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MAGNETIC-FIELD-INDUCED DAMAGE IN A SUPERCONDUCTING $YBa_2Cu_3O_{7-x}$ FILM

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ABSTRACT

During investigations of the magnetic flux dynamics in thin superconducting $YBa_2Cu_3O_{7-x}$ films we have observed the spontaneous formation of a damage in the film, apparently induced by the applied magnetic field of 0.1T. The damage developed within less than 40 ms (the time resolution of the experiment) and showed up in the magnetooptically recorded image of the flux above the sample as a path for massive flux penetration. A subsequent analysis revealed a 1μm wide gap in the $YBa_2Cu_3O_{7-x}$ film which had developed over a major portion of the $1 \cdot 1 cm^2$ sample. It is suggested that the film locally melted as a result of an instability of the superconductor in the critical state.

INTRODUCTION

One of the central aspects of thin epitaxial HTSC films is their ability to carry very high current densities, so far exceeding all the other forms of HTSC. Closely related is the behavior of these films in high magnetic fields. As a magnetic field is applied, macroscopic shielding currents are induced which increase up to the critical current density. Beyond that field strength flux will enter the sample giving rise to field distributions which in principle are often similar to those predicted by the Bean critical state model, modified by the fact that the demagnetization factor for the film geometry (with an external field perpendicular to the plane of the film) is very close to 1 [1].

One could imagine that for the film being in the critical state a quench process could take place due to some sudden local dissipation, like for the quench of a superconducting magnet, transforming part of the magnetic energy into heat. Such an event may be the origin for the observation that under certain conditions thin HTSC films were destroyed after exposing them to a magnetic field in the 100mT range [2]. In this letter we present results which show such a quench process in situ for a quadratic $YBa_2Cu_3O_{7-x}$ film ($1\cdot 1cm^2$) immersed in superfluid ^4He. Using a magnetooptic technique we recorded the sudden penetration of magnetic flux as part of the shielding currents were interrupted by a narrow gap in the film, which developed spontaneously on a timescale of less than 40ms. Microscopic investigations after the measurement showed that this magnetic field-induced damage extended across nearly half of the sample at a width of about 1μm.

EXPERIMENT

The thin epitaxial $YBa_2Cu_3O_{7-x}$ film (thickness d=150nm, specific resistance at 100K ρ=70μΩcm) investigated here was thermally evaporated onto $1\cdot 1cm^2$ MgO substrate. A description of the preparation process can be found in [3]. The transition temperature of the film was 88K, and the critical current density j_c was approximately $2\cdot 10^6 A/cm^2$.

The magnetic flux distribution was investigated with a magnetooptic technique [4]. The light intensity distribution of the resulting images as in Fig.1 is a measure for the field distribution, where bright and dark areas correspond to high and low magnetic fields, respectively. The images are recorded continuously with a video system allowing to reconstruct and analyze not only slowly varying field patterns, but also spontaneous changes in the flux distribution. Up to now the time resolution is mainly limited by the camera to about 40ms. The spatial resolution of the experiment is approximately 50μm. The measurements were carried out with the sample being immersed in superfluid helium at a temperature of 2K.

RESULTS

The penetration of the magnetic flux in thin $YBa_2Cu_3O_{7-x}$ films perpendicular to the external field has already been the topic of an earlier paper [4]. For our square samples the field is found to penetrate preferentially from the middle of the edges as shown in Fig.1, for an external field B_{ext}=30mT. Since the pinning forces vary on a local scale, the resulting field distribution is not completely symmetric and smooth, but displays structures in the sub-millimeter range. In contrast to the phenomenon to be discussed below, however, the formation of these structures does not lead to an irreversible damage of the superconducting film.

According to our experiments the formation of the structures, i.e. the arrangement of the flux distribution, typically follows changes of the external field within less than a second, with only minor effects on a longer time scale due to flux creep. As an example, Fig.2a shows the same film as in Fig.1, with B_{ext} now being increased to 100mT. The picture corresponds to a quasi static situation 1 min after B_{ext} had reached its final value, but the pattern is practically indistinguishable from those of the preceding 60 sec.

Then, however, within one video frame (40ms) a dramatic change occurred, as displayed in Fig.2b: Superimposed on the original field distribution is now a filigree "snow flake" structure, which also extends into formerly dark regions of the film, where shielding was large. The structure essentially develops within a time t<40ms, which we have checked by comparison with the following frames, apart perhaps from some of the outer branches. After this event the pattern was stable again for more than 10min. It should be pointed out that the underlying field distribution, which was already present before this momentary event, hardly changed during the whole process. This is already suggested by a direct comparison of Figs.2a and 2b, and is more quantitatively illustrated by Fig.2c which displays the intensity distribution obtained by subtracting Fig.2a from 2b using an image processing system.

