Low and Midrange Modulation Frequency Response for YBCO Infrared Detectors: Interface Effects on the Amplitude and Phase

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***Abstract*— Bolometers were designed and fabricated from $YBa_2Cu_3O_{7-x}$ films on MgO, $SrTiO_3$, and $LaAlO_3$ substrates. Both the magnitude and phase of the IR-response of the detectors were investigated from 0.5 Hz to 100 kHz modulation frequencies, and from 0.8 to 20 micron wavelengths. Effects of the film-substrate thermal boundary resistance, R_{bd}, and the substrate-cold head thermal boundary resistance, R_{s-c}, were investigated. The effect of R_{bd} is shown to be significant in the response only at high frequencies, above 100 kHz. The response at low frequencies is found to be determined by R_{s-c} up to "knee" frequencies of 15, 60, and 600 Hz, for 0.05-cm thick $SrTiO_3$, $LaAlO_3$, and MgO substrates, respectively. A model for the bolometric response is developed, that correctly predicts the "knee" frequencies and the measured phase and amplitude of the response versus frequency up to about 10 kHz, including the predicted change from a f^{-1} to a $f^{-1/2}$ dependence at the "knee" frequency. At the low bias currents used to operate the bolometers, Joule heating effects are negligible. From the model and experimental data, a specific heat of 0.59 J/K-cm^3 has been deduced for $LaAlO_3$ at $T \approx 90$ K.**

I. Introduction

THE BOLOMETERS consist of thin films of YBCO deposited on various substrates (MgO, $SrTiO_3$, and $LaAlO_3$) and etched into meander line patterns. The substrate is attached to the cold head using vacuum grease. Thermal modeling is essential to analyze and predict the response of bolometers to radiation signals. To perform a thermal design of a bolometer, it is necessary to find the thermophysical properties of the superconducting film, substrate and the interfaces at the operating temperature. Most of the contemplated uses of superconducting bolometers involve mechanical chopping of the incident light; hence frequencies of up to a few kilohetz are of interest for applications. There have been several attempts at thermal modeling of superconducting bolometers for different ranges of modulation frequencies [1]–[4], but they do not account for all the effects observed. We have investigated the magnitude and phase of the IR-response of YBCO superconducting detectors versus modulation frequencies from 0.5 kHz to 100 kHz, and found that the observed frequency dependence requires a model that includes the thermal boundary resistances, and proper consideration of different regimes of heat flow in the substrate.

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We have developed such a model, and from the frequency dependence of the amplitude and phase of the bolometric response deduced the values of the thermophysical properties needed for design purposes.

In the basic model for the bolometer [5], [6], the responsivity, r_v, defined as the ratio of the voltage signal to the input power, is

$$r_v = \frac{\eta I}{G + j2\pi fC}\frac{dR}{dT} \tag{1}$$

where I is the dc bias current, dR/dT is the slope of the resistance versus temperature curve at the bias (or operating) temperature, and $\eta = W/P_t$, with W the incident power absorbed by the bolometer, and P_t the total incident radiation power at the surface of the detector. G is the total thermal conductance between the bolometer and its environment, and C is the heat capacity of the bolometer. However, at frequencies in the range of 100 Hz and above, the measured response deviates significantly from the values predicted by the above model [7], [8]. Instead of a f^{-1} dependence, $f^{-1/2}$ is found. We propose an equivalent circuit model for the bolometric response to radiation signals for modulation frequencies ranging from dc to high values, at which the response is determined by the heat capacity of the film, and the film-substrate thermal boundary resistance.

In this paper we present measurements and analysis of the magnitude and phase of the response of YBCO bolometers to radiation signals, with modulation frequencies up to 100 kHz. In this range of frequencies the only film property of importance is dR/dT. The IR-response to radiation signals with 0.8–20 μm wavelengths was studied, and found to be essentially independent of wavelength. The effect of Joule heating due to the dc bias current on the response of the samples was found to be negligible for the test currents used.

