Low field magnetoresistance in a 2D topological insulator based on wide HgTe quantum well

2016 J. Phys.: Condens. Matter 28 345801

(http://iopscience.iop.org/0953-8984/28/34/345801)

J. Phys.: Condens. Matter **28** (2016) 345801 (7pp)

doi:10.1088/0953-8984/28/34/345801

Low field magnetoresistance in a 2D topological insulator based on wide HgTe quantum well

E B Olshanetsky[1], Z D Kvon[1,2], G M Gusev[3], N N Mikhailov[1] and S A Dvoretsky[1]

[1] Institute of Semiconductor Physics, Novosibirsk 630090, Russia
[2] Novosibirsk State University, Novosibirsk 630090, Russia
[3] Instituto de Física da Universidade de São Paulo, 135960-170, São Paulo, SP, Brazil

E-mail: eolsh@isp.nsc.ru

Received 2 March 2016, revised 13 May 2016
Accepted for publication 31 May 2016
Published 29 June 2016

Abstract

Low field magnetoresistance is experimentally studied in a two-dimensional topological insulator (TI) in both diffusive and quasiballistic samples fabricated on top of a wide (14 nm) HgTe quantum well. In all cases a pronounced quasi-linear positive magnetoresistance is observed similar to that found previously in diffusive samples based on a narrow (8 nm) HgTe well. The experimental results are compared with the main existing theoretical models based on different types of disorder: sample edge roughness, nonmagnetic disorder in an otherwise coherent TI and metallic puddles due to locally trapped charges that act like local gate on the sample. The quasiballistic samples with resistance close to the expected quantized values also show a positive low-field magnetoresistance but with a pronounced admixture of mesoscopic effects.

Keywords: topological insulator, 2D, HgTe quantum well, magnetoresistance

(Some figures may appear in colour only in the online journal)

Introduction

The 2D Topological Insulator is a solid state system that in the absence of magnetic field has an energy gap for the bulk states and two specific one-dimensional gapless states characterized by opposite spin orientation counter propagating along the sample edge, [1–4]. Even when the Fermi energy lies in the energy gap for the bulk states so that the bulk is insulating, the system is still conducting due to the edge states running along the sample perimeter. These 1D edge states are supposed to be protected by the time reversal symmetry (TRS) against backscattering (and, hence, localization) by elastic disorder. Therefore, it was originally expected that 2D TI samples would have the resistance quantized in the units of 1D resistor quantum h/e^2. First experiments on HgTe-based 2D TI showed that contrary to these expectations quantized resistance is a quite rare phenomenon, observed only in samples of submicron size (termed ballistic) and even then overlaid with mesoscopic fluctuations [5, 6]. Larger samples, while preserving all signatures of a transport via edge states, display much higher resistance, both local and nonlocal (up to 10^5 Ohms and higher) [7]. These 2D TI samples are termed diffusive. It is surprising that in these samples where the resistance sometimes exceeds hundreds of quanta h/e^2 it is found to be temperature independent at low temperatures, contrary to what one would expect from the localization theory viewpoint [8]. Several theoretical models have been proposed lately to explain the drastic increase in resistance of the 2D TI samples with dimensions just above few microns. One of the models [9], regarded now as more promising, envisages interaction of the helical edge states with metallic puddles created by local fluctuations in the donor density. It is assumed that edge states interacting with these puddles experience dephasing and backscattering that result in a sample resistance increasing above the quantized values. Unfortunately, however, this model in its present form fails to account for the lack of the resistance temperature dependence in these high-ohmic 2D TI samples.

A closely related problem that at present similarly lacks understanding is the behavior of low field magnetoresistance (MR) both in ballistic and diffusive 2D TI samples. The protection against localization due to elastic disorder scattering granted to the 1D edge states by the presence of the time reversal symmetry should be destroyed by application of even weak magnetic field [5]. Then, with magnetic field increasing, the question is how soon the edge states in ballistic samples will begin to show signs of backscattering and, eventually, of localization. In diffusive samples this problem is complicated by the lack of knowledge of the exact causes leading to the increase in their resistance in the absence of magnetic field. Experimentally, the problem has been so far studied in long diffusive HgTe-based 2D TI samples having slightly different QW width: 7.3 nm [5, 10] and 8.3 nm [7]. In both cases the presence of pronounced quasilinear positive magnetoresistance (PMR) has been confirmed that suggests a strong suppression of the edge transport already at low fields. However, while in [7] at the charge neutrality point (CNP) the low-field positive MR never exceed 20%, in [5, 10] the resistance was found to increase almost 30 times with respect to its zero field value in fields as low as 0.008 T. Also, recently beside the PMR a negative magnetoresistance around $B = 0$ followed by Aharonov–Bohm-like oscillations has been reported for 8.3 nm QW [11]. As for ballistic 2D HgTe TI samples in which the transport is assumed to be fully coherent, there is at present no corresponding experimental data available. However there is an opinion that such ballistic 2D TI systems should remain unaffected by magnetic fields and show no sign of MR up to sufficiently high fields.

