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Author

Lange, A.E.

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A.E. Lange, E. Kreysa, S.E. McBride, P.L. Richards,
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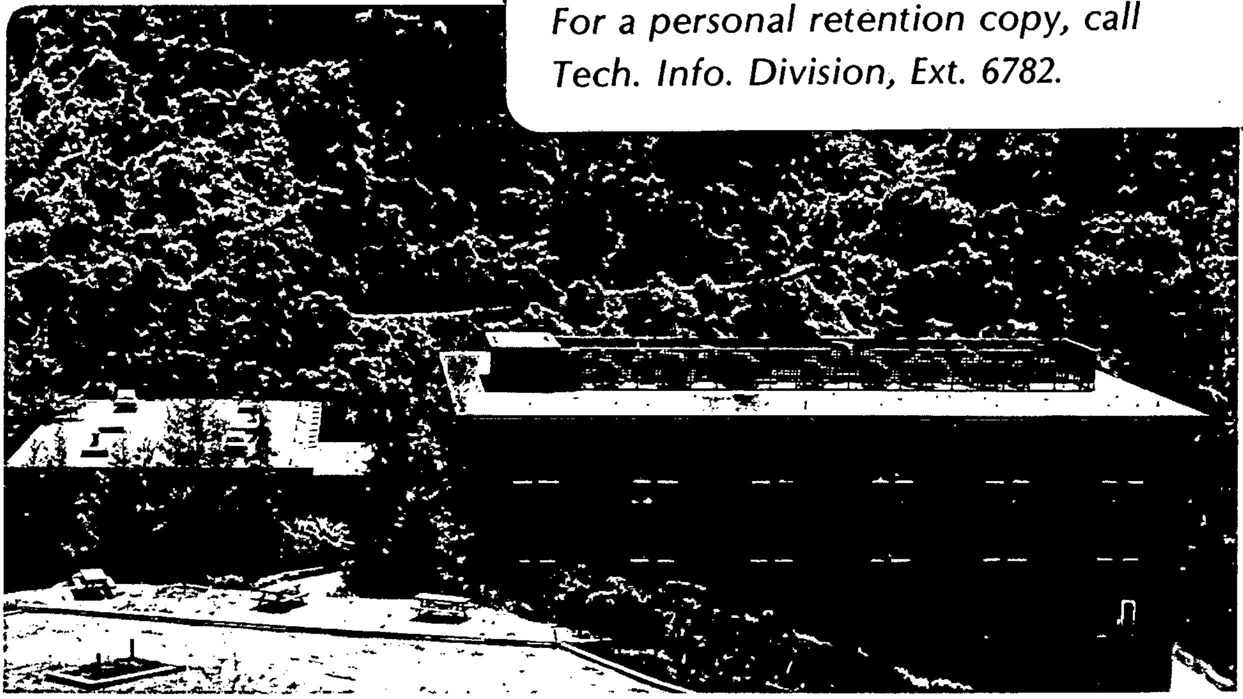

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IMPROVED FABRICATION TECHNIQUES FOR INFRARED BOLOMETERS

A. E. Lange, E. Kreysa,[†] S. E. McBride, and P. L. Richards

Department of Physics, University of California;
and Materials and Molecular Research Division,
Lawrence Berkeley Laboratory, Berkeley, CA 94720

and

E. E. Haller

Department of Materials Science, University of California;
and Materials and Molecular Research Division,
Lawrence Berkeley Laboratory, Berkeley, CA 94720

[†] Permanent address: Max-Planck-Institut für Radioastronomie,
D-5300 Bonn 1, West Germany

Abstract

Techniques are described for producing improved infrared bolometers from doped germanium. Ion implantation and sputter metalization have been used to make ohmic electrical contacts to Ge:Ga chips. This method results in a high yield of small monolithic bolometers with very little low-frequency noise. When one of these chips is used as the thermometric element of a composite bolometer, it must be bonded to a dielectric substrate. The thermal resistance of the conventional epoxy bond has been measured and found to be undesirably large. A procedure for soldering the chip to a metalized portion of the substrate is described which reduced this resistance. The contribution of the metal film absorber to the heat capacity of a composite bolometer has been measured. The heat capacity of a NiCr absorber at 1.3K can dominate the bolometer performance. A Bi absorber has significantly lower heat capacity. A low-temperature blackbody calibrator has been built to measure the optical responsivity of bolometers. A composite bolometer system with a throughput of $\sim$0.1 sr cm^2 has been constructed using our new techniques. In negligible background it has an optical NEP of 3.6 10^{-15} W/$\sqrt{\text{Hz}}$ at 1.0K with a time constant of 20 ms. The noise in this bolometer is white above 2.5 Hz and is somewhat below the value predicted by thermodynamic equilibrium theory. It is in agreement with calculations based on a recent nonequilibrium theory.

Introduction

Low-temperature semiconductor bolometers are commonly used as detectors of mid- and far-infrared radiation. They have high sensitivity, are easy to use, and are adaptable to a wide variety of experimental conditions. The bolometers constructed at Berkeley use germanium doped with gallium (Ge:Ga) and compensated with unknown shallow donors as the thermometric element. In applications where a large throughput is desired a composite structure is used.

The thermometric element is glued to a sapphire substrate with an absorbing metal film on one side [1]. This provides a large increase in absorbing area with only a modest increase in heat capacity. The surface resistance of the metal film is chosen to be $\sim 190\ \Omega/\Box$. Theory predicts that radiation incident from the sapphire side of the sapphire-metal interface should be absorbed with 50% efficiency, independent of frequency. This behavior has been verified experimentally [2].

Electrical NEPs as low as $3 \cdot 10^{-15}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ have been reported for ^{4}He temperature bolometers constructed in this manner [1]. However, there have been circumstances under which the performance of these bolometers has fallen far short of expectations. Excess, current dependent noise, thought to be associated with the contacts to the Ge thermometer, often dominates fundamental noise sources, especially at low frequencies. In addition, the optical efficiency of the composite bolometers occasionally appeared to be much less than the predicted 50%. The absorptivity of the metal film itself has been questioned, as well as the thermal conductivity of the epoxy bond between the sapphire substrate and the Ge thermometer. Although little has been published, these concerns about composite bolometers have been widely circulated and believed in the infrared community.

