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Response of the Microwave-Induced Cyclotron Harmonic Resistance Spike to an In-Plane Magnetic Field

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Microwave-induced resistance oscillations (MIRO) have been commonly observed in high-mobility *GaAs/AlGaAs* two-dimensional electrons systems (2DES) under microwave irradiation. In ultra-clean *GaAs/AlGaAs* quantum wells (QWs), we have recently observed an extraordinary resistance spike at the second harmonic of cyclotron resonance (CR). In order to elucidate its origin, we have studied the response of microwave photoresistances in a two-axis magnetic field configuration, where the perpendicular (B_z) and the in-plane (B_x) components can be independently applied to the sample. The experiments reveal a distinctive response of the spike to the B_x compared with that of the MIRO. While the major MIRO peaks show an increasing phase-shift towards a quarter in increasing B_x, the spike position shows an essentially zero shift. This finding lends an additional support for the notion that the spike is a new effect in the microwave-driven 2DES.
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Recent observation[1–3] of a $2\omega_C$ spike in the microwave (MW) photoconductivity, where $\omega_C = eB/m^\star$ is the cyclotron frequency of a two-dimensional electron gas (2DEG) with m* the electron effective mass, is quite surprising. In particular, in the prevailing models proposed to explain the microwave-induced resistance oscillations (MIRO) and zero-resistance states (ZRS)[4–10], a high-amplitude, singular resistance peak at the 2^{nd} harmonic position has never been predicted. Some experimental studies[10,11] in MIRO have emphasized a ubiquitous "phase shift" of the resistance maxima with respect to its corresponding ε, where $\varepsilon = \omega/\omega_C$ is the ratio of MW frequency over the cyclotron frequency. The $2\omega_C$ spike appears to be a high quality factor (Q) resonance, and its explanation remains to be a challenge to existing theories concerning MW response of a very high mobility 2DEG in GaAs/AlGaAs quantum well (QW) devices. Reported strong dependence of its amplitude on temperature[2], as well as the nonlinear I-V[12] suggest that the spike cannot be simply attributed to Landau level (LL) transitions in a homogeneous 2DEG. Rather, strong perturbations to a uniform current distribution, or even edge transport, cannot be ruled out. Recently, Inarrea et al. pointed out that based on the microwave-driven electron orbits model in the ultra-high mobility samples , the $2\omega_C$ spike can be understood by the reduced elastic scattering rate for its resonance peak position and the increased inelastic scattering rate for the large peak amplitude[13]. However, this model does not explicitly explain the narrow width of the spike, as well as the different behavior of $2\omega_C$ spike and MIRO in an in-plane magnetic field, as reported in the present paper.

In this Rapid Communication, we present the results of MW-induced magnetoresistivity ρ^{ω}_{xx} from ultra-clean GaAs/AlGaAs QWs under an in-plane magnetic field, B_x. The data show that the $2\omega_C$ spike is always aligned with ε=2 when B_x increases from 0 to 20 kG; it's amplitude first decreases and then saturates. This is in stark contrast to MIRO, where the ε=2 MIRO exhibits a large B_x-induced phase shift towards $\frac{1}{4}$ period while its amplitude is completely damped in a larger B_x, as previously reported in[1]. From these distinctive responses, it is self-evident that the spike is a new effect beyond MIRO and ZRS in a MW- driven 2DEG.

Two square QWs with Si modulation-doped $Al_{0.24}Ga_{0.76}As/GaAs/Al_{0.24}Ga_{0.76}As$ structures were used in this experiment. The primary sample (A) has a well width w = 30 nm and symmetrical spacers with a spacer distance d = 80 nm, with respectively an electron density $n_e = 2.9 \times 10^{11}/cm^2$ and a mobility $\mu = 3.0 \times 10^7 cm^2/Vs$ at T = 300 mK. A second sample (B) has a similar structure with w = 25 nm, d = 80 nm, $n_e = 4.6 \times 10^{11}/cm^2$, and $\mu = 1.2 \times 10^7 cm^2/Vs$. Hall bars were fabricated on the wafers, with a width W = 90 μm (180 μm) for sample A (B), using standard photolithography and wet etching. High quality ohmic contacts were made by Ge/Pd/Au alloy using lift-off technique and annealing. The experiment was conducted in a top-loading He-3 refrigerator (base T = 300 mK) fitted with a two-axis superconductor magnet; experimental details can be found elsewhere[1,2]. The orientation of the in-plane magnetic field B_x with respect to the electric current I, either parallel or perpendicular, has a negligible effect on experimental results, and therefore only the results in B_x // I direction are presented here.

