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Observation of different edge current states localization scenarios in a HgTe based two-dimensional topological insulator

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ABSTRACT

Resistance versus temperature dependence in several sets of 2DTI samples fabricated on the basis of 8.3 nm HgTe quantum well using the same technological procedure has been investigated both in the presence of weak perpendicular magnetic field and at B=0. The obtained results do not confirm the universality of the behavior previously interpreted as the Anderson localization of the edge states of a 2DTI induced by a weak magnetic field (Piatrusha et al., 2019). Some samples are found to be insensitive to weak magnetic field and show clear signs of localization even at B=0. In diffusive mode and at B=0 the variation of the edge states resistance with temperature depends on the initial resistance level and can be both weak and exponentially large.

The two-dimensional topological insulator (2DTI) is a topological phase, which is characterized by the presence in the bulk band gap of one-dimensional helical edge current states with a rigid coupling between the spin polarization and the momentum direction, a linear dispersion law, and time reversal symmetry (TRS) protection against backscattering, [1,2]. Thus, a pair of 2DTI current states flowing in opposite directions along the edge can be considered as an ideal one-dimensional conductor. At sufficiently low temperatures, when the Fermi level is located in the bulk band gap, electron transport occurs predominantly along these edge current states. Under these conditions, the theory predicts quantization of the 2DTI resistance in units of $h/2e^2$, which is a sign of a single-mode one-dimensional conductivity in the absence of scattering. A number of experiments have indeed confirmed such quantization [3], but only in structures that do not exceed a few microns in size. This indicates that the helical edge states of 2DTIs are subject to some sort of backscattering, which contradicts their above-mentioned topological protection. Yet, as it turned out, even very resistive 2DTI samples with strong backscattering ($R \gg e^2/h$) have a weak temperature dependence of resistance in the low-temperature limit [4]. The latter is in clear contradiction with Anderson's localization theory, according to which a one-dimensional system of non-interacting electrons at arbitrarily low disorder level is an insulator with a localization length of the order of the electron mean free path. The 2DTI samples resistance $R \gg e^2/h$ points out that the mean free path (and hence the localization length) is obviously smaller than the sample size, which should manifest itself in an exponential increase of the resistance with the temperature decreasing, which, however, for some reason is not observed. The discovered instability of the edge states of 2DTIs with respect to backscattering on the one hand and the absence of localization expected in such a situation, on the other, attracted much attention, and in recent years many attempts have been made to explain the observed behavior, a review of which can be found, for example, in [5]. Nevertheless, the situation is still far from clear.

An interesting data was recently reported in [6], where transport was investigated both in ballistic ($G \sim e^2/h$) and diffusive ($G \ll e^2/h$) 2DTI samples based on HgTe QWs at temperatures as low as 50 mK. This work confirmed the conclusion about the weak T-dependence of the resistivity of 2DTI samples at low temperatures and in the absence of magnetic field, regardless of whether the transport is diffusive or ballistic. However, the main result of this work is that the application of a weak perpendicular magnetic field of several tens of mT leads to a giant (up to five or more orders of magnitude) increase in the resistance at low temperatures. Under these conditions the temperature dependence of the resistance becomes exponential, i.e. exactly as expected according to Anderson's theory of localization. Based on these observations, the following conclusion was made [6]. The edge states of 2DTIs are not protected against backscattering, the nature of which remains to be determined. However, in the absence of magnetic field (i.e., when the TRS is maintained), this scattering is not accompanied

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Table 1
Sample parameters. V_{CNP} - gate voltage corresponding to the charge neutrality point. The density and mobility values correspond to the gate voltages (indicated) when the Fermi level lies in the conductance band.

Sample	Surface	V_{CNP} (V)	V_g (V)	N_s ($\times10^{11}$ cm^{-2})	μ (cm^2/Vs)
(A)	(013)	−5.75	−4	1.5	11 200
(B)	(100)	−5.75	−3	1.6	4000
(C)	(013)	−3	−1	1.6	7000

by interference of the electron wave function and, thus, does not lead to Anderson localization. The violation of TRS caused by the application of even a weak magnetic field makes such interference possible, which immediately leads to the localization of the 2DTI electronic edge states observed in the experiment.

