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Fast Track Communication

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Total number of authors:
11

Published in:
Superconductor Science and Technology

Link to article, DOI:
10.1088/0953-2048/28/7/072001

Publication date:
2015

Document Version
Peer reviewed version

Two level undercut-profile substrate for filamentary $YBa_2Cu_3O_7$ coated conductors

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Abstract

A novel substrate design is presented for scalable industrial production of filamentary coated conductors. The new substrate, called "two level undercut-profile substrate (2LUPS)", has two levels of plateaus connected by walls with an undercut profile. The undercuts are made to produce a shading effect during subsequent deposition of layers, thereby creating gaps in the superconducting layer deposited on the curved walls between the two levels. It is demonstrated that such 2LUPS-based coated conductors can be produced in a large-scale production system using standard deposition processes, with no additional post-processing. Inspection of the conductor cross-section reveals that the deposited superconducting layer is physically separated at the 2LUPS undercuts. Filament decoupling is also seen in maps of the remanent magnetic field and confirmed by transport measurements.

Keywords: Coated conductors, metal substrate, filamentary structures, critical current, remanent magnetic field

1. Introduction

Rare-earth barium-copper-oxide (REBCO) coated conductors (CCs) are promising high temperature superconductors for ultra-high magnetic field and power applications [1,2]. Due to the very high current density of such CCs even in strong magnetic fields and at liquid nitrogen temperatures, CC technology outperforms other types of superconductors [1,3] used in such conditions. The superior performance is achieved by bi-axial texturing of the thin REBCO layer, which is grown epitaxially using either physical or chemical deposition techniques [1]. A typical architecture of a commercial CC comprises a metal substrate, a stack of ceramic buffer layers, a superconducting REBCO layer, and an Ag layer possibly together with a mechanically supporting Cu layer [4,5]. There are two widely applied fabrication routes to obtain a strong bi-axial crystallographic texture in the superconducting layer: (i) the so-called rolling assisted bi-axially textured substrate method, where a very strong cube texture is formed during high temperature annealing of a heavily rolled substrate [6-8], and which is then transferred to the superconducting layer via epitaxy; and (ii) ion beam assisted deposition [9] or alternating beam assisted deposition (ABAD) [4], which involve deposition of a strongly textured buffer layer on a randomly textured metal tape.

Despite significant progress in commercialization and large-scale production of CCs, the standard design of flat superconducting tapes is still not well suited for alternating current (AC) applications. Such flat tapes are characterized by a very high (~10,000) aspect ratio between the width and the thickness of the REBCO layer, which results in considerable AC losses, i.e. eddy current, coupling and hysteretic losses [10], induced by applied alternating transport current and/or a varying magnetic field. These losses can cause large heat loads on cryogenic systems, when the CCs are used in transformers, fault current limiters and generators, thus making them less efficient [11-13]. Transposing or twisting of multiple CCs using either a Roebel configuration or conductor-on-round-core cables [10,14] is known to significantly reduce eddy current and coupling losses. Since the hysteretic loss scales inversely with the width of the superconducting layer, this loss can effectively be reduced if a superconducting layer consists of narrow filaments [15].

Filamentary structures in CCs have previously been produced using top-down processing techniques, such as mechanical striation [16], i.e. scribing into the buffer or REBCO layer, and by laser striation [5,17], where the filaments are formed by ablating material (figure 1(a)). Although these techniques do enable reduced hysteretic losses, their use also leads to large undesirable reductions in the critical current I_C (due to the significantly reduced functional CC width) [16-18].

In addition, since the filaments are formed after depositing the CC stack, it is reasonable to expect that the sensitive superconducting layer will be vulnerable to damage during filament formation.

We propose instead a new CC design that allows production of a filamentary superconducting tape with potentially full-width I_C. This novel design is based on a substrate with two levels of plateaus connected by walls with an undercut profile (figure 1(b)), in the following called "two level undercut-profile substrate (2LUPS)". The undercuts are made to produce a shading effect during subsequent deposition of additional layers, ultimately creating gaps in the superconducting layer on the curved walls between the two levels (see figure 1(b)). Therefore, it is expected that self-formed superconducting filaments can easily be deposited on such a 2LUPS using standard deposition processes with no additional post-processing. To verify this, a 2LUPS-based coated conductor is produced and investigated in the present work.

