DC Characteristics of Patterned $YBa_2Cu_3O_{7-x}$ Superconducting Thin-Film Bolometers: Artifacts Related to Joule Heating, Ambient Pressure, and Microstructure

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***Abstract*—Joule heating due to the bias current and resistance of the material in patterned $YBa_2Cu_3O_{7-x}$ superconducting films on 250–500-μm-thick MgO, $LaAlO_3$, and $SrTiO_3$ crystalline substrates, results in a number of effects: 1) a temperature rise in the film with respect to the measured temperature at the bottom of the substrate; 2) a possible thermal runaway, which may be local or uniformly distributed in the film, depending upon the dimensions of the superconducting pattern relative to that of the substrate; 3) an apparently sharper normal-to-superconducting transition in the measure R versus T curve; and 4) decrease of T_c to 60 K ($\Delta T_\chi > 20$ K) after being subjected to high-bias currents $j \sim 10^5$ A/cm^2 under vacuum, with recovery of T_c after exposure to room atmosphere. The magnitude of R at $T_{c\text{-onset}}$ is found to be dependent on bias current in granular samples, with a lower R at currents higher than some on-set value. The slope of R versus T in the transition region in our granular samples is found to be lower at higher bias currents, since the widening of the transition overcomes the shift caused by the Joule heating. These various phenomena impact the responsivity of bolometers made from these films, as well as the predictions of possible attainable responsivity and speculations of mechanisms occurring in the films. In particular, misinterpretation of the Joule heating sharpening of the R versus T curve has led to predictions of responsivities over one order of magnitude higher than are justified, and shifts in properties of the films due to heating have been misinterpreted as nonequilibrium responses of the films.**

***Index Terms*—Bolometer, Joule heating, superconductors, thin films.**

I. INTRODUCTION

IN MOST dc characterizations of patterned superconducting films, there can be considerable Joule heating associated with the resistance of the patterns at high-bias currents. This power dissipation can cause a temperature gradient across the thermal conducting path. This gradient can cause an error in the dc characterizations because in most of the setups the temperature of the cold finger (holder) or the bottom of the substrate is monitored [1]–[12], while the temperature of the film is higher [2], [3]. At high-bias currents this can cause a shift of $T_{c\text{-onset}}$ toward the lower temperatures in the measured R versus T curve, as has been observed in many cases [1]–[3], [7], [8], [11]. The shift is related to the temperature gradient across the film-substrate or the substrate–cold-finger interfaces, depending on the film and the substrate dimensions. This effect has been a misleading parameter in the analysis of the dc characteristics and the T_c stability of the films. This is especially true in the characterizations of some devices made of superconducting thin films on crystalline substrates, such as IR-detectors [1], [5], [6], [8], [12].

Mechanical stresses on the film under different atmospheres caused by the temperature gradients associated with Joule heating have also contributed to the degradation of the quality of the samples [13]–[16]. These stress effects are found to depend strongly on the dissipation of the Joule heating power in the samples, making the dc thermal conductance $G(0)$ a determining factor for dc characterizations. The dc thermal conductance of our devices, $G(0)$, is found to be limited by the thermal boundary resistance at the substrate–cold-finger interface, with $G(0)$ values dependent on the area of the superconducting path and the thickness of the substrate, for reasons which were presented elsewhere [3], [17].

One measure of the quality of the high-T_c superconducting films has been the presence of precipitates. The effects of the microstructure and the amount of precipitates in the film on the dc characteristics of the samples have been studied and reported by many different groups. Here we present a possible effect of the precipitates on the normal resistance of the samples due to their possible contributions in the electrical conduction at relatively high-bias currents. The response of our samples as IR-detectors and their potential improvement are linked to the dc effects indicated, and we point out where errors in the interpretation of the dc effects lead to unjustified claims for possible bolometer performance.

Our devices were made using off-axis planar magnetron sputtering with YBCO films of 120–600-nm thickness, patterned using standard photolithography [17]. Meander line patterns with 50–120-μm line widths were used. Sample substrates have a 0.5 by 1-cm area and a thickness of 0.25 mm for the MgO and 0.5 mm for the $SrTiO_3$ and $LaAlO_3$. The detailed sputtering conditions, patterning process, and complete characteristics of the devices were presented elsewhere [16], [17]. The second cold stage of a Cryo–Torr 100 (CTI-Cryogenics) was modified and used for our low-temperature measurements under vacuum. A gold-coated oxygen-free electronic grade

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Manuscript received August 1, 1997; revised January 5, 1998.

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Publisher Item Identifier S 1051-8223(98)04228-6.

(OFE) copper substrate holder, the temperature of which is monitored, was designed and attached to the cold stage of the cryopump. A complete detailed block diagram of the circuitry used was presented elsewhere [3], [16].

II. JOULE HEATING EFFECTS

Joule heating in the films inputs a power of I^2R, and the temperature rise depends on the heat conduction path in the sample. Since the heat is generated in the film, the film-substrate contact area and heat conduction through the substrate into the temperature reservoir need to be considered. The thermal conductivity and heat capacity of the substrate materials are also considerations. For the dc characterizations under stable conditions, the heat capacity of neither the film nor the substrate is necessary [17]. To study the effects of Joule heating in the samples, one can divide the samples into two main categories, and the samples can be considered as small or large area patterns compared to the dimensions of the substrate. The large area patterns are normally made of meander lines, while the small area patterns are usually microbridges consisting of a straight, narrow superconducting film. Here we will consider the effects of the Joule heating in R versus T measurements, using a transport current in either the two- or four-probe configurations.

