Spatial Distribution Analysis of Critical Temperature in Epitaxial Y–Ba–Cu–O Film Using Variable Temperature Scanning Laser Microscopy

C. Kwon, L. B. Wang, S. Seo, B. H. Park, and Q. X. Jia

***Abstract*—We have investigated the spatial distribution of superconducting transition in an epitaxial $YBa_2Cu_3O_7$ film using variable temperature scanning laser microscope (VTSLM). VTSLM creates an image of the ac voltage response, $\delta V(x, y)$, due to an ac modulated laser beam, which is proportional to $\mathrm{d}R\mathrm{d}T(x, y)$. In the resistive transition region, there is a strong correlation between the VTSLM images and the resistance of the sample. When the sample is making a poor thermal contact to the heat bath, the large $\delta V(x, y)$ region shifts toward the ends of the bridge while the sample resistance decreases. This result is due to the variation of surface temperature along the sample created by the heating at the contact resistance and/or the poor thermal contact between the sample and the heat bath. However, even after improving thermal contact, we still observe the distribution of superconducting transition. Since the local superconducting transition occurs within 1 K, we conclude that any samples with superconducting transition width larger than 1 K have local nonuniformity.**

***Index Terms*—Critical temperature, films, high temperature superconductor, nonuniformity, scanning laser microscope.**

I. INTRODUCTION

SINCE the discovery of superconductivity in cuprate oxides, a tremendous amount of research has been devoted at understanding the fundamental properties of these materials and developing various power and device applications. The complicated crystal structure of high T_c superconductors (HTS) leads to their substantial spatial inhomogeneity, which is especially important because of the very short coherence length in those materials. Consequently, spatially resolved studies of HTS are very effective both to evaluate the general quality of the samples and to determine local values of important parameters. In conventional transport measurements of superconducting samples, the measured quantities such as critical current densities and critical temperatures are averaged over the whole sample and do not reflect the local distribution of the quantities. Thus, spatially resolved studies of HTS are needed to determine local values of important parameters of the samples. Recently, magneto-optical (MO) imaging technique has been successfully employed to study the flux penetration on coated conductors [1], [2]. Another technique is Hall-probe magnetometry using Hall probe arrays to map the local magnetic field distribution [3]. Scanning tunneling microscopy and spectroscopy were also employed to study the spatial variation of superconductivity with nanometer resolution [4]. More direct measurement techniques to study local variations of superconducting properties in HTS are the hot-spot scanning method such as low temperature scanning electron microscopy (LTSEM) [5] and low temperature scanning laser microscopy (LTSLM) [6], [7]. In LTSEM experiments, a dc current biased sample is scanned with the electron beam causing a local perturbation at the point (x, y) of the beam focus. The perturbation can be treated in good approximation as a local heating effect. LTSLM uses a focused laser beam as a heating source. The detected voltage signal $\delta V(x, y)$ yields information about critical temperatures $T_{co}(x, y)$, transition width $\Delta T_c(x, y)$, and critical current densities $j_c(x, y)$ [5]–[7].

Earlier we reported that there is a strong correlation between the VTSLM images and the resistance of the sample in the resistive transition region [8]. In this paper, we studied the spatial distribution of superconducting critical temperature, $T_c(x, y)$ from an epitaxial YBCO film in two different situations. In the first case, the large $\delta V(x, y)$ region shifts toward the ends of the bridge with decreasing sample resistance. Even though the VTSLM images are real, we believe the images represent the surface temperature variation. The situation is possibly due to the heating at the contact resistance and/or the poor thermal contact between the sample and the heat bath.

However, after the improvement of contact resistance and thermal contact, VTSLM images still show nonuniform superconducting transition in the YBCO film. The results show that the local superconducting transition occurs within 1 K suggesting that any samples with superconducting transition width larger than 1 K have local nonuniformity.

