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PhD Thesis booklet

Spin-orbit interaction and superconductivity in InAs nanowire-based quantum dot devices

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Introduction

The recent decade brought an explosion in the research field of quantum computation due to the progress on experimental platforms and invention of novel concepts like topological protected architectures. Quasiparticles with exotic statistics like Majorana fermions or parafermions are promising building blocks of such topological hardwares. The realization of such particles requires the interplay of superconductivity, spin-orbit interaction, the tunability of the chemical potential, and in certain proposals magnetic field as well.

InAs nanowires provide a promising platform to host those exotic particles due to the presence of strong spin-orbit interaction, the ability to form transparent contacts to superconductors and to change the electron density by electrical gating.

Objectives

In my thesis I have investigated various InAs nanowire based hybrid devices in order to explore spin-orbit interaction-, superconductivity- and topology-related phenomena. For the realization of the exotic topological states it is important to quantify the strength and the character of the spin-orbit interaction, the role of the superconductivity generated non-local couplings (like crossed Andreev reflection), their relative strength and tunability. The experimental and theoretical works presented in my thesis contributes to the understanding of these questions.

Thesis points

1. Based on topological considerations it is shown that degeneracy points almost always exist in the magnetic spectrum of a coupled spin system. The necessary condition is that the total topological charge associated with the system is non-zero. For general parameters the degeneracies are localized to discrete points in the magnetic field space, which are named magnetic Weyl points using their analogy with the band degeneracies of Weyl semimetals. I implemented a coupled two-spin system in a spin-orbit coupled double quantum dot, defined in an InAs nanowire. I demonstrated the presence of the magnetic Weyl points in the magnetic spectrum of the double dot by electrical transport measurements. I compared the experimental findings with a two-site Hubbard model of the double quantum dot and I found a good, quantitative agreement. Furthermore, I carried out a numerical analysis using the Hubbard model with random parameters to determine the possible degeneracy configurations, besides the fine tuned cases I identified two possible scenarios with

2 and 6 Weyl points. I pointed out that the configuration with 6 Weyl points is inconsistent with the Rashba model of the spin-orbit interaction frequently used to describe nanowires. [1]

2. I fabricated multi-gated devices from InAs nanowires, in which the electron density and the electric field across the nanowire are independently tunable by the gate voltages. I investigated the weak antilocalization effect by low temperature magnetocunductance measurements, which is a widely used tool to study the spin relaxation mechanisms in nanoelectronic devices. Performing the measurements at different gate voltage configurations I showed that spin relaxation length is considerably reduced when an electric field is applied across the nanowire. Assuming that the spin relaxation is dominated by the spin-orbit interaction, the experiments imply the increased strength of the spin-orbit interaction, in accordance with the external electric field induced Rashba picture. I constructed the framework of an electrostatic model that is capable to simulate the experiments. The sole fitting parameter of the model was the strength of the built-in – independent of the external electric field – spin-orbit interaction. Despite of the simplicity of the model I found a good agreement with the experiments, which supports my claim that the spin-orbit interaction is indeed tuned by the external electric fields across the nanowire. [2]

3. I investigated the spatial extension of a Shiba state formed in a superconductor – quantum dot hybrid structure by electrical transport measurements. I found a significant current enhancement in the tunnel coupled probe electrode placed $50-250$ nm away from the quantum dot when the Shiba state was tuned to zero energy. The presence of the current enhancement implies that the Shiba state extends to such large distances into the superconductor, in contrast to STM measurements, where the Shiba state was observed up to 10 nm. I explained the larger extension of the Shiba state by the geometrical properties of the device: the setup is effectively one dimensional, since the distance of the tunnel probe and the quantum dot is comparable to the diameter of the nanowire. I explored the effect of the magnetic field on the conductance enhancement. I found a large, an order of magnitude enhancement in the non-local signal, indicating the increase of the extension of the Shiba state in magnetic field. This is consistent with the expectations that the Shiba state is localized on the length scale of the magnetic field-dependent superconducting coherence length. Experimental findings were compared with NRG simulations and reasonable agreement was found. [3]