We have investigated and resolved each of these issues. In this paper, we describe new techniques for constructing composite bolometers that greatly reduce the excess noise and improve the thermal link between the thermometer and the substrate. The optical efficiency of the bolometer system has been measured directly using a low temperature blackbody source, and agrees with predicted values. The presence of small amounts of helium exchange gas has been identified as a likely cause of poor performance of some bolometer systems. Bolometers produced using our new techniques consistently approach the ideal limits of performance.

Bolometer Noise

Doped semiconductor bolometers have long been observed to exhibit an excess current-dependent noise voltage which often seriously degrades their performance. Although not fully understood, the excess noise often appears to be associated with the electrical contacts to the semiconductor material. In the Ge:Ga composite bolometers developed at Berkeley [1], the contacts were formed by soldering leads to the etched germanium chip using pure indium and a flux containing zinc-chloride. Similar techniques have been traditionally used by others to produce both monolithic and composite bolometers [3]. Our bolometers produced by this method exhibit a contact noise of the form $V_n^2 = NI^2R^2/\omega$ where N is a dimensionless number $\lesssim 10^{-11}$; I is the bolometer current, and R its resistance.

In order to appreciate the effect of this noise source on the bolometer's performance, we examine the expression for the electrical noise equivalent power (NEP_E). The NEP_E is the product of the optical NEP and the optical absorptivity ε. It is the amount of power which must be absorbed in the bolometer to yield a signal to noise ratio of unity, and thus provides a measure of the bolometer's performance which is independent of the optical coupling to the bolometer. The NEP_E for a bolometer operating at temperature T with voltage responsivity S can be written [4] in the form:

$$(NEP_E)^2 = 2kT_B \varepsilon P_B + 4kT^2G + \frac{4kTR}{S^2} + \frac{4kT_LR_L}{S^2}\left(\frac{R}{R_L + R}\right)^2 + \frac{NI^2R^2}{\omega S^2}$$
$$+ \text{(amplifier noise terms)} \qquad (1)$$

These contributions to the NEP_E are, respectively, the fluctuations in the background power P_B from a Rayleigh-Jeans source at temperature $T_B \gg T$, phonon noise arising from fluctuations in the transport of energy through the thermal conductance G, Johnson noise in the thermometer resistance R, and load resistance R_L, and the excess noise term. A bolometer for which the first term in (1) dominates the NEP_E can be referred to as ideal, because further improvements in the bolometer's performance would not yield a higher signal to noise ratio.

Figure 1 shows the contribution to the NEP_E due to background fluctuations, and also the contribution due to all other terms in Eq. (1) as a function of background loading in the limit of wave statistics. The curves were calculated [1] using parameters typical of a composite bolometer operated at 1.2K. The solid curves include the excess noise term with $N \approx 10^{-11}$, while the dashed curves are plotted for N = 0. As the curves show, the excess noise dominates the NEP_E for all values of P_B, its relative contribution becoming larger as P_B increases. This is because the optimized values of G and I_{bias} scale as P_B and $P_B^{1/2}$ respectively, while the responsivity scales as $S \propto I/G \propto P_B^{-1/2}$. Thus, the phonon and Johnson noise scale as $P_B^{1/2}$ while the excess noise scales as P_B.

Ion-Implanted Contacts

In an effort to increase the yield of bolometers that will perform well, particularly at high backgrounds, we have investigated the use of ion-implanted electrical contacts to the germanium chips. A process involving the implantation of boron ions has been shown to produce low noise contacts on Ge:Ga photoconductors [5]. Related techniques have been used to implant low noise thermometers in silicon bolometers [6]. We have applied the boron implantation techniques to the production of Ge:Ga thermometers and have obtained a high yield of thermometers which have very little current noise, even at high bias currents and low frequencies.

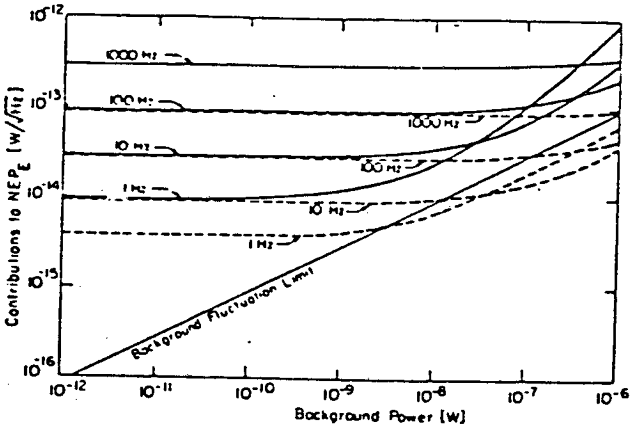

Fig. 1. Calculated contributions to the electrical NEP_E of a composite bolometer which has been optimized for varying amounts of absorbed Rayleigh-Jeans background power. The straight line is the background fluctuation contribution, and the curved lines are the contributions from all other terms in Eq. (1) at four different modulation frequencies. The solid lines include the excess noise term with $N = 8.8 \times 10^{-12}$. The dashed lines show the performance that could be achieved with $N = 0$.