Beginning from 2011 there are some indications that, contrary to the theoretical prediction, the time reversal symmetry (TRS) breaking associated with the application of parallel or perpendicular magnetic field has no effect on the edge states transport in both ballistic and diffusive InAs/GaSb-based 2D TI samples. This evidence remains, however, rather fragmentary and inconclusive. It is based on resistance measurements performed at discrete and large (1 T and higher) values of magnetic field, rather than on continuous magnetoresistance measurements through zero B at low fields, [12–14].

MR in HgTe-based 2D TI systems subject to a perpendicular magnetic field has been addressed in a number of theoretical works [15–21]. Here we will review some of the more popular theoretical models to date.

The authors of [18] address the problem of how the localization of the helical edge states occurs as a weak magnetic field is gradually turned on. The disorder in this model is introduced as the sample boundary roughness leading to the formation of closed loops of helical edge states (see figure 1(a)). The helical states running along the edge interact with these loops. The model predicts a low field PMR proportional to B^2.

A closely related scenario that might be important in HgTe QWs with the well width close to the critical value is shown in figure 1(b). In such systems a random variation of the QW width may result in alternating regions of normal and topological insulator. An interaction would be expected between the helical states running along the sample edge and those circling around the normal insulator regions. The physics of MR in such such case would be similar to that considered in [18].

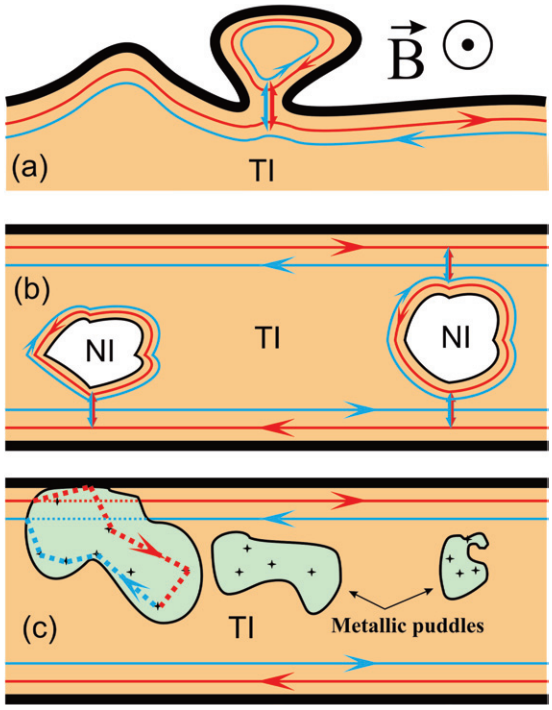

Figure 1. Different theoretical approaches to explain MR in 2D TI: (a)—helical edge states coupled to random magnetic fluxes (closed edge state loops formed due to the sample boundary roughness), [18]; (b)—helical edge states coupled to the states circling around normal insulator regions resulting from the QW width fluctuations; (c)—helical edge states backscattered in the disordered metallic puddles, [21].

In [15] the authors have considered a combined effect of a perpendicular magnetic field and nonmagnetic disorder in a coherent 2D TI system. The calculations predict a strong linear positive low field magnetoresistance in the presence of even weak disorder similar to what is actually observed in larger samples with diffusive transport. The slope of the linear magnetoresistance is predicted to depend on the ratio of the disorder strength W and the bulk gap E_g. This result is somewhat unexpected since the model [15] deals only with fully coherent edge states transport and therefore should apply to ballistic samples with quantized conductance (assumedly robust against magnetic field) rather than to larger diffusive samples.

