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Transport in disordered two-dimensional topological insulators

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The transport properties of the "inverted" semiconductor HgTe-based quantum well, recently shown to be a two-dimensional topological insulator, are studied experimentally in the diffusive regime. Nonlocal transport measurements are performed in the absence of magnetic field, and a large signal due to the edge states is observed. This shows that the edge states can propagate over a long distance, ∼1 mm, and therefore, there is no difference between local and nonlocal electrical measurements in a topological insulator. In the presence of an in-plane magnetic field a strong decrease of the local resistance and complete suppression of the nonlocal resistance is observed. We attribute this behavior to an in-plane magnetic-field-induced transition from the topological insulator state to a conventional bulk metal state.

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Recently, a topological class of quantum condensed matter states has been discovered, called topological insulators.[1–4] The best known example of a two-dimensional (2D) topological insulator (TI) is the integer quantum Hall-effect (QHE) state,[5] which is a 2D electron gas in the presence of a strong perpendicular magnetic field when all current is carried by the edge states, while the electrons in the bulk region are localized.[6,7] The number of the edge states is determined by the Landau level filling factor ν. The edge states are unidirectional because of the magnetic field induced time-reversal (TR) symmetry breaking and are robust against impurity scattering. Note that disorder is crucial for the finite width of the Hall plateau versus magnetic field or electron density.

Another class of 2D TI is the quantum spin Hall-effect state, which can be realized in a 2D system with strong spin-orbit interaction in the absence of magnetic field.[8–11] It has been shown that the HgTe/CdTe quantum well with an inverted energy-band structure[10,11] has an insulating gapped phase in the bulk and a single pair of counterpropagating or helical edge states for two opposite spin polarizations. A remarkable consequence of the presence of the edge states in ballistic 2D TI is the quantized longitudinal resistance $R = h/2e^2$, which has been observed in micrometer-scale Hall bars.[11,12] The edge states are expected to be insensitive to weak, nonmagnetic impurity scattering due to destructive interference between the clockwise- and counterclockwise-propagating backscattered trajectories (see reviews in Refs. 1 and 13). It is worth noting that the backscattering does not destroy the edge states; therefore any 2D TI sample represents an almost ideal, natural, one-dimensional (1D) wire localized near the sample edge.[14–16]

In this Rapid Communication we present an experimental study of the transport properties of the "inverted" HgTe-based quantum well. When the Fermi level enters the energy gap in the bulk, samples show an unusual behavior, which is characterized by a high resistance $R \gg h/e^2$ with a metallic temperature dependence. Since the scattering between the helical edge states is topologically protected due to the time-reversal symmetry, we attribute the high resistance value to spin-flip scattering between the pair of the helical edge states induced by two-particle backscattering, which breaks the TR symmetry. As mentioned above, the edge state at the periphery of the disordered TI is equivalent to a single one-dimensional wire. Using nonlocal transport measurements, we demonstrate that the edge-state transport in a 2D TI does really persist over macroscopic distances of ∼1 mm in the absence of magnetic field. The in-plane magnetic field strongly reduces the local magnetoresistance and completely suppresses the resistance measured in a nonlocal configuration. This observation is attributed to the in-plane magnetic-field-induced transition from a 2D TI state to a bulk metallic state.

The $Cd_{0.65}Hg_{0.35}Te/HgTe/Cd_{0.65}Hg_{0.35}Te$ quantum wells with the (013) surface orientation and two different widths of 8 and 8.3 nm were prepared by molecular beam epitaxy. A detailed description of the sample structure has been given in Refs. 17 and 18. The schematic view of a typical experimental sample is shown in Fig. 1(a). The sample consists of three narrow (5 μm wide) consecutive segments of different length (8, 20, and 8 μm) and eight voltage probes. The ohmic contacts to the two-dimensional gas were formed by the burning of indium. To prepare the gate, a dielectric layer containing 100 nm of SiO_2 and 200 nm of Si_3Ni_4 was first grown on the structure using the plasmochemical method. Then, the TiAu gate was deposited. The gate dimension is macroscopic (1000×500 μm^2), which is crucial for the formation of long edge states. The density variation with gate voltage was 1.09×10^{15} m^{-2} V^{-1}. The magnetotransport measurements in the described structures were performed in the temperature range 0.050–4.1 K and in magnetic fields up to 15 T using a standard four-point circuit with a 2–3-Hz ac current of 0.1–1 nA through the sample, which is sufficiently low to avoid the overheating effects.

