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MACROSCOPIC PERSISTENT CURRENTS IN LASER DEPOSITED $YBa_2Cu_3O_7$ FILMS

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We have investigated persistent currents in a superconducting $YBa_2Cu_3O_7$ ring of about 1 cm diameter, which was deposited as c-axis textured film on a $SrTiO_3$ substrate by laser ablation. The currents were registered, via their magnetic field distribution, with a small vibrating pick-up coil. At 77 K persistent currents with negligible decay over 10^3 s have been observed below a critical current density $j_c = 0.9 \times 10^5$ A/cm², both for a field-cooled and a zero-field-cooled sample. This demonstrates that it is possible to fabricate dissipationless devices of such films on a relatively large scale.

1. Introduction

One of the characteristic properties of a superconductor – and one of the most important when it comes to applications – is the magnitude of the critical current. In conventional superconductors, such as NbTi, critical current densities of about 10^6 A/cm² are reached at 4.2 K. In this respect, sintered pellets made of the new high-T_c materials which are are presently available are rather poor superconductors having critical current densities (j_c) typically in the range of only several hundred A/cm². For *films* of high-T_c material, however, values for j_c have been reported which are 3–4 orders of magnitude higher and are thus comparable to good conventional superconductors [1–3].

The origin of the low critical currents in sintered material is the rather weak coupling of the individual grains, generally assumed to be of the Josephson type, due to the loose packing and the arbitrary orientation of the grains. Films, on the other hand, can be prepared with the c-axis perpendicular to the substrate so that the supercurrents – supposedly flowing in the copper–oxygen planes – are not impeded so strongly. Even for these "epitactic" films, however, the problem remains that one may have some grain boundaries, especially if one considers films of large dimension. Besides, it is known that the value obtained for the critical current density is often strongly dependent upon the experimental technique applied [4,5]. The question arises, therefore, whether the high critical currents determined in a typical measurement using resistivity or AC susceptibility are truly dissipationless. It is particularly important, from the practical point of view, whether films can be prepared such that dissipationless currents are possible on a centimeter scale.

The most accurate way to determine low level dissipation is the measurement of persistent currents. This letter will report investigations of a superconducting YBaCuO-ring which demonstrates that currents with J_c of the order of 10^5 A/cm² can indeed exist at 77 K as persistent currents, that is with negligible decay on a scale of hours.

2. Experimental details

2.1. Sample preparation by laser ablation

Single phase orthorhombic material of the nominal composition $YBa_2Cu_3O_{7-x}$ with a T_c of about 92 K and transition width of less than 1 K was grinded and sintered into pellets (1 cm diameter, 2–5 mm thickness). These targets for laser ablation were glued onto a rotatable stage mounted within a vacuum chamber and irradiated during deposition through a sapphire window with a focused beam from a KrF excimer laser (248 nm, 40 ns) as shown in fig. 1. The incident beam had an angle of about 45° with respect to the target surface plane and was fired at a repetition rate of 5 Hz to a total of 100 to several thousand shots.

At a distance of about 3 cm from the pellet surface single crystalline (001)-$SrTiO_3$ substrates were mounted such that the deposited material eminated from the target in the normal direction. A platinum wire heating stage provided substrate surface temperatures as high as 850°C. This heating stage was switched off after deposition, the chamber was ventilated with O_2-gas and the sample was immediately unmounted without any slow cooling or annealing cycle. Resistance was determined by a standard four-point probe technique. More details on the resulting films are given in ref. [6].

For the persistent current measurement a film of 450 nm thickness was evaporated onto a 10×10 mm^2 substrate of (001)-$SrTiO_3$. $T_c(R=0)$ was at 88 K, a typical value for such a thick film. Then laser etching removed this film completely in all areas which were not covered by a ring mask. The resulting superconducting ring (inner and outer diameter 6.5 and 9.5 mm, respectively) was used for the further measurements.

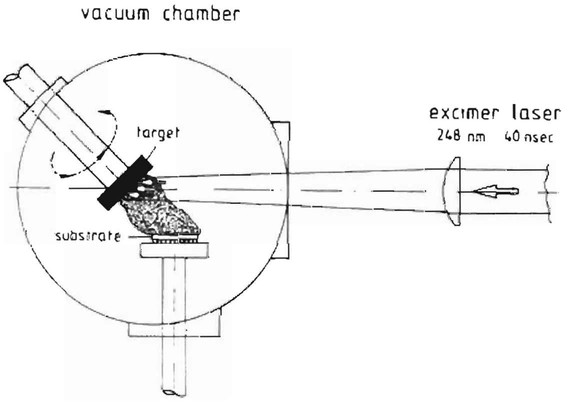

Fig. 1. Experimental setup for laser ablation.

