Letter

Circular polarization immunity of the cyclotron resonance photoconductivity in two-dimensional electron systems

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Studying the cyclotron resonance (CR) induced photoconductivity in GaAs and HgTe two-dimensional electron structures under circularly polarized terahertz illumination, we observed an anomalous resonant photoresponse for the CR inactive helicity of almost the same magnitude as for the CR active helicity. This observation conflicts with simultaneous transmission measurements and fundamentally contradicts the conventional theory of CR. We provide a possible route to explain such a basic failure of the conventional description of light-matter interaction and discuss a modified electron dynamics near strong impurities that may provide a local near-field coupling of the two helicity modes. This should result in a CR enhanced absorption for both magnetic field polarities.

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Cyclotron resonance is a fundamental and well established textbook phenomenon widely used in solid-state research to study energy dispersion, scattering times, energy structure of excitons, and impurities as well as other electronic properties of bulk and two-dimensional systems (2DES) [1]. Under the condition of cyclotron resonance (CR) in a magnetic field B, an electromagnetic wave with frequency $f = qB/2\pi m$ is resonantly absorbed by the conduction carriers with charge q and mass m, accelerated on spiral or circular cyclotron orbits. Basic approaches to investigate CR include (i) radiation transmission/reflection, (ii) photoconductivity, and (iii) quenching of the photoluminescence due to CR absorption (for review, see [2]).

The transport approach using microwave and terahertz (THz) photoconductivity/photoresistance, originally termed the cross-modulation method, has been suggested for CR studies by Zeiger *et al.* in 1958 [3]. An advantage of this technique is that the sample itself acts as a detector. Thus, it can be applied even to micrometer-size structures where reliable CR transmission and reflection measurements are impossible. Since the first observation of the CR in 1953 it is known that, for circularly polarized light propagating along or against the magnetic field, CR is only possible if the helicity of light and the sense of cyclotron motion match. Indeed, resonant acceleration requires that the light's electric field rotates synchronously and in the same (opposite) sense as the positively (negatively) charged carriers undergoing a cyclotron motion. The strong B asymmetry of CR controlled by the wave helicity (CR active/inactive polarity of B) is confirmed by many CR experiments and is widely used to determine the type of conduction carriers.

In sharp contrast to this textbook behavior, our present experiments using several GaAs- and HgTe-based 2DES reveal that the CR photoconductivity becomes insensitive to the radiation helicity when the measurement temperature T is lowered to that of liquid helium or below: The amplitude of the CR signals excited by a circularly polarized THz radiation is observed to be almost the same for both CR active and inactive polarities of B, and for both helicities. Strikingly, the conventional behavior of the photoconductivity, i.e., the CR present for the active polarity only, is gradually restored at higher T. Unlike the anomalous photoconductivity, simultaneous measurements of CR in transmission show the ordinary helicity dependence at all T.

Our experiments, performed on large structures with lateral size strongly exceeding the THz laser spot, unambiguously demonstrate that (i) the helicity-insensitive photoresponse can be detected in CR photoconductivity which directly reflects resonant CR absorption and associated heating of electrons, (ii) the anomaly disappears at higher temperature, (iii) the anomaly is not present in transmission, and (iv) the observed immunity is not related to external factors, like antenna effects or diffraction at the metallic parts of the experimental setup, contacts, or sample's edges. We argue that the observed CR anomalies in the photoconductivity can be attributed to an enhanced near-field absorption and suppressed reflection of THz radiation in the vicinity of rare strong impurities or inhomogeneities in 2DES. Such near-field effects can locally destroy the rotational and translational symmetries of electron transport leading to strong mixing of both helicity modes in the dynamically screened nonuniform THz field acting on 2D electrons. These effects are not detectable in transmission measured in the far field at a large distance from the sample, and can be suppressed at high T where electron transport is dominated by electron-phonon scattering. Within this interpretation, the CR photoconductivity in response to a circularly polarized THz radiation can serve an indispensable tool to test the technological quality and nature of disorder in 2DES.

