

Measurement of the Mean Free Path of Edge Magnetoplasmons Revealed in the Spectra of Magnetic Oscillations of Photovoltage in a Two-Dimensional Electron System under Microwave Radiation

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In the spectrum of photovoltage oscillations that are periodic with respect to the magnetic field and appear on Hall structures under microwave irradiation, two frequency components of oscillations are observed and analyzed. The appearance of these two frequencies in photovoltage oscillations is explained by the existence of two trajectories of edge magnetoplasmons and by the effects of the interference of collective excitations on these trajectories. The effects of the temperature, microwave radiation frequency, and magnetic field strength on the mean free path of edge magnetoplasmons are analyzed.

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The electromagnetic frequency scale has a problem range of 300–1000 GHz, where available, cheap, miniature, and effective generators, as well as detectors and spectrometers of electromagnetic radiation, are almost completely absent. At the same time, it is well known that this frequency range has remarkable prospects for applications and scientific investigations. Recently, we discovered and analyzed a new type of magnetic oscillations of photovoltage and longitudinal magnetoresistance in two-dimensional electron systems when a structure was continuously irradiated by microwave electromagnetic radiation [1]. The feature of these oscillations is their periodicity with respect to the magnetic field (rather than with respect to the inverse magnetic field as in most magneto-oscillation effects). The period of the oscillations is determined by the frequency of the radiation, the density of the electron gas in the structure, and the distance between the potential contacts. Such behavior of the oscillations is explained by the interference of edge magnetoplasmons that are coherently excited by electromagnetic radiation in the inhomogeneity region associated with potential contacts and propagate along the boundary of the two-dimensional electron gas. Edge magnetoplasmons are particular plasma excitations that are characterized by an almost linear dispersion law, and their velocity is easily tuned by varying two parameters, the magnetic field and the electron density [2, 3]. When the structure is irradiated by an electromagnetic field, edge magnetoplasmons are coherently excited in contact regions and, when the distance between the contacts is equal to an integer number of the wavelength of the edge magneto-

plasmon excitations, the resonant enhancement and, as a result, photovoltage occur due to interference. The effect is observed up to high temperatures (near 100 K) and is pronounced even for weak magnetic fields (0.02–0.2 T) and for frequencies of 10–160 GHz [4]. The observed effect enables one to detect millimeter and submillimeter radiation at an excitation power of less than 1 nW. Moreover, the radiation spectrum in the range of 20–160 GHz can be measured with an accuracy of better than 0.3 GHz by scanning the magnetic field. Owing to the small detector size (0.1–0.5 mm), the creation of a multipixel matrix of detectors can be expected, which is necessary for obtaining the images of various objects in millimeter and submillimeter ranges of wavelengths. For observation of the effects of interference of edge magnetoplasmons and detection of microwave radiation, the mean free path of the edge excitations must be longer than the distance between the contacts. For this reason, the mean free path of the edge magnetoplasmons and its dependence on the temperature, the magnetic field, and the frequency are of current interest. In this work, we investigate the spectrum of the magnetic oscillations of the photovoltage of two-dimensional electrons under microwave radiation and find two frequency components of oscillations that are associated with the existence of two trajectories on which the interference of edge magnetoplasmons occurs in the Hall structure. We also analyze the mean free path of the edge magnetoplasmons as a function of the temperature, the magnetic field, and the frequency.

The experiments were carried out with single doped AlGaAs/GaAs quantum wells manufactured in the form of Hall bars (see Fig. 1a) with a width of $W = 0.4$ mm, supplying a strip width of $c = 0.05$ mm, a distance between neighboring strips of $a = 0.5$ mm, and a strip length $b = 0.2$ and 0.1 mm. The typical electron density and mobility are $n_s = 2.6 \times 10^{11} \text{ cm}^{-2}$ and $\mu = 0.8 \times 10^6 \text{ cm}^2/(\text{V s})$, respectively. A sample mounted in a 16-mm waveguide at the loop of the electromagnetic field was placed in a helium cryostat inside a superconducting solenoid. Microwave radiation was supplied through the waveguide to the sample. Microwave generators covered the frequency range from 25 to 80 GHz at an output power of no more than 10 mW. The sample temperature was measured using calibrating resistance. The procedure of synchronous detection of the photovoltage signal with modulating incident radiation with a modulating frequency of 1 kHz was used for the measurements.

