Density dependence of microwave induced magneto-resistance oscillations in a two-dimensional electron gas

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We have measured the magneto-resistance of a two-dimensional electron gas (2DEG) under continuous microwave irradiation as a function of electron density and mobility tuned with a metallic top-gate. In the entire range of density and mobility we have investigated, we observe microwave induced oscillations of large amplitude that are B-periodic. These B-periodic oscillations are reminiscent of the ones reported by Kukushkin et al.1 and which were attributed to the presence of edge-magneto-plasmons. We have found that the B-periodicity does not increase linearly with the density in our sample but shows a plateau in the range \( (2.4-3) \times 10^{11} \text{cm}^{-2} \). In this regime, the phase of the B-periodic oscillations is found to shift continuously by two periods.

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The recent discovery of the vanishing of electrical resistance in a ultra-high mobility 2DEG under microwave irradiation has sparked a large interest in the photoresponse of quantum Hall systems. The so-called microwave-induced “zero-resistance” states have been observed in the magnetic field regime where the cyclotron and microwave frequencies, \( \omega_c \) and \( \omega \) respectively, are such that \( \omega_c \leq \omega \). A key-aspect of this phenomenon lies in its strong dependence on the mobility. In particular, for \( \mu = 3 \times 10^6 \text{cm}^2/\text{Vs} \), some oscillations with a periodicity determined by the ratio \( \omega/\omega_c \) are discerned in the magneto-transport \( \omega_c \) while for \( \mu = 2.5 \times 10^7 \text{cm}^2/\text{Vs} \), these minima fully drop to zero, thereby revealing a sharp suppression of the dissipative processes in the 2DEG.

Independently of this discovery, a different type of microwave related effects, also leading to a strong modulation of the magneto-resistance, has been recently reported to occur in samples with a moderately high mobility of \( \mu = 1.3 \times 10^6 \text{cm}^2/\text{Vs} \). In contrast to the 1/B-periodic oscillations mentioned above, these are B-periodic and develop in the field range where \( \omega \leq \omega_c \). The same experiment performed on samples of different sizes and electron densities has shown that the period of these B-periodic oscillations increases with density and is inversely proportional to the length of the Hall bar.

As discussed in ref \( \omega_c \), these features can be reasonably understood on the basis of edge-magneto-plasmon excitations. Several scenarios for the understanding of the 1/B-periodic oscillations have been put forward recently. It is unclear whether the two effects, namely the B-periodic and the 1/B-periodic oscillations, can coexist in one sample, for there has been no report so far on their coexisting together and to the best of our knowledge, the issue has not yet been addressed. Some recent theoretical and experimental works \( \omega_c \) have stressed the importance of considering plasmon-related excitations to account for the properties of the 1/B-oscillations but a clear understanding of the electrodynamics at work in these systems is still lacking.

In this report, we present a study of the microwave-induced oscillations versus electron density and mobility in a Hall bar patterned on a high-mobility GaAs – Al\(_x\)Ga\(_{1-x}\)As heterostructure. In contrast to previous experiments where the values of \( N_s \) and \( \mu \) were obtained from a brief exposure to light at low temperature, \( N_s \) and \( \mu \) here are tuned continuously by adjusting a top-gate voltage. This permits a systematic study of microwave-induced effects in a large range of densities and mobilities. By increasing the electron density from 0.5 to \( 5 \times 10^{12} \text{cm}^{-2} \), we could tune the mobility in the range of \( (1-7) \times 10^8 \text{cm}^2/\text{Vs} \). In the entire range of densities and mobilities investigated we have observed oscillations of large amplitude that are B-periodic accompanied with a dependence to light exposure. Furthermore, the period of the oscillations does not increase linearly with \( N_s \) but shows unexpectedly a plateau in the range of \( (2.4-3) \times 10^{11} \text{cm}^{-2} \) which occurs concomitantly with a continuous phase shifting of the oscillations by two periods.