We studied several 2DES including AlGaAs/GaAs quantum wells (QWs; van der Pauw 10×10 mm^2 samples),

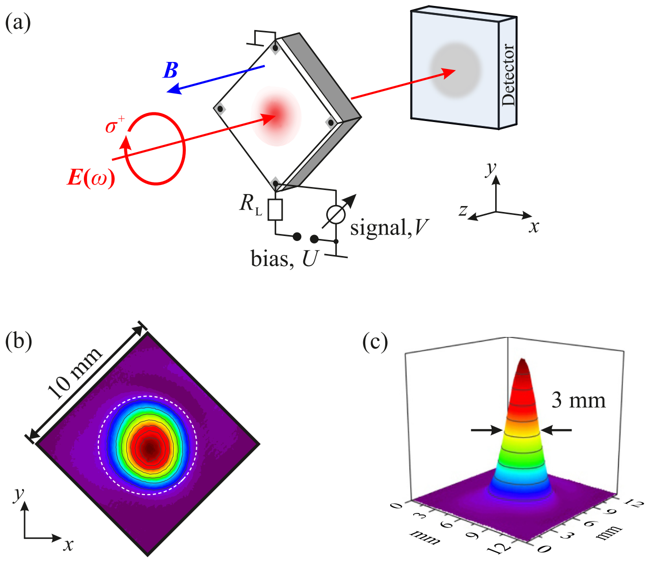

FIG. 1. (a) Sketch of the experimental setup. (b) and (c) Measured intensity profile of the $f = 0.69$ THz beam focused at the 10×10 mm^2 GaAs sample. The edges of the sample are not irradiated. Dashed circle in (b): Spot diameter of 6 mm at 13.5% of the peak intensity. Arrows in (c): Full width at half maximum.

HgCdTe/HgTe QWs of 8.1 and 5.7 nm thickness (7×7 mm^2), and a high quality hexagonal boron nitride (hBN) -encapsulated monolayer graphene (MLG) (Hall bar, 24×5 μm^2). Magnetotransport measurements at $T = 4.2$ K yielded electron densities from 1 to 20×10^{11} cm^{-2} and mobilities from 2 to 10×10^5 cm^2/V s (GaAs) and 1 to 2×10^4 cm^2/V s (HgTe). For details of technological design, magnetoresistance data, and transport parameters of individual samples, see Supplemental Material [4], and Refs. [5–10] therein.

To study the CR, the samples were placed in an optical cryostat with z-cut crystal quartz windows covered by black polyethylene films to avoid uncontrolled illumination by ambient light. An optically pumped continuous wave molecular gas laser [11] operating at $f = 0.69$, 1.63, and 2.54 THz provided normally incident radiation parallel to applied magnetic field [see Fig. 1(a)]. The intensity distribution of the THz laser beam focused on the sample center was measured by a pyroelectric camera, Figs. 1(b) and 1(c), revealing a nearly Gaussian profile with spot diameters $d = 6$, 4.2, and 2.8 mm at the level of $e^{-2} \approx 13.5\%$ of the maximum intensity (few W/cm^2). This assured a negligible contribution of the sample edges and contacts in both photoresistivity and transmission obtained on QW samples. Right- (σ^+) and left- (σ^-) handed circularly polarized radiation was produced by x-cut crystal quartz quarter wave plates. To measure the photoresistance ΔR (i.e., the radiation-induced change of resistance) in QW structures, either a dc or ac bias voltage U was applied over a load resistor to point contacts at opposite corners of the sample; simultaneously, radiation transmission was measured with a pyroelectric detector [see Fig. 1(a)]. In graphene, the bias voltage was applied to two end terminals of the Hall bar structure [4]. The signal V was measured using a standard lock-in technique. The photoresistance was extracted either by subtracting signals for opposite polarities of the dc bias, or by applying the double modulation technique [4,12,13].

