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Anomalous Thermal Behavior in Microcalorimeter Gamma-Ray Detectors

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Abstract. Improving the resolution of gamma-ray detectors is important for many fields, including determinations of the Lamb shift in atoms with high atomic numbers, nuclear treaty verification, and environmental monitoring. High-purity germanium detectors are currently the tool of choice for precision gamma-ray spectroscopy. The resolution of these detectors is limited to about 500 eV full-width-at-half-maximum at 100 keV by Fano statistics. In comparison, low-temperature microcalorimeters can provide over an order of magnitude improvement in photon resolution. For instance, a gamma-ray microcalorimeter has achieved 25 eV FWHM resolution at 103 keV. These calorimeters consist of two components, a bulk absorber to stop incident gamma rays and a thermometer made from a thin film electrically biased in the superconducting-to-normal phase transition, called a Transition Edge Sensor, or TES. The standard absorber is bulk, superconducting tin. While tin has historically been the best performing absorber, pulse decays in Sn devices are much slower than predicted. We have begun a systematic study of absorber behavior in order to assess and improve response times. This study leverages two capabilities: the ability to microfabricate highly uniform arrays of gamma-ray detectors and the ability to read out many detectors in a single cool-down using SQUID multiplexer circuits. Here, we present two experiments to identify the source of thermal time constants. The first involves varying properties of the Sn absorber including purity, vendor, and crystal grain size. The second examines the role of the other elements in the microcalorimeter assembly.

Keywords: Microcalorimeter; absorber; gamma-ray spectroscopy.
PACS: 61.80.Ed, 85.25.Oj

INTRODUCTION

The resolution of current state-of-the-art gamma-ray spectrometers hinders measurements as varied as: determinations of the Lamb shift in atoms with high atomic numbers[1], environmental monitoring, and nuclear treaty verification[2]. These measurements are presently performed using high-purity germanium (HPGe) detectors. However, the resolution of HPGe is Fano limited to approximately 500 eV full-width-at-half-maximum at 100 keV[3]. Consequences of this resolution limit include the inability to resolve nuclear isotope mixtures for treaty verification or to distinguish enriched uranium from the radium signature in clay-bearing materials such as cat litter. Low-temperature microcalorimeters provide over an order of magnitude improvement in energy resolution. For instance, a gamma-ray microcalorimeter has achieved 25 eV FWHM resolution at 103 keV[4].

Microcalorimeters consist of two main elements, an absorber to convert photon energy into thermal energy, and a thermometer to read the resulting change in temperature. The thermometer fabricated by our group is a transition edge sensor (TES) comprised of a thin film, electrically biased in the superconducting-to-normal transition so that the electrical resistance is extremely sensitive to temperature[5]. The TES is operated using negative electrothermal feedback where energy absorption in the thermometer is compensated by a reduction in electrical bias power, resulting in rapid thermal recovery[6]. Operating temperatures near 0.1 K reduce the thermal noise and give technologically interesting resolving powers.

The second major element of the detector is the absorber, which is a bulk superconductor. The

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absorber rests on a solid post made from a photoimagable resist that is lithographically attached to the TES. A cryogenic epoxy attaches the absorber to the top of the post. A superconducting absorber is ideal for two reasons. First, superconductors have lower heat capacities than normal metals increasing sensitivity to temperature changes. Second, the smaller excitation gap in superconductors as compared to semiconductors reduces statistical fluctuation due to electronic excitations. Fluctuations in excitation behavior, such as varying levels of loss, can degrade resolution. Details of the physics governing microcalorimeters with absorbers are described by Zink *et al.* [7]

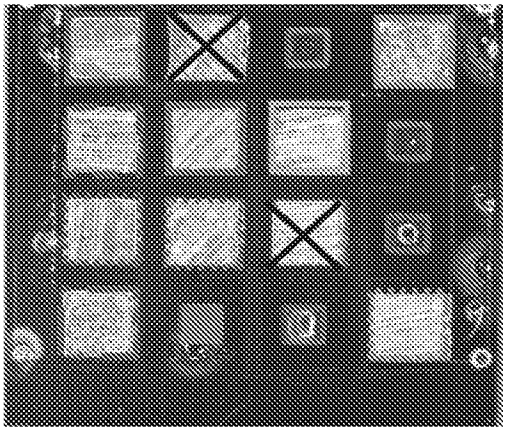

FIGURE 1. Micrograph of 16-pixel TES array with Sn absorbers. The absorbers have varying properties by column. The blue highlighted pixels are 99.99% pure from manufacturer #1 with 200 μm crystal grains. The green are 99.99% pure from manufacturer #1 with 20 μm crystal grains. The pink is from manufacturer #2 and is 99.8% pure. The red are 99.8% pure from manufacturer #1 with unknown grain size. Pixels without absorbers show posts in the center. Absorbers with crosses broke after this picture was taken.

