Monolithic Arrays of Absorber-Coupled Voltage-Biased Superconducting Bolometers

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We describe a design for bolometric detectors of infrared and mm-wave radiation produced in large-format filled arrays by standard planar lithography. A square grid of metallized silicon nitride absorbs the radiation. The bolometer suspension, sensor, and wiring occupy a small fraction of the area. We have produced a 1024 element array of fully released and suspended 1.5mm×1.5mm bolometer micro-meshes with a filling factor of 88%. We describe a voltage-biased superconducting bolometer built as a prototype for one array element. We have measured $NEP = 2.3 \times 10^{-17}$W/$\sqrt{\text{Hz}}$, $\tau = 24$ms, and $G = 2.7 \times 10^{-11}$W/K at 304mK.

The far-infrared to mm-wave region is one of the least explored yet one of the most interesting frequency regimes for astrophysics in general and for cosmology in particular. In this wavelength range, scientific progress is tightly tied to the development of better detector technology, specifically to the development of large-format arrays of low-temperature bolometers. Absorber-coupled bolometer arrays currently in use fall significantly short of filling the diffraction-limited field of view for mm-wave telescopes. In this letter, we describe a novel approach for making large-format filled focal plane arrays. Such filled arrays can Nyquist sample (or even oversample) the focal plane and thus the sky. Low-temperature multiplexers are currently being developed[1,2] to read out the large number of detectors needed to create filled arrays.

Recently, Moseley et al.[3] have presented a "pop up" bolometer design for large-format arrays of semiconducting as well as voltage-biased superconducting bolometers (VSB) with a high filling factor. One row of devices is made from a single substrate which is subsequently folded so that the mechanical supports and wiring are perpendicular to the plane of the absorber. Agnese et al.[4] have described a different array architecture which is assembled from two wafers by indium bump bonds. There is room for wiring on the lower wafer at the cost of a complicated assembly. They have used this architecture to make large-format arrays of high impedance implanted Si bolometers.

Our design uses a single wafer for simple robust fabrication. As with the Agnese design the mechanical suspension structures and the leads lie in the plane of the absorber and extend only marginally beyond its limits. Our suspension design, however, keeps the mesh under tension and allows us to use a much thinner, less rigid silicon nitride structure. This makes it possible to manufacture *monolithic* two-dimensional arrays with a high filling factor.

Figure 1 shows a photograph of our prototype for a single detector element. The absorber is a mesh with a square lattice spacing much smaller than the wavelength to be detected. Mesh absorbers have a low heat capacity and a low cross section for cosmic ray background. They were pioneered by Bock et al.[5] for semiconducting bolometers in a "spiderweb" geometry which is not suitable for making close-packed arrays. Our group has previously produced VSBs in this geometry.[6]

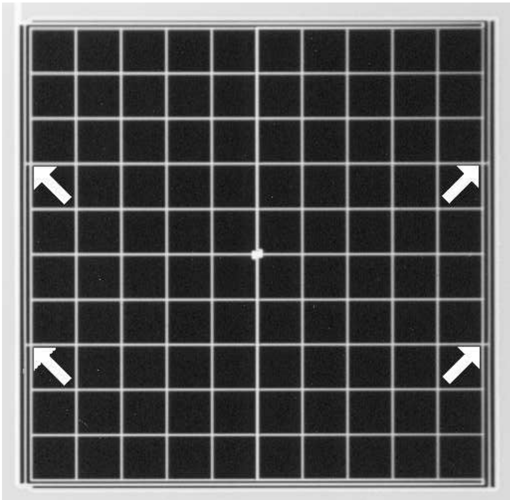

FIG. 1. The prototype bolometer fills a square area of 1.5mm×1.5mm. It consists of a rigid square grid (light lines) of 11×11 beams, each 7μm wide and metallized for absorption. The grid is suspended at four points (arrows) by 7μm wide free-standing tensioned silicon nitride beams which run along the left and right sides. Two additional beams of silicon nitride run along the top and bottom sides of the grid. They are not under tension and merely serve to support 3μm wide superconducting leads making electric contact to the sensor in the center of the mesh as shown in Fig. 2. This geometry maximizes the thermal path along the leads and thereby minimizes their contribution to the thermal conductance.

