Control of the responsivity and the detectivity of superconductive edge-transition $YBa_2Cu_3O_{7-x}$ bolometers through substrate properties

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The detectivity D^* limits of $YBa_2Cu_3O_{7-x}$ bolometers on 0.05-cm-thick crystalline substrates are investigated, and a method to increase D^* to greater than 10^9 (cm $Hz^{1/2}$)/W at a 20-μm wavelength is proposed. Because the response increases proportionally with the bias current I_b, whereas the noise near T_c (the transition or critical temperature) of our MgO and $SrTiO_3$ substrate samples does not, an increase in D^* of these samples is obtained by an increase in I_b. Another limiting factor is the dc thermal conductance $G(0)$ of the device, which, although controlled by the substrate-holder thermal boundary resistance for our samples, can be changed by means of thinning the substrate to increase D^*. The optimal amount of thinning depends on the substrate's thermal parameters and the radiation modulation frequency. D^* in our samples is also found to follow the spectral-radiation absorption of the substrate material. © 1999 Optical Society of America

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1. Introduction

There have been many reports of observations of the intrinsic and the nonintrinsic responses of high-T_c (the critical temperature from the normal to the superconducting state) superconductive bolometers [primarily when using $YBa_2Cu_3O_{7-x}$ (YBCO) materials] that are higher than the expected values for a purely bolometric response. The interpretation and the analysis of the higher-than-expected values are found to be strongly dependent on the thermal properties of the substrate, the substrate's dimensions, the superconducting pattern, the modulation-frequency regime with respect to the effective thermal-diffusion length into the substrate, and the electrical and the thermal operating conditions of the detectors. For superconductive edge-transition bolometers with flat crystalline substrates that are in direct contact with the cold finger, the effects of limited dc thermal conductance $G(0)$ and Joule heating on the response of the detectors have been misleading factors, resulting in unrealistic values for responsivities and detectivities.[1,2] This is particularly so for the low and the midrange modulation-frequency responses of detectors with large-area superconductive meander-line patterns on crystalline substrates such as MgO, $LaAlO_3$, and $SrTiO_3$.[3,4]

One major source for the above-described misinterpretation has been the overestimation of the total thermal conductance G_t of the detectors, which is limited by the thermal boundary resistances at the substrate interfaces and not directly by the substrate materials themselves.[3–5] These effects are strongly dependent on the dimensions of the pattern of the superconducting film with respect to those of the substrate and on the electrical connections.[5] Edge-transition bolometers can be classified as small-area pattern samples (microbridges) and large-area pattern samples with respect to the substrate dimensions and the substrate thermal parameters. The electrical connections can also be classified as voltage-biased (current response) and current-biased (voltage response) four-probe (or two-probe) configurations.[5]

The thermal resistances at the substrate–cold-finger and the superconductor–substrate interfaces need to be used in the design considerations to improve the detectivity D^*. For an optimal design both

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the electrical and the thermal properties of the detectors should be considered. The optimal design parameters are also strongly dependent on the application and the operating circumstances, mainly the modulation frequency f.

In this paper we present an analysis of the responsivity and the detectivity D^* of samples with large-area patterns on crystalline MgO, $LaAlO_3$, and $SrTiO_3$ substrates when measured under a dc bias current in the four-probe configuration. The characterized samples are made of 120- to 230-nm-thick c-axis-oriented YBCO film deposited by use of off-axis dc planar magnetron sputtering. The samples were patterned by use of standard photolithography that was modified to be less destructive for YBCO materials. Details of the structural and the electrical characteristics of the samples with their deposition parameters and patterning process are given elsewhere.[3,4] The holder or the cold finger in our experimental setup was made of a gold-plated oxygen-free copper disk with an embedded silicon temperature sensor. The sensor was calibrated to a 0.1-K accuracy, and the OFE copper disk was etched and coated with a layer of gold without being exposed to the atmosphere. A lantern or a Sol-Gel battery with a low-noise metal-film resistor was the current source for measurements of the noise voltage under the four-probe configuration. The measurements were taken with a lock-in amplifier (Princeton Applied Research, Model PAR-5204) with an ultralow-noise preamplifier (Perry, Model 030B; noise limit of 0.4 $nV/Hz^{1/2}$) to amplify the voltage signal.

