Space science applications of thermopile detector arrays

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ABSTRACT

Thermal detectors, while typically less sensitive than quantum detectors, are useful when the combination of long wavelength signals and relatively high temperature operation makes quantum detectors unsuitable. Thermal detectors are also appropriate in applications requiring flat spectral response over a broad wavelength range. JPL produces thermopile detectors and linear arrays to meet space science requirements in these categories. Thermopile detectors and arrays are currently being fabricated for two space applications. The first is the Mars Climate Sounder (MCS) instrument, to fly on the Mars Reconnaissance Orbiter mission, scheduled to launch in 2005. MCS is an atmospheric limb sounder utilizing nine 21-element thermopile arrays. The second application is the Earth Radiation Budget Suite (ERBS), part of the National Polar Orbiting Environmental Satellite System (NPOESS). This instrument measures upwelling radiation from the earth in the spectral range 0.3-100 μm.

1. INTRODUCTION

While quantum detectors have been enormously successful for detection of photons from the ultraviolet through long-wave infrared, there are some applications in this wavelength range where other detector types are more appropriate. In Figure 1, each data point represents the operating temperature versus cutoff wavelength of a quantum detector, with values taken from scientific and commercial literature.[1-5] As the wavelength of interest increases, the required operating temperature decreases roughly as $T = 1/\lambda$, reflecting the requirement that kT must be significantly less than the material bandgap in order to minimize thermally excited carriers. The dashed line denotes kT roughly equal to one-tenth the energy of a photon at the cutoff wavelength. Quantum detectors are fundamentally limited to the regime below the dashed line in Figure 1.

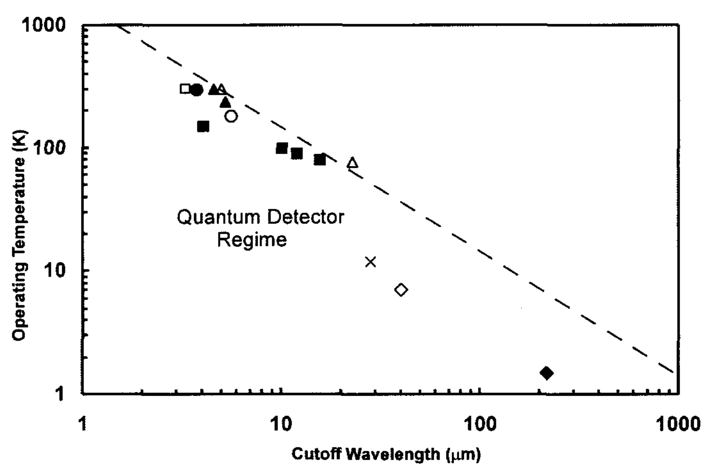

Figure 1. Operating temperature versus cutoff wavelength for several types of quantum detectors: PbS (□, Ref. 1), InAs (●, Ref. 1), PbSe (▲, Ref. 1), InSb (O, Ref. 1), HgCdTe (△, Ref. 1), QWIP (■, Ref. 2), Si:As BIB (×, Ref. 3), Si:Sb BIB (◇, Ref. 4), Ge BIB (◆, Ref. 5). The dashed line denotes kT roughly equal to one-tenth the energy of a photon at the cutoff wavelength.

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Thermal detectors, a class of detectors including thermistor bolometers, pyroelectric detectors, and thermopiles, operate with a fundamentally different detection mechanism from that of quantum detectors. Incoming photons, rather than exciting carriers across a semiconductor bandgap, heat a thermally isolated absorbing structure. The resulting heat rise is sensed by a process that differs between the different types of detectors in this class. Thermistor bolometers sense the resistance change of a thermistor element on the absorber, pyroelectric detectors measure a polarization change in a pyroelectric material, and thermopiles measure the temperature difference between the absorber and a heat sink (substrate) using thermocouples. The thermal detection mechanism typically provides lower D* values than can be obtained by quantum detectors. However, thermal detectors are not limited to the quantum detector operating range shown in Figure 1,and, in fact, are only limited in wavelength by their absorbing structure.

Thermal detectors are often used in two types of applications: those that involve longer wavelengths and higher operating temperatures than are accessible to quantum detectors, and those that require flat spectral response over a broad wavelength range. The most common example of an application ideal for thermal detectors is uncooled night vision, in which a 300 K array detects a signal in the 8-12 μm range. Space science applications offer a broad range of thermal detector applications. Planetary and astronomical targets often have spectral and thermal signals well beyond 12 μm, and spacecraft infrared instruments are not limited to observation within the 3-5 and 8-12 μm atmospheric windows. While often required to detect long wavelengths, space-based instruments are uncooled whenever possible to reduce mass, size, and cost with increased reliability. In addition, radiation balance measurements of planetary bodies often require flat spectral response. This paper will discuss two space applications where JPL thermopile detectors and arrays will be used. The applications discussed require both flat spectral response and operation at higher temperature and longer wavelengths than quantum detectors can achieve.

