Technology Development for Diffuse X-ray Science: Cryogenic Microcalorimeter Detectors and High Efficiency Infrared/Visible/Ultraviolet Blocking Filters

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Abstract- **Our investigations of the diffuse X-ray background funded by the Science Mission Directorate (SMD) have always included technology development as a major component. The technology advances are required to make progress on our own science, but most of them are also applicable to future SMD missions addressing several NASA objectives. Since a science investigation requires many different technologies, we have been working in several areas and report here on those related to cryogenic microcalorimeter detectors and filters. The detector work includes studies of thermometer physics and thermalization efficiency and heat capacity in absorbers for low energy X-rays. The filter work is motivated by the need to obtain high spectral resolution data down to photon energies as low as 60 eV for interstellar plasma diagnostics. We describe the development of a monolithic silicon mesh support structure that allows us to fly thin large area filters with very high transmission on our sounding rocket experiment. These same support meshes will allow filters with vastly improved low energy response to be sufficiently robust to be flown on high-value major missions, where they have been considered too risky in the past. The filter supports include an integrated deicing heater that can be used to safely remove in-flight contamination buildup such as that which has severely degraded detector performance on the Chandra and Suzaku X-ray missions.**

I. Introduction

Our goal is to study the diffuse soft X-ray background as a necessary part of understanding the interstellar medium and its effects on both the life cycle of stars and the origin of the elements. Sounding rocket experiments discovered the presence of Galactic emission at energies below 1 keV in the late 1960s [1, 2, 3]. Later studies revealed that this diffuse emission has several sources, most of which are still not well identified [4]. The diffuse soft X-rays could be produced by a variety of mechanisms with profoundly different implications for the nature of the interstellar medium.

Learning about the interstellar medium through studying the soft X-ray background sets some unique requirements on the technology. One requirement is the need for high spectral resolution coupled with high throughput. High resolution is critical for resolving atomic emission lines in order to understand the astrophysical X-ray emission mechanisms. Observing an extended low surface brightness source requires a very large throughput.

Previous technologies are unable to satisfactorily meet these needs. Dispersive spectrometers have excellent energy resolution, but lack sufficient throughput. Non-dispersive spectrometers such as solid state detectors and CCDs can have a high throughput, but have inadequate energy resolution. The recent development of thermal calorimeters capable of resolving the energy deposited by single photons avoids the fundamental limitations of ionization statistics and opens the possibility of excellent spectral resolution combined with the high throughput of non-dispersive detectors.

Developing this technology allows us to study the soft X-ray background from sub-orbital rockets and also lays the groundwork for state-of-the-art detector systems for future satellite missions. Our work advances the technological capabilities of the nation as well as improves scientific understanding.

II. Cryogenic Microcalorimeter Detector Technology

A. Microcalorimeter Description

There are three basic parts to a cryogenic microcalorimeter as can be seen in Fig. 1: an absorber to stop the photon and contain its energy, a thermometer to sense the absorber temperature, and a weak thermal link to cool the detector to a fixed temperature. When an incoming X-ray hits the absorber, its energy is converted to thermal phonons. Initially, this will cause the detector temperature to rise. Due to the weak thermal link, the temperature gradually falls back to the fixed bath temperature. This basic model assumes the calorimeter is one piece at one temperature [5]. Much of our work with calorimeters requires moving beyond this assumption.

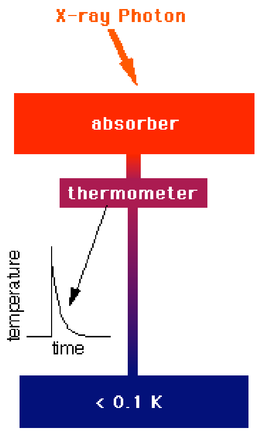

Fig. 1. The three basic parts of a calorimeter are an absorber, a thermometer, and a weak thermal link connecting the detector to a heat sink. The inset shows the behavior of temperature with time after the absorption of an incident photon.

The absorber needs to satisfy several requirements. One is to absorb and fully thermalize incident X-rays. In order to maximize the temperature change for a given absorbed photon, it also needs a low heat capacity. Finally, positional uniformity is required across the absorber.

The thermometers need to be extremely sensitive at low temperatures. They should have a small heat capacity so as not to add significantly to that of the absorber.

