Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER
Nuclear Instruments and Methods in Physics Research A 520 (2004) 285–288
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

Design of transition edge sensor microcalorimeters for optimal performance

S.R. Bandler[a,b,*], E. Figueroa-Feliciano[b], C.K. Stahle[b], K. Boyce[b], R. Brekosky[b], J. Chervenak[b], F. Finkbeiner[b], R. Kelley[b], M. Lindeman[a,b], F.S. Porter[b], T. Saab[b]

[a] Department of Astronomy, University of Maryland, Greenbelt, MD 20771, USA
[b] NASA-Goddard Space Flight Center, Code 662, Greenbelt, MD 20771, USA

Abstract

We have developed a model for transition edge sensors to optimize performance under a variety of different conditions. There are three design trade-offs when engineering a microcalorimeter for a particular application: energy resolution, energy range and maximum count rate. All three are interdependent and are determined by various design parameters such as the detector heat capacity, the sharpness of the transition, and the thermal conductance of the detector to the frame. Our model includes all known sources of intrinsic noise in our calorimeters including the observed broad band excess noise. We will present the results of this model, and its predictions for optimally designed microcalorimeters.

PACS: 07.85.F; 07.07.D; 85.25

Keywords: Microcalorimeters; Superconductivity

1. Model description

The optimal design of transition edge sensor (TES) microcalorimeters is typically based upon the assumption that the only significant noise sources are the thermodynamic noise sources, the Johnson noise of the detector (N_J), and the amplifier noise—most often included as the SQUID noise. However, recent results indicate that a wide bandwidth "excess" noise exists that cannot be explained by this model. Recent attempts to suppress this excess noise are encouraging [1,2], however, it may not be possible remove all sources entirely. We have modeled the microcalorimeters we are developing for the Constellation-X mission that includes "excess" noise, which we can empirically adjust. In addition we included all other possible thermodynamic noise sources that may exist due to thermal fluctuations between the large number of thermal systems in our detector design. We discuss the achievable performance under a variety of different conditions and also present analysis of the change in expected performance when different design parameters are adjusted from their optimum value.

In our modeling software, we input all known heat capacities and thermal conductances between

*Corresponding author. Department of Astronomy, University of Maryland, Greenbelt, MD 20771, USA.
E-mail address: sbandler@milkyway.gsfc.nasa.gov (S.R. Bandler).

0168-9002/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2003.11.239

the different thermal systems, and how each of them varies with temperature. We also added details about the read-out circuit such as the shunt resistance R_{sh}, the inductance of the input circuit, the normal resistance of the TES, the logarithmic temperature dependence of the TES resistance (α), and details about the amplifier noise. Our modeling software is able to calculate the TES current–voltage characteristic, the detector noise spectrum (including all thermal noise terms), the noise equivalent power, the expected energy resolution, the expected impedance variation, and the expected pulse shape. This pulse-shape is calculated in two ways. In the first, it is calculated based upon the assumption that the superconducting transition is a purely linear function. In the second, the transition is assumed to have the shape of a hyperbolic tangent function with a slope that matches the α given at the 50% bias point.

2. Model results

For Constellation-X, we have designed a reference detector that meets the count rate and energy bandwidth requirements, which places limits on the achievable energy resolution of the detector. The detector has a 300 μs decay time and a linear region defined such that an 8 keV X-ray corresponds to a resistance excursion from the optimum bias point to 80% of the transition. Fig. 1 shows the expected noise spectrum for the Constellation-X TES microcalorimeter where the excess noise is 3.4 times higher than the N_J at the 30% bias point. To calculate the expected resolution shown of 2.0 eV for any energy X-ray up to 8 keV, all the noise contributions listed in the caption are included to determine the noise equivalent power as a function of frequency. The heat capacity of the absorber was 1.7 pJ/K and α was 125. In Fig. 2 we show how the energy resolution changes assuming that the excess white noise (N_{ex} increases for lower regions of the transition, and varies approximately as $N_{ex} \sim N_J r^{-3/2}$, where N_J is the calculated Johnson noise and r is the proportion of total resistance in the transition ($r = R/R_0$). This is an empirical relation that fits the variation of our noise data reasonably well. The magnitude of N_{ex} is labeled by how large each noise level is compared to N_J at 50% bias. At each bias point we have adjusted C and G (for fixed α) so that the reference time constant and energy bandwidth are maintained. This is reasonable since the required C is substantially larger than C for absorber materials such as bismuth. It is clear that even with