2. Effects of Substrate Properties and Biasing on the Responsivity and the Detectivity Limits

The responsivity of a bolometer is defined as the ratio of the voltage response (in current-biased detectors) to the radiation power received by the detector.[3,4] The equilibrium responsivity of thin-film superconductive edge-transition bolometers is mainly a function of the substrate properties because the mass of the substrate material is usually much greater than the mass of other components in this type of detector. The thermal and the structural characteristics of the substrate also affect the electrical properties of the superconducting film[6]; these effects are considered in Subsection 2.B, below. The electrical biasing is also a major determining factor in the response, and it needs to be considered before further discussion of the effects of substrate properties on the response.

A. Responsivity and Effects of Biasing Configurations

Self-heating, or Joule heating, is a major factor in the bolometric response because the bolometer operates within the resistive transition region of the superconductor near the maximum in $\mathrm{d}R/\mathrm{d}T$. The ac component is caused by the change in the operating-point resistance that results from the input radiation power and produces positive feedback for current-biased (dc) detectors in the four-probe measurement configuration. Taking the positive feedback into account in the equation for the responsivity of bolometers[4] allows the overall frequency-dependent responsivity r_f to be obtained from[7]

$$r_f = \frac{\eta I_b}{G_t + j2\pi f C_t - I_b^2(\mathrm{d}R/\mathrm{d}T)} \frac{\mathrm{d}R}{\mathrm{d}T}, \tag{1}$$

where I_b is the dc bias current, η is the fraction of the incident power absorbed by the bolometer (the absorption coefficient), $\mathrm{d}R/\mathrm{d}T$ is the slope of the resistance R versus the temperature T curve at the bias point, and G_t and C_t are the frequency-dependent total thermal conductance and heat capacity of the bolometer, respectively, which are governed mainly by the substrate properties in most cases.[4] As shown in Eq. (1), there is a stability criterion in the voltage response that has the same form as that obtained for dc biasing at zero frequency.[4]

For dc voltage-biased detectors (constant voltage across the samples), the response is in the form of current variations, and Joule heating in the film produces negative feedback.[8] This negative feedback decreases the responsivity, changing the sign of the Joule heating term $[I_b^2(\mathrm{d}R/\mathrm{d}T)]$ in Eq. (1). This negative feedback can improve the dynamic range of voltage-biased detectors by stabilization of the bias temperature at high radiation intensities. This is the situation when the sample is biased such that the Joule heating is comparable with the total absorbed-radiation power. The effects of different electrical connections on the thermal runaway of such detectors with different patterns were studied and presented elsewhere.[5] The effect of the Joule heating term in Eq. (1) in our samples is negligible for the bias currents used, regardless of the substrate material.[3,4]

B. Effects of Substrate-Dependent Film Properties on the Detectivity D^*

The detectivity D^* of the bolometers is a function of the responsivity, the absorbing area (and its absorption coefficient), and the intrinsic noise in the device. The detectivity D^* of an edge-transition superconductive bolometer versus the temperature is a function of the voltage responsivity and the noise, defined as $D^* = (A\Delta f)^{1/2} r_f/V_n$, where A is the radiation-absorbing area in centimeters squared, V_n is the voltage noise, and Δf is the frequency range used to obtain the noise measurement. The frequency range Δf is 1 Hz in this study, giving D^* in units of centimeters times square-root hertz per watt. With Eq. (1), D^* might be improved by an increase in the responsivity by use of higher dc bias currents. This possibility depends on the dependence of the ultimate responsivity and the noise voltage on the bias current, which is discussed in Subsection 2.C.

When ac Joule heating is negligible, as is the case for the currents in our samples, the responsivity increases linearly with I_b, as given in Eq. (1). Hence D^* can be improved by an increase in I_b if the signal-to-noise ratio also increases. This increase in the signal-to-noise ratio requires that the noise increase with I_b at a rate less than that of the responsivity. Noise in our YBCO samples was found to be depen-

