Final Report

SuperTop - Topologically protected states in double nanowire superconductor hybrids NN-127900

I. Introduction

In quantum computational architecture unwanted decoherence constitutes a major challenge. There are strategies to handle decoherence, like performing the operations fast within the coherence time or using quantum feedback, but their application and scaling run into further limitations. The emerging field of topological quantum computing (TQC) holds a remarkable promise to overcome this serious issue, since the built-in topological protection of the system allows decoherence-free quantum operations. The theory of TQC progressed very rapidly during the last decade, as various qubit realizations and computational protocols were proposed and investigated. However experimental realization of these concepts lags well behind the theory. Parafermions are promising candidates as building-block of topological superconductor architectures thanks to their peculiar statistics. Recent theoretical proposals suggested double nanowire with strong spin-orbit interaction interconnected by a superconductor as a platform where Parafermions could exist.
The experimental realization of Parafermions is challenging, since they are based on the combination of various ingredients, such as crossed Andreev reflection, electron-electron or spin-orbit interaction, and high quality quantum conductors. Our goal in this project was to investigate all these ingredients in superconductor-semiconductor nanowire hybrids and to explore novel bound states.

II. Results

II.1 Ground state degeneracies of two qubit system in the presence of strong spin-orbit interaction

When quantum dots are defined in InAs nanowires, dots shows a reach spin texture due to strong spin-orbit interaction: Zeeman splitting of the states is described by large anisotropic g-tensor and exchange interaction between two dots is also complex. With topological tools we proved that despite these complications there should be minimum two points in magnetic field space where ground state degeneracy should exist (see Fig. 1). These so-called magnetic Weyl-points are topologically robust, with deformation of the system (e.g. gate voltages) they could change their position however they could not disappear. In experiments carried out on double quantum dot defined in InAs nanowire, we also confirmed the existence of these Weyl degeneracies [1]. The degeneracies of interacting quantum dots with strong spin-orbit interaction could have different structures besides isolated Weyl-points. Classification study was carried out to understand what other type of structures the degeneracy points could have. Conditions where the degeneracies positioned along lines or surfaces where found. Altogether ten different patters were identified, and there stability was also determined. [5]

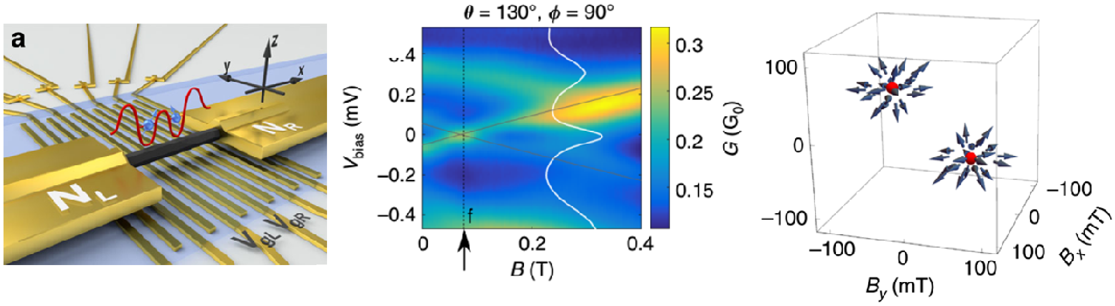

Fig. 1 Magnetic Weyl-points *(Left) Double quantum dot setup realized in an InAs nanowire with strong spin-orbit interaction. (Middle) Magneto transport measurements via the dots showing the magnetic Weyl-point (black arrow) as a zero bias conductance enhancement. (Right) Position of the two magnetic Weyl-point in the magnetic field space [1].*

II.2 Transport signatures of Andreev-molecules

The most elementary system to investigate the strength of crossed-Andreev reflection contains two quantum dots coupled to one superconductor between them. In this setup the dot states could hybridize due to crossed-Andreev reflection resulting a so-called Andreev-molecule (see Fig. 2). However other processes like elastic co-tunneling or direct electron tunneling could also hybridize the states of the dots. We described how these different non-local mechanism controls the measurable quantities, and thereby find experimental fingerprints that allow one to identify and quantify the dominant non-local mechanism using experimental data. Furthermore, we also studied the triplet blockade effect and the associated negative differential conductance, and show that they can arise regardless of the nature of the dominant non-local coupling mechanism. [2]

