# A fully lithographed voltage-biased superconducting spiderweb bolometer

J. M. Gildemeister,[a),b)] Adrian T. Lee,[c)] and P. L. Richards[b)]
*Department of Physics, University of California Berkeley, Berkeley, California 94720-7300*

(Received 9 September 1998; accepted for publication 8 December 1998)

We describe the fabrication and characterization of superconducting transition-edge bolometers for astrophysical applications at far-infrared and mm wavelengths. The sensor is voltage biased and the current is measured with a superconducting quantum interference ammeter. Strong negative electrothermal feedback keeps the sensor temperature nearly constant, reduces the response time significantly, and improves linearity. It also makes the responsivity relatively insensitive to changes in optical background loading and refrigerator temperature. The bolometers are made using standard microlithographic techniques suitable for fabrication of large scale arrays. Detailed measurements of optical response are presented for a range of bias conditions and are compared with theory. Measured noise spectra are shown and a model for the noise is presented. © *1999 American Institute of Physics.* [S0003-6951(99)04206-0]

Bolometers are the most sensitive detectors of electromagnetic radiation for wavelengths between 200 $\mu$m and 3 mm. Bolometers are used at these wavelengths for laboratory as well as astronomical measurements, for example, those of the cosmic microwave background and dust emission from early (strongly redshifted) galaxies. Arrays of hundreds of sensitive bolometers are needed to instrument more than ten ground-based telescopes in addition to airborne, balloon-borne, and space-borne instruments.

The voltage-biased superconducting bolometer (VSB) is an attractive technology for meeting these needs. The entire bolometer structure described here is produced by thin-film deposition and optical lithography. This technique is suitable for producing large bolometer arrays. The device employs a voltage-biased superconducting transition-edge sensor[1,2] and is read out with a superconducting quantum interference device (SQUID) ammeter. The voltage bias results in large negative electrothermal feedback.[3] This makes the device a null detector which has a reduced response time and enhanced linearity. Furthermore, the responsivity is relatively insensitive to changes of optical loading and refrigerator temperature. The noise equivalent power (NEP) can approach the thermal fluctuation limit, due to negligible Johnson noise and the low noise of SQUID ammeters.[1,2] The large noise margin of the SQUID readout opens the possibility of time multiplexed readouts for large arrays.[4]

In previous publications we presented the device concept[1,5] and tested the device theory with a bolometer prototype,[2] which used an electrical heater to simulate infrared radiation. In this letter we describe the fabrication and optical characterization of a complete fully lithographed VSB for use with a $^3$He refrigerator.

The bolometer reported here is supported by a 1 $\mu$m thick silicon nitride ($Si_3N_4$) mesh patterned to resemble a spiderweb to reduce the cosmic-ray cross section[6] (see Fig. 1). The 3.5 mm diam mesh has 7 $\mu$m wide members and $\approx 150\,\mu$m spaces. The mesh is metallized to absorb far-infrared and mm waves. It is supported by eight 7 $\mu$m wide and 1 mm long legs which thermally isolate the mesh from the heat sink. The $200\,\mu\text{m}\times 200\,\mu$m superconducting thermistor is defined on a continuous region of $Si_3N_4$ at the center of the mesh. Both the absorber and the thermistor consist of a trilayer of 500 Å of Ti, 500 Å of Al, and 500 Å of Ti. This ''proximity sandwich'' was chosen to achieve a useful transition temperature of $T_c = 380$ mK. The width of the resistive transition was 2.0 mK (10%–90%) and the maximum value of $\alpha = d\log R/d\log T$, which measures the steepness of the transition, was 800. In future devices the two upper layers can be removed from the absorber to reduce its heat capacity and to increase its impedance, thereby optimizing the optical efficiency. Superconducting contact to the thermistor is made by 3 $\mu$m wide leads with $T_c \approx 1$ K, which are a sandwich of 1000 Å of Al on top of the trilayer. These leads dominate the $G = 1.0\times 10^{-10}$ W/K thermal conductance of the bolometer.

