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Physica C 419 (2005) 79–84

PHYSICA C

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Mapping the current distribution in $YBa_2Cu_3O_{7-x}$ thin films with striations

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Received 10 June 2004; received in revised form 20 December 2004; accepted 20 December 2004

Abstract

We have studied the transport current distributions in striated $YBa_2Cu_3O_{7-x}$ (YBCO) films and coated conductors using variable temperature scanning laser microscopy (VTSLM). VTSLM images reveal the location of incomplete separation between filaments due to un-optimized sample processing parameters. When the current flows parallel to the completely separated striations, the current seems to flow within a strip without inter-mixing via the substrate. Initial resistivity measurements on metallic inter-filamentary connections (gold dots) exhibit a semiconducting behavior. VTSLM images clearly show that the current flows between filaments via the metallic inter-connect, indicating the semiconducting resistive behavior is due to the interface between YBCO and metallic layer. The results demonstrate the potential of VTSLM technique in investigating current sharing and normal metal inter-connect issues for the coated conductor development for ac applications.

PACS: 74.72.Bk; 74.80.Dm; 74.25.Fy

Keywords: Striated YBCO film; Ac loss; Current distribution; Variable temperature scanning laser microscopy

1. Introduction

The second-generation high temperature superconducting (HTS) wire is based on coated conductor technology, where a textured $YBa_2Cu_3O_{7-x}$ (YBCO) film is deposited on a buffered flexible metal substrate. The texture in the epitaxially grown YBCO can be initially created by ion-beam assisted deposition (IBAD) of an underlying buffer layer [1,2], rolling assisted biaxially textured substrate (RABiTS) [3], and incline substrate deposition (ISD) [4] techniques. Using these techniques,

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doi:10.1016/j.physc.2004.12.007

self-field critical current density (J_c) values above 10^6 A/cm^2 at 77 K have been achieved in YBCO coated conductors up to several meters in length [5,6]. However, the architecture of the HTS coated conductor (CC) has not been optimized for ac applications such as motors, generators, and transformers leading to significant ac losses in the conductor. One example of this is the hysteretic loss of the HTS CC due to the high aspect ratio of the width and the thickness. In order to minimize ac hysteretic losses, Carr and Oberly [7] proposed subdividing the HTS layer of the CC tapes into long thin linear filamentary stripes, or striations. Cobb et al. have demonstrated that striated epitaxial YBCO films created by laser ablation have greatly reduced hysteretic losses [8].

The design of CCs based on long thin filamentary stripes makes it susceptible to defects, since a single defect may block the flow of current in a filament causing it to carry zero current. To overcome this problem, one has to allow current sharing between striations [9]. Therefore, it is important to understand the current distribution between superconducting stripes as well as the current sharing via adjacent layers of the CC architecture [10,11]. In addition, the possible existence of higher grain boundary angles in CC processes may create non-uniform current percolation [12]. Direct and indirect mapping of the current distribution in the HTS layer has been accomplished by a variety of methods including magneto-optical imaging [12], scanning Hall probe [13], and hot spot scanning techniques such as low temperature scanning electron microscopy (LTSEM) [14], low temperature scanning laser microscopy (LTSLM) [15], and variable temperature scanning laser microscopy (VTSLM) [16,17]. In this letter, we use VTSLM to map the transport current distributions in striated YBCO films and coated conductors.

2. Experimental

The patterning of the YBCO films into parallel superconducting filaments is achieved by ablating narrow strips of the superconductor with YAG laser. Earlier research [8] has demonstrated that the resulting striated filamentary structure, which reduces the effective width of the YBCO films, proportionately reduces the hysteretic loss in the superconducting samples. Samples used in this investigation consist of two YBCO epitaxial thin films on $LaAlO_3$ (LAO) and one RABiTS sample, each patterned with parallel filaments. The samples are prepared for four-probe transport measurements by depositing gold contacts. When measuring current flow in the direction of the striations, extra care is devoted to ensure good gold coverage over each stripe of the sample providing uniform contact resistance for all stripes. Detailed information about VTSLM can be found in our earlier publications [16,17].

3. Results and discussion

Fig. 1(a) and (b) exhibits the temperature dependence of resistance for current flow perpendicular to the striations (transverse resistance) with an optical image insert of an epitaxial YBCO film on LAO (Sample A) and a YBCO coated conductor on RABiTS (Sample B), respectively. Striations are clearly visible in the photographs as well as the electrical contacts at the edges of the sample. These samples represent cases where one expects the current flow to be curtailed by the striations if the ablation is complete. The temperature dependence of resistance of Sample A (solid line in Fig. 1(a)) reveals an on-set of superconducting transition at 90.0 K with the sharp drop of resistance. However, zero resistance is not reached at 29.1 K indicating the presence of a non-superconducting connection. The resistance of Sample B, Fig. 1(b), falls to zero at T_c (89.1 K) indicating a superconducting linkage between the stripes even though they are clearly visible in the photograph.

