Influence of the illumination on weak antilocalization in an Al$_x$Ga$_{1-x}$N/GaN heterostructure with strong spin-orbit coupling


1Key Laboratory of Polar Materials and Devices, Ministry of Education, East China Normal University, Shanghai 200062, People’s Republic of China
2Physical Science and Technology College, Guangxi University, Nanning, Guangxi 530004, People’s Republic of China
3National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, People’s Republic of China
4State Key Laboratory of Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, People’s Republic of China

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The weak antilocalization effects of the two-dimensional electron gas in a high mobility Al$_x$Ga$_{1-x}$N/GaN heterostructure have been investigated by means of magnetotransport measurements before and after illumination. The zero-field spin splitting mainly arising from the Rashba spin-orbit coupling effect as a function of electron concentration as well as a function of temperature is studied using the weak antilocalization analysis. The Rashba spin-orbit coupling constant $\alpha$ deduced using the weak antilocalization analysis shows a rapid decrease with the increase of the measured electron concentration. © 2008 American Institute of Physics.

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Two-dimensional electron gases (2DEGs) in Al$_x$Ga$_{1-x}$N/GaN heterostructures are very promising candidates for future spintronic applications based on the facts that GaN-based diluted magnetic semiconductors are prospective materials for spin injection or spin analyzer because they show Curie temperatures above room temperature and are expected to be a good match to Al$_x$Ga$_{1-x}$N/GaN heterostructures. Besides, 2DEGs in Al$_x$Ga$_{1-x}$N/GaN heterostructures are potential candidates for gate-controlled spin precession utilizing the Rashba effect induced by structural inversion asymmetry (SIA) of quantum well.

In wurtzite Al$_x$Ga$_{1-x}$N/GaN heterostructures, the zero-field spin splitting can originate from the Rashba effect and the effect induced by the lack of inversion symmetry of the wurtzite-type lattice, i.e., the bulk inversion asymmetry (BIA). The electric field originating from the BIA in wurtzite Al$_x$Ga$_{1-x}$N/GaN heterostructures is oriented along the (0001) direction and thus parallel to the macroscopic electric field in the SIA quantum well. And both the Rashba and BIA terms are linear scaling of the Fermi wave vector $k_F$. The Rashba spin-orbit (SO) coupling is of particular interest due to its potential applications in spin-field-effect transistor in the ballistic regime, as it can be controlled by an applied gate voltage.

The zero-field spin splitting in Al$_x$Ga$_{1-x}$N/GaN heterostructures has attracted considerable and continuously growing interest for the application in the spintronic devices. Recent experiments based on Shubnikov–de Haas (SdH), weak antilocalization (WAL), and circular photogalvanic measurements have given conflicting results such as the original mechanisms for the zero-field spin splitting of the 2DEG, as well as the magnitude of SO interaction in wurtzite Al$_x$Ga$_{1-x}$N/GaN heterostructures.

Thillosen et al. found that the SO coupling constant $\alpha$ obtained from the WAL analysis is identical though the Al$_x$Ga$_{1-x}$N barrier layers as well as the electron concentration are different. The deduced SO coupling constant $\alpha$ from the WAL analysis independent of the Al$_x$Ga$_{1-x}$N barrier layers as well as the electron concentration was also presented by Kurdak et al. and Schmutt et al. Thillosen et al. concluded that the SO coupling present in Al$_x$Ga$_{1-x}$N/GaN heterostructures seems to be completely determined by the BIA of the GaN lattice and cannot be controlled by a gate. In a recent study, it was suggested that the zero-field spin splitting mainly arises from the Rashba effect in wurtzite Al$_x$Ga$_{1-x}$N/GaN heterostructures in virtue of the investigation of the shift of the beating nodes and the change of WAL by the illumination. To help resolve these issues, we have performed WAL measurements under different illumination time on Al$_x$Ga$_{1-x}$N/GaN heterostructure in this letter. The deduced Rashba SO coupling constant $\alpha$ using the WAL analysis showed a rapid decrease with the measured electron concentration.

Al$_{0.22}$Ga$_{0.78}$N/GaN heterostructure was grown by means of metal organic chemical vapor deposition (MOCVD) on the (0001) surface of sapphire substrate. The layer sequence is depicted in the inset of Fig. 1(a). Previously, the MOCVD growth process has been discussed for a similar sample in detail. SdH and WAL measurements were performed in low temperatures and magnetic fields were applied perpendicularly to the heterointerface. A light-emitting diode with the wavelength of 390 nm was used to illuminate the sample at the temperature of 1.4 K. The 2DEG concentration is gradually increased after each illumination. Due to the persistent photoconductivity effect, the increased 2DEG concentration persists for a long time, which is much longer than the time of the WAL measurements.