2.2. Persistent current measurements

Persistent currents in this sample were determined via the spatial distribution of their magnetic field, as described earlier [7]. The detector was a small, rectangular pick-up coil (length $l = 10$ mm, width $w = 1.5$ mm, thickness $b = 0.8$ mm), which was vibrated by a piezoelectric bimorph in such a mode that mainly the end, A, facing the sample was in motion and the opposite side was nearly at rest (see fig. 2). In this way the coil acts as a *local* detector, registering essentially only the magnetic field perpendicular to the sample plane at position A.

The resolution of this device is demonstrated in fig. 3. The magnetic field, in this case, was generated by a flat circular coil with an inner and outer diameter of 6.5 and 10 mm, respectively, similar to the dimensions of the superconducting film sample. The probe was scanned across the plane of the coil at a distance of 0.3 mm. The pick-up signal thus obtained agrees well with the expected field distribution. (The structure is not as smeared compared to the results in ref. [7] because the reduced size im-

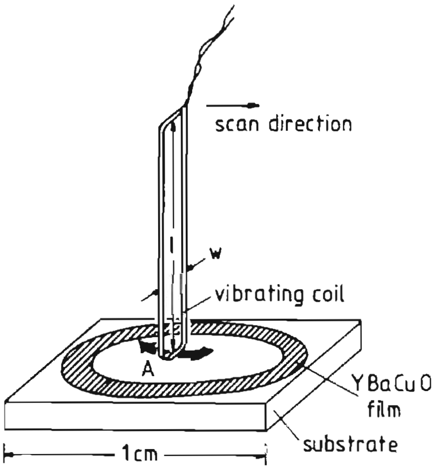

Fig. 2. Sketch of the sample with the vibrating coil geometry.

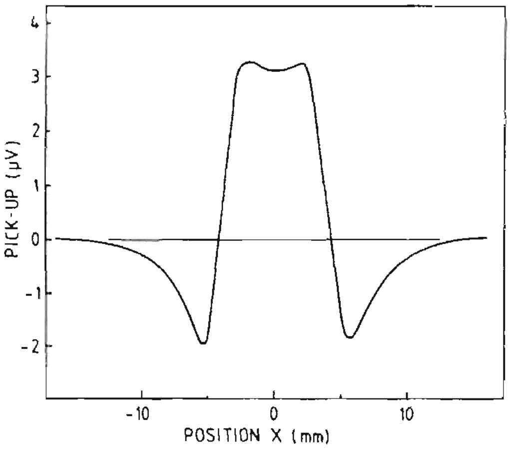

Fig. 3. Pick-up signal of the vibrating detector, proportional to the local magnetic field $B(x)$, for a flat calibration coil. The coil consisted of 4 full turns of a copper wire which carried a current of 150 mA. The inner and outer diameter was 6.5 and 10 mm, respectively.

proves the resolution of the present detector.) Since the magnetic field in the center of a ring current I is given by:

$$B=4\pi\times10^{-7}I/2r \qquad (1)$$

this measurement also serves to calibrate the sensitivity of the probe.

A crucial criterium for the overall quality of a superconducting film is whether the persistent currents truly do follow a closed path around the ring or whether they are localized to certain portions of the film. The spatial distribution of the magnetic field of a ring-shaped sample allows one to distinguish, unequivocally, between these possibilities:

i) For a ring current, a field distribution such as the one in fig. 3 is expected.
ii) Conversely, if the ring current is suppressed by imperfections or by a scratch, so that the magnetic field is due only to flux trapped within the ring material itself, the field in the center has, then, the opposite sign and is much weaker than directly above the superconducting film [7].

3. Results and discussion

Critical currents have been studied at 77 K under three different conditions:

A) The current in a field cooled (fc) sample, which is induced as the external field B_{ext} is removed.
B) The shielding current induced in a zero field cooled (zfc) sample when an external field is applied at 77 K.
C) The current in a zfc sample at $B_{\text{ext}}=0$ which arises from the flux trapped in the ring after it had been exposed briefly to an external field exceeding a critical value B_{crit}.

The direction of the external field was always perpendicular to the plane of the film.

Case A. For an *fc sample* in zero field, results are displayed in figs. 4 and 5. In the sample shown in fig.

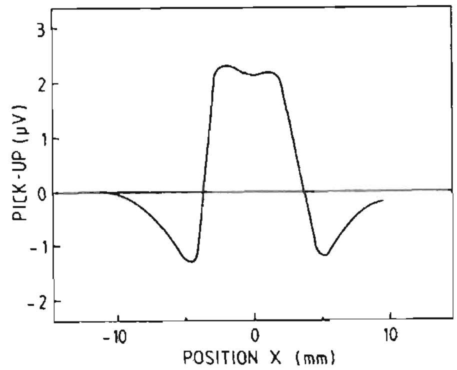

Fig. 4. Magnetic field distribution of a field-cooled sample. The field during cool-down was 1.08 G.