Figure 2a shows the magnetic field dependence of the photovoltage appearing between two neighboring supplying strips as measured on Hall bars with $b = 0.2$ mm at a fixed incident-radiation frequency of 55.21 GHz. It is seen that this dependence exhibits modulated oscillations. The frequencies of the oscillations and the envelop can be easily determined by the Fourier transform of the photovoltage as a function of the magnetic field (as is shown in the inset in Fig. 2a). It is seen that the Fourier transform has two maxima; i.e., the analyzed function has two components as a function of the magnetic field frequency. The dependence of the period ΔB of each of these components on the inverse frequency $1/f$ of the incident radiation is shown in Fig. 2b. As is seen, this dependence is linear.

The oscillations in the photovoltage are explained by the interference of edge magnetoplasmons [1] excited in the contact regions of the structure. Indeed, the velocity of the edge magnetoplasmons is proportional with logarithmic accuracy to the Hall conductivity $v_{\text{emp}} \propto \sigma_{xy} \propto n_s/B$ [2]. Assuming that the wavenumber of the edge magnetoplasmons is equal to $\pi N/L$, where L is the distance along the boundary of the system from the place of the emission of the edge magnetoplasmons to the interference place, we obtain the oscillation period

$$\Delta B \propto n_s/fL. \quad (1)$$

According to Eq. (1), using the ratio of the tangents of the slope angles of two straight lines shown in Fig. 2b, which correspond to different edge modes, one can determine the ratio of the paths L_h and L_l covered by high- and low-frequency edge magnetoplasmons, respectively, before the interference. Thus, it is possible to determine the regions of the excitation and interference of magnetoplasma waves on the sample. Substituting the numerical data, we obtain $L_h/L_l \approx 2.2\text{--}2.7$. Assuming that magnetoplasmons are emitted through the modulation of the potential by a metallic contact in

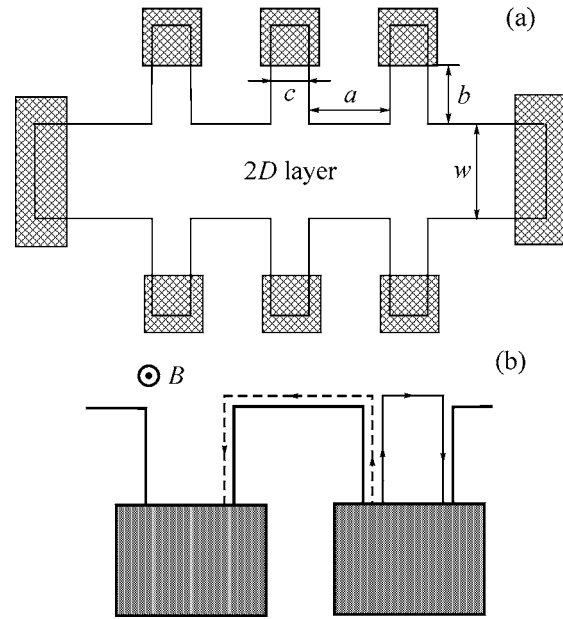


Fig. 1. (a) Layout of the structures used in the experiments and (b) the scheme of the trajectories of the edge magnetoplasmons that correspond to (dashed line) high-frequency and (solid line) low-frequency modes.

