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Details of the fabrication process and figures of merit of resistive YBaCuO microbolometers are reported. Thin films of YBaCuO were prepared on Si wafers under conditions that promote formation of the semiconducting phase at room temperatures. Temperature coefficient of resistance with values of up to 0.04 K^{-1} was uniformly achieved on 10 cm wide wafer. Bulk micromachining was used to create $60\times 60\,\mu m^2$ bolometers on Si_3N_4 bridges with a thermal conductance of $\sim 7.6\times 10^{-7}$ W/K. The optical responsivity and detectivity of these bolometers were respectively $\sim 7\times 10^4$ V/W and $3\times 10^9\,\mathrm{cm\,Hz^{1/2}/W}$ at low frequencies. These figures are consistent with those derived from the thermal properties of the bridge and are better than figures of other classes of room temperature bolometer. Good agreement was found between the spectral response of the bolometer and the spectral absorptance of the Si_3N_4 bridge, confirming the role of the latter as the heat absorber in the device. Under normal operating conditions and assuming $F/1$ optics, the noise equivalent temperature difference of focal planes that make use of YBaCuO microbolometers was estimated to be less than 50 mK in the spectral range of 8–14 μm. *© 2000 American Vacuum Society.* [S0734-2101(00)02202-8]

I. INTRODUCTION

Since the discovery of copper oxide superconductors, there has been tremendous interest in their use for infrared imaging.[1,2] In this application, thin film superconductors operate commonly as resistive bolometers at temperatures near the resistance transition. Because the temperature coefficient of resistance (TCR) of superconductors is positive, thermal runaway instabilities occur when a large bias current is supplied to the bolometer. This condition limits the highest level of responsivity attainable in this class of devices. In this work we prepared thin films of copper oxide compounds under conditions that promote formation of the semiconducting phase, so as to achieve negative TCR. This article reports on the results obtained specifically for the YBaCuO compound at room temperatures.

When the bolometer is illuminated, it is necessary that the heat transfer rates from the thermally active element to its surrounding be minimized in order to achieve large responsivities. One approach to achieve this is to fabricate the bolometer on structures with good thermal isolation. We used bulk micromachining to create YBaCuO microbolometers on suspended Si_3N_4 bridges. The fabrication processes and properties of the microbolometers are presented in the following sections. On the basis of the performance of the fabricated microbolometers, their potential use in infrared imaging applications will be discussed.

II. EXPERIMENTAL DETAILS

Magnetron radio frequency (rf) sputtering was used to deposit YBaCuO films on Si_3N_4 coated Si wafers. The preparation of the YBaCuO sputter targets consisted of a blending of precursor powders, followed by solid state reactions and pressing of the reacted compound. Targets having diameters of 5 and 10 cm were prepared using a starting cation ratio of Y:Ba:Cu = 1:2:3 for the metal constituents. The distance between the target and substrate table was in the range of 11–17 cm. The deposition was performed typically in an Ar pressure of 80 mTorr for a rf power of 80 W. After the deposition, four probe Au contacts were formed and patterned on YBaCuO films by means of magnetron sputtering and wet etching. It was found that the YBaCuO films showed semiconducting behavior at room temperatures when the substrate was not intentionally heated during the deposition. Conversely, the films deposited on heated substrates exhibited metallic behavior. TCR values of up to 0.04 K^{-1} were measured commonly on the semiconducting films with electrical resistivity, ρ, of $\sim 1\ k\Omega$ cm.

The uniformity of ρ and TCR values of the YBaCuO films was examined across the wafer area. It was found that ρ and TCR were almost constant when moderate levels of sputter pressure were used. For instance, sputtering from a 10 cm target in an Ar pressure of 80 mTorr resulted in films with uniform ρ over an 8 cm wide area. Under similar conditions, essentially constant values of TCR were measured within a 12 cm wide area.

