

Progress on background-limited membrane-isolated TES bolometers for far-IR/submillimeter spectroscopy

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ABSTRACT

To determine the lowest attainable phonon noise equivalent power (NEP) for membrane-isolation bolometers, we fabricated and measured the thermal conductance of suspended Si_3N_4 beams with different geometries via a noise thermometry technique. We measured beam cross-sectional areas ranging from $0.35 \times 0.5 \mu\text{m}^2$ to $135 \times 1.0 \mu\text{m}^2$ and beam lengths ranging from $700 \mu\text{m}$ to $8300 \mu\text{m}$. The measurements directly imply that membrane-isolation bolometers are capable of reaching a phonon noise equivalent power (NEP) of $4 \times 10^{-20} \text{ W/Hz}^{1/2}$. This NEP is adequate for the Background-Limited Infrared-Submillimeter Spectrograph (BLISS) proposed for the Japanese SPICA observatory, and adequate for NASA's SAFIR observatory, a 10-meter, 4 K telescope to be deployed at L2. Further, we measured the heat capacity of a suspended Si_3N_4 membrane and show how this result implies that one can make membrane-isolation bolometers with a response time which is fast enough for BLISS.

Keywords: transition-edge sensor; far-IR spectrometer; submillimeter spectrometer; Si_3N_4 thermal transport

1. INTRODUCTION

At the interface between incoherent and coherent detection techniques, the far-IR/submillimeter ($40 \mu\text{m}$ – $600 \mu\text{m}$) is the final frontier for observational astronomy. Space-based background-limited broadband far-IR/submillimeter spectroscopic measurements will greatly enhance our understanding of the origin of stars, of galaxies and of life, but novel detectors and ambitious new instruments with unparalleled, sensitive spectroscopic capabilities and wide-field imaging must be developed to perform these measurements. Spitzer, Herschel, and Astro-F are capable missions that will advance our knowledge of the far-IR/submillimeter, but the next generation of far-IR/submillimeter missions will deliver large cold telescopes to L2 that offer the potential for routine observations of stars and of galaxies with redshifts up to $Z=5$.

Detectors for these proposed missions must be scalable to large arrays on the order of at least 10^3 pixels, must be broadband over $40 \mu\text{m}$ – $600 \mu\text{m}$, and must have a noise equivalent power (NEP) on the order of $10^{-20} \text{ W/Hz}^{1/2}$. Membrane-isolation superconducting transition-edge sensing (TES) bolometers are direct detectors that potentially meet the demands of these future far-IR/submillimeter space-borne spectroscopic instruments, but their NEP must be lowered by almost two orders of magnitude. Substantial investment in recent years in this detector technology and in a SQUID-based multiplexer^{1–3} readout has made this technology flight-ready for some applications, but the NEP of these detectors is still too high for their use in background-limited space-based far-IR/submillimeter spectroscopy.

The low NEP for these future missions is set by the photon noise due to the diffuse astrophysical backgrounds – zodiacal light and galactic cirrus – at our position in the solar system. With a 3+ meter telescope cooled to a few degrees kelvin, looking toward directions with low zodi and cirrus, this photon background permits spectroscopy of galaxies to redshifts of 5 and beyond, probing through the epoch of galaxy assembly, as shown in Fig. 1.⁴ Such missions are now under serious study. The SPace Infrared Telescope for Cosmology and Astrophysics (SPICA) is presently the most mature concept for a cryogenic far-IR observatory and, thus, the first potential opportunity for sensitive measurements at the background limit.⁵ SPICA is under study by the Japanese infrared astrophysics community and their space agency JAXA (Japanese Aerospace and Exploration Agency)

The Background-Limited Infrared-Submillimeter Spectrograph (BLISS) is a proposed spectrometer instrument for SPICA. BLISS offers unparalleled performance in the far-IR/submillimeter, could be launched aboard

