Optically activated high T_c superconducting microbolometer

V Yefremenko [1], **E Gordiyenko** [1,2], **G Shustakova** [2], **S D Bader** [1], **G Karapetrov** [1] **and V Novosad** [1,*]

[1] Materials Science Division, Argonne National Laboratory, Argonne, IL 60439, USA

[2] B. Verkin Institute for Low Temperature Physics and Engineering, Kharkiv 61103, Ukraine

 Abstract. A laser beam, precisely focused on the patterned superconducting structure, was used to nucleate a resistive area that is sensitive to external thermal effects. The electron beam lithography and wet chemical etching were applied as pattern transfer processes in epitaxial Y-Ba-Cu-O films. Two different sensor designs were tested: (i) 3 millimeters long and 40 micrometers wide stripe and (ii) 1.25 millimeters long, and 50 micron wide meander -like structure. It is shown experimentally that scanning the laser beam along the stripe leads to physical displacement of the sensitive area and, therefore may be used as a basis for imaging over a broad spectral range. For example, patterning the superconducting film into a meander structure is equivalent to a two-dimensional detector array. In additional to the simplicity of the detector fabrication sequence (one step mask transfer), a clear advantage of this approach is the simplicity of the read-out process: an image is formed by registering the signal with only two electrical terminals. The proposed approach can be extended for imaging over a wide spectral range.

1. Introduction

The sensitivity of high-temperature superconducting (HTSC) bolometers can be comparable to the best liquid nitrogen-cooled semiconducting infrared detectors, but with the advantage that the detection range extends to longer wavelengths [1-5]. The traditionally accepted approach to detector design is based on a discrete array of pixel with electronic signal commutation. Here we propose an alternative method for registering the spatial distribution of the thermal radiation intensity. It is based on the idea that localized heating or magnetic fields may be used to create normal or transition resistive states at well controlled spatial locations. In our experiments a laser beam, precisely focused on a superconducting stripe, is used to nucleate a resistive area that is sensitive to external thermal effects. By displacing the laser beam along the stripe we obtain a voltage signal that is modulated by the temperature distribution due to the external thermal effects. The similar laser induced hot spot scanning method is used for investigation of spatial distribution of superconducting parameters and defects visualization [6-7].

2. Experiment

The HTSC material was a 200-nm-thick c-oriented epitaxial Y-Ba-Cu-O (YBCO) film grown on one side of a double-side-polished $LaAlO_3$ substrate by laser beam ablation [8]. The detector geometry was defined by means of electron beam lithography. The film was spin-coated with a 500-nm-thick single layer of ZEP-520A resist. All exposures were made with a RAITH – Model 150 system operating at 30 kV with a beam current of 300 pA. The baking and post-exposure-development of the resist were performed according to supplier recommendations [9]. The patterns were then transferred by wet chemical etching in a 0.5% aqueous H_3PO_4 solution. Finally, gold contact pads for four-probe transport measurements were deposited by magnetron sputtering through a shadow mask.

The sample holder was mounted into an optical cryostat with controllable temperature feedback from 80 to 95K (accuracy ~5mK). A comparison of resistivity measurements of "as-grown" films and the

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[*] To whom any correspondence should be addressed. Electronic address: novosad@anl.gov

microfabricated detector as a function of temperature show that the patterning process does not affect the transport properties of the YBCO. The critical temperature T_c (zero resistivity) is 87.2K, with a transition width of ~ 0.8K. A locally sensitive element (small region of the stripe) was created using a 3 mW laser diode operating at a wavelength of 630 nm. The estimated dimensions of the beam focused on the stripe were 40 x 10 μm^2. A micro-screw (10 μm per step) served to displace the probe. The temperature and electrical resistance of the detector were recorded using a four-probe method. Low-noise electronics and a frequency lock-in detection scheme were used to improve the signal-to-noise ratio. The temperature of the sample biased with a 1.3 mA current was cycled (cooling - heating) around the superconducting transition. The resistance was measured in 20 mK steps while the sample was illuminated with a laser beam with the intensity modulated at 1 Hz.

