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Laser patterning: A new approach to measure local magneto-transport properties in multifilamentary superconducting tapes

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Abstract

The determination of inter- and intra-filament characteristics in superconducting composites such as BSCCO-Ag tapes is of great importance for material evaluation towards applications. Most attempts to separate the two contributions have relied on indirect methods based on magnetic measurements such as SQUID or magneto-optic imaging techniques. Here we show that laser patterning of superconducting BSCCO-Ag tapes constitutes a simple approach to measure local transport properties in a direct way, even able to separate inter- and intra-filament contributions to the overall transport behavior of the sample.

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1. Introduction

One of the most difficult goals in the measurement of superconducting properties of inhomogeneous samples such as ceramic materials, polycrystalline films or multifilamentry tapes is to separate the contributions of intra- and inter-grain currents to the overall behavior of the samples. This is a fundamental issue for materials optimization, since there is no trivial correspondence between the microstructure and the connectivity in most samples. When macroscopic methods are used to separate intra- and inter-granular contributions, theoretical models are involved, which typically imply strong assumptions and approximations when interpreting results from magnetometric techniques such as SQUID [1,2] and conventional transport measurements [3,4].

A number of methods have been created to measure transport properties on different ‘‘stripes’’ along the axis of the tape: mechanical cuts [5,6], the application of ‘‘local’’ strong magnetic fields [7–9] and the use of a photolithographic technique [10]. Recently, a laser technique was used to prepare for transport measurements individual filaments extracted from a tape [11]. In this paper, we propose a new method to measure directly the transport properties at different locations and along different directions of a multifilamentary $Bi_2Sr_2Ca_2Cu_3O_{10+x}$-Ag (BSCCO-Ag) tape using the conventional four-probe technique on samples locally patterned using laser cutting. The patterning is designed in such a way that local measurements of parameters such as the critical current could be performed along the superconducting filaments, probing intra-filament properties, and transverse to the filaments, probing the inter-filament properties. The transport measurements along the filament could even be done at different locations along the lateral dimension of the tapes.

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2. Experimental

Tapes of BSCCO-Ag were fabricated by the powder-in-tube technique with subsequent drawing and rolling [12]. The tapes were 4.32 mm wide and 0.23 mm thick, and contained 61 filaments. Each filament was 0.3–0.4 mm wide and a few microns thick. The overall long length critical current of the tape was 65 A at 77 K, corresponding to an engineering critical current density, J_e, of 6.6 kA/cm^2, defined by dividing the critical current by the total cross section perpendicular to the current flow. The upper panel of Fig. 1 shows an image of the tape cross section.

Pieces of tape were patterned using a Nd:YAG PLC-Cut pulsed laser, with free running regime fundamental harmonic of 1064 nm, which produced a cutting spot on the sample through an appropriate optical system. A suitable beam expander and an achromatic focusing lens with a focal length of 100 mm were used to control the spot size. The samples were glued on pieces of circuit board with a hole under the region to be laser-patterned, and then mounted on a x–y micro-stepping stage that could be moved along the focal plane of the lens. Parameters were adjusted empirically to minimize the formation of debris, leading us to use a pulse duration and energy of 130 μs and 300 mJ, respectively, applied with a repetition rate of 2–3 Hz. Straight cuts were then obtained as a chain of holes of 90 μm diameter, with 70% overlap between one hole and the next. The overall cutting speed was 5 mm/min.

Transport measurements were performed using the four-probe technique with Ag-paste contacts. The temperature was controlled with a resolution of $\pm$0.02 K using a Lake Shore 330 temperature controller with a DT470 silicon diode as thermometer. In the resistivity measurements, the sample was excited with an AC current of 1 mA at 1 kHz. The output voltage was measured using a Scitec Instruments 500 MC lock in amplifier, with an output resolution better than 100 nV. We define the zero-voltage critical temperature, T_{cz}, as the temperature where the resistance starts to deviate from the low-temperature horizontal line. The critical current was measured using a pulsed-current technique [13] with a voltage criterium of 1 μV, and J_e was calculated by dividing it by the smallest cross section of the sample perpendicular to the current flow.

