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Quantitative magneto-optical analysis of the role of finite temperatures on the critical state in YBCO thin films

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Abstract
We use quantitative magneto-optical microscopy to investigate the influence of finite temperatures on the critical state of thin YBCO films. In particular, temperature and time dependence of supercurrents in inhomogeneous and anisotropic films are analyzed to extract the role of temperature on the supercurrents themselves and the influence of thermally activated relaxation. We find that inhomogeneities and anisotropies of the current density distribution correspond to a different temperature dependence of local supercurrents. In addition, the thermally activated decay of supercurrents can be used to extract local vortex pinning energies. With these results the modification of vortex pinning introduced by substrate structures is studied. In summary the local investigation of supercurrent densities allows the full description of the vortex pinning landscape with respect to pinning forces and energies in superconducting films with complex properties under the influence of finite temperatures.

Keywords: current density, magneto-optics, YBCO, thin films

(Some figures may appear in colour only in the online journal)

1. Introduction

Superconductors are highly attractive for electric applications because of their loss of electrical DC resistance below the transition temperature. In addition, a remarkable feature is the extremely high electrical current density that can be realized inside the materials. High current densities are directly related to an effective pinning of magnetic vortices at inhomogeneities inside the materials \cite{1}. For most technical applications such as electrical transport systems \cite{2,3}, magnets \cite{4-6} or sensors \cite{7} it is desirable to control flux pinning and thus the local current density of the material. The supercurrent density can be nicely obtained when measuring the magnetic moment that is created by the supercurrents. Since the size of the magnetic moment is given by the magnitude of the electric current and the shape of the current path a spatially resolved characterization technique is often a prerequisite. This is accomplished by quantitative magneto-optical investigations that provide spatially resolved information on the current density distribution in superconducting films \cite{8-10}. In the present work the method is now used to investigate the role of pinning and thermally induced depinning of magnetic vortices in optimally doped YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-\delta} (YBCO) thin films that are prepared on engineered substrates to create inhomogeneous or anisotropic current transport inside the superconducting material. In particular, the role of finite temperatures on the critical state is studied. The consequences are two-fold, first, the supercurrent density decreases with increasing temperature and, second, the role of thermally activated vortex motion increases \cite{11}. Both phenomena when investigated locally provide information about the vortex pinning landscape in superconducting films with complex geometry.
The application of the magneto-optical technique, in particular using ferromagnetic iron garnet films as field-sensing layers allows a mapping of the local supercurrent density distribution in thin superconducting films with a spatial resolution of about 5 μm [12]. The current density distribution is determined via a numerical two-dimensional inversion of the measured magnetic flux pattern via Biot–Savart’s law which relates the magnetic stray field of the sample with the supercurrents flowing inside the material. A detailed description on the method is found in the review article of Jooss [9]. In this work the focus lies on the determination of the temperature dependence and the time evolution of the supercurrent density in inhomogeneous and anisotropic superconducting films, respectively. For that purpose we present magneto-optical data of two particular categories of superconducting films that are realized in thin YBCO films on engineered substrates. Our temperature- and time resolved current density data allow for the first time the determination of corresponding pinning landscape present in such engineered structures. Section 3 describes measurements at unmodified films for comparison. Based on that, section 4 focuses on films with inhomogeneous current density and, finally, section 5 describes the role of current anisotropy. The presented results clearly show that local data are a prerequisite for the determination of the corresponding vortex pinning scenario. In addition, the pinning energy responsible for the thermally activated relaxation and the pinning force density determining the current density at low temperatures have to be distinguished to fully describe the behavior of thin superconducting films in external magnetic fields.

