Abnormal Shubnikov–de Haas oscillations of the two-dimensional electron gas in $Al_xGa_{1-x}N/GaN$ heterostructures in tilted magnetic fields

Ning Tang, Bo Shen,* Kui Han, Fang-Chao Lu, Zhi-Xin Qin, and Guo-Yi Zhang
State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, People's Republic of China

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$Al_xGa_{1-x}N/GaN$ heterostructures are investigated by magnetotransport experiments in high magnetic fields tilted with respect to the sample normal at low temperatures. The spin splitting is observed at high filling factors. For some particular tilt angles when the spin-splitting energy is close to a half of the cyclotron energy $\hbar\omega_C$, it is found that there is a crossover from even-integer-dominated Shubnikov–de Haas (SdH) minima at low magnetic fields to odd-integer minima at high magnetic fields. The zero-field and exchange enhancement of the Zeeman spin-splitting effects can hardly interpret the abnormal SdH crossovers. We believe that large variation in the effective mass in the tilted magnetic field contributes to the crossovers.

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I. INTRODUCTION

$Al_xGa_{1-x}N/GaN$ heterostructures have been extensively studied for their applications in high-power, high-frequency, and high-temperature microwave devices.[1–3] The performance of the electronic devices based on $Al_xGa_{1-x}N/GaN$ heterostructures depends on the transport properties of the two-dimensional electron gas (2DEG) confined in the triangular quantum well at the $Al_xGa_{1-x}N/GaN$ heterointerface. Due to the large conduction-band offset and the large polarization-induced field, a 2DEG with large sheet carrier concentration can be obtained. Many $Al_xGa_{1-x}N/GaN$ 2DEG properties such as the effective mass, mobility, and spin have been investigated in normal magnetic fields, but relatively little work has been done in tilted magnetic fields.[4] For magnetic fields tilted with respect to the sample normal, the Landau splitting, which is proportional to the component of the field perpendicular to the 2DEG, can be tuned with respect to the Zeeman splitting which is proportional to the total magnetic field. This is used in the so-called coincidence method, which is a useful method to study the spin splitting of the energy levels.[5]

In this study, the appearance and disappearance of minima in Shubnikov–de Haas (SdH) oscillations in $Al_xGa_{1-x}N/GaN$ heterostructures are investigated by the coincidence method. For some particular tilt angles when the spin-splitting energy is close to a half of the cyclotron energy $\hbar\omega_C$, it is found that there is a crossover from even-integer-dominated SdH minima at low magnetic fields to odd-integer minima at high magnetic fields. The crossover moves to lower magnetic field with increasing tilt angle. The magnetointersubband scattering (MIS) and the zero-field spin-splitting effects can lead to beating patterns in the oscillatory magnetoresistance,[6–8] which are similar to the above crossovers. However, the MIS and the zero-field spin-splitting effects can hardly interpret the abnormal SdH crossovers observed in this study. Furthermore, exchange enhancement of the Zeeman spin-splitting effect can be excluded. Due to the large 2DEG concentration and the high tilted magnetic fields, large variation in the effective mass may contribute to the crossovers.

II. EXPERIMENTS

$Al_{0.22}Ga_{0.78}N/GaN$ heterostructures were grown by means of metal-organic chemical vapor deposition on the (0001) surface of sapphire substrates. 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 18-nm-thick unintentionally doped $Al_{0.22}Ga_{0.78}N$ (*i*-AlGaN) layer was grown at 1080 °C. High-resolution x-ray diffraction reciprocal space mapping demonstrates that the $Al_{0.22}Ga_{0.78}N$ layer is pseudomorphically grown on GaN and the heterostructures have been fabricated with high crystal quality and sharp heterointerface.

