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

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We have measured the magnetoresistance 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.* [Phys. Rev. Lett. **92**, 236803 (2004)] 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 $(2.4\text{–}3)\times 10^{11}\ \text{cm}^{-2}$. 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 an ultrahigh 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, ω_c and ω, respectively, are such that $\omega_c \leqslant \omega$.[2,3] A key aspect of this phenomenon lies in its strong dependence on the mobility. In particular, for $\mu = 3\times 10^6\ \text{cm}^2/\text{V s}$, some oscillations with a periodicity determined by the ratio ω/ω_c are discerned in the magnetotransport[4] while for $\mu = 2.5\times 10^7\ \text{cm}^2/\text{V s}$, these minima fully drop to zero, thereby revealing a sharp suppression of the dissipative processes in the 2DEG.[2,3]

Independently of this discovery, a different type of microwave related effects, also leading to a strong modulation of the magnetoresistance, has been recently reported to occur in samples with a moderately high mobility of $\mu = 1.3\times 10^6\ \text{cm}^2/\text{V s}$.[1] In contrast to the $1/B$-periodic oscillations mentioned above, these are *B*-periodic and develop in the field range where $\omega \leqslant \omega_c$. 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. 1, 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.[5–14] 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[15,16] 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-$\text{Al}_x\text{Ga}_{1-x}$As heterostructure. In contrast to previous experiments where the values of N_s and μ were obtained from a brief exposure to light at low temperature, N_s and μ 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 $5\times 10^{11}\ \text{cm}^{-2}$, we could tune the mobility in the range of $(1\text{–}7)\times 10^6\ \text{cm}^2/\text{V s}$. 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 $(2.4\text{–}3)\times 10^{11}\ \text{cm}^{-2}$ which occurs concomitantly with a continuous phase shifting of the oscillations by two periods.

Our sample is a high-mobility $(\mu \geqslant 1.4\times 10^7\ \text{cm}^2/\text{V s})$ two-dimensional electron gas in GaAs-$\text{Al}_x\text{Ga}_{1-x}$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 lithographically defined, the mobility drops significantly, its maximal value depending on experimental conditions. The Hall bar is 200 μm long and 50 μm wide. A TiAu top-gate (100 nm) has been evaporated on the Hall bar structure in order to tune the density and the mobility independently of illumination. Increasing the top-gate voltage from −100 mV to 640 mV increases the electron density N_s and the mobility μ from 0.5 to $5\times 10^{11}\ \text{cm}^{-2}$ and 0.5 to $7.50\times 10^6\ \text{cm}^2/\text{V s}$, respectively. N_s was found to vary linearly with the top-gate voltage within this range. The mobility increases linearly up to $N_s = 3\times 10^{11}\ \text{cm}^{-2}$ 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 5 dB and the sample was placed in the near field of the waveguide aperture. The frequency was fixed to

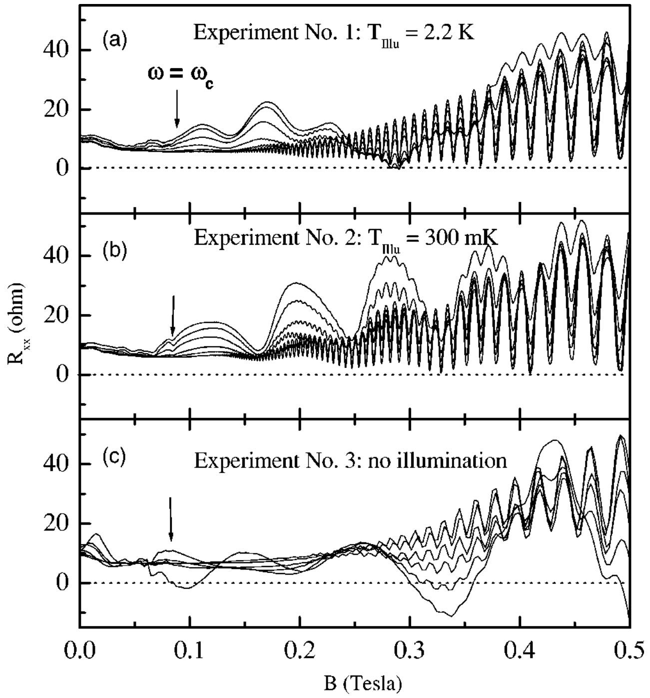

FIG. 1. Magnetoresistance measured under continuous microwave irradiation for different powers is compared for three different illumination conditions. The microwave power P lies in the range ($1\ \mu$W–1 mW). $N_s=5\times10^{11}$ cm^{-2} and $\mu=7.50\times10^{6}$ cm^2/V s for (a) and (b) while $N_s=4\times10^{11}$ cm^{-2} and $\mu=5.3\times10^{6}$ cm^2/V s for (c).

