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PhD Thesis

Gating experiments in superconductor-semiconductor nanowire hybrids

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Introduction

Bound states in superconductor-nanowire hybrid devices play a central role, carrying information on ground-state properties (Shiba or Andreev states) or on the topological properties of the system (Majorana states). The spectroscopy of such bound states relies on the formation of well-defined tunnel barriers, usually defined by gate electrodes, which result in smooth tunnel barriers. However, well-defined, sharp barriers can be formed by embedding InP segments into the InAs wire during the growth procedure. The barrier originates from the different band alignments of InAs and InP conduction bands. Furthermore, the width of these built-in barriers (InP segments) can be controlled with the precision of a single atomic layer during the growth process. Moreover, they do not contain internal resonances, so they will not hybridize with the states to be probed. Therefore, the InP barriers can be easily integrated into various quantum circuits, and in addition, they can be promising tunnel barriers to probe various subgap states.

Very recently, a striking new effect was observed in metallic nanostructures. In superconducting nanobridges, the supercurrent can be controlled by applying a voltage to a closely spaced gate electrode. By increasing the gate voltage beyond a certain threshold, the supercurrent in the nanobridge can be quenched and it can switch to its normal state. Since the superconducting nanobridge can switch between two different resistance states, the gate-controlled supercurrent (GCS)-based switches can provide the superconducting equivalent of the CMOS transistors. In addition, their configuration can be easily scaled up, which provides a promising building block for superconducting switches in modern architectures of both classical and quantum computers. Despite the clear advantages of GCS for applications, the origin of the effect is still under debate. Understanding the microscopic origin of the GCS in superconducting nanobridges is crucial for engineering superconducting switches suitable for a variety of electronic applications.

Objectives

In this thesis, I have characterized InAs nanowires with short InP segments to form sharp built-in tunnel barriers. I have used various measurement techniques in order to confirm the presence and estimate the height of these barriers. In addition, to demonstrate the possibility of using these built-in barriers to probe subgap states, the NW is contacted with a superconductor. Furthermore, I have extensively investigated the GCS effect in InAs nanowires with epitaxially grown superconducting shells with various device geometries and characterization techniques. The goal of my work is to help settle the ongoing debate about the origin of this effect, which is crucial for using the GCS in electronic applications.

Thesis points

1. I have characterized built-in InP barriers embedded into InAs nanowires (NWs) during the growth process. I have fabricated NW-based devices with three Al contacts such that the middle contact divides the NW into two segments: one contains the InP barrier, whereas the other is a pure InAs segment. The comparative measurements of the gate dependence of the conductance of the two segments have confirmed the presence of the barrier with a barrier height of 80 meV. The low-temperature transport measurements of the barrier segment have shown an induced gap-like structure, which is described by the presence of Andreev-bound states between the InP segment and the superconducting electrode. I have also shown that the induced gap is gate-tunable. I have also studied the influence of the InP barrier thickness on sub-gap suppression. Barriers with a thickness of 5.2 nm lead to a sub-gap suppression of ~ 0.1. Further increasing the barrier thickness did not enhance the softness of the gap, which can be attributed to the sub-gap states present in the proximity-induced region. Finally, the characterization of these built-in tunnel barriers has proven that they are ideal spectroscopic tools [1].

2. I have realized for the first time the gate-controlled supercurrent (GCS) in a highly crystalline superconducting Al shell epitaxially grown on top of InAs NWs. I have used a novel device configuration in which the supercurrent of the superconducting NW has been tuned by a bottom gate separated from the NW by a high-quality single-crystalline hBN layer. The device shows full suppression of the supercurrent by applying $\simeq \pm 23\,\mathrm{V}$ on the bottom gate. Moreover, I have shown that the suppression of the supercurrent in the NW device and in a small segment of the Al leads contacting the NW is associated with a corresponding enhancement of the gate leakage. I made a detailed characterization of the GCS for both the NW device and the contact segment by using magnetic field and temperature-dependent measurements. The GCS, independent of the gate voltage polarity, suggests that the simple ballistic hot electron injection does not provide a complete explanation of the observed gating. Moreover, the strong correlation between the suppression of the critical current and the increase in leakage current suggests that the electric field is unlikely to be the origin of the gating effect in the investigated device [2].

3. I have investigated the GCS in the Ta half-shell layer deposited on InAs NW. I have fabricated NW-based devices with four Al contacts and two opposite side gates unequally spaced from the NW. The influence of the gate and elevated temperatures on the magnetic field dependence and the switching current distribution (SCD) was strictly different, excluding any Joule heating scenarios. Furthermore, the comparison of the switching cur-

rent distributions at opposite gate polarities as well as the gate dependence of two opposite side gates at different NW-gate spacings show that the power dissipated at the gate P_{G} is the relevant describing the suppression of the supercurrent. The measurements on the investigated devices are consistent with the non-equilibrium superconducting state resulting from the absorption of phonons generated by the leakage current and contradict the microscopic pictures proposing electric fields or ballistic injection of high-energy electrons as the origin of the GCS effect. Moreover, I made a detailed analysis of the switching dynamics of the NW device under strong gate influence, showing that the device is driven into the multiple phase slips (MPS) regime by the high energy fluctuations originating from the leakage current [3].

