Breakthrough Energy Resolution in Close-Packed Arrays of Superconducting Transition-Edge X-ray Microcalorimeters

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***Abstract*—We are fabricating superconducting transition-edge x-ray microcalorimeter pixels with absorbers designed to provide both rapid thermalization of the x-ray energy and a high-fill factor in arrays. We have designed absorbers that are cantilevered over the active part of the sensor itself, making contact only at normal metal features, and only in a manner that does not allow current to flow through the absorber. We mechanically stabilize the absorber via additional contact points on the silicon-nitride membrane that provides the thermal isolation for the sensor, and we have demonstrated that these contacts do not provide a significant path for energy loss. We have made absorbers with an initial evaporated gold layer followed by either electroplated gold or electroplated bismuth. With both absorber configurations, we are routinely obtaining FWHM energy resolution at 6 keV in the range 2.1 - 3.3 eV. This is an important step towards the high-resolution, high-fill-factor, microcalorimeter arrays needed for x-ray astrophysics missions such as Constellation-X.**

I. Introduction

An x-ray microcalorimeter measures the heat from the thermalization of an individual x-ray photon. At low temperatures, with low total heat capacity and a sensitive thermometer, extremely high energy resolution can be obtained [1.2]. When a superconducting transition-edge sensor (TES) is used as the thermometer, the device is operated in the narrow temperature range between the onset of non-zero resistance and the fully normal state. Irwin[3] demonstrated that a stable bias point within the sharp transition can be maintained naturally via electrothermal feedback – a change in temperature causes a change in resistance that results in a change in Joule power of the opposite sign. We use a superconductor/normal-metal bilayer and tune the critical temperature (T_c) by choice of the layer thicknesses, typically aiming for $T_c \sim 0.1$ K. We measure the change in resistance by monitoring the current through a voltage-biased TES using a SQUID ammeter.

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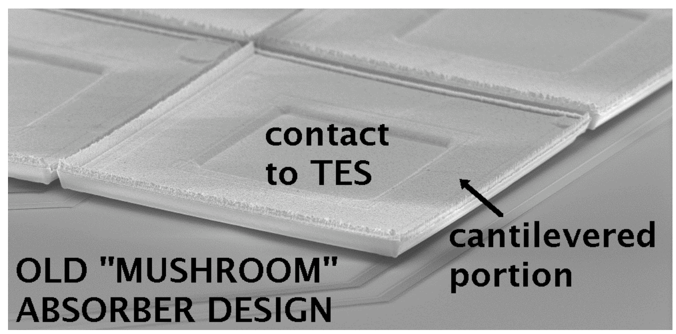


Fig. 1. Original design for the cantilevered x-ray absorbers of TES x-ray calorimeters. The central square is in direct contact with the underlying TES.

We have been producing 8×8 TES arrays with the 0.25-mm pitch of XMS for over three years. Our basic TES device consists of a 0.14-mm-square Mo/Au bilayer transition-edge thermometer, a silicon-nitride membrane to form an engineered thermal link to the heat sink, and an x-ray absorber to increase the quantum efficiency. The membranes are defined by using deep reactive ion etching (DRIE) to etch straight from the back of a silicon wafer to the front-side nitride layer. We make Mo/Au bilayers using electron-beam deposition under ultra-high vacuum conditions. Atop the bilayer we pattern additional Au features. Banks of thick Au are put along the edges parallel to the current flow to define the superconducting boundary condition and make the transition shape more uniform than if the superconducting boundary were etch-defined. Interdigitated gold stripes are oriented perpendicularly to the current flow, which has been shown to diminish the excess white noise associated with TES devices [4,5]. For most of our work in the last three years, we have been making arrays using devices with three interdigitated stripes.

In order to achieve detector-noise-limited energy resolution, the x-ray absorber must thermalize the energy of incident photons rapidly, reproducibly, and without dependence on the location of absorption. Prior to the results reported in this paper, we were making x-ray absorbers out of layers of bismuth (low specific-heat semi-metal, high opacity) and copper (high specific heat) in order to design our devices to a particular heat capacity and x-ray opacity. Implicit in this design philosophy was the assumption that the Bi thermalizes the energy of the x-rays adequately, or that any shortfall in the ability of the Bi to thermalize is compensated by the Cu layers. The Bi/Cu absorber was designed to contact a TES in the middle and extend cantilevered into the space around the TES, thus taking on a "mushroom" shape, shown in Fig. 1. The electron density of Bi is sufficiently low that it does not alter the superconducting transition of the underlying Mo/Au bilayer (in the absence of chemical interaction). However, if Cu were in direct contact with the bilayer, its high electron density would suppress the T_c. Therefore, we had to deposit Bi first.

