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Occupation of the double subbands by the two-dimensional electron gas in the triangular quantum well at $Al_xGa_{1-x}N/GaN$ heterostructures

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Magnetoresistance of modulation-doped $Al_{0.22}Ga_{0.78}N/GaN$ heterostructures has been studied by means of magnetotransport measurements at low temperatures and high magnetic fields. The double periodicity of the Shubnikov–de Haas oscillations was observed. It was found that the occupation of the first two subbands by the two-dimensional electron gas (2DEG) in the triangular quantum well at the $Al_{0.22}Ga_{0.78}N/GaN$ heterointerface took place when the 2DEG sheet concentration reached $7.2\times10^{12}\,cm^{-2}$. The energy separation of the first and the second subbands in the quantum well was determined to be 75 meV just before the second subband was occupied. The quantum scattering time related to the first subband was determined to be 8.4×10^{-14} s.

$Al_xGa_{1-x}N/GaN$ heterostructures are of special interest for the fabrication of heterostructure field-effect transistors (HFETs) for high-power, high-temperature, and high-frequency applications.[1–3] In $Al_xGa_{1-x}N/GaN$ heterostructures, the sheet concentration of the two-dimensional electron gas (2DEG) as high as $10^{13}\,cm^{-2}$ is easily achieved, mainly due to the strong piezoelectric polarization of the $Al_xGa_{1-x}N$ barrier.[4] Although $Al_xGa_{1-x}N/GaN$ heterostructures have been studied extensively in the past several years,[5–9] there still are many open problems about the formation of the 2DEG at the heterointerface and the scattering processes that limit the 2DEG mobility. In order to optimize the performance of $Al_xGa_{1-x}N/GaN$ HFETs, detailed characterization of the 2DEG in $Al_xGa_{1-x}N/GaN$ heterostructures is necessary.

On the other hand, the triangular quantum well at an $Al_xGa_{1-x}N/GaN$ interface is much deeper than that at an $Al_xGa_{1-x}As/GaAs$ one due to the large conduction-band offset between $Al_xGa_{1-x}N$ and GaN, and the strong piezoelectric polarization of the $Al_xGa_{1-x}N$ barrier.[4] Therefore, an $Al_xGa_{1-x}N/GaN$ heterostructure is a very suitable system for research in the field of low-dimensional quantum physics.

The occupation of the subbands in the triangular quantum well in an $Al_{0.22}Ga_{0.78}N/GaN$ heterostructure has been studied theoretically by Hsu and Walukiewicz.[7] They calculated the energy levels of the lowest three subbands as a function of the 2DEG density. Li *et al.* studied the occupation of the first two subbands by monitoring the 2DEG mobility as a function of the 2DEG density through analysis of the persistent photoconductivity of $Al_xGa_{1-x}N/GaN$ heterostructures.[10] According to their studies, the sheet concentration at which the second subband became occupied was about $1.4\times10^{12}\,cm^{-2}$. Bergman *et al.* reported that they observed the photoluminescence feature that came from the population of the first excited electron level at the $Al_{0.3}Ga_{0.7}N/GaN$ heterointerface.[9] There are two other groups who showed much interest in the occupation of the second subband in the triangular well in $Al_xGa_{1-x}N/GaN$ heterostructures by means of magnetotransport measurements.[11,12] But the occupation of the double subbands was not identified through these experiments.

It is well known that magnetotransport study is a powerful method for the investigation of transport properties of the 2DEG in various heterostructures.[11–20] In this study, the magnetoresistance of modulation-doped $Al_{0.22}Ga_{0.78}N/GaN$ heterostructures was investigated by means of magnetotransport measurements at the temperature of 3.0 K and the magnetic field up to 9.0 T. The double periodicity of the Shubnikov–de Haas (SdH) oscillation is observed, which indicate that the second subband in the triangular quantum well at the $Al_{0.22}Ga_{0.78}N/GaN$ interface has been occupied.

Figure 1 shows the schematic diagram of a modulation-doped $Al_{0.22}Ga_{0.78}N/GaN$ heterostructure used in this study. The samples were grown by means of atmospheric pressure metal-organic chemical-vapor deposition (MOCVD). On the (0001) surface of a sapphire substrate, a nucleation GaN buffer layer was grown at 488 °C, followed by a 2.0-μm-thick unintentionally doped GaN (*i*-GaN) layer deposited at 1071 °C. Then, an unintentionally doped $Al_{0.22}Ga_{0.78}N$ (*i*-$Al_xGa_{1-x}N$) layer (spacer), followed by a 25-nm-thick Si-doped $Al_{0.22}Ga_{0.78}N$ (*n*-$Al_xGa_{1-x}N$) layer were deposited, both at 1080 °C. Two samples were employed in this study. They have the similar structure except that the spacer thickness is 10 nm for sample 1 and 3 nm for sample 2, respectively.

