Transport in a gated $Al_{0.18}Ga_{0.82}N/GaN$ electron system

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(Received 31 March 2003; accepted 4 June 2003)

We have investigated the low-temperature transport properties of front-gated $Al_{0.18}Ga_{0.82}N/GaN$ heterostructures. At zero gate voltage, the Hall mobility increases with decreasing temperature ($20\,K \leqslant T \leqslant 190\,K$) due to a reduction in phonon scattering. For $T \leqslant 20\,K$, the mobility decreases with decreasing temperature. This is due to weak localization in a weakly disordered two-dimensional system. By changing the applied gate voltage, we can vary the carrier density n from 3.11×10^{12} to $6.95\times10^{12}\,cm^{-2}$ in our system. The carrier density shows a linear dependence on the applied gate voltage, consistent with a simple parallel-plate capacitor model. The average distance between the GaN electron system and the AlGaN/GaN interface is estimated to be 240 Å. At high carrier densities ($n > 4.65\times10^{12}\,cm^{-2}$), the measured mobility (μ) is found to be a decreasing function of carrier density as $\mu \sim n^{-0.31}$. Loss of mobility with increasing carrier density is dominated by interface roughness scattering. At low carrier densities ($n < 4.24\times10^{12}\,cm^{-2}$), the measured mobility is found to be an increasing function of carrier density as $\mu \sim n^{0.34}$. This is consistent with remote ionized impurity scattering, although the measured exponent 0.34 is smaller than the typical value (0.7–1.5) observed in an AlGaN/GaN electron system. A possible reason is that our sample mobility is approximately five times lower than those in other devices for a similar electron density. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1594818]

I. INTRODUCTION

Recent efforts in developing III–V nitride family, InN, GaN, and AlN have led to significant progress in improving material quality. Alloys and heterostructures based on these materials are therefore being studied with great interest.[1–4] Due to the large band gap of AlGaN/GaN heterostructures, it is ideally suited for making light-emitting diodes, lasers, and detectors operating in the visible to ultraviolet range as well as high-power transistors with operating frequencies in the microwave region.[5–7] It should be noted that in addition to proving semiconductors with large band gaps the nitrides have two interesting features. One is a spontaneous polarization present in the structures as a result of the cation and anion position in the lattice. In heterostructures the difference between spontaneous polarizations of two layers can be used to create a high carrier density. The other is the piezoelectric polarization for a nitride system in heterostructures with strain. The effective built-in internal fields can be produced near the interface. These two features have been exploited to design nominally undoped AlGaN/GaN high electron mobility transistors (HEMTs) with high sheet charge densities.[8–14]

Given its promising device applications, it is important to understand the underlying physics of transport in AlGaN/GaN electron systems. In this article, we report magnetotransport measurements on a gated $Al_{0.18}Ga_{0.82}N/GaN$ electron system. At zero gate voltage $V_g = 0$, the electron mobility increases with decreasing temperature ($20\,K \leqslant T \leqslant 190\,K$). This is due to the formation of the GaN two-dimensional electron gas (2DEG) near the AlGaN/GaN interface and a reduction in phonon scattering. For $T \leqslant 20\,K$, the electron mobility *decreases* with decreasing temperature. We ascribe this to weak localization effects in a weakly disordered system.[15] This result clearly demonstrates the existence of weak localization effects in low-mobility GaN electron systems. By changing the applied gate voltage, we are able to vary the electron density in our system. The carrier density n shows a linear dependence on gate voltage, consistent with a parallel-plate capacitor model in which one plate of the capacitor is the metallic surface gate while the other is the 2DEG. Our simple model allows us to estimate the averaged distance between the 2DEG and the AlGaN/GaN interface to be ~240 Å. Since our system is of lower mobility, it allows us to study the mobility dependence on electron density in the high disorder regime. The sample mobility is typically five times lower than those of the other devices for a similar electron density. At high n ($n > 4.65\times10^{12}\,cm^{-2}$), the mobility μ is a decreasing function of n ($\mu \sim n^{-0.31}$). This can be ascribed to interface roughness scattering. At low n ($n < 4.65\times10^{12}\,cm^{-2}$), μ is an increasing function of

