Photovoltaic oscillations due to edge-magnetoplasmon modes in a very high-mobility two-dimensional electron gas

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Using very high-mobility GaAs/Al_xGa_{1-x}As two-dimensional electron Hall bar samples, we have experimentally studied the photoresistance and/or photovoltaic oscillations induced by microwave irradiation in the regime where both $1/B$ and B-periodic oscillations can be observed. In the frequency range between 27 and 130 GHz, we found that these two types of oscillations are decoupled from each other, consistent with the respective models that $1/B$ oscillations occur in bulk while the B oscillations occur along the edges of the Hall bars. In contrast to the original report of this phenomenon [I. V. Kukushkin *et al.*, Phys. Rev. Lett. **92**, 236803 (2004)], the periodicity of the B oscillations in our samples is found to be independent of L, the length of the Hall bar section between voltage measuring leads.

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The magnetoplasmons[2] in a two-dimensional electron gas (2DEG) are coupled modes of two-dimensional (2D) plasmons and cyclotron orbits in the presence of a perpendicular magnetic field B. It has long been known that on the edge of the 2DEG, chiral edge modes, or edge magnetoplasmons (EMPs), can also exist.[2–11] In transport experiments, both types of mode have been observed in the microwave photoresistance measurements.[1,8,12,13] One remarkable recent result is the discovery of a new type of B-periodic oscillation in Hall bar samples consisting of a high-mobility GaAs/Al_xGa_{1-x}As heterostructure,[7] where the oscillations are explained by the interference effect between EMPs being emitted from adjacent electrical contacts and propagating along the same edge of a Hall bar. Quantitatively, the period of the oscillation is found to be $\Delta B \propto n_s/\omega L$, where n_s is the 2D electron density, $\omega = 2\pi f$ the microwave frequency, and L the distance between the contacts.

The B-period oscillations have so far been observed[1,8] in the magnetic field range corresponding to $\omega_c > \omega$, where $\omega_c = eB/m^*$ is the cyclotron frequency and $m^* = 0.068\, m_e$ is the electron effective mass in GaAs. In a lower B range, $\omega_c \leqslant \omega$, the microwave-induced resistance oscillations (MIROs), which are periodic in $1/B$, are observed.[13] As the sample's mobility increases, the MIROs become stronger. It is then possible to create zero-resistance states (ZRSs) under sufficiently high microwave irradiation.[14,15] While the exact nature of these effects has not been conclusively established, it has been theoretically proposed that the MIRO and ZRS result from the nonequilibrium 2DEG driven by microwave (MW) irradiation and the consequent symmetry breaking into current domains.[16,17]

We have measured the MW photoresistance and photovoltage in a very high-mobility (mobility $\mu \approx 1 \times 10^7$ cm^2/V s) 2DEG in GaAs/Al_xGa_{1-x}As heterostructures. In contrast to previous results, in our samples, we are able to observe both the MIRO/ZRS effects and the B-periodic oscillations (i.e., the EMP modes) in the same sample, where both features overlap at a certain magnetic field and MW frequency range. Analysis shows that these two types of oscillations are essentially decoupled from each other. Detailed comparisons of data in the B-periodic regime confirm the previous conclusion[1] that the period ΔB is inversely proportional to the MW frequency. However, in stark contrast to those reported by Kukushkin *et al.*,[1] in our very high-mobility samples, ΔB is found to be independent of L, the distance between the contacts. Such observation is not understood at this point, but it could be indicative that the photoresponse to the EMP is strongly nonlocal in our very high-mobility samples.

