Two-dimensional Dirac fermions system in CdHgTe quantum wells

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We report on transport and capacitance spectroscopy study of two kinds of quantum wells, namely Cd0.02Hg0.98Te and Cd0.06Hg0.94Te with the thicknesses of 7.4 and 11.5 nm, accordingly. The fraction of Cd was chosen in a way that the both quantum wells are expected to have gapless band structure typical for a Dirac fermions system. We have established that the first quantum well exhibits a massless Dirac fermions system with a quality slightly better then in conventional HgTe quantum wells of critical thickness. Second quantum well exhibits a high-quality two-dimensional topological insulator state with the energy gap of around 10 meV and well-defined edge transport making it as a good candidate for further study and applications of topological insulators.

INTRODUCTION

The two-dimensional single valley gapless Dirac Fermions (DF) system implements in a HgTe quantum well (QW) with a critical thickness $d$ of around 6.5 nm.1 The band diagram of the system is very similar to graphene but without the valley degeneracy and with Dirac point located in a center of the Brillouin zone. The system consists of a great interest for a condensed matter physics because of the wide variety of effects demonstrated. It was studied by transport measurements both in classical and quantizing magnetic fields2–7, the linearity of it’s band structure was shown by cyclotron resonance studies in THz range8–10 as well as by the capacitance spectroscopy11. The striking results specific for DF system were obtained by Faraday rotation study, where the quantization of the rotation angle in the units of fine structure constant was observed12 and by non-local transport measurements13, where the existence of edge mode with the filling factor of $i = 0$ was shown.

Further study of the system is limited by several issues, including the disorder which hinders the observation of subtle effects and reduces the carriers’ mobility. One could note the following regularity of HgTe QWs: the electron mobility increases with QW’s thickness. Indeed, the electrons in QW of critical thickness demonstrate a moderate mobility $\mu$ not exceeding $1.5 \cdot 10^5$ cm$^2$/V·s which becomes even smaller for thinner QWs ($2.5 \cdot 10^4$ for $d = 5.7$ nm14), while QWs with $d > 10$ nm could demonstrate the mobilities almost one order bigger3,15. The possible reason for the observed $\mu(d)$ dependence is the spatial fluctuations of the QW’s thickness $\Delta d$ leading to the energy gap inhomogeneities and additional scattering3,15. The thickness fluctuations is expected to be independent from $d$, making thinner QWs more subjected to that kind of imperfection since the relative fluctuations $\Delta d/d$ are bigger. While the issue itself desires a separate study, the fact that thicker QWs shows higher electron mobility could be used in order to increase the mobility of DF system. On the one hand, the gapless state implements in QWs of critical thickness $d_c$ corresponding to the transition from normal band structure to the inverted one1. The value of $d_c$ depends on the QW orientation and strain but it is well-defined and lies in the range of 6.3-6.6 nm. However, the value of $d_c$ could be efficiently increased if one replaces a part of Hg atoms in the HgTe QW with Cd ones. In particular case of Cd$_{0.17}$Hg$_{0.83}$Te alloy the critical thickness tends to the infinity and DF are formed in bulk material16,17.

In the current work we report on the magnetotransport and capacitance spectroscopy study of two kinds Cd$_{1-x}$Hg$_x$Te QWs with the thickness of $d = 7.4$ nm (type 1 QW) and $d = 11.5$ nm (redtype 2 QW). The fraction of Cd was chosen in a way that the both QWs are expected to have gapless band structure typical for DF system. However the found that type 2 QW is characterized by a small energy gap and an inverted band structure typical for two-dimensional topological insulators. Both QWs demonstrate higher values of electron mobility, than conventional pure HgTe QWs with the critical thickness of around 6.5 nm.

METHODS

We study Cd$_{0.02}$Hg$_{0.98}$Te (HgTe with 2% of Hg atoms replaced by Cd, type 1 QW) and Cd$_{0.06}$Hg$_{0.94}$Te (6% of Cd, type 2 QW) quantum wells with the thicknesses of 7.4 and 11.5 nm, accordingly. The structures have been grown by molecular beam epitaxy on GaAs(013) substrate (Fig. 1 (a)). Wet chemical etching was used to make 10-contacts Hall bars (Fig. 1 (b)). The central part of the Hall bars was covered by 200 nm thick SiO$_2$ insulator and Ti/Au gate. Several samples from the same wafers have been studied showing similar results.

The measurements were performed in a temperature range of 1.8 – 50 K and in perpendicular magnetic fields up to 3 T. The magnetotransport data were obtained using standard 4-terminal lock-in technique with the exci-

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tation current within the range of 20 – 200 nA (depending on the sample resistance and temperature) and the frequency of 12 Hz. The capacitance was measured by applying a sum of DC voltage \( V_g \) and a small probing AC voltage \( V_{ac} = 20 \text{ mV} \) at frequencies of 10 – 700 Hz to the gate and measuring the AC current flowing through the QW. Both real and imaginary parts of the signal were recorded in order to avoid leakages and resistive effects.

