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Investigation of spin-orbit interaction in AlGaN/GaN heterostructures with large electron density

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Magnetotransport phenomena in the high-density two-dimensional electron gas of AlGaN/GaN heterostructures are investigated. Peculiarities of low- and high-field magnetotransport measurements in the temperature range from 0.3 to 10 K are discussed. The weak localization and antilocalization effects are observed and analyzed. The Rashba constant describing the spin-orbit interaction is extracted from the results of low-field magnetotransport for the structure with 33% aluminum content in the barrier and an electron sheet density of 1.1×10^{13} cm^{-2} and appears to be of 1.01×10^{-10} eV cm.

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I. INTRODUCTION

Gallium nitride (GaN) and the nanostructures based on it are promising materials for semiconductor spintronics.[1] Therefore, it is important to study the spin-orbit interaction (SOI) which determines the spin dynamics in these systems. The quantum wells forming at the heterojunction AlGaN/GaN and containing two-dimensional electron gas (2DEG) are the useful objects for the investigation of SOI. The confining potential in the quantum well, which is determined by the growth, structural features, and the applied electric field E, has structural inversion asymmetry. As a result, the 2DEG energy spectrum, in the lowest order of the wave vector $\mathbf{k}$, is described by the Rashba Hamiltonian,[2]

$$\hat{H} = \hbar\hat{\boldsymbol{\sigma}}\cdot\boldsymbol{\Omega}(\mathbf{k}), \tag{1}$$

where $\hat{\boldsymbol{\sigma}}$ is the vector of Pauli matrices, $\boldsymbol{\Omega}$ is an antisymmetric function of $\mathbf{k}$, $\hbar\boldsymbol{\Omega}(\mathbf{k})=\alpha_{SO}(\sin\varphi,-\cos\varphi)$, φ is the angle between $\mathbf{k}$ and [100] axis, and α_{SO} is the Rashba constant. The splitting of the electron states at the Fermi level is given by $\Delta_{SO}=2\hbar\Omega(k_F)$, where $\Omega(k)=|\boldsymbol{\Omega}(\mathbf{k})|$ and k_F is the Fermi wave number. The constant α_{SO} depends on the parameters of the energy spectrum (the band gap E_g and the spin-orbit splitting Δ_{SO} of the valence band at the zone center) of the bulk material, as well as on the parameters of the 2DEG itself.[3]

It is known that the SOI manifests itself in the magnetoconductivity of the 2DEG. In low magnetic fields (of the order of 1 mT), the effect of weak antilocalization is observed,[4] while in the magnetic fields of the order of 1 T, the beating pattern of the Shubnikov–de Haas (SdH) oscillations is found,[5] owing to the splitting of the energy spectrum. The investigations of the SdH effect[6–8] for GaN/AlGaN heterostructures have not revealed any splitting of the energy spectrum caused by the SOI. The reasons for this are the comparatively large effective mass ($m\sim0.2m_0$) and low mobility ($\mu<10\,000$ cm^2/V s) of the carriers in the two-dimensional systems based on the gallium nitride. As a result, the SdH oscillations are observed in high fields ($B>5$ T), and the Landau level broadening owing to the collisions, η/τ_{tr}, suppresses the spin-orbit splitting at the Fermi level.

On the other hand, the low-field magnetotransport in 2DEG is a more suitable tool for investigation of the SOI in GaN-based heterostructures. Owing to the SOI, the anomalous negative magnetoresistance, which is caused by the weak localization effect, become positive in low magnetic fields (the antilocalization effect).[4] Studies[9–11] of the conductivity of AlGaN/GaN heterostructures have revealed the antilocalization minimum where the magnetoresistance reverses its sign. The densities of 2DEG in these heterostructures differ (from 5×10^{11} to 10^{12} cm^{-2} in Ref. 9, from 1.32×10^{12} to 3.66×10^{12} cm^{-2} in Ref. 10, and 6.2×10^{12} cm^{-2} in Ref. 11), whereas the position of the magnetoconductivity minimum observed in the investigations appears to be nearly the same, about 2 mT. Therefore, the values of the Rashba constant α_{SO} determined in these references are approximately the same: 6×10^{-11}, 5.5×10^{-11}, and 8.54×10^{-11} eV cm in Refs. 9–11, respectively. According to the conclusion of the authors of Ref. 9, the effects of spontaneous and piezoelectric polarizations in GaN and AlGaN (Ref. 12) can increase α_{SO} because of an additional electric field E appearing at the AlGaN/GaN heterojunction, $\alpha_{SO}\sim E$. By increasing the Al content in this system, not only is the 2DEG density increased, but the polarization field is also enhanced thereby achieving the larger value of the Rashba constant.