Our specimens are Hall bars defined by lithography and wet etching from a GaAs/$Al_{0.3}Ga_{0.7}$As heterostructure grown by molecular-beam epitaxy. Sample A has a Hall bar width (W) of 100 μm and has two sections of 1 and 2 mm (L) that make up 10 and 20 square sections, respectively. The contact leads have the same width of 100 μm. Sample B has a similar geometry but with a width (both bar and leads) of 200 μm, giving the 1 and 2 mm sections of five and ten squares, respectively. High quality Ohmic contacts to the 2DEG were made by high temperature diffusion of indium. After a brief illumination with visible light, at $T = 0.3$ K, sample A (B) attained a sheet density $n_s \approx 2.27 \times 10^{11}$/cm^2 ($2.45 \times 10^{11}$/cm^2) and a mobility $\mu \approx 8.3 \times 10^6$ cm^2/V s (11×10^6 cm^2/V s). Our measurement was performed in a ^{3}He refrigerator equipped with a superconducting magnet. The MWs were generated by a set of Gunn diodes and sent via a rectangular waveguide (WG-28) to the sample immersed in the ^{3}He coolant. The mutual orientations of the waveguide, 2DEG plane, and the magnetic field corresponded to Faraday configuration. For MW frequencies $f < 44$ GHz, the waveguide operated in single mode and the $\vec{E}$ polarization of the MW was perpendicular to the Hall bar direction.

The magnetoresistance under MW irradiation, R_{xx}^{ω}, was measured by standard low frequency (23 Hz) lock-in technique and using a sample excitation current $I = 1\ \mu$A. The photoresistance $\Delta R = R_{xx}^{\omega} - R_{xx}^{0}$, where R_{xx}^{0} is the "dark" resis-

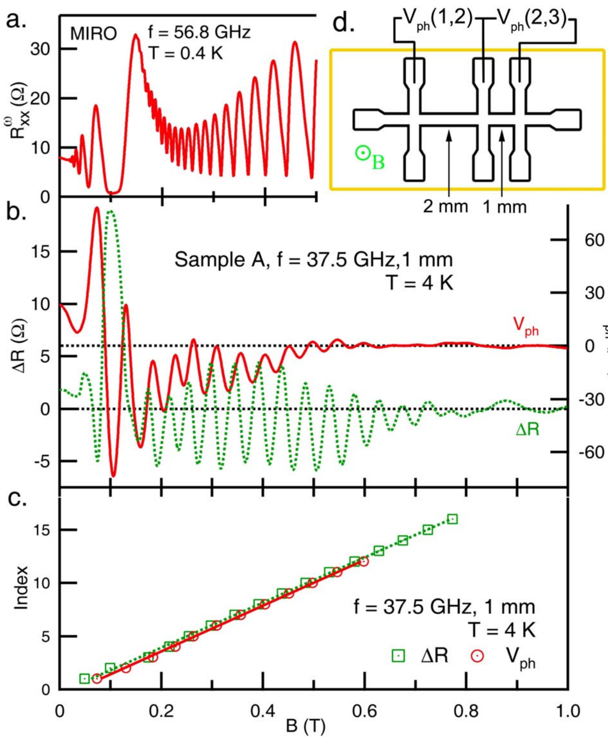

FIG. 1. (Color online) (a) Typical low temperature (T=0.4 K) photoresistance data showing microwave-induced resistance oscillations and the corresponding zero-resistance state. (b) Differential photoresistance (ΔR) and photovoltage (V_{ph}) were measured simultaneously at 37.5 GHz irradiation along the 1 mm section of sample A at T=4 K. B-periodic oscillations are clearly observed at B >0.2 T; at lower magnetic fields, MIRO also contributes to the signal. (c) Plot of the field position of oscillation maxima vs their index. Linear fits give a slope of 21.16/T and 21.47/T for ΔR and V_{ph}, respectively. (d) Schematic of Hall bar sample, geometry of the waveguide cross section, and the contact configuration for the photovoltage measurement.

tance, was measured by a double-modulation technique, whereas V_{ph}, the photovoltage signal, was measured in the absence of an external excitation current I.

Figure 1 shows typical data of R^{ω}_{xx}, ΔR, and V_{ph} measured in sample A. We first notice that in the low B range, B <0.2 T, and at a low temperature T=0.4 K, the R^{ω}_{xx} is completely dominated by the MIRO signal [Fig. 1(a)], and in an increasing B range, $B>0.2$ T, usual Shubinikov–de Haas (SdH) oscillations take over. Through the contacts for the ten-square Hall bar section in sample A, strong B-periodic oscillations in both ΔR and V_{ph} are observed [shown, for example, in Fig. 1(b) for ω=38.9 GHz] in a wide temperature range from 0.4 to 20 K. These are the characteristic signals that originate from the EMP, as first reported by Kukushkin *et al.*[1] Conforming to their results, the period of the oscillations ΔB are found to be identical to ΔR and V_{ph} [Fig. 1(c)] with some phase shift with respect to each other.

