THERMOPILE DETECTOR ARRAYS FOR SPACE SCIENCE APPLICATIONS

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ABSTRACT

Thermopile detectors are widely used in uncooled applications where small numbers of detectors are required, particularly in low-cost commercial applications or applications requiring accurate radiometry. Arrays of thermopile detectors, however, have not been developed to the extent of uncooled bolometer and pyroelectric/ferroelectric arrays. Efforts at JPL seek to remedy this deficiency by developing high performance thin-film thermopile detectors in both linear and two-dimensional formats. The linear thermopile arrays are produced by bulk micromachining and wire bonded to separate CMOS readout electronic chips. Such arrays are currently being fabricated for the Mars Climate Sounder instrument, scheduled for launch in 2005. Progress is also described towards realizing a two-dimensional thermopile array built over CMOS readout circuitry in the substrate.

INTRODUCTION

Thermopile detectors have some desirable characteristics that make them better suited for certain applications than are uncooled bolometers and pyroelectric/ferroelectric detectors. They are passive devices, require no electrical bias, and generate a voltage output that is proportional to the input radiation signal. They are also typically uncooled and are insensitive to substrate temperature variations, making temperature stabilization unnecessary. They are highly linear, which combined with their insensitivity to substrate temperature, make them ideal for accurate radiometry. Finally, they require no optical chopper and they have negligible 1/f noise, provided the readout amplifier has high input impedance. These properties make them well suited for broadband and spectral radiometers for space science applications.

In spite of these properties, the development of thermopile arrays is much less mature than that of bolometers[1,2] and pyroelectric[3] detectors. Linear thermopile arrays with both metal[4] and $(Bi_{1-x}Sb_x)_2(Te_{1-y}Se_y)_3$ alloy[5,6] thermoelectric materials have been reported. Reports of two-dimensional (2D) thermopile arrays have been limited to CMOS materials,[7,8] which are ideal for manufacturability but yield only moderate thermoelectric performance. The lack of maturity in thermopile detector array development is due in part to the fact that the thermoelectric materials with the highest figure of merit (ZT) are $(Bi_{1-x}Sb_x)_2(Te_{1-y}Se_y)_3$ alloys, which are not compatible with conventional semiconductor fabrication lines. More importantly, however, is the difficulty in implementing low-noise readout circuitry for thermopile arrays. While a bolometer array can be multiplexed by sequentially biasing pixels with large bias currents, each thermopile detector output signal must be continuously integrated to achieve the full detector signal-to-noise ratio. Thus, each pixel must have a dedicated low-noise amplifier and integrating circuit.

Here we report progress towards the realization of high-performance thermopile arrays with CMOS readout circuitry. Linear thermopile arrays, formed by bulk micromachining and wire bonded to adjacent readout chips, are currently being fabricated for the Mars Climate Sounder (MCS) instrument. MCS will fly on the Mars Reconnaissance Orbiter (MRO) scheduled to launch in 2005. Engineering models of these detector arrays, with readout, exhibit a specific detectivity D^* value of 8×10^8 cmHz$^{1/2}$/W in the frequency range

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0.03-0.25 Hz. Additionally, we report on an effort to build 2D arrays of thermopile detectors using surface micromachining to build thermally isolated detector structures over readout circuitry imbedded in the substrate. The 2D detectors and readout chips have been developed separately so far, but efforts will soon be under way to integrate the detectors on the readout chips.

THERMOPILE LINEAR ARRAYS

The JPL thermopile linear arrays have been described in detail previously.[6,9] They consist of 0.5 micron thick silicon nitride membranes formed by backside etching of the underlying silicon substrate. On each membrane are a number of Bi-Te and Bi-Sb-Te thermocouples running along narrow legs between the substrate and membrane. The detectors are closely spaced, with slits through the membrane separating the detectors from each other and defining the detector legs. Typical detectors have D^* values in the range 1-2x10^9 cmHz$^{1/2}$/W and response times less than 100 ms.

Thermopile detector arrays are currently being fabricated at JPL for the Mars Climate Sounder (MCS) instrument. MCS is a limb-sounding radiometer to fly on the Mars Reconnaissance Orbiter (MRO) mission, scheduled to launch in 2005. MCS will measure temperature, pressure, water vapor, and the combination of dust and condensates as a function of altitude in Mars' atmosphere in addition to polar radiative balance. Nine 21-element linear arrays of thermopile detectors, distributed between two focal planes in twin telescopes, sit behind spectral bandpass filters spanning the wavelength range 0.3-45 microns. The requirements for the detector-readout subsystem are listed in Table 1. Note that D^* is specified in the 0.03-0.25 Hz range, corresponding to two-second integration times and a 30 second cycle between views of space. Thus, low 1/f noise in both the detectors and the readout circuitry is essential.