Although a resolution of ~2 eV FWHM was predicted from models and the measured signal and noise, the best resolution achieved using this design was 4.4 eV at 6 keV. This suggested that variations in the transport of energy across the loosely packed Bi grains to the thermalizing Cu layer was limiting the resolution despite adequate diffusivity in the Cu layer. This design also proved to be vulnerable to diffusion and the formation of intermetallics at the interface between the absorber and the TES, which would alter the superconducting properties. Thus, we invented a new absorber design that would provide both robustness and good thermalization.

II. New X-ray Absorber Design

In order to avoid interface chemistry entirely, we introduced a vacuum gap between the absorber and the TES [6]. We designed absorbers that are cantilevered over the active part of the TES itself, making contact only at the normal metal features that are already part of the design. These regions are available for making good thermal contact between the TES and absorber without changing the properties of the TES. We needed to avoid any contact geometry that would place a low resistance absorber in parallel with the TES. The normal-state resistance of our TES devices is 8 – 10 mΩ, and they are typically operated at a resistance of a few mΩ. The resistance of the bottom Bi layer in our standard absorber was sufficiently high that it did not allow the absorber to shunt current from the TES, but improving the electron transport in such an absorber to accelerate thermalization could also render it an electrical shunt that would diminish the sensitivity of the device. Thus, we designed the absorber contacts not only to avoid the active region of the TES, but also to avoid contact that would provide a parallel current path through the absorber. The new absorber designs include contacts to the membrane outside of the TES to provide adequate mechanical support for the cantilevered absorber. Old and new absorber attachment schemes are shown in Fig. 2. In each of the figures, the absorber is supported only at the regions shown in red. Designs c and d have worked well, but e had a wide superconducting transition with a ~2 mΩ offset resistance. Designs f-h have not yet been tested. Fig. 3a shows the architecture of an array using design c, illustrating how absorbers are built up from such contact points. Fig. 3c is an SEM micrograph of a cross-sectioned absorber, showing clearly the contact and the overhanging regions.

Our invention of vacuum-gap absorbers is a significant breakthrough in x-ray TES technology. This design enables deposition of a high-conductivity thermalizing film as the first layer. It also enables the use of electroplating for absorber formation, since it accommodates a Au seed layer at the bottom of the absorber. Indeed, a solid Au absorber can be electroplated up from this seed layer, providing good thermalization at the expense of higher heat capacity. With 4-μm-thick electroplated Au absorbers (which corresponds to a quantum efficiency of 97% at 6 keV) we are now regularly obtaining better than 3-eV resolution at 6 keV, with the best measured result being 2.3 ± 0.2 eV. Fig. 3b shows one such array; a seed layer was evaporated into a photoresist mold, thick Au was electroplated atop this layer, the absorber edges were delineated by ion-milling, and then the photoresist was removed. Fig. 4a is an ^{55}Fe spectrum demonstrating the spectral resolution, and 4b is a histogram of the resolution obtained in 13 different pixels. These devices can be characterized as simple calorimeters with a single heat capacity and thermal conductance. Using the best-fit

