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Temperature dependence of the phase of the response of YBCO edge-transition bolometers: effects of superconductivity transition and thermal parameters

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Abstract

The variation of the phase of the response of YBCO edge-transition bolometers on crystalline MgO substrate is found to be dependent on the normal–superconducting transition. The phase of the response for $T < T_c$ increased at low modulation frequencies where the thermal diffusion length into the sample substrate from the top absorbing YBCO film is longer than the substrate thickness. The substrate/cold-head boundary resistance mainly dominates the thermal conductance of our samples at low frequencies. This transition-dependent change of the phase of the response is interpreted to be due to the effects of the order parameter of the YBCO material on the phonon spectrum and hence the determining Kapitza boundary resistance. The phase of the response decreased at high modulation frequencies where the thermal diffusion length into the substrate is less than the substrate thickness. The results of our analytical model for the low modulation frequencies agree well with the measured values for temperatures close to the $T_{\text{c-zero}}$.

1. Introduction

Since the discovery of high-temperature superconductors, many works have been focused on the application of these materials in different types of bolometers for the near and far infrared wavelength regime [1–6]. The physical principle operation of the edge-transition bolometers is based upon the steep drop in their resistance, R, at critical temperature T_c. The responsivity versus modulation frequency and versus the temperature of superconducting bolometers has previously been investigated and reported [7, 8]. A simple RC-model [8] for the amplitude of bolometric response results in the following expression:

$$r = \left(\frac{\varsigma I}{G(1 + j\omega\tau)}\right)\frac{\mathrm{d}R}{\mathrm{d}T}, \tag{1}$$

where $\tau = C/G$, I is the dc bias current, ς is the fraction of the incident power absorbed by the bolometer, ω is the modulation frequency, r is the frequency-dependent responsivity in units of V W^{-1}, and G and C are the thermal conductance and the heat capacity of the bolometer, respectively. As shown in (1), thermal conductance G is a major parameter in the amplitude of the response function.

According to (1) the temperature-dependent phase of the response can be calculated by the formula

$$\tan\theta = -\frac{\omega C}{G}. \tag{2}$$

It is important to understand the factors that determine G and C of the bolometers as a function of the temperature, frequency and other parameters of the bolometer configuration.

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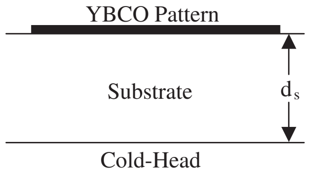

Figure 1. Sample configuration in contact with gold-coated OFE copper cold-head. d_s is the substrate thickness.

We have developed thin-film YBaCuO on crystalline MgO bolometers. Here we report on the phase of the response to infrared signal of the edge-transition bolometers versus temperature at high and low modulation frequencies. We propose a model that can explain the observed discrepancy in the measured response versus temperature compared to that expected from other models. According to our model, the thermal constants G and C change as a film goes into the superconducting state. This might also partly be accounted for some observed non-bolometric component of the response in these types of bolometers.

2. Experimental results and their analysis

The typical configuration of the studied samples is shown in figure 1. A sample holder was designed and made of high purity and high conductive oxygen-free copper. 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 maximum of about 200 mA with a precision of 0.1 K. As shown in figure 1, there are two thermal boundary resistances at the substrate interfaces, one at the film interface and the other at the holder interface. There are also two major bulk areas which constitute the overall heat capacity of the samples, one due to the superconducting film and the other due to the substrate material. The thickness of the superconducting YBCO film was about 200 nm. The phase and magnitude of the response versus temperature at different frequencies were measured using a lock-in amplifier. A light emitting diode with a peak radiation wavelength of about 0.85 μm was used as the radiation source for the response versus modulation frequency studies in all the measurements.

In analysing the different operation regimes of the edge-transition bolometer parameters, the frequency dependence of the thermal diffusion length plays an important role. It is well known that thermal diffusion length into substrate, L_f, is determined as [9, 10]

$$L_f = \left(\frac{D}{\pi f}\right)^{1/2}, \tag{3}$$

where $D = K/C$ is the thermal diffusivity of the substrate material, and K and C are the thermal conductivity and specific heat (per unit volume) of the substrate material, respectively. At high chopping frequencies, L_f becomes comparable to or smaller than the substrate thickness changing G. Then G is limited by the thermal conductance of the substrate material and can be obtained from

$$G = \frac{KA}{L}, \tag{4}$$

where L and A are the thickness of the substrate and the area of the superconducting pattern, respectively.