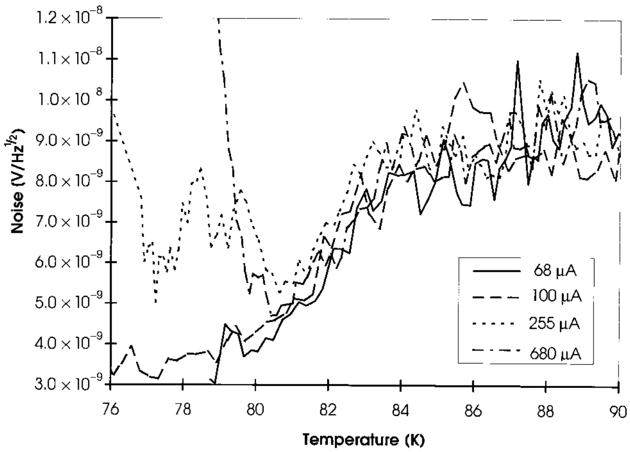

Fig. 1. Noise versus the temperature of sample 064-02b on a 0.025-cm-thick MgO substrate at 10 KHz for 68-, 100-, 255-, and 680-μA bias currents with $T_{c\text{-zero}}$ (at 100 μA) = 73 K and $T_{c\text{-onset}}$ = 85 K.

dent on the bias current and the modulation frequency and also was found to be strongly temperature dependent. Four major types of voltage noise are identified in our dc current-biased samples according to where they occur in the temperature range relative to $T_{c\text{-onset}}$ and $T_{c\text{-zero}}$.[3–9] The $T_{c\text{-onset}}$ in our samples is considered to be the point above which the resistance starts to show linear behavior versus the temperature, and $T_{c\text{-zero}}$ is considered to be the point below which the resistance drops to less than 1% of its value at $T_{c\text{-onset}}$. Although both T_c values are dependent on the bias current, the values of $T_{c\text{-zero}}$ of our samples are found to be strongly decreased versus the bias current, depending on the granularity of the films.[5] The measured voltage noise versus the temperature at different values of I_b in the region of interest for sample 064-02b, which was made of 120–130-nm-thick patterned granular YBCO film on a crystalline MgO substrate, is shown in Fig. 1, and the resistance versus the temperature of the sample is reported elsewhere.[5]

The noise from approximately the middle of the transition to $T_{c\text{-onset}}$ in our samples with MgO and $SrTiO_3$ substrates is found to be dependent on the bias current I_b and scaled as

$$V_n = C_1 + C_2 I_b, \tag{2}$$

where C_1 and C_2 are constants and differ from one sample to another, with $C_1 > C_2 I_b$ just less than $T_{c\text{-onset}}$, for almost all the samples measured on MgO and $SrTiO_3$ substrates.[9] The noise in our samples with $LaAlO_3$ substrates is found to be much higher in this region. The observed high level of noise in films on $LaAlO_3$ substrates may be due to the high granularity (twined grains) typical of this type of material. As shown in Fig. 1, the voltage noise of the sample with a MgO substrate near $T_{c\text{-zero}}$ increases strongly with increasing bias current. But, in the temperature region near the middle of the transition from T = 81 K to $T = T_{c\text{-onset}}$, the voltage noise follows Eq. (2). In this region the noise increases by only approximately 20%, whereas the bias current increases by a factor of 10. This type of noise is interpreted to be current-dependent fluctuations in the volume fraction of the superconducting phase along the current path.[9] The same types of bias-current and temperature dependence of the noise voltage in the same temperature region is observed for our other samples on MgO and $SrTiO_3$ substrates.[3,9] If we consider the current dependence of the noise, sample substrates that have sharper transitions (higher dR/dT), which lead to lower I_b values for the maximum responsivity, are more favorable in this respect. The highest dR/dT is also found to be at the lower end of the above-given noise-voltage temperature region.[9] Hence, because the responsivity is proportional to the bias current I_b, the detectivity D^* of samples on MgO and $SrTiO_3$ substrates will increase by means of increasing the bias current I_b if the sample is biased in this temperature region. This increase is limited by the thermal runaway that results from the dc Joule heating in the device and the limits of the responsivity, which are discussed in Subsection 2.C.

C. Effects of Substrate Properties and the Bias Current on Responsivity Limits

Owing to the limited thermal conductance of the detectors, which is determined mainly by the substrate properties, dc Joule heating (self-heating) is a major limiting factor to the use of high bias currents to obtain higher responsivity, hence higher D^*, values. Self-heating can cause an excessive temperature rise ΔT_{dc} in the film with respect to the temperature of the sample holder in which the temperature sensor is normally placed. The resulting ΔT_{dc} can occur mainly across the substrate material or across the substrate–cold-finger thermal boundary resistance region. The region is determined by the relative dimensions of the superconductive-film pattern compared with the thickness of the substrate. The relative dimensions of the film and the substrate determine the dominating factor that limits the dc thermal conductance $G(0)$.