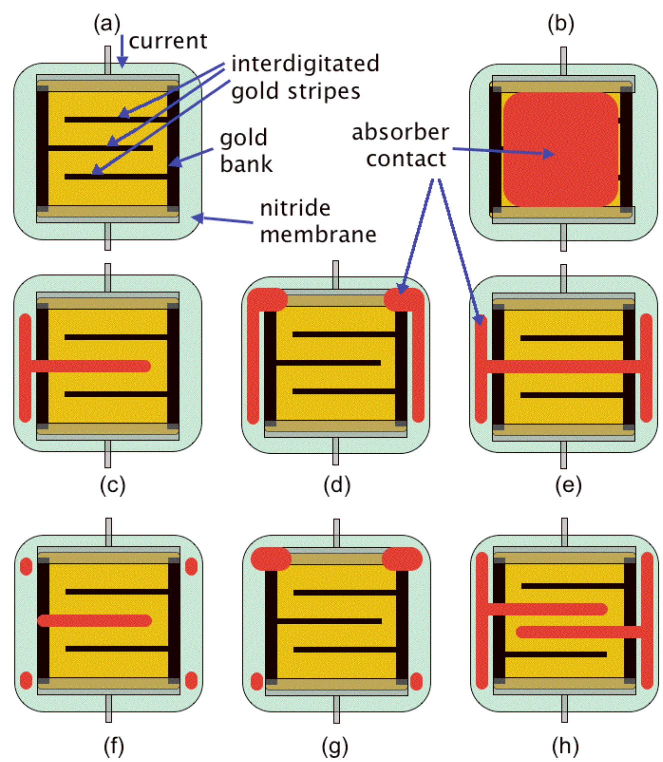
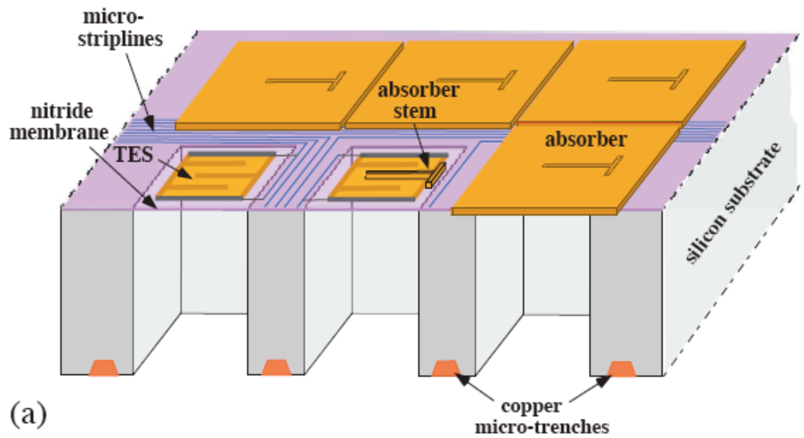
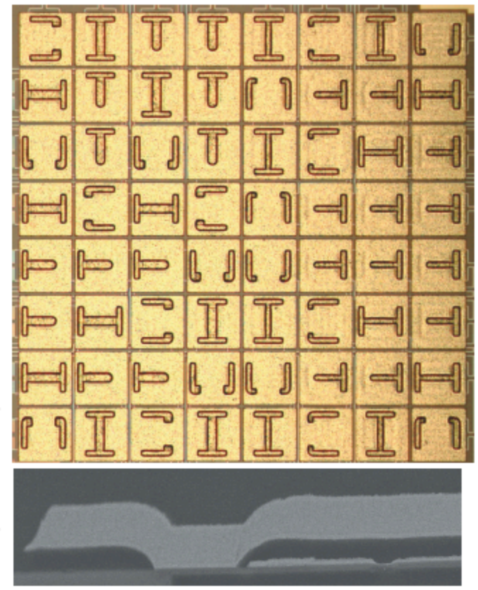


Fig. 2. Layouts of TES, nitride, and absorber contact areas; absorbers only contact at the regions shown in red: (a) bare TES with components labeled, (b) original "mushroom" contact, (c-h) vacuum-gap absorbers



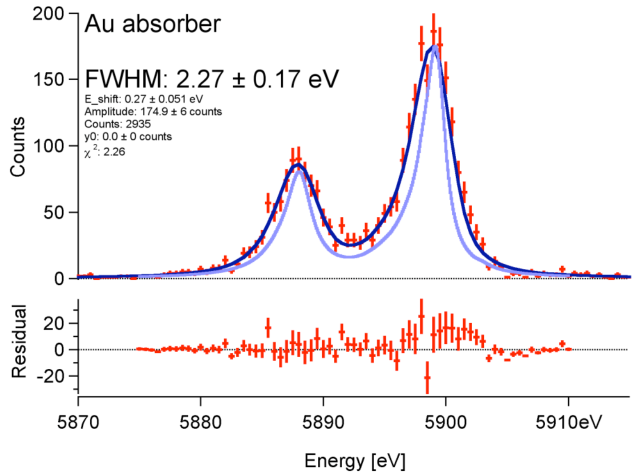
(a)



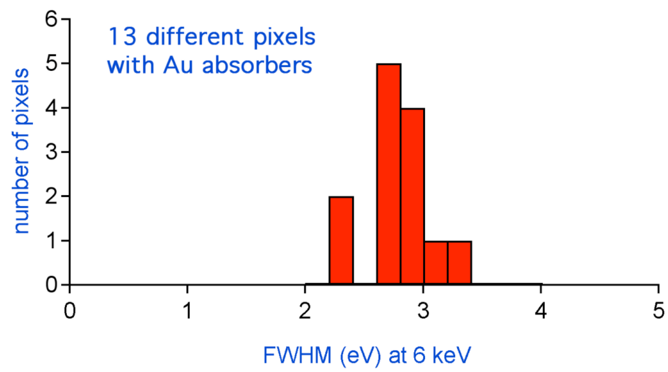
(b)

