Terahertz photoresistivity of a high-mobility 3D topological insulator based on a strained HgTe film

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(Dated: 19 August 2020)

We report on a detailed study of the terahertz (THz) photoresistivity in a strained HgTe three-dimensional topological insulator (3D TI) for all Fermi level positions: inside the conduction and valence bands, and in the bulk gap. In the presence of magnetic field we detect a resonance corresponding to the cyclotron resonance (CR) in the top surface Dirac fermions (DF) and examine the nontrivial dependence of the surface state cyclotron mass on the Fermi level position. We also detect additional resonant features at moderate electron densities and demonstrate that they are caused by the mixing of surface DF and bulk electrons. At high electron densities, we observe THz radiation induced 1/B-periodic low-field magneto-oscillations coupled to harmonics of the CR and demonstrate that they have a common origin with microwave-induced resistance oscillations (MIRO) previously observed in high mobility GaAs-based heterostructures.

Three-dimensional TIs based on strained HgTe films have been the subject of an intensive study in the last ten years. This system is a strong topological insulator with electronic properties mediated by conducting surface helical states with close to linear dispersion with spins locked to the electron’s momentum1, 2, and is characterized by a very high mobility of the surface DF, reaching 5 × 10⁵ cm²/Vs in these systems, and low bulk conductivity. The properties of the surface states have been comprehensively studied using magneto-transport, phase-sensitive SQUID and capacitance spectroscopy3–11. These experiments resulted in the observation of the quantum Hall effect and probing of quantum capacitance in a 3D topological insulator, demonstrated a non-trivial Berry phase of Shubnikov – de Haas oscillations in transport and capacitance responses, provided an access to a detailed study of the surface states transport properties, and demonstrated highly efficient spin-to-charge current conversion. Presence of the topologically protected conducting surface states in strained HgTe 3D TIs also gives rise to a number of phenomena driven by THz electric fields. Observation of universal Faraday and Kerr effects12, 13 predicted in Ref. 14; THz quantum Hall effect15 and photogalvanic currents16, 17 excited in the surface states; study of surface states dynamic applying time domain spectroscopy18 and cyclotron resonance spectroscopy15–17, 19, where values of the effective mass of DF from top and bottom surfaces were determined, are only some examples of the achievements in this field.

While THz radiation induced optical and photocurrent phenomena have been widely investigated there has been no work so far aimed at the study of the photoconductive (photoresistive) response of the surface states. Such measurements, however, would not only yield information on tiny details of carrier scattering mechanisms and CR (for HgTe 2D systems see Ref. 20) but also may result in the observation of novel phenomena in 3D TI, such as, e.g., MIRO previously detected in 2D systems with parabolic dispersion21, 22 and, most recently, in DF in graphene23.

In this paper we report on the investigation of the THz photoresistence of HgTe-based 3D TIs for all Fermi level, 𝐸_周转, positions: inside the conduction and valence bands, and in the bulk energy gap. Studying the magnetic field dependence of the photoresponse we observed pronounce CR and, at high electron densities, THz radiation induced MIRO-like oscillations coupled to CR. Furthermore, for the intermediate electron densities we detected an additional set of oscillations which behave similarly to magneto-inter-subband oscillations (MISO) detected in coupled double quantum wells (QWs)24, 25.

Experimental samples are field effect transistor-like Hall-bar structures with semi-transparent Ti/Au gates fabricated on the basis of strained 80-nm HgTe films that have been grown by molecular beam epitaxy on a GaAs (013) substrate4 (Fig. 1). The Hall-bar channel width is 50 µm and distances between potential probes are 100 and 250 µm. The samples are placed into an optical cryostat. We apply a molecular far-infrared laser as a source of THz radiation with frequency 𝑓 = 0.69THz (wavelength λ = 432µm)26, 27. The incident power P ≈ 20mW is modulated at about 160Hz by

FIG. 1. (a) Schematic cross section of the structure under study. Bright red lines represent surface DF on the top and bottom surfaces of the HgTe film. (b) Optical micrograph of the device; faint lilac area corresponds to the gated region. (c) Schematic experimental setup.

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an optical chopper. Photoresistance is measured by means of a double modulation technique\(^{28}\) with a low modulation frequency of 6 Hz and a high one corresponding to the chopper frequency. The temperature range of the experiment is (2 – 20) K.

