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Nondestructive Magneto-Optical Characterization of Natural and Artificial Defects on 3" HTSC Wafers at Liquid Nitrogen Temperature

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Abstract—Double-sided 3" HTSC Wafers were characterized by the magneto-optic technique. The presented apparatus allows a nondestructive and fast detection of local and extended inhomogeneities in the critical current density with high lateral resolution in the micrometer range. Additional gold-layers on the HTSC wafers, as they are sometimes used for the device production, do not influence the characterization result. The high sensitivity of the presented apparatus allows even the detection of local defects at higher temperature (77 K) where contrasts in the critical current are weaker and the magneto-optical characterization of HTSC thin films is much more difficult than at lower temperatures. So the apparatus can be used even under conditions where cooling with liquid helium or closed-cycle refrigerators is not available. The sensitivity was tested on natural and artificial defects, the latter being prepared by means of a focused laser beam.

I. Introduction

In the past several magneto-optical investigations have contributed to the understanding of the flux structure in HTSC thin films (e.g. [1]–[3]) and have confirmed theories of the critical state in thin type-II superconducting layers [4]–[6]. The magneto-optical method 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 rotation angle depends on the magnetic field one can visualize the flux distribution as optical contrasts in a polarization microscope.

Due to the growing number of applications there is an increasing need for reliable characterization methods of HTSC thin films to guarantee a steady quality of devices. In principle the magneto-optical method has a high potential for the quality control of HTSC thin films due to its high lateral resolution and sensitivity to inhomogeneities in the critical current density. Yet in the past most magneto-optical investigations have been carried out only on small samples (10 mm × 10 mm and smaller, see [3] and references therein). That was sufficient for solving fundamental questions, but the experimental set-ups that were used for these experiments are not suitable to characterize larger HTSC thin films. In particular this applies to HTSC wafers with 3" diameter, a standard size for the production of several devices, e.g. microwave stripline filters. Widely used characterization methods for HTSC wafers are inductive and R_s-measurements, which supply important information about the film quality. Compared to the magneto-optical method the lateral resolution of these techniques is very limited. Magneto-optics could complement these techniques by providing additional information about local mesoscopic defects in the μm-range, like cracks, microscratches, structural irregularities and small holes in the HTSC layer. In addition the local critical current density can be determined with high lateral resolution from the measured flux distribution [7].

In a first approach to magneto-optic measurements on larger samples, a 2" wafer was characterized at 50 K [8], [9]. The sample was cooled with a closed-cycle refrigerator and instead of a homogeneous external field an inhomogeneous field of a permanent magnet was used that was scanned across the YBCO thin film [10]. For a standard characterization of HTSC thin films a simple and fast determination of the film properties is desirable. Cooling with liquid nitrogen to 77 K is the simplest way to reach temperatures below T_c, because it is more easily available than liquid helium and especially large samples can be cooled faster than with a closed-cycle refrigerator. However at higher temperatures the contrast in magneto-optically observed flux distributions decreases very strongly [11], because of the smaller critical current density. That is the reason why in contrast to the thicker YBCO crystals most magneto-optical investigations on YBCO thin films have been done at temperatures below 65 K.

By optimizing magneto-optics with regard to larger samples and higher magnetic sensitivity this promising method could be more widely accepted for the characterization of large HTSC thin films. In the following we will present our efforts towards this direction.

II. Experimental Technique

The investigated 3" double-sided YBCO thin film was deposited by pulsed-laser deposition [12] on r-plane sapphire with CeO_2 buffer layer. Both layers had a thickness of 300 nm. The first side had a critical current density J_c(77 K)=5×10^6 A/cm^2 and the second J_c(77 K)=3.5×10^6 A/cm^2. Both wafer sides were additionally gold coated.