We have developed a fabrication method using standard microfabrication techniques that is simpler, results in more robust devices, and gives a higher manufacturing yield than our earlier method[6] for making spiderweb bolometers. A 1μm thick layer of low-stress (non-stoichiometric) silicon nitride (LSN) is deposited on a standard Si wafer by Low Pressure Chemical Vapor Deposition (LPCVD). Four layers of Ti (500Å), Al (400Å), Ti (500Å), and Al (1000Å) are deposited in situ by sputter deposition in a system with a base pressure of 5×10^{-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 upper Ti layer. The sensor and absorber are defined and etched into the Ti/Al/Ti trilayer with a $Cl_2/CHCl_3$ plasma. This also completes the leads which consist of all four metal layers. The structural elements are defined and etched into the LSN with an SF_6/He plasma. The wafer is diced and the Si is removed from underneath each individual device using XeF_2 gas until the bolometer is freely suspended. The photoresist on the front is ashed in an O_2-plasma and contact to the devices is made with Al wire bonds. Figure 2 shows that the absorber mesh is sufficiently rigid to keep its edges, which are not kept under tension by the suspension structure, from curling. As can be seen, the surface of the etched Si shows a roughness on a length scale of $\approx 10\mu$m . We expect this roughness to be averaged over the much larger wavelength of the signal and therefore not to affect optical efficiency.

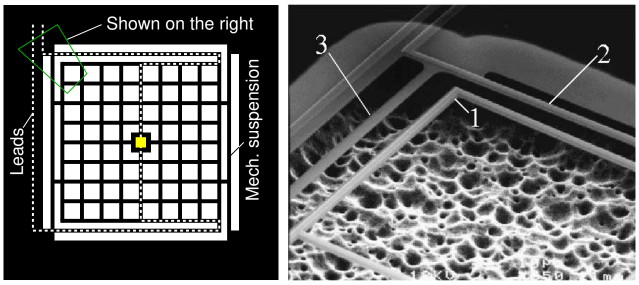

FIG. 2. Left: A simplified drawing of the mechanical structure of the prototype bolometer. Right: A scanning electron micrograph taken at an angle of $\approx 45°$ with respect to the bolometer plane shows the corner of the absorber grid (1), one of the leads (2), and one of the suspension structures (3). The rough surface of the Si substrate is due to the XeF_2-etch.

In a VSB, bias power is dissipated in the sensor, which is biased in the steep part of its resistive superconducting transition. Any change in the absorbed optical power is compensated by a change in bias power. This effect is called strong electrothermal feedback and it makes the bolometer a null-detector, increasing its speed and strongly enhancing its linearity.[7]

The prototype bolometer was tested in a dark enclosure cooled to $T_0 = 264$mK by a ^{3}He sorption refrigerator. The Ti/Al/Ti sensor has a normal resistance of $R_N = 1.3\Omega$ and shows a resistive transition at $T_c = 304$mK with the maximum transition steepness $\alpha = d\log R/d\log T$ of 740. The maximum value of the loop gain, which is a measure of the strength of the feedback, was estimated to be $\mathcal{L} \approx 50$. In future devices the proximity effect trilayer can be optimized to give $T_c \approx 1.5 \times T_0 = 400$mK for best sensitivity and $\mathcal{L} > 200$.

Voltage bias was achieved by current biasing a 20mΩ shunt resistor. An unwanted resistance of 15mΩ in series with the device was accounted for in the data analysis. The bolometer current was measured with a commercial SQUID ammeter.[8] Noise spectra were computed with a spectrum analyzer.[9] An attenuated cold light-emitting diode[10] with $\lambda = 626$nm was used as an optical stimulator. The power emitted by the diode was stepped up abruptly and the resulting change in the bolometer output was fitted to an exponential to determine the bolometer time constant.

The average thermal conductance was found to be $G = 2.7 \times 10^{-11}$W/K. We estimate that half of this conductance is due to the leads. Figure 3 shows the noise equivalent power when the device is biased at a resistance of 80mΩ. The measured noise level is close to the fundamental limit $\sqrt{4k_BT^2G}$ set by simple thermal fluctuation theory. The rise in the noise spectrum above 3Hz can be explained with a more complicated thermal model which will be published elsewhere.[11] The $1/f$ knee at 300mHz is higher than expected from SQUID noise alone and is possibly caused by the cryogenic system.

