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THE DISTRIBUTION OF TRANSPORT CURRENT IN YBCO COATED CONDUCTOR WITH ZIPPER STRIATIONS

L.B. Wang, P. Selby, C. Khanal, George Levin,
Timothy J. Haugan, Paul N. Barnes, and C. Kwon

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George Levin, Timothy J. Haugan, and Paul N. Barnes (AFRL/PRPG)
L.B. Wang, P. Selby, C. Khanal, and C. Kwon (California State University, Long Beach)

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Long Beach, CA 90840

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14. ABSTRACT
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The Distribution of Transport Current in YBCO Coated Conductor With Zipper Striations

L. B. Wang, P. Selby, C. Khanal, George Levin, Timothy J. Haugan, Paul N. Barnes, and C. Kwon

***Abstract*—An YBCO coated conductor with a zipper pattern striation is investigated by scanning laser microscopy (SLM). The distribution of transport current deduced from the VTSLM images shows that striations act as artificial barriers forcing the current to flow around them. Current sharing and redistribution are observed at the zipper area. We find the major dissipation mechanism in the sample in the superconducting state to be the current crowding at bottleneck areas. The bottleneck seems to be caused by the disabled filaments at and around the zipper area. Some filaments show the dissipation away from the zipper area. In general, we find that the lower J_c^* areas have lower T_c^* and high δV_m, which we consider as a sign of the current crowding. For the first time, we have demonstrated that there is a high temperature signature of the lower J_c^* (high dissipation) area and VTSLM can detect the signature.**

***Index Terms*—Critical current density, the distribution of transport current, YBCO coated conductor, zipper striations.**

I. Introduction

THE REALIZATION of high critical current ($J_c > 10^6\ \mathrm{A/cm^2}$) in YBCO coated conductors (CCs) has opened the door for high power applications [1]–[4]. In AC applications such as generators, AC loss is a problem due to the large aspect ratio in CCs. In order to reduce the AC loss, it is important to modify the design of CCs. Carr and Oberly have divided the YBCO coated conductor cables into long filamentary strips with a little twist to reduce AC loss [5]. Cobb *et al.* used laser ablation to create striated epitaxial YBCO film and demonstrated the decrease in AC loss [6]. However, in long filamentary strip, a single defect may block the flow of current in a filament making it useless. In order to provide current sharing among filaments, striations are interrupted to provide openings between filaments. The openings are placed in different patterns such as a zipper and a brickwall. Finding the optimum geometry for those patterns to reduce the AC loss without compromising the performance of CCs is an ongoing research.

In this paper, we use scanning laser microscopy (SLM) to investigate the transport properties in a zipper-patterned CC sample. In the superconducting transition region, we have studied the current distribution and T_c distribution using VTSLM. In $T < T_c$, we have measured the local dissipation in order to locate the lower J_c^* area. Our results show that there are correlations between VTSLM images and the dissipation maps.

II. Experiments

Linear striations were made to divide the HTS layer of the IBAD CC samples into parallel filamentary stripes with a zipper pattern. The linear striations were made using a YAG laser by ablating parallel strips of the superconductor. The samples were prepared for four-probe transport measurements by depositing gold contacts. Extra care was taken to ensure good gold coverage over each striation in the sample to ascertain uniform contact resistance among the strips. The bias current was applied along the direction of the striations. Detailed information about VTSLM can be found in our earlier publications [7], [8].

III. Results and Discussion

Fig. 1 is the temperature dependence of resistance. $T_c(R = 0\ \Omega)$ is 89.3 K, and the transition width ΔT is about 2.0 K. The photograph of the sample (Fig. 2(a)) shows that a series of long striations on the left meet the striations on the right in a zipper pattern. The width of each filament is 0.5 mm, the width of each striation is 25–50 $\mu\mathrm{m}$, and the width of each opening is 0.2 mm.

Figs. 2(b) and (c) are VTSLM images of the photographed area taken at 90.2 K. The total scanned area is 3.0 mm × 3.8 mm. Fig. 2(b) is taken with 50 $\mu\mathrm{m}$ scanning steps and Fig. 2(c) with 10 $\mu\mathrm{m}$ steps. Even though they were taken at different times, the features look similar except that Fig. 2(c) is a sharper image than Fig. 2(b) confirming the consistency of VTSLM images. A series of VTSLM images were taken between 90.0 K and 90.8 K. However, only 90.2 K images are shown because the main differences between the images are the signal strength. As we have expected from the resistive transition curve shown in Fig. 1, 90.2 K has the highest $\delta\mathrm{V}$, giving the clearest image.