All studied samples have been characterized by magneto-transport measurements using a standard low-frequency lockin technique in a perpendicular magnetic field \(B\) up to 7 T and current \(I\) in the range of \((10 – 100)\,\text{nA}\). Typical gate voltage dependences of dissipative, \(\rho_x(V_g)\), and Hall, \(\rho_y(V_g)\), resistivities are shown in Fig. 2 (b) and (c). Using \(\rho_x(V_g)\) one can determine the gate voltages corresponding to the conduction band bottom and the valence band top\(^4\), see arrows in Fig 2.

Fig. 3 (a) demonstrates the main result of our work – magnetic field dependences of the photoresistivity \(\delta \rho_{ph}(B)\) normalized to the maximum of its absolute value \(|\delta \rho_{ph}^{\max}|\). The dependences are measured at \(\lambda = 432\,\mu\text{m}\) for three ranges of \(V_g\) corresponding to the Fermi level position in: i) the valence band \((V_g < -2.5\,\text{V})\), ii) in the gap \((-2.5\,\text{V} < V_g < 0\,\text{V})\), and iii) in the conduction band \((V_g > 0\,\text{V})\). All curves are measured at 20 K. This temperature is high enough to suppress the contribution of the Shubnikov – de Haas oscillations. One can clearly see that \(\rho_{ph}/|\rho_{ph}^{\max}|(B)\) dependences have resonant shapes with the maximum position lying in the magnetic field range \(B_{CR} = (0.7 – 0.9)\,\text{T}\) depending on the applied gate voltage, i.e., Fermi level position. Using the value of \(B_{CR}\) one can determine the cyclotron effective mass \(m_c = eB_{CR}/(2\pi f)\), where \(e > 0\) is the elementary charge. In Fig. 3 (b) we show the gate voltage dependence of \(m_c\). One can see that this dependence has a nonmonotonic behavior with a minimum value of \(m_c = 0.03 m_0\) near the valence band top; \(m_0\) is the free electron mass. The cyclotron mass approaches its maximum value \(m_c = 0.04 m_0\) at the highest gate voltages, corresponding to a DF density of about \(7 \times 10^{11}\,\text{cm}^{-2}\). In fact, such nonmonotonic behavior of the cyclotron mass and its values are in line to what was measured\(^{12,16,19}\), and calculated\(^{16,19}\) for surface DF in HgTe.

The temperature dependence of the resistance (not shown)
suggest that at all gate voltages the photoresistivity sign observed under resonance conditions corresponds to carrier heating. Then, it can be expressed as

\[ \delta \rho_{\text{ph}} = \alpha A (dR/dT), \]  

(1)

where \( A \) is the proportionality coefficient relating the incident power to the change in the temperature of the DF and \( \alpha \) is the absorption coefficient. As one can see from this expression the properties of the photoresistivity are expected to be determined primarily by the behavior of the absorption coefficient.

Now we analyze the shape of the CR photoresistivity. We begin from a gate voltage range corresponding to the Fermi level positions in the valence band (see Fig. 4 (a)). In this range the photoresistivity is quite satisfactory fitted by a Lorentzian curve. It is interesting to compare the Lorentzian width \( \gamma \) with the theoretical CR width \( \Delta_{\text{CR}} \) for separated Landau levels using a well-known expression for the latter in the case of a short range potential:\textsuperscript{22,29}

\[ \Delta_{\text{CR}}^2 = (2/\pi) h \omega_c (h/\tau), \]  

(2)

where \( \omega_c \) is the cyclotron frequency and \( \tau \) is the transport relaxation time. In the valence band the DF mobility is about \( 2 \times 10^5 \text{cm}^2/\text{Vs} \) which corresponds to \( \Delta_{\text{CR}} \approx 0.6 \text{meV} \). This value is two to three times larger compared to experimental resonance width \( \gamma \) values. It is likely that the origin of the indicated discrepancy is the inelastic scattering of surface DF by bulk holes which is very significant in the temperature range we used in our experiments.\textsuperscript{3} As a result the CR width is determined by principally different scattering processes: elastic impurity scattering and inelastic electron-hole one.

