THE HOT-ELECTRON MICROBOLOMETER AS AN ULTRASENSITIVE DETECTOR FOR MILLIMETER WAVELENGTHS

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ABSTRACT

The hot-electron microbolometer is a novel low-temperature thermal detector which has potential for very low-noise power measurements at millimeter wavelengths. We are investigating issues in the practical implementation of this detector for low-background applications. We present results from tests of an efficient scheme to couple the detector to waveguide, as well as the expected noise performance of a microbolometer optimized for balloon-borne measurements. The expected NEP of the microbolometer in such a measurement is 7×10^{-18} W/$\sqrt{\text{Hz}}$ which is nearly a factor of two better than bolometers currently in use.

INTRODUCTION

A bolometer is a thermal detector that converts electromagnetic radiation to heat. Power is coupled into an absorber which is thermally connected to a heat reservoir through a weak thermal link. The incoming power raises the temperature of the absorber above that of the reservoir; the temperature change is measured with an electrical resistance thermometer. Bolometers are used in a wide range of applications in astrophysics, particularly in low-background environments where sensitive detectors can be utilized efficiently. When cooled below 1 K, bolometers are the most sensitive broad-band detectors available at millimeter and sub-millimeter wavelengths [1].

In the hot-electron microbolometer, radiation is coupled from an antenna into a normal metal strip of sub-micron dimensions, where it is absorbed by the electrons. Phonons in the metal lattice of the same strip act as the heat reservoir, and electron-phonon scattering provides the thermal link. At low temperatures (less than ~500 mK) the coupling between electrons and phonons in the absorber is extremely weak. Consequently, radiation absorbed by the microbolometer raises the temperature of the electrons in the metal strip above that of the metal lattice. The strip forms the normal electrode of a superconducting-insulating-normal (SIN) junction (see Fig. 1), and the "hot" electrons then tunnel across the junction. The temperature rise of the electrons is measured from the I-V characteristics of the junction [2].

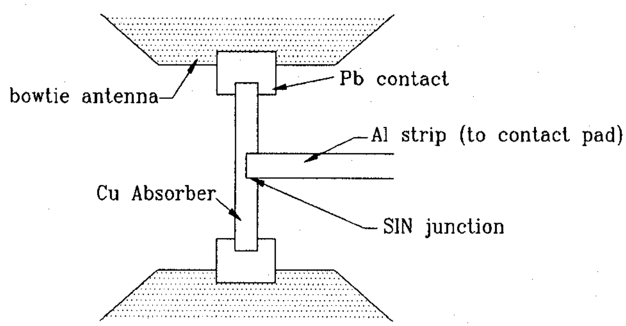

Fig. 1: A close-up view (not to scale) of the hot-electron microbolometer located between the bows of the antenna. The dimensions of the absorber are $\sim 10 \times 0.1 \times 0.04\ \mu m^3$

The hot-electron microbolometer was proposed by M. Nahum, C.A. Mears and P.L. Richards [2], and subsequently fabricated by M. Nahum and J. Martinis [3], who tested the detector's DC characteristics. Their tests showed that the microbolometer has potential for use in sensitive low-background astrophysical measurements, and we are in the process of fabricating and testing the detector for that purpose. A scheme for coupling radiation to the hot-electron microbolometer has been developed, and calculations of its expected sensitivity in a typical low-background measurement

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have been completed. The next step is to carry out tests of an actual device.

DESIGN AND OPTIMIZATION

The sensitivity of a thermal detector is generally characterized by the noise equivalent power (NEP), the thermal time constant τ, and the power responsivity S. If we model the absorber as a region of heat capacity C, coupled to a heat bath through a conductance G (see Fig. 2), then

$$\tau = C/G \quad (1)$$

and

$$S = \frac{dV/dT}{G\left(1+\omega^2\tau^2\right)^{1/2}}. \quad (2)$$

Here, V is the voltage across the junction when the electrons are at a temperature T, and ω is the modulation frequency. The NEP is given by

$$NEP = \left[4k_B T^2 G + V_j^2/S^2 + V_n^2/S^2\right]^{1/2} \quad (3)$$

where the first term, commonly known as phonon noise, is due to energy fluctuations in the absorber, V_j is the voltage noise across the SIN junction, and V_n is noise in the first stage of amplification [3].

