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Photoresponse of a two-dimensional electron gas at the second harmonic of the cyclotron resonance

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Terahertz spectroscopy experiments at magnetic fields and low temperatures were carried out on samples of different gate shapes processed on a high electron mobility GaAs/AlGaAs heterostructure. For a given radiation frequency, multiple magnetoplasmon resonances were observed with a dispersion relation described within a local approximation of the magnetoconductivity tensor. The second harmonic of the cyclotron resonance was observed and its appearance was interpreted as resulting from a high-frequency, inhomogeneous electromagnetic field on the border of a two-dimensional electron gas with a metallic gate and/or an ohmic contact.

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In a two-dimensional electron gas (2DEG) subject to a perpendicular magnetic field (B), electrical dipole transitions between Landau levels (LL) are restricted by the selection rule: $N \to N \pm 1$, where $N = 0,1,\ldots$ is the LL number. However, this strict selection rule was shown to be relaxed in some cases. Observations of harmonics of the cyclotron resonance (CR) were reported in a Si metal-oxide-semiconductor field-effect transistor at a sufficiently high gate polarization [1]. They were explained as a result of a simultaneous action of a short-range scattering by charged traps at the Si/SiO_2 interface and the electron-electron scattering [2]. Recently, Dai *et al.* reported a strong response of a 2DEG at the second harmonic of the cyclotron resonance (2CR) [3]. The experiments were carried out at temperatures (T) between 0.3 and 1.4 K on a GaAs/AlGaAs sample with a 2DEG mobility of $3 \times 10^7\,\mathrm{cm^2/Vs}$ and at radiation frequencies (f) from 60 to 120 GHz. The 2CR peak was shown to be distinct from microwave-induced resistance oscillations (MIRO) [4] and disappeared at about 1.4 K. A similar observation was reported by Hatke *et al.* on a 2DEG in a few GaAs/AlGaAs wafers with the electron mobility of the order of $10^7\,\mathrm{cm^2/Vs}$ in experiments carried out at $T = 0.5$ or 1.5 K. In a series of papers [5–7], properties of a peak appearing in the photoresponse in a proximity to the 2CR were analyzed in great detail. It was shown that the peak did not result from the MIRO and that its properties could not be explained within existing theoretical models.

In the present paper, we report on the observation of a photoresponse of a 2DEG at magnetic fields corresponding to the excitation of the 2CR. There are essential differences between our experiments and the experiments described in Refs. [3,5–7]. First, we investigated a 2DEG which resides in a single GaAs/AlGaAs heterostructure in comparison to modulation-doped AlGaAs/GaAs/AlGaAs single quantum wells. Second, our experiments were carried out at 4.2 K and not in a mK regime. For this reason, the electron mobility in our samples was of the order of $6 \times 10^5\,\mathrm{cm^2/Vs}$ and not $10^7\,\mathrm{cm^2/Vs}$. This clearly indicates that the conditions of our measurements did not correspond to that of the well-developed MIRO or its far-infrared analog [8,9]. Third, we explored both the low (120–660 GHz) and high (1.5–2.5 THz) frequency bands, which essentially enlarges the frequency range used previously, and we show that the 2CR response is observed at any of these frequencies. Finally, we investigated both gated and ungated structures, in each case supplied with ohmic contacts, and we show that the presence of a metallic gate is crucial in generating a photoresponse at the 2CR, although cases might occur in which this is not true.

We propose that the observed response at the 2CR is caused by a nonlinear cyclotron motion of an electron circulating in a strongly inhomogeneous electric field created by an incident radiation at a border of a metallic part of a sample (a gate or an ohmic contact) with a 2DEG. We discuss our results within predictions of a theory exploring a strongly inhomogeneous high-frequency electric field at a border of a metallic contact and a 2DEG [10].

An important part of our reasoning is devoted to proving that the observed photoresponse results from the 2CR and is not caused by avoided crossings of the Bernstein-mode–magnetoplasmons interactions [11–14]. This argument is important in the case of our results because excitations of magnetoplasmons were found to be the main mechanism of the photoresponse observed in the samples investigated [15,16].