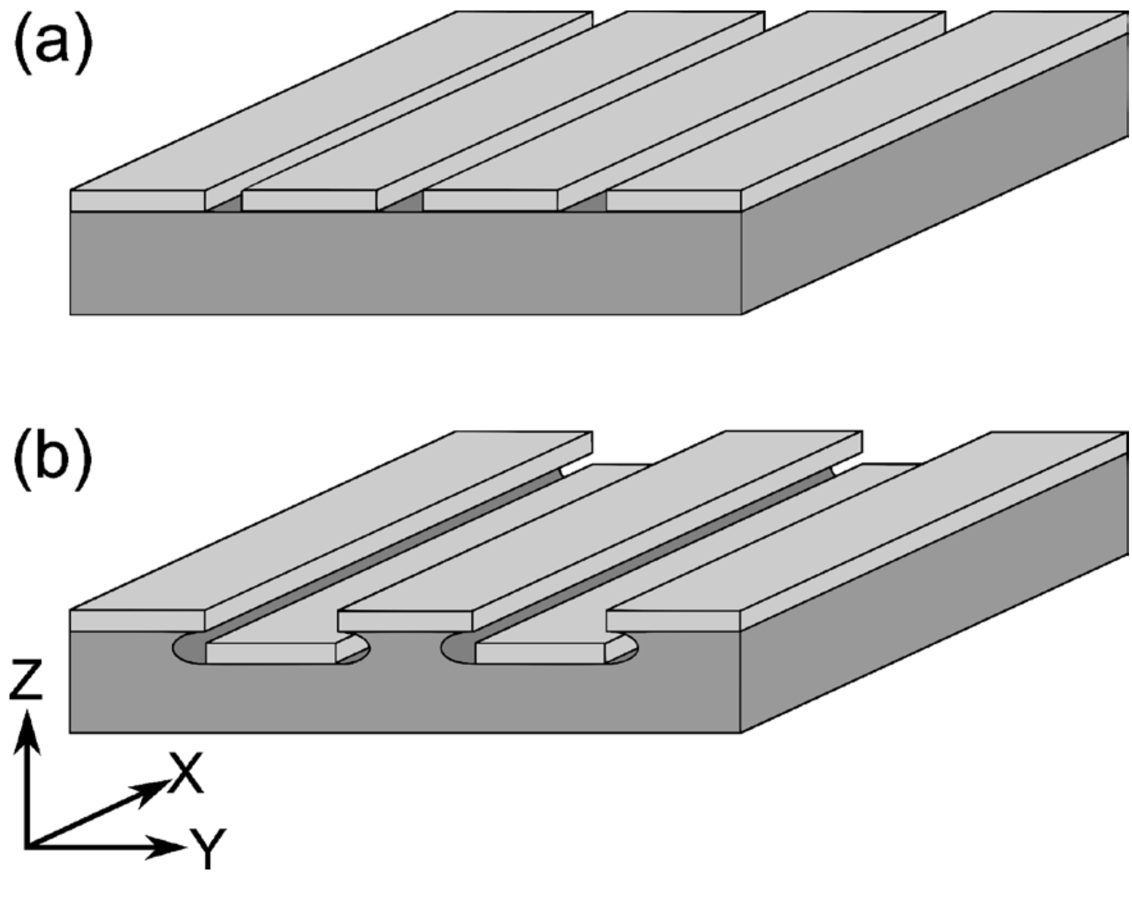

Figure 1. Schematic illustration of different types of filamentary CCs, where the substrate and a coating are shown in dark gray and light gray, respectively: (a) state-of-the-art design of laser-striated CCs; (b) 2LUPS design.

