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Two dimensional topological insulator in quantizing magnetic fields

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A B S T R A C T

The effect of quantizing magnetic field on the electron transport is investigated in a two dimensional topological insulator (2D TI) based on a 8 nm (013) HgTe quantum well (QW). The local resistance behavior is indicative of a metal-insulator transition at $B \approx 6$ T. On the whole the experimental data agrees with the theory according to which the helical edge states transport in a 2D TI persists from zero up to a critical magnetic field B_c after which a gap opens up in the 2D TI spectrum.

1. Introduction

2D TI is characterized by the absence of bulk conductivity and the presence of two gapless edge current states with a linear dispersion and an opposite spin polarization that counter-propagate along the sample perimeter [1,2]. Such edge current states are called helical as opposed to the chiral edge states of the quantum Hall regime that circulate in the same direction independent of spin polarization. The described property of the 2D TI results from the energy spectrum inversion caused by a strong spin-orbit interaction. Up to date the presence of the 2D TI state has been established in HgTe QWs with an inverted energy spectrum [3,4]. The observation of a 2D TI has also been reported in InAs/GaSb heterostructure [5]. The later, however, require further verification since edge transport has also been reported in InAs/GaSb heterostructure with a non-inverted spectrum [6].

The effect of a perpendicular magnetic field on the properties of a 2D TI has two distinct and important aspects. On the one hand, even a weak magnetic field breaks down the time reversal symmetry protection of the topological edge states against backscattering. This effect is expected to manifest itself as a positive magnetoresistance (PMR) of a 2D TI in the vicinity of B = 0. Such PMR has indeed been observed experimentally in diffusive and quasiballistic samples of 2D TI based on HgTe QWs [3,7–9] and is found to be in qualitative agreement with the existing theoretical models [10,11].

The other aspect of a perpendicular magnetic field is related to the transformation of the edge current states spectrum under the influence of quantized magnetic fields and, eventually, to the transition of the 2D TI system to the quantum Hall effect regime. The goal of the present work is an experimental investigation of the effect of a strong quantizing magnetic field on the transport properties a quasiballistic sample of 2D TI. In the beginning a few words about the existing theoretical and experimental results related to this problem. Theoretically this problem has been investigated in [12–15] but the conclusions at which the authors of these works arrive are quite controversial. Indeed, Tkachev et al. [12] come to the conclusion that the gapless helical edge states of a 2D TI persist in strong quantizing magnetic fields but are no longer characterized by a linear energy spectrum. Similarly, Chen et al. [13] suggest that the gapless helical states of a 2D TI survive up to 10 T, but there will also emerge several new phases with unusual edge states properties. By varying the Fermi energy one should be able to observe transitions between these phases accompanied by plateaux in the longitudinal and Hall resistivity. The results of the work [14] by Scharf et al. also attest a certain robustness of the helical edge states with respect to the quantizing magnetic fields. However, according to [14] the edge states persist only up to a critical field B_c while at higher fields a gap proportional to B opens up in the energy spectrum. Finally, a mention should be made of the results obtained by Durnev et al. in [15] that strongly differ from those cited above. The authors of [15] consider the effect of a perpendicular magnetic field on the properties of a 2D TI taking into account the strong interface inversion asymmetry inherent in HgTe QW. The key conclusion of this study is that the spectrum of the 2D TI helical edge states becomes gapped at arbitrary small magnetic fields. The size of this gap depends on the width of the gap separating the bulk energy bands and grows monotonically with magnetic field reaching, on average, a noticeable value of several meVs already in fields of the order of 0.5 T.

As for the experimental investigation of the effect of quantizing magnetic fields on the 2D TI, there are lacking at present direct transport