2. Experimental

Figure 1 depicts the magneto-optically determined flux and current density distribution in a regular, optimally doped YBCO thin film at $T = 7$ K. Film ‘A’ is grown by pulsed laser deposition on a single-crystalline (001) SrTiO$_3$ (STO) substrate. It represents the first category of homogeneous films. The left panel shows the magnetic flux penetration into the superconductor at an external field of $\mu_0 H = 16$ mT after zero-field cooling. Magnetic flux displayed in light gray penetrates from the edges into the film. The adjacent panel depicts the corresponding current density distribution that can be calculated from the flux density distribution. Flux filled regions exhibit a finite and in this case nearly constant supercurrent density of slightly more than 20 MA cm$^{-2}$. The two images on the right display the same properties after the application of $\mu_0 H = 300$ mT and the subsequent reduction of the external magnetic field to zero. The measurement has been performed about 5 s after the magnetic field reached zero. In this remanent state magnetic flux is trapped into the sample visible as a white cross in the flux density distribution. The corresponding current density pattern shows supercurrents flowing throughout the whole film depicted in white in the image on the right. The corresponding profile extracted along the solid black line again shows a current density of slightly above 20 MA cm$^{-2}$ [13]. Along the diagonals the so called discontinuity line arise where due to geometrical constraints the local current density is reduced by a factor of square-root of 2 [14].

Note, that there is small slope in all the current profiles indicating that the current densities increase with increasing local magnetic flux density. This is only found for very small flux densities generated by the current of the superconductor itself (‘self-field scenario’). The reason is an increase of (average) vortex pinning by next-neighbor interaction [15]. In larger magnetic fields beyond the self-field the typical decrease due to a loss of effective pinning sites is found. In the following we will use superconducting films in the remanent state to study inhomogeneous and anisotropic supercurrent distributions with respect to temperature and time dependent behavior.

In particular, we will investigate temperature and time dependence of the supercurrent density in epitaxially grown YBCO thin films with inhomogeneous and anisotropic current densities introduced by substrate structures. A first characterization of the objects of interest gives figure 2. It depicts the magneto-optically determined current density distribution of two modified YBCO thin films in the critical state at $T = 7$ K. Film ‘B’ has been deposited on top of an ion beam patterned substrate. Gallium ions are implanted into the STO surface to create surface structures on a sub-micron length scale. Details of the preparation can be found in [16]. The substrate pattern can be prepared in a way that the current density in the YBCO grown on top increases [17]. In case of film ‘B’ a rectangular-shaped area was created that exhibits a significantly enhanced current density. Exemplarily, this sample represents superconducting films with an inhomogeneous supercurrent distribution. Finally, film ‘C’ refers to the category of anisotropic superconducting films. In particular, it has been prepared on a vicinal cut (106) STO surface. The presence of surface steps on the substrate during deposition leads to $c$-axis oriented YBCO thin films which form planar antiphase boundaries along the direction of the substrate steps [18]. As a consequence the current density becomes anisotropic [19]. In the following the current direction along the antiphase boundaries will be denoted as ‘parallel’ direction, $j_{\text{par}}$, the direction across these structures will be denoted as ‘perpendicular’, $j_{\text{perp}}$.

These films have generally been chosen to introduce the role of current inhomogeneity and current anisotropy in thin superconducting films. All superconductors shown in this paper are thin, optimally doped YBCO films deposited on STO by pulsed laser deposition. The typical thicknesses are 100–300 nm and the transition temperatures are between 87 and 91 K.

The two gray scale images displayed in figure 2 show the current density distribution in these superconducting films. Bright gray or white refers to a high magnitude of the current density; black regions are areas without electrical current. All current carrying states have been prepared at $T = 7$ K. The superconductors have been cooled in zero field; afterwards a magnetic field of about $\mu_0 H = 200$–300 mT has been applied along the film normal and subsequently reduced to zero. Having prepared this critical state the magnetic stray field
Figure 1. Magneto-optically obtained results of a regular, optimally doped YBCO thin film (category ‘A’) obtained at $T = 7\,\text{K}$. The two images on the left display flux and current density distribution after zero-field cooling in an external magnetic field of $\mu_0 H = 16\,\text{mT}$. Having exposed the superconductor to an external field of $\mu_0 H = 300\,\text{mT}$ the magnetic field is reduced to zero. Flux and current distribution in the so called remanent state are displayed in the two images on the right. The diagonal lines refer to the discontinuity lines where the supercurrents are bent.

