Critical Currents of Narrow YBCO Rings on Ni and $LaAlO_3$ Substrates

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***Abstract*—Low loss YBCO based flexible conductors for AC operation must have a filamentary structure with filament width below 0.1 mm. MO images of structured YBCO films showed that the flux penetration is less homogeneous in YBCO filaments on Ni substrates than that in filaments on LaAlO, which indicates that the patterning may affect the critical current density in narrow filaments. To see the effect of patterning on the filament critical current we studied I–V curves and critical currents of YBCO rings with various widths ranging from 0.3 mm down to 0.02 mm. The rings were prepared by a standard lithographic process. To avoid problems with current contacts, the current in the rings was induced by external magnetic field and electric field-current characteristics were determined by a Hall probe method.**

***Index Terms*—Critical currents, filaments, losses, YBCO.**

I. Introduction

YBCO coated conductors in the form of with a continuous YBCO layer several millimeters wide are not suitable for AC applications due to large losses when exposed to an AC magnetic field perpendicular to the tape plane.

A conceptual design of an AC YBCO based conductor was proposed by Oberly *et al.* [1]. To reduce the hysteresis losses the continuous YBCO layer should be divided into parallel filaments with the width of the order of ten micrometers. A possible negative effect of patterning technology on filament critical current of narrow filaments can be expected. Another negative effect could be associated with the existence of grain boundary grooving in Ni substrates [2]. Non-uniform etching and variation of YBCO grain growth in the space adjacent to grooves may also locally reduce the filament critical current density.

Feldmann *et al.* [3] showed that in an YBCO layer there are multiple current paths of both higher and lower critical current density resulting from the variation of inter- and intragrain critical current density J_c. They also showed that Ni grains have a typical dimension of ~50 μm and each Ni grain acts as its own single crystal template. Thus one could expect that the critical current density in narrow YBCO filaments could be considerably reduced if the width becomes comparable with the typical Ni grain size.

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We studied a possible effect of filament width on the critical current per unit filament width (I_{c1}) and hysteresis losses P_h in YBCO rings with various width (300 μm, 50 μm and 20 μm). Samples were prepared from YBCO layers deposited on $LaAlO_3$ and also on Ni substrates.

II. Experiment

The first set of samples was prepared from a 0.328 μm thick YBCO layer deposited on $LaAlO_3$ substrates with dimensions of 1×2 cm. Sample R was a reference sample with dimensions of 5.3×14 mm. Using optical litography and wet etching we prepared rings with the mean diameter of $2R_0 = 3$ mm and width $2w = 300$ μm (sample 1), 51 μm (sample 2) and 20 μm (sample 3). Rings with $2R_0 = 3$ mm were prepared also from 0.6 μm thick YBCO layers deposited on 0.1 mm thick Ni substrates via a buffer layer: ring with $2w = 300$ μm (sample 4) and 100 μm (sample 5).

The electric field-current $(E$–$I)$ curves of the rectangular sample were determined by the method described in [4], and those of the rings by a similar method described in [5]. The later one is based on the measurement of the magnetic field B produced by the current induced in the ring due to the external magnetic field B_e applied perpendicular (B_e/z) to the ring plane and varying with a constant rate dB_e/dt. The z-component of this field, B_z, was measured by a Hall probe located at distance z from the ring plane. Supposing that the ring width $2w$ is much smaller than R_0, the component B_z is given by

$$B_z(r=0,z) = \left(\frac{\mu_0 I R_0^2}{2}\right)\left[1 + \left(R_0^2 + z^2\right)^{2/3}\right] \quad (1)$$

where I is the total current induced in the ring.

The average electric field along the ring is

$$E = \left(\frac{R_0}{2}\right)\frac{dB_e}{dt}. \quad (2)$$

We measured $B_z = f(B_e)$ curves at various rates dB_e/dt and determined E–I characteristics of the YBCO filaments using (1) and (2).