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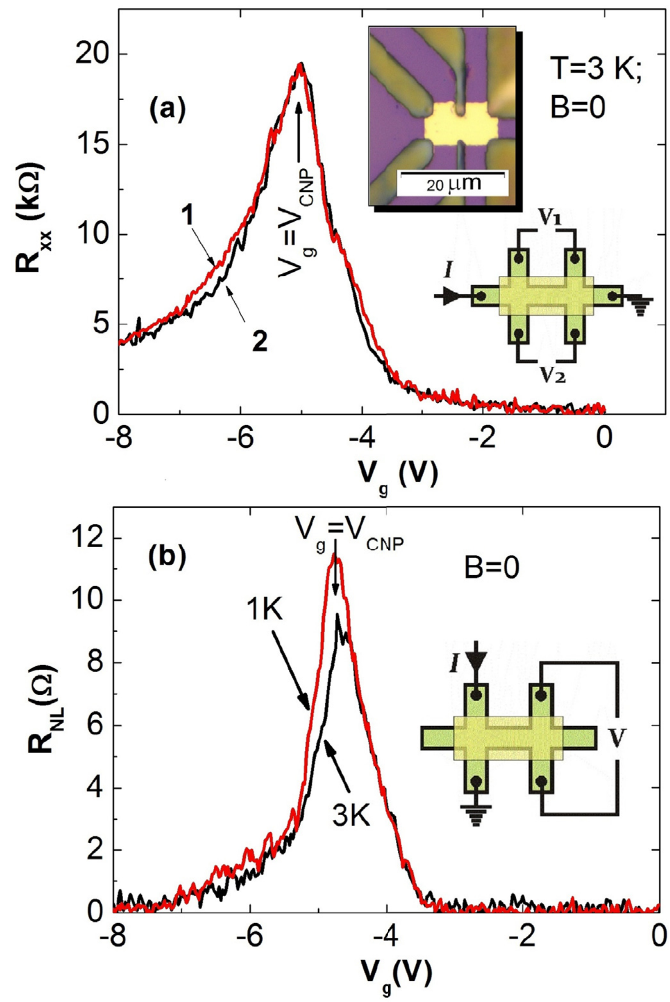

Fig. 1. The gate voltage dependences of the local (a) and nonlocal (b) resistance of the 2D TI sample at $B = 0$. The insert to Fig. 1a shows a photographic image of the experimental sample with a scale of 20 μm for comparison. The purple color indicates the mesa contours, the gold yellow in the middle is the gate. This and the following figures contain schematic representations of the configurations used to measure the corresponding transport parameters. The arrows mark the gate voltage corresponding to the charge neutrality point $V_g = V_{CNP}$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

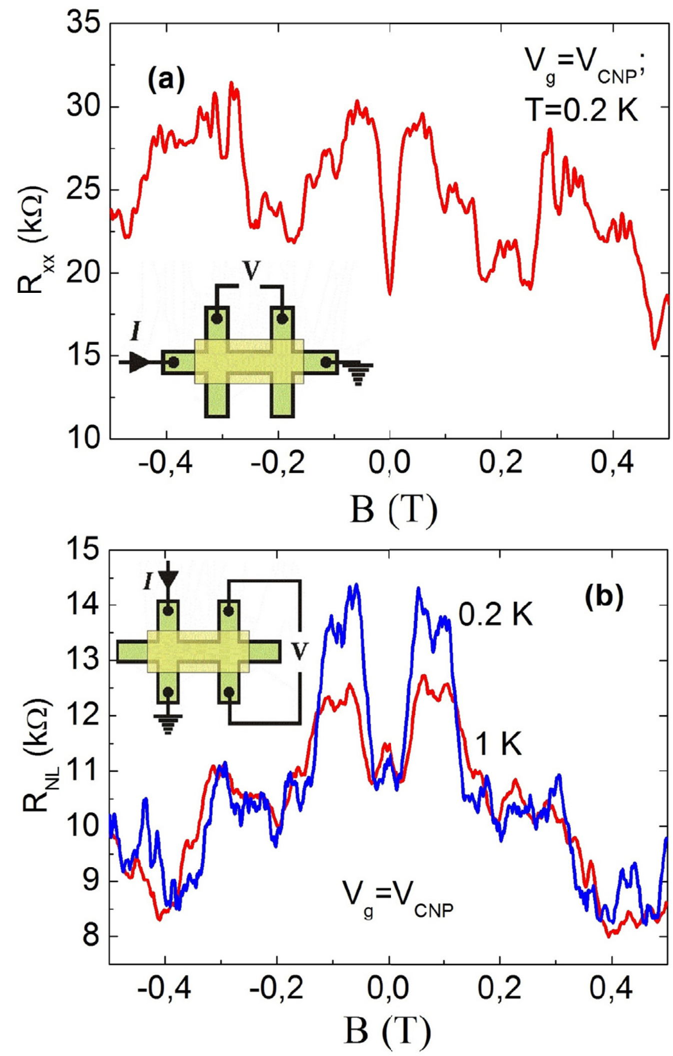

Fig. 2. Local (a) and nonlocal (b) 2D TI resistance at the CNP in classically weak magnetic fields $B \leq 0.5$ T.

measurements in the most interesting quasiballistic transport regime. In Refs. [16,17] far-infrared magnetospectroscopy has been used to probe the behavior of two peculiar "zero" Landau levels that split from the conduction and valence bands in an inverted HgTe QW and approach each other with magnetic field increasing. Instead of the anticipated crossing of these levels the authors have established that these levels anticross which is equivalent to the existence of a gap in the spectrum. In [18] a microwave impedance microscopy has been employed to visualize the edge states in a 2D TI sample. The authors come to the conclusion that there is no noticeable change in the character of the edge states up to 9 T.

