Magnetotransport studies of AlGaN/GaN heterostructures grown on sapphire substrates: Effective mass and scattering time

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Temperature-dependent magnetotransport measurements have been carried out on high-quality two-dimensional electron gas (2DEG) in AlGaN/GaN heterostructures with different Al content grown on sapphire substrates. The GaN electron effective mass and the quantum scattering time are determined by well-resolved Shunbikov–de Hass oscillations. The electron effective mass is determined to be $19m_0$. The ratio of the classic scattering time to the quantum scattering time increases with increasing 2DEG sheet carrier density, which agrees very well with the previous calculation based on an ideal 2DEG in conventional semiconductor systems. Our result indicates that a low density of deep centers results in the much higher mobility of our structure compared with other reports, which is of critical importance in fabricating a high-quality 2DEG structure in AlGaN/GaN systems. © *2000 American Institute of Physics.* [S0003-6951(00)03019-9]

In recent years, much progress has been made in developing III-nitride optical and electronic devices, for example, the blue laser diode with a lifetime of more than 10 000 h (Ref. 1) for continuous-wave operation at room temperature, and the high brightness of blue/green light-emitting diodes[2] and microwave field-effect transistors.[3] However, most of the basic properties of GaN are still unclear, in particular, the electron effective mass, which is very important for analyzing optical and transport data. In this case, there were some scattered reports since the early 1970s.[4–6] Due to poor crystalline quality, the early reported values for electron effective mass are scattered from 0.19 to $0.27m_0$ (Refs. 4–6). In recent years, there have been some reports on the electron effective mass.[7–9] Drechsler *et al.* reported a value of $0.2m_0$ for GaN electron effective mass measured by a cyclotron resonance technique.[7] Perlin *et al.* used infrared reflectivity measurement to study free-standing bulk crystalline GaN and determined a value of $0.22m_0$.[8] A value of $0.23m_0$ was reported for the two-dimensional electron gas (2DEG) formed at an AlGaN/GaN single heterostructure (SH) grown on a sapphire substrate using a cyclotron resonance technique.[9] Obviously, the data of the electron effective mass are still scattered due to poor crystalline quality.

Since the Shubnikov–de Haas (SdH) effect has long been an effective tool for the measurement of the properties of electrons in semiconductors, it can be used to determine electron effective mass m^* and quantum scattering time τ_q. However, due to the poor quality of the 2DEG in previous AlGaN/GaN heterostructures grown on sapphire substrates, the SdH oscillations can be observed only at very high magnetic fields,[10,11] which means that it is too difficult to obtain an accurate value of the GaN electron effective mass. SiC as a substrate can greatly improve the quality of 2DEG in the AlGaN/GaN heterostructure due to much less lattice mismatch. Based on such a structure, the GaN electron effective mass was reported to be $0.18m_0$.[12] However, the electron effective mass obtained from GaN grown on a SiC substrate cannot be used for that grown on a sapphire substrate due to a different strain effect.[12] In fact, most GaN-based optical devices are fabricated on sapphire substrates. Therefore, it is necessary to measure the GaN electron effective mass on a sapphire substrate, which is one of the purposes in this letter. Recently, using a specially designed metalorganic chemical-vapor deposition (MOCVD) technology, we obtained very high-quality 2DEG with a mobility of over 10^4 $cm^2/V\,s$ in an AlGaN/GaN SH grown on a sapphire substrate,[13] which is close to the reported highest mobility obtained on a SiC substrate. Based on this high-quality structure, well-resolved SdH oscillations are observed even at fields as low as 2 T. The GaN electron effective mass was determined to be $0.19m_0$. Also, this letter investigates the reason for this high mobility of the 2DEG by investigating the quantum scattering time obtained from the SdH effect. With increasing 2DEG sheet carrier density, the ratio of classic scattering time to quantum scattering time increases, which is in good agreement with the previous calculation based on an ideal 2DEG system in conventional semiconductors. Our result indicates that the very low density of the deep centers is one of the important reasons for the high mobility of our structure.