II. Experimental Setup

The characterization system for the low temperature measurements is the same as reported previously [6], [8], except that it has been automated to take simultaneous resistance and the IR-response measurement versus temperature, and IR-response versus modulation frequency. To cool the samples the cold stage of a Cryo-Torr 100 (CTI-Cryogenics) cryopump is used [7]. To improve the thermal contact between the substrate and the cold head a very thin layer of vacuum grease (Apiezon

TABLE I
MEASURED DIMENSIONS OF THE YBCO PATTERNS, AND THE DC THERMAL CONDUCTANCE OF THE BOLOMETERS

sample number	substrate material	d_f (nm)	d_s (cm)	A (cm^2)	Area of the meander line	$T_{c\text{-zero}}$ (K)	$T_{c\text{-onset}}$ (K)	R (kΩ)	G (W/K)
0644-01a	$SrTiO_3$	220–230	0.05	0.0168	50 μm × 1.9 cm	79	82	10.0	3×10^{-3}
0644-02a	MgO	120-130	0.025	0.075	90 μm × 3.35 cm	76	87	13.5	33×10^{-3}
064-02b	MgO	120–130	0.025	0.0168	50 μm × 1.9 cm	74	86	11.2	7.2×10^{-3}
064-03a	MgO	170–180	0.05	0.075	90 μm × 3.35 cm	68	82	7.7	11×10^{-3}
064-03b	MgO	170-180	0.05	0.0168	50 μm × 1.9 cm	69	83	6.5	5.1×10^{-3}
064–04b	$LaAlO_3$	190–200	0.05	0.075	90 μm × 3.35 cm	83	84.5	17.5	7.8×10^{-3}

N) is applied to the back of the substrate. A low noise resistance measurement using a four probe configuration is made, using a current source, consisting of a battery, and a bias resistor with a resistance of at least 20 times the normal resistance of the samples. The data is taken by a computer using the available dc outputs of a lock-in amplifier (EG&G 5406), and is plotted simultaneously during the measurement. A computer-controlled heater, stabilizes the temperature to within 0.1 K.

An LED (HFE4020, Honeywell) with a peak wavelength of 0.85 μm is used as the radiation source in most of the measurements. The intensity of the radiation can be controlled by either the current through the source, or the distance between the source and the samples. For longer wavelengths, a blackbody source with a maximum chopping frequency of 1500 Hz was used. The spectral response of the samples was measured by use of FT-IR spectrometers (*a*—Galaxy series FTIR-3000, Mattson Instruments, Inc.; *b*—20SXC FT-IR Spectrometer, Nicolet Inc.) especially modified for four probe measurements.

III. SAMPLE PREPARATION

Samples are made of YBCO films with about 120–230 nm thicknesses on single crystal substrates. The films are deposited using an off-axis dc planar magnetron sputtering technique with 715°C–725°C substrate temperatures, and ~0.9 nm/min deposition rate. X-ray patterns of the films show a preferential c-axis orientation. Details on the deposition parameters and the properties of the films are contained in [7], [9].

The samples are patterned using standard photolithography (positive photoresist) and etched in about 0.75% (by volume) dilute phosphoric acid. Higher concentrations of the acid are found to cause undercutting of up to a few micrometers [7], [8]. After etching, some loosely bound residue was observed on the surface of the substrate. SEM studies show this residue to consist of inclusions of a phase intrinsic to the film, which cannot be etched away by phosphoric acid.

From (1) the responsivity is proportional to dR/dT. Since the width of the transition is a material property determined by the deposition conditions, designs of meander line patterns with contact areas for 4-probe measurements have been used to control the value of dR/dT at the middle of the transition. A 50-μm linewidth pattern is used for samples 064-02b and 064-03b, and a 90-μm linewidth pattern is used for samples 064-02a, 064-03a, and 064-04b. Sample substrates have a 0.5 cm × 1 cm area, with 0.25 mm or 0.5 mm thickness. Transition temperatures ($T_{c\text{-zero}}$ and $T_{c\text{-onset}}$) total area of the patterns, and the area of the meander lines, with the substrate and film thicknesses are given in Table I. In Table I the dimension of the substrate is about 0.5 cm × 1 cm for all the samples and the substrates are attached to the cold head using a thin layer of Apiezon-N grease; d_f is the thickness of YBCO film, d_s is the thickness of the substrate, A is the total area of the pattern, and R is the resistance of the film at room temperature ($T = 300$ K). The resistance versus temperature of the samples are found to change due to high bias currents and thermal cycling [8], with the transition temperature of the samples shifting to lower temperatures due to high bias currents and recovering due to thermal cycling [7]. The contact areas for the four-probe measurement were coated with a ~85-nm layer of sputtered gold or ~60-nm layer of sputtered silver. Electrical contacts to the samples were made using copper wires (32-gauge) and silver epoxy dried at room temperatures overnight [7], [8].

