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COMPOSITE BOLOMETERS FOR SUBMILLIMETER WAVELENGTHS

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ABSTRACT

The fabrication and optimization of composite submillimeter wave bolometers with metal film absorbing elements and doped Ge thermometers is described. Performance characteristics are given for 4×4 mm bolometers designed for operation at both ^4He and ^3He temperatures. The performance expected from such bolometers when they are optimized for various values of background loading is calculated. Current dependent excess noise, which can arise from any of several sources, is included in the analysis. It can prevent bolometers from reaching the background fluctuation noise limit at any value of background power. Feed structures for these bolometers which employ Winston light concentrators are described.

Introduction

The optical NEP of a bolometer can be defined as the signal power which must be incident on the geometrical bolometer area to produce an output signal equal to the rms noise. The product of the optical NEP and the optical efficiency is called the electrical NEP_E . It is the signal power which must be dissipated in the bolometer to produce an output signal equal to the rms noise. Conventional ^4He temperature doped Ge or Si bolometer detectors of submillimeter wavelength radiation have historically had poor values of the optical NEP compared with bolometers designed for operation at shorter wavelengths. If the signal to be detected contains n modes and is focused into a solid angle of 1 steradian, the area of the bolometer required to intercept the signal is $A \approx n\lambda^2$. The thickness of a conventional bolometer required for high efficiency depends on the optical extinction length of the absorbing material. In many materials such as black paints and appropriately doped bolometer materials, this length increases with increasing wavelength in the submillimeter region. As a consequence of these factors, efficient conventional submillimeter wave bolometers have relatively large volume and thus large heat capacity C . The NEP_E is proportional to $C^{1/2}$ for applications in which the modulation frequency is fixed and the background power loading is small. Efficient conventional submillimeter wave bolometers thus have relatively large values of NEP_E . Small values of NEP_E can be obtained only by sacrificing optical efficiency or using bolometers which are too small to intercept the full signal.

Developers of submillimeter wave bolometers have begun to separate

the functions of absorber and thermometer to obtain improved performance. Black paints have been used directly on a Ge bolometer¹, or on metal foil substrates². This approach is not very attractive at long wavelengths because of the very large He temperature heat capacity of paint films of adequate thickness to absorb efficiently at low temperatures. A lossy dielectric with a relatively small heat capacity (doped Si) has been used with a Ge thermometer³. Because of its large dielectric constant, this absorber can be made to absorb efficiently at a chosen resonant frequency.

Several composite bolometers have been developed at Berkeley which are based on an absorbing element made from a transparent dielectric substrate coated on the back side with a thin metal film. This type of infrared absorber is well known from its use in the Golay cell, but had apparently not been applied to bolometers before it was used in conjunction with a Josephson effect thermometer⁴. It provides an efficient absorbing surface which is reproducible, is easily tailored to a chosen application, and which can have extremely low heat capacity per unit area.

In this paper, we describe the design and optimization of composite submillimeter wave bolometers which use a doped Ge thermometer attached to the metal absorber. Bolometers of this type were first used by the Caltech group⁵ in an astronomical application. We have used them for both astronomical and laboratory measurements. The bolometer described here is the easiest way for groups which are familiar with conventional Ge bolometer technology to take advantage of the efficiency and low heat capacity of the metal film absorber. They are not as sensitive in low background applications as the superconducting bolometers which are being

developed in a parallel program at Berkeley⁶. Some information about the absorption efficiency of a metal film on a transparent dielectric substrate, which is a result of the superconducting bolometer program, will be summarized here for completeness. A detailed discussion is given elsewhere^{4,6,7,8}.

Absorbing Element

The dielectric layer should be thin and strong, have good thermal conductance, and a low heat capacity. We have used sapphire sheets 30-135 μm thick (with Debye temperature $\theta_D = 600$ K), but diamond ($\theta_D = 2200$ K) would be better. Our $4 \times 4 \text{ mm}^2$ substrates have an internal thermal relaxation time of less than 10^{-4} sec.