The AlGaN/GaN heterostructures were grown on (0001) sapphire substrates by a horizontal MOCVD technique. The detailed description can be found in our previous letter.[13] After annealing the substrate in H_2 at 1150 °C, a 25-nm-thick GaN buffer layer was deposited at 450 °C, followed by a 2 μm undoped GaN layer and a 120 nm undoped AlGaN layer grown at 1075 °C with Al contents of 10% and 18%, respectively. The Al contents were measured based on (0006) x-ray diffraction measurement. For the temperature-dependent

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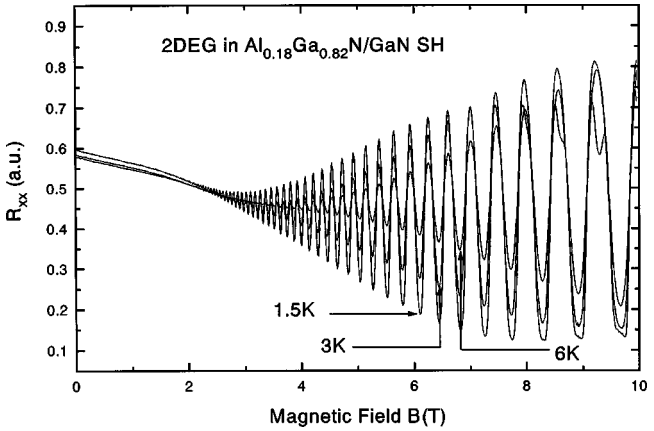

FIG. 1. Magnetoresistance (R_{xx}) of 2DEG in the $Al_{0.18}Ga_{0.82}N$/GaN SH as a function of magnetic field for different temperatures. At each temperature, the SdH oscillations can be observed clearly, in particular, at 1.5 K, the SdH oscillations begin at fields as low as about 2 T, which indicates the high quality of this structure.

transport measurements, the samples were mounted in a liquid-helium cryostat, containing a magnetic field up to 10 T, and the standard ac lock-in technique was used. In each sample, high-purity Al/Ti was used to form the contacts. In both samples, 2DEG has been confirmed to exist due to the generally accepted model based on a strong piezoelectric field.[13–16] At 1.5 K, the electron mobility is 10 300 $cm^2/V\,s$ at a carrier sheet density of $6.19\times10^{12}/cm^2$ and 5160 $cm^2/V\,s$ at a carrier sheet density of $2.78\times10^{12}/cm^2$ for the $Al_{0.18}Ga_{0.82}N$/GaN SH and $Al_{0.10}Ga_{0.90}N$/GaN SH, respectively, as we previously reported.[13] In order to investigate the reason for this high mobility, another 2DEG sample was also grown, in which the structure is the same as in the $Al_{0.18}Ga_{0.82}N$/GaN SH except that the AlGaN layer is intentionally silicon doped.[17]

Figure 1 shows the longitudinal resistance R_{xx} as a function of magnetic field for the $Al_{0.18}Ga_{0.82}N$/GaN SH at different temperatures from 1.5 to 6 K. At 1.5 K, the SdH oscillations can be observed at fields as low as about 2 T, which indicates the excellent quality of this sample. At high magnetic fields, the second oscillations appear. In this case, there are two possibilities, i.e., the second oscillations are due to second-level electrons or spin splitting. Based on the magnetic-field-dependent Hall resistance, the SdH oscillation electron density n_{SdH} is evaluated to be $6.1\times10^{12}/cm^2$, which is very close to the value of $6.19\times10^{12}/cm^2$ that was measured by the low-field Hall measurement mentioned above. In addition, when the temperature is increased to 3 K, the second oscillations disappear. These data mean that only the lowest-energy level is occupied, and also indicate that there is no parallel conduction from other epilayers. Therefore, the second oscillations appearing at high fields can be attributed to spin splitting, which is under further study. Since only the first electronic subband is occupied, the electron effective mass can be evaluated based on the standard treatment developed by Ando, Fowler, and Stern, and Coleridge, Stoner, and Flecter as follows:[18,19]

$$\frac{\Delta\rho_{xx}}{\rho_0}=4\,\frac{\chi}{\sinh\chi}\exp\left(\frac{-\pi}{\omega_c\tau_q}\right), \tag{1}$$

where ρ_0 is zero-field resistivity, $\omega_c=eB/m^*$ is the cyclotron frequency, χ is equal to $2\pi^2k_BT/\hbar\omega_c$, k_B is Boltzmann's constant, and T is absolute temperature. From the temperature dependent R_{xx}, the electron effective mass can be determined. Elhamri *et al.*[12] modified Eq. (1) into the following expression and used it to calculate the electron effective mass for the 2DEG in the AlGaN/GaN herterostructure grown on a SiC substrate:

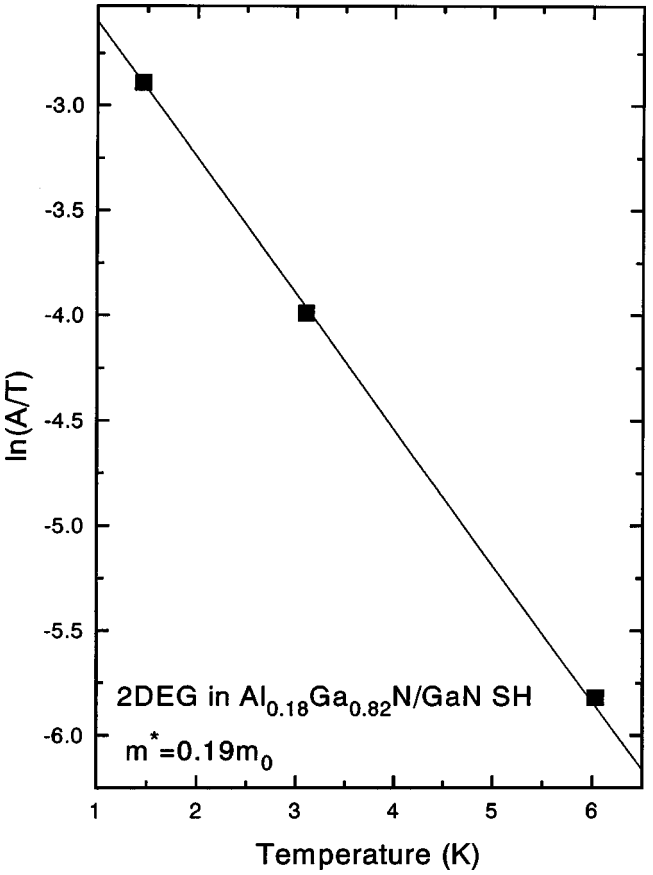

FIG. 2. ln(A/T) as a function of temperature at a magnetic field of 4.15 T. The line represents the fit to the data from Fig. 1. The electron effective mass is calculated at several magnetic fields, yielding an average value.

$$\ln\left(\frac{A}{T}\right)=C-\frac{2\pi^2k_Bm^*}{e\hbar B}T, \tag{2}$$

where C is a temperature-independent term and A is the amplitude of the SdH oscillation. Therefore, the electron effective mass m^* can be obtained by fitting the straight line ln(A/T) vs T.

Figure 2 shows a typical ln(A/T) as a function of temperature at a magnetic field of 4.15 T. The electron effective mass is evaluated at several magnetic fields, yielding an average value of 0.19 m_0, which is also shown in Fig. 2.

In order to obtain the quantum scattering time (τ_q), Fig. 3 gives the Dingle plot of the data at 1.5 K using the generally accepted expression as following:[18,19]

$$\ln\left(\frac{1}{4}\,\frac{\Delta R}{R_0}\,\frac{\sinh(\chi)}{\chi}\right)=C-\left(\frac{\pi m^*}{e\tau_q}\right)\frac{1}{B}, \tag{3}$$

where ΔR is the oscillation amplitude and R_0 is the zero-field resistance. From the slope of straight line, $\ln[\Delta R\sinh(\chi)/4R_0\chi]$ vs T, the quantum scattering time can be evaluated, which is about 0.33 ps at 1.5 K for 2DEG in