By means of Van der Pauw Hall measurements, the 2DEG mobility of 1240 cm^2/Vs and the 2DEG sheet concentration of $1.2\times10^{13}\,cm^{-2}$ in sample 1 were determined at room temperature (300 K). At 77 K, the mobility and the sheet concentration were 4450 cm^2/Vs and $9.0\times10^{12}\,cm^{-2}$,

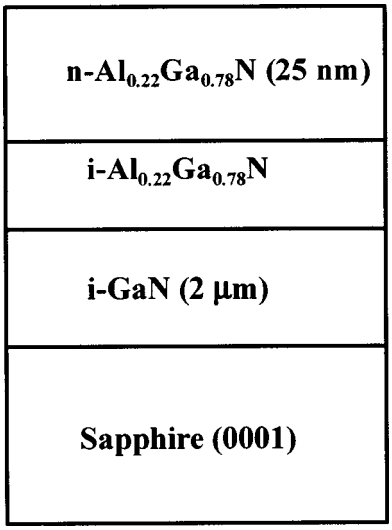

FIG. 1. Schematic diagram of a modulation-doped $Al_{0.22}Ga_{0.78}N/GaN$ heterostructure used in this study.

respectively. For sample 2, the 2DEG mobility of 896 cm^2/Vs and the 2DEG sheet concentration of $1.7\times10^{13}\,cm^{-2}$ were determined at room temperature. At 77 K, the mobility and the sheet concentration of sample 2 were 2730 cm^2/Vs and $1.3\times10^{13}\,cm^{-2}$, respectively. The magnetoresistance measurements were performed at the temperature of 3.0 K and the magnet field between 0 and 9.0 T, with the Van der Pauw configuration.

Figure 2 shows the diagonal magnetoresistance ρ_{xx} as a function of the magnetic field normal to the interface of the $Al_{0.22}Ga_{0.78}N/GaN$ heterostructure in (a) sample 1 and (b) sample 2. In each sample, the strong SdH oscillation is clearly observed. The most interesting phenomena are the double periodicity of the SdH oscillation in both samples. But the periods are different. The threshold magnetic field for observation of the SdH oscillation is also different: it is 4.7 T for sample 1, and 3.7 T for sample 2.

The double periodicity of the SdH oscillations indicates that there are at least two subbands in the triangular quantum well formed at the heterointerface to be occupied by the 2DEG. It is straightforward to obtain independently the 2DEG sheet concentration in the two subbands from the high-field oscillatory magnetoresistance.[17,18] According to the model in Ref. 14, the 2DEG sheet concentrations of $8.6\times10^{12}\,cm^{-2}$ for the short period and $7.4\times10^{11}\,cm^{-2}$ for the long period are determined from the SdH oscillation of sample 1. The two different concentrations correspond to the electrons in the first and the second subbands. The total 2DEG sheet concentration in the quantum well is $9.3\times10^{12}\,cm^{-2}$, which is very close to that determined by means of Van der Pauw Hall measurement. Here, it is pointed out that the 2DEG sheet concentration in an $Al_xGa_{1-x}N/GaN$ heterostructure is almost independent of temperature when the temperature is below 100 K.[15,20] For sample 2, the 2DEG sheet concentration of $1.1\times10^{13}\,cm^{-2}$ for the short period and $2.0\times10^{12}\,cm^{-2}$ for the long period are also obtained from the data shown in Fig. 2(b). The total 2DEG sheet concentration in the well is $1.3\times10^{13}\,cm^{-2}$, which is also consistent with that determined by means of Van der Pauw Hall measurement.