A typical contact fabrication procedure begins with a 330 μm thick slice from a boule of Ge:Ga which has long been used at Berkeley for He^4 temperature bolometers. Boron ion implantation is used to produce a thin, degenerately doped p^+-layer on both sides of the Ge:Ga slice. Both faces of the slice are lapped with 1900 mesh aluminum slurry, and then etched in a 4:1 HNO_3:HF mixture for one minute. The etching process is rapidly stopped by quenching with a large quantity of electronic grade methanol. Rinsing with methanol, soaking in 1% HF in H_2O for five minutes to remove oxides, and blowing dry with a nitrogen jet completes the pre-implantation steps. The two surfaces to be implanted are now shiny and free of damage. The implantation schedule consisted of two implants for each surface. Singly ionized boron ions with energies of 25 keV and 50 keV are implanted in random orientation with doses of 10^{14} cm^{-2} and 2×10^{14} cm^{-2} respectively. A simple annealing cycle in a nitrogen atmosphere (heating from room temperature to 250°C in a few minutes, holding at this temperature for 30 to 60 min. and cooling to room temperature slowly over more than 30 min.) activates more than 90 percent of the boron atoms. Etching of the two implanted surfaces with 5% NaOCl in H_2O for five seconds is followed by sputtering of a 400Å thick Ti and then an 8000Å Au layer on each contact face. The metal layers are annealed at 200°C for one-half hour in a nitrogen atmosphere to reduce the built-in stress.

The implanted and metalized slice of germanium is cut into cubic chips using a wire saw. The chips are etched in 5:1 (HNO_3:HF). The progress of the etching can be observed by watching the metalized side of the chip through a low power microscope. As germanium is removed, the free-standing gold-titanium film bends toward the gold side to relieve residual internal stress. Thus, the point of attack of the etch at the germanium-titanium interface is clearly defined. No significant undercutting of the metal film has been observed. Even starting with a roughly cut chip, a polished germanium surface is produced very quickly. Etching is terminated by quenching with electronic grade methanol. After rinsing several times with methanol, the chip is left to dry on a filter paper. In the next step the free-standing Au-Ti film is removed by pressing gently with a wooden stick along the sharp edges of the Ge chip. A neat and easy separation of the metal film from the edge of the chip is achieved this way. Finally, bolometer wires are soldered to the gold surfaces with indium, using a resin flux obtained from the core of commercial solder.

Composite bolometers with contacts made in this way were tested in a dark cavity, at a bath temperature of 1.0K. The noise was measured by a digital computer which sampled the voltage across the bolometer at discrete intervals and computed the spectral amplitude of the noise voltage.

Fig. 2 shows noise spectra of a high background ($P_B = 100$ nw) composite bolometer for a variety of bias currents. The sharp features are due to mechanical resonances that are sometimes present in our high background bolometers. The contributions to the noise due to phonon and Johnson noise (the second and third terms in Eq. 1) have been calculated at each of the bias currents and are indicated by dashed lines. With the exception of the mechanical resonances, there is little or no excess noise above 3 Hz. Below 3 Hz, the excess noise rises steeply, no longer obeying the simple form $V_n^2 \alpha I^2R^2/\omega$. At 2 Hz it is still an order of magnitude less than that reported by Nishioka et al. Similar results for a low background bolometer with essentially no microphonic noise are shown in Fig. 7.

In conjunction with the development of low noise contacts, we have developed a new method of bolometer construction which yields a stronger thermal link between the germanium thermometer and the sapphire substrate.

