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Mapping TES Temperature Sensitivity and Current Sensitivity as a Function of Temperature, Current, and Magnetic Field with *IV* curve and Complex Admittance Measurements

Y. Zhou,

Physics Department, University of Wisconsin – Madison, Madison, WI, USA

C. V. Ambarish,

Physics Department, University of Wisconsin – Madison, Madison, WI, USA

R. Gruenke,

Physics Department, University of Wisconsin – Madison, Madison, WI, USA

F. T. Jaeckel,

Physics Department, University of Wisconsin – Madison, Madison, WI, USA

K. L. Kripps,

Physics Department, University of Wisconsin – Madison, Madison, WI, USA

D. McCammon,

Physics Department, University of Wisconsin – Madison, Madison, WI, USA

K. M. Morgan*,

Physics Department, University of Wisconsin – Madison, Madison, WI, USA

D. Wulf,

Physics Department, University of Wisconsin – Madison, Madison, WI, USA

S. Zhang,

Physics Department, University of Wisconsin – Madison, Madison, WI, USA

J. S. Adams,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

S. R. Bandler,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

J. A. Chervenak,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

A. M. Datesman,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

M. E. Eckart,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

A. J. Ewin,

*Current address: NIST, Boulder, CO USA

NASA Goddard Space Flight Center, Greenbelt, MD, USA

F. M. Finkbeiner,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

R. L. Kelley,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

C. A. Kilbourne,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

A. R. Miniussi,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

F. S. Porter,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

J. E. Sadleir,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

K. Sakai,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

S. J. Smith,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

N. A. Wakeham,

NASA Goddard Space Flight Center, Greenbelt, MD, USA

E. J. Wassell, and

NASA Goddard Space Flight Center, Greenbelt, MD, USA

W. Yoon

NASA Goddard Space Flight Center, Greenbelt, MD, USA

Abstract

We have specialized astronomical applications for X-ray microcalorimeters with superconducting transition edge sensors (TESs) that require exceptionally good TES performance, but which operate in the small-signal regime. We have therefore begun a program to carefully characterize the entire transition surface of TESs with and without the usual zebra stripes to see if there are reproducible local “sweet spots” where the performance is much better than average. These measurements require precise knowledge of the circuit parameters. Here, we show how the Shapiro effect can be used to precisely calibrate the value of the shunt-resistor. We are also investigating the effects of stress and external magnetic fields to better understand reproducibility problems.

Keywords

TES; complex impedance; temperature sensitivity; current sensitivity; weak link effect; Josephson junction; Shapiro steps

1 Introduction

Spectral measurements of diffuse interstellar and intergalactic X-ray emission require very high throughput but only modest angular resolution. We would like to fly a sounding rocket instrument to obtain a fully-resolved spectrum of the 1×10^6 K Galactic background, which arises mostly in the local hot bubble (a low density region surrounding the Sun ~ 100 pc in extent) but has important contributions from other sources. This requires 1–2 eV FWHM resolution, and sufficient throughput to get a good spectrum in a sounding rocket flight will require about 3 cm^2 total detector area. Doing this with a readout whose cost and weight fit a rocket payload drives us to pixel sizes $> (0.5 \text{ mm})^2$ [1]. A larger array with similar pixels would be a good match for an ambitious satellite mission to study circumgalactic regions and the intergalactic medium.

The energy resolution of an optimally-biased microcalorimeter with a resistive thermometer is ideally $\sim 7 \sqrt{k_B T^2 C \frac{\sqrt{1+2\beta}}{\alpha}}$ FWHM [2], where α and β are the dimensionless temperature and current sensitivities of the thermometer, C is the heat capacity at device temperature T , and k_B is the Stefan-Boltzmann constant. Large pixels have relatively high heat capacities, so high α and low β are needed to achieve the required energy resolution. But most work with TESs has found high α to be correlated with high β and also with excess noise [3–5], although the nature of this correlation is not well-understood. Additional normal metal features (bars, fingers) are commonly added to the TES to reduce α and suppress excess noise. However, recent measurements by Wakeham et al. [6] indicate that under certain circumstances devices without these features may in fact perform better.

We are just starting this work, and have made maps of the $R(T, I, B_{\text{EXT}})$ surface of a small number of devices on a sufficiently fine scale that they can be differentiated everywhere to obtain α and β [7]. We are working on using complex admittance measurements instead to compute α and β more reliably without requiring such dense mapping. The devices exhibit an oscillatory dependence of current as a function of applied magnetic field, presumably due to weak link effects [5, 8]. During an X-ray event, the self-field effect can lead to the crossing of these features on the transition surface, potentially resulting in non-linearity and degradation of energy resolution. Hence it is generally necessary to carefully map the transition surface over some region around the operating point.