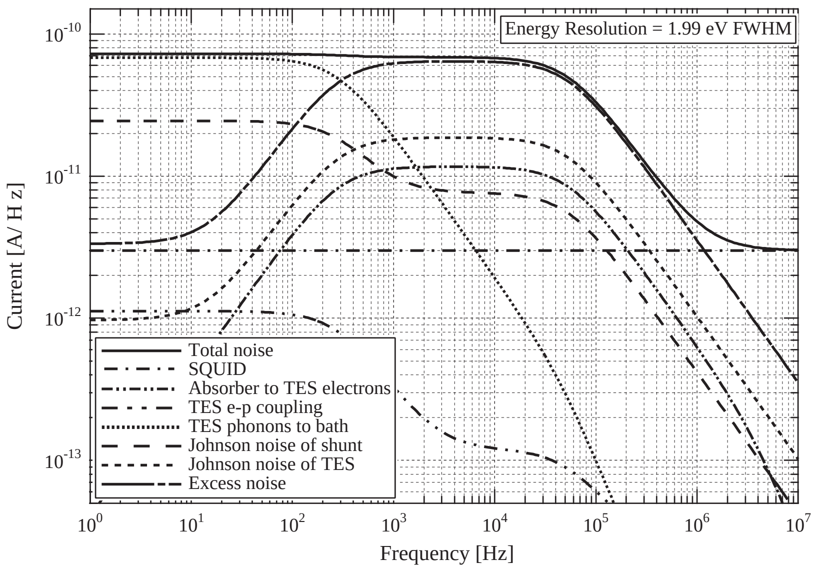

Fig. 1. Expected noise spectrum from a TES microcalorimeter.

substantial excess noise, the required energy resolution for Constellation-X of 4 eV is still achievable, and when the excess noise is still twice as large as N_J, the goal of 2 eV can in principle be met. Similar modeling suggested that, in the absence of unexpected additional noise sources and with a somewhat conservative excess noise level of three times the Johnson noise at the 30% bias point, the energy resolution of a detector optimized for photons up to 1 keV could have a resolution as low as 0.6 eV, and a hard X-ray detector with 90% quantum efficiency at 60 keV could have an energy resolution as low as 8 eV depending on the thermalizing properties of the absorber. In Fig. 3 we show how the energy resolution is affected when one of the design parameter values for the optimum resolution is not met. The resolution (and dynamic range) is affected most dramatically when either the heat capacity or α is not the designed value. However, as expected, the resolution is independent on the ratio C/α.

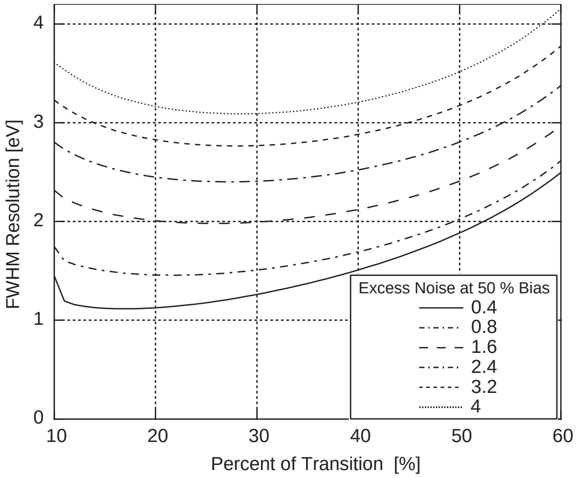

Fig. 2. Energy resolution versus operating point in superconducting transition for different levels of excess noise. C is adjusted at each bias point so that each case has the same saturation energy.

3. Optimum bias

It is possible to calculate the optimum bias point for a TES detector that has a fixed critical temperature, thermal conductance, and slope of the transition (dR/dT) when there is an excess white noise level (N_{ex}). Again we assume that heat capacity is a free parameter chosen to match the designed bias point. Since the white noise level typically increases as the position on the transition