The effect of adding a thin conducting film to one surface of the dielectric can be calculated using elementary transmission line theory. If the dielectric is lossless and if we ignore multiple internal reflections, the absorptance for radiation incident normally from the dielectric side is^{7,8}

$$A = \left[\frac{4n}{(n+1)^2} \right] \frac{4nZ_0/R_{\square}}{(n+1 + Z_0/R_{\square})^2} \quad (1)$$

This absorptance, which includes the effect of reflection from the dielectric surface, is larger than that for radiation incident on the metal side. In Eq. (1) the metal film is characterized by its surface resistance $R_{\square}$, $Z_0 = 377 \Omega/\square$ is the impedance of free space, and n is the index of refraction of the dielectric.

Multiple reflections inside the dielectric produce interference effects which cause large deviations from (1). Computer calculations show that 90 percent absorptance can be achieved over a narrow frequency

range by correctly selecting the thickness of the dielectric sheet and the surface resistance of the film.^{7,8} A frequency independent absorptance is achieved when there is no reflection from the dielectric-metal interface, i.e. when $Z_0/R_{\square} = n - 1$. The absorptance is then given correctly by Eq. (1). We use a surface resistance of $200 \Omega/\square$ for sapphire ($n = 3$) to obtain a frequency independent absorptance of 50 percent.

The absorbing films are produced by evaporating a Bi film $\approx 1 \times 10^{-5}$ cm thick onto the substrate. Bi is used because its low conductivity makes it relatively easy to obtain continuous metallic films with the required values of the surface resistance. Measurements of the transmittance which cover the frequency range from 3 to 300 cm^{-1} for several values of R are in good agreement with the calculations^{7,8}. This agreement shows that the effective submillimeter surface resistance of the Bi film is very close to the dc resistance. Direct measurements⁸ of the optical efficiency at $\nu \approx 20 \text{ cm}^{-1}$ (the fraction of the power incident on a 4×4 mm bolometer which is absorbed) confirm the theoretical prediction of 50 percent.

Thermometer

The most critical element of a composite bolometer is the temperature sensor which is attached to the absorbing substrate. It should have good temperature resolution, small power dissipation, and a small heat capacity. In this paper we discuss our use of doped Ge thermometers for this application. These are very similar to conventional small doped Ge bolometers and are attached to the substrate with a small amount of epoxy. The electrical leads which are soldered with In to the semiconductor chip also serve as the thermal link to the heat sink. Thermal conductances in the range from 10^{-10} to 10^{-4} W/K can be obtained at a temperature of

to 1.2 K by using 13 to 50 μm diameter copper, brass, or stainless steel wire. The substrate is rigidly held in place by 15 μm diameter nylon threads. The lowest mechanical resonance frequency is typically 50 to 100 Hz. An assembled bolometer is shown in Fig. 1.

Our semiconductor thermometers are typically constructed from chips of gallium doped germanium with a volume $\lesssim 3 \times 10^{-4} \text{ cm}^3$. The ^4He temperature resistivity of the material we use is well described by an energy gap relation $\rho(T) \approx 100 \exp(8/T) [\Omega\text{cm}]$. The Ga concentration of this material is unfortunately not known. It is thought to be essentially uncompensated. The thermometer chips are cut to size with a wire saw and lapped to give an even finish. They are next etched in 20:1 $\text{HNO}_3:\text{HF}$ for approximately 10 min. and quenched in methanol. The wire leads are then attached with a very small amount of In solder and Ruby FluidTM flux. Thermometers made in this way are mounted in a well-shielded low noise test apparatus with a cold 10 M Ω wire wound load resistor. The thermal response $R(T)$ and the spectral density of the voltage noise are then measured in the vicinity of the intended operating conditions. The noise spectrum is compared with that measured from a cold wire wound resistor in the same test apparatus. The voltage noise of a bolometer system at three different bias settings is shown in Fig. 2. The sharp features are mechanical resonances in the system. During normal operation the number of such resonances is reduced by anchoring the wiring firmly. The signal modulation frequency is then chosen to avoid any remaining resonances.