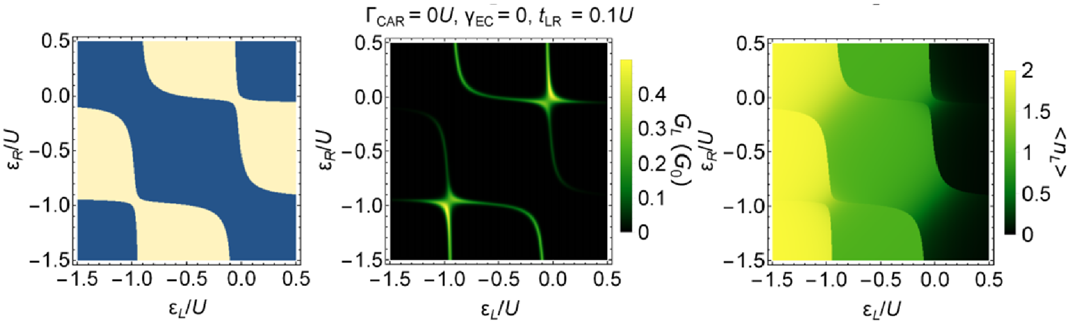

Fig. 2 Phase diagram of a QD-S-QD system *(Left) Phase diagram as a function of the level positions of the dots. (Middle) Differential conductance for the same parameters. (Right) Average occupation number on the left quantum dot. [2].*

II.3 Characterization of high quality spin-orbit materials

In order to carry out spectroscopy on exotic bound states a tunnel barrier with a weakly coupled electrode is highly desirable. When a short segment of InP is grown in InAs nanowire, it could serve as a tunnel barrier due to the higher band gap of InP. Our collaborators in NEST Pisa (L. Sorba) synthesized such wires with 4-5nm long InP segment and we started their transport characterization. We developed nanodevices where nanowire with InP barrier was compared to a similar segment without InP barrier (see Fig. 3). The transport measurements confirmed the presence of a sharp tunnel barrier. Gate and thermal activation measurements were carried out to estimate height of the barrier, which provide a barrier height of 80-100meV. Attaching superconducting leads to the nanowire Andreev bound states formed, which are generated by closed trajectories resulted by an Andreev reflection at the supra-nanowire interface and regular reflection at the barrier. The behavior of the bound state was analyzed in detail as a function of experimental parameters and they agrees well with prediction of a simple model. Thus our results show that built-in InP barriers are promising as future spectroscopic tools to study other exotic bound states. [3]

