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First results of a TES microcalorimeter AC-biased at 500 kHz

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Abstract

First performance results of a transition edge sensor (TES) microcalorimeter, AC-biased at 500 kHz, are presented in succession to earlier results at 46 kHz. Measurements on the bias circuit reveal a series resistance due to dielectric losses in the superconducting Nb/Ta-Oxide capacitor, which degrades the voltage bias. To improve frequency stability of the bias circuit against a large signal-amplitude range ways to reduce coupling between the SQUID feedback and input coil have been explored. I–V curves measured for different bath temperatures show hysteresis in the switch-on and switch-off behaviour of the TES for bias points low in the resistive transition.

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1. Introduction

Application of transition edge sensor (TES)-based microcalorimeter arrays are under consideration for Constellation-X (NASA) [1], XEUS (ESA and ISAS) [2]. In case of large imaging arrays, system complexity and cooling capacity require development of a multiplexed read-out system in order to reduce the number of SQUID amplifiers and wiring [3]. SRON in collaboration with VTT microsensing has chosen to develop frequency division multiplexing (FDM) to read out a 32×32 pixel X-ray microcalorimeter array. Initial AC-bias experiments at 46 kHz resulted in I–V characteristics close to the DC-bias case and an energy resolution of 6.9 eV for 5.9 keV X-rays [4]. That experiment did suffer from aliasing, since the carrier frequency was lower than the highest information frequency. The bias frequency envisaged for the XEUS detector is 5 MHz, a compromise between dimensions of the required LC filters and required bandwidth versus the need for large dynamic range. Given the fact that the SQUIDs required for this development are under development at VTT we have made use of SQUID arrays from the University of Colorado, Denver [5]. The choice to work at 500 kHz, the next step towards 5 MHz, results from the required dynamic range and minimum cable length that can be realized in our refrigerator.

2. Requirements and experimental set-up

A schematic of the electrical circuit used is shown in Fig. 1. The TES is voltage-biased at impedance Z_B by an AC-source with source

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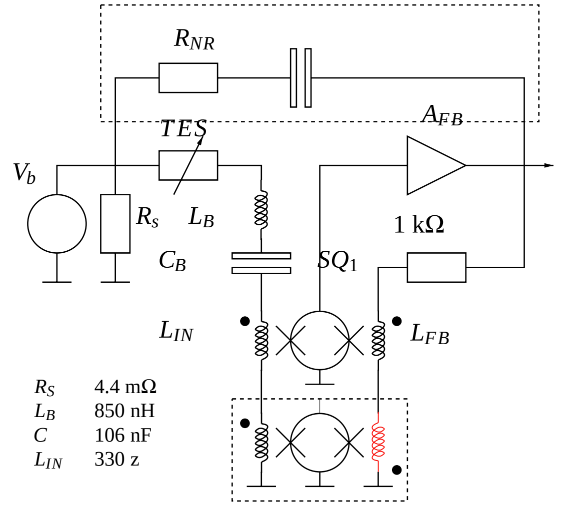

Fig. 1. Schematic bias circuit. A voltage source V_b with series resistance $R_s \approx 4\ \mathrm{m}\Omega$ produces AC bias at $f_0 = 500$ kHz. The left-hand side shows the TES bias circuit, the right-hand side the SQUID circuit. The dashed top box shows feedback to reduce the series resistance of the bias circuit. The dashed bottom box the 2nd SQUID used for decoupling.

resistance $R_S < |Z_B|$. For signal read-out a SQUID amplifier linearized by flux lock loop (FLL) electronics is used. Furthermore, the bias circuit contains a band-pass filter with resonance frequency $\omega = 1/\sqrt{LC}$ to block Johnson noise from neighboring pixels. Generally, the inductance L is maximized to minimize the required bandwidth $\Delta\omega = Z_B/L$ per frequency channel. The bandwidth should, however, be kept large enough to meet the criterion for critical damping of the X-ray signal. The bias frequency defines C. The bias circuit can be characterized by the Q-factor $Q_B = \omega L/R_S$ and should be at least 840 for the present set up, while 500 will be required for the XEUS read-out at 5 MHz.

In case of a FDM the SQUID input inductance L_{IN} is a common impedance for all frequency channels and thereby a crosstalk source [6]. Part of this inductance will be screened by feedback of the FLL. The alinearity of the SQUID results in FLL gain changes ΔG_{FLL} for a large amplitude range of signals, which result in inductance changes $\Delta L = \Delta G_{FLL} \times L_{IN}/(1 + G_{FLL})^2$ in the AC bias circuit with impedance $\omega\Delta L$. The best way to keep this effect small is by using a SQUID with a small input inductance. The SQUID array with $L_{IN} =$ 330 nH, however, dictates a very high FLL gain.

The total inductance is large given the input inductance L_{IN} of the SQUID array and the use of an additional coil L_B to reduce resonance frequency shifts between open- and closed-loop operation. Critical pulse damping is only met for TES with an effective time constant longer than 680 μs.

3. Q-factor of the bias circuit

The Q-factor of the bias circuit for a superconductive TES equals 70, more than an order of magnitude lower than engineered. This is due to losses in the Ta-oxide dielectric of the capacitor. Dielectric losses are characterized by $\tan\delta = 1/Q$, with δ the loss angle of the dielectric. The equivalent series resistance $R_{ESR} = \tan\delta/\omega_0 C$. A group at Berkeley has encountered a similar issue with Nb-oxide dielectric [7]. Either the quality of Nb or Ta-oxides has to be improved or other dielectrics should be used. Some data for potentially suitable capacitor dielectrics are given in Table 1. Obviously a high specific capacitance reduces the size of the capacitors required for the LC filters of each pixel.

