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Cyclotron Resonance of Dirac Ferions in HgTe Quantum Wells

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Cyclotron resonance of single-valley two-dimensional Dirac fermions in HgTe-based quantum wells has been experimentally investigated. The thickness of the wells is close to the critical value corresponding to the transition from the direct energy spectrum to the inverted spectrum. Under terahertz laser irradiation, transitions between the ground and first Landau levels, as well as between the first and second Landau levels, have been observed. Low magnetic fields corresponding to the cyclotron resonance, as well as the strong dependence of the position of the resonance on the electron density, indicate the Dirac character of the spectrum in these quantum wells. It has been shown that disorder plays an important role in the formation of the spectrum of two-dimensional Dirac fermions.

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Graphene is the first solid system in which a linear energy spectrum has been implemented. This has stimulated great interest in two-dimensional massless quasi-Dirac fermions [1]. It is worth noting that the mentioned linear spectrum consists of two nonequivalent valleys and is due to the special symmetry of the graphene lattice rather than to relativistic effects. At present, relativistic two-dimensional Dirac fermions can be implemented in the following two systems: (i) the surface of three-dimensional topological insulators and (ii) quantum wells based on semiconductors with an inverted band spectrum [2–6]. Unlike graphene, the Dirac cone in both cases is formed in the center of the Brillouin zone rather than at its edge. However, a more important feature of two-dimensional Dirac fermions in the indicated systems is a key role of the spin–orbit interaction. This interaction is responsible for spin-polarized two-dimensional Dirac fermions on the surface of three-dimensional topological insulators and unpolarized two-dimensional Dirac fermions in quantum wells based on semiconductors with an inverted band structure.

Although the existence of two-dimensional Dirac fermions on the surface of three-dimensional topological insulators has been demonstrated in various materials, a number of predicted interesting properties of two-dimensional Dirac fermions have not yet been observed [3]. The last circumstance is explained primarily by the difficulty of the separation of the surface and bulk contributions to the electron transport in three-dimensional topological insulators [3]. This difficulty is absent when studying two-dimensional Dirac fermions in highly mobile quantum-sized CdHgTe/HgTe/CdHgTe structures. Note that the modern technology of the growth of HgTe-based quantum wells makes it possible to obtain structures with the electron mobility much higher than 10^5 cm^2/(V s) [6, 7]. As was shown in early works on size quantization [8, 9], spin-degenerate two-dimensional Dirac fermions should appear in these quantum wells with the critical thickness d_c that corresponds to the transition from the direct energy spectrum to the inverted one. Previous numerical calculations indicate that $d_c = 6–7$ nm depending on the orientation of the quantum well and deformation stress in it [4–6]. It is difficult to obtain a quantum well with thickness d_c because the existing methods for controlling the growth of quantum wells are insufficiently accurate for this. The first indication of the implementation of relativistic single-valley two-dimensional Dirac fermions was obtained in recent experiments concerning the quantum Hall effect on samples where the quantum wells had a thickness close to d_c and were grown on (001) oriented substrates [6]. Note that analysis of the measurements of the quantum Hall effect in HgTe-based quantum wells is complicated because the g^* factor of electrons is large [6, 10]. Direct evidence of the existence of two-dimensional Dirac fermions in HgTe-based quantum wells can be obtained when studying phenomena directly associated with the features of the energy spectrum of two-dimensional Dirac fermions. One of them is the cyclotron resonance, which can provide information on the distances between Landau levels.

