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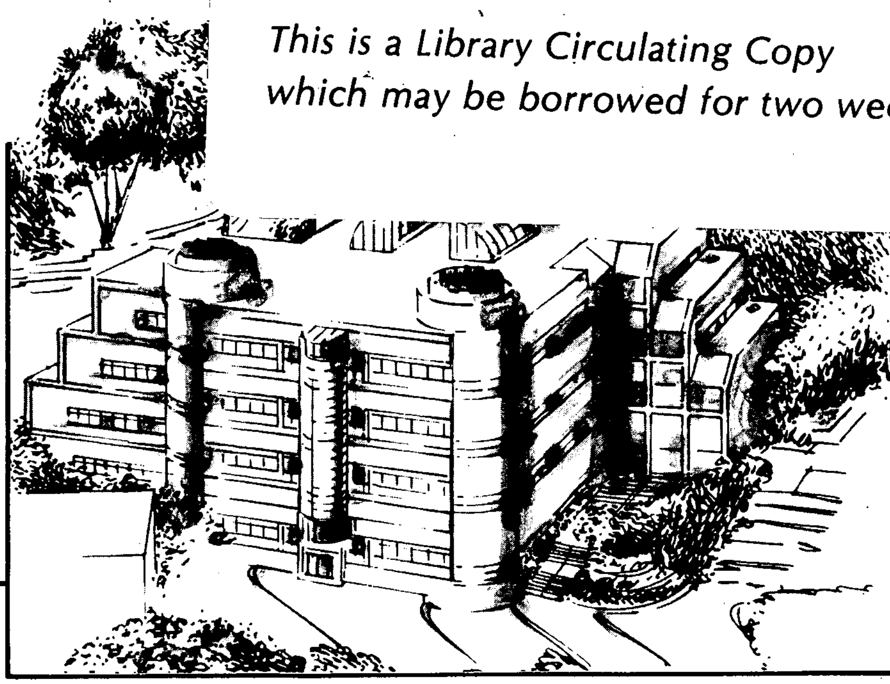

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THE HIGH T_c SUPERCONDUCTING BOLOMETER

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Abstract

A description is given of the optimization of a bolometric infrared detector which uses the resistive transition of a high T_c film as the thermometer. The performance of a LN cooled far infrared bolometer operated with a cooled low-pass filter is computed for the ideal case of a noise-free readout. The theory is then extended to include various contributions to the readout noise. Measurements are presented of the low frequency noise near T_c in current biased films of $ErBa_2Cu_3O_7$, which show that useful performance can be achieved. Comparisons are made with other infrared detection technologies which show that practical high T_c bolometers will be especially useful for wavelengths longer than the ~20 μm cutoff of LN cooled photovoltaic detectors. Potential applications include far infrared laboratory spectroscopy and passively cooled space observations of bright sources such as the earth.

I. Introduction

A bolometric detector consists of a radiation absorber, an electrical resistance thermometer and a thermal conductance to a heat sink. Bolometric detectors with a wide range of sensitivities are used from visible light wavelengths to microwaves for sensitive direct detection and for absolute power measurements. Bolometers are also used to detect phonons, and X rays, and to search for unknown particles that are candidates for the dark matter in the universe.

Superconducting bolometers have long been considered for applications to sensitive infrared detection. Although excellent performance has been achieved,[1] they are more complicated than bolometers with comparable performance which use doped semiconductor thermometers.[2] Consequently, they have rarely been used in practical applications.

The discovery of high T_c superconductors raises the question of whether there are practical applications for superconducting bolometers operating in the ~100 K temperature range. For wavelengths shorter than 20 μm, LN cooled photovoltaic detectors such as HgCdTe are widely used. For longer wavelengths, however, There is no satisfactory cooled detector technology above LHe temperatures. Room temperature thermal detectors such as the Golay cell or the pyroelectric detector are used in applications where LN would be acceptable. As we will show, the high T_c bolometer can be more sensitive at long wavelengths than these room temperature thermal detectors. It therefore appears to have an important range of applications.

