The resistance of 2D Topological insulator in the absence of the quantized transport

G.M.Gusev, Z.D.Kvon, E.B Olshanetsky, A.D.Levin,
Y. Krupko, J.C. Portal, N.N.Mikhailov, S.A.Dvoretsky
1 Instituto de Física da Universidade de São Paulo, 135960-170, São Paulo, SP, Brazil
2 Institute of Semiconductor Physics, Novosibirsk 630090, Russia
3 Novosibirsk State University, Novosibirsk, 630090, Russia
4 LNCMI-CNRS, UPR 3228, BP 166, 38042 Grenoble Cedex 9, France and
5 INSA Toulouse, 31077 Toulouse Cedex 4, France
(Dated: May 11, 2014)

We report unconventional transport properties of HgTe wells with inverted band structure: the resistance does not show insulating behavior even when it is of the order of $10^3 \times \hbar/2e^2$. The system is expected to be a two-dimensional topological insulator with a dominant edge state contribution. The results are inconsistent with theoretical models developed within the framework of the helical Luttinger liquid.

I. INTRODUCTION

The two-dimensional (2D) topological insulators (quantum spin Hall insulator) are characterized by a bulk energy gap and gapless boundary modes that are robust to impurity scattering and electron-electron interactions. The 2D quantum spin Hall insulator (QSHI) has been realized in HgTe quantum wells with inverted band structure. This novel state results from the intrinsic spin-orbit interaction, which leads to the formation of the helical edge modes with opposite spin polarization counter-propagating at a given sample boundary.

In the presence of electro-electron interactions, the edge states of 2D topological insulator (2DITI) can be regarded as an example of helical Luttinger liquid state (LL).

The helical liquid theory is an extension of the conventional spinless or spinfull LL theory. It provides a complete low-energy description of a one-dimensional metallic system even for strong interaction and predicts its stability to arbitrary disorder. Experimentally the existence of the Luttinger liquid state in a strongly interacting one dimensional electron system could be detected from the temperature dependence of its resistance. The first theoretical model developed within the framework of a pure LL without impurities in the presence of a single strong barrier predicted a power law dependence of the resistance on temperature. In a system containing many impurities the resistance is dominated by a combined effect of interaction and disorder potential and should exhibit a stronger temperature dependence. The presence of the Luttinger-liquid has been deduced from the resistance temperature dependence in many mesoscopic 1D systems, such as single-wall carbon nanotubes, cleaved-edge, split-gate and V-groove semiconductor wires.

The helical edge state in 2D topological insulator is the most prominent example of an ideal Luttinger liquid, as it is an inherent property of HgTe wells with an inverted band structure. Furthermore, it does not require nano manufacturing techniques and its presence has been observed over the distances of the order of one millimeters. The electronic conductance of the 2DITI is quantized in units of the universal value $2e^2/h$, as was observed in the short and clean micrometer-scale Hall bars. However, the quantized ballistic transport has not been observed in sample with the dimensions above...
a few microns. Further investigations are required to understand the absence of the resistance quantization in macroscopic samples. The evaluation of the deviation of the conductivity from the quantized value has been performed in several theoretical models. Particulary, the combined effect of the weak interaction and disordered scattering in helical LL channel results to the temperature dependent deviation from $2e^2/h$ which scales with temperature to the power of $12$ or $67$. Another way to explain the observation of 2DII resistance in excess over its expected quantized value requires the consideration of possible scattering processes at the edge. The classical and quantum magnetic impurity introduces a backscattering between the counter propagating channels. Such magnetic impurity could be an accidently formed quantum dot, which can trap odd number of electrons. For strong enough electron-electron interaction the formation a Luttinger liquid insulator with a thermally induced transport has been predicted. Using a somewhat different approach, an edge state transport theory in the presence of spin orbit Rasba coupling has developed. According to this model, the combination of the spatially nonuniform Rashba spin-orbit and strong electron-electron interactions leads to localization of the edge electrons a the low temperatures.

