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Multiplexed microcalorimeter arrays for precision measurements from microwave to gamma-ray wavelengths

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Abstract

Cryogenic microcalorimeters are a promising technology for ultrasensitive measurements of electromagnetic radiation from microwave to gamma-ray wavelengths. Cryogenic microcalorimeters derive their exquisite sensitivity from the minimal thermal noise at typical operating temperatures near 0.1 K. The core technology of the microcalorimeters under development at NIST is independent of the application wavelength: thin-film thermometers whose temperature and resistance change in response to absorbed energy. However, the absorbing structures used to couple radiation into the thermometers depend strongly on the application wavelength. Here, we describe microcalorimeter technology and its application to microwave, X-ray, and gamma-ray measurements. In particular, we present results from a 13 pixel gamma-ray microcalorimeter array with a coadded energy resolution of 51 eV FWHM at 103 keV and a single pixel with resolution of 27 eV FWHM at 103 keV. One application for gamma-ray microcalorimeters is to deconvolve the complex spectrum of a mixture of Pu isotopes near 100 keV.
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Keywords: Microcalorimeter; Transition-edge sensor; Gamma-ray

1. Basic technology

Microcalorimeters (microbolometers) are sensing elements whose temperature rise is used to measure deposited energy (power). A range of technologies can be used to measure the ∼.001 K temperature rise caused by the absorption of a photon (see, for example, Ref. [1]). Here, we emphasize transition-edge sensor (TES) thermometers which consist of thin-films electrically biased in the superconducting-to-normal transition where the dependence of electrical resistance on temperature is large. The TES sensors in use at NIST consist of a bilayer of molybdenum and copper with a controllable transition temperature near 0.1 K. Additional normal metal features are used to reduce noise and engineer the temperature width of the superconducting-to-normal transition [2]. An important property of TESs is the use of a stiff voltage bias; as a result, the absorption of energy produces a compensating reduction in the electrical bias power that accelerates the return of the devices to thermal equilibrium. Because of their voltage bias, TES sensors must be read out with low-noise SQUID current amplifiers. We fabricate and use sophisticated time-domain SQUID multiplexer circuits to read out many sensors with a much smaller number of amplifier channels [3]. SQUID multiplexing has enabled TES arrays larger than 1000 pixels.

2. Microwave/submillimeter

The microwave and submillimeter wavebands are exceptionally active areas of astronomical research. For instance,

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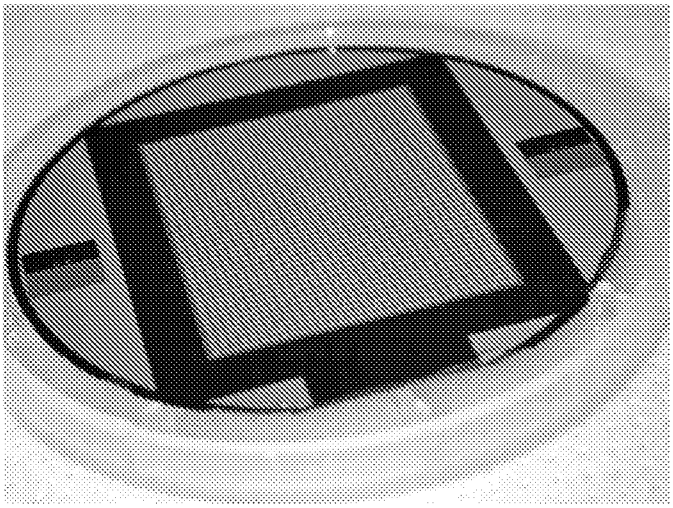

Fig. 1. About 1280 microbolometer subarray for the SCUBA2 submillimeter camera on a 3 in. silicon wafer. The full instrument will include eight such subarrays. These submillimeter pixels are similar in size to gamma-ray pixels so this photo shows the scale of a 1000 pixel gamma-ray array.

measurements of the cosmic microwave anisotropy and polarization are some of the best probes of the early universe available [4].

We are presently supplying microbolometers and/or SQUID readout circuitry for almost every planned microwave or submillimeter bolometer-based instrument including SCUBA2 (United Kingdom/Canada), Constellation-X (NASA), CLOVER (United Kingdom), the Atacama Cosmology Telescope (Princeton), the South Pole Telescope (University of Chicago), APEX-SZ (Berkeley), EBEX (University of Minnesota), PAPPA (GSFC), POLARBEAR (Berkeley), and SPIDER (JPL/Caltech). The SCUBA2 submillimeter camera is presently the largest TES instrument under development. The SCUBA2 camera will consist of eight subarrays totaling 10,240 pixels and an active area of 102.4 cm^2. Each subarray consists of an NIST-fabricated 3 in. multiplexer wafer indium bump bonded to a NIST-metallized 3 in. sensor wafer with 1280 TES bolometers (Fig. 1). To absorb submillimeter radiation, the 1 mm^2 pixels include a micromachined quarter-wave backshort and an implanted silicon absorbing layer matched to free space.

