Institute of Solid State Physics Russian Academy of Sciences

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Electronic transport, localization and charge transfer statistics in quasi-one-dimensional conductors

PhD Dissertation Summary

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DISSERTATION TOPIC

One of the key goals in modern condensed matter physics is finding the materials with new electronic properties. With the appearance of material classification from topological principles, the list of known material classes (semiconductors and metals, differing in terms of band structure, and superconducting, magnetic and some other materials with ordering mechanisms) has been expanded by topological material classes with new physical properties.

Topological insulators are a promising class of materials with an insulating bulk and special electronic states on the surface, characterized by a linear gapless spectrum and absolute spin polarization [6, 9]. The experimental realization of such a material opens wide possibilities for the implementation of superconductors and Josephson junctions with non-trivial pairing [2, 8], observation of Majorana modes [1, 5] and spintronics [3, 4]. At the same time, despite the optimistic progress of experimental and theoretical studies in this area, some key properties of topological insulators are still not completely understood, which may raise doubts in the correspondence of these topological insulator realizations to the proposed model.

The main concerns are connected to the topological protection - the phenomenon, that should ensure the ballistic electron transport when no spin-flipping disorder is present. Experiments demonstrate, that in real systems the electrons do backscatter, and the ballistic transport is observed only for the shortest samples [7], with a poor quantization. Namely this fact is a significant obstacle to the practical realization of the potential benefits, which distinguish the topological insulators from the other materials. Despite the widespread interest in the scientific community, at the moment there is no consensus present, regarding the microscopic properties of electron transport and scattering in the edges, the nature of edge conductance and the realization of topological protection.

Two-dimensional topological insulators based on mercury telluride quantum wells (HgTe / CdHgTe) are the first and certainly the most studied material belonging to this group. Considering that the other materials, that are proposed as two-dimensional topological insulators, do not demonstrate any significant advantages (see section 1.2) in the observed electron transport properties, the study of this material as a one with the most developed manufacturing technology seems to be the most appropriate choice for the purpose of solving fundamental problems of topological insulator physics.

The main goal of this dissertation is to study the edge conduction in mercury telluride quantum wells to obtain the evidence that either is supporting or is in disagreement with the helical origin of edge electron states. To achieve this goal the following **objectives** were considered:

1. The effect of magnetic field on the edge conductance of HgTe/CdHgTe quantum wells was studied at low temperatures in a dilution refrigerator.

2. The conductance and non-equilibrium electron noise of the $p-n$ junctions formed at the gate boundary of 14 nm HgTe/CdHgTe quantum wells were investigated.

3. A study of non-equilibrium electron noise in the long resistive (with a resistance exceeding

the quantum h/e^2) edges of the HgTe/CdHgTe quantum wells was performed at various cryogenic temperatures and in a magnetic field.

4. A sensor based on an elastic diffusion nanowire probe was considered, which makes possible the measurements of the local electron energy distribution function and is promising in the context of studying electron scattering in the edge states of a two-dimensional topological insulator. The operation of such a sensor was experimentally studied on a model system.

The theoretical significance of the obtained results is due to the new information on the properties of electron transport in quantum wells of mercury telluride. This information is critical for answering the fundamental question of whether this system is a realization of the concept of a two-dimensional topological insulator, as well as the question of an unknown effective scattering mechanism that violates the topological protection. These issues have been causing significant interest in the scientific community over the past years, which is discussed in detail in chapter 1.

Considering **the practical significance**, the extreme sensitivity of the edge states of two-dimensional topological insulators to the magnetic field can be used to create sensors/devices that operate based on this property. Measurements of the distribution function using electronic noise are a powerful experimental technique for studying nonequilibrium electronic systems, which can expand the capabilities of experimental physics in studying various thermoelectric and optoelectronic systems.

The reliability of the results is confirmed by their comparison with the existing theoretical predictions, as well as the correspondence of the measurement results on several different samples (in chapters 3.4).

KEY RESULTS AND CONCLUSIONS

Key aspects to be defended:

1. It has been demonstrated for the first time that in 14 nm and 8.3 nm wide HgTe quantum wells in the edge conduction mode and at 50 mK temperature, the application of a small external magnetic field around 50 mT causes a sharp increase in resistance up to 10^3 times both for edges with the initial resistance (without a magnetic field) equal to h/e^2, and for edges with higher initial resistance. The resistance increase is accompanied by the appearance of reproducible mesoscopic fluctuations and a pronounced activation temperature dependence, in contrast to a weak temperature dependence in zero field. Additionally, when applying a magnetic field, a non-linear current-voltage characteristic is observed with a transport gap reaching 1 mV, where the current does not exceed 1 pA. This behavior can be explained by the Anderson localization of the helical edge states due to the processes of coherent backscattering arising in the magnetic field.

2. In 14 nm wide HgTe quantum wells, when the p type conductivity is archived under the gate, $p-n$ junctions with resistance close to $h/2e^2$ are formed, which have linear current-voltage

characteristics. The studies of electron noise in such $p-n$ junctions have been performed for the first time. Via variation of an unknown hole-phonon heat coupling parameter, the observed non-equilibrium noise can be fully explained by the overheating of the resistive leads of the sample structure, without any shot noise of the $p-n$ junction. This data is in agreement with the model of electronic transport in such $p-n$ junction by two ballistic helical edge channels on the junction sides.

3. For the first time, the studies of electronic noise in HgTe quantum wells in the edge transport mode have been performed at temperatures below 0.5 K. In the long edges, when applying electric current I, a shot noise with a Fano factor (the relation of noise spectral density to the Poisson value $2eI$) of $0.1 < F < 0.3$ is observed. The Fano factor grows with the temperature decrease. This data unambiguously indicate an incoherent mode of electron transport and can be compared with the existing models of electron scattering in helical edge states.