Table 1. *Mars Climate Sounder detector requirements.*

Parameter	Requirement
Detector Size	240 μm x 480 μm
Number of detectors per array	21
Arrays in Focal-Plane A	6
Arrays in Focal-Plane B	3
D* (0.03-0.25 Hz, 0.3-45 μm)	10^9 cmHz$^{1/2}$/W
Response Time	≤100 ms
Pixel Crostalk	≤1%
Yield	100%
Dynamic Range for 2 sec Integration Time	13,000
Linearity	1%

Figure 1 shows an unblackened MCS thermopile detector pixel. Each pixel is 480 μm by 240 μm and has 12 Bi-Sb-Te / Bi-Te thermocouples connected in series to measure the temperature difference between the absorber and substrate. After detector fabrication, the chips are coated with gold black to provide high absorptivity and flat spectral response from 0.3 to 45 μm. During deposition, the gold black bridges the membrane slits, thermally shorting detectors to each other and to the substrate. These gold-black bridges are eliminated by laser ablation from the detector backside with 248 nm radiation, using the detector membrane as a mask. A detector array after gold black deposition and laser ablation is shown in Figure 2.

The MCS thermopile arrays are read out using a custom CMOS readout integrated circuit. The architecture of this circuit is shown in Figure 3. This readout chip is connected to the thermopile array with two wire bonds per detector. The roughly dc signal from each detector is modulated at 64 kHz by an electronic chopping circuit. The resulting ac signal is amplified, demodulated, and integrated. Because the amplification occurs at 64 kHz rather than near dc, the 1/f noise in the CMOS amplifier is dramatically reduced. Integrated signals from 64 channels are multiplexed into a single analog output stream. Thermopile detector noise is dominated by Johnson noise, which for the 80 kΩ MCS detectors is

36 nV/Hz$^{1/2}$. With a 80 kΩ source, the readout chip has an input-referred noise of 70 nV/Hz$^{1/2}$ in the 0.03 to 0.25 Hz range. Thus, the readout chip is the dominant focal-plane noise source. Even with this excess readout noise, the MCS engineering model focal plane has demonstrated D^* values of 8x10^8 cmHz$^{1/2}$/W, close to the required 10^9 cmHz$^{1/2}$/W. Without readout, the detectors have D^* values of 1.7x10^9 cmHz$^{1/2}$/W.