Previous experiments have studied individual microcalorimeters for gamma-ray detection and achieved the best results using bulk tin (Sn) absorbers[7-11]. We also use Sn aborbers, and the thermal properties of our detectors theoretically predict an exponential relaxation time after a photon strike of about 1 ms. This time constant limits the practical count rate of a single detector to about 100 Hz. Experimentally, we find in addition to the 1 ms time constant, there is also an anomalous 10 ms time constant[8].

We have developed the ability to fabricate and measure uniform arrays of gamma-ray microcalorimeters, to overcome limitations on collection area and photon count rate posed by the small area and slow response of single pixels. Also, the fabrication of arrays overcomes limitations in experimental throughput and repeatability that have prevented investigation of the longer time constant. Some groups have proposed long-lived quasiparticle excitations as an explanation for the anomalous thermal decay, but this hypothesis is unverified. By understanding and eliminating the 10 ms decay, the count rate of an array may be increased by an order of magnitude. Here we describe two experiments we performed to find the source of the anomalous time constant. The first looks at an array of microcalorimeters with varying absorber properties to determine the effect of the absorber on the long time constant. The second probes the role of the other parts of the microcalorimeter.

EXPERIMENTAL DETAILS

The enabling technology for reading out detector arrays is the ability to read out the signals from many TESs with a smaller number of wires. The low noise amplifier used is a superconducting quantum interference device (SQUID). The TES current is inductively coupled to the SQUID amplifier. In actuality, each TES is amplified by a single 1st stage SQUID held at 0.1 K that selectively routes its signal to a shared 2nd stage SQUID also at 0.1 K and on to a 100 SQUID array held at 4 K due to its larger power dissipation. In a two-dimensional sensor array, each sensor has a 1st stage SQUID but each column shares a 2nd and 3rd stage SQUID. When multiplexing, the elements of the column are polled much faster than the timescale of a photon pulse so all information from every sensor is recovered. If each TES in a detector array were amplified individually, the heat load and mechanical complexity of the additional amplifiers and wires to 0.1K would be prohibitive.

The process of array fabrication for this experiment began with a 1/4-inch chip with 16 TES devices. The posts seen in figure 1 on devices without absorbers are 150 μm in diameter and 20 μm tall. The posts are patterned on the center of each TES using a negative photo resist capable of producing thick layers and high aspect ratio features. A thin, spin-coated layer of glue is then uniformly applied on the top of all posts. Finally, the absorbers are cut into appropriate dimensions and placed in a micromachined form that aligns the absorbers for mating with the glue-covered posts of the TESs. The array used for the absorber experiment is shown in figure 1.

A detector array was prepared using four types of Sn. Column 1 contains typical absorbers consisting of 99.99% pure polycrystalline Sn purchased from

vendor #1. Column 2 contains the same Sn that has been mechanically worked to reduce the grain size. A micrograph of the Sn grains from columns 1 and 2, before and after mechanical work, are shown in figure 2. Column 3 has a 99.8% pure polycrystalline Sn absorber purchased from vendor #2. Finally, column 4 contains 99.8% pure polycrystalline Sn purchased from vendor #1. The grain size of column 4 was not measured, but is assumed to be identical to column 1. Comparison of columns 1 and 4 probes the role of impurities on the anomalous time constant.

A separate experiment was performed to address the role of other parts of the microcalorimeter besides the absorber. For this experiment a 16 pixel array was fabricated where some of the TESs had the epoxy post removed, some had the post with no glue on top, and some had the TES, post, and glue on top of the post. The volume of the glue was visually estimated to be 200-400 pL. None of these devices had an absorber.

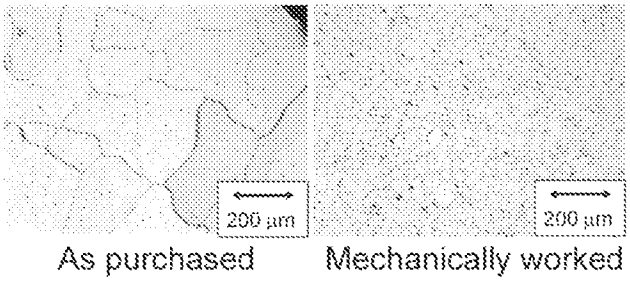

FIGURE 2. Micrographs of 99.99% pure Sn before and after mechanical work on the absorber. Grain sizes were reduced from 200 μm to 20 μm by mechanical work.