Finally the authors of the more recent theoretical work [21] also take into account only elastic coherent disorder scattering but, contrary to [15], come to the conclusion that in such case no MR should be observed in the case of realistic disorder strength. Nevertheless they do obtain MR similar to that observed in long diffusive 2D TI samples but only if they incorporate in their model the concept of metallic puddles proposed in [9] and assume that all elastic scattering takes place in such puddles, figure 1(c). Then the whole picture looks plausible if one supposes that elastic coherent scattering

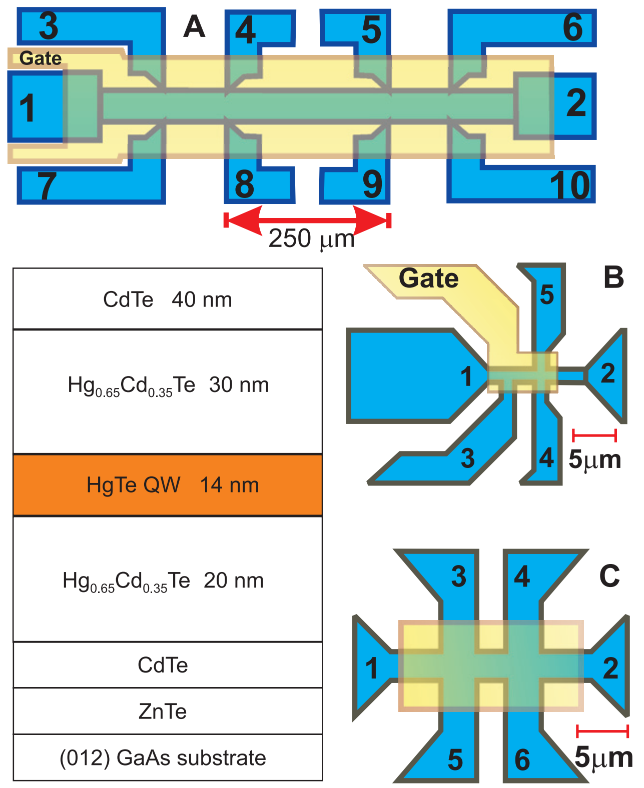

Figure 2. The quantum well cross section and the layouts of the three types of the samples **A**, **B** and **C** used in the experiment.

taking place in these puddles in the presence of perpendicular magnetic field accounts for the low field MR while zero field backscattering responsible for higher resistance of diffusive samples at zero field is due to other processes, the common root of both being the existence of these charge puddles.

It is important to emphasis here, that in all these models the disorder alone without magnetic field does not cause backscattering of the helical edge states. So, strictly speaking, these models are not exactly applicable to diffusive TI samples with the zero field resistance much higher than h/e^2. The authors of [21] propose to enlarge their model by taking into account the scattering mechanisms in the metallic puddles that increase the zero field resistance. But this is not done yet.

Up till now the experimental study of the low field MR in 2D TI due to the TRS breaking has been restricted to large diffusive samples on the basis of narrow (7.3 nm and 8.3 nm) HgTe QWs. On the other hand in order to arrive at general conclusions it is necessary to increase the diversity of experimental samples. For this purpose in the present work we investigate the low-field MR in a 2D TI on the basis of 14 nm HgTe QW with a different sequence of energy bands and a much smaller band gap. Both large diffusive and small quasiballistic samples are studied.

Samples and experimental procedures

As is well known, the energy spectrum in a HgTe QW can be either normal or inverted depending on whether the well width is below or above the critical value 6.3–6.5 nm [22–24]. QWs HgTe with the width just above the critical value represent the simplest variety of inverted energy spectrum: the s-p inversion. It is in such QWs that the 2D TI has been first experimentally discovered and most of experimental material concerning transport properties of 2D TI obtained. However, as has been shown recently with a 14 nm (1 1 2) HgTe QW, the 2D TI state does also persist in wider HgTe QWs with a more complicated inverted spectrum and a narrower bulk gap [6]. Besides, as compared to a narrower QW, a wider QW has the advantage of a smaller scattering potential amplitude resulting form the inhomogeneity of the well width. This fact is favorable for the observation of ballistic transport as has been demonstrated in [6]. Whereas [6] deals with the transport in the absence of magnetic field, in the present publication we report the experimental study of low field MR in both diffusive and quasiballistic 2D TI samples fabricated on the basis of 14 nm wide HgTe QW with surface orientation (1 1 2). Figure 2 shows the QW layer structure and the experimental samples layout. The experimental samples are Hall bridges provided with electrostatic gate. Their fabrication technology is described in detail in [25]. Three different types of experimental samples were used: macroscopic Hall bridges of type **A** (see figure 2) with the width 50 μm and the distance between the voltage probes 100 μm and 250 μm, and two types of microscopic samples of type **B** and **C**. The transport measurements were conducted in a dilution refrigerator in the temperature range 0.2–0.5 K and in the magnetic fields $\leqslant 0.5$ T using the standard phase detecting scheme at frequencies 3–12 Hz and the driving current 0.1–1 nA to avoid heating effects. The electron mobility μ in all samples studied was above 10^5 cm^2 V^{-1} s^{-1} for the carrier density 3×10^{11} cm^{-2}.