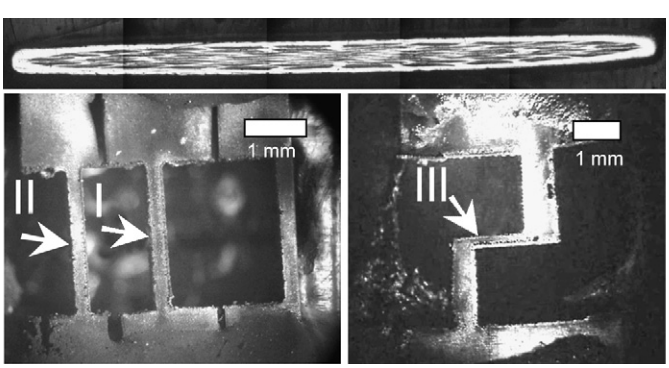

Fig. 1. Images of the BSCCO-Ag superconducting tape. Upper panel: transversal section of the original tape. Lower panels: laser-cut bridges (the plane of the tape is parallel to the page, and its long direction runs from bottom to top).

3. Results and discussion

The lower panels of Fig. 1 show some of the laser-cut bridges where electrical measurements were performed. The left one shows a piece of tape longitudinally sliced with the laser technique in such a way that three bridges were obtained. Two of them—one at the center of the tape (bridge I), and a one near the left edge (bridge II)—were investigated, as well as the transversal bridge shown in the right panel (bridge III). Even more longitudinal and transversal bridges not shown in Fig. 1 were also studied, among them a bridge similar to III, but being 1 mm wide, and denoted below as IIIwide.

Fig. 2 shows the resistive transition for the original tape, and for bridges I–III and IIIwide. The curves are normalized to the resistivity of bridge I at $T = 115$ K. The critical temperature always decreased less than 1.5 K after the laser cutting. Note that the T_c reduction is not exclusively connected to the laser heating effect, but also to the local microstructure "selected" in each bridge. For example, bridge I shows the smallest decrease in T_c, since it runs through the center of the tape, where filaments are probably quite uniform, as suggested by the magneto-optical images presented by Cai and co-workers [11]. Our bridge II shows a bigger shift, which is expected because it runs near the edge of the tape, where unhealed micro-cracks are more commonly found [11].

Bridge III displays the smallest T_c value, which may be related to the current here being forced transversally from one filament to another. While bridge IIIwide is also transverse, the bridge itself is wider, so the region affected

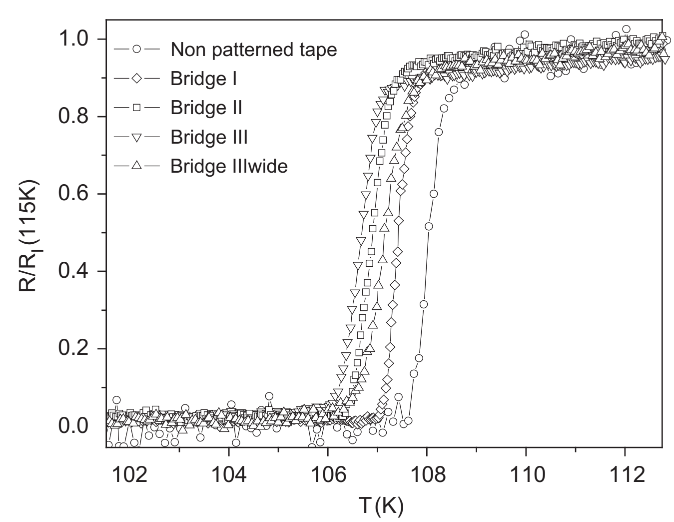

Fig. 2. Resistive transitions measured on laser-cut bridges (some of them shown in Fig. 1).

by laser heating comprises a smaller proportion of the bridge's cross section perpendicular to the current flow. All in all, the resistivity measurements, showing only minor shifts of the curves, indicate that our laser cutting technique affects very little the superconducting properties of the tape.

Fig. 3 shows curves for the engineering critical current density J_e versus T for the bridges I and III near T_c. As expected, J_e for bridge III is the smaller of the two since in that transverse geometry the transport current is forced to cross through different filaments. The almost linear behavior of the $J_e(T)$ curve of bridge I is typical of good BSCCO tapes measured along their long axis [14]. In contrast, the strongly curved $J_e(T)$ characteristic of bridge III can be interpreted as weak-superconductivity behavior, commonly observed in the inter-granular critical currents of sintered high T_c polycrystalline samples [15]. The engineering critical current densities at 77 K for bridges I and III where found to be 6500 ± 500 and 3500 ± 500 A/cm^2, respectively.