For the magneto-optical investigation the sample was zero field cooled in a continuous flow cryostat, which had an optical window with a diameter of 80 mm. As a magneto-optical layer placed onto the superconductor we

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used a doped ferrimagnetic iron-garnet layer grown onto 3" gadolinium-gallium-garnet substrate by liquid phase epitaxy. The ferrimagnetic domains of the garnet layer with in-plane anisotropy are not visible under the polarization microscope, if illuminated perpendicular to the film surface [13]. To increase the light reflection an aluminium layer is evaporated onto the iron-garnet film that is directed towards the superconductor. In contrast to magneto-optical indicator film layers of europium chalcogenides (EuS/EuF_2, EuSe, EuS) whose Verdet constant decreases strongly for temperatures higher than 16 K, iron-garnet layers with proper doping show similar sensitivity from low up to room temperature [14], [15].

The magnification of the used microscope could quickly be changed over a very wide range. This allows to obtain full-length images of the whole wafer and at higher magnification to detect very small defects in the micrometer range. The flux distribution was measured with almost perfectly crossed polarizer and analyzer, so bright areas indicate a high flux density component perpendicular to the superconducting layer. For measuring the distribution of the local light intensity we used slow-scan CCD cameras with different dynamic ranges.

III. Results and Discussion

Fig. 1 shows a full-length image of the flux distribution of a 3 " double-sided YBCO-wafer. The sample was zero field cooled to a temperature of 10 K and exposed to a homogeneous magnetic field of 86 mT. At low magnetic field the external field is perfectly shielded by screening currents in the superconducting wafer. At H_{c1} flux-lines begin to form at the edges of the wafer, where the magnetic field is highest due to the large demagnetization factor of the sample. The flux lines are pinned at the edge of the wafer until the external field is high enough that the screening current density J locally exceeds the critical value J_c and the vortices are driven towards the center of the sample under the action of a Lorentz force. In a superconducting disk with a perfectly homogeneous critical current density a symmetric flux penetration towards the center of the disk is expected.

During the YBCO deposition the wafer of Fig. 1 had been fixed on four positions at the edge (black arrows). At these positions the sapphire substrate was not coated on semicircles with radius of 2 mm (see dotted black semicircle in Fig. 2a). Because the screening currents have to follow more or less the perimeter of the sample, this deviation from the perfectly round disk geometry leads to a different screening current distribution and an easier flux penetration near the uncoated parts of the wafer (see below).

This effect of the sample geometry can clearly be seen in Fig. 1. Besides a more or less uniform flux penetration that points to a quite homogeneous critical current density of the wafer, one observes a more pronounced flux penetration from the uncoated parts which leads to a fourfold symmetry. This interpretation is in accordance with the homogeneous critical current density distribution of this thin film, that could be determined by inductive measurements with a lateral resolution of a few millimeters (determined by the size of a small coil used for the experiment).

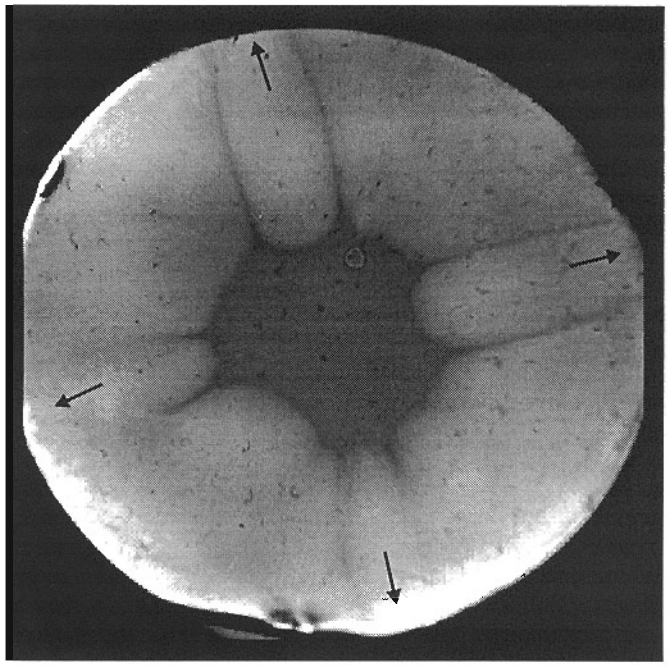

Fig. 1. Flux distribution of a 3" double-sided YBCO-Wafer at 10 K (ZFC) at an homogeneous magnetic field of 86 mT. The image was taken with a 12-bit CCD camera.