The aim of this work was to verify the conclusions of [6] on a wider experimental base, including 2DTI samples fabricated from 8 nm HgTe QWs (QWs) with surface orientation (100) and (013) and a large spread in the conducting edge resistance at B = 0. The obtained results do not confirm the universality of the conclusions of [6], and also indicate the need to revise some existing concepts, in particular, the weak T-dependence of the resistance of highly resistive 2DTI samples in the absence of magnetic field.

In this work three types of samples based on 8.3 nm HgTe QW with surface orientation (013) (type **A** and **C** types) and (100) (type **B**) were studied (see Table 1). All QWs **A, B, C** were fabricated using the same technological procedure. 8.3 nm HgTe QWs are known to be 2DTI with an inverted energy band structure and a band gap of about 30 meV. The experimental structures were identical Hall bridges with conducting segments of various length (see Fig. 2a) equipped with an electrostatic top gate (Ti–Au). Varying the gate voltage V_g, the Fermi level could be located in the center of the bulk band gap, thus realizing the QSHE regime with a predominantly edge state conductivity, which was confirmed by measurements in non-local configurations. The presence of segments of different length between adjacent voltage probes makes it possible to choose for investigation edge states segments of different length in the range from 3 to 33 μm. Generally the resistance of the edge segment increases with its length. Transport measurements were carried out in several configurations (indicated in figures): the 4-point current source scheme and the 2-point voltage source scheme. Taking into account the fact that the resistance of the samples varied within wide limits, reaching at the low-T limit the values of 10^9–10^{10} Ω, the main configuration was the 2-point voltage source scheme with characteristic source–drain voltages of the order of 0.1–0.5 mV. All measurements were performed using an alternating current with a frequency of 1–3 Hz, the phase detection of the signal and in the temperature range 80 mK–10 K.

Let us first consider the results obtained with sample **A**. Fig. 1 illustrates the behavior of the shortest edge segment ≈3 μm. Its resistance value $R(V_{CNP}) \approx 90$ kΩ indicates the diffusive nature of the edge states transport on the scale of ≈3 μm. As can be seen from Fig. 1a, this edge segment resistance does not practically change with temperature in the range 6.8 K–80 mK, which agrees well with the results of [6]. Only the mesoscopic fluctuations amplitude increases with the temperature lowering. The results of the non-local resistance measurement shown in Fig. 2 furnish evidence that these mesoscopic fluctuations relate specifically to the edge transport. From Fig. 2 it can be seen that the fluctuations pattern is well reproduced if the time interval between successive measurements is not very large (of the order of several minutes), which gives an idea of the characteristic lifetime of the random electrostatic potential configuration with which edge current states interact.

Fig. 1b shows the reaction of the 3 μm edge segment of sample **A** to a weak magnetic field perpendicular to the plane of the QW. It can be seen that at T = 80 mK, the application of magnetic field of 100 mT increases the resistance of this segment by about three times. Note