2. JPL THERMOPILE DETECTOR ARRAYS

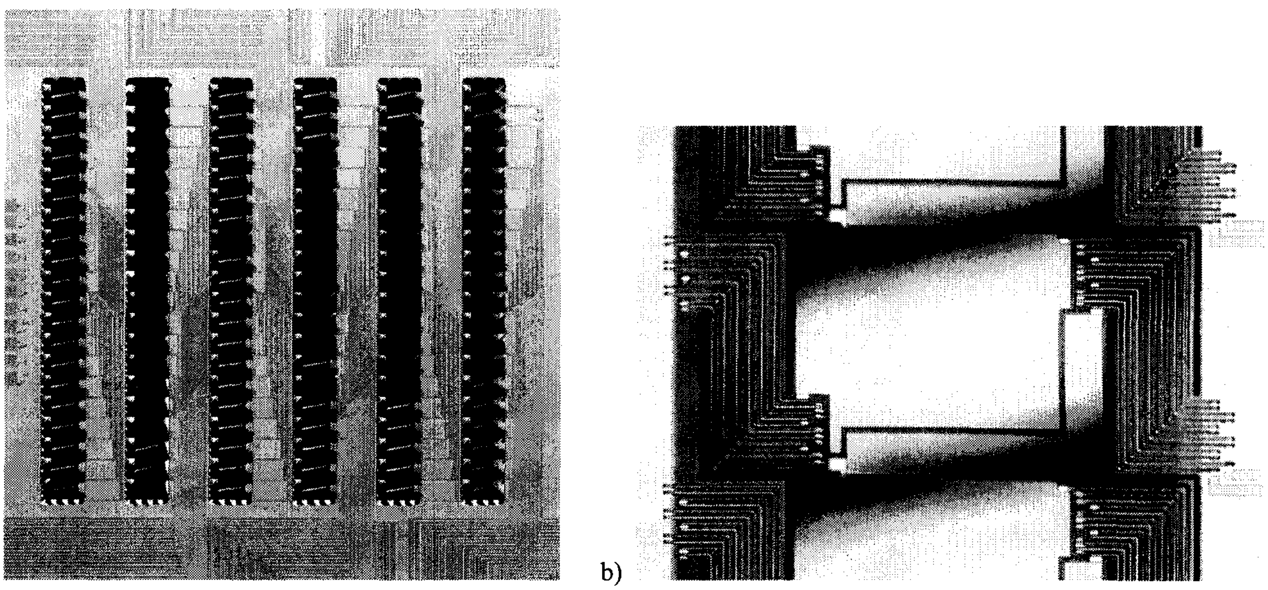
The fabrication, structure, and performance of JPL thermopile detector arrays has been described in detail previously.[6,7] In brief, three-inch diameter, 400 μm thick silicon wafers are coated with 1 μm of silicon dioxide and about 150 nm of silicon nitride. Four metallization layers are then deposited and patterned using lift-off techniques with photoresist stencils. The first metal layer, 50 nm of platinum, provides electrical contact between subsequent layers that overlap it. Then a gold interconnect layer is deposited. Two thermoelectric layers are deposited by single-target sputtering from targets with approximate compositions $Bi_{2.0}Te_{3.6}$ and $Bi_{0.4}Sb_{0.6}Te_{3.3}$. A silicon-nitride cap layer roughly 400 nm thick then covers the metal layers. The silicon substrate is then removed under the arrays using a deep-reactive-etch technique from the wafer backside. This step differs from that described in references 6 and 7, in which a chemical etch was used to etch the silicon substrate. The removal of the substrate under the arrays results in a well thermally isolated membrane structure. Slits are then etched through this membrane to physically and thermally separate the detectors from each other and to further thermally isolate the detectors from the substrate. Finally, a gold-black absorbing layer is deposited over the array. This gold-black layer bridges across the slits, so it is removed in these regions by laser ablation from the wafer backside, using the detector membranes as a mask. Thermopile detectors produced with this method routinely display D* values greater than 10^9 $cmHz^{1/2}/W$ in vacuum at room temperature. Response times vary from 10 to 100 ms.