35.5 GHz 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 magnetoresistance R_{xx} was measured under continuous microwave irradiation while the photovoltage V_{xx}, which develops across the Hall bar independently of the applied current was measured via dc and ac techniques using for the latter a 2 kHz-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 Nos. 1, 2, and 3, respectively. For experiment No. 1, the sample was briefly illuminated at the temperature $T=2.2$ K and then cooled down to 100 mK which is the base temperature we could reach with our setup. Note that with microwaves on, the mixing chamber of our dilution fridge heats up to $T=300$ 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 $T=300$ 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 magnetoresistance 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 where $\omega_c>\omega$. It is obvious, however, that the properties of the B-periodic oscillations are strongly affected by the exposure to light. Their period ΔB and their damping with magnetic field differ strongly while N_s is the same in experiment Nos. 1 and 2 and only 20% less for experiment No. 3. In addition, we see in panel (c) of Fig. 1 that the sign of ΔR_{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_{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.

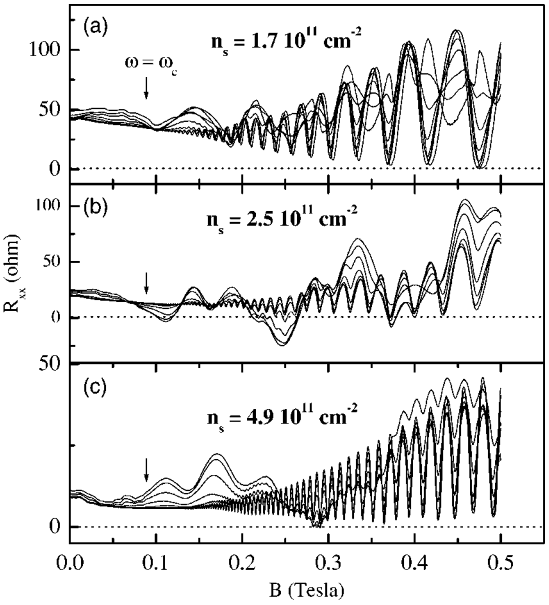

FIG. 2. Experiment No. 1: illumination at $T_{\mathrm{Illu}}=2.2$ K. Magnetoresistance measured for three different densities versus the microwave power P in the range ($1\ \mu$W–1 mW). The value of the B-field at which $\omega_c=\omega$ is marked with an arrow.

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 as 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 Figs. 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 Figs. 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.

