MONOLITHIC SILICON BOLOMETERS AS SENSITIVE MM-WAVE DETECTORS

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ABSTRACT

We report the development of a waveguide-coupled monolithic Si bolometer for applications in low-background millimeter-wave astrophysical observations. In this device, the absorber of the bolometer is a narrow Bi-coated Si substrate oriented along the E-plane of the waveguide. This design allows efficient coupling of bolometers to waveguide. We measured these devices to have a high coupling efficiency, an electrical responsivity $\approx 2 \times 10^9$ V/W, and electrical noise equivalent power (NEP) $\approx 10^{-17}$ W/$\sqrt{\mathrm{Hz}}$ at ~100 mK.

INTRODUCTION

Bolometers are thermal detectors which convert electromagnetic radiation to heat in an absorber; the resultant temperature rise is measured with a thermistor. When cooled below 1 K, bolometers are the most sensitive broad-band detectors available from millimeter to submillimeter wavelengths [1]. They are commonly used in far-infrared spectrometers and for measurements of continuum radiation in astrophysics. Cooled bolometers are used at many ground-based observatories, as well as on aircraft and satellite-borne observatories, where both signal and background levels are low. We are developing 100 mK monolithic Si bolometers for astrophysical observations on a balloon-borne telescope called the Medium Scale Anisotropy Measurement (MSAM) [2]. The telescope has a chopping secondary mirror which modulates the optical signal at 2 Hz. The instrument is designed for sensitive observations of the cosmic microwave background radiation in five channels spanning E, W, and D bands: 65-80 GHz, 80-95 GHz, 95-110 GHz, 130-150 GHz, and 150-170 GHz.

At wavelengths shorter than a few millimeters, efficient coupling to bolometers is typically achieved with multimode optical systems, including multimode feed-horns, light pipes, and Winston concentrators. However, an extremely powerful method at millimeter-wavelengths is to couple bolometers directly to waveguide to exploit the advantages of single-mode waveguide technology, such as high quality filters and low sidelobe antennas. Another advantage of this approach is that the detectors can be much smaller than a wavelength; for thermal detectors this means that the time constant is small, the NEP can be reduced, and the cross section for cosmic rays is small.

COUPLING SCHEME

Monolithic Si bolometers, introduced by Downey *et al.* [3], have been fabricated at the NASA Goddard Space Flight Center [4]. The device consists of a micromachined thin Si substrate suspended from a Si frame by Si 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 good control of detector parameters. A layer of Bi is evaporated on the Si substrate to serve as the radiation absorbing surface. The thermistor, the absorber, and the thermal link can be optimized independently. Our waveguide-to-bolometer coupling scheme is similar to that introduced by Peterson and Goldman for composite bolometers

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[5]. However, in our design (Fig. 1), the absorber of the bolometer consists of a thin resistive Bi film deposited on the narrow Si substrate oriented along the E-plane and followed by an adjustable backshort. The thermistor is located outside the waveguide cavity. The Si substrate and legs pass through a small hole to ensure that the bolometer is electrically and thermally isolated from the waveguide walls. Since the thermal contraction of the Si frame is much less than that of the Al waveguide mount, the frame is glued to a small piece of Invar which in turn is press-fit into the mount.

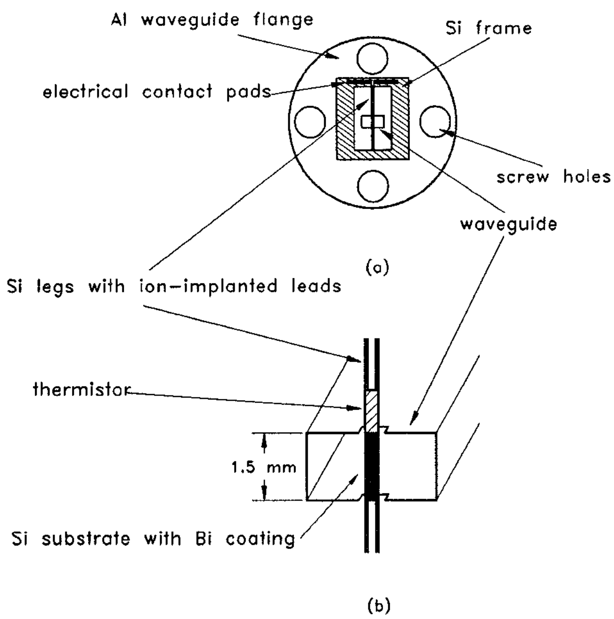

Fig. 1: (a) A cutaway view of the waveguide mount and bolometer for E band (60 - 90 GHz). The silicon chip is glued into a waveguide mount which is at 100 mK. (b) Expanded, perspective view of the bolometer and the waveguide. Si legs ($2500 \times 18 \times 10$ microns) provide support and thermal connection. The electrical contact to the thermistor is achieved through ion-implanted traces along two of the legs. The traces terminate in two contact pads on the Si frame. The substrate is 10 microns in thickness.

To determine the absorber impedance which maximizes power absorption, we measured the reflectance of this design using an X-band scale model. The reflectance was found to be less than -10 dB from 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 1/10 to 1/4.