IV. DISCUSSIONS AND EXPERIMENTAL RESULTS

As given in (1), r_v is a complex number with a magnitude of

$$|r_v| = \frac{\eta I}{G\sqrt{1+(2\pi f \tau)^2}} \frac{dR}{dT} \tag{2}$$

where $\tau = C/G$, and I is the constant dc bias current. Effects due to the variation of the bias current have been studied and can be found in [7]. If one assumes G and C are constant and independent of modulation frequency, then based on the above model, at frequencies where $2\pi f\tau \gg 1$, the voltage response of a bolometer exposed to incident radiation should scale as f^{-1}. The phase of the response in any frequency range is

$$\theta = \tan^{-1}\left(\frac{-2\pi f C}{G}\right) = \tan^{-1}(-2\pi f \tau). \tag{3}$$

In the samples τ is on the order of 0.3 s, hence the $2\pi f\tau \gg 1$ regime holds at as low as a few Hz, where the model above works quite well [6]–[8].

A. *Calculation of the Response*

To compare our results to (2), we have determined the dc thermal conductance of the YBCO film to the surrounding environment, $G(0)$, in several different ways [7], [8]. The most convenient way is to make use of the slope of the resistance versus temperature curves of the films in the normal state near T_c [8], [10]. At high bias currents, the resistance of the

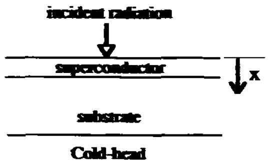

Fig. 1. A typical experimental configuration of a superconducting film bolometer on ceramic substrate, with thermal contact to a holder (cold-head).

bolometer increases due to power dissipation heating the film. This creates a temperature gradient across the substrate and the thermal interfaces. The increase in the resistance of the film due to the Joule heating is [10]

$$\Delta R = I^2 R \frac{dR}{G dT}. \tag{4}$$

Using the measured values for R, I, and dR/dT, values of G were obtained and are given in Table I.

The heat capacity, C, and the time constant, τ, can be found by use of (3) as

$$\tau = -(\tan\theta)/2\pi f = C/G \tag{5}$$

where θ is the measured value of the phase of the response. Using (5) and the measured values of θ at low frequencies, τ is calculated for sample 064-04b and is found to be ~0.32 s at frequencies less than 2 Hz. Using the measured values of G = 7.8 mW/K, τ = 0.32 s, and dR/dT = 3850 Ω/K (from R versus T curve), the response versus frequency of the sample is calculated for $\eta = 1$ using (2), and is given in Fig. 2. The calculation is done for 0.68-mA bias current, 2.13 mW/cm^2 incident radiation power and an effective absorbing area of 0.03 cm^2, corresponding to the values used in the measurement.

In the calculation of the response, the effect of Joule heating in the film, caused by the bias current, should be considered. The change in the film resistance due to the input radiation power is augmented by the I^2R heating, and is a form of positive feedback. This can enhance the response resulting in an overall responsivity of

$$r_{v-t} = \frac{r_v}{(1 - I r_v/\eta)} \tag{6}$$

where r_v is given as in (1). As observed in (6), there is a stability criteria in the voltage response which has the same form as obtained for dc biasing at zero frequency [5], [7]. Since the bias current in our samples is on the order of 10^{-3} A, and the responsivity maximum is on the order of 10^0 V/W, even at low frequencies, the effect of the Joule heating is negligible. However, in very sensitive devices or at high currents, it could become a significant factor.

