Development of Superconducting Single-Particle Detector Transition-Edge Sensor

PhD Thesis Summary

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This thesis presents the development and advancement of superconducting single-particle detectors, specifically Transition-Edge Sensors (TESs), focusing on enhancing their performance for various scientific fields. TESs are highly sensitive microcalorimeters capable of detecting radiation across a wide spectrum, from sub-millimeter wavelengths to gamma rays, due to their intrinsic energy resolution. They are also known for their near-unit system detection efficiency, low dark count rate and photon-number resolution capabilities. This work was conducted at the Istituto Nazionale di Ricerca Metrologica (INRiM), the National Metrology Institute of Italy, where I worked in the Innovative Cryogenic Detectors Laboratory using TES devices fabricated at QR Laboratories, a micro and nanofabrication lab.

The primary motivation for this research is to improve TES performance to enhance their use in physical and metrological experiments in particular three main application are driving the research:

- The PontCorvo Tritium Observatory for Light, Early-Universe, Massive-neutrino Yield (PTOLEMY) experiment, which seeks to detect the Cosmic Neutrino Background (CNB). TES devices with an energy resolution of 0.11 eV are required to detect electrons produced by CNB via neutrino captures on beta-unstable nuclides, providing insights into the early universe and the nature of neutrinos.

- The Quantum Haloscope Search experiment (QHaloS) aims to search for light dark matter in the form of dark photons using a dielectric haloscope equipped with a TES for photon detection. This innovative detector aims to convert non-relativistic dark photons into Standard

Model photons, which are then detected by the TES. Since the experiment searches for rare events, it requires a detector with high efficiency and low dark count rate (DCR).

- The Single and Entangled Photon Sources for Quantum Metrology (SEQUME) project aims to develop high-purity single-photon sources and high-efficiency entangled-photon sources for quantum-enhanced measurements in quantum metrology. A TES with high efficiency is crucial for characterizing these single-photon sources.

Considering the three main applications presented above, the primary objectives of the thesis are:

1. Achieve excellent energy resolution with TES devices covering large areas to facilitate future realization of TES arrays. This is crucial for applications where the detection area required exceeds the capability of a single device.

2. Demonstrate that TESs can function as single-electron detectors with energy resolution comparable to that of photons.

3. Characterize and study the dark counts in TESs for rare events applications.

4. Attain a system detection efficiency greater than 90%, enabling the establishment of a single-photon source calibration facility.

5. Reduce the recovery time of TES to reach detection rate higher then 1 MHz as requested by state-of-the-art single photon sources.

To address these objectives, the thesis is structured as follows.

In Chapter 2, I present a detailed description of superconducting single-photon detectors, beginning with an overview of superconductivity and the energy down-conversion process that occurs when a photon is absorbed by a superconductor. I discuss the four most relevant types of SSPDs: STJ, TES, SNSPD, and KID, and provide an analysis of the state-of-the-art performances of TES detectors.

In Chapter 3, I present a theoretical model of TES operation where I describe the thermal model of a superconductor coupled to a thermal bath, discuss electrothermal feedback, and explain how a Superconducting Quantum Interference Device (SQUID) can serve as a transimpedance amplifier to read out the TES response. In this chapter are also explored figures of merit and outlines theoretical parameters that can be optimized to enhance TES performance.

In Chapter 4, I detail the experimental setups essential for developing and characterizing the TES devices used in this thesis. This includes the configuration of the low-temperature setup, integration of the SQUID amplifier and its associated electronics. Additionally, I describe the alignment system utilized for coupling optical fibers to the TES devices. The chapter also covers the specific setups employed for evaluating the System Detection Efficiency (SDE) crucial for the SEQUME project, as well as the configurations used for integrating an electron source based on Carbon Nanotubes (CNT) within the cryostat. Furthermore, I highlight the fabrication methods employed in the development of the TES devices.

Chapter 5 is divided into five main sections that highlight the results corresponding to the five objectives of this thesis:

1. **Energy Resolution :** Two TiAu TES, with areas of 20 µm × 20 µm and 50 µm × 50 µm, were characterized, achieving energy resolutions of 0.114 eV and 0.158 eV, respectively. These results are particularly noteworthy as they match state-of-the-art energy resolutions reported in the literature but with TES devices of significantly larger area. This advancement is critical for the PTOLEMY project because it facilitates the implementation of large-area detectors based on an array of TESs.

2. **Detection of Low-Energy Electrons:** This thesis demonstrates the first detection of electrons with kinetic energy in the 100 eV range using a TES. This was achieved with a 100 µm × 100 µm TiAu TES. Electrons were produced directly in the cryostat by a cold-cathode source based on field emission from vertically-aligned multiwall carbon nanotubes. The energy resolution obtained for fully-absorbed electrons in the $(95 - 105)$ eV energy range was between 1.8 eV and 4 eV, compatible with the resolution for photons in the same energy range. This measurement opens new possibilities in electron detection, crucial for PTOLEMY, where TES devices must detect electrons with high precision, but also in electron spectroscopy.

3. **Study of Dark Counts for Rare Event Searches:** I present the test runs conducted to measure the intrinsic DCR of TES and the efforts to understand the origin of these dark counts. In the thesis, I presented the characterization of the dark count of a TiAu TES, for which we measured a DCR of 3.6×10^{-4} Hz in the 0.8 eV to 3.2 eV range. Moreover, through experimental runs involving radioactive sources, cosmic ray coincidence setups, and GEANT4 simulations, we proved that cosmic

rays and environmental gamma rays are the primary contributors to high-energy DCR. We also assessed that the rate of photon-like events is not correlated with the rate of high-energy events.

4. **System Detection Efficiency Measurement:** The results for the SEQUME project were obtained at the PTB in Braunschweig (Germany) during a four-month period abroad in my third year of PhD. In this thesis I present the measurement on a TiAu TES fabricated at AIST (Japan) with a system detection efficiency of 98%, a significant milestone for the SEQUME project's objectives.

5. **Preliminary Results for Fast TES:** Finally, the thesis describes preliminary results on the development of TES with fast recovery time to enhance operation above 1 MHz. Two distinct approaches are presented: one involving the use of Al TES with a high critical temperature, and the second utilizing Au pads to increase thermal conductance.

Chapter 6 concludes the thesis, summarizing the key findings and discussing potential future work.

Overall, this thesis encompasses the development, characterization and application of advanced TES devices, significantly contributing to their potential use in metrological and fundamental physics research, pushing the boundaries of their performance.