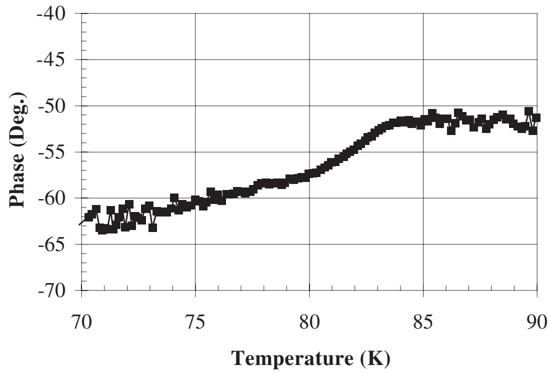

Figure 2. Phase of the response versus temperature at low modulation frequency of 20 Hz and 680 μA dc bias current. The phase increases by the lowering of the temperature.

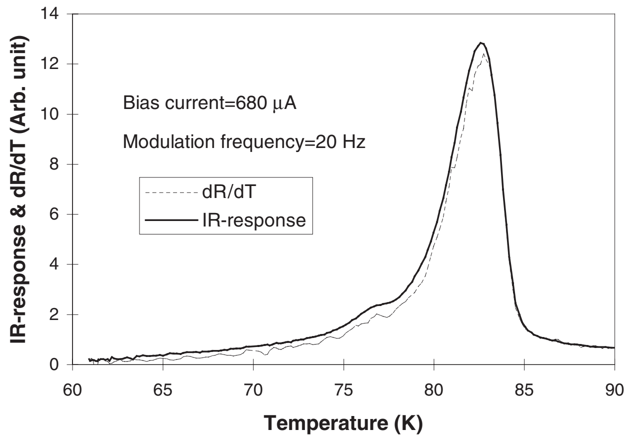

Figure 3. Amplitude of the response versus temperature at 20 Hz modulation frequency and 680 μA dc bias current.

The phase of the response of the samples is found to be more sensitive to the values of the characteristic parameters of the bolometers than the magnitude of the response. The phase of the response has shown a strong variation as the sample goes through the normal–superconducting transition both at low and high modulation frequencies also showing modulation frequency dependence. At low frequencies, the phase of the response starts to decrease as the temperature decreases below about the onset temperature of the normal to superconducting transition (i.e., at $T < T_{\text{c-onset}}$). Opposite behaviour has been observed at high modulation frequencies, i.e. the phase of the response starts to decrease at $T < T_{\text{c-onset}}$. This clearly indicates that large changes in the phase and magnitude of response are mainly associated with the differences in the conduction mechanisms in the normal and superconducting states, rather than the well-known temperature dependence of the interface boundary resistance.

2.1. Low-frequency regime

At low modulation frequencies the phase of the response versus temperature increases by decreasing the temperature starting at $T < T_{\text{c-onset}}$ as shown in figure 2. The respective amplitude of the response normalized to the measured $\mathrm{d}R/\mathrm{d}T$ of the superconducting film at $T < T_{\text{c-onset}}$ for low modulation frequencies is shown in figure 3. The amplitude of the response in figure 3 increases above the expected value determined by the dR/dT of the film as the temperature is lowered towards the $T_{\text{c-zero}}$. Such behaviour would be consistent with a decrease of the thermal conductance of the bolometer. The variation of the heat capacity at low temperatures, reveals typical T^3 dependence behaviour [11]. At low modulation frequencies ($\omega = 20$ Hz), the thermal conductance in the studied samples is determined by the substrate/cold-head interface conductance, or the so called Kapitza boundary resistance, caused by the acoustic mismatch impedances of the interfaced materials [7, 8]. According to (3), by lowering the frequency the thermal diffusivity length into the substrate becomes longer than the substrate thickness and phonons emitted by the superconducting film into the substrate will reach the substrate/cold-head boundary.