The CR was clearly detected in both transmission and photoresistance in a wide temperature range between 2 and 90 K. Typical results for GaAs, HgTe, and MLG samples are shown in Figs. 2–4, respectively, and confirmed by measurements at other frequencies and samples [4]. As expected, the transmission traces (top panels in Figs. 2 and 3) clearly show that the CR excited by circularly polarized radiation appears for one B polarity only (CR active polarity, $B < 0$ for σ^+ helicity and $B > 0$ for σ^- helicity). Strong wide dips at the position of CRs in transmission (arrows) are produced by resonant reflection and absorption of radiation, the latter mechanism playing a minor role in high-mobility and high-density 2DES studied here [14–21]. Importantly, the transmission remained the same at all T showing no resonant features on the CR inactive side under all conditions.

At the CR active side, photoresistance traces (see bottom panels in Figs. 2 and 3, and Fig. 4) display the well established behavior associated with resonant electron gas heating under CR absorption. At high T, we observe a single CR peak in ΔR caused by heating-induced decrease of the electron mobility [22]. At low T, the CR enhanced heating reduces the amplitude of the Shubnikov–de Haas oscillations (SdHO) reflecting their exponential sensitivity to electron temperature (for more detailed analysis, see Supplemental Material [4]). SdHO are completely suppressed at high T, while at low T the photoresistance shows $1/B$ oscillations with the period of SdHO. These oscillations are resonantly enhanced near CR where the heating is maximized. Traces at intermediate temperatures demonstrate a combined effect of CR heating on SdHO and mobility.

While the results on the CR active side are conventional, the CR inactive side clearly shows an anomalous behavior. Strikingly, at low T the CR enhanced photoresistance in Figs. 2 and 3 has almost the same magnitude for positive and negative B, as well as for both helicities—a result which one would expect not for circular but rather for linear polarization where both circular components have equal weights. Furthermore, the relative magnitude of the signal on the CR inactive side becomes progressively weaker at higher measurement temperatures, and disappears at the highest T thus restoring the behavior expected for circular polarization. Importantly, the T dependence of the anomaly excludes any extrinsic mechanisms related to possible breakdown of the circular polarization in the optical setup, and shows that it has an intrinsic origin reflecting an anomalous high-frequency current response to the THz driving inside the 2DES. The large size of GaAs and HgTe samples in comparison to the THz beam spot excludes the influence of samples' edges and contacts. Moreover, the CR photoresistance measured on a small MLG sample, where illumination of the edges and contacts could not be avoided, shows regular CR behavior with no resonant features on the CR inactive side (see Fig. 4). This demonstrates that the helicity anomaly in the CR absorption is not universal but rather reflects peculiarities of the dynamic response in specific 2DES.

The observed polarization immunity suggests that the conventional description of light-matter interaction in terms of local dynamic conductivity $\hat{\sigma}(\omega, q \to 0)$ is not applicable.

