Characterisation of a TES-based X-ray microcalorimeter in the energy range from 150 to 1800 eV using an Adiabatic Demagnetisation Refrigerator

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Abstract We characterised a TES-based X-ray microcalorimeter in an adiabatic demagnetisation refrigerator (ADR) using synchrotron radiation. The detector response and energy resolution was measured at the beam-line in the PTB radiometry laboratory at the electron storage ring BESSY II in the range from 200 to 1800 eV. We present and discuss the results of the energy resolution measurements as a function of energy, beam intensity and detector working point. The measured energy resolution ranges between 1.5 to 2.1 eV in the investigated energy range and is weakly dependent on the detector set point. A first analysis shows a count-rate capability, without considerable loss of performance, of about 500 counts per second.

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1 Introduction

We are developing an imaging array of Transition Edge Sensor (TES) microcalorimeters for future X-ray astronomy mission like EDGE (Explorer of the Diffuse emission and Gamma-ray burst Explosions), XEUS and Constellation-X. The experiment described here is part of the European-Japanese project EURECA, which aims to demonstrate technological readiness of a 5 x 5 pixel array of TES-based micro-calorimeters read-out by two SQUID-amplifier channels using frequency-domain-multiplexing (FDM). We discuss here the details of the detector set-up.
and the first results of the tests made using synchrotron radiation at the PTB beamline of the BESSY II. The aim of the campaign was to test the sensor behaviour to investigate crucial detector issues like calibration of the energy scale, non-linearity, large signal analysis and energy resolution retrieval from pile-up events.

2 Experimental details

A cross section of the experimental set-up is shown in Fig. 1. Tab. I gives a summary of the cooler and sensor main parameters.

| Parameter         | Value                  | Parameter         | Value                  |
|-------------------|------------------------|-------------------|------------------------|
| ADR               |                        | TES sensor        |                        |
| Pulse tube temp   | 3.5 K                  | Ti/Au area        | 146µm × 150µm          |
| PT cooling power  | 350 mW                 | Ti/Au thickness   | 25 nm (Ti), 50 nm (Au) |
| GGG salt pills T  | 880 mK                 | Cu abs. area      | 100µm × 100µm          |
| FAA salt pills T  | 48 mK                  | Cu abs. thickness | 1000nm                 |
| Hold time at 73 mK| ∼ 24 h                 | C                 | 0.36 nW/K              |
| Magnetic field    | 4 T                    | G at Tc           | 0.36 mΩ               |
|                   |                        | R(N)              | 143 mΩ                |
|                   |                        | C                  | 0.3 pJ/K               |
|                   |                        | Power at T_{bath} | 6.5 pW                |

Table 1 ADR and TES microcalorimeter main parameters. At a TES resistance of $R \simeq 0.5 R_N$ the thermometer sensitivity to temperature and current is respectively $\alpha \simeq 380$ and $\beta \sim 2.5$.

The sensor is a single-pixel of a 5x5 array and consists of a Cu absorber on top of a Ti/Au TES deposited on a Si$_x$N$_y$ membrane, which provides a weak thermal link to the ADR bath temperature. The TES is voltage-biased with a $R_{th} = 10 m\Omega$. 

Fig. 1 (Color online) Cross section of the detector integrated in a two-stage Adiabatic Demagnetisation Refrigerator precooled by a Pulse Tube.
(thevenin equivalent) load resistance, and kept at the transition by negative electro-
thermal feedback (ETF). The current through the TES was measured by a 100-SQUID array operated in flux locked loop (FLL). The inductance of the SQUID input coil is $L_s \sim 70 \text{ nH}$. The SQUID array is directly read out by a low noise commercial PTB-Magnicon electronics.

The detector has been integrated in a Janis two-stage ADR cooler precooled at 3.5 K by a mechanical Cryomech Pulse Tube (PT).

To reduce the electro-magnetic interferences from the external environment, the detector cold-head, the harness and the room temperature electronics is fully enclosed in a dedicated Faraday cage. In the cold stage, the Faraday cage is formed by a double shield anchored at 3.5K consisting of a cryoperm shield and a copper load-tin plated superconducting shield. The cryostat is foreseen of windows along the optical path of the detector. We employ two 150 nm aluminium filters, each supported on a 200 nm parylene substrate, respectively placed on the 60 and 3.5 K cryostat shields.

We characterised the detector using the soft X-ray two plane grating monochromator beam-line (SX700) in the PTB laboratory at BESSY II synchrotron facility in Berlin. The photons energy can be selected with high resolution ($< 0.5 \text{ eV}$) in the range from 50 to 1800 eV. The radiation flux can be easily change from a few tenths to thousands of photons per second.

3 Results

We report here the results of the measurement campaign at PTB-BESSY. A detailed characterisation of the single pixel thermal and electrical responsivity can be found in\textsuperscript{5,6}.

We study the microcalorimeter detector by measuring the energy resolution in the energy range from 150 eV to 1.8 keV and for the microcalorimeter optimum bias point observed at $R/R_N = 0.46$ and zero perpendicular magnetic field, $B_\perp \sim 0 \text{ mG}$ obtained by cancelling the remanent magnetic field with an auxiliary superconducting coil. The base temperature was $T_{\text{bath}} = 73 \text{ mK}$ and stabilised at a level of $7 \mu \text{K} \text{ rms}$ for all the measurements described in this paper. The dependence from the TES bias point and the applied perpendicular static magnetic field was also studied and will be discussed.

