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ScienceDirect
Nuclear Instruments and Methods in Physics Research A 579 (2007) 161–164
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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Multiplexed microcalorimeter arrays for precision measurements from microwave to gamma-ray wavelengths

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Available online 6 April 2007

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.
Published by Elsevier B.V.

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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0168-9002/$ - see front matter Published by Elsevier B.V.
doi:10.1016/j.nima.2007.04.030

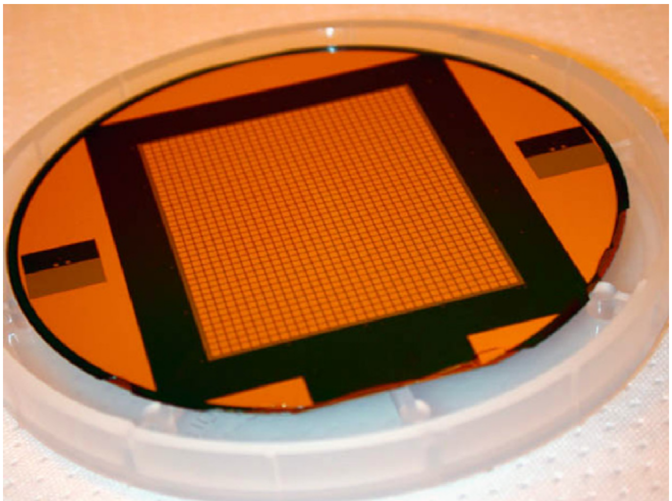

Fig. 1. About 1280 microbolometer subarray for the SCUBA2 submillimeter camera on a 3 in. silicon wafer. The full instrument will include eight such subarrays. These submillimeter pixels are similar in size to gamma-ray pixels so this photo shows the scale of a 1000 pixel gamma-ray array.

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 $\times$ 0.95 mm $\times$ 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

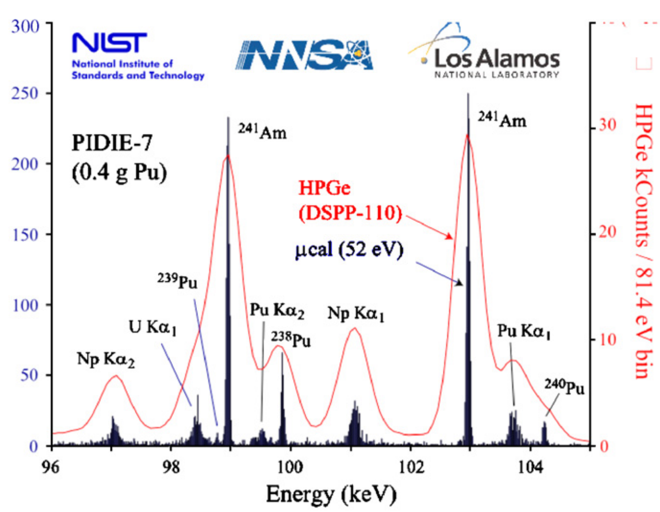

Fig. 2. Microcalorimeter and high-purity germanium spectra of a mixture of plutonium isotopes. The superior resolution of the microcalorimeter is clearly visible.