For patterns with dimensions much smaller than the substrate thickness d_s, $G(0)$ is limited by the lateral heat flow through the superconductive film and the heat diffusion into the substrate material.[10–14] $G(0)$ and the heat diffusion are highest for the samples with MgO substrates because they have the highest thermal conductivity. In samples with pattern dimensions comparable with or larger than their substrate thickness d_s, $G(0)$ is limited by the thermal resistance at the substrate boundaries and is not strongly dependent on the substrate material.[3,15] In our samples ΔT_{dc} is found to occur mainly at the substrate–cold-finger interface because the dimensions of the meander-line patterns are comparable with those of the substrate.[3,4]

Regardless of the dominating factor that determines the total thermal conductance G_t, the dc bias current at any temperature higher than $T_{c\text{-zero}}$ is lim-

Table 1. Thermal and Electrical Parameters and Dimensions of the Superconductive Film and the Substrates of Samples with $SrTiO_3$, MgO, and $LaAlO_3$ Substrates[a]

Sample Number	Substrate Material	C_s (J/k cm^3)	K_s (W/k cm)	d_s (cm)	$G(0)$ (mW/K)	dR/dT (Ω/K)	d_f (nm)	A (cm^2)	$I_{b\text{-max}}$ (mA)	r_{max} (V/W)	D^* (cm Hz$^{1/2}$)/W
064-01	$SrTiO_3$	0.43	0.052	0.05	3	1800	220	0.017	0.66	400η	3.6×10^7
064-02b	MgO	0.53	3	0.025	15.5	950	120	0.075	2.08	127η	0.3×10^6
064-03a	MgO	0.53	3	0.05	11	1000	170	0.075	1.66	151η	
064-04	$LaAlO_3$	0.59	0.16	0.05	7.8	2200	190	0.075	1.0	274η	1.8×10^6

[a]The value of D^* given was obtained for a 100-Hz modulation frequency and a 20-μm wavelength. The term d_f is the thickness of the YBCO film, d_s is the thickness of the substrate, $G(0)$ is the measured dc substrate–cold-finger thermal boundary resistance, A is the total area of the superconducting pattern, r_{max} is the maximum zero modulation-frequency response, and $I_{b\text{-max}}$ is the maximum allowed bias current, which is limited by the thermal runaway obtained for a stability factor of $\alpha = 0.4$.

ited by thermal runaway, which is characterized by the factor α, defined as[4]

$$\alpha = \frac{{I_b}^2}{G(0)} \frac{\mathrm{d}R}{\mathrm{d}T}, \tag{3}$$

with $\alpha < 1$ required for stability. As given in Eq. (3), for substrates that yield films with sharper transitions such as $SrTiO_3$ the ultimate allowed bias current I_b would be lower. The effect of instability in the temperature of the film caused by high bias currents will appear as an unrealistically sharp transition in the R versus T curve.[2,5,16] The increase of the response that is due to the sharper transition dR/dT dominates the effect of this decrease in the maximum allowed I_b in Eq. (3), producing an overall increase in the responsivity for films with sharper transitions. The maximum bias currents $I_{b\text{-max}}$ of the characterized samples obtained for $\alpha = 0.4$ are given in Table 1. If we consider the maximum I_b determined by Eq. (3) the magnitude of the maximum responsivity follows

$$|r_f|_{max} = \frac{\eta}{G_t} \left[\frac{\alpha G(0)}{1 + (2\pi f \tau)^2} \frac{\mathrm{d}R}{\mathrm{d}T} \right]^{1/2}, \tag{4}$$

where $\tau = C_t/G_t$.[4] Hence from Eq. (4) we can see that devices on substrates with lower thermal conductivities and lower heat capacities and that allow a higher dR/dT in the transition region will yield the highest responsivities. This result favors devices with $SrTiO_3$ substrates when compared with devices with MgO and $LaAlO_3$ substrates for the same superconducting-film and substrate dimensions. This relation is confirmed by the measurements in the modulation-frequency range of the responsivity governed by Eq. (4). The r_{max} obtained for the characterized samples and their superconducting-pattern dimensions are given in Table 1.

