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Flux visualization in high-T_c superconductors using a high-resolution magneto-optical microscope

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We report on the first observations of magnetic flux structures in high-T_c superconductors using a newly designed low temperature polarization microscope. Magnetic flux in the superconductor is visualized by detecting the rotation of the polarization vector of light (Faraday effect) within a magneto-optically active EuSe layer which is evaporated onto the surface of the sample. The low temperature microscope as a whole is built as an insert into a commercial cryostat equipped with a superconducting coil, enabling us to achieve magnetic fields up to 7 T. The optical system (lenses, polarizers and translation table) is cooled together with the sample in order to minimize the distance between the sample and the objective. Key properties are a large numerical aperture, a high extinction ratio of the polarizers and a high sensitivity of the image-intensified camera system. This should allow in the near future the visualization of *individual* vortices using the Faraday effect in transmission in low magnetic fields.

There is a great interest to obtain information on the magnetic flux distribution in a superconductor in the mixed state. Magnetometry can only provide global data (i. e. averaged over the whole sample), whereas a local technique enables one to study the effect of the geometry, the anisotropy and the interaction of flux with the microstructure of the sample. Various local techniques have been used so far: magneto-optic microscopy, scanning tunneling microscopy, Bitter decoration, Lorentz microscopy, etc. Of these techniques magneto-optical imaging is fast enough for real-time observation of the flux line lattice. It is well suited for visualization of flux flow, flux creep, flux avalanches etc. [1-4]. Up to now, magneto-optical imaging setups consist typically of a commercial polarization microscope modified to carry an optical cryostat [5,6]. In this way, all advantages of a commercial microscope are used. However, it is then impossible to use a superconducting coil due to space limitations, and the maximum field is thus limited to ≈ 0.3 T using a copper coil. Considering the low observation temperatures required by the High Resolution Faraday effect (HRF) technique using thin layers of EuSe, this field region is not sufficient in the case of single crystals or bulk samples of high-T_c superconductors, since the full penetration field is typically around 2 - 5 T. Another disadvantage is the long distance between the objectives and the sample. For high resolution, a large numerical aperture is required. Together with the mechanical constraints of the magnet this necessitates a short distance between the objective and the sample. In our microscope this is realized by cooling the optics and polarizers together with the sample. It may be inserted into either an Oxford Instruments cryostat equipped with a 1 T superconducting coil or in one with a 7 T coil. Both are equipped with a variable temperature insert (1.5...300 K). The sample is in Helium exchange gas which guarantees a good thermal equilibrium. The microscope is built for two operation modes, reflection and transmission. The images are recorded in both cases using an image-intensified CCD camera system. In the future, the transmission mode should allow the observation of individual vortices.

Here, we concentrate on the first observations performed on a $DyBa_2Cu_3O_{7-\delta}$ (DyBCO) single crystal in reflection mode. It is important to note that the well characterized [7] DyBCO single crystal used in the experiments was irradiated with lead ions and hence had a very high critical current density j_c and also a very strong pinning. The figs. 1 (a) to (c) show flux distributions at three different temperatures. The sample was in every case zero-field cooled to the choosen tem-