In contrast to the inductive method the magneto-optical technique has a much higher lateral resolution. In Fig. 1 it was about 200 μm and not limited by the optical resolution but by the ratio of the imaged area and the number of pixels of the used CCD (384 $\times$ 576).

Fig. 2 shows the magnetic flux distribution near the edge of the YBCO-wafer with higher magnification and lateral resolution. Compared to Fig. 1 the wafer was turned, i.e. the second side is facing the magneto-optic indicator layer. The main difference between Fig. 1 and Fig. 2 is however, that the latter shows the flux distribution at 77 K and not at 10 K. At 77 K the flux penetrates the YBCO thin film at considerable lower external field, and the contrast in the magnetic flux distribution and hence the light intensity is much weaker. To achieve an equivalent image quality, i.e. signal to noise ratio, we used a 16-bit CCD camera with a very high dynamic range instead of the 12-bit CCD camera used before.

Looking at the flux distribution at the lowest magnetic field in Fig. 2a) in more detail one clearly observes the influence of the uncoated semicircle, where the wafer was held during film deposition. At small magnetic fields in the Meissner state the screening currents have to flow around this uncoated part. This changed direction of the screening current shields the external field less effectively at the apex of the uncoated semicircle, and the current density has to adjust locally to higher values to screen the superconductor perfectly. With further increase of the external magnetic field flux starts penetrating the layer at this apex, because the current density exceeds the critical value J_c there first. At higher fields like in Fig. 1 on both sides of this enhanced flux penetration one clearly observes a dark line. At these so-called discontinuity lines the critical current density has a very small curvature radius and screens the external field very effectively [16],

