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Terahertz Radiation-Induced Magnetoresistance Oscillations of a High-Density and High-Mobility Two-Dimensional Electron Gas

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The terahertz response of a high-density and high-mobility two-dimensional electron gas in 13-nm GaAs quantum wells at frequencies of 0.7 and 1.63 THz has been investigated. Terahertz radiation-induced magnetoresistance oscillations have been discovered. The oscillation maxima coincide with the harmonics of cyclotron resonance. It has been shown that a large number of harmonics (up to the ninth) appear under irradiation at a frequency of 0.7 THz. In this case, the effect is the analogue of microwave-induced oscillations. At a higher frequency, the oscillation amplitude decreases drastically with an increase in the harmonic number. This indicates a transition to the regime of ordinary cyclotron harmonics.

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One of the remarkable phenomena discovered in two-dimensional electron systems in the past decade is the phenomenon of microwave-induced magnetoresistance oscillations [1], which under certain conditions exhibit zero-resistance states [2, 3]. Until recently, the great majority of works in this direction have been devoted to experiments in the microwave range (1–250 GHz) [4], although the question of existence of these oscillations in the terahertz range is of undoubted interest. However, investigations in this direction are so far limited to a single work [5] on the magnetoresistance of a high-mobility two-dimensional electron gas (2DEG) in heterojunctions with a lateral lattice. This allowed investigation of far-infrared-induced resistance oscillations, similar to microwave-induced resistance oscillations, under the conditions of terahertz generation of magnetoplasmons. At the same time, far-infrared-induced resistance oscillations in heterojunctions without a lateral lattice have not been observed so far. It is noteworthy that such investigations are hindered by a drastic decrease in the oscillation amplitude with an increase in the radiation frequency [6–8]. Thus, investigation of the terahertz response of a 2DEG, especially at frequencies of about 1 THz, remains currently topical. In this work, we present the results of studying the terahertz response of a 2DEG to irradiation at a frequency of 0.7 and 1.63 THz. The most interesting result is the first observation of terahertz radiation-induced magnetoresistance oscillations of a high-mobility 2DEG.

In this work, we measured the terahertz response (photoresistance and photovoltage) of the above structures at wavelengths of 432 and 184 μm in magnetic fields of up to 7 T. A molecular laser with an optical pumping by a CO_2 laser was used as a terahertz source [9, 10]. The active medium used to generate radiation at a frequency of 0.7 and 1.63 THz (the wavelength $\lambda = 432$ and 184 μm) was formic acid and difluoromethane, respectively. The terahertz radiation power was about 80 and 5 mW at the 184- and 432-μm lines, respectively. Photoresistance was measured with the use of a standard lock-in detection at a modulation frequency of 200–270 Hz and the dc bias current across the sample $I = (10–40)$ μA. The current source was disconnected to measure photovoltage.

The experimental samples were Hall bars with a width of 50 μm and a distance between the voltage contacts of 350 μm fabricated from GaAs heterojunctions with a 13-nm quantum well and a high-density ($N_s = (0.8–1.0) \times 10^{12}$ cm^{-2}) and high-mobility ($\mu = (1.5–2) \times 10^6$ cm^2/V s) 2DEG. The side barriers of the well were formed by an AlAs/GaAs superlattice, which made it possible to produce a high-mobility 2DEG with a high electron density in the well [11]. A semi-

