Weak localization and magnetointersubband scattering effects in an $Al_xGa_{1-x}N/GaN$ two-dimensional electron gas

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(Received 8 November 2003; published 24 March 2004)

Magnetotransport measurements have been carried out on a two-dimensional electron gas in a modulation-doped $Al_{0.22}Ga_{0.78}N/GaN$ heterostructure. The weak localization and magnetointersubband scattering effects have been studied. The measurements show that the inelastic scattering time is inversely proportional to the temperature, following the prediction by weak localization theory. Furthermore, fitting the inelastic scattering time indicates an enhanced phase-breaking rate compared to the theoretical predication. At the same time, a magnetoresistance oscillation induced by intersubband scattering has also been observed. This magnetoresistance oscillation persists to a relatively high temperature in contrast to the Shubnikov–de Haas oscillation.

DOI: 10.1103/PhysRevB.69.125335 PACS number(s): 73.20.−r, 72.10.−d, 73.43.−f, 73.61.−r

I. INTRODUCTION

In a system with time-reversal symmetry, the quantum interference of electron waves propagating along the same path in opposite directions leads to a weak localization (WL) of electrons. WL has been intensively studied in many two-dimensional systems.[1–3] Conductivity in a WL system shows a logarithmic dependence on the temperature.[4] When a magnetic field is applied perpendicular to the plane of a two-dimensional electron gas (2DEG), the time-reversal symmetry is broken. The field induces a nonzero phase difference between the time-reversal electron orbits, which has been demonstrated in studies of anomalous negative magnetoresistance (NMR). If more than one subband is occupied in a 2DEG, the WL effect is strongly affected, depending on the intersubband scattering intensity.[5,6] Since the intersubband scattering is accompanied by a transfer of a large momentum, the scattering gains intensity in systems such as an AlGaN/GaN 2DEG, in which there exists high density of short-range disorders including interface roughness and impurities.[7] It should be noted that a high electron sheet density can be readily achieved due to the large conduction-band discontinuity at the AlGaN/GaN heterointerface and the strong piezoelectric polarization in the materials. This gives rise to electron filling up to second, even third subbands.[8]

Intersubband scattering might also affect the oscillatory magnetoresistance.[7,9,10] The intersubband scattering is enhanced each time the staircases of Landau levels in two subbands are completely aligned, which is termed magnetointersubband (MIS) scattering. The MIS scattering rate varies periodically in $1/B$, leading to an oscillation similar to the Shubnikov–de Haas (SdH) oscillation. In contrast to the strong temperature dependence of the SdH oscillation, the MIS oscillation does not contain a temperature-damping factor. The MIS oscillation may therefore take the leading role in oscillatory magnetoresistance with increasing temperature.[10,11]

In this paper, we report on an investigation of WL and MIS effects in a modulation-doped $Al_{0.22}Ga_{0.78}N/GaN$ heterostructure in which two subbands are occupied by electrons, so that intersubband scattering has to be taken into account. From the magnetotransport measurements, the inelastic scattering time associated with electron-electron interaction is determined and a MIS related oscillation was observed. The paper is organized as follows. The experimental aspects are described in Sec. II, and detailed analysis of the WL and MIS effects is presented in Sec. III. Finally, the conclusion is given.

II. EXPERIMENT

Modulation-doped $Al_{0.22}Ga_{0.78}N/GaN$ heterostructures were grown by atmospheric pressure metal-organic chemical-vapor deposition. 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 a 3-nm-thick unintentionally doped $Al_{0.22}Ga_{0.78}N$ (i-AlGaN) layer (spacer), followed by a 100-nm-thick Si-doped $Al_{0.22}Ga_{0.78}N$ (n-AlGaN) layer, were deposited, both at 1080 °C. The doping concentration is 1.2×10^{18} cm^{-3}. The samples were cut by 4×4-mm^2 squares and four Al/Ti Ohmic contacts were made on the sample in a Van der Pauw configuration. Magnetotransport measurements were performed using dc techniques under a magnetic field up to 10 T in the temperature range from 3 to 25 K.