2. Samples and experimental procedures

In the present work we study the effect of quantizing magnetic fields on the transport properties of a quasiballistic samples of 2D TI fabricated on the basis of 8 nm $Cd_{0.65}Hg_{0.35}Te/HgTe/Cd_{0.65}Hg_{0.35}Te$ QW with the surface orientation (013). Detailed description of the structure is given in [19,20]. The samples were shaped as six-terminal Hall bridges (two current and four voltage probes) with the lithographic size ≈ 3 × 3 μm. The ohmic contacts to the two-dimensional gas were formed by the inburning of indium. To prepare the gate, a dielectric layer containing 100 nm SiO_2 and 200 nm Si_3Ni_4 was first grown on the structure using the plasmochemical method. Then, a 8 × 14 μm $TiAu$ gate was deposited on top. The density variation with gate voltage was 1.09×10^{15} m^{-2}V^{-1}. The electron density at $V_g = 0$ V, when the Fermi level lies in the bulk conduction band is $N_s = 3.85 \times 10^{11}$ cm^{-2}. The magnetotransport measurements in the described structures were performed in the temperature range 0.2–10 K and in magnetic fields up to 10 T using a standard four point circuit with a 3 – 13 Hz ac current of 0.1–1 nA through the sample, which is sufficiently low to avoid the overheating effects. Several samples from the same wafer have been studied.

3. Results and discussion

Fig. 1 shows the gate voltage dependences of the local (a) and nonlocal (b) resistance of the experimental sample in zero magnetic field. Both dependences have a maximum that corresponds to the passage of the Fermi level across the charge neutrality point (CNP) in the middle of the bulk energy gap. In the vicinity of the CNP and at low temperatures the charge transfer is realized predominantly by the helical edge states. The coincidence of the curves in Fig. 1a taken from the opposite sides of the sample prove the sample homogeneity. With the temperature

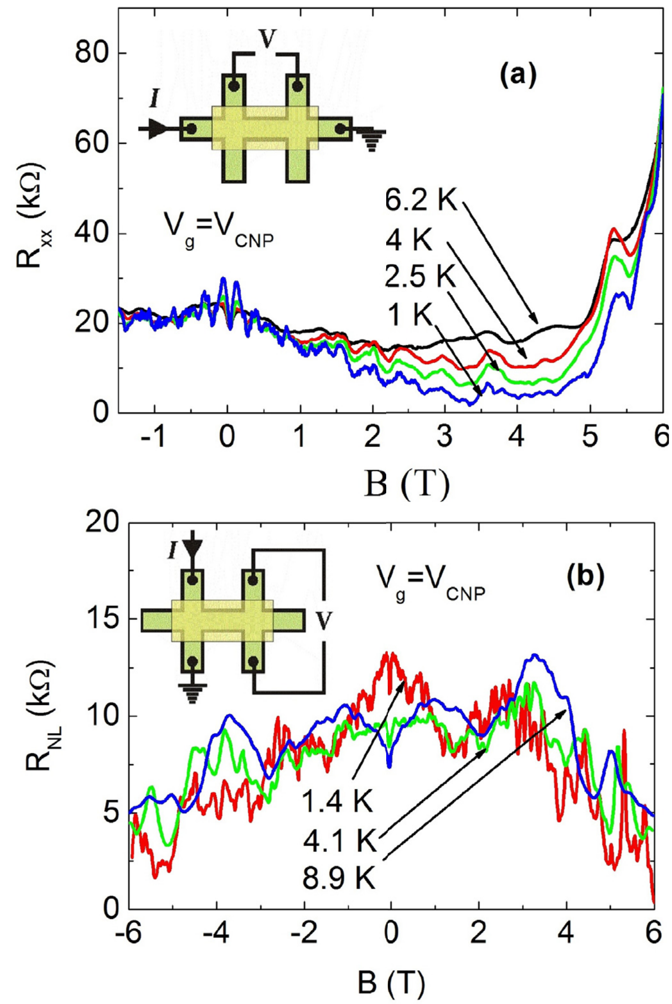

Fig. 3. The local (a) and nonlocal (b) sample resistance in the intermediate field range ≤ 6 T at different temperatures.