As given in Eq. (4), $|r_f|_{max}$ can be increased by an increase in $G(0)$ when scaled as $G(0)^{1/2}$. This increase in $|r_f|_{max}$ occurs when the value of G_t at the operating frequency is different from that of $G(0)$ at midrange or higher frequencies.[4] At very low frequencies, i.e., lower than a critical value f_1, G_t may become equal to or comparable with $G(0)$.[4] The value of f_1 depends on the substrate properties and is the frequency at which the thermal-diffusion length into the substrate approaches the substrate thickness. Then $|r_f|_{max}$ decreases by an increase in $G(0)$ when scaled as $G(0)^{-1/2}$. The change of the determining factor for G_t affects the slope of the curve of the response magnitude versus the modulation frequency. For $f < f_1$ the response scales as f^{-1}, and for $f > f_1$ it scales as $f^{-1/2}$ (Refs. 4 and 17). This scaling is a function of substrate properties and is discussed in Subsection 2.D.

D. Substrate-Material Dependence of the Substrate-Thickness Effects on the Responsivity Limits

We consider the thermal resistance at the film–substrate interface to be negligible compared with that of the substrate material and the substrate–cold-finger interface in the low and the midrange frequencies.[3,4] Then the overall thermal conductance G_t is determined by the thermal-diffusion length L_f of the absorbed energy (by the superconductive film) into the substrate. The quantity L_f, the thermal-diffusion length, represents the characteristic penetration depth of the temperature variation into the substrate and is given by

$$L_f = \left(\frac{D}{\pi f} \right)^{1/2}, \tag{5}$$

where $D = k_s/c_s$ and k_s and c_s are the thermal conductivity and the heat capacity, respectively, of the substrate material.

If we consider L_f to be the effective length for the ac heat flow into the substrate in the modulation-frequency range where L_f is less than the substrate thickness (i.e., $f > f_1$), G_t will be determined by the substrate material and will increase with the frequency, scaling as $f^{1/2}$ (Ref. 4). Hence, for a detector operating above f_1, the substrate thickness doesn't affect the responsivity, and $|r_f|_{max}$ is governed by Eq. (4), with the substrate thermal parameters as the determining factors. This trend is valid for frequencies at which the thermal conductance of the superconductive film and the film–substrate interface are negligible.[4]

When the frequency decreases to less than the values at which L_f becomes comparable with or larger than the substrate thickness (i.e., $f < f_1$), G_t approaches $G(0)$, and the substrate–cold-finger boundary resistance $R_{s-c} = 1/G_{s-c}$ will be the determining

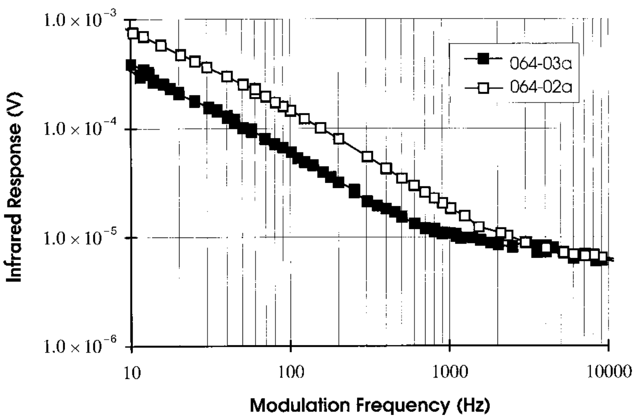

Fig. 2. Measured response versus the modulation frequency for samples with a 0.05-cm-thick MgO substrate (sample 064-03a) and a 0.025-cm-thick MgO substrate (sample 064-02a) by use of a 1-mA bias current and a 2.13-mW/cm^2 radiation intensity.

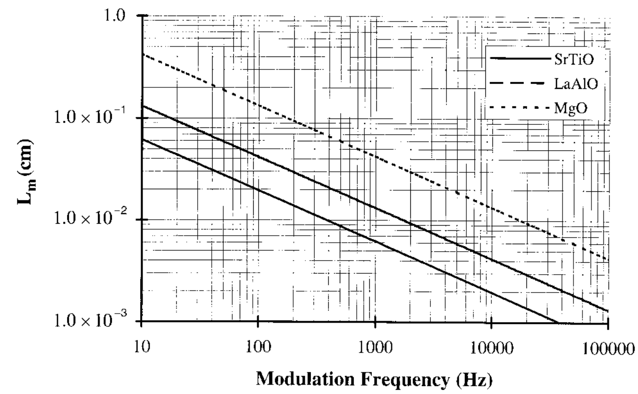

Fig. 3. Calculated L_m versus the modulation frequency for bolometers on crystalline $SrTiO_3$, $LaAlO_3$, and MgO substrate materials.

