Ultasensitive TES detectors for FIR space astronomy.

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***Abstract*—We present results of the development of ultrasensitive transition edge superconducting (TES) detectors for the SAFARI far infrared (FIR) spectrometer, one of the instruments proposed for the Japanese-led SPICA telescope. Future FIR space missions require a combination of cooled optics and ultrasensitive detectors with noise equivalent power (NEP) levels on the order of 10^{-19} W/$\sqrt{\mathrm{Hz}}$ or lower to be able to perform detailed spectroscopic surveys of the nearby and distant universe. We have developed TES detectors based on the mechanical suspension of an absorbing film connected to a TiAu bilayer thermometer on a thin SiN membrane. We describe the design of these detectors and measurements of their performance.**

I. Introduction

The FIR band from 1–10 THz (30–300 μm) is only accessible from space and contains half of the energy radiated by material since recombination. This radiation is primarily from dust and gas that absorbs starlight and reradiates at longer wavelengths. Measurements of this radiation are particularily important for detailed studies of star formation both in nearby galactic molecular clouds and in distant galaxies at high redshift. The amount of power from distant sources is small and therefore requires sensitive detectors.

Future FIR space missions such as SPICA [1], SPIRIT, SPECS, and FIRI will require detectors with sensitivities of $\leq 10^{-19}$ W/$\sqrt{\mathrm{Hz}}$. In this paper, we describe the design of transition edge superconducting bolometers for the SAFARI (formerly ESI) instrument [2] on the SPICA telescope. SPICA is a Japanese-led mission to fly a 3 metre diameter IR telescope with cryogenically cooled ($\simeq 5$ K) optics.

The SAFARI instrument is an imaging Fourier Transform Spectrometer (FTS) with three bands covering the wavelength ranges: $35-60$ μm, $60-110$ μm and $110-210$ μm. The loading in these bands is estimated to be dominated by emission from the Zodiacal light at a level of $0.3-1$ fW[2]. This gives a photon NEP at the detectors of $1-3\times10^{-18}$ W/$\sqrt{\mathrm{Hz}}$. Therefore, we require detectors with electrical NEPs at least 3 times lower than the photon noise limit, i.e. $\leq 3\times10^{-19}$ W/$\sqrt{\mathrm{Hz}}$. The requirement for the response time of the detectors for SAFARI is set to $\tau \leq 10$ ms.

There are several different types of detectors under development for potential use on the SAFARI instrumentIn this paper, we describe the status of the design and testing of silicon nitride suspended TES bolometers for SAFARI.

II. Detector design

The theoretical performance of a TES bolometer is determined by the thermal conductance of the support legs, G, the heat capacity of the absorber and superconducting thermometer, C , the superconducting transition temperature, T_c , and the loop gain of the electrothermal feedback, L_0 [3]. The baseline design for the SAFARI TES detectors is similar to the design of TES detectors for longer wavelengths incorporating a thermally isolated silicon nitride membrane supporting a free space absorber with dimensions of approximately $1.5\lambda\times1.5\lambda$ and a TES thermometer with dimensions of approximately 100 μm $\times$ 100 μm.

Device	Leg $l\times w\times t(\mu\mathrm{m})$	TES size $l\times w(\mu\mathrm{m})$
3-1	$2490\times6\times1$	110×110
3-7	$1310\times6\times1$	110×110
4-3	$1830\times6\times1$	110×110
4-4	$1825\times11\times1$	110×110

TABLE I
Dimensions of prototype devices. The TES size is close to 1.5λ for the shortest wavelength SAFARI band.