The ΔR (38.9 GHz) for sample A at various T is shown in Fig. 2. At T=0.3 K and in the range $B<0.2$ T, sharp MIRO can be identified as a pair of peaks and valleys around the ω/ω_c=1 (solid arrow). Beyond ω/ω_c=1, a second pair of

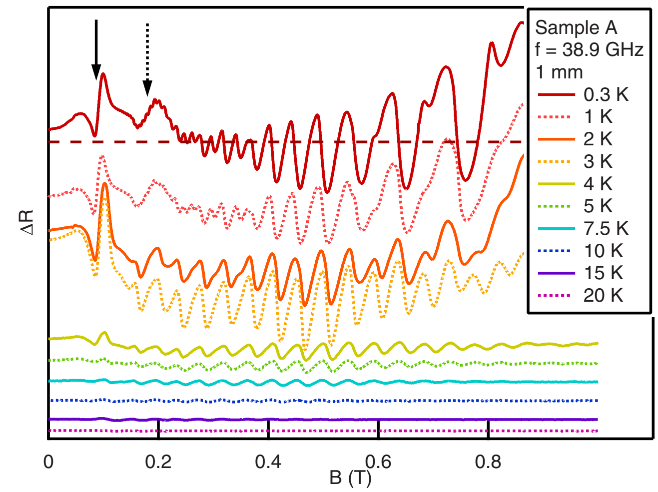

FIG. 2. (Color online) Temperature dependence of the photoresistance ΔR for sample A at a microwave frequency of 38.9 GHz. The arrows mark the microwave-induced resistance oscillations (MIROs). At low temperature, $T<2$ K, ΔR is dominated by $1/B$ oscillation (MIRO and SdH), and at higher temperatures, $T>4$ K, by B-periodic oscillations.

peaks and valleys surrounding ω/ω_c=1/2 (dotted arrow) is also observed; this is the photoresistance feature associated with the two-photon nonlinear process reported elsewhere.[13] In an increasing B range, $B>0.2$ T, the ΔR is dominated by $1/B$ oscillations originating from the MW heating effect in SdH; the oscillations are 180° out of phase with respect to the SdH in R_{xx}. In general, the B-period oscillations are best resolved at an elevated temperature ($T>4$ K) where both MIRO and SdH are damped out. In our samples, the B-periodic oscillations are found to persist up to 20 K. This temperature is somewhat lower than that reported by Kukushkin *et al.*; the difference could be due to the fact that we use a relatively low MW power (typically 10–100 μW at the sample location).

We have carefully measured V_{ph} for samples A and B over a frequency range from 27 to 130 GHz and found that B-periodic oscillations are generic features in our samples. As examples, the V_{ph} for the sample A (1 mm section) is shown in Fig. 3(a) for various values of f. Linear fits to the B positions of the peaks vs their index [Fig. 3(b)] are generally satisfactory. As shown in Fig. 4(c), our data, in particular, confirm the reported[1] inverse-linear relation $\Delta B \propto 1/\omega$.

While the data from our very high-mobility samples have, by and large, confirmed the reported B-periodic oscillations and its inverse scaling with the MW frequency, we found that the period ΔB appears to be independent of L for both samples A and B. Such a lack of length scaling can be clearly shown in the data presented in Fig. 4. Taking sample A and referring to Fig. 1(d) for the contact configuration, we observe that the $V_{ph}(1,2)$ and the $V_{ph}(2,3)$ have almost identical oscillations except that the phase differs by 180°. Since the leads were both connected the same way and the center junction of the Hall bar lines up closely with the center of the waveguide, we can assume that the opposite signs in V_{ph} originate from the opposite gradients of the microwave elec-