Our bolometers are made entirely by standard microfabrication techniques. A 1 $\mu$m thick layer of low-stress

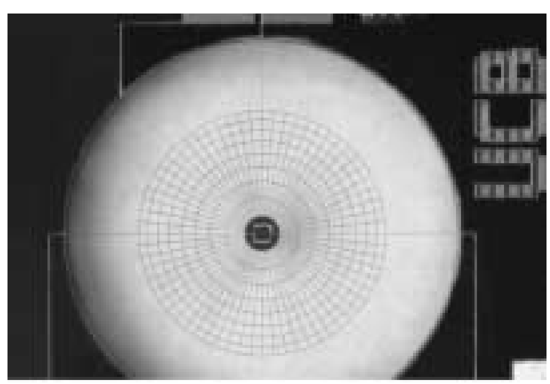

FIG. 1. Photograph of the fully lithographed bolometer on a $Si_3N_4$ membrane. The circular mesh is metallized to absorb radiation and is supported by eight radial legs. The voltage-biased trilayer thermistor is located on a continuous region of membrane in the center and is electrically connected with superconducting leads.

a)Electronic mail: jmg@physics.berkeley.edu
b)Also with the Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720.
c)Also with the Center for Particle Astrophysics and Space Sciences Laboratory, University of California, Berkeley, California 94720.

 

(nonstoichiometric) silicon nitride is deposited on a standard Si wafer by low-pressure chemical vapor deposition (LPCVD). Three 500 Å and one 1000 Å thick layers of Ti, Al, Ti, and Al, respectively, are deposited *in situ* by sputter deposition in a system with a base pressure of $10^{-8}$ Torr. All features are defined using a 10:1 reduction wafer stepper and a standard photolithographic process. The leads are defined first and etched with a commercial Al wet etch which stops at the first Ti layer. The absorber and thermistor are defined and etched in a $Cl_2/CHCl_3$ plasma. Square windows are defined on the backside of the wafer and etched into the silicon nitride with a $SF_6$ plasma. The spiderweb structure is defined on the front and etched by the same process. The photoresist is left in place to protect the devices in a later step. Square windows are etched with aqueous KOH at 67 °C into the bulk silicon from the back down to a thickness of 30 $\mu$m using the $Si_3N_4$ as a mask. The wafer is diced and the remaining Si is removed from the individual spiderwebs using a mixture of $XeF_2$ and $N_2$ gases. The photoresist on the front is ashed in an $O_2$ plasma and contact to the devices is made with Al wire bonds.

These devices were tested in a dark enclosure cooled to $T_0 = 264$ mK by a $^3$He sorption refrigerator. The bolometer has a normal resistance of $R_N = 1.2\,\Omega$ and was operated at resistances $R \geqslant 300\,\mathrm{m}\Omega$. Voltage bias $V_b$ was achieved by current biasing a 20 m$\Omega$ shunt resistor. An unwanted resistance of 27 m$\Omega$ in series with the bolometer was accounted for in the data analysis. The bolometer current was measured with a Quantum Design series 50 SQUID ammeter and 550 controller. An attenuated cold HLMP-1000 light-emitting diode (LED) with $\lambda = 626$ nm was used as an optical stimulator. We estimate that >70% of the LED power absorbed in the bolometer was absorbed in the mesh, making the response measurements a valid test for the detection of far-infrared and mm waves, which are almost entirely absorbed in the mesh.

The time constant of the VSB was measured from the observed (single-exponential) response to a small step in the LED current. The time constant measured when the VSB was biased high on the transition where the feedback is weak was 200 ms. This should be close to the intrinsic time constant $\tau_0 = C/G$, which was estimated from materials properties to be $\approx 350$ ms. The strength of the electrothermal feedback in a VSB is given by $\mathcal{L} = P_b \alpha / G T_c$, which is referred to as loop gain in analogy to control circuits.[2] Here, $P_b$ is the bias power, $G$ is the differential thermal conductance, and $T_c$ is the temperature of the thermistor. When the bias point was moved lower in the transition, the time constant, which is expected[2] to vary as $\tau = \tau_0/(\mathcal{L}+1)$, decreased rapidly as shown in Fig. 2 until it reached the 13 ms time required for heat absorbed in the mesh to reach the thermistor (internal time constant). The frequency dependence of the optical responsivity $S_I$ was measured using a sinusoidal modulation of the LED current at frequency $\omega/2\pi$. The data in Fig. 2 (inset) agree with the theoretical prediction $S_I = -(\mathcal{L}/V_b)/(1 + \mathcal{L} + i\omega\tau_0)$.