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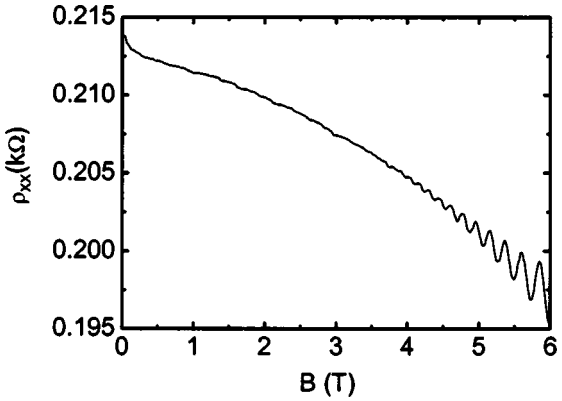

FIG. 1. Magnetoresistivity measurements ρ_{xx} as a function of perpendicular magnetic field at $V_g=0$.

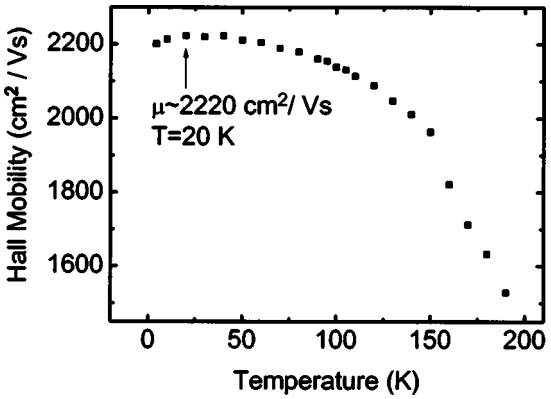

FIG. 2. Hall mobility as a function of temperature T.

n ($\mu \sim n^{0.34}$). The possible physical origin for this is due to remote ionized impurity scattering,[16,17] although the exponent 0.34 is smaller than the typical value (0.7–1.5) in a GaN electron system.[14,18]

II. EXPERIMENT

The sample that we studied is a front-gated $Al_{0.18}Ga_{0.82}N/GaN$ heterostructure. The following layer sequence was grown on a sapphire substrate by metalorganic chemical vapor deposition (MOCVD): 3 μm GaN and 400 Å nominally undoped $Al_{0.18}G_{0.82}N/GaN$. The sample was first processed into a $800\times 80\ \mu m^2$ Hall-bar-shaped mesa. Ti/Al/Ni/Au ohmic contacts and AuPd front gate were made by conventional UV lithography. Experiments were performed in a ^{4}He cryostat equipped with a superconducting magnet of a maximum field of 6 T. Four-terminal magnetoresistivity was measured using standard phase-sensitive techniques. By changing the applied gate voltage, we are able to vary the electron density in our system. Over our measurement range ($-3.5\ V \leqslant V_g \leqslant 0.5\ V$), the gate-2DEG leakage current is kept lower than 10 nA.

Figure 1 shows the four-terminal magnetoresistivity measurements ρ_{xx} as a function of perpendicular magnetic field at $V_g=0$. The carrier density determined from the period of the Shubnikov–de Haas (SdH) oscillations and that measured from the Hall effect are within 2.8% difference. These results, together with the fact that we only observe one series of SdH oscillations, show that there is only one 2D subband occupied in the GaN quantum well.

To further investigate the underlying physics of transport in our GaN electron system, we study the Hall mobility dependence on temperature. Figure 2 shows the mobility as a function of temperature T at $V_g=0$. For $20\ K \leqslant T \leqslant 190\ K$, the mobility increases with decreasing temperature. This is consistent with a reduction in phonon scattering which plays an important role in limiting the electron mobility in III–V semiconductors. It is interesting to note that for $T \leqslant 20$ K, the mobility *decreases* with decreasing temperature. This is in contrast to previous studies[10,18] in which the Hall mobility increases with decreasing temperature over the whole measurement range. We ascribe this effect to weak localization in a weakly disordered 2D system.[15] As shown in Fig. 3 the resistivity shows a logarithmic dependence on temperature, characteristics of weak localization effects observed in a weakly disordered 2D electron system.[15] The decrease of the resistivity ($\sim 1\%$) is also consistent with the magnitude $1/k_F l$ in a weakly disordered two-dimensional system[19] where k_F is the Fermi wave vector and l is the elastic mean free path, respectively. The amount of disorder within our system is larger than that in previous work[10,18,20] thus we are able to observe weak localization effects in our case.