In addition to requirements of the absorbers and thermometers, the connection between them must be taken into account. The presence of a weak thermal link introduces unavoidable thermodynamic fluctuation noise. Also, the strength of the thermal conductance in conjunction with the heat capacity sets the time constant for the system.

Since microcalorimeters are thermal devices, they are sensitive to any energy including that deposited by infrared (IR) photons radiated from mirrors or other parts of the instrument. Thermal radiation from room temperature must be attenuated by a factor of greater than 10^9 or shot noise from these photons will dominate the detector noise. The challenge is to develop filters that can provide this large attenuation in the IR and lesser amounts in the visible and ultraviolet (UV) while still maintaining a reasonable transmission for the 0.05 – 1.0 keV X-rays that are of interest for many astrophysics targets.

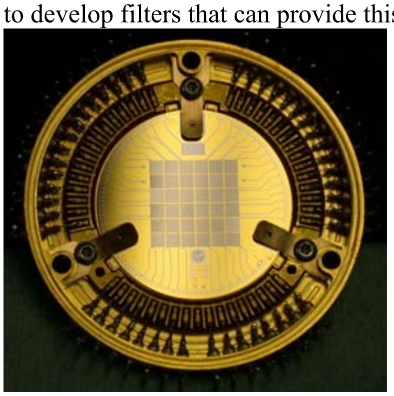

Fig. 2. Microcalorimeter array for the upcoming X-ray Quantum Calorimeter sounding rocket flight. The array has 36 pixels with 2mm x 2mm HgTe absorbers.

An example of how we are currently addressing the requirements for calorimeters is shown in Fig. 2. This picture is of the microcalorimeter detector array for the upcoming X-ray Quantum Calorimeter (XQC) sounding rocket flight. The array has 36 pixels with 2 mm x 2 mm HgTe absorbers. The array is micromachined from a single piece of silicon with ion-implanted doped silicon thermometers. The absorbers are glued on by hand.

B. Furthering The Development Of Technology

Our contributions to furthering the development of technology have a variety of forms. We study the physics of microcalorimeters to understand how they work. To predict how well they should work, we model the physics. We work on fabrication techniques to achieve the required characteristics. Additionally, we characterize the microcalorimeters to see how well the requirements are met. In the following paragraphs, we discuss these contributions as appropriate to the topics of absorbers, thermometers, thermal transport, calorimeter modeling, and IR/visible/UV blocking filters.

1) Absorbers: Much fabrication and testing is done to find absorber materials that have a low heat capacity, but are conducive to complete thermalization of incident photons. Materials such as metals thermalize well, but in general have too high a heat capacity. We make absorbers just thick enough to have high quantum efficiency over the required energy range. Bi and HgTe are two materials that were tested as potential XQC absorbers [6]. To find the heat capacity, the measured complex impedance of the thermistor was fit with a thermal model of the detector. In general, Bi was found to have a heat capacity too high for our purposes [7]. HgTe was better, but still a factor of three above its theoretical minimum value. This is usable for the upcoming XQC flight, but we continue a program to see if this can be further reduced. Getting to the theoretical minimum heat capacity should result in an additional improvement in energy resolution by almost a factor of two.

2) Thermometers: In elementary calorimeter theory, the thermometer is considered to be an ideal thermistor with resistance a function only of temperature, Johnson noise as the only intrinsic noise source, and no intrinsic time constants [5]. We have undertaken a systematic study of the fundamental behavior for doped semiconductor thermistors and have characterized three types of non-ideal behavior that limit detector performance. All of these appear to be intrinsic to the variable-range hopping conduction mechanism [8]. These include 1/f fluctuations in resistance [9, 10], limited thermal contact between the electron and phonon systems, and a separate heat capacity of the electron system resulting in an intrinsic time constant [9, 11, 12]. All of these tend to make detector performance worse than that predicted by simple calorimeter theory. However, by understanding and characterizing these behaviors, designs can be optimized and the ultimate performance for a given set of application requirements can be predicted. For example, 1/f noise was determined to be a 2-D effect that can be made negligible through appropriate choice of thermistor geometry.