III. RESULTS AND DISCUSSION

Figure 1 presents the diagonal magnetoresistance R_{xx} of the $Al_{0.22}Ga_{0.78}N/GaN$ system as a function of the perpendicularly applied magnetic field at 3K. At $B>4$ T, the measurement reveals quick oscillations superimposed on a slowly varying background of a parabolic line shape that is attributed to the parallel conduction in the n-AlGaN barrier. R_{xx} displays a fast decrease with B at very low magnetic

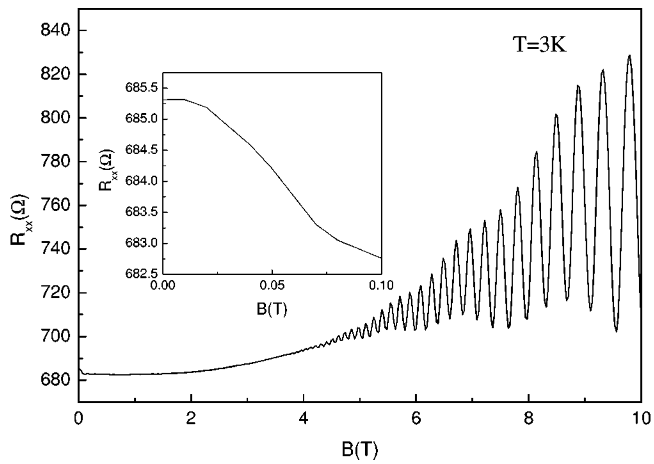

FIG. 1. The diagonal magnetoresistance R_{xx} as a function of the magnetic field at 3 K. The inset shows the negative magnetoresistance behavior.

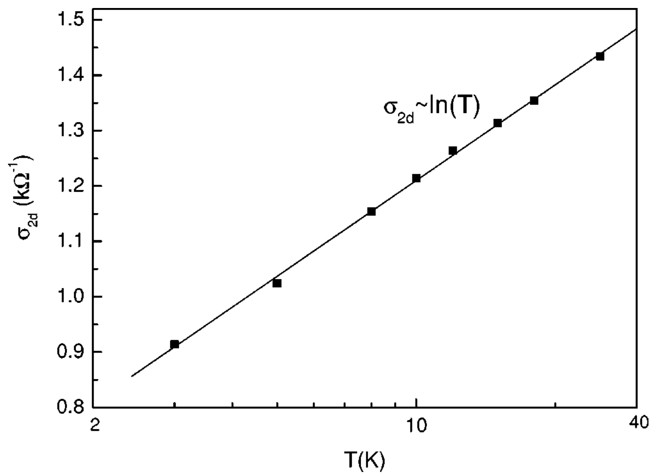

FIG. 2. The conductivity of the 2DEG vs temperature, the solid line is logarithmic fit of conductivity.

field (see the inset in Fig. 1). The clear double periodicities in the SdH oscillations (see Fig. 1) indicate that two subbands are occupied by electrons. By fast Fourier transforms (FFTs) of R_{xx} as a function of $1/B$, the electron densities in the 2DEG system are obtained to be 9.2×10^{12} cm^{-2} for the first subband and 1.5×10^{12} cm^{-2} for the second subband. The electron sheet density and the mobility of the 2DEG system can be obtained by means of a two-carrier simulation process[12] (i.e., electrons in the doping layer and in the channel), which gives an electron concentration of $\sim1\times10^{13}$ cm^{-2} and an electron mobility of ~850 cm^2/Vs at 25 K. From the temperature dependence of the SdH amplitudes, the electron effective mass m^* is determined to be $0.22m_0$, which is in good agreement with reported values measured by other techniques such as cyclotron resonance.[13] The subbands are separated from the Fermi energy by $E_F-E_1=100$ meV and $E_F-E_2=16$ meV obtained by $E_F-E_j=\pi\hbar^2n_j/m^*$ [where n_j is the electron concentration in the first ($j=1$) or second ($j=2$) subband]. Since the electrons in $Al_{0.22}Ga_{0.78}N$/GaN are well screened due to their large effective mass,[14] the effect of the electron-electron Coulomb interaction on the conductivity is expected to be negligible so that weak localization is the dominant feature for the 2DEG system. This is confirmed in Fig. 2 in which the conductivity of the 2DEG system exhibits a logarithmic temperature dependence, typical of a weakly localized 2DEG. From the transport measurement, the estimated localization criteria, $k_Fl_e\gg1$, (where k_F and l_e are Fermi wave vector and the mean free path, respectively) is satisfied for both subbands.[15]

