

# Making kilopixel x-ray microcalorimeter arrays a reality

#### Megan E. Eckart and W. Bertrand Doriese

Advances in high-resolution microcalorimeters, with improved readout, will enable unprecedented x-ray imaging spectroscopy.

X-rays from astrophysical objects provide a view into some of nature's most violent and extreme environments. Telescopes sensitive to 0.1–100keV photons provide unique probes of, e.g., accreting black holes and the warped spacetime around them, clusters of galaxies (the most massive gravitational potential wells in the universe), and the growth and evolution of galaxies. To study these sources we want not only to take pictures in the x-ray band but also to know the precise arrival time and energy of every photon in each picture. This 'imaging spectroscopy' allows us to derive, e.g., the temperature, velocity, composition, and mass distributions of these systems. CCDs for imaging spectroscopy on present x-ray observatories provide a moderate energy resolution of about 120eV at photon energies of 6keV. However, many unanswered questions require detector arrays with much better spectral resolution.

The next generation of astrophysical x-ray missions will deploy arrays of microcalorimeters. These detectors have an unprecedented combination of high spectral resolution and high quantum efficiency over a broad energy range (0.1–10keV). The International X-ray Observatory (IXO)<sup>1</sup> mission is currently being formulated by NASA, the European Space Agency, and the Japanese Aerospace Exploration Agency. One of IXO's primary instruments will be a high-resolution imaging spectrometer with a 5 arcminute field of view and an energy resolution of 2.5eV at 6keV. Our team, a collaboration between NASA's Goddard Space Flight Center and the National Institute of Standards and Technology (NIST), is working to develop the detector technology that will meet the mission's requirements.

## Transition edge-sensor microcalorimeters

A microcalorimeter is a type of x-ray detector designed for very high energy resolution. It consists of an x-ray absorber, a sensitive thermometer, and a weak link to a thermal bath. The absorber converts the energy of an incoming photon to heat, thus



**Figure 1.** Transition-edge-sensor (TES)-based microcalorimeters with overhanging absorbers.<sup>2,3</sup> The front-left pixel shows the 300nm-thick TES without an absorber. It is located on top of a membrane acting as the weak link to the thermal bath. The electrical bias lines (blue) are routed to either end of the TES. The middle-front pixel shows the several-microns-thick T-shaped absorber stem connected to the TES. The remaining pixels are illustrated with their absorbers in place, each of which overhangs its TES and the substrate.

raising the temperature of the absorber. Desired absorber properties include low heat capacity (to magnify the temperature rise) and high quantum efficiency. The weak link cools the device after photon absorption to reset it for the next photon. Thermodynamic noise associated with this link makes microcalorimeters work best at cryogenic temperatures. Several thermometer technologies are under development. They rely on various semi- or superconducting material properties. For the IXO imaging spectrometer we have chosen a superconducting technology: the transition-edge sensor (TES).

A TES exploits the narrow superconducting-to-normal-state transition of a thin metal film as an exceedingly sensitive thermometer. A small change in temperature creates a large change in resistance. TES microcalorimeters typically operate under voltage bias. An absorbed x-ray causes a brief increase in the TES resistance, and thus a pulsed decrease in the device current. The height of the current pulse—measured by an inductively

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*Figure 2.* Electron micrograph of a uniform  $8 \times 8$ -pixel TES array.<sup>6</sup> The closeup view on the right shows an individual pixel with its absorber hanging over the wiring and substrate.

coupled superconducting quantum-interference device (SQUID) ammeter—is proportional to the energy of the photon. A more detailed introduction is available elsewhere.<sup>4,5</sup>

Over the past few years our team developed a microcalorimeter design that incorporates a microns-thick gold (Au) or Au/bismuth absorber-designed to thermalize the absorbed energy quickly-and a TES made from a molybdenum (Mo)/Au proximity-effect bilayer. The bilayer combines a superconducting Mo film with a transition temperature of  $T_c$ =0.92K with a normal-metal Au film that pushes the combined-film  $T_c$  to lower values. The relative film thicknesses and the interface determine the final  $T_c$ . Tunable bilayers allow a device  $T_c$  around 100mK, which is compatible with many standard cryogenic platforms (e.g., adiabatic demagnetization or dilution refrigerators). Figures 1 and 2 illustrate the device architecture. These high filling-fraction, high quantum-efficiency devices consistently achieve energy resolutions of 2-3eV (full width at halfmaximum) at  $6 \text{keV}_{\ell}^{2,3}$  meeting IXO performance requirements. These results follow years of worldwide research in device physics and fabrication techniques. Constructing and reading out large arrays while retaining such exquisite performance in individual devices is a major remaining challenge.