Hall-bar structures (1000 μm long, 75 μm wide) with two current contacts and six potential probes were defined by photolithography for the magnetoresistance measurements. Low-damage inductively coupled plasma etching formed the Hall-bar structures. Ohmic contacts were made by evaporating Ti/Al/Ni/Au metal multilayer structure, followed by a rapid annealing at 900 °C for 10 s in N_2 ambient. Magnetotransport measurements were performed at temperatures below 6 K and magnetic fields up to 14 T. The Hall mobility and sheet electron density are $8.26\times10^3\ \text{cm}^2/\text{V s}$ and $8.62\times10^{12}\ \text{cm}^{-2}$, respectively, at 2 K. The effective mass $0.21m_0$ of the 2DEG was obtained from the temperature dependence of the SdH oscillations at 4.2 T.

III. RESULTS AND DISCUSSION

Figure 1 shows the magnetoresistance R_{xx} of the 2DEG in the $Al_{0.22}Ga_{0.78}N/GaN$ heterostructure as a function of magnetic field B normal to the heterointerface at 2 K. Only one subband is occupied by the 2DEG. The 2DEG concentration $n_e=8.64\times10^{12}\ \text{cm}^{-2}$ is obtained from the fast Fourier transformation. The filling factor is defined by $v=n_eh/eB\cos\theta$ and counts the number of occupied energy levels below the Fermi energy. θ is the angle between the sample normal and the magnetic field orientation. One Landau number corresponds to two filling factors. In SdH oscillations, minima occur in the magnetoresistance R_{xx} if the Fermi energy lies in the gap between two energy levels. Since the spin splitting is

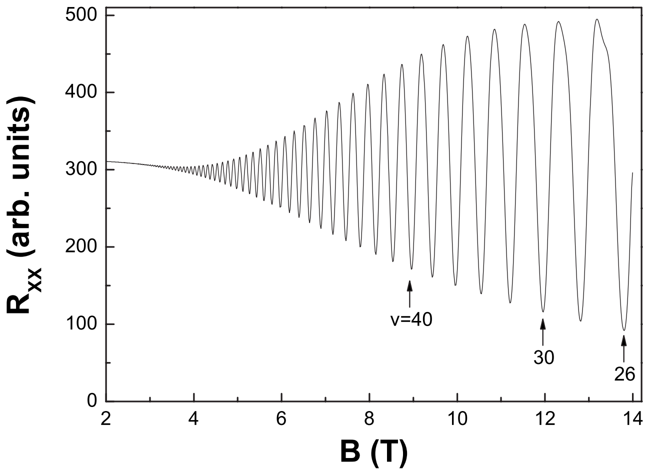

FIG. 1. Magnetoresistance R_{xx} of the 2DEG in an $Al_{0.22}Ga_{0.78}N/GaN$ heterostructure as a function of magnetic field B normal to the heterointerface at 2 K.

a minor contribution, all of the SdH minima are at even filling factors in Fig. 1. There is no beating pattern, which indicates that the MIS effect and the density inhomogeneities can be ignored. The split peaks, which originate from the Zeeman effect, are observed at SdH maximum ($v=27$).[9]

The coincidence situations are characterized by the parameter r, the ratio of spin, and the cyclotron energies,

$$r=\Delta_{\text{spin}}/\hbar\omega_C. \quad (1)$$

When r is equal to the half integer values $(1/2,3/2,5/2,\ldots)$, the energy levels have equal gaps and the amplitude of the SdH oscillations reaches its minimum. Even filling factors dominate the SdH minima when $r<1/2$, while odd filling factors dominate the SdH minima when $1/2<r<3/2$. Even and/or odd minima change in turn at higher r (half integer). In the case of zero-field spin splitting, r decreases with an increase in the cyclotron energy (i.e., the increase in the magnetic field B) and the last beating node occurs when $r=1/2$. Usually, there is a phase reversal through the beat. At the last node the SdH minima are changed from odd filling factors ($r>1/2$) to even filling factors ($r<1/2$) with an increase in magnetic field. When the radiation-induced spin preserving inter-Landau-level and spin-flip transitions occur, there is no phase reversal through the beat, which was reported by Mani *et al.*[10] In the case of Zeeman spin splitting, r increases with an increase in the tilt angle and the first minimum in SdH amplitude at a given filling factor occurs when $r=1/2$.

