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remoTES: a novel cryogenic detector for rare-event searches

M.R. Bharadwaj,[1,*] G. Angloher,[1] M. Cababie,[5,7] I. Dafinei,[2,3] N. Di Marco,[3,4] L. Einfalt,[5,7] F. Ferroni,[2,3] S. Fichtinger,[5] A. Filipponi,[4,6] T. Frank,[1] M. Friedl,[5] Z. Ge,[8] M. Heikinheimo,[9] M.N. Hughes,[1] K. Huitu,[9] M. Kellermann,[1] R. Maji,[5,7] M. Mancuso,[1] L. Pagnanini,[3,4] F. Petricca,[1] S. Pirro,[4] F. Pröbst,[1] G. Profeta,[4,6] A. Puiu,[3,4] F. Reindl,[5,7] K. Schäffner,[1] J. Schieck,[5,7] D. Schmiedmayer,[5,7] P. Schreiner,[5,7] C. Schwertner,[5,7] K. Shera,[1] M. Stahlberg,[1] A. Stendahl,[9] M. Stukel,[3,4] C. Tresca,[4,6] F. Wagner,[5] S. Yue,[8] V. Zema[1] and Y. Zhu[8]

[1] *Max-Planck-Institut für Physik, 80805 München - Germany*
[2] *INFN - Sezione di Roma, 00185 Roma - Italy*
[3] *Gran Sasso Science Institute, 67100 L'Aquila - Italy*
[4] *INFN - Laboratori Nazionali del Gran Sasso, 67100 Assergi - Italy*
[5] *Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, 1050 Wien - Austria*
[6] *Dipartimento di Scienze Fisiche e Chimiche, Università degli Studi dell'Aquila, 67100 L'Aquila - Italy*
[7] *Atominstitut, Technische Universität Wien, 1020 Wien - Austria*
[8] *SICCAS - Shanghai Institute of Ceramics, 200050 Shanghai - P.R.C*
[9] *Helsinki Institute of Physics, University of Helsinki, 00014 Helsinki - Finland*

E-mail: mukund@mpp.mpg.de

In recent years, high sensitivity, low-threshold detectors employing transition edge sensor (TES) read out technology have garnered significant interest in the field of rare-event searches. Numerous experiments have incorporated these detectors for direct dark matter detection and coherent elastic neutrino-nucleus scattering (CEνNS) studies. As these experiments scale up and operate larger arrays, a key challenge is to enhance the reproducibility among detectors while promoting modularity in terms of both the choice of absorber and sensor. COSINUS (Cryogenic Observatory for SIgnatures seen in Next-generation Underground Searches) has experimentally demonstrated that a novel cryogenic detector scheme, known as remoTES, can address these challenges. This contribution outlines findings from a systematic study of Si prototypes, highlighting ongoing optimization efforts to achieve better detector performance.

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1. Introduction

Detectors operating at low temperatures within the range of tens to hundreds of millikelvin (mK) are pivotal in particle physics. These cryogenic detectors record particle interactions through the minuscule temperature elevation of the order of (μK) triggered by energy deposition in an absorber material, utilizing highly sensitive cryogenic sensors like Transition Edge Sensors (TESs), Neutron Transmutation Doped-thermistors (NTDs), Kinetic Inductance Detectors (KIDs), or Metallic Magnetic Calorimeters (MMCs) to read out the signals [1, 2]. Over the past three decades, TESs based on superconducting thin films have been employed by various cryogenic experiments, ranging from world-leading, low-mass dark matter limits for direct detection searches [3–5] to coherent elastic neutrino-nucleus scattering (CEνNS) searches [6, 7] and space based sky-mapping surveys [8].

The direct deposition of the TES onto the absorber optimizes the transmission of non-thermal phonons to the thin film and has been the standard fabrication process followed by a number of experiments. This integrated setup is favored as long as the absorber material can endure the requisite fabrication processes for the temperature sensor, which includes multiple electron-beam evaporation cycles, sputtering, chemical etching, and photolithography. This can induce internal stress in the crystal lattice [9]. However, certain absorber materials with a low melting point or hygroscopic property are incompatible with these processes. Additionally, sensor fabrication may compromise the radio-purity of the absorber crystal. An alternative solution for fragile materials, exemplified by sodium iodide (NaI) crystals employed in the COSINUS experiment [10], is the innovative remoTES detector design [11]. Here, the TES is fabricated onto a separate, remote wafer substrate and is coupled to the absorber crystal via a gold (Au) link that transmits the phonon signal from an interaction in the absorber to the TES. A schematic is depicted in Fig. 1.

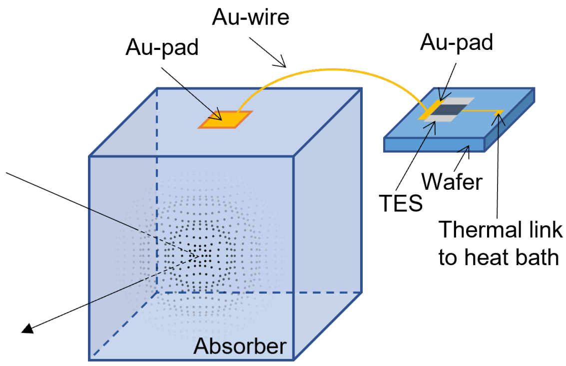

Figure 1: Schematic representation of the remoTES design. The Au-link is comprised of two Au-pads on the absorber and TES respectively, connected via an Au-wire.

