Journal of Low Temperature Physics, Vol. 105, Nos. 5/6, 1996

Structures in superconducting $YBa_2Cu_3O_{7-\delta}$ thin films investigated by magneto-optic technique

J. Eisenmenger, S. Kambach, S. Saleh, A. Tihi, and P. Leiderer
M. Wallenhorst*, and H. Dötsch*

Fakultät für Physik, Universität Konstanz, 78434 Konstanz, Germany
**Fachbereich Physik, Universität Osnabrück, 49069 Osnabrück, Germany*

Using a reflection magneto-optic technique we have investigated natural inhomogeneities and artificial structures in YBCO thin films exposed to an external magnetic field. The artificial structures were mechanically scratched by scanning a diamond tip with different loading over the film surface. Alternatively planar structures with reduced oxygen content could be patterned by heating the YBCO film with a focused laser beam in nitrogen atmosphere. Depending on the laser annealing parameters different screening properties concerning the applied magnetic field could be achieved.

As a magneto-optically active layer we used EuS films evaporated on glass as well as bismuth- and gallium-doped lutetium-iron-garnet films grown onto (111) oriented gadolinium-gallium-garnet substrates by liquid phase epitaxy. In contrast to measurements with EuS films that show only weak faraday rotation for temperatures higher than 20 K the magneto-optic studies have been expanded to about 60 K by using the garnet films.
PACS numbers: 74.25.Ha, 74.76.Bz, 74.80.-g, 78.20.Ls, 85.70.Sq

1. INTRODUCTION

Magnetic measurements like magnetometry, AC susceptibility or inductive methods are often used to characterize HTSC films without destroying or patterning the samples. An alternative method the magneto-optical investigation of HTSC allows the direct observation of the local flux distribution combined with a high time resolution. The magneto-optical investigation is based on the Faraday effect, i.e. the rotation of the polarization plane of linearly polarized light which passes a magneto-optically active layer exposed to the magnetic field of the underlying superconductor. Since the angle depends on the magnetic field one can visualize the flux distribution as optical contrasts in a polarization microscope.

For technical applications the detection of microscratches, structural irregularities and variations of the YBCO film thickness is very interesting. These inhomogeneities influence the flux distribution in HTSC-films very sensitively as could be proved in former magneto-optical investigations of HTSC films where a homogeneous external magnetic field was applied perpendicular to the film surface. These investigations show that the flux distribution is not only influenced by the film quality itself but also very strongly by the geometry of the whole YBCO film.[1–4]

To visualize local defects in YBCO films we did preliminary experiments with inhomogeneous magnetic fields that were scanned across the defects. For estimating the influence of the geometry of the defects we structured artificial defects that were either isolating or oxygen reduced.

2. EXPERIMENTAL TECHNIQUE

As a magneto-optical indicator film layers of europium chalcogenides (EuS/EuF_2, EuSe, EuS) or doped iron-garnet film are suitable.[5] Especially for high lateral resolution where the indicator film is evaporated directly onto the HTSC sample[6] and for measurements with high time resolution[7] Eu chalcogenides are very useful. As the Verdet constant of the Eu chalcogenides decreases strongly for temperatures higher than 16 K our experiments with EuS indicator films[1,2] were limited to temperatures below this value. For higher temperatures we have used bismuth- and gallium-doped lutetium-iron-garnet films grown onto (111) oriented gadolinium-gallium-garnet substrates by liquid phase epitaxy.[8] In contrast to bubble films[9] with an anisotropy perpendicular to the film these films with in-plane anisotropy[10] show no domains if illuminated perpendicular to the film surface. To increase the light reflection an aluminium layer is evaporated on the iron-garnet film that is directed towards the superconductor.

For the magneto-optical measurements either a homogeneous or inhomogeneous magnetic field was applied. During the measurements the sample was cooled in an optical continuous flow cryostat or a closed cycle refrigerator, respectively.

