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Dislocation-free high-quality AlGaN/GaN heterostructures have been grown by molecular-beam epitaxy on semi-insulating bulk GaN substrates. Hall measurements performed in the 300 K–50 mK range show a low-temperature electron mobility exceeding 60 000 $cm^2/V\,s$ for an electron sheet density of $2.4\times10^{12}\,cm^{-2}$. Magnetotransport experiments performed up to 15 T exhibit well-defined quantum Hall-effect features. The structures corresponding to the cyclotron and spin splitting were clearly resolved. From an analysis of the Shubnikov de Hass oscillations and the low-temperature mobility we found the quantum and transport scattering times to be 0.4 and 8.2 ps, respectively. The high ratio of the scattering to quantum relaxation time indicates that the main scattering mechanisms, at low temperatures, are due to long-range potentials, such as Coulomb potentials of ionized impurities. © *2000 American Institute of Physics.* [S0003-6951(00)01042-1]

Since the first demonstration of the existence of a two-dimensional electron gas (2DEG) at the AlGaN/GaN interface in 1992,[1] tremendous progress has been realized[2] in the field of AlGaN/GaN high electron mobility transistors deposited on various substrates by different growth techniques. For example, Gaska *et al.*[3] reached a room-temperature mobility slightly over 2000 $cm^2/V\,s$ ($n_s=1.3\times10^{12}\,cm^{-2}$) in an $Al_{0.2}Ga_{0.8}N$/GaN structure deposited on 6H–SiC substrate by low-pressure metalorganic vapor-phase epitaxy. Smorchkova *et al.*[4] succeeded in obtaining a mobility of 51 700 $cm^2/V\,s$ at 13 K in $Al_{0.09}Ga_{0.91}N$/GaN structure grown on sapphire by rf plasma-assisted molecular-beam epitaxy (MBE), with a 2DEG density of $2.2\times10^{12}\,cm^{-2}$. In these devices, a very large lattice mismatch between the substrate and the active layer leads to a high density of threading dislocations.[5] A recent theoretical study by Jena, Gossard, and Mishra[6] showed that the effect of dislocations on the 2DEG mobility becomes noticeable for densities above 10^8–$10^{10}\,cm^{-2}$, which correspond to the values typical for heteroepitaxial nitride layers.

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In this letter, we report on dislocation-free AlGaN/GaN single heterostructures grown on semi-insulating GaN single-crystal substrates. We present the evidence of a 2DEG in such structures and characterize the 2DEG by magnetotransport experiments—low-field transport, Shubnikov de Hass, and quantum Hall effect (QHE) in magnetic fields up to 15 T at temperatures down to 50 mK. These measurements yield a low-temperature two-dimensional (2D) electron mobility that is one of highest ever reported for GaN-based heterojunctions.[4]

GaN single crystals were grown by a self-seeding process under high-N_2 pressures of 10–20 kbar and at temperatures ranging from 1400 to 1700 °C from an atomic solution in Ga. Usually, such crystals are highly *n* doped and can be made semi-insulating by adding compensating magnesium atoms to the Ga solution. The typical dimensions of the bulk crystals are $8\times8\times0.1$ mm with the *c* axis perpendicular to the surface. These crystals were tested to be semi-insulating with a perfect crystallographic structure.[7]

Prior to growth, the (0001) Ga face, which was found to be the best face polarity for a homoepitaxial layer,[8] was prepared by mechanical polishing and reactive ion etching in a $Cl_2+Ar+CH_4$ plasma. The AlGaN/GaN single heterostructures were grown by MBE in a Riber system. NH_3 was used