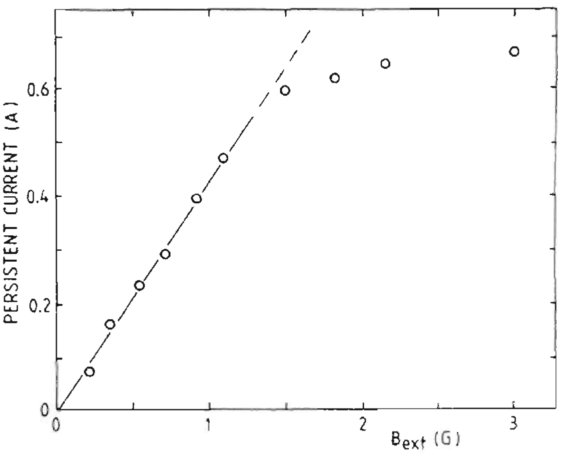

Fig. 5. The persistent current, $I_{\text{ring,fc}}$, in the superconducting ring at $T=77$ K and zero external field, plotted as a function of the external field B_{ext} during cool-down.

4 the film was cooled in a field $B_{ext}=1.08$ G, which was reduced to zero after reaching a temperature of 77 K. (The earth's magnetic field was compensated by a pair of Helmholtz coils.) The resulting field $B(x)$ closely resembles the distribution in fig. 3, which clearly demonstrates that here the magnetic field originates from a current $I_{ring,fc}$ which encloses the whole ring area. Using eq. (1) the ring value of $I_{ring,fc}$ can be calculated, yielding 0.46 A in this case. A slight inhomogeneity of the film properties can be inferred from the asymmetry of the field distribution.

In order to determine the *critical* current I_{crit} we measured the dependence of $I_{ring,fc}$ on the external field applied during the cool-down. As expected, the induced ring current varies proportionally to B_{ext} for fields below a critical value (see fig. 5). For higher fields, $I_{ring,fc}$ saturates at 0.65 A, which we identify as the critical current in this sample. Under the assumption that the current is distributed uniformly over the cross section of the film (1.5 mm×450 nm) this yields a critical current density $j_c=0.9\times10^5$ A/cm^2.

From measurements on polycrystalline samples, single crystals and films it is known [4,8–10] that flux creep gives rise to a pronounced time dependence of the sample magnetization. Flux creep would also imply a decay of the ring current. We have therefore studied the change of I_{ring} with time. A slight drop by a few percent was observed for the highest currents $I\sim I_c$ during the first few seconds after B_{ext} was switched off, but subsequently no significantly decay was found over a period of 1 h. Hence the ring current in these films may truly be considered "persistent". (A more detailed investigation of the flux creep in these films will be the subject of a separate paper.)

Case B. When an external field is applied to a *zfc sample*, a current is induced which partly shields the region enclosed by the ring. An example of the resulting field is given in fig. 6a for a field $B_{ext}=3.2$ G, which is distinctly larger than the field, 1.1 G, which can be sustained by the critical current in our sample geometry. Consequently, flux partially penetrates the superconductor and enters the ring area. Also in this case, however, one can conclude from the field distribution that a ring current I_{shield} flows. The direction of this shielding current is the opposite of $I_{ring,fc}$ shown in fig. 4. Again, I_{shield} does not decrease noticeably over one hour. The persistent currents, therefore, are not affected by the presence of the external magnetic field investigated here ($\leqslant 50$ G, a limit given by the detector's decreasing signal to noise ratio with increasing field).

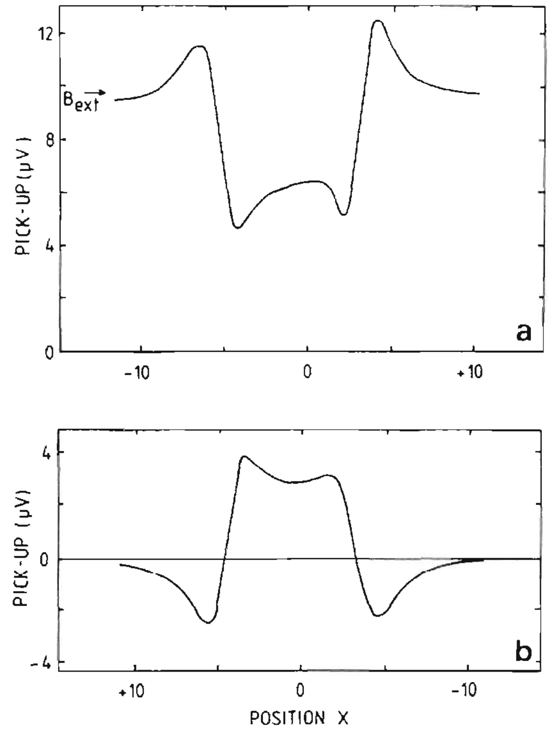

Fig. 6. (a) Magnetic field distribution of a zfc ring after applying an external field 3.16 G. The field is reduced in the ring center due to the shielding currents. (b) After the external field is switched off, the field distribution displays trapping of magnetic flux which results from persistent ring currents flowing in the direction opposite to the shielding current in fig. 6a.