A. WL effect

The WL effect in the similar system was investigated previously,[16] where only one subband is populated by electrons. As a result, no intersubband scattering needs to be considered in the system. The WL in systems with two occupied subbands has been theoretically studied by Averkiev *et al.*[5] and Iwabuchi *et al.*[6] It was shown that, if the short-range scattering is dominant and at the same time the intersubband scattering is strong, subbands are coupled and mixed up and electrons behave as if they are in one subband with an average kinetic parameter. The WL system can be treated by a diffusion approximation[17] valid at $B<B_c=\hbar/2el_e^2$. Based on this WL theory, the quantum correction on magnetoconductivity can be expressed as

$$\Delta\sigma^{WL}(B)=\frac{\alpha e^2}{2\pi^2\hbar}\left[\psi\left(\frac{1}{2}+\frac{\hbar}{4eDB\tau_i}\right)-\psi\left(\frac{1}{2}+\frac{\hbar}{4eDB\tau_e}\right)+\ln\left(\frac{\tau_i}{\tau_e}\right)\right], \quad (1)$$

where τ_e and τ_i are the elastic and inelastic scattering times, respectively, α is a constant, ψ is the digamma function, and D is the mean diffusion coefficient equal to $(1/n)\Sigma_{j=1,2}n_j(\hbar k_F^{(j)}/m^*)^2\tau_j/2$ (where $n=n_1+n_2$ and τ_j is the transport scattering time for the first or the second subband). Here we assume that the transport scattering times of the two subbands coincide so that $\tau_1=\tau_2=\tau_t=\mu m^*/e=0.11$ ps. The average electron mean free path of two subbands, $\overline{l_e}=\overline{v_F}\tau_t$, is roughly equal to 40 nm. Hence the critical field B_c is roughly 0.2 T, much higher than that in other high mobility samples (e.g., AlGaAs/GaAs heterostructures).[18]

$\Delta\sigma^{WL}$ as a function of B is plotted in Fig. 3 for low B at various temperatures. From the least-square fit to the experimental data using Eq. (1) (the solid lines in the figure), both the elastic scattering time τ_e and the inelastic scattering time τ_i are extracted. Similar to the transport scattering time τ_t, the obtained elastic scattering time $\tau_e\sim0.1$ ps is temperature independent, since the short-range scatters (interface roughness, etc.) dominate the scattering process. In the whole temperature range, the inelastic scattering time τ_i is inversely proportional to temperature, $\tau_i\propto T^{-1}$ (see Fig. 4). This is an indication that τ_i, corresponding to phase-breaking time, is dominated by inelastic electron-electron scattering with small energy transfer in the dirty limit $\hbar/k_BT\tau_t>1$ ($\tau_i\propto T^{-2}$ if the scattering is accompanied by a large energy transfer).[19,20] Those values agree well with reported ones.[16] A

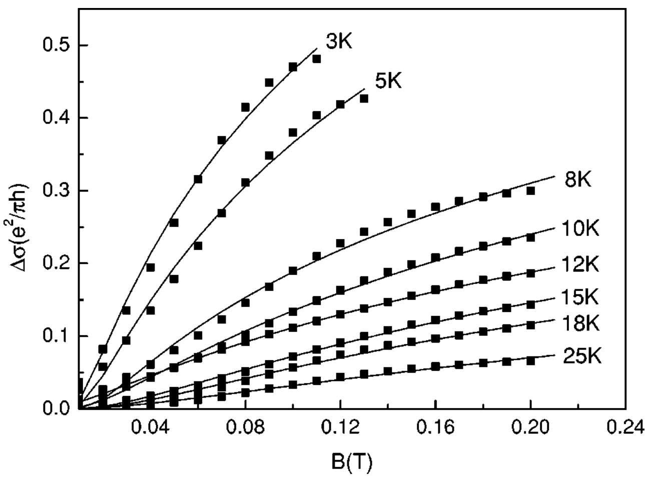

FIG. 3. The magnetic field dependence of $\Delta\sigma$ at different temperatures. The results of the fitting to WL model [Eq. (1)] are superimposed in continuous lines.