Figure 1(b) shows the diagonal R_{xx} and Hall R_{xy} resistances as a function of the gate voltage at zero and fixed magnetic field in 8.0-nm-wide HgTe wells, which indicate a high quality of the sample. The measured electron mobility is

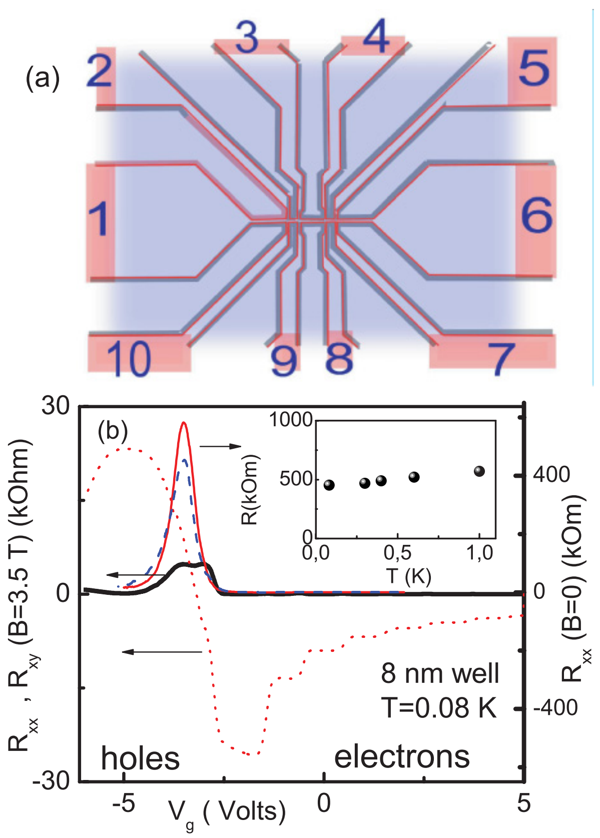

FIG. 1. (Color online) Schematic top view of the central part of the sample, covered by the gate (shown in blue or light grey) (a) Red thin lines are edge states localized at the periphery of the sample under a TiAu metallic gate in the TI state. Red areas are the regions with n-type HgTe. (b) The diagonal R_{xx} (thick line, $I = 1,6$, $V = 9,8$) and Hall R_{xy}(dotted line, $I = 1,6$, $V = 9,3$) resistances as a function of the gate voltage at zero and fixed magnetic field. The inset shows the temperature dependence of the peak at zero magnetic field. Two traces at zero field are shown in (b) (red solid line, $T = 1$ K; blue dashed line, $T = 0.08$ K).

approximately $\mu_n = 250\,000$ cm^2/V s, and the hole mobility $\mu_p \approx 25\,000$ cm^2 V s, which is comparable to that found in wider HgTe wells.[17,18] Sweeping the gate voltage V_g from positive to negative will then depopulate the electron states and populate the hole states. One can see this from the Hall resistance behavior: R_{xy} changes smoothly through zero from its negative quantized value on the electron side to a positive quantized value on the hole side, whereas R_{xx} moves from a zero on the electron side through a maximum at the bulk energy gap to another zero minimum on the hole side.