The variation of the shielding current with respect to the external field, applied at 77 K, is plotted in fig. 7a. Similar to the persistent current in the fc sample (fig. 5) one observes a linear relation between I_{shield} and B_{ext} in small fields, and saturation at essentially the same critical current as for the fc sample.

Case C. After removing the external field from the zfc sample, a certain fraction of the applied flux remains trapped in the ring provided B_{ext} has exceeded the critical value, in our case 1.3 G. As an example, fig. 6b shows the field distribution after the sample

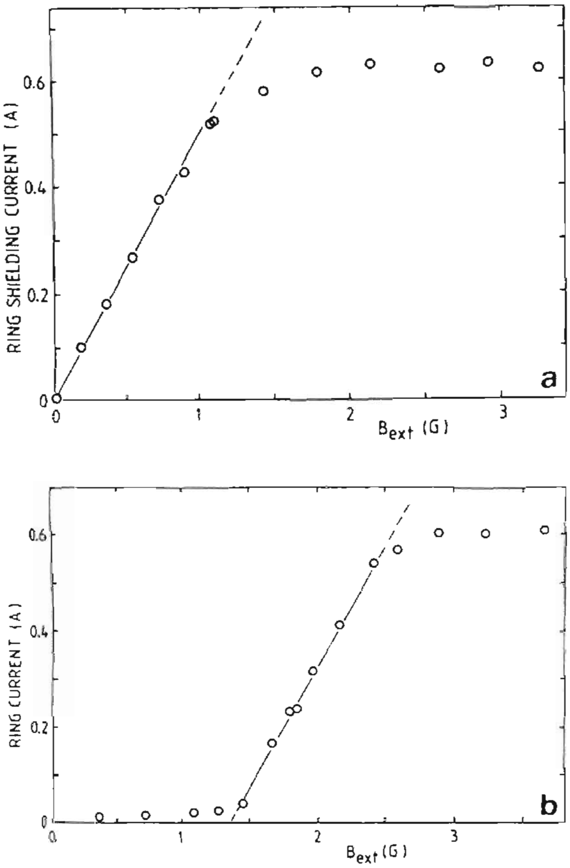

Fig. 7. (a) The shielding current I_{shield} in a zfc ring at 77 K as a function of the applied external field. (b) The ring current $I_{\text{ring,zfc}}$ at 77 K and zero external field, plotted vs. the field B_{ext} to which the sample had been exposed before taking the datum point.

had been exposed to $B_{\text{ext}} = 3.2$ G. It closely resembles the situation for fc samples, which again is indicative of a persistent current, $I_{\text{ring,zfc}}$, trapped in the ring. The magnitude of the critical field for flux penetration directly follows from fig. 7b. Whereas at low fields the current and hence the flux trapped in the ring is close to zero, a steep linear increase is observed beyond $B_{\text{crit}} = 1.3$ G. Note that the slope in this linear region is the same as that for I_{shield} in fig. 7a and also close to the slope of $I_{\text{ring,fc}}$ in fig. 5. As before the persistent ring current saturates at about 0.65 A. This implies usual hysteretic behavior: That part of the flux which cannot be shielded by the ring current on increasing the field penetrates into the ring centre, and remains trapped as the field is reduced again (as long as the ring current necessary to produce this trapped flux does not exceed the critical current).

It appears worth mentioning that the values obtained for the critical current density in a series of measurements were essentially constant over the three week period of the experiments. During this time the sample was exposed to numerous temperature quenches by direct immersion into liquid nitrogen, and to moisture condensing on the film when it was warmed up. This is the more remarkable since the critical current should be very sensitive to surface corrosion because of the small sample thickness. Moreover, the thermal cycling apparently does not develop cracks in the film because these, as indicated above, would suppress the ring current completely.

In summary we have shown that persistent currents exist in textured YBaCuO-films at 77 K under three different conditions for field-cooled and zero-field-cooled samples. The value obtained for the critical current density j_c is 0.9×10^5 A/cm^2 for all cases. It does not depend on the presence of an external magnetic field of about 50 G. This is in contrast to polycrystalline samples where a field of some 10 G is known to destroy the superconducting contacts between the grains. Our results suggest that the fabrication of devices which rely on dissipationless current transport should be possible with these laser-deposited films even on relatively large scales in the range of centimeters.

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