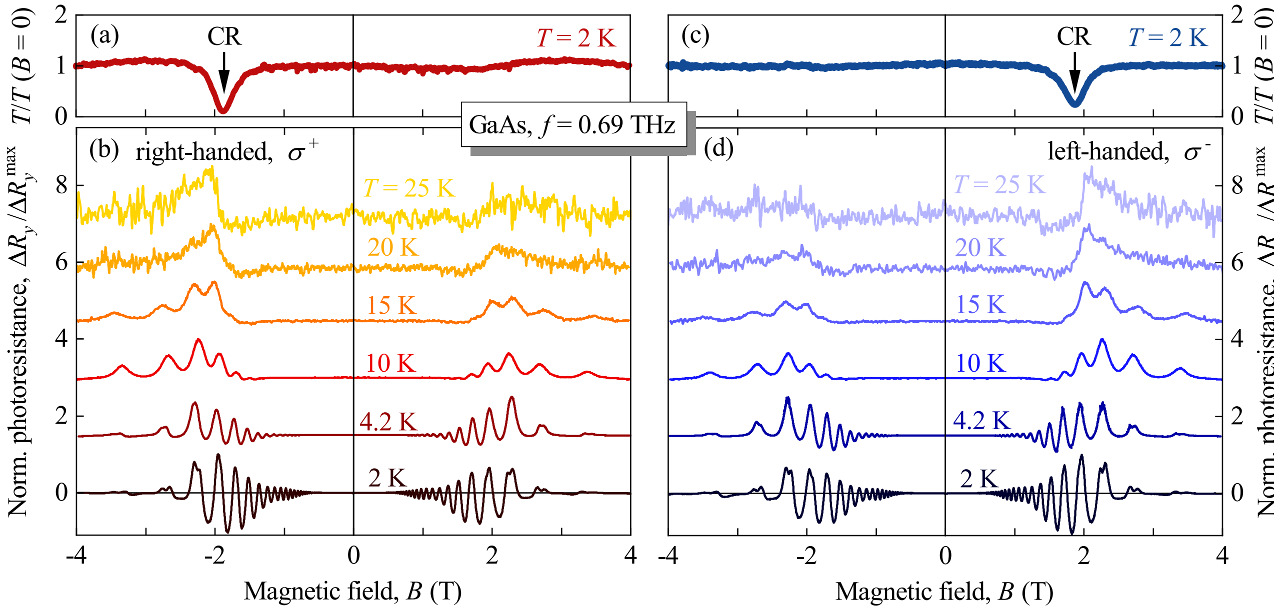

FIG. 2. Normalized transmittance, $T(B)/T(0)$, measured at $T = 2$ K on the GaAs sample #1 for right-handed (a) and left-handed (c) $f = 0.69$ THz radiation. Black arrows mark the positions of CR. (b) and (d) The corresponding photoresistance, ΔR_y, normalized to its maximum value, $\Delta R_y^{\max}$, measured at T from 2 to 25 K. Traces are shifted by 1.5 for clarity.

Within this standard approach, the electric field **E** of a plane circularly polarized wave, acting on electrons in an isotropic uniform 2DES, induces a uniform circular electric current $\mathbf{j} = \hat{\sigma}\mathbf{E}$ of the same helicity. Both quasiclassical and quantum kinetic theory predict that this current should be resonantly enhanced at the CR at positive or negative B only, depending on helicity [1,2,19]. As long as both the 2DES and the THz field remain uniform and isotropic, there is no coupling between the two helicity modes and thus such description is incompatible with the polarization immunity.

To overcome this apparent paradox, we thus need to consider some intrinsic source of broken translational or rotational symmetry leading to mixing of the otherwise independent helicity modes. A plausible resolution comes from understanding that the standard approach assumes uncorrelated scattering by a large number of weak impurities which,

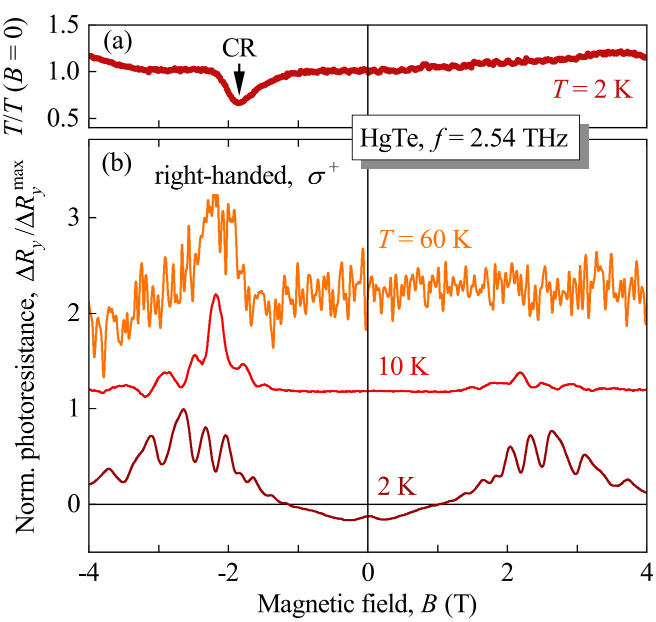

FIG. 3. Normalized transmittance at $T = 2$ K (a) and normalized photoresistance at $T = 2$, 10, and 60 K (b) measured on the HgTe sample #3 with 8.1 nm QW width for right-handed $f = 2.54$ THz radiation. Black arrow marks the position of CR. ΔR traces are shifted by 2 for clarity.