The observed thermal boundary conductance at the substrate/cold-head interface can be explained by the theory of Kapitza conductance. It is well known that Kapitza conductance is the derivative of the net heat flux transmitted across an interface with respect to the temperature difference between the two materials [12]. Therefore, if we consider an interface between materials A and B, we can write G_K as

$$G_K = \frac{1}{V}\frac{\partial}{\partial T}\sum_k \sum_j^A \hbar\omega_{kj} n(\omega_{kj}, T) v_{kjz} t_{kj} \tag{5}$$

$$= \frac{1}{V}\frac{\partial}{\partial T}\sum_k \sum_j^B \hbar\omega_{kj} n(\omega_{kj}, T) v_{kjz} t_{kj}, \tag{6}$$

where the labels A and B on the sums indicate that all quantities in each sum correspond to phonons incident on the interface from the materials A and B sides, respectively. In equations (5) and (6), ω_{kj} is the phonon frequency, v_{kjz} is the component of the phonon group velocity normal to the interface, $n(\omega_{kj}, T)$ is the Bose–Einstein distribution function, t_{kj} is the probability that a phonon of wave vector **k** and polarization j will be transmitted across the interface between materials A and B, and V is the volume. The Kapitza conductance can be calculated at low temperatures ($\hbar\omega_D/kT \gg 1$) analytically taking into account Debye phonon density of states, which can be obtained from

$$D(\omega) = V^{-1}\sum_{kj}\delta(\omega - \omega_{kj}) = \frac{\omega^2}{2\pi^2 c^3}, \tag{7}$$

where c is the velocity of sound in the material. As a result of calculations, the thermal conductance has T^3 characteristics at low temperatures and remains constant at high temperatures. The phonon system in each material in the above calculations is considered to be of the equilibrium nature. However, in the calculation of the boundary conductance of the substrate/cold-head interface we should take into account the phonon density of the state spectrum of the non-equilibrium phonons, which propagate into the MgO substrate and reach boundary substrate/cold-head (the diffusion regime of propagation of phonons). Hence, one should determine the differences in the photo-absorption process in normal and superconducting states. As shown by the analysis of thermalization and photo-absorption in YBaCuO superconductors [13], interaction between hot quasi-particles and Cooper pairs condensate continues to divide the excess energy by forming three quasi-particles. The hot quasi-particles continue to break additional pairs by the electron–electron interaction process as they thermalize toward the energy gap by discrete energy steps. As a result we have a characteristic feature—a jump at frequency $\omega = 2\Delta(T)$ due to the activation of the recombination mechanism of phonon generation [14] (for $\omega \leqslant 2\Delta(T)$, phonons are generated as a result of the energy relaxation of high energy quasi-particles). The phonon distribution function (product of $D(\omega)n(\omega, T)$) has fairly narrow maximum near $\omega = 2\Delta(T)$ [15], i.e. in our calculation we should replace Debye phonon density of states by the Einstein phonon density function

$$D(\omega) = \omega^2\delta(\omega - 2\Delta(T)). \tag{8}$$

Assuming that transmission probability and normal component of the group velocity to the interface to be independent of temperature, equation (5) can be rewritten as

$$G_K = \frac{1}{V}\sum_j \int_0^{\omega_{\text{Debye}}} d\omega\, \hbar\omega_{kj} D(\omega)\frac{dn(\omega_{kj}, T)}{dT} v_{kjz} t_{kj}, \tag{9}$$

where for $dn(\omega, T)/dT$ we have the following expressions:

$$\frac{dn(\omega, T)}{dT} = \begin{cases} \dfrac{k}{\hbar\omega} & \dfrac{\hbar\omega}{kT} \ll 1 \\ \frac{k}{\hbar\omega}x^2\exp(-x) & x = \frac{\hbar\omega}{kT} \gg 1. \end{cases} \tag{10}$$