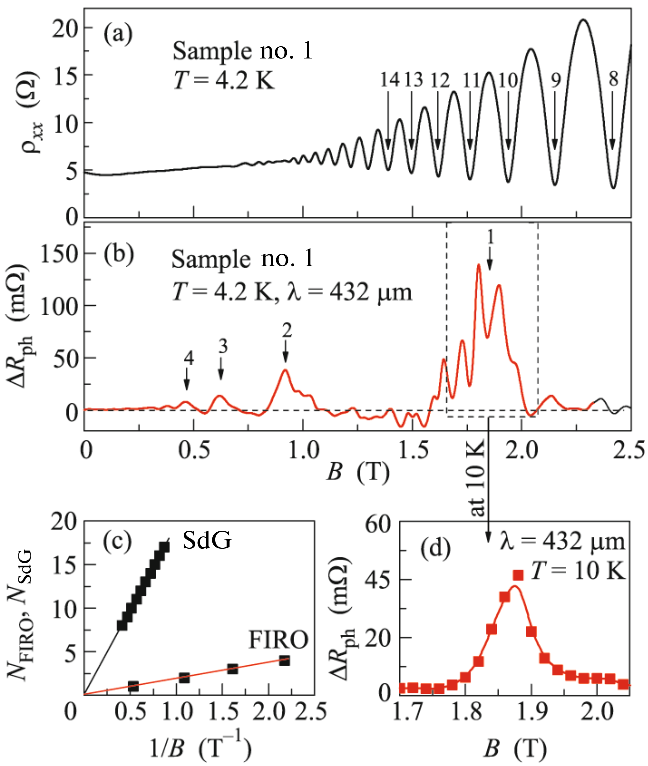

Fig. 1. (a) Magnetic-field dependence $\rho_{xx}(B)$ of the component of the resistivity tensor at $T = 4.2$ K for sample no. 1 ($N_s = 9.3 \times 10^{11}$ cm^{-2}, $\mu = 1.45 \times 10^6$ cm^2/V s). The numbers of Shubnikov–de Haas oscillation minima corresponding to the numbers of occupied Landau levels are indicated. (b) Magnetic-field dependence of the photoresistance $\Delta R_{ph}(B)$ of the same sample at the same temperature exposed to radiation at the wavelength λ = 432 μm (0.7 THz). The numbers of the cyclotron resonance harmonics are indicated. (c) Positions of the minima of Shubnikov–de Haas oscillations (N_{SdG}) and the maxima of photoresistance oscillations (N_{FIRO}) versus the inverse magnetic field. (d) The same as in panel (b) in the region of cyclotron resonance at $T = 10$ K.

transparent metallic gate was deposited onto the surface of one of the samples (no. 1). The magnetic-field dependence of the dissipative component $\rho_{xx}(B)$ of the resistance tensor of sample no. 1 in the field range from 0 to 2.5 T is shown in Fig. 1a. As is clearly seen, the behavior of $\rho_{xx}(B)$ is usual for the 2DEG in GaAs quantum wells: a weak dependence on the magnetic field is observed below 1 T, whereas Shubnikov–de Haas (SdH) oscillations emerge at $B > 1$ T with the amplitude increasing exponentially with B. The dependence of the position of the ρ_{xx} maxima on the inverse magnetic field lies on a straight line (Fig. 1c). The period of these oscillations corresponds to the density $N_s = 9.3 \times 10^{11}$ cm^{-2}.