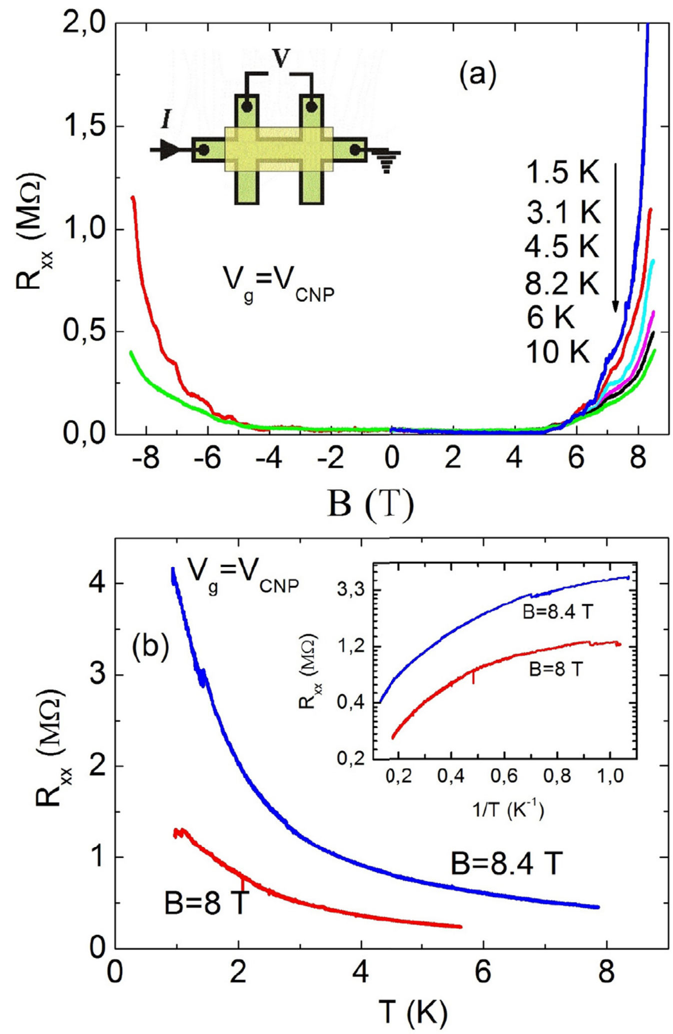

Fig. 4. (a) - the local resistance at the CNP in the magnetic field range $|B| \leq 8.5$ T and in the temperature interval 1.5 – 10 K, (b) - the temperature dependence of the local resistance at the CNP for magnetic fields 8 and 8.4 T. Insert: the same data presented versus 1/T and on a logarithmic scale.

lowering both the local and nonlocal CNP resistance values increase (Fig. 1b) due to the reduction of the bulk contribution to transport. In the case of a purely ballistic helical edge states transport and with the bulk contribution taken to be zero the calculation yields the following CNP resistance values for the local and nonlocal measurement configurations shown in Fig. 1: $h/2e^2 \approx 12.9$ kΩ (experimental value - ≈ 20 kΩ) for local resistance and $2h/3e^2 \approx 17.2$ kΩ (experimental value ≈ 11 kΩ) for nonlocal resistance. The discrepancy between the calculated and the experimental values is supposedly the result of the following two factors: the backscattering of the edge states, the nature of which is not yet quite clear, and the contribution of the bulk states. Nevertheless, the affinity between the calculated and experimental resistance values allows us to characterize the transport in our samples as quasiballistic.

Fig. 2 shows the local (a) and nonlocal (b) 2D TI resistance at the CNP as a function of classically weak magnetic fields (≤ 0.5 T). In both cases the dependences reveal well pronounced mesoscopic fluctuations. The presence of such fluctuations is typical in small (~1 μm) 2DTI samples (the fluctuations are absent in larger ≈ 100 μm samples fabricated from the same wafer). The observation of these fluctuations at the CNP is an additional evidence of the helical edge states experiencing backscattering. Further, in the field interval $|B| \leq 0.1$ T in Fig. 2 one can see a characteristic positive magnetoresistance (PMR) analogous to that studied previously in larger diffusive 2D TI samples based on a 8 nm HgTe QW [8] and also in macro and microscopic 2D TI samples based on a 14 nm HgTe QW [9]. Much as in samples studied previously, this PMR most likely results from the magnetic field induced breakdown of the topological protection of the edge states against backscattering. However, compared to larger samples, the PMR in the quasiballistic samples has some specific features: a different (compared to larger samples) temperature dependence of the PMR amplitude, the presence of a fine structure in the PMR in nonlocal measurements (see, for example, the MR features at $B = 0$ in Fig. 2b.). These features require further investigation and their discussion is out of scope of the present paper.