In the present study, we have investigated the magnetoresistivity of a single $Al_xGa_{1-x}N$/GaN ($x=0.33$) heterojunction with a 2DEG density $n=1.1\times10^{13}$ cm^{-2}, which essentially exceeds the densities for the samples studied in the papers of Refs. 9–11. We observed a maximum in the dependence of the resistivity on the magnetic field. The height of this maximum decreased with increasing temperature. Using the expression for the magnetoconductivity from Ref. 13, a fit of the experimental data to the theoretical results was performed. Based on this procedure, the Rashba constant α_{SO}, the spin-orbit splitting at the Fermi level Δ_{SO}, and the spin-

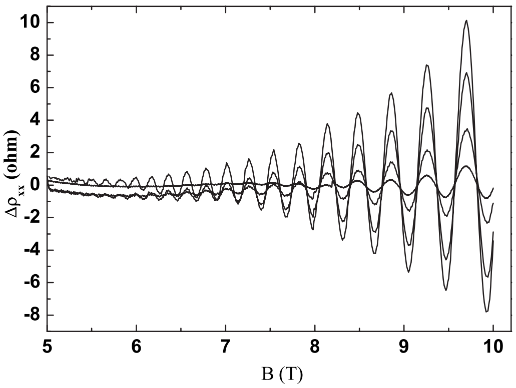

FIG. 1. Diagonal component of the 2DEG resistance for the heterostructure $Al_{0.33}Ga_{0.67}N/GaN$ as a function of the magnetic field B at the temperatures T of 0.3, 1.3, 2.0, and 3.0 K (corresponding to lowering the oscillation amplitude).

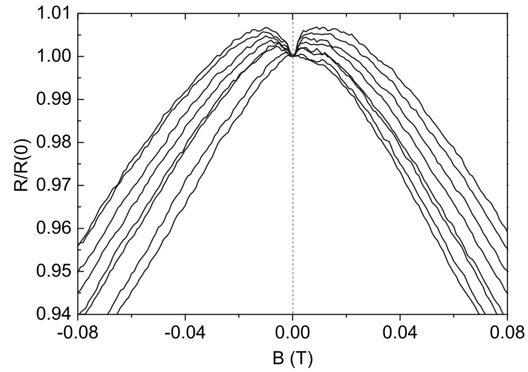

FIG. 2. Dependence of the 2DEG resistance for the heterostructure $Al_{0.33}Ga_{0.67}N/GaN$ on the magnetic field B at T of 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1 K (from the upper to the lower plots, respectively).

orbit (Dyakonov-Perel) relaxation time τ_{SO} were estimated.

II. EXPERIMENTAL DETAILS

The wafer for the investigation was grown by the metal organic chemical vapor deposition. The structure details are as follows. On the SiC substrate, there were grown in series a bulk GaN layer (1.1 μm), a barrier layer $Al_{0.33}Ga_{0.67}N$ (23 nm), and a passivation layer Si_3N_4 (320 nm).

The 2DEG was formed at the lower GaN/AlGaN interface without modulation doping due to the effects of spontaneous and piezoelectric polarizations. The sample with a width of 100 μm and a length of 3.5 μm had Ti/Al/Ni/Au Ohmic contacts. The magnetoresistivity was investigated at temperatures $T=0.3$, 0.6, 1.3, and 1.6 K, as well as at the temperatures from 2.0 to 10.0 K with an interval of 0.5 K. The current through the sample was 3 μA.

III. RESULTS AND DISCUSSION

The diagonal component of the 2DEG magnetoresistance $\Delta\rho_{xx}$ for the AlGaN/GaN heterojunction is shown in Fig. 1 as a function of the magnetic field B at the temperatures of $T=0.3$, 1.3, 2.0, and 3.0 K. The SdH oscillations are observed at $B>5$ T, and the amplitude of the oscillations deacreased with increasing temperature. The absence of the beating in the plots of $\Delta\rho_{xx}$ indicates that only one level in the quantum well of the heterostructure is populated by electrons. The 2DEG density is obtained from the period of the oscillations, $n=1.1\times10^{13}$ cm^{-2}. The other parameters extracted from the magnetoresistance measurements are the effective mass of the carriers, $m=0.22m_0$, and their scattering time, $\tau_q=0.1$ ps. Comparing τ_q with the momentum relaxation time τ_{tr} determined from the zero-field mobility $\mu=e\tau_{tr}/m$, we find that the ratio τ_{tr}/τ_q is approximately equal to 3. Since this ratio is not large in comparison to unity, we conclude that the small-angle scattering does not dominate, and the main scattering mechanism of the carriers in our sample is the short-range scattering processes (possibly, the alloy scattering).