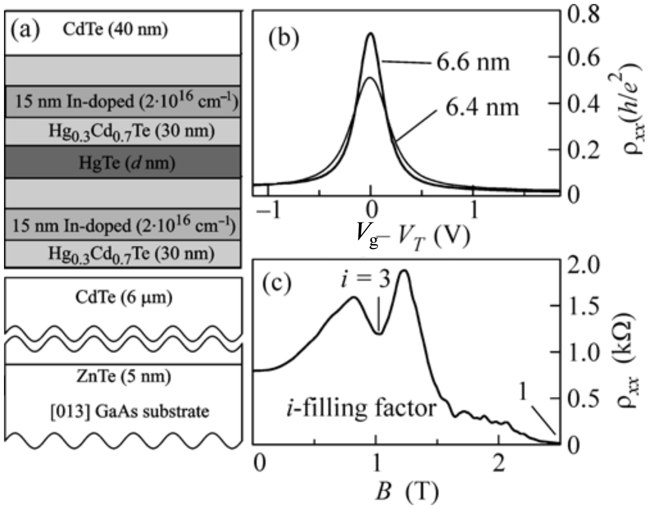

Fig. 1. (a) Schematic cross section of the structures under study. (b) Dependences $\rho_{xx}(V_g - V_T)$ in zero magnetic field for the $Cd_{0.7}Hg_{0.3}Te/HgTe/Cd_{0.7}Hg_{0.3}Te$ quantum wells 6.4 and 6.6 nm in thickness at a temperature of 4.2 K (V_T is the gate voltage corresponding to the maximum of the resistance $\rho_{xx}(V_g)$). (c) Magnetic-field dependence of the magnetoresistance $\rho_{xx}(B)$ at $N_s = 7.2 \times 10^{10}$ cm^{-2} for the 6.6-nm-thick quantum well at the same temperature.

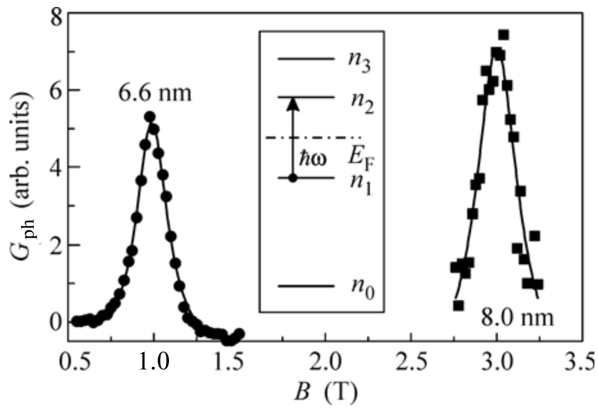

Fig. 2. Magnetic-field dependences of the photoconductivity $\Delta G_{ph}(B)$ for the $Cd_{0.7}Hg_{0.3}Te/HgTe/Cd_{0.7}Hg_{0.3}Te$ quantum wells with a thickness of 6.6 nm ($N_s = 7.2 \times 10^{10}$ cm^{-2}) and 8.0 nm ($N_s = 9.6 \times 10^{11}$ cm^{-2}) irradiated by laser radiation with a wavelength of 118 μm. The solid lines are Lorentzian approximations with the half-widths of 0.22 T ($d = 6.6$ nm) and 0.15 T ($d = 8.0$ nm). The inset schematically shows the Fermi level and the 1 ⟶ 2 optical transition between the Landau levels.

In this work, we report on the observation and investigation of cyclotron resonance of single-valley two-dimensional Dirac fermions in HgTe-based quantum wells. Terahertz photoconductivity and photocurrents in 6.4- and 6.6-nm quantum wells grown on (013)-oriented substrates are measured. It is found that the cyclotron resonance in these structures appears in magnetic fields that are several times lower than those in thicker quantum wells, which are characterized by the usual parabolic dispersion law. Moreover, the position of the resonance is strongly shifted toward lower fields with a decrease in the electron density. It is shown that the unusual behavior of the cyclotron resonance is caused by the linear energy spectrum in these structures and is attributed to the appearance of transitions between the ground and first Landau levels or the first and second Landau levels, depending on the position of the Fermi level.

Quantum wells $Cd_{0.7}Hg_{0.3}Te/HgTe/Cd_{0.7}Hg_{0.3}Te$ were grown by molecular beam epitaxy described in [7]. Figure 1a shows the schematic cross section of structures studied in this work. Samples were 50-μm-wide Hall bars, where the distance between electrometric contacts was 100 μm, with and without a gate. We examined quantum wells with thickness $d = 6.4$, 6.6, and 8.0 nm with the electron mobility $\mu \approx 10^5$ cm^2/(V s) at $T = 4.2$ K. The electron density N_s in the samples under study varied from 1.6×10^{10} to 8×10^{10} cm^{-2} by varying background irradiation. The electron density N_s at various irradiation levels was determined from magnetotransport measurements. Figures 1b and 1c show the typical dependences of the resistivity of the samples under study on the gate voltage ($\rho_{xx}(V_g)$) and magnetic field ($\rho_{xx}(B)$), respectively. The dependences $\rho_{xx}(V_g)$ in Fig. 1b are symmetric curves with the maximum reaching $0.5h/e^2$ and $0.7h/e^2$ in quantum wells with $d = 6.4$ and 6.6 nm, respectively.

