Properties of the Two-Dimensional Electron Gas Confined at a GaN/AlGaN Interface Studied by Electron Spin Resonance

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We present electron spin resonance investigations of the two-dimensional electron gas confined at a GaN/AlGaN interface. On a single spectrum we observe (i) Shubnikov-de Haas oscillations, from which we determine the sheet carrier concentration of the order of $2*10^{12}$ cm^{-2}, (ii) the coupled plasmon-cyclotron resonance, from which the free electron mobility as high as about 140 000 cm^2/Vs is determined, and (iii) a narrow resonance line with a g-factor close to 2. We assign the narrow line to the conduction electron spin resonance. The g-factor close to the free electron value, small anisotropy and a narrow linewidth of the resonance indicate that the spin-orbit fields are small in the investigated heterostructure. This is in contrast to the high value of the effective Rashba parameter reported in the literature determined from transport experiments. On the other hand our result is in agreement with the weak spin-orbit interaction expected for wide band-gap materials, such as GaN.

Introduction

GaN-based heterostructures are used in blue optoelectronics and high-frequency electronics. Now, they are also considered for spintronics, which wants to exploit not only the electron's charge, but also its spin. In order to establish GaN-based heterostructures in spintronics, the spin-orbit interactions governing, *e.g.* electron spin dynamics need to be investigated. Contradictory reports regarding these issues have appeared up to now in literature. Early papers evaluating the g-factor of free electrons in GaN give a value between 1.94 ± 0.01 in bulk crystals [1] and 2.06 ± 0.04 in heterostructures [2], indicating rather weak spin-orbit interaction, which actually is expected for GaN. On the other hand, recent weak antilocalization experiments give rather large values of the Rashba spin-orbit coupling parameter in GaN, of the order of $6*10^{-13}$ eVm [3]. For comparison, in SiGe asymmetric quantum wells, conduction electrons are also characterized by a g-factor close to 2, and the Rashba parameter is about an order of magnitude lower [4].

In order to investigate spin-orbit interaction in GaN, GaN/AlGaN heterostructures have been grown by plasma assisted molecular beam epitaxy on bulk GaN substrates. The two-dimensional (2D) electron gas formed at the GaN/AlGaN interface exhibits a record-high mobility of a several thousand cm^2/Vs and above, as determined from Hall measurements and confirmed later by spin resonance experiments. The samples are of wurtzite structure with their c-axis normal to the plane of the 2D electron gas.

The electron spin resonance (ESR) experiments have been performed using a standard Bruker ELEXSYS E-580 spectrometer operating at the X-band microwave frequency (9.48 GHz). The measurements have been performed at the temperatures between 2.4 K and 300 K, using an Oxford constant-flow cryostat.

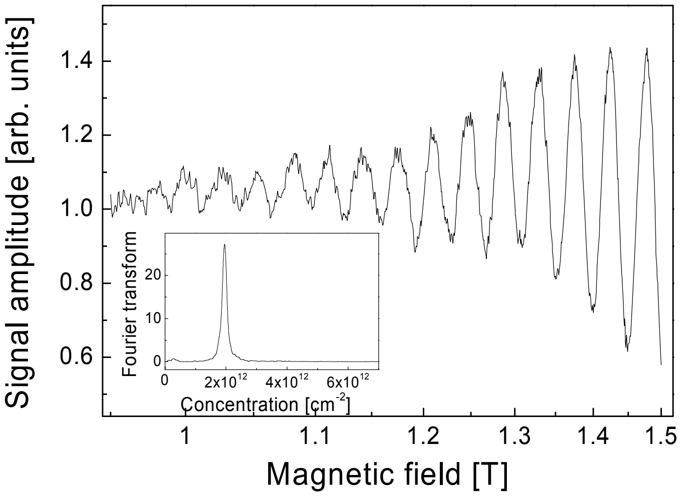

Fig. 1: Shubnikov-de Haas oscillations measured in a GaN/AlGaN sample. Inset: Fourier transform of the signal showing a dominant oscillation frequency corresponding to a sheet electron concentration of $n_{2D} = 1.95 * 10^{12}$ cm^{-2}.

Electron Spin Resonance Experiments

An essential prerequisite to observe signals from the 2D electrons in the ESR technique is a high mobility of the electron gas. This requirement is met by our GaN/AlGaN samples, thanks to the high-quality and low dislocation density of the used substrates. On single ESR spectra we observe (i) Shubnikov – de Haas oscillations, (ii) a broad and strong resonance, which can be explained as a plasma-shifted cyclotron resonance, and (iii) a narrow line with a g-factor close to 2, which we attribute to the conduction electron spin resonance.

