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Imaging Transport Current Distribution in High Temperature Superconductors Using Room Temperature Scanning Laser Microscope

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ABSTRACT

We report the feasibility of room temperature scanning laser microscopy (RTSLM) for the study of high temperature superconducing films. RTSLM images from $SmBa_2Cu_3O_7$ and $YBa_2Cu_3O_7$ thin films show that the ac-voltage response exists only in the section of the bridge where the transport current produces a voltage drop. A photolithographically defined 60 μm x 60 μm void in a 300 μm-wide bridge was clearly visible in a RTSLM image giving the spatial resolution smaller than 60 μm. In addition, the void disturbs the transport current distribution beyond itself generating an elongated shape void of 64 μm x 85 μm with the longer side along the direction of current flow in the RTSLM image. Our results indicate that the RTSLM is a useful tool to investigate the transport current distribution in high temperature superconductors.

INTRODUCTION

High critical temperature and high critical current density are prerequisites for many high temperature superconductor (HTS) applications. However, these properties are strongly influenced by grain boundaries and other local defects. A study of the local electrical transport properties in HTS is of interest both for fundamental and applied reasons. In conventional transport measurements for superconducting samples, the measured quantity (T_c or I_c) is averaged over the whole sample and does not reflect the local distribution of the quantity. Hence, spatially resolved studies of HTS are needed to determine local values of physical parameters and to evaluate accurately the global quality of the samples. Several techniques have been employed to study local variations of superconducting properties in HTS. Recently, magneto-optical imaging technique is successfully employed to study the flux penetration on coated conductors [1,2]. Hall-probe magnetometry was used for similar functions [3]. Scanning tunneling microscopy and spectroscopy was employed to study the spatial variation of superconductivity with nanometer resolution [4].

More direct measurement techniques to map the spatial distribution of transport properties are so called “hot spot” scanning methods such as low temperature scanning electron microscopy (LTSEM) and low temperature scanning laser microscopy (LTSLM). LTSEM uses an electron beam as a local heating source and measures a response signal of a sample as a function of the electron beam position [5]. LTSEM has demonstrated that it can not only measure the spatial distribution of I_c and T_c in superconducting films and grain boundary junctions but also produce images of the trapped magnetic flux quanta and RF-induced states in Josephson junctions and locate defects in single crystals. LTSLM is similar to LTSEM, but uses a laser beam instead of an electron beam as a local heating source [6-8]. LTSEM has been very successful in many regards, however, it is a modified scanning electron microscope system with a low temperature sample stage; i.e. expensive and hard to operate. LTSLM is less expensive, can be performed in a magnetic field, and does not require a high-vacuum system since it uses a laser beam instead of an electron beam. The comparison of LTSLM and LTSEM images taken from $YBa_2Cu_3O_7$ (Y123) crossover multi-layer devices demonstrated that the two techniques produce equivalent images of I_c and T_c [7].

Since both LTSEM and LTSLM use bolometric response, the maximum sensitivity is achieved near the superconducting transition temperature where dR/dT is the largest. Hence, majority of “hot spot scanning” has been performed near the superconducting transition temperature. Using epitaxial $SmBa_2Cu_3O_7$ (Sm123) and Y123 films on $LaAlO_3$ (LAO) substrate, we demonstrate that this technique is capable of imaging the transport current distributions at room temperature. We report the feasibility of room temperature scanning laser microscopy (RTSLM) for the study of HTS films.

EXPERIMENTAL DETAILS

The RTSLM uses a HeNe laser, which is modulated at a frequency, $f_{m,}$ using a standard mechanical chopper. The laser beam is coupled into an optical fiber, and on the other end we used a microscope objective lens to focus the beam on the sample. The fiber and the lens are fastened to a 3-axis movable stage system that scans the beam across the sample in both the horizontal and vertical directions. Using a computer interface program we scan the laser beam on the sample while simultaneously gathering the ac voltage (δV) from the sample with a lock-in amplifier. A diagram of the final setup is shown in Fig. 1. We studied the frequency of 5 Hz – 1.5 kHz and a bias current of 1 μA to 5 mA. The laser spot size diameter was varied from about 150 μm to 25 μm.

