Plasmon-Cyclotron Coupling in a High-Mobility Two-Dimensional Electron Gas in GaN/AlGaN Heterostructures

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We report on the observation and theoretical modeling of sample-size dependent plasma oscillations coupled to the cyclotron motion [1] in a high-mobility two-dimensional electron gas (2DEG) confined at the GaN/AlGaN interface. We record plasmon-cyclotron features using standard microwave resonance spectrometry (electron spin resonance, ESR), which provides a convenient, contact-less method to characterize transport properties of the 2DEG.

Introduction

In this communication we report on the observation of sample-size dependent plasma oscillations coupled to the cyclotron motion in a high-mobility two-dimensional electron gas, 2DEG, confined at the GaN/AlGaN interface. We record plasmon-cyclotron features using standard microwave resonance spectrometry, which provides a convenient, contact-less method to characterize transport properties of the 2DEG.

Experimental

The heterostructures used in these studies were grown on semi-insulating GaN bulk substrates, on the Ga-polarity (0001) surface, by plasma-assisted molecular beam epitaxy (MBE). The surface of the substrates was prepared for the growth by the standard method including mechanical polishing followed by mechano-chemical polishing. The MBE-grown heterostructure consisted of a 0.9 µm GaN layer followed by the 25 nm-thick $Al_{0.09}Ga_{0.91}N$ barrier, and a 3 nm-thick GaN cap layer.

It has been observed, *e.g.* for GaAs-based 2D heterostructures, that the cyclotron motion of an electron and the plasma oscillations hybridize, when the frequency of the two modes approach each other. The two resonance frequencies for plasmon-cyclotron coupling are then given by: [1]

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

where ω_c stands for the cyclotron frequency and ω_p is plasma frequency, which scales with plasmon wave vector, and thus with the sample size. For a disc-shaped sample with a radius *R* this dependence is given by:

$$\omega_p^2 = \frac{n_{2D} e^2}{m^* \left(1 + \varepsilon_{GaN}\right) \varepsilon_0 R} \quad . \tag{2}$$

Here, n_{2D} is the sheet electron concentration, $m^* = 0.2\ m_0$ the electron effective mass, ε_0 vacuum permittivity, and $\varepsilon_{GaN} = 10.4$ is a static dielectric constant of GaN.

To describe the line shape of the coupled resonance recorded by ESR in our GaN/AlGaN heterostructures, we assumed a Lorentzian shape for the absorption of circular polarized electromagnetic waves in the frequency domain, with two resonance frequencies given by Eq. (1):

$$F^{\pm}(\omega, B) = \frac{2A}{\pi} \frac{\Delta}{\Delta^2 + 4\left(\omega - \omega_{res}^{\pm}(B)\right)^2} , \tag{3}$$

for σ^+ and σ^- polarization, respectively. The final expression for the line shape has a following form, which takes into account the linear polarization of the absorbed microwaves, and the fact that we measure the first derivative of the absorption *vs*. magnetic field due to the use of modulation of $\mathbf{B_0}$ and lock-in detection:

$$f(\omega, B) = \frac{1}{2} \frac{\partial}{\partial B} \left(F^+(\omega, B) + F^-(\omega, B) \right). \tag{4}$$

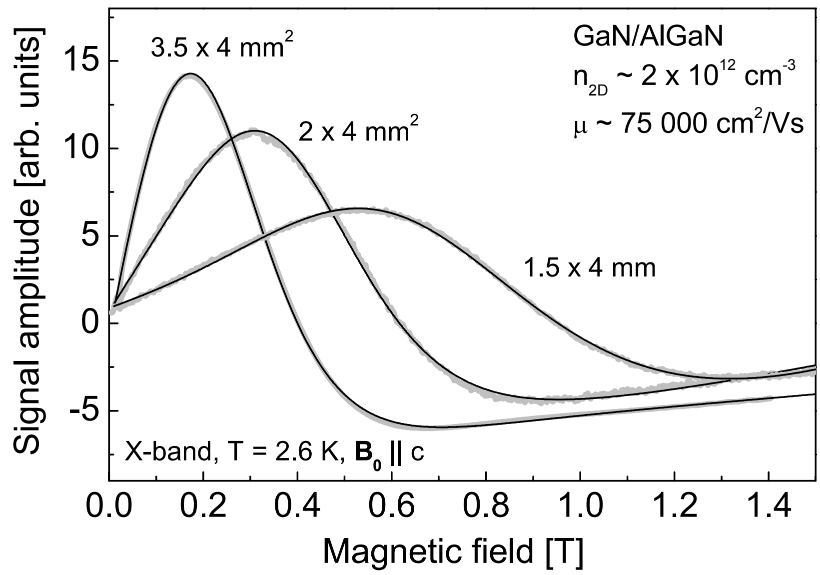

Fig. 1: Plasma-cyclotron resonance in GaN/AlGaN with different sample dimensions: 3.5 x 4 mm^2, 2 x 4 mm^2, and 1.5 x 4 mm^2 respectively ($n_{2D} = 1.95 \times 10^{12}$ cm^{-2} and μ_{tr} = 70 000 – 80 000 cm^2/Vs for each sample). Grey lines are experimental spectra. The black lines represent least squares fits of Eq. (4).

Results

With help of Eq. (4) we can reproduce the characteristic asymmetric line shape of the recorded resonance. Figure 1 shows the ESR spectra for three GaN/AlGaN samples having the same sheet electron concentration and mobility, but different sample dimensions. Together with recorded spectra, fits using Eq. (4) are shown. Best fit parameters, plasma frequency (dependant on both sheet electron concentration and a sample dimension, Eq. (2)), and a line width Δ (which can be translated to the mobility using Drude relation) are listed below:

Sample size [mm^2]	$\omega_p/2\pi$ [GHz] ± 2	$\Delta/2\pi$ [GHz] ± 1	μ_t [cm^2/Vs] ± 5000
3.5 x 4	26	18.4	76 000
2.0 x 4	32	16.8	83 000
1.5 x 4	41	18.3	77 000

Conclusion

The observation of a coupled plasmon-cyclotron resonance by the ESR technique provides a contact-less method to characterize electronic properties of the 2D electron gas. Both the sheet electron concentration and the mobility may be determined with high precision from the resonance position and the line shape of coupled magneto-plasma modes, for which we have derived a simple formula basing on the theory for dimensional resonances.

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References

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