New Type of *B*-Periodic Magneto-Oscillations in a Two-Dimensional Electron System Induced by Microwave Irradiation

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We observe a new type of magneto-oscillations in the photovoltage and the longitudinal resistance of a two-dimensional electron system. The oscillations are induced by microwave radiation and are periodic in magnetic field. The period is determined by the microwave frequency, the electron density, and the distance between potential probes. The phenomenon is accounted for by interference of coherently excited edge magnetoplasmons in the contact regions and offers perspectives for developing new tunable microwave and terahertz detection schemes and spectroscopic techniques.

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Studies of two-dimensional electron systems (2DES) have revealed a variety of magneto-oscillations of both classical and quantum nature. The quantization of the spectrum into Landau levels manifests itself in $1/B$-periodic Shubnikov–de Haas oscillations [1] and in the quantum Hall effect [2]. Other examples of $1/B$-periodic oscillations include magnetophonon resonances, geometrical commensurability effects between the cyclotron radius and the period of a potential modulation [3], as well as the recently discovered microwave-induced zero-resistance states [4–8]. The latter are governed by the ratio of the microwave frequency ω to the cyclotron frequency ω_c in the regime $\omega > \omega_c$. There also exist magnetotransport phenomena that yield B-periodic oscillations, such as the quantum Aharonov-Bohm effect and the classical effect of ballistic electron focusing between point contacts [9,10].

In this Letter, we report on a new type of B-periodic magnetotransport oscillation in GaAs/AlGaAs quantum wells. The effect is observed under incident microwave radiation when $\omega < \omega_c$ (in contrast to the work in Refs. [4–8]) and consists of an oscillatory B-field dependence of the microwave-induced photovoltage and the longitudinal resistance R_{xx}. The oscillation period $\Delta B \propto n_s/\omega L$ depends on the microwave frequency ω, the electron density n_s, and the distance between potential probes L placed along the long side of the Hall bar. We interpret the observed oscillations as the manifestation of interference between edge magnetoplasmons (EMPs) [11–26], coherently emitted near the contact regions under the influence of microwaves. The effect was observed in samples with macroscopic distances between contacts ($\sim$1 mm), in moderate fields (below 1–3 T), and across a wide range of microwave frequencies and temperatures (up to 70 K).

Samples were processed from the same heterostructure into Hall bars with differing width W and distance between adjacent potential probes L: $(W, L) =$ (0.4 mm, 0.5 mm) — type *A*; (0.5 mm, 0.2 mm) — type *B*; (0.5 mm, 0.4 mm) type *C*; (0.5 mm, 1.6 mm) — type *D*. In the dark, the electron density and mobility were equal to 1.6×10^{11} cm^{-2} and 6×10^5 cm^2/V s. In the majority of cases, a brief initial exposure of the sample to white light was necessary to bring out the B-periodic oscillations under incident microwave radiation. The density increased up to 3.3×10^{11} cm^{-2} and the mobility improved to 1.3×10^6 cm^2/V s. The sample was placed in an oversized 16 mm waveguide near the maximum of the microwave electric field. Generators covered frequencies from 12 to 58 GHz with input powers up to 1 mW. A 12 Hz sinusoidal current between 0.1 and 1 μA was driven through the sample. For these amplitudes, Ohmic behavior was satisfied. The microwaves were modulated at 2 kHz. The double modulation technique enabled us to simultaneously measure the influence of microwaves on the longitudinal magnetoresistance R_{xx} (at 12 Hz) as well as to detect a microwave-induced photovoltage V_{xx} (at 2 kHz), which appears across any pair of contacts along the side of the Hall bar and is independent of current flow through the sample. Control experiments verified that the same photovoltage was generated in the absence of an imposed current and that magnetoresistance oscillations occurred for unmodulated microwaves.

Figure 1(a) shows the B dependence of R_{xx} measured without and with microwave irradiation for frequencies of 23 and 53 GHz. Apart from the $1/B$-periodic Subnikov–de Haas oscillations, new B-periodic oscillations emerge under incident radiation. As seen in Fig. 1(a), the period of these oscillations depends on the microwave frequency. Figure 1(b) illustrates the microwave-power