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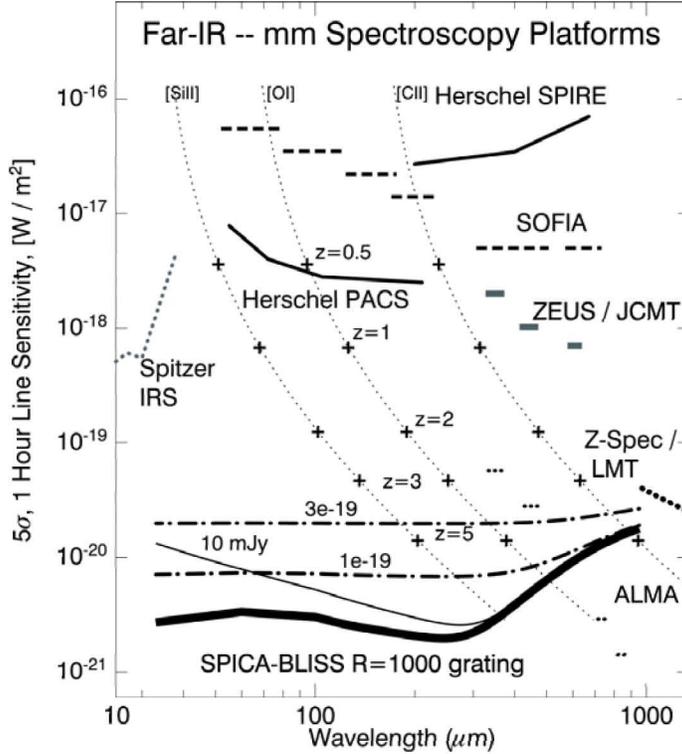


Figure 1. Spectral sensitivity of background-limited spectrograph (BLISS) on a cold 3.5 m space telescope such as SPICA. Background noise is calculated from the fluctuations in the zodiacal and cirrus backgrounds, toward patches of low intensity. The heavy solid black curve at the bottom corresponds to the photon background in a dispersive grating spectrometer, assuming 25% instrument efficiency, 75% aperture efficiency, single polarization and chopping. The heavy dotted-dashed black curves show the degradation of the instrument sensitivity due to finite detector NEP – units are $W / Hz^{1/2}$. The thin solid black line shows the degradation due to photon noise from a 10 mJy continuum source. The vast improvements over Herschel (medium solid black line) and SOFIA (medium dashed black line) are possible because for these platforms, the background from the telescope (+ atmosphere) limits the sensitivity. The three light dashed lines show spectral lines from $Z=0.5$ to $Z=5$. The performance of other platforms are shown including Spitzer (gray dotted line), ALMA (medium black dotted line), ZEUS (solid gray line), and Z-Spec (heavy dotted black line.)

SPICA in the relatively near future, and would pave the way for an even more capable spectrometer flying on NASA’s Single Aperture Far-Infrared (SAFIR) observatory. However, the noise equivalent power (NEP) of current direct detectors needs to be lowered by almost two orders of magnitude to about $4 \times 10^{-20} W/Hz^{1/2}$ to be suitable for BLISS.⁴

In this paper,⁶ we present the results of measurements on the thermal conductance of suspended Si_3N_4 beams for different beam geometries via a noise thermometry technique. The results directly imply that it is possible to make membrane-isolation superconducting TES bolometers with an NEP that is low enough for BLISS. This is possible because the thermal conductance of the support beams can be made very small. Specifically, the NEP of bolometers limited by intrinsic temperature-fluctuation noise⁷ is

$$NEP = \sqrt{4k_b T^2 G}, \quad (1)$$

where k_b is Boltzmann’s constant, T is the temperature of the thermistor, and G is the thermal conductance between the substrate and the thermistor. (We have neglect a term in Eq. 1 that accounts for the temperature gradient across the support beam because the gradient is small for this application and the term is close to 1.) Current state-of-the-art cryocoolers suitable for space-based spectroscopy limit T to about 60 mK. Therefore,

one must lower G to about 8 fW/K to obtain an NEP of 4×10^{-20} W/Hz^{1/2}. The support beams we have measured have values of G on this order.