4. I have used noise correlation measurements to characterize the GCS effect in Al/InAs-based devices. The $I-V$ characteristics of the investigated devices under the influence of the gate show the presence of voltage fluctuations with a corresponding enhancement in the noise level at bias current values slightly below the switching current. The noise correlation measurements show a large coherence between the leakage current noise and the induced voltage noise in the NW device, suggesting that the presence of voltage fluctuations in the NW device is induced by the fluctuations in the leakage current. Furthermore, The leakage current measurements suggest the generation of charge traps in the oxide layer by the stress-induced leakage current (SILC). Since inelastic tunneling combined with phonon emission is the dominant conduction mechanism in the SILC, these phonons can couple to the superconducting NW and cause the GCS effect. By using the detailed analysis of the time domain measurements of these voltage fluctuations, I showed that the induced voltage fluctuations in the NW device have Poissonian dynamics. In addition, I shed light on the microscopic origin of the GCS effect by analyzing the time-domain switching of the NW device at low and high bias currents at finite gate voltages [4].

Publications related to thesis points

[1] **Tosson Elalaily**,Olivér Kürtössy, Valentina Zannier, Zoltán Scherübl, István Endre Lukács, Pawan Srivastava, Francesca Rossi, Lucia Sorba, Szabolcs Csonka, and Péter Makk: *Probing Proximity-Induced Superconductivity in In As Nanowires Using Built-In Barriers*, Physical Review Applied, 14(4):044002, 2020.

[2] **Tosson Elalaily**, Olivér Kürtössy, Zoltán Scherübl, Martin Berke, Gergö Fülöp, István Endre Lukács, Thomas Kanne, Jesper Nygård, Kenji Watanabe, Takashi Taniguchi, Péter Makk, and Szabolcs Csonka: *Gate-Controlled Supercurrent in Epitaxial Al/InAs Nanowires*, Nano Letters, 21(22):9684–9690, 2021.

[3] **Tosson Elalaily**, Martin Berke, Máté Kedves, Gergő Fülöp, Zoltán Scherübl, Thomas Kanne, Jesper Nygård, Péter Makk, and Szabolcs Csonka: *Signatures of Gate-Driven Out-of-Equilibrium Superconductivity in Ta/InAs Nanowires*, ACS nano, 17(6):5528–5535, 2023.

[4] **Tosson Elalaily**, Martin Berke, Gergő Fülöp, Thomas Kanne, Jesper Nygård, Pertti Hakonen, Péter Makk, and Szabolcs Csonka: *Noise characterization of gate-induced fluctuations in Al/InAs nanowires*, **under preparation**.

Publications unrelated to thesis points

[5] **Tosson Elalaily**, Martin Berke, Péter Makk and Szabolcs Csonka: *Universal logic circuit for gate-controlled superconducting-based switches.* Patent. **Under processing**

[6] Leon Ruf, Claudio Puglia, **Tosson Elalaily**, Giorgio De Simoni, Francois Joint, Martin Berke, Jennifer Koch, Andrea Iorio , Sara Khorshidian, Péter Makk, Antonio Vecchione, Simone Gasparinetti, Szabolcs Csonka, Wolfgang Belzig, Mario Cuoco, Francesco Giazotto, Elke Scheer and Angelo Di Bernardo: *Gate control of superconducting current: relevant parameters and perspectives.* arXiv:2302.13734. **Under review in Nature Review Materials**

[7] Leon Ruf, **Tosson Elalaily**, Claudio Puglia, Yurii P. Ivanov, Francois Joint, Martin Berke, Andrea Iorio, Péter Makk, Giorgio De Simoni, Simone Gasparinetti, Giorgio Divitini, Szabolcs Csonka, Francesco Giazotto, Elke Scheer and Angelo Di Bernardo: *Effects of fabrication routes on the control of superconducting currents by gate voltage.* arXiv:2304.07084. **Accepted in APL Materials**

[8] Zoltán Scherübl, Gergő Fülöp, Cătălin Paşcu Moca, Jörg Gramich, Andreas Baumgartner, Péter Makk, **Tosson Elalaily**, Christian Schönenberger, Jesper Nygård, Gergely Zaránd, Szabolcs Csonka: *Large spatial extension of the zero-energy Yu–Shiba–Rusinov state in a magnetic field.* Nature communications 11 (1), p.1834, 2020.