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Two-dimensional plasma excitations in a random array of quantum antidots

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Plasmon excitations in two-dimensional electron systems in an AlGaAs/GaAs heterojunction containing a layer of self-organizing antidots at the heterointerface are experimentally studied. In a magnetic field, in the terahertz absorption spectra obtained by Fourier spectroscopy, along with the cyclotron resonance, a magnetoplasmon mode is observed. With an increase in the magnetic field, an extreme decrease in the width of the magnetoplasmon line occurs, which can be explained by the localization of plasmons by the magnetic field in a random array of antidots.

Keywords: plasmon, two-dimensional electron system, array of antidots, heterojunction, cyclotron resonance.

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1. Introduction

Plasma oscillations in two-dimensional electronic systems have been studied for a long time [1]. To excite plasmons with a frequency ω_p, the condition $\omega_p\tau \gg 1$ is required, where τ is the electron relaxation time. Therefore, experiments on the study of plasmons, as a rule, are carried out at cryogenic temperatures in the terahertz frequency range. In addition, the complexity of such studies is associated with the fact that plasma waves do not interact with light in free space due to the large mismatch of their pulses. There are various approaches for pulse matching based on light diffraction, for example, low-dimensional structures (stripes and disks) are formed [2,3], light scattering on diffraction gratings and on various kinds of inhomogeneities is used [4]. Alternatively, efficient coupling of light to plasma oscillations can be achieved in periodically modulated structures such as the array of antidots [5]. In this work, the excitation of two-dimensional plasmons in a disordered array of quantum antidots is studied. Due to the absence of periodicity, broad plasma modes are excited in such a grating. The impressing of magnetic field leads to the formation of a very narrow magnetoplasma mode, which can be explained by the localization of plasmons by the magnetic field.

2. Samples and experimental procedure

The samples used in the experiment consist of an inverted single AlGaAs/GaAs heterojunction with an array of self-organized AlInAs quantum islands formed in the junction plane on the AlGaAs surface. The data obtained by scanning tunneling microscopy and atomic force one show that the islands have a round shape with a diameter of 6 to 12 nm and „height“ in the growth direction ~ 1 nm. Their concentration is about $10^{11}\,\mathrm{cm}^{-2}$, thus, the average distance between them is ~ 10 nm. Due to the higher conduction band minimum energy and band gap of AlInAs compared to GaAs, AlInAs islands are electron-free regions and therefore have antidot characteristics, providing a short-range repulsive potential for electrons in GaAs. Below are the results of the study of sample with electron concentration of $n_s = 0.52 \cdot 10^{11}\,\mathrm{cm}^{-2}$, in which the change in the electron concentration was carried out using an upper metal gate.

Two-dimensional plasma excitations in a two-dimensional electron gas (2DEG) of a heterojunction were studied by the terahertz absorption method at a temperature $T = 2\,\mathrm{K}$ using a Fourier spectrometer in magnetic fields up to 12 T impressed perpendicular to the sample. All spectra were normalized to the spectrum in the absence of magnetic field in order to eliminate the influence of the substrate on the measurements. The carrier concentration 2DEG at various gate voltages was estimated from the Shubnikov–De Haas oscillations.

3. Results and discussion

Typical form of terahertz absorption lines is shown in Fig. 1 for the sample with carrier concentration $n_s = 0.52 \cdot 10^{11}\,\mathrm{cm}^{-2}$. The absorption spectra were obtained at fixed magnetic fields. It can be seen that the linewidth decreases strongly with increasing magnetic field and becomes very narrow at high magnetic fields. The measured spectra were analyzed by estimating the full width at half maximum (FWHM), which is plotted as a function of magnetic field in the insert to Fig. 1. The value of FWHM is equal to $1\,\mathrm{cm}^{-1}$ at magnetic fields ~ 4 T and then gradually decreases to $0.4\,\mathrm{cm}^{-1}$ for stronger fields. Such small linewidth is unexpected for that sort of disordered system. In weak magnetic fields, the transport mobility, determined from the measurements of Shubnikov–De Haas, $\mu_T = 9.3 \cdot 10^4\,\mathrm{cm}^2/(\mathrm{V{\cdot}c})$ is consistent with the expected

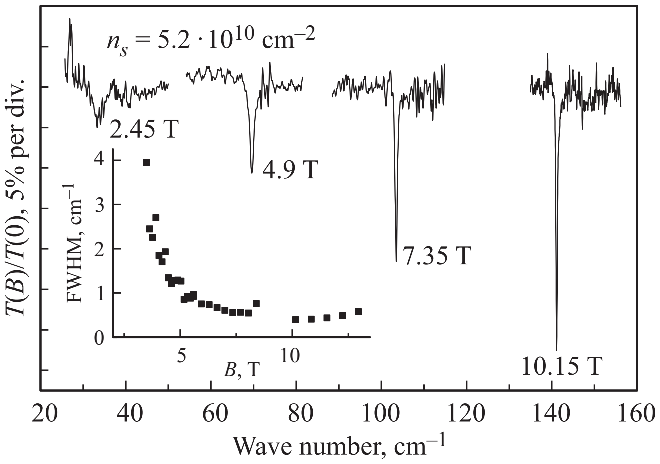

Figure 1. Absorption spectra at fixed magnetic fields and linewidth depending on magnetic field B.