(c)

Fig. 3. (a) schematic of array structure, showing the TES's, membranes, absorbers, and silicon frame around and between the pixels. (b) photograph of 8×8 array with electroplated Au absorbers. (c) SEM of absorber cross-section, showing cantilever over the TES.



a)



b)

Fig. 4. (a) ^{55}Fe spectrum measured with a TES with a 4-µm electroplated Au absorber; data are red, fit is dark blue, natural lineshape is light blue. (b) distribution of resolutions measured with thirteen different gold-absorber pixels.

parameters to complex-impedance [7] and current-voltage measurements, the predicted resolution is 2.3 eV.

We have made similar arrays in which we plated only 0.5 µm of Au on a 0.2-µm Au seed layer, then electroplated 6 µm of Bi atop that. The electroplated Bi has larger grains (5-10 µm) and a factor of 10 lower electrical resistivity than our evaporated Bi films. We measured 2.1 ± 0.1 eV FWHM at 6 keV (Fig. 5) with such a device; the noise level and slope of the gain curve suggest that 1.4-eV resolution should be possible at low energies. When we made vacuum-gap absorbers with the same Au and Bi thicknesses, but evaporated both metals instead of electroplating, we obtained 4-eV resolution and a low-energy shoulder on the instrument response. Thus, it is the combination of the vacuum-gap design and the high-quality absorbers possible through electroplating that is the critical breakthrough.

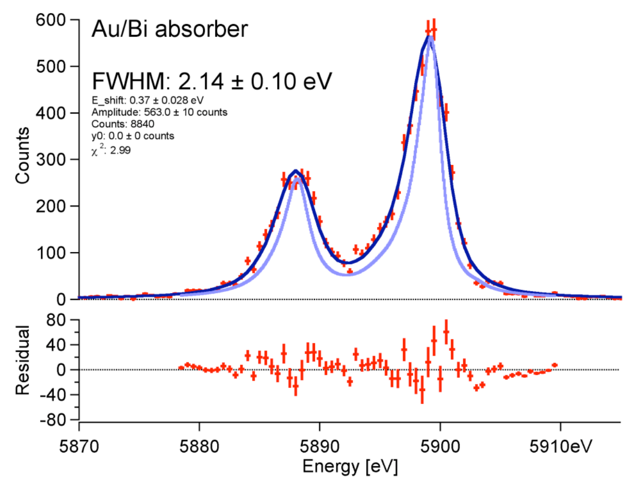


Fig. 5. ^{55}Fe spectrum measured with a TES with an electroplated Au/Bi absorber (0.7 µm Au and 6 µm Bi). Data are red, fit is dark blue, natural lineshape is light blue

III. NEXT STEPS

The invention of electroplated vacuum-gap absorbers represents a significant advancement of the readiness of the reference detector technology for the XMS instrument on Constellation-X. A uniformity demonstration (16 pixels in one array) is scheduled for later this year. Although optimization of the pixel design will continue, the next milestones deal with the electrical and thermal design of large arrays.

REFERENCES

[1] S.H. Moseley, J.C. Mather, and D. McCammon, "Thermal Detectors as X-ray Spectrometers", J Appl. Phys. 56, 1257, 1984.

[2] C.K. Stahle, D. McCammon, and K.D. Irwin, "Quantum Calorimetry," Physics Today, 52, 32, 1999.

[3] K.D. Irwin, et al., "X-ray Detection Using a Superconducting Transition-edge Sensor Microcalorimeter with Electrothermal Feedback", App. Phys. Lett., 69, 1945, 1996.

[4] M.A. Lindeman, et al., "Characterization and reduction of noise in Mo/Au transition edge sensors", Nucl. Inst. and Meth. A, 520, 348, 2004.

[5] J.N. Ullom, et al., "Characterization and reduction of unexplained noise in superconducting transition-edge sensors", Appl. Phys. Lett., 84, 4206, 2004.

[6] C.A. Kilbourne, et al., "High-density arrays of x-ray microcalorimeters for Constellation-X", SPIE, 6266, 626621, 2006.

[7] M.A. Lindeman, et al., "Impedance measurements and modeling of a transition-edge-sensor calorimeter", Rev. Sci. Inst. 75, 1283, 2004.