Voltage-biased superconducting bolometers for infrared and mm-wave astronomy

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Abstract

We describe bolometers for infrared and mm-wave astronomy that use superconducting transition-edge thermometers. The superconducting film is voltage biased and the current is measured by a SQUID. Strong electrothermal feedback maintains the thermometer temperature within the transition, gives a current responsivity that is simply proportional to the inverse of the bias voltage, and reduces the response time by two orders of magnitude.

We present experimental data on two bolometers with Ti thermometers operated with a ^{3}He sorption refrigerator. The first is a composite device; the titanium film and its silicon substrate are thermally isolated with NbTi supports that also provide electrical connections. The second device is entirely photolithograpically defined. A Ti thermometer is located at the center of a Si_3N_4 mesh absorber, which has the advantages of reduced heat capacity and cross section to cosmic rays compared to a solid absorber.

1 Introduction

Within the last decade, observations in the mm-wave to infrared bands have begun to yield much useful cosmological information. Measurements of the spectrum and spatial anisotropy of the Cosmic Microwave Background, for example, have bolstered the Big Bang model and promise to yield precise values for many of the cosmological constants. For much of this wavelength regime, cryogenic bolometers are the most sensitive radiation detectors[1]. In this paper, we describe the development of voltage-biased superconducting bolometers (VSB) [2-4], which have many advantages compared to the semiconductor-thermistor bolometers that are most commonly used.

The strong electrothermal feedback effect [5] that occurs with voltage bias of a superconducting transition-edge thermometer reduces the bolometer response time by up to two orders of magnitude and gives a current responsivity that is proportional to the inverse of the bias voltage. A rapid bolometer response time is essential to produce high resolution maps of the sky on time scales short enough to avoid low-frequency noise such as that from the atmosphere. Calibration of observational data can be greatly simplified with a responsivity that is independent of refrigerator base temperature fluctuations and background optical power loading. Finally, the high sensitivity given by the large dlogR/dlogT of a superconducting transition combined with the low noise of SQUID ammeters results in a noise equivalent power (NEP) that can be at the thermal fluctuation noise limit [2].

We present results from two bolometers. Both employ a Ti transition-edge thermometer. The first (bolometer 1) is a conventional composite bolometer, where the Ti thermometer and its Si substrate are suspended with NbTi wires. The second (bolometer 2) employs a Si_3N_4 mesh to give a large absorbing area while having a low heat capacity and low cosmic ray cross section. The "spider web" mesh pattern (see Fig. 1) was first employed by Bock et al. [6].

2 VSB Theory

We simply summarize VSB theory results here and refer the reader to more detailed references [2, 3, 5]. The strength of electrothermal feedback for bolometers with resistive thermometers is controlled by the quantity $\;\; = P_b\alpha/GT$ which is analogous to the loop gain in control circuits [3]. Here P_b is the bias power, α = dlogR/dlogT, G is the differential thermal conductance, and T is the temperature. The current responsivity, defined as the ratio of changes in thermometer current to those in absorbed optical power of the bolometer is given by $S_i = (-1/V_b)(\;\;/(1 + i\omega\tau_0 + \;\;))$ [3]. Here, ω is the modulation frequency of the infrared signal, $\tau_0 = C/G$ and C is the heat capacity of the bolometer. Two features of the VSB are immediately apparent from this expression. First, in the limit $\;\;>>1$, $S_I = -1/V_b$ for $\omega << 1/\tau$, where τ is the VSB response time. Second, negative feedback reduces the response time from τ_0 to $\tau = \tau_o/(1 + \;\;)$ [3].

The noise equivalent power (NEP) for a VSB with $\omega << 1/\tau$ can be written [2, 3, 5, 7]

$$NEP^2 = \gamma 4kT^2G + \frac{1}{S_I^2}\left(i_n^2 + \frac{1}{\left(1+\;\;\right)^2}\left(\frac{4kT}{R}\right) + a(f)\right),$$

where the terms describe thermal fluctuation noise, readout noise, Johnson noise, and excess low-frequency (often 1/f) thermometer noise respectively. Here, i_n is the current noise due to the readout, R is the resistance of the thermometer, and γ describes the reduction of thermal fluctuation noise due to the temperature difference between the thermometer and the heat sink [7]. Thermal fluctuation noise should dominate the other sources in the above equation. However, statistical photon noise will contribute in any astronomical observation and would ideally dominate the bolometer noise [1].

3 Device Design

The thermometer and substrate of bolometer 1 are 1.5 mm x 1.5 mm in size. The 40 nm thick Ti film thermometer (T_c = 370 mK) is RF sputtered on a 300 µm thick Si substrate, and has a ~8 Ω normal resistance [4]. The thermometer has 0.2 mm wide superconducting metal strips of 200 nm Au on 80 nm Al deposited on top of the Ti at opposite ends of the thermometer to facilitate electrical contact and to promote uniform current flow by providing a constant electrical potential. A NiCr heater chip is epoxied to the back of the Si substrate to simulate absorbed radiation. A Bi film would normally be deposited on this side of the substrate to absorb radiation. The thermometer and substrate are suspended by six 12.5 µm diameter, 5-8 mm long NbTi wires, four of which provide electrical connections to the thermometer and heater. These wires are purchased with a 2 µm thick Cu cladding which is etched away to reduce the thermal conductance except at the ends where Ag epoxy is used for electrical contact and physical support.