Results and discussion

Diffusive samples

We will start our discussion by considering MR in diffusive macroscopic Hall bridges, type **A**. In figure 3 we present typical dependencies of local (a) and nonlocal (b)resistance versus gate voltage in such samples in the absence of magnetic field. These dependencies have been analyzed in detail in [6]. Both in local and non-local measurements the resistance reaches a maximum at the so called charge neutrality point (CNP), supposedly when the Fermi level lies approximately in the middle of the bulk gap. Figure 2 shows the local (c) and non-local (d) magnetoresistance measured at the CNP in measurement configurations corresponding to figures 3(a) and (b) respectively. The behavior of local and nonlocal MR in our samples was found to be similar. Figure 3(e) shows the temperature dependence of a normalized MR measured in the same configuration as in figure 3(b). The temperature range in figure 3(e) is chosen so that at the CNP the bulk remains frozen out and all transport is due to the edge states only. The onset of the edge-states-only transport regime is marked by a transition from the exponential to a power-law temperature dependence of the local and non-local resistance at the CNP. In figure 3(e) we see that depending on magnetic field there are two distinct types of MR for all experimental temperatures. At low fields we observe a sharp positive MR with a quasi linear

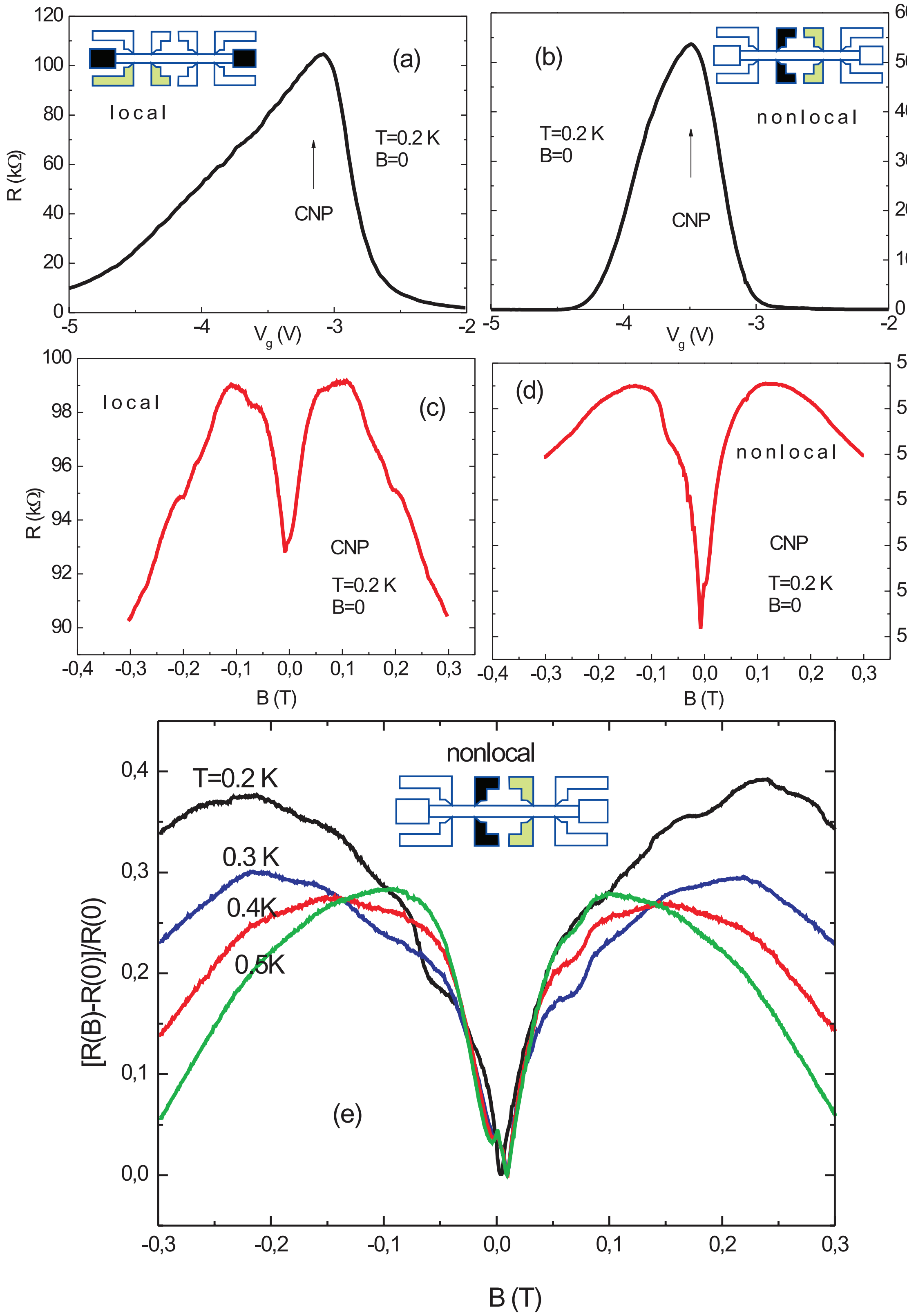

Figure 3. Resistance versus gate voltage dependencies measured in a macroscopic sample type **A** in a local—(a) and non-local—(b) configuration at zero magnetic field. The arrows indicate the gate voltage corresponding to the CNP; Magnetoresistance measured at the CNP in the local—(c) and nonlocal—(d) configurations (shown in (a) and (b) respectively); (e)—Temperature dependence of a normalized MR measured at the CNP in a non-local configuration.

slope. Then, with the field increasing the MR goes through a maximum and then turns negative at higher fields which we interpret as a turnover to the quantum Hall regime [7].

Let us discuss the quaisi linear PMR at low fields. The normalized PMR maximum decreases from approximately 37% to 27% with temperature increasing from 0.2 to 0.5 K.