Both of our applications require operation only up to ~ 500 eV, or some 20 times less than a general-purpose X-ray observatory. This means that with the relatively high heat capacity detectors we will be running in the small-signal regime where excursions from the quiescent bias point are very small. This opens the possibility of finding limited regions of the transition surface where the performance is much better than average. Taking advantage of this will then require reproducible control of the location of such regions.

2 Devices overview

Four $140 \text{ }\mu\text{m}$ square Mo/Au TES devices fabricated at NASA's Goddard Space Flight Center were tested in the experiment. The bilayer films consisted of 50 nm of Mo and 260 nm of Au. Two devices (MXW1213, MXW4647) have 350 nm thick gold banks on each

side in parallel with the net current flow and three gold “zebra stripes” of the same thickness extending from the banks perpendicular to the net current flow, as shown in Fig. 1. The other devices (MXW0203, MXW4950) are bare Mo/Au bilayers without any banks or stripes (zero finger devices). The contact electrodes and electrical leads are 150 nm niobium. MXW0203 and MXW1213 do not have thermally isolating membranes. These are TES diagnostic devices and do not have X-ray absorbers. Table 1 gives the device parameters. A 60-turn NbTi coil inside the shielded test box provides a uniform magnetic field perpendicular to the TES plane.

3 Effects of an external B-field

A periodic dependence of critical current on applied magnetic field is generally observed in small to medium-sized ($< \sim 500 \mu\text{m}$) TES devices and is taken to be evidence that these sensors operate as superconducting weak links [9]. We observe that the current of the TES in all four of these devices shows Fraunhofer-like fluctuations when the B-field is varied at constant temperature and applied bias current. It has been shown that the addition of normal metal features on top of the TES drastically alters critical current $I_C(B, T)$ as a function of magnetic field B and temperature T and therefore changes the transition shape [8]. Figure 2 shows that the current in the zero finger TES (MXW0203) drops off much more rapidly with applied field than in the TES with three fingers (MXW1213). Since no theory has emerged to predict these variations in detail, one has to map out large swaths of the transition surface to determine an optimal operating point. This, along with variations seen between devices of the same design, complicates the comparison between devices of different designs.

4 Shapiro Steps of TESs in the presence of alternating B-field

Sadler et al. [10] pointed out that the observation of Shapiro steps [11] in the IV curve recorded with an added small AC bias is an additional indication that the TES is actually functioning as a superconducting weak link, and that this could serve the practical function of providing a convenient way to make a very precise absolute measurement of the shunt resistor value *in situ*. The current through the device undergoes step changes at junction voltages $V_n = n \frac{h\nu}{2e}$, where h is Planck’s constant, e is the electron charge, and ν is the frequency of the applied RF field. Instead of adding an AC signal to the bias, here we used the external field coil to apply a small AC magnetic field. Fig. 3 shows the voltage steps in the IV curves for MXW0203 and MXW1213 with an external alternating magnetic field at about 250 kHz. We find that the steps are most readily observed at base temperatures below, but close to T_c , i.e. where proximity effect-induced weak-link behavior dominates. For the no-finger device, steps up to $n \approx 50$ are clearly resolved, while for the 3-finger device only about 16 steps can be discerned. The difference may possibly be connected to differences in current distribution, but this will require further study.

From the Shapiro steps of the calculated IV curve we were able to determine the shunt resistance in the TES circuit with $\sim 1 \mu\Omega$ precision. We obtain the shunt resistance by aligning the calculated TES voltage jump intervals with the predicted Shapiro steps, which should depend only on the external magnetic field frequency. We thus measured the shunt resistance for all four TES devices with the results listed in Table 2. Two of these TESs

(MXW1213 and MXW4647) were measured in separate runs and used the same shunt resistor; the two independent measurements agree to $< 1 \mu\Omega$. Measurements performed over a range of frequencies between 150 kHz and 680 kHz also agree within the errorbars of $1 \mu\Omega$.

Shapiro steps were also observed when a brass shunt resistor was used instead of the microfabricated shunt resistors (nom. $300 \mu\Omega$) on the SQUID chips we normally use (model SQ1006R from STAR Cryoelectronics, Santa Fe, NM), confirming that the junction-like behavior stems from the TES, and is not associated with the integrated shunts.