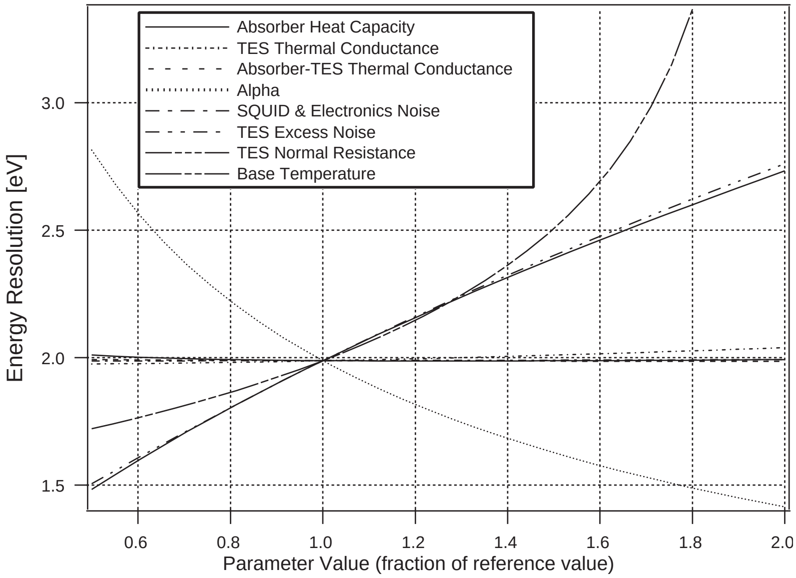

Fig. 3. Energy resolution as a function of normalized variations in the design parameter values.

decreases, we can define this variation as a generalized power law: $N_{ex} \propto N_J \times r^{-m}$ where m is variable. Since electro-thermal feedback effects the phonon noise and white noise equally, we can consider just the non-feedback case. The energy resolution is determined by the signal-to-phonon noise ratio over a bandwidth up the frequency where the phonon noise is equal to the white noise—f_{max}. Then

$$N_{ph}(f) = N_{ph}(0)\frac{\sqrt{1+f^2}}{1+f^2} \sim \frac{N_{ph}(0)}{f}. \tag{1}$$

This gives us $N_{wh} \sim N_{ph}(0)/f_{max}$, and so

$$dE \propto \frac{1}{\sqrt{f_{max}}} \propto \sqrt{\frac{N_{ex}}{N_{ph}(0)}}. \tag{2}$$

Thus dE is minimized if $N_{ex}/N_{ph}(0)$ is minimized. Now $N_{ph}(0) \propto \alpha/C \times \sqrt{R}$. By definition $\alpha \propto 1/R$. $C \propto 1/(1-r)$ is a reasonable approximation for the case of the optimum design, where we utilize as much of the transition region as we can with constant dR/dT. Thus minimizing dE leads to

$$r = \frac{m-1}{m}. \tag{3}$$

So for $m = \frac{3}{2}, r = \frac{1}{3}$; for $m = 2, r = \frac{1}{2}$; and $m = \frac{5}{2}, r = \frac{3}{5}$. Since we typically find that $m = \frac{3}{2}$ in our devices, our optimum resolution should be obtainable when the TES is biased at 33% of the full resistance. This is roughly in agreement with what we found for the optimum bias using the model, shown in Fig. 2. When $m \leqslant 1$, this formula breaks down, as this is the case where it is best to bias the TES as low in the transition as possible.

4. Linearizing pulses

With our typical read-out circuit, we measure a change in resistance via a current change, in a circuit that is inherently non-linear. It is far more sensitive to resistance changes at the bottom of the transition than it is at the peak of a pulse. This non-linearity makes it difficult to calibrate the detector responsivity for a wide range of signal sizes, and also requires changing the optimal filter for different pulse energies. It is, however, relatively easy to transform the pulse signals back to a resistance change by

$$\Delta T \propto \Delta R = -(R_0 + R_{sh})\frac{\Delta I/I_0}{(1 + \Delta I/(I_0))}. \tag{4}$$

An additional potential benefit is that the optimal filter is better matched to more uniform noise across the pulse. We have tested this idea and found some ($\sim 10\%$) improvement in the apparent energy resolution of one of our microcalorimeters. However this spectrum had relatively poor statistics, and further studies are needed to draw reliable conclusions. To obtain the best possible energy resolution with non-stationary noise, and in particular when some pulses saturate the TES transition, ideally the method developed by Fixsen et al. [3] should be implementing.

References

[1] Lindeman, et al., Nucl. Instr. and Meth. A, (2004) these proceedings.
[2] Ullom, et al., Nucl. Instr. and Meth. A, (2004) these proceedings.
[3] D.J. Fixen, S.H. Moseley, B. Cabrera, E. Figueroa-Feliciano. LTD-9, Wisconsin, AIP Conference Proceedings, Vol. 605, 2002, p. 339.