In the present paper we investigate the resistance of the 2D TI with a dominant edge states contribution to the transport. These edge channels are described by the helical Luttinger liquid model. The experiment demonstrates an unexpected weak temperature dependence of the resistance at a level 100 times higher than the quantum unit $h/2e^2$.

II. EXPERIMENT

The $Cd_{0.65}H_{90.35}Te/HgTe/Cd_{0.65}H_{90.35}Te$ quantum wells with (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 [21-23]. Device A is designed for multiterminal measurements, while device B is a six-probe Hall bar. The device A consists of three 4$\mu$m wide consecutive segments of different length (2, 8, 32$\mu$m), and 7 voltage probes. The device B was fabricated with a lithographic length 6$\mu$m and width 5$\mu$m (Figure 1, top panel). The ohmic contacts to the two-dimensional gas were formed in the in-burning of indium. To prepare the gate, a dielectric layer containing 100 nm SiO$_2$ and 200 nm Si$_3$N$_4$ was first grown on the structure using the plasmochemical method. Then, the TiAu gate with the dimensions $62 \times 8 \mu m^2$ (device A) and $18 \times 10 \mu m^2$ (device B) was deposited. Several devices with the same configuration have been studied. The density variation with gate voltage was $1.09 \times 10^{15} n^{-2} V^{-1}$. The transport measurements in the described structures were performed in an variable temperature insert (VTI) cryostat (the temperature range 1.4-60 K), in $He_3$ cryostat (the temperature range 0.3-3 K) and in dilution fridge (the temperature range 0.05-2 K). We used a standard four point circuit with a 3-13 Hz ac current of 0.1-100 nA through the sample. A typical 100 Mohm resistance connected in series has been used in order to keep the current constant.

The carrier density in HgTe quantum wells can be varied with the gate voltage $V_g$. The typical dependence of the four-terminal $R$ resistances of the devices A and B as a function of $V_g$ is shown in Figure 1. The resistance $R$ of device A corresponds the configuration, when the current flows between contacts 1 and 5, and the voltage is measured between contacts 7 and 6, as a function of the inverse temperature at charge neutrality point. The solid line is a fit of the data with the Arrenius function where $\Delta = 200 K$. The insert shows a schematic view of the sample. (b) The resistance $R_{1,5,7,6}$ as a function of the gate voltage for different temperatures. (T(K): 1.5, 2.5, 3, 3.5, 4.2, 10, 19, 29, 40, 53, 62), $I=10^{-7}A$. 

![FIG. 2: (Color online) Color online) (a) The resistance $R_{1,5,7,6}$ corresponding the configuration, when the current flows between contacts 1 and 5 , and the voltage is measured between contacts 7 and 6, as a function of the inverse temperature at charge neutrality point. The solid line is a fit of the data with the Arrenius function where $\Delta = 200 K$. The insert shows a schematic view of the sample. (b) The resistance $R_{1,5,7,6}$ as a function of the gate voltage for different temperatures, (T(K): 1.5, 2.5, 3, 3.5, 4.2, 10, 19, 29, 40, 53, 62), $I=10^{-7}A$.](image-url)
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. Therefore the effective length of the 1D channels L exceeds the distance between the probes of the Hall bar by 3-4 $\mu$m. It may be expected that a reflection occurs when a 1D electron wave hits the interface between the ungated and the 2DTI regions, which may account for a resistance greater than $h/2e^2$. However, a linear dependence of the resistance on L rules out this possibility and confirms that the high resistance value very likely is a result of backscattering between the counter propagating edge channels.

One can see in the figure 1 that the device B shows a smaller and more narrow resistance peak. The Hall coefficient (not shown) reverses its sign and $R_{xy} \approx 0$ when $R$ approaches its maximum value, which can be identified as charge neutrality point (CNP). The variation of the gate voltage changes the charge carrier content in the quantum wells, driving them from n-type conductor to p-type conductor via an QHSI state.

