electron mobility exceeding 160 000 $cm^2/V\,s$ in AlGaN/GaN heterostructures grown by molecular-beam epitaxy

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We report on the transport properties of a two-dimensional electron gas (2DEG) confined in an AlGaN/GaN heterostructure grown by plasma-assisted molecular-beam epitaxy on a semi-insulating GaN template prepared by hydride vapor phase epitaxy with a threading dislocation density of $\sim 5\times 10^7$ cm^{-2}. Using a gated Hall bar structure, the electron density (n_e) is varied from 4.1 to 9.1×10^{11} cm^{-2}. At $T=300$ mK, the 2DEG displays a maximum mobility of 167 000 $cm^2/V\,s$ at a sheet density of 9.1×10^{11} cm^{-2}, corresponding to a mean-free-path of ~ 3 μm. Shubnikov–de Haas oscillations, typically not observed at magnetic fields below 2 T in GaN, commence at $B=0.6$ T. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1824176]

For the AlGaN/GaN two-dimensional electron gas (2DEG) it is now established[1–3] that alloy scattering and interface roughness scattering limit the low temperature mobility for densities above $\sim 2\times 10^{12}$ cm^{-2}, producing a characteristic decrease in mobility for increasing density. In AlGaN/GaN structures with 2DEG density below 1×10^{12} cm^{-2} and with low background impurity levels, however, recent studies[4,5] have shown that long-range Coulomb scattering from charged threading dislocations limits the maximum low temperature mobility for dislocation densities $\geqslant 10^8$ cm^{-2}. One implication of Ref. 4 is that low temperature mobility can be further improved as the density of charged dislocations propagating through the AlGaN/GaN heterostructure is reduced. Given the large effective mass in GaN ($m^*\sim 0.2m_e$) and a g-factor close to 2, high quality 2DEGs in AlGaN/GaN may be used in the future for study of the metal–insulator transition and spin-related phenomena. In addition, very low-density AlGaN/GaN samples will allow for the investigation of electron correlation effects at more readily accessible values of magnetic field.[3]

In this letter we report on the achievement of very high low temperature mobility for an AlGaN/GaN 2DEG structure. Using an insulated gate Hall bar structure we have produced an AlGaN/GaN 2DEG with low temperature mobility of 167 000 $cm^{-2}/V\,s$ at a sheet density $n_e=9.1\times 10^{11}$ cm^{-2}. Shubnikov-de Haas oscillations are observed at magnetic fields as low as 0.6 Tesla. At the lowest achieved 2DEG density $n_e=4.1\times 10^{11}$ cm^2, the $\nu=2$ quantum Hall state is clearly resolved at B=8.5 T.

Since large area bulk nitride substrates are not commercially available, GaN structures are typically grown heteroepitaxially on lattice-mismatched substrates. The investigation of the intrinsic properties of the 2DEG in AlGaN/GaN structures requires that the number of extended defects propagating through the heterostructure be minimized. The heterostructure used in this study was grown by plasma-assisted molecular beam epitaxy (MBE) on a thick GaN template prepared by hydride vapor phase epitaxy (HVPE) on a sapphire substrate. Improvements in the HVPE substrate quality have directly led to improvements in 2DEG low temperature mobility. The HVPE GaN template discussed here is 75 μm thick and is known to have threading dislocation density of $\sim 5\times 10^7$ cm^{-2}. The HVPE GaN has been compensated with Zn at a level of $\sim 10^{17}$ cm^{-3} to suppress any residual conductivity that may obscure observation of the 2DEG properties at very low sheet charge densities. In these structures no parasitic conduction is observed from $T=300$ K down to low temperature, even at electron densities $n_e\sim 5\times 10^{11}$ cm^{-2}. In addition to the reduced threading dislocation density, the large diameter (2 in.) and smooth surface morphology of the HVPE substrates facilitate careful study of the MBE growth conditions necessary for the achievement of high mobility.