FIG. 1. (a) - The schematic cross-section of the structures under study. The Cd\(_{0.6}\)Hg\(_{0.4}\)Te film (type 1 QW with thickness 7.4 nm for \( x = 0.02 \) and type 2 QW with thickness 11.5 nm for \( x = 0.06 \)) is sandwiched between thin Cd\(_{0.6}\)Hg\(_{0.4}\)Te buffer layers, covered by 40-50 nm of CdTe and a 200 nm SiO\(_2\) insulator and a metallic gate. (b) - The schematic top view of studied Hall bars.

RESULTS AND DISCUSSION

We performed the magnetotransport study for both types of QW. The analysis of the data obtained from each QW was pointed to the further questions: 1. Does the QW have an energy gap? 2. What is the maximum value of the electron mobility? Additionally we performed the capacitance \( C \) spectroscopy of the first type QW. From the \( C(V_g) \) dependence we extracted the velocity of DF and also estimated the magnitude of disorder at Dirac point. For the second QW the capacitance spectroscopy was not performed since we have discovered the presence of energy gap between conduction and valence bands. In order to extract a value of the gap and to check if QW is characterized by normal or inverted band structure we additionally measured the resistance in non-local geometry and checked the temperature dependence of the resistance maximum both in local and non-local geometries. Next we present the detailed analysis of the experimental data.

A. Type 1 QW

Fig. 2 (a) shows the gate dependence of the sheet resistance \( \rho_{xx}(V_g^{\text{eff}}) \) of 7.4 nm HgTe quantum well with 2% of cadmium measured at \( T = 4.2 \text{ K} \), where \( V_g^{\text{eff}} = V_g - V_{g}^{\text{DP}} \) and \( V_{g}^{\text{DP}} \) is the gate voltage corresponding to the Dirac point. Note that the value of \( V_{g}^{\text{DP}} \) is determined by the random charge trapped in the insulating layer and may vary from the cooling cycle to cycle. However, every measured dependence is highly reproducible if shifted with respect to \( V_{g}^{\text{DP}} \) and plotted versus \( V_g^{\text{eff}} \). At \( V_g^{\text{eff}} = 0 \) the resistivity reaches its maximum with the value of about 13.3 k\( \Omega \) \( \approx 0.5 \, \frac{h}{e^2} \). The obtained value and general dependence agree with the results from previous works on conventional HgTe QWs of critical thickness\(^2,7,13\) and points out to the gapless band structure. Fig. 2 (b) shows the gate dependence of the Hall resistance \( \rho_{xy} \) in perpendicular magnetic fields \( B = 1 \, \text{T} \) (black) and 3 T (red). In the vicinity of DP the \( \rho_{xy}(V_g^{\text{eff}}) \) dependence changes its sign.

At strong magnetic field (3 T) one could clearly recognize several quantum Hall plateaux for electron filling factors \( i \) from 1 to 3 and much longer hole plateaux with corresponding \( i = -1 \). The asymmetry between electron and holes plateau is remarkable. Moreover, at 1 T there are only hints of \( \rho_{xy} \) quantization on the electron side, whereas there is clear \( h/e^2 \) plateau on the hole one. The similar effect was observed in conventional HgTe QWs of critical thickness\(^7\) and was explained by the existence of side valleys in the valence band, situated on some distance \( E_{HH} \approx 30 \text{ meV} \) below the DP. When the Fermi level touches the top of the side valleys an additional kind of heavy holes emerges in the system. The heavy holes efficiently screen the charge disorder and thereby increasing scattering time for Dirac holes. At the same time the existence of heavy holes strongly decreases the partial filling rate of Dirac holes and prolongs the quantum Hall plateau for \( i = -1 \). One could suggest that our system could be characterized by the similar band structure with side valleys and therefore demonstrate the same kind of behavior.

In order to quantitatively compare the value of disorder in the QW under investigation and in conventional QWs we performed the capacitance spectroscopy study. The capacitance measured between the gate and QW could be represented as two capacitors connected in series: geometric capacitance \( C_g \) and quantum capacitance \( C_q = e^2 D \), where \( D \) is the thermodynamic density of states (DoS) of the system\(^{18} \). Fig. 3 shows the gate voltage (top axis) or density (bottom axis) dependence of
In contrast to the first QW, the quantized Hall resistance depends on the density of carriers, modification of the DoS with a spatial scale of about 1 nm. The fluctuations do not allow DoS to drop to zero in DP. In real case the spatial fluctuations of trapped charge lead to the fluctuation of the Fermi energy in the vicinity of DP. The fitting model and procedure is explained in details in Ref. 11.

