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Resistive YBaCuO micro bolometers for infrared imaging applications

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ABSTRACT

Details of the fabrication process and figures of merit of resistive YBaCuO micro bolometers are reported. Thin films of YBaCuO were prepared on Si wafers under conditions that promote formation of the semi-conducting phase at room temperatures. Effects of the preparation conditions on activation energy of YBaCuO were studied to obtain films with a large temperature coefficient of resistance (*TCR*). *TCR* with values of up to 0.04 K^{-1} was achieved uniformly on 10-cm wide wafer areas. Bulk micromachining was used to create 60 x 60 μm^2 bolometers on Si_3N_4 bridges with a thermal conductance of ~ 7.6 x 10^{-7} W / K. The low frequency responsivity and detectivity of the micro bolometers were respectively ~ 7 x 10^4 V / W and 3 x 10^9 cm.$Hz^{1/2}$ / W at room temperatures. These figures compare favorably with figures of other classes of un-cooled micro bolometer and are consistent with those derived from thermal properties of the bridge. Under normal operating conditions and assuming f / 1.0 optics, the NETD of focal planes that make use of these micro bolometers was estimated to be less than 50 mK in the spectral range of 8 to 14 µm.

Keywords: YBaCuO, Si micromachining, bolometer, infrared focal plane

1. INTRODUCTION

Since the discovery of copper oxide superconductors, there have been tremendous interests 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 superconductor 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 investigated the preparation conditions that promote rather formation of the semiconducting phase in copper oxide compounds, 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 this end is to fabricate the bolometer on thermal isolation structures. We used bulk micromachining to create YBaCuO micro bolometers on suspended Si_3N_4 bridges. Details of the fabrication process and properties of the micro bolometers are presented in the following. On the basis of the performance of the fabricated micro bolometers, their potential use in infrared imaging applications will be discussed.

2. GROWTH AND CHARACTERISTICS OF YBaCuO FILMS

The effects of preparation conditions on electrical resistivity, ρ, and *TCR* of YBaCuO films were first studied. Magnetron 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 in Ar pressures between

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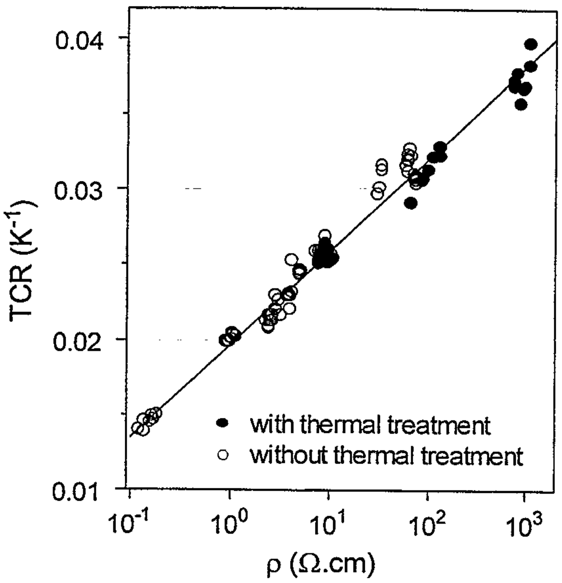

FIG. 1 – Absolute values of *TCR* as a function of resistivity of YBaCuO films for different preparation conditions. The solid line is provided as visual aids.

-1 and 30 mTorr or in O_2 partial pressures in the same extent, with the O_2 content being varied from 3 to 30 %. The magnitudes of the rf power were from 20 and 240 W. No intentional heating was applied to the substrate during the deposition. After the deposition, four probe Au contacts were formed and patterned on YBaCuO films by means of magnetron sputtering and wet etching.

Under the preparation conditions used in this work, films with room temperature resistivity in the range of 0.1 - 1000 Ω.cm were obtained. Data obtained from a series of experiments revealed that: (i) ρ increases with increasing Ar pressure and rf power; and (ii) ρ decreases with increasing O_2 partial pressure. Heat treatment experiments were also performed on selected samples. The as-deposited films were annealed in O_2 at temperatures from 300 to 400 °C for a period of time varying between 1 and 20 hrs. After the heat treatment, the films were rapidly quenched to room temperatures. It was found that the treated films exhibit larger values of ρ as compared with the untreated films. The increase in temperature and duration of the heat treatment resulted as well in an increase of ρ. In Fig. 1 the *TCR* of the treated and untreated films is plotted as a function of ρ. These results showed that *TCR* values increase linearly with ρ to an extent, regardless of the treatment conditions applied to the films. Within the limits of ρ of the prepared films, *TCR* values of up to 0.04 K^{-1} were achieved.