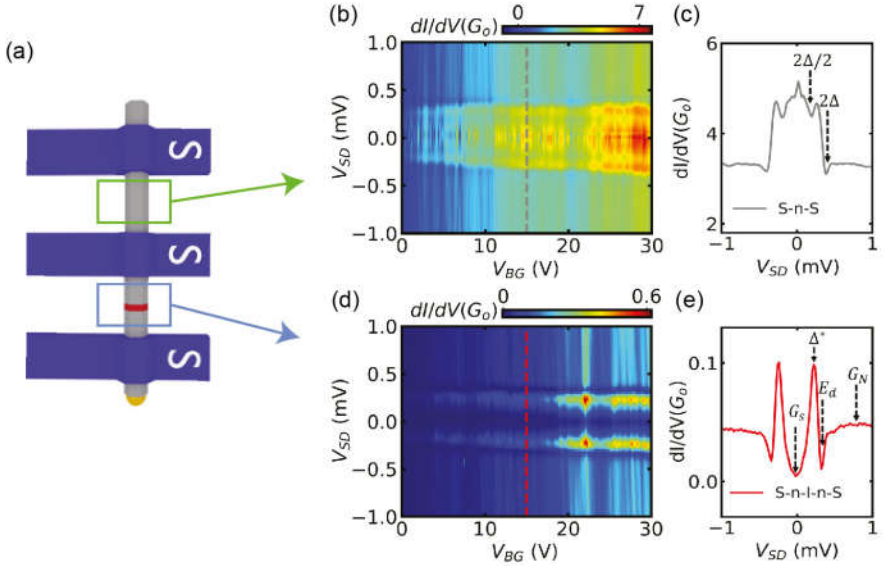

Fig. 3 ***InAs NW with/without InP barrier in the SC state*** *(a) A schematics of the measured device. Differential conductance as a function of source-drain voltage V_{SD} and back-gate voltage V_{BG} for a device segment without barrier (b) and with barrier (d). Corresponding cuts indicated by dashed lines in (b,d) are shown in panel (c) and (e). [3]*

II.4 Development of Double Nanowire devices

Coupling two InAs nanowires with a thin superconducting layer between is a promising system to generate large Crossed-Andreev reflection between two wires. As a first step we deposited NWs with micromanipulator, connected them with evaporated Al and defined dots with side gates. Ultralow temperature measurements showed the signature of crossed-Andreev reflection, its signal was superimposed on crossed charging effect. Since the two dots are defined in nanowire segments right next to each other, there is a large cross capacitance between the dots, thus the energy level of dot 1 is strongly shifted (20% of the self charging energy) when an additional electron added to dot 2.

In order to get better superconducting proximity effect epitaxial Al shell provides a better alternative as a superconducting contact [8]. The group of J. Nygard (Univ. Copenhagen) has grown in MBE system for us such double InAs nanowires where the semiconductor cores linked by a common Al superconducting shell. First we optimized the device fabrication technique based on this new nanoobject: like the etching technique to remove the Al layer and also the deposition of double wires, which is not straightforward, since the two nanowires could fall apart during manipulation. First supercurrent measurements were carried out on double nanowires between two epitaxial S contacts, where we were looking for the role of the Crossed-Andreev reflection. To achieve accurate resolution in supercurrent measurement, we develop a dedicated cold finger of our dilution fridge with dissipative high frequency filtering stages.

II.5 First experimental realization of an Andreev-molecule

Coupling individual atoms via tunneling fundamentally changes the state of matter: electrons bound to atomic cores become delocalized resulting in a change from an insulating to a metallic state, as it is well known from the canonical example of solids. A chain of atoms could lead to more exotic states if the tunneling takes place via the superconducting vacuum and can induce topologically protected excitations like Majorana or parafermions. Toward the realization of such artificial chains, coupling a single atom to the superconducting vacuum is well studied, but the hybridization of two sites via the superconductor was not yet reported. The peculiar vacuum of the BCS condensate opens the way to annihilate or generate two electrons from the bulk resulting in a so-called Andreev molecular state. Thanks to the double InAs nanowires covered with epitaxial Al shell, we managed to engineer two artificial atoms, which are created at a minimal distance (<10nm) with an epitaxial superconducting link between (see Fig. 4). Based on our detailed finite bias spectroscopy measurement at 30mK, we managed to identify signature of the hybridization of the two artificial atoms via the BCS vacuum. We also carried out model calculation of the system and the simulated spectrum reproduced the main unusual features observed in the experiments. Thus we showed the first realization of Andreev-molecule induced by tunnel coupling via a BCS vacuum. [6]