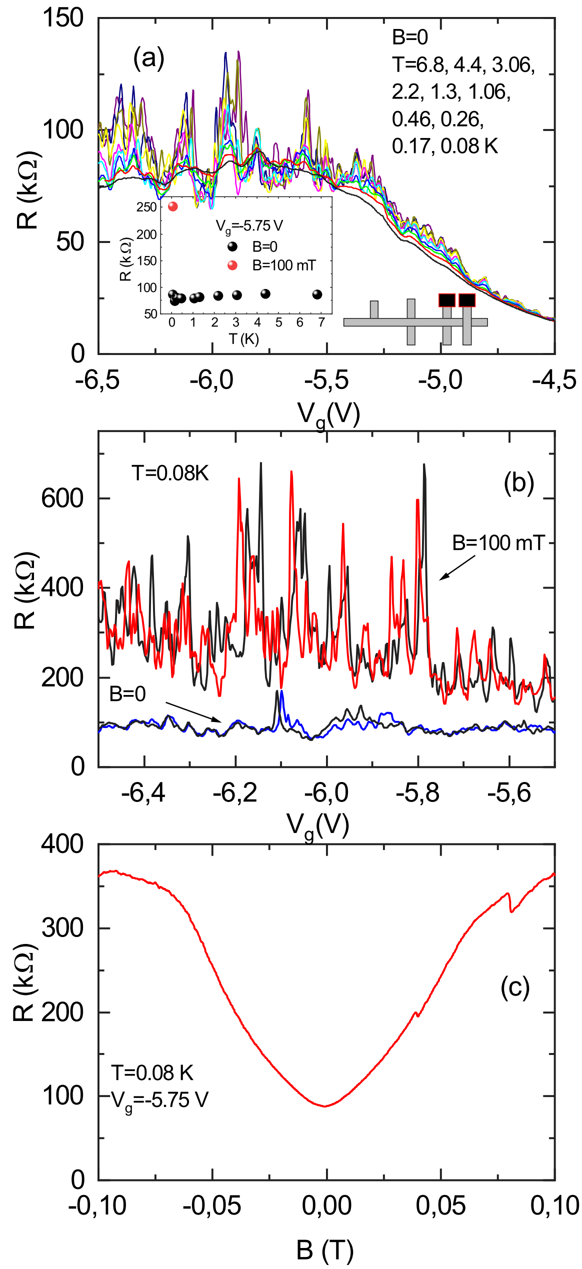

Fig. 1. Sample **A**, 3 μm edge segment: (a) - $R(V_g)$ at different temperatures. The inset shows the temperature dependence of $R(V_{CNP} = -5.75$ V); (b) - two pairs of consecutive $R(V_g)$ traces taken at 10 min interval for B = 0 and B = 100 mT at T = 80 mK; (c) - $R(B)$ at $V_{CNP} = -5.75$ V and T = 80 mK.

that this is a very weak reaction compared to that observed in [6], where for similar temperatures and resistance values application of magnetic field of several tens of mT led to the resistance growth of several orders of magnitude. Fig. 1c shows the magnetoresistance of the 3 μm edge segment at $V = V_{CNP}$ and T = 80 mK. A characteristic feature of this approximately parabolic magnetoresistance is the absence of mesoscopic resistance fluctuations in contrast to the resistance versus gate voltage dependencies.

Fig. 3 shows the results corresponding to the longest edge segment of sample **A**, measuring ≈32 μm. Fig. 3a shows $R(V_g)$ dependencies taken at different temperatures and in the absence of magnetic field. In the range from 1 K to 80 mK, $R(V_{CNP})$ increases approximately threefold from ≈1 MΩ to ≈3 MΩ. Fig. 3b shows a similar series of dependencies, but in the presence of magnetic field 20 mT. In this

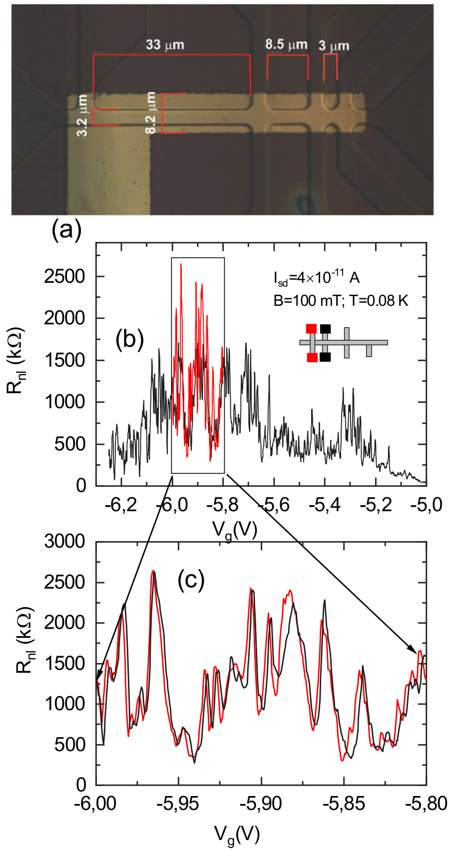

Fig. 2. (a) - Sample image, showing Hall bar segments of different length, the width of the Hall bar (3.2 μm) and the width of the gate (8.2 μm) (yellow in color). Sample **A**. (a) - Mesoscopic fluctuations in $R(V_g)$ in a non-local measurement configuration at B = 100 mT and T = 80 mK. The area highlighted in (a) is shown in (b) on an enlarged scale. Two dependencies in (b) were obtained with an interval of ≈5 min.