It is clear that at high phonon frequencies, $2\Delta(T)$ is about the equilibrium temperature of the substrate T and the contribution of the non-equilibrium phonons to the heat transfer has exponential behaviour. As shown by the above calculations, at temperatures close to critical temperature $2\Delta(T) \ll T$, where $\Delta(T) = \Delta_0(1 - T/T_c)^{1/2}$ (standard BCS theory, see for example, [16]), low frequency phonons do not influence heat transfer process and boundary conductance at substrate/cold-head. Hence, the calculated normalized conductance based on expressions (8)–(10) are in good agreement with the experimental data for the thermal conductance versus temperature at low modulation frequency. The discrepancy between the experimental data and calculations at temperatures close to T_c shown in figure 4 is interpreted to be associated with the tendency of the emitting phonon frequency to zero. Here we also consider superconducting materials without fluxons. It is clear that temperatures close to the T_c can easily lead to Abrikosov vortexes in the films. In the equilibrium, fluxons are present in the film and move due to the thermal activations. The optical photons also create additional fluxons and the flux motion (creep and flow). This factor can lead to the non-bolometric component in the optical response, not considered in the above calculations. In our opinion, discrepancy between theory and experiment can also be related to flux dynamics near T_c. This argument is suggested by the experimental data from [7]. As shown in this paper, for the samples with sharper transition, the change in the phase of the response and the discrepancies at low frequencies are smaller. One of the possible reasons for the broadening of the transition into a superconducting state is the penetration of the fluxons into the samples. Another possible improvement of our model is connected with using realistic behaviour of the order parameter close to T_c and d-wave characteristics of the pairing in YBaCuO compounds

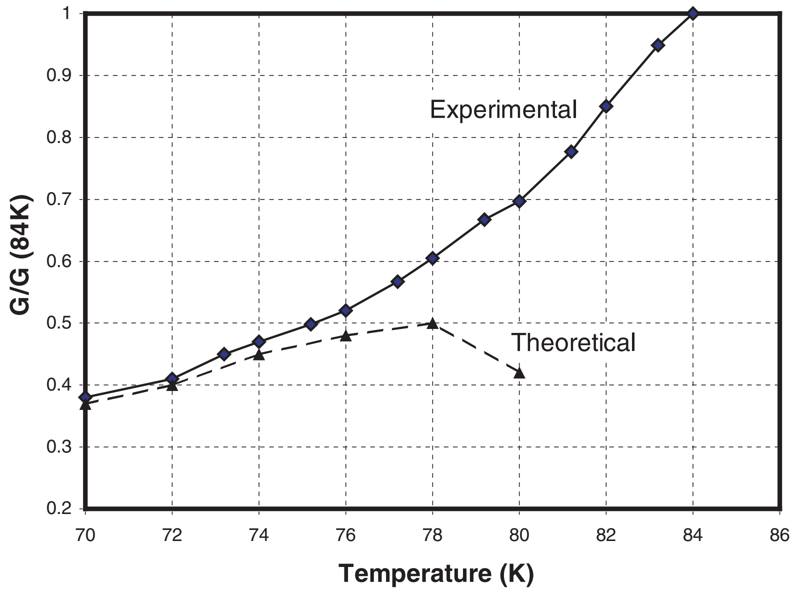

Figure 4. Calculated and measured normalized conductance of 200 nm thick YBCO film on MgO substrate versus temperature at low modulation frequencies.

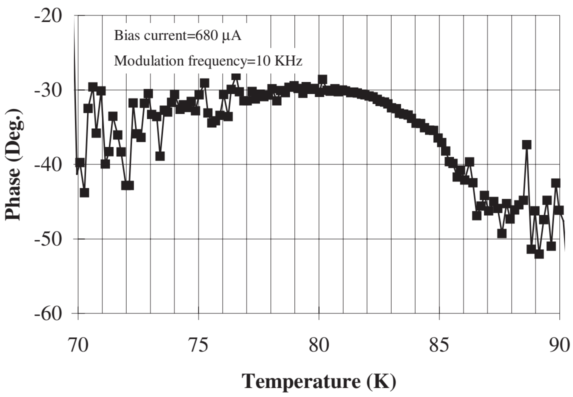

Figure 5. The phase of the response versus temperature at high modulation frequency of 10 kHz and 680 μA dc bias current.

