**YBa$_2$Cu$_3$O$_{7-\delta}$ infrared bolometers: Temperature-dependent responsivity and deviations from the $dR/dT$ curve**

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The phase and amplitude of the response to infrared radiation of superconducting bolometers was investigated. The detectors were fabricated with 120–550 nm Y$_1$Ba$_2$Cu$_3$O$_{7-\delta}$ films on MgO, SrTiO$_3$, and LaAlO$_3$ substrates. A model for the response is developed and compared to the experimental results. The response versus frequency of the samples shows bolometric behavior, in agreement with the measured time dependence of the signals at low frequencies. Different techniques were developed to measure the key parameter in the response of the bolometers, $G$, the thermal conductance. Several anomalies were observed in the study that provide insight into heat conduction in these devices. The dc or low modulation frequency thermal conductance, $G(0)$, of the samples is found to be limited by the substrate/cold-head thermal boundary resistance. It was also found to decrease with increasing substrate thickness, but still limited by the substrate/cold-head interface. This thickness dependence of $G(0)$ is attributed to scattering of phonons within the substrate, that changes their transmission rate through the substrate/cold-head interface. The results from simultaneous measurements of the IR response and $dR/dT$ (using $R$ versus $T$) at low modulation frequencies (20 Hz) show that the magnitude of the response differs by up to 30% from the $dR/dT$ curve. The discrepancy is found to be frequency dependent, increasing with decreasing modulation frequency. This can be treated by use of temperature-dependent thermal constants ($G$ and the heat capacity, $C$) in the model for the bolometric response. The discrepancy is also observed to be dependent on the superconducting transition, which suggests a possible correlation between the heat conduction through the substrate (and its interfaces) and the absorption mechanism in the superconductor. The phase of the response versus temperature shows an abrupt change at the transition. This is evidence for a change in thermal constants in the bolometer as it goes through the superconducting transition, affecting both the phase and magnitude of the response. Joule heating at even high bias currents has little effect on the response (and its deviation from the $dR/dT$ curve) in our samples, and the effect of noise on the response is significant only at very low bias currents. © 1995 American Institute of Physics.

**I. INTRODUCTION**

One of the promising devices made of high temperature superconducting (HTSC) materials are edge transition bolometers. They can be used to detect electromagnetic radiation. Since the fabrication and testing of the first detectors, there has been a debate on the mechanism of the response at low frequencies. Different techniques were developed to measure the key parameter in the response of the bolometers, $G$, the thermal conductance. The phase and amplitude of the response to infrared radiation of superconducting bolometers was investigated. The detectors were fabricated with 120–550 nm Y$_1$Ba$_2$Cu$_3$O$_{7-\delta}$ films on MgO, SrTiO$_3$, and LaAlO$_3$ substrates. A model for the response is developed and compared to the experimental results. The response versus frequency of the samples shows bolometric behavior, in agreement with the measured time dependence of the signals at low frequencies. Different techniques were developed to measure the key parameter in the response of the bolometers, $G$, the thermal conductance. Several anomalies were observed in the study that provide insight into heat conduction in these devices. The dc or low modulation frequency thermal conductance, $G(0)$, of the samples is found to be limited by the substrate/cold-head thermal boundary resistance. It was also found to decrease with increasing substrate thickness, but still limited by the substrate/cold-head interface. This thickness dependence of $G(0)$ is attributed to scattering of phonons within the substrate, that changes their transmission rate through the substrate/cold-head interface. The results from simultaneous measurements of the IR response and $dR/dT$ (using $R$ versus $T$) at low modulation frequencies (20 Hz) show that the magnitude of the response differs by up to 30% from the $dR/dT$ curve. The discrepancy is found to be frequency dependent, increasing with decreasing modulation frequency. This can be treated by use of temperature-dependent thermal constants ($G$ and the heat capacity, $C$) in the model for the bolometric response. The discrepancy is also observed to be dependent on the superconducting transition, which suggests a possible correlation between the heat conduction through the substrate (and its interfaces) and the absorption mechanism in the superconductor. The phase of the response versus temperature shows an abrupt change at the transition. This is evidence for a change in thermal constants in the bolometer as it goes through the superconducting transition, affecting both the phase and magnitude of the response. Joule heating at even high bias currents has little effect on the response (and its deviation from the $dR/dT$ curve) in our samples, and the effect of noise on the response is significant only at very low bias currents. © 1995 American Institute of Physics.
normal state; the shift in the temperature of the peak of IR response versus bias current; the instability criteria in both the IR response and the resistance versus temperature. We have observed several anomalies in studying these bolometers, that provide insight into the heat conduction process in these devices, and may be used to study both the superconducting films and heat flow across interfaces. The frequency response analysis for the thermal modeling, and the frequency-dependent characteristics of the thermal parameters of the above bolometers were presented elsewhere. Here we report on the phase and amplitude of the response to IR signals of edge transition bolometers versus temperature. The measured amplitude and the phase of the response versus temperature of our devices deviate from the existing thermal models. We propose a model that can explain the observed discrepancy in the response versus temperature from the $dR/dT$ curve in our samples, and some of the reported discrepancies from the bolometric response by others. Based on our model, the thermal constants, $G$, and $C$, change as the film goes into the superconducting state; $G$ becomes strongly temperature dependent, and decreases with decreasing temperature. A probable cause for the change in $G$ is a shift in the nature of the phonons emitted by the superconductor as it goes through $T_c$. In this study a dependence of the measured total dc thermal conductance, $G(0)$, on the thickness of the substrate of the samples is observed. From our analysis $G(0)$ is always limited by the substrate/cold-head thermal boundary resistance. This conclusion is confirmed by comparing our results to a model of the device’s frequency response. Also using the low frequency response of the bolometers, the specific heat and thermal conductance of the substrate material can be obtained. Such a study was done in the frequency range of 0.5 Hz–100 kHz and reported elsewhere.