The current dependent noise (in excess of Johnson noise) is an important limitation to the performance of this type of bolometer. Our measurements show that the spectral density of this noise can be generally described by $\langle V_n^2 \rangle = NI^2 R^2 / \omega$ where N is a constant $\lesssim 10^{-11}$, I is the

bias current, R is the thermometer resistance and $\omega/2\pi$ is the frequency. The value of N is sensitive to the method of etching and soldering of the contacts. Four terminal noise measurements have been carried out to see whether a residual excess noise from the bulk of the Ge can be identified. If we interpret these experiments in terms of a model in which the noise arises from a modulation of both the contact resistance and the bulk resistance, we conclude that under the most favorable conditions, most of the observed noise arises from the bulk of our Ga:Ge. This noise is not affected when the thermometer is attached to the sapphire substrate. Noise with the same general features can also arise elsewhere in the electrical circuit.

Current dependent excess noise is not discussed quantitatively in the literature of semiconducting bolometers. Our experience is that it is always present to some degree. This is true of all of the bolometers we have made from our own As and Ga doped Ge, as well as several Ga:Ge bolometers we have obtained from Infrared Laboratories, Inc., Si bolometers from Molectron Inc., and As:Ga:Ge elements from Lake Shore Cryotronics, Inc. The physical mechanism for this noise is not understood. It can be a serious limitation in the optimization of any bolometer which uses a doped semiconductor as a thermometer.

Bolometer Optimization

Bolometers are operated in widely different circumstances with different values of the background power and the modulation frequency. We have systematically investigated the various noise contributions encountered during actual operation and have been able to individually optimize our composite bolometers for the conditions under which they are

to be used⁹. The constant (absorbed) background power ϵP_B appears in the dc power balance equation which determines the operating temperature T of the bolometer. The fluctuations in this background radiation contribute directly to the NEP. In the Rayleigh Jeans limit of a blackbody background source, and for a background temperature $T_B \gg T$, the background power fluctuation¹⁰ can be written in terms of the absorbed Rayleigh-Jeans power ϵP_B as

$$(\text{NEP}_E)_B = (2kT_B \epsilon P_B)^{1/2}. \quad (2)$$

Other terms which contribute to the NEP_E are the phonon fluctuation noise which arises from the thermal conductance G between the bolometer and the heat sink, Johnson noise from the resistance R of the bolometer, excess noise which arises from current flow in the thermometer, Johnson noise from the load resistor R_L at temperature T_L , and voltage noise and current noise in the amplifier. The (voltage) spectral densities of these amplifier noise contributions are K/ω and LR^2 respectively.

Following the procedure of Low and Hoffman¹¹ we write each noise term in the form of an absorbed power at the bolometer input. Assuming that the contribution of each term to the bolometer voltage is statistically independent, we add their squares to obtain an expression¹² for the square of the electrical noise equivalent power (NEP_E) which we can compare to that obtained from an electrical evaluation¹³ of the bolometer under operating conditions,

$$(\text{NEP}_E)^2 = 2kT_B \epsilon P_B + 4kT^2 G + \frac{4kTR}{|S|^2} + \frac{NI^2 R^2}{\omega |S|^2} + \frac{4kT_L R_L}{|S|^2} \left[\frac{R}{R_L + R} \right]^2 + \frac{K}{\omega |S|^2} + \frac{LR^2}{|S|^2}. \quad (3)$$

The modulus squared of the voltage responsivity S of a bolometer is given by

$$|S|^2 = \frac{R^2 I^2 \gamma^2 (1 - \delta)^2}{G_e^2 [1 + \omega^2 C^2 / G_e^2]} \quad (4)$$

where $\gamma = d \ln R / dT$, $\delta = R / (R_L + R)$, and $G_e = G - I^2 R \gamma (1 - 2\delta)$. The effective thermal conductance G_e and the effective time constant $\tau_e = C / G_e$ enter because of the (negative) feedback which arises from heating by the bias current. In our optimized bolometers G_e differs from G by ~ 20 percent. The parameters C , G , R , and γ are functions of the operating temperature T which is set by the dc power balance equation

$$T = T_S + (\epsilon P_B + I^2 R) / G. \quad (5)$$

The ideal bolometer for a given experiment has optical efficiency near unity, is large enough in area to intercept the signal, and has an NEP_E limited by background fluctuations, that is, by the first term in Eq. (3).