The plasma-assisted MBE grown epitaxial layer consists of a 1.5 μm GaN buffer followed by a ~ 16 nm $Al_{0.06}Ga_{0.94}N$ undoped barrier layer that is capped with a 3 nm GaN layer. The termination of the heterostructure with a GaN capping layer provides a stable surface for processing and can be used to tailor the 2DEG density. The entire heterostructure is grown under slightly Ga-rich conditions at a growth temperature of 745 °C with the nitrogen plasma source set to 205 W forward power and a nitrogen flow rate of 0.5 sccm. The growth temperature is not changed for the deposition of the AlGaN barrier layer. The MBE operating pressure is 1.5×10^{-6} Torr during growth. The low operating pressure is maintained by two closed-cycle He cryopumps.

Following MBE growth, insulated gate Hall bars were fabricated. The Hall bar is 100 μm wide by 2.0 mm long. Fourteen voltage probes are placed symmetrically along the device. Mesas of 100 nm height are defined with a chlorine-based dry etch. Ohmic contacts consist of a Ti/Al/Ni/Au metal stack that is thermally annealed at 750 °C for 30 s. After Ohmic contact definition, 50 nm of SiO_2 is deposited on the device. Finally, 10 nm of Ni and 100 nm of Au are deposited over the SiO_2 along the Hall bar forming an insulated gate structure. At $T=0.3$ K, the gate leakage is insignificant (<1 nA) over the voltage range of −0.75 to 0.5 V.

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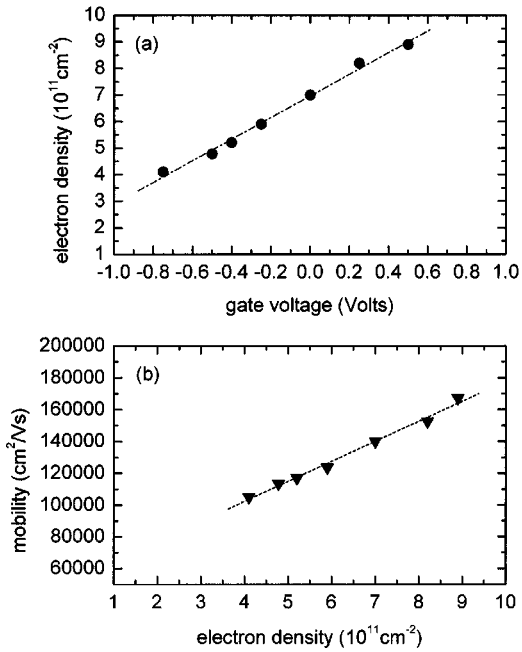

FIG. 1. (a) The measured 2DEG density at $T=0.3$ K as a function of gate voltage V_G between −0.75 and +0.5 V. In this regime, n_e vs V_G is linear function indicating that our device is behaving as a parallel plate capacitor. (b) 2DEG mobility as a function of electron density at $T=0.3$ K.

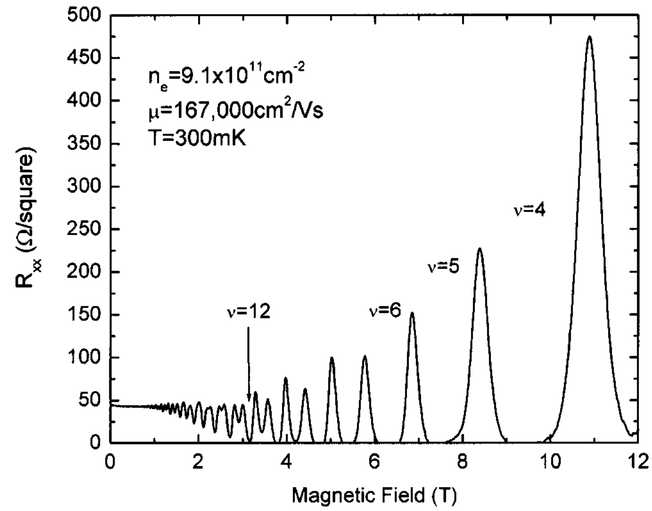

FIG. 2. Longitudinal magnetoresistance R_{xx} measured at $T=300$ mK. At a gate bias of $V_G=0.5$ V the 2DEG density is 9.1×10^{11} cm^{-2} and the mobility is 167 000 cm^2/V s.

