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# Zero Field Spin Splitting in GaN/AlGaN Heterostructures Probed by the Weak Antilocalization

K. Dybko[a,*], M. Siekacz[b] and C. Skierbiszewski[b]

[a]Institute of Physics, Polish Academy of Sciences
al. Lotników 32/46, 02-668 Warsaw, Poland
[b]High Pressure Research Center, PAS
Sokołowska 29/37, 01-142 Warsaw, Poland

We present the magnetoconductivity measurements of a high mobility two-dimensional electron gas confined at GaN/AlGaN interface. The sensitive measurements of low field conductivity revealed both quantum corrections, the weak localization and antilocalization effects. It indicates the importance of the spin–orbit coupling in this wide band gap material. The analysis of the data provided the information about the temperature dependence of the dephasing time and total spin–orbit relaxation time. The conduction band spin splitting energy amounts to 0.23 meV and 0.35 meV at electron densities $2.2 \times 10^{12}$ cm$^{-2}$ and $5.7 \times 10^{12}$ cm$^{-2}$, respectively.

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## 1. Introduction

The heterostructures based on wide band gap gallium nitride are promising candidates for semiconductor spintronics [1, 2]. Therefore, it is important to study their fundamental property, zero field spin splitting of conduction band due to spin–orbit interaction. Two experimental techniques are used in magnetotransport for studying the spin-dependent effects in semiconductors: the analysis of the beating patterns in the Shubnikov–de Haas effect and the quantum correction to the conductivity in the form of weak antilocalization. While the former can be easily misinterpreted leading to erroneous results, the latter is an unambiguous indication of the presence of spin–orbit interactions. In the system in quantum diffusion regime, the phase coherent electronic waves propagating in opposite directions along self-crossing trajectories interfere constructively. This phenomenon is called weak localization. The application of the external magnetic field breaks

*corresponding author; e-mail: dybko@ifpan.edu.pl

time reversal symmetry leading in effect to negative magnetoresistance. In systems possessing spin–orbit coupling, the quantum interference becomes destructive, giving rise to weak antilocalization, which manifests as a positive magnetoresistance at still lower magnetic fields. Spin relaxation time, $\tau_{\text{so}}$, is the main quantity characterizing weak antilocalization. The electronic spins in two-dimensional system lacking the inversion symmetry relax by the Dyakonov–Perel mechanism [3], which yields splitting of the conduction band.

In this report we show the weak antilocalization measurements performed on GaN/AlGaN heterostructures. The experimental data were fitted within the theoretical model giving the information about characteristic phase coherence time and spin relaxation time. The obtained zero-field spin splitting increases from 0.23 to 0.35 meV as the electron density increases from $2.2\times10^{12}$ cm$^{-2}$ to $5.7\times10^{12}$ cm$^{-2}$.

## 2. Experiment

The GaN/AlGaN heterostructures were grown by plasma assisted MBE on low dislocation density bulk GaN substrates (on Ga polarity side) [4]. The samples consist of a 1 $\mu$m GaN layer which is followed by 250 Å of $\text{Al}_{0.09}\text{Ga}_{0.91}\text{N}$ barrier and covered by 3 nm GaN cap layer. All layers were nominally undoped. For electrical measurements 100 $\mu$m $\times$ 600 $\mu$m Hall bar was fabricated using standard photolithographic technique and reactive ion etching. The longitudinal low field magnetoresistance was measured by Delta mode offered by Keithley 6221 current source and 2182A nanovoltmeter at temperatures ranging from 1.5 K to 5 K. The mentioned measurement method basically consists of alternating the current source polarity and calculating a moving average of three consecutive voltage readings. This simple approach enables cancellation of the thermoelectric voltage offsets and their linear drift as well, delivering much better accuracy than conventional ac lock-in technique. We have chosen two samples of considerably different electron densities ($2.2\times10^{12}$ cm$^{-2}$ and $5.7\times10^{12}$ cm$^{-2}$). The electron mobilities were 16000 cm$^2$/(V s) and 10000 cm$^2$/(V s), respectively.

## 3. Results and discussion

The experimentally obtained data are expressed as a magnetoconductivity, $\Delta\sigma(B)=\sigma(B)-\sigma(0)$, and are shown in Fig. 1. The magnetoconductivity minimum is evident for two studied samples and its position does not depend on electron density. The solid lines represent fits to the data by the use of the model developed by Iordanskii, Lyanda-Geller, and Pikus (ILP model) [5]. The ILP model considered the spin–orbit Hamiltonian of conduction electrons composed of two parts: the Dresselhaus term (proportional to the cube of the wave vector $k$) due to the bulk inversion asymmetry and the Bychkov–Rashba term (linear in wave vector $k$) due to structure inversion asymmetry i.e. with the asymmetry of the confining potential. In two-dimensional systems the Dresselhaus term gives rise to an additional, linear in $k$, contribution which is related with decreased