The samples used in the present study were processed on a high electron mobility GaAs/AlGaAs heterostructure grown by a molecular-beam epitaxy [16]. Hall-effect measurements

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at 4.2 K allowed us to estimate an electron concentration and a mobility to be about 3.0×10^{11} cm^{-2} and 6×10^5 cm^2/Vs, respectively. Samples were fabricated with an electron-beam lithography. The processing started with a wet etching of a rectangular mesa (a typical dimension was 65 μm × 1.3 mm). Next, ohmic contacts were fabricated by deposition of 160 nm of Au/Ge/Ni alloy and heating up to 430 °C for a few minutes. The Au/Pd gates were deposited directly on the sample surface. We investigated both gated and ungated samples. Gated samples differed by the gate shape; they were in the form of a rectangle, a meander, or a comb. In the last two cases, the period of the gate structure was of the order of a few μm and a geometrical aspect ratio of about 0.5. In each case, the gate covered all of the distance between the ohmic contacts, with the exception of 10-μm-wide slits adjacent to the contacts. More details on the samples can be found in Ref. [15].

Samples were placed in a liquid-helium cryostat and cooled to 4.2 K with an exchange gas. A magnetic field, produced by a superconducting coil, was perpendicular to the sample surface. A THz radiation was guided to the sample with an oversized waveguide of the diameter of 12 mm. Two filters were used. A black polyethylene filter, placed next to the sample, filtered out a visible and a near-infrared light of the frequency higher than about 20 THz (including a room-temperature thermal radiation from warmer parts of the cryostat). A teflon filter stopped the radiation in the range from 15 to 40 THz. A THz beam was generated by an electronic source in the frequency range of 630–660 GHz, a backward-wave oscillator (BWO) generating at 100–170, 200–315, and 315–485 GHz, and a molecular THz laser pumped with a CO_2 laser (a few lines in the range 1.5–3.1 THz).

A source-drain photovoltage (PV) signal was registered as a function of a magnetic field at a constant radiation frequency. The photovoltage is generated by an incoming THz radiation only (without any bias of the sample). It appears due to an asymmetrical connection of the sample with one of the ohmic contacts grounded and the other connected to a high-resistance input of a lock-in. A physical mechanism responsible for the observed photovoltage is a rectification of plasma excitations [17–19]. We used a phase-sensitive lock-in measurement system with an electronic on/off modulation of the radiation intensity. The modulation frequency was in the range of 13–500 Hz. Typically, the signal amplitude was between a few μV up to 1 mV, depending on the radiation power coming to the sample and the magnetic field.

Results obtained for a meander-gated sample are plotted in Fig. 1, which shows a PV as a function of the magnetic field in the frequency range of 200–700 GHz. At fields higher than the cyclotron resonance field $B_{CR} = 2\pi f m^*/e$ (where $m^* = 0.070 m_e$ is the GaAs/AlGaAs heterostructure cyclotron mass, as determined from current experiment) [16], the dominant feature is Shubnikov-de Haas (SdH) oscillations. Arrows mark positions of the second harmonic of the cyclotron resonance ($B_{CR}/2$). Other features visible in $B < B_{CR}$ fields are a superposition of magnetoplasmon excitations and SdH oscillations [15].

Figure 2 shows positions of maxima in the spectra plotted as a function of the radiation frequency f used. The maxima change their positions following the relation for a magneto-

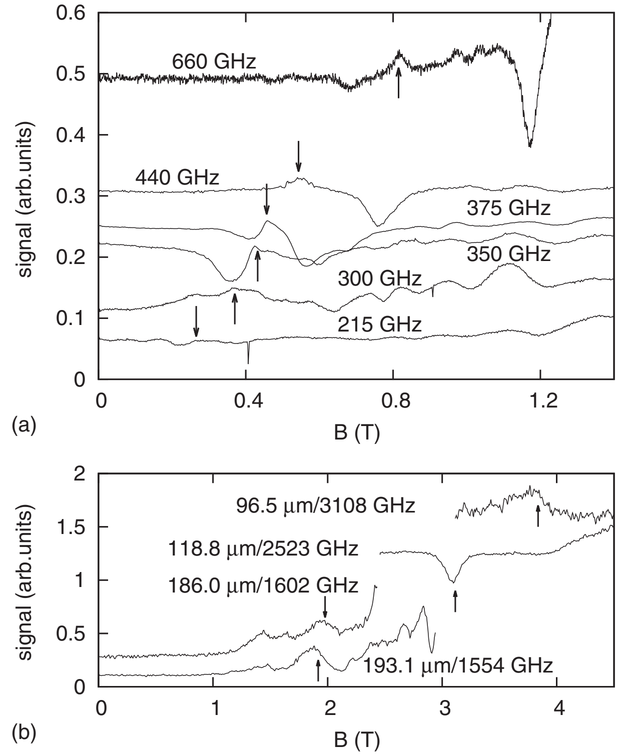

FIG. 1. Typical PV spectra collected for a meander-gated sample. Arrows show magnetic fields corresponding to the second harmonic of the cyclotron resonance. Results in (a) were obtained with the electronic source and the BWO, while in (b), results were obtained with the THz laser.