II. SETUP AND EXPERIMENTS

The VTSLM uses a Helium–Neon laser (632.8 nm) that 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 horizontal and vertical directions while

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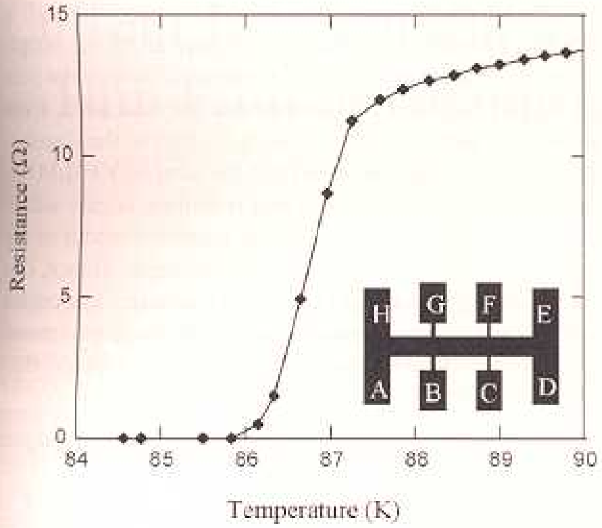

Fig. 1. The resistance versus temperature measured from the right section of the bridge (using E-F for current and C-D for voltage). (Inset) Schematic diagram of the sample.

simultaneously gathering the ac voltage (δV, with f_m) from the sample using a lock-in amplifier. The detailed VTSLM setup can be found in [8], [9]. We used a DC bias current of 5.0 mA and the laser beam was modulated at about 1.0 kHz.

The sample investigated by VTSLM was an epitaxial $YBa_2Cu_3O_7$ (YBCO) film on a $LaAlO_3$ substrate, and it has been photo-lithographically patterned to a 300 μm-wide bridge as shown in Fig. 1 (inset). Fig. 1(b) shows the resistance versus temperature measured from the right section of the bridge (using E-F for current and C-D for voltage).

III. Results and Discussion

A. *Surface Temperature Variation*

Fig. 2 shows VTSLM images of the right section taken when the resistance was (a) 8.43 Ω, (b) 4.64 Ω, (c) 2.19 Ω, (d) 0.35 Ω, and (e) 0.19 Ω. The bias current was 5 mA. The area with large voltage response shifts toward the ends of the scanned area with decreasing resistance. Since δV is related to the $\mathrm{d}R(x, y)/\mathrm{d}T$, the results suggest that the superconducting transition starts in the middle and spreads along the bridge. With decreasing temperature and resistance, δV in the middle of the images changes from the largest value when the sample resistance is 8.43 Ω in Fig. 2(a) to almost zero in Fig. 2(b). That manifests superconductivity with zero resistance in the middle section, even though the resistance of the sample has not reached zero. Similar images were obtained with the same resistance values when we varied the laser power between 5.2 mW and 20 mW and the bias current between 0.1 mA and 5 mA.

Even though we obtained reproducible images from the sample, some results make us to question if there is nonuniform temperature distribution at the sample. The image taken at the lowest resistance [Fig. 2(e)] shows that the bright area in one side is shifting toward the current lead (E in Fig. 1) suggesting the closer to the current contact area the lower the T_c. In addition, the other end closer to the center of the sample is still undergoing superconducting transition. VTSLM images taken from the left section taken using G-H for current and A-B for voltage show the same trend: the superconducting transition starts in the middle, spreads along the bridge to both ends, moves toward a current lead (H in Fig. 1), and the lowest T_c occurs at the side closer to the center of the sample. From the close inspection of the images, we concluded the results are due to the heating at the contact areas and/or the poor thermal contact between the sample and the heat bath (the sample holder). However, it does not discount the capability of VTSLM to map the local superconducting properties.

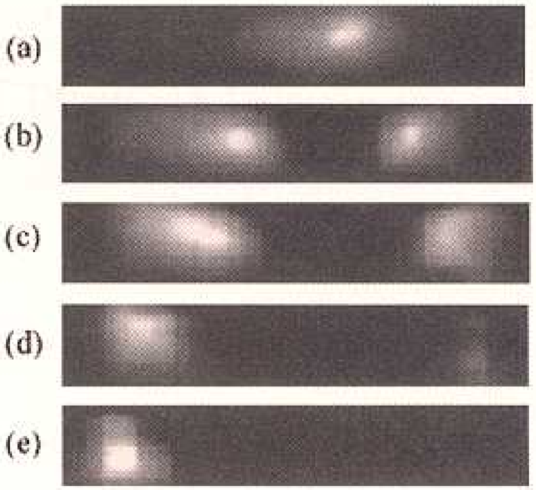

Fig. 2. VTSLM images taken at (a) 8.43 Ω, (b) 4.64 Ω, (c) 2.19 Ω, (d) 0.35 Ω, and (e) 0.19 Ω using E-F for current and C-D for voltage. The images are 2.70 mm × 0.45 mm scans with 10 μm steps.