Figure 2 shows the magnetoresistance R_{xx} as a function of $(B\cos\theta)^{-1}$ at various tilt angles around 60° in the regime of coincidence $r=1/2$. The tilt angles were determined from the slope of the Hall trace in the low magnetic field domain as well as the SdH frequency. For some particular tilt angles, there is a crossover from even-integer-dominated SdH minima at low magnetic fields to odd-integer minima at high magnetic fields. The crossovers are notated by the arrows. With an increase in tilt angles, the node of the crossover first appears at high magnetic field. Then it shifts to lower magnetic field. Finally, it is not resolved at very low magnetic field. The crossovers are resolved at very high filling factor. Figure 3 shows the crossover at high magnetic field when the crossover just appears with an increase in tilt angle. The spin-resolved SdH oscillations can be clearly seen in Fig. 3. The peak heights are different between spin-up and spin-down electrons. Thus, the amplitudes of the SdH oscillations at the crossover node are not exactly zero. At the lower magnetic field domain, the peaks belonging to the same Landau number are closer. At the crossover domain, the peaks are equally spaced and the SdH amplitude reaches its minimum.

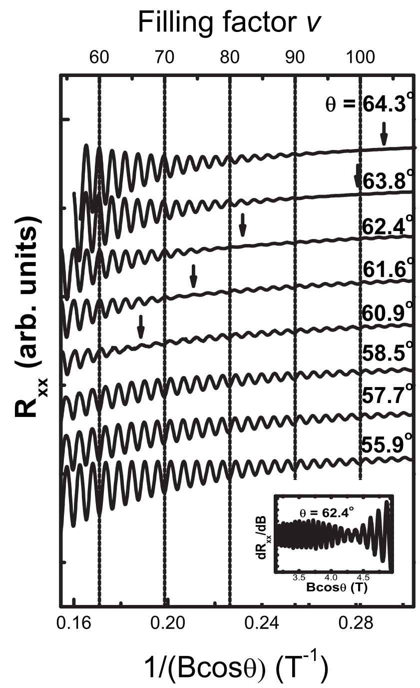

FIG. 2. Magnetoresistance R_{xx} as a function of $(B\cos\theta)^{-1}$ as well as filling factor $v=n_e h/eB\cos\theta$ at various tilt angles in the regime of coincidence $r=1/2$ at 2 K. For particular tilt angles, there is a crossover from even-integer-dominated SdH minima to odd-integer minima as a function of magnetic field. The crossovers are notated by the arrows. The inset manifests the node at 62.4°.

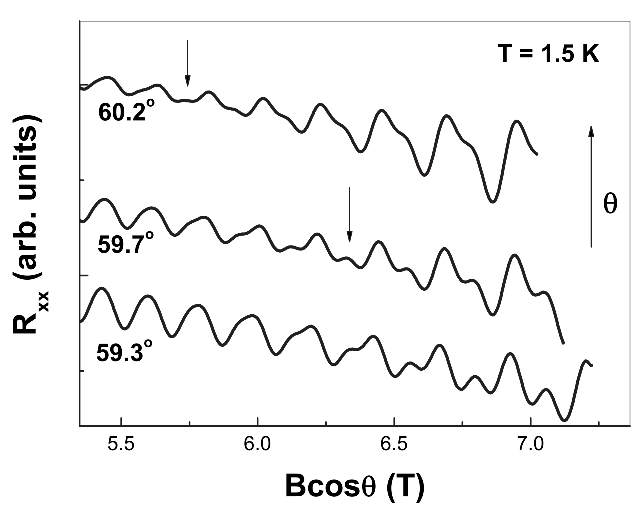

FIG. 3. Magnetoresistance R_{xx} as a function of the perpendicular component of magnetic field B at various tilt angles.