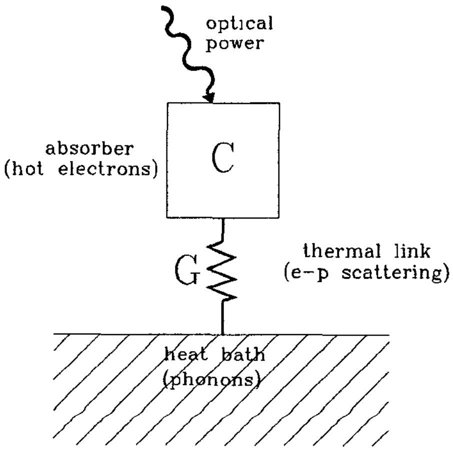

Fig. 2: A schematic diagram of the components of the thermal region of a bolometer; these are identified in parentheses for the hot-electron microbolometer.

.From (2) and (3) it is clear that the detector sensitivity can be improved by making G small. However, for a given power, a small G results in a higher temperature in the absorber, and thus G cannot be made arbitrarily small or the phonon noise will become large. Thermal conductance out of the absorber region through the superconducting Pb contact pads (see Fig. 1) and through the SIN junction is negligibly small. The dominant means of heat transfer is due to electron-phonon scattering in the absorber region. This is made small by cooling the substrate (and therefore the phonons) to 100 mK.

The power transferred from the electrons to the phonons is given by

$$P = \Sigma V\left(T_e^5 - T_p^5\right) \quad (4)$$

where T_e is the electron temperature and T_p (100 mK) is the temperature of the phonons. V is the volume of the absorber and Σ is a constant which depends on the absorber material. For Cu, $\Sigma \approx 1\times10^{-9}$ $W\mu m^{-3}K^{-5}$. Then

$$G = dP/dT = 5\Sigma V T_e^4. \quad (5)$$

Nahum and Martinis [3] performed tests on a hot-electron microbolometer in the dark, i.e. with no optical power coupled to the detector. They found that at 100 mK the detector's responsivity $S \sim 10^9$ V/W. The NEP of the microbolometer was found to be 3×10^{-18} $W/\sqrt{Hz}$ and was limited by the amplifier noise of 3 $nV/\sqrt{Hz}$

We have carried out calculations of the performance of the hot-electron microbolometer when optical power is coupled into the absorber region. Because of the low junction resistance (~20 kΩ), V_j in (3) can be ignored.

The NEP can thus be minimized by choosing an amplifier with low noise voltage and optimizing G, which depends on T_e and the absorber volume V. The relationship between T_e, the volume V and the power P coupled into the detector is given by (4). Thus, for a given P, the minimum value for the NEP can be found by varying V. For our application, the V which gives the lowest NEP is $\sim 10\times0.1\times0.04$ μm^3.

Calculations of the expected performance of the microbolometer in a typical balloon-borne experiment are summarized in Table 1. Since the heat capacity of the absorber is just due to the electrons in the normal metal strip, the time constant is several orders of magnitude smaller than that of semiconductor bolometers. Because of the relatively low responsivity, it is very important that the amplifier's voltage noise be as low as possible, as otherwise the NEP would be limited by amplifier noise. We are using a matched pair of Interfet NJ3600 Si JFET amplifiers [4] with a voltage noise of $0.6\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$ at 100 Hz and a 1/f knee at 10 Hz [5]. Modulation is achieved by AC-biasing the device. The NEP of the hot-electron microbolometer can be further improved in the future as quieter amplifiers become available.

Bandwidth	95-110 GHz
Amplifier noise	$0.6\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$
Optical loading	3×10^{-13} W
Thermal conductance, G	9.1×10^{-12} W/K
Responsivity, S	1.2×10^{8} V/W
Time constant, τ	3.6 μs
Photon noise	$6.5\times10^{-18}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$
Detector NEP	$6.1\times10^{-18}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$
Total NEP	$8.9\times10^{-18}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$
Receiver sensitivity	$140\ \mu\mathrm{K}\sqrt{\mathrm{sec}}$

Table 1: Performance characteristics of a hot-electron microbolometer cooled to 100 mK and optimized for use in a balloon-borne measurement. The optical loading is the power coupled into the detector from emissive optical surfaces, astrophysical backgrounds, and atmospheric emission. This power introduces its own photon noise. The receiver sensitivity is for a total power measurement of a Raleigh-Jeans source with a 15 GHz bandwidth, assuming an optical efficiency of 30%.