B. *T_c Distribution*

In order to improve the thermal contact between the sample and the heat bath, we used cryogrease instead of GE vanish for sample mounting. Fig. 3 shows the resistive transition measured using F-H for current and A-C for voltage. We used the same configuration of VTSLM measurements with 5 mA bias current. Fig. 4 is VTSLM images taken at (a) 31.6 Ω, (b) 22.5 Ω, and (c) 3.85 Ω. The images are 4.6 mm × 0.8 mm scans with 40 μm steps. The edges of the bridge are marked with arrows, and the sample is slightly tilted with respect to the scan directions.

At the lowest resistance [Fig. 4(a)], the image shows two bright regions. With increasing resistance, the bright regions are shifting toward left of the image. The images show that there is a spatial distribution of T_c.

In Fig. 4, bright regions are rather randomly placed in the sample. Compared with Fig. 2, we do not observe any systematic change in the images to indicate nonuniform thermal distribution. Hence, we conclude that the distribution of T_c in Fig. 4 is genuinely due to sample.

Since the images are a map of δV, we can determine the temperature in which each point undergoes superconducting transition. The middle spot in Fig. 4(b) is brighter than those around, but the same area gets dimmer in Fig. 4(c). It indicates that superconducting transition at that spot begins around 31.6 Ω and has the largest $\mathrm{d}R(x, y)/\mathrm{d}T$ around 22.4 Ω. More detailed study suggests that the width of superconducting transition is less than 1 K in a localized scale, even though that measured by

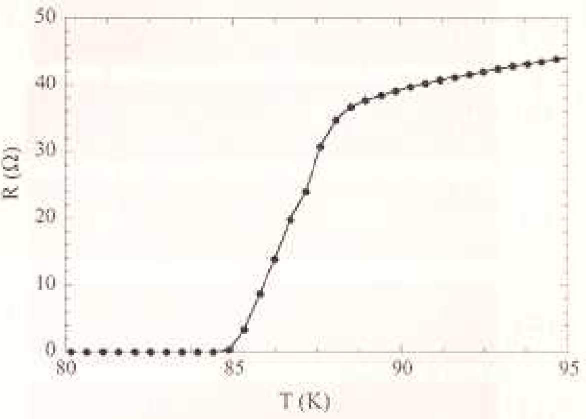

Fig. 3. The resistance versus temperature measured from the left section of the bridge (using F-H for current and A-C for voltage).

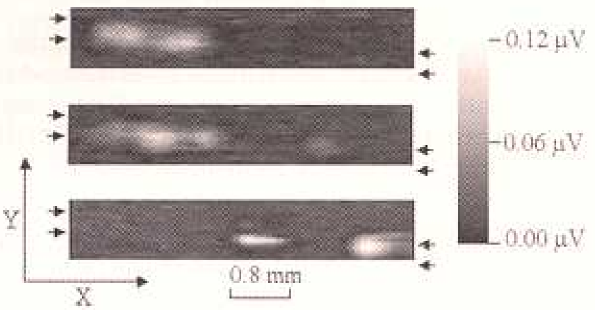

Fig. 4. VTSLM images taken at (a) 3.85 Ω, (b) 22.5 Ω, and (c) 31.6 Ω using F-H for current and A-C for voltage. The images are 4.6 mm × 0.8 mm scans with 40 μm steps. The edges of the bridge are marked with arrows, and the sample is slightly tilted with respect to the scan directions.

traditional 4-probe technique is much wider. Hence, any samples with superconducting transition width larger than 1 K have local nonuniformity in T_c.

IV. Conclusion

We observed a strong correlation between the VTSLM images and the overall resistance of the sample in the resistive transition region. In one case, we observe a systematic shift of T_c due to the variation of surface temperature along the sample created by the heating at the contact resistance and/or the poor thermal contact between the sample and the heat bath. Even after improving thermal contact, we still observe the distribution of superconducting transition from the sample. VTSLM images show that local superconducting transition occurs within 1 K, even though the superconducting transition width of the sample is 3 K measured by 4-probe measurements. Hence, Our result proves that VTSLM provides local properties that cannot be obtained by 4-probe transport measurements. Furthermore, we can conclude that any $YBa_2Cu_3O_7$ films with superconductiZng transition width larger than 1 K have nonuniformity.

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