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Mo/Au Bilayer TES Resistive Transition Engineering

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***Abstract*—We have investigated two types of superconducting Transition Edge Sensors (TES) modified with structures on the surface. One is a Mo/Au TES modified with Nb stripes, which increase the transition temperature and broaden the transition width. Another is a Mo/Au TES modified Au stripes, which decrease the transition temperature and broaden the transition width. It is experimentally demonstrated that the resistive transition profile of a TES can be desirably engineered with a superconductor and/or a normal metal by properly choosing the width and spacing of the modification stripes on the surface.**

***Index Terms*—Superconductivity, proximity effect, transition edge sensor, bolometer.**

I. Introduction

The superconducting Transition Edge Sensor (TES) [1] has been developed as the most sensitive detector in precision measurements of the Cosmic Microwave Background (CMB) [2], [3]. In CMB experiments such as SPTpol [4], [5], large TES arrays are readout with frequency division multiplexing electronics [6]. Stable operation of these TES bolometers [7]–[9] requires in this multiplexing scheme that the thermal time constant of a TES bolometer be much larger than the electric time constant of a readout circuit [8]–[10]. This stability criteria yields an upper limit on the thermal loop gain [1] of a TES of ~30. Linearity of the TES response places a lower limit on the thermal loop gain of ~10.

The constraint that the thermal loop gain be larger than 10 and less than 30 mootivates the investigation of techniques to engineer TES resisitve transition with the goal of achieving intrinsic operational stability and linearity.

The thermal loop gain is proportional to a dimensionless parameter $\alpha=(T/R)(dR/dT)$, which characterize the temperature dependence of the resistance of a TES. The resistive transition profile of a TES can be tuned with modification structures using lateral proximity effect [11]–[13]. For example, the lateral proximity effect has motivated experimental research tuning TES transition with Nb structures on the surface [14], [15] and with magnetic field [16]. Similarly, a normal metal can be used for the transition tuning [12], [17]. Normal metal stripes, stems and banks have been successfully used to suppress the excess noise of a TES [18], [19].

In this paper, we report on our investigation of two types of Mo/Au bilayer TESes with modification structures on the surface, one using Nb stripes, the other using Au stripes. We start with an introduction of devices and measurements in section II. We present experimental results of the TESes with Nb and Au modification structures in sections III and IV. We study the characteristic parameter α in detail. We also discuss $\beta=(I/R)(dR/dI)$, which describes current dependence of a TES resistance. We conclude in section V.

II. Devices and Measurements

We have measured two types of modified TESes. The first type has a number of Nb stripes equally spaced between the

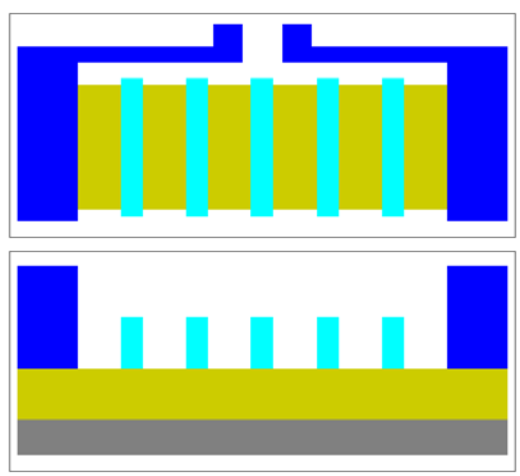

Fig. 1. Top panel: the top view of a modified Mo/Au bilayer TES. Bottom panel: the side view. Grey is for Mo, yellow for Au, blue for Nb leads. The cyan bars, which are equally spaced between two Nb leads and across the TES, can be either Nb or Au stripes. Dimensions are not in scale.

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leads [15]. The second type has Au stripes in place of the Nb stripes [17]. See Fig. 1. In both cases, the unmodified TESes are 40 μm wide and 70 μm long Mo/Au bilayer with two Nb leads. The Mo film is 20 nm thick, and the Au film is 30 nm thick. In the first type of modified TESes, the Nb stripes are 100 nm thick and 3 μm wide. In the second type, the thickness of Au stripes is 30 nm. Their separation from edge to edge varies between 1.60 μm and 8.33 μm. And their width is 2 μm, 3 μm, or 4 μm.