The selection of parameters to minimize the NEP_E for a given background power ϵP_B is a complicated problem. We can identify certain "fixed" parameters whose values are set by practical considerations. The sink temperature T_S , for example, is set by the type of cryostat chosen. If we set $T_L = T_S$ and use the largest available ($\approx 10 \text{ M}\Omega$) wire wound resistor for R_L , the thermal (and current) noise from the load resistor are negligible. The current noise parameter N should be made as small as possible by the selection of the proper material and contact fabrication techniques.

One approach which can be used to get a qualitative understanding of the optimization problem is to observe that the rapid dependence of R and C on $T - T_S$ limits the range of useful values of $(\epsilon P_B + I^2 R) / G$ in Eq. (5). Consequently, the maximum value of $I^2 R \approx \epsilon P_B$ and the minimum value of $G \approx \epsilon P_B / T_S$ are essentially determined by ϵP_B . If ϵP_B is small, Eq. (4) shows that C should be as small as possible to maximize S . For

large ϵP_B , however, the value of G required by Eq. (5) to keep the bolometer cold makes the heat capacity term $(\omega C/G)^2$ in Eq. (4) negligible. The transition between these limits depends on the modulation frequency $\omega/2\pi$. Like the heat capacity, the modulation frequency is most important in the low background limit. It is often determined by the experiment being contemplated, but can usually be shifted over a wide enough range to avoid mechanical resonances and electrical pickup.

Since $I^2 R \approx \epsilon P_B$, $|S|^2$ varies as R . From Eq. (3) we see that the current noise terms for the thermometer and the amplifier vary as R , but the amplifier voltage noise term varies as R^{-1} . The optimum value of the bolometer resistance R is therefore limited to a range close to $1 \text{ M}\Omega$ by the properties of FET preamplifiers. Since the optimum R is considerably less than R_L , the parameter δ in Eq. (4) is not very important. The material parameter γ should be as large as possible so as to maximize S , so long as the thermometer geometry can be adjusted to obtain a useful value of R .

We use a digital computer program to perform detailed optimization calculations. The program is versatile enough to treat any set of the parameters as fixed and let the remaining parameters vary within specified limits. In these calculations, G , I , and to a more limited extent, R , were treated as free parameters. The bolometer temperature T is then a dependent variable.

A bolometer was designed using this optimization program to operate at a modulation frequency of 17 Hz in the low background limit. The design parameters and the performance of this bolometer were thoroughly characterized and are given in Table I. The responsivity is determined

from the measured ac and dc impedance characteristics under operating conditions¹³. Dividing the observed voltage noise by the responsivity yields the measured NEP_E . There is good agreement between the performance calculated from the measured parameters using Eq. (3), (4), and (5), and the actual measured NEP_E . The NEP_E is degraded by less than 10% by background power levels up to 10^{-8} W. This bolometer was designed for use in a measurement of the 3 K cosmic background radiation¹⁴.

We have used the optimization program to estimate, from the parameters of this bolometer, what the bolometer performance would be when G and I were optimized for other operating frequencies and finite values of the absorbed background power ϵP_B . In Fig. 3 we compare the background fluctuation limit from Eq. (2) for a 300 K Rayleigh-Jeans source (which has been filtered to give the value of ϵP_B indicated on the abscissa) to the NEP expected if there were no fluctuations in P_B . That is, we compare $(NEP_E)_B$ to the NEP_E from all other terms in Eq. (3) combined.

The curves in Fig. 3 for the contributions to NEP_E in the absence of background fluctuations rise at high values of P_B because of background heating which enters through Eq. (5). Thus the performance of this bolometer can be limited by the background power. Since the other contributions to NEP_E are always larger than the background fluctuation term $(NEP_E)_B$, however, this bolometer can never reach the ideal background fluctuation limit.

The benefit to be gained by decreasing the excess current noise are illustrated by the dashed lines in Fig. 3 which are computed using the same bolometer parameters except that we set $N = 0$. It would be possible to achieve background fluctuation limited operation in the absence of current noise.