The first investigated sample is an epitaxial Sm123 film on a LAO substrate and it has been photo-lithographically patterned for 4-probe measurements. The schematic diagram of the patterned sample is shown as the inset in Figure 2. The Sm123 film has the thickness of 280 nm, and the bridge is 100 μm wide. Figure 2 shows a resistive transition of the Sm123 bridge. The sample has T_c (R=0) of 87.4 K and the temperature coefficient of resistance (dR/dT) at room

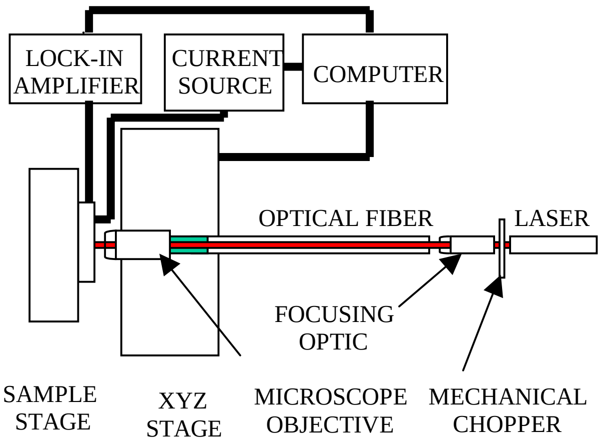

Figure 1. Schematic diagram of RTSLM setup.

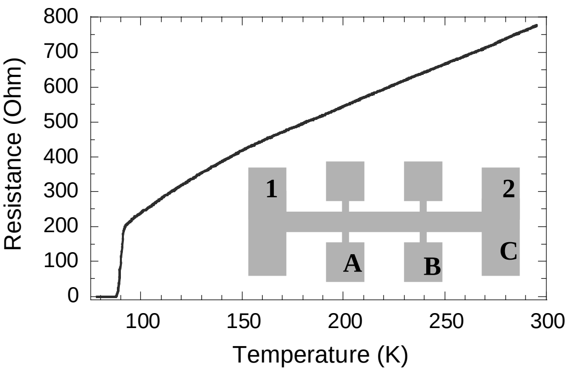

Figure 2. Resistive transition of the 100 μm wide Sm123 bridge. (Inset) Schematic diagram of the patterned sample.

temperature of 2.75 Ω/K as can be seen in Fig. 2.

RESULTS AND DISCUSSIONS

Since the major effect of the laser beam is local heating, the ac response of the sample is given by

$$\delta V(x,y)=\left[j_b(x,y)\left(\frac{d\rho(x,y)}{dT}\right)+\rho(x,y)\left(\frac{dj_b(x,y)}{dT}\right)\right]\times\Lambda\times\delta T(x,y) \qquad (1)$$

where $j_b(x,y)$ is the local current density, $\rho(x,y)$ is the local resistivity, Λ is the area disturbed by the laser beam, and δT (x,y) is the local temperature change.

When the current was passing between the leads #1 and #2 and the voltage was measured between the leads #A and #B separated by 2.5 mm (see the inset in Fig. 2), the line scans taken

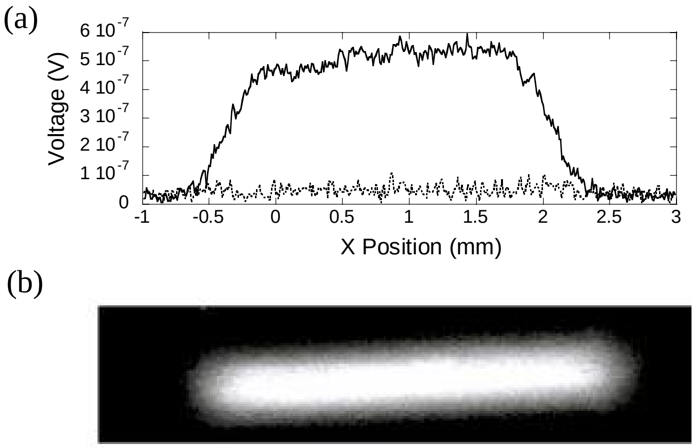

Figure 3. (a) The line scans taken from the Sm123 bridge. (b) RTSLM image of the Sm123 bridge.

