Towards hybrid and topological qubits based on semiconductor-superconductor core-shell nanowire Josephson junctions

P. Zellekens[1,2], R. Deacon[1,3], P. Perla[4], A. Pawlis[4], D. Grützmacher[4], T. Schäpers[4] and K. Ishibashi[1,3]

[1]*RIKEN Center for Emergent Matter Science, 351-0198 Saitama, Japan*

[2]*Special Postdoctoral Researcher (SPDR), 351-0198 Saitama, Japan3*

[3]*Advanced Device Laboratory, RIKEN, 351-0198 Saitama, Japan*

[4]*Grünberg Institute, Forschungszentrum Jülich, 52428 Jülich, Germany*

Contact: patrick.zellekens@riken.jp

If a normal conductor is used as the weak link of a Josephson junction, coherent Andreev reflection occurs on both superconductor/normal-conductor interfaces. In the case of a high interface transparency [1] [2], the thereby formed Andreev bound states are decoupled from the dissipative quasiparticle spectrum and form independent two-level systems. These so-called mesoscopic Josephson junctions [3] can act as building blocks for quantum systems such as the Gatemon, Andreev level/spin qubit or novel topological devices.

The state-of-the-art technique to set, manipulate and probe individual Josephson-junction-type qubits is based on superconducting microwave circuits realized in an extended coplanar waveguide geometry. However, instead of using a single substrate that has to host all kinds of different structures and materials, here I present a design that consists of two independent chips that are later on mechanically coupled by means of a Flip-Chip approach [4]. This general-purpose platform allows the characterization of all different kinds of mesoscopic systems such as semiconductor nanowires, topological insulators or 2D materials.

Together with a detailed study of the resonator properties, I will present single-tone and two-tone spectroscopy measurements of individual Andreev bound states. The latter one reveals an unconventional state structure that is connected to the occurrence of single quasiparticle transitions caused by a Rashba-induced lifting of the spin degeneracy.

In addition, I will present measurements on semiconductor/superconductor core/fullshell nanowires that are predicted to host pairs of Majorana fermions. Here, the radial symmetry gives rise to the so-called Little-Parks effect. This mechanism can, under the right circumstances, induce an additional “phase twist” that produces, effectively, the same outcome as a real “braiding” process without the need for a complex spatial exchange.

However, recent experimental results indicate that “bulk wires” such as InAs/Al are not an ideal choice due to the possibility of transport channels through the center of the wire. As an alternative, core/shell/fullshell nanowires like GaAs/InAs/Al can be used. Here, the combination of the wide bandgap material, which effectively acts as an insulator, and the enhancement of the accumulation layer in the InAs promote the radial symmetry of the system as well as the strength of the spin-orbit interaction. In my talk I will give an overview of this nanowire system that has already been extensively studied in the past in terms of Aharonov-Bohm-type oscillations and recently got new attention due to the possibility of phase-pure crystal formation and the epitaxial growth of the superconducting shell.

[1] P. Perla, P. Zellekens et.al., ***Nanoscale Adv.***, 2021, **3**, 1413-1421

[2] P. Perla, P. Zellekens et.al., ***Phys. Rev. Materials***, 2022, **6**, 054019

[3] P. Zellekens et al., ***Phys. Rev. Applied***, 2021, **14**, 054019

[4] P. Zellekens, R. Deacon et.al., ***Commun. Phys.***, 2022, **5**, 267

[5] P. Zellekens et al., ***Semicond. Sci. Technol.***, 2020, **35**, 085003