

The project concerns theoretical description of the properties of hybrid nanostructures—devices with dimensions of tenths or hundreds of nanometers, which are constructed by combining semiconductor and superconducting materials. These structures can be used to construct novel topological phases of matter (the discovery of topological phases of matter was awarded the Nobel Prize in 2016). In particular, they can realize the topological superconductivity phase in which exist exotic quasiparticles, which are their own antiparticles and which have long been sought among elementary particles—Majorana fermions. In the last decade, hybrid structures have aroused exceptional interest, which is motivated on the one hand by the implementation of topologically protected quantum computing (Majorana states can be used to store quantum information resistant to external noise), but also by the fundamental attractiveness of the structures themselves—non-trivial phases of matter and the resulting unique quasiparticle states, that are possible to be realized in these structures are very often impossible to be achieved in bulk materials.

As part of our research work, we will study topological superconductivity in systems that have only become available in recent years—planar Josephson junctions—flakes of semiconducting material containing two-dimensional electron gas connected to superconducting contacts. We will explain how topological states at the system edges interact with trivial boundary states that may arise due to the electrostatic potential distribution or those induced by a magnetic field. Structures of this type will be built and tested experimentally in the group of our foreign partner. Our modeling will precede the experimental work by exploring physical phenomena that can be demonstrated in the experiment. In particular, we will examine the unprecedented possibility of visualizing the paths along which charge carriers carry superconducting current (the current that flows when the material has no resistance) flow in a hybrid structure. The project will also address recent and so far unexplained current measurements in nanowires connected to superconducting contacts, resulting from multiple conversion of quasiparticles in the normal part to Cooper pairs in the superconductor. This analysis will be used to determine the properties of the semiconductor-superconductor interface.

In small semiconductor islands, electron-electron repulsion determines the electronic structure in a similar way as in natural atoms. The situation becomes more complex when such an island is connected to a superconductor that can naturally combine two electrons into a Cooper pair. As part of our project, we will describe this phenomenon and explain the influence of electron-electron interactions on the possibility of creating of Majorana states located at the edges of the structure. In addition, we will present a realistic description of superconducting quantum information carriers—qubits—implemented on hybrid nanostructures. In recent years, superconducting qubit circuits have allowed the construction of working quantum processors. Nevertheless, the need to scale the number of quantum gates results in the desire to create better controlled and better protected qubits. Our research will result in determining the properties of such structures made of superconducting hybrids, in which quantum information is stored in the excitation of a quantum oscillator built on a superconductor-semiconductor-superconductor junction.

The successful implementation of the project will be ensured by the appointment of a new research team and the use of the state-of-the-art computational methods for quantum transport. The theoretical description of superconducting hybrid devices that will be developed within the project will not only provide theoretical predictions to guide upcoming experiments and explain the so far elusive measurements, but also provide a theoretical basis for understanding the complex relationship between effects appearing in semiconductors and superconductors in nano-scale.