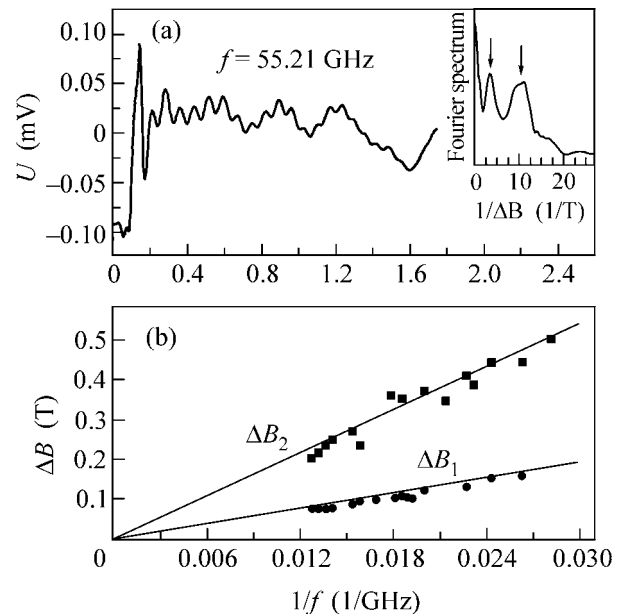


Fig. 2. (a) Magnetic field dependence of the photovoltage $U(B)$ appearing between two neighboring contacts as measured at a fixed frequency $f = 55.21$ GHz and power $w = 0.1$ mW of incident radiation. The inset shows the Fourier spectrum of $U(B)$. (b) Two periods of magnetic oscillations (lower line corresponding to L_h) ΔB_1 and (upper line corresponding to L_l) ΔB_2 vs. the inverse frequency of incident radiation; $n_s = 2.6 \times 10^{11} \text{ cm}^{-2}$ and $T = 4.2$ K.

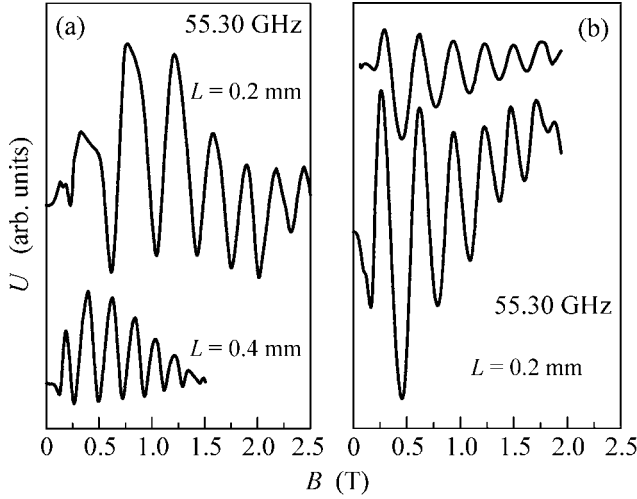


Fig. 3. (a) Photovoltage oscillations measured at the frequency $f = 55.3$ GHz for two lengths $L_1 = 0.2$ mm and $L_2 = 0.4$ mm at a temperature of 4.2 K. (b) Photovoltage oscillations measured at a frequency of $f = 55.3$ GHz for $L = 0.2$ mm at the temperatures 4.2 and 77 K; $n_s = 2.6 \times 10^{11}$ cm $^{-2}$.

the adjacent region of the two-dimensional electron layer and that interference occurs either on an emitting or neighboring contact (see Fig. 1b) and using the geometric sizes of the sample, we obtain

$$\frac{L_h}{L_l} = \frac{a + 2b}{2b} \approx 2.3. \quad (2)$$

This value is in good agreement with the experimental data.

Thus, the interference of high- and low-frequency modes occurs on the (dashed line) neighboring and (solid line) emitting contacts, respectively, as is schematically shown in Fig. 1b. The latter mode was not mentioned in the literature. Its origin can be attributed to the hopping of an edge magnetoplasmon from one edge of the supplying strip to another due to the induced potential. Such hopping is possible when the wavelength of the edge magnetoplasmon is comparable with the distance between the edges. This condition is satisfied in our experiments.

The damping of the edge magnetoplasmons is determined, first, by electron scattering and, second, by radiation losses. Since the diagonal component of the resistance tensor under our experimental conditions is much larger than the wave resistance of the vacuum, the radiative losses can be disregarded [5, 6].

Let us express the amplitude of the oscillations of the photovoltage U in terms of the mean free path L_{emp} of edge magnetoplasmons. Since the emitted wave and the wave covering the distance L interfere with each other on contact and their amplitudes are summed, the voltage U_r on contact, which is associated with qua-

dratic nonlinearity and rectification on the contact, is given by the expression

$$U_r = U_0 |1 + e^{-iqL}|^2. \quad (3)$$

Here, $q = q_1 - iq_2$, where $q_1 \propto \omega B/n_s$ is the wavenumber of the incident plasmon and $q_2 = 1/L_{\text{emp}}$ is the term responsible for its relaxation. Thus,

$$U_r = U_0 (1 + e^{-2q_2 L} + 2e^{-q_2 L} \cos q_1 L). \quad (4)$$

According to Eq. (4), as L increases, the amplitude of the photovoltage oscillations decreases as

$$U \propto e^{-q_2 L} = e^{-L/L_{\text{emp}}}. \quad (5)$$

Figure 3a illustrates the applicability of estimate (5) to our experiments by the example of two modes with different L values. As is seen, the photovoltage oscillation amplitude decreases as the magnetic field increases; this behavior is explained by a decrease in L_{emp} with increasing B . It is worth noting that, since the velocity of an edge magnetoplasmon is inversely proportional to the magnetic field [2]