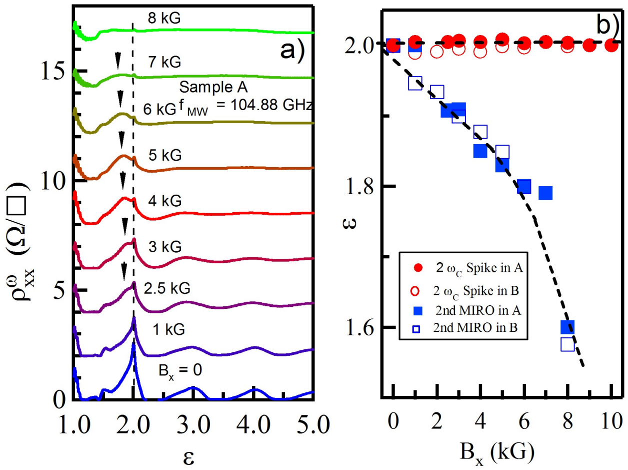

Figure 1: (Color online) a) Respective resistivity traces versus ε are shown, for a fixed in-plane magnetic field from $B_x = 0$ to 8 kG. For clarity, the traces are shifted upward by $2\Omega/\Box$ consecutively. The arrows mark the 2^{nd} harmonic peaks in MIRO, whereas a dashed vertical line marks the $2\omega_C$ spikes. b) Variations of ε for the $2\omega_C$ spike and that for the 2^{nd} harmonic peak in MIRO are shown as a function of in-plane magnetic field. The positions of the $2\omega_C$ spikes (open and filled circles) can fit to a horizontal line; the dashed line along the 2^{nd} harmonic peaks in MIRO (open and filled squares) is a guide for eye.

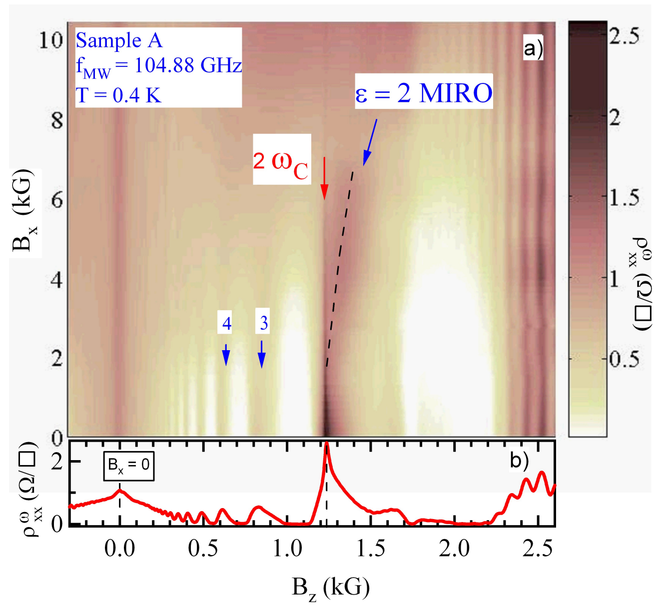

Figure 2: (Color online) a) A resistivity map in gray scale is shown in the plane of B_z (horizontal axis) and B_x (vertical axis) for the sample A with f_{MW} = 104.88 GHz and T = 0.4 K. b) A representative resistance trace is shown, where $B_x = 0$.