Figure 1(a) shows the diagonal magnetoresistance $\rho_{xx}$ and the transverse magnetoresistance $\rho_{xy}$ of the 2DEG in the Al$_{0.22}$Ga$_{0.78}$N/GaN heterostructure as a function of the applied magnetic field...
applied magnetic field perpendicular to the heterointerface at 1.5 K. The electron concentration \( n = 8.87 \times 10^{12} \text{ cm}^{-2} \) and mobility \( \mu = 0.81 \times 10^4 \text{ cm}^2/\text{V s} \) of the 2DEG are extracted from the SdH measurements at 1.5 K. The electron effective mass of the 2DEG in the Al\(_{0.23}\)Ga\(_{0.77}\)N/GaN heterostructure is 0.23\( m_0 \) (where \( m_0 \) is the free electron mass) obtained from the temperature dependence of the SdH oscillations. According to \( B_T = h/2e l_F^2 \) (where \( B_T \) is the transport field, \( h \) is the Planck constant over 2\( \pi \), \( l_F = u_F \tau_F \) is the mean free path, and \( u_F \) is the velocity of electron at Fermi surface), \( l_F \) is estimated to be 2.08 mT, below which electrons move diffusively.\(^{14,15}\) And the transport scattering time \( \tau_F \) and the mean free path \( l_F \) are estimated to be 1.06 ps and 397 nm, respectively.

Figure 1(b) presents the measured low-field magnetoresistance as a function of the applied magnetic field for the sample at different temperatures. A clear WAL peak was observed in the vicinity of \( B = 0 \) for all temperatures. The WAL peak decreases with the increase of the temperature. In order to extract estimates of the spin splitting from the WAL effect, the experimental curves were fitted by the theoretical model developed by Golub\(^ {14}\) which is valid in a wide range of magnetic field and parameters \( \Omega \tau_\sigma \), where \( \Omega \) is the SO frequency. It should be noted that only Rashba effect or the linear BIA term is considered in this model quantifying both contributions.

The curves of experimental conductivity correction of the 2DEG in the sample as a function of the transport field \( B_T \) in the range of very low magnetic field at different temperatures are shown in Fig. 2(a). A good fit to the experimental curves has been achieved at different temperatures [see Fig. 2(a)]. The corresponding values of \( \Omega \tau_\sigma \), are obtained to be 0.89 and is almost a constant value in the measured temperature range. The extracted value of \( \tau_{\sigma}^{\text{tr}}/\tau_\sigma \) by fitting the experimental conductivity corrections increases with the increase of temperature. Since the Rashba term and the linear BIA term cannot be distinguished here, an effective SO coupling still labeled as Rashba term \( \Delta_R \) comprising both contributions is considered. Accordingly the zero-field spin splitting energy is defined to be \( \Delta_R = 2\Omega \tau_{\sigma} \).\(^ {16-18}\) The zero-field

![FIG. 1. (Color online) (a) The oscillatory magnetoresistance \( \rho_x \) and the transverse magnetoresistance \( \rho_{xy} \) of the 2DEG as a function of the applied magnetic field \( B \) parallel to the heterointerface at 1.5 K. The inset shows a schematic illustration of the layer sequence of the sample. (b) The magnetoresistance \( \rho_{xx}(B) - \rho_{xx}(0) \) as a function of the magnetic field \( B \) in the low magnetic field range at different temperatures. The vertical dash line at \( B = 0 \) mT is merely a guide for the eye.](image-url)

![FIG. 2. (Color online) (a) Quantum conductivity correction curves \( \Delta \sigma = \sigma(B) - \sigma(0) \) as a function of the transport field \( B_T \) at different temperatures (solid symbols). Solid lines represent the fit by a model in Ref. 14. (b) Temperature dependence of the inelastic scattering rate \( 1/\tau_\sigma \) extracted from the fits of the WAL curves (solid symbols). The solid line shows the linear dependence of \( 1/\tau_\sigma \) on temperature at \( T \leq 8 \) K.](image-url)
If the zero-field spin splitting originates from the BIA contribution, the increased $k_f$ should increase the spin splitting energy, which is contrary to the results. Therefore, the zero-field spin splitting mainly arises from the Rashba effect. It should be noted that in Fig. 3 the magnetic field $B_{\text{min}}$ will shift to higher value of $B/B_{\text{tr}}$ when the electron concentration increases if the zero-field spin splitting originates from the BIA contribution, which also gives the evidence of the zero-field spin splitting mainly arising from the Rashba effect. According to the theoretical expression $\alpha = \hbar^2 E/4\pi m^* E_g$ (where $E$ is the electric field at the heterointerface of Al$_{x}$Ga$_{1-x}$N/GaN heterostructure, and $E_g$ is the width of the gap of quantum well), the electric field at the heterointerface is also weakened after each illumination. In order to extract the expectation value of the electric field variation along with the increase of electron concentration, a detailed calculation of the electron concentration and conduction and valence band edges of AlGaN/GaN heterojunction based on a self-consistent solution of the Schrödinger and Poisson equations, including the charge balance equation and the effect of exchange correlation on the Coulomb interaction should be performed based on the assumptions of the origin of the carriers and the change of the carriers under illumination. And the quantitative expression between the Rashba SO coupling constant and the 2DEG concentration in AlGaN/GaN heterostructures is needed to investigate in a future study. Also, these observations in the study may evoke further experimental and theoretical investigations to clarify the relation between Rashba SO coupling constant and the 2DEG parameters quantitatively in AlGaN/GaN heterostructures. Those works will be carried out in a future study.

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