The difference between the measured and calculated response at low frequencies is mostly expected to be due to the assumption of $\eta = 1$. Results similar to those reported by other groups [11]–[13] have been obtained for our test samples. The spectral response of sample 064-01a was measured with radiation from blackbody source; 3–20 μm wavelengths were used, as shown in Fig. 3. While one interference fringe with a period of about 10 μm was observed, the response was found

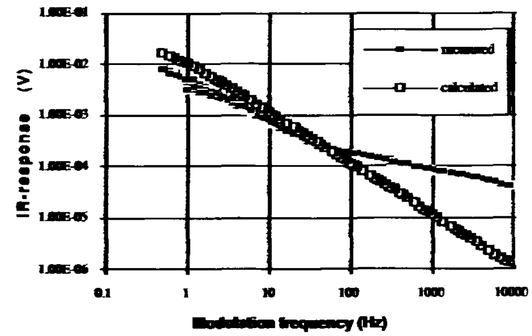

Fig. 2. Measured and calculated IR-response versus modulation frequency of sample 064-04b (0.05-cm thick $LaAlO_3$ substrate). The measurement is done at 81.7 K with 0.68 mA dc bias current and 2.13 mW/cm^2 radiation intensity.

to be essentially independent of the wavelength. The frequency response of the sample at longer wavelengths was carried out using a 500 K blackbody source, and modulation frequencies up to 1.5 kHz [7]. The frequency response observed, was the same as seen for the 0.85 μm source.

As reported earlier [8] and shown in Fig. 2, the model based on constant C and G (1), can explain the response of the bolometers only for relatively low frequencies, where the response is limited by the thermal boundary resistance, R_{s-c}, between the substrate and cold head. A more accurate model requires consideration of the thermal diffusion length for the radiation-induced temperature rise into the substrate, and both thermal boundary resistances. At very low frequencies the response does follow (1) [8], where C and G are constant, and G is interpreted to be mainly due to the substrate-cold head thermal boundary resistance, as will be verified below.

B. Calculations of the Frequency Dependent Thermal Parameters

To study the thermal response of the samples, we model our substrates as a cylinder and use the heat diffusion equation. In this model the radiation absorbing area is at one end of the cylinder [7]. This assumption will turn out to be valid since the film thickness of our samples is much smaller than the substrate thicknesses and the patterns of the superconducting films are relatively large in comparison to the substrate thicknesses (see Table I).

Solving the diffusion equation in the substrate material, $D\nabla^2 T = \partial T/\partial t$, as a function of the distance from the surface, x, and time, t, and knowing the temperature at the surface will result in [7]

$$T(x,t) = T_0 \exp\left[i\left(\left(\frac{i2\pi f}{D}\right)^{1/2} x - 2\pi f t\right)\right] \tag{7}$$

where T_0 is the temperature at $x = 0$ and $t = 0$, $D = k_s/c_s$ has units of centimeter square per second in the CGS system, and is called the diffusivity of the material, and k_s and c_s are the thermal conductivity and the specific heat (per unit volume) of the substrate material, respectively.

A quantity L, called the "thermal diffusion length," can be used in (7), and is defined as

$$L = \left(\frac{D}{\pi f}\right)^{1/2}. \tag{8}$$

It represents the characteristic penetration depth of the temperature variation into the substrate. Considering the thermal diffusion length as the effective length for heat flow into the substrate, the corresponding thermal conductance can be found from [2]

$$G = ak_s\frac{A}{L} \tag{9}$$

where k_s is the thermal conductivity of the substrate material and a is a correction factor for the above approximation of the length of the heat flow. Substituting the value of L from (8) in (9), and using $D = \frac{k_s}{c_s}$

$$G_s = aA\sqrt{c_s k_s \pi f}. \tag{10}$$

Thus G_s will be a function of frequency and scales as $f^{1/2}$, increasing with the frequency. Similarly, the volume of the substrate in which the temperature variation occur changes with the frequency due to the thermal diffusion length. Hence, for the total heat capacity, C_s, we can write

$$C_s = bc_s AL = bA\sqrt{c_s k_s/\pi f} \tag{11}$$

where b is a constant to compensate for the drop of the amplitude of the temperature variation along L. Hence, C_s will also be a function of frequency and scale as $f^{-1/2}$. Under the above assumptions, τ will be

$$\tau = \frac{C_s}{G_s} = \frac{b}{a\pi f} \tag{12}$$

which will be frequency dependent, scaling as f^{-1}.