A. Small Area Patterns

For microbridges with small dimensions compared to the substrate dimensions, the temperature gradient generated by Joule heating is mostly expected to be at the film-substrate interface or across a thin layer of the substrate in the vicinity of the superconducting path [1], [18]–[22]. The reasons for this are that only a small area of the substrate underneath the pattern conducts the heat, while the substrate behaves like a heat reservoir for the heat generated in the pattern, due to its large dimensions compared to that of the pattern. In samples with this configuration, the heat conductivity of the substrates is the determining factor in the temperature gradient. For R versus T measurements of such microbridges, the temperature rise in the film can cause a thermal runaway, overheating the whole film if a constant current source is used [3], [4], [10], [19], [23]. If the measurement is done with a voltage-controlled source, then the overall heating will be limited by a local thermal runaway creating a hot spot in the bridge [4], [24], [25]. Based on thermal stability, the hot spot would be at a point of the bridge which has the maximum thermal conductance, G. Hence, despite contrary expectations [4], it will not happen in the middle of the bridge where one expects G to be at its minimum. Taking the thermal conduction through the film into consideration, the hot spot as reported [4] would be located at either end of the microbridge where it has the maximum thermal conductance. In the Appendix we show that the position of the hot spot is determined by the bias temperature relative to the zero resistance temperature T_{co} and the variation of G with position. The appearance of the initial hot spot where $G(x)$ is maximum, i.e., at the ends of the microbridge, is counterintuitive. The distinction between cases where the hot spot occurs in the center ($G_{\min}$) or ends ($G_{\max}$) is whether the normal state dissipation I^2R_N is greater or less than $G_{\max}\Delta T/t$ (see the Appendix). The counterintuitive case, (A4), occurs when I^2R_N is greater than $G_{\max}\Delta T/t$. In this case steady state can only occur near the regions of maximum heat conduction and with $T > T_c$ in those regions.

B. Large-Area Patterns

For our samples with dimensions of the patterned superconducting film comparable to that of the substrates, the temperature gradient is found to be mainly across the substrate–cold-finger interface [3], [17], [26]. Hence, the whole pattern of the samples is found to be at the same temperature under any stable circumstances [3], [17]. The thermal boundary resistance at this interface (substrate–cold finger) is found to be the determining factor in the overall thermal conductance of our samples [3], [17]. In such samples, there will not be a hot spot. The heat conduction is blocked mainly by the substrate–cold-finger interface, giving an almost uniform heat distribution over the superconducting pattern. The total thermal resistance of the samples is found to be a few order of magnitudes higher than the values due to just the substrates [3], [26]. So, the whole superconducting film can be considered at the same temperature to a very good approximation.

At high-bias currents there can be a stable heating over the complete path of the pattern, creating a higher temperature in the film relative to the monitored temperature of the cold finger. The temperature rise in the film is proportional to the resistance of the film and is given by [3], [16]

$$\Delta T = \frac{RI^2}{G(0)} \tag{1}$$

with R the resistance of the film, I the bias current, and $G(0)$ the dc thermal conductance of the system.

In R versus T characterizations using a constant current source, this can cause a false sharper transition at high currents. At values close to $T_{c\text{-onset}}$, as resistance of the film increases the Joule heating increases and creates a higher ΔT with respect to the temperature of the cold finger. Fig. 1 shows this effect for one of our samples. The shifting of $T_{c\text{-onset}}$ to lower temperatures has been interpreted to be an intrinsic shift by some groups [1], [5], [8], [12]. At high-bias currents this shift increases the dR/dT value of the film obtained from the measured R versus T curve, but this is different from the real R versus T of the film. One way to investigate this effect is to use the responsivity of these samples to radiation intensities (i.e., measuring ΔR due to known values of absorbed radiation) [17]. Calculations of responsivity of bolometers based on these patterns, if based on this unrealistically high dR/dT, will lead to values much higher than those possible for such configurations [1], [27]. In granular samples with wide normal-to-superconducting transitions, the further widening of the transition due to high-bias currents dominates the shift of observed $T_{c\text{-onset}}$ to the lower temperatures. While these granular samples have lower intrinsic values of dR/dT, they also show the steep dR/dT artifact at higher bias currents. This is discussed in more detail later in this paper.

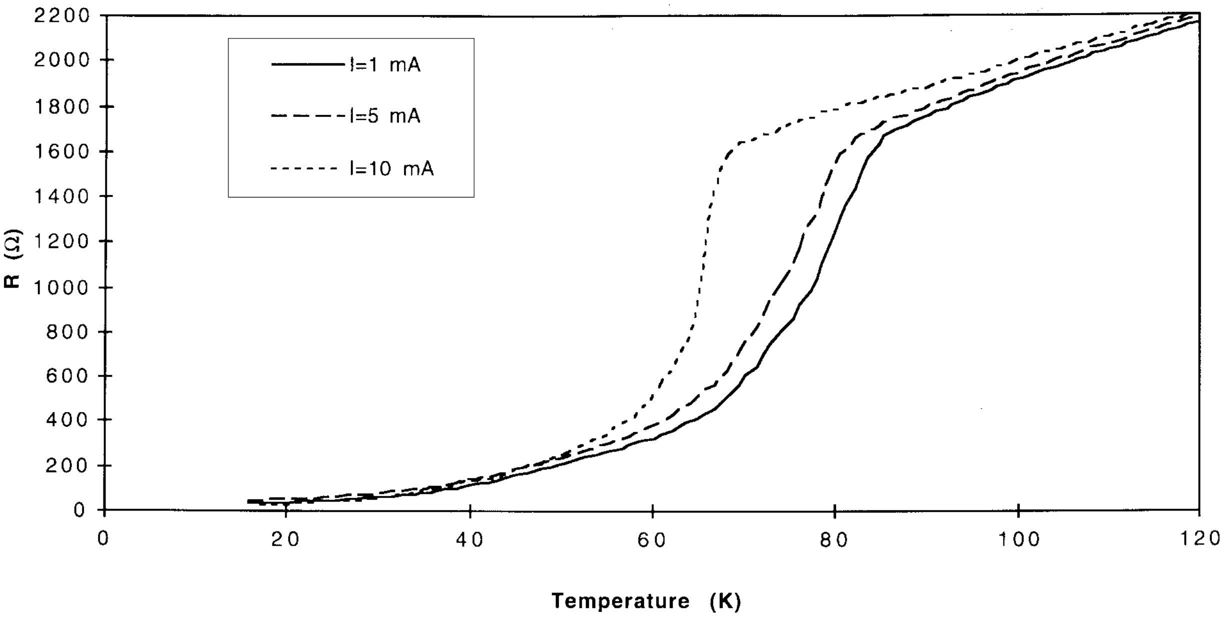


Fig. 1. R versus temperature of sample 057-04b at 1-, 5-, and 10-mA dc bias currents and 2-K/min heating rate. The sample has a 4.8-mm-long and 120-μm-wide meander line pattern of YBCO film with 600-nm thickness on crystalline $LaAlO_3$ substrate.

