Published in final edited form as:

J Appl Phys. 2017 February 21; 121(7): . doi:10.1063/1.4976562.

Mapping of the resistance of a superconducting transition edge sensor as a function of temperature, current, and applied magnetic field

Shuo Zhang¹, Megan E. Eckart², Felix T. Jaeckel¹, Kari L. Kripps¹, Dan McCammon¹, Kelsey M. Morgan^{1,3}, Yu Zhou¹

¹Physics Department, University of Wisconsin-Madison 1150 University Avenue, Madison, WI 53706, USA

²NASA Goddard, Space Flight Center, Greenbelt, Maryland, 20771, USA

³National Institute of Standards and Technology, Boulder, CO 80305, USA

Abstract

We have measured the resistance $R(T, I, B_{\text{ext}})$ of a superconducting transition edge sensor over the entire transition region on a fine scale, producing a 4-dimensional map of the resistance surface. The dimensionless temperature and current sensitivities ($\alpha \equiv \partial \log R / \partial \log T|_I$ and $\beta \equiv \partial \log R / \partial \log I|_T$) of the TES resistance have been determined at each point. α and β are closely related to the sensor performance, but show a great deal of complex, large amplitude fine structure over large portions of the surface that is sensitive to the applied magnetic field. We discuss the relation of this structure to the presence of Josephson “weak link” fringes.

Keywords

TES; weak link effect; superconducting transition

I. INTRODUCTION

Detectors employing superconducting temperature sensors that operate within the transition region have been remarkably successful in the soft X-ray range, with demonstrated energy resolution up to 100 times better than theoretically possible with a silicon ionization detector. However, predictability of new designs and uniformity across large arrays is a continuing problem.¹⁸ “Excess noise” in addition to the expected Johnson noise is often observed, particularly when the temperature sensitivity of the sensor resistance is high – an otherwise desirable goal.¹⁷ The best performing sensors usually employ structures such as normal metal “zebra stripes” based on empirical evidence of improved performance¹⁹, but the reason for the improved performance is poorly understood. There is currently no complete model for the behavior of a TES in the transition region, and thus it is not yet possible to calculate the theoretical limits on performance of these sensors.^{1,7,14}

We are developing large area (1 mm²) microcalorimeters with transition edge sensors to study the 0.1 – 1 keV diffuse X-ray background.¹² Large pixels are required to achieve the

required total collecting area with a reasonable number of detectors. The energy resolution of an ideal microcalorimeter with a resistive thermometer is given approximately by:

$$\Delta E_{FWHM} \approx 7\sqrt{k_B T^2 C \frac{\sqrt{1+2\beta}}{\alpha}}, \quad (1)$$

where T and C are the detector temperature and heat capacity, and α and β are the dimensionless temperature and current sensitivities.^{5,11} To achieve the required < 2 eV resolution with the relatively high heat capacity C associated with these large absorbers, we need a TES with high temperature sensitivity (α), a low current sensitivity (β), and little excess noise.^{1,10}

Expression 1 assumes an optimized value for the thermal conductance between the sensor and substrate G (which depends on the TES bias power at the chosen operating point), and that there is no excess noise. The $\sqrt{1+2\beta}$ term accounts for the first order increase in Johnson noise due to the current dependence of the sensor resistance.⁴ To this approximation, one figure of merit for the energy resolution of a TES at a particular operating point is a high value of $k \equiv \alpha/\sqrt{1+2\beta}$. By measuring α and β over the superconducting transition on a fine scale, we can further investigate the correlation between these quantities and see how they are related to the operating point, including the magnetic field. Our design goal has a simpler optimization problem than most soft X-ray TES applications. Arrays of small pixels that cover an energy range up to 10 keV need a well-behaved T path that covers a substantial fraction of the resistive transition. Our low energies of interest and the relatively high heat capacities of our large pixels make the temperature excursions small, so only the local derivative values are important. Thus, we need only to find a local “sweet spot” in the parameter space of TES operation.

II. DEVICE AND CIRCUIT

The Mo/Au bilayer TES devices tested in this paper were fabricated at NASA’s Goddard Space Flight Center (GSFC). The bilayer sensor is $140 \mu\text{m} \times 140 \mu\text{m}$ and consists of 50 nm of Mo capped by 260 nm of Au, which lowers the zero-current transition temperature T_{c0} from about 900 mK to 105 mK by proximity effect, and results in a normal resistance $R_N = 11.2 \text{ m}\Omega$. Gold banks, 350 nm thick, are added on both edges parallel to the current flow to avoid superconducting shorts along the edges, and three interleaved gold “zebra stripes” of the same thickness extend from the banks perpendicular to the current flow as shown in Fig. 1. The contact electrodes and electrical leads are 150 nm niobium.^{2,6} These devices are normally thermally isolated by a $\sim 1 \mu\text{m}$ thick silicon nitride membrane, but to minimize sources of variability in this study we chose a test device with the nitride directly on the silicon substrate. This gives the device a high thermal conductance to the substrate $G \approx 5.8 \text{ nW/K}$ at 100 mK. The bias circuit for the TES is also shown in Fig. 1. The TES is biased using a load resistor, R_L , that is small compared to the normal resistance of the TES, providing approximately constant voltage bias except close to the bottom of the transition. The connections in the loop from the load resistor through the TES and SQUID input coil and back are all superconducting.