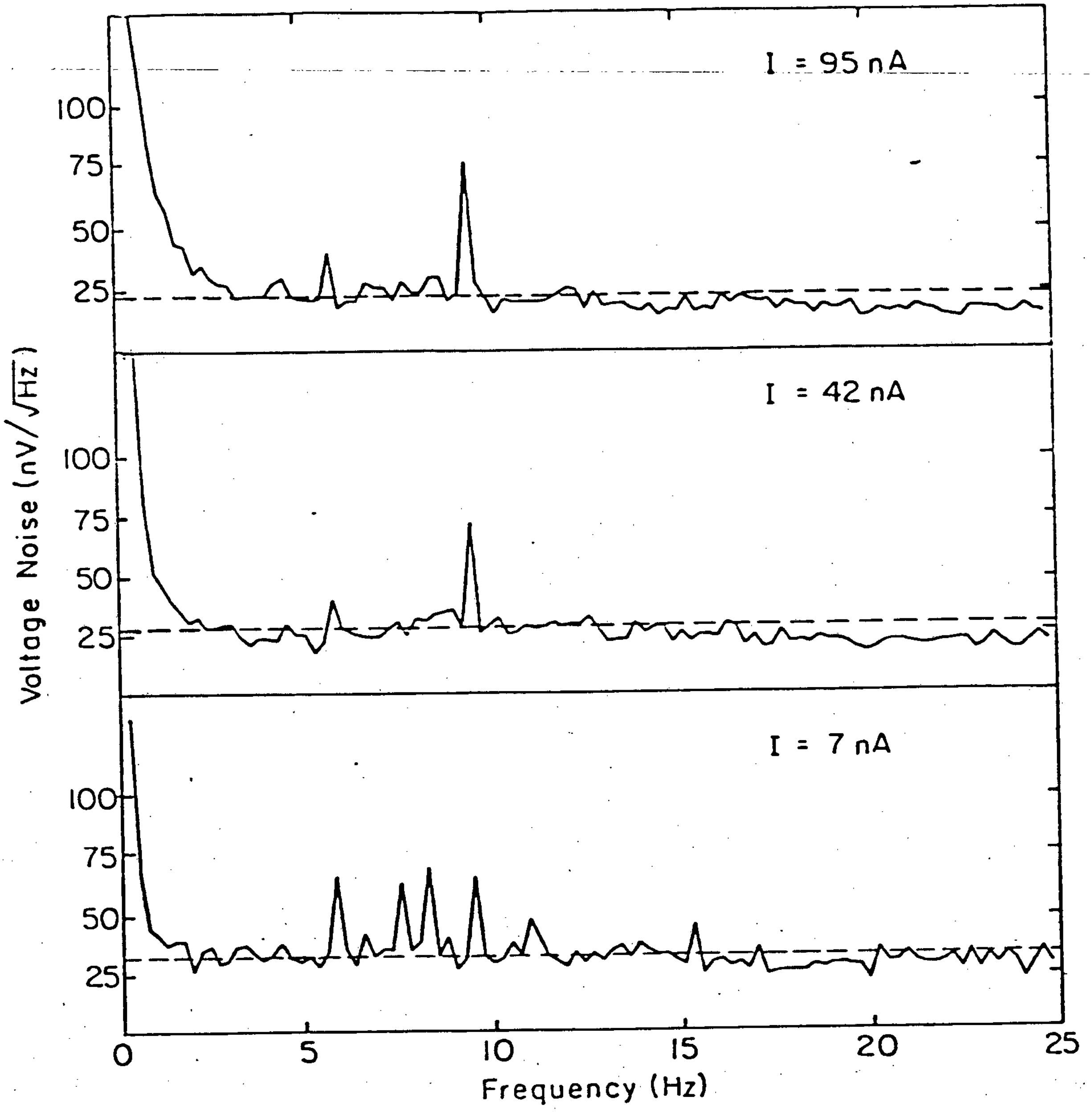

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Fig. 2. Noise spectra of a high background composite bolometer with ion-implanted contacts. The sharp spikes are due to mechanical resonances in the bolometer and its leads. The dashed lines indicate the estimated fundamental noise $V_n^2 = 4kT^2G|S|^2 + 4kTR$. This white noise level decreases with increasing bias current in the way expected from the decreasing bolometer impedance. Current-dependent excess noise is apparent, rising steeply below 3 Hz.

Previous methods of bolometer construction employed an epoxy bond. The relatively high heat capacity of epoxy limits the amount that can be used in making such bonds to $\sim 10^{-7}$ cm^3. Occasional discrepancies between calculated electrical responsivities and measured optical responsivities suggested that the thermal link provided by the epoxy was not always adequate and could be effectively shorted by the presence of very small amounts of exchange gas in the bolometer cavity.

In order to measure the thermal conductivity between the germanium thermometer and the sapphire substrate, we constructed a composite bolometer with two germanium thermometers attached with epoxy in the usual way [7] as is shown in Fig. 3(a). Each thermometer had one 50 μm copper lead with high thermal conductivity and one 25 μm manganin lead with low thermal conductivity. Attached to one of the high conductivity leads was a heater through which we could introduce a known amount of power. By measuring the temperature difference between the two thermometers as power flowed from one, through the sapphire, and into the other, we found the thermal conductance of the two Ge-epoxy-sapphire interfaces. For a typical bond made with $\sim 3 \cdot 10^{-7}$ cc of Stycast epoxy [7], with a heat capacity of $2 \cdot 10^{-10}\ T^3$ J/K, we measured a thermal conductance of $G \approx 1 \cdot 10^{-6}\ T^3$ W/K. This is considerably smaller than one would expect from the bulk properties of the material, but is consistent with measurements of the thermal boundary resistance across metal-dielectric interfaces [8]. For high background bolometers, where the conductance between the thermometer and the heat sink is typically $G \sim 10^{-5}$ W/K, the low conductance of the epoxy bond leads to increased time constants or, if small quantities of exchange gas are present, discrepancies between calculated electrical and measured optical responsivities, as is illustrated in Fig. 4.

The new method of construction, shown in Fig. 5, eliminates the use of epoxy altogether. A small area of the substrate is first coated with

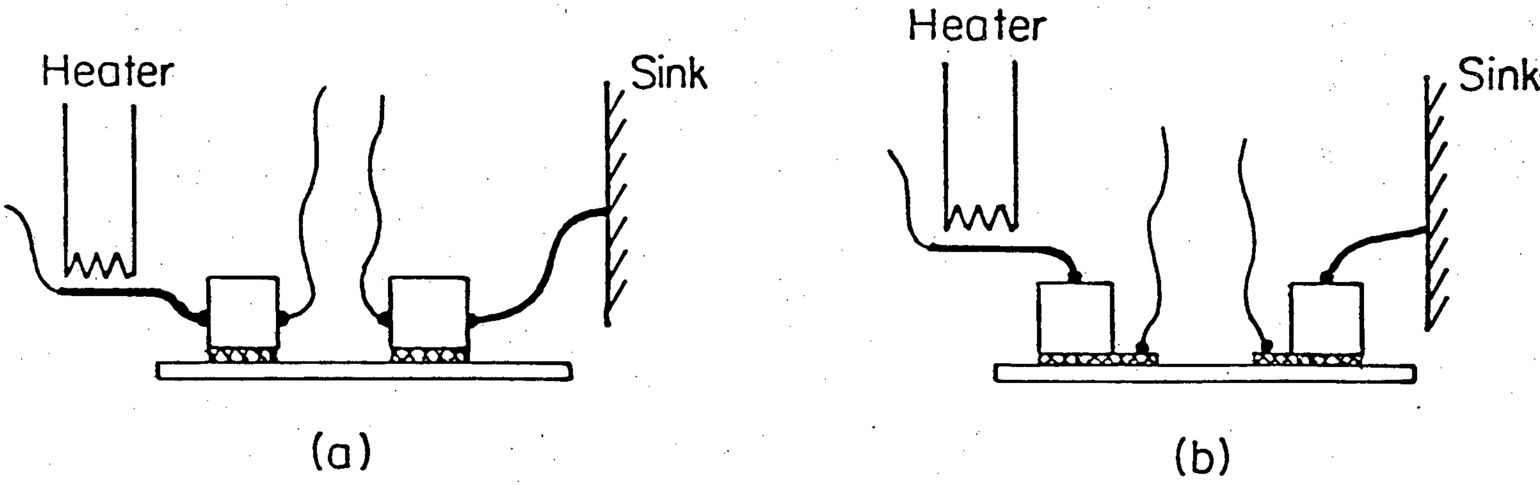

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Fig. 3. Configurations used to measure the thermal conductance G_B of the bond between the thermometer and the substrate of a composite bolometer, (a) with epoxy bond, and (b) with solder bond. Low thermal conductance manganin leads are shown as thin lines, high conductance copper leads as thick lines.