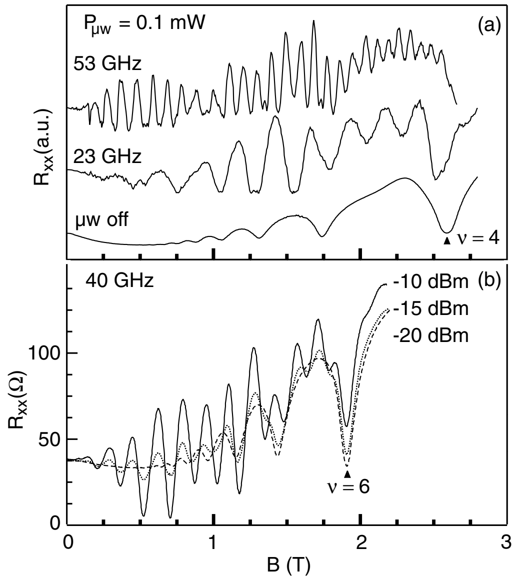

FIG. 1. (a) R_{xx} as a function of B without microwaves (the lower curve) and in the presence of microwaves for two different frequencies at the electron density $n_s = 2.5 \times 10^{11}$ cm^{-1} (the arrow marks the Landau-level filling factor $\nu = 4$). (b) Evolution of R_{xx} vs B with microwave power $P_{\mu w}$ (from bottom to top: 10, 30, and 100 μW) at $n_s = 2.75 \times 10^{11}$ cm^{-2}. The temperature $T = 4.2$ K and the distance between the contacts $L = 0.5$ mm are the same for both plots.

dependence of the effect and shows that the power level strongly influences the amplitude (but not the period). At low microwave frequencies, where the waveguide supports only a single mode, the influence of the microwave polarization has been investigated. The amplitude of the oscillations was found to be always stronger for a microwave electric field perpendicular to the current direction. A threshold behavior as a function of microwave power was established and the threshold power value is approximately 1 order of magnitude lower for microwave radiation polarized perpendicular to the long direction of the Hall bar. Furthermore, the oscillation period is independent of temperature T, and the amplitude drops only by a few percent upon increasing T from 1.5 to 10 K.

In Fig. 2 the oscillation maxima have been assigned an index N and their B-field position is plotted. The B-periodic behavior is apparent and holds for a wide range of frequencies (at least from 12 to 58 GHz). Figure 3 illustrates in more detail how the period ΔB (extracted from a fast-Fourier-transform analysis) depends on microwave frequency as well as on electron density. ΔB is inversely proportional to the frequency and superlinearly increases with the density. By studying different Hall bar geometries, it was also established that ΔB is approximately proportional to the inverse distance between potential probes L [see Fig. 3(b)].

Apart from the oscillations in R_{xx}, we also observed a B-periodic photovoltage V_{xx} across any voltage contact pair along the side of the Hall bar at the modulation frequency of the microwaves. The B periodicity (see

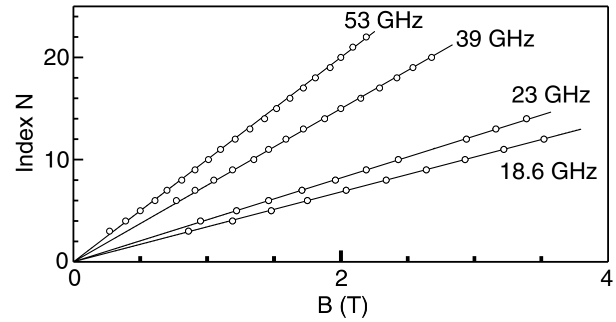

FIG. 2. Oscillation maxima are assigned an integer index N. Their B-field position is plotted versus this index for various microwave frequencies ($n_s = 2.61 \times 10^{11}$ cm^{-2}; $L = 0.5$ mm).

Fig. 4) is identical (although with a 1/4-period phase shift) and suggests a similar physical origin. However, the microwave-power and the temperature dependencies of their amplitude are different. The amplitude of the photovoltaic oscillations is linear in microwave power without a threshold and saturates at a value of approximately 2 mV for 0.1 mW of power. This is close to the threshold power of the R_{xx} oscillations. In addition, the photovoltaic effect is even less sensitive to temperature and drops only by 1 order of magnitude when raising the temperature to 70 K.

The dependence of the period ΔB on microwave frequency, electron density, and distance between potential contacts suggests that the effect is related to the excitation of EMPs in the vicinity of potential probes. EMPs are plasma waves propagating along the edge of the 2DES in the direction dictated by the external B field [11–26]. Their velocity is proportional to the Hall conductivity $\sigma_{yx} \propto n_s/B$. Hence, assuming that their wave vector is given by $2\pi N/L$ with integer N, one immediately finds the qualitatively correct dependencies $\Delta B \propto n_s/\omega L$.