In the following we will concentrate on the electronic behavior of the system when the Fermi energy is in the gap of the bulk energy spectrum at zero magnetic fields and at low temperatures. It is expected that the transport under these conditions is implemented by the pair of counterpropagating or helical edge states with opposite spin polarizations, and the resistance has a quantized value of $h/2e^2$. The resistance measured in our sample (8.3-nm well) $R \approx 300$ kΩ is significantly higher than $h/2e^2$. This agrees with the previous results obtained in samples with the length $L = 20$ μm, which has been attributed to inelastic scattering between helical edge states.[19] Similar to the conventional quantum Hall effect, the origin of this resistance is the processes in the contact regions. The contacts are assumed to be thermal reservoirs,[20] where the mixing of electron states with different spins will occur. Note that, in contrast to the QHE, where the mixing of the edge states occurs within metallic Ohmic contacts, in our samples its takes place in the 2D electron gas region outside of the metallic gate due to a finite bulk conductivity. Figure 1(a) illustrates the geometry. One can see that the lengths of the edge states are determined by the perimeter of the sample part covered by metallic gate (mostly side branches) rather than by the length of the bar itself. We calculate the length of 1D wires between the probe contacts and find it to exceed 1.0 mm. For such macroscopic distance it is natural to expect strong backscattering between states with opposite spin polarizations due to spin-flip scattering or scattering by magnetic impurities. Elastic magnetic scattering is unlikely to explain our data because the background magnetic impurity content of the molecular beam epitaxy (BE) machine is very low. The high resistance $R \gg h/e^2$ may be attributed to three basic mechanisms: (i) inelastic scattering,[19] (ii) spin-flip scattering of Rashba type, and (iii) two-particle processes.[21,22] The inelastic mechanism is ruled out since we did not observe any temperature dependence of the resistance peak. The second mechanism induced by spin-orbital interaction is somewhat similar to transition between the spin-split states in the quantum Hall-effect regime, considered theoretically in Ref. 23. It is worth noting that the spin-orbit term that is expected to mix the counterpropagating channels is the Rashba term[24] and not the intrinsic spin-orbit interaction term that causes the band inversion. However, such elastic backscattering should lead to localization and hence to a T-dependent resistance,[25] which is not observed. Two-particle excitation[21,22] leads to a dephasing due to inelastic interaction between electrons. Such a process would suppress the interference, which is responsible for the Anderson localization in 1D wires. It is consistent with the absence of localization effects in our long wires with high resistance. However, the lack of any theoretical prediction does not allow us to compare results with expected temperature dependence.

Note that the 2D TI at zero magnetic field is equivalent to the QHE state at $\nu = 0$ near the charge neutrality point in graphene considered in the model.[26] Within this model the transport in graphene at strong magnetic field is dominated by the the pair of gapless edge excitations, which, however, have magnetic nature. In the absence of transport through the bulk, if both edges carry the same current, the resistance is $R = \frac{h}{2e^2}(1 + \gamma L)$, where γ^{-1} is the mean free path for 1D backscattering and L is the length of the 1D channel between contacts, or thermal reservoirs, which in our case are related to the 2D electron gas. Comparing this model, which applies equally well to the transport in 2D TI at zero magnetic field, with our results, we obtain $\gamma^{-1} = 400$ μm.

We have studied several samples from different wafers and found that the peak resistance is varied from 300 kΩ to 2 MΩ, which is likely to stem from variation of the disorder parameters. The application of the current between any pair of the probes creates net current along the sample edge and can be detected by any other pair of the voltage probes.

