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

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Abstract. Terahertz absorption in two-dimensional electron systems in an AlGaAs/GaAs heterojunction containing a layer of self-organizing antidots is experimentally studied. A magnetoplasmon mode is observed in a magnetic field. When the electron density at the heterojunction is less than the density of the disorder potential minima induced by the antidots we found the drastic narrowing of the absorption line with magnetic field. We interpret this effect by magnetic field induced localization. The localized plasmon resonances are coupled by the Coulomb electron-electron interactions leading to collective magnetoplasmon excitations.

Keywords: heterojunction, magnetoplasmon, antidots, terahertz absorption

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Двумерные плазменные возбуждения в неупорядоченном массиве квантовых антиточек

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Аннотация. Экспериментально изучаются плазменные возбуждения в двумерных электронных системах в гетеропереходе AlGaAs/GaAs, содержащем слой самоорганизующихся антиточек. В магнитном поле в спектрах терагерцового поглощения, наблюдается плазмонная линия, ширина которой сильно уменьшается с ростом магнитного поля, что можно объяснить локализацией плазмонов магнитным полем и возникновением коллективной магнитоплазменной моды.

Ключевые слова: гетеропереход, магнитоплазмон, антиточки, терагерцовое поглощение

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Introduction

Plasma oscillations in two-dimensional electron gas (2DEG) 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 with plasmons, as a rule, are carried out

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at cryogenic temperatures in the terahertz frequency range. In addition, the complexity of such studies is due to the fact that plasma waves do not interact with light in free space due to the large mismatch of their wave vectors. There are various approaches to overcome these limitations based on light diffraction. For example, low-dimensional structures (stripes and disks) [2, 3], light scattering on diffraction gratings and on various types of inhomogeneities are used [4]. Alternatively, efficient coupling of light to plasma oscillations can be achieved in periodically modulated structures such as an array of antidots [5].

In this paper, we study the excitation of two-dimensional plasmons in a random array of quantum antidots. Due to the absence of periodicity, broad plasma modes are excited in such a grating. Remarkably, the application of a strong enough magnetic field leads to the formation of a very narrow magnetoplasmon mode, which can be explained by the localization of plasmons by the magnetic field and the excitation of the collective plasma mode. It is generally accepted that strongly correlated states both in the liquid and in the solid phases form only in pure systems without disorder. Here we present results on terahertz transmission demonstrating the appearance of a strongly correlated phase in a disordered 2DEG. We study a system where the disorder potential is induced by a random array of self-organized islands embedded at the plane of 2DEG. An in-plane electron-density modulation provides coupling to the wave vectors, q ~ l/lo, (lo is the magnetic length) that allows excitation of the 2DEG. When the electron density is less than the density of the disorder minima we observed that the Coulomb electron-electron interactions are dominant and govern the in-plane distribution of electrons. This observation allows us to suppose a formation of a strongly correlated state in a disordered 2DEG that couples the localized plasmon resonances together.

Materials and Methods

Plasma excitations in a 2DEG of a heterojunction were studied by the terahertz transmission method at a temperature T = 2 K using a Fourier spectrometer in magnetic fields up to 12 T applied perpendicular to the sample. All spectra were normalized to the spectrum in the absence of a magnetic field in order to exclude the influence of the background on the measurements.

The samples used in the experiment (Fig. 1, left) consist of an inverted single AlGaAs/GaAs heterojunction with an array of self-organized AlInAs quantum islands formed in the heterojunction interface. The data obtained by scanning tunneling and atomic force microscopy show that the islands are round in shape with a diameter of 6 to 12 nm and a “height” in the growth direction of ~ 1 nm. Their concentration is about 10^{11} cm^{-2}, so the average distance between them is ~10 nm [6]. 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 we present the results for a sample with an electron concentration of $n_s = 5.2\times10^{10}$ cm^{-2}, in which the change in the electron concentration was carried out using a metal gate.

