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Current dependence of performance of TES microcalorimeters and characteristics of excess noise

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Abstract

We are developing transition edge sensor (TES) microcalorimeter arrays for future Japanese astronomy missions. Although 6.6 eV energy resolution for 5.9 keV and 74 μs decay time are achieved, our energy resolution was limited by the excess noise of unknown origin. The dominant noise showed $1/R$ dependence and it only appeared when the current through the TES, I, is larger than 10 μA. This is explained if we assume a constant voltage noise source with a level of $\sim 2(4kT_C R_n)^{1/2}$. We also investigated the influence of I on the TES performance and found the TES sensitivity α is reduced when the ratio of current to the critical current I/I_C is large. It can explain the reduction of α observed when operated without a magnetic shield. We also found a strong correlation between I_C and α or the baseline width. Thus, we conclude that I_C is an essential parameter for the TES performance.

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Keywords: X-rays; Microcalorimeter; Transition-edge sensor (TES)

1. Introduction

We are developing transition edge sensor (TES) microcalorimeter arrays for future Japanese astronomy missions [1]. A TES microcalorimeter array is a promising detector for high-resolution spectroscopy and imaging simultaneously. While $\sim$4 eV energy resolution is reported [2,3], it is limited by excess noise of unknown origin. We also observed excess noise in our devices, which limited the energy resolution. The features of the excess noise are reported in this paper. We also found the dependence of performance of TES microcalorimeters on the bias current and/or critical current.

2. Device and experimental setup

The TES microcalorimeter used in this work has a TES of a 500 μm × 500 μm Ti/Au bilayer, whose thickness is 40 nm and 110 nm, respectively, and a

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300 nm × 300 nm Au X-ray absorber at the center of the TES, whose thickness is 300 nm. They were stacked on a 700 μm × 1700 μm bridge-type silicon-nitride membrane with the thickness of 1 μm, which was fabricated from the front side [4]. The device was mounted in a dilution refrigerator, and was cooled to ~50 mK, and irradiated by X-rays from a ^{55}Fe isotope onto the absorber, through a 300 μm thick sapphire collimator of 200 μm diameter. The signal was read out by a 420-series SQUID array (420-SSA) ammeter [5]. The detector was optionally shielded by a 1 mm thick lead sheet around the dilution insert.

We obtained the transition temperature $T_C = 151$ mK, the normal resistance $R_n = 80$ mΩ, and the TES sensitivity $\alpha \equiv \partial \ln R / \partial \ln T \sim 150$. The heat capacity and the thermal conductance G are estimated to be 1.7 pJ K^{-1} and 0.91 nW K^{-1}, respectively, at 151 mK. We achieved the energy resolution of 6.6 ± 0.4 eV (FWHM) at 5.9 keV and a decay time constant of 74 μs [6].

3. Characteristics of excess noise

The expected energy resolution from intrinsic and readout noise is 3.1 eV, while the baseline width actually obtained is 6.4 ± 0.2 eV. As shown in Fig. 1 (top), the observed noise spectrum is by a factor of ~3 higher than the expected level in the frequency range above 1 kHz. The energy resolution of our device is limited by this excess noise.

Fig. 1 (bottom) shows the relation between the noise level at 4 kHz in units of pA Hz$^{-1/2}$ and the TES resistance R at the operating point, The observed noise level depends only on R, and does not depend on other operating parameters such as bath temperature. Its level is much higher than expected and is roughly proportional to $1/R$, which is shown with a dashed curve in the figure. Hereafter, we call this noise $1/R$ noise. On the other hand, the noise level is almost consistent with the Johnson noise plus readout noise, and the $1/R$ noise does not exist when $I < 10$ μA. These features are common for other devices with different TES size and thickness.

By comparing the normalization of $1/R$ noise among the devices, we found it is proportional to

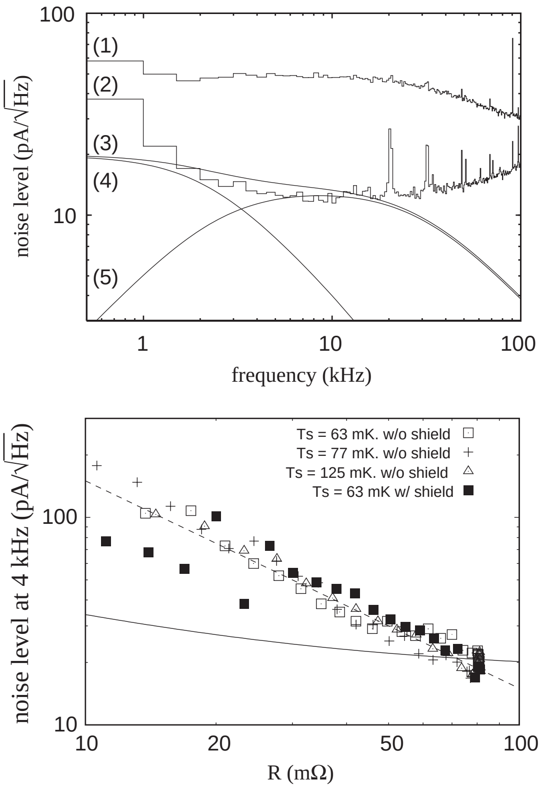

Fig. 1. (Top) Observed noise spectra and theoretical curves of well-known noise sources: (1) Measured noise spectrum at the optimal operating point. (2) Noise spectrum of the readout noise. (3) Expected intrinsic noise spectrum, i.e., r.m.s. of (4) phonon noise and (5) Johnson noise. (bottom) Operating point dependence of noise level at 4 kHz. The solid and dashed curves represent the noise level of the Johnson noise plus readout noise and the dependence of R^{-1}, respectively.

