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CONTROL OF CHARGE AND HEAT IN NANOSCALE QUASI-1D CONDUCTORS

PhD Dissertation Summary

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DISSERTATION TOPIC

One of the most promising research directions of modern condensed matter physics is the investigation of the topological aspects of electronic band theory. Unlike the classical Bloch theory of crystals, here, the interconnection of the spin and spatial degrees of freedom originating from strong spin-orbit interaction plays the central role. It turns out that this relationship takes place in entire classes of new materials, for example, in topological insulators.[1,2] In these materials, tuning of the Fermi level in the bulk energy gap does not lead to vanishing of electrical conductivity due to the presence of gapless helical states. These states emerge on the boundary between topological and trivial insulators (surface in the three-dimensional case or edge in the two-dimensional case), and the spin and the momentum of such states are rigidly locked.

A fundamental property of the helical states is the complete backscattering suppression, which has a purely quantum origin and is also called topological protection. The most impressive manifestation of topologically protected states occurs in a one-dimensional case. They provide ballistic transfer of a spin-polarized electric current along the edge of a quantum spin Hall insulator.[3] In addition to the edge states of the spin Hall insulator, helical states can also be realized in pure semiconductor nanowires with strong spin-orbit interaction placed into a high parallel to a nanowire magnetic field.[4]

The helical states are of great interest, particularly due to predictions for Majorana zero modes (MZMs) emergence valuable for fault-tolerant quantum computing. Among several proposals for MZM implementations in the real systems, proximitized semiconducting nanowires with strong spin-orbit coupling and topological insulator-superconductor hybrids got the most attention from the scientific community. Nowadays, still, there is no unambiguous observation of all signatures of Majorana zero modes in a single experiment. Thus, the experimental research in this area mainly focuses on the fabrication advances to obtain better devices (mostly growth techniques) and on the novel detection schemes for topological phase transition.

This work is dedicated to the most widespread materials used in Majorana research: topological insulators and proximitized nanowires. There was no goal to observe signatures of MZM in the experiment but to investigate the electronic transport in the helical edges and to implement a new measurement technique in the semiconductor-superconductor hybrid structures. A significant part of this work is dedicated to the development of fabrication techniques for delicate materials.

Aims and objectives

1. Development and tuning of fabrication routine for devices based on HgTe QWs, investigation of the different processing steps influence onto properties of a 2D electron gas. Measurement of the typical conductance against the magnetic field at the charge neutrality point to estimate Luttinger liquid constant, K.

2. Analytical derivation for the current noise spectral density in NSN-devices based on a diffusive nanowire with either grounded central superconducting terminal or floating superconducting island. Calculation of superconducting gap suppression in the floating island geometry due to nonequilibrium electronic energy distribution (EED). Fabrication of InAs NW based devices with central superconducting terminal and normal contacts on both sides.

3. Development of delicate lithographic technique and its basis – water-soluble resist. Investigation of developer properties influence on the development procedure, proof of chelation-dissolution mechanism. Tailoring of lithographic parameters to obtain 100 nm-wide lifted-off metal individual lines.

KEY RESULTS

Key aspects to be defended:

1. For the first time, localization of 2D TI edges of 8 nm HgTe QW was demonstrated at millikelvin temperatures in the absence of an external magnetic field. The behavior of typical conductance at the charge neutrality point suggests Luttinger liquid constant $K \approx 0.8$-0.9, which on its own theoretically does not explain the observed localization. Current noise measurements revealed the Fano factor $F \approx 0.5$-0.7, greater than values for diffusive conductors even with strong electron-electron scattering. The latter can point to the disordered nature of the electronic transport through the edge and be the signature of upcoming localization, but still, the main scattering mechanism is unclear.

2. The expressions for local and nonlocal shot noise are obtained analytically for NSN diffusive devices with either grounded central superconducting terminal or floating superconducting island. It is demonstrated that the thermal conductance of the proximitized nanowire segment can be extracted from the nonlocal current noise slope $\partial S/\partial V$. In the layout with the floating superconducting island, the nonequilibrium EED suppresses the superconducting gap for the arbitrary asymmetry between normal nanowire segments, which manifests itself in two stable branches of $\Delta(V)$. Experimentally nonlocal shot noise is measured in InAs NSN devices, and its subgap values can be fitted with a single parameter – thermal conductance. The average charge of a transmitted through proximitized segment quasiparticle is estimated from above using both nonlocal shot noise and nonlocal conductance.

3. Genuine water-based lithographic technique was developed and employed to fabricate devices based on delicate materials. The main lithographic processing liquids are a chitosan derivative (resist), an aqueous solution of transition metal salt (developer), and a solution of a weak acid (remover). The chelation-dissolution competition allows achieving residue-free development and lift-off capability. The best obtained sensitivity is $\approx 130\,\mu C/cm^2$

(at 50 kV accelerating voltage), the narrowest individual metal line obtained via lift-off is 100 nm-wide. This lithographic approach was successfully utilized to fabricate carbon nanotube, organic semiconductor, and porcine brain microtubule-based devices.