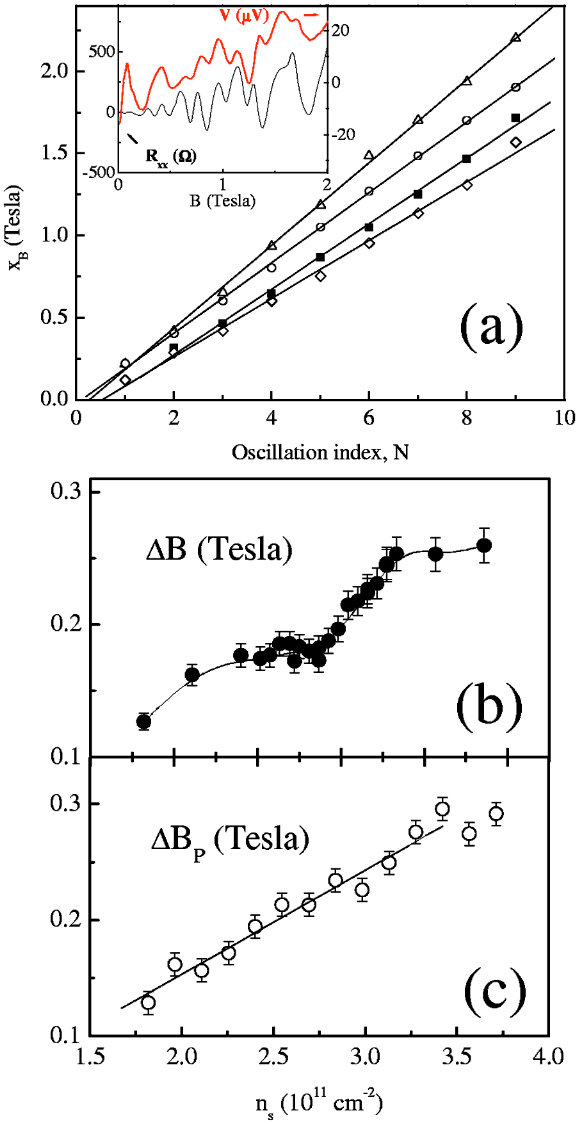

FIG. 3. Experiment No. 3. (a) Position of the maxima vs oscillation index for various density ranging between 2.4 and 3.6 $\times 10^{11}$ cm^{-2}. The period ΔB is deduced from a linear fit with a reliability factor fluctuating between 99.7% and 99.9%. Inset: magnetoresistance (continuous line) and photovoltage (dotted line) measured for $N_s = 2.4 \times 10^{11}$ cm^{-2}. The current through the Hall bar is 200 nA and $P \sim 300$ μW. (b) Period of the photoresistance vs N_s. (c) Period of the photovoltage vs N_s.

3(a). 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 ΔB of the resistance as well as the period ΔB_P of the photovoltage are shown vs N_s in Figs. 3(b) and 3(c), 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, ΔB_P increases linearly with N_s, on the other hand, ΔB shows a steep increase through a narrow plateau for N_s between 2.4 and 2.9×10^{11} cm^{-2}.

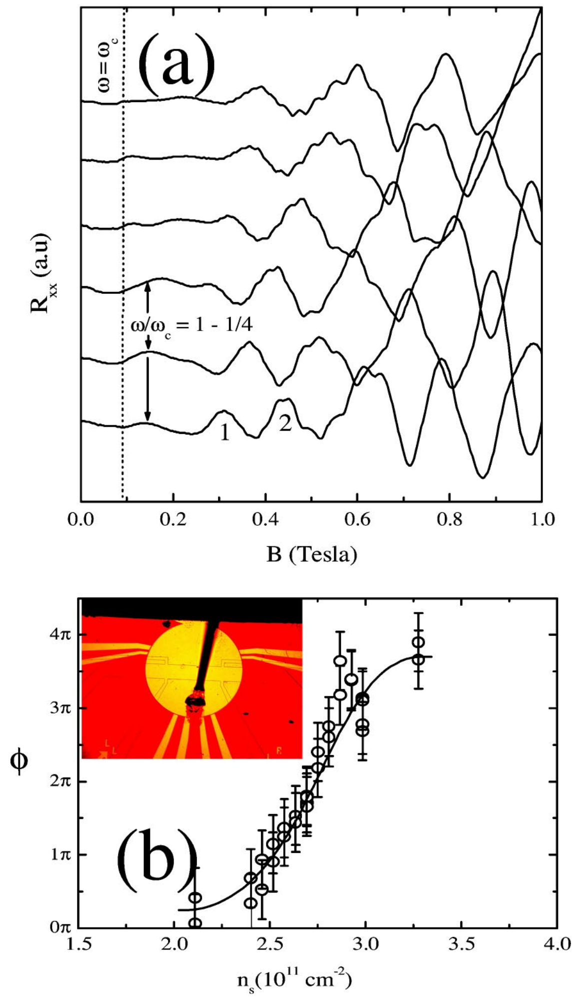

FIG. 4. Experiment No. 3. (a) Microwave-induced oscillations in the low field range measured for various N_s ranging between 2.4 and 2.9×10^{11} cm^{-2}. The curves are offset for clarity and correspond to a step upward in density of 0.1×10^{11} cm^{-2} from the lowest one. (b) shows the phase ϕ of the B-periodic oscillations vs N_s. The phase was determined from the maxima denoted by 1 and 2 in (a) with respect to the B-field at which $\omega_c = \omega$, i.e., 0.09 T for $\omega = 35.5$ GHz. The continuous line is a guide to the eyes. Inset: picture of the Hall-bar sample with its TiAu top-gate (circle). The distance between the voltage probes is 200 μm.

The details of the oscillations at low field are displayed in Fig. 4(a) 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. 4(b), 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. 4(a), this additional peak can be resolved from the B-periodic oscillations for N_s ranging between 2.4 and 2.9×10^{11} cm^{-2}, thereby indicating the sharpness of the feature in terms 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 $\mu \geqslant 4 \times 10^6\ \mathrm{cm}^2/\mathrm{V\,s}$ in Fig. 4(a) which is a value comparable to $\mu \geqslant 3 \times 10^6\ \mathrm{cm}^2/\mathrm{V\,s}$ 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 reports concerning the phase of the B-periodic oscillations. Nevertheless, the fact that the plateau in ΔB 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-magneto-plasmons and the phenomenon of $1/B$-periodic oscillations but the lack of any clear pattern of maxima in the range $\omega_c < \omega$ 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 $(2.4–2.9) \times 10^{11}\ \mathrm{cm}^{-2}$ 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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