In Section II of this paper we present a design analysis of a high T_c bolometer. Numerical estimates are given for a far infrared bolometer which uses a heat sink temperature of 77 K. Section III presents the preliminary results of an experimental study of voltage noise in narrow strips of the high T_c superconductor $ErBa_2Cu_3O_7$. The constraints of practical bolometer designs and the implications of the measured noise for bolometer performance are discussed in Section IV.

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II. Bolometer Theory

A far infrared high T_c bolometer which views the room at T_B = 300K through a cooled low pass filter with cutoff at $x_c = h\nu_c/kT_B$ and throughput AΩ will see a steady infrared power,

$$P_o = \frac{2k^4T_B^4 A\Omega}{c^2h^3} \int_0^{x_c} \frac{t^3dt}{e^t-1} \quad . \qquad (1)$$

The thermal conductance G to the heat sink at T_0 must be large enough to keep the bolometer near the midpoint of the resistive transition, so $G = P_0/(T_c-T_0)$. In practice this condition will be met by adjusting T_0 to some temperature $77K<T_0<T_c$. The saturation power for the bolometer will be $P_s = G\delta T = P_0\delta T/(T_c-T_0)$, which gives adequate dynamic range for most applications. The constant bias current will dissipate an electrical power $P = I^2R$, where $R=R_N/2$ is the resistance at the midpoint of the transition. Since the resistance of the bolometer increases with T, the current-biased bolometer is unstable. It will be shown below that the condition for thermal stability is equivalent to the condition that the temperature rise due to bias heating is small compared with the width δT of the resistive transition.

Once the cryogen, the operating temperature T_c and the cutoff frequency are chosen, limits to the performance of an ideal thermal detector with a noise-free readout can be computed. Assuming that the radiation absorber on the bolometer is black, and the optical system is perfectly efficient, the contribution from photon noise to the noise equivalent power (NEP) per unit bandwidth is

$$NEP_{phot} = \left| \frac{4k^5T_B^5 A\Omega}{c^2h^3} \int_0^{x_c} \frac{t^4e^tdt}{(e^t-1)^2} \right|^{1/2} \quad . \qquad (2)$$

Given a thermal conductance G, the thermal fluctuation, or phonon, noise contributes a term of the form

$$NEP_{phon} = [4kT^2G]^{1/2} \qquad (3)$$

to the NEP. Equations (1-3) have been plotted as a function of ν_c in Fig. 1 for the case $A\Omega = 10^{-2}$ sr cm² and $T_c-T_0=10K$. The noise is dominated by phonon noise unless a larger value of T_c-T_0 is used. This would require a cryogen temperature below that of LN, or a T_c above 90 K.

The NEP of an ideal thermal detector obtained by summing the values of $(NEP)^2$ from the statistically independent sources (2) and (3) is also shown in Fig. 1. The computed values of $NEP_{(ideal)} = 0.3\text{-}3\times10^{-12}$ $WHz^{-1/2}$, which depend on the value of ν_c chosen, are very favorable when compared with the typical $NEP = 5\times10^{-10} WHz^{-1/2}$ for a commercial pyroelectric detector with relatively slow response and high sensitivity.[3]