We ascribe the formation of the snow flake structure to an instability of the current-carrying superconducting state, if due to some fluctuation, e.g. the depinning of a flux bundle, dissipation starts at one point of the film, leading to a local temperature increase above T_c. Ohmic losses of the shielding currents can then lead to an expansion of the dissipative region. We suggest that depending on the experimental details this expansion can be very rapid, and branching can appear similar to other instabilities, like dendritic growth. Details of this model will be published in a separate paper. Here we concentrate in the following on an irreversible change of the film during this process, namely a local destruction of the $YBa_2Cu_3O_{7-x}$ material. The region where the damage of the film took place is visible in Fig. 2b as a bright stripe extending in the left half of the picture marked by the arrow. That one is really dealing with an irreversible change becomes apparent from Figs.3a and b, obtained after cycling the whole sample above T_c. Although the gross features of the flux pattern are similar to those of

Figs.1 and 2a (in comparable external fields), penetration of the flux along the damage is obvious.

Inspection of the film after warming up to room temperature showed that a gap about 3mm long and 1μm wide had developed in the film, which coincided with the trace of flux penetration in Fig.3. The cross section of the gap was determined by electron microscopy (Fig.4) and by a scanning near field acoustic microscope [5] (Fig.5). The profile obtained by the latter reveals that most of the $YBa_2Cu_3O_{7-x}$ material was removed during the process of the gap formation. Obviously part of it was deposited along both rims of the gap. From the electron microscope picture we infer that the deposited material is insulating, because that part of the picture becomes blurred (due to local charging of the surface), whereas the rest remains sharp. These results suggest that, although our sample was immersed in superfluid helium, a sufficient amount of heat developed that the film temperature locally not only increased up to T_c, but became even one order of magnitude higher. Consequently the $YBa_2Cu_3O_{7-x}$ material melted and partly evaporated so that material was removed (leading to the gap) or changed in stochiometry (along the rims of the gap).

A simple estimate shows that the energy stored in the sample due to the shielding currents is about 10^{-5}J, which is comparable with the energy necessary to evaporate the $YBa_2Cu_3O_{7-x}$ film along the gap ($450\mu m^3$). Hence most of the stored energy is necessary to generate the damage, so that, as observed in Fig.2c, a major part of the redestribution of flux must decrease the flux gradients and thus the shielding currents. It should be mentioned that the heat carried away by the superfluid He is limited by film boiling for the process suggested here and is negligible on a time scale of 40ms.

Details of the dynamics of the damage formation are presently under investigation. From the shape of branches which are found at some points of the gap one might conclude that the damage developed from the center towards the edge of the sample. This will be studied more accurately by generating deliberately a non-superconducting spot on a virgin $YBa_2Cu_3O_{7-x}$ film, e.g. by irradiation with a focussed laser beam, and following the development using a high speed camera.

In summary, we have shown that spontaneous destruction of a superconducting film can occur when the film is exposed to a magnetic field in the 100 mT range. The damage is ascribed to an instability of the superconductor in the critical state. In addition, the results also demonstrate that the magnetooptic technique is a well-suited method for testing the quality of superconducting films. It appears interesting to note that the event observed here will be the more likely the higher the critical current density of a film, because the stored energy is directly proportional to the square of the shielding currents.

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FIGURE CAPTIONS

Fig.1: Magnetic flux distribution for an epitaxial $YBa_2Cu_3O_{7-x}$ film on a 1·1cm^2 MgO substrate in an external field B_{ext}=30mT (after zero field cooling to T=2K). Bright areas correspond to high field. The contour of the sample is outlined by the expelled flux along the edges. Most of the sample is still in the Meissner state, and therefore the central part appears dark.

Fig.2: Flux distribution for the same sample as in Fig.1 with B_{ext}=100mT after zero field cooling. a) About 1 minute after the external field reached its final value. b) Sudden appearance of additional flux, mainly in the central part, which was best shielded in a). c) Flux distribution after subtracting the intensity distribution of Fig.2a and 2b by image processing.

Fig.3: Flux distribution for B_{ext}=20mT (Fig.3a) and B_{ext}=100mT (Fig.3b) for the same sample as in Fig.2 after heating the supercondutor above T_c and zero field cooling back to T=2K. The flux enters preferentially through the gap near the middle of the edge on the left side.

Fig.4: Electron microscope image of the $YBa_2Cu_3O_{7-x}$ film showing a small fraction of the gap which had developed during the spontaneous change of the flux distribution depicted in Fig.2. In total the gap is about 3mm long and 1µm wide.