III. EFFECT OF AMBIENT ATMOSPHERE AND THE JOULE HEATING

Some of our samples have shown T_c's, sensitive to bias currents, shifting to lower temperatures after being exposed to high currents. This is found to happen when the high-bias currents are applied to the sample under vacuum in the normal state close to the transition temperature. The magnitude of the shift is found to be dependent on the maximum applied current and therefore the maximum temperature gradient generated by Joule heating. Further, R versus T measurements, after cycles of applied high-bias currents, have shown that T_c can be reduced by nearly 20 K. This is shown in Fig. 2 for sample 064-01a with a film thickness of 220 nm on 0.5-mm-thick crystalline $SrTiO_3$, having substrate area of 5 mm by 1 cm. The R versus T curve with the lowest T_c in Fig. 2 (Cyc. 4) is measured after applying a bias current with a maximum of about 6 mA ($j = 5.5 \times 10^4$ A/cm^2, the sample at a bias temperature of 97±0.1 K for the cold finger). This extreme change of T_c has been mostly observed in samples with low and relatively sharp transition temperatures. The transition region near T_c of $YBa_2Cu_3O_{7-x}$ films on $LaAlO_3$ and $SrTiO_3$ substrates are found to be sharper than the films on MgO substrates, while the T_c of the latter is found to be more stable [16]. When samples with very low T_c's produced by high-bias current treatment are exposed to room temperature at atmospheric pressures, their T_c's return to higher values close to the initial values that were measured in the first cycle under low bias currents. A possible cause of the depression of T_c is the loss of oxygen induced by the strain produced at the film-substrate interface by Joule heating at relatively high-bias currents in the normal state in vacuum. The increase in R_N that is associated with this effect can be clearly observed when the sample is held at a constant temperature of the cold finger, under variable applied bias currents. This measurement is used for the determination of the dc thermal conductance of the samples [3], [17], [19]. The result of such a measurement for sample 064-01a is shown in Fig. 3, showing both changes in R_N due to the temperature rise in the film with respect to the cold finger and the shift in T_c due to changes of the oxygen stoichiometry of the sample. As observed in the figure, the later change which happens at bias currents over about 5 mA in this sample is not recovered when the current and excess temperature are removed. Considering the measured value of 3 mW/K for the $G(0)$ of this sample [17], the temperature rise caused by the Joule heating at a bias current of 5 mA is about 37 K. The temperature rise and $G(0)$ of our samples versus bias current were presented elsewhere [16].

R versus T measurements of our samples at atmospheric pressures using liquid nitrogen have shown higher T_c's [16]. The above shift of T_c to lower values can be controlled by the ambient atmosphere and the highest temperature to which the sample is exposed. This has potential uses in applications, such as superconducting bolometers, where one generally wants the highest dR/dT at the fixed temperature of the system. Some effects of ambient atmospheric pressures were presented elsewhere [16].

Some samples (064-02b) with an initially unstable T_c have revealed a stable and higher T_c after being exposed to high mechanical stresses under ambient atmosphere. The stress occurred when the back of the substrate was mechanically scratched in an attempt to remove residual silver paint which acted as a thermal shunt during the deposition of the films. The increase in T_c is interpreted as due to the release of residual strains existing in the film from the growth of the superconducting crystalline film on the highly strained substrate. The T_c of sample 064-02b before and after mechanical stresses are shown in Fig. 4(a) and (b), respectively. As shown in Fig. 4(a), the T_c of the sample decreases by further thermal cycles to stable lower values, even under low bias currents, and higher bias currents can still decrease the T_c to lower values. This is

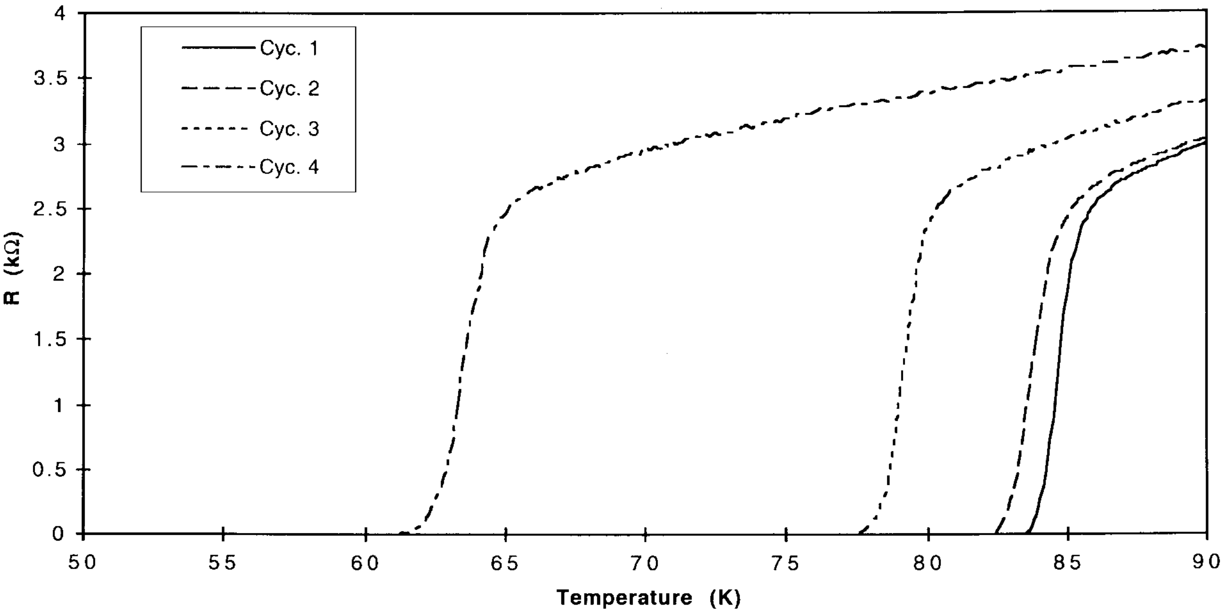


Fig. 2. R versus temperature measurements for sample 064-01a at 250-μA dc bias current and 2-K/min heating rate. The R versus T curve with the lowest T_c (Cyc. 4) is measured after applying a maximum current of about 6 mA at a bias temperature of 97±0.1 K. The sample has a 1.9-cm-long and 50-μm-wide meander line pattern of YBCO film with 220-nm thickness on crystalline $SrTiO_3$ substrate.