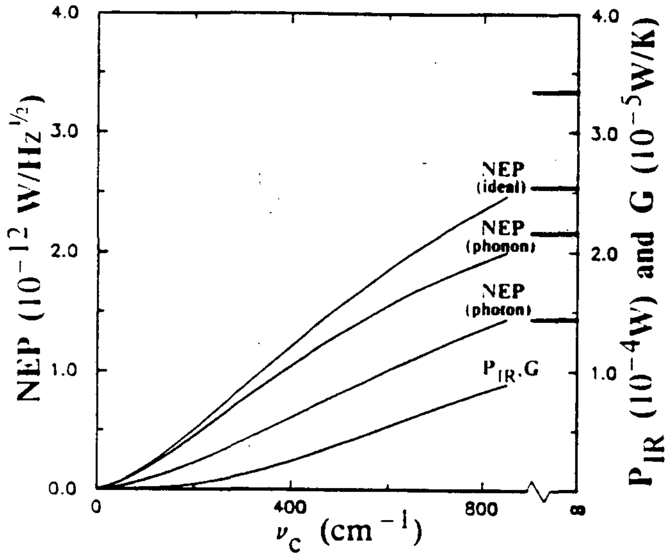

Figure 1. Infrared power loading P_{IR} and thermal conductance G for an ideal thermal infrared detector plotted as a function of the cutoff frequency ν_c of the cold low-pass filter. The detector is assumed to view 300 K background radiation with a throughput $A\Omega = 10^{-2} sr cm^2$ and perfect optical efficiency and to operate 10 K above the heat sink temperature. The NEP of the ideal detector is shown along with the separate contributions from phonon noise and photon noise. Asymptotic values for $\nu_c = \infty$ are shown as tics at the right margin.

Two additional requirements must be met before a successful high T_c bolometer can be constructed. A temperature readout must be designed which contributes little additional noise to that shown in Fig. 1. Also, a bolometer structure must be devised with sufficiently low heat capacity C that a useful response speed is obtained. To understand the trade-off between these quantities, it is first necessary to compute the bolometer responsivity. The voltage responsivity, the rate of change of output voltage with incident infrared power for a current biased bolometer, can be obtained from arguments based on the conservation of energy. It is often written in the form

$$S = \frac{IR\alpha}{G_{eff}(1+i\omega\tau_{eff})} , \tag{4}$$

where $\alpha = d(\ln R)/dT$, $G_{eff} = G - I^2R\alpha$, $\tau_{eff} = C/G_{eff}$ and ω is the modulation frequency of the infrared signal. For a superconducting bolometer we can write $\alpha = (\delta T)^{-1}$, the inverse of the transition width. Thermal runaway of the bolometer occurs for bias currents such that $G_{eff} \le 0$. We choose a bias power $I^2R = aG\delta T$ with $a = 0.3$, to insure stable operation. Then $G_{eff} = G$, so

$$S = \frac{IR}{G\delta T(1+i\omega\tau)} = \frac{(aR/G\delta T)^{1/2}}{(1+i\omega\tau)} . \tag{5}$$

The contribution to the NEP from Johnson noise in the thermometer is

$$NEP_{John} = \frac{b[4kTR]^{1/2}}{|S|} = b\left|\frac{4kT\delta TG(1+\omega^2\tau^2)}{a}\right|^{1/2} , \tag{6}$$

for b=1. This noise is independent of R, but increases with ω for frequencies above τ^{-1}. The additional factor b expresses the fact that the measured voltage noise near T_c in current biased films is larger than Johnson noise. Measurements are reported in Section III that give an upper limit for b.

The contribution to the NEP from voltage noise V_n in the amplifier is

$$NEP_{amp} = \frac{V_n}{|S|} = V_n\left|\frac{G\delta T(1+\omega^2\tau^2)}{aR}\right|^{1/2} . \tag{7}$$

For a readily achievable $V_n = 2nVHz^{-1/2}$, amplifier noise is less than Johnson noise for R>800Ω. If it is necessary to use films with smaller R, the effective V_n can be reduced by an AC bias on the bolometer and a transformer.[1]

Since the largest contributions to the noise in a high T_c bolometer are phonon noise from (3) and Johnson noise (or excess noise) from (6), the performance can be optimized by equating these terms. For our nominal values of T = 90 K, δT = 1 K and a = 0.3, the resulting expression gives $1 + \omega^2\tau^2 = Ta/\delta Tb^2 - 1 = 27/b^2$. For the ideal case of no extra noise, b=1, so the bolometer can be operated at $\omega\tau$=5. This eases the requirements on heat capacity. If the heat capacity can be made small enough that $\omega\tau$=1, then values of b up to 3 have no adverse effect.