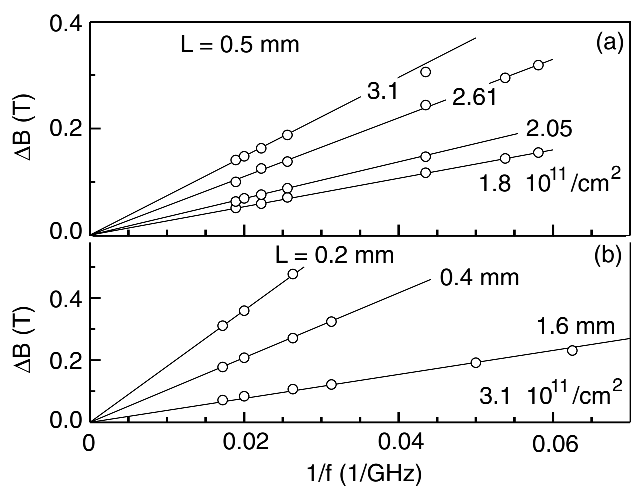

FIG. 3. (a) The period ΔB of the oscillations versus inverse microwave frequency for various electron densities and $L = 0.5$ mm (Hall bar geometry of type A). (b) ΔB versus $1/f$ for different distances between potential contacts (types B, C, and D) and $n_s = 3.1 \times 10^{11}$ cm^{-2}.

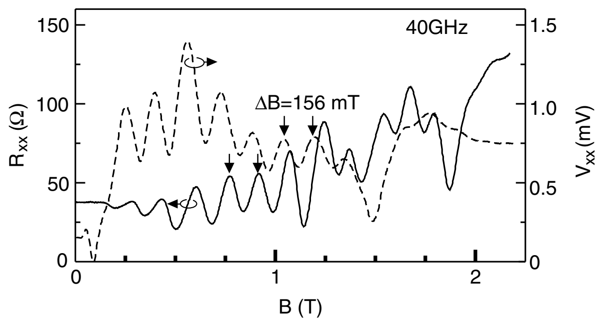

FIG. 4. Magnetoresistance R_{xx} and photovoltage V_{xx} versus applied B field for 40 GHz incident microwave radiation, $n_s = 2.75 \times 10^{11}$ cm^{-2}, $L = 0.5$ mm, and a 1 μA sample current.

Now, we consider the phenomenon in more detail. The inset in Fig. 5 schematically shows the contact region in our samples. The contact may be regarded as a piece of wire of width w attached to the 2DES. The oscillating external electric field $\mathbf{E}(t) = \mathbf{E}_0 e^{-i\omega t}$ induces an oscillating current inside the wire and produces oscillating line charges near its sides, with the linear charge density ρ estimated as [27]

$$\rho = \frac{\sigma_{yx}(\omega)E_x^0 + \sigma_{yy}(\omega)E_y^0}{i\omega\zeta(\omega)}. \tag{1}$$

Here $\sigma_{\alpha\beta}(\omega)$ is the dynamical conductivity tensor, $\zeta(\omega) = 1 - \omega_p^2/(\omega^2 - \omega_c^2)$, and ω_p are the dielectric response function and the plasma frequency of the wire ($\omega_p^2 \propto n_s/w$). We assume the collisionless Drude model for $\sigma_{\alpha\beta}(\omega)$. Because the potential probes violate the translational invariance of the 2DES edge, they create oscillating dipoles, which serve as antennas emitting EMPs. The frequency of the excited EMPs equals the microwave frequency ω, and their wave vector q_y is determined from the dispersion equation $D(q_y, \omega) = 0$, where [17]

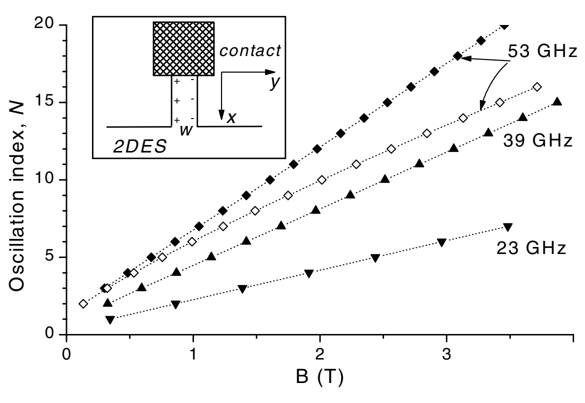

FIG. 5. The oscillation index N calculated from the dispersion equation $D(2\pi N/L, \omega) = 0$ as a function of B for the parameters of our samples: $n_s = 2.61 \times 10^{11}$ cm^{-2}, $L = d_2 = 0.5$ mm, and $d_1 = 0.21$ μm (solid symbols). The curve with open symbols is plotted for $f = 53$ GHz and $d_1 = 0$ μm (no cover layers). The inset schematically illustrates the distribution of microwave-induced charges near contacts.