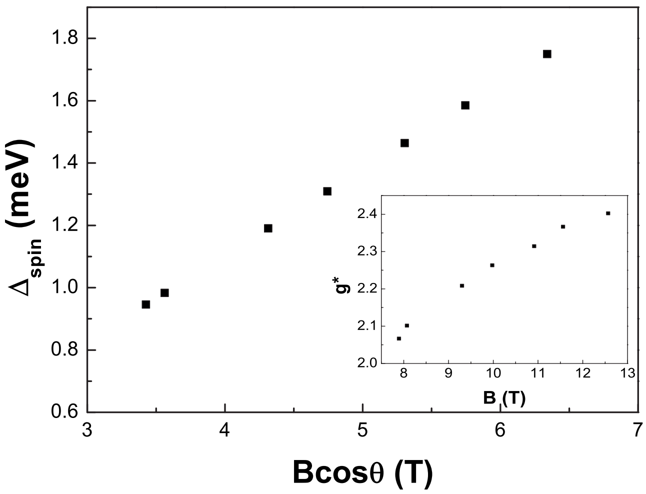

FIG. 4. The spin-splitting energy as a function of the perpendicular component of magnetic field B at the nodes in Figs. 2 and 3. The inset shows the effective g factor at the nodes.

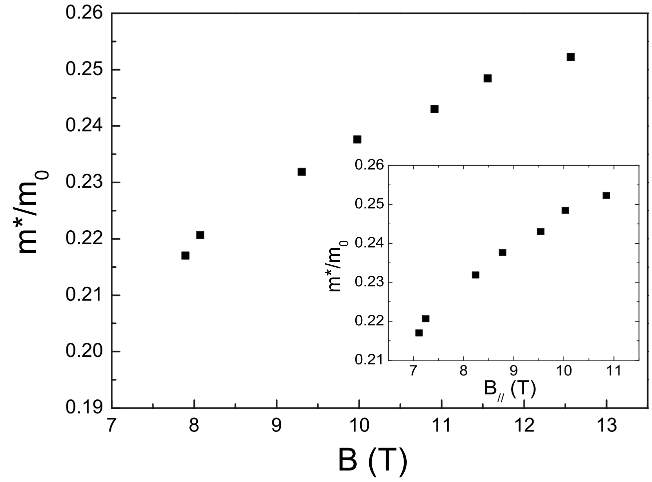

FIG. 5. The effective masses as a function of the magnetic field B at the nodes. The inset shows the effective masses as a function of $B_{\parallel}$ at the nodes.

At higher magnetic field domain, the peaks belong to the adjacent Landau number are closer. These nodes correspond to $r=1/2$. r is greater than 1/2 at higher magnetic fields (odd minima) and less than 1/2 at lower magnetic fields (even minima), which is different from that of the zero-field spin-splitting effect. Therefore, the crossovers are not caused by zero-field spin splitting in tilt angles.

The split Landau levels are caused by Zeeman spin splitting. The Zeeman spin gap is expressed as[11]

$$\Delta_{\text{spin}} = g^* \mu_B B = g_0 \mu_B B + E_{\text{ex}}, \tag{2}$$

where μ_B is the Bohr magneton and E_{ex} is the many-body exchange energy which lifts the g factor from its bare value (2.0 in GaN) to its enhanced value g^*. The exchange energy can be written as $E_{\text{ex}}=\alpha\hbar\omega_C$. The exchange enhancement of the spin splitting is a function of the perpendicular component of the magnetic field. In the condition of $r=1/2$, the linear increase exchange energy will result in[11]

$$\cos\,\theta = g^* \frac{m^*}{m_0} = \frac{g_0}{1-2\alpha} \frac{m^*}{m_0}. \tag{3}$$

This equation is dependent on tilt angle and independent of magnetic field B. Thus, the bare Zeeman splitting ($\alpha=0$) or the linear increase exchange energy ($\alpha \neq 0$) will not result in the crossover from even-integer-dominated SdH minima to odd-integer minima unless α is dependent on magnetic field B.