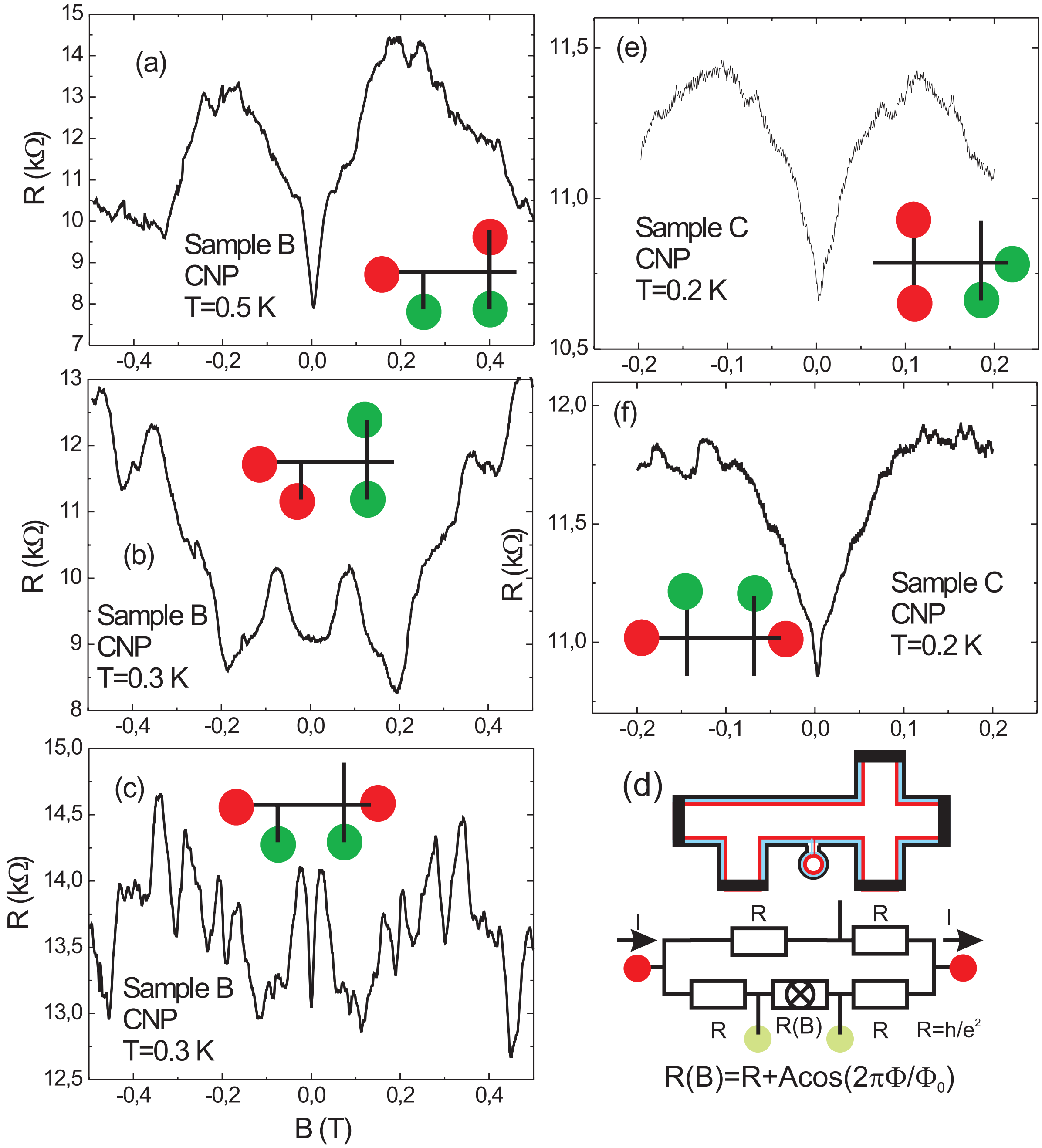

Figure 4. Typical magnetoresistance behavior in quasiballistic samples: MR in sample **B** in local—(a) and non-local—(b) configurations. MR in sample **C** in non-local—(e) and local—(f) configurations. (c)—example of oscillating MR in a quasiballistic sample. (d)—a model describing the oscillating MR in (c).

The slope of the PMR is constant in this temperature range. Qualitatively this behavior of MR is similar to that predicted theoretically in [15] and also to that observed earlier in 2D TI on the basis of QWs with the width 8–9 nm [7, 26]. According to [15] the positive linear MR is a result of the time-reversal symmetry breaking by magnetic field and is in some respect analogous to the weak antilocalization effect. The magnetic field range for MR observation in our samples is narrower by an order of magnitude as compared to that found in [7, 26], while its temperature dependence is more pronounced. This fact can be accounted for by a difference in the size of the insulating bulk gap in our system and that studied in [7, 26]. As shown in [15] the behavior of MR is governed by the ratio of the disorder strength (W) to the insulating bulk gap. If $W/\Delta < 1$, i.e. when the gap is larger than the disorder amplitude, the situation is similar to that of 1D antilocalization for which the characteristic magnetic fields are large. If, on the other hand, $W/\Delta > 1$, then the random potential fluctuations cause intensive exchange between the 1D channels and the 2D bulk. This results in a MR behavior which is similar to that of 2D antilocalization where the magnetic field range for MR observation is narrower while its temperature dependence is sharper. As a result, in the first case the half width of the MR profile may be an order of magnitude larger than that in the second, which is, probably, what we observe in the experiment. A 2D TI fabricated on the basis of 8–9 nm wide HgTe QWs has the insulating bulk gap of about 30–40 meV, i.e. two orders of magnitude larger than that determined for our samples (about 1.2 meV). Then, the observed MR behavior in our samples may be attributed to the fact that contrary to the 2D TI studied in [7, 26] where $W/\Delta < 1$, in our samples the gap is much smaller than the random potential fluctuation amplitude, i.e. $W/\Delta \gg 1$.