We examined also the effects of preparation conditions on the changes of ρ and *TCR* across the wafer area. In this experiment, YBaCuO films were deposited on discrete substrates placed along the diameter of the projection of target area on the substrate table. Measurements performed on these substrates showed that ρ and *TCR* vary negligibly when moderate levels of sputter pressure were used. For instance, sputtering of a 10-cm target in Ar pressure of 80 mTorr resulted in films with ρ uniform over an 8-cm wide area. Under similar conditions, uniform values of *TCR* were measured within a 12-cm wide area.

3. MICROFABRICATION AND FIGURES OF MERIT OF YBaCuO BOLOMETERS

Processes were devised for the photolithographic microfabrication of YBaCuO bolometers in view of investigating the properties of these devices. After the description of the process flow, results of an experimental study on the fabricated bolometers will be presented and discussed.

The process flow can be divided into two generic phases. Firstly, Si_3N_4 bridges were created on Si wafer so as to prepare thermal isolation supports for the bolometers. Secondly, 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 rf sputtering or chemical vapor deposition. A sacrificial Cr layer was 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 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

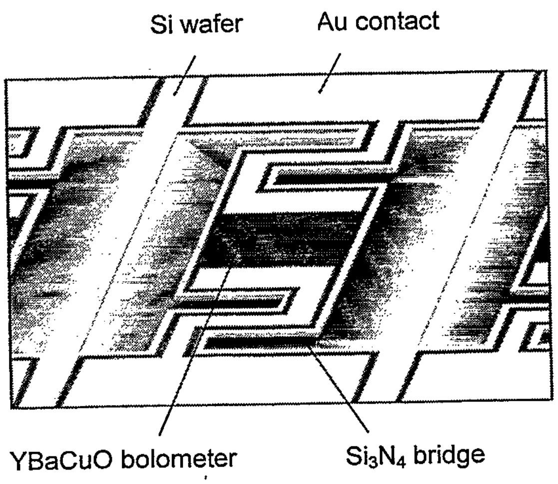

FIG. 2 - Schematic of an YBaCuO micro bolometer (not on scale)

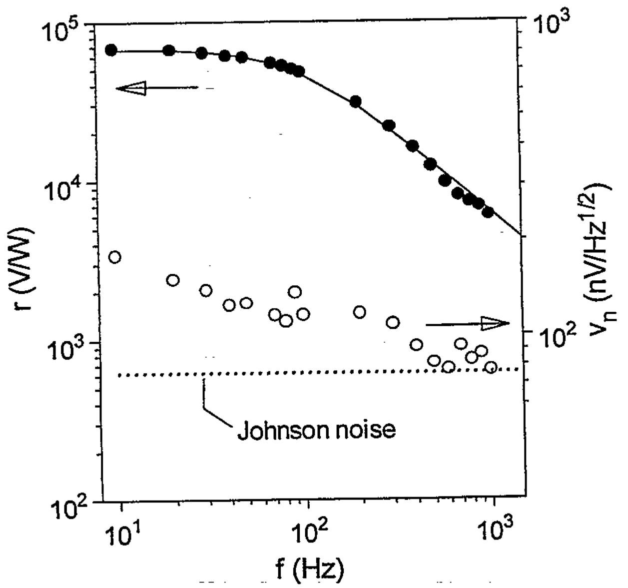

FIG. 3 - Frequency dependence of responsivity and noise of a YBaCuO micro bolometer for $I = 10$ μA and $T = 300$ K. The solid curve depicts the theoretical bolometric responsivity for $\tau = 1.65$ ms. The dashed line shows the Johnson noise computed for the device.

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 micro bolometer is shown in Fig. 2. The respective dimensions of the Si_3N_4 bridge and YBaCuO active area, A, were 60 x 70 and 60 x 60 μm². 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.