Let us turn our attention to the mobility dependence on electron density. Our system is of lower electron mobility thus it is useful to compare our results with previous work.[14,20] By changing the applied gate voltage (V_g) from -3.5 to $+0.5$ V, we can vary the electron density from 3.11×10^{12} to $6.95\times 10^{12}\ cm^{-2}$ in our system. Figure 4(a) shows the electron density as a function of V_g. We can see that the electron density shows a linear dependence on V_g, consistent with a simple parallel-plate capacitor model. From the linear fit the depth of the 2DEG is estimated to be 640 Å below the surface. This is somewhat larger than the as-grown thickness of the AlGaN layer 400 Å. Our simple model allows us to estimate the averaged distance between the 2DEG and the AlGaN/GaN interface to be 240 Å. This is not unexpected since in a triangular quantum well, the maximum of the electron wave function distribution is at a certain distance away from the semiconductor interface. Figure 4(b) shows the mobility as a function of gate voltage. The measured

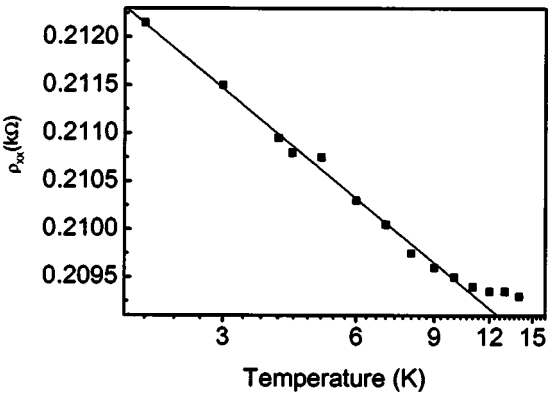

FIG. 3. ρ_{xx} as a function of temperature. There is a good linear fit over the temperature range ($2K \leqslant T \leqslant 11$ K).

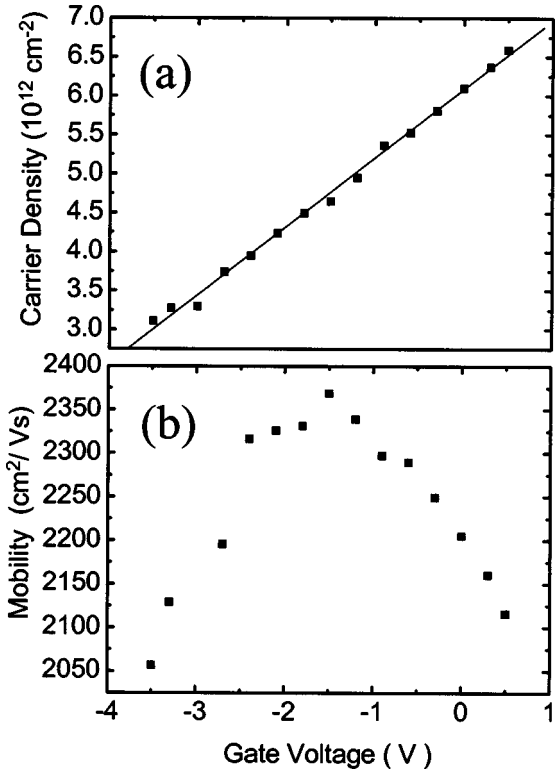

FIG. 4. (a) The electron density and (b) electron mobility vs gate voltage at the temperature $T=4.3$ K

electron mobility increases from $\mu=2060\,\mathrm{cm^2/V\,s}$ ($n=3.11\times10^{12}\,\mathrm{cm^{-2}}$) at $V_g=-3.5$ V up to the maximum mobility $\mu=2370\,\mathrm{cm^2/V\,s}$ ($n=4.65\times10^{12}\,\mathrm{cm^{-2}}$) at $V_g=-1.5$ V, and then decreases to $\mu=2120\,\mathrm{cm^2/V\,s}$ ($n=6.59\times10^{12}\,\mathrm{cm^{-2}}$) at $V_g=+0.5$ V.