Figure 2. Magneto-optically obtained current density distribution of two different YBCO thin films in the critical state at $T = 7\,\text{K}$. Left: YBCO film on a partly ion-patterned substrate exhibiting an increase of the supercurrent density in the irradiated, rectangular-shaped area in the center of the film. Right: YBCO films on a vicinal cut (106) substrate exhibiting surface steps along the vertical direction. The current density in vertical direction ($j_{\text{par}}$), along the substrate steps, is more than a factor of two larger than the currents in horizontal direction ($j_{\text{perp}}$). The arrows mark defects in the film. In all cases a profile is depicted below that is extracted along the solid black line, respectively.
distribution has been measured subsequently with a time delay of about 5 s by magneto-optical means. The data are then quantitatively analyzed to calculate the current density distribution. This quantitative information is provided by the corresponding profiles below that are extracted along the horizontal solid lines in the gray scale images.

In the left panel the current density distribution in a YBCO film (film ‘B’) is depicted where a rectangular-shaped area exhibits an increased current density. The profile below indicates a distinct increase of about 2–3 MA cm⁻² or 10%–15%, respectively. The local enhancement of the current density can nicely be identified in the magneto-optically obtained data as bright rectangular-shaped area in the top part of the image. Finally, the right panel depicts the current density that occurs in a superconducting film with an anisotropic current density. The current density along the vertical direction \( j_{\text{par}} \) is about a factor about 2.5 larger than \( j_{\text{high}} \) in horizontal direction. This is generated by anisotropic defect structures that evolve in YBCO thin films grown on vicinal cut substrates [18].

The advantages of the magneto-optical analysis providing spatially resolved data are now demonstrated when investigating different particular samples of categories ‘A’ to ‘C’, respectively, in more detail. The current density distribution that evolves in the critical state after preparation analog to the results shown in figures 1 and 2 is now systematically investigated with respect to varying temperatures and to the time evolution caused by thermal activation of vortex motion. This analysis uniquely allows the quantitative description of the underlying vortex pinning landscape.

3. Homogeneous and isotropic films

Figure 3 depicts the temperature dependence of the supercurrent density measured at the homogeneous and isotropic YBCO film ‘A’ by quantitative magneto-optical imaging. The data are taken in the remanent state without external magnetic field. To reduce vortex–vortex interaction to a minimum the current density is extracted at the neutral line where the local flux density is close to zero [20]. For comparison magnetization data are depicted in the inset collected from an MPMS Quantum Design SQUID magnetometer system. In case of the Bean model assuming a non-varying current density in the superconductor we find \( m \sim j \) [21], thus the magnetization is directly converted into corresponding values of the (averaged) current density \( j \).

Both the magneto-optically obtained current density (red) and the magnetization (black, inset) nearly show the same temperature dependence. We find a decay of \( j(T) \) with temperature and the current density/magnetization vanishes at the irreversibility temperature which is in case of YBCO close to \( T_c \). The similar shape of the curves refers to the fact that in case of homogeneous superconducting films the current density is nearly constant inside the material. Summing up local data to an integral average as done by magnetometry therefore leads to a corresponding signal. It is to state that the information about the temperature dependence of the supercurrent that is crucial for most applications can also be nicely extracted from non-local magnetization measurements in case of homogeneous and isotropic films.

Next we want to consider the thermally activated decay of the supercurrent density. For that purpose a homogeneous film in the category of ‘A’ is investigated. After the preparation of the critical state the time evolution of the current density is measured using magneto-optics (figure 4) and SQUID magnetometry (inset, figure 4).