II. EXPERIMENTAL SETUP

A computer controlled cryogenic system using a Cryo-Torr 100 cooling stage (CTI-Cryogenics) was developed for simultaneous optical and electrical characterization of the samples. A complete block diagram and detailed circuitry of the system are presented elsewhere. To cool the samples, the cold stage of a Cryo-Torr pump is used as the cold finger. The configuration of the sample holder is shown in Fig. 1. The OFE copper is etched and coated with a layer of gold without being exposed to the atmosphere. The heater is made of resistive paste on a sapphire substrate using hybrid microelectronics technology, and can control the temperature with a dc current up to a maximum of about 200 mA with a precision of 0.1 K. To improve the thermal contact between the substrate and the cold head a very thin layer of vacuum grease is applied to the back of the substrate. Two different greases, Apiezon-N grease (Kurt J. Lesker Co., PA) and silicone vacuum grease (Dow Corning Corp., MI) were used at the substrate/cold head interface, and similar results were obtained.

A low noise four-probe configuration is made possible by the use of a battery and a metal film bias resistor. The bias resistor has a value at least 20 times the normal resistance of the samples. The data are taken by a computer using the outputs of a lock-in amplifier (EG&G 5406), and is plotted simultaneously during the measurement. By use of the computer, the temperature can be controlled and stabilized to 0.1 K accuracy. To measure low voltage signals, an ultralow noise preamplifier (model 030B, Perry Amplifier) with a noise limit of 0.4 nV/√Hz was used. A light-emitting diode (LED) (HFE4020, Honeywell Inc.) with a peak wavelength of 0.85 μm was the radiation source in our measurements. The intensity of the radiation was controlled by the current through the source using square wave signals. The response of the samples was found to be proportional to the radiation intensity up to 2.13 mW/cm², limited by the maximum output power of the LED.

III. SAMPLE PREPARATION

Samples are made of YBCO thin films with 150–500 nm thicknesses on single crystal MgO, LaAlO₃, and SrTiO₃ substrates. The films are deposited using an off-axis dc planar magnetron sputtering technique with 715–725 °C substrate temperatures, and ~0.9 nm/min deposition rate. X-ray patterns of the films shows a preferential c-axis orientation, and scanning electron microscope pictures of the surfaces of the films show the presence of inclusions in the films. More details on the deposition parameters and the properties of the films are reported in Refs. 8 and 9.

Meander line patterns with contact areas for four-probe measurement have been used to control the value of $dR/dT$ at the middle of the transition. Samples have a 0.5 cm by 1 cm substrate area, with either 0.5 or 0.25 mm thicknesses, and are half of an original sample with 1 cm by 1 cm substrate area. The samples are patterned using standard photolithography (positive photoresist) and etched in about 0.75% dilute phosphoric acid. The total and active area of the patterns with the substrate and film thicknesses are given in Table 1. The contact areas for the four-probe measurement were coated with a layer of about 85 nm of gold or about 60 nm of silver, deposited using dc planar magnetron sputtering in a different unit than the one used to deposit YBCO. Contacts on silver-coated areas have shown better electrical properties and mechanical durability against vibration and thermal cycling. The contact areas of sample 064–02b are coated with 60 nm layer of silver. Electrical contacts to the samples were made using copper wires (32 gauge) and silver epoxy (Tra-Duct BA-2902, TRA-Con, MA) dried at room temperature overnight.
TABLE I. The measured dimensions of the YBCO patterns, and the dc thermal conductance of the bolometers. The dimensions of the substrates are about 0.5 cm by 1 cm for all the samples, and the substrates are attached to the cold head using a thin layer of Apiezon-N grease. \(d_s\) is the thickness of the substrate, \(d_f\) is the thickness of the YBCO film, and \(A\) is the total area enclosed by the meander line pattern and is roughly twice the area of the meander line. The resistance of the samples are measured at room temperatures \((T=300 \text{ K})\) by the four-probe technique. The values of \(G\) were obtained by the joule heating of the sample at temperatures above \(T_c\).