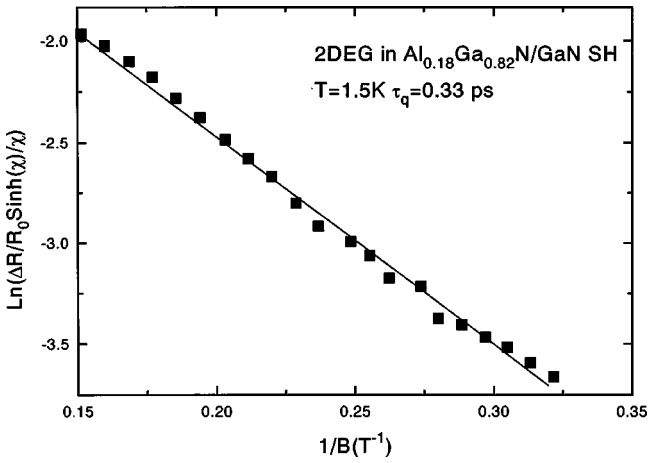

FIG. 3. $\ln[(\Delta R/4R_0)\sinh(\chi)/\chi]$ as a function of inverse magnetic field at $T=1.5$ K for the 2DEG in the $Al_{0.18}Ga_{0.82}N$/GaN SH. The fitting line (solid line) is also shown. The slope of this line was used to calculate the quantum scattering time.

the $Al_{0.18}Ga_{0.82}N$/GaN SH, as shown in Fig. 3. Similarly, the quantum scattering time for the 2DEG in the $Al_{0.10}Ga_{0.90}N$/GaN SH at 1.5 K is determined to be 0.38 ps, which is almost the same as that for the 2DEG in the $Al_{0.18}Ga_{0.82}N$/GaN SH. As we have known, the quantum scattering time τ_q (i.e., the single-particle lifetime) is sensitive to all scattering events, while the classic scattering time is insensitive to small-angle scattering due to an extra $(1-\cos\theta)$ factor compared with the expression of the τ_q, where θ is the scattering angle.[20,21] The τ_c is determined by low-field Hall measurements such as $\mu=e\tau_c/m^*$. Although τ_q is almost the same for the 2DEG in the $Al_{0.18}Ga_{0.82}N$/GaN SH and in the $Al_{0.10}Ga_{0.90}N$/GaN SH, the τ_c/τ_q is significantly larger for the former than for the latter because the mobility of the former is much higher than that of the latter. On the other hand, the 2DEG sheet carrier density in the $Al_{0.18}Ga_{0.82}N$/GaN SH is about 2.5 times that in the $Al_{0.10}Ga_{0.90}N$/GaN. Consequently, in our case, the τ_c/τ_q increases with increasing 2DEG sheet carrier density, which is in a good agreement with the calculation made by Das Sarma and Stern based on an ideal 2DEG in conventional semiconductor systems.[22] In an ideal 2DEG system, the long-range Coulomb interaction due to the remote charged center produces mostly small-angle scattering. The 2DEG carrier sheet density increases, which means that more electrons enter the 2DEG region and then leave behind more charged centers. Hence, small-angle scattering is enhanced by increasing the 2DEG sheet carrier density, i.e., the τ_c/τ_q normally increases with increasing 2DEG sheet carrier density. However, if there exist more deep centers, the τ_c/τ_q decreases with increasing 2DEG sheet carrier density, which has been observed in the previous GaAs/AlGaAs system.[21] Therefore, despite a high defect density normally occurring in GaN-based material systems, which normally results in a high density of deep levels, our 2DEG structures belong to an ideal case, i.e., meaning that the deep center density in our structure is not significant due to our special growth technology,[13] which may result in the much higher mobility in our structure compared with other reports. Therefore, if there are many deep centers in the AlGaN layer, the 2DEG mobility should decrease greatly. In order to confirm this conclusion, we also measured the mobility of the 2DEG sample with an intentionally silicon-doped AlGaN layer, in which the density of the deep centers is increased. It is well known that intentional silicon doping for *n*-type GaN (or AlGaN) normally results in a yellow luminescence band because silicon doping generally produces deep levels.[23] The 2DEG mobility of the silicon-doped AlGaN sample was actually found to decrease dramatically compared with the case of undoped AlGaN, which has been reported in our previous paper.[17] In particular, at 1.5 K the mobility decreases to only 3348 $cm^2/V\,s$ from 10 300 $cm^2/V\,s$ in the case of undoped AlGaN, which confirms our conclusion very well.

In summary, by measuring the temperature-dependent SdH effect of high-quality 2DEG in the AlGaN/GaN SH, the GaN electron effective mass and quantum scattering times were evaluated. The electron effective mass was determined to be $0.19m_0$. The ratio of classic scattering time to quantum scattering time increases with increasing 2DEG sheet carrier density, which is in a good agreement with the calculation based on an ideal 2DEG semiconductor system. Our result indicates that decreasing the deep center density is of critical importance in obtaining a high mobility 2DEG structure.

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