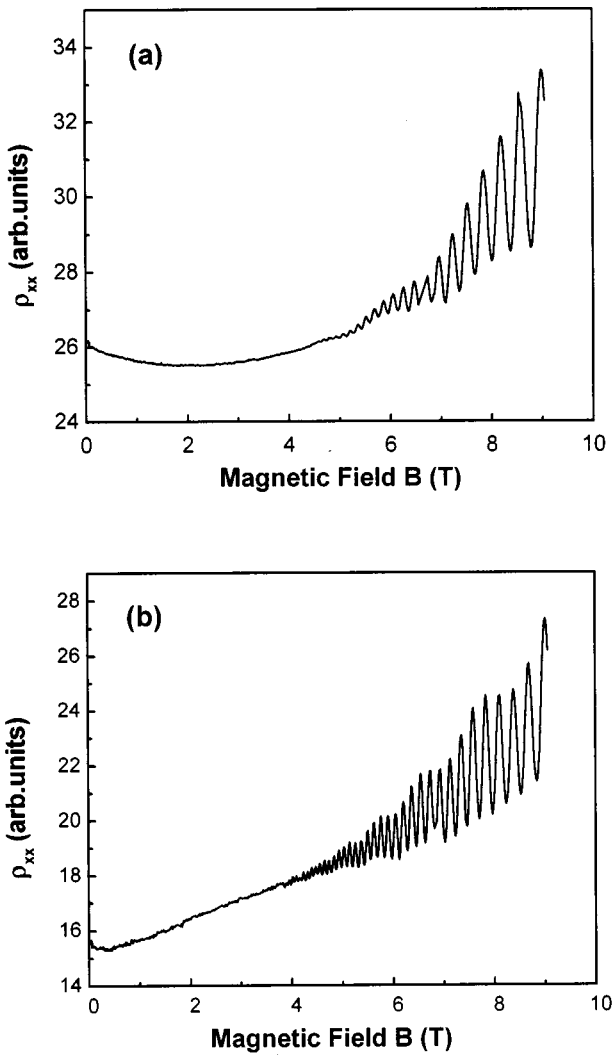

FIG. 2. Diagonal resistivity ρ_{xx} as a function of the magnetic field normal to the $Al_{0.22}Ga_{0.78}N/GaN$ interface at 3.0 K in (a) sample 1 and (b) sample 2, respectively. The Shubnikov–de Haas oscillation in both samples has double periodicity.

The number of subbands that are occupied in the triangular quantum well at a heterointerface has a notable influence on transport properties of the 2DEG, and thus influences the characteristics of the corresponding devices. By modifying the parameters of the heterostructures, such as the thickness of the $Al_xGa_{1-x}N$ barrier, the band offset at the heterointerface, and the doping level of the $Al_xGa_{1-x}N$ barrier, one can control the number of subbands in the well that are occupied. Therefore, it is important to determine the energy position of each subband level in the well, especially the position of the first two subband levels, in order to optimize the performance of the $Al_xGa_{1-x}N/GaN$ HFETs.

Conduction-band potential profile, the Fermi level, and the first three Landau subbands, as well as the squares of the wave function of the quantum states in the triangular well at an $Al_{0.22}Ga_{0.78}N/GaN$ heterointerface are illustrated schematically in Fig. 3. The piezoelectric field in the strained $Al_xGa_{1-x}N$ epilayer makes the quantum well become deeper and confines the electrons to a narrower strip at the heterointerface. Thus the quantization of the energy band in an $Al_xGa_{1-x}N/GaN$ heterointerface is more evident in compari-

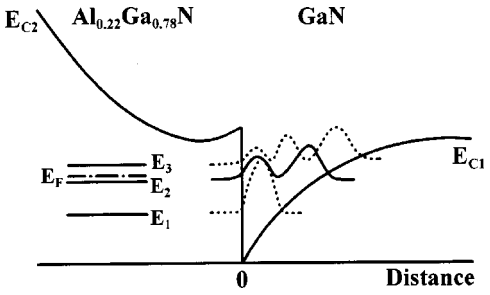

FIG. 3. Schematic diagram of the conduction band potential profiles, the squares of the wave function of the quantum states of $n=0$, 1, 2 in the triangular quantum well at an $Al_xGa_{1-x}N/GaN$ heterointerface. The position of the Fermi level and the first three subband levels in the well are also schematically shown.

son with that without piezoelectric field. When the first two subbands are partially occupied as shown schematically in Fig. 3, the two periods (the short period and the long period) of the SdH oscillations are observed as shown in Fig. 2.