The measurements are conducted in a cryostat cooled with liquid helium and a three-stage Simon Chase absorption refrigerator with a base temperature of 235 mK. The TES is wired in parallel with a 20 mΩ shunt resistor. The TES current is measured with a NIST three-stage time division SQUIDs multiplexer. The TESes and the third stage SQUIDs are in an Al superconducting enclosure with a temperature around 400 mK to minimize the impact from external magnetic fields. A 20 nA RMS AC current at 37.1 Hz is used as the excitation with active feedback using a lock-in amplifier and a Labview vi. The R–T curves are measured with a temperature sweep at a step size between 0.05 and 0.20 mK with a waiting time of 8 s. The thermal hysteresis is calculated by scanning the temperature up and down. In addition, the current dependence of the TES resistance is measured by an I–V sweep starting from zero bias with a waiting time of 2 s each step, which is 4 meV with a series bias resistor of 5100 Ω.

III. TESes Modified With Nb Stripes

Due to the lateral proximity effect [11]–[13], the Nb stripes increase the TES transition temperature, broaden the transition width, and reduce the resistance. See Fig. 2. For a 40 μm wide and 70 μm long TES between two Nb leads, the transition broadening depends on the number of Nb modification stripes, or equivalently, the spacing between the Nb stripes and leads. The resistive transition profile can be characterized with a dimensionless parameter, $\alpha=(T/R)(dR/dT)$. Fig. 3 shows a comparison of several modified TESes. α is effectively reduced with an increase of the number of Nb stripes.

To see the dependence of the resistance of a TES on both temperature and current, we analyze I-V curves measured at a set of bath temperatures, T_{bath}, ranging from above to below

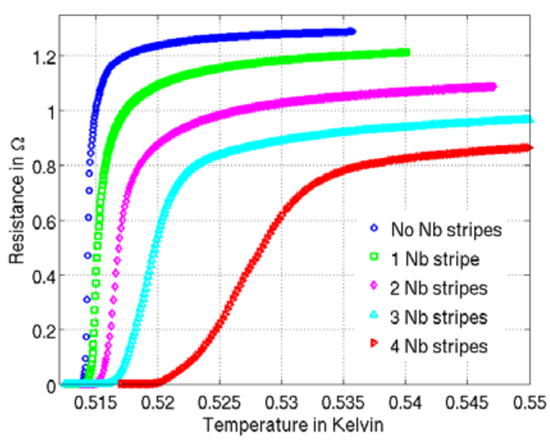

Fig. 2. R-T relation of TESes with and without 3 μm wide Nb stripes. The edge to edge separation between Nb stripes and leads is 70 μm, 33.5 μm, 21.3 μm, 16.3 μm, and 11.6 μm for the TES without and with 1, 2, 3, or 4 Nb stripes respectively. A 20 nA AC current is used in the measurements.

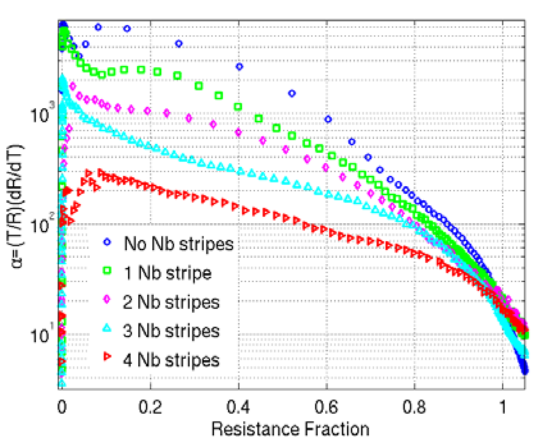

Fig. 3. Calculated $\alpha=(T/R)(dR/dT)$ using the data in Fig. 2. The resistance fraction is defined as R/R_N, where R_N is 1.17 Ω, 1.04 Ω, 0.89 Ω, 0.82 Ω, and 0.74 Ω for the TES without and with 1, 2, 3, or 4 Nb stripes respectively.

