Photovoltaic Oscillations Due to Edge-Magnetoplasmon Modes in a Very-High Mobility 2D Electron Gas

K. Stone, C. L. Yang, Z. Q. Yuan, and R. R. Du
Department of Physics and Astronomy, Rice University, Houston, Texas 77005

L. N. Pfeiffer and K. W. West
Bell Laboratories, Alcatel-Lucent, Murray Hill, New Jersey 07974

Using very-high mobility GaAs/Al$_x$Ga$_{1-x}$As 2D electron Hall bar samples, we have experimentally studied the photoresistance/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 (Ref. 1) the periodicity of the $B$-oscillations in our samples are found to be independent of $L$, the length of the Hall bar section between voltage measuring leads.

The magnetoplasmons in a two-dimensional electron gas (2DEG) are coupled modes of 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 (EMP), can also exist. In transport experiments, both types of mode have been observed in the microwave photoresponse measurements. 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$_x$Ga$_{1-x}$As heterostructure, 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 in the magnetic field range corresponding to $\omega_e > \omega$, where $\omega_e = eB/m^*$ is the cyclotron frequency, and $m^* = 0.068 m_e$ is the electron effective mass in GaAs. In a lower $B$ range, $\omega_e < \omega$, the microwave-induced resistance oscillations (MIRO), which are periodic in $1/B$, are observed. As the sample’s mobility increases, the MIRO become stronger. It is then possible to create zero-resistance states (ZRS) under sufficiently high microwave irradiation. 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 non-equilibrium 2DEG driven by MW irradiation and the consequent symmetry-breaking into current domains.

We have measured the MW photoresistance and photovoltage in a very-high mobility (mobility $\mu \approx 1 \times 10^7 \text{cm}^2/\text{Vs}$) 2DEG in GaAs/Al$_x$Ga$_{1-x}$As heterostructures. 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 that the period, $\Delta B$, is inversely proportional to the MW frequency. However, in stark contrast to those reported by Kukushkin et al., in our very-high mobility samples $\Delta B$ 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 $\mu$m 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 $\mu$m. Sample B has a similar geometry but with a width (both bar and leads) of 200 $\mu$m, giving the 1 and 2 mm sections 5 and 10 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 $T = 0.3 K$ the sample A (B) attained a sheet density $n_s \approx 2.27 \times 10^{11}/\text{cm}^2$ (2.45 $\times 10^{11}/\text{cm}^2$), and a mobility $\mu \approx 8.3 \times 10^6 \text{cm}^2/\text{Vs}$ (11 $\times 10^6 \text{cm}^2/\text{Vs}$). Our measurement was performed in a $^3He$-refrigerator equipped with a superconducting magnet. The microwaves (MW) were generated by a set of Gunn diodes and sent via a rectangular waveguide (WG-28) to the sample immersed in the $^3He$ coolant. The mutual orientations of the waveguide, 2DEG plane, and the magnetic field corresponded to Faraday configuration. For MW frequencies $f < 44 \text{GHz}$, the waveguide operated in single-mode and the $E$ polarization of the MW was perpendicular to the Hall bar direction.

The magnetoresistance under MW irradiation, $R'_{xx}$, was measured by standard low frequency (23 Hz) lock-in technique and using a sample excitation current $I = 1 \mu$A. The photoresistance, $\Delta R = R'_{xx} - R'_{xx}^0$, where
We have carefully measured $V_{ph}$ for samples A and B over a frequency range from 27 GHz 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. 3a for various values of $B$. In an increasing $B$ range, $B > 0.2$ T, the $\Delta R$ 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 in Kukushkin et al.; the difference could be due to the fact that we use a relatively low MW power (typically 10-100 $\mu$W at the sample location).

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, $\Delta B$, 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. 1d for the contact configuration, we observe that the $V_{\text{ph}}(1,2)$ and the $V_{\text{ph}}(2,3)$ have almost identical oscillations except that the phase differs by $180^\circ$. 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 $V_{\text{ph}}$ originate from the opposite gradients of the microwave electric field inside the waveguide. The fact that the contacts for the 1 mm and 2 mm sections have resulted in a “mirror image” $V_{\text{ph}}$ 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 $\Delta B$ and $1/f$ is almost identical for the 1 mm and 2 mm portion of both samples with slopes 1.86 $T \cdot GHz$ and 1.84 $T \cdot GHz$, 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 $V_{\text{ph}}$ in sample B which had a width of 200 $\mu m$ and respective sections are 5 and 10 squares. As shown in FIG. 3b, 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 $\Delta B$ scales with $n_s$. From FIG. 4c, 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 photvoltage 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, and the $B$-periodic oscillations which originate from edge magneto-plasmon modes, have been observed in the same sample. We confirm that the oscillation period of the later inversely scales 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 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, $\Delta B$ is proportional to $n_s/\omega$, 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 appears irrelevant. Even more puzzling is the fact that both the $1\text{ mm}$ and $2\text{ mm}$ sections exhibit photovoltage signals that completely mirror each other.

Our results strongly suggest that in very-high mobility Hall samples the microwave photoresponse 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 wavevector (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 $V_{\text{ph}}$ 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 2D electron gas irradiated by GHz microwaves. For the first time, 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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