Improvements in Bolometer Performance

There are several ways in which the sensitivity of the Ga:Ge composite bolometer can be improved. The current noise dominates the low frequency operation below ≈ 50 Hz so that any reduction in this noise translates directly into better sensitivity. Our recent attempts to produce thermometers with smaller values of the current noise parameter N have met with some success. The sensitivity scales as the square root of the heat capacity in the low background flux regime so that it is helpful to decrease the heat capacity by using diamond substrates or thinner sapphire substrates, by reducing the size of the Ge thermometer, and by using thinner wire for leads. Sapphire substrates $30\text{ }\mu\text{m}$ thick have recently become available to us which improve NEP_E by approximately a factor ≈ 2 . The heat capacity can be dramatically reduced by operating at a lower temperature since the dominant heat capacity comes from non-metallic materials whose heat capacity scales at T^3 . This involves developing sensitive thermometers which operate at the lower temperature. It should be noted that to utilize the lower heat capacity to improve sensitivity for low background applications requires a reduction in G which in turn limits the maximum background that a given bolometer can tolerate. Some progress has been made in bolometer sensitivity since the careful evaluation was made of the properties of the bolometer described in Table I. The present status of our composite bolometers is described in Table II.

In a parallel project at Berkeley, composite bolometers are being developed with superconducting thin film thermometers⁸. These bolometers require more complicated electronic systems than the present bolometers,

and are not as fully developed. The superconducting thermometers and leads, however, have slightly lower heat capacity than the combination of wires, solder, Ge, and epoxy used for the bolometers described in this paper. A more important advantage is that the superconducting thermometers have negligible current noise, so they can be operated more slowly. In the low background limit, the best of these bolometers approach the thermal fluctuation noise limit at a significantly lower NEP_e than we have achieved with the composite bolometers with doped semiconducting thermometers⁸. These results are also summarized in Table II.

Feed Optics

To obtain high sensitivity in practice, it is critical to control the background radiation which reaches the bolometer. When the performance of a bolometer is independent of its heat capacity or the heat capacity is nearly independent of its area, there can be advantages in the use of an external structure to limit the modes (throughput) which enter the system to those which contain signal information, and to illuminate the bolometer with radiation whose angular spread is independently adjusted to obtain high absorption efficiency.

For this purpose, we use a primary concentrating element, a cooled aperture stop, and a collimating element. This could be done with image forming components such as lenses or mirrors, but we have found it convenient to use conical metal Winston¹⁵ light concentrators in the configuration shown in Fig. 5. Cone A limits the throughput of the system while cone B partially recollimates the radiation. The partly collimated portion of the beam which follows the mode limiting structure can be a

convenient place to install cold spectrometers¹⁴, or transmission filters. Scattering or diffraction from these elements and from any reflecting surfaces placed behind the bolometer cannot affect the field of view of this system. Since the elements we use for spectral definition often require well collimated radiation, we generally re-concentrate the light onto the bolometer. This is accomplished with cone C. Rabl and Winston have provided a design analysis of the optimum cone for this function¹⁶. The solid angle at which the bolometer is fed is chosen by considering the dependence of the NEP_e of the bolometer on its area, and the angular dependence of its absorptivity. For most of our applications, this is not a difficult optimization, since calculated broad band absorption in the sapphire-Bi system is essentially independent of angle out to ~ 70 degrees from normal incidence as is shown in Fig. 5. Our use of the Winston concentrator is different from one which has been proposed for bolometers whose heat capacity is proportional to their area¹⁷.