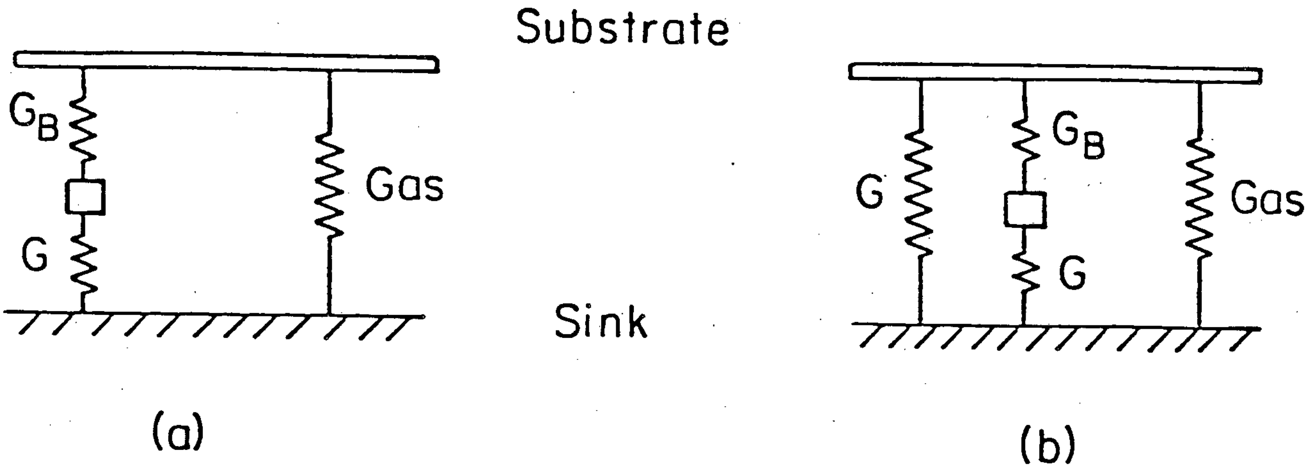

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Fig. 4. The thermal circuits for composite bolometers with the conventional epoxy bond (a) and with the solder bond (b). If the thermal conductance G_B of the bond is too small, then the presence of a thermal shunt due to unwanted He exchange gas can seriously degrade the optical sensitivity of a bolometer whose electrical properties appear quite satisfactory.

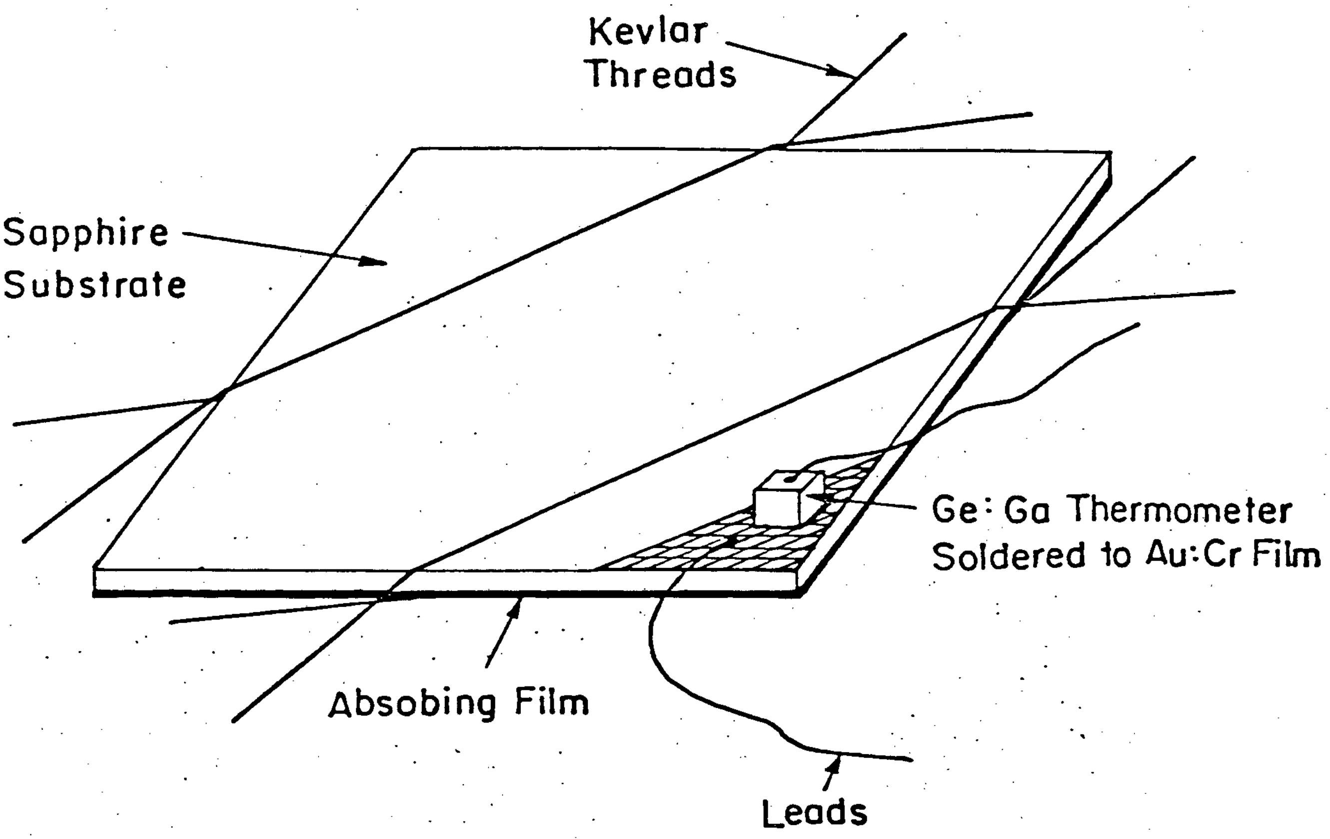

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Fig. 5. Schematic diagram of a composite bolometer. The doped Ge thermometer is soldered to a metalized portion of the sapphire substrate.