Supposing the effective mass is a constant, the spin-splitting energy as a function of the perpendicular component of magnetic field B at the nodes can be calculated according to Eq. (1), which is shown in Fig. 4. The inset shows the effective g factor at the nodes. It is found that the effective g factors are close to its bare value 2.0 and become larger with an increase in the magnetic field. The enhancement takes place both at high magnetic fields with well resolved SdH split peaks of the spin splitting and at low magnetic fields without split peaks at very high filling factors. The broadening of the density of state will reduce the spin-population difference of the system and thus cause the exchange energy to reduce, especially at high filling factors. The quantum-scattering time $\tau_q=0.158$ ps was obtained by means of a Dingle plot. The density of state broadening $\Gamma=\hbar/2\tau_q=2.09$ meV is much larger than the spin-splitting energy shown in Fig. 4. Therefore, the exchange contribution will disappear and only bare Zeeman splitting will remain. The existing models of the exchange enhancement can hardly interpret the crossover from even-integer-dominated SdH minima to odd-integer minima.

According to Eq. (3), if the effective mass is dependent on the magnetic field, the condition of $r=1/2$ will also depend on the magnetic field and the crossover from even-integer-dominated SdH minima to odd-integer minima will occur at some tilt angles. Supposing $\alpha=0$ in Eq. (3), the effective masses as a function of the magnetic field at the nodes can be obtained. As shown in Fig. 5, there is a large variation in the effective mass. The inset of Fig. 5 shows the effective masses as a function of $B_{\parallel}$ at the nodes.

The nonparabolicity effect,[12] with large 2DEG concentration in high magnetic fields, is likely a contribution to the variation in the effective mass. In the simple two-band approximation the increase in the effective mass due to the nonparabolicity can be described by $m^*(E)=m_0^*(1+2E/E_g)$, where E_g is the energy band gap, E is the electron energy relative to the conduction band edge, and m_0^* is the band-edge mass. GaN has a wide energy band gap and is expected to have small nonparabolicity of the conduction band. However, due to a large conduction-band offset and a strong polarization-induced electric field in $Al_xGa_{1-x}N/GaN$ heterostructures, a 2DEG with large sheet density can be obtained in a very deep triangular quantum well at the heterointerface. Thus, high energy levels can be occupied by the 2DEG. Strong magnetic field enhances the energy of the electrons. Thus the effective mass depends on the total magnetic field B.[13,14]

Furthermore, when an in-plane magnetic field $B_{\parallel}$ is applied in the heterostructure, the originally isotropic "Fermi loop" of a two-dimensional electron system is distorted to "egglike" form due to the asymmetric triangular confining potential at the heterointerface.[15,16] The effective mass is also affected by $B_\parallel$ due to the distortion of the Fermi loop. The effective mass increase up to 25% of its zero in-plane magnetic field value at high $B_\parallel$ was observed in AlGaAs/GaAs heterostructures.[17] In this study, $Al_xGa_{1-x}N/GaN$ heterostructures are investigated in high magnetic fields tilted with respect to the sample normal. With an increase in magnetic field at the tilt angles, the in-plane magnetic field $B_\parallel$ increases, which also contributes to the effective mass increase. Therefore, large variation in the effective mass in the tilted magnetic field is believed to be a major contribution to the crossover from even-integer-dominated SdH minima to odd-integer minima.

IV. CONCLUSIONS

In summary, $Al_xGa_{1-x}N/GaN$ heterostructures are investigated by magnetotransport experiments in high magnetic fields tilted with respect to the sample normal at low temperatures. The spin splitting is observed at high filling factors. For some particular tilt angles when the spin-splitting energy is close to a half of the cyclotron energy $\hbar\omega_C$, it is found that there is a crossover from even-integer-dominated SdH minima at low magnetic fields to odd-integer minima at high magnetic fields. The zero-field and exchange enhancement of the Zeeman spin-splitting effects can hardly interpret the abnormal SdH crossovers. We believe that large variation in the effective mass in the tilted magnetic field contributes to the crossovers.