$R_n^{1/2}$ and/or $(T_C R_n)^{1/2}$. These features of the $1/R$ noise can be explained if we assume the existence of a constant voltage noise source with a level of $\sim 2\sqrt{4k_B T_C R_n} = 2$–$5$ pV/$\sqrt{\text{Hz}}$ when $I < 10$ μA.

We also observed low-frequency $1/f$-like noise. By comparing the devices with different thermal conductance, we found that it is well understood as a result of the fluctuation of the bath temperature.

4. Critical current and TES performance

Transition temperature decreases with I. According to the Ginzburg–Landau theory [7], the decrease of T_C, ΔT, is expected to be

$$\frac{\Delta T}{T_{C0}} = \left(\frac{I}{I_{C0}}\right)^{2/3} \quad (1)$$

where T_{C0} is the critical temperature at $I = 0$, and I_{C0} is the critical current at $T = 0$ [8]. Here, we assume that all the current is carried by superconducting electrons and thus I is regarded as a critical current at that temperature in the transition edge. With constant voltage bias or constant Joule heat, the current becomes larger as R decreases. This causes larger ΔT for smaller R, and hence the TES sensitivity is effectively reduced. Note that this effect is more significant if I_{C0} is small.

Effective TES sensitivity α_{eff} is given by $\alpha_{\mathrm{eff}} = \alpha/(1+\beta)$ for constant voltage and $\alpha_{\mathrm{eff}} = \alpha/(1+\beta/2)$ for constant Joule heat, where $\beta \equiv \partial \mathrm{d} \ln R / \partial \mathrm{d} \ln I$. If I/I_{C0} is large, β becomes large and α_{eff} is reduced. Assuming $\Delta R/\Delta I = (\Delta R/\Delta T)(\Delta I/\Delta T)$,

$$\beta = \frac{2\alpha}{3}\left(\frac{I}{I_{C0}}\right)^{2/3} \quad (2)$$

is satisfied.

Without the magnetic shield, pulse height became half and decay time constant became doubled compared to the values with the shield. It indicates that the TES sensitivity α_{eff} becomes about half without the shield. It can be understood as a result that I_{C0} became small. Fig. 2 shows the relation between $I_C(T)$ and T/T_C. Results taken with and without the magnetic shield are shown with different symbols. We fitted the data with Eq. (1), and obtained $I_{C0} = 19.8 \pm 0.5$ mA for the data obtained with the magnetic shield, and 2.9 ± 0.2 mA without the magnetic shield. This means that, in our setup, the critical current was reduced by a factor of 7, due to a residual magnetic field. From Eq. (2), β is calculated to be ~ 0.9 and ~ 3 for the case with and without shield, respectively.

We also investigated the relation between I_{C0} and the TES performance among different devices. Fig. 3 shows the relation between the baseline width and I_{C0}. Clearly, there is a strong correlation between these two parameters; the baseline width is better with larger I_{C0}. This is because the TES sensitivity improves with large I_{C0}, whereas the noise level is not affected. We conclude that the critical current is one of the essential parameters to determine the performance of TES microcalorimeters. We could not find any clear correlation between the critical current and the size or the thickness of the TES. Thus, I_{C0} is primarily determined by quality of the TES.

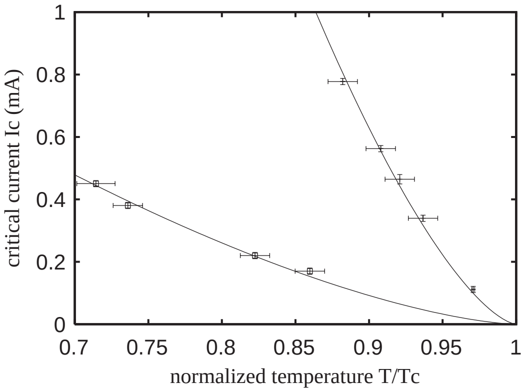

Fig. 2. Relation between $I_C(T)$ and T/T_C. Cross (+) and square (□) symbols represent the data obtained with, and without the magnetic shield, respectively.

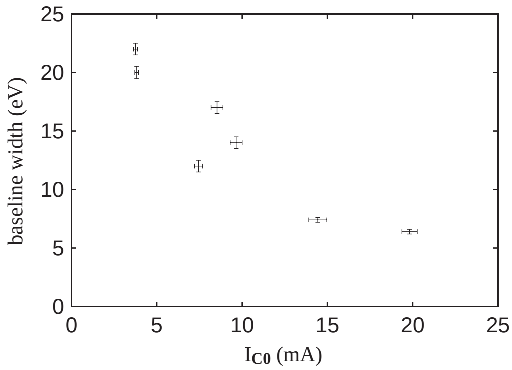

Fig. 3. Relation between baseline width and I_{C0} among devices.

Acknowledgements

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