In order to elucidate the underlying physics of the mobility dependence on electron density, we plot $\ln(\mu)$ as a function of $\ln(n)$, as shown in Fig. 5. In our system at higher electron concentration ($n>4.65\times10^{12}\,\mathrm{cm^{-2}}$) the measured electron mobility is found to be a decreasing function of electron concentration $\mu\sim n^{-0.31}$. The decreasing mobility with increasing concentration is consistent with interface roughness scattering.[20,21,22,23] The effect of interface roughness is expected to diminish mobility with increasing electron concentration as the electron wave function is pressed closely against the AlGaN/GaN heterointerface. At lower electron densities ($n<4.65\times10^{12}\,\mathrm{cm^{-2}}$), the measured electron mobility is found to be an increasing function of electron concentration as $\mu\sim n^{0.34}$. This is consistent with remote ionized impurity scattering in high-mobility AlGaN/GaN electron systems,[21–23] although the measured exponent 0.34 is somewhat smaller than the typical value (0.7 – 1.5). A possible reason for this is that the mobility in our system is approximately five times lower than those reported for a similar carrier density.[14,20,24]

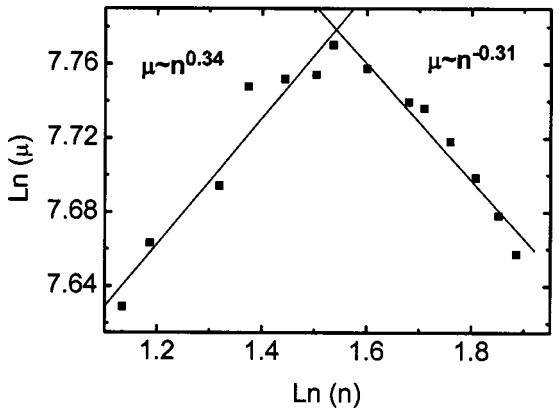

FIG. 5. The logarithm of mobility $\ln(\mu)$ as a function of the logarithm of electron density $\ln(n)$. There is a fit $\mu\sim n^{0.34}$ in the low-n regime and a fit $\mu\sim n^{-0.31}$ in the high-n regime, respectively.

III. CONCLUSION

In conclusion, we have measured the transport properties of a gated $Al_{0.18}Ga_{0.82}N/GaN$ heterostructure. At high temperatures, the electron mobility decreases with increasing temperature due to an increase in phonon scattering. When the temperature is below 20 K, the electron mobility *decreases* with decreasing temperature due to weak localization effects. This result clearly demonstrates the existence of weak localization in a low-mobility GaN electron system. Low-temperature measurements of the mobility dependence on electron density were performed. The measured mobility is found to be a decreasing function of carrier concentration as $\mu\sim n^{-0.31}$ at high carrier concentration. Loss of mobility with increasing carrier concentration is dominated by the interface roughness scattering. At low carrier densities, the measured mobility is found to be an increasing function of carrier concentration as $\mu\sim n^{0.34}$. This is consistent with Coulomb scattering due to remote ionized impurities, though the measured exponent 0.34 appears to be lower than the typical value (0.7 – 1.5). A possible reason is that our device mobility is approximately five times lower compared with other systems at a similar electron density. Further studies are required in order to understand the exact physical origin of the smaller exponent (0.34) observed in our low-mobility system.

ACKNOWLEDGMENTS

This work was funded by the NSC, Taiwan, (NSC 91-2112-M-002-043) the MOE program for Promoting Academic Excellence of Universities (89-N-FA01-2-4-3), and in part, by the KOSEF through the Quantum Photonic Science Research Centre at Hanyang University. C. T. L. acknowledges financial support from the Department of Physics, National Taiwan University. G. H. K. acknowledges support by National R&D Project for Nano Science and Technology (Contract No. M1-0212-04-0003) of MOST.

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