We measured the terahertz response (photoconductivity and photocurrent) of two-dimensional electrons in quantum wells in magnetic fields up to 3 T. A continuous-wave molecular laser based on methanol with optical pumping by a CO_2 laser was used as a source of 2.5-THz radiation (wavelength $\lambda = 118$ μm and photon energy $\hbar\omega = 10.4$ meV). The power of the radiation incident on the sample was varied from 30 to 100 mW. Photoconductivity was measured using the standard modulation method when direct current $I =$ 1–10 μA was passed through the sample. When the photocurrent was measured, the external source was disconnected.

Figure 2 shows the magnetic field dependence of the photoconductivity $\Delta G_{ph}(B)$ for the 6.6-nm-thick quantum well with the electron density $N_s = 7.2 \times 10^{10}$ cm^{-2} obtained at $T = 4.2$ K. Pronounced cyclotron resonance of the photoconductivity in the magnetic field $B_c = 1$ T is observed. A decrease in the electron density from $N_s = 7.2 \times 10^{10}$ cm^{-2} to $N_s < 2.5 \times 10^{10}$ cm^{-2} is accompanied by the shift of the photoconductivity resonance toward much lower (lower than one-third) magnetic fields ($B_c = 0.29$ T); see Fig. 3. A close position of resonance was detected in the samples with the 6.4-nm-thick quantum well. The results obtained in these structures for $N_s = 1.8 \times 10^{10}$ cm^{-2}

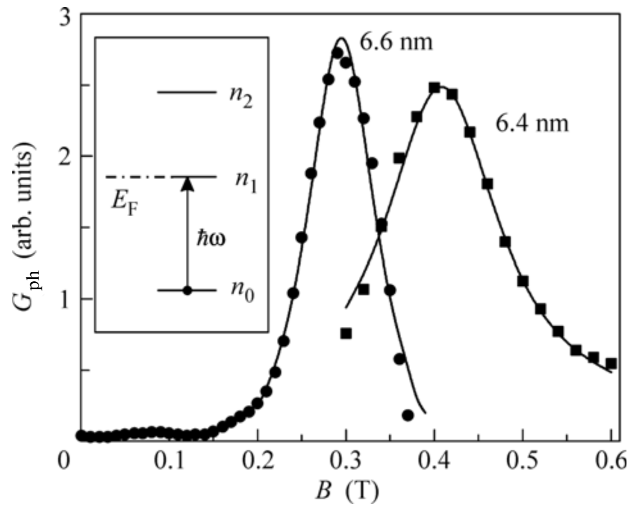

Fig. 3. Magnetic-field dependences of the photoconductivity $\Delta G_{ph}(B)$ for the $Cd_{0.7}Hg_{0.3}Te/HgTe/Cd_{0.7}Hg_{0.3}Te$ quantum wells with the thickness d = (squares) 6.4 and (circles) 6.6 nm measured at low electron density N_s = (squares) 1.8×10^{10} and (circles) 1.65×10^{10} cm^{-2}. The solid lines are Lorentzian approximations with the half-widths of 0.15 and 0.10 T for $d = 6.4$ and 6.6 nm, respectively. The inset schematically shows the Fermi level and the $0 \longrightarrow 1$ optical transition between the Landau levels.

are also shown in Fig. 3. An increase in the thickness of quantum wells to 8.0 nm leads to a strong shift of the position of the cyclotron resonance toward much higher magnetic fields (see Fig. 2) and to the absence of the strong dependence of the resonance position on the electron density. In addition to the photoconductivity, photogalvanic currents were observed [11–13]. It was revealed that the magnetic field dependence of the photocurrent is also resonant. The position of the photocurrent resonance and its shift upon change in the thickness of the quantum well and electron density correspond to the behavior of the photoconductivity signal. Consideration of photocurrent generation mechanisms is beyond the scope of this work, which is devoted to analysis of the position of the resonance.