The gate voltage dependence of the 2DEG density at $T=0.3$ K is displayed in Fig. 1(a). The 2DEG density at each gate voltage is determined from the periodicity of the Shubnikov–de Haas (SdH) oscillations. In all cases, the longitudinal magnetoresistance, R_{xx}, goes to zero at the integer quantum Hall states at high magnetic field. The linear dependence of density implies that our device behaves as a simple parallel-plate capacitor. The density dependence of the low temperature mobility at $T=0.3$ K is shown in Fig. 1(b). The linear behavior-$\mu\sim n_e^{\alpha}$, with $\alpha\sim1.0$ over the measured density range is consistent with the findings of Ref. 4. We note that the mobility has not saturated at $n_e=9.1\times10^{11}$ cm^{-2}, and indeed, may be higher at slightly higher 2DEG density. Our measurement is limited to positive gate voltages $\leqslant0.5$ V as the gate leakage becomes significant beyond this point and the data become unreliable.

The intrinsic limit to low temperature mobility in AlGaN/GaN heterostructures remains an open question. The linear dependence of mobility on density observed in our data suggests that dislocation scattering is still a determining factor for mobility in our sample.[4,6] Nevertheless as the dislocation density continues to decrease with higher quality substrates, scattering mechanisms other than dislocation scattering will play an increasingly important role.[7] Interestingly, Hsu *et al.*[8] have calculated, in the *absence* of dislocation scattering, the maximum 2DEG mobility for GaN at slightly above 10^5 cm^2/V s for an $Al_{0.07}Ga_{0.93}N$/GaN heterostructure with a 15 nm $Al_{0.07}Ga_{0.93}N$ barrier. In the case considered in Ref. 8, remote donors on the sample surface and uniformly distributed residual impurities are the principle scattering sources at low electron density. While the thickness and aluminum content of the barrier layer used in the calculation are similar to our structure, the calculated mobility depends sensitively on the chosen impurity concentration and distribution. The chosen background impurity concentration used in the calculation is quite high ($\sim10^{16}$ cm^{-3}) and parameters used in Ref. 8 are unlikely to apply to the higher purity GaN grown in our MBE system.[3] Thus a more rigorous comparison between experiment and theory will require precise knowledge of the impurity distribution in high purity heterostructures.

Magnetotransport measurements were performed at $T=0.3$ K in magnetic fields up to 14.5 T using standard low frequency (11 Hz) lock-in techniques. Measurements are typically made with an excitation current $\leqslant100$ nA. At 300 mK, no electron heating effects are observed. Figure 2 displays the longitudinal magnetoresistance (R_{xx}) for the highest measured electron density of 9.1×10^{11} cm^{-2}. This trace is distinguished by the early onset of SdH oscillations which were observed for filling factors as high as $\nu\sim50$. Spin splitting is observed at $\nu=17$ at 2.2 T, and the integer quantum Hall effect (QHE) is fully developed at $\nu=12$. Here $R_{xx}\rightarrow0$ at $B=3.14$ T.

Figure 2 displays the low field magnetoresistance taken at $V_G=0$ V and $T=0.3$ K. At zero gate bias, the 2DEG den-

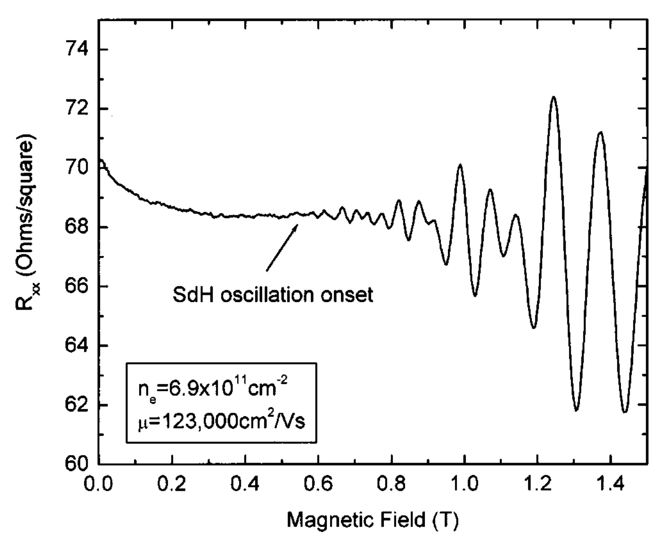

FIG. 3. R_{xx} at low magnetic field for an electron density 6.9×10^{11} cm^{-2} at $T=300$ mK. At very low magnetic fields (<100 mT) negative magnetoresistance associated with weak localization is evident. Shubnikov–de Haas oscillations commence at $B=0.6$ T.