Our sample is a high-mobility \( \mu \geq 1.4 \times 10^7 \text{cm}^2/\text{Vs} \) two-dimensional electron gas in GaAs – Al\(_x\)Ga\(_{1-x}\)As heterostructures grown by molecular-beam epitaxy. The 2DEG is located 100 nm below the sample surface. This high mobility is obtained after brief illumination with a red light-emitting diode on a macroscopic Van der Pauw geometry. After the Hall bar has been lithographed \( \omega_c \), some experiments where the values of \( N_s \) and \( \mu \) were obtained from a brief exposure to light at low temperature, \( N_s \) and \( \mu \) here are tuned continuously by adjusting a top-gate voltage. This permits a systematic study of microwave-induced effects in a large range of densities and mobilities. By increasing the electron density from 0.5 to \( 5 \times 10^{12} \text{cm}^{-2} \), we could tune the mobility in the range of \( (1-7) \times 10^8 \text{cm}^2/\text{Vs} \). In the entire range of densities and mobilities investigated we have observed oscillations of large amplitude that are B-periodic accompanied with a dependence to light exposure. Furthermore, the period of the oscillations does not increase linearly with \( N_s \) but shows unexpectedly a plateau in the range of \( (2.4-3) \times 10^{11} \text{cm}^{-2} \) which occurs concomitantly with a continuous phase shifting of the oscillations by two periods.

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The microwave power \( P \) lies in the range (1 \( \mu \)W-1 mW). \( N_s=5 \times 10^{13} \text{cm}^{-2} \) and \( \mu = 7.5 \times 10^7 \text{cm}^2/V \text{s} \) for panel (a) and (b) while \( N_s=4 \times 10^{12} \text{cm}^{-2} \) and \( \mu = 5.3 \times 10^6 \text{cm}^2/V \text{s} \) for panel (c)

The mobility increases linearly up to \( N_s=3 \times 10^{13} \text{cm}^{-2} \) and gradually reaches saturation above. A signal generator operating at 0.001-40 GHz, with typical output power from 10 to 0.1 mW was used as the source of microwaves. They were guided into a dilution fridge via an oversized waveguide with an attenuation of 5dB and the sample was placed in the near field of the waveguide aperture. The frequency was fixed to 35.5GHz for all experiments. The values of microwave power mentioned in what follows are the power levels estimated at the sample location. All data presented here are obtained in the regime where the measured voltages are linear in the applied sinusoidal current (21 Hz) ranging between 50 and 200 nA. The magneto-resistance \( R_{\text{xx}} \) was measured under continuous microwave irradiation while the photovoltage \( V_{\text{xx}} \), which develops across the Hall bar independently of the applied current was measured via dc and ac techniques using for the latter a 2kHz-ac-modulation of the microwave power. The two ways of measuring provided consistent results.

The data can be divided into three distinct experiments which differ in the condition of exposure to a red light emitting diode. For the sake of clarity we refer to these three experiments as experiment No. 1, 2 and 3 respectively. For experiment No. 1, the sample was briefly illuminated at the temperature \( T = 2.2 \text{K} \) and then cooled down to 100 mK which is the base temperature we could reach with our set-up. Note that with microwaves on, the mixing chamber of our dilution fridge heats up to \( T = 300 \text{mK} \) for the maximum power investigated. Experiment No. 2 was performed during the same cool down. The 2DEG was first depleted by applying a negative top-gate voltage and then charged again and exposed to a brief red light illumination at \( T = 300 \text{mK} \). Experiment No. 3, however, involves a different cool down during which the sample was not exposed to illumination at all.

In Fig. 1 we compare the longitudinal magneto-resistance observed for the three experiments at comparable \( N_s \) for various microwave powers ranging between 1 \( \mu \)W and 1 mW. In each case, oscillations of large amplitude induced by microwave irradiation develop on top of Shubnikov de Haas (SDH) oscillations starting at about the threshold \( \omega_c=\omega \). It is obvious, however, that the properties of the B-periodic oscillations are strongly affected by the exposure to light. Their period \( \Delta B \) and their damping with magnetic field differ strongly while \( N_s \) is the same in experiment No. 1 and 2 and only 20% less for experiment No. 3. In addition, we see in the panel (c) of Fig. 1 that the sign of \( \Delta R_{\text{xx}} \) can be negative. This is not specific to experiment No. 3 but was also observed in experiment No. 1 by lowering the electron density as shown in Fig. 2. The B-periodic oscillations can therefore lead to an increased, a reduced or a negative absolute longitudinal resistance depending on the details of the parameter setting. Also, when scaling the amplitude of the oscillations in Fig. 2 to the value of \( R_{\text{xx}} \) without microwaves, we have observed (not shown) that the magnitude of the effect increases with electron mobility and saturates for
microwave powers beyond 500 µW.

We have seen that the detailed features of the oscillations depend significantly on how the sample has been exposed to red light. Independently of these variations, however, their behavior is reminiscent of the B-periodic oscillations observed in ref [1] and which were attributed to edge-magneto-plasmon excitations. Also like in ref [1], we have observed that a photovoltage develops across the Hall bar which shows a similar periodicity. A striking fact is that there is no clear feature of the 1/B-periodic oscillations for $\omega_c < \omega$ in Fig. 1 and 2 despite the high mobilities achieved.

