Progress Towards High-Performance Thermopile Imaging Arrays

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ABSTRACT

Thermopiles are uncooled, broadband detectors that require no chopper or temperature stabilizer. Their wide operating-temperature range, lack of temperature stabilization, and radiometric accuracy make thermopiles well suited for some space-based scientific imaging applications. These detectors may also offer advantages over bolometers for night vision. Previous work at JPL has produced thermopile linear arrays with D* values over 10^9 cmHz$^{1/2}$/W by combining high-performance thermoelectric materials Bi-Te and Bi-Sb-Te with bulk micromachining processes. To date, however, 2-D thermopile arrays have demonstrated only moderate performance. The purpose of the present work is to improve thermopile 2-D arrays substantially by combining Bi-Te and Bi-Sb-Te thermoelectric materials with a unique pixel structure and low-noise readout circuitry. The initial goal is a 128x128 array with a single multiplexed analog output stream, with system D* values (including readout noise) of 10^9 cmHz$^{1/2}$/W, and with a focal-plane power dissipation of 20 mW. 100 μm square detectors have been demonstrated with D* values of 2×10^8 cmHz$^{1/2}$/W and response times of 4 ms. Models predict D* values well over 10^9 cmHz$^{1/2}$/W for optimized detectors. Modeling of a preliminary readout design shows that, for the expected detector resistance of 100 kΩ, the total noise will be 50% higher than the detector Johnson noise. CMOS test chips containing front-end circuits presently display a noise about 2.5 times higher than modeled and a power dissipation of 0.6 μW per pixel.

Keywords: detector, thermopile, infrared, uncooled, array, imaging

1. INTRODUCTION

Thermal detectors, a class which includes thermistor bolometers, ferroelectric/pyroelectric detectors, and thermopiles, are useful for detecting relatively long-wavelength infrared radiation when cooling is undesirable or impractical. Bolometer[1] and ferroelectric[2] 2-D staring arrays have recently found widespread use in video-frame-rate thermal-imaging cameras used for night vision. These cameras operate near room temperature and are sensitive in the 8-14 μm infrared band. NASA's thermal detector needs encompass a much broader range of operating-temperature and wavelength sensitivity than does night vision. For example, a thermal image of Pluto will require wavelength sensitivity out to 100μm or more, and operation near 100 K. In general, night vision applications require good sensitivity to temperature variations within the scene, while NASA applications additionally require highly accurate radiometry.

Thermopile detectors, while only in limited use for imaging applications,[3] have a combination of characteristics that make them well suited for some low-power radiometric applications. They are highly linear, require no optical chopper, and can have high values of D*. They typically operate over a broad temperature range with little or no temperature stabilization. They require no electrical bias, leading to negligible 1/f noise and no voltage pedestal in their output signal. The wide operating-temperature range, lack of temperature stabilization, and radiometric accuracy make thermopiles well suited for some space-based scientific imaging applications.

Bolometers are currently used for two-dimensional uncooled thermal-imaging arrays because they can be pulse biased and multiplexed without loss of signal-to-noise ratio. A single transistor switch at each pixel is sufficient for a two-dimensional bolometer readout. In contrast, maintaining the signal-to-noise ratio of a thermopile requires amplification and signal

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integration at the pixel level. For the cost of this pixel-level complexity, however, thermopiles can offer unstabilized operation, reduced analog-to-digital conversion requirements due to the lack of output voltage pedestal, and radiometric accuracy. Bolometer output-voltage pedestals result in the need for high materials uniformity to reduce readout dynamic range requirements. Materials uniformity in thermopiles is less critical.

Some success has been achieved in eliminating the bolometer temperature stabilizer for night-vision applications.[4] This approach involves calibrating the array as a function of substrate temperature, storing this information in camera memory, and correcting each image based on this calibration data. While removing the stabilizer, this technique requires extensive calibration and image processing, and produces good images only over a limited range of operating temperature. For night vision, thermopiles offer the potential for operation without temperature stabilization, extensive calibration or image processing. Removal of the stabilizer reduces power, reduces packaging complexity, increases reliability, and allows instant power-up capabilities.