Figure 1 shows Shubnikov – de Haas oscillations measured by this contactless resonance technique. Fourier transform of the signal indicates only one oscillation frequency, from which a sheet carrier density $n_{2D} = 1.95*10^{12}$ cm^{-2} can be calculated. The obtained concentration agrees well with the dc transport results.

As it was shown, *e.g.* for GaAs-based heterostructures, when the frequency of the electron cyclotron motion approaches plasma frequency of the two-dimensional electron gas, the two modes hybridize in a collective magnetoplasma excitation. The lower resonance frequency of a coupled plasmon-cyclotron mode is then given by:

$$\omega_{res} = -\frac{\omega_c}{2} + \sqrt{\omega_p^{\,2} + \left(\frac{\omega_c}{2}\right)^2}\,, \qquad (1)$$

where ω_c and ω_p stand for the cyclotron- and the plasma-frequency, respectively. Figure 2 shows such a combined resonance recorded for a GaN/AlGaN sample, for different angles Θ between the external magnetic field and the direction normal to the sample plane. The resonance field shows a 1/cos(Θ) dependence, typical for the cyclotron resonance of the 2D electron gas. The resonance is shifted, however, from the cyclotron frequency, according to the Eq. (1). Assuming a Lorenzian lineshape in the frequency domain, we can fit the shape of the spectrum recorded in the magnetic field domain. Results are shown in the inset (b) of Fig. 2. The fitted linewidth yields a record-high mobility of the 2D electron gas of 136 000 cm^2/Vs. It is worth to note, that the plasma frequency of the 2D electrons depends on the dimension of the sample what gives the possibility of tuning the coupled magnetoplasma mode in a wide range of frequencies (the examined sample is a few mm in diameter).

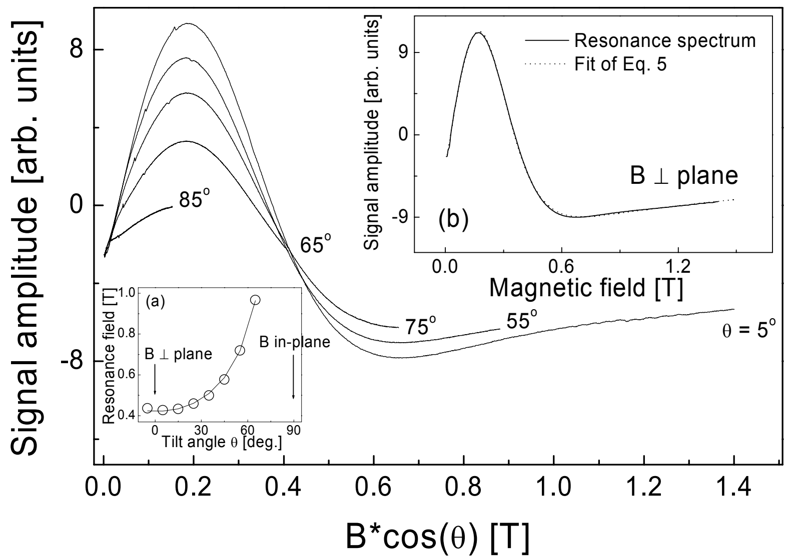

Fig. 2: Coupled plasmon-cyclotron resonance in GaN/AlGaN measured for different angles Θ between the external magnetic field and the direction normal to the sample plane. Inset (a): Open points – resonance magnetic field versus the tilt angle Θ; solid line – $1/\cos(\Theta)$ fit. Inset (b): Solid line – the spectrum; dotted line – theoretical fit.

Figure 3 shows the recorded narrow resonance line with $g_{||} = 2.00175$ (B || c) and $g_{\perp} = 2.00196$ (B $\perp$ c) at T = 2.4 K. The anisotropy of the g-factor slightly changes with the temperature from negative $g_{||} < g_{\perp}$ at very low temperatures to positive $g_{||} > g_{\perp}$ at the room temperature. The linewidth of this resonance is extraordinarily narrow, below 1 G, which is characteristic for the motional narrowing of the conduction electrons. The integrated amplitude of the line is practically temperature-independent, indicating Pauli-type of paramagnetism, which is also characteristic for free carriers. Thus, we attribute this line to the conduction electron spin resonance.