linear fit gives $1/\tau_i = 5.5\times 10^{10}T(s^{-1})$. To estimate the order of magnitude, we use the Nyquist rate formula for the electron phase-breaking time:[21,22]

$$\frac{1}{\tau_N} = \frac{k_B T}{2E_F\tau_t}\ln\left(\frac{E_F\tau_t}{\hbar}\right), \tag{2}$$

which gives $1/\tau_N = 1.2\times 10^{10}T(s^{-1})$ by putting in all the known numbers. Hence the experimentally observed phase-breaking rate is approximately five times larger than that calculated by this simplified Nyquist model, which is also observed in many other semiconductor samples,[3,23] suggesting that there exists more than one phase-breaking mechanism. Electron-electron scattering with a small energy transfer requires some scattering centers as mediators. In the Nyquist model, electron-electron scattering is mediated only by electromagnetic fluctuations induced by other electrons. It is thus expected that alloy disorder, interface roughness or intersubband scattering might also play roles.

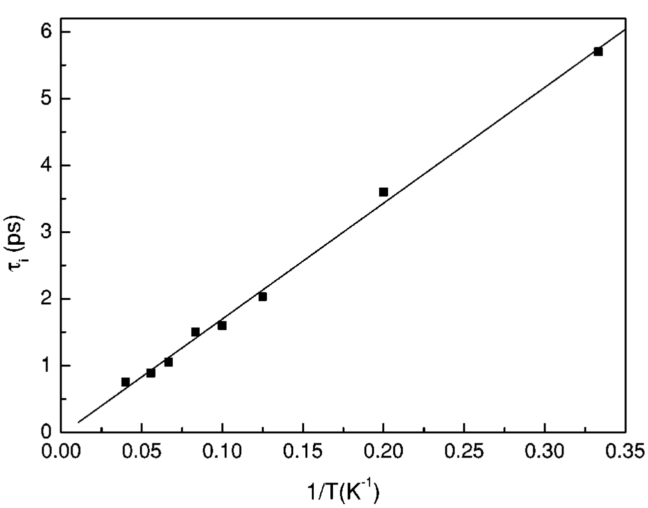

FIG. 4. The temperature dependence of the inelastic scattering time τ_i. The line is the dependence $\tau_i \propto T^{-1}$.

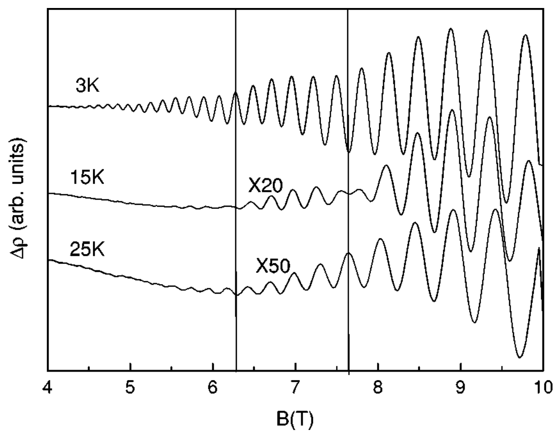

FIG. 5. The oscillatory magnetoresistance at different temperatures as marked. The straight lines indicate the particular magnetic fields where the phase shifts take place.