We are currently undertaking a similar investigation of non-ideal behavior in transition-edge sensor (TES) detectors. This includes modeling the TES excess noise as a series of resistors fluctuating between superconducting and normal states [13] and characterizing the excess noise in an unsuspended TES [14]. We recently produced the first complete map of the superconducting transition of a TES three dimensionally in terms of temperature and bias current as seen in Fig. 3 [15]. We are also producing similar maps of heat capacity variations within the transition and intend to study excess noise this way as well.

3) Thermal Transport: With large area absorbers, energy resolution can vary with position on the absorber. While we are not yet able to realistically model heat propagation in absorbers, it is clear that energy resolution in the presence of position dependence can be optimized by varying the thermal conductivity between the absorber and the thermometer. If this thermal conductivity is low, the absorber has time to reach an internal equilibrium before the thermometer registers the temperature change.

We have made position dependence measurements to find optimal values empirically. Our absorbers are held above the thermistors with mounting tubes made of SU8 epoxy. In initial tests of the position dependence, the tubes were all located close to the center of the absorber. By scanning a 300 micron diameter X-ray spot across the absorber, a map was made of the pulse height as a function of position. It was found that significant position dependence occurs with variations in pulse heights of up to roughly 50 eV across the absorber [7]. A new design has been put in place where the mounting tubes are arranged equidistantly between the center and the corners. This minimizes the distance the phonons must travel before being detected by the thermistor.

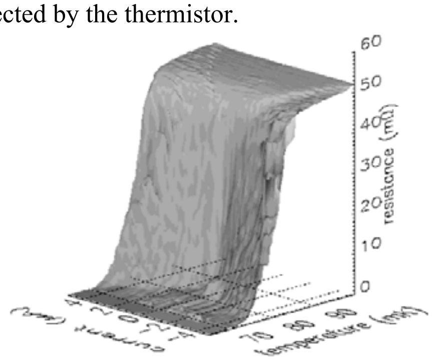

Fig. 3. This surface maps the temperature and current dependence of the resistance of a transition-edge sensor. These data can be used to choose an operating configuration that maximizes sensitivity.

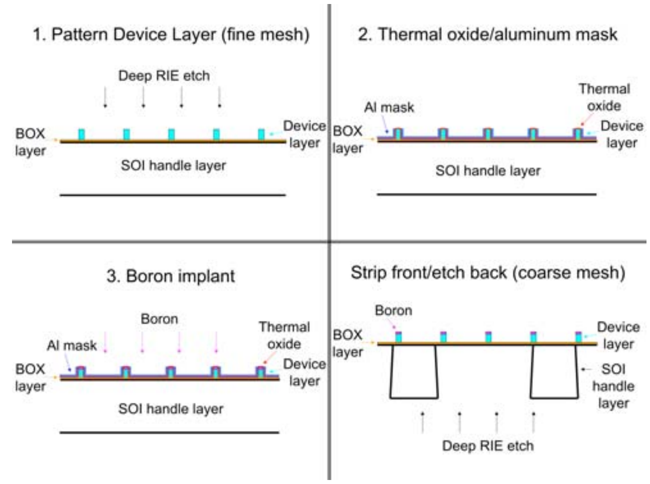

Fig. 4. A schematic of the fabrication steps. The starting material is an SOI wafer with a device layer and handle layer connected by a BOX layer. Initially, the fine mesh is patterned into the 8 μm device layer on the top of the SOI wafer. The fine mesh is then masked off for the deicing heater's boron implant. Finally the aluminum mask is removed and the coarse mesh is patterned into the 200 μm handle layer on the bottom of the wafer. The newly exposed BOX layer is then removed to free the filter.

4) Improving Microcalorimeter Theory: If the thermal and electrical properties of a detector's components are known, its performance can be predicted and optimized. To this end, we have extended the standard microcalorimeter and bolometer model. We have developed algebraic representations of models that include thermal decoupling in the thermometer between the phonons and the electrons, thermal decoupling between the thermometer and the absorber, and non-ohmic thermometer behavior [16, 17, 18]. This more accurately predicts the behavior of real microcalorimeters. We have also developed a practical method for precisely measuring the thermal parameters of a microcalorimeter that is now widely employed. This method utilizes measurements of the complex ac impedance of the thermometer to help determine the heat capacity, thermal time constants, thermal resistance, and sensitivity [19]. One recent advance is an improved method in accounting for stray reactances in the electrical measuring circuit [20].

