Linear magnetoresistance in HgTe quantum wells

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We report magnetotransport measurements in a HgTe quantum well with an inverted band structure, which is expected to be a two-dimensional (2D) topological insulator. A small magnetic field perpendicular the 2D layer breaks the time reversal symmetry and thereby, suppresses the edge state transport. A linear magnetoresistance is observed in low magnetic fields, when the chemical potential moves through the the bulk gap. That magnetoresistance is well described by numerical calculations of the edge states magnetotransport in the presence of nonmagnetic disorder. With magnetic field increasing the resistance, measured both in the local and nonlocal configurations first sharply decreases and then increases again in disagreement with the existing theories.

The topological insulators are a novel type of system with a gap in the energy spectrum of the bulk states and a gapless energy spectrum of a special class of electron states located at their surface or edges. The two-dimensional (2D) topological insulator (TI) has gapless states propagating along its edges. There are two famous examples of such system: the quantum Hall effect (QHE) state, which exists in a strong magnetic field perpendicular to the plane and is characterized by chiral edge states, and the time-reversal-symmetric quantum spin Hall effect state (QSH), which is induced by a strong spin-orbit (SO) interaction and is characterized by counter propagating states with opposite spins in the absence of magnetic field.

The QSHE has been realized in HgTe/CdTe quantum wells with inverted band structure. The existence of edge channel transport in the QSH regime has been proved experimentally, when a 4-probe resistance in an HgTe/CdTe micrometer-sized ballistic Hall bar demonstrated a quantized plateaus \( R_{xx} \approx h/2e^2 \). One more experimental evidence for edge states in QSHE is a nonlocal transport, since 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. It is expected that the stability of helical edge states in the topological insulator is unaffected by the presence of weak disorder. Note however, that the quantized ballistic transport has been observed only in micrometer-sized samples, and plateaux \( R_{xx} \approx h/2e^2 \) is destroyed, if the sample size is above a certain critical value about a few microns.

A magnetic field perpendicular to the 2D layer breaks time reversal symmetry (TRS) and thereby enables elastic scattering between counterpropagating chiral edge states. However, a number of the different theoretical models has previously been proposed and different conflicting scenarios have been developed for TRS breaking in QHSE system, which requires detailed experimental investigation.

A sharp magnetoresistance spike has been observed in the previous study of a HgTe-based sample few microns in size. Nevertheless, it is very likely that these experiments have been done in the regime, when the disorder strength \( W \) is of the same order or even larger than the bulk energy gap \( E_g \). In this paper we report on the observation and a systematic investigation of a positive linear magnetoresistance in HgTe quantum wells with inverted band structure corresponding to the QSHE phase. The magnetoresistance in low fields is described by a theoretical model that takes into account the combined effect of disorder and TRS breaking in a weak disorder regime.
when $W < E_g$. In magnetic fields above 2 T we observe a decrease of the resistance with a saturation, corresponding to the QHE phase, followed by a transition to a state with a higher resistance and nonlocal transport in fields above 6 T.

The $Cd_{0.65}Hg_{0.35}Te/HgTe/Cd_{0.65}Hg_{0.35}Te$ quantum wells with the (013) surface orientations and the width $d$ of 8.8-3 nm were prepared by molecular beam epitaxy. A detailed description of the sample structure has been given in Ref. 21. The six-probe Hall bar was fabricated with the lithographic length 6 $\mu$m and the width 5 $\mu$m (Figure 1, insert). The ohmic contacts to the two-dimensional gas were formed by the in-burning 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 TiAu gate with the size $18 \times 10 \mu m^2$ was deposited. Several devices with the same configuration have been studied. The density variation with gate voltage was $1.09 \times 10^{15} m^{-2} V^{-1}$. The magnetotransport measurements in the described structures were performed in the temperature range 1.4-25 K and in magnetic fields up to 12 T using a standard four terminal circuit with a 3-13 Hz ac current of 0.1-10 nA through the sample, which is sufficiently low to avoid the overheating effects.

The carriers density in HgTe quantum wells can be varied electrostatically with the gate voltage $V_g$. The typical dependence of the four-terminal $R_{xx} = R_{1=1.4, V=2.3}$ and Hall $R_{xy} = R_{I=1.4, V=3.5}$ resistances of one representative sample as a function of $V_g$ is shown in Figure 1a. The resistance $R_{xx}$ exhibits a sharp peak that is $\sim 20$ times greater than the universal value $h/2e^2$, which is expected for QSHE phase. This value varies from 150 to 300 kOhm in different samples. The Hall coefficient reverses its sign and $R_{xy} \approx 0$ when $R_{xx}$ approaches its maximum value, which can be identified as the charge neutrality point (CNP). This behavior resembles the ambipolar field effect observed in graphene. The gate voltage induces charge density variations, transforming the quantum well conductivity from n-type to p-type via a QHSE state.

