THE SINGLE-MODE MONOLITHIC SILICON BOLOMETER AS AN ULTRASENSITIVE DETECTOR FOR MILLIMETER WAVELENGTHS

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Abstract

We report on the development of a single-mode waveguide-coupled monolithic silicon bolometer for applications in low-background astrophysical observations at millimeter wavelengths. In this device the absorber of the bolometer is a 250 μm wide bismuth-coated silicon substrate oriented along the E-plane of a waveguide. Reflection measurements performed between 75 and 170 GHz show that this coupling scheme is better than 90% efficient. The time constant of these devices is between 2 and 5 milliseconds at the nominal operating temperature of 100 mK. The devices have an electrical responsivity $\approx 2 \times 10^9$ V/W and an electrical noise equivalent power (NEP) $\approx 10^{-17}$ W/$\sqrt{\text{Hz}}$ at ~100 mK.

Introduction

Bolometers are thermal detectors that measure electromagnetic radiation power by converting it to heat. Incoming power is coupled to an absorber which is connected to a heat reservoir through a weak thermal link. The conversion of radiant power to heat in the absorber causes the temperature of the absorber to increase. This rise in temperature is measured by a thermistor (Figure 1).

Bolometers are used in a wide range of applications in astrophysics, particularly in low-background environments where sensitive detectors can be utilized effectively. When cooled below 1 K, bolometers are the most sensitive broadband detectors at millimeter and sub-millimeter wavelengths [1].

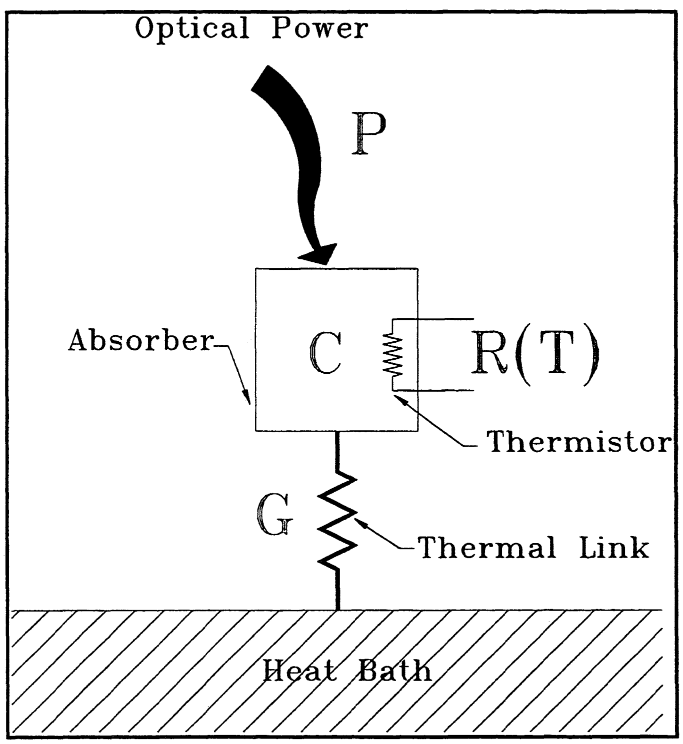

Figure 1: A schematic of a typical bolometer. The absorber has a heat capacity C and is linked to the heat bath by a thermal conductance G. Optical Power P coupled to the absorber causes a rise in temperature above the bath temperature; this change is measured by the thermistor.

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. As a result, large integration times (~ 100 seconds) are required to obtain enough sensitivity on a single patch of the sky. Our approach is to measure the anisotropy in the CMB using a balloon-borne telescope called the Medium Scale Anisotropy Measurement (MSAM II) [2]. The low atmospheric background at an altitude higher than 30 km allows the use of ultra-sensitive detectors.

The MSAM II radiometer [9] has five channels spanning E, 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 the window in the atmospheric opacity at microwave frequencies. The broad bandwidth allows higher power coupling to the detectors and increases the sensitivity to the CMB blackbody spectrum. The multiple bands are essential for spectral discrimination between astrophysical foregrounds and the CMB.

At wavelengths shorter than a few millimeters, bolometers are typically coupled to radiation using multimode optical systems such as multimode feed-horns, light pipes and Winston concentrators. However, we have coupled our detectors directly to single-mode waveguide, thereby utilizing the advantages of single-mode technology such as low-sidelobe antennas and high quality filters. In addition, by coupling the detector directly to waveguide, the absorber can be made much smaller than a wavelength. This greatly reduces the time-constant of a thermal detector. Moreover, the cross-section for cosmic ray hits is small.