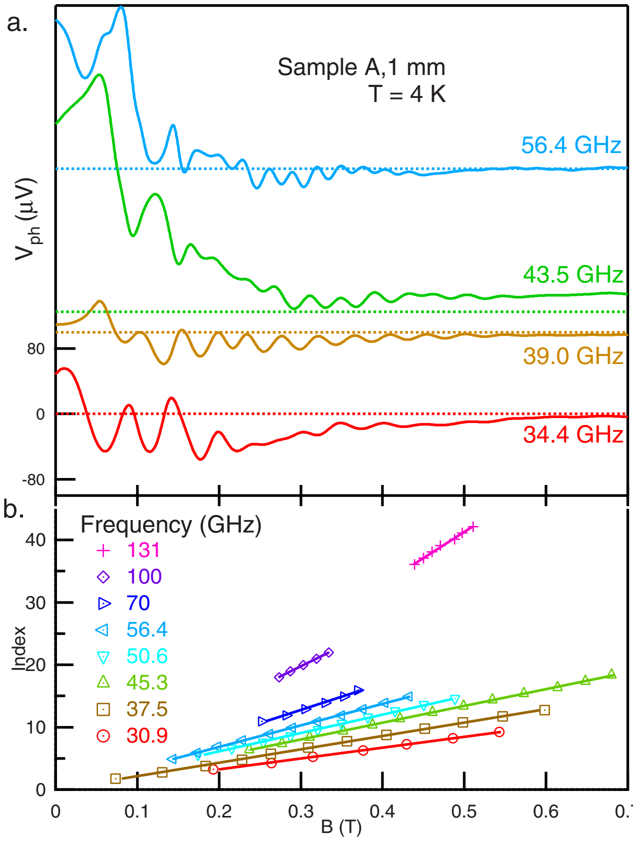

FIG. 3. (Color online) (a) Examples for photovoltage signal V_{ph} as a function of the magnetic field B for selected microwave frequencies. (b) Linear fits to B positions of the V_{ph} peaks show that the oscillations are periodic in B; from the slope of the fitting line, the oscillation period ΔB is determined.

tric field inside the waveguide. The fact that the contacts for the 1 and 2 mm sections have resulted in a "mirror image," V_{ph} was completely unexpected. We have measured the same quantities over a wide range of frequencies and found consistent results. In particular, we found that the relationship between the period ΔB and $1/f$ is almost identical for the 1 and 2 mm portions of both samples with slopes of 1.86 and 1.84 T GHz, respectively. From these results, we conclude that the B-periodic oscillations are not visibly dependent on length of the Hall bar between the leads. To confirm this result, we also measured V_{ph} in sample B which had a width of 200 μm and respective sections are five and ten squares. As shown in Fig. 3(b), the B-periodic oscillations in this second sample also have no L dependence.

Since samples A and B have different electron densities n_s, it is worthwhile to examine if ΔB scales with n_s. From Fig. 4(c), we found a slope ratio of $2.50/1.85=1.35$, which is about 25% larger than the ratio of density $2.45/2.27=1.08$. We consider this to be qualitatively consistent with the result from Kukushkin *et al.*, i.e., $\Delta B \propto n_s$.

To summarize, we have experimentally measured the photoresistance and photo voltage signals in a very high-mobility 2DEG and observed B-periodic oscillations over a wide range of microwave frequencies. Both the $1/B$ oscillations, which originate from electron Landau level transitions,