3. X-ray

The energy resolution of commercially available energy-dispersive X-ray sensors is not sufficient to resolve many closely spaced low-energy X-ray lines. However, it is precisely these lines that are excited during microbeam analysis of nanometer-scale films and particles relevant to the semiconductor industry. We have demonstrated X-ray microcalorimeters with energy resolutions of 2.0 eV FWHM at 1.5 keV and 2.4 eV FWHM at 5.9 keV, more than ten times better than commercial SiLi sensors. The X-rays are absorbed in a thin film of a high-Z material such as Bi deposited on top of the TES thermometer. Our microcalorimeters are easily able to resolve overlapping elemental X-ray peaks and can even measure certain chemical shifts indicative of the bonding state of an element. For an early review, see Ref. [5] and Ref. [6]. We presently operate X-ray microcalorimeter instruments on scanning electron microscopes at both NIST Boulder and NIST Gaithersburg. In addition, several private-sector efforts to commercialize X-ray microcalorimeters are now underway.

Microcalorimeters are also of considerable interest for X-ray astronomy and we are collaborating with NASA GSFC to develop a 1000 pixel X-ray array suitable for the planned mission Constellation-X.

4. Gamma ray

Low-temperature microcalorimeters offer spectral resolution approximately ten times better than high-purity germanium detectors for hard X-rays and soft γ-rays and thus are interesting tools for nuclear materials analysis. [7,8] In a measurement conducted at Los Alamos National Laboratory, we demonstrated an energy resolution of 52 eV FWHM at 100 keV and easily resolved the closely spaced X- and gamma-ray lines near 100 keV from the isotopes of Pu and their daughter products (Fig. 2).

In contrast to X-ray detectors, a bulk absorber is needed to stop gamma rays. Superconducting materials are attractive absorbers because of their low heat capacity and good thermalization properties (see, for example, Ref. [9]). We are using Sn absorbers approximately 0.95 mm × 0.95 mm × 0.25 mm in size. We have successfully developed micromachining techniques to attach these absorbers to thin-film thermometers and are now fabricating arrays of gamma-ray microcalorimeters for nuclear materials accounting and treaty verification applications.

Microcalorimeter arrays are required to achieve useful collection areas and count rates since individual pixels are

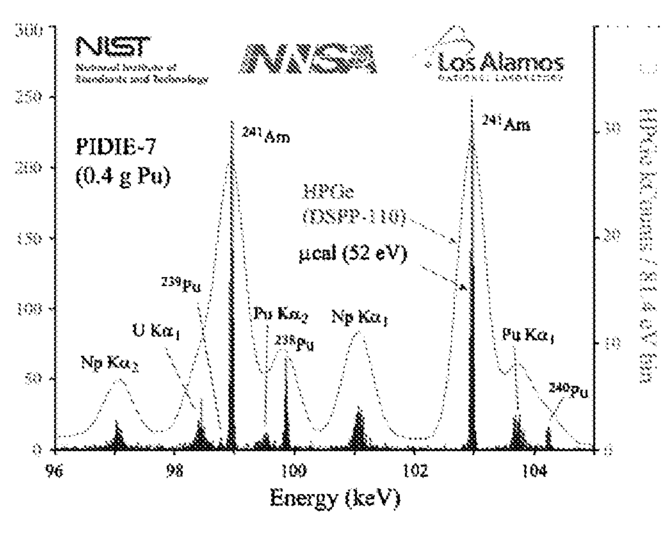

Fig. 2. Microcalorimeter and high-purity germanium spectra of a mixture of plutonium isotopes. The superior resolution of the microcalorimeter is clearly visible.

$\sim$1 mm^2 and limited to counting at $\sim$100 Hz because of thermal recovery times near 1 ms. A pair of gamma-ray microcalorimeter arrays are shown in Fig. 3 in a multiplexed testbed capable of reading out up to 128 pixels. Before proceeding to fully populate the testbed, we conducted measurements on a different pair of chips from those shown in Fig. 3 totaling thirteen active pixels. The chips were cooled to 0.05 K in an adiabatic demagnetization refrigerator and we obtained gamma-ray spectra from the pixels using a ^{153}Gd source mounted outside the cryostat. As shown in Fig. 4, the coadded spectrum of the thirteen pixels had an FWHM energy resolution of 50.6 eV at 103 keV. This result significantly exceeds the performance of high-purity germanium.

