Towards Ultra-Low-Noise MoAu Transition Edge Sensors

24.05.2011

Keywords  Transition Edge Sensor, bolometer, far-infrared imaging array, space telescope

Abstract  We report initial measurements on our first MoAu Transition Edge Sensors (TESs). The TESs formed from a bilayer of 40 nm of Mo and 106 nm of Au showed transition temperatures of about 320 mK, higher than identical TESs with a MoCu bilayer which is consistent with a reduced electron transmission coefficient between the bilayer films. We report measurements of thermal conductance in the 200 nm thick silicon nitride SiN$_x$ support structures at this temperature, TES dynamic behaviour and current noise measurements.

PACS numbers: 85.25Oj,95.55Fw

1 Introduction

Transition edge sensors (TESs) have become the detectors of choice for current and future ground and space-based astronomical instruments. For example, the far infrared instrument SAFARI that will operate on the joint JAXA/ESA mission SPICA requires state-of-the-art TESs with phonon-noise limited noise equivalent powers (NEPs) and fast response times.$^1$ We recently reported our first measurements on ultra-low-noise MoCu TESs with saturation powers, response times and dark NEPs close-to SAFARI requirements.$^2$ These MoCu TESs have reached a high degree of sophistication in terms of their reliability in processing and reproducibility of characteristics. There are draw-backs, however, not least the complex chemistry of Cu etching and the necessity for a passivating SiO$_2$ layer to prevent Cu corrosion. The additional heat capacity of the passivation increases response...
times and contributes additional noise. MoAu TESs are expected to have comparable performance and have already been demonstrated by a number of groups. Here we explore MoAu TESs fabricated on very thin silicon nitride (SiN$_x$) suitable for ultra-low-noise detectors. These are the first measurements of MoAu TESs fabricated by the Detector Physics Group in Cambridge.

2 Experimental details

Fig. 1 (Color online) (a) A single Mo/Au TES with longitudinal and partial lateral Au bars across the bilayer. The SiN$_x$ island has an area 110 $\times$ 110 $\mu$m$^2$ and is 200 nm thick. The supporting legs are 4 $\mu$m wide. (b) Photograph of the blackened light-tight experimental enclosure. The TES array is in the upper corner of the box. Wiring enters through a meandering labyrinth and a cover completes the assembly.

The TESs reported in this paper consisted of a superconducting MoAu bilayer formed on a 200 nm-thick SiN$_x$ island isolated from the heat bath by 4, long, narrow nitride legs with widths of 2.1 or 4.2 $\mu$m and lengths ranging from 220 to 960 $\mu$m. The TESs were formed from a bilayer consisting of 40 nm of Mo with 106 nm of Au deposited under ultra-high vacuum by dc magnetron sputtering. In contrast to our earlier MoCu TESs a passivation layer to prevent corrosion of the exposed metal surface was not necessary. Fig. 1(a) shows a photograph of one of the MoAu TESs measured in this study. The released TES is almost completely flat and we estimate a curvature of order 100 nm into the plane of the figure due to slight stress in the Nb wiring which had a transition temperature $T_c = 9.2$ K. This curvature is much reduced from that seen in our MoCu TESs on such thin nitride where the residual stress associated with the passivating SiO$_2$ determines the flatness. More details of the fabrication techniques, resistivities and resistance ratios are given in Glowacka et al.

The TESs were cooled in a closed-cycle, sorption-pumped dilution refrigerator mounted on a pulse-tube cooler giving a base temperature of 68 mK. The chip, which had 16 individual TESs formed in a 4 $\times$ 4 square array, was enclosed in a Au-plated Cu box the inside of which is coated with light-absorbing SiC granules.
and carbon black mixed in Stycast 2850 to minimize scattered light. A photograph of the experimental enclosure is shown in Fig. 1(b). The sample space was surrounded by multiple layers of Nb foil and Metglas to provide magnetic shielding. We used a NIST SQUID multiplexer with analog electronics readout that keeps the multiplexer in a fixed state but none-the-less permits readout of multiple channels. We identify the individual TESs by their row and column numbers (r,c).