III. Noise Measurements

The voltage noise near T_c in current-biased films of $ErBa_2Cu_3O_7$ has been measured in order to estimate the noise in the readout of the high T_c bolometer. The films were deposited on (100) $SrTiO_3$ by electron beam co-evaporation of metallic Er and Cu, and the salt BaF_2 using previously described methods.[4,5] The use of BaF_2 rather than metallic Ba favors the growth of films with the c-axis oriented perpendicular to the substrate. The films were post-annealed at 850°C for one hour in "wet" oxygen to remove the fluorine and to form the perovskite structure. The samples were cooled in dry oxygen over several hours. Films 3200 angstroms thick gave ~2 K wide resistive transitions at 90 K. X-ray diffraction showed them to be well crystallized and almost completely oriented with the c-axis perpendicular to the plane.

Conventional optical lithography with a 0.04 molar nitric acid etch was used to pattern the films into lines 10 and 20 μm wide and 2 mm long. The narrow lines were used to obtain noise voltages large enough to measure with a conventional FET amplifier. Current and potential pads at each end of the line were cleaned by ion milling a few hundred angstroms with argon and gold was evaporated to form low resistance contacts.

The patterned films were mounted on a variable-temperature stage attached to the cold plate of a LHe cryostat. The temperature of the stage had a time constant of about 1 min and was feedback-regulated using a Si diode thermometer. Bias currents from 1 to 500 μA were supplied from a battery. The noise was amplified by a conventional FET preamplifier, and measured with a digital spectrum analyzer. The bandwidth was limited by an active analog filter.

Preliminary measurements of voltage noise at 10 Hz for a 20 μm wide c-axis film of $ErBa_2Cu_3O_7$ with a 2 K wide resistive transition at 90 K and a normal resistance of 590 Ω are shown in Figs. 2 and 3. The measured noise shown in Fig. 2 is dominated by the 7 nV $Hz^{-1/2}$ noise in the measurement system at low temperatures. It rises rapidly above ~80 K and then flattens above T_c. The noise from the film increases with bias current and is significantly larger than Johnson noise, which is 1.2 nV $Hz^{-1/2}$ at the midpoint of the transition.

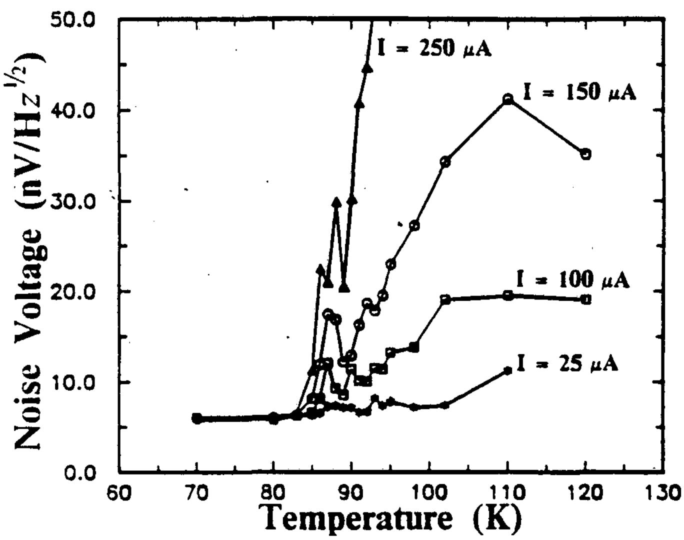

Figure 2. Voltage noise at 10 Hz as a function of temperature for a current biased 590 Ω film with a 2 K wide resistive transition at T_c = 90 K. The noise in the measuring system was 7 nV $Hz^{-1/2}$.