3. MARS CLIMATE SOUNDER FOCAL PLANES

Mars Climate Sounder is a atmospheric limb sounder that will measure temperature, pressure, water vapor, dust and condensates in Mars' atmosphere, in addition to radiative balance at the planet's poles. These science goals originally were to be met by the Pressure Modulator Infrared Radiometers (PMIRR and PMIRR2), which were lost on the Mars Observer and Mars Climate Orbiter spacecraft. PMIRR was a sophisticated instrument containing pressure modulator gas cells, an optical chopper, a scanning mirror, and a radiative cooler for detectors. It weighed 40 kg and consumed 40 W of power. MCS is intended to do comparable science in a much smaller package weighing 9 kg and consuming 10 W. This size reduction is enabled by the use of uncooled thermopile arrays. Nine 21-element linear arrays, each behind a different spectral filter, will allow MCS to observe 21 different altitudes in nine spectral bands simultaneously. While PMIRR scanned highly sensitive cooled detector, MCS will stare with less sensitive uncooled arrays, using longer integration time to achieve comparable signal-to-noise ratios as PMIRR.

MCS will consist of two bore-sighted telescopes, labeled *A* and *B*. Focal plane *A* will have six 21-element detector arrays with spectral filters covering the ranges 0.3-3.0 μm (polar radiative balance), 11.5-12.2 μm (dust and condensates), 15-15.7 μm (temperature, pressure), 15.5-16.3 μm (temperature, pressure), 16.3-16.8 μm (temperature), and 20-25 μm (temperature, dust and condensates). The 0.3-3.0 μm band is required to be spectrally flat. The second focal plane will have three 21-element detector arrays with spectral filters covering the ranges 29.4-34.5 μm (temperature, dust and condensates), 38.5-45.5 μm (water vapor, dust and condensates), and 40.8-43.5 μm (water vapor, dust and condensates). The detector width will be 240 μm, corresponding to a vertical instantaneous field of view (IFOV) of 3.6 mrad, or roughly 5 km vertical resolution on the atmospheric limb. The detector length will be 480 μm, corresponding to a horizontal instantaneous field of view (IFOV) of 6.2 mrad, or roughly 9 km horizontal resolution in the atmosphere.

Figure 3a shows a prototype MCS focal-plane A, while Figure 3b is a close up photograph of a single detector and parts of the two adjacent detectors. Each detector in this prototype array has 12 thermocouples composed of 3 μm wide thermoelectric lines spaced by 3 μm. Unblackened detectors, with a thin platinum absorbing layer, exhibit responsivity values of 1450 V/W, resistances of 130 kΩ, D* values of $1.0x10^9$ $cmHz^{1/2}/W$, and response times of 85 ms.



a) b)

Figure 3. a) Prototype MCS focal plane *A*, consisting of six 20-element thermopile arrays on a single substrate.

4. EARTH RADIATION BUDGET SUITE DETECTORS

A second space instrument to use JPL thermopile detectors will be the Earth Radiation Budget Suite (ERBS), to fly on the National Polar Orbiting Environmental Satellite System (NPOESS). This instrument will be similar to the Earth Radiation Budget Experiment (ERBE), and the Clouds and the Earth's Radiant Energy System (CERES) instruments, which have been continuously mapping radiation leaving the Earth since 1984. ERBS will have three radiometers covering the spectral ranges 0.3-5 μm, 8-12 μm, and 0.3-100 μm. The first two channels are defined with bandpass filters, while the broadband channel has no filter. Each channel will have a single thermopile detector with area roughly 1.44 mm^2. The telescopes are scanned cross track to map the Earth's radiation field, and also look into space and at a warm blackbody target every six seconds for calibration.

The ERBE and CERES detectors[8] are thermistor bolometers of similar construction. The ERBE devices date to the early 1980's and were produced by Barnes Engineering. These devices were about 2 mm square and provided an noise-equivalent power (NEP) of about 10^{-8} W (0.3-30 Hz) with a response time of 12 msec. The CERES devices were produced by Servo Corporation of America and are about 1.5 mm in size, have an NEP of 7×10^{-9} W (0.3-30 Hz), and have response times of 8-9 ms. Both the ERBE and CERES detectors use an absorber layer to produce a response that is spectrally flat over the entire broadband channel range of 0.3 to 100 μm. The ERBS detectors have requirements similar to those of the CERES devices, except for a lower NEP of 2×10^{-9} W. JPL Thermopiles were chosen for ERBS in part because of increased sensitivity and reduced temperature control requirements.