$$D(q_y, \omega) = \frac{i|q_y|\sigma_{xx}(\omega)}{q_y\sigma_{yx}(\omega)} - \tanh\left\{\int_0^{\pi/2} \ln\epsilon\left(\frac{|q_y|}{\sin t}, \omega\right)\frac{dt}{\pi}\right\}. \tag{2}$$

Here, we have assumed a sharp, steplike equilibrium density profile $n_s(x) = n_s\theta(x)$ and

$$\epsilon(q, \omega) = 1 + \frac{4\pi i\sigma_{xx}(\omega)q}{\omega\kappa\left[\frac{\kappa\tanh qd_1 + 1}{\kappa + \tanh qd_1} + \frac{\kappa\tanh qd_2 + 1}{\kappa + \tanh qd_2}\right]} \tag{3}$$

is the wave vector and frequency dependent dielectric function of the system composed of (i) the substrate with thickness d_2 and dielectric constant κ, (ii) the 2D electron layer, and (iii) cover layers with total thickness d_1 and dielectric constant κ consisting of the AlGaAs spacer, the dopant layer, and the usual capping layers.

The excitation of coherent EMPs in adjacent contacts on the same side of the Hall bar a distance L apart may be in phase or out of phase depending on the wave vector q_y of the EMPs. If the chiral EMP exiting the left contact propagates to the right, it may constructively interfere with the EMP injected by the second contact provided that the traveled distance L is such that q_yL takes on a multiple of 2π. The amplitude of the combined wave propagating to the right from the second contact will thus oscillate as a function of q_yL, with maxima/minima occurring each time when $q_yL = 2\pi N$. In experiment, this manifests itself in the observed magneto-oscillations of the photovoltage and the photoresistance. We calculate the "oscillation index" N as a function of B field by solving the EMP dispersion equation $D(2\pi N/L, \omega) = 0$ numerically. The results (Fig. 5, solid symbols) demonstrate a nearly linear dependence $N(B)$. The slope of the $N(B)$ curves is somewhat smaller than in experiment (Fig. 2), which implies that the "theoretical" EMPs are running faster than in experiment. There are two factors which may help to explain this quantitative discrepancy: inaccurate descriptions of either the dielectric environment surrounding the 2DES or of the equilibrium density profile $n_s(x)$. The curve with open symbols in Fig. 5 for $d_1 = 0$ demonstrates, for instance, the importance of including a very thin, but nonvanishing cover layer. It substantially improves agreement with experiment both in terms of the linearity and slope. Incorporating the presence of metallic pieces around the sample (wires and the waveguide), as well as a more realistic density profile $n_s(x)$ with soft walls (smoothed over a μm-scale length [22–25]) will further reduce the EMP velocity and improve the agreement.

The validity of the EMP-based interpretation was additionally tested by measuring the photovoltage on a sequence of three potential probes (1, 2, and 3) on the same side of the Hall bar in positive and negative B fields. Because of the chiral nature of EMPs, the observed photovoltage oscillations for a given B orientation were stronger between contacts (2,3) and smaller for potential probe pair (1,2). When inverting the B orientation, the

EMP propagation direction was concomitantly reversed and the oscillations became pronounced between contacts (1,2) and weak for pair (2,3). Also the polarization dependence of the effect is consistent with the proposed model. Since at high magnetic fields $\sigma_{yx} \gg \sigma_{yy}$, the amplitude of the EMP emitting dipoles, Eq. (1), is much stronger for microwave fields polarized across the Hall bar in agreement with observations.

A quantitative microscopic model for nonlinearities, which enable the detection of EMPs through a measurement of the induced photovoltage and photoresistance, is yet to be developed. Qualitatively, the photovoltaic effect may be caused by rectification of the oscillating EMP field in the potential probes and/or by local *dc* currents dragged along the edges by propagating EMP waves. Both mechanisms yield the linear dependence of the photovoltage on microwave power. The nonlinear dependence of the photoresistance could be accounted for as follows. At low power levels, the oscillating EMP field causes a *dc* voltage between potential probes but does not significantly modify equilibrium properties of the 2DES such as the density. At stronger microwave powers, n_s is locally altered (near the contacts) and the longitudinal resistance is affected. The same EMP-emission mechanism may therefore produce the B-periodic oscillations in R_{xx}, but only at large enough powers. The classical nature of EMPs explains why the effect is weakly influenced by T and why it is observable even at liquid nitrogen temperatures.

In summary, we have observed a novel type of B-periodic microwave-induced oscillation in the photovoltage and the photoresistance of the 2DES. We ascribe it to the coherent excitation and interference of edge magnetoplasmons, which generate a nonlinear response. The phenomenon was seen across a broad range of frequencies, in moderate B fields and up to liquid nitrogen temperatures. It opens prospects for developing innovative microwave and terahertz detection schemes and spectroscopic techniques.

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