Previous work at JPL[5,6] has produced linear arrays of thermopile detectors with D* values over 10^9 cmHz$^{1/2}$/W by combining the high-performance thermoelectric materials Bi-Te and Bi-Sb-Te with bulk micromachining processes. Two-dimensional thermopile arrays have been previously reported by two groups.[7,8] In both cases, a desire for low cost and manufacturability led to the use of polysilicon thermoelectric materials, which have relatively low thermoelectric figures of merit.

The purpose of the present work is to improve the performance of thermopile 2-D arrays substantially by combining Bi-Te and Bi-Sb-Te thermoelectric materials with a unique pixel design and low-noise readout circuitry. The detectors have a three-level structure using two sacrificial layers to allow for high fill factor and the incorporation of a large number of thermocouples per pixel. The thermally isolating legs are composed only of the thermoelectric materials, without a dielectric support structure, which produces parasitic thermal losses. The initial goal is a 128x128 array with a single multiplexed analog output stream, with system D* values (including readout noise) of 10^9 cmHz$^{1/2}$/W, and with a focal-plane power dissipation of 20 mW.

At present the detectors and readout circuitry are being fabricated and tested seperately. When optimized, they will be combined onto a single silicon substrate. To date, the number of working detectors is small. 100 μm square detectors have demonstrated D* values of 2×10^8 cmHz$^{1/2}$/W and response times of 4 ms. Models suggests that, when optimized, the detectors will have D* values well over 10^9 cmHz$^{1/2}$/W. Modeling of a preliminary readout design shows that, for the expected detector resistance of 100 kΩ, the total noise will be 50% higher than the detector Johnson noise. CMOS test chips containing front-end circuits display a noise about 2.5 times higher than modeled and a power dissipation of 0.6 μW per pixel.

2. DETECTOR STRUCTURE

Figure 1 shows the detector structure. The detectors, constructed on a silicon substrate that will eventually contain the CMOS readout electronics, are fabricated by surface micromachining using two polyimide sacrificial layers. An interconnect wiring layer on the substrate connects individual thermocouples in series within a pixel, and connects each detector to its readout electronics. Aluminum interlevel contacts connect this lower interconnect layer to the thermoelectric lines on the second level. The thermoelectric materials Bi-Te and Bi-Sb-Te are formed by single-target sputtering.[5] Thin metal contact pads on this second level make electrical contact between the two thermoelectric materials and the interlevel contacts. The third level contains a silicon-nitride absorber with a thin platinum absorbing layer. This absorber is connected structurally and thermally to the isolated thermocouple junctions. The lower interconnect wiring and the second-level thermoelectric lines are interlaced to form a mirror behind the absorber to increase total absorption. This three-level structure is formed by using two polyimide sacrificial layers during processing. In the final step, the polyimide is removed with a dry oxygen plasma etch.

This detector structure offers several advantages over previous thermopile 2-D pixels. Bismuth-based thermoelectric materials have substantially higher performance than polysilicon. The three-level structure allows nearly 100% fill factor while still accommodating many thermocouples per pixel. In addition, parasitic thermal losses due to dielectric materials in the legs are eliminated.

