Variable Temperature Scanning Laser Microscopy of Wider Width High Temperature Superconducting Films

L. B. Wang, M. B. Price, C. Kwon, and Q. X. Jia

Abstract—**We have investigated the spatial distribution of resistive properties in 2 mm wide and 10 mm long epitaxial superconducting films using a variable temperature scanning laser microscopy (VTSLM). This technique measures ac voltage of bolometric response created by a laser beam. We have observed the spatial nonuniformity of superconducting transition temperature in the resistive region, which has never been reported in samples wider than 300 μm using scanning laser techniques. This result is a significant step toward developing VTSLM for coated conductor diagnosis.**

Index Terms—**Epitaxial superconducting film, spatial nonuniformity, superconducting transition temperature, variable temperature scanning laser microscopy.**

I. Introduction

THE DISCOVERY of high temperature superconductor has been stimulating scientists and engineers to develop practical applications. For power applications, high critical current density is necessary. Many experiments have shown that the critical current density of high temperature superconductors is controlled by the microstructure of the materials [1]–[4]. The critical current density J_c and critical temperature T_c from the transport measurement reflect the average value of the whole sample. The conventional transport measurement does not provide information about J_c and T_c in local regions. Therefore, it is important to develop techniques to study the spatial distribution of J_c and T_c. This will provide us some information about J_c and T_c in local regions, so that we can improve the microstructure and achieve higher critical current density. In order to evaluate local J_c and T_c, some techniques have been developed, such as magneto-optical (MO) imaging [5], [6], Hall-probe [7], scanning tunneling microscopy [8], low temperature scanning electron microscopy (LTSEM) [9], and low temperature scanning laser microscopy (LTSLM) [10]–[14]. We have used a variable temperature scanning laser microscope (VTSLM) to detect and map the spatial distribution of J_c and T_c of larger-scale high temperature superconductors. Using this technique to investigate 2 mm wide and 10 mm long epitaxial $SmBa_2Cu_3O_7$ and $NdBa_2Cu_3O_7$ on $LaAlO_3$ films, we have found a spatial nonuniformity of T_c in the resistive region. Such results have never been reported in samples wider than 300 μm using LTSLM and LTSEM. The resistive transition shows the signature of different transition temperatures, and the areas with different transition temperatures are clearly visible in VTSLM images.

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II. Experiment

A 5.2 mW Helium-Neon laser beam (wavelength 632.8 nm), which is modulated at 1 KHz by a standard mechanical chopper, is coupled into an optical fiber and focused on the surface of the sample by a lens. The fiber and lens assembly is fastened to a three-axis movable stage system which scans the laser beam on the sample surface in both the horizontal and vertical directions. The temperature dependence of resistance of the samples was measured by a four-probe technique. The platinum wires were soldered on the surface of the sample using indium. The ac voltage data were acquired by a lock-in technique using a program written in Labview. The ac voltage data was transform into an image by a commercial software. The temperature of the sample was controlled by the cryogenic system of the cryostat and a temperature controller. The detailed experimental setup can be found in [13] and [14].

The samples investigated by VTSLM were $SmBa_2Cu_3O_7$ and $NdBa_2Cu_3O_7$ epitaxial films on $LaAlO_3$ deposited by pulsed laser deposition (PLD). The films were 250 nm thick, 2 mm wide, and 10 mm long.

III. Results and Discussion

Köelle *et al.* [9] have studied superconducting films by low temperature scanning electron microscopy (LTSEM). The electron beam is treated as a local heating source and causes a local perturbation at the point focused on the sample. The detected voltage signal $\delta V(x,y)$ will reflect the information of local T_c and J_c. The voltage signal is given by [9]

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

where $j_b(x,y)$ is the local current density, $\rho(x,y)$ the local specific resistance, and Λ the diameter of the disturbed area. Similarly, in scanning laser microscopy, the only change is that a laser beam replaces an electron beam. The laser beam causes a $\delta V(x,y)$ from the local heating effect. Previously, the spatial distribution of the critical current was studied in epitaxial YBCO films, devices, and $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}$ wires using LTSEM and LTSLM [10]–[12], [15].

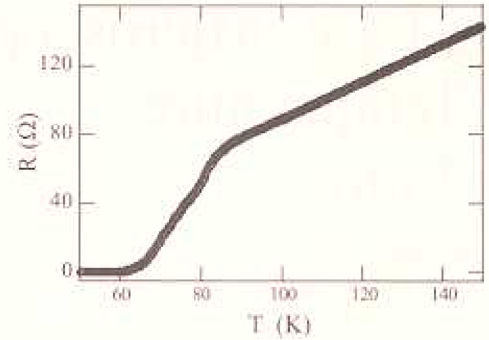

Fig. 1. Temperature dependence of the resistance of the $SmBa_2Cu_3O_7$ film.