2. Experimental

A commercial Hastelloy C276 tape (L×W×T=150×10×0.89 mm^3) was used in this work for producing a 2LUPS. The tape was first electrochemically polished at 55 °C in a H_2SO_4/H_3PO_4-based electrolyte applying a current density of 200 mA/cm^2 for 3 min to obtain a smooth surface. The tape was then covered with a protective adhesive film and several cuts were made manually on the film parallel to the tape rolling direction to divide the film into 12 strips, each with a width of 0.8 mm. The adhesive film on every second film strip was peeled off and the tape was etched in the same solution to form lower plateaus with undercuts [19], after which the adhesive films on the remaining adhesive film strips were also peeled off. Yttria-stabilized-zirconia (YSZ) was then deposited on the tape using the ABAD method, followed by pulsed laser deposition of first a 70 nm CeO_2 layer and then a ~1.5 µm superconducting $YBa_2Cu_3O_7$ (YBCO) layer. Each deposition process was carried out using a large-scale production system at Bruker HTS by simply attaching the 2LUPS to the end of a standard 4 mm wide stainless steel substrate. The sample was then protected by an Ag layer deposited via thermal vacuum deposition and finally oxygenated [4].

A Carl Zeiss 1540 XB scanning electron microscope (SEM) was used for inspecting the sample cross section prepared by focused ion beam milling. The milling was performed using a Ga-ion source operated at an accelerating voltage of 30 kV. Trenches were made using a 10 nA ion-probe followed by surface polishing using a 500 pA beam. SEM images were then taken at 3 kV.

A four-point probe I_C analysis was conducted on a 50 mm long specimen with current $\mathbf{I}_i$ and voltage $\mathbf{V}_i$ taps (i = 1–4) soldered directly onto the Ag cap layer over groups of five filaments numbered 1 to 5 and 8 to 12, as shown in figure 2. Transport currents were applied by a Sorensen DCS 12-250E power supply and voltages were recorded using a Keithley 2010 multimeter. Another 20 mm long specimen of the 2LUPS CC (filaments 2 to 6) was scanned using a Hall probe [20] within 75 minutes at a temperature of 77 K (zero field-cooled) after a magnetic field was applied perpendicular to the tape normal, ramped from 0 to −20 mT and then back to 0. The distance between the superconducting layer and the Hall probe was 180 µm and 195±2 µm for the upper plateaus and lower plateaus, respectively. No significant flux creep was identified during these measurements.

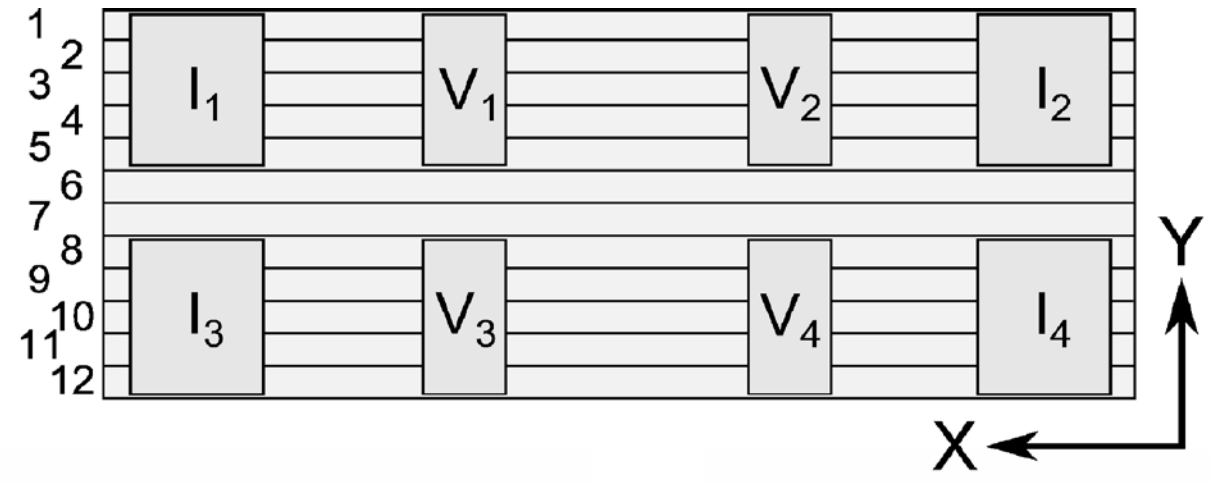

Figure 2. A schematic illustration showing positions of the current $\mathbf{I}_i$ and voltage $\mathbf{V}_i$ taps for the four-point probe analysis of the 2LUPS CC, where i=1-4. Labels 1 to 12 on the Y-axis indicate filament numbers, where even and odd numbers correspond to lower and upper plateaus, respectively.