In general, there is no difference between local and nonlocal electrical measurements in a topological insulator. For example, for nonlocal resistance, shown in Fig. 2(b), application of the current between leads 1 and 10 produces current along two paths: longer, 1–2, 2–3, 3–4, 4–5, 5–6, 7–8, 8–9, 9–10, and shorter, 1–10. Figure 2 shows several traces for local and nonlocal resistance taken at different configurations for an 8-nm HgTe well. The data demonstrate that the nonlocal resistance is negligibly small in the region with homogeneous 2D electron and hole gases, outside of the TI peak, as expected for classical dissipative transport [see inset in Fig. 2(a)]. The nonlocal resistance in the TI regime has a comparable amplitude and qualitatively the same position and width of the peak. The occurrence of the nonlocal resistance of comparable amplitude implies that the potential difference extends over the macroscopic distance of ∼1 mm away from the dissipative bulk current path. It is only possible if the bulk conductivity is completely suppressed and conductivity of the TI sample is governed by the edge states. Note that to simplify the calculations of the local and nonlocal resistances of a 2D TI, we can use the Kirchhoff circuit laws. We substitute the 1D channel between any contacts by the quantum resistance $R = h/e^2$. In the diffusive case we can roughly estimate the nonlocal effect by assuming that the quantum resistance can be substituted with $R = h/e^2\gamma L$. If all probes are located at the same distance from each other, we obtain the same ratio as in the ballistic case, which is 2 times smaller than that found in the experiment. We can reduce this discrepancy by considering a realistic geometry. However, for an exact estimation of the magnitude of the nonlocal resistance one needs to consider a transport theory in the presence of fluctuations caused by position dependence of the scattering rate, which is out of the scope of our experimental Rapid Communication. Note that in the ballistic case the nonlocal transport indeed has been observed in mesoscopic samples[27] when nonlocal resistance has been obtained within the general Landauer-Büttiker formalism.[20]

Application of a strong perpendicular and an in-plane magnetic field would be important for understanding the physics of topological insulators, and one may expect some other interesting phenomena as well. Previous experiments in ballistic structures[11] demonstrated a sharp spike at $B = 0$ and a decrease of the conductance with an increase of the perpendicular magnetic field $B_\perp$. No magnetoresistance has been observed in the presence of the in-plane magnetic field $B_\parallel$. This observation has been attributed to the opening of a gap between the edge states due to the Zeeman splitting. An

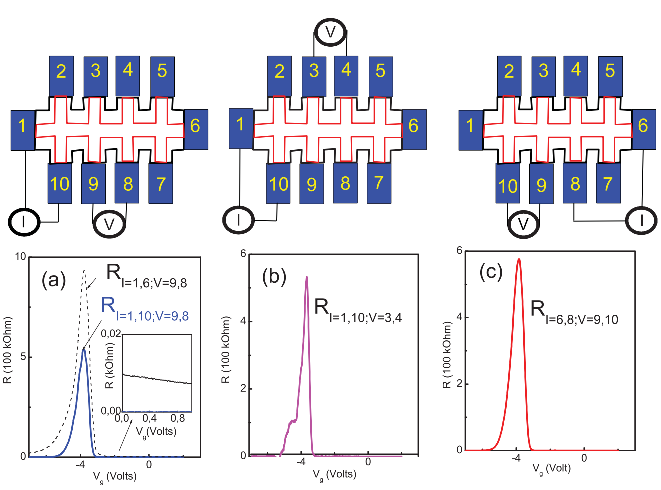

FIG. 2. (Color online) (a) Local and (b, c) nonlocal resistances at zero magnetic field as a function of the gate voltage for different configurations, which are shown in the top panel. Red (grey) lines represent a 1D wire along the sample edge. The inset in (a) shows the local and nonlocal resistance in the region with bulk dissipative transport. $T = 80$ mK.