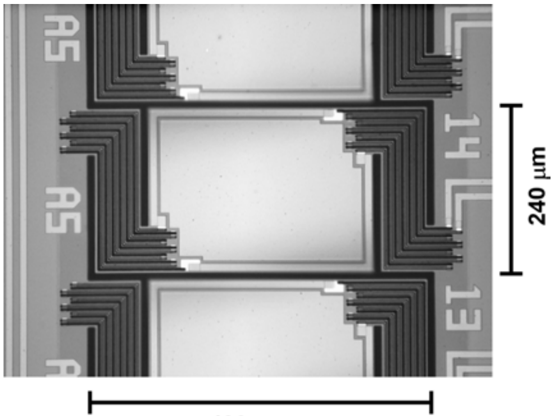

Figure 1. *Unblackened MCS detector pixels.*

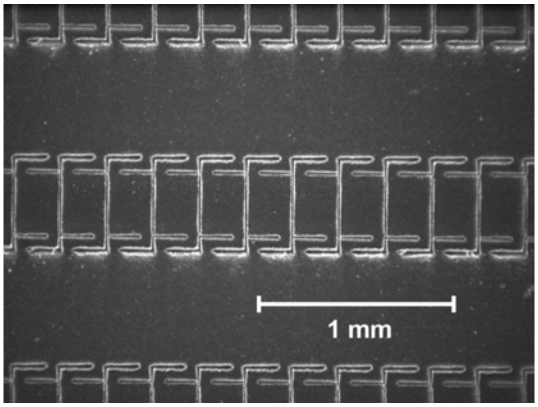

Figure 2. *MCS detector array with gold black.*

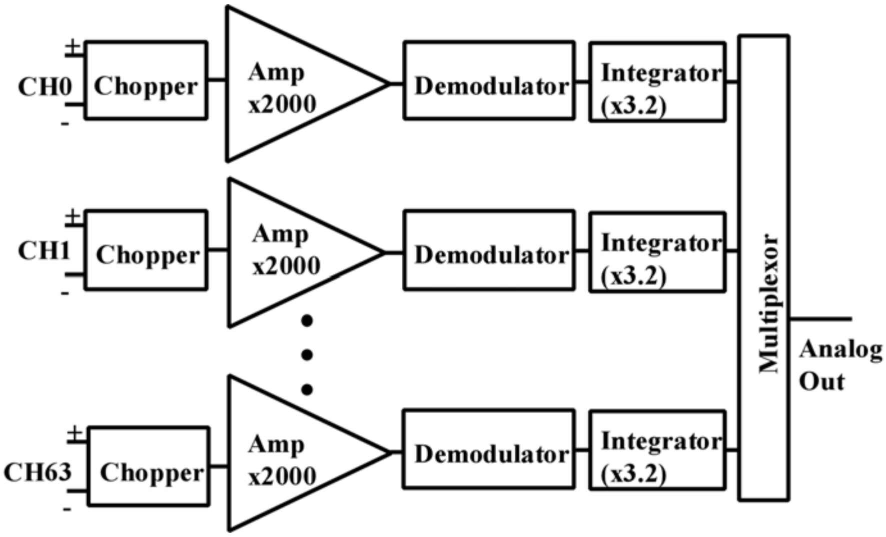

Figure 3. *Architecture of MCS readout integrated circuit.*

THERMOPILE 2D ARRAYS

In contrast to the linear thermopile arrays where membranes are formed by etching away the silicon substrate under the detectors, the 2D thermopile array effort at JPL involves using surface micromachining to build detectors over CMOS readout circuitry in the substrate. The design allows pixels to be arranged with a fill factor close to unity. To date, two parallel efforts have developed the detector pixels and the readout circuitry. Work will soon be underway to build detectors on readout chips.

A schematic diagram of a 2D thermopile detector pixel is shown in Figure 4. The pixel consists of three layers – a gold interconnect layer on the substrate surface, a middle layer consisting of the thermoelectric legs with a thin dielectric support structure, and a top absorbing layer. Two polyimide sacrificial layers present during detector fabrication are removed with a dry oxygen plasma etch in the final process step. The two thermoelectric layers are sputtered from targets with composition $Bi_{0.4}Sb_{1.6}Te_{3.3}$ (p-type) and $Bi_{1.6}Sb_{0.4}Te_{3.3}$ (n-type). Originally Bi_2Te_3 was used for the n-type thermoelectric, but it degraded in the oxygen plasma polyimide etch step. N-type Bi-Sb-Te has been found to be more stable throughout the fabrication process.