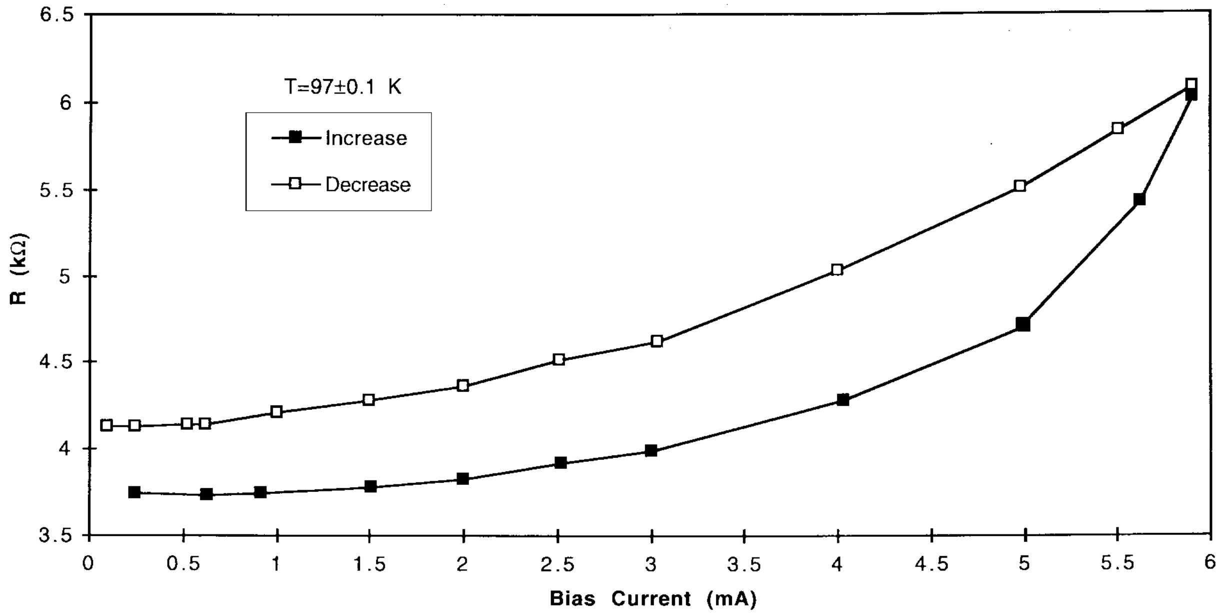
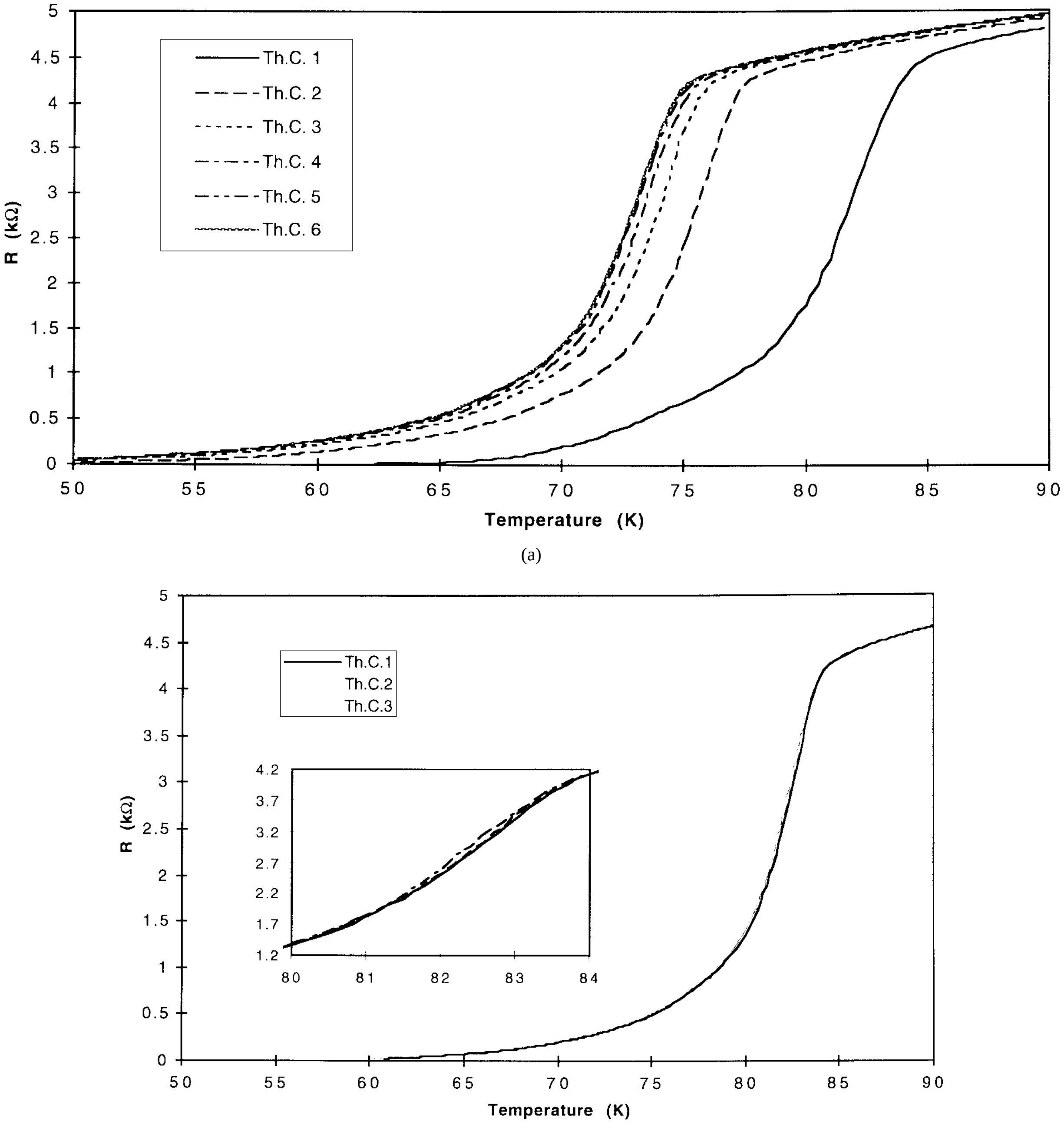


Fig. 3. Resistance versus dc bias current measurement of sample 064-01a at a bias temperature of 97±0.1 K. The measurement is done in two directions of increasing I (filled squares) and decreasing I (empty squares) after reaching a maximum current of 5.9 mA. The data points are taken after reaching a relatively stable R value in the sample at each bias current.

observed for our samples on $LaAlO_3$ and $SrTiO_3$ substrates as well. The T_c of sample 064-01a in Fig. 2, measured in its first cooling cycle after being taken out of the deposition system, was about 90 K; after some thermal cycles it reached its stable value at about 85 K as shown in Fig. 2, Cycle 1. It is also found that all the samples are sensitive to the ultimate vacuum and the thermal cycle to which the sample is exposed. The lowering of T_c at low bias currents, which is interpreted to be due to the thermal cycles under vacuum, is not recoverable by exposing the sample to room temperature and atmosphere. The decrease of T_c caused by high-bias currents under vacuum was found to be recoverable for sample 064-02b even after mechanical stresses, the same as shown in Fig. 2 for sample 064-01a.