3. Results and discussions

The results are plotted in figure 1. A detectable signal first appears at 86.3K. As we have mentioned above, the critical temperature of the sample is 87 K, therefore one can speculate that the focused laser beam produces a local increase in temperature of approximately 0.7 K.
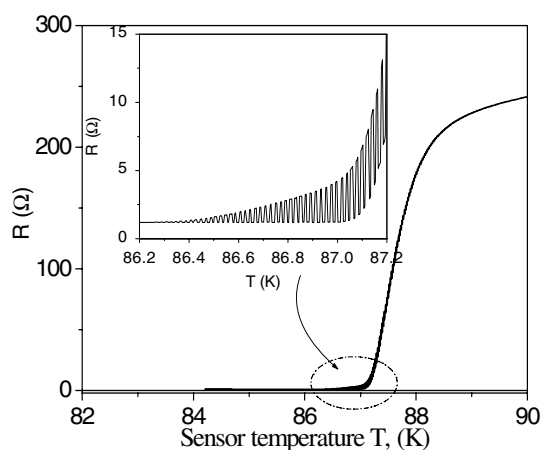

Figure 1.Temperature dependence of the sample resistance illuminated with a micro-focused laser beam modulated at 1 Hz. The insert shows the appearance of resistivity spikes due to the formation of the sensitive probe area on the stripe

The full resistance of the sample has two contributions: r - the resistance of the illuminated part, and R - the resistance of the rest of the sample. The behavior of the temperature dependence and the magnitude of $(R + r)$ between 86.3 and 87 K is defined by the superconducting – to - normal state transition in the illuminated area only. The unaffected part of the stripe has effectively zero R up to 80K. Therefore, only the illuminated area is sensitive to the external infrared radiation. The size of this area is determined by the laser probe size, power, duration, and, most importantly, on the substrate and HTSC film properties (absorption, thermal conductivity and specific heat capacity). We have estimated these dimensions experimentally by comparing the value of the sample's resistance $R = \rho_o L/S$ and $r = \rho_o l/S$ measured with and without the laser beam, where ρ_o denotes the resistivity, L and l are the linear size of the whole YBCO stripe and the resistive area, respectively, and S is the cross-section of the stripe. Hereafter we assume that all parts of the sample are identical in terms of the chemical composition and defect distribution. This is justified by the fact that the laser beam is much larger than the expected inhomogeneities that can affect the transport properties of the epitaxially grown film. The characteristic resistance values at the maxima of dR/dT and dr/dT is $R=60$ Ω for the whole sample ($dR/dT=286$ Ω/K at 87.36 K) and $r = 0.92$ Ω for the illuminated area ($dr/dT = 4.7$ Ω / K at 86.70 K). The linear size l of the sensitive area is therefore determined as $l = (r/R) \times L = 46$ μm, where $L = 3$ mm is the stripe length. Since the stripe width is equal to 40 μm, the lateral dimensions of the sensitive area can be estimated as 46 x 40 μm^2. It is clear that such a small area with local sensitivity to infrared radiation can be created at any location along the stripe simply by

displacing the laser beam. The estimated sensitive area appears to be larger than the size of the laser beam ($10 \times 40 \, \mu m^2$) that was used to create it, possibly due to some excess heating effect.

To demonstrate the imaging function of our sensor, we performed a test-experiment where the spatial distribution of the heating effect from an external point-like infrared source was detected. The operation of patterned superconducting stripe as an IR sensor is similar to the pixel-by-pixel read-out scheme for a one-dimensional chain of single element detectors.

The geometrical configuration of our sensor can be modified to satisfy more complicated imaging tasks. A patterned, meander-like superconducting structure, for example, is equivalent to a two-dimensional matrix detector.
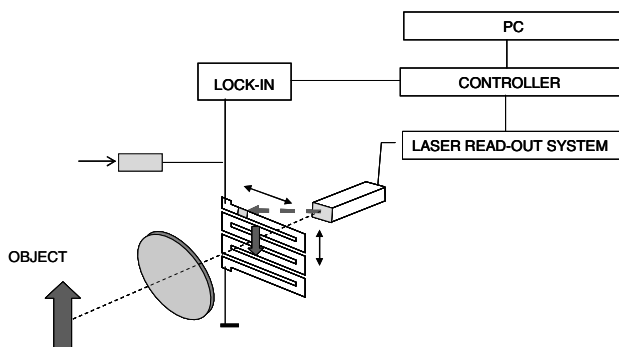

Figure 2.Block diagram of the sensor device design for 2D imaging.