case $R(V_{CNP})$ changes by more than two orders of magnitude from ≈1.3 MΩ to ≈150 MΩ. Fig. 3c shows $R(V_{CNP})$ versus $1/T$ in a semi-logarithmic scale for B = 0, 20 mT and 40 mT. It can be seen that at the high-temperature end of the 1 K–80 mK range, the $R(T)$ dependencies have an activation form $R(T) \sim exp(\Delta/2kT)$ with the activation energies $\Delta = 0.026$ meV, 0.086 meV and 0.12 meV for B = 0, 20 mT and 40 mT, respectively. With the temperature decreasing, a more or less pronounced tendency towards saturation is observed in some dependencies. Fig. 3d shows the magnetoresistance of the longest edge segment at $V = V_{CNP}$ on a logarithmic scale. As in the case of the short segment, there are no mesoscopic fluctuations in $R(B)$ dependence in contrast to $R(V_g)$.

Let us now consider sample **B**. The resistance $R(V = V_{CNP})$ of the 3 μm edge segment in this sample at $T \approx 100$ mK is approximately four times higher than the corresponding value in sample **A**, which indicates a stronger scattering of the electrons at the edge states. Fig. 4 shows the temperature dependencies of the resistance of the short (3 μm) (Fig. 4a,b) and the medium (8.5 μm) edge segments (Fig. 4d,c). In the temperature range 4.2 K to 120 mK, the $R(V_{CNP})$ of the short segment grows quite moderately from ≈200 kΩ to ≈370 kΩ. Moreover, in contrast to sample **A** where a weak but nevertheless noticeable reaction of the resistance of the 3 μm segment to magnetic field was observed, in sample **B** a magnetic field of 100 mT does not cause any change at all, which can be seen from a comparison of the curves for B = 0 and B = 100 mT at T = 120 mK in Fig. 4a. Clearly this does not agree with the observations made in [6], according to which at such low temperatures the CNP resistance should increase by several orders of magnitude on application of even a weak magnetic field of only a few tens of mT regardless of whether the transport is diffusive or ballistic. A significant difference in the behavior of segments of different lengths at B = 0 is also unexpected. Indeed, in the temperature range in which the resistance of the 3 μm segment changes by less than two times, the resistance of the 8.5 μm segment increases by almost 300 times. And this despite the fact that the initial resistance values of these two segments at the CNP and T = 4.2 K differ only by factor two, Fig. 4a,c. However, the most important feature of this sample, which distinguishes it from **A**, is that despite the observed huge difference in the temperature dependence of the shorter and longer segments' resistance, their behavior is equally insensitive to magnetic field.

Samples **A** and **B** differ in surface orientation. However, sample **C**, which, like **A**, has the (013) orientation, exhibits behavior similar to **B**. Fig. 5a shows the resistance versus gate voltage dependence of the shortest segment (3 μm) in the temperature range from 4.2 K to 80 mK. It can be seen that this sample is the most resistive of the three. The short edge segment resistance $R(V = V_{CNP})$ at T = 100 mK is approximately two times higher than the corresponding value in **B** and approximately eight times higher than in **A**. The sample resistance $R(V_{CNP}) \gg h/e^2$ indicates the diffusive nature of transport via 1D edge current states. The dependence corresponding to 80 mK was measured in the presence of a perpendicular magnetic field of 100 mT. As can be seen, it almost completely reproduces the $R(V_g)$ dependence measured at B = 0 and T = 100 mK. At B = 0, a moderate temperature dependence of the insulating type is observed in the studied gate voltage range (from 4.2 K to 80 mK the $R(V_{CNP} = -3.17$ V) resistance increases less than twice from approximately 470 to 750 kΩ, Fig. 5b). As in **B**, the behavior of longer edge segments with a higher initial resistance ($R >$ 1–2 MΩ at T = 2 K) is characterized by a much stronger temperature dependence. In the range from 4.2 K to 80 mK, the resistance of these segments can vary by more than 200 times from ≈3 MΩ to ≈650 MΩ. It is important, however, that, as well as in **B**, there is a complete lack of resistance response to a weak magnetic field. The summary of the experimental data is given in Table 2.