The position of the cyclotron resonance in samples with $d = 8.0$ nm is in good agreement with investigations of quantum wells with a parabolic spectrum. This position corresponds to optical transitions between energetically equidistant Landau levels [14]. The appearance of the resonance in fields that are at least a factor of two lower than B_c in wide quantum wells ($d = 8.0$ nm or wider) and, particularly, its strong shift toward lower fields with a decrease in the carrier density are extraordinary. This behavior can be explained only by the fundamental difference between the spectra of two-dimensional electrons in 6.6- and 8.0-nm-thick quantum wells, namely, by the implementation of the system of massless two-dimensional Dirac fermions at $d = d_c$. As is well known, Landau levels in these systems are not described by the standard formula

$$E_n = \hbar\omega_c(n + 1/2), \quad (1)$$

their positions are rather given by the expression [12–14]

$$E_n = \mathrm{sgn}(n)\sqrt{2|n|}(\hbar V_{DDF})/l_B, \quad (2)$$

where $l_B = (\hbar c/eB)^{1/2}$ is the magnetic length and V_{DDF} is the velocity of Dirac fermions. According to Eq. (2), the distance between the mth and nth Landau levels ($m, n > 0$) is given by the expression

$$\Delta E_{mn} = (\sqrt{2m} - \sqrt{2n})(\hbar V_{DDF})/l_B. \quad (3)$$

Using the value $V_{DDF} = 7 \times 10^7$ cm/s obtained from the energy spectrum calculated in [6], we conclude that the cyclotron resonance for the $1 \longrightarrow 2$ transition induced by radiation with $\hbar\omega = 10.4$ meV should be observed at $B_{12} = 0.97$ T. This value is in good agreement with the experimental data presented in Fig. 2. One of the consequences of Eq. (2) is the difference between the cyclotron resonance energies upon the excitation of transitions between different Landau levels. This difference is particularly large for lower levels. For example, the field B_{01} corresponding to the $0 \longrightarrow 1$ transition between the ground and first Landau levels should be lower by a factor of 5.8 than the field B_{12} corresponding to the $1 \longrightarrow 2$ transition between the first and second Landau levels. A significant decrease in B_c was indeed observed in samples with $d = 6.6$ nm (see Figs. 2 and 3). In these experiments, different Fermi energies E_F were ensured by varying the electron density. The insets in Figs. 2 and 3 schematically show the position of the Fermi level and possible optical transitions for radiation with a photon energy of 10.4 meV ($\lambda = 118$ μm). According to magnetotransport measurements, the ground and first Landau levels are completely filled at $N_s = 7.2 \times 10^{10}$ cm^{-2} and, therefore, transitions occur between the first and second Landau levels ($B_{12} = 1.0$ T). When the electron density decreases to $N_s < 2.5 \times 10^{10}$ cm^{-2}, the filling factor of the first Landau level decreases significantly and optical transition occurs from the zeroth Landau level to the partially filled first Landau level (Fig. 3). This means that resonance at a fixed photon energy should appear in a much lower magnetic field; this behavior is observed in the experiment ($B_{01} = 0.29$ T). The detected shift of the position of resonance upon change in the position of the Fermi level is direct evidence that the energy spectrum in structures with $d = 6.6$ nm corresponds to two-dimensional Dirac fermions. Indeed, in wide quantum wells characterized by a parabolic spectrum and equidistant Landau levels, the position of the resonance is independent of E_F. The gapless or narrow-gap character of the energy spectrum of the quantum well with $d = 6.6$ nm is also confirmed by the maximum value $\rho_{xx} = 0.7h/e^2$ (see

Fig. 1b), i.e., smaller than h/e^2, which determines the boundary between the quasimetallic and dielectric behaviors of a two-dimensional system.

The significant shift of the position of cyclotron resonance ($B_{01} \approx B_{12}/3$) that is revealed in samples with $d = 6.6$ nm is in qualitative agreement with Eq. (2), but its value differs from the predicted value. This result indicates that, in the energy range under study (with a width of 10–20 meV near the Dirac point), the effect of disorder is likely noticeable, which can distort the ideal linearity of the energy spectrum in the indicated energy range. In a real system, both structural disorder (fluctuations of the thickness of a quantum well) and impurity disorder always exist and can significantly change the behavior of the density of states near the Dirac point and lead to the appearance of nonzero effective mass. Another reason for imprecise agreement between the experimental shift B_c and Eq. (2) can be a small deviation of the real thickness of the quantum well from the ideally exact value d_c. The unusual behavior of the width of the resonance for the $1 \longrightarrow 2$ and $0 \longrightarrow 1$ transitions is also remarkable. Comparison of Figs. 2 and 3 indicates that the half-width of the $0 \longrightarrow 1$ resonance is more than a factor of 2 smaller than the half-width of the $1 \longrightarrow 2$ resonance, although the mobility in the former case ($\mu = 9.5 \times 10^4$ cm^2/(V s)) is lower than that in the latter case ($\mu = 1.1 \times 10^5$ cm^2/(V s)). Further study of this result is of apparent interest.