4. I proposed an experimental scheme that is capable to prove the spin singlet character of individual split Cooper pairs in a quantum dot – supercon-

ductor – quantum dot setup using the spin qubit tool kit. Two spins of single electrons localized in the quantum dots serve as detectors. The spin states are prepared by electrically driven spin resonance pulses in finite magnetic field. Following the initialization a Cooper pair is tried to be extracted from the superconductor to the dots by a gate sweep. The success of the extraction, which depends on the initialized spin states of the detector and the spin state of the split Cooper pair, is determined by the measurement of the charge on the dots. I analyzed the performance of the scheme in the presence of hyperfine interaction, anisotropic g-tensors of the quantum dots, different timing of the pulses and gate sweep speed. I showed that all of these effect can decrease the fidelity of the proposed detection scheme, but the latter three can be overcame by the suitable designing of the experiment. However, materials with weak hyperfine effect is required perform a reliable experiment. [4]

5. I investigated the so-called Andreev-molecule setup (quantum dot – superconductor – quantum dot) in the large superconducting gap limit to understand the effect of different hybridization mechanisms like: crossed Andreev reflection, elastic cotunneling and interdot tunneling, and their signatures on the measurable quantities. I showed that the elastic cotunneling, which is either completely neglected or merged into the direct interdot tunneling term in the literature, can be energy-dependent and has to be distinguished from the other coupling mechanisms. Using different coupling strengths I have calculated the phase diagram of the setup, the ground state occupation of the dots. I demonstrated that these provide enough information to distinguish the superconductivity-related coupling mechanisms from the interdot tunneling. I introduced additional normal leads in the model, coupled to the quantum dots, that allow to study the transport properties of the system. I calculated the finite bias transport spectrum of the setup, and obtained the following results. I demonstrated how the non-local coupling mechanisms hybridize the local Andreev bound states of the dots to the extended Andreev molecular state. I have showed that the finite bias signatures of the Andreev molecule allows for the determination of the dominant coupling mechanism. Furthermore, I have argued that the triplet blockade effect – which is usually attributed to the interplay of crossed Andreev coupling and the spin incompatibility of a triplet electron pair with the spin singlet Cooper pairs – is present in the transport even in the absence of non-local couplings. In addition, any of the non-local coupling mechanisms reveals the blockade effect by the appearance of negative differential conductance lines. [5]

List of related publications

[1] **Z. Scherübl**, A. Pályi, Gy. Frank, I. Lukács, G. Fülöp, B. Fülöp, J. Nygård, K. Watanabe, T. Taniguchi, G. Zaránd, Sz. Csonka: *Observation of spin-orbit coupling induced Weyl points and topologically protected Kondo effect in a two-electron double quantum dot*, Nat. Comms. Phys. **2**, 108 (2019)

[2] **Z. Scherübl**, G. Fülöp, M. H. Madsen, J. Nygård, Sz. Csonka: *Electrical tuning of Rashba spin-orbit interaction in multigated InAs nanowires*, Phys. Rev. B **94**, 035444 (2016)

[3] **Z. Scherübl**, G. Fülöp, C. P. Moca, J. Gramich, A. Baumgartner, P. Makk, T. Elalaily, C. Schönenberger, J. Nygård, G. Zaránd, Sz. Csonka: *Large spatial extension of the zero-energy Yu-Shiba-Rusinov state in magnetic field*, ArXiv:1910.02831, submitted Nature Communications (with referees)

[4] **Z. Scherübl**, A. Pályi, Sz. Csonka: *Probing individual split Cooper-pairs using the spin qubit toolkit*, Phys. Rev. B **89**, 205439 (2014)

[5] **Z. Scherübl**, A. Pályi, Sz. Csonka: *Transport signatures of an Andreev molecule in a quantum dot – superconductor – quantum dot setup*, Beilstein J. Nanotechnol. 2019, **10**, 363-378 (2019)