From the fitting one extracts the following parameters: $v_{DF}$, the velocity of DF; $E_{HH}$, the distance from DP to the top of the side valleys; $\sigma_{DF}$ and $\sigma_{HH}$, the spatial fluctuations of the Fermi energy in the vicinity of DP and side valleys accordingly. The values of the parameters extracted from the fitting are shown in the Fig. 3. The "band diagram parameters" $v_{DF}$ and $E_{HH}$ are found to be slightly smaller compare to previously reported values. What is essential that the "disorder parameters" $\sigma_{DF}$ and $\sigma_{HH}$ are also smaller in comparison to conventional HgTe QWs of critical thickness ($\sigma_{DF}$ has a value of 16 / 12 meV and $\sigma_{HH}$ of 5.1 / 4.5 meV for the QW under investigation / conventional QWs, accordingly). That gives a confirmation that the quality of HgTe QWs could be increased by using thicker QW.

B. Type 2 QW

In our work we also investigated second type QW which consists of Cd$_{0.06}$Hg$_{0.94}$Te alloy (HgTe with 6% of Cd) with the thickness of 11.5 nm and performed the same transport measurements as for the QW of type 1. The $\rho_{xx}(V_{g})$ dependence for the type 2 QW is shown in Fig. 4 (a). While its general behavior is very similar to the previous case, the resistivity value in the maximum for the type 2 QW is much bigger (90 kΩ ≈ 3.5 h/\e^2) indicating to the presence of the energy gap between conduction and valence bands. The second difference between QWs could be found in $\rho_{xy}(V_{g})$ dependence, shown in Fig. 4 (b). In contrast to the first QW, the quantized plateaux in $\rho_{xy}$ of the second QW on the electron side becomes visible already at $B = 1$ T and completely absent on the hole side. The detailed study of quantum Hall effect in new QW is out of scope of the research.

In the inset of Fig. 4 (a) one could see the density dependence of the electron mobility $\mu$. The maximum value of mobility is found to be of about 2.8⋅10^5 cm^2/V·s that is significantly higher compare to both QWs of critical thickness as well as thicker (d = 8...8.3 nm) QWs, known as 2D TIs. The later inspired us to check if the QW under investigation also demonstrate topological properties. The energy gap appears when QW's thick-
ness is smaller or bigger than critical. The both options are possible in our case, though only the second one results in the formation of topological edge channels.

The non-local transport response is indefeasible sign of the edge transport\textsuperscript{22-24}. In order to check the existence of topological states we have performed a comparison of transport response in local and non-local geometries. Three gate dependencies of 4-terminal resistance $R_{ij,kl}(V_{\text{eff}})$ measured in different geometries are shown in Fig. 5 (a). Each measured trace is supported by the pictogram explaining the current and voltage probes configuration. The resistance traces both in local (black) and non-local (blue) geometries shows similar behavior with the maximum located in the energy gap. While the value of the non-local resistance in its maximum is from $1$ to $3$ orders smaller than the local one, it is still much bigger than expected in a case of trivial band structure and pure bulk conductivity. Therefore the non-local resistance results from edge transport and the QW under investigation is a 2D TI. The absolute value of non-local resistance in its maximum indicates that the transport is diffusive (non-ballistic)\textsuperscript{23,24}.

The most important parameter characterizing 2D TI's band structure is the energy gap $E_g$. One could estimate $E_g$ by analyzing the temperature dependence of local or non-local resistance in the gap\textsuperscript{23,25}. By increasing temperature one increases the number of bulk carriers that exponentially shunt the measured signal. By fitting the resistance maximum $R_{\text{max}}$ with the relation $R_{\text{max}} \propto \exp(\Delta/kT)$, where $k$ is the Boltzmann constant and $T$ is the temperature, we have found that the gap is about $10\text{meV}$ ($8\text{meV}$ from fitting of local resistance and $11\text{meV}$ from non-local one). The obtained value of the gap is significantly bigger then observed in wide QW-based 2D TIs\textsuperscript{23}, making the QW under investigation a promising candidate for further studies and applications of 2D TIs.

\section{Conclusion}

In conclusion, we have performed a transport and capacitance spectroscopy study of two kinds of quantum wells, namely Cd$_{0.02}$Hg$_{0.98}$Te and Cd$_{0.06}$Hg$_{0.94}$Te with the thicknesses of 7.4 and 11.5 nm, accordingly. We have...
established that the first quantum well exhibits a massless Dirac fermions system with a quality slightly better then in conventional HgTe quantum wells of critical thickness. Second quantum well exhibits a high-quality two-dimensional topological insulator state with the energy gap of around 10 meV and well-defined edge transport making it as a good candidate for further study and applications of two-dimensional topological insulators.

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