The optical response of the YBaCuO micro bolometers was measured at the wavelength $\lambda \sim 0.83$ μm. The incident light was obtained from a laser diode and was modulated using a waveform generator connected to the diode. The rms power density of light incident into the bolometer, p, was ~ 0.4 mW / cm². 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 v_n) or in the presence of light (photoresponse V) was detected by a lock-in amplifier. All measurements were performed in a vacuum pressure of ~ 10 mTorr.

Figure 3 shows the frequency dependence of responsivity and noise of a micro bolometer biased at $I = 10$ μA. The electrical resistance R and TCR of this device were measured to be 360 kΩ and 0.02 respectively. At low frequencies, a responsivity magnitude of $r = V / pA \sim 7 \times 10^4$ V / W was obtained. This value remained unchanged regardless of the size of the beam illuminating the wafer, excluding possibilities of crosstalk contribution. Also seen in Fig. 3 is the good agreement between experimental data and theoretical bolometric responsivities $r = r_0 (1 + 4\pi^2 f^2 \tau^2)^{-½}$, 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 (~ 2.2 x 10^{-9} cm³), density (~ 3.44 g / cm³), 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 $r = \eta IR\ TCR / [G (1 + 4\pi^2 f^2 \tau^2)^{-1/2}] \sim 6 \times 10^4$ V / W for $f = 30$ Hz, assuming an optical absorptance $\eta = 0.7$ of Si_3N_4. It can be seen that the magnitude of the computed responsivity corroborates with that recorded experimentally. On the basis of this consistency, 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. 3. Noise voltages contained in the frequency bandwidth $\Delta f = 1.2$ Hz, υ_n, were measured. When f was increased by two orders of magnitude, υ_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. The $1/f$ noise could be estimated through deduction of the Johnson noise (also shown in Fig. 3) from experimental data. It was found that the $1/f$ noise fell behind the Johnson noise at frequencies beyond 30 Hz. This 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 YBaCuO and the quality of ohmic contacts between Au and YBaCuO films. Using the data of noise and responsivity, detectivities D^* of YBaCuO bolometers could be derived. For $\lambda = 830$ nm, $T = 300$ K, $I = 10$ µA, $f = 30$ Hz, $D^* = r\,(A\,\Delta f)^{1/2} / \upsilon_n \sim 3 \times 10^9$ cm. $Hz^{1/2}$ / W, which is less than one order of magnitude below the thermodynamic limit of 1.8×10^{10} cm. $Hz^{1/2}$ / W of room temperature bolometers.[5]

4. CONCLUSIONS

Details of the fabrication process and figures of merit of resistive YBaCuO micro bolometers were reported. 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 ~ 7.6×10^{-7} W / K. The low frequency responsivity and detectivity of the micro bolometers were respectively ~ 7×10^4 V / W and 3×10^9 cm.$Hz^{1/2}$ / W at room temperatures. These figures compare favorably with figures of other uncooled micro bolometers [4,6] and are consistent with those derived from thermal properties of the bridge. Noise measured on YBaCuO bolometers is neighboring theoretical Johnson noise and is many times smaller than typical noise of their counterparts.

We would like to comment on possible gains in using resistive YBaCuO micro bolometers for infrared imaging. Firstly, the thin film fabrication of YBaCuO bolometer is a much less complex process in that, unlike its counterparts, *in-situ* or post deposition annealing of the film is not required. This condition eases the monolithic construction of focal planes on wafers with imbedded readout electronics. Secondly, 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 x 120 bolometer pixels with $F / 1.0$ 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 $(\Delta p / \Delta T) = 2.62 \times 10^{-4}$ W / cm².K. The frequency bandwidth of the device is assumed to be haft of the column pixel rate, that is, $\Delta f \sim 1.9$ kHz for a display frame rate of 30 Hz. The noise contained in this bandwidth was measured to be $\upsilon_n \sim 4$ µV. Hence, assuming a far infrared absorptance $\eta = 0.7$ of Si_3N_4 and using the measured figures of merit of YBaCuO micro bolometers, the anticipated *NETD* could be derived as $(4\,F^2 + 1)\,\upsilon_n / \eta\,A\,r\,(\Delta p / \Delta T) \sim 47$ mK. Such a value is seen to be close to the theoretical performance limit [7] computed for micro bolometers with a similar thermal conductance.

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