To determine the thermal conductivity of Si₃N₄ suspended beams of different geometries, we fabricated devices similar to those of K. Schwab *et. al.*⁸ The devices consist of a suspended, thermally isolated Si₃N₄ membrane onto which two thin-film Au resistors are integrated. One is used for measuring the temperature of the island through measuring its Johnson noise. The other is a heater. The thermal conductivity G is determined by applying thermal power P to the heater, by measuring the temperature T of the thermistor, and by using the definition for thermal conductance $G \equiv dP/dT$. The value of G is controlled by the geometry and the physical properties of the four Si₃N₄ support beams that connect the membrane to the substrate.

Finally, we measured the heat capacity for one of our noise thermometry devices. Detectors with low thermal conductance are intrinsically slow, but we show that the small heat capacity of the thermally isolated Si₃N₄ membrane coupled with electrothermal feedback⁹ make the response time of these detectors fast enough for BLISS.

2. MEASUREMENT

Figure 2 shows a micrograph of five noise thermometry devices we used to measure the thermal conductance of the suspended Si₃N₄ beams. We fabricated the devices from bare 4" Si wafers to working samples at the Microdevice Laboratory (MDL) at JPL. We study the thermal conductance of the Si₃N₄ support beams of our devices using a ³He-⁴He dilution refrigerator (DR) at JPL to cool the devices. We mount the devices inside a Nb box which is thermally anchored to the mixing chamber (MX) of the DR. A current source supplies a power $P = I^2 R_H$ (I is the current through and R_H is the resistance of the heater) to the heater on the thermally isolated Si₃N₄ membrane (see Fig. 3). We determine the temperature of the membrane by measuring the Johnson noise of a thin Au film integrated on the membrane. The Johnson noise is defined as

$$S_I \equiv \sqrt{4k_b T / R_N}, \quad (2)$$

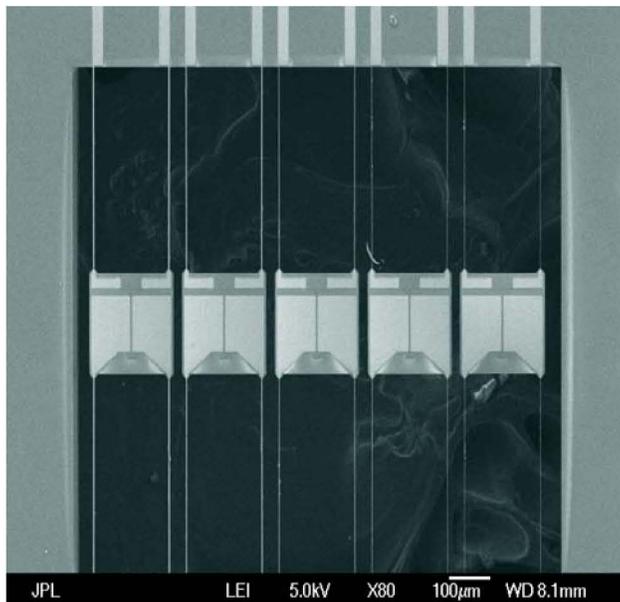


Figure 2. Micrograph of five devices with suspended Si₃N₄ beams of different geometries. Each suspended, thermally isolated Si₃N₄ rectangular membrane is connected to the substrate (substrate on bottom of image is not visible) through four 400 μ m long and 0.5 μ m thick Si₃N₄ support beams. The width of the beams from left to right in the micrograph are 3 μ m, 2 μ m, 1 μ m, 0.5 μ m, and 0.35 μ m. A thin Nb film (whitish shapes on top of the Si₃N₄ rectangular membrane) connects the thermistor and heater to bond pads (not visible in image).

where k_b is Boltzmann's constant and T is the temperature and R_N is the resistance of the thermistor. We measure S_I with a spectrum analyzer connected to the output of a SQUID readout circuit. We typically hold the MX temperature constant and raise the membrane temperature by applying heat. The thermal conductance $G(T)$ is determined by using the definition $G(T) \equiv dP/dT$. To figure out the power we apply to the heater, we measure the value of R_H by performing a four-point resistance measurement at 4K. To convert S_I to the temperature of the isolated membrane we must measure R_N . This is done by measuring S_I for a series of MX temperatures and fitting $S_I^2(T)$ to a straight line where the slope equals $4k_b/R_N$ (see Eq. 2).