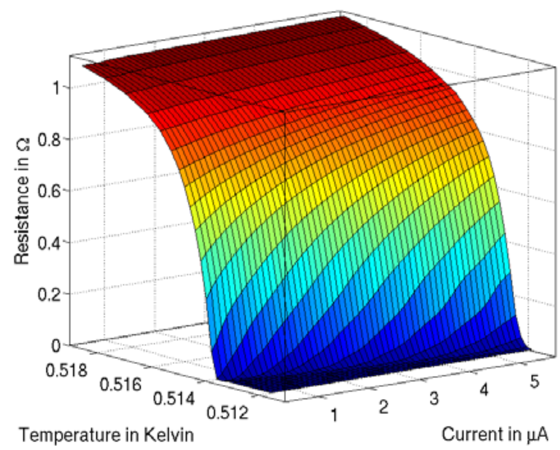

Fig. 4. R(T,I) of a Mo/Au TES with a 3 μm wide Nb stripe across it in the middle and with two Nb leads at both sides. R(T,I) is calculated with I-V data collected at a set of bath temperatures.

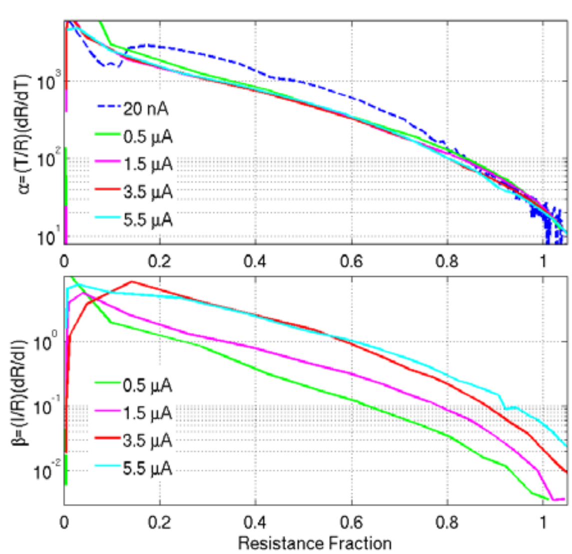

Fig. 5. α (top panel) and β (bottom panel) of a TES modified with a 3 μm wide Nb stripe. The resistance fraction is calculated with R_N=1.04 Ω.

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the transition temperature. From these data, we calculate the two dimensional TES resistance matrix as a function of current and bath temperature, $R(T_{bath}, I)$. The TES temperature T is related to the bath temperature T_{bath} through the hot electron effect [20], $T=(P/(\sum V)+T_{bath}^{5})^{1/5}$, where $P=I^2R$ is the TES Joule heating power, $\sum=2.4\times10^{9}\ Wm^{-3}K^{-5}$, and V is the TES volume. We use a polynomial surface fit algorithm to estimate $R(T, I)$ from $R(T_{bath}, I)$. The TES characteristic parameters, such as $\alpha=(T/R)(dR/dT)$ and $\beta=(I/R)(dR/dI)$, are calculated directly from $R(T, I)$.

Fig. 4 shows the three dimensional graph of $R(T,I)$ of a TES with one 3 μm wide Nb stripe in the middle and two Nb leads at both sides. Fig. 5 shows the dependence of α and β on the normalized resistance. α increases monotonically as resistance decreases, and it has little dependence on current above 0.5 μA. β increases as resistance decreases, and it has a current dependence.

Nb stripes primarily modify the resistive transition of a Mo/Au bilayer TES at large resistance. This leads to a resistive transition profile that has small α high in the transition and very large α deep in the transition. There is only a small range of good α around 70% R_N.