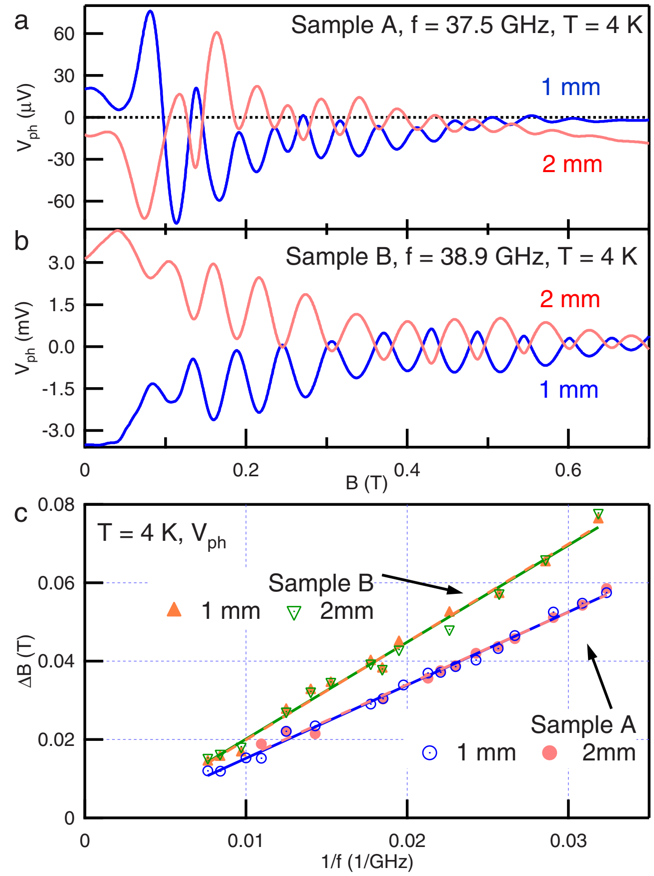

FIG. 4. (Color online) (a) Example traces of photovoltages $V_{ph}(1,2)$ (measured in the 2 mm section) and $V_{ph}(2,3)$ (1 mm section) in sample A at a microwave frequency 37.5 GHz. The V_{ph} oscillations from the two sections have approximately the same magnitude but with opposite signs. (b) Examples of similar data from sample B at 38.9 GHz. (c) The plot of ΔB vs inverse microwave frequency $1/f$ shows a linear relation; the data from 1 and 2 mm sections from the same sample collapse on the same line, indicating that the ΔB is independent of contacts in a wide frequency range. From the plot of ΔB vs $1/f$, slopes of 1.85 and 2.50 T GHz are determined for samples A and B, respectively.

and the B-periodic oscillations, which originate from edge-magnetoplasmon modes, have been observed in the same sample. We confirm that the oscillation period of the latter scales inversely with the microwave frequency, $\Delta B \propto 1/\omega$. However, our data in the very high-mobility samples do not conform to the previous result[1] that $\Delta B \propto 1/L$.

Our observations from the very high-mobility samples are rather puzzling, and we cannot find a satisfactory explanation at this point. On one hand, several major features observed in our samples clearly support the interpretation of the B-periodic oscillations as being associated with the EMP. In particular, ΔB is proportional to n_s/ω, showing a characteristic relation for propagating EMP modes in a 2DEG. On the other hand, without a length scale, the interpretation based on a simplistic interference model[1] appears irrelevant. Even more puzzling is the fact that both the 1 and 2 mm sections exhibit photovoltage signals that completely mirror each other.

Our results strongly suggest that in very high-mobility Hall samples, the microwave photoresponses are predominately nonlocal in the sense that the photovoltaic signal can propagate along the edge of the entire sample. It is plausible that long-wavelength EMP modes, which are chiral in nature, can circulate around the whole sample perimeter and dominate the dynamics of the 2DEG. This process would be more favorable in our very high-mobility samples due to the extremely long decay length of the EMP modes in these samples. Moreover, the photocurrents that are presumably generated by dragging of the EMP propagation could be strongly dependent on the EMP wave vector (both in terms of magnitude and direction). Consequently, the interference signal generated in one pair of contacts could propagate along the edge of the entire sample and dominate the photovoltaic signal on the other pairs. In an alternative scenario, the mirror V_{ph} signals measured from the adjacent contact pairs could be driven by the Hall field in the presence of photocurrents running in the central contact lead, exciting oscillations with the same period in B.

In conclusion, we have experimentally investigated the magneto-oscillations in both resistance and photovoltage in a very high-mobility 2DEG irradiated by gigahertz microwaves. MIRO, ZRS, and EMP were observed in the same sample, indicating that these are decoupled effects. Our central finding that the B-periodic oscillations observed in our samples have no apparent dependence on the contact configuration (including the contact separation distance) can be interpreted tentatively as resulting from the chiral dynamics of the EMP and the strong nonlinear response in photovoltage to such properties.

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