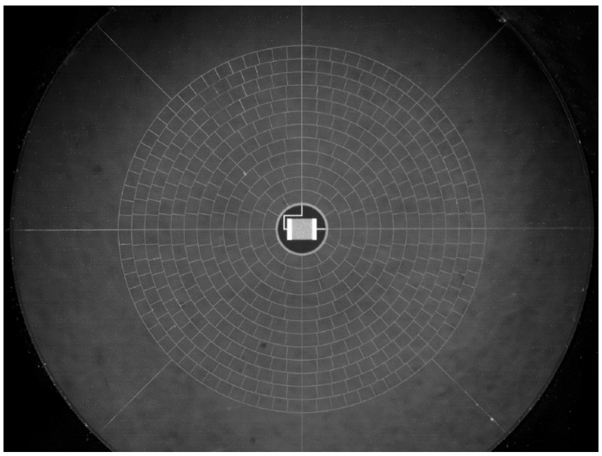

Fig. 1. Photograph of mesh-absorber VSB with Ti thermometer (bolometer 2). The free-standing Si_3N_4 structure is 5.5 mm in diameter.

Bolometer 2 is fabricated entirely with photolithographic techniques. A 200 µm x 200 µm 50 nm thick Ti thermometer (Tc ~ 300 mK) with a 6.7 Ω normal resistance is located at the center of a free-standing 1.0 µm thick Si_3N_4 membrane. The substrate has a mesh pattern reminiscent of a spider web (see Fig. 1) [6]. The central 3.5 mm diameter mesh is supported by eight 5 µm wide 1 mm long legs. The Si_3N_4 is deposited on a silicon substrate which is subsequently etched away. Electrical contact is made with superconducting bilayer leads of 100 nm Al on 50 nm Ti which also form strips at opposite ends of the thermometer (see Fig. 1). Although mm-wave/infrared radiation is absorbed efficiently by the mesh pattern since the mesh spacing is shorter than a wavelength [6], heat capacity and the cross section for cosmic rays is reduced compared to a solid membrane. This bolometer does not have the metal absorber layer deposited on the mesh which is required for radiation absorption, although fabrication of devices with an absorber is in progress.

4 Results

Both bolometers were tested in a dark enclosure cooled by a ^{3}He sorption refrigerator with a base temperature of 260 mK. Transition temperatures and widths (10%-90%) were measured to be 370 mK and 3 mK for bolometer 1 and 300 mK and 2 mK for Bolometer 2. We voltage biased the bolometers with a current-biased ~15 mΩ shunt resistor whose resistance is much lower than typical operational bolometer resistances [2, 5] . The shunt resistor was mounted on the ^{3}He cooled stage. The output current was measured with a Quantum Design series 50 SQUID ammeter and 550 controller. This SQUID has a 0.5 pA/√Hz white noise and a 0.5 Hz 1/f knee.

Strong ETF holds the temperature constant by varying the bias power. The resistance changes to compensate for changes in absorbed power. The resistance of the bolometer also depends on the voltage bias; the operating point in the resistive transition can be varied with the voltage.

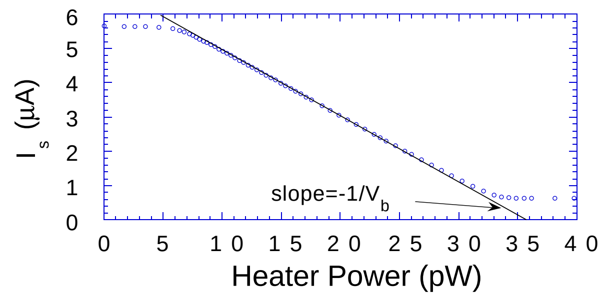

Fig. 2. Current responsivity data for bolometer 1. The response is linear over a large range in absorbed power in the strong ETF regime and matches theory well.

The linear response of bolometer 1 to heater power is shown in Fig. 2. The dc responsivity is given by the slope of current versus heater power. We see that the response is linear even for large changes in heater power, and that the responsivity is equal to $-1/V_b$ to 1% over a wide range of heater power. Measurements at several values of V_b gave similar results. We measured the responsivity for bolometer 2 by introducing a step in bias voltage that is small compared to the bias voltage [2]. The responsivity was found to be equal to $-1/V_b$ for R > 4Ω, below which difficulties with the SQUID prevented accurate measurement. For both bolometers, the responsivity is expected to be close to $-1/V_b$ since >> 1 for operation within the transition.

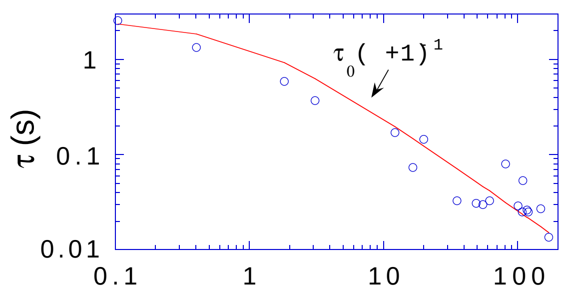

Fig. 3. Time constant data for bolometer 1. The minimum time constant is a factor ~200 less than the intrinsic time constant C/G. The data match the theoretical curve reasonably well.