Considering frequencies low enough to allow the total heat conductance $G_t \approx G_s$ and the total heat capacity $C_t \approx C_s$, then by use of (12) in (1), we get

$$r_v = \frac{r'}{1 + j2b/a} \tag{13}$$

where $r' = \frac{\eta I}{G_t}\frac{dR}{dT}$. Equation (13) shows that the phase of the response is constant and frequency independent for the frequency range where the thermal diffusion length is smaller than the thickness of the substrate; yet since G_s scales as $f^{1/2}$, r' will scale as $f^{-1/2}$, and the magnitude of the response will be frequency-dependent. This is valid at frequencies where the thermal conductance of the YBCO film, G_f, and the film-substrate interface, $G_{\text{bd}} = 1/R_{\text{bd}}$, are negligible compared to G_s.

A circuit diagram of the proposed thermal model of a superconducting bolometer is shown in Fig. 4. In this model, the substrate-cold head thermal boundary resistance and the total YBCO film-substrate thermal boundary resistance are considered as $R_{s\text{-}c}$ and $R_{\text{bd-}t}$, respectively. The substrate is considered to be made of small increments (thin layers of substrate material) which can be shown by a combination of R_i and C_i in the circuit diagram.

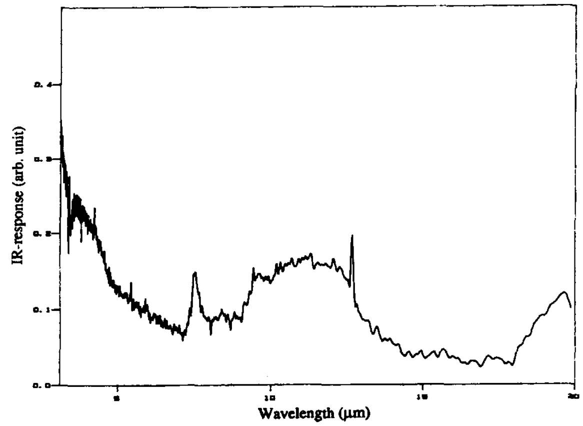

Fig. 3. Spectral response of sample 064-01a, up to 20-μm wavelength (measured at EG&G, Judson Infrared Inc.). The response is measured at the middle of the superconducting transition with 0.55 mA bias current.

Now, for the overall frequency response analysis (from dc to high frequencies) assume that $C_f \ll C_s$ and $R_{\text{bd-}t} \ll R_s \ll R_{s\text{-}c}$ (or, $G_{s\text{-}c} = 1/R_{s\text{-}c} \ll G_s \ll G_{\text{bd-}t} = 1/R_{\text{bd-}t}$), which will be shown to be the case in our samples. Where $R_{\text{bd-}t}$ is the total thermal boundary resistance at the film-substrate interface. Based on these assumptions, at very low frequencies, the heat capacity of the film can be ignored compared to that of the substrate, and the total thermal conductance will be

$$\frac{1}{G_t} = \frac{1}{G_{s\text{-}c}} + \frac{1}{G_s} + \frac{1}{G_{\text{bd-}t}}. \tag{14}$$

Since $G_{s\text{-}c} \ll G_s(0) \ll G_{\text{bd-}t}$, we will have $G_t \approx G_{s\text{-}c}$ which is not frequency-dependent. Then, the response can be obtained from [7]

$$\Delta T_f = \frac{1}{G_{s\text{-}c} + j2\pi f C_s(0)} W \tag{15}$$

where ΔT_f is the temperature variation at the film and $\tau_0 = C_s(0)/G_{s\text{-}c}$. Then, ignoring the effect of the Joule heating, the responsivity of the bolometer is given by (1) with a frequency dependence of f^{-1}, and a phase angle of $-90°$, for frequencies at which $2\pi f \gg 1$, but not so high as to limit the thermal diffusion length.