The non-Gaussian wings in the spectrum of Fig. 4 indicate that some pixels had worse resolution than the aggregate. A histogram of pixel resolutions is shown in Fig. 5. It can be seen that the pixels from chip 1 were comparatively uniform having resolutions clustered near 50 eV. The spread in pixel performance was larger on chip 2; resolutions ranged from 26.7 to 124 eV. The pixel with the best resolution, 26.7 eV FWHM at 103 keV, establishes a new performance record in this energy range.

We are studying the reason for the range of pixel resolutions. At present, we believe an important factor is the use of a common bias signal for all the sensors in order to reduce the lead count. Because of this common bias, it is not possible to bias every pixel at the same resistance or point in the superconducting-to-normal transition if the pixels are inhomogeneous. Fig. 6 shows that slight variations in the superconducting transition temperature of the pixels result in variations in the sensor resistance under common bias. Pixels with transition temperatures above (below) the average, even by a 2–3 mK, require more (less) bias power to heat to the same resistance, and consequently bias lower (higher) in the transition than

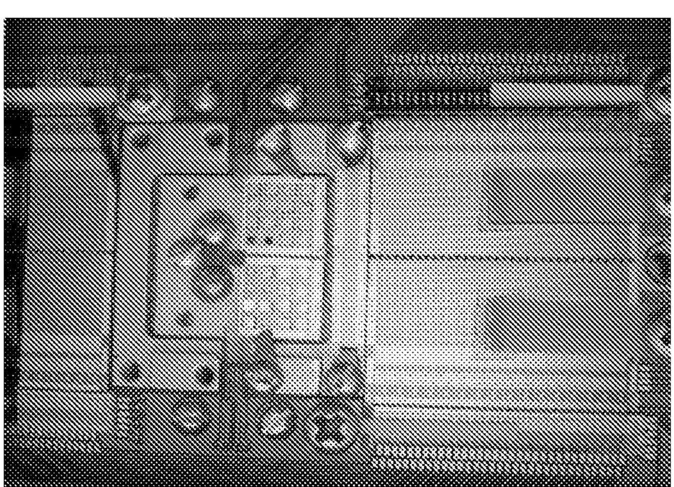

Fig. 3. Photograph of two gamma-ray array chips in multiplexed testbed. It can be seen that two pixels failed to yield on the upper chip and four on the lower. The multiplexed testbed includes four 32:1 multiplexer chips and thus has all the readout circuitry needed for 128 pixels.

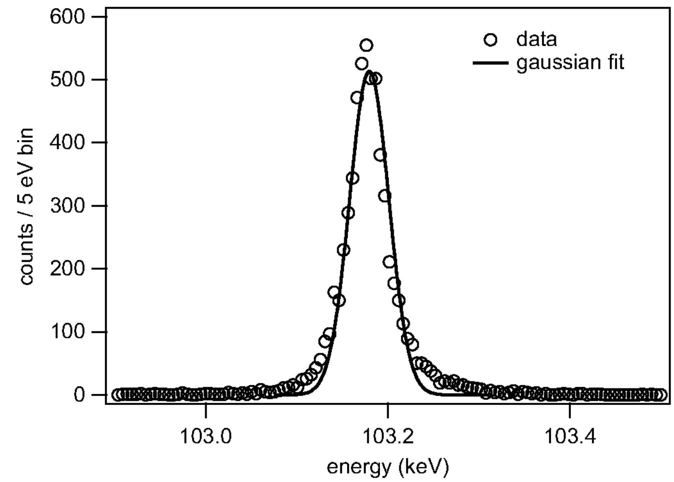

Fig. 4. Coadded spectra from 13 gamma-ray pixels demonstrating 50.6 eV resolution at 103 keV.