We measured bolometer time constants for bolometer 1 by observing the response to a step in heater power. We measured an intrinsic time constant C/G = 2.6 s by biasing the detector above the transition where α is small and << 1. For bolometer 1, we found a minimum time-constant of

13 ms, giving a factor ~200 reduction. The measured time constant versus is shown in Fig. 3. We varied by varying both the heater power and the bias voltage. The large scatter arises from the difficulty in making an accurate measurement of α.

We measured the time-constant for bolometer 2, by introducing a small voltage step in addition to the constant bias. We measured an intrinsic time constant of 180 ms and a minimum time constant of 2 ms. The time constant versus plot flattens at large indicating that the internal time constant of the bolometer is limiting the response time. The addition of the metal absorber may increase the internal time constant. It must therefore be designed carefully.

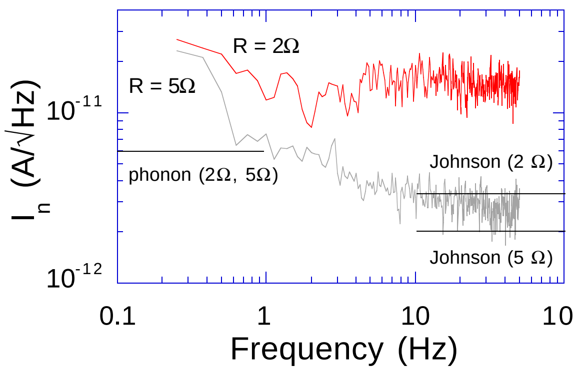

Fig. 4. Noise for bolometer 1 referred to the input coil of the SQUID. For R = 5Ω, the data match theory. For lower resistances there is excess noise for f > 1 Hz, which may be due to an oscillation of the ETF.

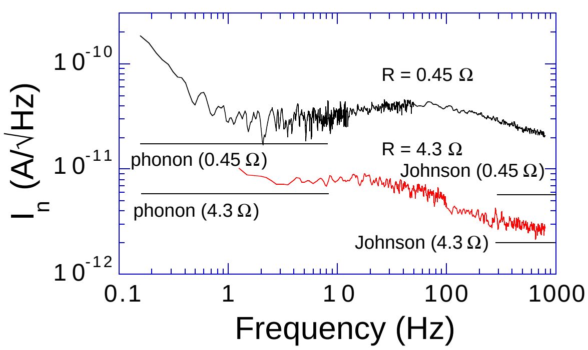

Fig. 5. Noise for bolometer 2 referred to the input coil of the SQUID. For R = 4.3Ω, the data approach theory. For R = 0.45 Ω, there is excess noise peak at ~80 Hz, which may be due to an oscillation of the ETF.

The measured noise as a function of frequency for bolometer 1 is shown in Fig. 4. along with estimates for the expected phonon and Johnson noise. The noise for R = 5 Ω matches theoretical expectations well. For lower bolometer resistances, the noise is larger than estimated above 1 Hz. We interpret the excess noise as a broad peak in responsivity at f ~ $1/2\pi\tau$. This resonant peak may occur due to an oscillation in the electrothermal feedback when τ is sufficiently small that it approaches the internal time constant of the bolometer. The time constant is reduced at low resistance since α, and therefore , is high. The NEP for R = 5 Ω, where the noise agrees with theory, is 6×10^{-17} W/√Hz (G = 4.7×10^{-10} W/K). The noise rolls off at $1/2\pi\tau$ ~2 Hz as expected. The excess low frequency noise below 1 Hz may be largely due to microphonics. We have explored this effect using an acoustic driver and a white noise source.

Noise as a function of frequency for bolometer 2 is shown in Fig. 5. The noise for R = 4.3Ω is a factor of 1.2 larger than that expected from phonon noise alone at 3 Hz (G = 2×10^{-11} W/K). The NEP at 3 Hz is equal to 1.1×10^{-17} assuming $S_i = -1/V_b$. As with bolometer 1, the excess low frequency noise below 1 Hz is at least partly due to microphonics. The roll-off at ~30 Hz is consistent with the measured time constant of 5 ms. A resonant noise peak is clearly visible at 100 Hz for the R = 0.45 Ω data where τ ~ 2 ms is roughly equal to the internal time constant.

5 Conclusion

The Voltage-biased Superconducting Bolometer has several attractive advantages compared to the semiconductor-thermistor bolometers that are most commonly used. The time constant decrease due to ETF will allow bolometers to be used in new applications where conventional bolometers are too slow. In applications where the speed requirement limits G for a conventional bolometer, a substantial reduction in NEP should be possible. In applications where the background power limits G for a conventional bolometer, the VSB should yield essentially the ideal NEP with relaxed constraints on heat capacity. Both absorber- and antenna-coupled designs are realizable with lithographic techniques, facilitating implementation in arrays.

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