Figure 4 depicts the current density as a function of time after the preparation of the critical state at low temperatures. An external field of \( \mu_0 H_{\text{ext}} = 200 \text{ mT} \) has been applied after zero-field cooling to \( T = 10 \text{ K} \). Subsequently, the magnetic...
field is reduced to zero during \( t = 1 \) s. In equidistant time steps of \( \Delta t = 4 \) s magneto-optical images are captured from which the local current density is calculated as described above. We find a substantial decay of the observed supercurrent density of about 10% during \( t_1 = 600 \) s. Responsible for the observed decrease of the current density is thermally activated depinning of vortices at finite temperatures \([22]\). This process leads to a reduction of flux gradients and thus to a nonlinear decay of the observed current density after the magnetic field controlled preparation of the critical state. When measuring the decay of the supercurrents in a magnetometer depicted in the inset of figure 4 similarities and differences are found. The characteristic decay is also seen in the magnetization curve which is again directly converted into averaged current density values. However, the decay that is measured in the magnetization experiment is about a factor of two smaller. This is related to the fact that the activation energy for the depinning of vortices depends on the local magnetic vortex density in the film \([23]\). The magneto-optical data are collected in the inner part of the film where the local flux density is quite high. For the magnetization the contribution of large current loops running along the border of the sample are dominant. Here, the flux density is low and the thermally activated decay of the supercurrents is smaller. This result shows that integral relaxation measurements not completely describe the role of thermally activated vortex motion in thin films at low fields.

4. Inhomogeneous superconductors

In case of homogeneous and isotropic superconductors the properties of the supercurrent transport can be measured in some cases quite well both by non-local magnetometry and magneto-optical microscopy. This is no longer possible when considering inhomogeneous or anisotropic superconductors. Figure 5 depicts the results of a temperature-dependent analysis of the current increase due to a prepatterned substrate surface.

Two greyscale images are displayed in the left part of figure 5 that visualize the current distribution as gray scale in YBCO film ‘B’ at two different temperatures. The top panel is obtained at \( T = 7 \) K the bottom panel at \( T = 25 \) K. The comparison of both images yields an increasing influence of the substrate pattern with increasing temperature.

More detailed information is provided from the graph on the right. The current densities for film areas on pristine \( (\j_0) \) and patterned \( (\j_m) \) surfaces are averaged and their ratio is plotted over temperature. We find a distinct increase from about 1.1 at low temperatures to more than 1.35 close to \( T_c \). Obviously both current densities exhibit a different temperature dependence which is related to modified underlying vortex pinning properties \([13]\). The fact that the ratio of both current densities changes with temperature directly excludes magnetization measurements for the detailed characterization of the current carrying capability of such more complex structures. At different temperatures the relative contribution of both current carrying areas to the magnetic moment changes continuously. Only a spatially resolved analysis provides the required information for a quantitative description of the magnetic properties of the superconductor.

The analysis of the decay of supercurrents in inhomogeneous films due to thermally activated vortex depinning requires local information as well. The time evolution of the current density state is obtained again after preparation of the critical state as remanence after exposition to an external magnetic field.
A description that holds well for small magnetic fields is given by Kim and Anderson [24]

\[ j(t) = j_0 \left( 1 - \frac{kT}{U_0} \ln \left( \frac{t}{t_0} \right) \right). \] (1)

The decisive property for the decay of the current density \( j(T) \) is the ratio of the vortex pinning energy \( U_0 \) and the thermal energy \( kT \) [22]. \( j_0 \) is the initial current density after preparation of the critical state and \( t_0 \) a characteristic time that is correlated with the sequence of preparation and measurement of the critical state [23, 25]. \( t_0 \) is of the order of few seconds. Numerical fitting routines allow a precise determination of the vortex pinning energy \( U_0 \) at least for our case of weakly interacting vortices at small magnetic fields. For higher magnetic fields \( U_0 \) has to be interpreted as pinning energies of vortex bundles.

Figure 6 depicts the time evolution of the current density on a logarithmic scale for the region with enhanced super-currents in film ‘B’. Equation (1) leads to a linear fit of the data in this representation. Extraction of the slope allows the calculation of the pinning energy \( U_0 \). A local determination of the values of \( U_0 \) in pristine and irradiated areas of film ‘B’ are performed for more than 1000 data points in each area. The calculated values of \( U_0 \) are summarized in the histogram displayed in the right panel of figure 6.