The bolometer was found to be linear to 2% over a wide range of LED power and then to saturate quickly. This linearity may be limited by that of the LED. The saturation is identified with the optical power $G(T_c - T_0) - V_b^2/R_N$, which

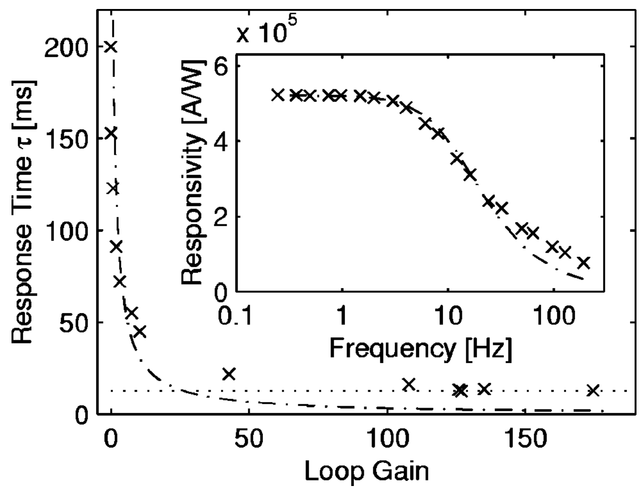


FIG. 2. Measured response time $\tau$ compared with theory (dash-dot line). As expected, $\tau$ decreases with increasing feedback, which is parametrized by the loop gain $\mathcal{L}$. At high gain $\tau$ is limited by the internal time constant of the absorber (dotted line). The inset gives a comparison of the measured current responsivity as a function of frequency with theory (dash-dot line). The discrepancy at high frequencies probably arises from light absorbed directly in the thermistor.

drives the bolometer out of the transition. This identification calibrates the absorbed power from the LED to $\approx 10\%$ accuracy. This calibration is consistent with the expected low-frequency responsivity $S_I = -1/V_b$.

Figure 3(a) shows the measured output noise for the device presented here as a function of frequency together with our noise model. Figure 3(b) shows similar results from an earlier spiderweb bolometer[5] with $G = 2 \times 10^{-11}$ W/K, which

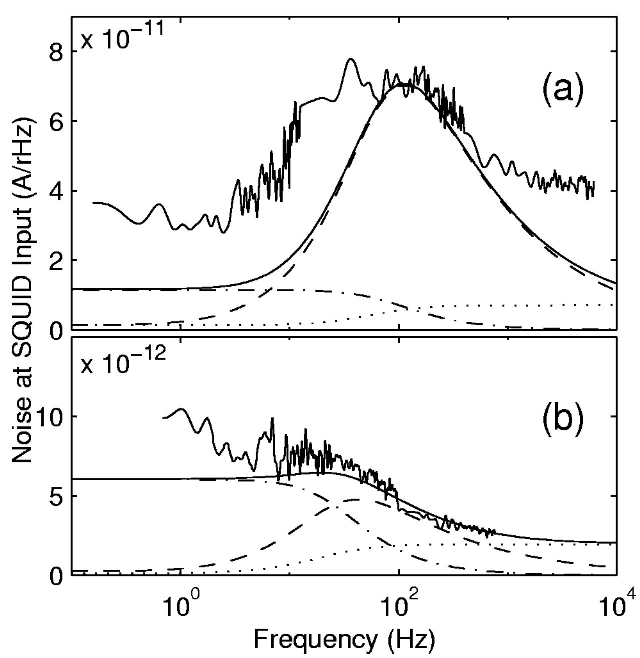


FIG. 3. Measured noise referred to the SQUID input. (a) for the device described in this letter biased at $R = 409\,\mathrm{m}\Omega$. (b) for an earlier device with a Ti thermistor biased at $R = 4.25\,\Omega$. The total calculated noise (solid line) is the quadrature sum of independent contributions from thermal fluctuations in the thermistor (dashed line), phonon fluctuation noise (dash-dot line), and Johnson noise (dotted line), as influenced by the feedback. Deduced values of NEP are $8 \times 10^{-17}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ at 1 Hz for (a) and $1.1 \times 10^{-17}\,\mathrm{W}/\sqrt{\mathrm{Hz}}$ at 3 Hz for (b). These values are 2.5 and 1.3 times the energy fluctuation noise for a bolometer with the value of $G$ employed.

had a Ti film thermistor with $R_N = 8\ \Omega$ and $T_c = 300$ mK. At low frequencies in an ideal VSB the noise should be dominated by energy fluctuation noise from the thermal conductance $G$ while Johnson noise is suppressed by electrothermal feedback.[1,2,7] At high frequencies Johnson noise from the thermistor should dominate. The SQUID noise is negligible.