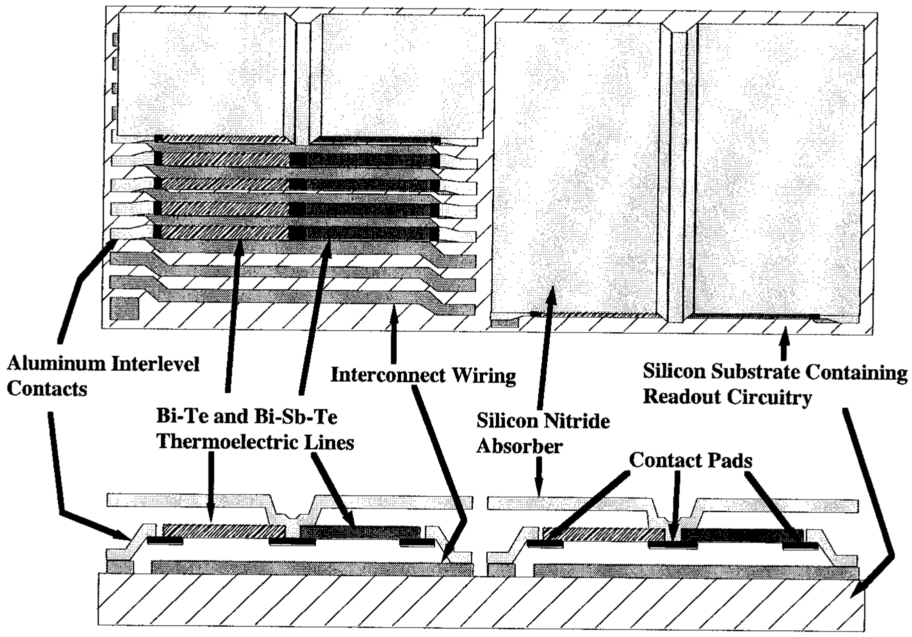

Figure 1. Schematic diagram of detector structure. The top diagram shows two pixels viewed from the top, with part of the left pixel cut away to show the underlying structure. The lower diagram shows a cross-section side view of two pixels.

3. DETECTOR RESULTS

Figure 2 is a scanning electron microscope (SEM) photograph of the edge of a 50 µm detector, showing the absorber on top and the thermoelectric leg structure underneath the absorber. Figure 3 is an SEM top view of an array of 50 µm pixels. Small holes through each membrane aid the oxygen plasma in etching away the polyimide sacrificial layers. Although the pixel structure can be reproducibly fabricated, the majority of detectors produced to date are not electrically continuous. A few detectors have produced reasonable infrared performance. Measured values of these detectors are tabulated in Table 1.

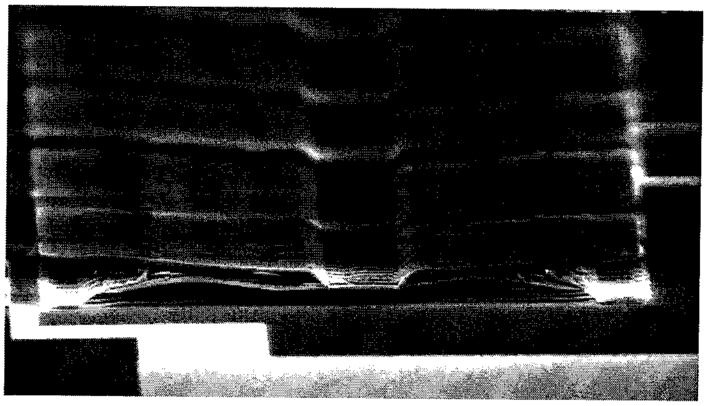

Figure 2. Side view scanning electron microscope photograph of a 50 µm detector, showing the thermoelectric legs underneath the absorber.