Variable temperature scanning laser microscopy (VTSLM) was used to investigate the transport current distribution across the sample. The intensity of signal (δV) in hot-spot scanning techniques including scanning laser microscopy is proportional to the local current density, j_B, and the slope of local temperature dependence of resistance, $(\partial\rho/\partial T)$, provided the redistribution of current due to the heating can be neglected [14].

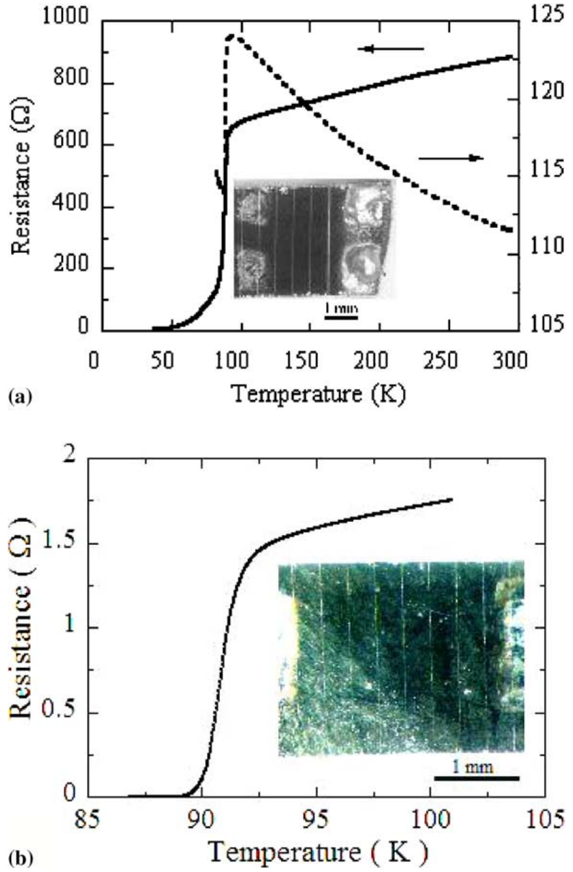

Fig. 1. The solid lines are the temperature dependent transverse resistance of (a) Sample A (an epitaxial YBCO film on LAO substrate) and (b) Sample B (a coated conductor on RABiTS substrate). The dotted line in (a) is the transverse resistance of Sample A after YBCO and silver bridging are removed and gold dots are deposited to connect the filaments.

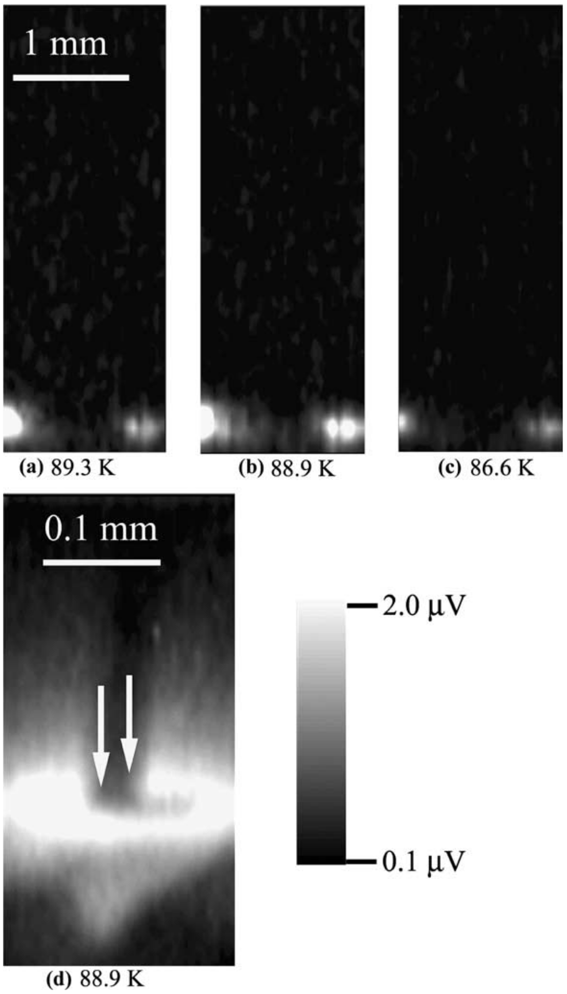

Fig. 2. VTSLM images of Sample A. The images in (a–c) are taken at 1.4 mm × 3.8 mm area between electrodes, which contains three scribes. (d) Magnified VTSLM image of the inter-filamentary connection at the bottom edge. The arrows mark the strip where YBCO is ablated.