Coupling Scheme

Monolithic silicon bolometers, introduced by Downey *et al.* [3], have been fabricated at NASA Goddard Space Flight Center [4]. 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. Fabrication by optical lithography allows precise control of detector

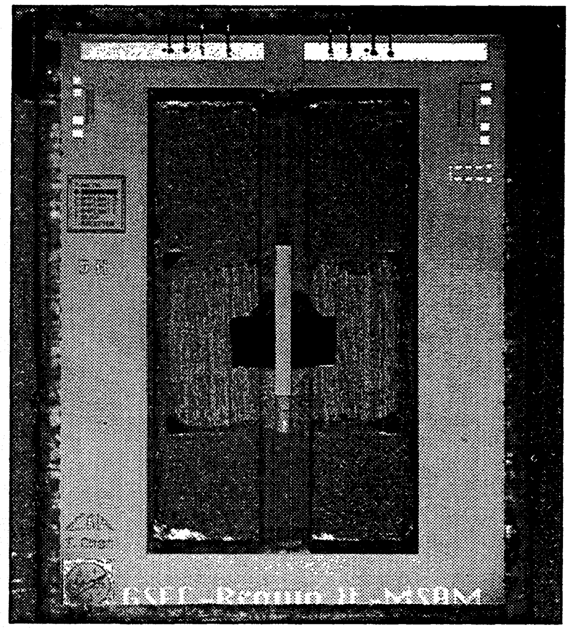

Figure 2: A view of a monolithic silicon bolometer mounted on a WR-6 waveguide block. The block is at 100 mK. The rectangular absorber, oriented along the E-plane of the waveguide, is suspended on 4 silicon legs, which also provide the thermal connection to the silicon frame surrounding the waveguide opening. For scale the inside dimensions of the waveguide are 1.651×0.825 mm.

parameters. 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 [5] for composite bolometers. However, in our design (Figures 2 and 3) 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 backshort 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, and the silicon substrate and legs pass through a small slot in the broad wall of the waveguide. Since the thermal contraction of the silicon frame is much smaller than that of the aluminum waveguide mount, the frame cannot be glued directly to aluminum, as it would shatter upon cooling. Instead, a small piece of Invar is press-fit into the mount, and the frame is glued to the Invar piece. The thermal contraction of Invar is close to that of silicon.

To determine the absorber impedance that maximizes power absorption, we measured the reflectance of this design using an X-band scale model. The reflectance was determined to be less than –10 dB across the full waveguide band (8 to 12 GHz) for film resistances from 75 Ω/square to 180 Ω/square, and was found to depend only weakly on the fraction of the waveguide cross-section covered by the absorber; this fraction was varied from 10% to 25%. Thus, a single bolometer design can be used interchangeably in our E-band, W-band and D-band waveguide mounts.

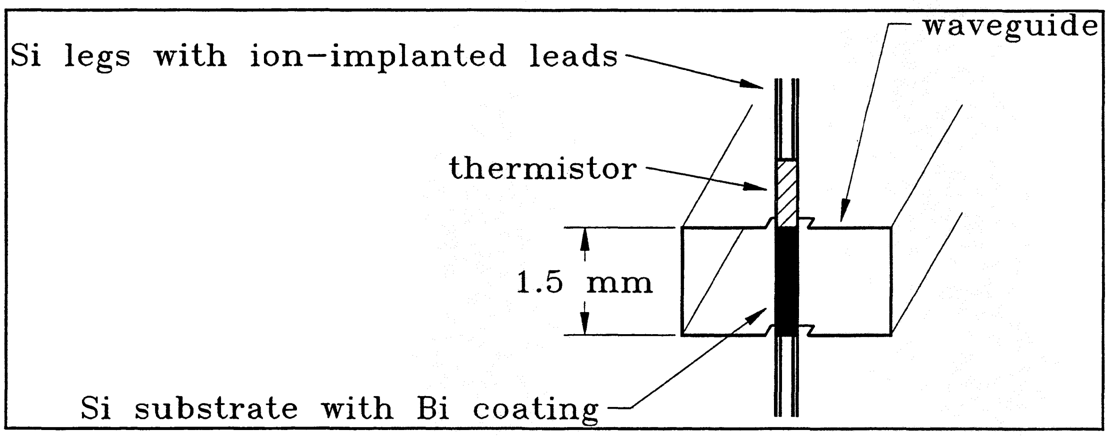

Figure 3: Expanded, perspective view of the bolometer and the waveguide. Silicon legs ($2500\times18\times10$ μm) provide support and thermal connection to the silicon substrate. The electrical contact to the thermistor is achieved through ion-implanted traces along two of the legs. The substrate thickness is 10 μm. The thermistor is ion-implanted in the substrate.