The 2DEG resistivity of the $Al_{0.33}Ga_{0.67}N/GaN$ heterojunction was also investigated in weak magnetic fields $B<0.08$ T at several temperatures ranging between 0.3 and 1 K (Fig. 2). The dependences shown in Fig. 2 are nonmonotonic and have maxima at characteristic fields $B=B_{SO}$. The height of the magnetoresistivity maxima decreases with increasing temperature, and the extremum disappears at $T>0.9$ K. The position of the maxima for the curves in Fig. 2 for our sample is not stable, in contrast to that of Refs. 9–11. The characteristic magnetic fields B_{SO} are close to 0.01 T, which exceeds B_{SO} for the systems with low 2DEG density. In order to obtain detailed information about the SOI in our AlGaN/GaN system, we have used a recently developed theory[13] of weak antilocalization for two-dimensional systems, where the SOI is described by the Rashba Hamiltonian [Eq. (1)]. The expression[13] obtained for the magnetoconductivity $\sigma(B)$-$\sigma(0)$ is valid in a wide range of magnetic fields and parameters $\Omega\tau_{tr}$. Fitting of the theoretical curves to the measured conductivity is carried out using two dimensionless parameters, $\Omega\tau_{tr}$ and τ_{tr}/τ_φ, where τ_φ is the inelastic scattering time. The first parameter mostly influences the position of the minimum in the magnetoconductivity dependence, while the second one describes the depth of this minimum. The experimental and theoretical curves for the magnetoconductivity at the temperatures $T=0.3$ and 0.5 K are shown in Fig. 3. The theory of weak antilocalization satisfactorily describes our experimental data in the region of fields $B<0.02$ T by using the reasonable parameters $\Omega\tau_{tr}\approx0.37$ and τ_φ ranging from 70 to 25 ps. The results presented above give the Rashba constant $\alpha_{SO}=1.01\times10^{-10}$ eV cm, the spin-orbit splitting energy at the Fermi level $\Delta_{SO}=1.7$ meV, and the spin-orbit relaxation rate $1/\tau_{SO}=0.98$ ps^{-1}. The value $\alpha_{SO}=1.01\times10^{-10}$ eV cm is higher than the values obtained in Refs. 9–11 using the theory of Ref. 14. It should be noted that the difference obtained in the Rashba constant is not a consequence of the difference in the fitting procedure (we have made a fit to the experimental data of Ref. 9 using the theory of Ref. 13, and found that the Rashba constant extracted in this way is very close to the value of 6×10^{-11} eV cm reported in Ref. 9).

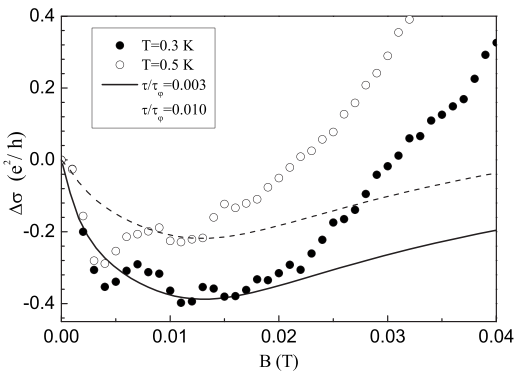

FIG. 3. Experimental dependence of the 2DEG resistivity for the heterostructure $Al_{0.33}Ga_{0.67}N/GaN$ on the magnetic field B measured at $T=0.3$ and 0.5 K together with calculated results according to the theory of Ref. 13 using the parameters indicated in the insert to the figure.

IV. CONCLUSIONS

We investigated the magnetotransport in AlGaN/GaN high electron mobility transistor (HEMT) structures. The anomalous negative magnetoresistance, caused by the weak localization effect, is registered in the low magnetic field range. The antilocalization minimum is revealed in the conductivity of AlGaN/GaN heterostructures in low magnetic fields where the magnetoresistance changed its sign. The Rashba constant obtained from the experimental data on low-field magnetoconductivity is 1.01×10^{-10} eV cm. This value exceeds the values previously obtained for AlGaN/GaN HEMT structures. Quantitatively, such a difference may be related to higher electric fields at the heterojunction owing to the increase of Al content, which also determines the higher sheet carrier density of 2DEG in our structures in comparison to the structures studied by other research groups. Further experimental and theoretical investigations are necessary to clarify the relation between the Rashba constant and the 2DEG parameters in AlGaN/GaN structures.

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