factor in the total thermal conductance. In our samples R_{s-c} values are found to be much larger than the thermal resistance of the substrates, giving $G(0) \cong G_{s-c}$. For $(2\pi f\tau)^2 \gg 1$ and while still valid in the above frequency range[4] with $G_t \cong G(0)$ in Eq. (4), the maximum responsivity is

$$|r_f|_{\max} = \frac{\eta}{2\pi f C_t}\left[\alpha G(0)\,\frac{\mathrm{d}R}{\mathrm{d}T}\right]^{1/2}. \tag{6}$$

Hence under the above conditions and within this frequency regime ($f < f_1$) thinning the substrate will increase r_f by means of decreasing C_t as long as the bias current does not exceed the critical current value I_c of the superconducting film. The thermal boundary resistance at the substrate–cold-finger interface $1/G(0)$ is also found to decrease from thinning of the substrate, regardless of the substrate materials. Possible mechanisms for this result were presented elsewhere.[3] For large-area patterns the decrease in $G(0)$ is found to be approximately proportional to the substrate thickness d_s. Hence, by considering C_t also to be proportional to the substrate material's thickness, we find that thinning the substrate is expected to increase $|r_f|_{\max}$ by approximately $(d_{si}/d_{sf})^{3/2}$, where d_{si} and d_{sf} are the initial and the final substrate thicknesses, respectively.

The effects of the modulation frequency on the response in different frequency regimes for two samples with identical meander-line patterns on 0.025- and 0.05-cm-thick crystalline MgO substrates are shown in Fig. 2. At high frequencies at which L_f is less than the substrate thickness for both samples, the responsivities are equal, and the response is determined by the characteristics of the superconducting pattern and the substrate material. For lower frequencies at which L_f is greater than the thickness of the substrates the response of the sample with the thinner substrate (sample 064-02a) is higher. This result is mainly due to differences in the values of C_t, which is approximately proportional to the thickness of the substrates because the bias currents are same (1 mA). The maximum responsivity of the 0.025-cm-thick substrate sample (064-02a) is approximately 2.8 times higher than that of the 0.05-cm-thick substrate sample (064-03a), also because of the differences in the $G(0)$ values as well as the in C_t values.

If a detector is used in a bridge (microbolometer) configuration,[18] G_t will be determined primarily by the lateral heat flow through the substrate. Because d_s is still much larger than the film thickness, the resulting heat flow through the film is negligible. In this configuration thinning the substrate will also increase r_f, mainly by means of lowering C_t.[10,18] Thinning the substrate in this case will cause a decrease in the value of $G(0)$ of the detector by reduction of the area of the lateral thermal-conduction path through the substrate material. This reduction yields an increase in $|r_f|_{\max}$ that is lower than the expected value and scales as $(d_{si}/d_{sf})^{1/2}$. The minimum required thickness of the substrate L_m versus the modulation frequency beyond which the responsivity increases by means of further thinning is calculated for the three substrate materials, and the results are shown in Fig. 3.

3. Spectral Responsivity and Substrate-Material Properties

The spectral responsivity of sample 064-01a when measured to as high as 20 μm at two bias currents is shown in Fig. 4. The sample is made of a 220–230-nm YBCO superconductive film on a 0.05-cm-thick crystalline $SrTiO_3$ substrate. The superconductive pattern is a 50-μm-wide and 1.9-cm-long meander line with a total area of 0.0168 cm^2 (Ref. 9). The magnitude of the response shown in Fig. 4 is proportional to I_b, whereas the spectral response follows the spectral absorption of the substrate material, as shown in Fig. 5. This relation is interpreted to be due to the absorption of radiation in the open areas of the substrate between the meander lines with the flow of heat to the superconductor. The spectral absorption of the substrates is derived directly by use of the spectral reflectance and transmittance of a 0.05-cm-thick bare substrate. The measured spectral absorption of the $SrTiO_3$ substrate