IV. EFFECT OF MICROSTUCTURE AND BIAS CURRENT

We have also observed a repeatable and stable lowering of the normal resistivity of some of the samples in the R versus T measurements. This occurs with a change in bias current as shown in Fig. 5. This change in the resistance versus bias current is found to be separate from the shift in T_c discussed previously, which raised R_N. Two causes for the observations have



(a)

(b)

Fig. 4. R versus temperature of sample 064-02b at 680 μA: (a) for sequential thermal cycles right after the deposition and patterning process reaching a relatively stable T_c after a few cycles, (b) for subsequent thermal cycles after exposing the sample to high mechanical stresses under the ambient atmosphere revealing a high and stable T_c. The sample has a 1.9-cm-long and 50-μm-wide meander line pattern of 120-nm-thick YBCO film on a crystalline MgO substrate.

been identified. One is instrumental, while the other appears to depend on the microstructure of the films. For the samples with stable T_c, some of the changes are due to the instrumentation in the R versus T characterization systems using constant bias current. This is partly caused by the nonideality of the current source, specifically in a system with a current source made of a resistor and a battery. This configuration is essential for ultra low-noise measurements which were presented elsewhere [2]. Knowing the output impedance of the current source and the relative changes of R versus T at the transition, this error can be corrected. The R versus T of sample 064-02b in Fig. 5, corrected for this effect, is shown in Fig. 6. The R versus T changes of other samples without the above correction were presented elsewhere [16]. As shown in Fig. 6, there still exists a dependence of R on bias current, showing a nonlinear decrease of the normal resistance when the current is increased. This decrease of the R at higher bias currents (at the same T) is the opposite of the expected change due to the shift in T_c caused by Joule heating as shown in Fig. 3.

A. Microstructure Effects on the DC Characteristics

As shown in Fig. 6, there is a lowering of the normal state resistance at higher bias currents in highly granular samples. Possible mechanisms for this phenomenon are: 1) current flows

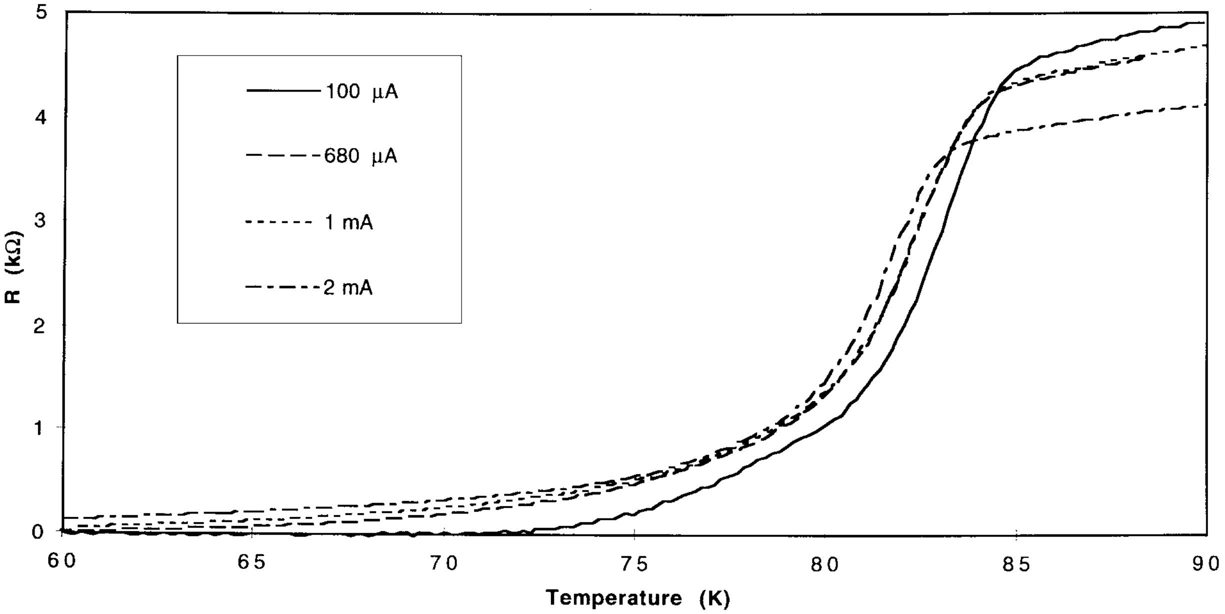


Fig. 5. R versus temperature of sample 064-02b at 100-μA, 680-μA, 1-mA, and 2-mA dc bias currents with 2-K/min heating rate. The measurements were done using a 68-V lantern battery and metal-film resistors.