$$v_{\text{emp}} \propto \sigma_{xy} \ln\left(\frac{1}{qa}\right) \propto \frac{1}{B} \ln\left(\frac{1}{qa}\right), \quad (6)$$

where q is the wavenumber and a is the characteristic transverse size of the edge magnetoplasmon, respectively; the effective scattering time increases with the magnetic field, i.e., $\tau_{\text{emp}} \propto B$ [7], and the field dependence of the mean free path of the edge magnetoplasmon is determined by the weak logarithmic term

$$L_{\text{emp}} = v_{\text{emp}} \times \tau_{\text{emp}} \propto \ln(1/B). \quad (7)$$

In view of the significant interest in various applications using physical properties of plasma excitations in low-dimensional systems [4, 8], investigation of the temperature dependence of the mean free path of edge magnetoplasmons is of current interest. We found that, as temperature increases, the amplitude of the magnetoplasma oscillations decreases noticeably (see Fig. 3b), which indicates that the mean free path decreases. Figure 4 shows the temperature dependences of the amplitude of the fast Fourier transform of the photovoltage signal for modes with various L values in the semilogarithmic scale. It is seen that an increase in L is accompanied by a sharp decrease in the critical temperature T_c at which a sharp drop in the amplitude of the magnetoplasma oscillations is observed. This result can be treated as follows. As was mentioned above, the mean free path of edge magnetoplasmons decreases as the temperature increases; for this reason, oscillations disappear (the kinks in Fig. 4) when $L_{\text{emp}}(T_c)$ is equal to L . Correspondingly, $L_{\text{emp}}(T_c = 23 \text{ K}) \approx 0.9$ mm, $L_{\text{emp}}(T_c = 75 \text{ K}) \approx 0.4$ mm, and $L_{\text{emp}}(T_c = 125 \text{ K}) \approx 0.2$ mm at an incident radiation frequency of 46 GHz and electron density $n_s = 2.6 \times 10^{11}$ cm $^{-2}$. We emphasize that an increase in the critical temperature

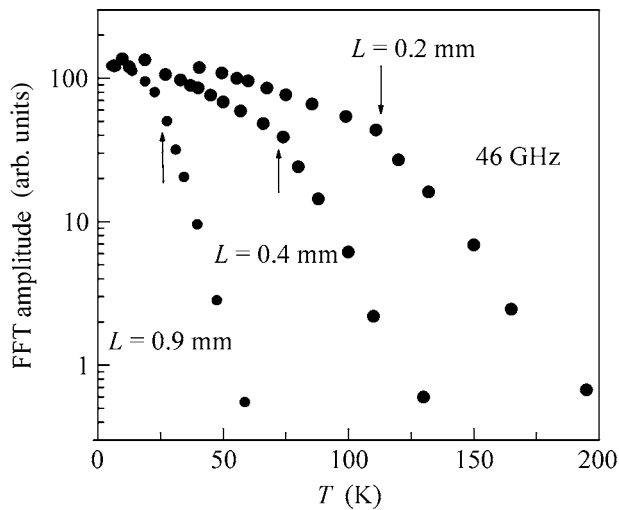


Fig. 4. Temperature dependences of the amplitude of the fast Fourier transform of the photovoltage signal as measured at the frequency $f = 46$ GHz for modes with various lengths L ; $n_s = 2.6 \times 10^{11} \text{ cm}^{-2}$. The arrows show the critical temperatures T_c for various L values.

above 150 K is not observed with a further decrease in L . A possible explanation for this fact is that the rectifying property of the near-contact region disappears at these temperatures, because the temperature becomes equal to the Fermi energy of the electrons. The restriction mentioned above can be overcome by increasing the electron density. Moreover, we find that the mean free path of the edge magnetoplasmons decreases as the frequency increases or the electron mobility decreases. Detailed investigations of the dependence of L_{emp} on the

frequency, the magnetic field, the electron density, and the temperature will be reported elsewhere.

Thus, the effect of the temperature, the magnetic field, and the frequency of the microwave radiation on the mean free path of edge magnetoplasmons has been investigated in this work. The spectral analysis of photovoltage magnetic oscillations reveals two different frequencies corresponding to different trajectories of edge magnetoplasmons and effects of the interference between collective excitations on these trajectories.

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