The decoupling of the TES fabrication from the absorber crystal can streamline the production process, while enhancing TES reproducibility and expanding the choice of absorbers to accomodate even delicate materials. This manuscript covers the experimental implementation and results of the remoTES detector design concept [12]. It also outlines follow-up optimization tests carried out to improve the baseline resolution, identify, and remove the bottlenecks introduced by such a design change [13].

2. Proof-of-principle tests

A first set of studies were undertaken with silicon (Si) and tellurium dioxide (α-TeO_2) to test the viability of this design as a sensitive cryogenic detector [10]. A 2.33g Si crystal served as a first study given the wide prevalence of Si as a cryogenic detector. A follow-up with α-TeO_2 was carried out, mainly due to the fact that it shares similar solid-state properties with sodium iodide (NaI), the absorber which will be operated in the COSINUS experiment [14]. A summary of the measurement results is provided in Tab. 1.

The successful studies demonstrated the remoTES design as a sensitive cryogenic detector [12] that could be operated without exposing materials to harsh fabrication processes, thus preserving initial radiopurity and lattice conditions of the sample.

Absorber	Si	α-TeO_2
Volume	20x10x5 mm^3	20x10x2 mm^3
Au-link	**Au-pad on Si**	**Au-pad on α-TeO_2**
	Thickness: 200 nm	Thickness: 400 nm
	Magnetron sputtering	Glue: EPO-TEK 301-2 [15]
	Au-wire	**Au-wire**
	Diameter: 17 µm	Diameter: 17 µm
	Wedge bonded	Silver-loaded epoxy
Al_2O_3 wafer	Volume: 10x10x0.4 mm^3	Volume: 10x10x0.4 mm^3
W-TES on wafer	Area: 220x300 μm^2	Area: 220x300 μm^2
	Thickness: 100 nm	Thickness: 100 nm
	T_C: 28 mK	
Heater on wafer	Area: 200x130 μm^2	Area: 200x130 μm^2
	Thickness: 100 nm Au	Thickness: 100 nm Au
Effective exposure	1.06g d	2.28g d
Baseline resolution	87.8±5.6 eV	193.5±3.1 eV

Table 1: Summary of proof-of-principle tests.

3. Experimental studies

The addition of an Au-link, while motivated by theoretical modelling [11], introduces a new set of additional parameters that need to be optimized to ensure a good collection of the athermal phonons and their effective coupling to the electronic system of the Au-link, and consequently the response of the TES film. A Si absorber was used to characterize and study the effects of each individual component on the detector performance.

3.1 Fabrication and assembly

For the following studies, a holder made from NOSV copper (Cu) was used to house a 2.33g Si absorber with dimensions 20x10x5 mm^3. The crystal rests on a trio of sapphire (Al_2O_3) balls to thermally insulate it from the Cu holder. Two additional metallic support tips were used to fix the crystal's position. A low count-rate ^{55}Fe X-ray source is taped onto the Cu holder such that it irradiated one of the faces of the crystal while an additional collimated ^{55}Fe source is shining onto the Au-pad . The K_α (5.89 keV) and K_β (6.49 keV) lines are used to calibrate the detector in the offline analysis. Fig. 2 shows a schematic of the assembled Si-remoTES detector. For a

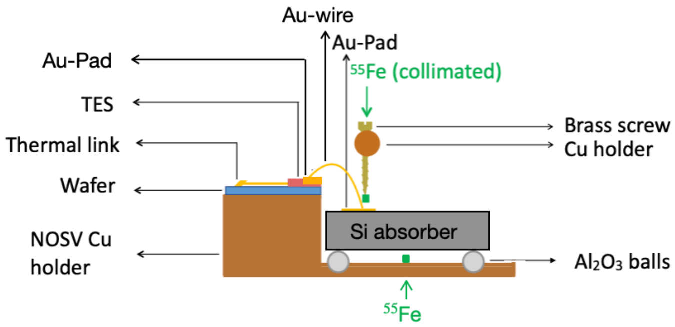

Figure 2: Schematic representation of the Si remoTES detector design

reference measurement, it was equipped with a 1 µm thick Au-pad having an area of 7.5 mm^2 glued to the absorber using EPO-TEK 301-2 [15], a low-outgassing two component epoxy. A 17 µm thick Au-wire was used to connect the Au-pad on the absorber side to the Au-pad on the TES side, employing a wedge bonding method on both ends. The TES is a tungsten (W)-based thin-flim which was deposited onto an Al_2O_3 wafer. With the following setup, a baseline resolution, σ, of 280±9 eV was reached.