In the actual bolometers, a 100 nm Bi layer is deposited on the waveguide portion of the Si, which gives an expected impedance ~160 Ω/square at liquid helium temperature and ~50 Ω/square at room temperature [6]. By adjusting the backshort position and measuring the reflectance of the detector-backshort system as a function of frequency [5], we determined the admittance of the absorber. It is found that the absorber is capacitive with the imaginary part of the impedance ~0.7 of the waveguide impedance. Measurements in W band at room temperature have shown that the reflectance of this structure is -14 dB from 80 GHz to 110 GHz with a backshort placed 0.85 mm (~1/5 λ_g at 95 GHz) away from the absorber. Similar measurements at liquid helium temperature showed that the reflectance is -5 dB with a backshort distance of 0.5 mm (~1/8 λ_g at 95 GHz), which is worse than that observed at X-band. This may be due to aging of the Bi film, i.e., the increase of the resistance of the Bi film after exposure to air [7]. This aging may result in an increase in the resistance of the Bi film to much more than 160 Ω/square at liquid helium temperature. We are making new devices in which a thin layer of SiO will be deposited on top of the Bi film to inhibit this effect.

DESIGN AND FABRICATION

The electrical and thermal properties of the bolometer are characterized by the operating temperature, the temperature sensitivity of the thermistor, the thermal conductance of the legs, the heat capacity of the detector, and the optical loading and modulation frequency. Bolometer optimization, including the non-equilibrium noise analysis of Mather [8], is described by Griffin and Holland [9].

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

$$R = R_0 \mathrm{Exp}\sqrt{\frac{T_0}{T}}, \qquad (1)$$

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> Si using anisotropic chemical etching. Si wafers 300 microns thick are initially back-etched to produce membranes 20-30 microns 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 microns) 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 P and B thermistor implants. The B implant is patterned slightly larger than the P 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 Fig. 1. 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 Si legs, the thermal conductance can be described by:

$$G = G_0 T^3, \qquad (2)$$

where G_0 is mainly modified by the design of the leg geometry. Finally, Bi is deposited on the unimplanted region of the detector to act as the absorber.

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 a typical band of 95-110 GHz, with radiative loading from sky, atmosphere, and warm optics, the optical power and background photon noise are estimated to be 0.3 pW and 6.6×10^{-18} W/$\sqrt{\mathrm{Hz}}$ respectively (assuming an optical efficiency of 0.3). The bolometers are operated at 100 mK and are designed to have T_0 = 10 K, R_0 = 2000 Ω, and G = 2×10^{-11} W/K at 100 mK. By the theory of Griffin and Holland [9], which assumes that the only contributions to the bolometer noise are Johnson noise, thermodynamic fluctuations (phonon noise), amplifier noise, and background photon noise, the total NEP is calculated to be 9.8×10^{-18} W/$\sqrt{\mathrm{Hz}}$ which translates to receiver sensitivity of 160 μK$\sqrt{\mathrm{sec}}$ for a total power measurement of a Rayleigh-Jeans source at 15 GHz bandwidth. The heat capacity of the detector is dominated by the thermistor and can be described as [10]:

$$C \approx 8 \times 10^{-14}\, T \text{ [J/K]}. \qquad (3)$$

Therefore, the time constant is predicted to be less than 3 ms.

BOLOMETER PERFORMANCE

An adiabatic demagnetization refrigerator [11] is used to cool the bolometers to ~100 mK. The bolometer is current-biased with a battery and an 80 MΩ load resistor. In order to minimize capacitive loading of the high-impedance bolometers and electromagnetic interference from long wires, signals from the bolometers are amplified by Si JFETs (2N6451 from Interfet Corp. [12]) placed inside the dewar within a short distance (~10 cm) of the detectors. The JFETs are mounted inside a copper box attached to the 4.2 K plate and are temperature regulated to 110 K [13]. The JFET voltage noise is 5 nV/$\sqrt{\mathrm{Hz}}$ at 2 Hz, and the current noise is less than 2×10^{-16} A/$\sqrt{\mathrm{Hz}}$. Signals are further amplified by room-temperature amplifiers.

Typical data from the measurements of our bolometer are shown in Table I. R_0 and T_0 are obtained by fitting the measured resistance values with formula (1) from 80 mK to 200 mK, while both the thermal conductance and DC responsivity are deduced from the bolometer's load curves (I-V curves). The measured NEP at 10 Hz is only a factor of 1.3 higher than that calculated using the theory of Griffin and Holland [9]. However, the measured noise at 2 Hz is about 2 times higher than that at 10 Hz. This may indicate the presence of 1/f noise.

T_b	0.096 K
T_0	10.2 K
R_0	610 Ω
G(T)	$1.6 \times 10^{-8} T^3$ W/K
DC responsivity	2.4×10^9 V / W
NEP (at 10 Hz)	7.5×10^{-18} W/$\sqrt{Hz}$

Table I: Measured electrical performance of a waveguide-mounted Si bolometer. The optimal sensitivity is achieved with a bias current of 0.1 nA which heats the bolometer to 0.104 K while the cold stage temperature is 0.096 K.

The resposivity and the NEP in Table I are measured without external optical power which would both raise the detector NEP and introduce photon noise. In our low-background observations, the noise contributions from the background are about the same as the NEP value in Table I. For example, for the typical band of 95-110 GHz, the total NEP, including the effects of optical power and background photon noise, is estimated to be 1.1×10^{-17} W/$\sqrt{Hz}$.

CONCLUSION

The measurements of monolithic Si bolometers coupled to waveguide appear extremely promising for future balloon-borne and space-based observations. The measured electrical NEP is about 3 times better than that of composite bolometers [14]. The remaining task is to measure the responsivity and the NEP under optical loading by a low temperature blackbody calibrator. Compared with an ideal coherent detector which has a quantum limit noise of 40 $\mu K \sqrt{sec}$ for the typical band of 95-110 GHz, our bolometer noise is a factor of three higher. However, since the detector NEP is already comparable to the photon noise from low-background sources, further reduction of the detector NEP will not significantly improve the receiver sensitivity.

This work is supported in part by NASA grant NAGW-2797 and PT's NSF Presidential Young Investigator Award. GW is supported by a NASA GSRP Fellowship.

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