∿100Å of chromium followed by 1000Å of gold. The germanium chip is indium soldered directly to the gold film. A small flake of indium is pressed onto the gold film and the Ge chip is placed on top. The entire substrate is then heated briefly by an electrical strip heater with a short (∿0.5 s) time constant. A small amount of pressure applied to the Ge chip during heating results in a thin, uniform contact between the chip and substrate. Leads are then indium soldered using resin flux to the exposed contact on the Ge chip and to the gold film to complete the electrical circuit. The controlled temperatures and the short duration of heating used result in contacts which are mechanically sturdy and consistently low in noise.

The thermal conductance of the indium bond between thermometer and sapphire was measured using the same technique described above. For a bond made with $\sim 3 \cdot 10^{-7}$ cm^3 of indium, with a heat capacity of $4 \cdot 10^{-11} T^3$ J/K, the thermal resistance was measured to be $G = 2 \cdot 10^{-5}\ T^2$ W/K. The solder bond both reduces heat capacity and increases the thermal conductance by one order of magnitude.

Absorbing Element

Composite bolometers produced previously in Berkeley used a bismuth film of about 200Ω/□ as an absorbing layer on the sapphire substrates. While this technique was generally satisfactory, reports of problems with bismuth led us to look for better alternative materials for the absorbing film. The evaporated bismuth film is rather fragile. It was necessary to do the evaporation as the last step in the bolometer fabrication in order to avoid damage to the film. Also, some workers have reported that bismuth undergoes slow chemical changes on exposure to the atmosphere.

Because of these disadvantages, we have investigated the use of nichrome as the material for the absorbing film. An extensive literature exists which describes the use of this material for thin film resistors [9]. We adopted a deposition technique which involves the sublimation of the alloy from the solid state [10]. A 1.3 mm diameter nichrome wire (80:20 Ni:Cr) was bent into a circle and was suspended in a horizontal plane. The distance from the circle to the base plate was equal to its radius. This ring source geometry, which is described by Holland [11], produces a uniform deposition on substrates placed on the base plate within the nichrome ring. The nichrome ring was heated by current to just below the temperature at which it began to sag. Due to the higher evaporation rate of chromium, it is necessary to age the source for a few hours until equilibrium is reached between the preferential evaporation of chromium from the surface and the diffusion of chromium from deeper layers [12]. After aging the nichrome wire once, it can be used for many depositions. Once equilibrium is reached, the alloy should be deposited with the original composition which was 80:20 Ni:Cr. Sublimation downward from the ring-source has the advantages of coating many substrates in one operation and avoiding the problem of supporting the very thin substrates in a downward-looking configuration. The substrates were placed on a glass cloth to thermally insulate them from the base-plate so that their temperature rose during coating, as is recommended for nichrome [12]. Finally, the films were heated in air at 300 C for 3 hours to improve adhesion [13]. Resistances values around 200Ω/□ were obtained without difficulty in about five minutes of evaporation. The resistance decreased by ∿4 percent when the film was cooled to 1.2K. Changes of this magnitude are not important for the optical properties of the film [2].

The nichrome films are mechanically very tough and may, therefore, be preferable to bismuth films in many applications. The films that we have prepared, however, show an undesirably large heat capacity. A nichrome film with an area of 4 mm^2 and a surface resistance of 200Ω/□ was measured to have a heat capacity of $3 \cdot 10^{-9}$ J/K at 1.3K. This is twice that of the rest of the bolometer, and thus seriously compromises the bolometers performance in the low-background limit. A bismuth film of the same area and surface resistance has a heat capacity of $3 \cdot 10^{-10}$ J/K, an order of magnitude less than the nichrome film.

Because of its low heat capacity, we continue to use bismuth films in our low-background ($P \lesssim 3 \cdot 10^{-8}$ W) bolometers. Resistance measurements on bismuth films stored in air for several years have not revealed any sign of deterioration. We have found, however, that composite bolometers which undergo a bismuth evaporation as the last step in the construction process consistently show a marked increase in low-frequency noise. Although the thermometric element is in the shadow of the sapphire substrate during the evaporation, we speculate that a very thin layer of bismuth forms an alternate conduction path on the surface of the Ga:Ge chip. Because of the increase in noise associated with the bismuth evaporation, we now attach the Ga:Ge thermometer to the sapphire substrate after the absorbing film has been deposited.

Optical Efficiency

A blackbody calibrator was constructed to directly measure the optical responsivity of our bolometers and thus to determine their optical efficiency. This calibrator, shown in Fig. 6, uses a blackbody cavity formed by casting an infrared absorbing epoxy [7] in a copper form. A heater and a calibrated thermometer are mounted on the copper form with the same epoxy. In order to minimize the size of the blackbody required to fill the aperture of the detector optics, the exit to the blackbody is a Winston light concentrator [14] with an aperture of f/1.5. This whole structure is separated from the bolometer vacuum by a 50 μm thick Mylar window. The bolometer itself is fed