Striations are clearly visible in VTSLM images of Figs. 2(b) and (c). The inside of striations has a weaker signal ($\delta\mathrm{V}$), and the filaments have a stronger signal along the striations. The detailed atomic force microscopy (AFM) and VTSLM measurements around a striation show that the width of striation trench is 25 $\mu\mathrm{m}$ and that the distance between stronger $\delta\mathrm{V}$ areas around a striation is 110 $\mu\mathrm{m}$. Meanwhile, the stronger signals are found in the zipper area. Since the stronger signal in a VTSLM image usually means larger local current density [8], our results reveal

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L. B. Wang, P. Selby, C. Khanal, and C. Kwon are with the Department of Physics and Astronomy, California State University, Long Beach, CA 90840 USA (e-mail: wanglb1@yahoo.com; pselby@mail.nmusd.k12.ca.us; ckhanal@gmail.com; ckwon@csulb.edu).

G. Levin, T. J. Haugan, and P. N. Barnes are with the Air Force Research Laboratory, WPAFB, OH 45433-7919 USA (e-mail: george.levin@wpafb.af.mil; timothy.haugan@wpafb.af.mil; paul.barnes@wpafb.af.mil).

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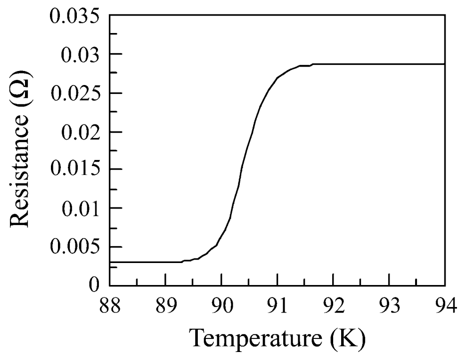

Fig. 1. The temperature dependence of resistance.

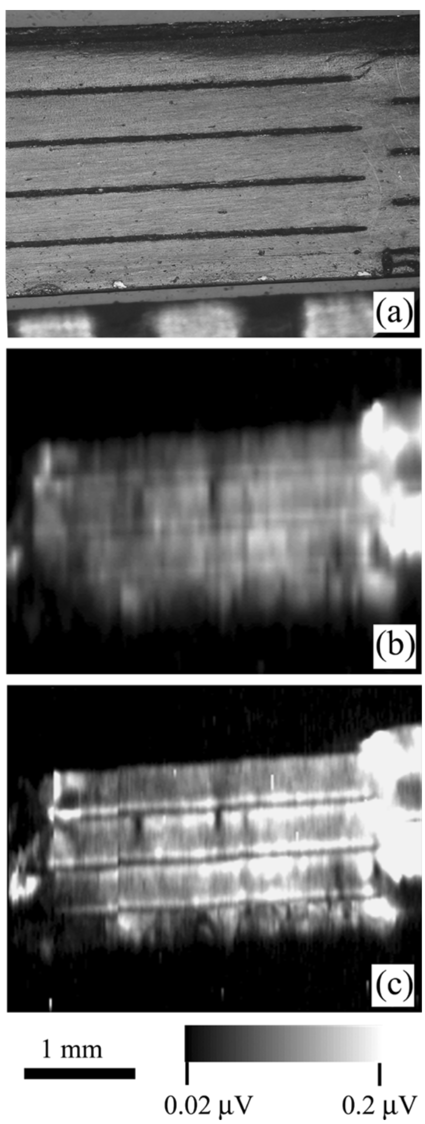

Fig. 2. (a) The photograph of the sample. VTSLM images taken at 90.2 K (b) with 50 μm scanning step and (c) with 10 μm scanning step.