3. Results and discussion

A representative fragment of the sample cross-section shown in figure 3 provides evidence that a gap in the YBCO layer exists in region A near the undercut B even though the undercut length L, defined as shown in the inset, is only 0.3 µm. There is also a gap in the Ag layer, which is expected to have an additional beneficial effect as it reduces resistive coupling losses through the stabilizing layer [21]. The deposited layers also have cracks in the corner region (C in figure 3). One of these cracks is clearly seen to initiate at the substrate tip, while other cracks appear to initiate in the Ag layer on the top surface. Figure 3 also shows that each deposited layer on the horizontal surface has a relatively uniform thickness and that the thickness within each layer starts to vary on the curved wall. Furthermore, rather coarse pores are seen along the interface between the substrate and the YSZ layer (D in figure 3). Note that whereas this layer is not physically separated near the undercut B, the thickness of this layer is reduced here by a factor of 3-4 compared to the thickness of the YSZ layer in other locations. This reduction is due to deviations from the optimum 55° incident angle for the assisting argon beam [4] at the undercut. Such deviations also result in a non-uniform thickness and rough surface of the layers deposited on the wall.

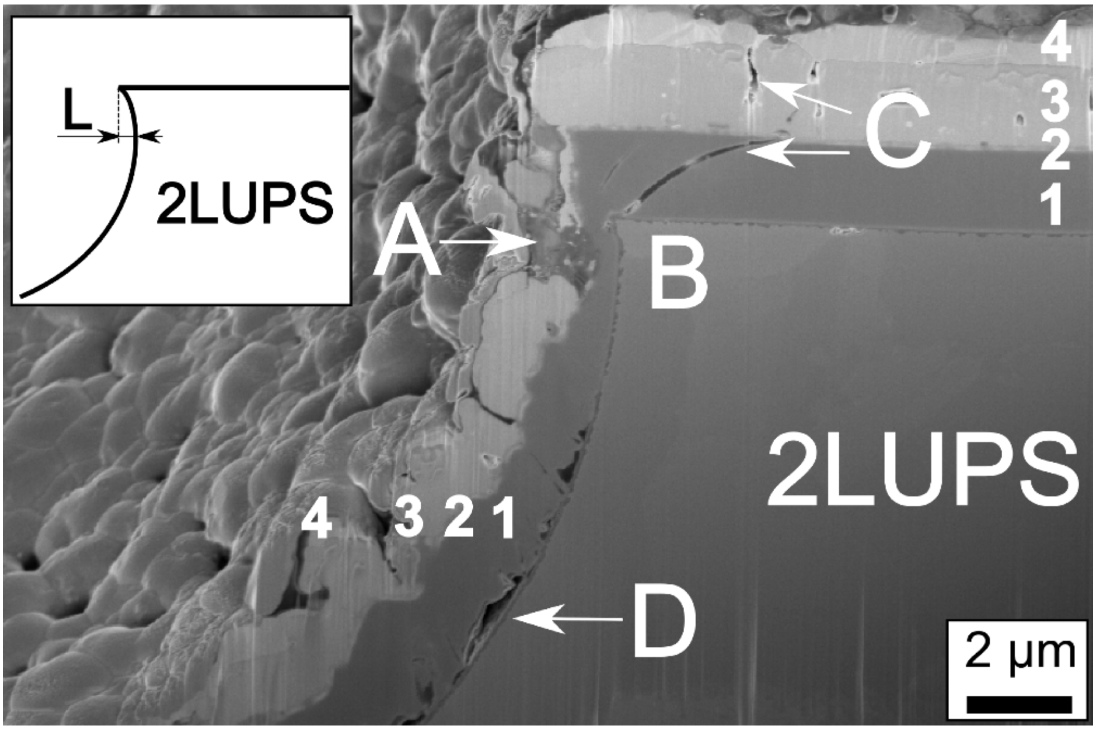

Figure 3. SEM image from the cross-section of a 2LUPS CC showing the effect of the undercut. Numbers 1 to 4 mark deposited layers: YSZ (1), CeO_2 (2), YBCO (3) and Ag (4). Labels A to D mark different features: gap in the YBCO and Ag layers (A), undercut (B), cracks (C) and pores (D). The inset defines the undercut length L.