The electron concentration in each subband in an $Al_xGa_{1-x}N/GaN$ heterostructure as a function of the total concentration is assumed as a linear relation, like the experimental result of a GaInP/GaAs heterostructure, as well as the experimental and theoretical results of an $Al_xGa_{1-x}As/GaAs$ heterostructure.[18,19,21] We extrapolate that the second subband starts to be populated at the concentration of about $7.2\times10^{12}\,cm^{-2}$. The relation between the Fermi energy level E_F, the level of each subband E_i, and the sheet electron concentration of ith subband N_i is given by

$$E_F=E_i+N_i\pi\hbar^2/m^*, \tag{1}$$

where m^* is the electron effective mass, $\hbar$ the reduced Planck constant, and $m^*/\pi\hbar^2$ is the two-dimensional state density in the well. Through changing the sample parameters as mentioned above, we can control the number of subbands that are occupied in the triangular quantum well at an $Al_xGa_{1-x}N/GaN$ heterointerface. There must be the suitable sample parameters, which make the Fermi level be higher than the first subband, but just below the second subband level. When the 2DEG sheet concentration in the first subband is N_1, the Fermi energy level is given by

$$E_F=E_1+N_1\pi\hbar^2/m^*. \tag{2}$$

Taking the electron effective mass m^* as $0.23m_e$,[22] and N_1 as $7.2\times10^{12}\,cm^{-2}$, we obtain that E_F-E_1 is 75 meV for sample 1. This means that the energy separation between the first and the second subbands is about 75 meV when the Fermi energy level is just below the second subband. If considering the occupation of the second subband, we obtain that E_2-E_1 is 81 meV for sample 1 when taking N_1 as $8.6\times10^{12}\,cm^{-2}$ and N_2 as $7.4\times10^{11}\,cm^{-2}$.

It is important to analysis the quantum scattering time τ_q related to the subband in the triangular quantum well, which is given by the total scattering rate and the transport scattering time τ_ρ. The quantum scattering time can be obtained by the equation[20]

$$Y=\ln\left[AB\sinh\left(\frac{2\pi^2k_BTm^*}{e\hbar B}\right)\right]=C_3-\frac{\pi m^*}{e}\frac{1}{\tau_q}\frac{1}{B}, \tag{3}$$

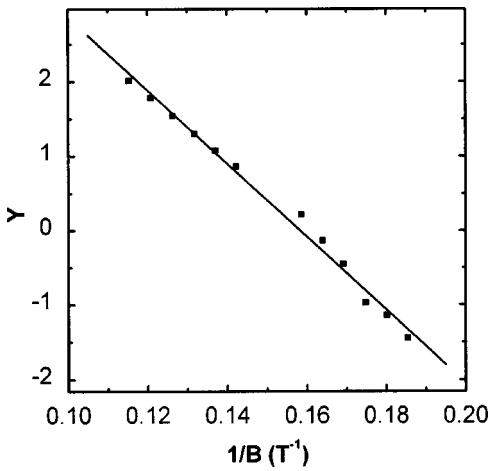

FIG. 4. Dingle plot of the short period oscillation amplitude of sample 1 against the reciprocal of magnetic field. The straight line is the one-parameter fit in order to obtain the value of the quantum scattering time τ_q related to the first subband.

where A is the amplitude of the SdH oscillation, k_B is Boltzmann's constant, C is a constant at a given temperature T, and e is the electron charge. Y as a function of the reciprocal of the magnetic field $1/B$ is shown in Fig. 4. The oscillation amplitude A at different magnetic field is obtained from Fig. 2(a). By fitting the data in Fig. 4, we obtain that the quantum scattering time related to the first subband of sample 1 is 8.4×10^{-14} s. This leads to the Landau level broadening of about 3.9 meV. It should be pointed out that the quantum scattering time related to the first subband is influenced by the electrons in the second subband to some degree, and thus the amplitude of the SdH oscillation related to the first subband is influenced by that related to the second subband. However, due to the small amplitude and the low frequency of the SdH oscillation of the second subband, the influence is weak. It is difficult to determine the quantum scattering time related to the second subband of sample 1 because of the strong oscillation of the first subband.

In summary, magnetoresistance in modulated-doped $Al_{0.22}Ga_{0.78}N/GaN$ heterostructures has been studied by means of magnetotransport measurements at low temperatures and high magnetic fields. The double periodicity of the SdH oscillation of the 2DEG is observed. By calculating the 2DEG sheet concentration from the SdH oscillation spectrum, it is found that the second subband in the triangular quantum well at the $Al_{0.22}Ga_{0.78}N/GaN$ interface is occupied when the 2DEG density reaches $9.0\times10^{12}\,cm^{-2}$. It is determined that the energy separation between the first two subband levels E_2-E_1 in the quantum well is 75 meV just before the second subband is occupied. The quantum scattering time related to the first subband is determined to be 8.4×10^{-14} s.

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