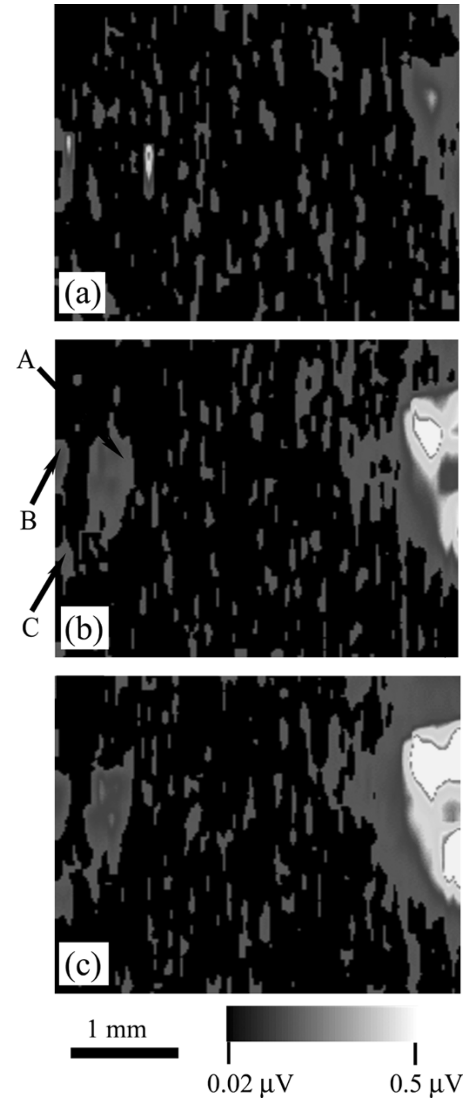

Fig. 3. LTSLM images at 89.0 K. The applied current is (a) 200 mA, (b) 230 mA, and (c) 250 mA.

that the larger current flows along the striations and the current seems to accumulate at the zipper area.

We have reported that an artificial hole in an YBCO film increases VTSLM signal along the current direction of the hole [9], and a computer simulation program for VTSLM has confirmed that this due to modification of current flow by the hole. We believe that the striations perform as artificial trenches to block the current and to compel the current to flow around them. In this case, the current density increases along the striations so that the signals become stronger in the filaments along the striations.

From the photograph, we will label the first filament from the top in the left side as L1, the second as L2, etc.; and the first filament from the top in the right side as R1, the second as R2, etc. It is interesting to observe that L1, R1, R5, and R6 are not noticeable in VTSLM images while the zipper area around R2 and R4 has the strongest δV. Since the filaments with smaller δV mean lower or no current flow, we examine the photograph of the sample and find visible signs that may explain it. L1 and R1 are darker than the rest of the sample, there are black scratches in the zipper between L1 and R1, and R6 has a scratch blocking the filament. All these may be the visible confirmation of defects blocking or reducing the current flow in the filaments.

VTSLM images also show the zipper area acts as a place to share and to redistribute the current between right-side and left-side filaments as intended. However, we notice a problem

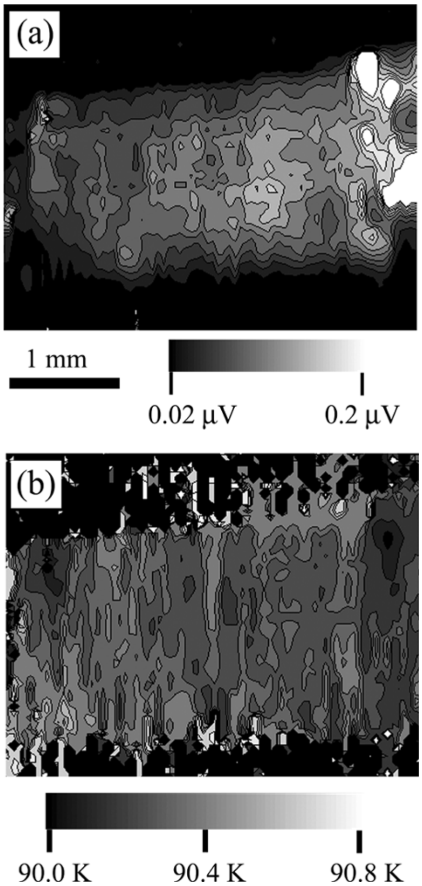

Fig. 4. (a) δV_m, (b) T_c^* images.

with the zipper pattern. Due to the numerous disabled filaments on both sides, the current is accumulated in the zipper area as shown in Fig. 2. It looks as if only two filaments on the right-side (R2 and R4) can carry current creating high current density in the zipper and those filaments.