Table I

Design and Performance Parameters for a
4 × 4 mm Ga:Ge Composite Bolometer

Electrical Parameters	
Resistance:	$R(T) = 7.2 \times 10^3 \exp(7.4/T) [\Omega]$
Excess Noise:	$V_{\text{excess}}^2 = 8.8 \times 10^{-12} R^2 I^2 / \omega [V^2/\text{Hz}]$
Preamplifier Noise:	$V_{\text{preamp}}^2 = 2.0 \times 10^{-15} / \omega + 3.6 \times 10^{-29} R^2 [\text{V}^2/\text{Hz}]$
Cold Load Resistor:	$R_L = 10^7 [\Omega]$
Estimated Heat Capacity	
0.4 × 0.4 × 0.0135 cm sapphire:	$8.2 \times 10^{-10} T^3 [\text{J/K}]$
0.1 × 0.04 × 0.03 cm ³ Ga:Ge:	$4.2 \times 10^{-10} T^3 [\text{J/K}]$
3 × 10 ⁻⁷ cm ³ epoxy:	$2.1 \times 10^{-10} T^3 [\text{J/K}]$
0.4 × 0.4 × 10 ⁻⁵ cm ³ Bi film:	$2.5 \times 10^{-10} T [\text{J/K}]$
3 × 10 ⁻⁷ cm ³ In solder:	$0.4 \times 10^{-10} T^3 [\text{J/K}]$
1 cm × 0.0025 cm brass leads:	$6.7 \times 10^{-10} T [\text{J/K}]$
TOTAL:	$9.2 \times 10^{-11} T + 1.5 \times 10^{-9} T^3 [\text{J/K}]$
Temperature of heat sink and load resistor:	
	1.15 [K]
Performance	
Bolometer Temperature:	$T = 1.25 [\text{K}]$
Thermal Conductance:	$G = 9.3 \times 10^{-8} [\text{W/K}]$
Bias Current:	$I = 4.5 \times 10^{-8} [\text{A}]$
Effective Time Constant:	$\tau_e = 3.5 \times 10^{-2} [\text{sec}]$
Chopping Frequency:	$\omega/2\pi = 17 [\text{Hz}]$
Responsivity:	$S = 1.7 \times 10^6 [\text{V/W}]$
Calculated NEP _E :	$3.8 \times 10^{-14} [\text{W}/\sqrt{\text{Hz}}]$
Measured NEP _E :	$3 \times 10^{-14} [\text{W}/\sqrt{\text{Hz}}]$

Table II

Present Status of 4×4 mm Composite Bolometers

Thermometer	Ga:Ge	Ga:As:Ge	Superconducting Al
Bolometer Temperature [K]	1.2	0.5	1.27
Thermal Conductance [W/K]	6×10^{-8}	1.3×10^{-8}	2×10^{-8}
Time Constant [ms]	25	30	83
Measured NEP_E [W/ $\sqrt{\text{Hz}}$]	5×10^{-15}	2×10^{-15}	1.7×10^{-15}

Figure Captions

1. Schematic diagram of a composite bolometer with a metal film absorber and a doped Ge thermometer.
2. Spectral density of the voltage noise from a bolometer system for three values of bias current. The sharp features are mechanical resonances in the bolometer and the electrical wiring. Since these data were obtained by sampling and Fourier transformation, some of the sharp peak have been aliased (reflected) about the maximum frequency of 250 Hz.
3. Calculated contributions to the electrical NEP_E of a bolometer similar to that described in Table I which has been optimized for varying amounts of absorbed 300 K Rayleigh-Jeans background power. The straight line is the background fluctuation contribution and the curved lines are the contributions from all other terms in Eq. (3) at four different modulation frequencies. The solid lines include the excess current noise term with $N = 8.8 \times 10^{-12}$. The dashed lines show the performance that could be achieved with $N = 0$.
4. Bolometer feed optics system to limit background radiation. Winston concentrator A defines the input solid angle Ω_i . Winston concentrator B re-collimates the radiation for a filter or a spectrometer. Winston $\Omega_f - \Omega_b$ converter reconcentrates the signal onto the bolometer.

5. Calculated absorptance of a 30 μm sapphire substrate backed with a thin film with a surface resistance of $188 \Omega/\square$. This quantity has a weak frequency dependence. It has been averaged over the spectral range from 1 to 100 cm^{-1} .

COMPOSITE Ge BOLOMETER

XBL 7611-7706

Fig. 1

Fig. 2

XBL 7612-7928

Fig. 3

Fig. 4

XBL 7611-7708A

XBL 7612-7929

Fig. 5

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