5) IR/Visible/UV Blocking Filters: To maintain the high energy resolution of the calorimetric detectors, ambient IR radiation must be attenuated by about a factor of 10^9. The difficulty is in maintaining a reasonably high transmission for the very interesting soft X-rays.

Our previous rocket filters used 100 nm parylene films mounted on titanium rings. Filters were made of a layer of roughly 20 nm of aluminum deposited on a thin plastic film. While soft X-ray transmission was reasonably high in these filters, they were extremely delicate to handle. For this reason, they were considered too much of a risk for satellite missions and the filters for the X-ray Spectrometer detectors on ASTRO-E had to be made considerably thicker.

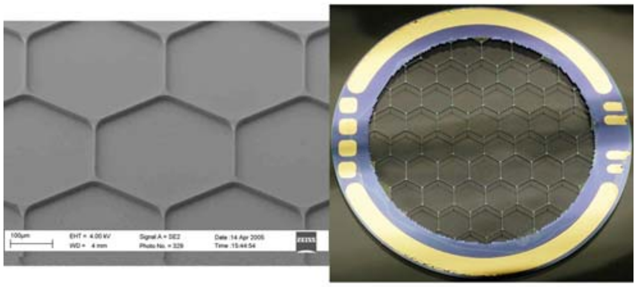

Fig. 5. *Left:* Close-up of the 350 µm pitch silicon support mesh. *Right:* A complete support mesh. The thicker backing mesh has a pitch of 5 mm and net transmission for the pair is 95%. The gold contacts are electrical connections for the integrated deicing heater.

In order to make a more mechanically robust filter, we have been developing a monolithic silicon support structure comprising of a fine with a 350 µm pitch supported on a backing mesh with a 5 mm pitch. We have included in the

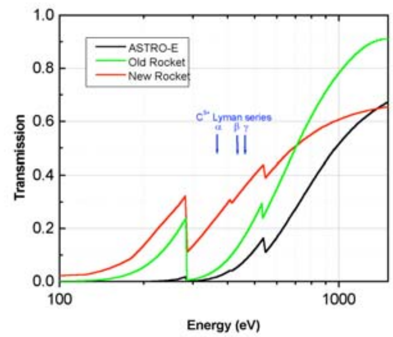

Fig. 6. Transmission of the new mesh-supported filters compared to those used for the ASTRO-E mission and a previous XQC flight.

fine mesh an integrated deicing heater. The starting material is a silicon-on-insulator (SOI) wafer consisting of two single-crystal silicon layers. One layer, called the device layer, is