from the sample are shown in Figure 3(a). Figure 3 was taken using a nominal laser beam diameter of 150 μm. The dotted line scan is taken when the laser beam is not on the bridge, showing the noise level. The solid line is one of the line scan taken when the laser beam is passing through the bridge. By combining the line scans, we obtain the image of the ac-response (δV) across segments of the bridges as seen in Figure 3(b). The scan area is 4 mm x 0.8 mm and each pixel has dimension of 10 μm by 10 μm determined by xy-scanning step size. We should mention that the scanning step size could be smaller than 1 μm; however, it was not practical to use a smaller scan step in a large area scan.

Figure 3(b) shows that δV exists only in the section of the bridge where the transport current produces a voltage drop. Since the local variation of the temperature coefficient of resistance (dR/dT) in the epitaxial Sm123 is small at room temperature, Fig 3(b) is the map of transport current distribution.

In order to understand the meaning of δV in RTSLM, we have performed two controlled experiments. First, we examined the spatial relationship between the bias current and the ac-voltage response (δV). Second, we created a sample with non-uniform current distribution and used RTSLM to investigate the spatial current distribution.

Figure 4(a) is the photograph taken from the sample. The thick black line in the middle is the 100 μm wide SmBCO bridge patterned using photolithography. One can see eight leads connected to the bridge for the 4-point measurements and electric contacts made using indium (bright blobs). Figure 4(b) and (c) are RTSLM images taken when the voltage was measured between #A and #B (the middle section of the bridge) and between #B and #C (the right section of the bridge), respectively, while the bias current is applied between #1 and #2 according to Fig.2. The images in Fig. 4 show that even though the current is flowing in the whole bridge, the ac-voltage is measured only when the voltage drop is generated between the voltage leads similar to the 4-probe measurement. However, unlike a regular 4-probe measurement RTSLM can generate the spatial images of the optical response (δV). One of the interesting features of this sample was the non-uniform optical response within the bridge marked by the arrows in the figure, which we believe to be related to the non-uniform current distribution in the sample.

Compared with Fig. 3, RTSLM images in Fig. 4 were taken with smaller diameter beam (nominal diameter of 25 μm). Hence, both edges of the bridge are more rectangular in Fig. 4 than Fig. 3, closer to the actual shape, indicating better spatial resolution.

In order to create a non-uniform current distribution in a bridge, a single crystalline Y123

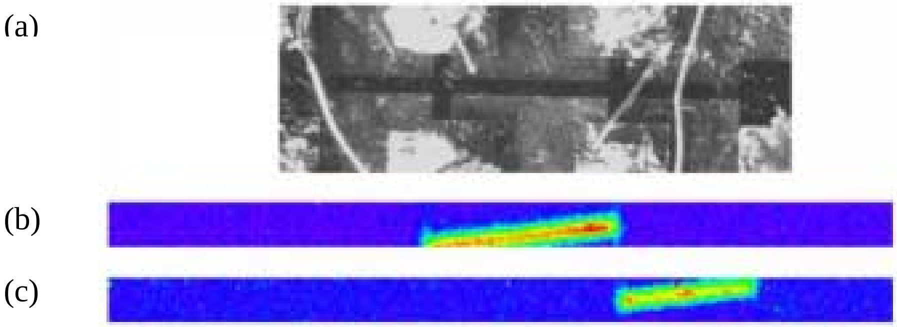

Figure 4. (a) A photograph of the Sm123 bridge. RTSLM images of (b) middle section and (c) right section.

