MONOLITHIC SILICON BOLOMETERS COUPLED TO WAVEGUIDE

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Abstract

We have measured the performance of ion-implanted silicon bolometers developed for observations of faint astrophysical sources at millimeter wavelengths. These devices are mounted in waveguide to couple to a single mode of electromagnetic radiation. We measure optical coupling efficiencies of ~ 90% across a full waveguide band. When cooled to 0.1 K and operated under low background conditions, the devices have a time constant of 1.5 – 4 ms and NEP ~ $1\times10^{-17}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$. They have a small cross-section to cosmic rays. We describe an application of these bolometers to a balloon-borne measurement of the 2.7 K cosmic microwave background radiation at frequencies between 65 and 170 GHz.

Introduction

We have developed monolithic silicon bolometers for use in an experiment to measure the spatial structure (anisotropy) in the Cosmic Microwave Background (CMB). Since the CMB is an unperturbed relic of the hot Big Bang, studies of its structure can yield a wealth of information about the early Universe. Measurements of anisotropy in the CMB are difficult because the level of anisotropy is five orders of magnitude below the 2.7 Kelvin CMB. Our approach is to measure the anisotropy in the CMB using a balloon-borne telescope called the Medium Scale Anisotropy Measurement (MSAM2) [1]. The low background from the atmosphere at an altitude higher than 30 km allows the use of ultra-sensitive detectors.

The MSAM2 radiometer has five channels spanning the W and D bands: 65-80 GHz, 80-95 GHz, 95-110 GHz, 130-150 GHz and 150-170 GHz. The bands were chosen to take advantage of windows in the atmospheric opacity at millimeter wavelengths and to allow discrimination between astrophysical foregrounds and the CMB. We have coupled our detectors directly to single-mode waveguide, thereby utilizing the advantages of single-mode technology such as low-sidelobe antennas, high quality filters, and diffraction-limited angular resolution. In addition, by coupling the detector directly to waveguide, the absorber can be made much smaller than a wavelength. This approach greatly reduces the time-constant of a thermal detector and allows rapid scanning of the sky without loss of sensitivity. Moreover, the cross-section for cosmic ray hits is small.

Coupling Scheme

Monolithic silicon bolometers, introduced by Downey *et al.* [2], were been fabricated at the NASA Goddard Space Flight Center [3]. The device consists of a micromachined thin silicon substrate suspended from a silicon frame by silicon legs which also function as the thermal link to the heat bath. The thermistor is ion-implanted in the substrate. The thermistor, the absorber and the thermal link can be optimized separately. Our waveguide-to-bolometer coupling scheme is similar to that introduced by Peterson and Goldman [4] for composite bolometers. However, in our design (Figure 1) the absorber of the bolometer consists of a thin resistive bismuth film deposited on the narrow silicon substrate oriented along the E-plane. An adjustable backs in the waveguide behind the absorber is used to match the impedance of the absorber to the waveguide. The thermistor is located outside the waveguide. The silicon substrate and legs pass through a small slot in the broad wall of the waveguide. The reflectance has been measured to be better than –10 dB across an entire waveguide band.

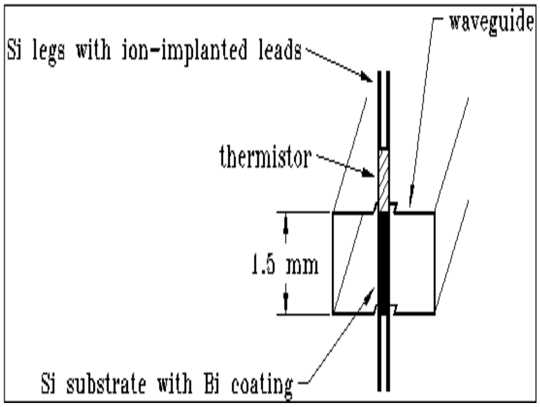

Figure 1

Design and Fabrication

In our bolometers the thermistors are produced by implanting silicon wafers with phosphorus and 50% boron compensation to a concentration near the metal-insulator transition. At this concentration, the phonon-assisted hopping conduction mechanism has a strong dependence on temperature. The behavior of resistance with temperature of the thermistor is described by:

$R = R_0 \mathrm{Exp}\sqrt{T_0/T}$ where R_0 and T_0 are experimentally derived constants which are extremely sensitive to doping density. The thermal conductance of the legs can be described by:

$G = G_0 T^3$ where G_0 is mainly modified by the design of the leg geometry.

Bolometer Performance

Load curves of the bolometers are measured at a variety of cold plate temperatures from ~ 100 mK to 200 mK in the dark. From these we determine that a typical device has T_0 = 13 K, R_0 = 380W, and G = 2.2 X 10^{-11} W/K at 0.1 K.

During observations, signals from the telescope are coupled to the detectors through corrugated feedhorns with transitions to rectangular waveguide, followed by an IR-blocking filter. These optics are cooled to 1.5 K. The filter is made of quartz beads embedded in polypropylene melted into a 1 cm length of waveguide. A suspended-stripline mulitplexer, band-defining filters, and the bolometers themselves are cooled to 0.1 K by an adiabatic demagnetization refrigerator (ADR). They are thermally isolated from the warmer optics by a small (0.005”) gap in the waveguide.

In the lab, we simulate the optical loading from the sky by inserting a cold termination in the microwave feedhorns. The temperature of this termination can be adjusted from ~ 5 K to 20 K over several minutes. From these measurements we determine the DC responsivity of the bolometers and the optical efficiency of each wavelength channel. Results from these measurements, and measurements made during the MSAM2 flight of June 1, 1997 are in Table 1. The NEP measured in the lab is limited by 1/f noise in the JFET readout electronics. In flight, excess in-band optical loading from a telescope tertiary optics at 77 K caused the bolometer loading and BLIP to increase considerably over the expected loading from the sky. The optical efficiency is limited by the IR and bandpass filters.

	Lab	**Flight**
Optical Loading	5 K	20K
Optical Efficiency	20%	20%
NEP (including BLIP)	1.6×10^{-17} W/$\sqrt{\mathrm{Hz}}$	3.2 $\times 10^{-17}$ W/$\sqrt{\mathrm{Hz}}$

Sensitivity (80-95GHz) Rayleigh-Jeans	$320 mKs^{1/2}$	$620 mKs^{1/2}$
Cosmic ray rate	-	1/20 Hz
Time Constant	-	1-4 ms

Table 1. Measurements of the detector system before and during the flight of MSAM2. The NEP measured in the lab is 2.2 times the BLIP noise from a 5 K source.

Conclusion

We have fabricated and tested in the lab and in a balloon flight monolithic silicon bolometers coupled to waveguide. These devices are particularly promising for sensitive measurements at millimeter wavelengths

References

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