The thermally activated behaviour of the resistance above 25 K corresponds to a gap of 17 meV between conduction and valence bands in the HgTe well. Recent theoretical calculations based on the effective $6 \times 6$ matrix Hamiltonian predicted the gap $\approx 30\text{meV}$ for 8 nm HgTe wells with a [013] interface. The mobility gap can be smaller than the energy gap due to disorder. It is worth noting that the disorder parameter, which can reduce the energy gap in QHSI, is rather related to the random deviations of the HgTe quantum well thickness from its average value, then to the random potential due to charged impurities. The saturation of the resistance at low temperature is completely unexpected, because the electrons are in the supposedly strongly localized regime, where the electrical resistivity of the system is two orders of magnitude greater than the resistance quantum $h/2e^2$.

Figure 3a shows the resistance of device B as a function of the inverse temperature. The data above 25 K is nicely fitted with the activation dependence, however the activation gap is 2 times larger than in device A. We attribute the larger value of $\Delta$ to the better quality of the sample. For example, figure 1 shows that the resistivity peak in device B is narrower, and it could be argued that the disorder in this sample is considerably smaller. In order to prevent overheating effects by the applied current we study the current dependence of the resistance. The resistance does not change very much with the current when the current is varied by three orders of magnitude. However, it does not depend on T. The tendency of increasing with the temperature decreasing, however, it does not show any significant temperature dependence in the temperature interval (4K -0.3 K). This behavior is also inconsistent with what is expected for Anderson localization, Fermi liquid or Luttinger liquid models.

In figure 4 we present the T dependence of the resistance in device A. We see that the resistance exhibits the tendency of increasing with the temperature decreasing, however, it does not show any significant temperature dependence in the temperature interval (4K -0.3 K). This behavior is also inconsistent with what is expected for Anderson localization, Fermi liquid or Luttinger liquid models.
FIG. 4: (Color online) The resistance $R$ of the sample A as a function of the temperature at the charge neutrality point ($V_g - V_{CNP} = 0$) measured from various voltage probes in the temperature interval 4-0.3 K, $I = 10^{-9}$ A. The top panel shows a schematic view of the sample.

III. DISCUSSION

In the rest of the paper we will focus on the several possible models that can explain the deviation of the resistance from the expected quantized value. The first one describes the helical edge liquid state interacting with a single quantum impurity\(^{19}\). The spatially inhomogeneous electrostatic potential leads to a bound state which traps an odd number of electrons and forms a magnetic-like impurity. For a large Luttinger parameter $K > 1/4$ corresponding to a weak electron-electron interaction the conductance is suppressed at low but finite temperatures and is restored again to a quantized value for $T \to 0$. For a strong interaction which corresponds to a small Luttinger parameter $K < 1/4$ the system becomes a LL insulator, and conductance scales with the temperature as $G(T) \propto T^{2(1/4K - 1)}$. Note, however, that for samples with a top gate parameter $K$ can be estimated from the expression given in\(^{10}\). In particular, for our samples we obtain $K \approx 0.6$, which corresponds to a weak coupling regime.

The second model relies on the localization of electrons due to the fluctuations of the Rashba spin-orbit interaction caused by charge inhomogeneity in the presence of the e-e interactions\(^{20}\). The localization length strongly depends on the Luttinger parameter $K$ and can exceed 10 $\mu$m for $K > 0.35$. Note, however, that the suppression of the conductivity due to localization leads to an exponential dependence on the temperature. Moreover, Rashba-induced localization model predicts strong dependence on the sample length which disagrees with our observations.

In conclusion, we find that even in an apparently strongly localized regime, where the resistance of a HgT quantum well is two orders of magnitude greater than the resistance quantum $\hbar/2e^2$, the resistance of the 2DTI is independent of temperature indicating the absence of an insulating phase. The existing theoretical models do not seem to explain neither such strong deviation from the quantized value nor the absence of the temperature dependence.

IV. ACKNOWLEDGMENTS

We thank M. Feigelman for helpful discussions. A financial support of this work by FAPESP, CNPq (Brazilian agencies), RFBI grant N 12-02-00054-a and RAS program "Fundamental researches in nanotechnology and nanomaterials".