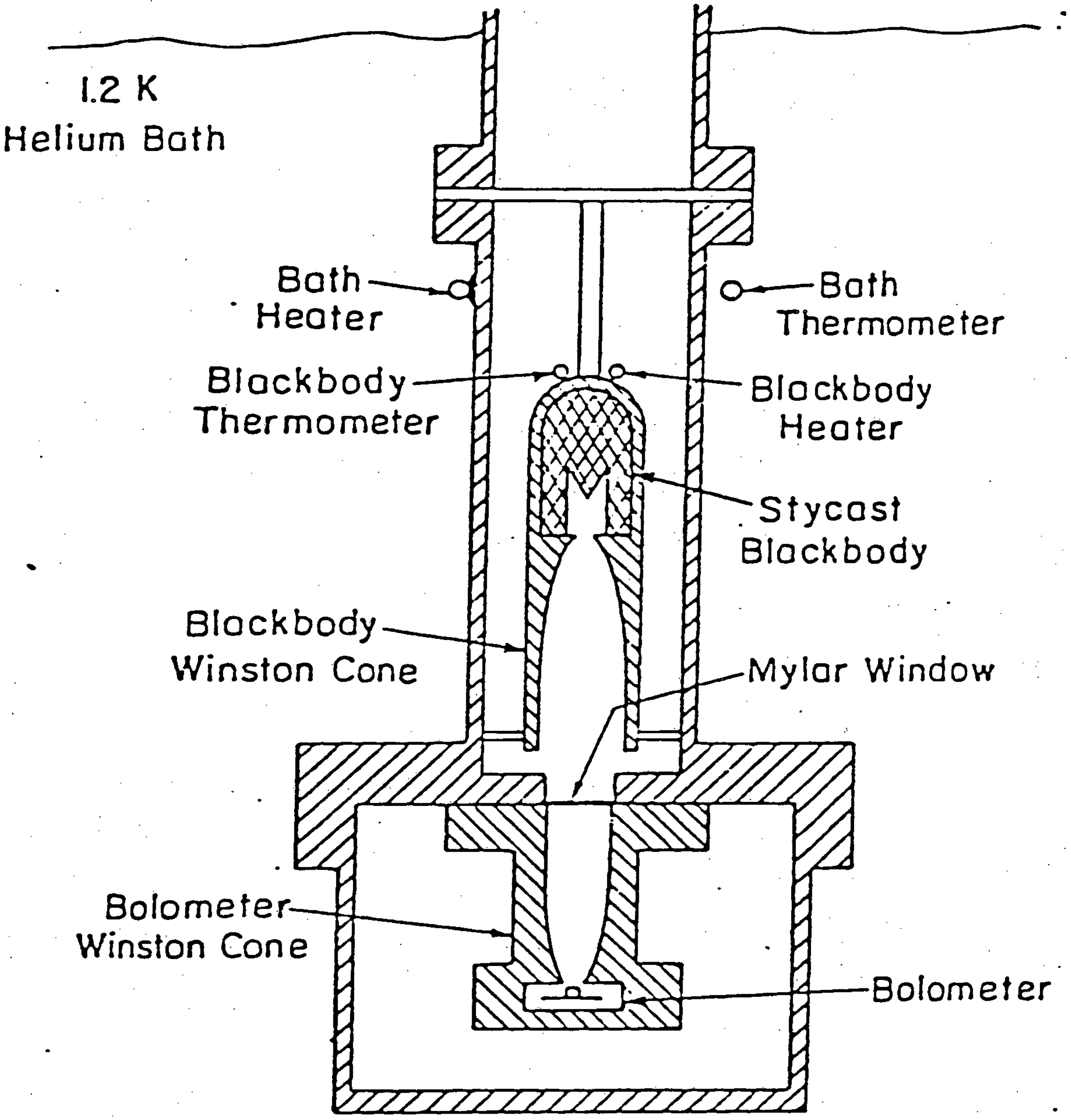

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Fig. 6. Low temperature blackbody calibrator used to measure the optical responsivity of detector systems. A detailed description is given in the text.

by a Winston light cone with an aperture of f/2. All rays entering the acceptance angle of the lower Winston cone come from inside the acceptance angle of the upper cone, and thus from the blackbody. The Winston concentrator closest to the bolometer determines the throughput of the system. The calibrator thus measures the total efficiency of the bolometer system, including the transmission of the window, the lower Winston concentrator, the absorbing film on the bolometer, and the cavity surrounding the bolometer.

In order to compare the optical power absorbed by the bolometer with the power expected from the blackbody, we must measure the bolometer's electrical responsivity. The conventional procedure is to compute this quantity from the measured I-V curve. This procedure is not reliable if the I-V curve contains significant nonlinearity at fixed temperature due to non-ohmic contacts. To avoid this problem, we attached low thermal conductance leads to the metal absorbing film of a composite bolometer so that a known quantity of power could be dissipated in a way that closely mimics the absorption of optical power. With our bolometers, the two methods agree within 20 percent. This effect of non-ohmic contacts has been important in the past, but it does not appear to be important with our new ion-implanted contacts.

The measurement procedure involved choosing a bias current for the bolometer and measuring the DC responsivity using the metal absorbing film to heat the substrate. The blackbody heater was then turned on and the system was allowed to come to equilibrium. The blackbody temperature, the bolometer voltage, and the bath temperature were recorded when equilibrium was reached. A rise in the bath temperature of order 0.1K typically occurred due to power dissipation in the blackbody heater. Power to the blackbody was removed and a heater in the bath was then adjusted until the bath was at the temperature previously measured with the blackbody hot. The power absorbed by the bolometer was computed from the difference in bolometer voltage divided by the responsivity measured with the metal film heater.

The total optical power expected to reach the bolometer was calculated by multiplying the spectral intensity of the blackbody radiation by the previously measured transmission of the cold Mylar window, and integrating to find the total flux. The bolometer system efficiency is then just the ratio of the power absorbed to this expected power.

A bolometer on which the metal film was painted with Nextel Velvet Black paint [15] was mounted with the painted surface facing the Winston concentrator and tested as described above. The optical efficiency of the bolometer system measured with a variety of blackbody temperatures between 25K and 45K was found to be 70± 5 percent. The paint was then removed and the bolometer was remounted with the metal film facing away from the entering radiation. The optical efficiency of this system was measured to be 44 ±4 percent.

The integrating cavity around the bolometer had larger than normal openings to accommodate the extra leads attached to the absorbing film. Because of this, the efficiency of the cavity used in these experiments was less than could normally be achieved. The measured efficiencies are thus somewhat less than the best that can be expected from an optimized cavity.

These measurements also point out the efficacy of black paint as an absorber in the 50 cm^{-1} to 100 cm^{-1} frequency range. Unfortunately, its heat capacity slows the response time of the bolometer to the extent that it cannot be used to obtain high sensitivity, low background bolometers.

Summary

The dominant source of excess noise in our germanium bolometers is connected with the contacts to the Ge and can be greatly reduced by the use of ion-implanted contacts.