Next we consider the CR photoresistivity shape when the Fermi level enters into the gap (Fig. 4 (b)). The fitting of the photoresistivity by a Lorentzian function also demonstrates quite good agreement. It gives a resonance width of about 0.3 T when the Fermi level lies near the top of the valence band, and it decreases when the Fermi level moves to the bottom of the conduction band. More careful analysis of the \( \gamma \) behavior shows an interesting feature (inset to Fig. 4 (b)): as the Fermi level moves through the gap from the valence band top to the conduction band bottom a significant CR peak narrowing occurs, while \( \Delta_{\text{CR}} \) has no change. This indicates that the shape of the surface Dirac fermion CR is determined not only by the transport relaxation time as it is the case in text book 3D cases, see Eq. (2). It is well-known that there is a topological back scattering protection in 3D TIs, but in contrast to two-dimensional TIs this protection does not work for the scattering on finite angles and therefore only weakly changes \( \tau \). To explain this fact one can assume that, in contradiction to the transport relaxation time, the CR lifetime is much more sensitive to the topological back scattering protection that plays a more important role as the DF moment becomes larger.

As the Fermi level leaves the gap and enters the conduction band (see a \( \delta \rho_{\text{ph}}/\delta \rho_{\text{ph}}^{\text{max}}(B) \) dependence in Fig. 3 (a) at \( V_g = 0.5 \text{V} \) photoresistivity oscillations at magnetic fields below \( B_{\text{CR}} \) emerge. Note that these oscillations are absent when the Fermi level intersects only the surface states. Since the top surface DF have higher density and mobility in the stud-
ied systems, the oscillations are presumably generated by the mixing of a top surface DF band and the bulk conduction band, which, more accurately, contains a set of the size-quantized subbands. So the observed oscillations are similar to magnetointersubband oscillations (MISO) in coupled double QWs studied in Ref. 24 and 25. But in our case we have two significantly different sets of interacting bands: the spin-polarized surface DF band and the size-quantized subbands of the 80 nm HgTe film. Moreover, in our experiment we have an important advantage: due to the field effect transistor structure we are able to change the position of the Fermi level and correspondingly the subband densities.

As the Fermi level moves further inside the conduction band, these oscillations are superimposed with THz induced MIRO-like oscillations that have nearly the same structure for several gate voltages ranging from 6 to 10 V, see Fig. 5 (a). Arrows in this figure show the positions of subsequent extrema of MIRO, numbered as \( N = 2, 3, \ldots \). It is well known that for MIRO

\[
\delta \rho_{ph} \propto -\sin(2\pi B_F/B),
\]

where \( B_F = 2\pi \hbar m_0^{\text{MRO}} / e \). Thereby, the slope of the \( N/2 \) v.s. \( B^{-1} \) dependence, see Fig. 5 (b), is equal to \( B_F \) that allows us to determine the corresponding effective mass \( m_0^{\text{MRO}} = (0.038 \pm 0.001)m_0 \). This value is close to the cyclotron mass values at high positive \( V_g \), where it is possible to mark out CR (\( V_g = 2 \) and 3 V). We note that approximation lines \( N/2(B^{-1}) \) start near \( N/2 = -0.25 \) as it is predicted for MIRO. The detailed study of the observed transformation of the photoresponse from one CR peak to MIRO-like oscillations through a rich picture of interband interaction induced oscillations will be reported later.

To conclude, we have observed and studied the THz cyclotron resonance photoresistivity of 80-nm-thick strained HgTe 3D TI. The photoresistivity was studied at all Fermi level positions: inside the conduction and valence bands and in the bulk gap. For the Fermi level lying in the valence band or the gap, we observed a single resonance of the photoresistivity, which is caused by the cyclotron resonance of DF in the top surface. For higher positions of the Fermi level, i.e., for \( E_F \) lying in the conduction band, the CR-photoresistivity becomes superimposed fist with magnetointersubband oscillations, and, at further increase of \( E_F \), with MIRO oscillations.

ACKNOWLEDGMENTS

We are grateful to Ivan Dmitriev for discussions. Novosibirsk team acknowledges the financial support by the Russian Science Foundation (Grant No. 16-12-10041-P). M. Otteneder and S.D. Ganichev gratefully acknowledge the support of the Deutsche Forschungsgemeinschaft (DFG) - Project-ID 314695032 - SFB 1277, and the Volkswagen Stiftung Program (97738). S.D.G. also thanks the IRAP program of the Foundation for Polish Science (grant MAB/2018/9, CENTERA) for the support.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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