We also determined the "remanent critical currents" in zero external field. We increased the external field up to 0.2 T, reduced it to 0 and measured the magnetic field due to remanent induced current approximately 1 minute after the external field was set to zero. In this mode the relaxation of the induced current was "very slow" resulting in very low electric field E along the ring.

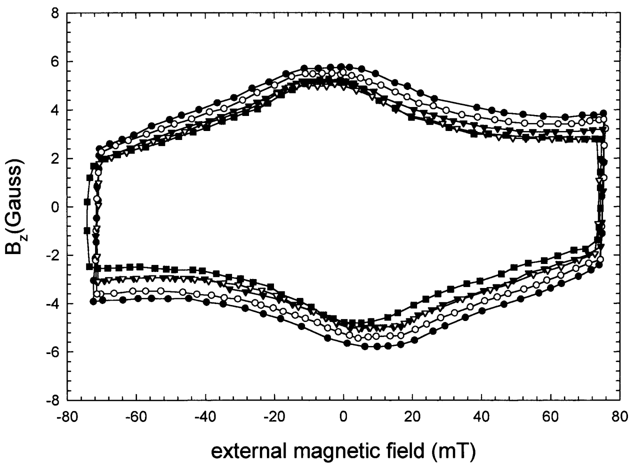

Fig. 1. Hysteresis curves $B_z(B_e)$ of sample 1 measured at $z = 0.3$ mm for various frequencies f (from the largest to the smallest curve): 100 mHz, 20 mHz, 5 mHz, 2 mHz, 1 mHz.

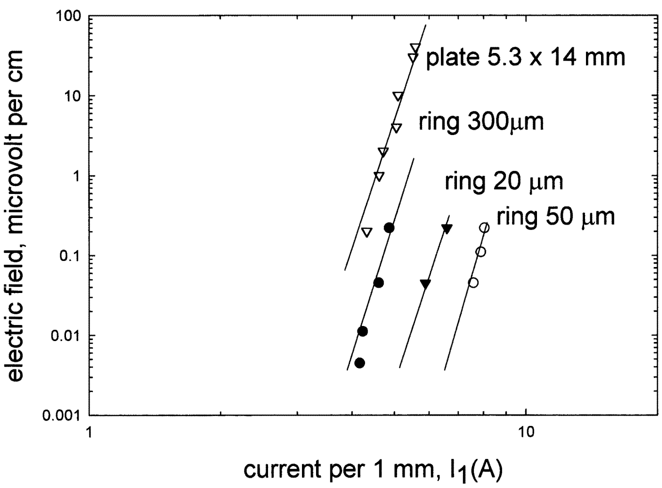

Fig. 2. E–I characteristics of samples R, 1, 2 and 3 for $B_e = 0$ determined from hysteresis $B_z(B_e)$ curves.

Hysteresis losses per one cycle of external magnetic field with amplitude B_e and rate of change dB_e/dt are proportional to the area of the hysteresis loop $B_z = f(B_e)$, since the magnetic moment of the filament per unit length, $\boldsymbol{M}_{f,1m}$, is given in [6]

$$M_{f,1m} = \left[\frac{I}{(2w)}\right] w^2 = \left(\frac{1}{2}\right) Iw \qquad (3)$$

where I is proportional to B_z, see (1). We note that the induced current I at a given field B_e increases with increasing dB_e/dt (as shown below in Fig. 1), which results in frequency dependence of the hysteresis losses.

To obtain information on the uniformity of the local critical current density along the rings we observed also the structure of magnetic flux in the rings using magneto optical imaging.

III. Results and Discussion

We measured hysteresis loops $B_z(B_e)$ of samples 1, 2 and 3 with triangular waves of the external magnetic field $0 \rightarrow 75$ mT $\rightarrow 0 \rightarrow (-75$ mT$) \rightarrow 0$ ($dB_e/dt = \text{const}$) with 4 different frequencies. As an example, we show these curves in Fig. 1 for sample 1 measured at $z = 0.3$ mm.