B. MIS effect

The MIS oscillation survives with increasing temperature while the SdH oscillation gradually diminishes. According to the work by Coleridge[9] and Sander *et al.*,[10] the MIS correction to the resistance takes the form

$$\Delta\rho^{MIS} \propto \exp\left[-\frac{\pi}{\omega_c}\left(\frac{1}{\tau_1}+\frac{1}{\tau_2}\right)\right]\cos\left[\frac{2\pi(E_2-E_1)}{\hbar\omega_c}\right], \tag{3}$$

while a SdH oscillation with a temperature damping factor is written as

$$\Delta\rho_j^{SdH} \propto \frac{X}{\sinh X}\exp\left(-\frac{\pi}{\omega_c\tau_j}\right)\cos\left[\frac{2\pi(E_F-E_j)}{\hbar\omega_c}+\pi\right]$$

$$(j=1,2), \tag{4}$$

where $X = 2\pi^2 k_B T/\hbar\omega_c$. Since $E_F > E_2$ in a 2DEG, the MIS oscillation frequency $f_{MIS} = (E_2-E_1)m^*/\hbar e$ is located between the two SdH oscillation frequencies of the first and second subbands but closer to that of the first subband.

Figure 5 shows the measured oscillatory magnetoresistances at several temperatures. The oscillations are enhanced by removing the slowly varying background. At 3 K, the oscillatory magnetoresistance is dominated by the SdH oscillation of the first subband, as evidenced by the 3-K FFT spectrum depicted in Fig. 6. With an increase of temperature, the SdH oscillations become weaker and weaker while the MIS oscillation remains essentially unchanged. At $\sim$15 K, the magnetoresistance shows significant beating effect, as the amplitude and frequency of the SdH oscillation of the first subband approach those of the MIS oscillation. With a further increase in temperature up to 25 K, the MIS oscillation starts to dominate the oscillatory magnetoresistance, as shown in Fig. 6. This process is also demonstrated in Fig. 5, showing that, at certain magnetic fields, the oscillation phase changes by π degree, as temperature increases from 3 to 25 K.

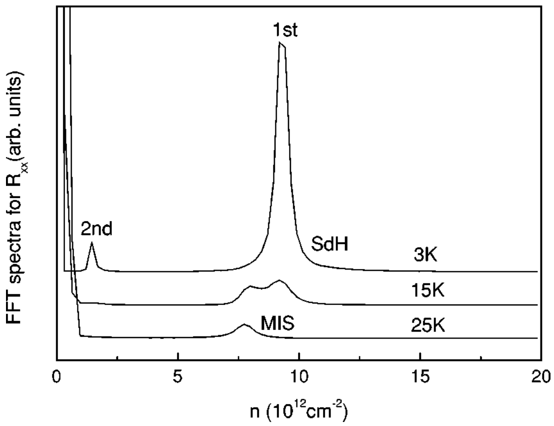

FIG. 6. FFT spectra of R_{xx} at different temperatures. All traces are shifted vertically for clarity.

IV. CONCLUSIONS

In summary, we have investigated the WL and MIS effects in a modulation-doped $Al_{0.22}Ga_{0.78}N/GaN$ heterostructure. The least square fit to the experimental data gives the temperature dependence of the inelastic scattering time τ_i, showing that the electron-electron scattering with small energy transfer dominates the inelastic scattering processes from $\tau_i \propto T^{-1}$. The experimental phase-breaking rate was found to be significantly larger than the Nyquist rate, indicating that other phase-breaking mechanisms appear to be present. The MIS oscillation induced by resonant intersubband scattering has been observed and found to be insensitive to temperature in contrast to a strongly temperature-dependent SdH oscillation.

ACKNOWLEDGMENTS

This work was supported by the special funds for Major State Basic Research Projects of China (Nos. G001CB3095 and G20000683), the National Natural Science Foundation of China (Nos. 10374094, 60136020 and 60290080), the Research Fund for the Doctoral Program of Higher Education (No. 20020284023), and the National High Technology Research & Development Project of China (No. 2002AA305304). One of the authors (N.D.) would like to thank the support of ''Outstanding Young Scholar'' Foundation by Chinese National Science Foundation (No. 60225004) and the Key Program of the National Natural Science Foundation of China (No. 10334030).

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