When the frequency increases to the values where the thermal diffusion length in the substrate, L, becomes comparable to the thickness of the substrate, G and C will no longer be constant. Based on the above assumptions, $G \approx G_s$ and $C \approx C_s$, they are frequency-dependent following (10) and (11), respectively, and the response is governed by

$$r_v = \frac{\eta I}{G_s + j2\pi f C_s}\frac{dR}{dT} \tag{16}$$

where still $C_f \ll C_s, G_s \ll G_{\text{bd-}t}$. By applying the frequency dependence of the G_s and C_s in (16), the response will be in the form of (13), i.e., $r_v \sim f^{-1/2}$. As the frequency increases further, $G_s(f)$ increases further (or $R_s(f)$ decreases) until it becomes comparable to $G_{\text{bd-}t}$ where C_f and $R_{\text{bd-}t}$ can no

TABLE II
THERMAL CHARACTERISTICS OF SINGLE CRYSTAL SUBSTRATE

Substrate	k_s (W/K-cm^3)	c_s (J/K-cm^3)	D (cm^2/s)	$f_{L=0.05\ \mathrm{cm}}$ (Hz)
MgO	3[a]	0.53[a]	5.66	720
$LaAlO_3$	0.32[b]	0.59	0.55	70
$SrTiO_3$	0.052[c]	0.43[c]	0.12	15.4

[a]From [2].
[b]From [14].
[c]From [17].

longer be ignored. At high enough frequencies, the G_s and C_s can be ignored and the response will be determined by G_{bd} (or $1/R_{bd}$) and C_f as reported by others [14], [15].

C. Frequency Response Analysis and the Experimental Results

Based on above analysis, the point at which the response start to scale as $f^{-1/2}$ occurs at frequencies where the thermal diffusion length, L, becomes comparable to the thickness of the substrate. Since from (8), L is proportional to the square root of the thermal diffusion constant, $D = k_s/c_s$, substrate materials with higher k_s, will have knee points in the response at higher frequencies (assuming the substrate thicknesses are the same and c_s of the substrates are within the same range). The values of k_s, c_s and the calculated frequency of the knee point, f_L, of three different substrates used in this work are given in Table II; in Table II f_L is the calculated "knee" frequency at which the thermal diffusion length becomes equal to the thickness of the substrate, k_s is the thermal conductivity, c_s is the heat capacity per unit volume, and D is the diffusivity of the substrate material. The substrate thicknesses are 0.05 cm. The value of c_s for $LaAlO_3$ is derived using the phase of the low frequency response [7], [8], and is consistent with the measured experimental values shown for MgO and $SrTiO_3$. However, we know of no measured values of c_s for $LaAlO_3$.

The values of f_L are calculated by use of (8). For example, to find the frequency at which the thermal diffusion length is 0.05 cm for a $SrTiO_3$ substrate, we can use (8) in the form of

$$f_L = \frac{D}{\pi L^2}. \tag{17}$$

For the $SrTiO_3$ substrate from Table II we have

$$D = \frac{k_s}{c_s} = \frac{0.052}{0.43} = 0.121\ \mathrm{cm^2/s}. \tag{18}$$

By applying (18) and $L = 0.05$ cm in (17), we get $f_L = 15.4$ Hz as given in Table II. The measured responses versus frequency for 0.05-cm thick single crystal $LaAlO_3$, MgO, and $SrTiO_3$ substrates are shown in Figs. 2, 5, and 6, respectively. From the figures, the knee points in the response versus frequency are about 15, 60, and 600 Hz, for 0.05-cm thick $SrTiO_3$, $LaAlO_3$, and MgO substrates, respectively, in good agreement with the calculated values in the table.

To verify the above analysis and to investigate the effect of the thickness of the substrate on the frequency response, we consider two samples with identical meander line patterns on 0.25- and 0.5-mm thick MgO substrates. The response of the samples 064-02a and 064-03a are shown in Fig. 5. As shown in the figure, the knee point is found to be dependent on the substrate thickness, and it is found not to be dependent on the pattern area. The knee point for the thinner substrate sample 64-02a occurs at higher frequencies, about 2.5–3 kHz, whereas for the thicker substrate sample 64-03a, it occurs at about 700–800 Hz. Setting the thickness of the substrate equal to L in (17), and using the values of c_s and k_s from Table II for MgO, knee points at frequencies of 720 Hz and 2.8 kHz are calculated for samples 64-03a (0.05-cm thick) and 64-02a (0.025-cm thick), respectively. The above calculated values of frequency agree with the break frequencies seen in Fig. 5.