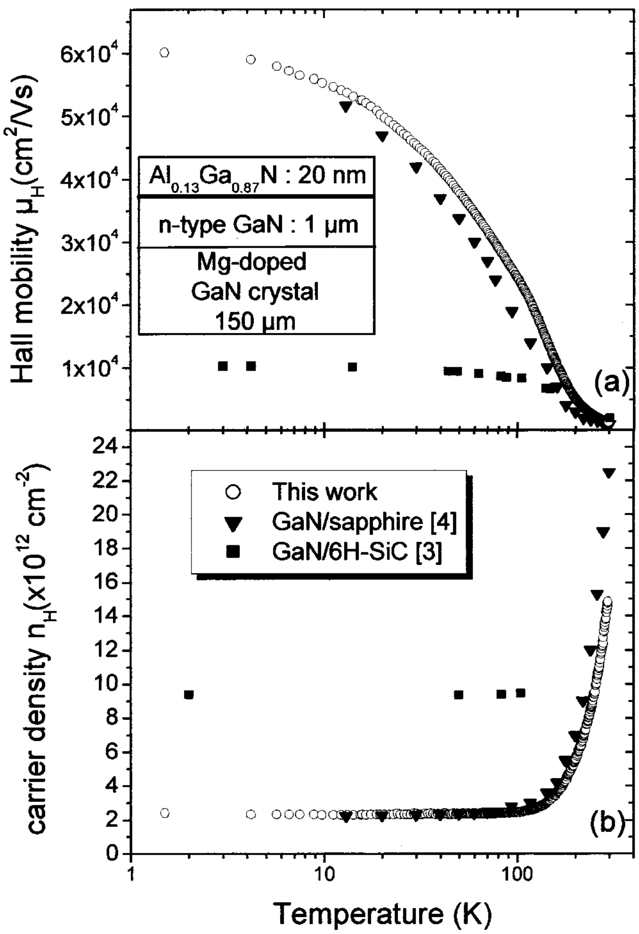

FIG. 1. Hall mobility (a) and electron sheet density (b) vs temperature for heterostructures deposited on GaN bulk substrates. The inset in (a) shows the sample structure.

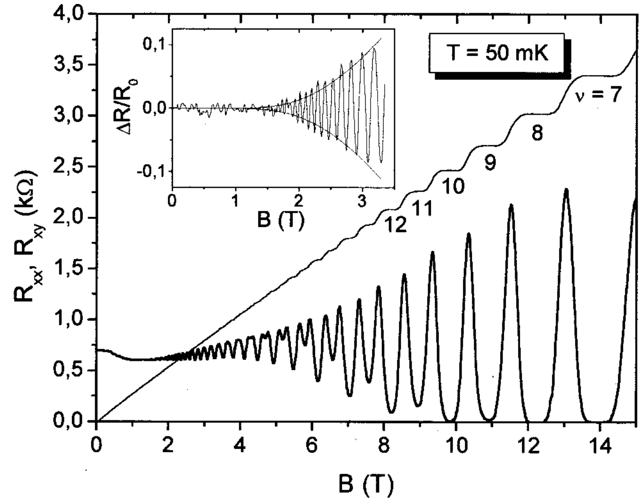

FIG. 2. Longitudinal (R_{xx}) and transverse (R_{xy}) magnetoresistance vs magnetic field at 50 mK. Shubnikov de Hass oscillations begin at 1.8 T. The inset shows $\Delta R/R_0=(R_{xx}-R_0)/R_0$—the low-field part of R_{xx} after normalization by the zero-field resistance value R_0. The best fit of the SdHOs amplitude yields the value of $T_D=3$ K.

as the nitrogen precursor and the group-III element were provided by standard solid-source effusion cells. An unintentionally doped GaN layer of about 1 μm was grown at 800 °C on a Mg-doped GaN single crystal, followed by a 200-Å-thick AlGaN layer. From photoluminescence experiments,[9] the Al composition was estimated to be around 13%. The high quality of homoepitaxial samples has already been demonstrated by the small photoluminescence linewidth (15–20 meV) measured on GaN/AlGaN quantum wells deposited using the same growth conditions.[10]

Figure 1 shows the Hall mobility μ_H [Fig. 1(a)] and the Hall carrier density n_H [Fig. 1(b)] obtained from the low-field-transport measurements using a lithographically defined Hall bar geometry. For the heterostructure grown on the GaN single-crystal substrate, the Hall measurements yield a 77 K mobility of 30 000 cm^2/V s and a 1.5 K mobility of 60 100 cm^2/V s. For comparison, we also show in Fig. 1 the best results obtained for the heterostructures grown on sapphire by Smorchkova *et al.*[4] and on 6H–SiC by Gaska *et al.*[3] As it is seen in Fig. 1, heterostructures grown on GaN and sapphire substrates show a strong decrease of the electron concentration and an increase of carrier mobility with decreasing temperature. This effect is weakly pronounced for heterostructures with SiC substrates. It is worthwhile to mention that the previous two samples are characterized by a reduced dislocation density.

We attribute the dramatic decrease of the Hall density n_H with lowering the temperature from 300 to 100 K, to the freeze-out of the parallel conduction in the GaN layer. A relatively high parallel conduction at high temperature might be related to the reduction of dislocation density. It is well known that dislocations in GaN act as trapping centers for free electrons.[6] Therefore, for standard structures grown on sapphire or SiC, the residual *n*-type conductivity of GaN layers is often reduced by the dislocations. In our case, because of the lack of dislocations, the GaN layer has an *n*-type conductivity due to the uncompensated residual donors with a density of the order of $1-2\times10^{17}\,\mathrm{cm}^{-3}$. In the same way, the reduction of dislocation density in the template layer of the sample on the sapphire (Ref. 4) leads to visible parallel conduction effects. This conductivity freezes out at low temperatures.

