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Observation of Plasma Waves with Anomalously Weak Damping in a Two-Dimensional Electron System

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The microwave absorption spectra of a stripe of two-dimensional electrons in a GaAs/AlGaAs heterostructure are investigated using the optical detection of microwave absorption. A previously unknown low-frequency microwave-absorption resonance corresponding to the excitation of a weakly damped plasma wave in the two-dimensional electron system is observed. The new plasma mode is anomalously narrow, its width being considerably smaller than the inverse relaxation time of two-dimensional electrons. The measured dependences of the frequency of this mode on the density of two-dimensional electrons and the magnetic field give evidence of its plasmon-polariton nature.

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The occurrence of plasma excitations in two-dimensional electron systems (2DES) was predicted theoretically in 1967 [1]. For the first time, they were observed in a system of electrons on the surface of liquid helium [2]. Subsequently came the observation of plasmons in solid-state structures, namely, in silicon MOS transistors [3]. Two-dimensional plasma excitations obey the dispersion relation [1]

$$\omega_p^2 = \frac{n_s e^2}{2m^* \varepsilon_0 \varepsilon(q)} q. \qquad (1)$$

Here, n_s and m^* are the density and effective mass of electrons in the two-dimensional system, respectively; $\varepsilon(q)$ is the effective dielectric constant characterizing the environment of the 2DES; and q is the plasmon wave vector, which is determined by the geometrical parameters of the structure. In particular, in the presence of a nearby metallic gate, the dispersion relation given by Eq. (1) becomes linear [4, 5]:

$$\omega_p^2 = \frac{n_s e^2 d}{m^* \varepsilon_0 \varepsilon} q^2. \qquad (2)$$

According to Eqs. (1) and (2), the velocity of plasma waves can be tuned in a broad range by varying the density of electrons in the 2DES. This makes two-dimensional plasmons a convenient and flexible object for basic studies and applications in the field of subterahertz plasmonics [6–8]. Two-dimensional plasma excitations can be observed if $\omega_p \tau \gg 1$, where τ is the relaxation time of two-dimensional electrons [9]. As a result, the observation of plasma waves in high-quality modern-day nanostructures is possible only at cryogenic temperatures. This fact hinders considerably the development of subterahertz applications of plasmon electronics.

Here, we report the observation of a high-quality-factor resonance in the microwave absorption spectrum of a 2DES stripe. The strong dependence of the resonance frequency on the density of two-dimensional electrons and the applied magnetic field gives unambiguous evidence of the plasmonic nature of the resonance. Remarkably, the frequency width $\Delta\omega$ of this plasma mode is much smaller than the inverse relaxation time of two-dimensional electrons $1/\tau$. The widths of conventional plasma modes observed in the same structure are an order of magnitude larger.

The measurements were carried out on a GaAs/Al$_x$Ga$_{1-x}$As heterostructure with a 20-nm-wide single quantum well located at a depth of 200 nm. The electron mobility in this structure was $\mu = 8 \times 10^6$ cm^2/(V s), and the electron density n_s was varied from 0.5×10^{11} to 1.9×10^{11} cm^{-2} using optical depletion [10]. A mesa shaped as a stripe of width $W = 100$ μm and length $L = 1$ mm was formed on the sample surface by photolithography (see Fig. 1, inset). Ohmic contacts C were made at both ends of the stripe. On the top of the mesa, two 30-μm-wide gates, which served for the excitation of plasmons, were deposited across the stripe at a distance of 10 μm from the contacts. The resonance excitation of plasma waves was studied using the method of optical detection of microwave absorption, in which the luminescence spectra of the 2DES subjected to microwave excitation and without such excitation were compared. A stabilized semiconductor laser with a power of about 100 μW emitting at 750 nm was used for photoexcitation. The photoluminescence signal was recorded using a CCD detector attached to a double spectrometer with a spectral resolution of 0.03 meV. An HP-83650B signal generator was used as a source of microwave radiation in the frequency range from 0.01 to 30 GHz. The output power of the generator was between 1 and 10 μW. The microwave signal was delivered into a helium cryostat by a coaxial cable and fed into the structure under study via a matched coplanar waveguide. The central conductor of the waveguide was connected to one of the metal gates G, and the grounded conductor was connected to the ohmic contact C at the end of the stripe. The intensity of the microwave absorption was characterized by the integral of the absolute value of the difference between the luminescence spectra in the relevant wavelength range recorded with and without microwave excitation. The sample was placed within a superconducting solenoid creating an external magnetic field up to 9 T oriented perpendicularly to the sample plane. All measurements were performed at a temperature of 1.5 K.