IV. TESES MODIFIED WITH AU STRIPES

When a Mo/Au bilayer TES is in contact with a normal metal, the superconducting order parameter is suppressed in the TES due to the inverse proximity effect [12], [21]. A comprehensive understanding of a TES modified with normal metal can be achieved by solving the Usadel equations [22] with boundary conditions [23]. We only report the experimental data in this paper.

The top panel in Fig. 6 shows for the R-T relations of three TESes modified with 30 nm thick Au stripes along with a TES without Au stripes. The bottom panel in Fig. 6 shows α, derived from this low current excitation data, as a function of normalized resistance. For a TES with Au stripes and two Nb leads, there exists a turning point around 0.8 Ω. Above the turning point, there is a resistive transition, but the transition slope is small. Below the turning point, the resistive transition first becomes steep, and then the transition slope is getting smaller. The transition profile below the turning point is similar to that of a superconducting mixer [24], which has a short superconducting film in contact with normal metals at both sides. The TES modified with 4 μm wide Au stripes in 8.3 μm apart (cyan triangle in the top panel in Fig. 6) is superconducting below 0.36 K.

Fig. 7 shows the three dimensional graph of $R(T,I)$ of a TES modified with 30 nm thick and 2 μm wide Au stripes in 8.3 μm apart. Fig. 8 shows α and β calculated with the data in Fig. 7. The resistive transition reaches the sharpest point around 85% R_N as indicated by α. Then α decreases until hitting a dip,

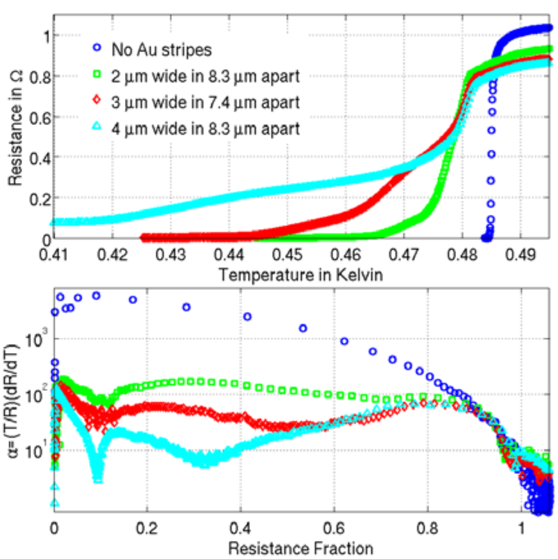

Fig. 6. Tops panel: R-T relations of TESes measured with 20 nA AC excitation current. Bottom panel: α calculated with the data in the top panel. Both panels have the same legends. R_N is 1.00 Ω for the TES without Au stripes, 0.84 Ω for the TES with 2 μm wide Au stripes in 8.3 μm apart, 0.81 Ω for the TES with 3 μm wide Au stripes in 7.4 μm apart, and 0.79 Ω for the TES with 4 μm wide Au stripes in 8.3 μm apart respectively.

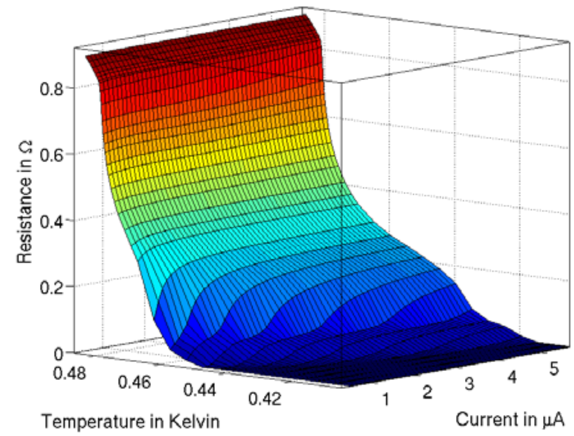

Fig. 7. R(T,I) of a Mo/Au TES with six 2 μm wide Au stripes equally spaced between two Nb leads on the surface. R(T,I) is calculated with I-V data collected at a set of bath temperatures.