The longitudinal (R_{xx}) and transverse (R_{xy}) magnetoresistance experiments were performed from 1.5 K down to 50 mK, using the 15 T static magnetic field of a superconducting coil. The current through the sample was 96 nA. The results for R_{xx} and R_{xy} are presented in Fig. 2. The Shubnikov de Hass oscillations (SdHOs) are correlated with the well-defined QHE plateaus confirming the presence of a 2DEG at the AlGaN/GaN interface. It is worth mentioning that the SdHOs start at low magnetic field (about 1.8 T). We also note that a second period of oscillations, due to the spin splitting, is clearly resolved.[11] From the period of the SdHOs, we extract the carrier sheet density to be about $2.4\times10^{12}\,\mathrm{cm}^{-2}$, which is in good agreement with the low-field Hall measurements (see Fig. 1). This shows that the parallel conduction is eliminated at low temperatures, probably due to the freeze-out of the electrons on donors in the GaN channel. The absence of a positive background superimposed on the SdHOs also shows that parallel conduction is negligible at low temperatures.[12] The inset in Fig. 2 shows the low-field part of the SdHOs after normalization by the low-field resistance value R_0. The magnetic-field dependence of the SdHOs amplitude γ_0 is described by the standard formula[11,13]

$$\Delta R/R_0=\frac{4A}{\sinh A}\exp\left(\frac{AT_D}{T}\right), \quad (1)$$

where $A=2\pi^2k_BT/\Delta E$, $T_D=\hbar/2\pi k_B\tau_q$ is the Dingle temperature determined by the quantum scattering time τ_q and $\Delta E=\hbar\omega_c$ is equal to the cyclotron resonance energy ($\omega_c=eB/m^*$), which depends on the effective 2D electron mass $m^*=0.240\times m_0$ (Ref. 14) and on the magnetic field B. From the fit of the SdHOs, we obtained $\tau_D=0.4$ ps. This time corresponds to the average time between the scattering event and is 20 times shorter than the transport scattering time $\tau_{tr}=\mu m^*/e=8.2$ ps, which is the average time between scattering events that efficiently changes the carrier momentum direction. This indicates that at low temperatures the main scattering mechanisms are due to long-range potentials such as Coulomb potentials of (i) ionized impurities in the GaN layer and/or (ii) remote scattering by impurities in the AlGaN barrier. Therefore, we believe that a further improvement of mobility in homoepitaxial structures can be achieved mainly by lowering the residual doping in the GaN layer and in the AlGaN barrier.

The comparison of the homoepitaxial sample of this work and the sample of Ref. 4, grown on a sapphire substrate, allows us to comment on the role of dislocations in the low-temperature mobility of 2DEG. Although the structure investigated in this work is dislocation-free, its low-temperature mobility is only slightly higher than that of the structure grown on sapphire, which has a dislocation density of 10^8 cm^{-2}. Both samples also have similar carrier densities (about 2×10^{12} cm^{-2}). From these results, we can then draw the conclusion that for a 2DEG with a density of about 2×10^{12} cm^{-2}, a dislocation density of 10^8 cm^{-2} or less does not influence the 2DEG carrier mobility. This result has been confirmed by the calculations of Jena, Gossard, and Mishra,[6] who showed that the mobility limit imposed on a 2DEG, with a carrier density of 2×10^{12} cm^{-2} and a dislocation density of 10^8 cm^{-2}, is around 200 000 cm^2/V s. This relative insensitivity of mobility to dislocation scattering can be explained by the strong screening effect of carriers in a 2DEG.[6,15] However, as the calculations of Jena, Gossard, and Mishra clearly show, the ultimate limit for the low-field mobility at cryogenic temperatures is affected by the dislocation density, and we expect that with a further reduction of ionized impurity concentration, dislocation-free samples will exhibit much higher mobility values.

In conclusion, high-quality AlGaN/GaN heterostructures have been grown by MBE on Mg-doped GaN single crystals. The presence of the 2DEG at the interface has been proved by the observation of the Shubnikov de Hass oscillations and by the well-defined quantum Hall-effect plateaus. The low-temperature mobility (60 100 cm^2/V s at 1.5 K) has been measured. Our results show that the homoepitaxial growth on GaN bulk substrates allows us to obtain high-quality GaN-based heterostructures for which the main scattering mechanisms are due to the long-range potentials such as Coulomb potentials of ionized impurities in the GaN layer and/or in the AlGaN barrier.

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