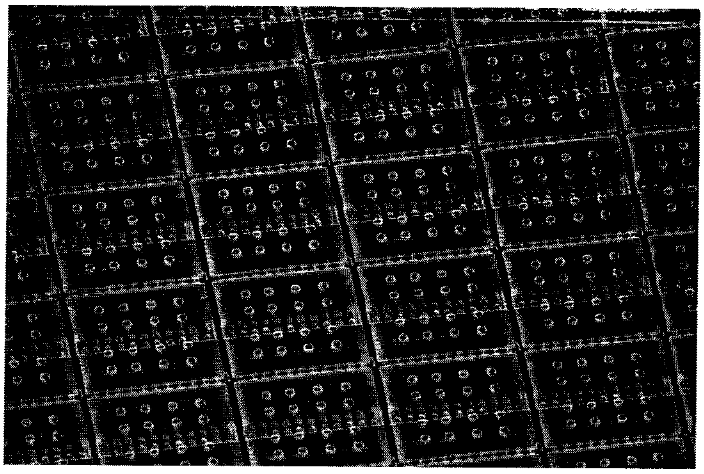

Figure 3. Scanning electron microscope photograph of a 50 μm detector array.

Detector Size (μm)	Responsivity (V/W)	Resistance (kΩ)	D* ($cmHz^{1/2}/W$)
50	650	200	$5x10^7$
100	1500	400	$2x10^8$

Table 1. Typical performance values of working pixels.

An electron microscope sample-current technique was used to determine the cause of detector discontinuity. In this technique, an electron beam is scanned across the sample. Current entering the sample is amplified and used to create an image of the sample. Areas that are connected electrically to the wire bond pads look bright in the image, while areas not connected to the bond pads are dark. This technique shows roughly where discontinuities occur in the series-connected thermocouples making up a detector. By looking closely at these identified areas using conventional SEM techniques, breaks were found in some thermoelectric lines where they intersect the contact pads. The breaks are apparently caused by curling in the contact pads due to film stress. Now that the primary cause of detector failure has been identified, efforts are underway to reduce stress in the various metal layers.

4. READOUT ELECTRONICS

Thermopile detectors have a dc response and noise dominated by Johnson noise of the detector resistance. Detector 1/f noise is negligible if the readout circuit has high input impedance because no current flows through the detector. The ideal readout, therefore, has no 1/f noise and a low noise figure (i.e. the readout adds little noise to the source Johnson noise). To achieve this result, each pixel of the CMOS readout design has a chopper-stabilized amplifier, demodulation, and integration. The input stage takes the dc signal from the detector and chops it at roughly 50 kHz, where 1/f noise of the amplifiers is low. After amplification, demodulation, and integration at the pixel level, the signals are multiplexed to a single analog output stream. The readout circuit goal is a 128x128 pixel array with low noise figure and 20 mW total power dissipation, or about 1 μW per pixel with a few mW for biases and multiplexing. Simulations of the initial design indicate that with a 1 μW per pixel power dissipation, the input-referred noise for a 100 kΩ source resistance is 61 $nV/Hz^{1/2}$, or only a 50% increase in noise over the source.

Test readout circuit chips containing the chopper and initial amplification stage of a single pixel have been fabricated and tested. The initial amplifier is expected to produce most of the noise and power draw of the unit cell. The test chip unit cell draws only 0.6 μW of power, and has a zero-input noise 2.5 higher than simulated. Additional noise appears for nonzero input voltage due to an interaction between reset noise and amplifier nonlinearity. The full readout will incorporate design changes to reduce the noise further.

5. CONCLUSIONS

A wide operating-temperature range, lack of temperature stabilization, and radiometric accuracy make thermopiles well suited for some space-based scientific imaging applications and may provide advantages over bolometers for night vision. The purpose of the present work is to substantially increase the performance of thermopile 2-D arrays. The initial goal is a 128x128 array with a single multiplexed analog output stream, with system D* values (including readout noise) of 10^9 cmHz$^{1/2}$/W, and with a focal-plane power dissipation of 20 mW. At present the detectors and readout circuitry are being fabricated and tested seperately. 100 μm square detectors have demonstrated D* values of $2x10^8$ cmHz$^{1/2}$/W and response times of 4 ms. Models suggests that, when optimized, the detectors will have D* values well over 10^9 cmHz$^{1/2}$/W. CMOS test chips containing front-end circuits presently display a noise about 2.5 times higher than modeled and a power dissipation of only 0.6 μW per pixel.

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