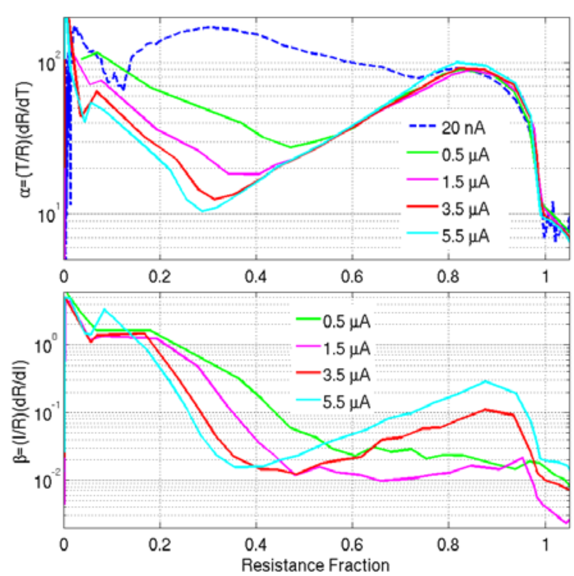

Fig. 8. α (top panel) and β (bottom panel) of a TES with six 2 μm wide Au stripes equally spaced between two Nb leads on the surface. The resistance fraction is calculated with R_N=0.84 Ω, which is right above a turning point of sharp resistive transition. This point is visible in the top panel in Fig. 6.

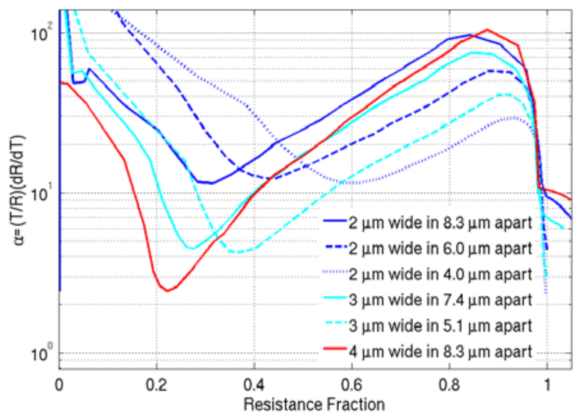

Fig. 9. The dependence of α on normalized resistance for six Mo/Au bilayer TESes modified with Au stripes. The α values are estimated at a current of 4.5 μA, which is typical for a TES operation.

which has a dependence on the current. α becomes large again at a small resistance.

Another noticeable characteristic of the TES modified with normal metal is that β decreases after reaching a peak around 90% R_N at a large bias current. In most cases, the β in Fig. 8 is smaller than the β for superconducting Nb stripes in Fig. 5.

Fig. 9 shows the dependence of α on the normalized resistance for six TESes modified with 30 nm thick Au stripes. The derived α curves all exhibit similar shapes, which have peaks near 85% R_N and dips between 20% and 60% R_N. Larger separation between stripes leads to a larger α at the peak, nearly independent of stripe width. Smaller stripe width increases α in the dip, nearly independent of stripe separation.

From the data, it is clear that Au stripes suppress α, but the suppression is different compared to Nb stripes. α becomes smaller when deeper in the resistive transition. At a large resistance, the suppression is dictated by the stripe separation. At a smaller resistance, the suppression depends on the stripe width.

V. Conclusion

We have studied the resistive transition profiles for TESes modified with Nb and Au stripes using two characteristic parameters α and β. For a TES modified with Nb stripes, α is effectively reduced, α's dependence on resistance is monotonic, the good α window is around 70% R_N, and β is relatively large in the range of bolometer operational current. For a TES modified with Au stripes, there are peaks and dips in α, the values of α at the peak depends on the separation between the Au stripes, the values of α at the dips depend on the width of Au stripes, and β is relatively small. Though none of the modified TESes with Au stripes exhibit a broad range of good α at relevant resistances, the data strongly suggests a clear technical path of TES resistive transition engineering where narrower Au stripes with larger separations may yield desired transition profiles.

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