We start from the description and analysis of the results obtained at a wavelength of 432 μm. Figure 1b shows the magnetic-field dependence of the photoresistance $\Delta R_{ph}(B)$ at $T = 4.2$ K. First of all, there is a remarkable sharp peak in a field of ≈1.85 T distorted by the contribution of Shubnikov–de Haas oscillations, which are already strongly developed in the magnetic fields $B > 1$ T. The position of the maximum of the envelope of this resonance corresponds to the cyclotron resonance of charge carriers with an effective mass of $0.075m_0$. To suppress the effect of SdH oscillations and determine the exact position of the cyclotron resonance, the temperature was raised to 10 K (see Fig. 1d). Clearly, the peak of the cyclotron resonance lies at $B_{CR} \approx 1.9$ T, in good agreement with the aforesaid. Note that the effective cyclotron mass is greater than the bulk value $0.067m_0$. This is caused by spectrum anharmonicity, which is already noticeable at high $N_s \approx 10^{12}$ cm^{-2} [12]. Under these conditions, the number of occupied Landau levels (indicated by arrows in Fig. 1a) at $B < 1.9$ T is $n > 10$; i.e., the condition of filling a large number of Landau levels is fulfilled quite well. In addition to the main peak with an amplitude of about 150 mΩ, we resolve a series of somewhat smaller peaks in low magnetic fields. It should be emphasized that SdH oscillations are not observed in these fields. Note also that the period of these photoresistance oscillations in the inverse magnetic field is much higher than the period of SdH oscillations (see Fig. 1c). According to the analysis of the data in Fig. 1b, the positions of the discovered photoresistance peaks coincide with the harmonics of the cyclotron resonance. The latter are marked by vertical arrows in Fig. 1b starting from the first harmonic at $B_{CR} = 1.9$ T. However, despite the coincidence of the positions, the observed photoresistance oscillations cannot be explained by ordinary harmonics of the cyclotron absorption. In fact, the amplitude of the harmonics decreases exponentially and already the amplitude of the second harmonic is two or three orders of magnitude smaller than the fundamental one [4]. At the same time, as was observed in the experiment, the amplitude of the oscillation corresponding to the second harmonic is only three times smaller than that of the fundamental one. Moreover, photoresistance peaks are resolved at $T = 1.9$ K up to the fields corresponding to the ninth harmonic. This behavior is similar to that of microwave-induced oscillations. The relatively small amplitude of the observed oscillations (fractions of a percent of the total sample resistance) is quite well understood. First, the very effect of microwave-induced resistance oscillations decreases with an increase in the frequency already at $f > 100$ GHz [4]. Second, the terahertz radiation power absorbed by the sample is considerably (one or two orders of magnitude) smaller than the power absorbed by the 2DEG in the microwave range. Thus, our results allow us to claim the first observation of magnetophotoresistance oscillations of a 2DEG, now induced by terahertz radiation.

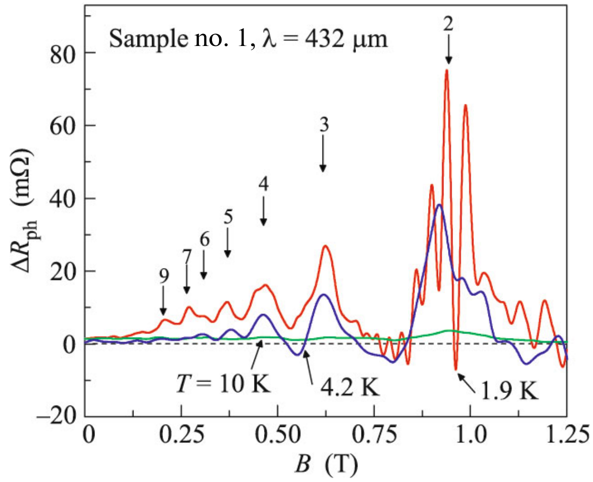

Fig. 2. Magnetic-field dependence of the photoresistance $\Delta R_{ph}(B)$ for sample no. 1 under irradiation at the wavelength $\lambda = 432$ μm at temperatures of 1.9, 4.2, and 10 K. Arrows indicate the values of B corresponding to the cyclotron resonance harmonics.