In Figure 1a), we display a series of photoresistivity ρ^{ω}_{xx} traces versus ε measured from sample A, with an irradiation MW frequency f_{MW} = 104.88GHz, but each under a different in-plane magnetic field. The $2\omega_C$ spikes align along a dashed vertical line located at exact $\varepsilon = 2$ from $B_x = 0$ to $B_x = 8$ kG, with a damped amplitude in a large B_x. The ε values of the $2\omega_C$ spikes (red filled circles) are extracted and presented versus B_x in Fig. 1b). In contrast, 2^{nd} harmonic peaks (marked by arrows in Fig. 1a)) in MIRO exhibit an increasing phase-shift as a function of the in-plane field. Their ε values are presented in blue filled squares in Fig. 1b). Higher order (3^{rd}, 4^{th}...) MIRO peaks are shifted and damped more quickly than 2^{nd} order peak. For comparison, we also present respectively the ε values of the $2\omega_C$ spikes (red open circles) and 2^{nd} harmonic MIRO peaks (blue open squares) for sample B in Fig. 1, which are measured with a frequency f_{MW} = 116.8 GHz and at T = 0.4 K. Again, in sample B, the $2\omega_C$ spikes shows no phase shift whereas the phase shifts of 2^{nd} harmonic MIRO peaks follow the same trend as in sample A.

Such contrasting characteristics can be clearly visualized by a gray-scale map of ρ^{ω}_{xx} as a function of both the B_z and B_x (measured on sample A with f_{MW} = 104.88 GHz and at T = 0.4K), as shown in Fig. 2a), where the dark areas stand for peaks and the light areas represent valleys, including the ZRS. Around the perpendicular field $B_z = 1.2$ kG, a dark, vertical line is composed of the $2\omega_C$ spikes. And a dark, curved dash line representing the 2^{nd} harmonic peaks in MIRO clearly marks the trend for increasing phase-shift from $B_x = 0$ to $B_x \approx 7$ kG. The ε =1 ZRS persists up to B_x = 7 kG, whereas the higher order ZRS minima disappear at a rather small B_x. A representative ρ^{ω}_{xx} trace in a zero in-plane field is shown in Fig. 2b), where the $2\omega_C$ spike dominates all resistive features.

We note that in a standard tilted magnetic field experiment, the perpendicular field $B_z = B \cdot cos\theta$, and the in-plane magnetic field $B_x = B \cdot sin\theta$, with B the total applied magnetic field, and θ is the angle of B with respect to the sample normal. Taking B_z =1.2 kG, and B_x= 7 kG cited above, our experiment using a two-axis magnet in fact corresponds to a large tilt angle $\theta \sim 80°$. As will be discussed in this paper, the responses of either the $2\omega_C$ spike or the MIRO must be considered in the context of a nearly parallel magnetic filed in the 2DEG plane.

Although the $2\omega_C$ spike does not show discernible phases shifts up to 8 kG, its amplitude damps dramatically with an increasing B_x, as is evident in both Fig. 1 and Fig. 2. To quantify this observation, in Fig. 3 we plot $H_{2\omega_C}$ (defined as net height of the $2\omega_C$ spike after subtracting MIRO background) as a function of B_x. As the B_x increases from 0 to 5 kG, $H_{2\omega_C}$ decreases from around $0.9(\Omega/\Box)$ to $0.1(\Omega/\Box)$ for sample A with f_{MW} =104.88 GHz and at T = 0.4 K. Above B_x = 5 kG, $H_{2\omega_C}$ is stabilized to a constant value around $0.1(\Omega/\Box)$. Together with the fact that the phase shift remains essentially zero, the initial precipitous drop of $H_{2\omega_C}$ in a small Bx indicates, while the in-plane magnetic field does

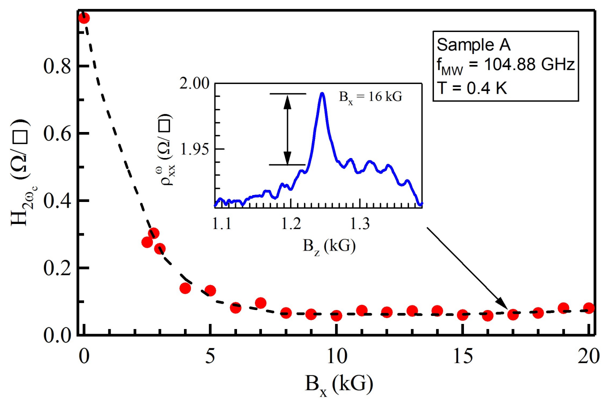

Figure 3: (Color online) The height $H_{2\omega_C}$ of the $2\omega_C$ spike is shown as a function of the in-plane magnetic field B_x for the sample A with f_{MW} = 104.88 GHz and T = 0.4 K. Red filled circles are experimental data. The dash line is a guide for eye. The inset is the $2\omega_C$ spike at $B_x = 16kG$ with $H_{2\omega_C} = 0.57\Omega/\square$.

not seem to alter the underlying physical mechanism, it plays a substantial role in suppressing the spike.