The process flow devised for the microfabrication of YBaCuO bolometers can be divided into two generic phases. First, Si_3N_4 bridges were created on Si wafer so as to prepare thermal isolation supports for the bolometers. Second, YBaCuO and Au films were grown and patterned on the bridges so as to form the bolometers and contact metallization. The wafers used in this work were made of n-type (100) Si and were coated with Si_3N_4 layers on both sides, either by magnetron sputtering or chemical vapor deposition. Sacrificial Cr layers were sputter deposited onto both sides of the wafer, serving as a mask to transfer the pixel patterns onto the front Si_3N_4 layer and to insulate the back of the wafer. After the etching of selected areas of the front Si_3N_4 layer

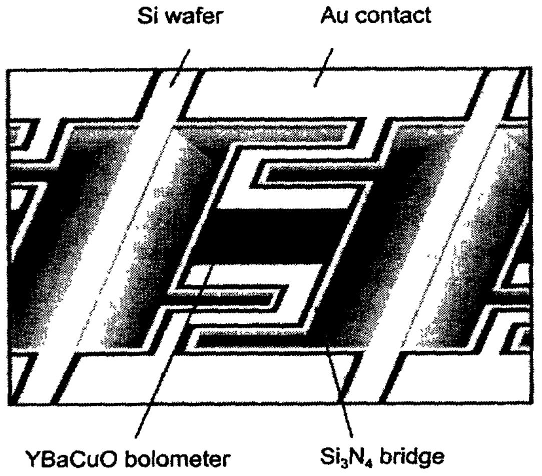

FIG 1 Schematic diagram of a YBaCuO microbolometer

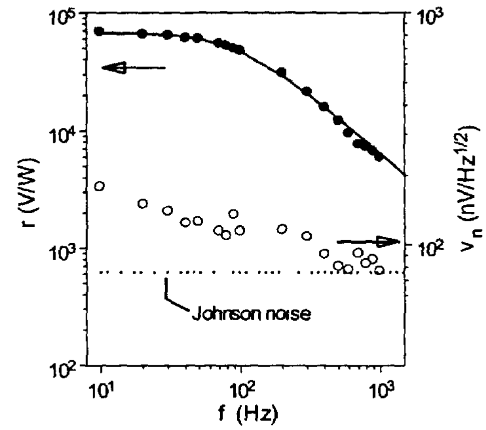

FIG 2 Frequency dependence of responsivity and noise of a YBaCuO microbolometer for $I = 10\ \mu A$ and $T = 300$ K The solid curve depicts the theoretical bolometric responsivity for $\tau = 1.65$ ms The dashed line shows the Johnson noise computed for the devices

where bulk micromachining was to take place, the Cr layers on both sides of the wafer were removed. Parts of the Si wafer under the defined pixel areas were then dissolved in a solution so that suspended Si_3N_4 bridges could be created on the wafer. In the subsequent phase, YBaCuO and Au films were sputter deposited successively onto the bridges without breaking the vacuum of the deposition chamber. After this, standard photolithography was applied sequentially to remove the unwanted areas of Au and YBaCuO. The schematic of the resulting microbolometer is shown in Fig. 1. The respective dimensions of the Si_3N_4 bridge and YBaCuO active area, A, were 60×70 and $60\times 60\ \mu m^2$. The thicknesses of the bridge, bolometer, and Au contact were respectively 600, 100, and 120 nm. To prepare the bolometers for the characterization experiments, they were mounted onto standard microelectronic packages. Thermosonic wire bonding was then performed to attach 17 μm wide Au leads to the Au contact pads on the devices.

III. RESULTS AND DISCUSSION

In the first series of experiments the frequency dependence of the optical response of the YBaCuO microbolometers was studied. One purpose of this study was to extract the thermal data of the bridge from the optical response in order to assess its role. A laser diode powered by a waveform generator provided the modulated incident light at the wavelength $\lambda \sim 0.83\ \mu m$. The root mean square (rms) power density of the incident light, p, was ~ 0.4 mW/cm^2. The temperature of the bolometer was maintained at 295 K by means of a temperature controller. All measurements were performed in a chamber with a vacuum pressure of ~ 10 mTorr. A low noise current source supplied constant currents I of up to several tens of μA in the bolometer. The rms voltage fluctuation under dark condition (noise voltage v_n) or in the presence of light (photoresponse V) was detected by a lock-in amplifier.