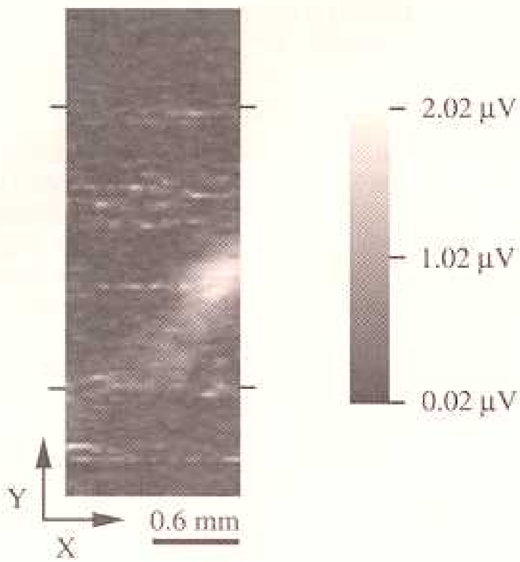

Fig. 2. Gray-scale image corresponding to the ac voltage $\delta V(x, y)$ of the $SmBa_2Cu_3O_7$ film. The bias current is 15 mA and the scanning step is 30 μm in both x and y directions.

In this work, we have measured the optical response where the sample undergoes a superconducting transition, but still is in the resistive state. The optical response of $\delta V(x, y)$ is dominated by $\partial\rho(x, y)/\partial T$ with minimal contribution from $\partial\rho(x, y)/\partial T$, hence we can obtain the distribution of the critical temperature in the sample.

Although many experiments have been made in superconductors, the samples were limited to narrow patterned films and devices of about a few μm wide. We have studied the optical respond from wide samples to develop scanning laser microscopy for coated conductor diagnosis.

Fig. 1 shows the temperature dependence of the resistance of $SmBa_2Cu_3O_7$ film. The wide superconducting transition width indicates the nonuniformity of T_c in the sample. We selected this sample in order to investigate whether or not the VTSLM can detect this nonuniformity.

With VTSLM, we measured the voltage response $\delta V(x, y)$ with respect to the beam position (x, y), and generated an image of $\delta V(x, y)$. Fig. 2 is a VTSLM image taken from the Sm123 film with a bias current of 15 mA at 78.1 K while the sample is in the resistive state.

The distance between the two voltage electrodes is 2 mm, and that between the two current electrodes is 7 mm. The electrodes are placed outside of the scanned area. The solid lines mark the edges of the sample. The total scanned area is 1.2 mm × 3.4 mm, and the scanning step is 30 μm in both the x and y directions. The gray-scale bar shows the range of the ac voltage δV. As shown in Fig. 2, there is a distribution of $\delta V(x, y)$ inside the sample. Bright regions correspond to the sample areas where $\delta V(x, y)$ is large. On the other hand, black and gray regions have lower $\delta V(x, y)$ values.

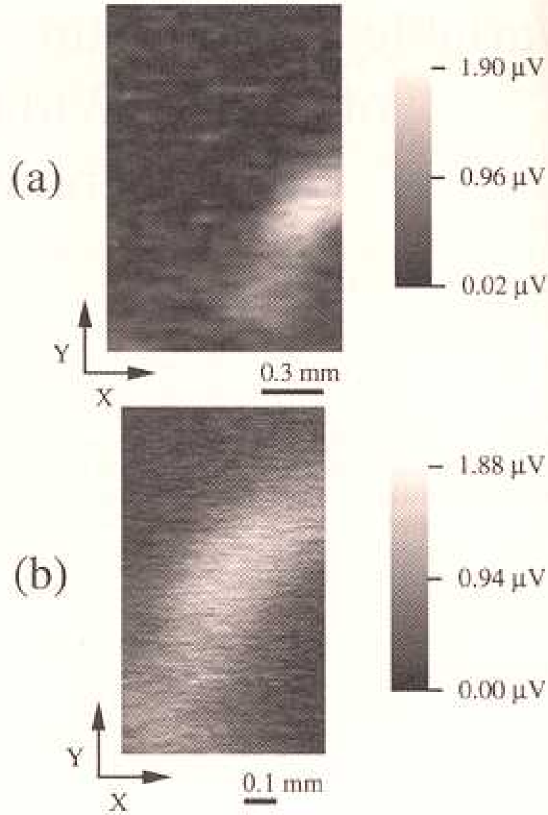

Fig. 3. Gray-scale images corresponding to the ac voltage $\delta V(x, y)$ of the $SmBa_2Cu_3O_7$ film. The bias current is 15 mA. (a) 30 μm scanning step in both x and y directions. (b) 5μm scanning step in both x and y directions for the large ac voltage $\delta V(x, y)$ signal region.

As seen from (1), there is an intimate relationship between $\delta V(x, y)$ and $\partial\rho(x, y)/\partial T$ when the sample is in the resistive state, i.e., $T > T_c(R = 0\ \Omega)$. The map of $\delta V(x, y)$ taken by VTSLM represents mainly the local distribution of $\partial\rho(x, y)/\partial T$. At the transition region, $\partial\rho(x, y)/\partial T$ of a superconductor is larger than that in the normal state ($\partial\rho(x, y)/\partial T \sim 1$ in YBCO) or in the superconducting state ($\partial\rho(x, y)/\partial T = 0$). We expect that the region with the highest $\partial\rho(x, y)/\partial T$ appears the brightest. Hence, the different brightness will correspond to different $\partial\rho(x, y)/\partial T$, which is related to different local T_c. In this way, Fig. 2 shows a spatial nonuniformity of T_c inside the sample.