On the other hand our results can also be considered using a more recent theory [21]. This theory also predicts a linear magnetoresistance but explains it is a combined effect of elastic disorder scattering restricted to metallic puddles situated along the sample edge and of the phase acquired by electrons along the diffusive trajectories in these puddles due to the magnetic field. The slope of magnetoconductance in this theory $\sigma_{xx}(B)/\sigma_{xx}(0) = -\alpha|B|$ is related to the total area of metallic puddles in the sample NA as $\alpha = NA/\phi_c$, where N-is the number of puddles, A—there average puddle area and $\phi_c = 0.5h/e^2$. The authors of [21] have already compared their theory to the available experimental data: $\alpha \approx 0.15$ 1/T [26] and $\alpha \approx 50$ 1/T [5]. The slope of our low-temperature MR in figure 3(e) is intermediate: $\alpha \approx 2.5$ 1/T. Translating the slopes to the total area of metallic puddles we obtain $NA \approx 300$ nm^2 [26], 100 000 nm^2 [5] and 5000 nm^2 for the MR data in this work . However, even the largest puddle area thus obtained, [5], corresponds to the total linear puddle size $\approx$ 300 nm, which according to [21] is too small to satisfy the premises of the theory. As a possible means that may help to reconcile their theory with experiment the authors of [21] consider taking into account backscattering and dephasing that takes place in the puddles at zero magnetic field. This looks quite reasonable since, according to [9] these processes lead to the increase in resistance of diffusive 2D TI samples above the expected ballistic values and as such should be included in a realistic theoretical model of MR.

Qusiballistic samples

Now let us discuss MR in type **B** and type **C** samples with a quasiballistic behavior [6]. The MR in these samples was found to be quite diverse. In our opinion this is a signature of mesoscopic effects, to which, apparently, the MR behavior in small quasiballistic samples is highly susceptible. As an illustration of this diversity, figure 4 shows several typical resistance versus magnetic field dependencies measured in these samples. In any given state of a quasiballistic sample obtained after a cooling-down, the MR dependencies measured in local and non-local configurations could either be very similar, as in figures 4(e) and (f) for sample **C**, or, on the contrary, quite different as in figures 4(a) and (b) for sample **B**.

However, in most measurements both local and non-local performed in quasiballistic samples, one would observe the same sharp quasilinear low field PMR (see figures 4(a), (c), (e) and (f)) as in the case of large diffusive samples discussed above. That means that the factor responsible for the difference in zero field resistance of diffusive and quasiballistic samples may probably not be important for how these two groups of samples respond to the magnetic field.

The dependence of the MR behavior on the measurement configuration or on the particular state of the sample obtained after a cooling down may mean that in these samples the effect of disorder is not fully averaged because its characteristic scale is comparable with the sample size. MR measured using different contacts is influenced by disorder potential located in different parts of the sample.

As a consequence, in some states of the samples, apart from the quasilinear PMR, there may also be present a pronounced oscillating component in the MR (see figure 4(c)). In our opinion these oscillations may result from the interaction of the edge current states running along the sample edge with closed loops of helical states formed by random potential in the quantum well.

Such loops can exist both in the bulk and at the sample edge. Indeed, as has been recently shown, in a semiconductor or a semimetal with a very small insulating gap or small bands overlap even a weak disorder will result in the formation of an effective two-component medium [27]. In such medium the formation of closed loops of helical edge states may be expected. On the other hand, as has been suggested in [18], the loops of helical edge states may also result from the sample edge roughness, (see figure 1(a)).

To describe the oscillating MR in figure 4(c) we offer a simple model based on the assumption that at the edge of the sample there is a loop of helical states due to the sample edge roughness, (see figure 4(d)). This loop interacts with the edge current states running along the same edge. In magnetic field the product of such interaction will oscillate with a period inversely proportional to the loop area. The resistance of a ballistic 2D TI sample may be calculated using a simple procedure where the stretch of the edge states path between any neighboring pair of contacts is replaced with an equivalent resistor h/e^2. The total of such resistor circuit will depend both on the sample layout and the measurement configuration. In the case shown in figure 4(c) it is expected to be $2/5 \times h/e^2$, which is quite close to the measured zero field resistance. The edge containing the loop will contribute an oscillating component to the total resistance. In figure 4(d) we placed the oscillating resistor between the voltage probes, but, actually, due to the non-local character of the transport we could place it in any other part of the circuit and still obtain an oscillating total resistance. The oscillations period allows us to estimate the characteristic size of the loop as 150 nm.

