

Superconducting Transition Edge Sensor Bolometer Arrays for Submillimeter Astronomy

**Dominic J. Benford, Christine A. Allen, Alexander S. Kutyrav,
S. Harvey Moseley, Richard A. Shafer**

NASA - Goddard Space Flight Center, Code 685, Greenbelt, MD 20771

**James A. Chervenak, Erich N. Grossman, Kent D. Irwin,
John M. Martinis, Carl D. Reintsema**

NIST - Boulder, MS 814.09, Boulder, CO 80303

Abstract

Studies of astrophysical emission in the far-infrared and submillimeter will increasingly require large arrays of detectors containing hundreds to thousands of elements. The last few years have seen the increasing from one to a few tens of bolometers on ground-based telescopes. A further jump of this magnitude, to a thousand bolometers, requires a fundamental redesign of the technology of making bolometer arrays. One method of achieving this increase is to design bolometers which can be packed into a rectangular array of near-unity filling factor while Nyquist-sampling the focal plane of the telescope at the operating wavelengths. In this case, the array becomes more nearly analogous to the arrays used in the near-infrared which underwent a substantial growth during the last decade. A multiplexed readout is necessary for this many detectors, and can be developed using SQUIDs such that a 32×32 array of bolometers could be read out using 100 wires rather than the >2000 needed with a brute force expansion of existing arrays. Superconducting transition edge sensors are used as the detectors for these bolometer arrays. We describe a collaborative effort currently underway at NASA/Goddard and NIST to bring about the first astronomically useful arrays of this design, containing tens of bolometers. This technology is well-suited to low-background instruments such as SPIRE on FIRST and SAFIRE on SOFIA, and can also be used in broadband, high-background instruments such as HAWC on SOFIA.

Keywords: bolometer, far-infrared, submillimeter, superconducting, SQUID, detector array, multiplexer, transition edge sensor

Introduction

Advances in bolometer fabrication have made possible the construction of submillimeter-wavelength cameras with several tens of detectors (e.g., CSO - SHARC (Wang *et al.* 1996), JCMT - SCUBA (Holland *et al.* 1996), IRAM 30m (Kreysa *et al.* 1998)).

Currently, the sensitivity of these instruments is background-limited, so deep- and wide-field surveys are limited by the number of detectors and the amount of observing time available. In order to achieve a leap to a thousand detectors (of order the largest size usable on current and foreseen telescopes), a scalable detector architecture must be demonstrated. Such an architecture should deal with both the fabrication of an array and the electronics used to read it out. Conventional technologies use semiconducting thermistors as the detection element, with the alternative being superconducting transition edge sensors. Another common feature of most bolometer arrays is the use of feedhorn-coupled (typically spaced by $2f\lambda$) arrays, with the alternative being a filled array ($f\lambda/2$) of close-packed square bolometers. In this paper, we present a suggestion for an architecture which can be readily scaled to kilopixel arrays using superconducting sensors and a multiplexed amplifier technique (Chervenak *et al.* 1999) to reduce the wiring overhead. In our implementation, we choose to use the close-packed geometry, which yields an improvement in mapping speed per focal plane area (Bock *et al.* 1998). However, the superconducting detectors can be used regardless of array geometry, and are equally feasible for arbitrary array implementations.

Detector arrays of this type are currently being developed for use in the SAFIRE instrument for SOFIA (Shafer *et al.* 2000) and for a ground-based spectrometer (Maffei *et al.* 1994). A common figure of merit for bolometers is the Noise Equivalent Power (NEP). This is the power that yield a signal-to-noise ratio of unity in a 1Hz bandwidth, and is expressed in units of W/\sqrt{Hz} . For SAFIRE, observations of the CII line at 1900GHz (158 μ m) with a spectral resolving power of 1000, the maximum NEP for the detectors must be $10^{-17} W/\sqrt{Hz}$. NEP can be converted into an equivalent noise temperature $T_N = NEP/(2k\sqrt{\Delta\nu})$ (Phillips 1988). In the above case, this yields a noise temperature of around 8K. While not achievable with heterodyne spectrometers due to the quantum limit, direct detection has no such restriction.

