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Fabrication of an Infrared Bolometer with a High T_c Superconducting Thermometer*

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FABRICATION OF AN INFRARED BOLOMETER WITH A HIGH T_c SUPERCONDUCTING THERMOMETER

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ABSTRACT

A sensitive high T_c superconducting bolometer has been fabricated on a 20μm thick sapphire substrate with a YBCO thin film transition edge thermometer. Optical measurements with a He-Ne laser gave a noise equivalent power of $2.4 \cdot 10^{-11}$ W/Hz$^{1/2}$ at 10 Hz and a responsivity of 17 V/W in good agreement with electrical bolometer measurements. Gold black smoke was then deposited on the back side of the assembled bolometer as an absorber. Spectral measurements on a fourier transform spectrometer show that the bolometer has useful sensitivity from visible wavelengths to beyond ~100μm. This performance is clearly superior to that of a commercial room temperature pyroelectric detector. Some improvement appears possible.

INTRODUCTION

A bolometer consists of a radiation absorber and an electrical resistance thermometer coupled to a heat sink via a thermal conductance. Bolometers are used as sensitive detectors of electromagnetic radiation at wavelengths ranging from microwaves to X-rays. One type of thermometer consists of a superconducting film near the midpoint of its resistive transition[1]. Although such devices have excellent performance when operated in the liquid ^{4}He (LHe) temperature range, they are more complicated to use than doped semiconductor thermometers[2], and therefore are rarely used in practical applications.

The sensitivity of available infrared detectors that operate above liquid ^{4}He (LHe) temperatures decreases with increasing wavelength. For wavelengths $\leq 20\mu$m conventional liquid nitrogen-cooled (LN) photovoltaic infrared detectors such as HgCdTe are widely used. For longer wavelengths, however, there is no satisfactory cooled detector technology above LHe temperatures, and room temperature detectors such as Golay cells or pyroelectric detectors are used. A bolometer which uses the resistive transition of a high T_c superconductor can offer higher sensitivity at these longer wavelengths[3,4,5]. This paper describes the design, fabrication, and evaluation of such a bolometer based on epitaxial $YBa_2Cu_3O_7$ (YBCO) on a 20μm thick Al_2O_2 substrate with gold black as the radiation absorber.

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THEORY AND DESIGN

The minimum heat capacity C of a practical bolometer is limited by materials considerations. The minimum thermal conductance G to the heat sink is limited by the background power loading and by the required response time $\tau = C/G$. The responsivity for a signal modulated at angular frequency ω can be written as

$$S(\omega) = I\frac{dR(T)}{dT}|G+i\omega C|^{-1} = \frac{IR}{G\delta T(1+\omega^2\tau^2)^{1/2}}\ , \qquad (1)$$

where δT is half the width of the superconducting transition and R is the resistance at the operating point near the midpoint of the transition[3]. We neglect the effects of the positive thermal feedback from the current bias which reduces the thermal conductance to an effective value $G - I^2R/\delta T$. To maintain thermal stability we constrain the current by the condition $I^2R \leq 0.3G\delta T$.

The noise equivalent power (NEP) is calculated by summing the important sources of incoherent noise in quadrature.

$$NEP = \left[4kT_c^2G + \frac{4kT_cR}{|S|^2} + \frac{e_n^2+(i_nR)^2}{|S|^2} + \frac{V_{1/f}^2}{|S|^2}\right]^{\frac{1}{2}}\ . \qquad (2)$$

Ideally, the dominant contributions of a fully optimized bolometer are the first and second terms, which are phonon shot noise and Johnson noise respectively. Parameters for an optimized bolometer are determined by equating these two contributions. The contribution of the last two terms, amplifier noise and 1/f noise in the high T_c film respectively, should be negligible in a well engineered bolometer. A high T_c bolometer on a $1\times1\times0.02$ mm^3 Al_2O_3 substrate with $\delta T = 0.5$K and $\omega/2\pi = 10$Hz could have an NEP $\approx 10^{-11}$ W/Hz$^{1/2}$. For comparison, a pyroelectric detector[6] with the same area that is optimized for 10 Hz operation has NEP $\approx 1-5 \cdot 10^{-10}$ W/Hz$^{1/2}$.