Figure 4(a) shows the *I-V* characteristics for the filaments connected by the taps measured at 77 K and in the absence of an applied magnetic field. Using the standard E_0 = 1 µV/cm criterion (see dashed lines in figure 4(a)) it is found that I_C for filaments 8 to 12 is lower (47 A) than that for filaments 1 to 5 (80 A). Thus, the average critical current per filament (I_C/5) is 16 A for filaments 1 to 5 and 9.4 A for filaments 8 to 12. Also, the n-parameter in the fitted power function $V=E_0 l\,(I/I_C)^n$, where l is the length between the voltage taps, is lower for filaments 8 to 12 (n=24) than for filaments 1 to 5 (n=46). The much lower I_C and n-values for filaments 8 to 12 are most likely due to aperture shielding during the vapor deposition, resulting from the fact that the aperture size was adjusted for the standard 4 mm wide substrates used in the Bruker HTS production system, whereas the width of the 2LUPS substrate was larger, 10 mm. *I-V* measurements across contacts $\mathbf{I_2,V_2}$ and $\mathbf{I_3,V_3}$, i.e. across the unconnected groups of filaments, show a linear relationship (figure 4(b)), with a resistance of 84 µΩ. This linear relationship is characteristic of normal metal conductivity provided by the Ag layer on the backside of the 2LUPS CC. The normal metal conductivity observed across these two groups of filaments proves that these groups are decoupled with respect to superconducting currents.

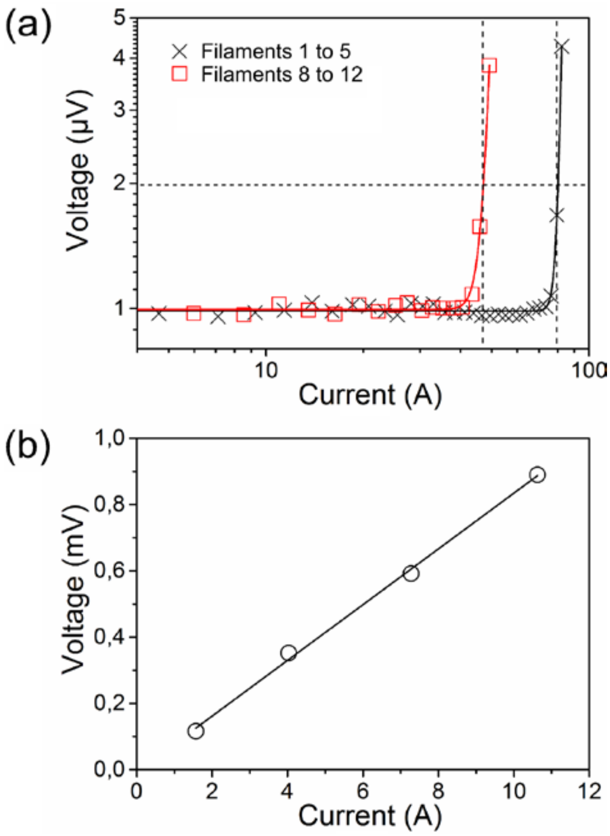

Figure 4. *I-V* characteristics of the 2LUPS CC: (a) *I-V* curves for filaments 1 to 5 and 8 to 12 measured at 77 K and in the absence of applied magnetic field. Symbols and lines indicate individual experimental data and fitted curves, respectively; (b) *I-V* curve measured using taps $\mathbf{I_2,V_2}$ and $\mathbf{I_3,V_3}$ (see figure 2) across the unconnected groups of filaments.

Figure 5 shows a remanent magnetic field map obtained from the 2LUPS CC, from which it is evident that the tape is divided into decoupled superconducting filaments, in agreement with the results of the *I-V* characterization. For each filament (seen as blue bands in figure 5), the remanent magnetic field decreases from the sides towards the center line in accordance with the Bean critical state model [22]. Field gradients across filaments 3, 4 and 5 are seen to be smaller than those across filaments 2 and 6, which is probably caused by stronger shielding currents induced in the outer filaments. Figure 5 also reveals variations in the magnetic field along the filaments which can be attributed both to incomplete magnetic penetration of the superconducting layer and to variations in either the critical current density or layer thickness due to non-optimized deposition parameters.