For the YBCO film on pristine substrate areas we find a distribution of vortex pinning energies around a peak value of \( U_0 = 109 \text{ meV} \) displayed in red in the histogram. A full width at half maximum (FWHM) of 11 meV is found. The variation of pinning energies is basically related to variations in the vortex density [23]. The green histogram depicts the pinning energies of vortices in the superconductor grown on the irradiated part of the substrate. The average pinning energies are enhanced to \( U_0 = 119 \text{ meV} \) with a FWHM of 14 meV. Interesting is the fact that the distribution has a pronounced tail at higher pinning energies up to 140 meV. This shows that the additional microstructural variation introduced by the substrate structures leads to a variety of different pinning sites partly exhibiting larger depths in the energy landscape of flux lines. However, the current density that is found in the modified region does not show larger variations than in the unmodified areas. This shows that pinning forces and pinning energies often provide complementary information on the properties of a superconductor.

5. Anisotropic superconductors

Another class of superconductors exhibiting complex transport properties is defined by thin YBCO films with anisotropic characteristics. Film ‘C’ is grown on a vicinal cut (106) substrate and exhibits a strong anisotropic defect structure containing linearly arranged anti-phase boundaries along a distinguished direction [18]. Temperature-dependent magneto-optical images obtained in the remanent state and converted into a map of current densities are shown in figure 7. The four top images show the current density pattern as gray scale image at \( T = 20 \text{ K}, T = 40 \text{ K}, T = 60 \text{ K} \) and \( T = 80 \text{ K} \) (from left to right). The profiles below are extracted along the solid horizontal lines. In addition the extracted current density...
versus temperature and the corresponding anisotropy are depicted below.

A close look on the gray scale images in the top part of figure 7 shows that the geometry of the current pattern is changing with temperature. At \( T = 20 \text{ K} \) the current domains with a current density \( j_{\text{par}} \) parallel to the substrate structures is small and narrow, nearly the whole film is filled by the domains with currents \( j_{\text{perp}} \) perpendicular to the structures. When increasing the temperature the areas of \( j_{\text{par}} \) grow and finally at \( T = 80 \text{ K} \) all four domains exhibit nearly the same size. A more detailed view is found when calculating the local properties \( j_{\text{par}} \) and \( j_{\text{perp}} \) extracted again at the neutral lines and plotting them versus temperature. This is done in the bottom left panel of figure 7. A large difference between parallel and perpendicular current direction is found at low temperatures. The parallel component reaches values that typically exceed current densities that are found in isotropic films [26] which can be explained by effective pinning at the planar defect structures [27]. With increasing temperature the difference between both directions decreases and finally vanishes towards \( T_c \) [19]. The calculated anisotropy values refer to the ratio of \( j_{\text{perp}} \) and \( j_{\text{par}} \), the geometrical analysis uses the angle of the discontinuity lines that arise from the films edges. Both the calculated and the geometrically determined anisotropy are displayed in the bottom right of figure 7. The properties exhibit the identical temperature dependence. A value for the anisotropy of about three is found for low temperatures and towards \( T_c \) the anisotropy vanishes.

When regarding the time evolution of parallel and perpendicular current components in anisotropic superconductors an interesting effect can be found. Figure 8 depicts the time-dependent decay of the current density \( j_{\text{perp}} \) and \( j_{\text{par}} \) flowing parallel and perpendicular to the antiphase boundaries in a YBCO film on a vicinal cut substrate in the category ‘C’. This film exhibits an even higher anisotropy as the previous film of category ‘C’. The data are measured by quantitative magneto-optical imaging and are again acquired after preparation of the critical state in the self-field of the superconductor. The black dots refer to individual measurements performed in time intervals of about \( \Delta \tau \approx 4 \text{ s} \), the solid red lines give the average over 20 data points, respectively. The occurring noise is mainly due to fluctuations of the illumination in combination with short exposure times.