COUPLING SCHEME

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. We couple the hot-electron microbolometer to radiation using the single-mode approach.

There are many possible ways to couple the small detector to waveguide. We have used a bow- tie antenna. Although bow-tie antennas are traditionally used in free-space, we have demonstrated that they provide a convenient and efficient means to couple to a device in waveguide. In free space, a bow-tie antenna has the advantage that its impedance is real and therefore frequency independent [6]. The impedance depends on the angle of the bows. The impedance of the absorber of the microbolometer is also mostly real; its inductive reactance is only ~5 Ω [7], compared to a real impedance of 100 Ω (see below). The absorber impedance can be varied by changing the resistivity of the normal metal (by varying the amount of impurities present in the metal) and by changing the volume of the absorber. The latter, however, affects the thermal conductivity and therefore the performance characteristics of the microbolometer; we kept the volume fixed and changed the dimensions of the absorber to achieve the desired impedance.

In a waveguide, however, the properties of the bow-tie antenna change considerably. We empirically matched the impedance of the bow-tie and detector to that of the waveguide by changing the bow angle and by using a backshort.

The microbolometer and the bow-tie antenna are supported by a quartz substrate which is 250 μm thick. The bow-tie antenna, signal wires and contact pads are made of 0.3 μm of evaporated gold, and are fabricated using photolithography. The microbolometer is made using e-beam lithography. The absorber is deposited between the fins of the bow-tie antenna. The quartz substrate is mounted on in a WR10 waveguide flange so that the fins are aligned in the E-plane of the waveguide, as shown in Fig. 3. The signal wires leave the waveguide through a slot in the H-plane wall. We will use this scheme in the E, W, and D band.

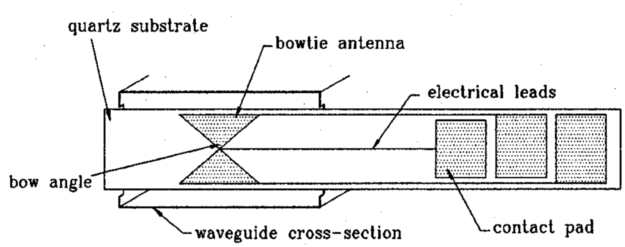

Fig. 3 (not to scale): The mounting scheme for the hot-electron microbolometer in WR10 waveguide.

Scale model tests done in the X band show less than -10 dB reflectance over the entire band for absorber impedances between 50 Ω and 150 Ω, with a backshort placed behind the bow-tie antenna to match the waveguide impedance. Based on these results we chose an impedance of 100 Ω for our detector.

The bow angle was 113°, and best results were achieved when the backshort was $\sim 0.07\lambda_g$ behind the bow-tie. This is considerably shorter than the quarter wavelength distance (0.9 cm) which would give the best coupling efficiency if the impedance was purely resistive [8]. As a result, we believe that there is capacitive coupling between the detector and bow-tie and the waveguide. The combined capacitive reactance of the detector, bow-tie and the backshort is measured to be ~22 Ω at 10 GHz.

CONCLUSION

The hot-electron microbolometer is an extremely sensitive thermal detector which is currently being developed for application in astrophysical experiments. We have tested a scheme for coupling the detector to radiation, and calculations of the expected sensitivity of the microbolometer optimized for a typical low-background astrophysical experiment have been completed. We can compare the performance of the hot-electron microbolometer with that of an existing HEMT amplifier that has a receiver temperature of ~50 K at close to 100 GHz [9]. The receiver sensitivity of such a device operating with a 15 GHz bandwidth would be $\sim 450\ \mu K\sqrt{sec}$, which is about three times less sensitive than that of the hot-electron microbolometer. The expected NEP of the microbolometer is about 5 times better than that of the best composite bolometers currently in use [10], and is already comparable to with the photon noise from the optical power; further improvement in the noise of the detector will not change the sensitivity of the device significantly. Tests of the characteristics of the actual device will be carried out in the near future.

This work is supported in part by NASA grant NAGW-2797, NSF grant AST-9318785, and PT's NSF Presidential Young Investigator Award. GW is supported a NASA GSRP Fellowship.

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