In Fig. 2a, the energy resolution is shown as a function of the incident photon energy. In the graph we plotted with full circles the X-ray energy resolution obtained after applying the matched filter to each single photon. The open circles show the baseline resolution obtained by filtering the detector noise with the same filter used for the X-ray pulses. When the instrumental resolution of the detector is dominated by random noise, the baseline resolution is equal to the X-ray resolution. At 250 eV we measured the best energy resolution of $1.52 \pm 0.03 \text{ eV}$ (see insert of Fig. 2a.). In the presence of electro-thermal feedback (ETF) and for large ETF loop gain $\mathcal{L}_0$, the energy resolution can be approximated, in the small signal

\textsuperscript{1} kindly provided by NIST
\textsuperscript{2} Magnicon-PTB, www.magnicon.com
Fig. 2 a) X-ray (full circle) and baseline (open circle) energy resolution as a function of the photon energy for the TES optimal working point. The photon flux was of about 50 photons/sec. The theoretical ($M=0$) energy resolution for this detector at the working point discussed here, is estimated to be $\Delta E_{th} \sim 0.6$ eV. b) Pulse fall time $\tau_{fall}$ as a function of energy. The dashed curve is the polynomial curve fitting the data.

The observed dependency of the energy resolution on the photons energy is related to the change of the pulse fall time as a function of energy shown in Fig. 2b. In a neighbourhood of this particular bias point the sensor parameters like $\alpha$, $\beta$, and $L_0$ are changing quite rapidly, leading to a strong dependence of the $\tau_{fall}$ on the signal amplitude and thus the energy. From Eq. 1 and the polynomial curve obtained to fit the experimental measurements of $\tau_{fall}$ as a function of energy we derive the dashed curve shown in Fig. 2b which gives the expected energy resolution in presence of excess noise for our sensor.

We used $M = 3$, $P_{th} = 6.5$ pW and we assumed them to be constant for all the energies. The behaviour of the X-ray and baseline resolution is qualitatively explained by Eq. 1. The discrepancy between the measured baseline resolution and the calculated resolution is of only about 15%. This could be due to the thermal fluctuation noise (not included in the estimated $dE$ due to the presence of a dangling heat capacitance thermally decoupled from the TES).

The X-ray energy resolution is about 20% worse than the baseline resolution. This may indicate that the applied matched filter is not optimal due to the non-stationary property of the noise. In that case one would expect however the difference to be larger at higher energy. Drifts due to fluctuations of the bath temperature or magnetic field could also explain the discrepancy.

Fig. 3 shows the energy distribution at 250 eV for a count-rate as large as 500 photons per second. When large photon fluxes are applied to the calorimeter
a slightly worse energy resolution is observed. However, as shown in the figure, for a radiation flux as large as 500 photons/sec we could still measure an energy resolution of $1.78 \pm 0.02$ eV. To produce the spectra we rejected about 30% of events due to pile-up. The energy degradation could be due to a non perfect pile-up rejection or non-linear effects in the detector caused by the large number of photons reaching the microcalorimeter. The excess energy counts observed in the low energy side of the spectrum are due to photons not directly absorbed in the microcalorimeter absorber. This is consequence of the fact that the collimator opening is slightly larger than the absorber size. The data analysis for high fluxes is still in progress. The complete results will be presented in a future paper.

The dependency of the photon energy resolution on the TES bias point and magnetic field is shown in Fig. 4 for an energy of 250 eV. The best energy resolution is observed for $R/R_N \simeq 0.46$ at zero perpendicular magnetic field $B_\perp$ in the TES. We observed a degradation of the energy resolution of about 20% from the optimum when the TES is biased between 20% and 60% of $R_N$. This is consistent with the results reported by Y. Takei et al. on this sensor, where it is shown that the responsivity scales accordingly with the noise in this bias region.

When a magnetic filed is applied the energy resolution becomes worse due to a lower thermometer superconducting transition steepness $\alpha$. For a magnetic field as large as $B_\perp = \pm 200$ mG the energy resolution becomes worse of about 50%.

4 Conclusions

We presented the response and energy resolution measurements of a single pixel TES microcalorimeter operating in an ADR performed at the beam-line in the PTB radiometry laboratory at the electron storage ring BESSY II in the range from 200 to 1800 eV. At $E = 250$ eV we measured an energy resolution of $1.52 \pm 0.03$ eV at the best bias point corresponding to a TES resistance $R/R_N = 0.46$, for zero perpendicular magnetic field and for a count rate of 50 photons/sec. The energy resolution was found to be dependent on the photon energy and is related
to the change of the pulses fall time. A small degradation of the energy resolution was observed for large count-rate. With 500 photons/sec reaching the detector an energy resolution of $1.78 \pm 0.02$ eV at 250 eV was measured with a pile-up rejection of 30%. Further we found a weak dependency of the energy resolution on the detector working point consistent with the responsivity and noise measurement reported in Ref.\textsuperscript{2}. The data analysis is still in progress. We aim to fully investigate crucial detector issues like the calibration of the energy scale, non linearity, energy resolution retrieval from pile-up events and large signal analysis.

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