Transport in a gated Al$_{0.18}$Ga$_{0.82}$N/GaN electron system

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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 ≤ T ≤ 190 K) due to a reduction in phonon scattering. For T ≤ 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 × 10$^{12}$ 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 × 10$^{12}$ cm$^{-2}$), the measured mobility (µ) is found to be a decreasing function of carrier density as µ ∝ n$^{-0.31}$. Loss of mobility with increasing carrier density is dominated by interface roughness scattering. At low carrier densities (n < 4.24 × 10$^{12}$ cm$^{-2}$), the measured mobility is found to be an increasing function of carrier density as µ ∝ 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 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 devices. 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 × 10$^{12}$ cm$^{-2}$), the mobility µ is a decreasing function of n (µ ∝ n$^{-0.31}$). This can be ascribed to interface roughness scattering. At low n (n < 4.65 × 10$^{12}$ cm$^{-2}$), µ is an increasing function of

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

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): $3 \mu$m GaN and 400 Å nominally undoped Al$_{0.18}$Ga$_{0.82}$N/GaN. The sample was first processed into a $800 \times 80$-mm$^2$ 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 ($-3.5 \text{ V} < V_g < 0.5 \text{ V}$), the gate-2DEG leakage current is kept lower than 10 nA.

Figure 1 shows the four-terminal magnetoresistivity measurements $\rho_{xx}$ 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 electron density. Our system is of lower electron mobility thus it is useful to compare our results with previous work. By changing the applied gate voltage ($V_g$) from $-3.5$ to $+0.5$ V, we can vary the electron density from $3.11 \times 10^{12}$ 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 resistivity shows a logarithmic dependence on temperature, characteristics of weak localization effects observed in a weakly disordered 2D electron system.

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. By changing the applied gate voltage ($V_g$) from $-3.5$ to $+0.5$ V, we can vary the electron density from $3.11 \times 10^{12}$ to $6.95 \times 10^{12}$ cm$^{-2}$ in our system. Figure 4 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 resistivity shows a logarithmic dependence on temperature, characteristics of weak localization effects observed in a weakly disordered 2D electron system.

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.

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

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

FIG. 3. $\rho_{xx}$ as a function of temperature. There is a good linear fit over the temperature range (2K $\leq T \leq 11$ K).
roughness scattering. The effect of interface roughness with increasing concentration is consistent with interface mobility being a decreasing function of carrier concentration as $\mu \sim n^{-0.34}$. This is consistent with remote ionized impurity scattering in high-mobility AlGaN/GaN electron systems, 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.

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

The electron mobility increases from $\mu = 2060 \text{ cm}^2/\text{V s}$ ($n = 3.11 \times 10^{12} \text{ cm}^{-2}$) at $V_g = -3.5$ V to the maximum mobility $\mu = 2370 \text{ cm}^2/\text{V s}$ ($n = 4.65 \times 10^{12} \text{ cm}^{-2}$) at $V_g = -1.5$ V, and then decreases to $\mu = 2120 \text{ cm}^2/\text{V s}$ ($n = 6.59 \times 10^{12} \text{ cm}^{-2}$) 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 ($n > 4.65 \times 10^{12} \text{ cm}^{-2}$) the measured electron mobility is found to be a decreasing function of electron concentration $\mu \sim n^{-0.34}$. The decreasing mobility with increasing concentration is consistent with interface roughness scattering. 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 ($n < 4.65 \times 10^{12} \text{ cm}^{-2}$), the measured electron mobility is found to be an increasing function of electron concentration as $\mu \sim n^{0.34}$. This is consistent with 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.

**Figure 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. 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.

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