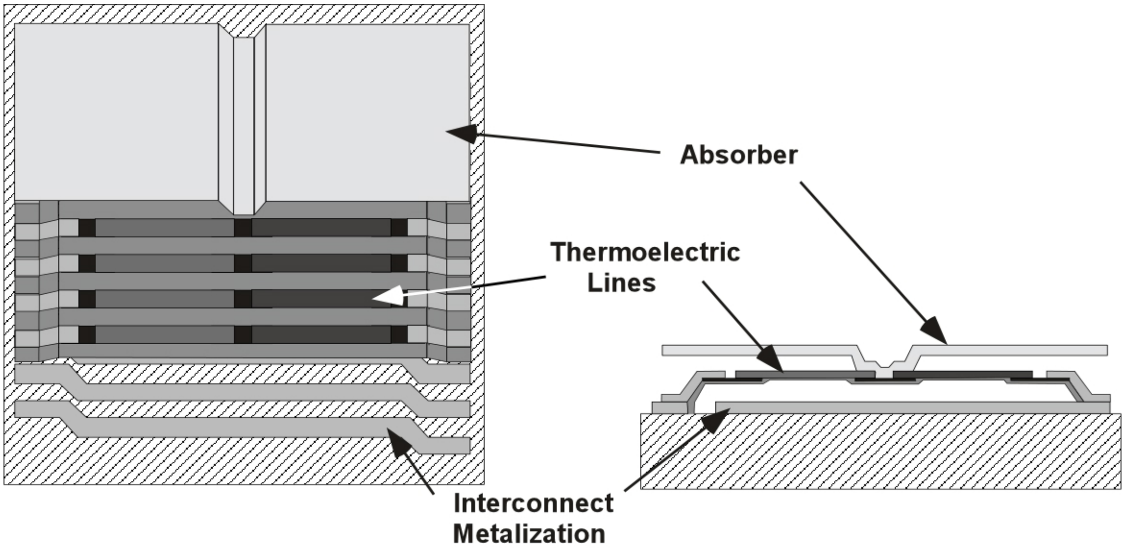

Figure 4. *Schematic diagram of 2D thermopile pixel structure.*

Figure 5 shows a scanning electron microscope picture of a single thermopile 2D detector. The holes through the absorbing structure allow the oxygen plasma to more quickly etch the polyimide film in the final fabrication step. The corrugation in the absorber is due to corrugation in the polyimide sacrificial layer below it, which in turn follows the contours of the thermoelectric lines underneath.

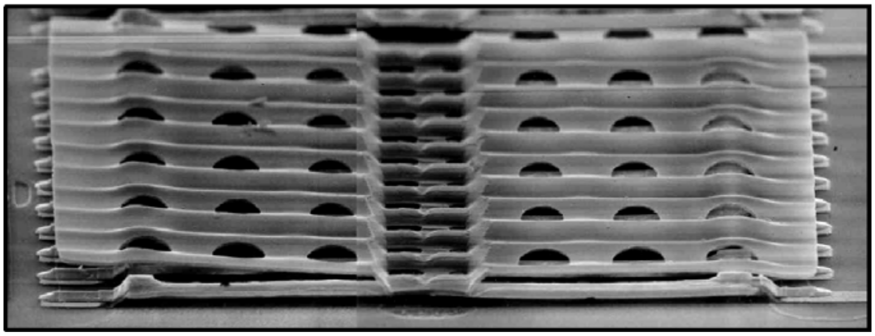

Figure 5. *Scanning electron microscope picture of a thermopile detector in a 2D array.*

Data from a 2D detector test chip are shown in Table 2. This chip consists of 21 detectors with a pixel size of 70 μm and 21 detectors with a pixel size of 100 μm. As Table 2 shows, D^* values for both pixel sizes thus far are only moderate. However, the response times of both the 70 μm and 100 μm pixel sized detectors are very fast. To increase D^* and improve the yield, we are currently building pixels with longer, narrower legs and reducing the number of thermoelectric legs per pixel.

Table 2. *Measured characteristics for a 2D thermopile test chip. The resistance R, the infrared responsivity $\mathcal{R}$, and the specific detectivity D^* are shown with their respective standard deviations.*

Pixel Size (μm)	Yield (%)	R (kΩ)	$\mathcal{R}$ (V W^{-1})	D^* (cm $Hz^{1/2}$ W^{-1})	Response Time (ms)
70	95	17.7 ± 3.5	726 ± 31	$3.1 \pm 0.3 \times 10^8$	2.1 ± 0.1
100	81	36.6 ± 3.6	1157 ± 25	$4.8 \pm 0.2 \times 10^8$	4.4 ± 0.3

CMOS readout chips have been fabricated, but not yet tested, for 32x32 arrays of 70 µm thermopile pixels. Under each pixel is a signal chain similar to that shown in Figure 3 for the linear arrays. The specification for these readout circuits is 60 nV/Hz$^{1/2}$ input referred noise for a 100 kΩ source resistance, and 1 µW power dissipation per pixel. Test chips with only the front end amplifier (expected to generate most of the noise and dissipated most of the power), exhibited 150 nV/Hz$^{1/2}$ input-referred noise and 0.6 µW power dissipation per pixel. The 32x32 array readout chips are expected to have lower noise due to an improved design and fabrication at a CMOS foundry with well-controlled 1/f noise.

CONCLUSIONS

The development of thermopile arrays has thus far lagged that of uncooled bolometers and pyroelectric/ferroelectric detector arrays. However, thermopiles have several advantages that make the pursuit of arrays worthwhile. In particular, their high linearity and insensitivity to substrate temperature variations make them ideal for radiometric applications. High performance linear arrays of thermopile detectors have been developed at JPL for space science applications. Linear arrays are currently being fabricated for the Mars Climate Sounder instrument. An additional effort, which seeks to develop 2D thermopile arrays, has resulted in pixel structures with moderate performance as well as readout integrated circuit chips. Future efforts will include integrating the current 2D detectors with readout circuitry, as well as optimizing the detector performance.

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