Superconducting Transition Edge Sensors

The transition between a superconducting and a normal state can be used as an extremely sensitive thermometer. A thin film, held at its transition temperature, requires only a tiny amount of power to warm it above its transition, increasing the resistance by a large fraction. In fact, the superconducting transition can be very sharp, yielding a dimensionless sensitivity $d \log R / d \log T \approx 1000$ at best. Recently, we have fabricated thin film superconducting bilayers of Molybdenum and Gold with transition temperatures of around 0.5K. One such transition is shown in Figure 1; it features a bilayer with 400Å of molybdenum and 750Å of gold, yielding a normal resistance of 220m Ω . Near its transition temperature of 440mK, the sensitivity approaches 200.

Because the transition region is narrow (~ 1 mK) compared to the temperature above the heat sink (140mK above a 3 He refrigerator at 300mK), the TES is nearly isothermal across the transition. In use as a detector, the power applied to raise the TES into its

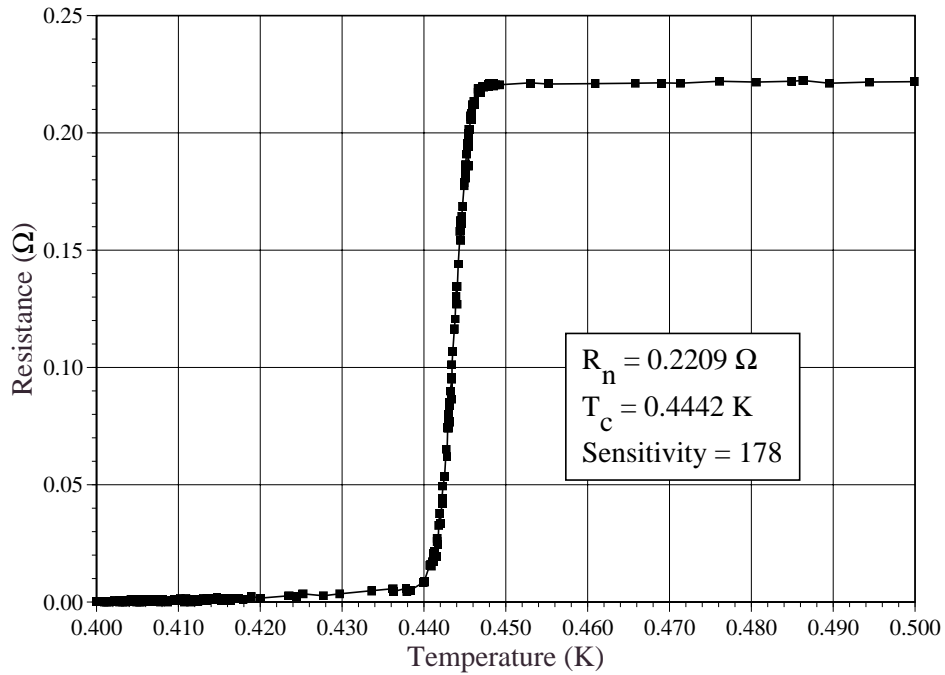


Figure 1. Superconducting transition at 444mK for a Mo/Au bilayer.

transition region is nearly constant. This has the effect that the response becomes linear to better than 1%, substantially better than the typical linearity achieved with semiconducting thermistors.

To date, the best transition we have achieved with Molybdenum and Gold has yielded a sensitivity of ≈ 1100 . Many such devices have been made, with transition temperatures reproducible to 2%. Additionally, the normal state resistances are very repeatable and stray resistances are less than $3\text{m}\Omega$. This bilayer process allows the transition temperature to be tuned by varying the relative thicknesses of the normal metal (Gold) and superconducting metal (Molybdenum) layers. In this manner, detectors optimized for performance in a variety of different optical loads (e.g. broadband imaging, narrowband spectroscopy) can be produced.

In order to bias the TES, a voltage source of output impedance less than the TES impedance – typically $100\text{m}\Omega$ – must be provided. In a cryogenic environment this is challenging, but can be solved simply by providing a current bias to a very small shunt resistor in parallel with the TES. Our bias circuit is shown in Figure 2, in which a constant voltage source across a $1\text{k}\Omega$ resistor produces a constant current through the $1\text{m}\Omega$ shunt resistor. The inductors shown are for coupling to the SQUID amplifiers described below.