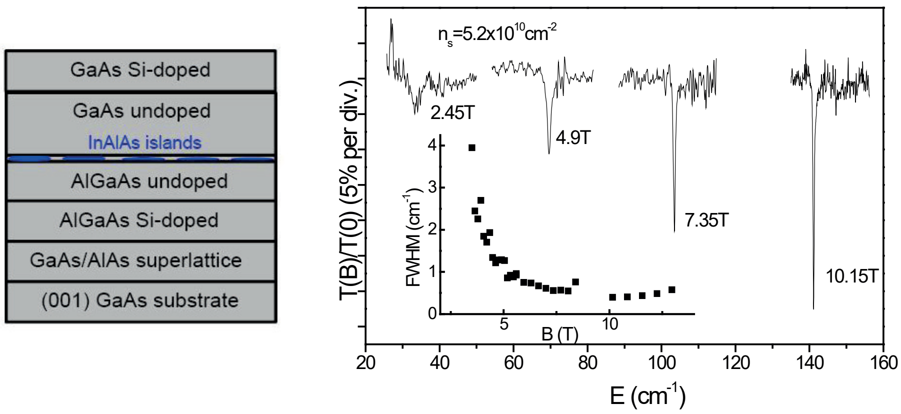

Fig. 1. A scheme of the structure with self-organized islands (left) and CR absorption spectra at fixed magnetic fields and the CR linewidth as a function of magnetic field (inset) at $n_s = 5.2\times10^{10}$ cm^{-2}

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Results and Discussion

A representative set of cyclotron resonance (CR) traces is shown in Fig. 1 (right) for a sample with a carrier density, n_s of 5.2×10^{10} cm^{-2}. The CR spectra were obtained at fixed magnetic fields. It is evident that the linewidth changes with magnetic field and becomes very narrow at high magnetic fields. The measured spectra were analyzed by evaluating the full width at half maximum (FWHM) which is plotted as a function of the magnetic field in the inset of Fig. 1. It is clearly seen that the CR line width considerably decreases with increasing magnetic field. The FWHM becomes as small as 1 cm^{-1} at magnetic fields around 4 T and further smoothly decreases down to 0.4 cm^{-1} for higher fields. Such a small linewidth is comparable to that reported for the highest-quality GaAs/AlGaAs heterostructures [7] and is surprising for such a disordered system. The very narrow CR line suggests that electron scattering is dramatically reduced by an increasing magnetic field. At low magnetic fields, the transport mobility has been determined from Shubnikov-de Haas (SdH) measurements (not shown) as $\mu_T = 9.3\times10^4$ cm^2/Vs, for a sample with $n_s = 8.5\times10^{10}$ cm^{-2}. The low transport mobility is expected because of the scattering by the inserted InAlAs islands. The absence of the spin splitting of the SdH oscillations [6] also indicates the presence of strong Landau level broadening due to disorder at low magnetic fields [8].

The absorption peak displays a shift towards higher energies when the electron density is increased as shown in Fig. 2, *a*. There we plotted the dependence of the peak position as a function of the electron density at B = 12.6 T. The position of the mode E is described by the expression

$$E = \omega_c / 2 + (\omega_c^2 / 4 + \omega_0^2)^{1/2} \tag{1}$$

where ω_c is the cyclotron frequency and ω_0 is the characteristic frequency of the confining random potential approximated by a parabola. The clear correlation between the confinement potential and the electron density (Fig. 2, *b*) supports the proposal that the cyclotron resonance in disordered systems is not only influenced by the confining potential of the disorder (in our case antidots) but also by electron-electron interaction. A possible explanation of the observed cyclotron resonance features is based on the picture in which resonant frequencies of electrons occupying different minima of the random potential are coupled via Coulomb interaction into a single collective mode. The coupling leads to the suppression of inhomogeneous broadening of the cyclotron line. The increase of the coupling frequency ω_0 with the electron density originates mainly from the electron-electron interaction.