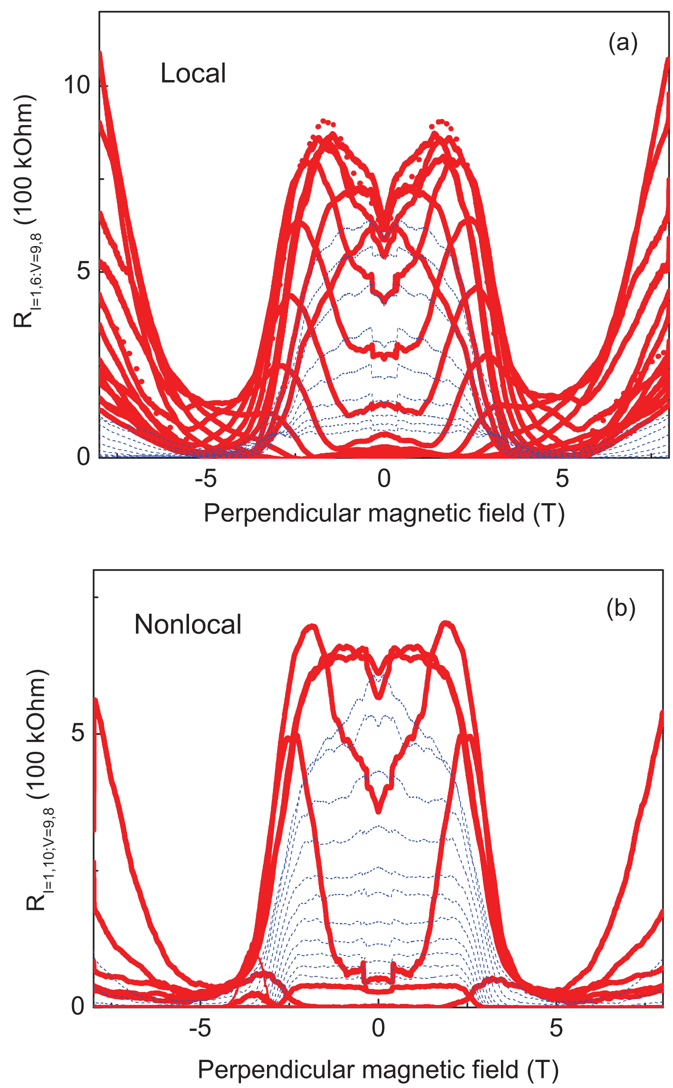

FIG. 3. (Color online) (a) Local resistance as a function of the perpendicular magnetic field for different gate voltages. Thick traces are taken for the electronic part of the TI peak, $V_g = -2.5$ to -3.8 V, step of 0.1 V. Thin traces are taken for the hole part of the TI peak, $V_g = -3.8$ to -4.8 V, step of 0.1 V. (b) Nonlocal resistance as a function of the perpendicular magnetic field for different gate voltages. Thick traces are taken for the electronic part of the TI peak, $V_g = -2.5$ to -3.8 V, step of 0.2 V. Thin traces are taken for the hole part of the TI peak, $V_g = -3.8$ to -4.8 V, step of 0.1 V. $T = 80$ mK.