### 3 Results

#### 3.1 Conductance measurements

Figure 2(a) shows the Joule power dissipation of TES (1,4) for bath temperatures \( T_b \) in the range 81 to 290 mK. The flatness of the power plateaux down to 0.2\( R_n \) are indicative of high values of the temperature-resistance coefficient \( \alpha \) and reflects the smoothness of the R(T) transition. Power dissipation as a function of \( T_b \) for 15 TESs on the chip was measured. The power-flow was modelled as \( P_J = K_b(T_n^b - T_c) \) where \( P_J \) is the Joule power which was used to fit the measurements with \( K_b, n \) and \( T_c \) as free parameters. Conductances to the heat bath \( G_b = nK_bT_c^{(n-1)} \) were then calculated. Results are shown in Table 1. \( T_c \) determined in this way

| TES# | w × L   | n   | \( K_b \) | \( T_c \) | \( G_b \) |
|------|---------|-----|----------|----------|----------|
| 1,1  | 2.1 × 420 | 2.0 | 1.4      | 323      | 0.88     |
| 1,2  | 4.2 × 420 | 1.95| 2.7      | 321      | 1.78     |
| 1,3  | 2.1 × 240 | 2.0 | 1.7      | 319      | 1.1      |
| 1,4  | 4.2 × 320 | 2.1 | 3.2      | 317      | 2.07     |
| 2,1  | 4.2 × 960 | 1.8 | 1.7      | 321      | 1.24     |
| 2,2  | 2.1 × 260 | 1.9 | 1.7      | 321      | 1.17     |
| 2,3  | 4.2 × 740 | 1.75| 1.6      | 316      | 1.18     |
| 2,4  | 2.1 × 160 | 2.0 | 2.1      | 315      | 1.34     |
| 3,1  | 2.1 × 380 | 1.8 | 1.6      | 319      | 1.17     |
| 3,2  | 4.2 × 540 | 1.8 | 2.5      | 316      | 1.81     |
| 3,3  | 2.1 × 220 | 1.7 | 1.8      | 315      | 1.35     |
| 3,4  | 4.2 × 380 | 1.8 | 2.2      | 312      | 1.55     |
| 4,1  | 4.2 × 840 | 1.8 | 1.9      | 314      | 1.39     |
| 4,2  | 2.1 × 320 | 2.1 | 2.4      | 313      | 1.46     |
| 4,3  | 4.2 × 640 | 1.8 | 1.8      | 312      | 1.29     |
agreed to within 2 mK with observations of the onset of supercurrent. The mean value of the exponent is $n = 1.9 \pm 0.1$. For our higher-$G_b$ MoCu TESs we found $n \sim 3$ using 500 nm thick SiN$_x$ for nitride widths down to 10 µm, lengths in the range 40 to 100 µm with $T_c$ in the range of 200 to 400 mK. For our ultra-low-$G_b$ TESs on 200 nm thick nitride and $T_c \sim 120$ mK we found $n$ in the range 1.1 to 2.4 and $n = 1.8 \pm 0.3$. This change in $n$ as a function of nitride thickness and measurement temperature is characteristic of a change in dimensionality of the heat transport. Normal state resistance $R_n$ was in the range 78 ± 3 mΩ for all of the TESs measured here.

### 3.2 $T_c$ variation

Figure 2(b) shows the derived, apparent $T_c$’s of 15 TESs on the measured chip plotted as a function of TES identification number. The variation in $T_c$ is greater than we measured in our earlier high-$G_b$ MoCu TESs (which had $G_b \sim 100$ pW/K), and shows a pattern of variation strikingly similar to that observed in our very low-$G_b$ MoCu TESs (with $G_b \sim 0.2$ pW/K), measured in the same cryostat and experimental set-up. The variation and pattern is independent of the chip position on the wafer. The spread of $T_c$’s ($\pm 3.5$ mK) is less than observed at the lower temperature. Note how the TESs in column 4 seem to show the greatest reduction in $T_c$ from the mean. Previously we thought that the variation in $T_c$ might be due to low levels of stray light and estimated a loading of order 2 to 4 fW. In the inset of the figure we plot estimates of the stray light power $P_{\text{stray}}$ as a function of the position of the TES in the array and we have assumed that the highest transition temperature $T_c^{\text{max}}$ is unaffected by stray light so that $P_{\text{stray}} = G_b(T_c^{\text{max}} - T_c)$. Strictly this means that $P_{\text{stray}}$ is the differential loading. The pattern of stray light is suggestive of power incident on the far corner of the array (i.e. Row 4 and Column 4) viewed from the perspective of the figure.
3.3 Dynamics, Noise and Modelling