Figure 4 shows an unblackened prototype ERBS thermopile detector. The central light colored square is the absorbing area, subsequently coated with gold black to provide good absorption over the entire spectral range. The dark border around the absorbing area contains 484 Bi-Te and Bi-Sb-Te thermocouples connected in series. Details of the thermocouples can be seen in the enlarged view on the right of Figure 4. The silicon substrate is etched away under both the absorbing region and the thermocouples to provide a thermally isolated membrane. The absorbing region consists of 150 nm silicon nitride and 200 nm gold. The gold layer provides a reflector under the gold black absorber to increase absorption, and additionally allows heat to flow easily across this region to provide uniform response and fast response time. The thermocouples must be short (20 μm in this detector design) to reduce the response time to roughly 10 ms.

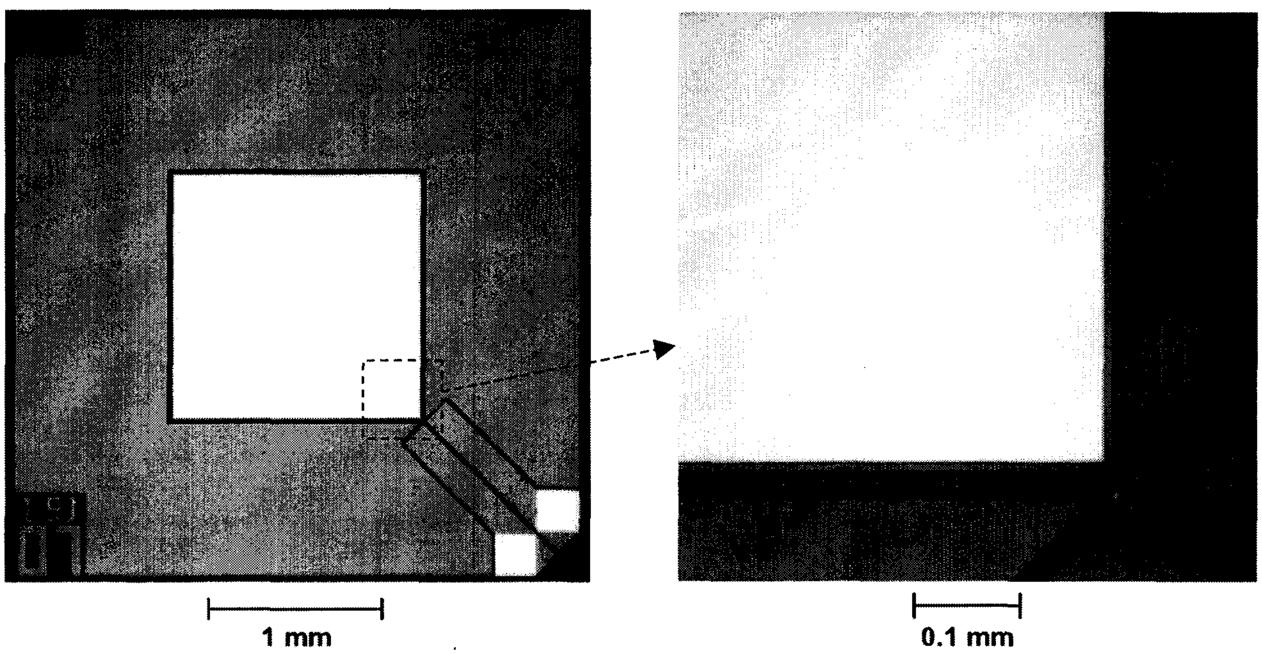


Figure 4. Prototype ERBS thermopile detector. The enlarged view on right shows details of the thermocouples.

Table 1 lists some measured performance parameters for the ERBS prototype thermopile detectors along with the corresponding ERBS requirements. The prototype detectors already exceed the response and NEP requirements, but are slightly slower than needed. A decrease in detector size can probably reduce the response time while also reducing NEP.

	Detector Size (mm)	Number of Thermocouples	Responsivity (V/W)	Resistance (kΩ)	Response Time (ms)	NEP (0.3-30 Hz) (W)
JPL Prototype	1.5	484	280	180	11	1.5×10^{-9}
ERBS Requirement	Active area 1.2	-----	>200	-----	≤ 9	$\leq 2\times10^{-9}$

Table 1. Measured parameters for ERBS prototype detectors compared to ERBS requirements.

5. CONCLUSIONS

Thermal detectors are ideally suited for applications that require a combination of long wavelengths with relatively high operating temperatures, or when flat spectral response is desired. JPL produces thermopile detector arrays using high performance bismuth-based thermoelectric materials combined with bulk micromachining for space science application. These arrays typically exhibit D* values over 10^9 $cmHz^{1/2}/W$ in vacuum and at room temperature. Efforts are underway to produce thermopile arrays for the Mars Climate Sounder and the Earth Radiation Budget Suite instruments.

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