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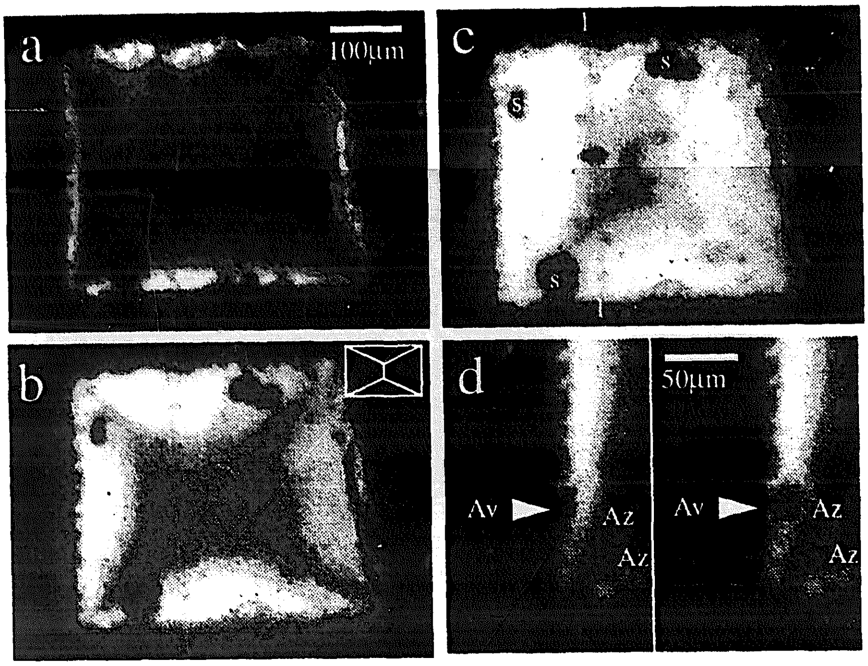

Figure 1. *Flux structures obtained on a DyBCO single crystal at $T = 4.2$ K (a), 20 K (b) and 30 K (c) and an external magnetic field of 1 T. The flux is imaged as bright domains, the Meissner area stays dark. The shape of the discontinuity lines is given in the upper right corner of (b). In (c), there are three spots (labeled S) of molten DyBCO on top of the crystal surface, and a line (l) is running along the crystal. (d): Lower left corner of the crystal; for magnetic history see the text. The so-called annihilation zone is labeled "Az"; the place there the avalanche occurs is labeled "Av".*

perature [$T = 4.2$ K (a), 20 K (b) and 30 K (c)], and subsequently a field of 1 T was applied at a rate of 10 mT/s. All images were taken after cooling down in field to $T = 4.2$ K. The validity of this procedure was ensured in Ref. [8]. Figure 1 (b) exhibits the characteristic magneto-optical pattern associated with the presence of so-called discontinuity lines [9] which is indicated schematically in the inset. In fig. 1 (c) we reach a practically fully penetrated state at 1 T. The discontinuity lines of the current are still present also in this image. In fig. 1 (d), we show the lower left corner of the crystal after applying a field of 1 T at $T = 50$ K, cooling down to 4.2 K and reversing the field. The annihilation zone separating the domains of flux with opposite polarity [10] are clearly visible (labeled Az). Sweeping the field at a rate of 10 mT/s leads to the occurence of flux avalanches (labeled Av). The left side of fig. 1 (d) shows the sample before an avalanche and the right side after it. The time interval between both frames is 40 ms; the avalanche region has a diameter of 20 μm.

In conclusion, we have shown first magneto-optic observations of flux using a newly designed setup. This work is part of the research program of the Stichting voor Fundamenteel Onderzoek der Materie (FOM), which is financially supported by NWO.

REFERENCES

1. H. Kirchner, *Phys. Lett. A* **30** (1969) 437.
2. H. U. Habermeier *et al.*, *Phys. stat. sol.* (a) **50** (1978) 187.
3. M. R. Koblischka *et al.*, *Physica C* **190** (1992) 557.
4. P. Brüll *et al.*, *Physica C* **182** (1991) 359.
5. R. P. Hübener, 'Magnetic Flux Structures in Superconductors', Springer, New York (1979), and references therein.
6. Th. Schuster *et al.*, *Cryogenics* **30** (1991) 811.
7. Th. Schuster *et al.*, submitted to *Phys. Rev. Lett.*
8. M. V. Indenbom *et al.*, *Physica C* **209** (1993) 259.
9. Th. Schuster *et al.*, *Phys. Rev. B* **49** (1994) 3443.
10. Th. Schuster *et al.*, *J. Appl. Phys.* **72** (1992) 1478.