Of particular importance for bolometer performance is the noise near the resistive transition. This noise is plotted in Fig. 3 as a function of bias current. After the system noise is subtracted, the measured noise at the midpoint of the resistive transition is 5 times Johnson noise (excess noise parameter b = 5) for bias currents of 100 μA, and increases rapidly at higher currents. In this sample, 100 μA corresponds to a current density of 1.6×10^3A cm^{-2}. Low frequency (1/f) noise makes a small contribution to these measurements at 10 Hz. Measured noise voltages above 20 Hz were typically 10 percent smaller. The measured noise varied with film morphology and patterning. The noise was larger in a-axis and granular films. A 10 μm line etched from the same film reported above gave a factor 1.5 wider transition and a factor 2 larger voltage noise at the same current density. Because of this variability, our noise measurements only provide an upper limit on the noise from a high T_c thermometer.

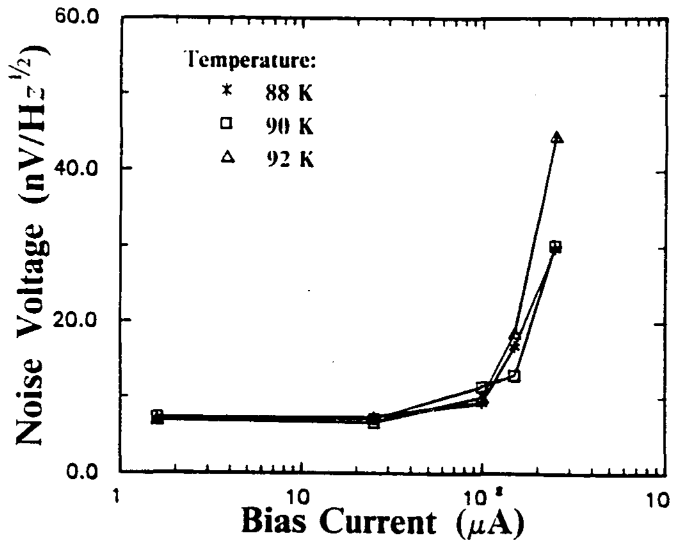

Figure 3. Voltage noise at 10 Hz as a function of bias current for a 590 Ω film at several temperatures near T_c = 90 K.

The importance of excess noise to bolometer operation depends on the bias current required. For $R=10^3\Omega$, so that amplifier noise is not a serious problem, then $I = (aG\delta T/R)^{1/2}$ varies from 20-70 μA, depending on the value of ν_c chosen. Consequently, the excess noise parameter defined in Section II is $b \lesssim 5$. It may well approach unity for better quality films.

IV. Bolometer Design

The major problem with the high T_c bolometer is to design a structure with sufficiently small heat capacity. The slowest conventional applications for thermal detectors require $\omega/2\pi$ = 10 Hz. Even for a thermometer with no excess noise, which can be operated at $\omega\tau=5$, the values of heat capacity required to obtain the ideal performance in Fig. 1 vary from 0.1 to 1 μJ/K. The dominant contribution to the heat capacity in straightforward bolometer designs come from the substrate. Other contributions, such as the high T_c film, metallic contacts, and metal film infrared absorber[2] can have contributions of order 0.1 μJ/K or less. Assuming a bolometer area of 1×1 mm^2, a 20 μm thick diamond substrate will have C = 1 μJ/K. The heat capacity per unit volume of the $SrTiO_3$ substrates traditionally used to produce high quality c-axis high T_c films is 20 times higher.

It seems possible, therefore, that a bolometer with C=10 μJ/K could be constructed on a chip of $SrTiO_3$. If it proves possible to produce low noise films on a diamond chip then C could be reduced to ~1 μJ/K. Monolithic[4] bolometer structures on submicron membranes such as silicon or boron nitride could approach 0.1 μJ/K. The analysis of Section II shows that in the absence of excess noise, these values of C correspond to NEP = 1×10^{-11}, 3×10^{-12} and 5×10^{-13} $WHz^{-1/2}$, respectively. These estimates are very favorable compared with typical values of $1\text{-}5\times10^{-10}$ $WHz^{-1/2}$ for commercial room temperature thermal detectors.

Acknowledgments

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[3] See, for example, the P-41 detector, Molectron Corp., Sunnyvale, California.

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