

# Superconductivity in low-dimensional Nb nanostructures

PhD Thesis Summary

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The increasing demand for miniaturized devices has shifted the focus of modern research on realizing nanostructures and exploring nanoscale phenomena. Low-dimensional systems such as nanofilms, nanowires, and nanodots, exhibit unique electronic and optical properties that make them promising candidates for nanoelectronics, nanophotonics, and energy conversion. In this scenario, superconducting nanowires offer a compelling solution for the realization of novel electronic devices, due to their dissipationless current transport and high-speed operation, allowing the realization of complex building blocks such as Cooper pair box, phase, flux, or charge qubits. Beyond their relevance in quantum computing, superconducting nanowires also play a crucial role in photon detection technologies, offering high detection efficiency, fast reset time, and low false-signal rate. Moreover, recent advances in gate-controlled superconductivity have demonstrated that strong electrostatic fields can modulate the superconducting state of low-dimensional systems, leading to the suppression of their superconducting current. New insights into gating effects may facilitate the development of superconducting field-effect transistors, potentially representing a groundbreaking advance in superconducting electronics. Despite these advancements, a comprehensive understanding of how superconductivity is affected by nanoscale confinement still remains a challenge. In this context, while superconducting thin films have been extensively studied, the dimensional crossover from 2D to quasi-1D superconductors introduces novel challenges.

In this work, superconducting properties of low-dimensional structures based

on Nb nanowires are explored. This dissertation starts with an introduction concerning the historical background of superconductivity and the establishment of its theoretical interpretation, the state-of-the-art of superconductivity in low-dimensional systems, and a deep description of the phase slip events theoretical model. Then, the technologies employed for the realization of the Nb nanostructures are presented, focusing on nanopatterning techniques based on Electron Beam Lithography, and thin-film deposition techniques exploited in this work for the realization of nanostructures. It is shown that the fabrication protocol enabled the realization of highly uniform Nb nanostructures with widths ranging from 5  $\mu\text{m}$  down to 80 nm. Then, methods exploited for the morphological and electrical characterization are summarized, with a focus on the techniques employed for the low-temperature characterization of these nanostructures.

The dissertation continues with the investigation of how the nanostructure geometry influences its superconductive properties. To investigate this effect, trapezoidal-shaped pads connected by a Nb nanowire have been studied. This configuration allowed the visualization of the influence of nanostructure geometry on the superconducting transition. In particular, two superconducting transitions were revealed when considering nanowires contacted by two trapezoidal pads, one affected by the gradual and continuous reduction in the width of the trapezoidal pads, and the other ascribed to the nanowire itself.

After visualizing the effects of superconductivity by passing from 2D to quasi-1D configuration, the electronic transport in Nb nanowires is investigated in a wide range of temperatures, allowing us to analyze how scattering mechanisms affect its conductive and superconductive properties. It was observed that the reduction of the cross-section of the devices resulted in a suppression of both the critical temperature and critical current density, with respect to the bulk and the equivalent 2D configuration. The emergence of phase slip events has been analyzed based on Thermal Activated Phase Slip and Quantum Phase Slip theoretical descriptions, on the basis of both  $R$  vs  $T$  and  $V$  vs  $I$  characteristics. These two phase slip mechanisms correspond to the passage of the Cooper pairs between two free energy local minimums, driven by thermal fluctuations or quantum tunneling, respectively. This process induces a  $2\pi$  shift in the superconducting phase, resulting in the appearance of a finite resistance within the superconducting state. The narrower Nb nanowires resulted in being more prone to phase slip events, and the analysis revealed the best results are provided by the linear combination of the two phase slip mechanisms, whose relative contributions vary depending on the vicinity to the superconducting transition.

In the last part, we propose an alternative strategy for the realization of

low-dimensional Nb nanostructures. This strategy is based on the realization of nanoscale Nb conductive filaments through electroforming, a technique that allows the definition of a conductive pathway within an oxide matrix by leveraging redox reactions and ion migration under the action of an applied electric field. The electronic transport of the Nb conductive filaments has been investigated through electrical characterization, revealing the transition from the insulating behavior of the pristine devices to the metallic-like behavior after the device electroforming. Even if further investigations are required to understand the conductive properties of these conductive filaments at cryogenic temperatures, preliminary results show that electroforming can represent a promising approach for exploring superconductivity in low-dimensional systems.

This dissertation aims to bridge the gap between low-dimensional superconducting systems and emergent quantum phenomena, paving the way for a comprehensive understanding of the interplay between device size and superconducting properties at the nanoscale.