From (13), for frequencies higher than f_L, the phase should be frequency independent. Fig. 7 shows the measured phase of

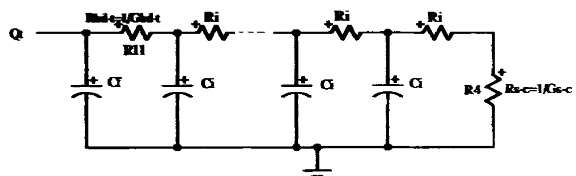

Fig. 4. Circuit diagram of thermal model for bolometric response of a high temperature superconducting bolometer.

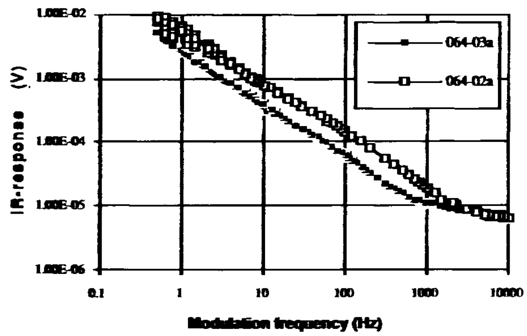

Fig. 5. Measured IR-response versus frequency for 0.05-cm thick MgO substrate sample 064-03a and 0.025-cm thick MgO substrate sample 064-02a. The measurements are done at middle of the superconducting transition with 1 mA dc bias current and 2.13 mW/cm^2 radiation intensity.

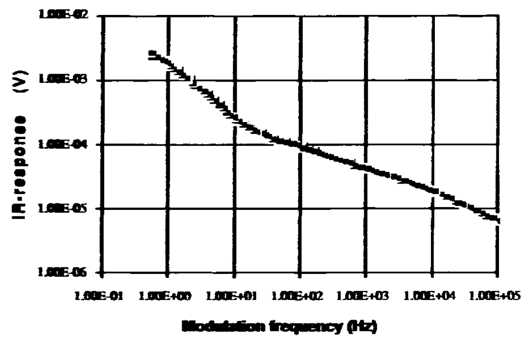

Fig. 6. IR-response versus modulation frequency of 0.05-cm thick $SrTiO_3$ substrate sample 064-01a measured at 0.25 mA bias currents. The measurement is done at 2.13 mW/cm^2 radiation intensity.

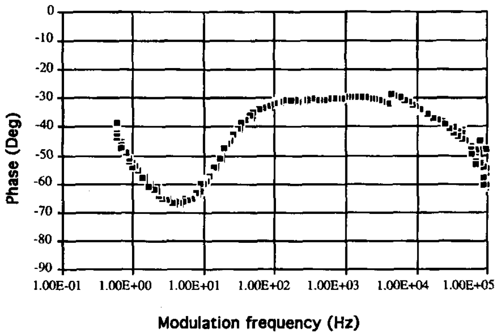

Fig. 7. Phase of IR-response versus modulation frequency of sample 064-01a (0.05-cm thick $SrTiO_3$ substrate) under the conditions given in Fig. 6.

the response for sample 064-01a, which confirms the position of the break frequency discussed above. The flat region in Fig. 7 extends only to about 10 kHz, but it should continue up to the frequencies where the response and its phase starts to be governed by the effect of R_{bd}, according to our model. Since the YBCO film is just a few 100-nm thick, the heat capacity of the film, C_f, is very low, and the phase of the response should approach 0° for the frequency range where the response is limited by the effect of R_{bd}, and continue until much higher frequencies. The frequency at which R_{bd}, the film-substrate thermal boundary resistance, becomes important varies with the thermal parameters of the substrate material. It is lower for substrate materials with higher k_s (assuming c_s of the substrates are within the same range) [7]. Using c_s and k_s from Table II, and a typical value for R_{bd} as 1.1×10^{-3} K·cm²/W [14], we can compare this with the frequency-dependent thermal resistance of the substrate, as calculated from (10). The thermal resistance due to R_{bd} is found to be equal to the thermal resistance of MgO, $LaAlO_3$, and $SrTiO_3$ substrates at modulation frequencies of 165.4 kHz, 1.413 MHz, and 11.67 MHz, respectively. These frequencies are calculated for the case that the corresponding thermal diffusion lengths are small compared to the width of the meander lines of the superconducting pattern, which is the case in our samples. For smaller patterns, the spacings between the lines should also be considered, which will result in frequencies lower than above [7].