Figure 2 shows the frequency dependence of responsivity of a microbolometer biased at $I = 10\ \mu A$. The electrical resistance R and TCR of this device were 360 kΩ and 0.02, respectively. At low frequencies, responsivity magnitudes of $r = V/pA \sim 6\times 10^4$ V/W were obtained. This value remained unchanged regardless of the size of the beam illuminating the wafer, excluding possibilities of crosstalk contribution. Also seen in Fig. 2 is the good agreement between experimental data and theoretical bolometric responsivities $r = r_0\ (1 + 4\pi^2 f^2 \tau^2)^{-1/2}$, for $\tau \sim 1.65$ ms. For a better understanding of the role of the bridge behind the measured data, we examined its thermal properties. The heat capacity of the Si_3N_4 bridge could be derived from its volume ($\sim 2.2 \times 10^{-9}$ cm^3), density (~ 3.44 g/cm^3), and specific heat (~ 0.17 J/g K) to be $C \sim 1.3\times 10^{-9}$ J/K. It follows that the thermal conductance of the bridge is in the order of $G \sim C/\tau \sim 7.8\times 10^{-7}$ W/K. Solving the heat transfer equation for the bolometer, the steady state responsivity could be estimated as $r = \eta I R \mathrm{TCR}/[G(1+4\pi^2 f^2 \tau^2)^{1/2}] \sim 2\times 10^4$ V/W for $f = 30$ Hz, assuming an optical absorptance $\eta = 0.2$ of Si_3N_4. It can be seen that the magnitude of the computed responsivity corroborates with that recorded experimentally. Therefore, it is believed that the large responsivity of the bolometer was a result of the small thermal conductance of the bridge.

The frequency dependence of noise is further depicted in Fig. 2. The noise voltage, v_n, was measured in the frequency bandwidth $\Delta f = 1.2$ Hz. When f was increased by two orders of magnitude, v_n was seen to decrease only by a factor of ~ 2. This behavior confirmed that the occurrence of the $1/f$ noise, reportedly predominant in certain classes of resistive bolometers,[2-4] is secondary in YBaCuO bolometers. In effect, the $1/f$ noise could be estimated through deduction of the Johnson noise (also shown in Fig. 2) from the experimental data. It was found that the $1/f$ noise fell behind the Johnson noise level at frequencies beyond 30 Hz. This fact lends support to the observation that the noise measured on YBaCuO bolometers is significantly smaller than the typical noise of other classes of uncooled bolometer, such as VO_x bolometers.[3] The smaller noise in YBaCuO bolometers may be inherent to the intrinsic properties of semiconducting

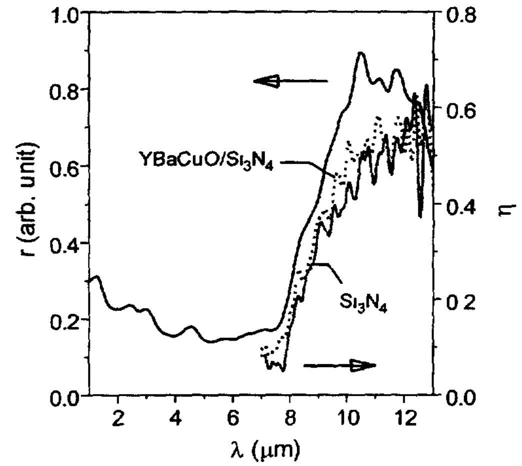

FIG. 3. Comparison between the spectral response of YBaCuO microbolometer and the spectral absorptance of YBaCuO/Si_3N_4 and Si_3N_4 structures The observed similitude of their spectral dependence confirms the role of the Si_3N_4 bridge as the primary heat absorbing element in the device

YBaCuO[5] and the quality of ohmic contacts between Au and amorphous YBaCuO films. Using the data of noise and responsivity, the detectivities D^* of YBaCuO bolometers could be derived. For $\lambda = 830\,\text{nm}$, $T = 295\,\text{K}$, $I = 10\,\mu\text{A}$, and $f = 30\,\text{Hz}$, $D^* = r(A\Delta f)^{1/2}/v_n \sim 3\times 10^9\,\text{cm}\,\text{Hz}^{1/2}/\text{W}$, which is less than one order of magnitude below the thermodynamic limit of $1.8\times 10^{10}\,\text{cm.Hz}^{1/2}/\text{W}$ of room temperature bolometers.[6]