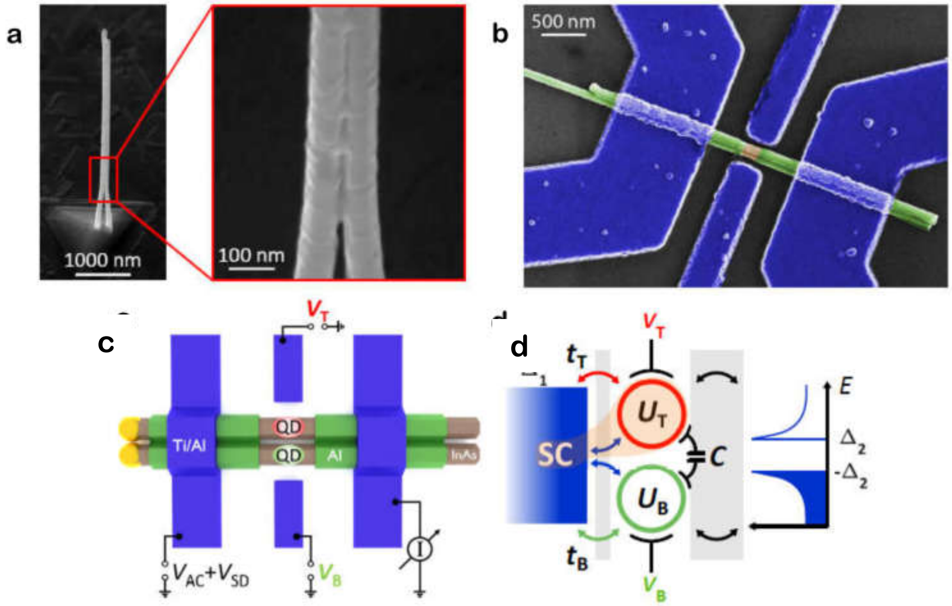

Figure 4 Andreev molecule in double InAs nanowires with SC contacts *(a) SEM image of the NWs grown on and connected by full-shell Al. (b) SEM image of the device. Brown: InAs, green: epitaxial Al, blue: ex-situ evaporated Al. (c) Measurement setup of the DNW device. The signals of the two QDs were captured simultaneously. (d) Sketch of the device displaying the relevant transport parameter. [6]*

II.6 Large spatial extension of Yu-Shiba-Rusinov state

Recently several promising novel qubit concepts have been put forward based on low energy bound states in superconducting environment. One of such bound state is the Yu-Shiba-Rusinov (YSR) state, which hold a promise to engineer protected quantum states, when several YSR states coupled to form a chain. Due to the very small extension of these states, their coupling was only possible by very delicate technique, depositing individual ferromagnetic atoms next to each other. We studied an alternative realization of YSR states, when an artificial atom is attached to a superconductor surface. Measurement of the extension of such YSR state for the first time resulted in a surprising outcome. The size of the state is significantly larger than for real ferromagnetic atoms, its dimension reaches even 50-200nm! With state-of-the-art nanotechnology artificial atoms can be routinely fabricated at such distances, which opens the way to realize YSR chains. [4]

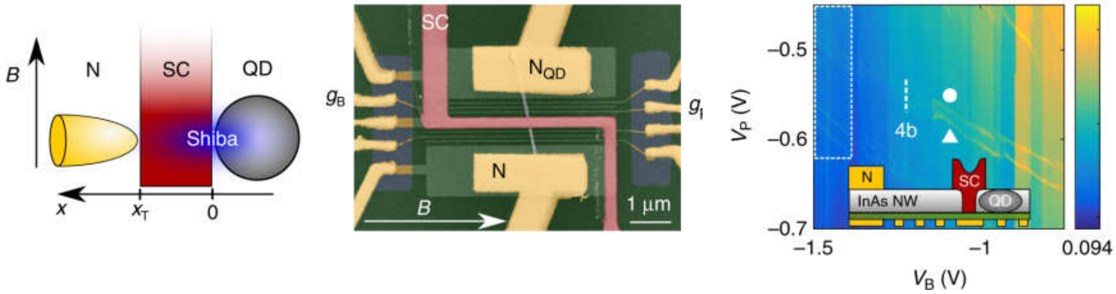

Fig. 5 ***Measurement of the spatial extension of YSR state*** *(Left) Yu Shiba Rusinov state forms at a quantum dot (QD) coupled to a superconductor (SC). A weakly coupled normal probe (N) attached to the other side of the SC allows to probe the state. (Middle) System realized in an InAs nanowire coupled to SC and normal leads. (Right) The current signal of the normal probe as a function of the gate voltages forming the quantum dot. Diagonal lines are the signature of the YSR state (circle anf triangle). [4]*

