Flux patterns of multifilamentary Ag-sheathed $(Pb,Bi)_2Sr_2Ca_2Cu_3O_{10+\delta}$ tapes

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Flux patterns of multifilamentary Ag-sheathed $(Pb,Bi)_2Sr_2Ca_2Cu_3O_{10+\delta}$ tapes comprising 19 filaments are visualized by means of magneto-optic imaging. In low fields, the shielding currents are seen to flow mainly in the outermost filaments. With increasing external magnetic field, the inner filaments also contribute to the current flow. To compare the local flux distribution with the integral magnetization values, magnetization loops are measured by a SQUID magnetometer on the same sample following the fields used in the magneto-optic imaging (±120 mT) and covering fields up to ±5 T at various temperatures. The magnetization loops also reveal that the multifilamentary tapes show the anomalous position of the central peak, but always less pronounced than in monofilamentary tapes. [S0021-8979(98)53111-8]

The Ag-sheathed multifilamentary tapes of $(Pb,Bi)_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi-2223) are an important development towards the practical use of high-T_c superconductors for power applications. These tapes show an improved mechanical stability and strain tolerance as compared to monofilamentary tapes.[1] For the development of Bi-2223 multifilamentary tapes in long lengths it is very important to control the defects introduced into the filaments during the deformation processes or during the formation of the superconducting phase, as defects within the filaments may alter or even impede the current flow.[2] Furthermore, magnetization measurements[3–6] on tapes revealed an anomalous position of the low field or central peak, which is caused by stray fields at the grain circumferences.[5,6] To understand the magnetic properties of such multifilamentary tapes, it is important to study in detail the flux entry, exit, and pinning within the various filaments. This task requires a *local* investigation technique, as the properties of a single filament are masked by the neighboring ones in an integral measurement. Here, we employ magneto-optic (MO) imaging,[7] which can be carried out using an intact tape, i.e., the visualization of the flux structures is done *through* the silver sheath.[8,9] In earlier work on Bi-2223 mono- and multifilamentary tapes using MO imaging, the flow of transport currents was visualized.[2,10] The MO imaging technique is based on the Faraday effect in a magneto-optical active layer. Here, we have used a Bi-doped YIG film with in-plane anisotropy with a thickness of 4 μm, half of which corresponds to the spatial resolution of our experiment. In order to obtain images with a relatively high contrast, an indicator film with a high field sensitivity (~ 0.1 mT) was used. The images are recorded using an 8-bit Kodak DCS 420 CCD digital camera and subsequently transferred to a computer for processing. In the MO apparatus the sample was mounted on the cold finger of an optical helium flow cryostat.[11] The magnetic field was applied perpendicular to the tape plane using a copper solenoid coil with a maximum field of ±120 mT. The MO images presented here are maps of the z component of the local magnetic field, B_z.

The multifilamentary Bi-2223 tapes (19 filaments) were prepared by the "powder-in-tube" method with subsequent drawing and rolling.[12] One piece with dimensions 5×3 mm^2 cut from the tape was used for both the magnetization measurements and the MO imaging. The magnetization loops (MHLs) were recorded using a Quantum Design MPMS5 SQUID magnetometer (max. $\pm$ 5 T); with $B_{ext}\perp$ tape plane.

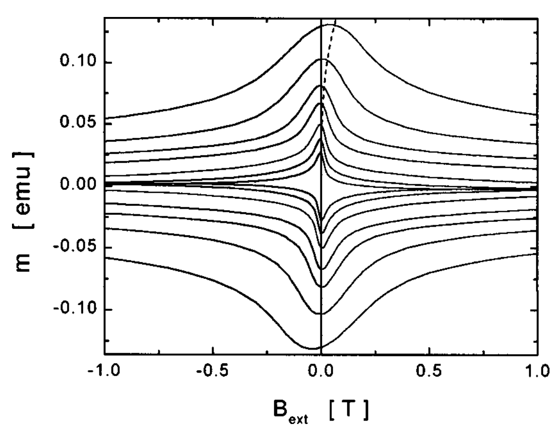

FIG. 1. MHLs measured on the multifilamentary tape at various temperatures 5 (outer loop), 10, 15, 20, 30, 40, and 50 K (inner loop). The anomalous position of the MHL maximum is indicated by a dashed line.