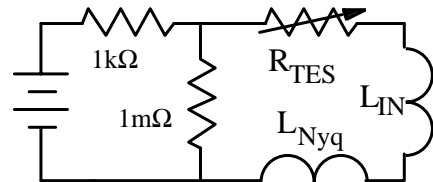


Figure 2. Bias circuit for a TES.

Because the sensitivity of a TES is so large (≈ 200 for the film in Figure 1 vs. ≈ 5 for a semiconducting thermistor), a voltage-biased TES is stabilized by strong electrothermal feedback (Irwin 1995). In this mechanism, an increase in temperature yields a sharp increase in resistance, which reduces the current flowing through the TES, lowering the bias power and decreasing the temperature. This enables the devices to be very fast (time constants of $\approx 1\text{ms}$) and has the added benefit of reducing Johnson noise so that phonon noise dominates at low frequencies.

TES Bolometers

In order to make a detector of the appropriate sensitivity, we have fabricated monolithic linear silicon bolometers using micromachining techniques (Figure 3). These bolometers have slim silicon legs which provide thermal isolation and a 1mm^2 absorber to couple to the far-infrared light. The thermal conductance at the operating temperature determines the optical power that the device is optimized for; current arrays are being fabricated for operation with $\approx 1\text{pW}$ of optical loading. These linear bolometer arrays can be folded such that the legs (and, therefore, electrical connections) are hidden completely behind the absorber, allowing close-packing perpendicular to the array. In this way, a two-dimensional array of large size can be made with near unity filling factor.

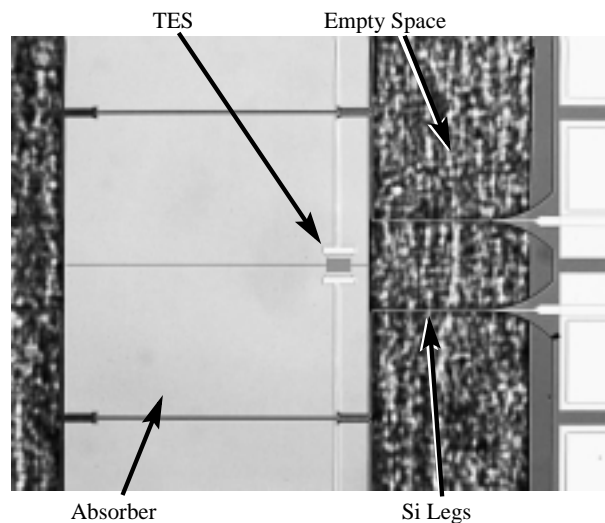


Figure 3. A single element from the middle of a linear array of TES bolometers. The absorber is 1mm on a side.

A single linear array of bolometers is shown in Figure 4. Each pixel measures 1mm on a side and is $1\mu\text{m}$ thick. The silicon legs are barely visible as two thin lines leading to each pixel. An enlargement of the area around a single TES bilayer is shown in an inset. The active area is approximately $50\mu\text{m}$ square. Once several of these linear arrays are folded, they can be stacked closely, as shown in Figure 5. This mechanical assembly test yielded a 5×32 array, as a proof-of-concept prototype for future 32×32 arrays.

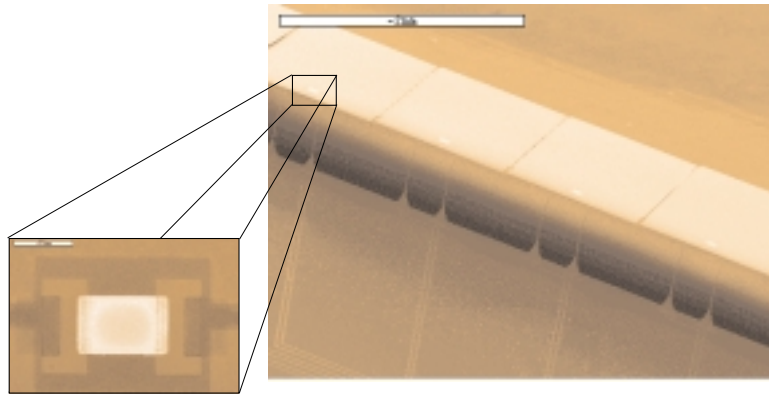


Figure 4. SEM photograph of a single row of bolometers. The enlargement shows the TES bilayer present on each detector.

