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Ultrafast Magneto-Optical Study of Flux Avalanches in High-T_c Superconductors

Bernd-Uwe Runge, Uwe Bolz, Johannes Eisenmenger, and Paul Leiderer
Universität Konstanz, Fachbereich Physik, D-78457 Konstanz, Germany

An ultrafast magneto-optic pump-probe technique has been used to trigger and image a flux instability in high-temperature superconducting thin films. Snapshots of the dendritic flux avalanche spreading into the film could be obtained with a time resolution in the picosecond range.

1. INTRODUCTION

The dynamics of magnetic flux avalanches in high-temperature superconductors (HTSC) is of great interest not only from a fundamental point of view, but also with respect to the application of these materials e.g. as current limiters in the field of electrical power distribution. Previous studies [1] have shown that much of the flux dynamics in $YBa_2Cu_3O_{7-\delta}$ takes place well below the nanosecond range. Therefore it is necessary to improve the time resolution into the picosecond regime to get more detailed information about the processes involved.

2. EXPERIMENTAL

All samples studied were 330 nm thick epitaxially grown c-axis oriented $YBa_2Cu_3O_{7-\delta}$ films deposited by thermal evaporation onto $SrTiO_3$ [2]. The experiments were carried out in a small continuous flow cryostat, which had two optical windows with a diameter of 25 mm. For detecting the magnetic field penetrating the superconductor we used a doped ferrimagnetic iron garnet layer grown onto gadolinium-gallium-garnet substrate by liquid phase epitaxy with an additional aluminum layer [3]. Iron garnet films allow very fast magneto-optic imaging with response times in the picosecond range [4]. This magneto-optical layer was placed just above the YBCO film. By using a home-built polarization microscope the local Faraday rotation of the linearly polarized light caused by the local magnetic field H_z in the magneto-optical layer was made visible with nearly crossed polarizer and analyzer as an intensity contrast and imaged with a 12 bit slow-scan CCD camera.

The YBCO film was zero field cooled down to 10 K. After reaching a stable temperature an external magnetic field B_{ext} perpendicular to the sample surface was applied. Magnetic flux penetrated into the superconducting film first from the edges until a local equilibrium of the flux distribution due to the pinning force and the magnetic force was reached. This induces a current distribution in the superconducting film. That current distribution can be disturbed to initiate a magnetic instability. For this purpose we used a single pulse of a Ti:sapphire laser ($\lambda = 800$ nm, half width $\tau = 150$ fs) which was focused onto the film from the substrate side to a spot diameter of about 50 μm. The sample temperature in the focus could not be measured directly, but from the pulse energy we estimate that the temperature rises well above the critical temperature.

If the perturbation is sufficiently strong, this triggers a magnetic instability, in which a magnetic flux avalanche penetrates into the film. In order to record snapshots of the flux moving into the sample a beam splitter is used to separate part of the trigger pulse and send it through a delay line for illumination of the sample at a well defined time after the trigger event. This time can be varied from below zero (illumination before trigger) to several 100 ns with an accuracy in the picosecond range.

3. RESULTS

Fig. 1 shows typical snapshots at delay times of 3.2 ns, 13.5 ns and 41.2 ns for a sample tem-

Figure 1. Snapshots of the flux penetration at delay times of 3.2 ns, 13.5 ns and 41.2 ns after the trigger event. Sample temperature $T = 10\,K$, external magnetic flux density $B_{ext} = 19\,mT$. The size of the images shown is $1.8 \times 1.8\,mm^2$.

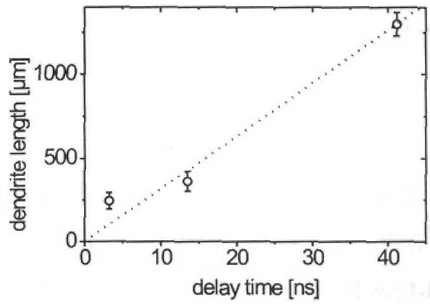

Figure 2. Length of a typical dendrite close to the center of the dendritic flux structure plotted as a function of time after the trigger event. The dotted line is a guide to the eye.

perature of $T = 10\,K$ and an external magnetic flux density of $B_{ext} = 19\,mT$. In order to have reproducible starting conditions, for each image the sample was heated above the critical temperature and zero field cooled again to 10 K. The form of the dendritic structure is found to be similar from image to image and for all delay times used, although the individual dendrites are not identical for subsequent laser pulses. The width of the dendrites and their mutual distance remains about constant during the process. A "typical spreading velocity" of the dendrites was calculated measuring the distance between the starting point of the avalanche (i.e. the laser focus) and the tip of a typical dendrite in the center of the avalanche. The average of this velocity over the first 41.2 ns is found to be $3.2(2) \times 10^4\,m/s$ which is far above the velocity of sound in YBCO, therefore excluding heat diffusion as explanation for the observed dynamics. In Fig. 2 we show the time dependence of the length of a typical dendrite.

4. CONCLUSIONS

We have improved the time resolution for the magneto-optical observation of magnetic flux avalanches in high-T_c superconductor thin films from nanoseconds to picoseconds by using laser pulses with a half width of less than one picosecond. This allows a much more precise determination of the spreading velocity of the dendrites. We find $3.2(2) \times 10^4\,m/s$. This value is slightly lower than the value of $5(2) \times 10^4\,m/s$ reported in an earlier study [1] which is probably due to differences in the sample preparation. The increased time resolution will allow us to study the very beginning of the flux avalanche and other phenomena caused by perturbation of superconducting films.

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