3.2 Optimization studies

An examination of the Au-wire connection under a high magnification microscope revealed tears in the Au-pad on Si around the wedge-bond foot, likely attributed to the shear forces concentrated around the small bond site. A ball bonding technique typically exerts lower shear forces compared to wedge bonding. This is due to the way the Au-wire is shaped into a ball towards the end, before being pressed onto the Au-pad. The shape of the ball and the bonding process distributes the stress over a larger area, reducing the risk of tears in the thin Au-pads. Consequently, a follow-up set of studies were carried out with ball-bonding being employed on the Au-pad (glued or sputtered on absorber side), while varying the thickness of the Au-pad.

A performance comparison of the different detectors with the reference measurement is shown in Tab. 2. It can be seen that by employing the ball-bonding technique, the performance of the detectors in comparison to the reference measurement was improved. The improvement in baseline resolution observed when using the 8µm Au-pad shows that heat capacity is not yet the dominant factor influencing detector performance. A closer look at the pulse shapes of particle interactions directly in the Au-pad for the ball-bond tests in Fig. 3 (left) shows a larger thermal component present in the 8µm Au-pad events as evident from the longer tail of the pulse.

In order to check if the effect was purely a consequence of the additional heat capacity and not due to signal bottlenecks on the TES side, a follow-up test was performed wherein the current design with a partial overlap of the Au-pad on the W-TES side (dubbed the TES Au-bridge design) was replaced with a new sensor wherein the Au-pad completely overlapped the W-TES (dubbed the TES Au-island design). The Au-pad thickness on the absorber side was kept unchanged at 8 µm. A comparison of the pulse shapes of Au-pad events of the two designs is depicted in Fig. 3 (right).

Test	Reference	Ball bond test - 1	Ball bond test - 2
Au-link	**Au-pad** Thickness: 1 µm Glue: EPO-TEK 301-2 **Au-wire** Diameter: 17 µm Wedge-bonding	**Au-pad** Thickness: 200 nm Sputtering **Au-wire** Diameter: 25 µm Ball-bonding	**Au-pad** Thickness: 8 µm Glue: EPO-TEK 301-2 **Au-wire** Diameter: 25 µm Ball-bonding
Resolution	280±9 eV	133±3 eV	89±2 eV
TES design	Bridge design	Bridge design	Bridge design

Table 2: Performance comparison among different Si-remoTES designs.

It shows that the modified Au-island design shows a much shorter tail, indicating a quicker decay time. A plausible explanation of the improvement due to the design change can be attributed to poor signal conductance between the Au/W interface in the design with the Au-bridge, which could impede signal transmission and cause a backflow of the signal back to the Au-pad on the absorber.

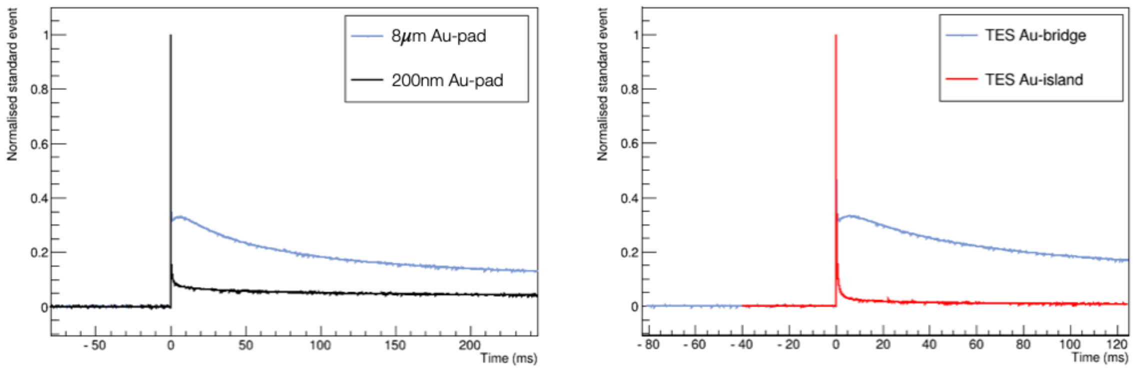

Figure 3: A comparison of pulse shapes of particle interactions directly in the Au-pad. Left: A comparison between pulse shapes of detectors having different Au-pad thickness read out with the TES bridge design; Right: Pulse shapes of detectors having different TES designs.

4. Conclusions

The remoTES design has proven to be a suitable readout technique for cryogenic detectors while offering important benefits of simplifying detector scalability, improving sensor reliability and providing the flexibility to use non-standard materials. Systematic optimization studies were carried out with a Si absorber in order to help resolve bottlenecks in the signal propagation introduced with the addition of the Au-link. The collective data resulted in a redesign of the TES coupling to the Au-pad and refining the bonding technique by switching to ball-bonding. Pairing the remoTES design with a NaI absorber, we were able to successfully operate and read out NaI at cryogenic temperatures for the first time [16, 17], enabling COSINUS to get one step closer in resolving the long standing DAMA/LIBRA tension. In order to ensure a good resolution while scaling up NaI absorber masses, the optimizations outlined in this study will be adapted to find a suitable balance between efficient athermal phonon collection and the additional heat capacity introduced to the system.

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