The TES test box is shielded with 0.5 mm of lead foil surrounded by nine layers of 0.025 mm met-glass. An external magnetic field B_{ext} can be applied perpendicular to the TES using a 60-turn NbTi coil. The field as a function of I_{coil} was modeled including the external superconducting shield, since induced currents significantly suppress the field at the detectors.

III. WEAK LINK EFFECT

It is well established that TESs can show weak link effects that become more pronounced as the TES size is decreased.^{3,14,15,20} The effects of this on α and β have been studied extensively by Smith et al., who qualitatively fit their data by a resistively-shunted-junction (RSJ) model on a TES device of similar design and size to the ones we tested.¹⁷ Our TES shows similar behavior, but is a poorer fit to the RSJ model.

Figure 2 shows I_{TES} vs B_{ext} curves at different TES temperatures and constant I_{bias} for two devices with identical geometries from the same wafer. After cooling down from room temperature, there is always some residual trapped flux in the shielding that results in B -fields at the TESs of magnitude 1 or 2 μT . This does not change over the duration of the run and is very nearly the same for nearby devices, so presumably it is quite constant across an individual TES. Its value is found empirically by adjusting the current in the field coil to maximize the zero-current critical temperature of the TES, and this point is defined as $B_{\text{ext}} = 0$. The coldest traces are flat on top because the TESs are superconducting at low fields for these temperatures and currents. Both devices show small fringes in the I vs B_{ext} traces that we believe are due to weak link interference effects. The shift in position of these with increasing current could be due to self-field adding onto B_{ext} . This would require that the current distribution change with large changes in B_{ext} , since the slope of the current effect changes sign. It is perhaps more likely that a changing current distribution increases the effective area of the weak link as the current increases, making it more sensitive to field of both polarities. In either case, this supports the conclusion of Smith et al., that the current distribution must change with temperature in devices with complex geometries.

The device on the left in Fig. 2 has systematically higher resistance than the one on the right at any given temperature, but all of the small irregularities in the fringe patterns are essentially identical (we do not understand the difference between the devices at $|B_{\text{ext}}| > 3\mu\text{T}$, where the fringes have disappeared). Subsequent data shown in this paper are from the device on the left.

IV. $R(T, I, B_{\text{ext}})$ MAPPING

Base temperature (T_{base}), external magnetic field (B_{ext}), and bias current (I_{bias}) are the three parameters that can be controlled directly. With the value of the current I in the TES measured by the SQUID, we can then calculate V_{TES} , R_{TES} , P_{TES} and T_{TES} , for which we henceforth use V , R , P , and T .

The procedure used was to fix B_{ext} and scan I_{bias} with a triangular wave of period 2 s while ramping T_{base} at 5.0 $\mu\text{K/s}$. We first determined the thermal conductance from the TES to the

substrate $G(T)$ from a set of points with the same R , choosing an R near the top of the transition where it has almost no I -dependence.⁸ Those points therefore have a constant T_{TES} , and the dependence of TES power on T_{base} can be used to determine $G(T)$. This $G(T)$ was used to calculate the TES temperature T for each point on the IV curves by integrating the dissipated power divided by $G(T)$ from the known substrate temperature up to T_{TES} , resulting in a densely measured $T(I, V)$ surface as shown in Fig. 3. This was repeated for different B_{ext} values with steps of $\sim 0.05 \mu\text{T}$. Taking a set of scans at ~ 1000 base temperatures required 33 minutes for each value of B_{ext} .

V. CALCULATION OF α AND β FROM THE IV CURVES

The temperature and current sensitivity of the TES resistance are defined by :

$$\alpha \equiv \left. \frac{T}{R} \frac{\partial R}{\partial T} \right|_I \approx \left. \frac{\Delta R}{R} / \frac{\Delta T}{T} \right|_I, \text{ and} \quad (2)$$

$$\beta \equiv \left. \frac{I}{R} \frac{\partial R}{\partial I} \right|_T \approx \left. \frac{\Delta R}{R} / \frac{\Delta I}{I} \right|_T. \quad (3)$$

Since $\log R = \log V - \log I$, R/R can be expressed as $V/V - I/I$ in Eq. 3 and

$$\beta = \left. \frac{I}{V} / \frac{\Delta I}{\Delta V} \right|_T - 1, \quad (4)$$

β can be calculated directly from the temperature-corrected IV curves. For $I=\text{constant}$, $R/R = V/V$ and

$$\alpha = \left. \frac{\Delta R}{R} / \frac{\Delta T}{T} \right|_I = \left. \frac{T}{V} / \frac{\Delta T}{\Delta V} \right|_I. \quad (5)$$

To calculate β , we find the slope I/V along an equal temperature line, interpolating as necessary between the nearest available data points. For the α calculation, we can take $T(V)$ at a constant I , find its slope $\Delta T / \Delta V|_I$ at each V point, then calculate α from Eq. 5 using the reciprocal of the slope.

