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Measurement of local currents in superconductors using an in-situ high field magneto-optical microscope

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A contactless method is used to measure the local current density in superconductors at fields up to 7 T with a spatial resolution better than 1 μm. The local currents are derived from magneto-optical images using a powerful inversion scheme. Various illustrative applications are discussed.

1. INTRODUCTION

The interpretation of global experimental data on flux flow, flux creep and relaxation phenomena is hindered if the magnetic moment of the sample as a whole is measured, while the current flow in the sample is not uniform. This problem can be overcome by the local measurement of the currents flowing in the sample that is discussed below.

2. EXPERIMENTAL TECHNIQUE AND DATA ANALYSIS

Just above the sample under investigation a 100 nm thick aluminum mirror and then a layer with a large Faraday effect is placed. The local magnetic field H_z is visualized as an intensity contrast by placing the sample assembly under a home built polarization microscope which is in the variable temperature insert of a 7 Tesla magnet system. The spatial resolution is 0.5 μm. From the intensity image the local magnetic field $H_z(x,y)$ is calculated. If the current flow in the sample is 2-dimensional [1], then the current density $\vec{j}(x,y)$ may be obtained from $H_z(x,y)$ by a powerful inversion scheme [1]. Consequently all components of the magnetic field can be calculated. In addition, from the time-dependence of $H_z(x,y)$ the electrical field as a function of position in the sample can be found.

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3. RESULTS AND DISCUSSION

We give here several examples of the application of our new method.

3.1. First Penetration field

The first penetration field H_p *as a function of position* along the edge of the sample is measured magneto-optically as follows. The sample is cooled in zero field; at the measurement temperature the external field is raised to a value $H_{\max}$ and reduced to zero again. If $H_{\max} < H_p$ the process is reversible and no flux remains in the sample. However, if $H_{\max} > H_p$ some flux is trapped in the sample and is easily detected

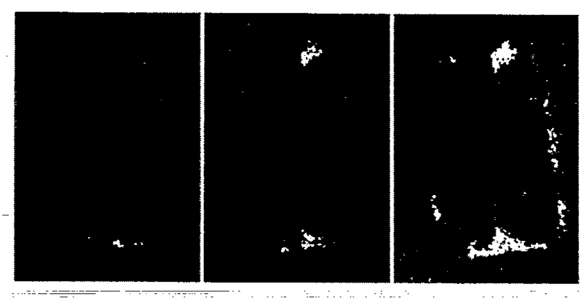

Figure 1. Magneto-optical images of a $Bi_2Sr_2CaCu_2O_8$ single crystal at zero field after field excursions to the indicated maximum field $H_{\max}$. In bright areas the penetration field H_p is lower than $H_{\max}$.

magneto-optically as illustrated in Fig.1 for a $Bi_2Sr_2CaCu_2O_8$ single crystal of $1.13 \times 0.67 \times 0.025$ mm^3. Clearly H_p is not uniform although this sample is one of the best presently available. In our determination of H_p we avoid the averaging over the sample done in bulk magnetometry.

3.2. Influence of twin planes on current flow in $YBa_2Cu_3O_7$

Our investigation [2] of the influence of twin planes in $YBa_2Cu_3O_7$ on flux penetration and current flow at 2 K reveals (i) that the current density across a twin plane is about half of the current density elsewhere and (ii) that current subloops arise; see Fig.2, which shows the absolute value of the current as a grey tone for a $YBa_2Cu_3O_7$ crystal of $0.7 \times 0.4 \times 0.025$ mm^3 with two twin planes only. Due to the current subloops one cannot calculate the currents from the bulk magnetization: knowledge of the entire flow pattern as obtained by our method is essential.

3.3. Relaxation in $Bi_2Sr_2CaCu_2O_8$

Due to quantum tunneling of vortices significant relaxation takes place in $Bi_2Sr_2CaCu_2O_8$ even at low temperatures. The same crystal as discussed above is cooled in zero field; after reaching a stable temperature of 2 K the external field is swept at 40 mT/s to 2 T, then kept constant. The time $t = 0$ is defined as the moment when 2 T is reached. Figure 3 shows selected intensity images over a time span of 600 s. Significant flux penetration due to quantum creep (observed here in a very visual way) is found.

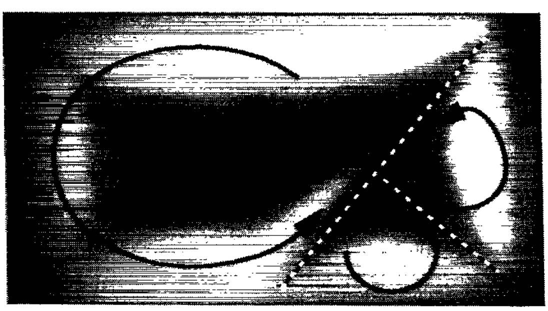

Figure 2. Absolute value of screening current flowing in a $YBa_2Cu_3O_7$ single crystal with two twin planes (dashed lines) at 240 mT and 2 K. Bright indicates high current, dark low current. Current subloops are indicated schematically by black curves.

3.4. Flux penetration in thin film samples

In isotropic films flux penetrates in a fractal manner. However, we found recently that in anisotropic (a,b)-oriented $YBa_2Cu_3O_7$ films [3] and in anisotropic vicinal $Tl_2Ba_2CuO_6$ films [4] a smooth flux front is observed. Further experiments exploring the crossover between the fractal and non-fractal regime as a function of anisotropy may elucidate the reason for fractal flux penetration in thin films.

4. CONCLUSION

A new in-situ magneto-optical set-up working up to 7 Tesla with a spatial resolution of 0.5 μm and a powerful inversion scheme enable the measurement of local currents in flat superconductors. Application of this technique to the study of single crystals and thin films is very fruitful.

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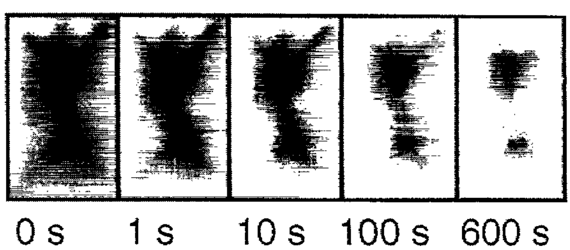

Figure 3. Quantum creep as seen in raw magneto-optical intensity images: flux penetration in $Bi_2Sr_2CaCu_2O_8$ as a function of time after the application of an external field of 2 T at 2 K. Bright areas correspond to high flux density and black areas to zero flux density.