Because of the low bias power (sub-fW) needed to measure these low thermal conductance values, we have filtered bias lines consisting of lossy coaxial cables running from room temperature to the mixing chamber of the DR and two low-pass filters mounted on the mixing chamber with 3dB rolloffs at 1.9 MHz and 300 MHz, respectively. With the addition of a cold resistance divider, the dark power on these lines is low enough to measure the electrical properties of these noise thermometry devices.

3. RESULTS

Figure 4a shows the results of the thermal conductance measures for suspended Si_3N_4 beams of several different geometries. On one wafer, we measured beams of length 900 μm by 1 μm thick by widths of 135 μm , 9 μm , and 3 μm . The longest beam we measured was fabricated on a separate wafer and has dimensions of 8300 μm long by 3 μm wide by 0.5 μm thick. Finally, we measured a very narrow beam with dimensions of 700 μm long by 0.35 μm wide by 0.5 μm thick on a third wafer. All the beams are straight except the 8300 μm long beam where it is patterned into a meander with straight segments of 60 μm and 5 μm .⁶

The data show that the thermal conductance does not follow a simple power law where $G \sim T^\beta$ and β is constant. Because the width and thickness of these beams are so small, the thermal transport is well inside the quantum regime, and the important modes for transmitting energy become the lowest vibrational modes of the Si_3N_4 support beams. While higher energy modes freeze out as the temperature T is lowered, these modes which are called the 1D modes do contribute to the thermal conductance at low temperature. The freezing out of higher energy modes causes the effective dimensionality of the beam to go from 3D to 1D, resulting in the temperature behavior of G crossing over from $G \sim T^3$ to $G \sim T^8$. The data in Fig. 5(a) are plotted as thermal conductance divided by the universal quantum of thermal conductance g_0 ($g_0 = \pi^2 k_b^2 T / 3h \sim 1\text{pW/K}^2 \times T$)⁸ to more clearly show the crossover in the temperature exponent. The data for the beam-isolated devices show the expected crossover from $G \sim T^3$ at high temperature, to $G \sim T$ as $T \rightarrow 0$. This data clearly shows that the thermal conductivity at lower temperature cannot be obtained with a simple power-law extrapolation of higher temperature data.

Although the temperature power-law shows interesting behavior, the beams with the smallest ratio of beam cross-sectional area to length have the lowest G . The phonon NEP corresponding to the measured conductance

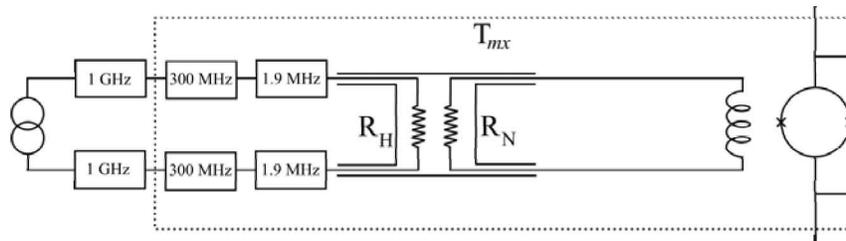


Figure 3. Schematic of measurement circuit. The device is mounted onto the mixing chamber of a dilution refrigerator and cooled to T_{mx} . The thin-film heater and thermistor with resistances R_H and R_N are connected to a current source and a d.c. SQUID, respectively. Several filters depicted by rectangular boxes (frequencies in boxes are the 3dB rolloff of filter) reduce the dark power to a small fraction of a fW.

