1.3.9 Topology in hybrid and multi-terminal Josephson junctions

Topologically protected systems have an large potential impact on quantum technologies, especially for quantum-computation purposes. Much attention was devoted to topological superconductivity and Majorana bound states (MBS) that are generated in hybrid platforms comprising semiconductors and superconductors with broken time-reversal symmetry. We explored both experimentally and theoretically possible signatures of topological transitions in these systems. Moreover, we investigated an alternative route to encode the topological protection in superconducting multiterminal Josephson-junction nanodevices. From tunneling conductance experiments we probed these new topological states that we proposed as an optimal platform to encode topologically-protected quantum-computation protocols.

Phase-controlled topological transitions

Hybrid devices based on superconducting proximity effect in multiterminal configurations offer also another opportunity to engineer topological non-trivial quantum states. We have realized the first double-loop Josephson interferometer [1] with three terminals (Fig. 1a) based on a proximized weak link and probed its characteristics via tunneling spectroscopy.

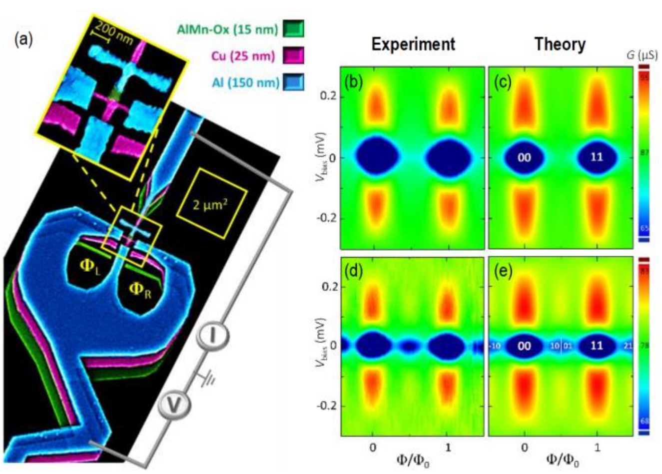

Figure 1. (a) The ω-SQUIPT, three-terminal double-loop Josephson interferometer based on the proximity effect. False-color tilted scanning electron micrograph. The inset highlights the core of the interferometer: a nanosized T-shaped proximized Cu weak link (magenta) in a clean metallic contact with two Al superconducting loops (blue). Loop area is around 2 μm^2. (b)-(e) Comparison between the tunneling conductance G vs V_{bias} measured at 30 mk (left panels) with theory (right panels) for symmetric (b and c) and asymmetric (d and e) length of the arm.

This structure promotes an additional phase control and allows an exotic phase-engineering of the weak-link topology which manifests in the peculiar behavior of the interferometer conductance.

Varying the phase differences between the three arms of the interferometer we observe transitions between gapped (insulating) and gapless (conducting) regions. The topological numbers characterizing such gapped states are given by superconducting phase windings over the two loops forming the Josephson interferometer. Since these gapped states cannot be transformed to one another continuously without passing through a gapless condition, they are topologically protected, demonstrating their non-trivial nature. The density of state of the three-terminal devices is accessed through a metallic tip tunnel-coupled to the weak link. Transitions between gapless and gapped regions are revealed by measurements of the tunneling conductance as a function of voltage bias and magnetic flux (Fig. 1b and Fig. 1d). Comparison with theoretical calculations fully confirms the mentioned scenario (Fig. 1c and Fig. 1e).

Topological nanodevices

We have recently proposed and theoretically examined a device based on a topological Josephson junction where the helical edge states of a two-dimensional (2D) topological insulator are in close proximity to two superconducting leads. The presence of a magnetic flux through the junction leads to a Doppler shift in the spectrum of Andreev bound states, and affects the quantum interference between proximized edge states. Such systems have been envisioned for several interesting applications, such as highly sensitive magnetometers [2], thermal switches and rectifiers [3]. Hybrid superconducting nanodevices are an ideal platform also to manipulate the entanglement in solid-state systems. Indeed, hybrid structures with topological insulators also show unique possibilities to manipulate the spin-symmetry of the entanglement by using external gates and easily addressed with measurement of the critical current [4].

References

[1] E. Strambini, S. D'Ambrosio, F. Vischi, F.S. Bergeret, Yu.V. Nazarov, F. Giazotto, *The ω-SQUIPT as a tool to phase-engineer Josephson topological materials*, Nature Nanotech. **11**, 1055 (2016).

[2] L. Bours, B. Sothmann, M. Carrega, E. Strambini, E. M. Hankiewicz, L. W. Molenkamp, F. Giazotto, *Topological SQUIPT Based on Helical Edge States in Proximity to Superconductors*, Phys. Rev. Applied **10**, 014027 (2018).

[3] L. Bours, B. Sothmann, M. Carrega, E. Strambini, A. Braggio, E.M. Hankiewicz, L.W. Molenkamp, F. Giazotto, *Phase-tunable thermal rectification in the topological SQUIPT*, Phys. Rev. Applied **11**, 044073 (2019).

[4] G. Blasi, F. Taddei, V. Giovannetti, A. Braggio, *Manipulation of Cooper pair entanglement in hybrid topological Josephson junctions*, Phys. Rev. B **99**, 064514 (2019).