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*bshen@pku.edu.cn

[1] Z. Fan, C. Lu, A. E. Botchkarev, H. Tang, A. Salvador, O. Aktas, W. Kim, and H. Morkoc, Electron. Lett. **33**, 814 (1997).
[2] U. K. Mishra, Y. F. Wu, B. P. Keller, S. Keller, and S. P. Denbaars, IEEE Trans. Microwave Theory Tech. **46**, 756 (1998).
[3] M. A. Khan, Q. Chen, M. S. Shur, B. T. Dermott, J. A. Higgins, J. Burm, W. Schaff, and L. F. Eastman, Electron. Lett. **32**, 357 (1996).
[4] W. Knap, E. Frayssinet, M. L. Sadowski, C. Skierbiszewski, D. Maude, V. Falko, M. A. Khan, and M. S. Shur, Appl. Phys. Lett. **75**, 3156 (1999).
[5] F. F. Fang and P. J. Stiles, Phys. Rev. **174**, 823 (1968).
[6] N. Tang, B. Shen, Z. W. Zheng, J. Liu, D. J. Chen, J. Lu, R. Zhang, Y. Shi, Y. D. Zheng, Y. S. Gui, C. P. Jiang, Z. J. Qiu, S. L. Guo, J. H. Chu, K. Hoshino, T. Someya, and Y. Arakawa, J. Appl. Phys. **94**, 5420 (2003).
[7] K. S. Cho, T. Y. Huang, H. S. Wang, M. G. Lin, T. M. Chen, C. T. Liang, Y. F. Chen, and I. Lo, Appl. Phys. Lett. **86**, 222102 (2005).
[8] N. Tang, B. Shen, M. J. Wang, K. Han, Z. J. Yang, K. Xu, G. Y. Zhang, T. Lin, B. Zhu, W. Z. Zhou, and J. H. Chu, Appl. Phys. Lett. **88**, 172112 (2006).
[9] K. S. Cho, T. Y. Huang, C. P. Huang, Y. H. Chiu, C. T. Liang, Y. F. Chen, and I. Lo, J. Appl. Phys. **96**, 7370 (2004).
[10] R. G. Mani, J. H. Smet, K. von Klitzing, V. Narayanamurti, W. B. Johnson, and V. Umansky, Phys. Rev. B **69**, 193304 (2004).
[11] D. R. Leadley, R. J. Nicholas, J. J. Harris, and C. T. Foxon, Phys. Rev. B **58**, 13036 (1998).
[12] S. Syed, J. B. Heroux, Y. J. Wang, M. J. Manfra, R. J. Molnar, and H. L. Stormer, Appl. Phys. Lett. **83**, 4553 (2003).
[13] D. R. Hang, C. T. Liang, C. F. Huang, Y. H. Chang, Y. F. Chen, H. X. Jiang, and J. Y. Lin, Appl. Phys. Lett. **79**, 66 (2001).
[14] N. Tang, B. Shen, M. J. Wang, Z. J. Yang, K. Xu, G. Y. Zhang, T. Lin, B. Zhu, W. Z. Zhou, and J. H. Chu, Appl. Phys. Lett. **88**, 172115 (2006).
[15] L. Smrcka and T. Jungwirth, J. Phys.: Condens. Matter **6**, 55 (1994).
[16] L. Smrcka, P. Vasek, J. Kolacek, T. Jungwirth, and M. Cukr, Phys. Rev. B **51**, 18011 (1995).
[17] H. Aikawa, S. Takaoka, K. Oto, K. Murase, T. Saku, Y. Hirayama, S. Shimomura, and S. Hiyamizu, Physica E (Amsterdam) **12**, 578 (2002).