plasmon frequency,

$$\omega = \sqrt{\omega_c^2 + \omega_{p,n}^2}, \tag{1}$$

where $\omega = 2\pi f$ is the magnetoplasmon (simultaneously, the radiation) frequency, $\omega_c = eB/m^*$ is the cyclotron frequency, and $\omega_{p,n}$ is the nth plasmon-mode frequency at $B = 0$. Using Eq. (1), we can fit the values of $\omega_{p,n}$, as shown in Fig. 2. The dispersion relation of a plasmon at $B = 0$ is given by [20]

$$\omega_{p,n} = \sqrt{\frac{Ne^2}{2m^*\epsilon_0}\frac{k_n}{\epsilon(k_n)}}, \tag{2}$$

where N is the electron concentration, and k_n is a wave vector of the nth plasmon mode. The effective dielectric function $\epsilon(k_n)$ depends on whether the 2DEG is screened by the gate (gated) [21],

$$\epsilon_g(k_n) = \tfrac{1}{2}[\epsilon_1 + \epsilon_2 \coth(k_n d)], \tag{3}$$

or not screened (ungated) [22],

$$\epsilon_{ug}(k_n) = \frac{1}{2}\left[\epsilon_1 + \epsilon_2 \frac{1 + \epsilon_2 \tanh(k_n d)}{\epsilon_2 + \tanh(k_n d)}\right]. \tag{4}$$

From fitted values of $\omega_{p,n}$, we deduced a dispersion relation of plasmons. A detailed description of the procedure leading from measured spectra to the dispersion relations was presented in Ref. [15]. What is important to a further analysis in the current paper—in the case of the meander-gated and the uniformly gated samples—is that we found that wave vectors

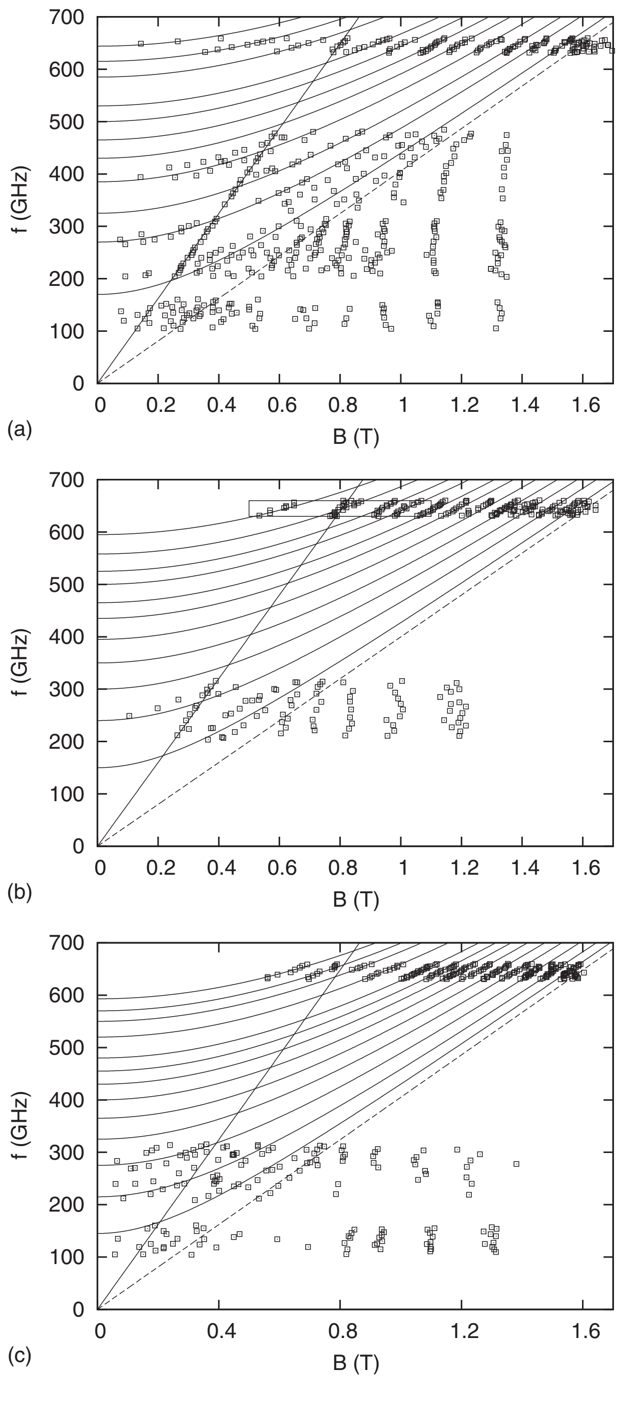

FIG. 2. Positions of maxima in photovoltage spectra in the case of (a) the meander-gated sample, (b) the uniformly gated sample, and (c) the ungated sample.