The sensitivity of a bolometer is given by: $NEP = \sqrt{\gamma 4k_\mathrm{B}T^2G}$, where γ is a number between 0.5 and 1 depending on the difference between the base temperature and T_c of the superconductor and the dependence of the thermal conductance on temperature. Ground-based and balloon-borne mm-wave instruments require detectors with sensitivities on the order of $NEP \simeq 10^{-17}$ W/$\sqrt{\mathrm{Hz}}$. In order to achieve sensitivities two orders of magnitude lower, we have to fabricate devices with extremely thin mechanical suspension and operate at temperatures ≤ 100 mK. For a detector electrical NEP of 2×10^{-19} W/$\sqrt{\mathrm{Hz}}$ at an operating temperature of 100 mK, we require a thermal conductance of $G \leq 7\times10^{-14}$ W/K.

We fabricated devices with suspended Ti/Au TES thermometers on silicon nitride membranes with comparable size

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Device (measured)	7-4-4 (SRON)	7-4-3 (SRON)	7-3-7 (Cardiff)	7-3-1 (Cardiff)
T_c (mK)	186	203	184	178
$k(\mathrm{W/K}^n)$	$(1.3 \pm 0.1) \times 10^{-11}$	$(4.9 \pm 0.1) \times 10^{-12}$	$(9.9 \pm 0.1) \times 10^{-12}$	$(7.7 \pm 0.1) \times 10^{-12}$
n	2.6 ± 0.1	2.6 ± 0.1	2.5 ± 0.1	2.8 ± 0.1
Th. G (pW/K)	1.9	1.0	2.0	1.0
$\mathrm{NEP_{ph}}$ $(\mathrm{aW}/\sqrt{\mathrm{Hz}})$	1.2	1.0	1.2	0.84
$\alpha = \frac{kln}{4wt}$ $(\mathrm{W/K}^n/\mathrm{m})$	1.4×10^{-3}	1.0×10^{-3}	1.3×10^{-3}	2.2×10^{-3}

TABLE II

TES PARAMETERS FOR DEVICES FABRICATED AT SRON.

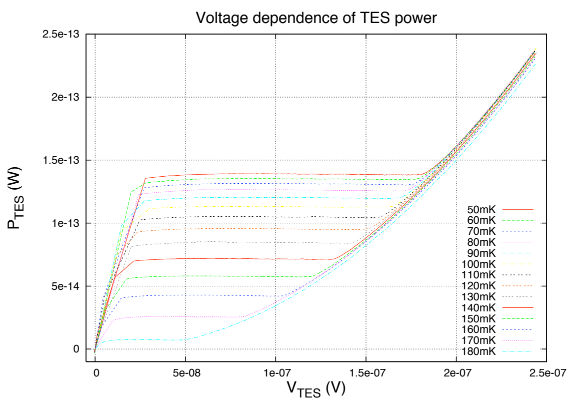

Fig. 1. Electrical power dissipated in TES 3-7 vs. applied voltage from the IV curves for different base temperatures.

to the dimensions required for SAFARI using a variety of leg geometries. Table I gives the detailed dimensions of the devices studied.

III. DEVICE CHARACTERIZATION

Devices were characterized in test facilities at SRON-Utrecht (dilution refrigerator), Cambridge (miniature dilution refrigerator) and Cardiff (double stage adiabatic demagnetization refrigerator (ADR)).

We used a NIST series array SQUID amplifier[4] mounted on the 1K stage to measure the TES current-voltage (IV) characteristics as a function of base temperature. The cold TES circuit contains shunt resistor $R_s = 5\mathrm{mOhm}$. The power dissipation in the TES, $P_{\mathrm{TES}} = V_{\mathrm{TES}} I_{\mathrm{TES}}$ at different base temperatures as a function of TES bias is shown in figure1.

The data are well fit by a single power law given by: $P_{\mathrm{TES}} = k(T_c^n - T^n)$, where k is a coefficient characterizing heat transfer. The thermal conductance, G, of the legs is equal to: $G = \mathrm{d}P/\mathrm{d}T = knT^{n-1}$.

After fitting the power vs. temperature data the values shown in TableII have been calculated for $T_c \simeq 200\mathrm{mK}$ devices measured at Cardiff and SRON. Overall, we find a consistent power law index for the temperature dependence of the power dissipation of $n \simeq 2.6$ for all devices.