Author's personal contribution to the aspects to be defended

Author fabricated most of the samples studied in this work, including cleanroom activity, engineering of fabrication techniques for particular samples and development of complete fabrication routines. Significant part of electronic transport measurements presented in this thesis were performed by the author, including measurements of shot noise and shot noise spectra. Theoretical semiclassical treatment of the NSN devices from Chapter 5 were performed analytically and numerically. This work was performed by the author in the Laboratory of Nanomaterials, Skoltech; Laboratory of Electronic Kinetics, ISSP RAS; and Shared Facilities Center, MIPT in the period from 2017 to 2021.

PUBLICATIONS AND APPROBATION OF RESEARCH

The main author or equally contributed authors are printed in bold in the following list of publications.

First-tier publications

1. **Bubis, A. V.,** Mikhailov, N. N., Dvoretsky, S. A., Nasibulin, A. G. & Tikhonov, E. S. Localization of Helical Edge States in the Absence of External Magnetic Field. *Phys. Rev. B* **104,** 195405 (2021)

2. **Bubis, A. V.,** Shpagina, E. V., Nasibulin, A. G. & Khrapai, V. S. Thermal Conductance and Nonequilibrium Superconductivity in a Diffusive NSN Wire Probed by Shot Noise. *Phys. Rev. B* **104,** 125409 (2021)

3. **Denisov, A. O.,** Bubis, A. V., Piatrusha, S. U., *et al.* Charge-Neutral Nonlocal Response in Superconductor-InAs Nanowire Hybrid Devices. *Semicond. Sci. Technol.* **36,** 09LT04 (2021)

4. **Grebenko, A., Bubis, A.,** Motovilov, K., *et al.* Green Lithography for Delicate Materials. *Adv. Funct. Mater.* **31,** 2101533 (2021)

Other publications

1. **Denisov, A. O.,** Bubis, A. V., Piatrusha, S. U., *et al.* Heat-Mode Excitation in a Proximity Superconductor. arXiv: `2006.09803 [cond-mat]` (2020)

Reports at conferences and seminars

This work results were reported on the following conferences: Interaction between Radiation and Quantum devices (November 2020, Moscow), XXV Symposium "Nanophysics and Nanoelectronics" (March 2021, Nizhny Novgorod).

CONTENTS

This dissertation contains an introduction, three main chapters and a conclusion. The total length of dissertation is 83 pages with 45 figures and one table. The reference list contains 152 items.

- Chapter 2 is dedicated to description of fabrication and measurement used in this study. The implementation of lithographic methods for fabrication of HgTe quantum wells (QW) and InAs nanowires (NW) based devices is discussed in detail. Also shot noise and noise spectrum measurement procedure is described thoroughly.

- Chapter 3 is devoted to the advanced lithographic technique developed for delicate objects. It is proposed to utilize chitosan derivatives (CD) – bio-inspired and water-soluble polysaccharides as an e-beam and deep-ultraviolet resist. CD exhibits molecular scissoring under irradiation, similar to commonly used poly(methyl methacrylate) (PMMA). In the proposed technology, the key feature is the chelation reaction, which allowed achieving clean enough development and, thus, lift-off capability while keeping the fabrication routine gentle and water-based.

- Chapter 4 is devoted to the first and well-studied 2D topological insulator, HgTe QW. Its bulk gap is quite large, $\approx 30\,\text{meV}$, so the temperature of $4.2\,\text{K}$ (liquid He) is already sufficient to get rid of bulk conduction, provided the Fermi level is tuned to the bulk gap. Of great interest is the main ingredient of topological protection – time-reversal symmetry (TRS), which protects the helical edges from a single particle backscattering. If TRS is broken, e.g., by an external magnetic field, the helical edges localize due to disorder. This work demonstrates that these edges can localize at low enough temperature even without an external magnetic field. Theoretically, several scenarios are known for such behavior, and in this chapter, they are discussed in view of the experimental observations.

- In Chapter 5 the alternative scheme for detecting topological phase transition is discussed using the example of hybrid semiconductor-superconductor structures based on InAs nanowires. The idea is to measure the heat conductance of the proximitized segment of a nanowire, which acquires a universal value at the point of topological phase transition. Although studied devices cannot exhibit topological phase, they serve as a minimal toy model to study the heat transport in proximitized nanowires. Using the semiclassical approach, it is demonstrated that heat conductance in such devices can be obtained from

nonlocal shot noise measurement, which is possible thanks to the charge-heat separation occurring at the normal metal-superconductor (NS) interface.

Bibliography

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2. Qi, X.-L. & Zhang, S.-C. Topological Insulators and Superconductors. *Rev. Mod. Phys.* **83,** 1057–1110 (2011).
3. König, M. *et al.* Quantum Spin Hall Insulator State in HgTe Quantum Wells. *Science* **318,** 766–770 (2007).
4. Alicea, J. New Directions in the Pursuit of Majorana Fermions in Solid State Systems. *Rep. Prog. Phys.* **75,** 076501 (2012).