In order to investigate the area with nonuniform T_c more clearly, we scanned the central region of the sample. Fig. 3(a) is a 1.2 × 1.8 mm scan with 30 μm step, and Fig. 3(b) is a 0.6 × 1.0 mm scan with 5 μm step. The overall shape of $\delta V(x, y)$ in Fig. 3(a) is the same as Fig. 2.

One can find that the brightness corresponding to $\delta V(x, y)$ changes more subtly in Fig. 3(b). This presents additional evidence for the reality of a signal inside the sample.

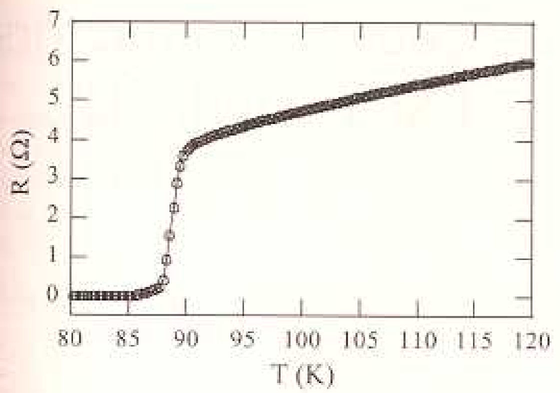

Fig. 4. Temperature dependence of the resistance of the $NdBa_2Cu_3O_7$ film.

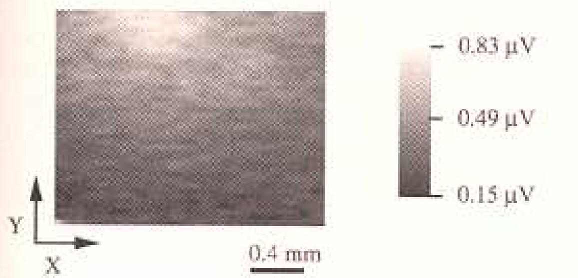

Fig. 5. Gray-scale image corresponding to the ac voltage $\delta V(x, y)$ of the $NdBa_2Cu_3O_7$ film. The bias current is 15 mA and scanning step is 40 μm in both x and y directions.

Fig. 4 shows the temperature dependence of resistance in a $NdBa_2Cu_3O_7$ film. Compared with the Sm123, the Nd123 film has a sharper superconducting transition with a higher $T_c(T_c(R = 0\ \Omega) = 85.7$ K) indicating no apparent distribution of T_c. Fig. 5 is a VTSLM image taken from the central region of the Nd123 film while the sample is in the resistive state at 88.8 K. It is an intensity plot of $\delta V(x, y)$ from a 2.0 mm × 1.6 mm scanned area with a scanning step of 40 μm in both x and y directions. Even though this sample has a sharper superconducting transition, the spatial nonuniformity of T_c is still clearly visible in the VTSLM image.

Despite of the differences seen from the resistive transitions, both samples show a distribution of T_c from VTSLM. It is puzzling as to what are the main differences between these two samples. So far, we have been able to relate the total area with larger $\delta V(x, y)$ to the sharpness of the superconducting transition. As mentioned above, the $\delta V(x, y)$ is proportional to the $\partial\rho(x, y)/\partial T$ which is related to the local T_c. Since the regions with the same $\delta V(x, y)$ have the same $\partial\rho(x, y)/\partial T$, the local T_c also is the same in these regions. This indicates that the bright area has the same T_c. These two samples are measured almost at the mid-point of the R verses T curve. Thus we can evaluate the uniformity of T_c distribution from the ratio of the bright area to the scanned area in the image. We find that the bright area of the Sm123 sample is about 0.023 mm^2 in Fig. 2, while that of the Nd123 sample is about 0.12 mm^2. For the Sm123 sample, the ratio of the bright area to the scanned area is 0.0094, while that of the Nd123 sample is 0.036. Hence, a larger section of the Nd123 sample has the same T_c. The distribution of T_c in the Nd123 sample is more uniform than that in Sm123. This agrees with their temperature dependence of the resistance.

Currently we are investigating the VTSLM images at different temperatures in the superconducting transition region as well as in superconducting region to study the distribution of critical current (J_c).

IV. Conclusions

Two wider-width superconducting films have been investigated by variable temperature scanning laser microscopy. A spatial nonuniformity of the superconducting transition temperature in the resistive region has been observed from the ac voltage images of large scanned areas. These experimental results have never been reported in samples wider than 300 μm using scanning laser techniques. Our experimental results have shown that the study of larger superconducting samples using VTSLM is feasible, which is a significant step toward developing VTSLM for coated conductor diagnosis.

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