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High responsivity $YBa_2Cu_3O_{7-x}$ microbolometers with fast response times

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To make high-responsivity $YBa_2Cu_3O_{7-x}$ microbolometers with response times in the tens of microseconds, heat capacity and hence physical size must be small. We measured the responsivities and response times of 2.5×2.5 μm and 10×10 μm $YBa_2Cu_3O_{7-x}$ microbolometers fabricated on ZrO_2 substrates and illuminated by an argon-ion laser focused to a 2 μm spot. Responsivities were found to be 975 and 700 V/W, respectively, with response times of 10 and 40 μs.

The development of a liquid-nitrogen operated long wavelength detector system provided the impetus for research into high T_c superconductor (HTS) bolometers.[1–8] Bolometers are broad-band thermal detectors independent of irradiation wavelength. The resistivity of a bolometer changes in response to temperature increases resulting from light irradiation. Bolometric principles were studied by Rutledge,[9] Kruse,[4] and Richards *et al.*[10,11] Most bolometers[3,7] investigated were slow because they were millimeters in size and had large heat capacities (response times were 32 s and 55 ms, respectively[3,7]). These speeds were too slow for an imaging detector system with TV-like frame rates. A faster bolometer of size 75×75 μm was constructed on a thin membrane substrate[4–6] in order to reduce substrate heat capacity, and attained a response time of 1 ms.[6] Further improvements in device response time can be obtained using a microbolometer design.[9,11] In a microbolometer, a small $YBa_2Cu_3O_{7-x}$ (YBCO) device sits on top of a low thermal conductivity substrate, which is in thermal equilibrium with a heat sink. The contact area between the microbolometer and the substrate is small. Therefore, the diffusion of heat generated in the microbolometer into the substrate is localized in a small region. The small contact area leads to a low thermal conductance between the microbolometer and the heat sink. A microbolometer of low heat capacity and low thermal conductance is expected to be both fast and sensitive.[11] A 2-μm-diam microbolometer should have a response time of microseconds.

In this study, an argon-ion laser beam at 514 nm was focused to a diameter of 2 μm, and the focused illumination aligned with microbolometers mounted inside a dewar. We fabricated microbolometers as small as 2.5×2.5 μm, and report on the response of these devices to the modulated laser beam. When both the illuminating beam and the detector size are on the order of 2 μm, precise alignment of the two inside a dewar is difficult. To our knowledge, response measurements of this type have not been previously reported for YBCO microbolometers.

To begin the microbolometer fabrication process, YBCO thin films were deposited onto ZrO_2 substrates ($k_s=0.015$ W/cm/K, $c_s=0.7$ J/cm^3/K)[2] by *in situ* rf magnetron sputtering. A typical thin film had a resistivity transition edge with an onset temperature of $T_c=88$ K, with device resistance vanishing at $T_{c0}=86$ K. The sheet resistivity was 20 Ω/sq for a 0.2 μm thin film at 100 K. The films were patterned into microbridges using photoresist lithography and argon ion milling. Under proper conditions of temperature and current biasing, laser light focused upon these microbridges produced the bolometric responses studied in this experiment. The size of these devices studied were 2.5×2.5 μm, 10×10 μm, and 100×100 μm.

The schematic set-up of the experiment is shown in Fig. 1. The devices were mounted in a miniature Joule–Thomson refrigerator[12] equipped with a sapphire window. Substrate temperature was measured at the cold head. An argon-ion laser source at 514 nm was mechanically chopped (50% duty cycle) and then focused by a lens (numerical aperture$=0.4$, focal length$=1.28$ cm) onto the microbolometer. The illumination was Gaussian in shape with a full width half at maximum (FWHM) of 2 μm at the focal plane. The rise time of the incident light pulses was limited by the velocity of the chopper blade and was found to be 40 μs at a chopping frequency of 100 Hz, decreasing to 5 μs at 4000 Hz. The average incident power was measured at 4.5 μW using a calibrated silicon detector. The YBCO thin film microbolometers were dark in appearance and absorbed most of the incident light power. The absorptivity as measured by a spectrometer of a 0.2-μm-thick YBCO film at 514 nm was 82%. The alignment between the laser beam and the microbolometer was achieved by viewing through the objective lens using a video camera. The microbolometers were current biased, and voltage re-