Excess noise appears in both devices over a wide frequency range. The noise below $\approx 3$ Hz was found to vary with time and with shielding conditions, indicating that it was dominated by external sources. At intermediate frequencies $3 < f < 300$ Hz a broad noise bump is observed in both devices, which is similar to that seen previously[2] in a prototype. In that work, we speculated that this feature was caused by a peak in the responsivity. The optical responsivity curve in Fig. 2, however, shows that this speculation was not correct. We find that the observed feature is consistent with noise resulting from thermal fluctuations in the thermistor as described by Clarke and co-workers.[8] For films in good thermal contact to the substrate they find a power spectral density $SD_T$ which is flat at low frequencies and rolls off at a knee frequency, which is determined by an internal thermal time constant of the film and substrate. In a voltage-biased film this results in current fluctuations $SD_I = SD_T \times V_b^2 (dR/dT)^2/R^4$. In a VSB this noise is suppressed at low frequencies by electrothermal feedback (in a manner similar to the suppression of Johnson noise) yielding a noise bump.

Two pieces of evidence support this model for the excess noise bump. First, the magnitude and the frequency of the measured bumps in Figs. 3(a) and 3(b) vary with $G$, $V_b$, $dR/dT$, and $R$ as predicted. The magnitude of the assumed $SD_T$ lies within the variations observed by Clarke and co-workers.[8] Second, we find that the bump is reduced when the bolometer is exposed to a magnetic field, in agreement with Clarke and co-workers[8] who ascribe this effect to a reduction in $dR/dT$. These scaling arguments suggest that the source of the noise bump is correctly identified, despite the discrepancies between model predictions and data in Fig. 3(a). A much more sophisticated thermal model would be required to provide a definitive test. Figure 3 shows that the noise can approach the thermal fluctuation limit for a proper choice of bolometer parameters, such as moderate loop gain. Practical devices may be obtained by reducing the heat capacity of our devices, which is unnecessarily high. This will move the noise peak to frequencies where the bolometer has no optical response because of the internal time constant.

In summary, we have built a VSB on a silicon nitride mesh structure using techniques suitable for the fabrication of future detector arrays. The thermistor is a trilayer film whose $T_c$ is determined by proximity effects and can, therefore, be tuned by varying the individual layer thicknesses. We have demonstrated that the optical time constant is reduced by feedback and the optical responsivity is constant over a wide range in optical power. A broad peak is observed in the noise power spectrum when the bolometer is operated at high gain. Much of this noise can be accounted for by energy fluctuation noise in the sensor. This effect is much less pronounced at moderate gain.

The authors thank W. Holmes for his support and B. Cabrera, J. Clarke, M. Hadley, S. Hanany, D. Lieberman, S. W. Nam, and T. Shaw for helpful discussions. This work was supported in part by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. One of the authors (A.T.L.) was supported by the National Science Foundation through the Center for Particle Astrophysics (cooperative Agreement No. AST91-20005) and Grant No. FD97-31200. All devices were fabricated at the Berkeley Microfabrication Laboratory.

[1] A. T. Lee, P. L. Richards, S. W. Nam, B. Cabrera, and K. D. Irwin, Appl. Phys. Lett. **69**, 1801 (1996).
[2] S.-F. Lee, J. M. Gildemeister, W. Holmes, A. T. Lee, and P. L. Richards, Appl. Opt. **37**, 3391 (1998).
[3] K. D. Irwin, Appl. Phys. Lett. **66**, 1998 (1996).
[4] J. A. Chervenak, E. N. Grossman, K. D. Irwin, J. M. Martinis, C. Reintsema, M. E. Huber, S. H. Moseley, and C. A. Allen, Bull. Am. Phys. Soc. **43**, 231 (1998).
[5] A. T. Lee, S.-F. Lee, J. M. Gildemeister, and P. L. Richards, *Proceedings of the 7th International Workshop on Low Temperature Detectors LTD-7* (Max Planck Institute of Physics, Munich, Germany, 1997).
[6] J. J. Bock, D. Chen, P. D. Mauskopf, and A. E. Lange, Space Sci. Rev. **74**, 229 (1995).
[7] J. C. Mather, Appl. Opt. **21**, 1125 (1982).
[8] J. Clarke and T. Y. Hsiang, Phys. Rev. B **13**, 4790 (1976); also, M. B. Ketchen and J. Clarke, *ibid.* **17**, 114 (1978).