TABLE I
Critical Currents and Critical Current Densities of Samples in Zero External Magnetic Field at 77 K

Sample	I_{c1} (A/mm) at 0.1 μV/cm	I_{c1} (A/mm) remanent	J_c (A/cm²) at (0.1μV/cm)	J_c (A/cm²) remanent
R	4.12		1.26 x 10⁶	
1	4.7	4.0	1.43 x 10⁶	1.22 x 10⁶
2	7.8	5.4	2.38 x 10⁶	1.64 x 10⁶
3	6.2	5.0	1.89 x 10⁶	1.52 x 10⁶
4	-	7.57	-	1.26 x 10⁶

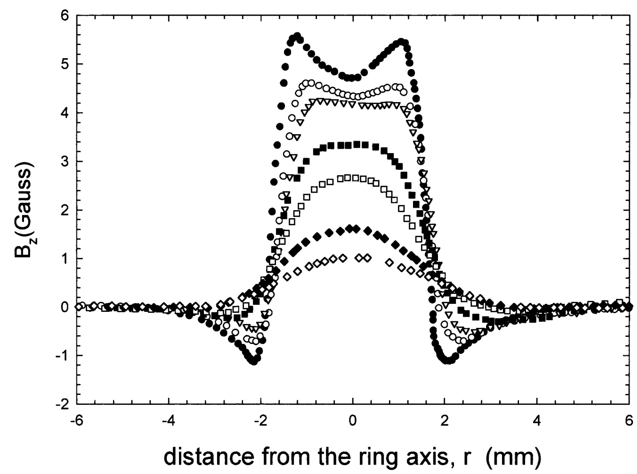

Fig. 3. Profiles $B_z(r)$ measured for sample 1 at various distances z from the ring plane (from the top to the bottom curve): $z = 0.3$ mm, 0.4 mm, 0.5 mm, 0.6 mm, 0.7 mm, 1.6 mm, 2.1 mm.

From the hysteresis loops of rings 1, 2 and 3 we determined E–I curves at $B_e = 0$. These curves are shown in Fig. 2.

For comparison we also measured the $B_z(B_e)$ curves of the reference sample R in AC sinusoidal external magnetic field with frequencies from 0.1 Hz up to 20 Hz and determined E–I curve at $B_e = 0$. We note that in this case the electric field E has its maximum value at the edges of the sample. The $E(I)$ curve obtained is also shown in Fig. 2. The straight lines in Fig. 2 are $E \sim I_1^n$ curves with $n = 18$. The critical currents per 1 mm width at 0.1 μV/cm and $B_e = 0$, I_{c1}, are listed in Table I. The ratio between the highest (sample 2) and lowest value of J_c is ~1.9. We believe that the different J_c values are mainly due to an inhomogeneous distribution of the critical current density in the original layer. This explanation is also supported by the fact that the largest sample R has the lowest J_c. In spite of data scattering in Table I, no evidence for a drastic reduction of J_c for filament width down to 20 μm was observed. It seems that some local inhomogeneities or defects revealed by MO images (shown below) are responsible for different J_c in samples 1, 2, 3 and 4.

We also measured the distribution of the remanent field B_z in the radial direction at various distances z. The critical current densities were deduced from $B_z(r = 0)$. The results for ring 1 are shown in Fig. 3 and similar families of curves were obtained for other samples.

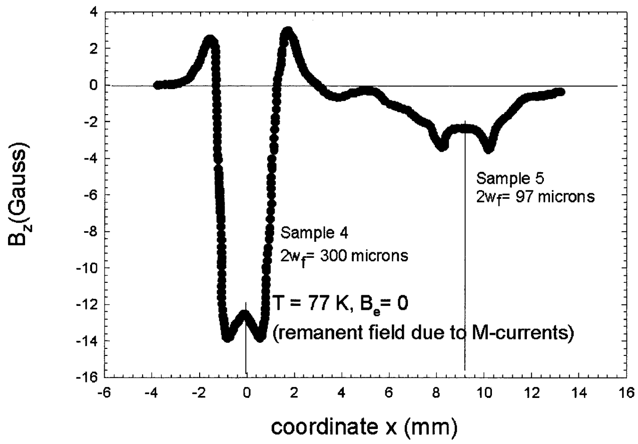

Fig. 4. Field component B_z measured at a distance of 0.4 mm from the plane on samples 4 and 5, which both are located on the 10×20 mm Ni substrate. The centers of the rings are separated by 9.1 mm.