Fig. 3a shows the temperature dependence of the 2D TI local resistance in the intermediate field range ≤ 6 T. The monotonic decrease of the local resistance with lowering the temperature from 6.2 to 1 K (metallic T-dependence) observed in the interval $B \approx 2 - 5$ T is not predicted by any of the theories cited in the introduction. Moreover the general run of the curves in Fig. 3a excludes the expected, according to [15], opening of a gap in the edge current states spectrum at low magnetic fields. On the whole the local resistance behavior is reminiscent of the behavior of $\rho_{xx}(B)$ in a low-mobility 2D electron system in the vicinity of quantum Hall liquid-quantum Hall insulator transition near the filling factor $\nu = 1$ of the quantum Hall effect regime (see, for example [21]). It should be mentioned that such similarity has been observed earlier in diffusive macroscopic 2D TI samples [8]. Finally, starting from $B \approx 5$ T, the local resistance begins to increase sharply with magnetic field. It is instructive to compare the described behavior of the local resistance with that of the nonlocal resistance in the same magnetic field range $B \leq 6$ T, Fig. 3b. As one can see in Fig. 3b, the temperature increasing is accompanied by a modification of the signal behavior in the PMR region and by a suppression of the mesoscopic fluctuations amplitude. At the same time, however, in contrast to the local resistance in Fig. 3a, the general run of the nonlocal resistance with magnetic field has no noticeable temperature dependence. Thus, showing no sign of temperature dependence the average value of the nonlocal resistance decreases monotonically with magnetic field up to $B \approx 6$ T, i.e. including in the interval $4.5 \leq B \leq 6$ T, where the local resistance first displays a metallic behavior and then starts to grow sharply. It is worth noting that in the case of a gap opening up in the spectrum at the Fermi level one would expect the following behavior of the local and nonlocal resistance: $R_{LOC} \equiv R_{xx} \to \infty$ and $R_{NL} \to 0$.

Fig. 4a presents the local CNP resistance dependence on magnetic field $B \leq 8.5$ T in the temperature range 1.5 – 10 K. As one can see, the sharp increase of the local resistance mentioned in the end of the previous paragraph persists in higher magnetic fields, leading to a multiple resistance value augmentation: from ≈ 10 kΩ at $B = 5$ T to ≈ 2 MΩ at $B = 8.5$T. To exclude possible heating effects resulting from such a rapid resistance growth, the measurements were carried out at the current level of 0.1nA. The temperature dependence of the local resistance in the region of its intensive growth ($B \geq 5$T) has a pronounced insulating character that supersedes to the metallic behavior observed in the vicinity of $B \approx 4$T. The transition between the metallic and the insulating behavior occurs at $B \approx 6$ T which is probably an indication of a gap opening up in the energy spectrum at this particular magnetic field. Fig. 4b shows the temperature dependence of the local CNP resistance for 8 and 8.4 T. The analysis of these curves shows that in the temperature range investigated the system behavior cannot be described by a simple activation law that one would expect in the case of a gap present in the energy spectrum (see Insert to Fig. 4b). A possible explanation is that the temperature dependences in Fig. 4b may result from a combination of a predominantly activation transport at higher temperatures and a hopping conductivity at lower temperatures [22,23].

4. Conclusion

To conclude, in the present work we have investigated the effect of quantizing magnetic field on the transport properties of a quasi-ballistic 2D TI sample based on 8 nm HgTe QW with the surface orientation (013). The behavior of the local resistance is indicative of a metal-insulator transition that occurs at $B \approx 6$ T. The insulating state on the high-B side of the transition is characterized by a strong resistance increase with the temperature lowering, which, however, is not described by a simple activation law. On the whole the obtained results seem to be in better agreement with the theoretical prediction [14], according to which there should be a critical magnetic field B_c that separates the transport via the gapless helical edge states at low fields from the activation transport due to a gap emerging in the spectrum at higher fields.

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