The resistive transition of Sample A in Fig. 1(a) shows a sharp drop of resistance around 88.9 K indicating that the sample has large $\partial\rho/\partial T$. Therefore, one expects the strongest signal at that temperature [16,17]. Elsewhere, the δV signal is within the noise level explained by the low current density due to the striations blocking the flow of transport current. Fig. 2 is VTSLM images from Sample A taken near T_c. With the variation of temperature, the strong signals only occur within a narrow area on the bottom of sample with the strongest signal at 88.9 K identifying the location of weak links where the current flows between the stripes. Fig. 2(d) shows the magnified view of the high signal area taken at 88.9 K. The end of the striation is clearly visible indicating the incomplete cutting of the film at this position. In addition, unusually large signal is observed outside of the sample resulting from residual silver paste on the sample edge which provides an additional metallic inter-filamentary connection in Sample A.

On the other hand, Sample B represents a uniform superconducting linkage between the stripes with the same T_c as the bulk of the sample. The link is produced by incomplete removal of YBCO. Fig. 3 is VTSLM images of Sample B taken between 90.0 K and 91.7 K. Unlike Fig. 2 where the low current density is observed in most of Sample A, current flow is almost unperturbed by the striations. The features observed in Sample B are primarily due to the non-uniform current flow in RABiTS coated conductors.

As shown in Samples A and B, when the sample is still superconducting after the striations are made, one understands there exists current path. However, one cannot predict where and what kind of current paths exist in the sample from the resistance measurement. We have demonstrated that VTSLM can uncover the effects of striations on the transport current flow. We find that the inter-filamentary connects in Samples A and B are due to the incomplete cutting at the edge and the incomplete ablation of YBCO, respectively.

Fig. 4 is photograph and VTSLM images of an epitaxial YBCO film on LAO substrate with completely segregated filaments. Longitudinal striations are clearly visible in Fig. 4(a) and the direction of transport current is along the isolated filaments. A series of VTSLM images shows the effect of striations; especially in Fig. 4(c), at 90 K, six clear straight-line boundaries indicated by arrows which separate the different intensity of δV. We have confirmed that these positions are corresponding to striations made by the laser cutting. A detailed study around the striated line yields that the δV signal is weak there, confirming that no current flows across. Of interest is that the intensity of δV gradually decreases from the middle to the edge stripes. Two possible explanations for the inhomogeneous current flow among the stripes are: (1) inhomogeneous current injection due to, for example, the non-uniform contact resistances in each stripe and (2) preferential current paths resulting from filamentary blockage due to the local defects. Further study is needed to determine if the different intensity of δV is due to either of the possibilities.

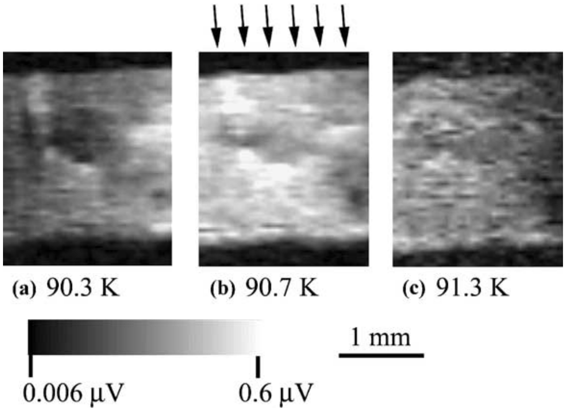

Fig. 3. VTSLM images of Sample B. The arrows mark the strips where YBCO is mostly ablated.

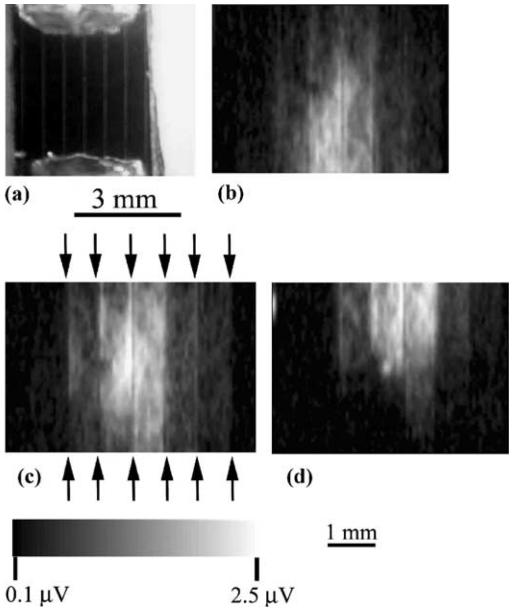

Fig. 4. Photograph and VTSLM images of an epitaxial YBCO film with longitudinal striations. The arrows mark the strips where YBCO is completely ablated.