As we mentioned above, that the edge state transport is unaffected by the presence of weak disorder. However, the quantized ballistic transport and plateaux $R_{xx} \simeq h/2e^2$ have not been observed in samples with dimensions above a few microns. One of possible explanations is presence of local fluctuations of the energy gap induced by smooth inhomogeneities, which can be represented as metallic islands. In accordance with Landauer-Büttiker formalism any voltage probe coupled to a coherent conductor introduces incoherent inelastic processes and modifies the ballistic transport. Metallic islands can result in similar effects, since an electron entering the island is dissipated and thermalized there and later on fed back into the system. Therefore ballistic coherent transport is expected only in the region between the islands, and the total 4-terminal resistance exceeds the quantized value. However, such long range potential fluctuations must have the amplitude of the order of the energy gap $E_g \sim 30 meV$ which is very unlikely, since such fluctuations should suppress the electron SdH oscillations in low magnetic fields, which is not observed in the experiment. The resistance of samples longer than 1 $\mu$m might be much higher than $h/2e^2$ due to the presence of the spin dephasing (electron spin flip backscattering on each boundary). Mechanisms of the back scattering are new and appealing task for theoreticians and is a matter of ongoing debate. The classical and quantum magnetic impurities may introduce a backscattering between counter propagating channels. An accidentally formed quantum dot with an odd number of trapped electrons could play a role of such magnetic impurity. For strong enough electron-electron interaction the formation of Luttinger liquid insulator with a thermally activated transport was predicted. In the frames of a somewhat different approach an edge state transport theory in the presence of spin orbit Rashba coupling has been developed. According to this model the combination of a spatially non-uniform Rashba spin-orbit interaction and a strong electron-electron interaction leads to localization of the edge electrons at low temperatures. However, the exact examination and comparison with theoretical models requires a further experimental investigation of the temperature, doping and disorder dependence of the resistivity which are out of the scope of the present paper.

![Figure 2](image-url)  

**FIG. 2:** (Color online) The longitudinal resistance $R_{xx}$ as a function of the gate voltage and magnetic field, $T=1.4$ K.
though less wide, and approximately in the same position as the local resistance. Outside of the peak the nonlocal resistance is negligible. One can see that the evolution of resistances with magnetic field is practically the same in both cases: resistance grows with field below 2 T, and then rapidly decreases and saturates. Figure 2 shows the longitudinal resistance $R_{xx}$ in the voltage-magnetic field plane. One can see the evolution of the resistance $R_{xx}$ with magnetic field and density, when the chemical potential crosses the bulk gap. The magnetoresistance demonstrates a striking V-shape dependence in magnetic fields below 1 T. It is worth noting that the V-shaped magnetoresistance is observed almost anywhere on the hole side of the peak and rapidly disappears on the electronic side.

In magnetic fields above 2 T the magnetoresistance starts to decrease marking a pronounced crossover to the quantum Hall effect regime. Note, however, that the resistance does not turn to zero, as would be expected for a conventional QHE state, but approaches the value $R_{xx} \approx \hbar/e^2$. Figure 3 shows the magnetic field dependence extended to 12 T of the local and nonlocal resistances at the gate voltage corresponding the peak maximum for another representative sample. Both the local and nonlocal resistances grow rapidly in fields above 6 T. The evolution of the magnetoresistance in strong quantized magnetic field disagrees with the theoretical models proposed recently for transport in HgTe quantum wells with inverted band structure. The growth of the local and nonlocal resistances in the field above 6 T can be attributed to the edge state transport via counter propagating chiral modes similar to the HgTe semimetal and graphene near $\nu = 0$. Further theoretical work would be needed in order to explain this behaviour.

Figure 4 shows the low field part of the relative magnetoconductivity $\sigma_{xx}(B)/\sigma_{xx}(0)$ for two values of the gate voltage, one at the CNP and the other just slightly below the CNP on the electron side of the TI peak. The conductivities have been recalculated from experimentally measured $\rho_{xx}$ and $\rho_{xy}$ by tensor inversion. Note, however, that around the CNP $\rho_{xy} \ll \rho_{xx}$ and $\sigma_{xx} \approx 1/\rho_{xx}$.
terval of the energy, when the chemical potential goes through this gap. Experimentally, though, a suppression of conductance is observed in a much wider interval of the chemical potential through the bulk gap \( E_g \sim 30 \text{meV} \), in contrast to the theoretical predictions. In this model the magnetic field does not create a gap. Instead, it modifies the energy spectrum of the edge states: one of the state merges with the lower bulk Landau level, while the other one remains unchanged. This transformation generates backscattering between the counter propagating modes in the presence of the weak disorder and leads to an increase in the resistance. However, the model\(^{15}\) does not suggest any realistic description of the scattering and can hardly be compared with experimental observations.