One can estimate the frequencies at which R_{bd} and c_s would change the phase, and this is found to be in the 10 to 50 MHz range. Hence this cannot account for the drop in the phase seen in Fig. 7. The drop in the phase at frequencies of about 10 kHz is also observed for samples with MgO and $LaAlO_3$ substrates. This departure from our model for the thermal response of the samples may be due to other effects, such as the system circuitry [7], or photo-induced conductivity changes in the YBCO film [16]. However, our model accurately accounts for the observed behavior below 10 kHz, which is important frequency range for bolometer applications.

V. Conclusion

To explain the observed behavior of YBCO bolometers it is necessary to include in the thermal modeling, the effects of thermal boundary resistances and the frequency dependence of the thermal diffusion length. We have developed such a thermal model that explains the modulation frequency dependence in the low and midfrequency range, up to ~10 kHz that is the range of interest for contemplated applications of bolometers. At dc and low frequencies, below the knee points, values of the total thermal conductance, G, of our samples are found to be due to the substrate-cold head interface. At higher frequencies, above the knee points, the thermal diffusion length into the substrate is less than the substrate thickness, and G is determined by the substrate material's thermal conductance. This change in G affects the slope of the response versus modulation frequency curve. From the measurements, the slope of the response changes at "knee" frequencies of about 15 Hz, 60 Hz, and 600 Hz for 0.05-cm thick $SrTiO_3$, $LaAlO_3$, and MgO substrates, respectively, from a f^{-1} to a $f^{-1/2}$ dependence, showing good agreement with model calculations. The effect of the substrate thickness was also investigated and the results are also in agreement with the model. The measured frequency response is found to be independent of the radiation wavelength out to 20 μm.

The effect of the film-substrate thermal boundary resistance, R_{bd}, on the IR-response was investigated, and is not expected to be important below modulation frequencies of 165 kHz, 1.4 MHz, and 12 MHz, in MgO, $LaAlO_3$, and $SrTiO_3$, respectively, which are higher than the frequency range used in our measurements.

To improve the responsivity of the bolometer in the various regimes of frequency, for a fixed transition region width, thinner films with narrow linewidth and a long meander line are favored (to increase dR/dT). The minimum thickness of the film is limited by the need for high absorption in the film, which gives a minimum thicknesses of about 150 nm [7]. From (1), one sees that a high G value, $G \gg 2\pi fc$, lowers the responsivity, and pins the phase of the response at $\theta = 0°$. A low G value, $G \ll 2\pi fc$, gives $\theta = -90°$, a f^{-1} dependence to the responsivity, and a magnitude inversely proportional to the heat capacitance of the bolometer. For this latter case a very thin substrate to reduce C is indicated.

In the regime of the $f^{-1/2}$ dependence for the responsivity, thinning the substrate underneath the pattern to increase the responsivity is dependent on the thermal diffusion length determined by the operating frequency. Minimum required thinning of the substrate to improve the responsivity can be obtained from (8). As an example, for a bolometer on a $LaAlO_3$ substrate working at a modulation frequency of 400 Hz, the thermal diffusion length will be about 209 μm. Hence, to improve the responsivity of such a bolometer, thicknesses less than 209 μm are required. While G can be made very small by isolating the substrate (underneath the pattern) from the cold head, the minimum $G(0)$ is needed to keep the sample in the superconducting state, and within a ΔT of its bias temperature. For our samples with measured G's on the order of 10^{-2} W/K, Joule heating power on the order of $I^2R = 10^{-2}$ W yields a shift temperature on the order of 1 K. Hence as a practical matter, a G much smaller than our values would present a problem in maintaining the bias temperature for currents on the order of 1 mA.

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