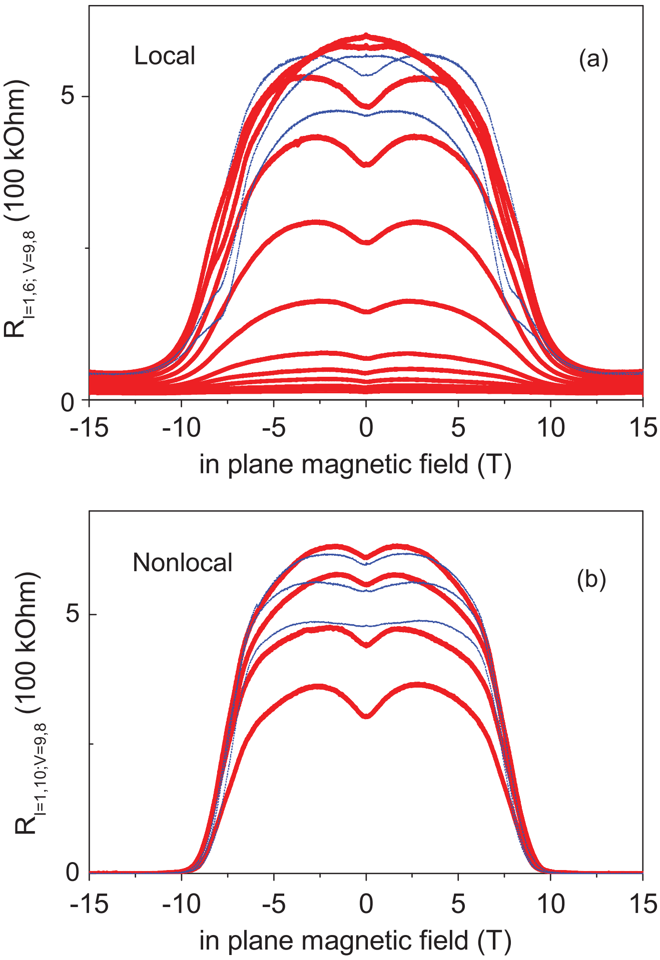

FIG. 4. (Color online) (a) Local resistance as a function of in-plane magnetic field for different gate voltages. Thick traces are taken for the electronic part of the TI peak, $V_g = -2.5$ to -3.7 V, step of 0.1 V. Thin traces are taken for the hole part of the TI peak, $V_g = -3.8$ to -4.0 V, step of 0.1 Volts. (b) Nonlocal resistance as a function of in-plane magnetic field for different gate voltages. Thick traces are taken for the electronic part of the TI peak, $V_g = -3.5$ to -3.8 V, step of 0.1 V. Thin traces are taken for the hole part of the TI peak, $V_g = -3.9$ to -4.1 V, step of 0.1 Volts. $T = 80$ mK.

alternative scenario has been suggested in Ref. 28, where the orbital effects and the effects of disorder have been included in the consideration. In a disordered TI we find a different behavior. Figure 3 shows the magnetoresistance in local and nonlocal configurations for different gate voltages when the Fermi level goes from the electron to the hole side of the peak in Fig. 2. It is worth noting the remarkable similarity between these two sets of curves. This confirms once again that the transport in a TI occurs only at the periphery of the sample. The existing theories predict several scenarios for a high magnetic field behavior. We believe that for a perpendicular magnetic field the scenario is as follows. The resistance first increases because of the enhanced backscattering owing to breaking of the time-reversal symmetry. In higher magnetic fields the resistance goes through a maximum and then drops down because of a low probability for backscattering with a large momentum transfer. Then, the transition to an ordinary quantum Hall state takes place. This scenario is consistent with our observations. Such a complex magnetoresistance behavior requires a more detailed analysis and a comparison with the theory. That will be done in future presentations.

Figure 4 shows the evolution of the local and nonlocal magnetoresistance with gate voltage in the presence of the in-plane magnetic field. Again, one may see a strong similarity between these two sets of magnetoresistance curves. In contrast to the previous measurements in ballistic devices[19] we observe a large positive magnetoresistance within 2 T. In magnetic field $B_{\parallel} > 6T$ both resistances decrease dramatically as the in-plane field increases. Examination of the traces in Fig. 4 in magnetic fields higher than 10 T reveals a drastic difference between R_{xx} and the nonlocal resistance: the nonlocal resistance data in this region are negligible compared to a large (10–50 kΩ) value of R_{xx}. Note that in a perpendicular magnetic field both resistances have comparable values in strong B (Fig. 3). Thus, the external parallel magnetic field strongly suppresses R_{xx} and completely destroys nonlocal resistance. The nonlocal resistance is very small in the presence of a dissipative transport in the bulk of the sample. Therefore it would be natural to suggest that the in-plane magnetic field destroys the edge-state transport and at the same time produces electronic states in the bulk. Alternatively, we may suggest that the in-plane field results in the formation of unidirectional edge states similar to the QHE state in perpendicular magnetic field. These states indeed are dissipationless, and the voltage drop between the probe contacts is zero. However, within this scenario, the local resistance R_{xx} would be zero as well, which disagrees with our observation [see Fig. 4(a)]. In the parallel (in-plane) magnetic field, the explanation of magnetoresistance is as follows. This field does not enhance the backscattering owing to the breaking of the time-reversal symmetry, so in weak fields the magnetoresistance is almost unchanged. The field, however, immediately opens the gap in the edge-state spectrum and decreases the bulk gap owing to the Zeeman effect. Approximately at 10 T, the edge states disappear, the bulk gap closes, and the the system becomes a 2D gapless semiconductor.

In summary, we report the observation of a disordered 2D TI state in HgTe quantum wells in zero magnetic field and the emergence of conductive bulk states in the presence of the in-plane magnetic field. We demonstrate the similarity between local and nonlocal resistance measurements in zero and perpendicular magnetic field in the TI regime. These data offer the evidence that in realistic samples edge-state transport really extends over a macroscopic distance of ∼1 mm in the absence of magnetic field.

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