Nanoscale stripe structures in SmBCO superconductors

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Abstract. AFM and STM scans on SmBa2Cu3Ox (SmBCO) melt processed samples revealed nanoscale stripe-like structures, sometimes parallel over several micrometers, sometimes wavy. These structures consist of chemical compositional fluctuations and act as effective GTc pinning centres due to their wavelength of typically 10-60 nm which is comparable to the ideal pinning center size 2ξ (~10 nm for YBa2Cu3Ox in the ab-plane). Compared to similar structures in ternary (Sm,Eu,Gd)Ba2Cu3Ox (SEG) and (Nd,Eu,Gd)Ba2Cu3Ox (NEG) systems, where the stripes appear either as plateau-like stripes or as chains of aligned clusters, the stripes in SmBCO always appear as plateau-like stripes with a height of 1Å–8Å. These pinning structures throughout the whole sample volume may be a key to improve critical current densities especially at high external magnetic fields.

1. Introduction

Recently, nanostripes were observed by means of STM/AFM in ternary light rare earth (LRE) superconductor systems (Sm,Eu,Gd)Ba2Cu3Ox (SEG) and (Nd,Eu,Gd)Ba2Cu3Ox (NEG), which also exhibit the highest critical current densities of all bulk superconductors [1-4]. However, such structures were not found up to now in any type of sample of the NdBa2Cu3Ox compound (single crystals, melt-textured samples), even though the Nd/Ba-composition fluctuations are playing here an important role as well. In this paper, we report on the observation of nanostripes in single crystals of SmBa2Cu3Ox grown by the top-seed pulling growth technique. This observation of nanostripes in a single-LRE, single-crystalline superconductor is another step towards the understanding of the role of these nanostripes for the flux pinning behaviour in these LRE-high-Tc superconductors.

2. Experimental procedure

We employed Digital Instruments Nanoscope III and IV controllers in atomic force microscope (AFM) and scanning tunneling microscope (STM) mode at ambient conditions. The use of both AFM and STM enables one to exclude effects of the tips. For comparison, AFM scans were done in contact mode and tapping mode using doped Si-cantilevers. A Q-control unit was used to improve the signal-to-noise ratio in the tapping mode. STM scans were done using cut Pt/Ir-tips [3].

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Sm$_{1+\delta}$Ba$_{2-x}$Cu$_3$O$_{7-\delta}$ single crystals were grown by top-seed pulling growth at 1072 °C under 1 atm pure oxygen [5]. Large single crystals with a few mm size could be grown. A small piece (about 2 × 2 × 2 mm$^3$) was cut and subject to annealing in flowing O$_2$ at 300 °C for 400 h. DC magnetization shows the onset $T_c$ value of 95 K while with the transition width of 0.7 K.

Since the as-grown surfaces of the samples were usually too rough to achieve good scanning results, the samples were polished prior to scanning, either dry from 12 µm to 0.5 µm diamond paper or wet from 320 grain SiO paper to 4000 grain SiO paper and then from 3 µm diamond polishing solution down to 40 nm colloidal silica [6]. After that, the samples were cleaned for several minutes in acetone in an ultrasonic bath and then for several minutes in an isopropanol bath.

3. Results and discussion

Figure 1 shows typical surface images of a SmBCO sample observed by tapping AFM and STM with a tunneling current of 0.9 nA, respectively. The nanostripes seen in these images originate from the ordering RE/Ba substitution shown by local compositional analysis [7]. Furthermore, stripe profiles along a straight line are taken, revealing a height of less than 1 nm and a wavelength of 50 nm, which is larger than in ternary LRE superconductors. The parallelity of the stripe pattern typically exceeds several tens of micrometers before the overall direction changes or gets distorted by inhomogenities. Variable spaces of similar dimensions are also observed in melt-processed (Sm,Eu,Gd)BCO melt-textured samples, where the structure height is usually continuously decreased in some areas from 2 nm to zero, opposed to all our observations in SmBCO crystals.

![Figure 1.](image_url)
Note the different depth (3 nm in the AFM image and 6 nm in the STM image) of the observed structures in Fig. 1, which is due to the different geometry of the tips of the two methods employed here. The tip radius of the AFM cantilever is considerably larger than that of the STM tip.

The nanostripe patterns extend usually over a relatively large area of several micrometres, analogous to our observations on the ternary LRE-compounds [8]. As the investigated SmBCO samples are single crystals, there is also considerable less influence of embedded secondary phase particles on the nanostripe arrangement.

**Figure 2.** STM scans of a SmBCO single crystal sample. The left image shows a ~200 nm wavelength structure superimposed perpendicular to the ~50 nm wavelength nanostripes. This kind of structure only covers some areas of the sample but it could never be seen in (Sm,Eu,Gd)BCO samples. Right: 3D representation of the nanostripe curvature induced by a distortion.

In Fig. 2, another type of nanostructure is observed which consists of the nanostripes and a ~200 nm wavelength structure superimposed perpendicularly. This kind of structure only covers some areas of the sample but it could never be seen in (Sm,Eu,Gd)BCO samples investigated previously [3,8]. The right image of Fig. 2 illustrates the behaviour of the stripe pattern around an inclusion which is probably a 211 particle. Such non-superconducting inclusions distort the otherwise nearly parallel running nanostripes. As the SmBCO single crystal does not contain such a large amount of non-superconducting inclusions as compared to the melt-textured samples, the nanostripes are found to run more or less in parallel in wide areas of the sample.

Another important issue for the observation of the nanostripes in high-$T_c$ superconductors is the aging effect as illustrated in Fig. 3. Directly after the surface preparation, the nanostripes can be clearly detected (left). The right image of Fig. 3 clearly reveals that even a short exposure to air (here 24 h) may make the nanostripe pattern practically invisible. After another polishing step, the nanostripes can again be observed.

**4. Conclusions**

SmBCO single crystals were found to contain nanostripe structures with a wavelength of about 50 nm. There are, however, several differences to the nanostripe patterns observed in ternary LRE-compounds, like the measured depth of the valleys. Furthermore, another unique arrangement of the nanostripes is observed in SmBCO samples. The observation of the nanostripes in a single-LRE superconductor poses a new view of the function of the nanostripes concerning flux pinning. Furthermore, it is shown that a short exposure of the freshly prepared sample surfaces to air may deteriorate the nanostripe pattern completely.
Figure 3. STM scans of SmBCO. (left): freshly prepared surface, (right): after 24 h being exposed to air.

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