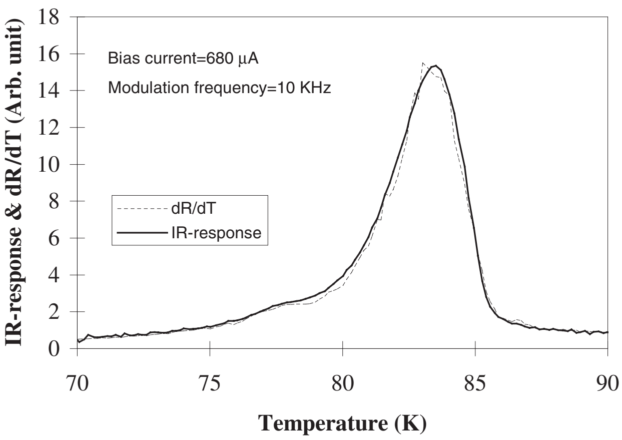

Figure 6. Amplitude of the response versus temperature at 10 kHz modulation frequency and 680 μA dc bias current.

[17]. On the other hand, influence of the order parameter relaxation near T_c on the bolometer characteristic should also be taken into account for more accurate calculations near critical temperature.

2.2. *High-frequency regime*

The variation of the phase of the response versus temperature at high modulation frequency (e.g., $\omega = 10$ kHz) is shown in figure 5. At frequencies above the knee frequency, f_L, the phase of the response decreases as the temperature is lowered. To describe the heat transfer in this regime we imply the phonon radiation limit [12] (ballistic regime of propagation of phonons). In the high-frequency regime, all phonons from the superconducting film are assumed to transmit across the film–substrate boundary and absorbed in the substrate media. That is, in equation (5), transmission probability t_{kj} can be considered 1. Such approximation is valid due to the low Kapitza resistance of the film–substrate boundary [8]. As shown by calculations [18], the thermal conductivity in high-T_c superconducting films has different behaviour in contrast to conventional low-temperature superconductors. In cuprate compounds, thermal conductivity below T_c versus temperature has a peak near the T_c which is lowered by decreasing the film thickness [18]. The thermal conductance of the studied devices at high modulation frequencies is previously shown to be mainly governed by thermal conductivity of the substrate material taking into account the processes in superconducting film [7, 8]. The thermal conductivity of the substrate can also increase as the temperature decreases below the $T_{c\text{-onset}}$. This is due to enhancement of the mean-free path of phonons emitted from the superconducting film into the substrate. As a result, the phase of the response in the temperature interval 75 K $< T <$ 85 K decreases and at lower temperatures, $T <$ 75 K, increases. The corresponding amplitude of the response at high frequencies is shown in figure 6. Response at temperatures $T <$ 75 K can be closer to the $\mathrm{d}R/\mathrm{d}T$ curve. The discrepancy in amplitude of response in the temperature interval 75 K $< T <$ 85 K is interpreted to be related to the variation of the thermal conductivity in the substrate material.

3. Conclusion and summary

At low modulation frequencies, the thermal conductance of the studied edge-transition bolometers in this work is determined by the substrate/cold-head boundary conductance. A shift in the position of the recombination phonons in the spectrum by changing the temperature leads to decreasing the boundary conductance of the substrate/cold-head interface for $T < T_c$. This, along with variation of the heat capacitance versus temperature, leads to an agreement between the theoretical and experimental results of the temperature dependence of the response of the edge-transition bolometers made of high-T_c superconductors. However, such a model is not adequate at temperatures close to the critical temperature at low modulation frequencies. In our opinion, such behaviour is related to creating fluxons and their dynamics near $T_{c.}$ Exact calculations of the phase of the response variation versus temperature is a subject of future work.

Experimental data on the phase of the response variation at high modulation frequencies is in qualitative agreement with changing the thermal conductivity of the substrate material. In this frequency range, the thermal conductance of the bolometers is determined by the conductance of the substrate, which has a broadening peak in the temperature interval 75 K $< T <$ 85 K. This is through the radiation limit in phonon propagation. Due to enhancement of the mean-free path of phonons emitted from the superconducting film, the limit of the thermal conductance at $T < T_c$ is increased and as a result the phase of the response decreases.

Thus, in this paper the influence of the superconducting state on the thermal parameters of edge-transition bolometers made of high-temperature superconductors is discussed. Different modulation-frequency regimes are analysed and good agreement between the theoretical calculations with experimental data is obtained, in particular for low modulation frequencies at temperatures closer to $T_{\text{c-zero}}$.

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