VI. DISCUSSION

Maps of α , β and our nominal figure of merit $k \equiv \alpha / \sqrt{1 + 2\beta}$ are shown as functions of V_{TES} and I_{TES} on the left side of Fig. 4 and as functions of P_{TES} and R_{TES} on the right side. These data were taken at $B_{\text{ext}} = 0.05 \mu\text{T}$. Figure 5 shows the same maps at $B_{\text{ext}} = -3.05 \mu\text{T}$. Although the IV curves in Fig. 3 look rather smooth, small wiggles that arise from the current-dependence of the position of the fringes seen in Fig. 2 create large excursions and

fine structure in the derivatives. The noise on the IV measurements is very small, so the extensive structure seen in α and β is stable and reproducible aside from some regions at large V where there are gross instabilities in the IV curves.

VII. CONCLUSION

We have generated 4-dimensional surfaces of the superconducting transition of a Mo/Au TES and have shown various quantities as cuts at constant B_{ext} . This is reasonable since usually one does not intentionally vary B_{ext} . However, Smith et al. showed how fringes such as those seen in the I vs B curve of Fig. 2 can produce large discontinuities in the derivatives α and β as you move up the resistance surface at constant B_{ext} and I_{bias} .¹⁷ They illustrated the source of this effect with plots of α and β vs B_{ext} . Our Fig. 6 shows $k \equiv \alpha/\sqrt{1+2\beta}$ as a function of B_{ext} and I_{bias} for our TES data at two different temperatures. The amplitude and narrowness of the features seen in these plots is consistent with the results of Smith et al. Some of our devices with very similar TES designs have shown far larger fringes in their I - B curves and would presumably have even more unpredictable α and β values in the presence of small variations in B_{ext} . This sensitivity to small changes in total field means that significant variations in performance could be caused by small changes in material properties or lead dress across arrays, minor design changes that alter the current distribution and self-fields, or by gradients in stray external fields that vary from run to run.^{13,16}

Our next step will be to extend these measurements to more devices to see if the basic behavior is similar, although clearly we cannot expect the details to remain the same. We also will need to take noise spectra at a variety of operating points, since our figure of merit assumes there is no excess noise beyond the first order non-linear Johnson noise necessarily associated with finite value of β .⁴ It is widely observed that excess noise is correlated with the otherwise desirable high α operating points, but it is less clear how much of this is due to the strong α - β correlation. We can map excess noise against $\alpha/\sqrt{1+2\beta}$ to see if this is really a useful figure of merit.

We will also try taking our I - V data while amplitude modulating the bias current at several frequencies, following the method developed by Lindeman et al.^{8,9} This will allow continuous acquisition of $A(\omega)$ admittance measurements at every operating point. The results should allow us to derive α and β directly (the separately determined $G(T)$ is required for α), without the necessity of taking differences to get the derivatives. We will then compare those values with the ones obtained from the $T(I, V, B_{\text{ext}})$ surface using the method described in this paper. If we can stably reproduce these results, this will eliminate the requirement for such dense sampling, allowing devices to be mapped out more quickly and facilitating the investigation of designs that might have more advantageous operating points.

VIII. ACKNOWLEDGMENTS

James Chervenak, Edward Wassell, Jennette Mateo and Caroline Kilbourne were instrumental in the design and construction of the devices tested here. We thank two anonymous referees for their careful reading and many suggestions that have greatly improved the paper. We acknowledge the support of NASA grant NNX13AH21G.

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FIG. 1.
left: Structure of the TES sensor; right: TES bias circuit with load resistor $R_L = 260\ \mu\Omega$

FIG. 2.

I_{TES} vs B_{ext} curves at different TES temperatures for two devices from the same wafer with identical geometries. $I_{\text{bias}} = 120 \mu\text{A}$ for both. The base temperature ranges from 99.5 to 104.5 mK (left) and 100 to 106 mK (right) in steps of 0.2 mK. The dashed lines show the linear shift in fringe position with increasing TES current

FIG. 3.

left: TES IV curves for TES temperatures ranging from 94 to 104 mK at $B_{\text{ext}} = 0.05 \mu\text{T}$.

right: Expanded view

FIG. 4.

a,b,c.: Values of dimensionless TES temperature and current sensitivities α and β and the figure of merit k (color bars) as functions of V_{TES} and I_{TES} for fixed $B_{\text{ext}} = 0.05 \mu\text{T}$; d.e.f.: same as a-c but as functions of P_{TES} and R_{TES} . Note that bias point powers less than ~ 0.5 pW require impractically low thermal conductivities and long time constants

FIG. 5.
Same as Fig. 4 except $B_{\text{ext}} = -3.05 \mu\text{T}$

FIG. 6.

Figure of merit $k \equiv \alpha/\sqrt{1+2\beta}$ vs B_{ext} at constant T . left: $T=101.5$ mK; right: $T=103$ mK