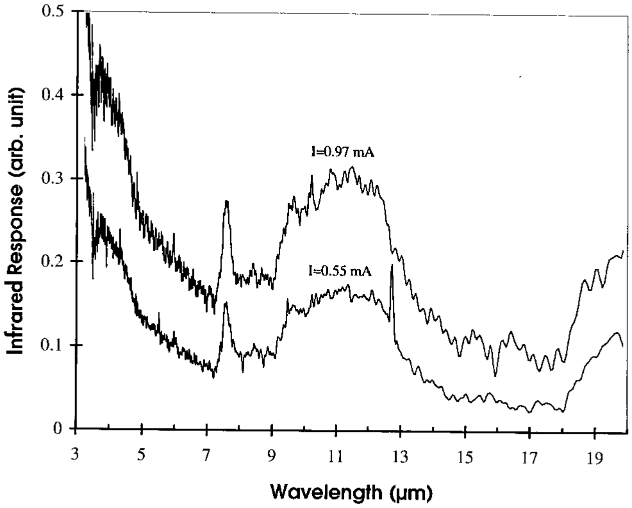

Fig. 4. Spectral response of a sample with a 0.05-cm-thick $SrTiO_3$ substrate (sample 064-01a) at 0.55- and 0.97-mA bias currents.

is slightly different from that obtained by use of classical dispersion theory[19–21] and shows a particularly strong peak at an approximately 7.5-μm radiation wavelength, as observed in both Figs. 4 and 5.

As shown in Fig. 4, the response of the $SrTiO_3$ substrate sample also follows the trend for the absorption in thin-film and single-crystal YBCO materials, increasing at shorter wavelengths.[22,23] Using the ratio of the change in the response resulting from substrate absorption with respect to that of the film shows that the fraction of the power absorbed by the substrate can be obtained at any wavelength. As derived for sample 064-01a (the $SrTiO_3$ substrate), approximately 50% of the response at 10 μm and more than approximately 75% of the response at 20 μm are due to the absorption of the incident radiation in the open areas of the substrate. The effects of substrate absorption on the response dominate at some longer wavelengths (i.e., 20 μm) at which absorption by the superconducting film is reduced even further.[22,23] The absolute value of the responsivity for the above-described sample was measured at 7.39 μm with a 500-K blackbody source. A response of 1.582 μV is obtained for a radiation intensity of 5.64×10^{-4} W/cm^2 at a 400-Hz modulation frequency and a 300-μA dc bias current. A responsivity of 0.5 V/W and a detectivity D^* of 0.72×10^6 (cm Hz$^{1/2}$)/W are obtained under the above conditions.

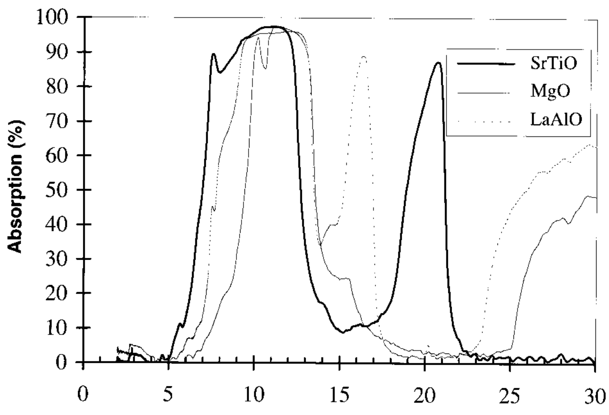

Fig. 5. Measured spectral absorption of samples with 0.05-cm-thick crystalline $SrTiO_3$, MgO, and $LaAlO_3$ substrates.

4. Engineering Changes for a Higher Detectivity *D**

As an example of the engineering changes required to increase D^* by use of the analysis presented in this study, we present an analysis of the sample on the $SrTiO_3$ substrate. From the spectral response shown in Fig. 4 and by use of a maximum bias current of 0.66 mA from Table 1 a D^* of approximately 3.6×10^7 (cm Hz$^{1/2}$)/W is obtained for the sample with the $SrTiO_3$ substrate (064-01a) at a 20-μm wavelength and a 100-Hz modulation frequency. The spectral detectivity at a constant bias current and a constant temperature follows the spectral response of the detector for a constant radiation intensity. The D^* of the characterized samples at the 20-μm wavelength is given in Table 1.