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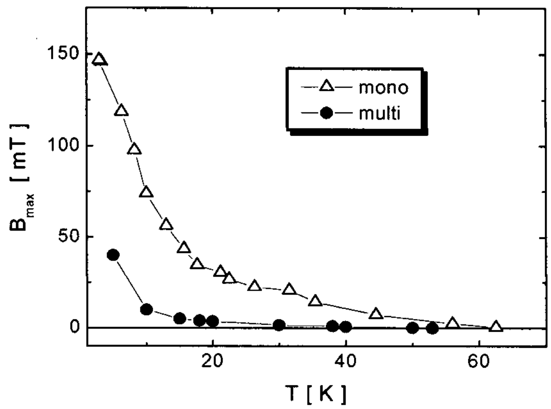

FIG. 2. The peak position, B_{max}, as a function of temperature for the multifilamentary tape (●) and a monofilamentary tape (△, from Ref. 5).

In Fig. 1, MHLs are presented in the temperature range $5\ K \leqslant T \leqslant 50\ K$. It is also clearly visible that the multifilamentary Bi-2223 tapes exhibit the anomalous position of the central peak like monofilamentary tapes. The position of the maximum, B_{max}, is plotted in Fig. 2 and compared to data of a monofilamentary tape. At low temperatures, the maximum position increases considerably, but is always found to be less pronounced than that of the monofilamentary tape.

Figure 3 presents a MHL measured at $T = 18$ K, using the same field steps as in the following MO experiment. For comparison, a full magnetization curve is shown. The positions, where the MO images are taken, are marked using open circles. In this way, a direct comparison of MHL data and the MO flux patterns becomes possible. In all MO images presented in this paper, flux is imaged as bright, whereas well-shielded areas stay dark.

Figure 4(a) shows a polarization image of a cross section of our tape. Flux patterns obtained in increasing external field after ZFC (virgin branch, I) are presented in Fig. 4. In Fig. 4(b), flux enters the sample like in a homogeneous sample (see, e.g., Ref. 7); the edges of the outermost cores are marked by arrows. Only the outermost filaments are contributing to the current flow. When increasing the field further (c),(d), more and more filaments contribute to the current flow. The filaments in our short sample are quite uniformly penetrated by the flux. Previous observations on longer sections of multifilamentary tapes have shown that when currents encounter a defect, they may switch into a neighboring filament, and after some distance, they may return to the original one.[2,9] This shows that the filaments in the tape are magnetically coupled together.

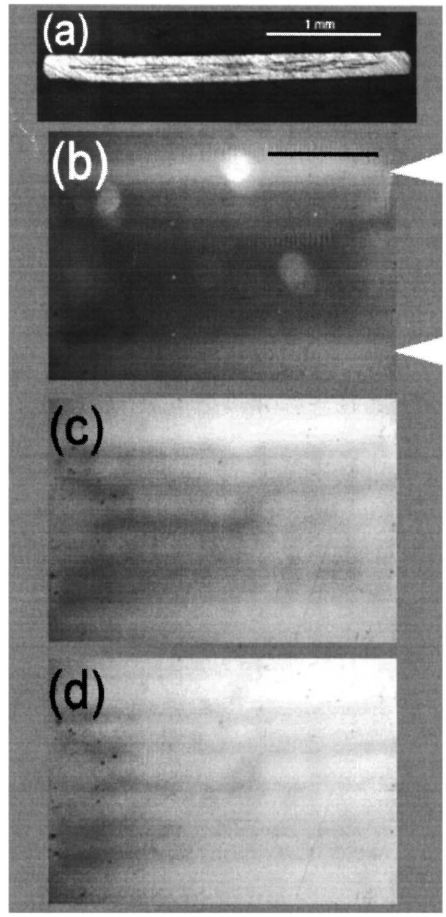

FIG. 4. Polarization image of the tape (a) and flux patterns of the virgin branch (I); (b) 12 mT, (c) 30 mT, and (d) 45 mT. The marker in (b) is 2 mm long.