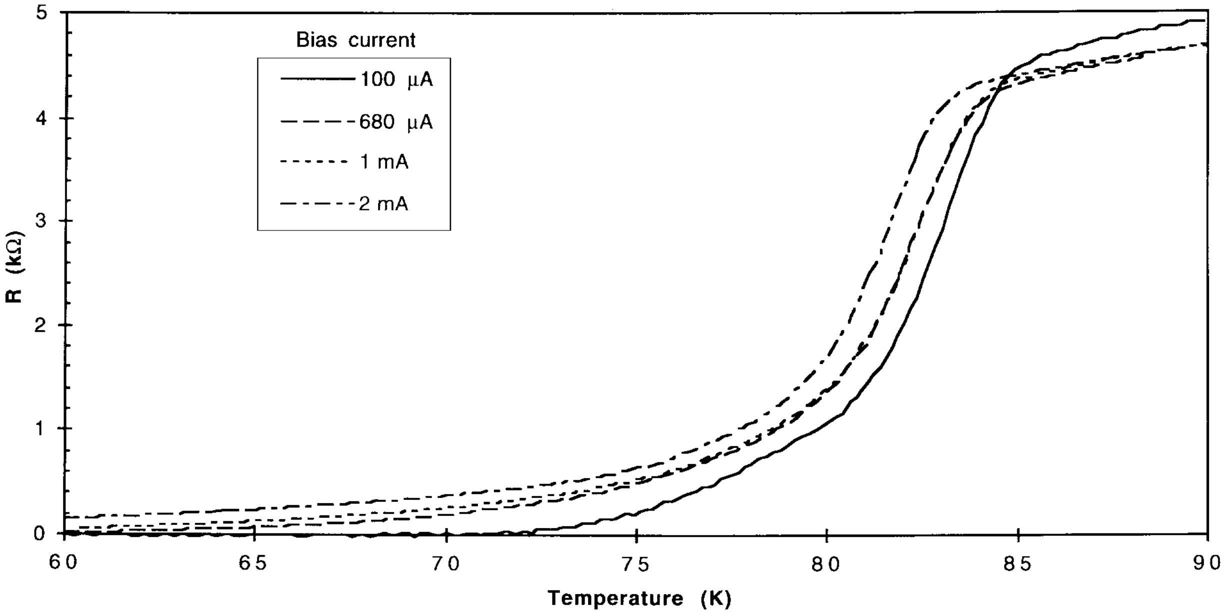


Fig. 6. R versus temperature curves of sample 064-02b (in Fig. 5) corrected for nonideality of the current source due to its limited output impedance and the change of the resistance of the YBCO film at different temperatures.

around the precipitates at low currents in the normal state due to potential barriers at the boundaries, while at higher currents the higher parallel voltages push current through these barriers lowering the effective resistance and 2) a possible tunneling mechanism at weak links mainly created during the patterning process, where some undesired etching around the large particle precipitates is observed. This may also have an effect on the responsivity of the bolometer made of such films [28], [29]. That a further increase of current ($I > 100$ μA) in Fig. 6 does not show any further significant changes in the normal state resistance is consistent with the above analysis. A scanning electron microscope (SEM) of sample 064-02b shows the precipitates clearly [16]. In addition to the above considerations there still is a shift in the $T_{c\text{-onset}}$ to lower temperature at higher bias currents which, as discussed before, is due to the Joule heating in the film and the limited G. This shift is used to find G and is discussed later.

As observed in Fig. 6, there is a decrease in $T_{c\text{-zero}}$ at high-bias currents which increases the width of the transition region. This widening of the transition, which occurs in highly granular samples, can override the apparent sharpening of the transition caused by the shift of the $T_{c\text{-onset}}$ to lower values due to the Joule heating, increasing the overall width of the measured transition. The dR/dT of the R versus T curves in

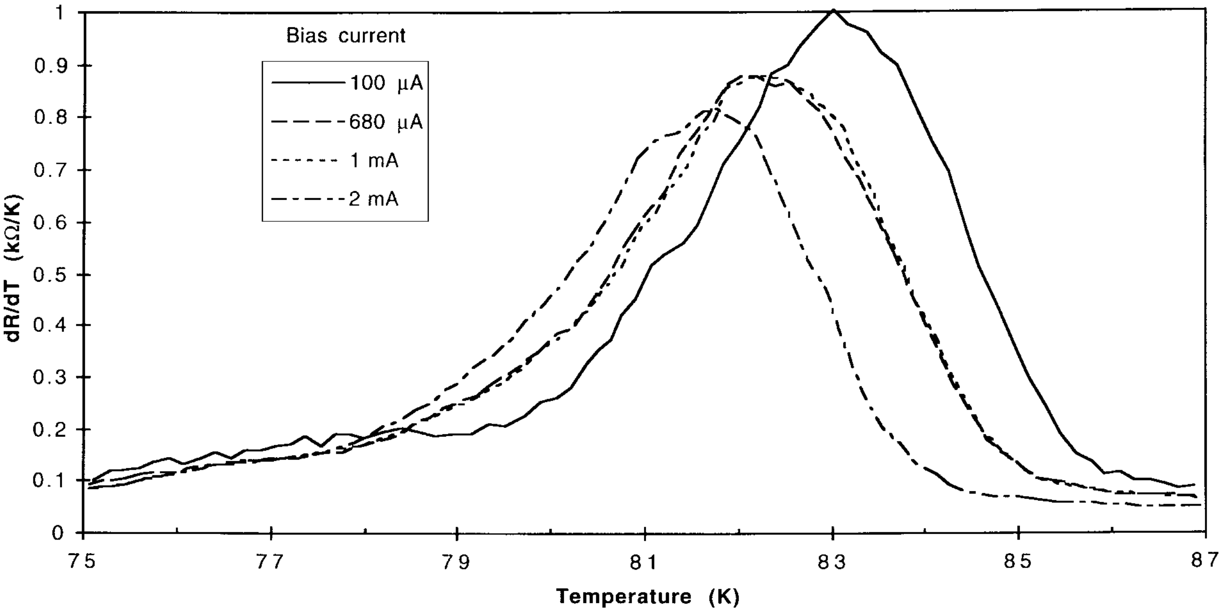


Fig. 7. dR/dT versus temperature of sample 064-02b at 100-μA, 680-μA, 1-mA, and 2-mA dc bias currents. The dR/dT is derived using the R versus T curves of the sample measured at a 2-K/min heating rate.