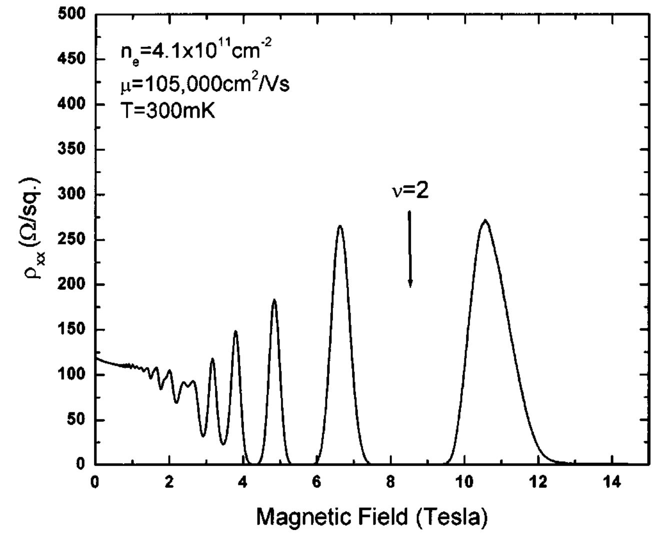

FIG. 4. Longitudinal magnetoresistance, R_{xx}, as a function of magnetic field at gate bias $V_G=-0.75$ V with a 2DEG density of 4.1×10^{11} cm^{-2} at $T=0.3$ K. The $\nu=2$ quantum Hall state occurs at 8.5 T.

sity and mobility are 6.9×10^{11} cm^{-2} and 123 000 cm^2/V s, respectively. At extremely small fields ($<$100 mT), negative magnetoresistance associated with weak localization is evident. Localization phenomena in GaN is a topic of current interest and will be discussed in more detail in a future publication. Between $\sim$0.1 and 0.5 T the magnetoresistance is nearly constant as expected in the classical Drude model of low field magnetoresistance. Shubnikov–de Haas oscillations, typically not observed at magnetic fields below 2 T in GaN,[9] commence at $B=0.6$ T. The onset of oscillations is limited by the degree of disorder broadening of the developing Landau levels, and in addition to zero-field mobility, can be used as a metric of material quality.[10] We can make a crude estimate of the average time between scattering events, known as the quantum scattering time τ_q, from the criterion $\omega_c\tau_q\geqslant 1$, where ω_c is the cyclotron frequency. This criterion states that the electron should be able to complete a full cyclotron orbit before scattering. Examination of the data presented in Fig. 2 suggests that τ_q is approximately 2 ps in this sample.

Figure 4 displays the longitudinal magnetoresistance at a gate bias $V_G=-0.75$ V. This gate bias produced the lowest 2DEG density ($n_e=4.1\times10^{11}$ cm^{-2}) studied in this work. Even at this low density, SdH oscillations and the QHE are clearly resolved. As can be seen, SdH oscillations continue to be resolved at very low magnetic fields less than 1 T. Around $B=8.5$ T a relatively wide zero in R_{xx} is observed corresponding to the $\nu=2$ quantum Hall state. At this point the only the two spin states of the lowest Landau level are occupied. Continued improvement in sample quality should allow for the observation of highly correlated electron states associated with the fractional quantum Hall effect at low magnetic field values.[3]

In summary we described the growth and transport properties of a very high mobility 2DEG in an AlGaN/GaN heterostructure. This sample displayed a peak mobility of 167 000 cm^2/V s with a density of 9.1×10^{11} cm^{-2} at $T=0.3$ K. Central to the achievement of high mobility is the use of thick HVPE GaN templates with reduced dislocation density and semi-insulating properties. This work suggests that further improvements in low temperature mobility can be achieved with continued improvements in substrate quality and MBE epilayer design.

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