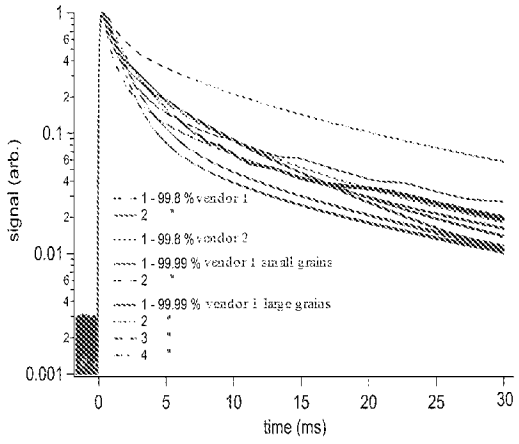

FIGURE 3. Response of microcalorimeters shown in Fig. 1. The pulses show a fast initial decay followed by an anomalous slow decay that is not explained by the thermal properties of the sensors.

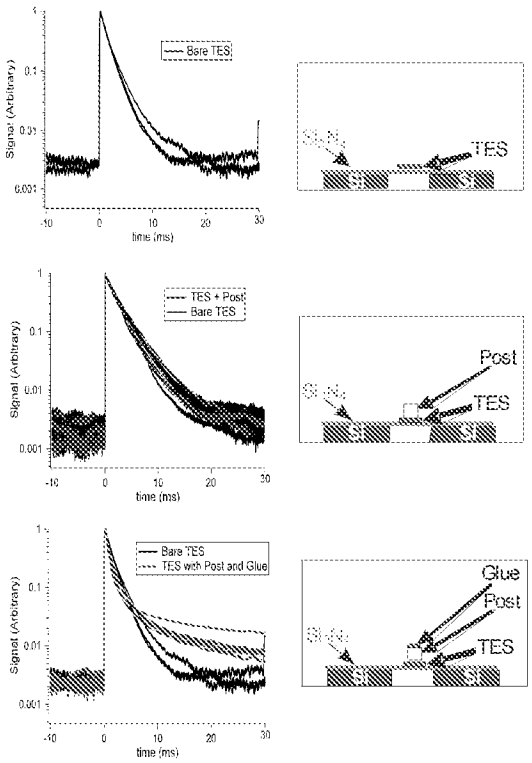

FIGURE 4. Experiment to determine role for each part of the microcalorimeter. The top of the figure shows the pulse response of a bare TES to and incoming x-ray photon, with a side view of the detector on the right. The next set of plots show the response of a TES with the epoxy post attached. The third set show the TES, epoxy post, and glue for attaching the absorber.

The sensors were cooled in an adiabatic demagnetization refrigerator. A gamma-ray photon source located outside the cryostat produced pulses in the Sn absorbers. An x-ray source inside the cryostat produced pulses in the TESs without absorbers.

RESULTS

The results of the absorber experiment are shown in figure 3. All of the pulses exhibit an initial decay of 1-2 ms consistent with the known thermal properties and a longer decay of 10-15 ms. There appears to be no dependence of the length of the anomalous decay on the absorber properties. This result suggests that quasiparticle excitations are not the source of the long decay constant since grain size and material purity are likely to affect the quasiparticle lifetime.

The results of the second experiment with sensors in various states of deconstruction are shown in Fig. 4. The bare TESs and the TESs with epoxy posts show single time-constant decays. When the glue used for

attaching absorbers is added to the posts (but without an absorber) the anomalous tail appears.

CONCLUSION

We have shown that the anomalous tail in our pulse shapes is caused by the epoxy that joins the superconducting absorbers to the micromachined posts. We have also shown that any effects of the absorber grain size, purity, and vendor on the pulse shapes are obscured by the strong effect of the glue. In order to increase the count rate of our gamma-ray sensors, we are actively exploring fabrication techniques that either use less glue, or avoid the use of glue altogether in the attachment of the absorber. We plan to reassess the effects of absorber grain size, purity, and vendor on pulse shape once the anomalous contribution of the glue has been sufficiently reduced.

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