Table 2
Experimental summary.

Sample	Edge segment length, (μm)	$R(V_{CNP})$ at B = 0 and LHT[a], (kΩ)	Temperature effect: (R(80 mK)/R(LHT) at V_{CNP} and B = 0)	Magnetic field effect (R(B)/R(0) at V_{CNP} and T = 80 mK)
A	3	80	Negligible	×3 in 100 mT
	32	1000	Moderate (×3)	×100 in 20 mT
B	3	200	Moderate (×2)	Absent
	8.5	800	Strong (×300)	Absent
C	3	480	Moderate (×2)	Absent
	32	3000	Strong (×200)	Absent
Piatrusha 2019 [6]	3	25.8	Negligible	$\times 10^4$ in 50 mT
	38	100	Negligible	$\times 10^4$ in 50 mT

[a]LHT — liquid helium temperatures of the order of 4.2 K.

As the results of our research show, there are two distinct Anderson localization scenarios observed in two sets of our 2DTI samples fabricated using the same technological procedure: the first one is the recently discovered magnetic field induced Anderson localization [6], and the second one, observed in the present study — an Anderson localization of the 2DTI helical edge states in the absence of any magnetic field. There is also a marked correlation between the conductor resistance temperature dependence and the conductor length. The emergence of exponential resistance growth with the temperature lowering coincides with the transition from shorter (L = 5–7 μm) to longer (L = 35 μm) 1D conducting edge segments, which is a clear signature of 1D Anderson localization. It is also worth noting that the 2DTI samples demonstrating Anderson localization behavior in the absence of magnetic field show virtually no response to the application of magnetic field. Let us consider these results taking into account the