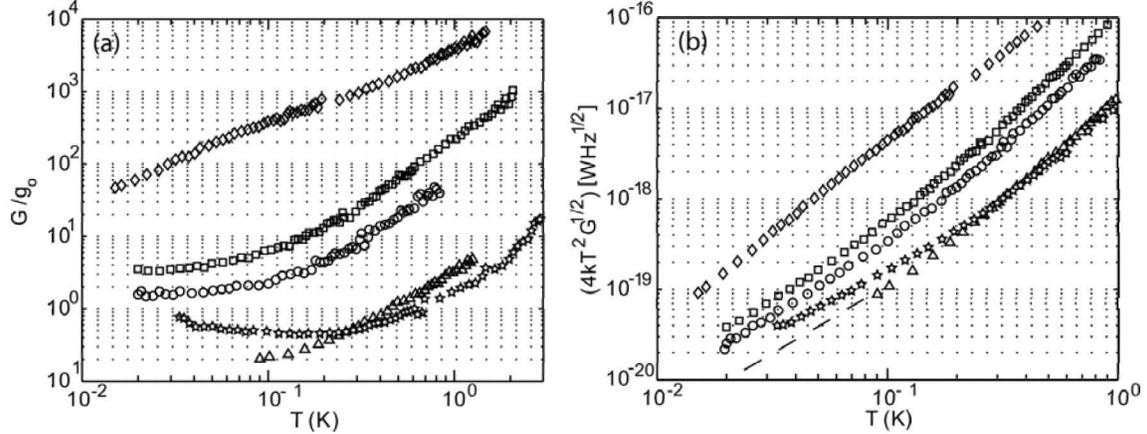


Figure 4. (a) Thermal conductance data for Si_3N_4 beams divided by g_0 . The data are the total conductance through (diamond) 2 beams $\times 900 \mu\text{m}$ long $\times 135 \mu\text{m}$ wide $\times 1 \mu\text{m}$ wide; (square) 4 beams $\times 900 \times 9 \times 1 \mu\text{m}^3$; (circle) 4 beams $\times 900 \times 3 \mu\text{m} \times 1 \mu\text{m}^3$; (star) 4 beams $\times 700 \times 0.35 \times .5 \mu\text{m}^3$; and (triangle) 4 beams $\times 8300 \times 3 \times 0.5 \mu\text{m}^3$. The data for the narrow beams show a crossover to 1D behavior ($G \sim T$) behavior at low T , whereas the data for the $135 \mu\text{m}$ wide beams show quasi-2D behavior.) (b) NEP derived from the thermal conductance data in (a).

data is shown in Fig. 4(b). The lowest conductance device has dimensions of $3 \times 0.5 \times 8300 \mu\text{m}^3$, has a phonon NEP of $5 \times 10^{-20} \text{ W/Hz}^{1/2}$ at 60mK, which is close to the photon noise expected for a BLISS bolometer.

The results shown in Fig. 4 imply that a membrane-isolation superconducting TES bolometer should be sensitive enough for BLISS. The very low thermal conductance necessary for background-limited performance, however, sets a strict limit on the heat capacity of the wire-grid absorber, Si_3N_4 support structure, and TES which comprise the thermally isolate parts of the detector. The heat capacity directly limits the time constant τ in a TES bolometer according to the equation $\tau = C/GA$ where C is the heat capacity, G is the thermal conductance, and A is a factor that arises because of electrothermal feedback.⁹ We expect A to be between 10 – 20 for TES bolometers suitable for BLISS. This implies that the heat capacity C must be less than about 80 – 160 fJ/K if $\tau = 1$ s, $G = 8 \text{ fW/K}$, and $A = 10 - 20$.