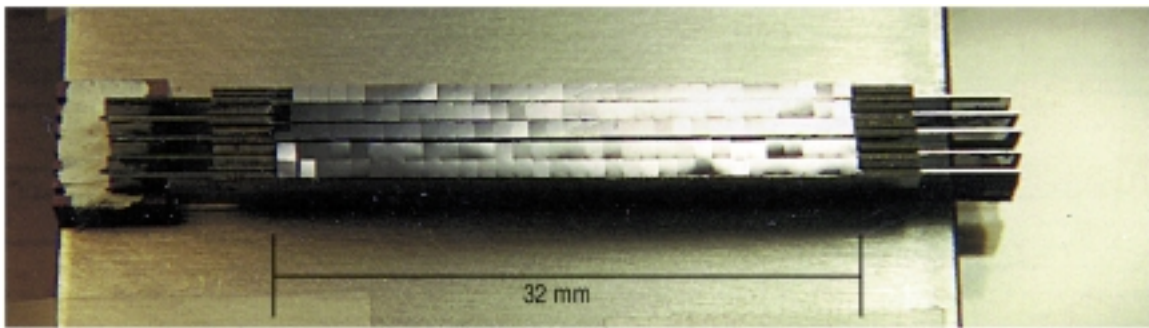


Figure 5. Mechanical assembly of a 5x32 array of bolometers.

Bolometer Performance

Optical performance was measured in a test setup designed to calibrate low-background detectors for SPIRE (Hargrave *et al.* 1999). This setup used a helium-cooled blackbody consisting of a textured, black, carbon-loaded epoxy (Epotek 920) wall in a gold-coated cavity. Selectable apertures allow the throughput to the blackbody to be chosen. The blackbody can be heated to cover temperatures between 2K and 40K. A metal-mesh bandpass filter at 350 μ m wavelength (850GHz) with a fractional bandpass of $\sim 1/10$ reduced the total transmitted power to be within the range of our bolometers, which were designed to saturate (i.e., be driven normal) at 5pW. The result of the blackbody calibration is shown in Figure 6, where the measured power has been corrected for a bolometer absorptivity of 90%. The measured response follows the theoretical power very well up to a saturation power of 2.1pW, about half the designed value. The excellent linearity of TES bolometers is one of their best features.

In addition to calibration with the blackbody, the test setup permits an external source to be used. In order to reduce the optical load to an acceptable level, a 1% transmissive neutral density filter is placed in the beam. The time constant was measured by using a