The detector electrical time constants have been measured using a small amplitude pulsed square waveform on top of the DC bias point of the TES. The time constant was computed by fitting an exponential decay to the time stream data.

The time constants for all of the devices measured in TableII range from $0.2 - 2\mathrm{ms}$. From this data and from the $R(T)$ data for the TES, we can estimate the heat capacity of the suspended silicon nitride membrane and TES. For the device 3–7, we estimate a maximum loop gain of $L_0 = 40 - 50$. This combined with the minimum time constant of $0.62\mathrm{ms}$ and thermal conductance of $2\mathrm{pW/K}$ gives a heat capacity of $50 - 60\mathrm{fJ/K}$. The estimated heat capacity of the Ti/Au TES at $180\mathrm{mK}$ is $36\mathrm{fJ/K}$ indicating a residual heat capacity of $10 - 20\mathrm{fJ/K}$ for the membrane corresponding to a heat capacity per unit volume of $0.7\mathrm{J/K/m}^3$.

Scaling these numbers to lower temperatures allows an estimate of the sensitivity and speed of response of a similar sized membrane at $100\mathrm{mK}$. Scaling the thermal conductance according to the index, n for the same leg geometry at $100\mathrm{mK}$ gives $G(100\mathrm{mK}) = 0.6\mathrm{pW/K}$ and a projected $NEP = 6 \times 10^{-19}\mathrm{W}/\sqrt{\mathrm{Hz}}$. Assuming that the heat capacity is proportional to temperature and assuming the same loop gain, we would expect this device to have a time constant of $\tau = 0.4 - 1.2ms$. Reducing the thermal conductance by a factor of 10 in order to achieve an $NEP \leq 2\times10^{-19}\mathrm{W}/\sqrt{\mathrm{Hz}}$ would give a projected detector time constant of $4 - 12\mathrm{ms}$. We have fabricated a second round of prototype devices with the same geometry but with a TES transition temperature of $80\mathrm{mK}$. Initial testing of the first of these devices (geometry 3-7) gives a measured $G \simeq 0.16\mathrm{pW/K}$, estimated phonon $NEP = 2 \times 10^{-19}\mathrm{W}/\sqrt{\mathrm{Hz}}$ and a time constant of $\simeq 1\mathrm{ms}$.

IV. CONCLUSION

We have begun an optimization of silicon nitride suspended TES bolometers for use in the SAFARI instrument on the SPICA IR telescope. We have characterized prototype devices with long thermally isolating legs of silicon nitride. We find the thermal conductance of the legs to be approximated by a power law with an index of 2.6 over a temperature range from $< 100\mathrm{mK}$ to $200\mathrm{mK}$. We measure the time constants of the suspended TES thermometers to be $0.2 - 2\mathrm{ms}$ at $200\mathrm{mK}$ both from the response to a small bias step and in the frequency domain using complex impedance measurements.

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REFERENCES

[1] H. Kaneda, T. Nakagawa, T. Onaka, T. Matsumoto, H. Murakami, K. Enya, H. Kataza, H. Matsuhara, and Y. Y. Yui, "Development of space infrared telescope for the spica mission," J. C. Mather, Ed., vol. 5487, no. 1. SPIE, 2004, pp. 991–1000.

[2] B. Swinyard, "Esi: the far-infrared instrument for the spica mission," J. C. Mather, H. A. MacEwen, and M. W. M. de Graauw, Eds., vol. 6265, no. 1. SPIE, 2006, p. 62650L.

[3] K. D. Irwin and G. C. Hilton, "Transition-edge sensors," *Cryogenic Particle Detection*, pp. 63–150, 2005.

[4] R. Welty and J. Martinis, "A series array of dc squids," *Magnetics, IEEE Transactions on*, vol. 27, no. 2, pp. 2924–2926, Mar 1991.

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