We have also investigated the distribution of the local dissipation in superconducting state using low temperature scanning laser microscopy (LTSLM). More information of this technique can be found in [10]–[12].

We measured LTSLM images shown in Fig. 3 at 89.0 K, which is 0.3 K lower than the $T_c(R = 0\ \Omega)$. From these images, we find that the signal distribution is different from the image in Fig. 2. Since LTSLM creates a map of the local dissipation in the superconducting state (J_c^*), the signaled area is where the local current density is larger than the critical current density (J_c) [10]. In Fig. 3, there are two lower J_c^* areas in the sample. When 200 mA current is supplied, the signals appear in the right side, while the signals in the left side are difficult to identify. When the current reaches 230 mA, three patches A (L2 and L3), B (L2), and C (L4) appear in the left-side and the signal from the right-side increases. At 250 mA, the signal from both areas increases and the overall areas are expanded. Meanwhile, two dots appear in A.

Since Fig. 3 is taken at the same position as Fig. 2 with the same scan area, the main dissipation occurs at the zipper and R2 and R3, and the secondary dissipation at L2, L3, and L4. In order to relate J_c^* and VTSLM results, we have calculated the T_c^* (the temperature corresponding to the maximum of δV (T)) and δV_m for temperature scanning images [8]. Fig. 4 is T_c^* and δV_m maps calculated from the series of 50 μm scanning step images as in Fig. 2(b).

Comparing Fig. 4 and Fig. 3, we find that the lower J_c^* areas have lower T_c^* and high δV_m. The zipper and R2 and R4 filaments areas have the strongest δV_m and the lowest T_c^*. A and C marked in Fig. 3 also show low T_c^* and high δV_m. We think that low T_c^* and high δV_m are the signature of a current bottleneck area caused by intrinsic or geometric defects. As we have shown in Fig. 2, the disabled filaments cause the current to accumulate at the zipper and a few filaments (R2 and R4). Hence, this area produces the main dissipation.

It is not clear what causes A and C in L2, L3, and L4 filaments to have the secondary dissipation. More detailed measurements are needed to confirm the nature of defects creating the current bottleneck. It is important to point out that this is the first time a correlation is made between VTSLM and LTSLM images. Since there is a higher temperature signature for the superconducting dissipation and it can be detected by VTSLM, we are confident that VTSLM will be a valuable tool for diagnosing and characterizing CCs.

We find that all low T_c^* and high δV_m areas are accounted in LTSLM as a dissipating area. However, B area is an exception. B shows a higher T_c^* with low nonuniform δV_m around it, so it is different from the current bottleneck area. Due to the nonuniform and low δV_m around B, we think that there may be a grain boundary across the filament (L2). Since the grain boundary has low J_c [13]–[15], it can cause the dissipation at lower current in superconducting state. Also the higher normal state resistance can create the disturbance of current flow in normal state.

IV. Conclusions

An YBCO coated conductor with a zipper-patterned striation is studied by scanning laser microscopy (SLM). VTSLM images show that the striations restrict current within the filaments and behave as artificial barriers causing the current to flow around. As intended, the zipper area acts as a place to share and to redistribute the current among filaments. In the superconducting state, the main dissipation in the sample occurs at the zipper and in a few filaments near the zipper instigated by the current crowding at a bottleneck area. In general, we find that the lower J_c^* areas have lower T_c^* and high δV_m, which is a sign of the current crowding.

References

[1] S. R. Foltyn, P. N. Arendt, P. C. Dowden, R. F. Depaula, J. R. Grovers, J. Y. Coulter, Q. X. Jia, M. P. Maley, and D. E. Peterson, “High-Tc coated conductors—performance of meter-long YBCO/IBAD flexible tapes,” *IEEE Trans. Appl. Supercond.*, vol. 9, pp. 1519–1522, Jun. 1999.

[2] J. O. Willis, P. N. Arendt, S. R. Foltyn, Q. X. Jia, J. R. Groves, R. F. DePaula, P. C. Dowden, E. J. Peterson, T. G. Holesinger, J. Y. Coulter, M. Ma, M. P. Maley, and D. E. Peterson, “Advances in YBCO-coated conductor technology,” *Phys. C*, vol. 335, pp. 73–77, Jun. 2000.