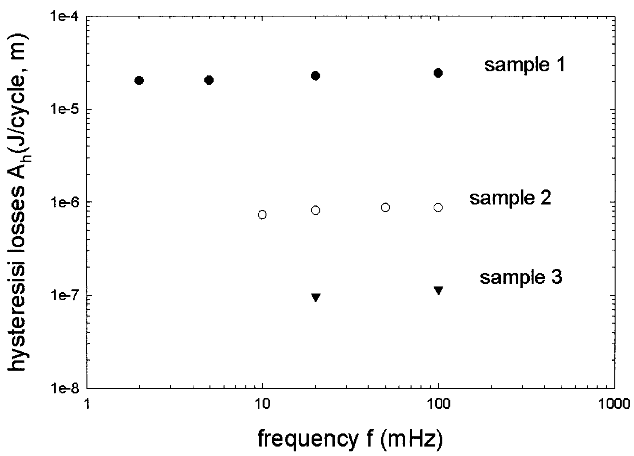

Fig. 5. Hysteresis losses of samples 1, 2 and 3 versus frequency for the field amplitude 75 mT.

The corresponding remanent critical currents I_{c1} calculated using (1) for samples 1, 2 and 3 are given in Table I. The comparison showed that the remanent currents represent 85%, 69% and 80% of the values corresponding to 0.1 μV/cm for rings 1, 2 and 3.

It is also interesting to note that the magnetization currents induced in sample R at 20 Hz are higher by a factor 1.36 than those induced at 0.1 Hz. The hysteresis losses must be also determined at the operating frequency of the AC conductor to avoid greatly underestimating them.

In Fig. 4 we present the signal B_z measured in the radial direction of sample 4 and 5 (rings with $2w = 300$ μm and 100 μm) prepared from an YBCO layer deposited on Ni substrate with dimensions 10×20 mm. As seen the signal B_z in the vicinity of sample 5 is strongly affected by the ferromagnetic Ni substrate. Due to this reason the evaluation of J_c from the experimental data was performed for the ring with the widest filament width $2w = 300$ μm only (sample 4), where the influence of Ni is assumed to be negligibly small. The values of I_{c1} and J_c for sample 4 are 7.57 A/mm and 1.26×10^6 A/cm^2, respectively.

We calculated the hysteresis losses of rings 1, 2 and 3 for triangular external field waves with the amplitude of 75 mT, measured at various frequencies up to 100 mHz The hysteresis losses per cycle and 1 m filament length are plotted in Fig. 5.

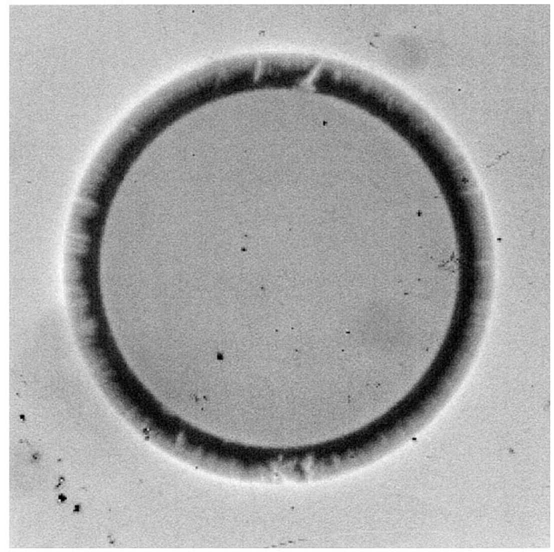

Fig. 6. MO image of sample 1 at 15 K (ZFC sample) in a field of 40 mT.