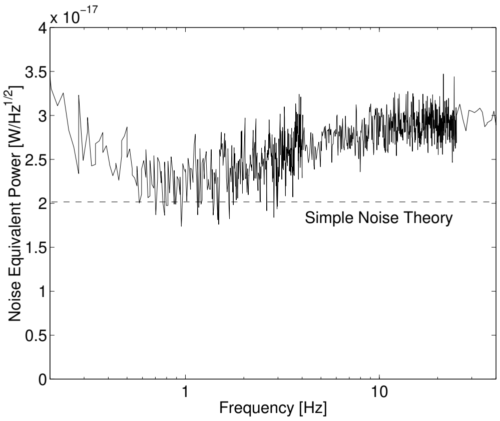

FIG. 3. Noise equivalent power measured at 304mK (see text for details).

Without electrothermal feedback, the time-constant of the bolometer was measured to be $\tau_0 = 127$ms. From this value we estimate the total heat capacity to be 3.2×10^{-12}J/K, which is in good agreement with prediction based on materials parameters. Electrothermal feedback reduces the time-constant[12] to $\tau = \tau_0/(\mathcal{L}+1)$ unless it is limited by an internal thermalization time τ_i of the absorber. We measure $\tau_i = 24$ms. Our noise model shows[11] that noise-performance can be optimized by using low heat capacity materials for leads and absorber. We have already successfully used Nb as a lead material on LSN. Because of its high $T_c \approx 9$K it should have negligible heat capacity and thermal conductance at the operating temperature of our devices. Using Au for the absorber would also reduce the present heat capacity considerably. Au-absorbers with internal thermalization times as low as 4.5ms have been demonstrated.[13]

We predict that a device with the described structure with Nb leads and an Au absorber would show white noise at the limit set by simple thermal fluctuation theory up to 300Hz. At temperatures around 400mK, Nb leads would not contribute appreciably to the thermal conductance. The current design would then give $G \approx 1.3 \times 10^{-11}$W/K and NEP $< 10^{-17}$W/$\sqrt{\text{Hz}}$, suitable for single-mode ground-based photometry from the best sites. Values as low as $G \approx 4 \times 10^{-12}$W/K could be achieved by using a thinner LSN film and narrower structures. If the bolometer was operated at $T_0 = 100$mK, G would be reduced by a further factor ≈ 10. The resulting NEP $< 10^{-18}$W/$\sqrt{\text{Hz}}$ would be adequate for single-mode photometry from an ideal cooled space-borne telescope which is background-limited by emission from galactic dust.

The low thermal conductance of Nb-leads would also allow us to run them directly along the mechanical support. This would make it possible to omit the structures currently supporting the leads and to suspend the bolometer mesh on all four sides, making the design even more rigid.

To optimize the coupling of the signal to the absorber a reflective layer (e.g. Al) will be deposited on the back of future devices so that there is a gap of thickness a and a Si layer of thickness b between the absorber and the reflector (see Fig. 4). The Si behind the bolometer must be thinned in a controlled way as can be done with silicon on insulator (SOI) wafers and trench etching techniques.[14]

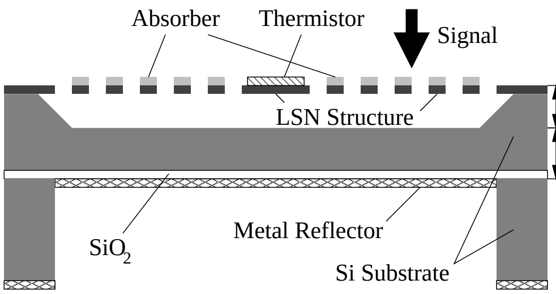

FIG. 4. Cross section of an individual bolometer with back reflector. The vertical scale has been exaggerated.

The optimal values of a and b depend on the wavelength λ of the signal. Our calculations show that for any $a < \lambda/4$ there is a value for b such that absorptivity is unity. Every 10% deviation from the optimal value of b translates into a reduction of the absorptivity by $\approx 2\%$. We find that the parameter b is uniform within the measurement accuracy given by the roughness of the etched Si surface. In a 32×32 element array we observe overetching of the elements at the very edge of the array. We expect to eliminate this problem by modifying the gas flow pattern in the etch apparatus. This should make it possible to produce arrays for wavelengths from $\approx$250μm to several mm with this approach. For shorter wavelengths one would etch away all the Si remaining underneath the bolometer, opening a window to the back of the wafer. A metal coated Si surface micromachined from another SOI wafer can then be brought in from the back to create a reflector precisely $\lambda/4$ behind the absorber.