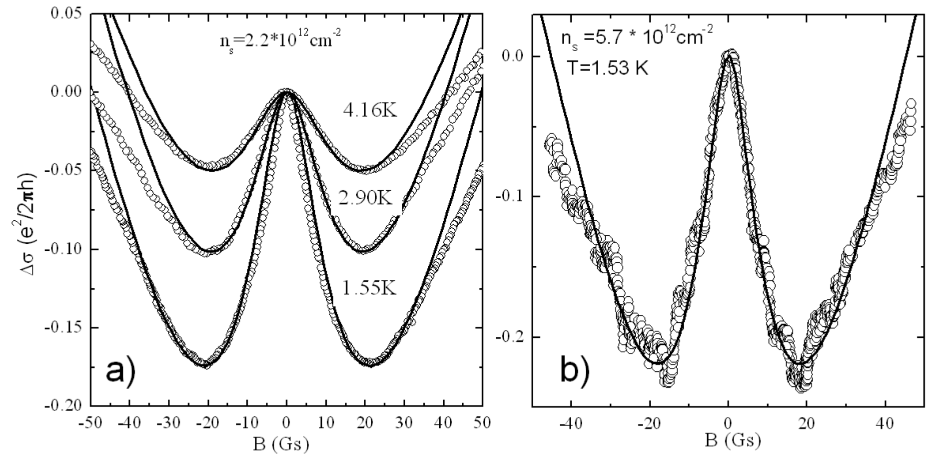


Fig. 1. Measured magnetoconductivity data (symbols) normalized to $e^2/2\pi h$ (a) sample with $n_s = 2.2 \times 10^{12}$ cm$^{-2}$; (b) sample with $n_s = 5.7 \times 10^{12}$ cm$^{-2}$. The solid lines denote fits within ILP theory (see text).

symmetry of the system. Here, in the case of GaN/AlGaN, this contribution is indistinguishable from that introduced by Rashba and Sheka [6] for bulk wurtzite type compounds. Although the ILP model provides necessary parameters to resolve all contributing to spin splitting mechanisms, it occurred that fits to our experimental data are not sensitive enough to all of them. Therefore we have used only total spin relaxation time, $\tau_{\mathrm{so}}$, and the phase coherence time $\tau_\varphi$ as fitting parameters. In this case the expression for conductivity correction reads

$$\Delta\sigma(B) = \frac{e^2}{2\pi^2 h}\left[\psi\left(\frac{1}{2}+\frac{B_\varphi + B_{\mathrm{so}}}{B}\right) + \frac{1}{2}\psi\left(\frac{1}{2}+\frac{B_\varphi + 2B_{\mathrm{so}}}{B}\right) - \frac{1}{2}\psi\left(\frac{1}{2}+\frac{B_\varphi}{B}\right) - \ln\frac{B_\varphi + B_{\mathrm{so}}}{B} - \frac{1}{2}\ln\frac{B_\varphi + 2B_{\mathrm{so}}}{B} + \frac{1}{2}\ln\frac{B_\varphi}{B}\right],$$

where $\psi$ is a digamma function, $B_i = \frac{\hbar}{4eD\tau_i}$ ($i$ denotes $\varphi$ or so), $D = \nu_{\mathrm{F}}^2\tau_{\mathrm{tr}}/2$ — diffusion constant, $\nu_{\mathrm{F}}$ — Fermi velocity, $\tau_{\mathrm{tr}}$ — momentum relaxation time.

The applicability of the model is limited to diffusive transport regime (i.e. magnetic field $B < B_{\mathrm{tr}} = \hbar/(4eD\tau_{\mathrm{tr}})$). Unfortunately, this limiting magnetic field falls in a close vicinity of the magnetoconductivity minimum for both samples. This fact forced us to involve into fitting procedure the increasing weights of the points approaching $B = 0$. The Table collects the sample parameters and fitted $\tau_\varphi$ and $\tau_{\mathrm{so}}$ obtained at 1.5 K. The total spin splitting energy is given within ILP model by: $E_{\mathrm{ss}} = 2\hbar\Omega$, where $\Omega$ denotes spin precession frequency and is expressed further by $\Omega = [1/(2\tau_{\mathrm{so}}\tau_{\mathrm{tr}})]^{1/2}$. The zero field spin splitting energy for two studied samples equals to 0.23 and 0.35 meV. These values are comparable with those obtained by other groups for GaN/AlGaN heterostructures [7–10], but also are close to spin splitting in GaAs based heterostructures, where definitely