In summary, the $2\omega_C$ spike displays a zero phase shift in an in-plane magnetic field while in the same B_x range MIRO shows a large phase shift towards $\frac{1}{4}$ period. These results, together with a remarkably narrow width and high amplitude of the $2\omega_C$ spike reported in[2], have provided unambiguous evidences that the $2\omega_C$ spike is a new effect in MW-irradiated 2DEG. Presently there exists no satisfactory theoretical explanation for this effect. In the following we offer some comments and discussions pertaining to the experiment.

For a 2DEG with a finite thickness, electron motion also has the z-axis degree of freedom. Consequently, electrons can acquire a finite momentum transfer in the plane even in a relatively small in-plane magnetic field. For illustration, we consider a situation where the field is applied along the x-axis, B_x. The motion in z, as characterized by $\triangle\ z \sim w$, should cause a finite momentum transfer along the y-axis, via $\triangle\ k_y = -(eB_x/\hbar)\cdot \triangle\ z$. For our QW the well width $w = 30nm$, and at B_x = 5 kG, $\triangle\ k_y \approx 0.024nm^{-1}$. Such a momentum transfer is quite significant, since it is about 17.5% of the Fermi vector $k_F = \sqrt{2\pi n_e} = 0.137nm^{-1}$.

It was first reported in[1] from a two-axis magnet experiment that an in-plane magnetic field will damp the MIRO, whereas in[14] from a sample - tilt experiment, the MIRO was reported to be observed up to a high tilt angle $\theta > 80°$. Since in[14] both the microwave incident angle and the in-plane magnetic field component vary in the experiment, the interpretation of the results is under debate. In the present experiments we confirm the results in[1] and the above analysis may help to elucidate the origin of the observed effect. In the prevailing models based on either the “displacement’ or “distribution” mechanism, in-plane momentum transfer between the initial and the final states of electron orbits has not been explicitly taken into account. On the other hand, it has been well-known by now that oscillations in differential resistance can be induced by a dc-field (instead of microwave ac-field) in a Hall bar sample of high mobility 2DEG[15,16] or 2D hole gas[17]; the effect has been explained by Zener tunneling between two spatially separated Landau orbits in a tilted Hall field. In this picture, a finite momentum transfer is required to satisfy the selection rule: $\triangle\ x \approx 2R_C = -(\hbar/eB_z)\cdot \triangle\ k_y$, where R_C is the orbital radius[15].

While both the ac- and the dc-induced oscillations show qualitatively similar behavior, their connection has not been firmly established. In the original paper reporting MIRO[4], the authors propose a model invoking the orbital transition similar to those in[15], with the energy required $\triangle\ E = j\hbar\omega_C, j = 1, 2, 3...$ provided by a microwave field instead of the Hall field. In[16] a sample subjected to both the ac- and the dc-fields shows very interesting behavior, in particular the MIRO positions can be shifted by a dc-current bias in a systematic fashion. All together, the experiments suggest that momentum transfer in the 2DEG plane may play a role in the MIRO as well as in ZRS. From this point of view, we suggest to examine theoretically, whether an in-plane field applied in a finite thickness 2DEG can smear out the LL transition and thereby suppress the MIRO.

An in-plane magnetic field can also increase the rate of short range scatterings by pushing electrons against the QW barriers. Evidence for this effect can be shown in Fig. 4a), where the zero field resistance $R^0_{xx}(B_x = 0)$ increases in an increased B_x. The values of $R^0_{xx}(B_x = 0)$ are extracted and drawn in open dots in the inset of Fig.4b). We can deduce the scattering rate $1/\tau_{tr} = 1/\mu m^\star = en_e\rho_{xx}/m^\star \propto R^0_{xx}$, where μ is the mobility. Since scatterings by interface roughness are the main source of short range scatterings in this ultra-high mobility 2DEG, the effect of a B_x is not negligible. Quantum scattering rate, $1/\tau_q = \omega_q = eB_z/m^\star$, also increased, becuase the onset of Shubnikov-de Haas oscillations moved to a higher value when the in-plane magnetic field increased[1].