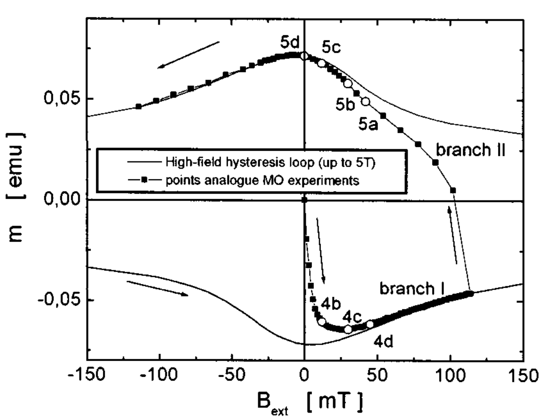

FIG. 3. MHLs measured at $T = 18$ K. The minor loop is obtained using the same field steps as in the MO experiment. The positions of the images shown in Figs. 4 and 5 are marked by open circles.

In Fig. 5, we show flux patterns on the return branch (II). In Fig. 5(a), a nearly homogeneous flux pattern is obtained and individual filaments cannot be resolved. On further reduction of the field (b),(c), the filaments reappear and carry pinned flux.

In the remanent state Fig. 5(d), flux remains trapped in the center of each individual filament. However, no vortices of opposite polarity can be detected in the remanent state as in the case of monofilamentary tape.[8] In the upper part of the sample, a broad dark stripe can be seen which is the result of field overlap between two different filaments as discussed in Ref. 9. The position of the maximum in the MHL corresponds to a flux pattern like the one presented in Fig. 5(c). This does not correspond to a minimum amount of flux in the sample, which is reached only when applying a small negative field. The flux distributions within a single filament are

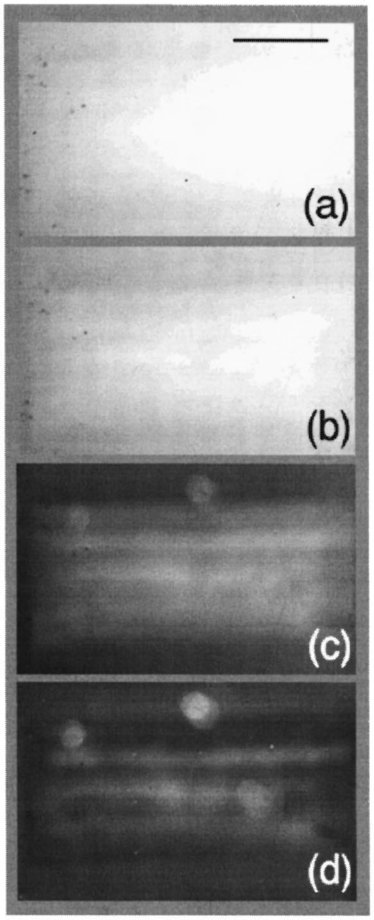

FIG. 5. Flux patterns of the return branch (II); (a) 45 mT, (b) 30 mT, (c) 12 mT, and (d) remanent state. The marker is 2 mm long.

found to be quite uniform. In contrast to this, most monofilamentary tapes show a ''rough-looking'' flux pattern at this low temperature, which is caused by a high intragranular current density; thus forcing the intergranular currents to flow around the well-shielded grains. This fact, and the large stray fields around such grains are probably responsible for the anomalous position of the central peak in the MHL.[5] As the grain coupling is improved along the silver sheath, this effect is not so strongly developed in the multifilamentary tapes. As a result, the peak is also shifted towards positive values, but much less pronounced as in the case of monofilamentary tapes.

In conclusion, we observed the anomalous central peak also in multifilamentary tapes, but always less pronounced than in monofilamentary tapes. Magneto-optic flux patterns reveal a quite uniform flux distribution within the filaments even at low temperatures which is a consequence of better grain growth and coupling along the silver sheath. This may be the reason for the less pronounced anomalous peak in multifilamentary tapes.

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