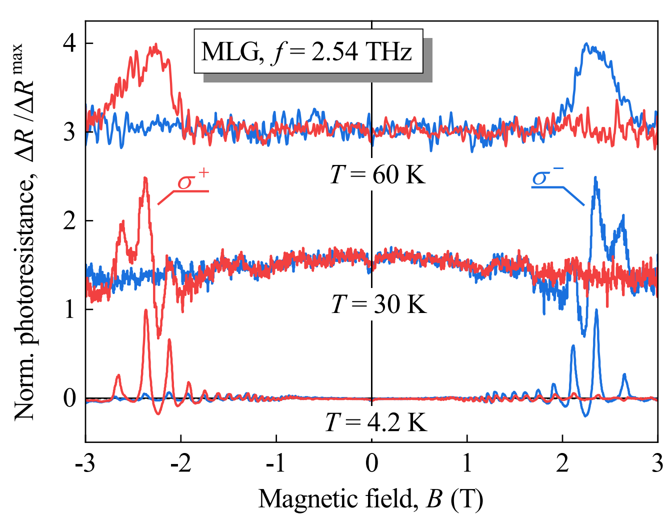

FIG. 4. Normalized photoresistance measured at $T = 4.2$, 30, and 60 K on the monolayer graphene sample #5 with 2.1×10^{12} cm^{-2} carrier density for right-handed (red) and left-handed (blue) $f = 2.54$ THz radiation. Traces are shifted by 1.5 for clarity. Transmittance measurements were not feasible due to the small size of the MLG sample.

after disorder averaging, yields a full description in terms of uniform and isotropic $\sigma(\omega, q \to 0)$. However, the electron flow can be essentially modified near rare strong impurities or inhomogeneities [19,23–30]. Near such impurities the system is neither translationally invariant nor isotropic leading to strong coupling between the two helicity modes and thus enabling the polarization immunity. Taking into account that in a uniform high-density and high-mobility 2DES the greatest part of radiation is reflected in the vicinity of CR [14–18], a 2DES with such strong impurities can be visualized as an old mirror with dark spots: Near impurities the 2DES is "dirty" and does not reflect the THz wave effectively. Therefore, the near field acting on the electrons is stronger. This yields double enhancement of absorption due to stronger scattering and stronger field at the "dark spots" which, therefore, are also "hot spots." Under such conditions, one faces the nontrivial task to self-consistently calculate inhomogeneous local currents induced by the external uniform THz field and corresponding dynamic screening of the external field by the 2DES before averaging over disorder. Moreover, the strongly nonuniform screened THz field implies local excitation of short-wavelength plasmons and possible viscous effects. Within this interpretation, the conventional behavior of CR can be restored at high T due to the increasing role of phonon and electron-electron scattering. Furthermore, the evanescent waves associated with the THz near field of opposite helicity emerging near strong impurities should not affect conventional CR in transmission, detected in the far field at a large distance from the sample. It is important to emphasize that, within this scenario, the observed helicity immunity is determined by the unusual correlation properties of the random potential rather than its integral characteristics, such as mobility that enters the conventional theory of CR. The nonuniversality of the proposed mechanism, implying a nonuniform response of the 2DES to a uniform radiation field, is supported by the ordinary CR photoresistance in MLG showing no helicity anomalies at all T.

The idea that strong impurities can strongly modify electron transport in 2DES is not new. It was extensively studied in both static and dynamic regimes in the context of non-Markovian classical memory effects (see, e.g., [19,23–30]). These studies, however, have mostly concentrated on electron transport in the presence of uniform dc or ac electric fields. Apart from Refs. [29,30] discussing related ideas, they did not consider the possibility of strong back action of inhomogeneous currents on the ac field acting on electrons.