For increasing D^* consider the 400-Hz and the 100-Hz modulation-frequency points in Fig. 3 as examples. The substrate of sample 064-01a should be thinned to less than 0.01 and 0.02 cm, respectively. The substrate can be thinned by use of a wet-etching method after the patterning process for the superconductive film. Thinning the substrate will also increase $G(0)$ while it is still limited by R_{s-c}. On the basis of the above analysis, thinning the substrate to 0.005 cm with an increase in the total area of the superconductive pattern of as much as 0.09 cm^2 yields a D^* of the order of 1×10^9 (cm Hz$^{1/2}$)/W at 20 μm for 200-nm-thick YBCO superconducting films on crystalline $SrTiO_3$ substrates. Also, as observed from Eq. (2) and Table 1, the detectivity of the samples can be enhanced by a sharper transition (favored by the substrates' lattice structures) because it allows lower $I_{b\text{-max}}$ values, hence lower current-dependent noise in the region. Again, this leads to the $SrTiO_3$ substrate as the most favorable of the substrate materials investigated in this study.

5. Summary and Conclusions

The ultimate detectivity of an edge-transition superconductive bolometer is determined by the maximum responsivity $|r_f|_{\max}$ and the current dependence of the noise at the operating temperature. The D^* of our samples with MgO and $SrTiO_3$ substrates has been found to increase with an increase in the bias current I_b because the noise voltage in the temperature region of interest (in the middle of the transition region) near T_c does not increase significantly with I_b in this region. For samples with $LaAlO_3$ substrates this trend has not been observed because there is excessive noise in the whole transition region. This result leads to the samples with $SrTiO_3$ substrates as the most favorable of the substrates investigated in this study because the films on $SrTiO_3$ substrates have a sharper transition dR/dT compared with those on MgO substrates. The maximum responsivity is set by the limits on the dc bias current that are determined from the dc Joule heating and the dc thermal conductance of the device $G(0)$, which is set by the substrate–cold-finger thermal boundary resistance in our samples.

Thinning the substrates of the samples to increase the maximum responsivity $|r_f|_{\max}$ depends on the variations of the total thermal conductance G_t and the total heat capacitance C_t of the device. The critical required thinning of the substrates L_m below which the responsivity increases has been found to be dependent on the substrate materials and the modulation frequency f, scaling as $f^{-1/2}$. In a frequency regime that is low enough that the thermal-diffusion length into the substrate is greater than the substrate thickness, $L_f > d_s$, thinning the substrate of the detector increases $|r_f|_{\max}$ by a factor of $(d_{\mathrm{si}}/d_{\mathrm{sf}})^{3/2}$, where d_{si} and d_{sf} are the initial and the final substrate thicknesses, respectively. In the higher-frequency regime in which $L_f < d_s$, thinning the substrate of the detector increases $|r_f|_{\max}$ by approximately $(d_{\mathrm{si}}/d_{\mathrm{sf}})^{1/2}$.

Substrate absorption has been shown to be the determining factor in the spectral responsivity, hence in the detectivity, for the infrared to the far-infrared wavelengths at which the absorption of the superconducting films is strongly reduced compared with their values at shorter-radiation wavelengths. This property of the substrates can be used for selective wavelength sensitivity for an edge-transition superconducting infrared detector. The spectral absorption of our $SrTiO_3$ substrates has been found to deviate from the theoretical values obtained by use of classical dispersion theory, particularly at 7.5 μm. A detector of 0.09 cm^2, an overall patterned superconducting area, and a D^* of the order of 1×10^9 (cm Hz$^{1/2}$)/W at 20 μm on a crystalline $SrTiO_3$ substrate can be obtained if the substrate is thinned to 0.005 cm.

In conclusion, the effective heat conductivity, the effective heat capacity, and the substrate-dependent film quality in terms of low noise and sharp transitions have been shown to be the major factors in choosing a substrate material in this type of bolometer. For a YBCO edge-transition bolometer operating at wavelengths from the near infrared to the far infrared the spectral absorption of the substrate material will also be another factor to be considered if the open areas of the substrate are comparable with or larger than the absorbing surface area of the superconducting film. For a uniform spectral response coating the superconducting pattern area with a material that has an absorbance that is independent of wavelength is advisable. However, for making the bolometer sensitive to a narrow band of wavelengths coating it with a material that absorbs strongly at those wavelengths is recommended if the selective absorbance of the substrate is not within the desired range of wavelengths.

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