Fig.5: Height profile of the $YBa_2Cu_3O_{7-x}$ film in the vicinity of the gap, detected with a scanning near field accoustic

microscope. The surface of the undamaged film is the zero level of the height scale. Obviously there is material deposited along the rim of the gap, and in the middle of the gap the $YBa_2Cu_3O_{7-x}$ film (thickness d=150nm) is removed.

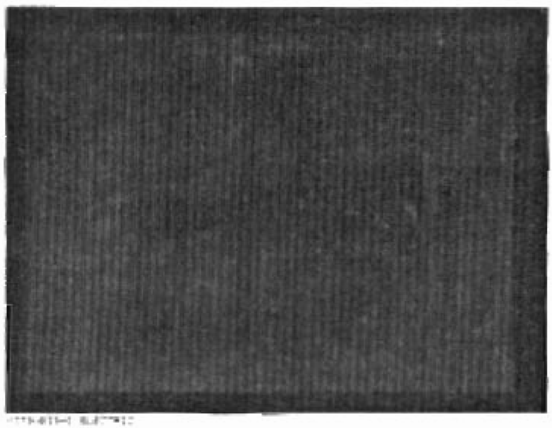

Fig 1

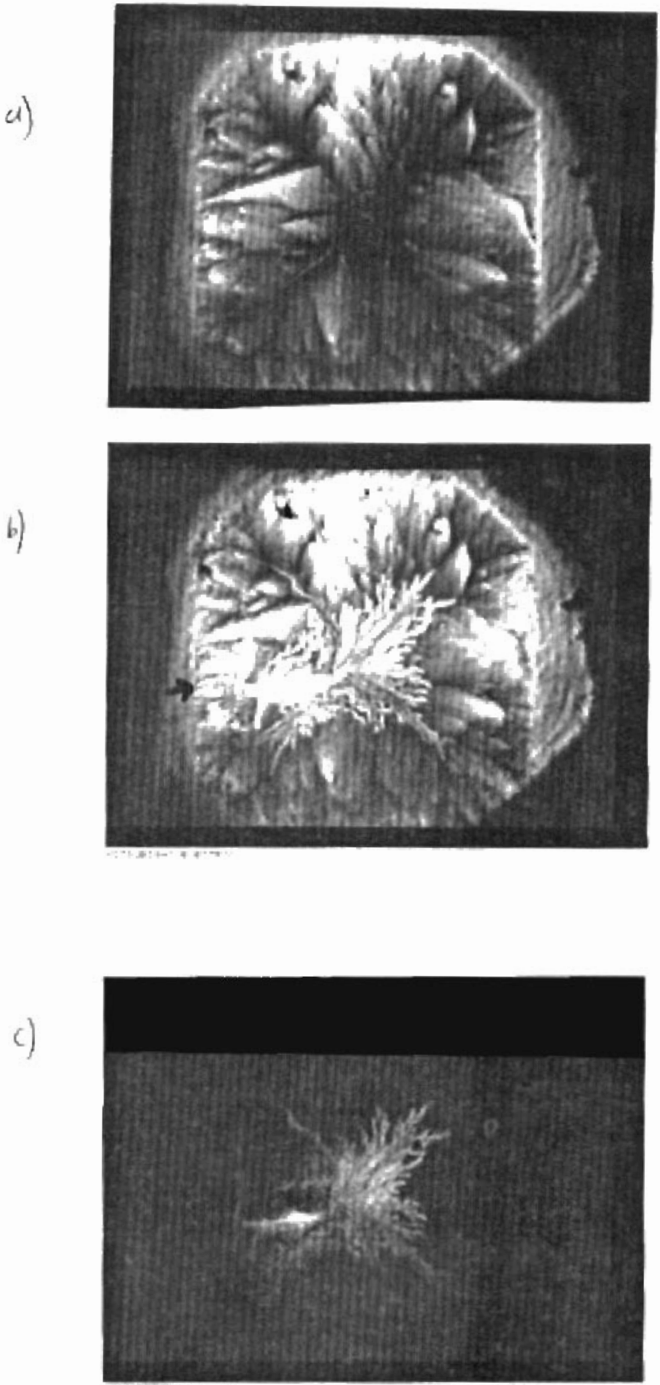

Fig 2

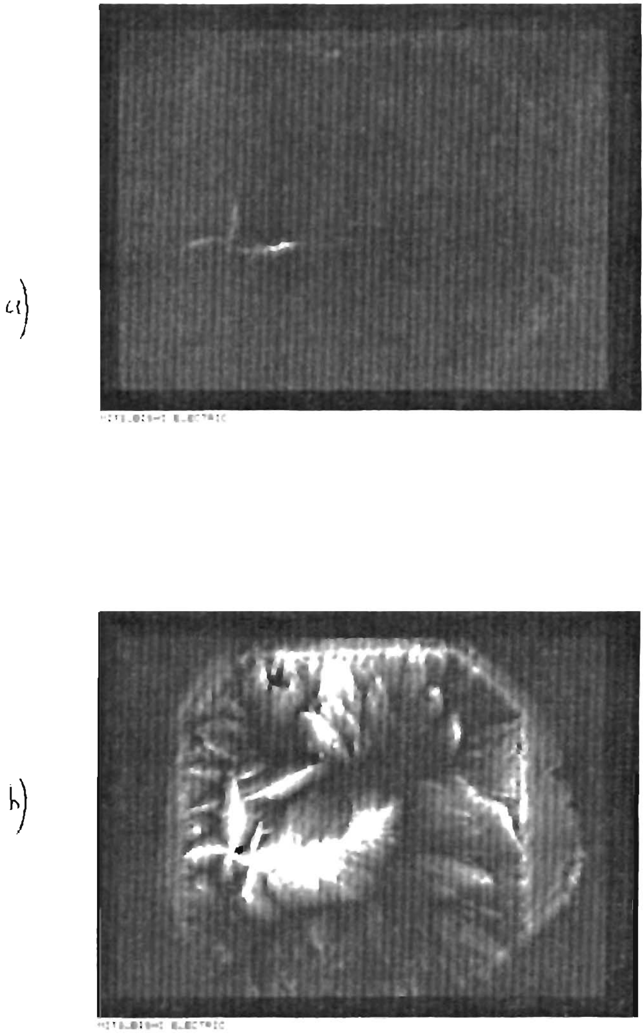

Fig 3

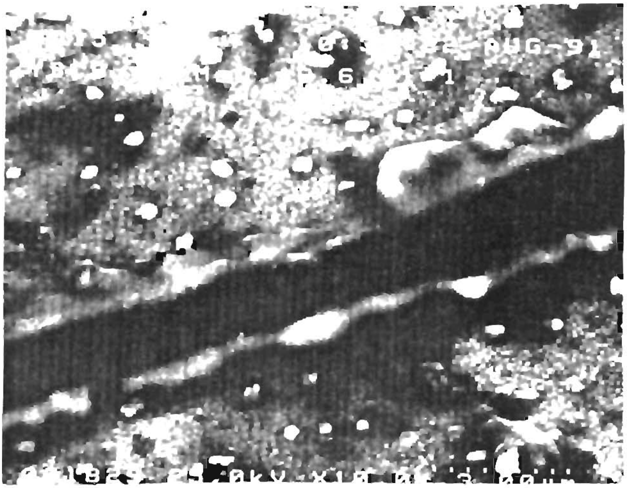

Fig 4

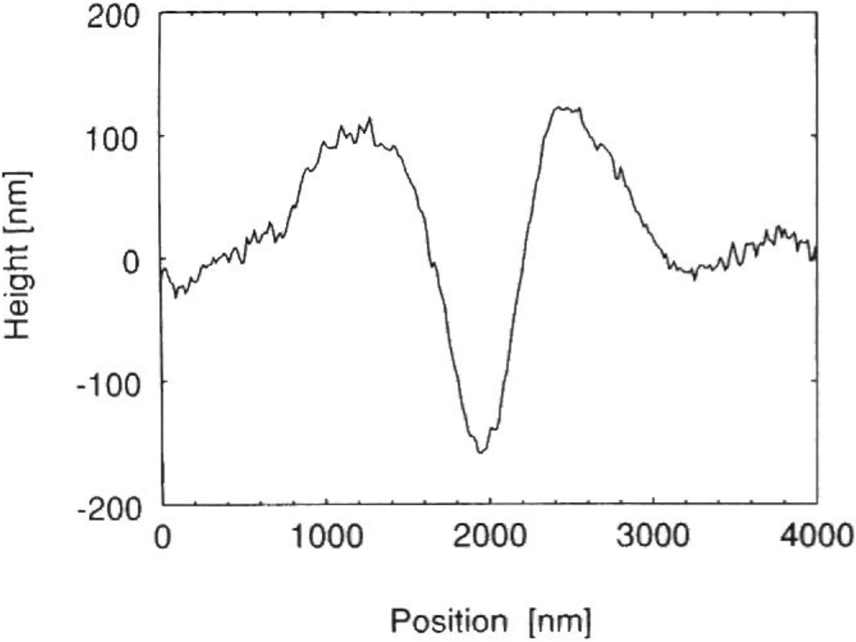

Fig5