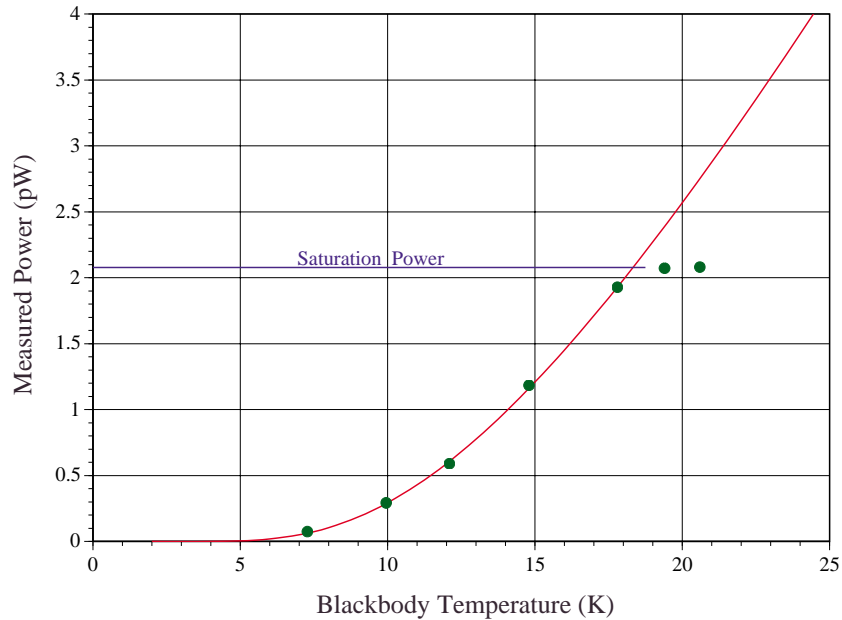


Figure 6. Measured power versus blackbody temperature for a helium-cooled calibration source, assuming a detector absorptivity of 90%.

rapidly chopping blade with a hot/warm load. An upper limit of $\tau \leq 2\text{ms}$ was found, limited by the speed of the chopper. A Fourier transform spectrometer was used to measure the frequency response, which was limited by the bandpass filter. No bandwidth degradation due to inefficiencies in the absorbing coating were seen. Also, a beam map was made, and excellent rejection of out-of-beam power was found.

In Figure 7, we show the Noise Equivalent Power (NEP) of a TES bolometer using an Aluminum/Silver bilayer operating at a transition temperature of 568mK. The NEP over the desired 10-100Hz bandwidth is $2.8 \times 10^{-17} \text{W}/\sqrt{\text{Hz}}$. The phonon noise calculation is shown as a blue curve, demonstrating that phonon-limited performance has been obtained. Over a 100GHz bandwidth at 850GHz, this noise level corresponds to a detector noise temperature of 3.2K. The measured noise levels of lower-transition (440mK) devices have been about 20% above the phonon noise level, indicating excess noise which is believed to arise from edge effects where the bilayer thicknesses are not well defined. Recent results using Molybdenum/Copper bilayers appear not to have this excess noise.

SQUID Amplifier

A low-impedance detector such as a superconducting TES is well-matched by a superconducting SQUID amplifier. From a fundamental standpoint, a SQUID amplifier functions as a magnetic flux to voltage converter, with extremely low output voltage noise). A voltage-biased TES in series with a “pickup” inductor placed near a SQUID

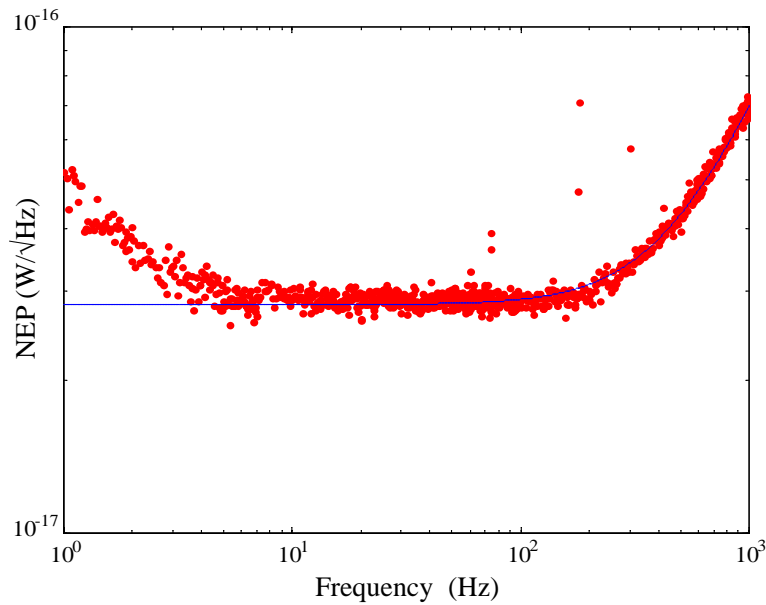


Figure 7. NEP of a detector operating at 568mK. The phonon noise calculation is shown as a blue curve, demonstrating that phonon-limited performance has been obtained over the 10-100Hz signal band.

will induce a changing flux through the SQUID when the TES resistance changes. As in Welty & Martinis (1993), we use the first stage SQUID to drive a series array of SQUIDs which yield a voltage gain of 100. This Series Array Amplifier can produce an output voltage of the order of a millivolt, readily amplified by room-temperature electronics. As shown in Figure 8, a single detector can be read out using eight wires.