Comparison of the positions of the resonances obtained on the samples with $d = 6.6$ nm ($B_{01} = 0.29$ T) and $d = 6.4$ nm ($B_{01} = 0.41$ T) in Fig. 3 shows that a decrease in the thickness of the quantum well by only 0.2 nm is accompanied by a noticeable shift of the resonance toward higher magnetic fields. This behavior makes it possible to assume that the 6.4-nm-thick quantum well has a narrow energy gap, which leads to a noticeable deviation of the spectrum from a linear form and, as a result, to the appearance of Dirac fermions with nonzero mass. Note that the maximum resistivity ρ_{xx} in this sample is $0.5h/e^2$ (see Fig. 1), which is lower than that for the quantum well with $d = 6.6$ nm. This result also indicates that the properties of two-dimensional Dirac fermions in the HgTe-based quantum well depend not only on the average thickness of the quantum well but also on the structural and impurity disorder in it.

To conclude, we note that the results of investigations of HgTe-based quantum wells with a nearly critical thickness provide important experimental evidence of the existence of both the gapless spectrum and two-dimensional Dirac fermions in these quantum wells. This conclusion is based on the data obtained when studying the cyclotron resonance, which is a phenomenon directly associated with the features of the energy spectrum. It is also noteworthy that fluctuations of the parameters of the problem (gap value, amplitude of the impurity potential, etc.) are of the same order of magnitude and can significantly affect the properties of two-dimensional Dirac fermions. For this reason, further investigation of the system of two-dimensional Dirac fermions in HgTe-based quantum wells is of interest not only for the physics of relativistic effects in condensed matter but also for the physics of disordered systems.

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REFERENCES

1. A. H. Castro Neto, F. Guinea, N. M. R. Peres, et al., Rev. Mod. Phys. **81**, 110 (2009).
2. B. A. Volkov and O. A. Pankratov, JETP Lett. **42**, 178 (1985).
3. M. Z. Hasan and C. L. Kane, Rev. Mod. Phys. **82**, 3045 (2010).
4. X.-L. Qi and S.-C. Zhang, Rev. Mod. Phys. **83**, 1057 (2011).
5. B. A. Bernevig, T. L. Hughes, and S. C. Zhang, Science **314**, 1757 (2006).
6. B. Büttner, C. X. Liu, G. Tkachov, et al., Nature Phys. **7**, 418 (2011).
7. Z. D. Kvon, E. B. Ol'shanetskii, N. N. Mikhailov, et al., J. Low Temp. Phys. **35**, 6 (2009).
8. L. G. Gerchikov and A. V. Subashiev, Sov. Phys. Semicond. **23**, 1368 (1989).
9. L. G. Gerchikov and A. V. Subashiev, Phys. Status Solidi B **160**, 443 (1990).
10. G. M. Gusev, E. B. Olshanetsky, Z. D. Kvon, et al., Phys. Rev. Lett. **104**, 166401 (2010).
11. S. D. Ganichev and W. Prettl, *Intense Terahertz Excitation of Semiconductors* (Oxford Univ. Press, 2006).
12. V. V. Bel'kov and S. D. Ganichev, Semicond. Sci. Technol. **23**, 114003 (2008).
13. H. Diehl, V. A. Shalygin, L. E. Golub, et al., Phys. Rev. B **80**, 075311 (2009).
14. Z. D. Kvon, S. N. Danilov, N. N. Mikhailov, et al., Physica E **40**, 1885 (2008).
15. J. W. McClure, Phys. Rev. **104**, 666 (1956).
16. G. W. Semenoff, Phys. Rev. Lett. **53**, 2449 (1984).
17. F. D. M. Haldane, Phys. Rev. Lett. **61**, 2015 (1988).

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