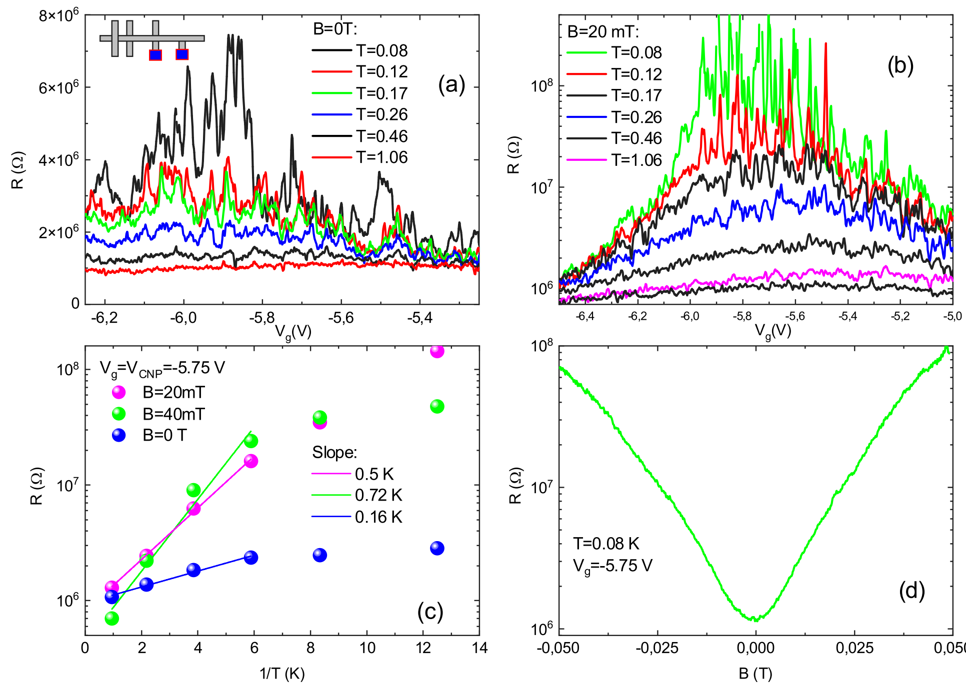

Fig. 3. Sample **A**, 32 μm edge segment. (a) - $R(V_g)$ at different temperatures and B = 0; (b) - $R(V_g)$ at different temperatures and B = 20 mT (the lowest black curve: T = 1.06 K, B = 0); (c) - R($V_{CNP} = -5.75$ V) as a function of $1/T$ for B = 0, 20 mT and 40 mT; (d) - $R(B)$ at $V_{CNP} = -5.75$ V and T = 80 mK.

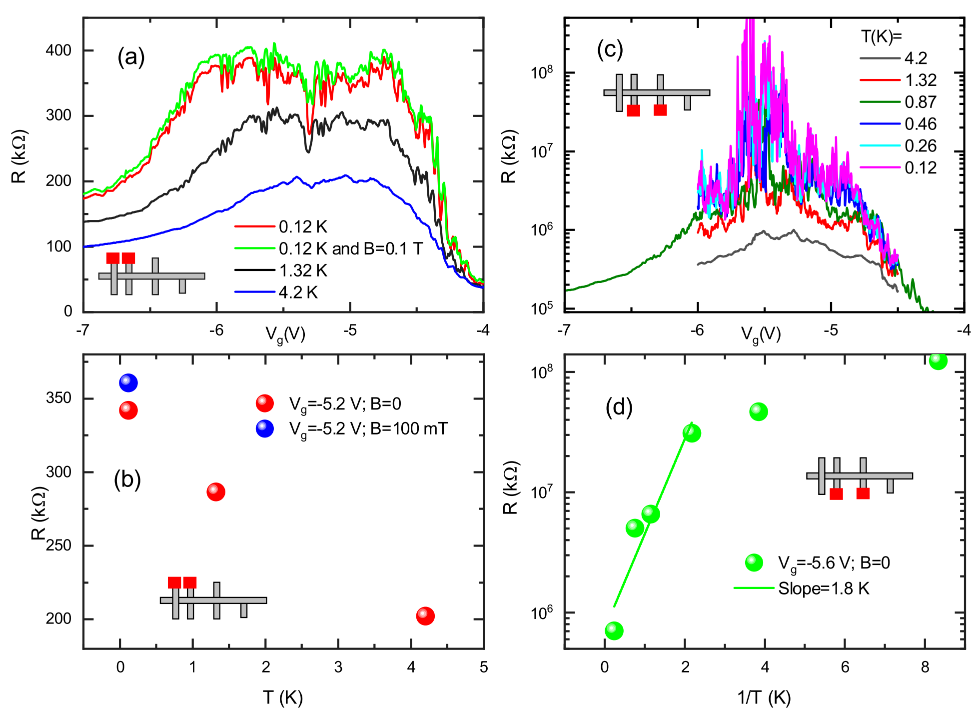

Fig. 4. Sample **B**. (a) - $R(V_g)$ for the 3 μm edge segment at different temperatures; (b) - Temperature dependence of $R(V_{CNP} = -5.2$ V), obtained from data in Fig. 4a; (c) - $R(V_g)$ for the edge segment 8.5 μm at different temperatures; (d) - Temperature dependence of $R(V_{CNP} = -5.6$ V), obtained from data in Fig. 4c.

currently available experimental data and theoretical concepts. First of all, we note that localization of the helical states of 2DTIs is directly related to their declared topological protection against backscattering. It is a well known fact, that the 2DTI does not exhibit the same complete absence of backscattering one finds in the QHE regime, [7]. For this reason, the observation of Anderson localization in this system is not unexpected. What is surprising is that this localization is not observed in all cases of diffusive transport. But, as our results show, while in some 2DTI samples insulating temperature dependence even at B = 0, in others, in order to turn the localization on, it is necessary to apply a magnetic field. At the present time there are many theoretical papers dealing with the suppression of the topological protection against backscattering in 2DTI [8–13]. In fact, the electron–electron interaction driven localization in 2DTI considered in [14,15] may be relevant in our case. According to [14] localization is due to the fluctuations of the Rashba spin–orbit interaction caused by charge inhomogeneity in the presence of e–e interactions. The localization length strongly depends on the Luttinger parameter K and can exceed 10 μm for $K > 0.35$.