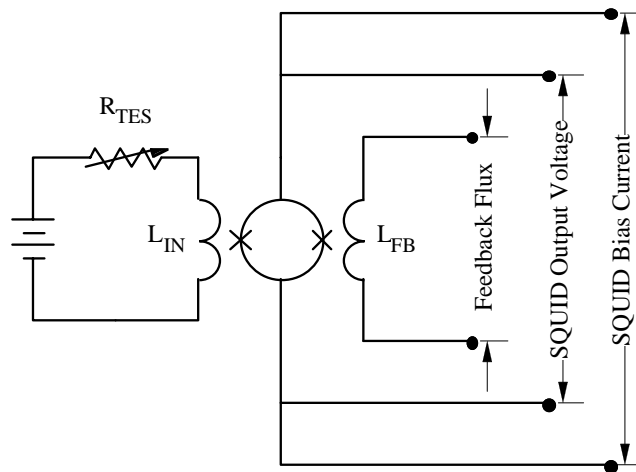


Figure 8. A single SQUID amplifier circuit. Eight wires are needed to read out one detector, assuming separate returns.

Multiplexed SQUID Amplifier

A SQUID amplifier can be switched rapidly between an operational state and an inoperational, superconducting state by biasing the SQUID with roughly $100\mu\text{A}$ of current. If we stack n SQUIDs in series with $n+1$ electrical “address” leads as shown in Figure 9, driving current between an adjacent pair of leads will result in only one SQUID being operational. With the other SQUIDs in the superconducting state, the output voltage across the entire array is exactly the voltage across the one active SQUID. In this manner, only one amplifier is necessary for n detectors, although at a data rate n times faster. Adding in connections for a common TES bias and feedback signal, and a total of $n+7$ wires are needed.

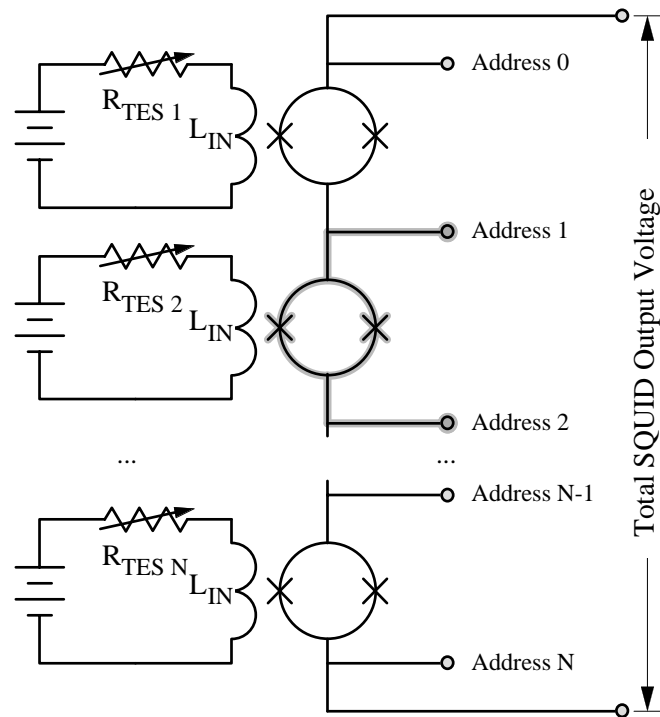


Figure 9. A multiplexed SQUID amplifier reading out n detectors. A total of $n+7$ wires are needed (assuming ganged biases).