\(^{1}\) C. L. Kane and E. J. Mele, Phys. Rev. Lett. 95, 146802 (2005).
\(^{2}\) B. A. Bernevig, T. L. Hughes, and S. C. Zhang, Science 314, 1757 (2006).
\(^{3}\) J. Maciejko, T. L. Hughes, and S-C Zhang, Annu. Rev. Condens. Matter Phys. 2, 31 (2011).
\(^{4}\) M. König et al, Science 318, 766 (2007).
\(^{5}\) H. Buhmann, Journal. Appl.Phys., 109, 102409 (2011).
\(^{6}\) C. Xu and J. E. Moore, Phys. Rev. B, 73, 045322 (2006).
\(^{7}\) C. Wu, B. A. Bernevig, and S. Zhang, Phys. Rev. Lett., 96, 106401 (2006).
\(^{8}\) J. C. Y. Teo and C. L. Kane, Phys. Rev. B, 79, 235321 (2009).
\(^{9}\) J. Voit, Rep. Prog. Phys. 57 977, (1994).
\(^{10}\) C. L. Kane and M. P. A. Fisher, Phys. Rev. B 46, 15233 (1992); C. L. Kane and M. P. A. Fisher, Phys. Rev. Lett. 68, 1220 (1992).
\(^{11}\) I. V. Gornyi, A. D. Mirlin, and D. G. Polyakov, Phys. Rev. Lett. 95, 206603 (2005); I. V. Gornyi, A. D. Mirlin, and D. G. Polyakov, Phys. Rev. B 75, 085421 (2007).
\(^{12}\) H. T. Man and A. F. Morpurgo, Phys. Rev. Lett. 95, 026801 (2005).
13 M. Auslaender, A. Yacoby, R. de Picciotto, K. W. Baldwin, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. 84, 1764 (2000); Science 295, 825 (2002);
14 M. Bell, A. Sergeev, J. P. Bird, V. Mitin, and A. Verevkin, Phys. Rev. Lett. 104, 046805 (2010).
15 E. Levy, I. Sternfeld, M. Eshkol, M. Karpovski, B. Dwir, A. Rudra, E. Kapon, Y. Oreg, and A. Palevski, H. T. Man and A. F. Morpurgo, Phys. Rev. B 85, 045315 (2012).
16 G. M. Gusev, Z. D. Kvon, O. A. Shegai, N. N. Mikhailov, S. A. Dvoretsky and J. C. Portal, Phys. Rev. B 84, 121202(R), (2011).
17 Thomas L. Schmidt, Stephan Rachel, Felix von Oppen, and Leonid I. Glazman, Phys. Rev. Lett. 108, 156402, (2012).
18 Francois Crepin, Jan Car Budich, Fabrizio Dolcini, Patrick Recher, and Bjorn Trauzettel, Phys. Rev. B 86, 121106(R), (2012).
19 J. Maciejko, C. X. Liu, Y. Oreg, X. L. Qi, C. Wu, and S. C. Zhang, Phys. Rev. Lett. 102, 256803 (2009).
20 A. Ström, H. Johannesson, G. I. Japaridze, Phys. Rev. Lett. 104, 256804 (2010).
21 Z. D. Kvon, E. B. Olshanetsky, D. A. Kozlov, et al., Pis’ma Zh. Eksp. Teor. Fiz. 87, 588 (2008) [JETP Lett. 87, 502 (2008)].
22 E. B. Olshanetsky, Z. D. Kvon, N. N. Mikhailov, E.G. Novik, I. O. Parm, and S. A. Dvoretsky, Solid State Commun. 152, 265 (2012).
23 G. M. Gusev et al, Phys. Rev. Lett. 104, 166401, (2010); G. M. Gusev et al, Phys. Rev. Lett. 108, 226804, (2012).
24 O. E. Raichev, Phys. Rev.B 85, 045310 (2012).
25 G. Tkachov, C. Thienel, V. Pinneker, B. Buttner, C. Brune, H. Buhmann, L.W. Molenkamp, and E. M. Hankiewicz, Phys. Rev. Lett. 106, 076802, (2011).