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Substrate material</th>
<th>(d_s) (nm)</th>
<th>(d_f) (cm)</th>
<th>(A) (cm(^2))</th>
<th>Area of the meander line ((\mu \text{m} \times \text{cm}))</th>
<th>(T_{c-\text{onset}}) (K)</th>
<th>(R) (k(\Omega))</th>
<th>(G) (W/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>064-02a</td>
<td>MgO</td>
<td>120–130</td>
<td>0.025</td>
<td>0.075</td>
<td>90 (\mu \text{m} \times 3.35 \text{ cm}) 87</td>
<td>13.5</td>
<td>(3.3 \times 10^{-3})</td>
<td></td>
</tr>
<tr>
<td>064-02b</td>
<td>MgO</td>
<td>120–130</td>
<td>0.025</td>
<td>0.0168</td>
<td>50 (\mu \text{m} \times 1.9 \text{ cm}) 86</td>
<td>11.2</td>
<td>(1.5 \times 10^{-3})</td>
<td></td>
</tr>
<tr>
<td>064-03a</td>
<td>MgO</td>
<td>170–180</td>
<td>0.05</td>
<td>0.075</td>
<td>90 (\mu \text{m} \times 3.35 \text{ cm}) 82</td>
<td>7.7</td>
<td>(1.1 \times 10^{-3})</td>
<td></td>
</tr>
<tr>
<td>064-03b</td>
<td>MgO</td>
<td>170–180</td>
<td>0.05</td>
<td>0.0168</td>
<td>50 (\mu \text{m} \times 1.9 \text{ cm}) 83</td>
<td>6.5</td>
<td>(5.1 \times 10^{-3})</td>
<td></td>
</tr>
<tr>
<td>064-01a</td>
<td>SrTiO(_3)</td>
<td>220–230</td>
<td>0.05</td>
<td>0.0168</td>
<td>50 (\mu \text{m} \times 1.9 \text{ cm}) 82</td>
<td>10.0</td>
<td>(3 \times 10^{-3})</td>
<td></td>
</tr>
<tr>
<td>061-02a</td>
<td>LaAlO(_3)</td>
<td>540–560</td>
<td>0.05</td>
<td>0.075</td>
<td>85 (\mu \text{m} \times 3.35 \text{ cm}) 80</td>
<td>4.4</td>
<td>(8 \times 10^{-3})</td>
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<tr>
<td>064-04b</td>
<td>LaAlO(_3)</td>
<td>190–200</td>
<td>0.05</td>
<td>0.075</td>
<td>90 (\mu \text{m} \times 3.35 \text{ cm}) 84.5</td>
<td>17.5</td>
<td>(7.8 \times 10^{-3})</td>
<td></td>
</tr>
</tbody>
</table>

IV. RESULTS AND DISCUSSIONS

A. Measurement of thermal conductance, \(G\)

The thermal conductance of a bolometer is defined as the total heat conduction from the bolometer to its environment per degree of temperature difference. The amount of input power (heat), \(P_{\text{in}}\), to a bolometer can be determined, and used to measure \(G\) from

\[
G = \frac{P_{\text{in}}}{AT}, \tag{2}
\]

where \(AT\) is the difference between the temperature of the bolometer and its environment. The thermal conductance of a superconducting bolometer can be measured in different ways, which are discussed here. In each technique there are different kinds of possible error associated with the nature of the characterization. Heat loss by radiation from the superconducting bolometer (superconducting film and the substrate) in typical systems is found to be negligible compared to the phonon heat conduction.

One of the effects of the finite thermal conductance in a sample can be observed in the \(R\) vs \(T\) curves at different bias currents. The thermal conductance of the sample puts a limit on the maximum bias current that can be used in the measurement. The bias current at any temperature higher than \(T_{c-\text{zero}}\) is limited by thermal runaway, characterized by the factor \(\alpha\) defined as:

\[
\alpha = \frac{I^2dR}{G(0)dT} \quad \text{with } \alpha < 1 \text{ required for stability}, \tag{3}
\]

where \(I\) is the bias current and \(G(0)\) is the dc thermal conductance. The effect of an instability in the temperature of the film, due to high bias currents, will appear as an unrealistically sharp transition in the \(R\) vs \(T\) curve. The instability and the shift in the \(T_{c-\text{onset}}\) can be used to measure \(G(0)\).