The large absorbing area of composite bolometers makes them exceptionally vulnerable to He exchange gas. Pressures as low as 10^{-5} Torr measured at 295K begin to degrade the performance of our low-background bolometers. For this reason, the use of a charcoal pump in the bolometer vacuum space is highly recommended. If the thermal link between the substrate and the thermometer is not good, the presence of exchange gas will not affect the electrical responsivity, but will degrade the optical efficiency. Our new method of construction improves the thermal link between substrate and thermometer by over an order of magnitude, while contributing one order of magnitude less heat capacity than on the epoxy bond previously used.

Using these new techniques, we have been able to significantly improve the performance of low-background bolometers. Table I lists the design and performance parameters for a well characterized low-background bolometer. The noise spectrum for this bolometer at its optimum bias point is shown in Fig. 7. The electrical NEP is $1.6 \pm 0.3 \times 10^{-15}$ $W/\sqrt{Hz}$, for modulation frequencies as low as 2 Hz. The calculated value for the electrical NEP given by the Johnson and phonon terms in Eq. (1) is 2.1×10^{-15} $W/\sqrt{Hz}$. A more detailed analysis of bolometer noise has been given by Mather [16] which takes into account the electrothermal feedback in the bolometer and the distributed nature of the thermal link to the heat sink. These effects lead to reductions in the Johnson and phonon noise,

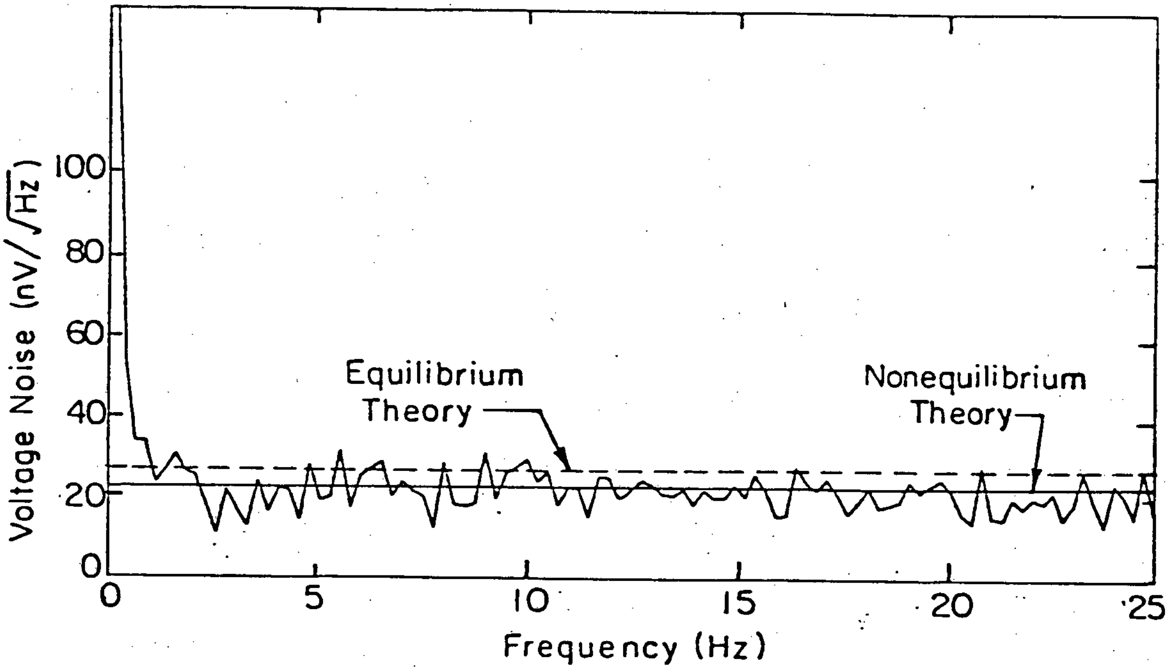

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Fig. 7. Noise spectrum of a low-background composite bolometer at its optimum bias point. The dashed line indicates the noise level $V_n^2 = 4kT^2G|S|^2 + 4kTR$ expected from thermal equilibrium bolometer theory. The solid line indicates the noise level predicted by a non-equilibrium treatment of bolometer noise. The detailed characteristics of the bolometer are listed in Table I.

TABLE I

Characteristics of a Low-Background Composite Bolometer

Estimated Heat Capacities	
$0.4 \times 0.4 \times .0025$ cm sapphire:	$1.6 \times 10^{-10}\ T^3$ J/K
$0.025 \times 0.025 \times 0.3$ cm Ga:Ge:	$0.7 \times 10^{-10}\ T^3$ J/K
1×10^{-6} cm^3 In solder:	$1.2 \times 10^{-10}\ T^3$ J/K
$0.4 \times 0.4 \times 10^{-5}$ cm Bi film:	$2.5 \times 10^{-10}\ T$ J/K
2×10^{-7} cm^3 Au film:	$0.3 \times 10^{-10}\ T$ J/K
0.6 cm x .00125 cm brass leads:	$\underline{0.9 \times 10^{-10}\ T\ \text{J/K}}$
	$(3.5\ T^3 + 3.7\ T) \times 10^{-10}$ J/K
Bolometer resistance:	$R_{(T)} = 616\ e^{9.43/T}$
Load resistance:	$R_L = 1 \times 10^7$
Temperature of heat sink and load resistor	0.97K
Bolometer temperature	1.00K
Thermal conductance to heat sink	3.1×10^{-8} (W/K)
Bias current	1.0×10^{-8} A
Measured electrical responsivity	1.3×10^7 V/W
Calculated NEP_E (nonequilibrium theory)	1.7×10^{-15} W/ Hz
Measured NEP_E	1.6×10^{-15} W/ Hz
Calculated time constant	17 ms
Measured time constant	20 ms

respectively. Applying these results to our bolometer yields a prediction of $NEP_E = 1.7 \times 10^{-15}$, in close agreement with our measured value of NEP_E.

Combining the measured value of electrical NEP with the measured value for the optical efficiency, we find the optical NEP for this bolometer system, including concentrator and cavity, to be 3.6×10^{-15} W/$\sqrt{Hz}$.

Acknowledgments

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