$k_n = (4n-1)\frac{\pi}{W}$ fit precisely to the theoretical dispersion, with $W = 65\ \mu$m being the width of samples. In the meander-gated sample, plasmons excited due to the periodicity of the gate (8 μm) are also excited, but their frequencies are much higher than those of plasmons excited due to the width [16]. Calculations based on Eqs. (1) and (2) show that only two grid-related magnetoplasmon modes could be observed in the spectral range used in the current experiment. However, since their amplitude and width is similar to W-related magnetoplasmons, they were not resolved in the spectra.

Let us note that a maximum occurring in the vicinity of the 2CR can be observed due to an interaction of a Bernstein mode [11] with magnetoplasmons. This interaction leads to a formation of avoided crossings in the magnetoplasmon spectrum which can be observed both in a bulk [23] and 2D plasma [12–14]. In such a case, the interaction is characterized by the following features. First, consistently with an avoided crossing character of the interaction, corresponding maxima occur at magnetic fields close to but not equal to that of CR harmonics and an amplitude of a measured signal at the magnetic field of the 2CR should show a minimum in the middle of the interaction region [12–14]. Second, an amplitude of a Bernstein mode is comparable with that of a plasmon only within the interaction region and rapidly decaying it off [12,24,25].

Based on the experimental data presented in Figs. 1–3, we argue that a spectral feature observed at 2CR does not

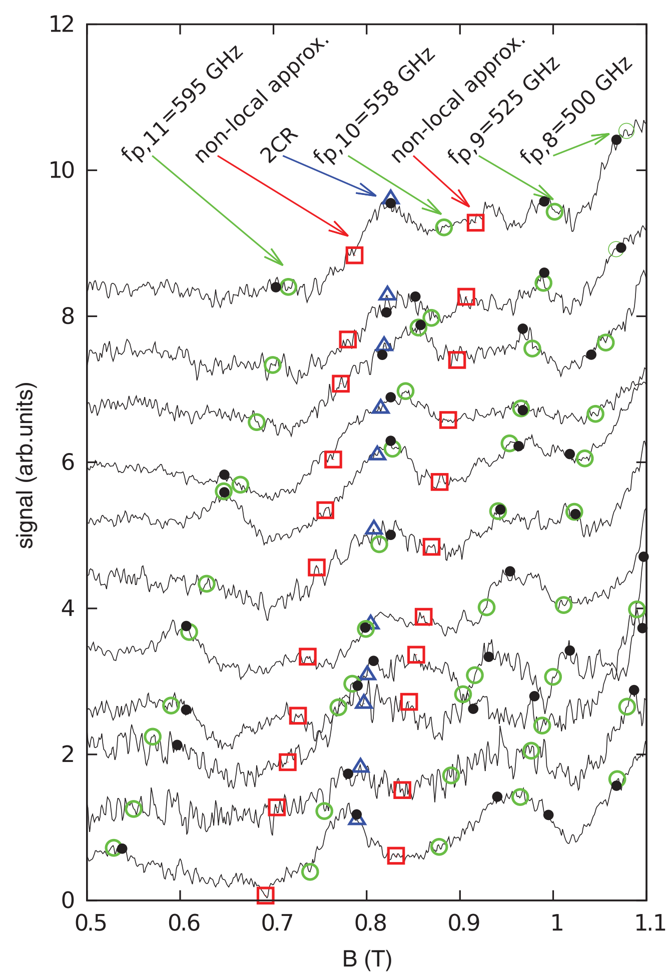

FIG. 3. (Color online) PV spectra at the vicinity of the 2CR for the uniformly gated sample. Results obtained in the 630–660 GHz range with a step of 2.88 GHz. Spectra are normalized and shifted for clarity. Maxima from these spectra are marked with black dots and are also shown in Fig. 2(b) within a rectangle comprising a part of the results obtained at above 600 GHz. Green circles, red rectangles, and blue triangles show magnetic fields corresponding to theoretically calculated positions of the magnetoplasmons in a local approximation, tenth magnetoplasmon mode–Bernstein mode, avoided crossing, and the 2CR, respectively.

follow the above characteristics. A B dependence of the 2CR is indicated in Fig. 2 with a solid straight line. As one can notice, there is a series of points which coincide with the 2CR with a high accuracy and show a B dependence clearly different from that of magnetoplasmons. Thus, the question is whether these points correspond to the 2CR or to the mixed Bernstein-mode–magnetoplasmon excitations. To answer this question, we show in Fig. 3 a detailed analysis of a series of spectra in which we could observe an avoided crossing between one of the magnetoplasmon modes and the Bernstein mode close to the 2CR, if such an interaction were present.