At low bias currents the temperature of the superconducting film is very close to the temperature of the cold head. As the bias current increases, a temperature gradient develops across the substrate and the interfaces due to joule heating in the film. Since it is the temperature of the holder which is commonly controlled, this results in a shift of the bias point in the superconducting film towards \(T_{c-\text{onset}}\) where \(dR/dT\) has lower values. The decrease of \(dR/dT\) lowers the detector response, which has been interpreted as the effect of the bias current on the intrinsic part of the response by some groups. The drop of the response at high currents can be used as a second method to measure \(G\). Knowing the \(dR/dT\) vs \(T\) curve, and the change in the response, the shift in the temperature of the superconducting film with respect to the holder can be found. Using the \(R\) and the bias current, the power dissipation in the film can be obtained. Then by use of the temperature shift and the dissipated joule power in Eq. (2), the value of \(G(0)\) can be calculated.

The most convenient way to obtain \(G(0)\) is to make use of the slope of the \(R\) vs \(T\) of the films in the normal state near \(T_c\) as shown for sample 064-02b in Fig. 2. At high currents, \(R\) increases due to the dc power dissipation heating the film. The relationship between the increase in the resistance of the film, \(R\), and the bias current due to joule heating is

\[
\Delta R = \frac{I^2R}{GdT}. \tag{4}
\]

Using the measured values for the \(dR/dT\) at the bias temperature of the holder, and the bias currents, values of \(G\) can

![FIG. 2. Resistance vs temperature of sample 064-02b, measured in the four-probe configuration with DC transport current of 100 µA and 2 K/min heating rate near \(T_c\). Inset shows full temperature range.](image-url)
be obtained for each data point. There is a slight error in the above method due to the change of the \(dR/dT\) at different temperatures.

Here we use a method which eliminates the above error. Considering joule heating by the bias currents as the source for the shift of the film temperature, \(T_f\), with respect to the temperature of the holder, \(G(0)\) can be found from:

\[
G(0) = \frac{P^2 R}{\Delta T},
\]

where \(\Delta T\) is the difference between \(T_f\) and the temperature of the cold head. The resistance of the film, \(R\), can be measured from \(VI\) at each point. Using the \(R vs T\) curve for the region of interest (90–70°C), and the measured value of \(R \) at different bias currents \(T_f\) can be obtained and used to determine \(\Delta T\). Then using \(\Delta T\) and \(P_{in} = -I^2 R\) in Eq. (5), values of \(G(0)\) can be obtained for each data point. This is the method used to find the averaged values given in Table I. To measure \(G(0)\) relatively high bias currents should be used for ease in monitoring the temperature change in the film. However, high currents through the material can affect the electrical properties of the films shifting \(T_c\) to lower temperatures.\(^{11,15}\)

### B. Dependence of \(G\) on the YBCO film pattern and the substrate thickness

The values obtained for the dc or low frequency thermal conductance of the bolometers are about 2–3 orders of magnitude lower than the values calculated from the properties of the substrate material, which can be obtained from

\[
G = \frac{A}{L_f}K\text{,}
\]

where \(k\) is the thermal conductivity of the substrate material and \(L\) and \(A\) are thickness of the substrate and area of the superconducting pattern. The measured \(G\) values in Table I are determined by the substrate/cold-head thermal boundary resistance.\(^{9,16}\) This is found from the frequency response of the devices. At low frequencies, the thermal diffusion length into the substrate, \(L_f\), is larger than the substrate thickness, and \(G\) is found to be constant with respect to \(f\), and much lower than the values calculated for the substrate from Eq. (6). As the frequency increases, \(L_f\) becomes comparable or smaller than the substrate thickness changing \(G\), which changes the slope of the response versus modulation frequency from a \(f^{-1}\) to a \(f^{-1/2}\) dependence.\(^{9,16,17}\) Then \(G\) is limited by the thermal conductivity of the substrate material, and can be obtained from Eq. (6), where \(L\) is proportional to the thermal diffusion length, \(L_f\).\(^{9,17,18}\)

The observed thermal boundary resistance at the substrate/cold-head interface can be explained by the thermal 'acoustic mismatch theory or Kapitza resistance.\(^{12,16,19}\) A thermal boundary resistance defined as the Kapitza resistance, is

\[
R_k = \frac{\Delta T}{Q'},
\]

where \(Q'\) is the heat flux per unit area through the interface, and \(\Delta T\) is the temperature difference across the boundary. This phenomenon is related to the reflection and refraction of the incident thermal phonons at the interface.\(^{19}\) Based on the thermal acoustic mismatch model, \(R_k\) was found to be temperature dependent with a dependence\(^{19}\) of \(\sim T^{-3}\). In the model, it is assumed that the heat is carried only by thermal phonons (only acoustic phonons are important at low temperatures), the two solids are perfect materials, and finally the interface is perfect or ideal.\(^{19}\) Based on the above assumptions the heat transfer through the interface is determined mainly by the acoustic impedance \(\rho S_1, S_2\) of the two attached materials at the boundary, where \(\rho\) is the mass density and \(S\) is the velocity of sound in the material.