In the actual bolometers, a 180 nm bismuth layer is deposited on the waveguide portion of the Si. This layer gives an expected impedance of about 80 Ω/square at 4.2 Kelvin, and 20 Ω/square at room temperature. We minimized the reflectance of this structure by adjusting the back short position, with the bolometer cooled to 4.2 Kelvin The reflectance has been measured to be better than –10 dB across the entire band. The bismuth layer is coated with a 100-nm layer of silicon monoxide to prevent exposure to air which has been observed to increase the surface-resistance of bismuth over time [6].

Design and Fabrication

The electrical and thermal properties of the bolometer are determined by the operating temperature, the temperature sensitivity of the thermistor, the thermal conductance of the legs, the heat capacity of the detector, the optical loading and modulation frequency. Bolometer optimization, including the non-equilibrium noise analysis of Mather [7], is described by Griffin and Holland [8].

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:

$$R = R_0 \mathrm{Exp}\sqrt{\frac{T_0}{T}} \tag{1}$$

where R_0 and T_0 are experimentally derived constants which are extremely sensitive to doping density. Thus, to accommodate run-to-run implant variations, a minimum of ten wafers are implanted with doses ranging around the optimum in steps of 2.5-5% variation of net dose.

The supporting structure is fabricated from <100> silicon using anisotropic chemical etching. Silicon wafers 300 μm thick are initially back-etched to produce membranes 20-30 μm thick using a thermal-oxide mask and 45% KOH etch bath. Standard photolithographic techniques are used to pattern the oxide mask on the back of the wafers. After thinning, a thick (1.8 μm) Al mask is deposited on the front of the wafer. This layer is subsequently patterned into three successive implant masks to produce first the degenerately doped contact and thermistor leads, followed by two separate implant-masks for the phosphorus and boron thermistor implants. The boron implant is patterned slightly larger than the phosphorus implant to prevent possible shorting of the thermistor around the perimeter by the much more mobile phosphorus during implant and subsequent annealing.

After annealing, an oxide film is deposited using chemical vapor deposition on the front of the wafer to act as an etch mask during the final KOH etching of the bolometer element. The silicon is etched into an "H" pattern as shown in Figure 3. The back of the detector is textured using a dilute ethylenediamine pyrocatechol (EDP) solution in a double boiler temperature bath to provide scattering sites down the legs to reduce thermal conductance due to phonons. Thus, for the silicon legs, the thermal conductance can be described by:

$$G = G_0 T^3 \tag{2}$$

where G_0 is mainly modified by the design of the leg geometry. Finally, bismuth is deposited on the un-implanted region of the detector to act as the absorber.

Bolometer Performance

The bolometer parameters are optimized for the optical loading and background photon noise expected in flight in each of the five spectral bands. For example, for the 95-110 GHz band, with radiative loading from sky, atmosphere, and 250 Kelvin optics: two mirrors with 0.5% emissivity (estimated), and a 0.020" polypropylene window with 0.5% emissivity (estimated). The optical power and background photon noise are estimated to be 0.3 pW and 6.5×10^{-18} W/$\sqrt{\text{Hz}}$ using a measured system optical efficiency of 30 %. The bolometer is operated at a bath temperature of 100 mK and has T_0 = 14.75 K, $R_0 = 87\Omega$, and $G = 2.2 \times 10^{-11}$ W/K at 100 mK The electrical responsivity at optimum bias was measured to be 1.0×10^9 V/W. According to Griffin and Holland [8], the only contributions to the bolometer noise are Johnson noise, thermodynamic fluctuations (phonon noise), amplifier noise, and background photon noise. Based on electrical noise measurements made in the dark, we can estimate the detector noise under flight conditions. By combining the estimated detector noise of 8.1×10^{-18} W/$\sqrt{\text{Hz}}$ with the estimated photon noise, we find that the total receiver NEP should be 1.0×10^{-17} W/$\sqrt{\text{Hz}}$. This translates to a receiver sensitivity of 114 μK$\sqrt{\text{sec}}$ for a total-power measurement of a Rayleigh-Jeans source at 15 GHz bandwidth with 30% optical efficiency. The time-constant of the detector has been measured to be 3.5 milliseconds at the optimum bias.