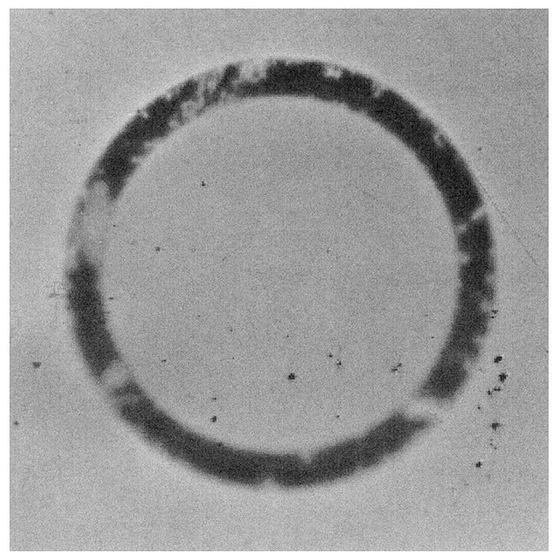

Fig. 7. MO image of sample 4 at 15 K (ZFC sample) in a field of 40 mT.

We see that at these low frequencies an observable increase of the hysteresis losses was detected.

To see the homogeneity of the flux penetration into rings we visualized the flux penetration using magneto optical (MO) imaging. In Figs. 6 and 7 we show MO images of sample 1 and 4 taken for zero field-cooled samples at 15 K in an external magnetic field of 40 mT.

As seen, sample 1 has many observable defects (white channels in Fig. 6); the two largest of them are marked by an arrow. However, as demonstrated by electrical measurements, the critical current density in the sample is still quite large.

Fig. 8 shows the surface of the nickel substrate (right half of the picture) and the surface of the deposited YBCO layer. In the original photograph we observed rectangular Ni-grains with dimensions ranging from ~5 μm up to ~8 μm, which, however, cannot be clearly seen in Fig. 8.

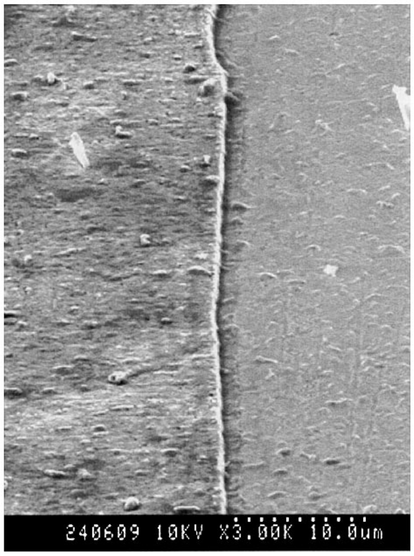

Fig. 8. SEM image of the ring 300 microns wide prepared from YBCO layer deposited on Ni substrate (sample 4).

Fig. 9. SEM image of 20 μm wide filament prepared of YBCO deposited on $LaAlO_3$ (sample 3).

SEM image of 20 microns wide filament on $LaAlO_3$ is shown in Fig. 9. The filament edges are quite uniform.

IV. Conclusions

Critical currents induced by an external magnetic field in YBCO rings with widths 300, 50 and 20 microns was measured. We believe that the variation of critical current density in filaments prepared from YBCO layers deposited on $LaAlO_3$ substrates can be ascribed to the inhomogeneity of the origin layer. No substantial reduction of the critical current density in the 20 microns wide filament was observed.

Hysteresis losses in filaments of YBCO on $LaAlO_3$ decreased with decreasing filament width and increased with increasing frequency. In the narrowest filament they were $\sim 10^{-7}$ J/m, cycle at 100 mHz and field amplitude of 75 mT.

For YBCO rings on Ni substrates we were able to measure the critical currents of the sample 300 microns wide only, as the signal from the substrate considerably affected the magnetic field in the vicinity of the narrower samples. To reduce the effect of Ni in experiments with YBCO on Ni, ring samples with smaller filament width should have the form of several concentric rings.

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