As shown in Fig. 1, there are two interfaces to be considered in our experimental configuration. The film/substrate interface and the substrate/cold-head interface. The film/substrate interface and its corresponding thermal resistance, \(R_{bd,1}\), have been studied by different groups.\(^{12,20,21}\) The effect of the \(R_{bd,1}\) on the response in our samples is observed only at high frequencies, at which the thermal resistance of the substrate becomes comparable to the film/substrate thermal boundary resistance. This frequency is found to be 53 kHz for 0.05-cm-thick MgO substrate sample,\(^{4,9}\) which is obtained from a typical value of \(R_{bd,1} = 1.1 \times 10^{-3}\) K-\text{cm}/W.\(^{9,20,21}\) However, based on our analysis, \(G\) is limited by the substrate/cold-head thermal boundary resistance, \(R_{bd,2}\), at modulation frequencies less than 720 Hz, and 2.8 kHz, for 0.05 and 0.025-cm-thick MgO substrate samples, respectively.\(^{4,9}\)

However, a dependence of \(G(0)\) on the substrate thickness and the pattern area is also observed, as given in Table I. It should be noted that the back of the substrate cannot be thoroughly cleaned due to the adhesion of silver epoxy applied to the back of the substrate for the in situ deposition of the YBCO and this causes a difference in the measured \(G\) compared to the \(G\) of a sample with a perfectly clean and smooth contact to the cold head. The roughness of the back of the substrates does not allow the accurate observation of the effect of the dimensions of substrate and patterns on the \(G\), for samples on MgO and SrTiO\(_3\) substrates. The effect of the texture of the backsurface of the substrates is observed for sample 064-02b. The thermal conductance, \(G(0)\), of the sample was increased by as much as a factor of 2 to 15.5 mW/K, by further cleaning, and by increasing the roughness of the back of the substrate. This may be caused by the removal of the remaining silver epoxy which reflected phonons back into the substrate, as well as by the increase in the contact area to the grease at the substrate/cold-head interface. The data presented here for sample 064-02b are after the increase in \(G(0)\).

As given in Table I, \(G(0)\) is found to increase for thinner substrates, while it is still limited by the substrate/cold-head thermal boundary resistance, as evidenced by the fact that for the thermal conductivity of the substrate material, the values of \(G\) are too small to be governed by Eq. (6). The dependence of the value of \(G(0)\) on substrate thickness can be attributed to scattering of phonons within the substrate, which changes the angular distribution of the phonons reaching the substrate/cold-head interface. Phonons with a larger angle of incidence to the normal at the interface will be in-
FIG. 3. IR response and resistance vs temperature of sample 064-02b, at 100 μA, 1 mA, and 2 mA bias currents with peak response of 386 nV, 3.28 μV, and 5.87 μV, respectively. The measurements were at 10 kHz modulation frequency, 1 mW/cm² radiation intensity, and 2 K/min heating rate.

ternally reflected at the boundary, lowering the value of $G(0)$. This is consistent with the acoustic mismatch theory\textsuperscript{19} for phonon interactions at interfaces, which is valid for both solid-solid and solid-liquid interfaces, and is expected to also hold for our rough substrate-vacuum grease interface. It is also consistent with the observed dependence of the $G(0)$ on the area of the superconducting pattern, it increases with an increase in the area of the pattern, suggesting that the conduction is mainly through the contact area below the pattern with direct on-line flow to the cold head.

C. Effect of bias current on the response and $dR/dT$ vs temperature

The shift of the temperature of the film with respect to the temperature of the cold head at high bias currents, used to measure $G(0)$ (in Sec. IV A), can also be observed in the bolometric response vs $T$ of the samples. The temperature of the peak in the response vs $T$ curve shifts to lower temperatures as higher bias currents are used. Though the response vs temperature will follow the measured $R$ vs $T$ curve (or the corresponding $dR/dT$ curve), the magnitude of the response follows the real slope of the transition, the $R$ vs temperature of the film (the slope at low bias currents).\textsuperscript{4} This effect for sample 64-02b is shown in Fig. 3. The values of thermal conductance obtained by the shift in the peak of the response vs $T$ of the samples, confirm the range of values given in Table I. A slight change in $G$ is expected, due to the difference of the temperature at the peak of the IR response and the temperature at which the $G$ values in Table I are measured. Also there is an error associated with the above method due to the continuous change of the temperature during the measurements.\textsuperscript{9}