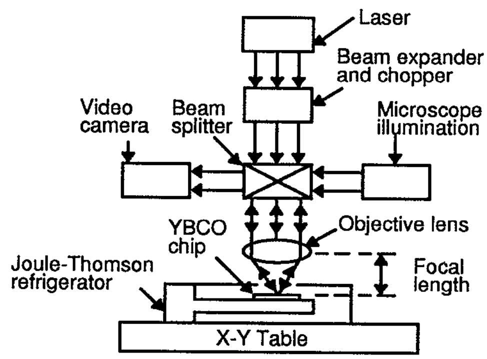

FIG. 1. Schematic of the experimental set-up.

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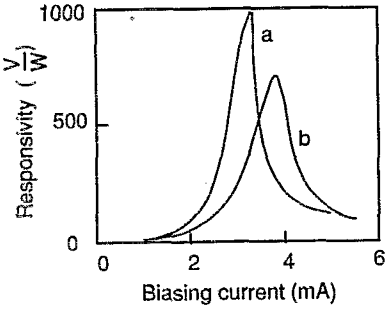

FIG. 2. Dependence of responsivity on biasing current for two YBCO microbolometers; (a) 2.5 μm, 82.5 K and (b) 10 μm, 83.5 K.

sponse due to incoming light was ac coupled to an oscilloscope for speed measurements. To determine microbolometer responsivities, rms voltage responses were picked up by a lock-in amplifier, and responsivities were calculated by measuring the ratio between the voltage response and 82% of the incident power. For noise measurements, the microbolometers were mounted inside a small liquid-nitrogen dewar with short and shielded electrical leads. Noise levels were sensed using a battery operated low-noise preamplifier, and analyzed by a spectrum analyzer.

The responsivity of all microbolometers was found to depend on both the substrate temperature and the device biasing current. The highest responsivity was obtained by finding the optimal combination of these two variables. In the following, we discuss microbolometer responsivity, speed, and noise measurements.

Responsivities of the 2.5×2.5 μm and the 10×10 μm microbolometers as a function of biasing current are shown in curves a and b of Fig. 2. The incident laser source was operated at 514 nm, chopped at 100 Hz, and had an average power of 4.5 μW. The best responsivity for the 2.5 μm microbolometer was 975 V/W, at a biasing current of 3.1 mA and a substrate temperature of 82.5 K. To the best of our knowledge, this is the highest value reported for a 2.5 μm YBCO microbolometer. The best responsivity for the 10 μm microbolometer was 700 V/W, at a biasing current of 3.7 mA and a substrate temperature of 83.5 K. For comparison, responsivity for the 100 μm-sized microbolometer was 42 V/W at a biasing current of 6 mA and a substrate temperature of 87.3 K.

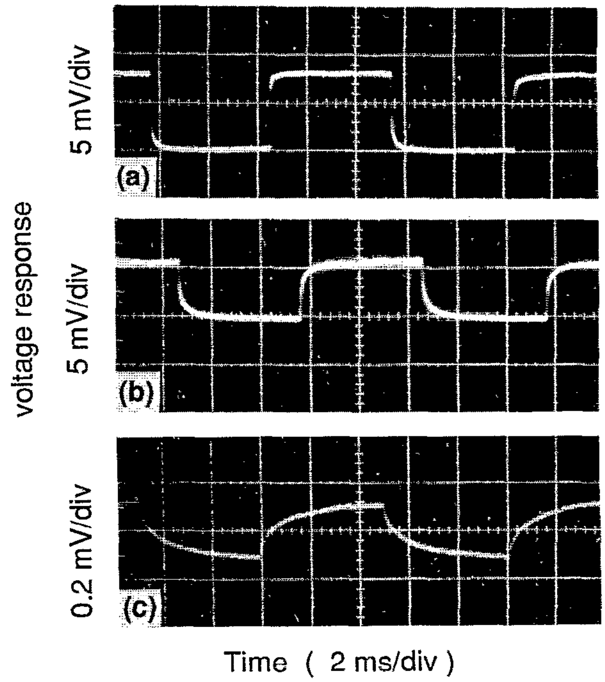

FIG. 4. Response of three YBCO microbolometers to laser light modulated at 100 Hz; (a) 100×100 μm, 3 mA, (b) 10×10 μm, 3.7 mA, (c) 2.5×2.5 μm, 3.2 mA.