In order to optimize the performance of the microbolometer, it is necessary to identify the heat absorbing element in the device. Previously, it was found that the performance of the bolometer is consistent with that derived from the thermal properties of the bridge. To confirm the role of the bridge as the primary heat absorber, we proceeded to compare its spectral absorptance with the spectral response of the bolometer. The spectral measurements were performed using a precision monochromator which provided incident light in the spectral range from 1 to 13 μm. Figure 3 shows a plot of the spectral response of the YBaCuO microbolometer. It is seen that the responsivity varies negligibly in the range from 1 to 7 μm but rises more than four times at longer wavelengths. Considering the large depth and irregular surface of the cavity under the bridge, it appears unlikely that the observed increase of responsivity is a result of interference effects alone. To determine whether this increase is inherent to changes in the absorptance of the Si_3N_4 bridge, we measured the reflectance and transmittance of a Si_3N_4/YBaCuO structure and of a bare Si_3N_4 film, both deposited on Si wafer. In this experiment the thicknesses of the Si_3N_4 and YBaCuO films are those selected for the bolometer devices. The measurement was performed in the spectral range beyond 7 μm, where changes in the responsivity of the bolometer were significant. The absorptance of both structures, as derived from reflectance and transmittance data, is also shown in Fig. 3. The spectral absorptance of the YBaCuO/Si_3N_4 structure is seen to be analogous to that of the Si_3N_4 film, thus eliminating the contribution of the YBaCuO film in the overall absorption. Furthermore, the spectral response of the bolometer is consistent with the spectral absorptance of the Si_3N_4 film. This result confirms the role of the Si_3N_4 bridge as the primary heat absorbing element in the device. The large absorptance of Si_3N_4 in the 8–12 μm atmospheric window makes the microbolometers effective for use in infrared imaging applications. With regards to these applications, we would like to comment on possible gains in using resistive YBaCuO microbolometers. First, the thin film fabrication of YBaCuO bolometer is a less complex process in that, unlike its counterparts (e.g., VO_x), *in situ* or postdeposition annealing of the film is not required. This condition eases the monolithic construction of focal planes on wafers with imbedded readout electronics. Second, the low noise of YBaCuO bolometers makes it possible to design them with large values of resistance so that even higher responsivities can be achieved. Finally, the combination of high responsivity and low noise would result in focal planes with small values of noise equivalent temperature difference (NETD). We estimated the NETD of a focal plane of 160×120 bolometer pixels with $F/1$ optics for a 300 K scene temperature in the spectral range of 8–14 μm. The integral of the temperature derivative of blackbody radiation in this spectral range was computed to be $(\Delta p/\Delta T) = 2.62\times 10^{-4}\,\text{W/cm}^2\,\text{K}$. The frequency bandwidth of the device is assumed to be haft of the column pixel rate, that is, $\Delta f \sim 1.8\,\text{kHz}$ for a display frame rate of 30 Hz. The noise contained in this bandwidth was measured to be $v_n \sim 4\,\mu\text{V}$. Hence, assuming a far infrared absorptance $\eta = 0.7$ of Si_3N_4 and using the measured figures of merit of YBaCuO microbolometers, the anticipated NETD could be derived as $(4F^2+1)v_n/\eta A r(\Delta p/\Delta T) \sim 47\,\text{mK}$. Such a value is close to the theoretical performance limit[7] computed for microbolometers with a similar thermal conductance.

IV. CONCLUSIONS

Thin films of YBaCuO were prepared on Si wafers under conditions that promote formation of the semiconducting phase at room temperatures. TCR with absolute values of up to 0.04 K^{-1} were achieved uniformly on 10 cm wide wafer areas. Bulk micromachining was used to create bolometers on Si_3N_4 bridges with a thermal conductance of $\sim 7.6\times 10^{-7}\,\text{W/K}$. The low frequency responsivity and detectivity of the microbolometers were respectively $\sim 7\times 10^4\,\text{V/W}$ and $3\times 10^9\,\text{cm}\,\text{Hz}^{1/2}/\text{W}$ at room temperatures. These figures are consistent with those derived from thermal properties of the bridge and are better than figures of other room temperature microbolometers.[4,8] The large detectivity of YBaCuO bolometers may be attributed in part to the low noise of the device; the noise measured on YBaCuO bolometers is neighboring the theoretical Johnson noise and is many times smaller than the typical noise of their counterparts. The role of the bridge as the primary heat absorber was confirmed from the agreement found between its spectral absorptance and the spectral response of the bolometer The large absorptance of the bridge in the 8–12 μm atmospheric window suggests that the fabricated microbolometer is effective for use in infrared imaging applications. Under normal operating conditions and assuming *F*/1 optics, the NETD of focal planes that make use of YBaCuO microbolometers was estimated to be less than 50 mK in this spectral range.

ACKNOWLEDGMENTS

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