It is also important to consider the effects of normal conduction layers in contact with the YBCO in designing the architecture of coated conductors. For this purpose, the inter-filamentary connections at the bottom edge of Sample A are removed, and gold dots are applied by sputtering for intentional bridging of the now segregated filaments. Prior to sputtering, the separation of the filaments is verified by resistivity measurements. The dotted line in Fig. 1(a) shows the transverse resistance of the filaments connected by gold bridging. The curve indicates a semiconducting behavior as opposed to an expected metallic behavior in the normal state as well as below superconducting transition temperature. This is particularly relevant if a metal is used for the inter-filamentary current sharing in CCs as is typical with other superconductors. A recent paper [18] reported that YBCO/gold interface showed a semiconducting behavior due to a Schottky barrier. A more extensive investigation is required to select ideal materials and processing conditions for current sharing in CCs.

We believe that the semiconducting behavior originates the interface between YBCO and gold. In the normal state, the semiconducting resistance may be explained by invoking *c*-axis transport [19]. However, Fig. 1(a) shows that the resistance of the sample does not reach zero after the sharp drop at the superconducting temperature. In addition, the semiconducting resistive behavior is observed below the superconducting temperature, clearly indicating the serial current path through a semiconducting area.

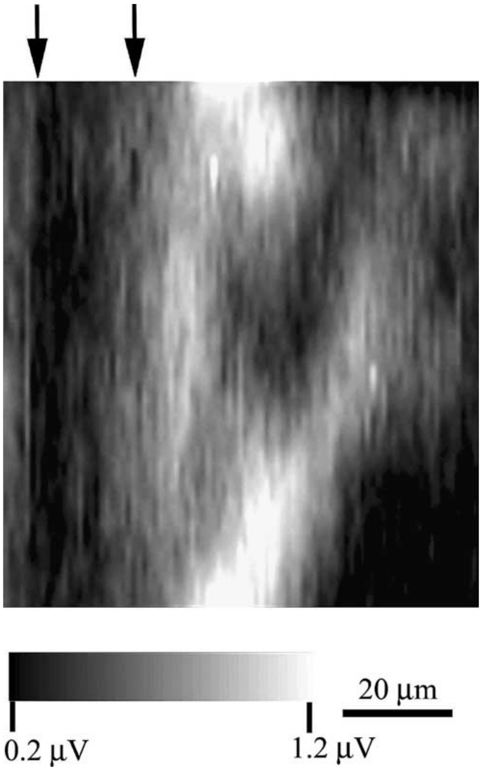

Fig. 5. VTSLM image of a gold dot area at 89.6 K. The scan area is 100 µm × 9 µm. The arrows indicate the striation.

Images of the whole sample (not shown) show that the current is concentrated around the gold dots supporting the current transport through YBCO/gold/YBCO at the striations. Fig. 5 is a detailed image around a gold dot. One can notice that the signal (δV) is not uniform on the gold dot. This implies that the current transport through the interface between the gold dot and YBCO is inhomogeneous. Since the gold dots were deposited after the sample was exposed to the first measurement and environmental damages, the surface of YBCO on which gold was deposited was not pristine. Hence, the YBCO/gold interface creates a non-uniform barrier for current transport as evidenced in Fig. 5. The interface barrier layer may have a semiconducting (or insulating) characteristic.

4. Conclusions

We have demonstrated the usefulness of VTSLM for investigation of the transport current distribution in striated YBCO superconductors. Results are provided detailing current distributions for fully isolated YBCO filaments and for incompletely separated YBCO filaments due to un-optimized parameters for sample processing. When the current flows parallel to the completely separated striations, the current seems to flow within a strip without inter-mixing. Of particular interest, gold bridging between the filaments has exhibited non-metallic behavior in the transverse resistance due to the interface resistance. One must consider these aspects when designing striated patterns to lower ac loss while incorporating current sharing in the architecture of coated conductors. VTSLM technique may provide valuable insights into the nature of current sharing between the stripes which is essential for the design of striated patterns intended for the reduction of ac losses.

Acknowledgment

This work was supported by the Air Force Office of Science Research (AFOSR) under grant No. F49620-01-1-0493. MBP would like to acknowledge the fellowship support from AFOSR, No. F49620-02-1-0439.

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