CONSTRUCTION

We chose sapphire as a bolometer substrate for its high Debye temperature and mechanical strength. We made the first bolometers using c-axis films of YBCO grown directly on $\{\bar{1}012\}$ Al_2O_3 by laser ablation[7]. Although these films had sharp resistive transitions, they had excess noise at the transition edge when current biased. The best bolometer made from such films had NEP $\approx 5 \cdot 10^{-9}$ W/Hz$^{1/2}$ at 10 Hz. Films without this excess noise were obtained by *in situ* laser ablation of

3000Å of YBCO on top of a 500Å thick buffer layer of $SrTiO_3$ on the Al_2O_3 substrate. The 6×6 mm^2 chip was then waxed face down to a polishing block and lapped to 20μm thickness. Electrical contact pads were made by sputter cleaning the YBCO surface in a 1:5 O_2 + Ar background and then sputter depositing 2000Å of Ag. The chip was diced into 1×1 mm^2 bolometer chips and the contacts were annealed in O_2 at 500°C for 1 hr.

Electrical leads of 25μm diameter copper wire were attached to the two silver contact pads with Ag paint. The length of the copper leads was selected to give the appropriate thermal conductance between the bolometer chip and the heat sink. The bolometer chip was then suspended by the electrical leads in a temperature regulated brass ring. Some electrical and optical measurements (in the visible) were made and then gold black smoke was deposited on the back side of the bolometer as a radiation absorber[8]. The bolometer assembly was finally mounted on the cold plate of an optical cryostat for infrared measurements using a fourier transform spectrometer.

MEASUREMENTS

The bolometer responsivity was calculated from electrical measurements. The inset of Figure 1 shows the resistive transition of the thinned bolometer chip for a 1mA current bias. Comparison with measurements made immediately after YBCO deposition showed no noticeable degradation. The steepest part of the resistive transition has a slope dR/dT = 6.2 Ω/K where R = 3Ω. Figure 1 shows the dependence of the bolometer resistance on power dissipated by the bias current. The shape of this curve is consistent with bias power heating, assuming that the isothermal film is ohmic. The thermal conductance G = 270 μW/K was obtained from R(T) and from the slope at small bias power I^2R.

The bolometer time constant τ = 55 msec was obtained by measuring the roll-off as a function of chopping frequency. We infer a value C = 15 μJ/K from the measured values of G and τ. This value is consistent with the value C = 12 μJ/K,

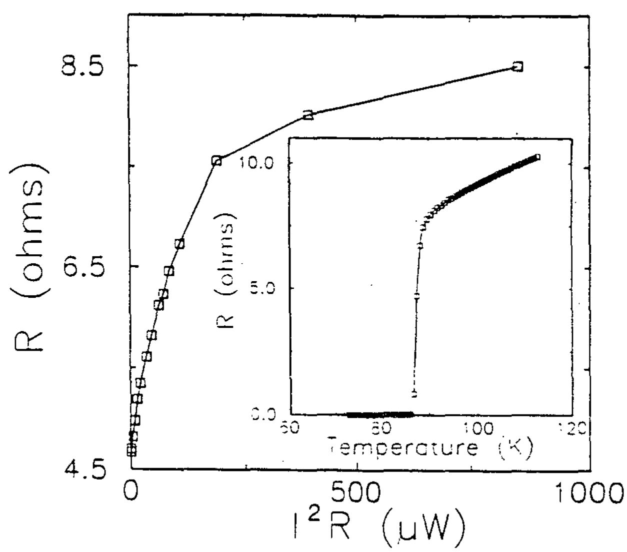

Figure 1: Resistance of the bolometer as a function of electrical heating from the bias current. The nonlinearity of this curve arises from the temperature rise and the shape of the resistance versus temperature. Inset: R(T) for the bolometer measured at 1mA.

computed from handbook data, and gives us confidence in the G calculated from Figure 1. From the measured values of G, dR/dT, and τ, we calculate a responsivity of 19 V/W at 10Hz and I = 3mA.

The spectral response of the bolometer was first measured at visible wavelengths with 632 nm He-Ne laser light. The YBCO film, which has an absorptivity[9] of 90% at this wavelength, was used as the radiation absorber. Figure 2 compares the response to chopped laser light with the slope of the resistive transition. These data are consistent with bolometric response. The peak signal corresponds to an optical responsivity of 17 V/W.