A more detailed study of the effect versus density has been carried out and the results are summarized in Fig.3 and 4. We first show the position $x_B$ of the maxima of the oscillations as a function of their oscillation index N in Fig. 3a. The B-periodicity is clear from the linear dependence and as seen in the inset, the oscillations can be followed up to 2 Tesla in the quantum Hall regime, the resistance oscillations being linear in the applied current. Under the present experimental conditions where the resistance is measured with ac current modulation the resistance signal is not modified by the dc photovoltage excited by the unmodulated microwave.

The period $\Delta B$ of the resistance as well as the period $\Delta B_P$ of the photovoltage are shown vs. $N_s$ in Fig. 3b and 3c respectively. In ref [1], the two were found to be equal and to increase linearly with $N_s$. In the present work, however, it can be seen in Fig. 3 that they behave differently upon varying $N_s$. On one hand, $\Delta B_P$ increases linearly with $N_s$, on the other hand, $\Delta B$ shows a step increase through a narrow plateau for $N_s$ between 2.4 and $2.9 \times 10^{11}$ cm$^{-2}$. 
The details of the oscillations at low field are displayed in Fig. 4a for very closely-spaced values of top-gate voltage. We see that the phase shifts considerably in a narrow voltage-range corresponding only to a 4% variation in $N_s$. This phase shifting, also shown in Fig. 4b, does not occur in the photovoltage signal and is accompanied with the emergence of a broad maximum located at $B \approx 0.11$ Tesla which belongs to a separate pattern than the B-periodic oscillations. As seen in Fig. 4a, this additional peak can be resolved from the B-periodic oscillations for $N_s$ ranging between 2.4 and $2.9 \times 10^{11}$ cm$^{-2}$, thereby indicating the sharpness of the feature in term of electron density. Its location would correspond to the first cyclotron resonance harmonic at $\omega/\omega_c = 1 - 1/4$ expected for the 1/B-periodic oscillations. This may suggest that the two phenomena, namely B-periodic and 1/B-periodic oscillations, could coexist in a very narrow range of density and mobility. We expect indeed to observe these 1/B-periodic oscillations, for $\mu \geq 4 \times 10^6$ cm$^2$/Vs in Fig. 4a which is a value comparable to $\mu \geq 3 \times 10^6$ cm$^2$/Vs as reported in ref [4]. Yet, the presence of only one multiplicity would mean an anomalously large damping of the 1/B-periodic oscillations in our sample which remains to be explained.

There have been so far no report concerning the phase of the B-periodic oscillations. Nevertheless, the fact that the plateau in $\Delta B$ and the phase shifting occur together, lends support to the idea that these two features are connected. This hints at the presence of hindered microwave absorption mechanisms in our system and some questions arise as to what extent they could be related to the microscopic mechanisms underlying the 1/B-periodic oscillations. The emergence of a broad maximum located where $\omega/\omega_c = 1 - 1/4$ in the plateau regime is indeed suggestive of a possible cross-talk between the edge-magnetoplasmons and the phenomenon of 1/B-periodic oscillations but the lack of any clear pattern of maxima in the range $\omega < \omega_c$ limits the discussion to this point.

An important result of our experiments is that the oscillations simultaneously observed in the resistance and the photovoltage, while both being B-periodic, may differ in phase and period in certain density regimes. The inset of Fig. 4(b) shows an optical microscope image of the gate covering the Hall bar. It is conceivable that magnetoplasmons are excited differently in the Hall bar (resistance signal) and in the contact regions outside of the Hall bar not covered by the gate (photovoltage).

To conclude, we have presented a study of the microwave-induced oscillations in 2DEG as a function of electron density and mobility. We have observed a clear pattern of B-periodic oscillations for $\omega_c > \omega$, the properties of which such as amplitude and period vary significantly for different exposure conditions to red light. A careful study of these oscillations versus electron density shows that the period does not increase linearly with density as it was initially expected from a classical picture based on edge-magneto-plasmon excitations. Rather, the period shows a plateau in the range $(2.4-2.9) \times 10^{11}$ cm$^{-2}$ together with a continuous phase shifting by two periods. These sharp features could be related to the coexistence of strongly damped 1/B-periodic oscillations and B-periodic oscillations in a narrow range of density and mobility although no quantitative explanation for such effect can be derived at this stage.

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