4. It has for the first time been demonstrated experimentally that the measurements of electronic noise as a function of voltage from one of the terminals of an elastic diffusive conductor can be directly converted to the electron energy distribution function at the second terminal of this conductor. This approach works both in the case of equilibrium and in the case of non-equilibrium electron distribution at the second terminal. In the present experiment, the distribution function in the studied metal strip corresponds to the local thermodynamic equilibrium.

Authors personal contribution to the aspects to be defended consists in performing all the experimental measurements presented in this paper, developing a methodology for measuring samples with high resistance, interpreting and processing the experimental results, and the mathematical modeling described in chapter 4. This work was performed by the author in the Laboratory of Electronic Kinetics of ISSP RAS in the period from 2015 to 2020.

PUBLICATIONS AND APPROBATION OF RESEARCH

The main author - Stanislau Uladzimiravich Piatrusha, except for the Nanotechnology 2020 paper.

First-tier publications

1. Piatrusha, S. U. *et al.* Edge states in lateral $p-n$ junctions in inverted-band HgTe quantum wells. *Phys. Rev. B* **96**, 245417 (2017). doi: `10.1103/PhysRevB.96.245417`.
2. Piatrusha, S. U. *et al.* Topological Protection Brought to Light by the Time-Reversal Symmetry Breaking. *Phys. Rev. Lett.* **123**, 056801 (2019). doi: `10.1103/PhysRevLett.123.056801`.
3. Denisov, A. O. *et al.* Strategy for accurate thermal biasing at the nanoscale. *Nanotechnology* **31**, 324004 (2020). doi: `10.1088/1361-6528/ab8c74`.

Second-tier publications

4. Piatrusha, S. U. *et al.* Noise Insights into Electronic Transport. *JETP Letters* **108**, 71–83 (2018). doi: `10.1134/s0021364018130039`.

Other publications

5. Piatrusha, S. U. & Khrapai, V. S. Measuring electron energy distribution by current fluctuations. *2017 International Conference on Noise and Fluctuations (ICNF)* 1–4 (2017). doi: `10.1109/ICNF.2017.7985929`.

Reports at conferences and seminars

The main results of this dissertation were reported by the author at the following conferences: XXI Ural International Winter School on the Physics of Semiconductors (Yekaterinburg, Russian Federation, February 2016), International Workshop Localization, Interactions and Superconductivity (Chernogolovka, Russian Federation, June-July 2016), 7th Russian conference for young scientists "Micro-, nanotechnologies and their application" named after Yu. V. Dubrovsky (Chernogolovka, Russian Federation, February 2017), 24th International Conference on Noise and Fluctuations (Vilnius, Lithuania, June 2017), XVI School-conference for young scientists ""Problems of solid state physics and high pressure physics" (Sochi, Russian Federation, September 2017), 34th International Conference on the Physics of Semiconductors (Montpellier, France, July-August 2018), XII Conference «Condensed matter physics and new generation materials» (Troitsk, Russian Federation, December 2018), XXIII International Symposium “Nanophysics and Nanoelectronics” (Nizhny Novgorod, Russian Federation, March 2019), 54th Rencontres de Moriond (La Thuile, Italy, March 2019), Interaction between Radiation and Quantum matter (Moscow, Russian Federation, July 2019), Conference on Spins in a Quantum 1D Multi-particle Environment: from Exotic Phases and Non-trivial Topology to Protected Transport (Munich, Germany, September 2019), XIV Russian conference on physics of semiconductors (Novosibirsk, September 2019), XVIII School-conference for young scientists "Problems of solid state physics and high pressure physics" (Sochi, Russian Federation, September 2019), Seminars on low temperature physics in ISSP RAS.

CONTENTS

This dissertation contains an introduction, six main chapters and a conclusion. The total length of dissertation is 94 pages with 39 figures and one table. The reference list contains 166 items.

In the **introduction** the confirmation of the dissertation topic relevance is given, the goals of the study and the aspects to be defended are formulated, the structure of the work is described, and also an author publications list on the dissertation topic is given

In **chapter 1** the review of experimental and theoretical studies concerning the HgTe/CdHgTe quantum wells and other two-dimensional topological insulators is provided.

In **chapter 2** the basic methods of experimental study and the process of data processing is described. Some information on the sample structure and fabrication process is also located here.

Chapter 3 is dedicated to the transport measurements of the edge transport in HgTe/CdHgTe quantum wells in external magnetic field. The observed behavior suggests the transition to an insulating state when the magnetic field is applied. Such behavior is expected from theoretical studies due to the breakdown of the topological protection mechanism in two-dimensional topological insulators is violated.

In **chapter 4** the experimental study of the conductivity and current noise of p-n junctions in HgTe/CdHgTe quantum wells is presented. The conduction of short edge channels shunting the depletion region is expected to dominate in electron transport through such junctions, which is confirmed here by the measurements of resistance and current noise.

In **chapter 5** the shot noise measurements in edge transport of HgTe/CdHgTe quantum wells is reported. The obtained results are compared with the existing models of helical electron scattering in two-dimensional topological insulators. A reasonable agreement with the phenomenological model of 1D-diffusion is present.

Chapter 6 describes a method of determining the local energy distribution function of electrons via measuring the electronic noise. This is the first experimental implementation of such technique. The wide possibilities for measuring nonequilibrium electronic systems, in particular the study of the boundary conductivity of two-dimensional topological insulators, are opened by this method.

The conclusion contains the list of main results of this dissertation.

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