5 α and β measurements: comparing methods

The temperature sensitivity α and current sensitivity β can be calculated from sufficiently densely-measured IV curves using measured G values to estimate the TES temperature at each point, making the necessary interpolations, and taking ratios of appropriate differences as described in reference [7]. Alternatively, we can derive α and β from fits to the complex admittance function, $A(f)$, taken at a single operating point. $A(f)$ is readily obtained from the $I_{\text{BIAS}}-I_{\text{TES}}$ transfer function [12]. The fits assume a thermal model of the detector. In our case we do not get good fits to the simplest thermal model, and require one with at least two separate heat capacities. The dominant time constants for devices on membranes are long enough that the imaginary part of the complex admittance nearly returns to zero at the upper (10 Hz) and lower limits (20 kHz) of our measurements, such that (together with independent measurements of R_{TES} and the thermal conductivity from the TES to the coldplate) the derived values of α and β become nearly model independent. Further work is needed to understand the thermal circuits of these devices.

Figure 4 shows α and β values calculated from IV curves compared to those derived from fits to the complex admittance measurements. The agreement is reasonably good for $R_{\text{TES}} > 0.3 R_N$. There is some scatter at small R_{TES}/R_N , but there is a great deal of structure in the derivatives there due to the interaction of self-generated B-fields and the weak-link oscillations, and these get smoothed over by the finite spacing of the IV curves, which were less densely sampled than in reference [7].

4 Conclusions

The observation of Shapiro steps lends support to the important role of weak-link physics for understanding the behavior of these devices. We find that it provides a convenient way to reliably determine the value of the shunt resistance with better than 1% precision, which is an important ingredient for the quantitative characterization of these detectors. We are now working on developing optimized schemes to characterize the transition surface of these devices to find optimum bias points and understand design- and fabrication-dependent systematics.

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Fig. 1.

Pictures of TESs. Left: MXW0203 (no stripes). MXW4950 has the same geometry. Right: MXW1213 (3 stripes and banks). MXW4647 has the same geometry.

Fig. 2.

TES current dependence on the external magnetic field. The applied bias current is 120 μA for all traces. The base temperature for the top trace is shown on the plot, and increases in steps of 0.2 mK for the lower traces. *Left:* MXW0203 (zero fingers, no membrane). *Right:* MXW1213 (3 fingers, no membrane). The small oscillations in TES current with applied field have approximately the same period for both devices.

Fig. 3.

Shapiro steps in two IV curves. An external AC B-field at 254.296 kHz was applied normal to the plane of the TESs. *Left:* MXW0203 (no-finger, no membrane) at $T_{\text{Base}} = 106.67$ mK. *Right:* MXW1213 (3-finger, no membrane) at $T_{\text{Base}} = 102.27$ mK. The light horizontal lines mark the predicted the Shapiro voltage steps dependent only on the magnetic field frequency. The value of the shunt resistance was adjusted to align the observed steps in the IV curve with theoretical values.

Fig. 4.

Example TES complex impedance fit (left), α (center), and β (right) derived from complex admittance measurements (*crosses*) compared with α and β values calculated from *IV* curves (*lines*). The data are from MXW4647 (3-finger, on membrane), taken at $T_{Base} = 97.6$ mK with different values of I_{Bias} . The model fit is based on a two-block thermal model with separate connections to the thermal bath (“parallel” model in reference [13]). Squares in the center and right plots mark the bias point where the complex admittance data shown in the left panel was acquired.

Table 1

TES device parameters. Here, T_{c0} is the superconducting critical temperature, R_n denotes normal resistance and G is the thermal conductivity to the bath.

Device	Fingers	T_{c0} (mK)	R_n (m Ω)	Thermal membrane	$G@100\text{mK}$ (nW/K)
MXW0203	0	106.5	8.73	No	2.98
MXW1213	3	103.0	8.20	No	3.58
MXW4647	3	97.0	6.58	Yes	0.295
MXW4950	0	101.0	8.56	Yes	0.294

Table 2

Measured shunt resistance value for all four devices. MXW1213 and MXW4647 used the same shunt resistor and were measured in separate runs

TES	MXW0203	MXW1213 (MXW4647)	MXW4950
Shunt Resistance	183 $\mu\Omega$	249 $\mu\Omega$ (250 $\mu\Omega$)	256 $\mu\Omega$
Material	Home-made brass wire	Integrated shunt resistor on the input SQUID chip SQ1006R	Integrated shunt resistor on the input SQUID chip SQ1006R