The third model\(^{18}\) also claims that edge states persist in relatively low magnetic fields, but in magnetic fields above a certain critical \( B_c \), the band structure becomes normal and the system turns into an ordinary insulator. For HgTe devices the critical magnetic field is estimated as \( B_c \approx 7.4T \), therefore the resistance increase at fields above 7 T (figure 3) can be attributed to the TI-ordinary insulator transition. However, the model can not explain the growth of the nonlocal resistance at high magnetic field. A similar, but a somewhat more complicated evolution of the energy spectrum with B has been proposed in\(^{12}\).

Finally a numerical study of the edge state transport in the presence of both disorder and magnetic field has been reported recently in Ref.18. The authors predict a negative linear magnetoconductance \( \frac{\Delta G}{\Delta V} = -A|B| \), where parameter A strongly depends on the disorder strength W. A physical interpretation of the linear magnetoresistance is given along with the effects analogous to the one dimensional (1D) or 2D antilocalization. We believe that the theoretical model\(^{18}\) describing the effect of the disorder and TRS breaking on the edge transport correctly explains the linear magnetoresistance observed in our experiment. The theory considers two regimes: one corresponding to a weak disorder, when \( W < E_g \), and the edge states are described by spinless 1D edge liquid, and a strong disorder regime, when \( W > E_g \) and the edge states can penetrate deeper into the bulk. Sensitivity to magnetic field strongly depends on which of the two regimes is realized: parameter A is small for weak disorder and abruptly increases by almost 10-100 times for \( W > E_g \). Supposing that the results are valid for a nonballistic case and \( A \sim \alpha \), we may conclude that in our samples \( W < E_g \). Unfortunately the precision of the numerical calculations in\(^{18}\) does not allow an unambiguous determination of the disorder parameter W from the B-slope of the magnetoconductance. It is worth noting that the B-slope of the sharp magnetoconductance spike observed in samples with similar size in\(^{18}\) is 120 times larger than that in our samples. Admitting that the model\(^{18}\) is applicable to this data, we obtain the disorder parameter \( W \approx 72 \text{meV} \), which is almost 2 time larger than the energy gap \( E_g = 40 \text{meV} \). The disorder parameter W is related to the local deviations of the HgTe quantum well thickness from its average value\(^{29}\), rather than to the random potential due to charged impurities. As has been shown in\(^{18}\), parameter W can be estimated from the value of the mobility. For example, the mobility \( \mu \approx 10^5 \text{cm}^2/\text{V} \cdot \text{s} \) corresponds to the momentum relaxation time \( \tau = 0.57 \text{ps} \), which can be derived from the equation \( \tau = \hbar/2\nu (W a)^2 \), where \( a = 30 \text{A} \) is the range of the disorder, \( \nu = m^*/\hbar^2 \), \( m^* \) is the effective mass. Substituting these parameters into the equation for the relaxation time yields \( W = 22 \text{meV} \). It is worth noting that the average band gap can be smaller due to the stress. For example the energy gaps considered in\(^{29}\) were \( E_g = 14 \text{meV} \) for the well width \( d = 7.3 \text{nm} \) and \( E_g \approx 20 \text{meV} \) for \( d = 8 \text{nm} \). This may explain the difference between our results and those obtained previously in narrow samples\(^{22}\), the fluctuations \( W \sim 15 \text{meV} \) result in a large B-slope in wells with \( d = 7.3 \text{nm} \) corresponding to a strong disorder regime in these wells \( W > E_g \) and to a small B-slope for wider a well \( d \approx 8 \text{nm} \) \( W < E_g \).

The physical mechanism behind the linear magnetoresistance can not be unambiguously identified from the numerical calculations\(^{18}\). It is expected, that this mechanism is rather related to a suppression of the interference between closed paths, than the orbital effect, and is analogous to the 1D or 2D antilocalization. Weak temperature dependence observed in our experiments supports this interpretation. The authors claim that for weak disorder the magnetic field has only a perturbative effect on the transport properties of the edge states and expect a quadratic dependence of the magnetoconductance on B, rather than linear. However, it is not evident from the figures, as has been mentioned by the authors themselves. Further theoretical study will be needed to better understand the mechanism of TRS breaking and the effect of disorder on the edge transport in the QSHE.

In conclusion, we have observed a linear negative magnetoconductance in HgTe-based quantum wells in the QSHE regime, when the edge state transport prevails. Our observation agrees with the numerical calculations of the magnetoconductance due to the edge states transport in the presence of nonmagnetic disorder. The B-slope of the magnetoconductance is small and corresponds to a weak disorder limit, when \( W < E_g \) and the magnetoconductance is analogous to a one dimensional antilocalization. In magnetic field above 2 T the resistance rapidly decreases and then saturates, which corresponds to the QHE phase. Above 6 T a transition to high resistance state is observed, accompanied by a large nonlocal response, which disagrees with the theory.

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