The magnitude of the response can also be affected by the ac component of the Joule heating in the film. This ac component is caused by the change in the operating point resistance due to the input radiation power, and is in the form of positive feedback.\textsuperscript{1} This can enhance the response resulting in an overall responsivity of

$$r_f - 1 \frac{r_f}{1 - Ir_f/\eta},$$

where $r_f$ is given as defined in Eq. (1). As observed in Eq. (8), there is a stability criteria in the voltage response which has the same form as obtained for dc biasing at zero frequency.\textsuperscript{1,9} The effect of the Joule heating in our samples was found to be negligible for the bias currents used up to a few milliamperes.

As shown in Fig. 3, there is a small peak at temperatures below the $T_{c-\text{onset}}$ for the response at 100 μA bias current. This peak is found to be the intrinsic noise of the sample. This excessive noise is found in all samples that have weak links, or are granular and show a long tail in their $R$ vs $T$ curves. The peak noise in this region is observed to decrease with increasing bias current, while it widens on the lower temperature end. A study of the different types of noise in the samples is given elsewhere.\textsuperscript{9}

D. Response vs temperature of the bolometers and deviations from the thermal model

Assuming the thermal parameters $G$ and $C$ to be independent of temperature as given in Eq. (1), the bolometric response is expected to follow the $dR/dT$ vs $T$ curve. Figure 4 shows the magnitude of the IR response of sample 064-02b to a 20 Hz modulation frequency, and the corresponding $dR/dT$ vs $T$ curve. Both curves are normalized to their values at the $T_{c-\text{onset}}$. The $dR/dT$ of the sample was obtained by use of the simultaneously measured $R$ vs $T$. As observed in Fig. 4, there is a slight discrepancy between the response and the $dR/dT$ curve at the lower part of the transition region closer to $T_{c-\text{onset}}$. There have been several reports on such discrepancies.\textsuperscript{6,10,22,23} The discrepancy in our samples is dependent on the modulation frequency of the signals, decreasing as the frequency increases. This was verified for the frequency range of 20 Hz–10 kHz for this sample, and the same type of behavior is observed for other samples as well. For samples with sharper transitions, the discrepancy is smaller.\textsuperscript{9}

The phase of the response of the samples is also found to vary as a function of temperature. This variation indicates a
FIG. 5. The phase of the IR response vs temperature of sample 064-02b at 20 Hz modulation frequency and 680 μA dc bias current.

change in the thermal constants of the bolometer. The measured phase of the response versus temperature of sample 064-02b at 20 Hz frequency, is given in Fig. 5. The response at this frequency was shown to be mainly bolometric, in agreement with the response versus time of the sample presented elsewhere. The variation of the phase versus temperature in Fig. 5 shows a dependence on the superconducting transition of the film. The magnitude of the phase of the response of the samples increases at the lower part of the transition. This variation of the phase versus temperature, which follows the superconducting transition, suggests a correlation between the thermal characteristics of the superconducting film and the response at low frequencies. We have already shown that the response at low modulation frequencies is mainly governed by the thermal constants of the substrate material and substrate/cold-head interface in our system, i.e., \( \tau = C/G \) with \( C \) determined from the heat capacity of the substrate and \( G \) the substrate/cold-head interface conductance. The same type of behavior of the phase of the response is observed for the other samples as well, and for samples with sharper transitions, the change is smaller. A possible explanation for the change in the response is that the character of the phonons changes as the film goes into the superconducting state. In the superconducting state the IR photons can break pairs, which upon recombination emit phonons that have an energy of \( 2\Delta(T) \). These phonons may have a different angular distribution than the thermal ones that are present in the normal state. The probability of escape of such phonons from a superconducting film can be very low. This aspect is discussed in some detail by Eisenmenger. Hence, the effective \( G \) includes this effect.

The increase in the amplitude of the response at the lower part of the superconducting transition at low frequencies, as well as the increase in the phase lag seen in Fig. 5, would be consistent with a decrease in \( G \), or an increase in \( C \) at lower temperatures. Experimental data for the \( C \) of MgO shows that \( C \) falls by nearly a factor of 2 in going from 85 to 70 K (1.22 cal/mol K at 85.5 K and 0.66 cal/mol K at 70.23 K). Hence, the change in \( C \) is opposite to that needed to account for the discrepancies in the amplitude and phase responses, and indicates that \( G \) must be decreasing significantly. The discrepancy in the magnitude of the response vs temperature of sample 064-02b is given in Fig. 6. This shows that the deviation increases as the temperature drops. The variations in the ratio is a measure of the noise present. The measurements at lower temperatures are limited by the small signal, which decreases the signal to noise ratio. The numerical analysis below gives the magnitude of the changes in \( G \) and \( C \) implied by the response results.