A block diagram of an imaging system equipped with such sensor is depicted in figure 2. Infrared radiation is focused on the top surface of a patterned superconducting sensor grown on a double-side-polished substrate. The spatial read-out is provided by a two-dimensional scanned laser beam. A patterned meander-structure consisting of 25 connected stripes (1.5mm long, 50 microns wide and 10 microns gap between stripes) served as a prototype sensor. The image obtained with the shutter closed reveals the presence of fabrication-originated defects shown in figure 3a. Nevertheless, the thermal radiation from an external source can still be effective detected in the 2D imaging mode, figure 3b.
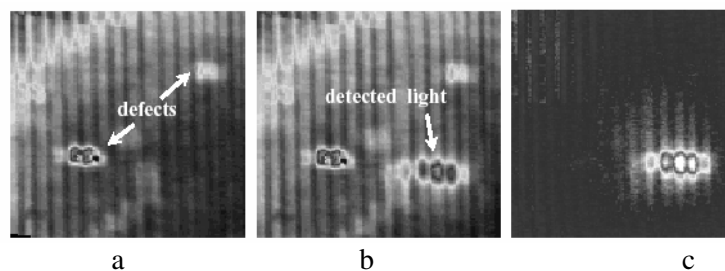

a   b   c

Figure 3. (a) Imaging with a closed shutter reveals presence of defects in a sensor structure; (b) the "as measured" two-dimensional image of point source of infrared radiation, and (c) the difference of images (a) and (b). The later allows eliminating undesirable contributions to the detected image such as defects or drift of the sensor temperature over time.

A laser beam 100 x 250 μm^2 in size was used to imitate infrared heating. Figure 3c demonstrates that subtraction of a scanned infrared image (figure 3b) and the sensors' intrinsic background signal (figure 3a) can be applied to improve the detection performance in real time by eliminating undesirable contributions such as defects or time drift of the sensor temperature.

The nature of the photoresponse is defined by the thermal processes. Illumination of the sample with infrared light is induces the transition of normal electrons into higher energy levels, followed by energy dissipation in the crystal lattice. Figure 4 compares the temperature dependence of the response obtained in three different spectral ranges: 3 - 5, 8 – 12 and 1 - 18 μm. Here, the etalon of a black body

with a temperature of 500K was used as a source of infrared radiation and optical filters served to select the specific wavelength range. The observed difference due to the wavelength variable optical properties of film-substrate system is on the order of 20% only. This demonstrates applicability of this detection scheme for multispectral measurements.
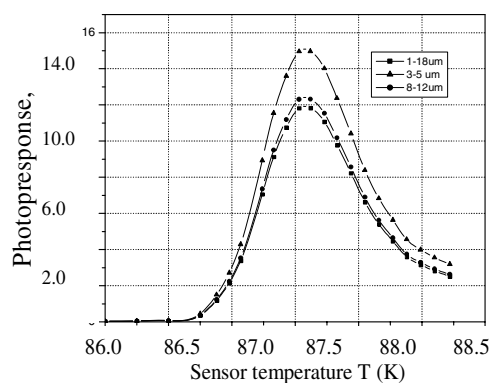

Figure 4. Temperature dependence of the photo-response for spectral ranges 1 - 18, 3 - 5, 8 - 12 μm.

4. Summary

We have demonstrated the feasibility of an optically activated superconducting microbolometer and method for registering the spatial distribution of the thermal radiation intensity. Successfully tested prototype sensors include 1D (stripe-like) and 2D (meander – like) patterned YBCO structures. Spectral measurements suggest that proposed approach can be extended for imaging over a wide range of wavelengths. The limiting factor is the wavelength dependent efficiency of thermal conversion in the film/substrate system. Integrating micro-antennas into the sensor and/or using absorption enhancing coatings will enable multi-spectral imaging for various applications. In additional to the straightforward detector fabrication sequence (one step mask transfer), this approach also has the clear advantage of a simple read-out process: an image is formed by registering the signal with only two electrical terminals.

5. References

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[8] The epitaxial thin films were supplied by NEOCERA Inc, http:// http://www.neocera.com/.

[9] The ZEP-520A polymer is a high sensitivity e-beam resist of positive tone produced by Nippon Zeon Co. (http://www.zeon.co.jp). ZEP consists of a copolymer of chloromethacrylate and methylstyrene.