4. SQUID amplifier and flux lock loop

The open loop circuit response for an input signal on the SQUID feedback coil has a resonance peak at $\omega = 1/\sqrt{(L_{IN} + L_B)C}$ and the resonance valley at $\omega = 1/\sqrt{(L_{IN} + L_B - L_C)C}$ with L_C the part of L_{IN} magnetically coupled to

Table 1
Relative dielectric constant ε_R and loss tangent $\tan\delta$

Material	ε_R	$\tan\delta$
SiN	7.8	0.0004
Ta_2O_5	17–26	0.014
Al_2O_3	9.8	0.0002
AlN	8.8	0.0005
Nb_2O_5	~40	0.003

the feedback coil. The data indicates that $L_C = 239$ nH, $\sim 70\%$ of L_{IN}. Such a large L_C makes the closed loop resonance frequency sensitive to gain changes in the FLL. Using a resonant amplifier, $G_{FLL} = 113$ has been realized, thereby stabilizing the resonant frequency. For the XEUS FDM these frequency shift effects can be discarded, since the input inductance of the designed SQUID, $\leqslant 1$ nH, is a very small fraction of the inductance (86 nH) of the band-pass filter. Notwithstanding this, decoupling between bias circuit and SQUID feedback has been explored through introduction of a second SQUID array with inverse connected feedback coil. For an unbiased 2nd SQUID array the effective coupling between input and feedback coils is reduced to 43 nH, a factor 5.6 smaller than in the single SQUID case. With the 2nd SQUIDs biased the decoupling can be made almost perfect.

However, the use of a 2nd SQUID turns out to be unpractical. Severe saturation in closed loop operation keeps the output constant as soon as the flux at the 2nd SQUID approaches $1\Phi_0$. At $1\Phi_0$ a flux quantum enters the SQUID loop, changes the screening current, which induces an inductance increase ΔL in the bias circuit. Due to the impedance increase $\omega\Delta L$ the bias current decreases, so that the flux quantum leaves the SQUID loop again. This results in high frequency oscillation with a mean output current at the observed saturation level.

5. Hysteresis in the *I–V* curves

To study stability of the AC-biased TES low in the resistive transition, the *I–V* curve has to be measured with a low series resistance in the bias circuit. However, losses in the capacitor dielectric ($Q = 70$) results in an additional series resistance of 43 mΩ. To compensate for this deficiency, positive feedback (see R_{NR} in Fig. 1) is used to create a negative resistance in the bias circuit. This reduces the effective series resistance to about 1.5 R_s.

The *I–V* curves for a TES with $T_C = 100$ mK have been measured at different bath temperatures. The curves for three bath temperatures are given in Fig. 2. The lowest bath temperature

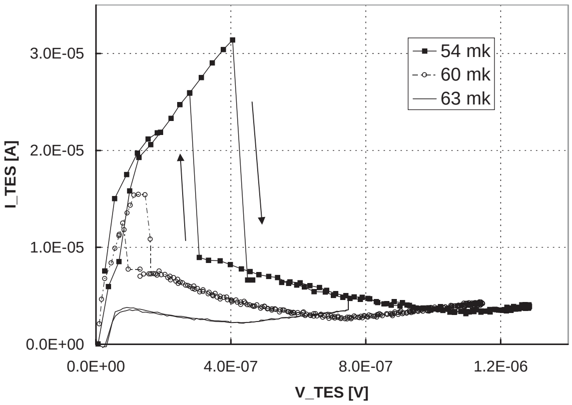

Fig. 2. *I–V* curves for an AC-biased TES at three different bath temperatures.

equals 54 mK and the highest 63 mK. The curves shown in Fig. 2 are measured by slowly varying the amplitude of the AC-bias voltage. When scanning from the high bias voltage towards lower bias voltage the TES switches off to the superconducting state at an impedance $\sim 0.11 R_N$ (at 54 mK). When scanning from low towards higher bias voltage the TES switches back to the resistive state at an impedance $\sim 0.21 R_N$. For 60 mK the TES switches off to the superconducting state at about $0.03 R_N$, the resistive state is created again at an impedance $\sim 0.07 R_N$.

Switching behaviour under AC bias is due to the fact that the TES impedance is both a function of temperature and current [8], i.e. $Z(T, I)$. For an AC-biased TES at high enough frequency T is constant. The current I, is however continuously varying. At low bias values Z/R_N becomes a function of I. Our hypothesis is that when measuring an *I–V* with decreasing bias voltage, the sensor switches off to the superconducting state when a biaspoint with $Z(T, 0) = 0$ is reached. To explain the observed switching behaviour from the resistive to the superconducting state and vice versa, hysteresis in $Z(T, I)$ is required. As observed the effect is influenced by the bath temperature. Higher power loading requires higher bias currents, which increases the switch-off impedance. The measurements also indicate that a low series resistance in the bias circuit is of importance. Furthermore, reduction of the TES impedance dependence on I would be beneficial. This can potentially be obtained by use of a magnetic shield under the TES or a current return.

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