Figure 1 shows a typical microwave absorption spectrum of the 2DES stripe under study. The spectrum was recorded in zero magnetic field for the electron density $n_s = 1.9 \times 10^{11}$ cm^{-2}. The spectral curve features three peaks. Two of them (marked by arrows), with frequencies $f = 13$ and 23.5 GHz, correspond to the excitation of the longitudinal plasma mode along the length of the stripe [11]. Indeed, in a stripe of two-dimensional electrons whose length L exceeds considerably the width W, longitudinal plasma modes are the lowest frequency ones, and in the limiting case $qW \ll 1$, their spectrum is given by the formula [12]

$$\omega_{1\mathrm{D}}^2 = \frac{n_s W e^2}{2\pi m^* \varepsilon_0 \varepsilon} q^2 \left(\ln \frac{8}{qW} - 0.577 \right), \tag{3}$$

where $q = N\pi/L$ ($N = 1, 2, \ldots$) is the wave vector. Longitudinal plasma excitations with $qW \ll 1$ are called one-dimensional plasmons. For the 2DES stripe under study, the two lowest frequencies of one-dimensional plasma waves calculated according to Eq. (3) are in good agreement with the experimental results.

The third peak, observed at a frequency f = 0.8 GHz, is quite unexpected. First, its frequency is much lower than that of any plasma excitation possible in the 2DES geometry under study. Indeed, as we discussed above, all longitudinal plasma waves in this 2DES stripe appear at frequencies exceeding 10 GHz. We can also consider the screened two-dimensional plasmon localized in the gate region. According to Eq. (2), the frequency of the screened plasmon with $q = \pi/W$ is $f = 5.9$ GHz. The spectrum does feature a weak resonance around this frequency (dashed arrow in Fig. 1). Second, the observed resonance has a considerably smaller frequency width ($2\Delta f$ = 0.4 GHz) than the resonance corresponding to the one-dimensional plasmon ($2\Delta f$ = 3 GHz). Since the frequency width of a plasma excitation is determined by the relationship $\Delta f = 1/\tau$, the parameters of the new resonance correspond to a record-high value of the mobility of two-dimensional electrons in the structure under study $\mu = 30 \times 10^6$ cm^{-2}/V s. Currently, there is no theoretical description of the observed resonance. However, we believe that such weak damping of this mode is explained by its plasmon-polariton nature.

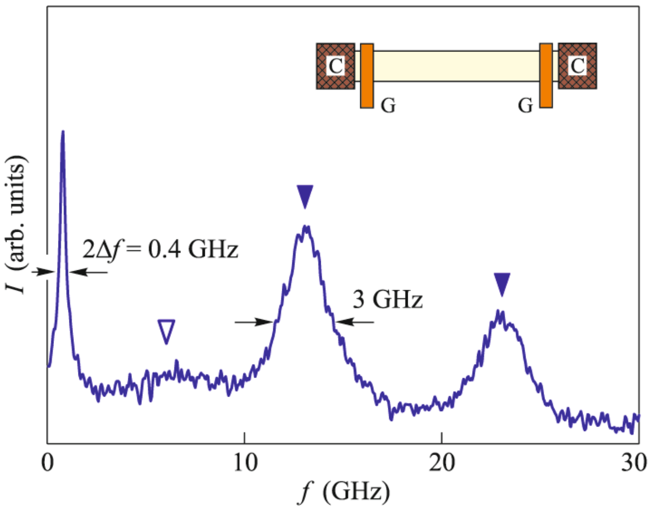

Fig. 1. (Color online) Absorption spectrum of a 2DES stripe with an electron density of $n_s = 1.9 \times 10^{11}$ cm^{-2} in zero magnetic field. Inset shows the schematic layout of the samples under study.

Figure 2a shows microwave absorption spectra obtained for different densities of two-dimensional electrons $n_s = 1.9 \times 10^{11}$, 1.2×10^{11}, and 0.5×10^{11} cm^{-2}. The density was varied using optical depletion. The spectra are shifted with respect to each other along the vertical axis for convenience. One can see that the frequencies of one-dimensional plasmon resonances and the screened-plasmon resonance (whose position is marked by arrows in Fig. 2a) vary proportionally to the square root of the electron density in the 2DES ($\omega_p \propto \sqrt{n_s}$). This behavior agrees with the theoretical calculation according to Eq. (3). The frequency of the new low-frequency resonance increases with n_s following the same square-root law. This can be seen in Fig. 2b, where the same spectra are displayed on an expanded scale for a narrower frequency range (0–2 GHz). Figure 2c shows the frequency of the new resonance as a function of the square root of the electron density. The square-root character of the density dependence gives evidence that the effect is caused by the electron–electron interaction. Thus, the observed resonance corresponds to the excitation of a weakly damped plasma wave in the 2DES.