Fig. 4 shows the field dependence of the normalized critical current density for a longitudinal, 100 μm-width bridge similar to bridge I, for different temperatures. The magnetic field, H, was applied perpendicular to the wide surface of the tape. A crossover from an almost field-independent critical current density to a strongly field dependent one is seen as the temperature rises. The latter is typical of granular samples, where it is interpreted as a superposition of Fraunhofer patterns associated to the Josephson behavior of weak links with a distribution of parameters [3,4,15]. So, in our sample, while pinning seems to control the critical current below 90 K, this mechanism switches to a Josephson-like behavior near T_c. It is likely that micro-cracks or other defects along the superconducting filaments get "enhanced" due to high temperatures, acting as *SIS* or *SNS* junctions. An analogous situation should be expected *even at lower temperatures* in the case of inter-filament transport like the one "forced" by measurements in trasversal bridges, which would explain the "bending" of the lower curve in Fig. 3. This hypothesis may be corroborated with further $J_e(H)$ measurements for transversal bridges, which will be published elsewhere.

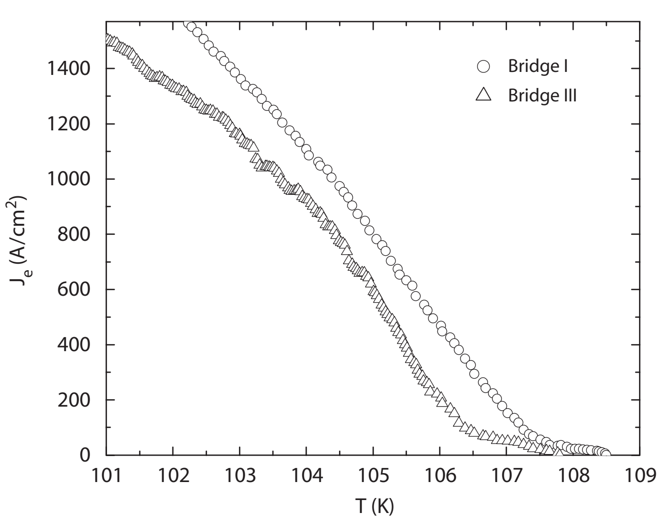

Fig. 3. Critical current density versus temperature curves for bridges I and III. The errors are ± 100 A/cm^2.

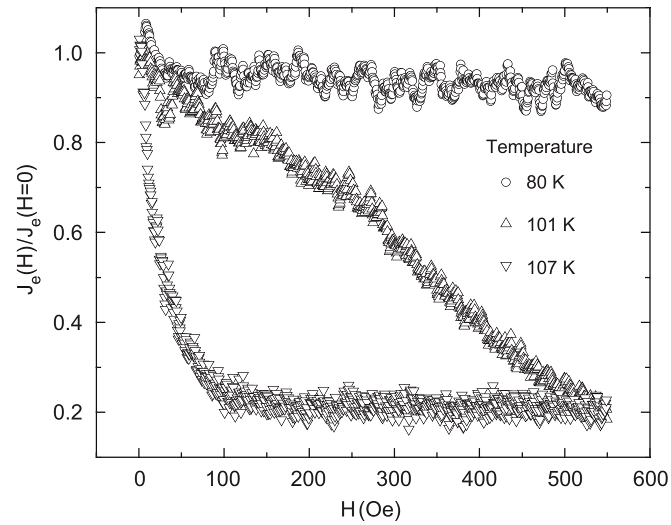

Fig. 4. Normalized critical current vs. magnetic field dependences at different temperatures for a longitudinal bridge qualitatively similar to bridge I.

Finally, it is worth noting that $J_e(H)$ curves for longitudinal bridges with the magnetic field parallel to the wide face of the tape do not show a "full" transition to Josephson-like behavior near T_c like the one displayed in Fig. 4. This may be due to the fact that in such case the field is parallel to the wide face of the filaments, so the effective area of any weak link perpendicular to the magnetic field is very small, implying very wide Fraunhofer patterns.

In summary, we have devised a laser technique that allows performing local transport measurements in regions and directions selected *ad hoc* within a BSCCO-Ag tape, which constitutes a new way for the characterization of superconducting tapes and related materials.

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