Conclusion

The single-mode monolithic silicon bolometers appear to be extremely promising for balloon- and space-borne observations. The 114 μK$\sqrt{\text{sec}}$ receiver sensitivity can be compared with the performance of a high electron mobility transistor (HEMT) system under similar conditions. For example, the state-of-the-art W-band HEMT amplifiers which have been developed for the Microwave Anisotropy Probe experiment have a noise temperature of 60 K [10]. For a 15 GHz bandwidth, these amplifiers would have a sensitivity of 490 $\mu K \sqrt{sec}$. The noise of our bolometric system is lower by a factor of 4.

In order to determine how much further our system noise may be reduced, we compare the detector NEP with the expected photon noise at 30 km. As shown in Figure 4, the detector NEP is already comparable to the photon noise from the low-background sources. Further reduction of the detector NEP will not significantly improve the receiver

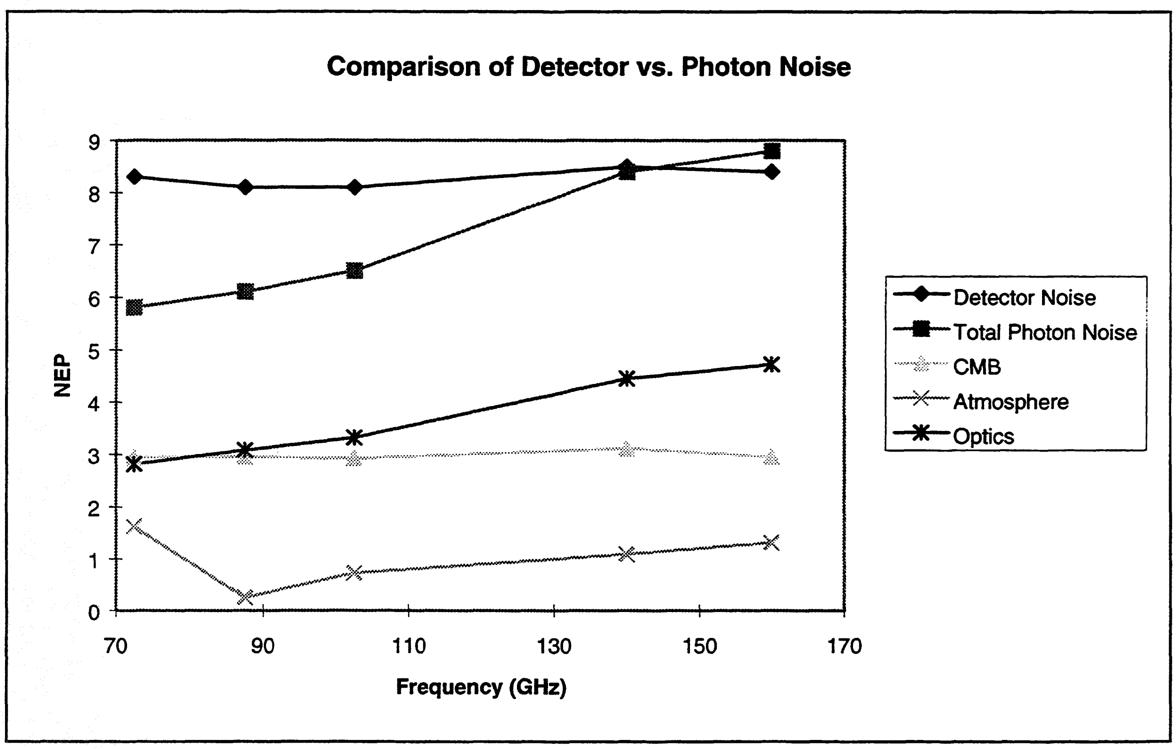

Figure 4: The expected performance of a typical MSAM II bolometer at 30 km is compared with the photon noise in each of the five bands. The total Photon noise is the quadrature-sum of the noise contributions from the CMB, the atmosphere [11] and the 250 Kelvin optics. The most significant contributor to the total photon noise, especially in the higher bands, is the noise from the 250 Kelvin Optics. At 140 GHz and above, the bolometer noise is less than the total photon noise; the instrument is limited by the photon noise.

sensitivity unless the noise contribution from the warm telescope optics is smaller than expected. We will verify our estimate of the noise contribution from the optics and the atmosphere in an upcoming flight of MSAM II.

Acknowledgments

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