II.7 Confining 1D structures in InAs 2DEGs

InAs nanowires are suitable to couple them to superconductors, their spin-orbit interaction is strong, however if we plan to engineer complex devices the 1D confinement places some limitations. In order to have more flexibility we started to work on InAs 2DEGs as well (in collaboration with G. Biasiol Trieste, AndQC). Recent MBE growth technique allows to create surface 2DEGs in InAs based heterstructures with large mobilities (50-100k) on which epitaxial Al layer can be grown. In order to create double nanowires for which the confinement can be flexibly vary we started to setup InAs 2DEGs based device fabrication. Mesa etching, creation of top gates, measurement of quantum point contact features (see Fig. 6), and super current measurements were demonstrated on this new type of surface 2DEG [10]. Thus all building blocks are demonstrated to create nanowires in 2DEGs.

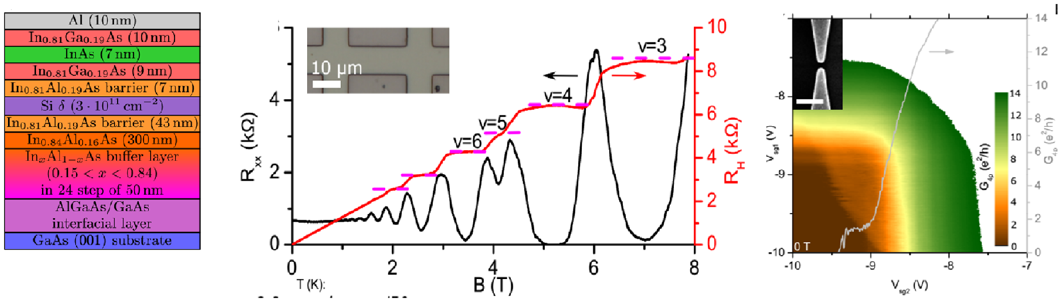

Fig. 6 QPC in InAs surface 2DEG (Left) Heterostructure of the InAs surface 2DEG grown on GaAs. (Middle) Hall measurement resulting Hall density is $n = 4.95 \cdot 10^{11}$ cm^{-2} *and mobility of* $\mu = 86000$ cm^2/Vs. *(Right) QPC measurements as a function of the two gate voltages, showing first quantized conductance plateau. [10]*

II.8 From Cooper pair splitting to non-local spectroscopy of Shiba state

Cooper pair splitting (CPS) is a way to create spatially separated, entangled electron pairs. To this day, CPS is often identified in experiments as a spatial current correlation. However, such correlations can arise even in the absence of CPS, when a quantum dot is strongly coupled to the superconductor, and a subgap Shiba state is formed [4]. We carried out a detailed experimental characterization of those spatial current correlations, as the tunnel barrier strength between the quantum dot and the neighboring normal electrode is tuned. The correlation of the nonlocal signal and the barrier strength reveals a competition between CPS and the nonlocal probing of the Shiba state. We describe our experiment with a simple transport model (see Fig. 7) and obtain the tunnel couplings of our device by fitting the model's prediction to the measured conductance correlation curve. Furthermore, we use our theory to extract the contribution of CPS to the nonlocal signal.