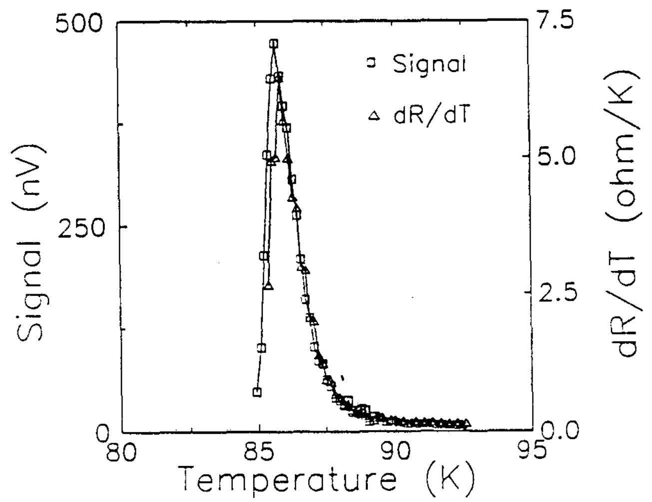

Figure 2: Voltage response of the bolometer to chopped laser light compared with dR/dT. The similarity of the two curves indicates that the response is bolometric.

We measured the voltage noise in the film for current biases up to 3mA. Figure 3 shows the voltage noise in the bolometer, measured by using an AC-coupled, room temperature transformer and a FET amplifier. Using the measured noise and optical responsivity, we compute the optical NEP = $2.4 \cdot 10^{-11}$ W/Hz$^{1/2}$. The maximum current allowed by the stability condition is I = 4mA. Assuming that the excess noise in a better sample would be less than Johnson noise, the NEP could be improved to 10^{-11} W/Hz$^{1/2}$ at 10Hz. Providing the excess noise stayed low, this bolometer could be used without a transformer by stepping up the resistance to at least 200 Ω and matching the thermometer to a sensitive bipolar amplifier. This could be done by patterning a meander strip in the YBCO film.

The spectral response of the bolometer is determined by the radiation absorber attached to it. Gold black is a matrix of weakly connected clusters of gold atoms with a density 0.1% that of solid gold; hence its heat capacity is small compared to the rest of the bolometer. Gold black absorbs light by multiple scattering and makes good thermal contact with the substrate. For operation from 1−100 μm a 10 μm thick layer of gold black is a good absorber[8]. We have measured the transmittance of gold black (thickness ≥ 20μm) and found it to be only 10% transmitting from 100−500 μm. During gold black deposition, radiation from the tungsten filament heated up the bolometer and the YBCO thermometer lost some oxygen. Consequently, the resistive transition broadened and the electrical noise increased slightly. Better shielding of the bolometer from the infrared emission of the tungsten filament might

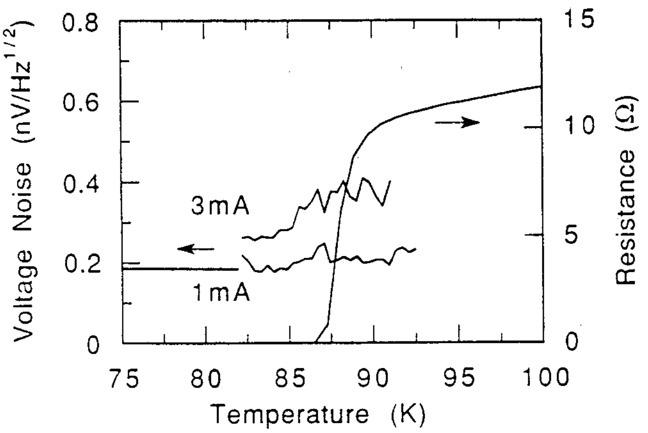

Figure 3: Voltage noise of the bolometer at 10 Hz for current biases of 1mA and 3mA. The straight line shows the system noise floor.

prevent degradation of the YBCO thermometer. We are also developing high T_c bolometers for use at longer wavelengths (100–3000 μm). These bolometers use resistive metal film absorbers, such as bismuth[1], which can absorb up to 50% of the incident radiation over a broad spectral range.