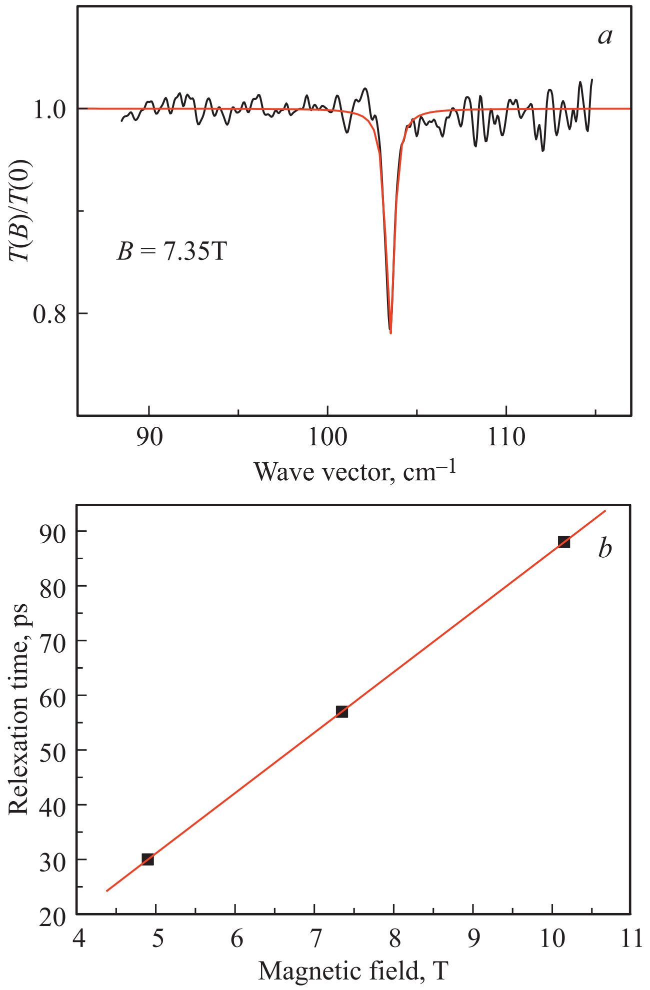

Figure 2. a — adjusting the terahertz absorption line in magnetic field of 7.35 T according to the formula for the damped oscillator model; b is dependence of the plasmon relaxation time on the magnetic strength.

low transport mobility due to scattering by InAlAs anti-dots. The very narrow absorption line suggests that electron scattering decreases sharply as the magnetic field increases.

The measured absorption lines are in good agreement with the calculations using the formula for the damped oscillator model [6]:

$$A \propto \frac{\gamma}{\gamma^2 + (\omega - \omega_+^2/\omega)^2},$$

where A is the absorption coefficient, ω_+ is the plasmon frequency, and $\gamma = 1/\tau$ is the plasmon relaxation rate. Example of such an adjusting is shown in Fig. 2, a. From the calculated curves, the plasmon relaxation time τ is obtained, which depends linearly on the magnetic field strength, as can be seen from Fig. 2, b, and can reach hundreds of picoseconds.

The classical ballistic motion of 2D electrons interacting with a disordered grating of antidots in a magnetic field was calculated in [7]. In addition to the usual percolation phase transition associated with geometric dimensions, a magnetic percolation threshold was found that separates unbounded motion for a large cyclotron radius R and complete localization of electrons for small R. This is due to the existence of localized trajectories in the two-dimensional electron system. The first type of trajectories are circular trajectories, on which no collisions are present. Another type are rosette-like trajectories resulting from the return of a free trajectory in a magnetic field to its starting point on the anti-dot. In the sufficiently weak magnetic field, most of the trajectories intersect with many anti-dots, so localized trajectories are rare. The average probability that an electron does not collide with anti-dots is determined by the cyclotron radius of the electrons R on the Fermi surface. This fraction of localized trajectories increases with increasing magnetic field. Among the scattering trajectories there are both localized trajectories and delocalized ones. If the magnetic field is strong enough, the delocalized trajectories disappear because the cyclotron diameter becomes smaller than the distance between the anti-dot surfaces. Similar reasoning is applicable to plasmons if we consider collective excitations instead of the single electron. Plasmon can be associated with the wave propagating inside region bounded by anti-dots. The collective motion of electrons becomes localized in sufficiently strong magnetic fields. The formation of localized plasmons is accompanied by decrease in the width of the absorption line. Moreover, the extremely narrow spectral width of the plasma mode indicates the collective effect. When a diffracted wave, originating upon the scattering of light on anti-dots, propagates in the plane of the array, it can couple together localized plasmon resonances associated with individual anti-dots, resulting in a sharp narrowing of the plasmon resonances.

4. Conclusion

Thus, the work presents the results of experimental study of the narrowing of the terahertz absorption line in the disordered array of anti-dots in strong magnetic fields, which is explained by the localization of plasmons by magnetic field.

Acknowledgments

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Conflict of interest

The author declares that he has no conflict of interest.

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