Conclusion

In conclusion, we have studied low field magnetoresistance in a two-dimensional topological insulator based on a wide (14 nm) HgTe quantum well. We observe a pronounced quasilinear positive magnetoresistance in accordance with the previously performed measurements in narrow (8 nm) HgTe wells with diffusive edge state transport. We compare our results with the existing theoretical models based on two different representations of disorder: quenched nonmagnetic disorder [15] and metallic puddles [21]. The apparent dependence of the linear PMR slope on the ratio between the disorder strength and the band gap allows us to rule out the edge roughness contribution. In addition we find a pronounced PMR in quassiballistic samples with a nearly quantized zero field resistance. At the same time this MR may vary from sample to sample and also depends on the contact configurations (local or nonlocal). We assume that the effect of disorder is not fully averaged in quassiballsitic samples and the transport is strongly influenced by mesoscopic effects. On the whole we conclude that the concept of metallic puddles [9] is the more promising at present and should be incorporated in a realistic theory of MR in 2D TI.

Acknowledgments

The work was supported by the RFBI Grant No. N15-02-00217-a, and by FAPESP CNPq (Brazilian agencies).

References

[1] Hasan M Z and Kane C L 2010 *Rev. Mod. Phys.* **82** 2045
Qi X-L and Zhang S-C 2011 *Rev. Mod. Phys.* **83** 1057
[2] Qi X-L and Zhang S-C 2010 *Phys. Today* **63** 33
[3] Moore J E and Balents L 2007 *Phys. Rev.* B **75** 121306
[4] Moore J E 2010 *Nature* **464** 194
[5] König M, Wiedmann S, Brune C, Roth A, Buhmann H, Molenkamp L W, Qi X-L and Zhang S-C 2007 *Science* **318** 766
[6] Olshanetsky E B, Kvon Z D, Gusev G M, Levin A D, Raichev O E, Mikhailov N N and Dvoretsky S A 2015 *Phys. Rev. Lett.* **114** 126802
[7] Gusev G M, Kvon Z D, Shegai O A, Mikhailov N N, Dvoretsky S A and Portal J C 2011 *Phys. Rev.* B **84** 121302
[8] Gusev G M, Kvon Z D, Olshanetsky E B, Levin A D, Krupko Y, Portal J C, Mikhailov N N and Dvoretsky S A 2014 *Phys. Rev.* B **89** 125305
[9] Vayrynen J I, Goldstein M and Glazman L I 2013 *Phys. Rev. Lett.* **110** 216402
[10] König M, Buhmann H, Molenkamp L W, Hughes T, Liu C-X, Qi X-L and Zhang S-C 2008 *J. Phys. Soc. Japan* **77** 031007
[11] Gusev G M, Kvon Z D, Shegai O A, Mikhailov N N and Dvoretsky S A 2014 *Solid State Commun.* **205** 4
[12] Knez I, Du R-R and Sullivan G 2011 *Phys. Rev. Lett.* **107** 136603
[13] Knez I, Rettner C T, Yang S-H, Parkin S S P, Du L, Du R-R and Sullivan G 2014 *Phys. Rev. Lett.* **112** 026602
[14] Du L, Knez I, Sullivan G and Du R-R 2015 *Phys. Rev. Lett.* **114** 096802
[15] Maciejko J, Qi X L and Zhang S C 2010 *Phys. Rev.* B **82** 155310
[16] Chen J C, Wang J and Sun Q F 2012 *Phys. Rev.* B **85** 125401
[17] Xue Y and Prodan E 2012 *Phys. Rev.* B **86** 155445
[18] Delplace P, Li J and Buttiker M 2012 *Phys. Rev. Lett.* **109** 246803
[19] Pikulin D I, Hyart T, Mi S, Tworzydlo J, Wimmer M and Beenakker C W J 2014 *Phys. Rev.* B **89** 161403
[20] Essert S, Krueckl V and Richter K 2014 *New J. Phys.* **16** 113058
[21] Essert S and Richter K 2015 *2D Mater.* **2** 024005
[22] Gerchikov L G and Subashiev A V 1990 *Phys. Status Solidi* **160** 443
[23] Raichev O E 2012 *Phys. Rev.* B **85** 045310
[24] Bernevig B A, Hughes T L and Zhang S-C 2006 *Science* **314** 1757
[25] Kvon Z D, Olshanetsky E B, Kozlov D A, Novik E G, Mikhailov N N and Dvoretsky S A 2011 *Low Temp. Phys.* **37** 202
[26] Gusev G M, Olshanetsky E B, Kvon Z D, Mikhailov N N and Dvoretsky S A 2013 *Phys. Rev.* B **87** 081311
[27] Knap M, Sau J D, Halperin B I and Demler E 2014 *Phys. Rev. Lett.* **113** 186801