The major part of the artificial inhomogeneities in the YBCO film were produced by a laser annealing technique at ambient temperatures. By heating the YBCO film with a focused laser beam (Ar-ion cw laser, $\lambda = 488\,\mathrm{nm}$)

in nitrogen atmosphere the oxygen content can be reduced locally yielding a T_c-reduced or even semiconducting behaviour.[11]

3. RESULTS AND DISCUSSION

To compare the influence of different inhomogeneities on the magneto-optically observed flux distribution natural and artificial defects on a YBCO film were visualized. Fig. 1 shows a part of the remanent flux structure inside a rectangular YBCO thin film ($10 \times 10\,\mathrm{mm}^2$) after saturation in a homogeneous magnetic field of 200 mT and following decrease to 0 mT at temperatures of 4 K and 60 K. On the right side (line 1) one and on the

Fig. 1. a) Remanent flux structure inside of a rectangular YBCO thin film ($10 \times 10\,\mathrm{mm}^2$) after saturation in a homogeneous magnetic field of 200 mT and following decrease to 0 mT at a temperature of 4 K. The numbered lines are explained in the text. b) The remanent flux structure at 60 K (image intensified). Bright areas indicate high flux density. An iron garnet film was used as magneto-optical indicator.

left side (line 2-4) three electrically isolating lines are clearly visible. These lines were scratched mechanically with a diamond tip into the film surface. By using a different loading variable line widths could be achieved. Due to the fuzzy edges of the scratched lines that allow an easy flux penetration the influence to the observed flux pattern is much broader than the originally scratched lines of about $30\,\mu$m (line 1-2) and $10\,\mu$m (line 3-4).

Between the scratched lines 6 shorter oxygen reduced lines (line 5-10) were structured perpendicular to them by means of the laser annealing technique (laser power: 0.45 W). Each line was structured with the same width of $10\,\mu$m and length of $340\,\mu$m, except for line 5 which has only a length of $250\,\mu$m. The laser scanning-velocities varied between $0.1\,\mu$m/s (line 5) and $100\,\mu$m/s (line 10). In four-point dc resistance measurements lines structured with similar scanning parameters have shown T_c-reduced at the higher or even semiconducting behaviour at the lower laser scanning-velocities. This correlation between the laser scanning-velocity and electrical properties is not clearly observable in the flux pattern due to the strong interference between different defects. For instance, the remanent flux in line 9 that is written with $20\,\mu$m/s is much higher than the one in line 7 in spite of the fact that this line was written much slower ($1\,\mu$m/s) than line 9. This observation can be understood by the marked defect at no. 11 which allows an easy penetration of flux in line 9. In contrast to that line 7 has no connection to a scratched line which allows an easy penetration of flux in the middle of the YBCO sample. Although all artificial defects were visible even at higher temperatures Fig.1 demonstrates the difficulties at high defect concentration to find an unequivocal relation between the observed flux distribution and the local critical current density.

One possible solution of this problem could be the use of an inhomogeneous magnetic field that is scanned across the YBCO film surface. With this method one can choose the "channel" through which the flux will penetrate into a defect which is located somewhere in the middle of the film. To demonstrate this method an oxygen-reduced structure was laser-patterned (scan-velocity: $0.1\,\mu$m/s, laser power density: $2.5\,\mathrm{mW}/\mu\mathrm{m}^2$) consisting of a rectangle (size: $60\,\mu$m $\times$ $65\,\mu$m) that was connected by a 2 mm long and $15\,\mu$m wide line to the edge of the YBCO film. As an inhomogeneous magnetic field we used a cylindrical permanent magnet (diameter: 2 mm, length: 10 mm) that was moved behind the YBCO film in a distance of 1.2 mm (B_{max} at YBCO film distance 300 mT). An iron-garnet film was used as magneto-optical indicator. Fig. 2a shows the flux distribution at 15 K during moving the permanent magnet from the outer left side of the sample along the oxygen reduced line. Flux already enters the sample along the line but does not reach the rectangle yet. Only after the external magnetic field was moved further to the right flux clearly penetrates the rectangle (Fig. 2b). In contrast to the flux distribution one would achieve with a homogeneous magnetic field flux is now removed from the parts of the line that were scanned before.

To estimate the influence of j_c reduced connections between the film edge and defects inside the film a second rectangle was laser patterned with the same parameters, the same size, and the same distance from the edge of the YBCO film. In this case no connecting line was structured. Scanning the magnet in the same way as in the first experiment yielded much lower flux penetration in the patterned rectangle (not shown).

The flux distribution of another laser-patterned structure (same parameters as before) with no connection to the film edge is visualized in Fig. 3. This structure consists of a laser patterned $15\,\mu$m wide and 5 mm long line that is interrupted in the middle by a $120\,\mu$m wide gap. The influence of this gap on the flux distribution can be seen in the left part of the figures.