Figure 3 shows the frequency of the observed resonance as a function of the magnetic field applied perpendicularly to the plane of the sample with the two-dimensional electron density $n_s = 1.9 \times 10^{11}$ cm^{-2}. The

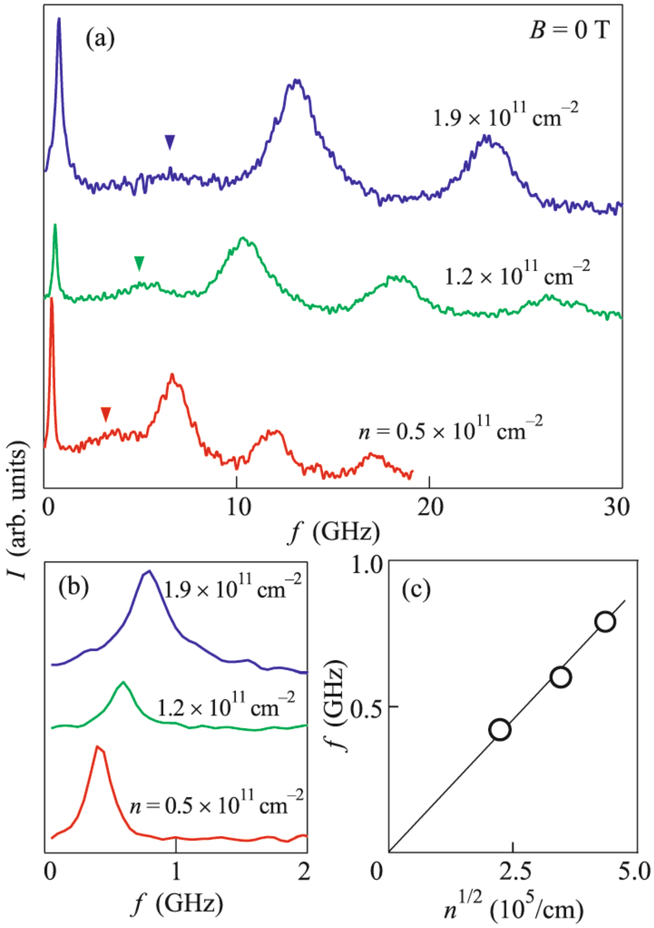

Fig. 2. (Color online) (a) Absorption spectra of the structures with electron densities of $n_s = 0.5 \times 10^{11}$, 1.2×10^{11}, and 1.9×10^{11} cm^{-2}. (b) Absorption spectra in the low-frequency region. (c) Frequency of the observed resonance versus the square root of the 2DES density.

magnetic-field behavior of the resonance frequency can be qualitatively described by the formula [11, 12]

$$\omega_p(B)^2 = \frac{\omega_p(0)^2}{1 + \omega_c^2/\omega_T^2}. \tag{4}$$

Here, $\omega_c = eB/m^*$ is the cyclotron frequency; $\omega_p(0)$ is the frequency of the plasma mode in zero magnetic field; and ω_T is some fitting frequency, which, for the case of the one-dimensional plasmon, is proportional to the frequency of the transverse plasma mode in zero magnetic field. The inset in Fig. 3 shows microwave absorption spectra obtained in different magnetic fields. The low-frequency shift of the resonance under study with increasing magnetic field is clearly visible. In addition, it is important to note that, with increasing magnetic field, the resonance becomes narrower and its amplitude decreases. A similar behavior is observed for edge magnetoplasmons [11, 12, 14] and is explained by the localization of the plasma wave in the vicinity of the edge of the 2DES with increasing magnetic field. The strong magnetic-field dependence of the new mode gives additional evidence of its plasmonic origin.

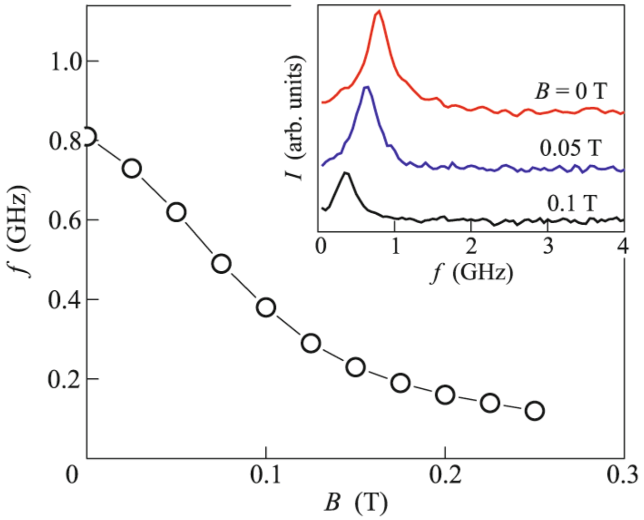

Fig. 3. (Color online) Frequency of the observed resonance versus the magnetic field applied perpendicularly to the plane of a 2DES with a density of $n_s = 1.9 \times 10^{11}$ cm^{-2}. The inset shows absorption spectra in magnetic fields of 0, 0.05, and 0.1 T.

Thus, we have investigated the microwave absorption spectra of a 2DES stripe. We have found a new high-quality-factor resonance corresponding to the excitation of a weakly damped plasma wave in the 2DES. The plasma character of the newly observed excitation is confirmed by the square-root dependence of the resonance frequency on the density of two-dimensional electrons and by a pronounced magnetic-field dependence. An unusual feature of the new mode is the fact that it is observed in the region $\omega\tau < 1$, where all known plasma excitations are damped. The discovered weakly damped plasma waves may be promising in the development of subterahertz plasmonic devices working at room temperature.

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