As it was shown, *e.g.* in Ref. [4], the conduction electron g-factor and the resonance linewidth are affected by the presence of the internal spin-orbit fields which add to the magnetic field externally applied in the experiment. These spin-orbit fields (called Rashba or Dresselhaus fields) originate from bulk- and/or structure-induced asymmetry of the investigated quantum well. A detailed quantitative analysis of the narrow resonance recorded for GaN/AlGaN is under progress. However, even now we can draw the conclusion that the spin-orbit interaction in the investigated heterostructure is very small. This is due to the fact, that the observed g-factor is very close to the free electron value, and the observed g-factor anisotropy and the resonance linewidth are small. Thus a value of the Rashba spin-orbit parameter similar to that obtained for SiGe quantum wells may be expected. In the contrary to SiGe heterostructures the negative anisotropy of the g-factor observed for GaN/AlGaN suggest also significant contribution of the cubic Dresselhaus term in the spin-orbit Hamiltonian, that should result in a Dresselhaus field perpendicular to the plane of the 2D electron gas.

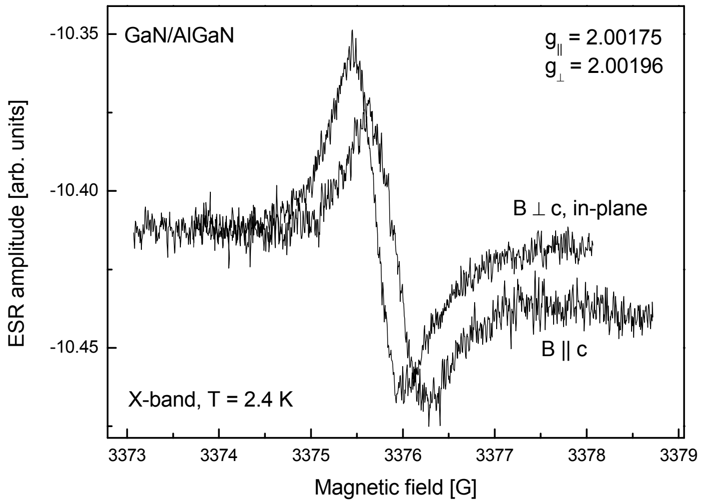

Fig. 3: Conduction electron spin resonance in GaN/AlGaN heterostructure.

Conclusion

We have investigated the properties of the high-mobility two-dimensional electron gas confined at the GaN/AlGaN interface by ESR techniques. For the first time a coupled plasmon-cyclotron excitation in GaN has been observed. As the frequency of this excitation depends on the dimension of the sample, one can predict that in micrometer-size structures the magnetoplasma frequency will fall into the THz range, making this phenomenon interesting for the field of generation or detection of THz radiation.

For the first time, the g-factor of the 2D conduction electrons in GaN has been measured with high precision in a direct experiment. The qualitative analysis of the resonance reveals weak spin-orbit interaction, in contrast to recently reported results of weak antilocalization experiments [3]. However, a weak spin-orbit coupling has been expected for GaN, and it is highly appreciated in spintronic materials as it leads to long spin lifetimes.

References

[1] B. Beschoten, E. Johnston-Halperin, D. K. Young, M. Poggio, J. E. Grimaldi, S. Keller, S. P. DenBaars, U. K. Mishra, E. L. Hu, D. D. Awschalom: “Spin coherence and dephasing in GaN”, Phys. Rev. B **63**, 121202-1/4 (2001).

[2] W. Knap, E. Frayssinet, M. L. Sadowski, C. Skierbiszewski, D. Maude, V. Falko, M. Asif Khan, M. S. Shur: “Effective g^* factor of two-dimensional electrons in GaN/AlGaN heterojunctions”, Appl. Phys. Lett. **75**, 3156-3158 (1999).

[3] S. Schmult, M. J. Manfra, A. Punnoose, A. M. Sergent, K. W. Baldwin, R. J. Molnar:”Large Bychkov-Rashba spin-orbit coupling in high-mobillity GaN/$Al_xGa_{1-x}N$ heterostructures”, Phys. Rev. B **74**, 033302-1/4 (2006).

[4] H. Malissa, W. Jantsch, M. Mühlberger, F. Schäffler, Z. Wilamowski, M. Draxler, P. Bauer: “Anisotropy of g-factor and electron spin resonance linewidth in modulation doped SiGe quantum wells” Appl. Phys. Lett. **85**, 1739-1741 (2004).