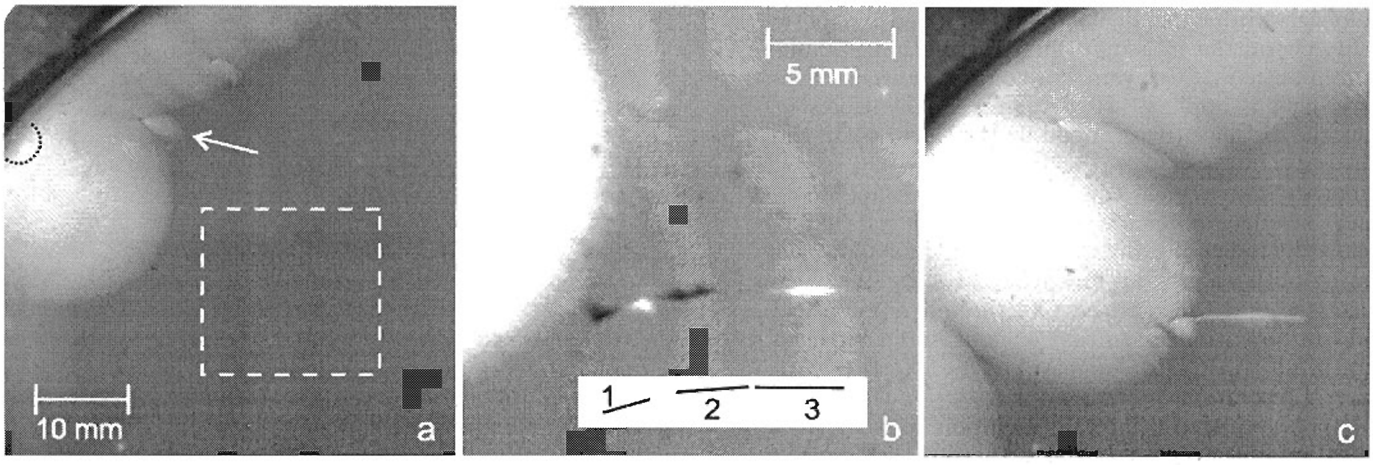

Fig. 2. Magnetic flux distribution near the edge of a 3" double-sided YBCO-Wafer at 77 K (ZFC) in different applied perpendicular magnetic fields B_{ext}. In contrast to Fig. 1 one had to use a 16-bit CCD camera with a much higher dynamic range to achieve a comparable image quality, i.e. signal to noise ratio. a) B_{ext} = 5.0 mT. At the position (black dotted semicircle) where the substrate was held during film deposition an enhanced flux penetration is observed. b) Marked area in a) with higher magnification and with higher external field B_{ext} = 6.6 mT. The influence of three defects (for dimensions see inset) on the Meissner current density affects the flux distribution quite clearly and leads to a characteristic black-and-white structure. c) Upon further increase of the external field (B_{ext} = 7.4 mT) the flux front reaches the defects and the perimeter of the defects results in an enhanced flux penetration from the defects.

[2]. A similar influence on the flux distribution can be observed when the flux front reaches small defects in the inner part of the wafer like in Fig. 2a) (white arrow). As in the case above they influence the direction of the screening currents and lead to an enhanced flux density in these regions.

So far we have only discussed defects, which are reached by the flux front and are at least partly connected to the Schubnikov region. A different situation arises for defects, which are still in the Meissner region. Fig. 2b) shows the marked area in Fig. 2a) with a higher magnification and a higher external field B_{ext} = 6.6 mT. One clearly notices the influence of three small cracks, whose dimensions are sketched in the inset. At defect 1 we observe a decreased magnetic flux density at the end, which is directed towards the edge of the sample, and an increase in the opposite direction. This agrees with similar observations of the flux distribution in the Meissner state on small (5 mm × 1.6 mm) single-sided YBCO thin films that were zero field cooled to 18 K [17]. The exact geometry of the defects, shown in the inset of Fig. 2b) was determined magneto-optically at lower fields, where also the defects 2 and 3 separately showed the characteristic black-and-white structure (after image processing). At higher magnetic fields like in Fig. 2b) the stray fields of both defects influence each other resulting in a neutralized region between them. Under a normal light microscope these defects could not been observed, because they were covered by the gold layer.

In contrast to a longitudinal geometry where demagnetization effects can be neglected, the Meissner state of a thin superconducting disk in a perpendicular magnetic field is accompanied by Meissner surface currents flowing along the *entire width* of the specimen [4]. In a flawless Meissner region of a thin film there are no perpendicular but only tangential magnetic field components and the magneto-optical image stays dark. In the presence of local defects the Meissner screening currents have to flow around these defects. In a simple model (Fig. 3) the influence of the local defect in the Meissner region can be described as a superposition of the undisturbed Meissner currents and an additional current path in the upper layer, that leads to an increased current density at both sides of the defect and a vanishing current density over the width of it. At the resultant flux distribution the flux lines are turned towards the defect, so the normal component is decreased at the side facing the edge of the wafer and increased at the opposite side. Since the wafer was zero field cooled and the defects are surrounded by superconductor in the Meissner state, the integrated flux through each defect has to remain zero. The flux distribution at the lower layer is not influenced by small defects in the Meissner region of the upper layer. After

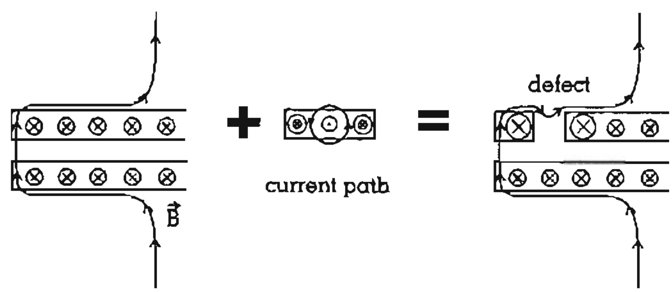

Fig. 3. A simple model for the influence of a local defect on the flux distribution in the Meissner state for a double-sided thin HTSC wafer.