Figure 8 shows a dramatic difference in the time evolution along the two directions. The large current density \( j_{\text{par}} \) that arises from efficient vortex pinning at the anti-phase boundaries in films on vicinal cut surfaces exhibits a substantial decay by thermally activated flux line motion. The current density decreases by about 4%–5% within the first 600 s after preparation of the critical state even at low temperatures of \( T = 7 \text{ K} \). The time evolution of the supercurrents

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**Figure 7.** Temperature-dependent current density distribution in film ‘C’. The top row depicts the magneto-optically determined magnitude of the supercurrent density for temperatures \( T = 20 \text{ K}, \ T = 40 \text{ K}, \ T = 60 \text{ K} \) and \( T = 80 \text{ K} \). The profiles below are extracted along the solid horizontal lines. The diagrams below depict the temperature-dependent current density in horizontal (\( j_{\text{perp}} \)) and in vertical (\( j_{\text{par}} \)) direction (left) and the temperature-dependent anisotropy (right). The anisotropy is calculated both from the current density ratio (open symbols) and from the geometry of the discontinuity lines (black, solid squares).
across the antiphase boundaries shows a completely different behavior, nearly no decay can be observed within the first 600 s. This gives rise to the fact that thermally activated depinning plays only a minor role along this direction. In addition the relaxation along both directions is drastically reduced compared to the typical relaxation that is found in isotropic YBCO thin films. This finding is very surprising because it means that the corresponding pinning energies are higher in case of the parallel component. Nevertheless, a much smaller current density is found along this direction. This apparent contradiction can be solved when distinguishing between pinning forces and pinning energies. At low temperatures the critical current is determined by the pinning force density in the material given by gradient of the energy landscape of vortices \[13\]. This pinning force density is at low fields directly proportional to the supercurrent density. However, thermally activated vortex depinning governing the decay of the supercurrent is related to the pinning energy of a vortex. As a consequence, an analysis of both the observed current densities and the corresponding time decay provides complementary information on the relevant pinning scenario. The depth and the slope of pinning sites within the energy landscape of a vortex can be addressed nearly individually. This combination can be used to create a microscopic model of the (anisotropic) pinning landscape at least for low magnetic fields.

Summarizing all locally performed measurements of \( j_{\text{par}} \) and \( j_{\text{perp}} \) in YBCO films on vicinal cut substrates we find that the current anisotropy is largest at low temperatures and directly after preparation of the critical state. With increasing temperature and due to thermally activated vortex motion the anisotropy substantially decreases.

6. Conclusion

We have shown that magneto-optical measurements performed at thin YBCO films with either inhomogeneous or anisotropic current densities allow a detailed analysis of the temperature dependence and the time evolution of supercurrents controlled by local vortex pinning. Magneto-optical imaging provides spatially resolved, quantitative data of local current densities, current directions and pinning properties. This information cannot be extracted from global magnetization experiments such as SQUID magnetometry. From the local current density data we could determine the change of the pinning energy distribution by substrate originated defect structures. We could show that the supercurrent anisotropy in films with planar defect structures decreases at higher temperatures and due to thermal relaxation. The comparison of isotropic and anisotropic films in particular showed that it is necessary to distinguish between pinning forces densities and pinning energies to fully describe the behavior of superconducting films in external magnetic fields.

Figure 8. Time evolution of the current density after preparation of the remanent state in a thin YBCO film of category ‘C’ on a vicinal cut surface. The left plot depicts the time dependent decay of the current density \( j_{\text{perp}} \) flowing parallel to the surface steps of the substrate, the right curve shows the same plot for the current density \( j_{\text{par}} \). The data are extracted from quantitative magneto-optical measurements at \( T = 7 \text{ K} \) and are depicted for the first 600 s after preparation of the critical state.
fields. With respect to applications of superconducting materials that often use inhomogeneous or anisotropic materials the magneto-optical technique offers a unique possibility for a quantitative characterization of the local supercurrent transport. In particular, the method allows the full analysis of local electric transport on small length and time scales even for complex and sophisticated geometries in thin superconducting films.

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