E. Effect of variation of \( G \) on the response and its frequency dependence

Considering the discrepancy at 20 Hz in Fig. 6, the response at 70 K is about 1.4 times higher than the expected values. This temperature is close to \( T_{c\text{-onset}} \) and will be noted as \( T_{c\text{-low}} \). From Fig. 5, the phase of the response, \( \phi \), at the onset temperature of \( \sim 85 \) K is about \( -51.5^\circ \) and at the \( T_{c\text{-low}} (~70 \) K) is about \( -62.5^\circ \). From Eq. (1) we get

\[
-\tan \phi = \omega \tau,
\]

where \( \phi \) is the temperature-dependent phase of the response. Then

\[
\omega \tau_{c\text{-onset}} = 1.26 = \omega C_{c\text{-onset}}/G_{c\text{-onset}}.
\]

Similarly for the phase at \( T_{c\text{-low}} \) we have

\[
\omega \tau_{c\text{-low}} = 1.92 = \omega C_{c\text{-low}}/G_{c\text{-low}}.
\]

Now, based on the above analysis, from the ratio of Eqs. (10) and (11) we get

\[
(\tau_{c\text{-onset}}/\tau_{c\text{-low}}) = 0.65,
\]

or

\[
G_{c\text{-low}}/G_{c\text{-onset}} = 1.53.
\]

Assuming the heat capacity of the bolometer, which is mainly due to the substrate material at this frequency, drops from \( T_{c\text{-onset}} \) to \( T_{c\text{-low}} \) according to its experimental results, then Eq. (13) requires that the thermal resistance of the bolometer increase (\( G \) decrease) at lower temperatures, and consequently there is an increase in the response which is consistent with the result in Fig. 6. The variation in the responsivity, taking the changes in the \( C \) into account, can be obtained by use of Eq. (1) from

FIG. 6. Deviation of IR response (Fig. 4) vs temperature from \( dR/dT \) vs temperature of sample 064-02b, at 20 Hz modulation frequency and 680 μA dc bias current.
\[
\frac{g_c(c\text{-onset})}{g_c(c\text{-low})} = \frac{G_{e\text{-onset}}\sqrt{1 + \omega^2 T_{e\text{-onset}}^2}}{G_{c\text{-low}}\sqrt{1 + \omega^2 T_{c\text{-low}}^2}}.
\]  

(14)

By use of the results from Fig. 6, and the values in Eqs. (10) and (11) in Eq. (14), a value of 1.89 can be obtained for \(G_{c\text{-onset}}/G_{c\text{-low}}\). By applying this to Eq. (13), a value of 0.81 is obtained for \(C_{c\text{-low}}/C_{c\text{-onset}}\). The change in the C is attributed to the change in the effective heat capacity due to the temperature dependence of the heat capacity of the substrate material. For MgO the experimental ratio of \(C_{c\text{-low}}/C_{c\text{-onset}}\) is 0.54, compared to the deduced value of 0.81 found by our analysis. This agreement is reasonable given the fact that other components of the bolometer, i.e., YBCO, metal contacts, interface grease, and the cold head may contribute to the effective heat capacity of the bolometer.

The thermal conductance at low frequencies is found to be determined by the substrate/cold-head thermal boundary resistance which can be strongly temperature dependent. Based on the above analysis, as the temperature decreases the substrate/cold-head thermal boundary resistance increases as expected for a solid/solid interface. However, the phase of the response shows its strongest variation as the sample goes through the superconducting transition, indicating that these large changes are associated with differences between the normal and superconducting state, rather than the temperature dependence of the interface boundary resistance. At higher modulation frequencies, the thermal diffusion length into the substrate material becomes comparable to or smaller than the substrate thickness. Then the thermal conductance becomes independent of the substrate/cold-head interface, and is expected to be mainly governed by the thermal conductivity of the substrate material, \(k_s\). The frequency at which the thermal diffusion length becomes equal to the substrate thickness of sample 064-02b is 2.8 kHz.\(^4\)\(^9\) For frequencies higher than this the \(G\) is shown to be governed by the \(k_s\).\(^4\)\(^9\) The thermal conductivity of the substrate material can increase as the temperature decreases. This can compensate for the decrease in the \(C\), reducing the discrepancy, and at higher frequencies it may even cause a decrease in the response at the \(T_{c\text{-low}}\) compared to the response at the \(T_{c\text{-onset}}\). Hence the response at higher frequencies can be closer to the \(dR/dT\) curve. The same type of behavior has been observed for all the measured samples. For samples with sharper transitions, the change in the phase of the response and the discrepancies at low frequencies are smaller. This can be attributed to the smaller change in the temperature range in the transition which varies from one sample to another,\(^9\) and hence a smaller variation in \(C\).