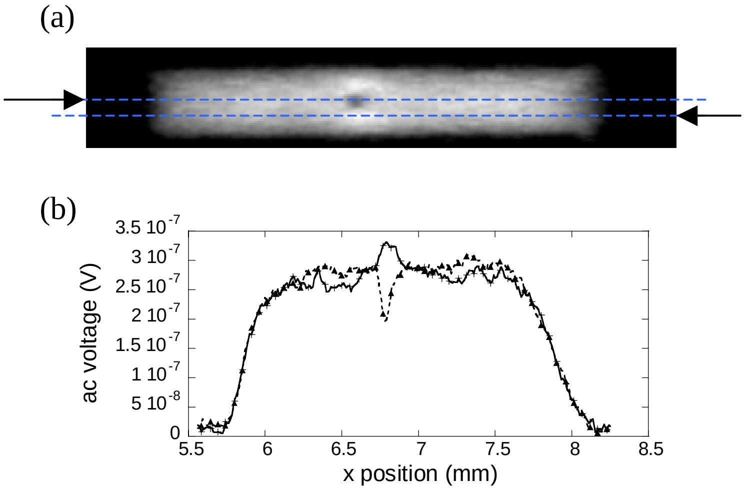

Figure 5. (a) RTSLM images of the Y123 sample with a void. (b) X-line scans taken from the arrowed lines.

film deposited on LaAlO$_3$ was photo-lithographically patterned to a 300 μm-wide and 2.0 mm-long bridge with a 60 μm x 60 μm void at the center of the bridge. Figure 5(a) is the RTSLM images of the Y123 sample. The scan size is 2.70 mm x 0.45 mm with each pixel of 10 μm x 15 μm. The void is clearly visible at the center of bridge; hence we estimate the spatial resolution of RTSLM being less than 60 μm. The arrows mark the positions where we took the x-line scans for Fig. 5(b). We have observed larger ac-response (δV) around the void than the area away from the void. We expected that the 60 μm-wide void would increase the transport current density by 25% via reduced cross sectional area compared with the other sections in the bridge. The close inspection of line scans yields that the ac-voltage response is increased by about 25% around the void. Hence, the enhanced response seems to be directly related to the increased current density around the void.

One more feature to point out is that the void in Fig. 5 looks to be close to oval shape than a square. Due to the size and shape of the laser beam, an edge of the square is expected to be rounded. However, the elongated shape observed in Fig. 5 is puzzling. We estimated the size of the void to be 64 μm x 85 μm from the RTSLM image. Also the areas with larger δV around the void are also stretched along the bridge, i.e. the current flow direction. Theoretical modeling of transport current distribution around a void is under way to simulate the images.

Previously, the LTSEM and LTSLM imaging techniques were restricted to study small volume samples (mostly less than 100 μm-wide samples) because the magnitude of the signal (δV) was estimated to be the ratio between the perturbed volume and the volume of the sample [5]. However, our results indicate that the images of δV can be obtained from large samples, and the magnitude of δV is increased with increasing bias current (I_b) and laser power (δT) and decreasing the modulation frequency (f_m). We believe that RTSLM is a powerful tool to evaluate current distribution and to detect a defective area that creates disturbance in current flow. We are planning to study HTS devices and coated conductor samples using RTSLM and to compare the current distribution at room temperature and the local superconducting parameters (I_c and T_c) at low temperatures.

CONCLUSIONS

We have used epitaxial Sm123 and Y123 thin films to investigate the feasibility of RTSLM. The RTSLM has successfully produced ac-voltage response images of transport current distribution of HTS films. The current distribution image around the void shows three main features; (1) the void is elongated along the current direction, (2) the area next to the void has 25% higher current density than the other section, and (3) similar to the void, the higher current area has an elongated shape. Our results indicate that the RTSLM is a promising technique to investigate the transport current distribution in thin film samples.

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