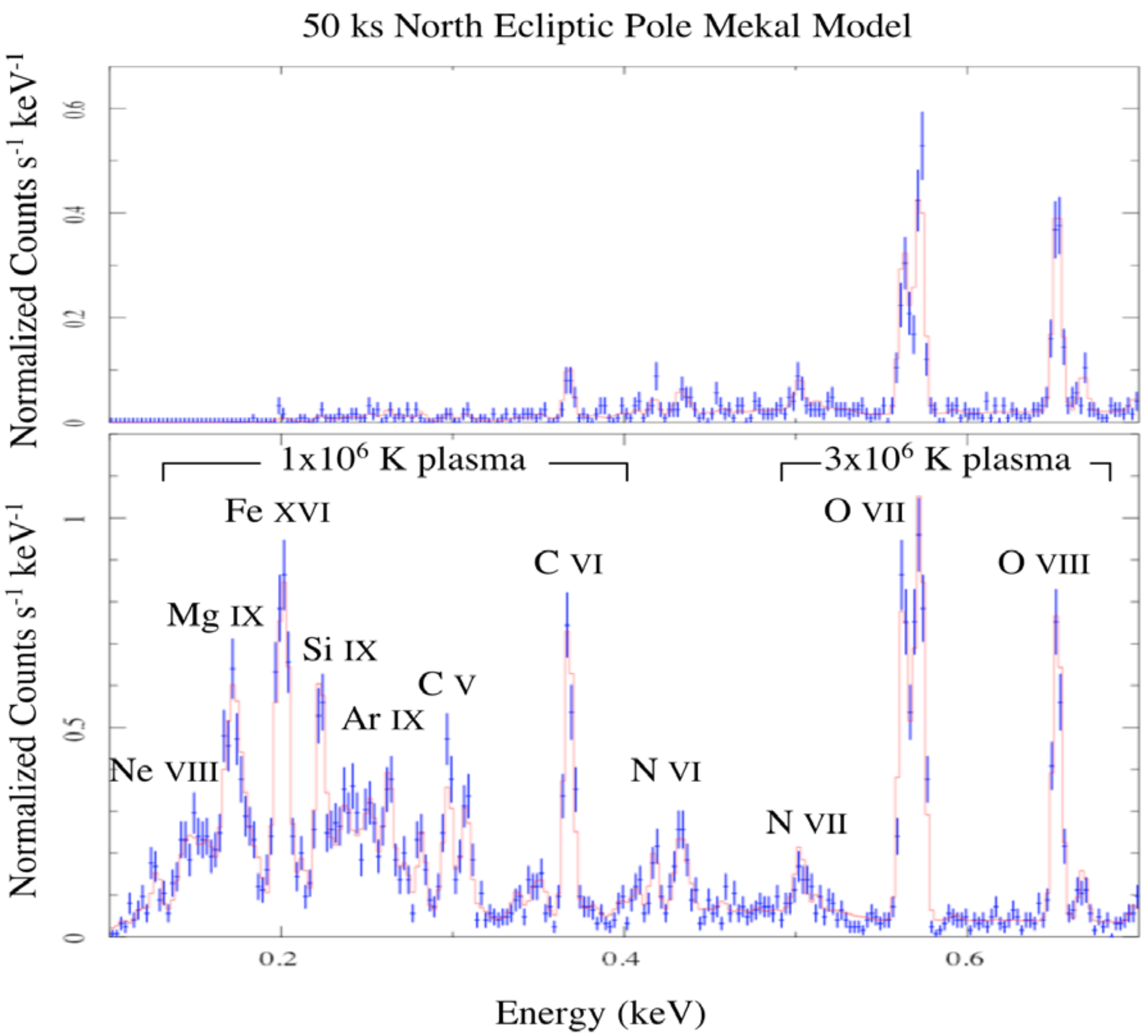

Fig. 7. Model spectrum from a calorimeter instrument proposed for an all-sky survey mission in 2011. This is the multi-component spectrum fit to Suzaku observations near the North Ecliptic pole and show lines expected from interstellar plasmas at different temperatures along the line of sight. The lower panel shows the result using the very thin filters enabled by the new silicon support meshes. The upper panel shows the same observation using the filters from the ASTRO-E mission. Note that there is almost no information about the ubiquitous 1x10^6 K component.

8 μm thick. The other is the handle layer with a thickness of 200 μm. These are connected by a buried silicon dioxide (BOX) layer. For fabrication, the first step is etching the fine mesh into the device layer. The fine mesh is then implanted with boron to provide the deicing heater. Next the coarse mesh is etched into the handle layer. Finally, the exposed BOX layer is removed, leaving only the parts connecting the two meshes. This process is outlined in Fig. 4. A close-up of the fine mesh is shown along side a complete mesh in Fig. 5.

With this support mesh we can use an even thinner 50 nm polyimide film. This improves the high X-ray transmission, particularly in the very interesting low energy range (see Fig. 6). Model spectra are shown in Fig. 7 for comparing transmission using filters from the Astro-E mission with the new silicon mesh supported filters. The mesh greatly increases the robustness of the filter, making the technology feasible for satellite missions.

The heater allows removal of any contamination that builds up during flight, preventing the kind of the contamination that has degraded detector performance on both Chandra and Suzaku.

III. Conclusions

Our technology development program works on improving and developing cryogenic microcalorimeter detectors and UV/visible/IR blocking filters. Through studying the thermalization efficiency and heat capacity of the detectors, we can assess the optimum materials to use in absorbers and the feasibility of using large-area absorbers. By studying the fundamental physics of doped semiconductor thermistors, we were able to understand and model for their non-ideal behaviors. Our work on characterizing the complex impedance of microcalorimeters developed a technique to test their performance. The development of a mesh-supported filter with a deicing heater greatly improves the low energy X-ray transmission while making it more safe and secure for flight.

Developing the technology to support our own science also supports major NASA objectives. Both microcalorimeters and filters have great potential for future SMD missions such as Constellation X. IR/visible/UV filters have a high X-ray transmission, contamination-reducing deicing heaters, and the mechanical strength for satellite missions. These technologies add to the nation's technological capabilities and advance its scientific understanding.

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