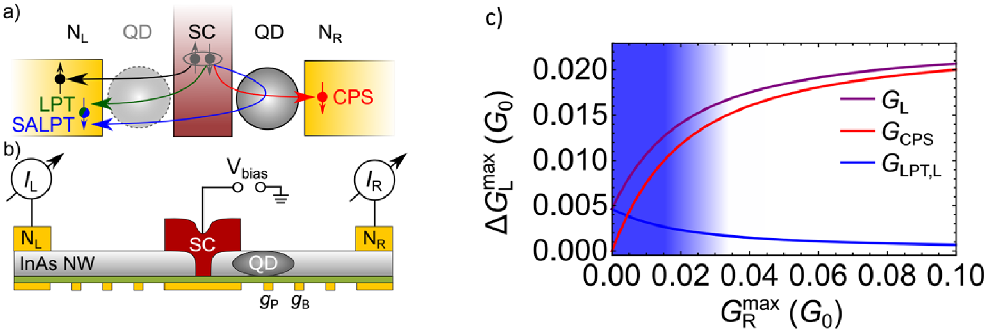

Fig. 7 Transition from CPSplitter to nonlocal YSR spectroscopy *(a) Schematic concept of the device with the relevant transport processes. (b) Realizaion with InAs nanowire contacted by superconducting and normal electrodes and placed on gate electrodes. (c) Contribution of Cooper pair splitting process (CPS) and local pair tunneling (LPT) to the total conductance on the left side. [11]*

III. Publications

[1] Z. Scherübl et al., Observation of spin-orbit coupling induced Weyl points in a two-electron double quantum dot, **Nature, Communication Physics** 2, 108 (2019)
[2] Z. Scherübl et al., Transport signatures of an Andreev molecule in a quantum dot–superconductor–quantum dot setup**, Beilstein J. Nanotechnol**., 10, 363–378 (2019).
[3] T. Elalaily et al., Probing proximity induced superconductivity in InAs nanowire using built-in barriers, **Phys. Rev. Apply**. 14, 044002 (2020). arXiv: 2001.09314
[4] Z. Scherübl et al., Large spatial extension of the zero-energy Yu-Shiba-Rusinov state in magnetic field, arXiv:1906.08531, **Nature Communications** 11, 1834 (2020), arXiv:1906.08531
[5] G. Frank et al., Magnetic degeneracy points in interacting spin systems: geometrical patterns, **Phys. Rev. B**, 101, 245409 (2020).
[6] O. Kürtössy et al., Andreev molecule in parallel InAs nanowires, **Nano Letters**, 21, 7929, 2021, arXiv:2103.14083
[7] T. Elalaily et al., Gate-controlled supercurrent in an epitaxial Al/InAs nanowire, **Nano Letters**, 21, 9684, (2021)
[8] T. Kanne et al., Double nanowires for hybrid quantum devices, **Advanced Functional Materials**, 32, 9, 2107926, (2022)
[9] O. Kürtössy et al., Parallel InAs nanowires for Cooper pair splitters with Coulomb repulsion, under review Nature PJ, Quantum Materials (2022). arXiv:2203.14397
[10] M. Sütő et al., Near-surface InAs 2DEG on GaAs substrate: basic characterization and superconducting proximity, under preparation (2022)
[11] Z. Scherübl et al., From Cooper pair splitting to nonlocal spectroscopy of a Shiba state, **Phys. Rev. Research** 4, 023143 (2022)

[d1] M. Berke, BSc Szakdolgozat, Szupravezető naovezetékek kapuzása, BME TTK (2021).
[d2] M. Berke, TDK Dolgozat, Kapuzási mechanizmus vizsgálata Ta szupravezető nanovezetékeken, BME, TTK, (2021).
[d3] M. Büki, BSc Szakdolgozat, Nanopálca alapú hangolható áramkörök készítése (2019).
[d4] M. Sütő, MSc Diplomamunka, Félvezető nanoáramkörök és szupravezető koplanáris rezonátorok fejlesztése (2020)
[d5] O. Kürtössy, MSc Diplomamunka, Superconducting bound states in InAs nanowires (2019)
[d6] M. Bodocs, BSc Szakdolgozat, Dupla nanopálcán alapuló kvantumáramkörök fejlesztése (2020)
[d7] T. Kalmár, TDK dolgozat, Nanoáramkörök rádiófrekvenciás vizsgálata szupravezető induktivitások segítségével (2020)
[d8] T. Kalmár, MSc Diplomamunka, Nanoáramkörök vizsgálata rádiófrekvenciás módszerekkel (2021)
[d9] Z. Scherübl, PhD Thesis, Spin-orbit interaction and superconductivity in InAs nanowire-based quantum dot devices (2019)