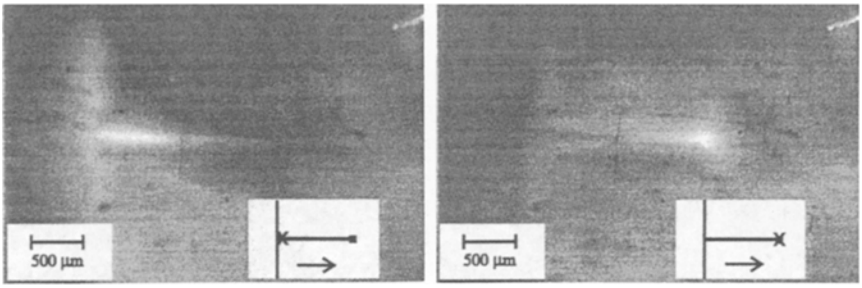

Fig. 2. Flux distribution at 15 K of a laser-patterned rectangle connected with the YBCO film edge by an additional line. Flux distribution during moving the permanent magnet (B_{max} at YBCO film distance 300 mT) from the film edge (left) towards the rectangle (right) (The crosses in the insets indicate the position of the magnet in each situation). a) Permanent magnet is located near the film edge. b) Same pattern but 1 sec later when the permanent magnet reached the rectangle.

By using opposite scan directions of the magnet inverse flux-patterns of the same structure could be achieved. In Fig. 3a the magnet is located at the right end of the line during a horizontal scan to the right; in Fig. 3b the magnet was moved to the left and was located in the region of the gap. Similarly to Fig. 2b flux enters the disturbed YBCO film in the region of the magnet and leaves it behind in a V-shaped structure. Flux barriers with higher critical current densities hinder the flux penetration.

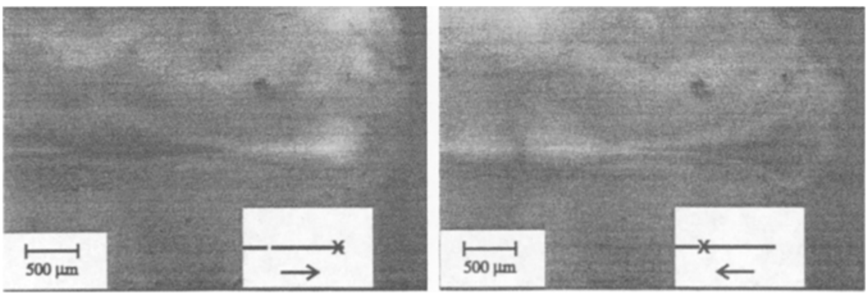

Fig. 3. Flux distribution of laser patterned 5 mm long line that is interrupted in the middle by a 120 μm wide gap (left side). a) During a horizontal scan to the right. The magnet (B_{max} at YBCO film distance 300 mT) is located at the right end of the line. b) During a horizontal scan to the left. The magnet is located in the region of the gap at the left side.

4. CONCLUSION

The results presented here show that magneto-optical investigations of YBCO films both with homogeneous and strongly inhomogeneous magnetic fields provide important information about the film quality. By applying a *homogeneous* field the influence of various defects and the effect of their mutual interference on the observed flux pattern could be demonstrated. First magneto-optical investigations using the *inhomogeneous* field of a small magnet that was scanned across laser patterned oxygen reduced test structures also clearly show the response due to the artificial structures and defects. The latter technique, being a local one, has the advantage that the resulting flux patterns are not influenced by the geometrical shape of the sample (as long as the sample size is large compared to the extension of the magnetic field). By contrast the flux penetration patterns in a homogeneous field depends crucially on details of the sample contours.[1–4] Moreover, the scanning method appears particularly suitable for the characterization of HTSC films with large diameter for application purposes, because is does not require voluminous homogeneous magnetic fields. In spite of the fact that defects are clearly visible with this method the obtained preliminary results have to be considered as qualitative. Attempts for a more quantitative analysis of the flux distribution in the presence of simple defects are discussed in literature.[3,12]

ACKNOWLEDGMENTS

The authors would like to thank M. Kuhn, W. Biegel , B. Stritzker, P. Berberich, R. Semerad, W. Prusseit and H. Kinder for providing YBCO samples.

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