We measured the response of the bolometer to infrared light using a Michelson fourier transform spectrometer in a step-and-integrate mode. We compared its performance to the response of a commercial pyroelectric detector[6] using nominally identical optical efficiency and throughput. Black body radiation from a quartz mercury arc lamp was coupled to the detectors through a brass light pipe and a light concentrating cone. Two warm filters of 25 μm thick black polyethylene were placed in the light pipe to block visible radiation. Figure 4 compares the ratio of two identical spectra with a resolution of 4 cm^{-1} measured with the pyroelectric detector and with the high-T_c bolometer. The deviation from unity of this ratio is a measure of the detector sensitivity. Clearly the high T_c bolometer is more sensitive. We suspect that the gold black matrix is partially collapsed because of the sample heating problem during gold black deposition and therefore allows some of the radiation to be absorbed by the sapphire substrate. The feature at 450 cm^{-1} is due to a strong reflection mode in the sapphire. As another measure of the sensitivity, we back-filled the light pipe with H_2O vapor and measured water absorption lines. Figure 5 shows the transmittance spectrum of 50 Torr of water vapor in 75 cm of 1.3 cm diameter light pipe. These data agree with previously published measurements [10] and show that the bolometer is functioning as expected.

We have designed, fabricated, and tested the first high T_c bolometer with higher sensitivity than competing room temperature detectors. At a 10 Hz chopping frequency, the lowest NEP is $2.4 \cdot 10^{-11}$ W/$Hz^{1/2}$ and the responsivity is 17 V/W. We were able to measure water vapor absorption lines from 20-50 μm and saw useful response for the bolometer from 10-100 μm. We are working to eliminate the slight degradation of the devices during gold black deposition.

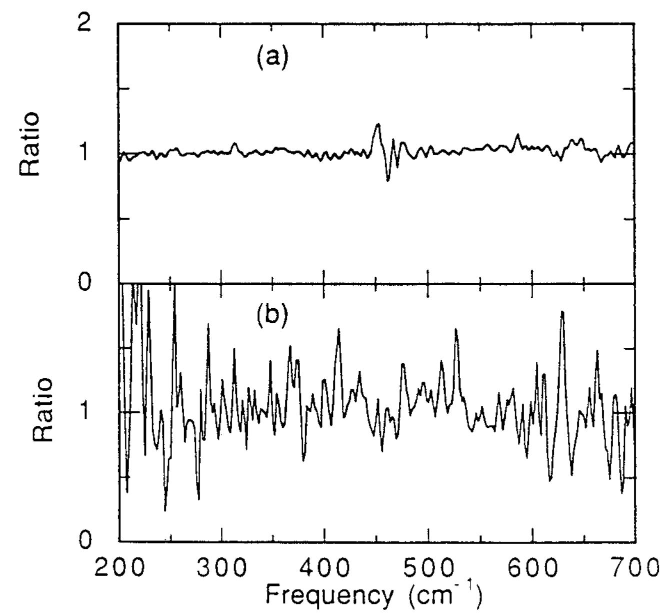

Figure 4: (a) Ratio of two identical spectra with 4 cm^{-1} resolution measured with the high T_c bolometer. (b) Ratio of two identical spectra with 4 cm^{-1} resolution measured with a pyroelectric detector. The optical efficiency was intentionally degraded so that the noise could be seen clearly. The throughput and efficiency was the same for both ratios.

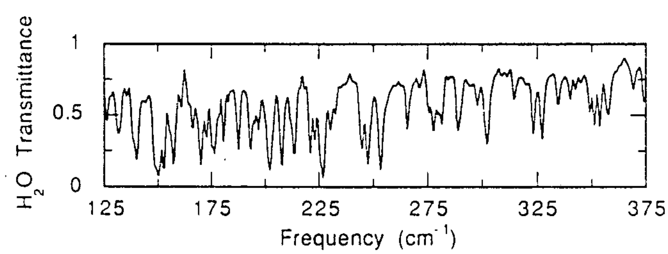

Figure 5: Transmission spectrum of 50 Torr of water vapor measured with a high T_c bolometer.

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