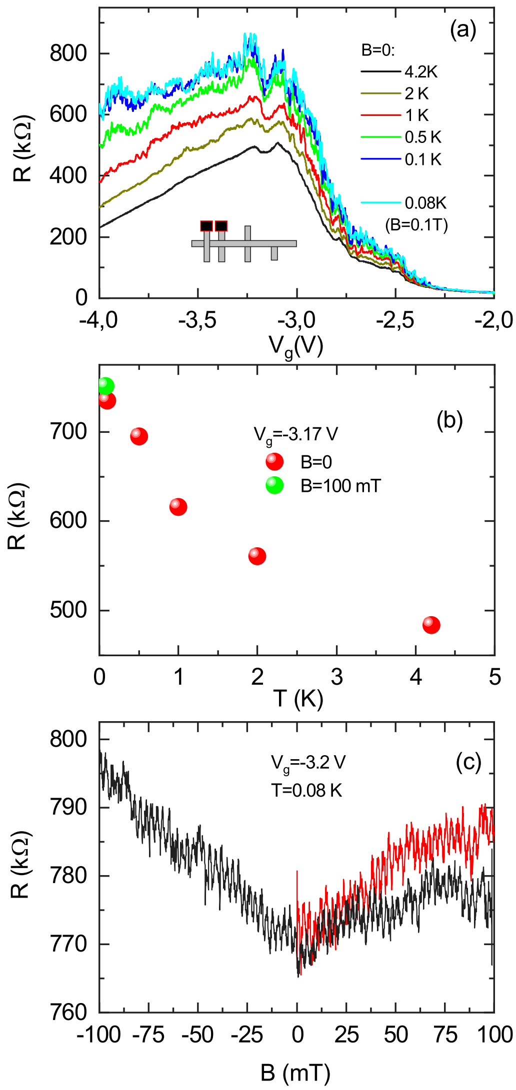

Fig. 5. Sample **C**. (a) - the 3 μm edge segment $R(V_g)$ at different temperatures. The dependence for T = 0.08 K was measured in the presence of magnetic field B = 100 mT. (b) - temperature dependence of $R(V_{CNP} = -3.17$ V), obtained from data in Fig. 5a. (c) - 3 μm edge segment magnetoresistance $R(B)$ for $V_{CNP} = -3.2$ V.

It should be borne in mind that the fluctuations of Rashba spin–orbit interaction exist in systems with a bulk inversion asymmetry [16]. The theory [15] also predicts localization, but one in which the localized states are sensitive to the magnetic field, which is not observed in our experiment. Thus, we conclude that none of the existing theories provides an explanation for the observation of two distinct scenarios of one-dimensional Anderson localization found in 2DTI samples based on HgTe QWs.

Thus, we report the results of the resistance versus temperature dependence study both in the presence of a weak perpendicular magnetic field and at B = 0 for several types of 2DTI samples fabricated on the basis of 8.3 nm HgTe using the same technological procedure. The obtained results do not confirm universality of behavior, previously interpreted as weak magnetic field-induced Anderson localization of edge states of a 2DTI, cite Khrapai. Some samples turned out to be insensitive to a weak magnetic field and, nevertheless, show clear signs of localization even at B = 0. We find that none of the existing theories provides explanation for the two distinct scenarios of one-dimensional Anderson localization observed in 2DTI samples based on HgTe QWs. Further efforts are required in the experimental and theoretical study of this important issue concerning the nature of helicoidal states in 2DTI.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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