[3] V. Selvamanickam, H. G. Lee, Y. Li, X. Xiong, Y. Qiao, and J. Reeves, “Fabrication of 100 A class, 1 m long coated conductor tapes by metal organic chemical vapor deposition and pulsed laser deposition,” *Phys. C*, vol. 392, pp. 859–862, Oct. 2003.

[4] H. Iwai, T. Muroga, T. Watanabe, S. Miyata, Y. Yamada, Y. Shiohara, T. Kato, and T. Hirayama, "Investigation of high J_c $YBa_2Cu_3O_{7-x}$ coated conductors prepared by pulsed laser deposition on self-epitaxial CeO_2 buffers," *Supercon. Sci. Technol.*, vol. 17, pp. S496–S499, Sep. 2004.

[5] W. J. Carr and C. E. Oberly, "Filamentary YBCO conductors for ac applications," *IEEE Trans. Appl. Supercond.*, vol. 9, pp. 1475–1478, Jun. 1999.

[6] C. B. Cobb, P. N. Barnes, T. J. Haugan, J. Tolliver, E. Lee, M. Sumption, E. Collings, and C. E. Oberly, "Hysteretic loss reduction in striated YBCO," *Phys. C*, vol. 382, pp. 52–56, Oct. 2002.

[7] C. Kwon, L. B. Wang, S. Seo, B. H. Park, and Q. X. Jia, "Spatial distribution analysis of ctitical temperature in epitaxial Y-Ba-Cu-O film using variable temperature scanning laser microscopy," *IEEE Trans. Appl. Supercon.*, vol. 13, pp. 2894–2896, Jun. 2003.

[8] L. B. Wang, M. B. Price, J. L. Young, C. Kwon, T. J. Haugan, and P. N. Barnes, "Observation of nonuniform current transport in eptiaxial $YBa_2Cu_3O_{7-x}$ film near the superconducting transition temperature," *Phys. C*, vol. 405, pp. 240–244, Jun. 2004.

[9] B. E. Klein, S. Seo, C. Kwon, B. H. Park, and Q. X. Jia, "Imaging transport current distribution in high temperature superconductors using room temperature scanning laser microscopy," *Rev. Sci. Isntrum.*, vol. 73, pp. 3692–3694, Oct. 2002.

[10] R. Gross and D. Koelle, "Low temperature scanning electron microscopy of superconducting thin films and Josephson junctions," *Rep. Prog. Phys.*, vol. 57, pp. 651–741, 1994.

[11] A. G. Sivakov, A. V. Lukashenko, D. Abraimov, P. Müller, A. V. Ustinov, and M. Leghissa, "Low-temperature scanning laser microscopy of individual filaments extracted from $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+x}$ tapes," *Appl. Phys. Lett.*, vol. 76, pp. 2597–2599, May 2000.

[12] T. Kiss, M. Inoue, S. Egashira, T. Kuga, M. Ishimaru, M. Takeo, T. Matsushita, Y. Ijima, K. Kakimoto, T. Saitoh, S. Awaji, K. Watanabe, and Y. Shiohara, "Percolative transition and scaling of transport E-J characteristics in YBCO coated IBAD tape," *IEEE Trans. Appl. Supercond.*, vol. 13, pp. 2607–2610, Jun. 2003.

[13] D. T. Verebelyi, D. K. Christen, R. Feenstra, C. Cantoni, A. Goyal, D. F. Lee, M. Paranthaman, P. N. Arendt, R. F. DePaula, J. R. Groves, and C. Prouteau, "Low angle grain boundary transport in $YBa_2Cu_3O_{7-\delta}$ coated conductors," *Appl. Phys. Lett.*, vol. 76, pp. 1755–1757, Mar. 2000.

[14] D. T. Verebelyi, C. Cantoni, J. D. Budai, D. K. Christen, H. J. Kim, and J. R. Thompson, "Critical current density of $YBa_2Cu_3O_{7-\delta}$ low-angle grain boundaries in self-field," *Appl. Phys. Lett.*, vol. 78, pp. 2031–2033, Apr. 2001.

[15] L. Fernández, B. Holzapfel, F. Schindler, B. de Boer, A. Attenberger, J. Hänisch, and L. Schultz, "Influence of the grain boundary network on the critical current of $YBa_2Cu_3O_7$ films grown on biaxially textured metallic substrates," *Phys. Rev. B*, vol. 67, pp. 052 503-1–052 503-4, Feb. 2003.