To explore the feasibility of large arrays, we have manufactured LSN structures for arrays of 4×4, 8×8, and 32×32 bolometers. Figure 5 shows the LSN structure for a 32×32 element array covered with a 500Å thick layer of Ti to facilitate photography. The production yield is excellent and all 1024 meshes are intact. Ten of them show defects which are clearly due to dust contamination in our cleanroom facility. The structures are much more robust than the spiderweb bolometers made previously[6] because they are protected by the Si substrate. The spacing between the bolometers was chosen such that contact to all devices can be made with 1μm wide leads and a 1μm spacing between leads. The absorbers fill 88% of the area.

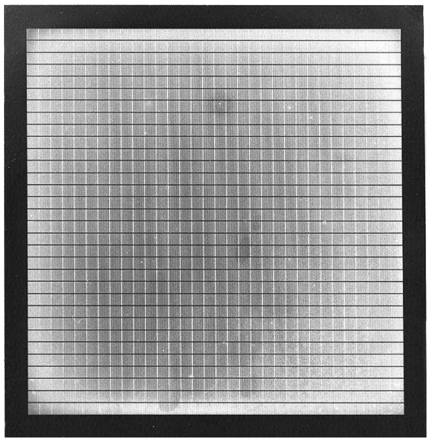

FIG. 5. Silicon nitride structure for a 1024 element array of 1.5mm×1.5mm bolometers.

The meshes in the arrays show a tendency to curl in the areas extending beyond the suspension points. This effect was not seen in our complete prototype bolometers. It could be due to the different metallization or a different degree of stress in the batch of LSN used for making the arrays. While the proposed suspension on all four sides would most likely remedy this problem, further investigation of the issue is necessary.

In summary, we have described a novel bolometer design which allows the production of large monolithic detector arrays with a very high filling factor by standard planar lithography. We have produced a prototype bolometer operating close to the fundamental noise limit and indicated changes necessary to produce optimized bolometers. There appear to be no major obstacles to the fabrication of large-format filled arrays of VSBs for $200\mu\text{m} \leq \lambda \leq 3$mm with values for G as low as 4×10^{-12}W/K for $T_0 = 264$mK and 4×10^{-13}W/K for $T_0 = 100$mK. Arrays for $\lambda < 200\mu$m can be fabricated with reflectors made on a separate wafer.

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[1] 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. of the Am. Phys. Soc. **43,** 231 (1998).

[2] J. Yoon, J. Clarke, J.M. Gildemeister, A.T. Lee, M. Myers, P.L. Richards, and J. Skidmore, submitted to Appl. Phys. Lett., manuscript #L00-2517.

[3] D.J. Benford, E. Serabyn, T.G. Phillips, and S.H. Moseley, Proceedings of Advanced Technology MMW, Radio, and Terahertz Telescopes, 1998 Kona, Hawaii, SPIE **3357**, 278 (1998).

[4] P. Agnese, C. Buzzi, P. Rey, L. Rodriguez, J.-L. Tissot, Proceedings of Infrared Technology and Applications XXV, 1999 Orlando, Florida, SPIE **3698**, 284 (1999)

[5] J.J. Bock, D. Chen, P.D. Mauskopf, and A.E. Lange, Space Science Reviews, **74**, Kluwer Academic Publishers, Dordrecht, 229 (1995)

[6] J.M. Gildemeister, Adrian T. Lee, and P.L. Richards, Appl. Phys. Lett. **74,** 1868 (1999).

[7] S.-F. Lee, J.M. Gildemeister, W. Holmes, A.T. Lee, and P.L. Richards, Appl. Opt. **37,** 3391 (1998).

[8] Quantum Design, series 50 SQUID and model 550 controller

[9] Stanford Research, model SR785

[10] Hewlett-Packard, model HLMP-1000

[11] J.M. Gildemeister, Adrian T. Lee, and P.L. Richards, submitted to Appl. Optics.

[12] A.T. Lee, P.L. Richards, S.W. Nam, B. Cabrera, and K.D. Irwin, Appl. Phys. Lett. **69,** 1801 (1996).

[13] J. Bock, J. Glenn, S. Grannan, K. Irwin, A. Lange, H. LeDuc, and A. Turner, Proceedings of Advanced Technology MMW, Radio, and Terahertz Telescopes, 1998 Kona, Hawaii, SPIE **3357**, 297 (1998)

[14] J. Bhardwaj, H. Ashraf, and A. McQuarrie, Proceedings of the Third International Symposium on Microstructures and Microfabricated Systems, Montreal, Canada, Electrochem. Soc., 118 (1997)