#### Array-scale performance

The IXO reference design calls for the 5 arcminute field of view to be composed of a 2.5 arcminute kilopixel core array of microcalorimeters with 2.5eV energy resolution surrounded by an array of detectors with 10eV resolution. Last year (2008) we reached several significant milestones toward both the core and extended arrays.

The first milestone was a successful demonstration of the key technologies for the core array: better than 4eV resolution at 6keV in at least 16 multiplexed pixels. Multiplexing, in which multiple detector pixels are read out through each amplifier chain, is essential in large arrays because it reduces the



**Figure 3.** Results of a 2×8 (columns by rows) multiplexing demonstration using a Goddard array and NIST SQUID multiplexing electronics at NIST. The black points show histograms of manganese (Mn)  $K\alpha$  x-rays from an <sup>55</sup>Fe source for each pixel acquired simultaneously, with vertical offsets for clarity and fits overlaid in blue and red. The finite energy resolution of the detector broadens the natural line shape to produce the measured line shapes.<sup>6</sup>  $\Delta E_{FWHM}$ : Full-width at half-maximum energy resolution.

wiring complexity, the mass and power required for the roomtemperature electronics, and the heat load on the cryogenic stage. Figure 3 shows spectra acquired simultaneously from 16 pixels in a 64-pixel Goddard array through a NIST time-division SQUID multiplexer.<sup>6,7</sup> The average energy resolution of the 16 pixels was better than 3eV. This is a major step toward the realization of an array suitable for IXO.

Goddard is presently building a kilopixel detector array based on the successful design of the 64-pixel array. It will incorporate novel heat-sinking techniques to minimize thermal crosstalk



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**Figure 4.** (Inset) A model of a position-sensitive TES in which four pixels are formed from four absorbers and a single TES. (Graph) 6keV pulses measured experimentally by such a device. The absorbers are each connected to the TES with a different thermal link, G, so x-ray events in the four absorbers produce different pulse shapes. Analysis of the pulse height and shape yields the energy of the photon and tells which absorber the x-ray impacted.<sup>8</sup>

between pixels. The larger arrays become, the more essential it is to mitigate this potential noise source. In addition, the large array will contain compact microstrip wiring to minimize electrical crosstalk. NIST is presently working to increase the clock speed of the room-temperature multiplexing electronics and to reduce the noise and increase the bandwidth of the cryogenic SQUID amplifiers. Our next joint milestone will be to read out a  $3 \times 32$  portion of the kilopixel detector array with better than 3eV average energy resolution at 6keV.

A second milestone was to develop a detector technology satisfying the IXO outer-array requirements: to tile the rest of the 5 arcminute field of view with pixels that maintained better than 10eV energy resolution but required relatively few readout channels. We approached this problem by developing position-sensitive TES devices—see Figure 4—which join multiple absorbers to a single TES. We demonstrated an energy resolution of 6eV at 6keV.<sup>8</sup>

# Conclusion

The next generation of x-ray space telescopes—such as IXO—will require large detector arrays with exquisite energy resolution. TES microcalorimeter technology development has progressed rapidly from single-pixel experiments to demonstrations of medium-scale uniform arrays. We have successfully demonstrated a 64-pixel uniform array as well as position-sensitive TES detectors, and continue to move closer to kilopixel, flight-ready arrays.

The Goddard x-ray TES detector development is led by Caroline Kilbourne. The X-ray Microcalorimeter Group at Goddard is led by Richard Kelley, Caroline Kilbourne, and F. Scott Porter, and includes Joseph Adams, Simon Bandler, Regis Brekosky, Ari-David Brown, James Chervenak, Megan Eckart, Fred Finkbeiner, Jack Sadleir, and Stephen Smith.

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Randy Doriese is part of a broad effort spearheaded by Kent Irwin's project at NIST to develop cryogenic detectors and associated SQUID-multiplexed readout. He earned his PhD in physics from Princeton University in 2002.

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