Before concluding, we shortly address polarization anomalies previously detected [18,31] in studies of microwave-induced resistance oscillations (MIRO) [19,32–34], magneto-oscillations in photoresistance coupled to harmonics of the CR. In Fig. 5 we present transmission and photoresistance data for the same GaAs sample as in Fig. 2 but now obtained after brief illumination by room light prior to measurements. This results in a higher electron density and mobility due to the persistent photoconductivity effect [4,35]. Here, the transmission still shows regular helicity dependence with no features on the CR inactive side. Similar to Fig. 2, the photoresistance in Fig. 5(b) shows an almost complete immunity to the helicity of the THz wave. However, in addition to the SdHO-related oscillations, new magneto-oscillations appear with nodes at the CR, B_{CR}, and its harmonics $B_{CR}/2$, $B_{CR}/3$, ..., see dashed lines in Fig. 5(c), which correspond to the MIRO effect [18,19,31–34].

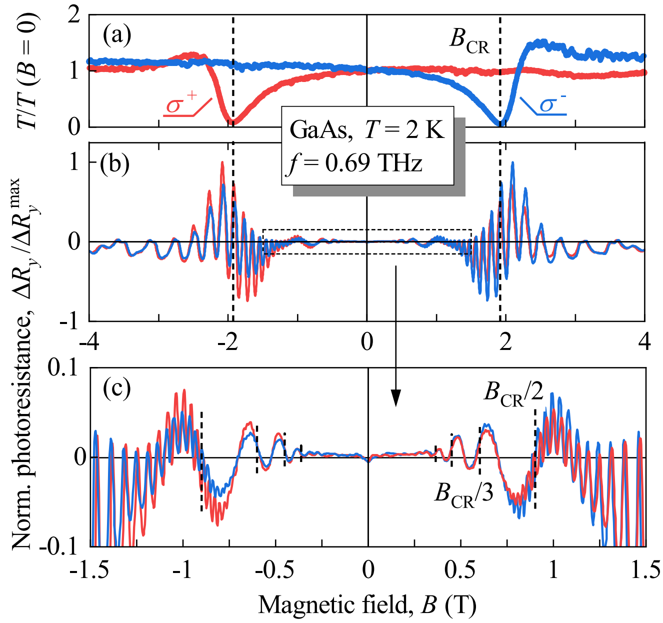

FIG. 5. Normalized transmittance (a) and photoresistance (b) measured at $T = 2$ K on the GaAs sample #1 for right-handed (red) and left-handed (blue) $f = 0.69$ THz radiation after brief illumination by room light prior to measurements. The dashed vertical lines labeled with B_{CR} mark the position of the CR. (c) Enlarged low-B data from the marked area in (b) showing MIRO with nodes at the CR harmonics (dashed lines).

The helicity immunity of MIRO detected in Refs. [18,31] is widely considered an inherent puzzling property of the MIRO phenomenon and remains the central unresolved problem in this field of research. Our present observations essentially modify and partially resolve this long-standing problem. Indeed, while this is not *a priori* clear from the MIRO experiments, observation of the helicity-insensitive CR in our present work explicitly shows that the helicity immunity has more fundamental character: It is not linked to specific microscopic mechanisms of MIRO but is rather a straightforward consequence of the helicity-insensitive absorption. From this perspective, MIRO just provide an alternative way to detect the helicity anomalies in the CR absorption [36]. Furthermore, the latest experiments of the Vienna group [21] show that the helicity immunity of MIRO is also not universal, confirming its sensitivity to details of disorder in particular solid-state 2DES (see also Ref. [37]). Using sub-THz illumination and a GaAs 2DES with similar density and mobility but with different technological design, they observed the expected [19] strong helicity dependence of MIRO accurately matching the usual CR line shape of the Drude absorption [21].

To summarize, we observed a puzzling polarization immunity of the CR-enhanced THz absorption pointing to a fundamental failure in the conventional description of light-matter interaction in 2DES. In contrast, the usual strong helicity dependence is detected in simultaneous CR transmission measurements. We find that the observed anomaly is not universal and does not show up in all systems. Moreover, the helicity anomaly disappears at elevated temperatures restoring the conventional textbook CR behavior. We propose that the anomaly is related to electron dynamics near strong impurities/inhomogeneities leading to a local near-field coupling of two otherwise independent helicity modes and to the CR enhanced absorption for both magnetic field polarities.

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