![Graphs showing current response and noise spectra](image)

**Fig. 3** (Color online) (a) Measured current response to a step change in the bias voltage and (black dashed line) the calculated response for TES(1,4) biased at 0.25$R_n$. The inset shows the real and imaginary components of the impedance and (black dashed line) calculation using the same parameter set. The calculations use an extended thermal model for the TES with an additional heat capacity of 15fJ/K loosely coupled to the TES. (b) Measured current noise for the same TES at the same bias. The solid (red) curve is calculated with the expected heat capacities, the dashed (black) curve has the additional 15fJ/K heat capacity used to model (a). In both cases $\gamma_0 = 1$.

The TES impedance $Z(f)$, the current response to a small step change in the bias voltage $\delta I$ and noise were measured for TES (1,4) as a function of bias. Figure 3(a) shows results with $R_0 = 0.25R_n$ which gave the fastest observed risetime. A distributed thermal model to account for the expected heat capacities and conductances, including the SiN$_x$, was used. Figure 3(a) shows both the measured risetime and (inset) the impedance and calculations with an additional heat capacity of $C_{ex} = 15fJ/K$ coupled to the TES with $G_{ex} = 12.5pW/K$. The excess is of unknown origin. For these calculations $\alpha_I = 380$, and the temperature-current sensitivity $\beta_I = 1.4$. The account of both the risetimes and impedance is very good using identical parameter sets and as expected $\alpha_I$ is large.

Figure 3(b) shows measured and calculated current noise spectra. At frequencies above the read-out $1/f$ knee, the measured spectrum is very well accounted for by the same extended thermal model used to describe $\delta I$ and $Z(f)$. The phonon noise modifier is here set to $\gamma_0 = 1$. This is an upper-limit on the noise modifier if the measurements are affected by stray light. Calculation of the possible contribution to the noise from stray light is difficult since the spectrum, and the absorption and coupling efficiencies are not known. However, spectrally, noise from stray light would contribute to the current noise just as phonon noise.

4 Summary and Conclusions

We have reported our first measurements on MoAu bilayer TESs consisting of 40 nm Mo, 106 nm Au. Conductances to the heat bath have been determined for 15 TESs each having four support legs, with widths of 2.1 or 4.2$\mu$m and
lengths of 220 to 960 µm on 200 nm thick SiN and are in the range 0.88 to 2.1 pW/K. For all geometries the exponent in the power-flow is \( n = 1.9 \pm 0.1 \) which is comparable with identical geometries measured at 120mK where we found \( n = 1.8 \pm 0.3 \). Both values are lower than those found for thicker nitride films of comparable dimensions measured with transition temperatures between 200 and 400mK where we found \( n \sim 3 \).

Transition temperatures derived from measurements of the Joule power were \( T_c = 317 \pm 3.5 \) mK and normal state resistances 78 ± 3 mΩ. The variation in derived \( T_c \)'s show similar geometric patterns to earlier measurements on very low-\( G_b \) TESs measured in the same experimental arrangement. This observation may be consistent with the presence of very low levels of stray light despite the use of custom-designed light shielding, held at the cryostat base temperature, to avoid radiation from higher temperature sources. Estimates of the levels of differential stray light give \( P_{stray} = 8.9 \pm 5 \) fW about a factor 4 higher than the earlier measurements. This emphasises the great care required when measuring low-\( G_b \) structures and the strict requirements on stray-light control on an instrument.

A good account of the dynamic behaviour is obtained using an extended thermal model for the TES with expected heat capacities and conductances plus a small additional heat capacity of unknown origin that is loosely coupled to the TES. The current noise is consistent with a phonon-noise modifier \( \gamma_b = 1 \) but this is an upper limit due to the possible influence of stray light. In future work we will iterate the Au thickness to achieve the lower \( T_c \)'s required for ultra-low-noise operation and also will include the thin-film absorbing structures required to fabricate complete infrared detectors. Results will be published separately.

5 Acknowledgments

This work was supported in part by ESA TRP Contract No. 22359/09/NL/CP. We are also very grateful to colleagues working on that contract within the Astronomy Instrumentation Group, Cardiff University, the Space Research Organization of the Netherlands, the National University of Ireland, Maynooth and the Space Science and Technology Department of Rutherford Appleton Laboratory for numerous stimulating discussions.

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