Figure 3 shows the dependence of the measured voltage response of the microbolometers on incident laser power. Curve a is for a 2.5 μm-sized microbolometer at the optimal biasing current of 3.1 mA and a substrate temperature of 82.5 K. Curve b is for a 10 μm-sized microbolometer at the optimal current of 3.7 mA and a substrate temperature of 83.5 K. For both devices, it was found that the voltage response is linearly proportional to the incident

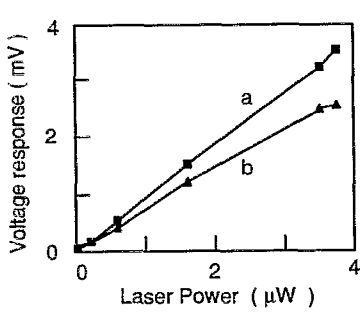

FIG. 3. Dependence of voltage response of two microbolometers on incident laser power; (a) 10 μm, 3.7 mA, and 83.5 K and (b) 2.5 μm, 3.1 mA, and 82.5 K.

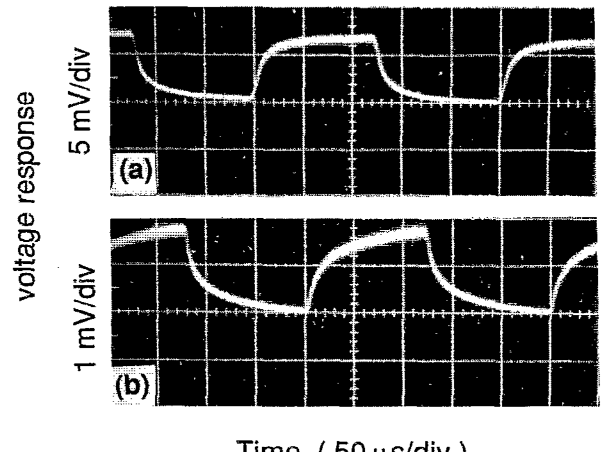

FIG. 5. Response of two microbolometers to laser light modulated at 4000 Hz; (a) 10 μm, 3.1 mA, (b) 2.5 μm, 3.1 mA.

power between the 37 nW and 3.7 μW range measured in the experiment.

The speed of three microbolometers of sizes 2.5×2.5 μm, 10×10 μm, and 100×100 μm deposited on ZrO_2 substrates are compared in Figs. 4(a)–4(c). Light incident upon the microbolometers was chopped at 100 Hz. The response of the 2.5 μm-sized microbolometer was faster than the response of the 10 μm-sized microbolometer, which in turn was much faster than the 100 μm microbolometer. The rise time (determined by 63% of the final response) of the 100 μm device was found to be 2 ms. The response of the 2.5 μm and 10 μm devices at a chopping frequency of 4000 Hz is shown in Figs. 5(a)–5(b). The rise times of the 2.5 μm and 10 μm devices were found to be 10 and 40 μs, respectively. The time constants $\tau=c_s A/(2k_s)$ estimated from the thermal model[11] for microbolometers on ZrO_2 were 2.5 μs, 40 μs, and 4 ms, respectively, for the 2.5, 10, and 100 μm devices (A is the area of the microbolometer).

These devices were found to have low noise. The total noise of a 2.5 μm device operating at the midpoint of the YBCO transition edge and a biasing current of 0.5 mA was measured to be 1.5 nV/Hz$^{1/2}$ at 1000 Hz. At 4000 Hz, this dropped to 1.2 nV/Hz$^{1/2}$, which represents the preamplifier noise limit.

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