V. CONCLUSIONS AND SUMMARY

The work reported here has been focused on the characteristics of YBCO films on MgO substrates in response to infrared radiation. By use of the four-probe technique, the voltage across the film was studied as a function of temperature, dc bias current, and the modulation frequency of the infrared radiation (\(\lambda=0.85\, \mu m\)). A model for the response was developed and compared with the experimental response. Since our measurements were made using a lock-in amplifier both the magnitude and phase of the response were studied. This, with simultaneously measured \(R\) vs \(T\), provided a more sensitive test of the model, and allowed us to detect deviations between the theory and experiments that other techniques would miss.

Several methods for measuring the major parameter in the response function, the thermal conductance \(G\), were used. The methods are based on: joule heating due to the bias current in the superconducting pattern, and the slope of \(R\) vs \(T\) in the normal state; the shift in the temperature of the peak of IR response versus bias current; the instability criteria in both the IR response and the resistance versus temperature. The dc thermal conductance, \(G(0)\), was found to be dependent on the substrate thickness, decreasing with increasing substrate thickness, but still limited by the substrate/cold-head thermal boundary resistance. The dependence of the value of \(G(0)\) on substrate thickness can be attributed to scattering of phonons within the substrate which changes the angular distribution of the phonons at the substrate/cold-head interface. Phonons with a larger angle of incidence to the normal will be internally reflected at the interface lowering the value of \(G(0)\). That this is a significant effect is suggested by two other observations; first, roughening of the substrate/cold-head interface increased \(G(0)\) by nearly a factor of 2; second, \(G(0)\) was found to increase with the area of the superconducting film, indicating that heat conduction directly from the region under the pattern is more effective than by radiating at large angles.

A shift in the position of the peak of the response versus temperature at different bias currents is observed. This shift is due to a thermal effect caused by the dc joule heating in the film and the limited dc thermal conductance, \(G(0)\). The response of our samples at low modulation frequencies is found to be bolometric, and limited by the substrate/cold-head thermal boundary resistance. Because of the small ratio of the superconducting film thickness to the substrate thickness, the effect of the film/substrate thermal boundary resistance at low frequencies is expected to be negligible,\(^9\)\(^12\) however, some phonon reflection appears to occur there as the sample makes its transition into the superconducting state.\(^24\) Also, the effect of the thermal conductivity of the substrate is negligible up to frequencies where the thermal diffusion length into the substrate material becomes comparable to or smaller than the substrate thickness.\(^4\)\(^9\)\(^16\)\(^17\) Then \(G\) becomes dependent on the substrate material and starts to scale as \(f^{1/2}\). A peak is also observed in the response vs \(T\) curve just below \(T_{c\text{-zero}}\). This is due to the intrinsic noise in the film, and is observed at low bias currents where the noise becomes comparable to the response. This behavior is found to be independent of the radiation signal.

Simultaneous measurements of the IR response and \(dR/dT\) vs \(T\) show a discrepancy between the magnitude of the response and the measured \(dR/dT\) of the bolometers, based upon the modeled relation between them. The discrepancy is frequency dependent and decreases with an increase in the modulation frequency. At 20 Hz modulation frequency, \(dR/dT\) is found to differ by up to about 30% in magnitude from that expected from the IR response at \(T_{c\text{-zero}}\), when both
curves are normalized to their values at $T_{onset}$. The discrepancy is caused by the temperature dependence of $G$ and $C$. The phase of the response vs $T$ also changes at temperatures below $T_{onset}$. The phase-angle change is consistent with the explanation for the magnitude discrepancy. The changes in the thermal constants of the bolometer, specifically $G(0)$, is found to be dependent on the superconducting transition, decreasing as the film goes into the superconducting state. One possible mechanism for such a change in $G(0)$ is that in the superconducting state the infrared photons are breaking pairs, which on recombining emit phonons with energy $2\Delta(T)$ rather than a purely thermal distribution of phonons. The ease with which the $2\Delta(T)$ phonons pass from film to substrate and from substrate to cold head may be significantly different from that for a thermal distribution that is expected to account for the observed change in $G$.

In summary we have developed techniques to determine the low frequency thermal conductance of YBCO (on MgO) bolometers, and have observed several anomalies in studying these bolometers that provide insight into the heat conduction process in these devices, and may be used to study both the superconducting films and heat flow across interfaces.

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