Inspection of spectra in Fig. 3 shows that at the magnetic field corresponding to the 2CR (marked with triangles), one systematically observes a single maximum of the signal, which would not be the case if an avoided crossing of the Bernstein mode–magnetoplasmon was present. In the latter case, one would observe two maxima in the magnetic fields slightly higher and lower than the 2CR magnetic field and a minimum at the 2CR magnetic field. A description of a magnetoplasmon dispersion within the local approximation is very accurate. A nonlocal approach is based on a solution of an equation,

$$1 - 4\frac{\omega_{p,n}^2}{X^2}\sum_{m=1}^{2}\frac{m^2 J_m^2(X)}{\omega^2 - (m\omega_c)^2} = 0, \qquad (5)$$

which describes the positions of excitations in the avoided crossing region of the interaction. Here J_m is the mth-order first-kind Bessel function and $X = k_n v_F/\omega_c$ is a nonlocal parameter, where k_n is equal to the nth-mode magnetoplasmon's wave vector and $v_F \approx 2.2 \times 10^5$ m/s is the Fermi velocity. The X value in our case is equal to about 0.15 for the tenth magnetoplasmon mode considered for the interaction. We cut the summation at the second term as we are only considering the interaction of a magnetoplasmon with the Bernstein mode coinciding with the 2CR. Parameter $\omega_{p,n}$ is the nth plasmon-mode frequency at zero magnetic field determined from the fitting of Eq. (1) to maxima presented in Fig. 2. Results of the calculations (open squares) are in a clear contradiction with the positions of maxima observed in the spectra. On the contrary, positions of the maxima in the spectra agree to a high accuracy with the positions of the 2CR and magnetoplasmons calculated within the local approximation. This allows us to argue that Bernstein modes are not observed in the present experiment. Finally, the 2CR feature was observed also in the measurements with the THz laser excitation [Fig. 1(b)] at magnetic fields which are much smaller than the field at which magnetoplasmons were observed, which means that they are far off the interaction region.

Since the 2CR peak was observed on all three gated samples and only on one among three ungated samples, we argue that it is generated due to processes that take place at a border of metallic parts of a sample under an influence of a high-frequency THz radiation. Such a situation was considered in Ref. [10]. Essentially, the theory explores the fact that the incoming THz radiation generates a very strong and spatially nonuniform high-frequency electric field at a metal-2DEG border. This field becomes particularly strong and oscillating in space when the radiation frequency approaches the double cyclotron frequency and falls within the band gap created by the Bernstein-mode–magnetoplasmon avoided crossing. Parametric resonance conditions give rise to a plasma instability causing a 2DEG heating, and therefore a photoresponse at the 2CR frequency. An ultrahigh electron mobility, proportional to ω^{-3}, is required to observe the signal at 2CR. According to the theory, we could see some 2CR signal at frequencies around 600 GHz in our samples. However, since the 2CR is observed at above 200 GHz, the required minimal electron mobility at this frequency should be about 15×10^6 cm^2/Vs, which is of an order of magnitude more than the electron mobility in our samples. Also, the theory predicts a photoresponse only in very narrow spectral regions in the gaps created by Bernstein-mode–magnetoplasmon avoided crossings. We, however, observe the 2CR feature in a very wide spectral range. Thus, the theory does not fully explain a feature observed at the 2CR in our experiment.

In Ref. [10], a 2DEG was assumed to border a metallic contact, which should be considered as an ohmic contact in a real experimental situation. The results of our experiments show that a metallic gate serves as a better source of this nonlinearity. This should not be surprising because of a much sharper edge of a gate in comparison with an edge of an ohmic contact, which is typically slightly diffused. However, experiments show that an ohmic contact may sometimes be good enough, which was probably the case of one of our ungated samples.

In conclusion, we presented experimental evidence of a response of a 2DEG at the second harmonic of the cyclotron resonance. We propose that this is a manifestation of a complicated electron motion at the border of a 2DEG and a metallic gate or an ohmic contact due to a highly nonuniform electric field generated there by an incident radiation.

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