In essence, one may find that an in-plane magnetic field should influence MIRO by introducing momentum transfer in the 2DEG plane, via large angle scattering events between the opposite QW interfaces. In our ultra clean 2DEG hosted in a 30 nm QW, such mechanism provides an additional scattering channel and therefore could play a crucial role in suppressing the MIRO.

We now turn to a discussion on the influence of an in-plane field on the newly-discovered $2\omega_C$ spike. From experimental observations, the position of the spike (in B_z) appears to be unaffected by B_x up to ~ 8 kG, which is in sharp contrast with that of MIRO. It indicates that the spike position is not sensitive to a finite momentum transfer in the 2DEG plane, a fact that should be considered in any theory dealing with the spike. On the other hand, the amplitude of the spike is drastically damped by a small B_x starting at about 1 kG.

Empirically, the influence of an in-plane field to the $2\omega_C$ spike is qualitatively similar to the temperature effect, in the sense that they both dramatically damp its amplitude, while retaining its position. This can be clearly seen comparing the data shown in Fig. 1,2,3 and that in Fig. 3 of[2]. In Fig. 4 we display the small-filed ($B_z < 1$ kG) magnetoresistance R^0_{xx} (i.e., without MW) in the case for increasing in-plane magnetic field (Fig. 4a) and that for raising the temperature (Fig. 4b)). We observe that in both cases the mobility decreases (see the inset of Fig. 4b)). Note that phonon modes in the hosting lattice which is thermally excited and carries finite momentum, should couple to 2D electrons by piezoelectric mechanism in GaAs/AlGaAs QWs.

In conclusion, our experiments in a two-axis magnet setting demonstrate that the newly discovered $2\omega_C$ spike shows negligible shift in its resonant position, which is in stark contrast to MIRO, where a systematic phase shift has been observed. From the momentum transfer point of view, we discuss possible influences from a small in-plane field to the electron orbital dynamics in a finite width, ultra clean 2DEG. These results should help to distinguish the underlying physics of $2\omega_C$ spike from the current theories.

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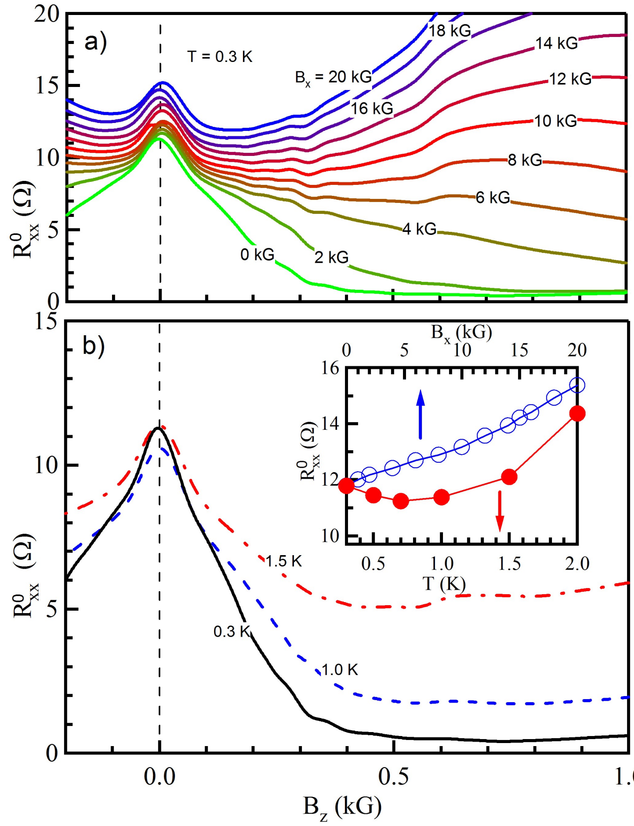

Figure 4: (Color online) a) Respective magnetoresistance traces are displayed for the different values of the in-plane magnetic field B_x ; b) Respective magnetoresistance traces for the different temperatures from 0.4 to 2 K. Inset: The resistances at zero perpendicular magnetic field are shown as a function of the in-plane magnetic field (blue open circles) or that of the temperature (red filled circles).

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