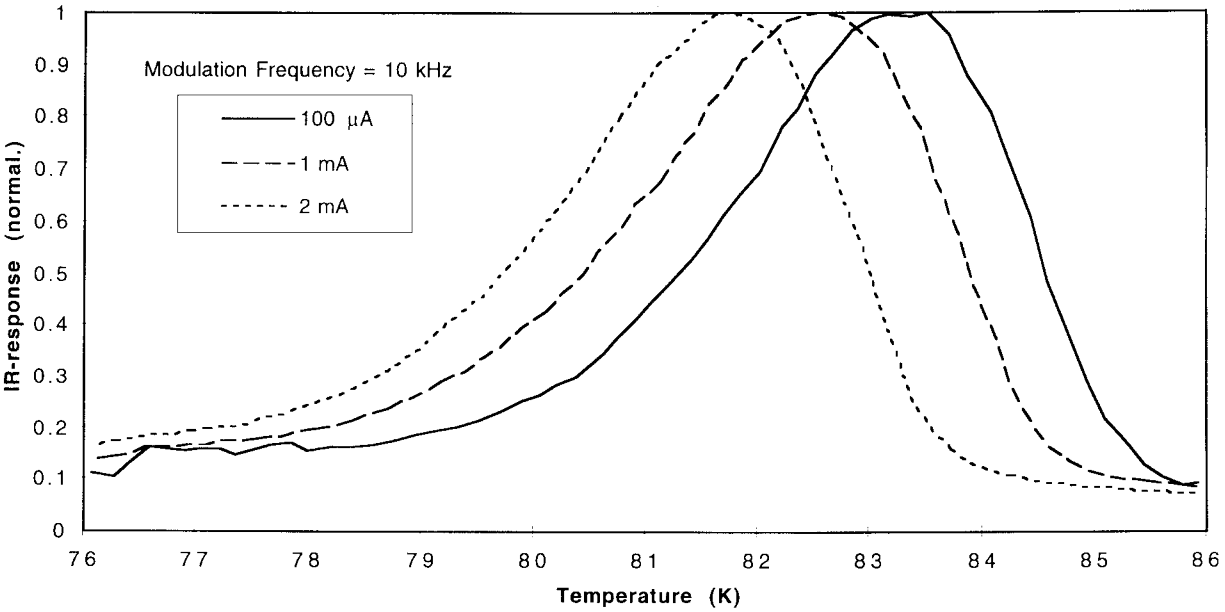


Fig. 8. Normalized response to IR radiation of sample 064-02b, at 100-μA, 1-mA, and 2-mA dc bias currents with peak response of 386 nV, 3.28 μV, and 5.87 μV, respectively. The measurements were at 10-kHz modulation frequency, 1-mW/cm radiation intensity with a peak wavelength of 0.85-μm, and 2-K/min heating rate.

Fig. 6 are shown in Fig. 7. As is observed in the figure, there is a decrease in T_c-onset of about 2° at 2-mA bias current. The sharpening of the transition region due to the shift of T_c-onset to lower values in the measured R versus T curves is found not to have an observable effect on the real magnitude of the dR/dT at any point which is investigated using the measured bolometric response of the samples (Fig. 8). However, the measured lowering of T_c-zero at high-bias currents due to the granularity of the film is found to be real and intrinsic, lowering the real peak magnitude of the dR/dT of the samples and also appearing in the bolometric response of the samples. This is discussed in the following section.

V. DETERMINING DC CHARACTERISTICS USING CURRENT NORMALIZED RESPONSE

For the measurement of the bolometric response versus the temperature of the cold finger at different bias currents (i.e., the temperature of the film can be different due to Joule heating), the lowering of the T_c-zero at higher bias currents should cause a decrease in the current normalized response (bolometer voltage divided by bias current of the bolometers [3]). The Joule heating only shifts the measured temperature of the onset of the transition and the peak temperature of the response (and also the dR/dT of the film) with respect to the temperature of the cold finger (i.e., the monitored temperature) toward lower temperatures. This shift is larger at higher bias currents and higher transition temperatures but can be found and corrected for, using (1). The current normalized response of sample 064-02b with the above characteristics is shown in Fig. 8. This shows the real dR/dT curve at the different bias currents of Fig. 6, since for the bolometric response we have [17]

$$r_v = \eta I \frac{dR}{dT}. \tag{2}$$

As shown in Fig. 8, the peak of the response is shifted to lower temperatures due to Joule heating, shifting the $T_{c\text{-onset}}$ to lower values. The magnitudes of the peaks of the measured response were 386 nV, 3.28 μV, and 5.87 μV for 100-μA, 1-mA, and 2-mA bias currents, respectively, showing a slight lowering due to the shift of $T_{c\text{-zero}}$ to lower temperatures following the changes in the maximum dR/dT curves of Fig. 7. These changes in the magnitude of the response due to real changes of dR/dT and the peak temperature, caused by the temperature rise of the film with respect to the substrate or the cold finger, have been interpreted as an effect of an intrinsic response of the high-T_c superconducting bolometers by some groups [1], [12], [27]. Based upon our analysis above, such an interpretation is not warranted.

A. Calculation of $G(0)$

As discussed above, the dc thermal conductance of the samples, $G(0)$, is the determining factor in the study of dc characteristics of high-T_c superconducting thin films on crystalline substrates and their T_c's. Knowing $G(0)$, I_{bias}, and the R or T values, one can investigate the exact effect of the Joule heating on the R versus T curves of the samples. Using (1) and the above parameters, the temperature rise of the film due to the Joule heating at any point can be monitored and corrected for in the dc characterizations. $G(0)$ can be found using several different methods [17]. One is based upon Fig. 3, using the value of R at different bias currents, since we can find the corresponding temperature of the film from a R versus T curve measured at very low bias currents, where the effect of Joule heating can be ignored. This method, which is also used by some other groups [19], may carry an error due to the shift of T_c at high-bias current as discussed previously. This can be eliminated by avoiding excessive currents or by repeated cycling to reach a stable value for T_c. Another method is the use of the shift in the peak temperature of the response which is insensitive to the changes of R where the value of R can be directly measured (i.e., using V and I) at any point to find the exact values of Joule heating to be used in (1) [3]. The derived $G(0)$ of the samples using different methods with detailed calculation of its dependence on the temperature are given elsewhere [3], [16].

B. Measured and Calculated Responsivity Using $G(0)$

The above derived G and the corrected measured dR/dT can be used to find the responsivity of superconductive thin-film bolometers. This can be done by use of (2) where the effect of the modulation frequency is also taken into the consideration [3], [17]. To avoid the frequency effect, the IR response can be measured at very low frequencies where the response is as follows [17]:

$$r_v = \frac{\eta I}{G(0)} \frac{dR}{dT}. \tag{3}$$

The measured responsivity of our samples matches the calculated values showing a good agreement with the above analysis [2], [17]. The misinterpretation of the shift of $T_{c\text{-onset}}$ and the dc characteristic of the samples can result in responsivity calculations that are more than one order of magnitude higher than are justified [1]. It can also cause the equilibrium response of such devices to be mistaken for nonequilibrium responses [27].