increasing the external magnetic field further (B_{ext} = 7.4 mT) the flux front reaches the defects, the characteristic black-and-white structure disappears and again the perimeter of the defects results in an enhanced flux penetration from the defect region (Fig. 2c). By investigating the flux distribution of the first side as in Fig. 1 an influence of the defects, which can be seen in Fig. 2, could not be observed, independently of the applied magnetic field. In general the measured flux distribution is influenced from both YBCO layers, if a homogeneous external magnetic field is applied. However for small defects in the back the distance (determined by the thickness of the sapphire substrate $\approx 430\,\mu m$) to the indicator layer is so large that their stray field can be neglected compared to the much stronger influence of the YBCO-layer that is just below the indicator film. In most cases this allows investigating both wafer sides independently. Fig. 2 clearly demonstrates that the sensitivity of the magneto-optical method can be optimized so that even at liquid nitrogen temperature 3" YBCO wafers can be characterized with high lateral resolution.

An impression of the lateral resolution at very high magnification gives Fig. 4. It shows the flux distribution of four nonconducting round defects which are located in the Meissner region near the flux front that approaches from the left. They were produced be burning small holes into the YBCO thin film by means of a focused laser beam. The diameter of the holes is only 40 μm and the distance between them 200 μm. Since the round perimeter of the artificial defects the drop-like black-and-white flux structure which could be observed at long defects in Fig. 2 is much less pronounced. The image was taken with a 12-bit CCD camera so we used lower temperatures at 10 K (ZFC) and a higher external field of 51 mT to get a good signal to noise ratio. To detect natural defects of this size and smaller at 77 K we had to use the 16-bit CCD camera with the higher dynamic range. Besides these artificial defects the influence of natural even smaller imperfections can clearly be observed near the flux front in Fig. 4. At very high magnifications like in this example the lateral resolution of the method is limited by the thickness of the garnet layer ($\approx$ 3–4 μm) and its spacing to the YBCO thin film ($\approx$ 3-5 μm).

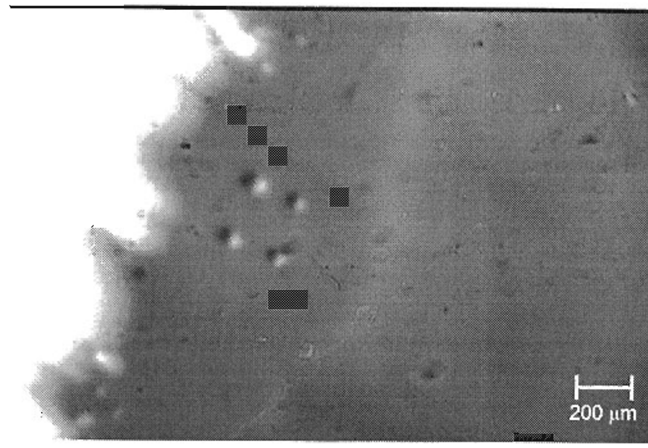

Fig. 4. Flux distribution of four electrical isolating round defects, that are located near the flux front but are still in the Meissner region. The image was taken with a 12-bit CCD camera at 10 K (ZFC) and an external magnetic field of 51 mT . The defects were produced by burning small holes into the YBCO thin film by means of a focused laser beam. The diameter of the points is 40 μm and the distance between them 200 μm. Because the round perimeter of the defects the drop-like black-and-white flux structure that could be observed at long defects in Fig. 2 is much less pronounced.

IV. Conclusion

We have demonstrated a magneto-optical apparatus that is suitable to investigate large 3" double-sided YBCO thin films. The magnetic resolution was optimized that even small defects in the Schubnikov and Meissner region could be detected at 77 K, where contrasts in the critical current are weaker and the magneto-optical characterization of HTSC thin films is much more difficult than at lower temperatures. So the apparatus can be used even under conditions were cooling with liquid helium or closed-cycle refrigerators is not available.

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