TABLE

The sample parameters for GaN/AlGaN heterostructures at 1.5 K: $\mu$ — electron mobility, $m^*$ — effective mass, $v_{\mathrm{F}}$ — Fermi velocity, $D$ — diffusion constant, $k_{\mathrm{F}}$ — Fermi wave vector, $L_{\mathrm{tr}}$ — mean free path, $B_{\mathrm{tr}}$ — transport field defined in text, $\tau_\varphi$ — phase coherence time, $\tau_{\mathrm{so}}$ — spin relaxation time, $E_{\mathrm{ss}}$ — zero field spin splitting of the conduction band.

| $n_s$ $[10^{12}$ cm$^{-2}]$ | $\mu$ [cm$^2$/(V s)] | $m^*$ $[m_0]$ | $\tau_{\mathrm{tr}}$ [ps] | $v_{\mathrm{F}}$ $[10^5$ m/s] | $D$ [m$^2$/s] | $k_{\mathrm{F}}$ $[10^8$ 1/m] |
|---|---|---|---|---|---|---|
| 2.2 | 16000 | 0.23 | 2.1 | 1.8 | 0.035 | 3.7 |
| 5.7 | 10000 | 0.24 | 1.4 | 2.9 | 0.058 | 6.0 |
| $n_s$ $[10^{12}$ cm$^{-2}]$ | $L_{\mathrm{tr}}$ [$\mu$m] | $B_{\mathrm{tr}}$ [Gs] | $\tau_\varphi$ [ps] | $\tau_{\mathrm{so}}$ [ps] | $E_{\mathrm{ss}}$ [meV] | |
| 2.2 | 0.38 | 22.8 | 14 | 7.7 | 0.23 | |
| 5.7 | 0.40 | 20.3 | 12 | 5.5 | 0.35 | |

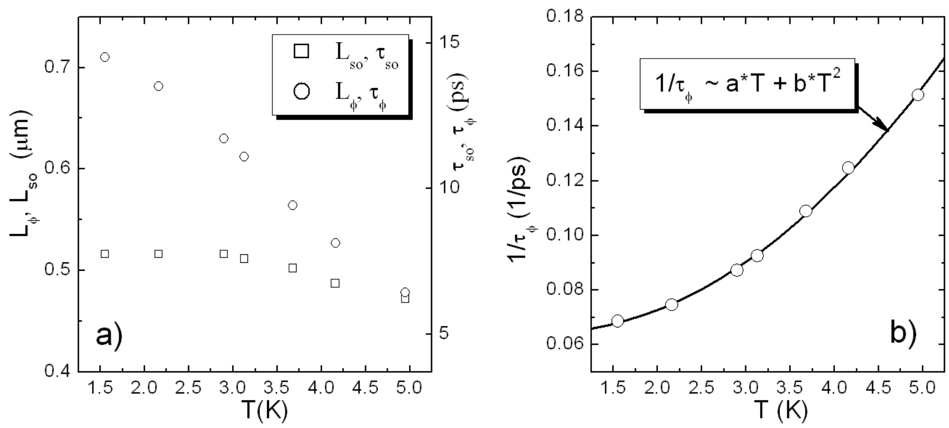


Fig. 2. (a) Phase coherence and spin relaxation lengths and times obtained for lower electron density sample ($n_s = 2.2 \times 10^{12}$ cm$^{-2}$) as a function of temperature. (b) Temperature dependence of the spin relaxation rate $(1/\tau_{\mathrm{so}})$ — circles; solid line represents theoretical fit.

both, bulk and structure inversion asymmetry are present [11]. The origin of such a large spin splitting in GaN/AlGaN could be revealed when bulk and structure inversion asymmetry contributions could be separated. It can be done by measurements of wide enough symmetrical quantum wells emulating the pure bulk behavior and then by comparison of the narrow symmetrical quantum well with triangular potential heterostructure in order to obtain the information about net Bychkov–Rashba contribution. This simple task can be completed, when proper structures will be grown.

In Fig. 2a we show the temperature dependence of the phase coherence length ($L_\varphi = (D\tau_\varphi)^{1/2}$) and spin relaxation length ($L_{\rm so} = (D\tau_{\rm so})^{1/2}$). On the right axis the respective times are rescaled. The spin relaxation time is almost independent of temperature, while phase coherence time decreases with increasing temperature. In Fig. 2b we present the fit of the phase coherence rate ($1/\tau_\varphi$) with linear and quadratic in temperature terms. Such a dependence is in accordance with theories of electron–electron scattering [12, 13], which essentially determines the phase coherence time at low temperatures.

## 4. Conclusion

In conclusion, we have studied weak antilocalization in two GaN/AlGaN heterostructures of different electron densities. The experimental data were fitted with theoretical model from which the spin relaxation time and phase coherence time were inferred. The obtained spin splitting of the conduction band in GaN/AlGaN is comparable to GaAs based heterostructures, however its origin remains unknown. The temperature dependence of the phase coherence rate confirmed the electron–electron scattering being the main phase breaking mechanism.

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