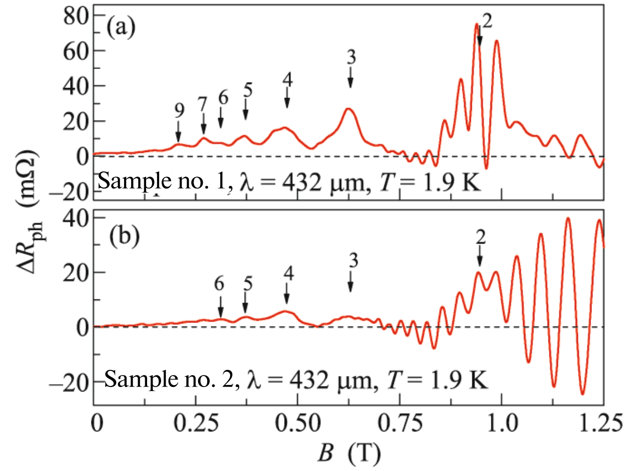

Fig. 3. Magnetic-field dependence of the photoresistance $\Delta R_{ph}(B)$ for (a) sample no. 1 ($N_s = 9.3 \times 10^{11}$ cm^{-2}, $\mu = 1.45 \times 10^6$ cm^2/V s) and (b) sample no. 2 ($N_s = 9.3 \times 10^{11}$ cm^{-2}, $\mu = 1.9 \times 10^6$ cm^2/V s) at $T = 1.9$ K.

The temperature variation of far-infrared-induced resistance oscillations is demonstrated in Fig. 2. As is clearly seen, the oscillations almost disappear with an increase in the temperature up to 10 K, whereas the oscillation amplitude increases by a factor of 1.5–2 with a decrease in the temperature to 1.9 K; in addition, new oscillations with ordinary numbers 5, 6, 7, and 9 emerge at 1.9 K. It is also noteworthy that the oscillation amplitude corresponding to the second harmonic at 1.9 K is as high as 2% of the total resistance of the sample.

Far-infrared-induced resistance oscillations for two samples with different mobilities are shown in Fig. 3. This demonstrates a paradoxical result: sample no. 2 with a higher mobility exhibits far-infrared resistance oscillations with a much lower amplitude than sample no. 1 with a lower mobility. In addition, the quantum time appeared to be identical for both samples. Note that samples no. 1 and no. 2 were made of the same heterojunction. Sample no. 1 had a metallic gate deposited on the heterojunction surface and was kept for several days under the gate voltage $V_g = -1$ V at a temperature of about 200 K before cooling to 4.2 K. Both the metallic gate screening the long-range component of a random potential and the gate voltage recharging impurities in the barriers can change considerably the character of the random potential, thus affecting the behavior of far-infrared-induced resistance oscillations. In this case, according to the results shown in Fig. 3, the mobility and even quantum time are not sufficient characteristics of the random potential, which determine the behavior of the oscillations. As is known, a similar situation takes place with microwave-induced oscillations, when, e.g., the states with zero resistance also appear in the samples with relatively low mobility and not the highest quantum time [13].

The measurements at a higher frequency of 1.63 THz showed that, although the photoresistance peaks at $B_{CR}/2$ and $B_{CR}/3$ are still resolved, their amplitude is 2–3 orders of magnitude lower than that of the main peak at B_{CR}. This drastic decrease in the amplitude of the photoresponse peaks at $B_{CR}/2$ and $B_{CR}/3$ with respect to the signal at B_{CR} was also observed in the measurement of the photovoltage. This signal, caused by the photogalvanic effect [14, 15], was reliably detected in our experiments only at a frequency of 1.63 THz. The magnitude of the photovoltage peak at B_{CR} differed from that of the fundamental mode by more than a factor of 20. A much stronger decrease in the magnitude of photoresponse peaks with respect to the main one at a frequency of 1.63 THz as compared to 0.7 THz indicates that the transition from the far-infrared-induced resistance oscillations to that of ordinary cyclotron resonance harmonics occurs in the frequency region of ≈1 THz.

In conclusion, it should be mentioned that the observation of far-infrared-induced resistance oscillations similar to microwave-induced ones makes it possible to extend the experiment on the investigation of 2DEG with a large number of Landau levels exposed to microwave and terahertz radiation. In particular, clearer and more direct answers to three principal questions can be obtained concerning the effect of radiation polarization and the character of the random potential on the oscillations and regarding the contact nature of the oscillations [4, 16, 17]. Especially interesting are polarization experiments, since they are technically much simpler. It is also important that, owing to a much higher frequency, the effects associated with the influence of contacts on both the polarization and the observation of the effect itself [17] should be considerably smaller.

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