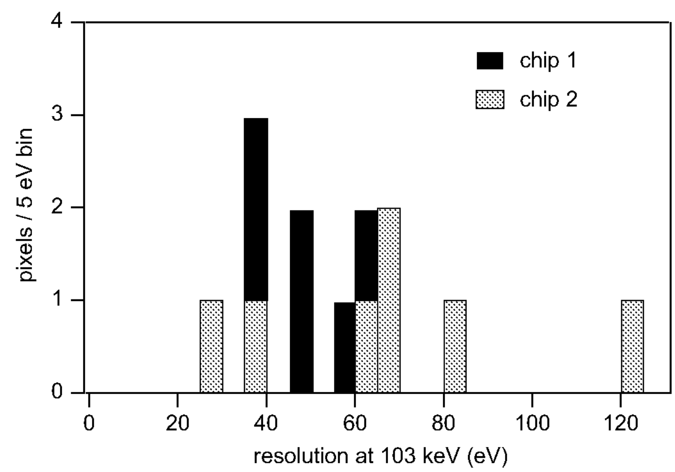

Fig. 5. Histogram of pixel count versus resolution at 103 keV. It can be seen that the resolution of sensors from chip 1 is well clustered around 50 eV, but that there is a significant spread in chip 2. Twelve of 13 pixels have resolution values below 85 eV. In addition, the pixel with 26.7 eV resolution establishes a new performance record.

pixels with the average transition temperature. Since detector response is a strong function of bias point, a spread in bias resistances results in a spread in resolutions. It can be seen that the pixels of chip 1 have the same transition temperature to within 1 mK and consequently all bias at 19–21% of the normal state resistance. In contrast, the transition temperatures for chip 2 range from 2 mK below the average to 3.5 mK above. As a result, the bias points range from 14% to 25% of the normal state value and the pixel resolutions are more inhomogeneous.

We are studying the reason for the range of pixel transition temperatures. The observed range on chip 2 greatly exceeds the variation expected from earlier measurements of witness films distributed across a 3 in. wafer. Hence, the spread on chip 2 is likely due to processing after the deposition of the transition-edge bilayer. The excellent

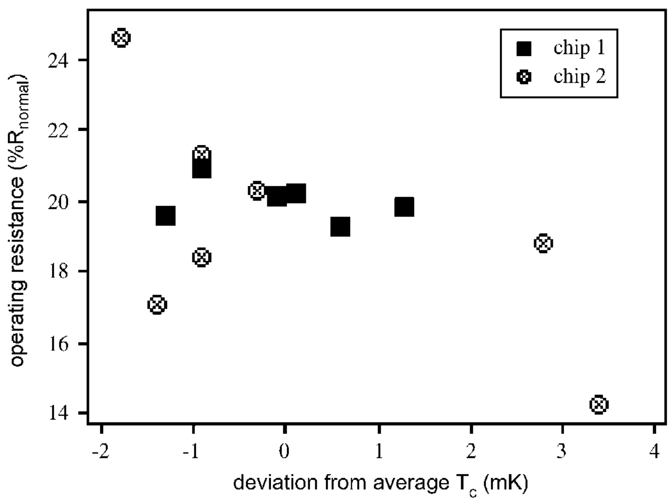

Fig. 6. Scatterplot of operating resistance (as a fraction of the normal state resistance) versus deviation from the average transition temperature. The pixels from chip 1 are well clustered, whereas a spread in transition temperatures on chip 2 contributes to a spread in operating resistances.

homogeneity of chip 1, a chip from the same wafer, also supports this theory. The only manner in which the processing of chip 1 differs from chip 2 is in the attachment of the Sn absorbers which is done on a chip-by-chip basis. We are exploring whether mechanical stresses on the bilayer introduced by the absorber attachment process caused the transition temperature variation observed in chip 2.

It is important that the software tools used to characterize arrays keep pace with array growth. We are developing tools to rapidly measure the current–voltage curves and complex impedance of all the pixels in an array. These tools will allow comparison of additional parameters such as the transition steepness and the thermal conductances within the devices of an array. These parameters play an important role in determining pixel resolution and therefore must also be characterized across an array [10].

5. Summary and future prospects

Microcalorimeters based on TESs are an attractive technology for precision measurements from microwave to gamma-ray wavelengths. We have completed a testbed with all the readout circuitry for up to 128 gamma-ray microcalorimeters. We have conducted an initial demonstration in this testbed with 13 active pixels. The coadded resolution of this array was 50.6 eV FWHM at 103 keV and one pixel had a resolution of 26.7 eV at 103 keV. We see no obstacles to the construction of arrays of 100–1000 pixels such as we have already demonstrated at other wavelengths. Using conservative estimates based on present performance figures, a gamma-ray array with 100 pixels will have a total count rate of $\sim 10^4$ Hz, a total area of 1 cm^2, and an efficiency of ~20% at 100 keV. Significant improvements in efficiency may be possible using other absorber materials. [11] A spectrometer with these performance figures will be a powerful tool for nuclear materials analysis. Potential applications include the analysis of mixtures of plutonium isotopes, the discrimination of ^{235}U from ^{226}Ra, and the measurement of Pu mass in spent reactor fuel. We are presently developing such a spectrometer for use at Los Alamos National Laboratory.

Acknowledgments

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