VI. CONCLUSION AND SUMMARY

In conclusion, the dc characteristics of the high-T_c YBCO films can be very different from sample to sample. The results strongly depend on the microstructure of the superconducting film, the measurement configuration, the thermal parameters of the samples, and also on details of the measurement setup. We have pointed out a number of phenomena related to the Joule heating of the samples under various conditions that lead to artifacts that can easily be misinterpreted. Among the pitfalls related to patterned films are: 1) the relation of the variation of the thermal conductance to the position of hot spots in the film; 2) the variation of T_c with Joule heating in vacuum; 3) the apparent sharpening of dR/dT due to Joule heating, when the temperature of the film itself is not measured; 4) shifts in properties related to the granularity of the films and the currents being carried by the films; and 5) shifts in dR/dT related to actual changes in the films due to Joule heating.

Hence, before a realistic assessment of the properties needed for sensitive superconducting bolometers can be obtained, one needs to be aware of the phenomena.

APPENDIX

SIMPLIFIED ONE-DIMENSIONAL MODEL FOR THE HOT SPOT LOCATION IN HEATED SUPERCONDUCTING FILMS

In this Appendix, in contrast to the more complex treatments of [4], [25], and [30] which neglect the transition region, we emphasize this region while neglecting heat flow along the film. Assume a superconducting film on a substrate, with the dominant heat flow through the substrate to a cold reference temperature T_r which can be varied and is the monitored temperature. In steady state the power supplied to the film is through Joule heating, while the film is in its transition region between $T_{\text{zero}} = T_{co}$ where it has zero resistance and $T_{\text{on-set}} = T_c$ where it has its normal resistance. Assume that in the transition region the resistance of the film is linear

$$R(T) = R_N \frac{(T - T_{co})}{(T_c - T_{co})} = \frac{R_N}{\Delta T}(T - T_{co}) \tag{A1}$$

where T is the actual temperature of the film. With these assumptions the steady-state heat flow equation is at any point

x along the length of the film (neglecting heat flow along the film)

$$G(x)\frac{dT}{dy} = I^2R(x) = I^2R_N\frac{[T(x)-T_{co}]}{\Delta T},; \qquad T(x) > T_{co} \tag{A2}$$

with $G(x)$ the conductance through the substrate and y the direction through the substrate. $G(x)$ may vary due to the contact of the substrate to the cold reference temperature or at the ends of the film, where current contacts or widening of the film provide additional heat paths. A more sophisticated model would require two or three dimensions. Solving (A2) for $T(x)$ yields

$$T(x) = \frac{T_r\left[G(x)\dfrac{\Delta T}{t} - I^2R_N\dfrac{T_{co}}{T_r}\right]}{G(x)\dfrac{\Delta T}{t} - I^2R_N}, \quad \text{for } T_c > T(x) > T_{co}. \tag{A3}$$

There are several cases that we wish to explore. First, consider the reference temperature T_r in relation to T_{co}.

Case 1: $T_r > T_{co}$. This is the usual case for use of a bolometer, where the reference temperature is set to place the film at a temperature where dR/dT is maximum, or at a convenient temperature within the transition region. For this case we can see that for $G(x) \rightarrow \infty$ the film will reach T_r everywhere, independent of I. For $G(x)$ finite, we see that as I is increased the denominator will pass through zero where $G(x)$ has its lowest value, while the numerator is still nonzero. This will lead to a hot spot at the position where G is minimum, usually the center of a bridge structure, since as mentioned above there are usually additional heat conduction paths near the ends.

Case 2: $T_r < T_{co}$. This is usually the case when liquid nitrogen is used as the coolant and high-quality films with the sharp transitions are used. In particular, in [4], the currents were set so that Joule heating would occur. In this case (A3) can be rewritten as

$$T(x) = \frac{T_r\left[I^2R_N\dfrac{T_{co}}{T_r} - G(x)\dfrac{\Delta T}{t}\right]}{I^2R_N - G(x)\dfrac{\Delta T}{t}}, \quad \text{for } T_c > T(x) > T_{co} > T_r. \tag{A4}$$

Here we see that $T(x)$ will have its highest value where $G(x)$ is maximum; this is opposite to Case 1 and hence we would expect a hot spot at the end of a superconducting bridge. Indeed, this is what was observed in [4], in contrast to their expectations. While this justifies our comment in Section II, a further point is worth noting. The current to the films can be supplied by a current source or a voltage source. For both types of sources the same current flows everywhere in the film regardless of the variations in temperature and hence in resistance of the film as a function of position. However, for Cases 1 and 2 above, there is a difference depending upon the type of source used.

- Case 1 plus current source: No change in our analysis; as I is increased a hot spot will appear first where $G(x)$ is minimum, and its presence will tend to cause the spot to spread with no further increase in current heating the whole bridge.
- Case 1 plus voltage source: As the voltage rises across the film the current will also rise, and again the hot spot will appear where $G(x)$ is minimum. However, now the presence of the hot spot by raising the resistance will lower the current everywhere. The hot spot will remain localized; an increase in voltage would be needed to make it spread.
- Case 2 plus current source: No change in our analysis; the hot spot appears first where $G(x)$ is maximum, and its spread will depend on the value of $G_{\max}$ and $G(x)$.
- Case 2 plus voltage source: As before, the hot spot will appear first where $G(x)$ is maximum. As the resistance of the hot spot increases, I drops everywhere; the spreading of the hot spot will depend on the distribution of $G(x)$ since both the numerator and the denominator are reduced.

The results of [4] were carried out for Case 2 with a voltage source, the temperature T_H found for the hot spot was 94 K, while $T_c = 85$ K, and the nonhot spot regions were deduced to be at $T_r = 77$ K. Both of these results fall outside the range of our simple model, and hence our model strictly does not apply to their results. However, our model should hold as one makes the transitions from these superconducting to the normal region with rising current or voltage and hence should be valid for predicting where the hot spot will first appear.

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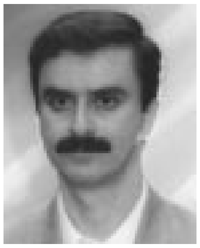

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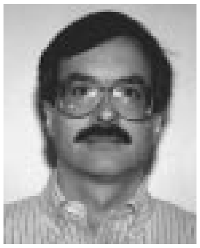

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