Finally, the positive magnetic field value of ~0.15 mT obtained at the edge of filament 3 (see figure 5) likely reflects an artifact caused by cutting [23].

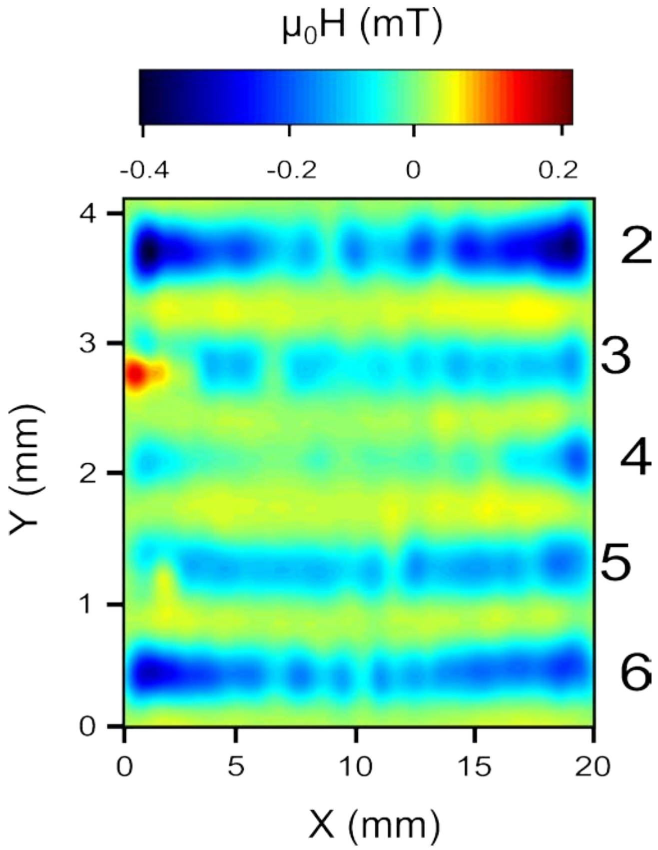

Figure 5. Remanent magnetic field map for filaments 2 to 6 measured at 77 K after ramping the magnetic field from 0 to -20 mT and back to 0. The color bar represents the strength and direction of the magnetic field. Labels 2 to 6 on the right side indicate filament numbers.

The critical current of filaments 1-5 can be compared to that of the standard flat Bruker HTS CC. Considering that the full width of these 5 filaments is ~4.2 mm, the critical current per unit width (I_C*) is 193 A/cm-width, which is 19% lower than I_C* of the standard flat CC from Bruker. This reduced I_C* can be explained by the very small undercut length L obtained in this experiment (see figure 3) and by a rougher surface [24] of the present 2LUPS as compared to the standard Bruker substrates (arithmetic surface roughness S_a is 7±1 nm and ~2 nm for the 2LUPS and the Bruker substrates [4], respectively). Although the present 2LUPS CC sample results in a lower I_C* compared to the standard CC, the 2LUPS-design has a strong technical potential as the AC losses of the filamentary CC are expected to be significantly lower than those of the standard CC. Apparently, further development of 2LUPS CCs should focus on improving the substrate surface quality and increasing the undercut length.

4. Summary

A novel 2LUPS design to manufacture filamentary CCs using the standard deposition processes in a large-scale coated conductor manufacturing system without additional post-processing has been developed. It has been verified that this new substrate enables self-forming filaments on the coated conductor. Superconducting layers deposited on the 2LUPS are physically separated, and decoupling of the filaments is confirmed by mapping the remanent magnetic field and measuring the critical current.

Acknowledgments

ACW acknowledges support from the DTU Energy project "Filamentary Coated Conductors". MS and FG acknowledge The European Union Seventh Framework Program under grant agreement number NMP3-LA-2012-280432 "EUROTAPES" and co-funded by the Slovak Research and Development Agency under the contract No. DO7RP-0003-12. Professor A Godfrey is acknowledged for his useful comments on the manuscript.

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