A 1×8 SQUID multiplexer has been built and tested using the circuit described in Chervenak *et al.* (1999). Two sine wave inputs were fed into a cold electronics setup so as to mimic the modulation of a signal from infrared light. The multiplexed amplifier was switched between these inputs, amplified, digitized. A sample time series of data at this point is shown in Figure 5 of Chervenak *et al.* (1999). This data can be demultiplexed to recover the original input sine waves, which demonstrates the excellent fidelity of the amplifier. It should be pointed out that the TES is biased at all times, and is low-pass filtered using an inductor with time constant $L/R \approx 2\mu\text{s}$ to a response time slower than the multiplex switching time. Effectively, the TES self-integrates so that the

multiplexer *samples* an integrated signal; no loss of signal-to-noise is introduced even though the signal from each TES is read out for a shorter time. This is true provided that the noise of the SQUID is substantially less (by a factor of more than \sqrt{n}) than that of the TES. Furthermore, in order to remain stable, the devices must be sampled faster than $f_{L/R}=(3+2\sqrt{2})f_{\text{TES}} \approx 100$ kHz.

Two-Dimensional Multiplexed SQUID Readout

When multiplexing a two-dimensional array consisting of m rows and n columns, an advantage can be gained in that the columns share common address lines and only one amplifier is needed. In the most straightforward wiring scheme, $4n+m+3$ wires are needed, as opposed to $8mn$ for a fully-wired array of discrete bolometers. Table 1 highlights the wiring advantage for multiplexed arrays, and describes the development status of these arrays at GSFC/NIST. Future advances using cold semiconducting shift registers (wherein a clock pulse will change the multiplex addressing, as opposed to the present direct addressing) may be possible, further reducing the multiplexer wiring requirements.

Table 1. Wiring advantage of multiplexed detectors versus directly-wired detectors and the current state of development.

Columns	Rows	Detectors	Wires (non-muxed)	Wires (muxed)	Status
1	1	1	8	8	Exists
2	4	8	64	15	Exists
2	8	16	128	19	Exists
4	8	32	256	27	In fabrication
1	32	32	256	39	In design
32	32	1024	8192	163	In design
64	64	4096	32,768	323	In design

Conclusion

We have demonstrated a superconducting transition in Molybdenum/Gold bilayers which looks promising for use as TES films on sensitive bolometers. Noise Equivalent Powers consistent with phonon noise have been measured, and optical efficiency of 90% has been achieved. A multiplexed SQUID amplifier has been fabricated and is shown to provide low-noise, high-fidelity readout of several TES detectors with a single signal output. This architecture can be extended to two-dimensional arrays with relatively little increase in the total number of wires. A large-format (thousands of detectors) bolometer array can be made with this technology, having application in future far-infrared instruments such as SPIRE on the FIRST telescope and SAFIRE on the SOFIA observatory.

References

- Benford, D.J., Hunter, T.R. & Phillips, T.G. 1998, *Int J. IR MM Waves*, **19**, **7**, 931.
- Bock, J.J., Glenn, J., Grannan, S.M., Irwin, K.D., Lange, A.E., LeDuc, H.G. & Turner, A.D. 1998, *Proc. SPIE #3357*, T.G. Phillips, ed., p.297
- Chervenak, J.A., Irwin, K.D., Grossman, E.N., Martinis, J.M., Reintsema, C.D. & Huber, M.E. 1999, *Appl. Phys. Lett.*, **74**, p.4043
- Hargrave, P.C. *et al.* 1999, *Proc. Low Temperature Detectors #8*, in press
- Holland, W.S. *et al.* 1996, *Int J IR MM Waves*, **17**, p.669
- Irwin, K.D. 1995, *Appl. Phys. Lett.* **66**, p.1998
- Kreysa, E. *et al.* 1998, *Proc. SPIE #3357*, “Advanced Technology MMW, Radio, and Terehertz Telescopes”, T.G. Phillips, ed., p.319
- Maffei, B. *et al.* 1994, *Infrared Phys. Technol.*, **35**, **2**, 321.
- Phillips, T.G. 1988, in “Millimetre and Submillimeter Astronomy”, Wolstencroft & Burton, eds., p.1
- Shafer, R.A. *et al.* 2000, in *SPIE Proceedings*, “Astronomical Telescopes and Instrumentation 2000”, Munich, Germany
- Wang, N.W. *et al.* 1996, *Applied Optics*, **35**, p.6639
- Welty, R.P. & Martinis, J.M. 1993, *IEEE Trans. App. Superconductivity*, **3**, p.2605