The exact upper limit on τ for the detectors in an instrument like BLISS is currently unclear due primarily to uncertainty in the control over the pointing of the spacecraft on which the instrument will fly and in the low-frequency noise of the detector and readout circuit. Nonetheless, a value of $\tau \approx 1$ s may be tolerable because the spectrometer will be used in a “point and stare” mode rather than scanning across the sky and we have measured noise spectra for membrane-isolation bolometers which exhibit very little low-frequency noise well below 0.1 Hz.

We measured the heat capacity C for a membrane-isolation device with support beams of dimensions $3 \times 0.5 \times 2560 \mu\text{m}^3$ and a Si_3N_4 membrane area of $140 \times 200 \mu\text{m}^2$ (see Fig. 5). To determine C , we applied heat pulses to the device through the heater on the Si_3N_4 membrane and measured the temperature T of the Si_3N_4 membrane as a function of time. By measuring the thermal conductance G of the device as a function of T (see Fig. 5), we determined the heat capacity by the relation $C(T) = \tau(T)G(T)$. The function $\tau(T)$ is determined by fitting the temperature relaxation curve to a tangent line at each temperature T . While there is considerable scatter in Fig. 7, at 60 mK C is between 100-200 fJ/K. This range of values for C is close to the upper limit set by BLISS.

It should be noted that this value for C is close to $10\times$ higher than the ideal heat capacity of the Si_3N_4 membrane and Au heater and thermistor. This particular device also has a thermally evaporated SiO film on the membrane. Excess heat capacity is typically seen in mesoscopic systems at low temperature. This excess heat capacity is thought to be related to the physics of disordered materials. Disordered materials contain a large number of configurational states with small energy differences between them, giving rise to a large density of states. Although the physics of glassy systems is relatively well understood, less well understood is the extent

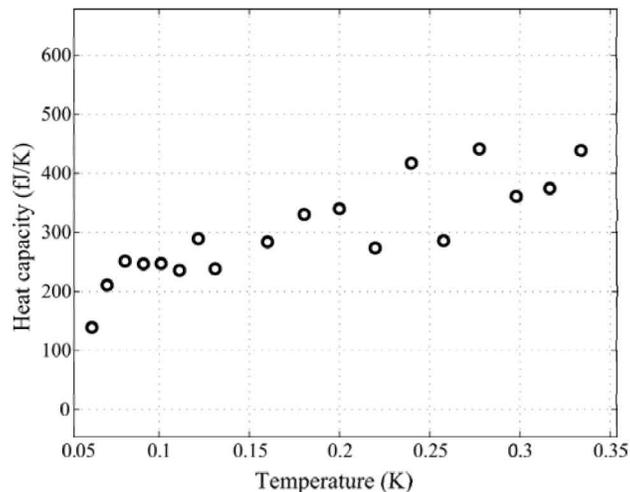


Figure 5. Heat capacity C versus temperature for noise thermometry device. The support beams have dimensions of $3 \times 0.5 \times 2560 \mu\text{m}^3$ and the Si_3N_4 membrane area is $140 \times 200 \mu\text{m}^2$. At 60 mK, C is between 100-200 fJ/K which is close to the upper limit on C of 80-160 fJ/K set by BLISS.

to which these low energy states show up in devices made up of crystalline material. We plan to perform further heat capacity measurements to better understand the excess heat capacity we measure; for it may be necessary in the future to reduce C further to speed up the detector response time.

4. CONCLUSIONS

The next generation of proposed background-limited far-IR/submillimeter space-based spectroscopic missions offer awesome improvements in spectral coverage and sensitivity over current missions today. However, the realization of these improvements rests on the development of new direct detectors a much lower NEP compared to the state-of-the-art. The thermal conductance measurements we made on suspended Si_3N_4 show that membrane-isolation superconducting TES bolometers are a strong candidate for these future missions. This detector technology is relatively mature, scalable, and broadband. Moreover, by reducing the thermal conductance in membrane-isolation bolometers, it is possible to achieve an NEP on the order $10^{-20} \text{ W/Hz}^{1/2}$ —a sensitivity demanded by a BLISS-SPICA and SAFIR mission.

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