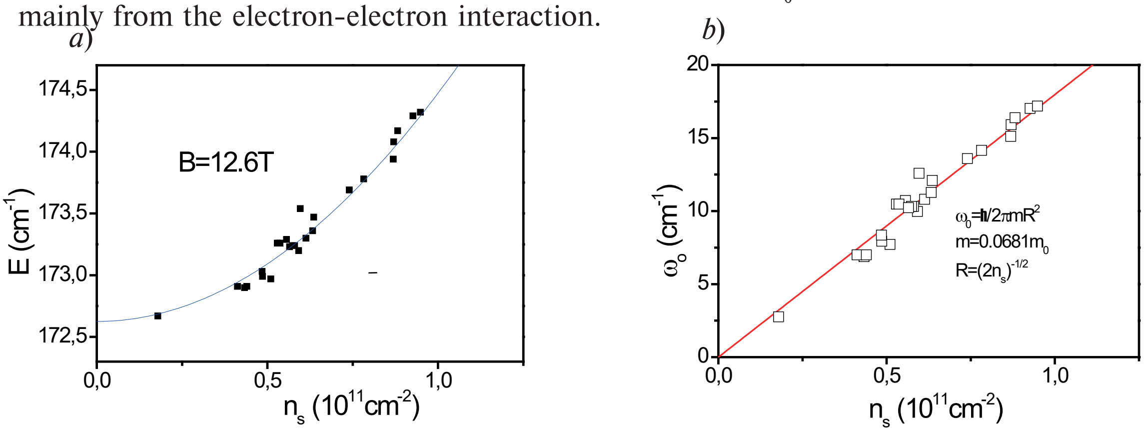

Fig. 2. Dependences of the peak position E (*a*) and the frequency of the confining random potential ω_0 (*b*) vs the electron density at B = 12.6 T

The presence of the antidots results in variation of the electron ground states due to the fluctuation of the effective width of the confining potential well. The amplitude of the bare random potential, created by the antidots, can be (very roughly) estimated as 1.5 meV, which is still far more than kT = 0.0172 meV (2 K). However, a 2D potential minimum of such an energy and lateral size of the order of 10 nm cannot effectively hold an electron. So, without a magnetic field the antidots act as an additional interface roughness. The situation changes drastically, when we apply a strong magnetic field and the magnetic length becomes comparable to the effective distance between the antidots. In this case each electron is confined in lateral directions by the magnetic field and the energy of the electron depends on the lateral position of the wave function center with respect to lateral positions of antidots. At these conditions it becomes "profitable" for the electrons to occupy the potential minima between the antidots. Electrons are shrunk into a size of $l_0 = (\hbar c/eH)^{1/2}$. Because the islands are neutral, the system can be considered as an insulator plate containing random neutral traps separated by a mean distance $N^{-1/2}$. N is the total number of the traps. The traps have different ionization energies. Also the distances between the traps are unequal. The electron density n_s is less than N and only some of the traps are occupied by electrons. The electrons occupy the traps such in a way as to minimize the energy of their mutual repulsion and to maximize their separation. The mean distance between occupied traps is $R \sim n_s^{-1/2}$. Since the traps are randomly distributed, the lattice created by the electrons is quasi-periodic. The lattice period R fluctuates with a characteristic scale of $N^{-1/2}$.

It is important to stress that the excitation correlated with the electron density could be observed in CR only for a lateral electron system with non-parabolic or random lateral potential. Indeed, in a periodic lateral array of parabolic quantum dots with interacting electrons, the collective excitation frequencies at zero in-plane wave vector are independent of the Coulomb interaction and the electron number according to the generalized Kohn's theorem [9–11]. In a random array of antidots, the electrons can be confined in randomly distributed lateral potential wells. In this case the frequencies may depend on the Coulomb interaction and the electron number because the center-of-motion coordinates are no longer separated from the internal motion coordinates.

We also note that to study collective excitations of 2DEG in the quantum Hall states requires overcoming experimental difficulties. To excite collective states by a light wave, it is necessary to introduce a certain period modulation into the system to provide excitation of the wave vector $\boldsymbol{q}$. Electron-electron interactions in the quantum Hall states require a transfer of large wave vectors, $\boldsymbol{q} \sim 1/l_0$, where l_0 is the magnetic length. Conventional grating diffraction does not provide such $\boldsymbol{q}$. We overcome these restrictions and successfully excite the required wave vectors in 2DES with density modulation induced by the random potential of antidots with average distance between them close to the magnetic length (~ 10 nm).

Conclusion

In conclusion, CR experiments were performed on GaAs/AlGaAs heterostructures containing self-organized antidots. An extremely sharp resonance line is observed in strong magnetic field with an energy position shifted to higher energies with electron density. Our results indicate the existence of a strongly correlated magnetoplasmon excitation present in disordered two-dimensional systems in the extreme quantum limit when the electron density is less than the density of the antidots and the magnetic length is less than the mean distance between the antidots. The effect of electron-electron interactions becomes visible in CR measurements due to the non-applicability of Kohn's theorem in the presence of an artificial scattering potential. The strongly correlated state in a random array of self-organized quantum antidots in the presence of an applied magnetic field may be one of the routes to experimental realization of magnetoplasmon qubits.

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