Patterned Irradiation of YBa$_2$Cu$_3$O$_{7-x}$ Thin Films

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We present a new experiment on YBa$_2$Cu$_3$O$_{7-x}$ thin films using spatially resolved heavy ion irradiation. Structures consisting of a periodic array of strong and weak pinning channels were created with the help of metal masks. The channels formed an angle of ±45° with respect to the symmetry axis of the photolithographically patterned structures. Investigations of the anisotropic transport properties of these structures were performed. We found striking resemblance to guided vortex motion as it was observed in YBa$_2$Cu$_3$O$_{7-x}$ single crystals containing an array of unidirected twin boundaries. The use of two additional test bridges allowed to determine in parallel the resistivities of the irradiated and unirradiated parts as well as the respective current-voltage characteristics. These measurements provided the input parameters for a numerical simulation of the potential distribution of the Hall patterning. In contrast to the unidirected twin boundaries in our experiment both strong and weak pinning regions are spatially extended. The interfaces between unirradiated and irradiated regions therefore form a Bose-glass contact. The experimentally observed magnetic field dependence of the transverse voltage vanishes faster than expected from the numerical simulation and we interpret this as a hydrodynamical interaction between a Bose-glass phase and a vortex liquid.

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I. INTRODUCTION

Heavy ion irradiation has proved to be a powerful method to investigate the vortex dynamics of the high temperature superconductors (HTSC). The introduced columnar defects (CD) are the most effective pinning centers and as a result of heavy ion irradiation the critical current density is increased. But beside this technological relevance the pinning properties of CD have a strong influence on the dynamics of vortices. Based on the theory of collective pinning and the vortex glass model of Fisher, Fisher and Huse (FFH) a Bose-glass phase transition is predicted by Nelson and Vinokur for the HTSC compounds in the presence of correlated disorder. The underlying scaling theory is characterized by universal dynamic and static critical exponents $z'$ and $\nu_\perp$ that describe the divergence of the glass correlation length $l_\perp(T)$ and the relaxation time $\tau$ at the characteristic glass temperature $T_{BG}$. One transport coefficient that is related to this glass transition is the shear viscosity $\eta$, controlled by the dynamic critical exponent $z'$ via $\eta \propto |T - T_{BG}|^{-z'}$ (Ref. 5). The divergence of the shear viscosity of the vortex liquid was shown on approaching the melting transition temperature of the vortex lattice.

A different realization of correlated defects is found in twin boundaries in YBa$_2$Cu$_3$O$_{7-x}$ (YBCO) single crystals. Their influence on the vortex dynamics was extensively studied during the last years in YBCO single crystals with unidirected twin boundaries (TB) using electrical transport measurements, ac screening experiments, simulation and analytical methods. For the case that the twin boundaries form an angle $\theta$ with the direction of an applied external current, the vortices feel an anisotropic pinning force. This leads to a guided vortex motion (GVM) that can be detected in measuring the even transverse voltage in the presence of an external magnetic field. In literature, two different mechanisms are proposed to be responsible for the guided motion of vortices in unidirected twins. In the first, vortices will be channeled by the deep pinning potential of the TB and will move in the TB (internal motion), whereas the second mechanism assumes the vortex-vortex interaction to be the dominating mechanism for a guided vortex motion also outside the TB (external motion).

The present work shows a new experiment to address the question of GVM. We create strong and weak pinning channels in YBCO thin films using heavy ion irradiation through patterned metal masks consisting of an array of fine stripes. The effects of homogeneous irradiation are analyzed using irradiated and unirradiated reference bridges on the same sample. The transverse voltage on a Hall bar structure shows a strong correspondence to that in YBCO single crystals with unidirected TB. However, in our experiment the weak pinning channels have a macroscopic width in contrast to the very narrow channels formed by twin boundaries. This results in a nontrivial current density distribution in the samples that is modelled using the longitudinal resistivities. Another difference to the planar TBs is that in our case the CDs are line-like pinning centers. Therefore a GVM can only result from vortex-vortex interaction at the interface of strong and weak pinning regions. If the interaction length becomes large the pinned vortices in the irradiated channels should induce a freezing of free
vortices in the unirradiated channels. At this freezing transition the GVM vanishes. Thus, the arrangement of strong and weak pinning regions represents a Bose-glass contact. A Bose-glass contact was introduced by Marchetti et al. in the definition of a new generation of experiments in order to study the Bose-glass transition in a hydrodynamical context. The voltage current characteristics of both test bridges was investigated in order to study the correlations between GVM effect and the Bose-glass transition.

II. SAMPLE PREPARATION

YBCO thin films have been prepared using the dc sputtering technique. The characterization with X-ray diffraction and scanning electron microscopy shows epitaxial growth and homogeneous surfaces of the films. The samples were patterned with standard photolithography and wet chemical etching into a conventional Hall structure (2 mm × 7 mm) and two identical test bridges (200 μm × 2000 μm). The irradiation of the samples was performed at the UNILAC of the Gesellschaft für Schwerionenforschung, GSI. The samples were irradiated with 0.75 GeV Pb-ions and 1.14 GeV U-ions in such a way that CD were arranged in a periodic array of strong (irradiated) and weak (unirradiated) pinning regions. Differently patterned 0.5 mm thick Ni-masks were used in order to stop the swift ions and to reproduce the irradiation pattern on the thin film structure.

Two arrangements were used in this experiment which differ only in the width of the irradiated channels that is 700 μm (1:7 ratio) and 400 μm (1:4 ratio) respectively, whereas the width of the weak pinning channel is 100 μm for each case. The angle θ between the edges of the Hall structure and the direction of the weak pinning channels is ±45°. In addition, one test bridge was irradiated entirely with the same ion dose (B_φ = 1.0 T ≡ 5 × 10^{10} Ions/cm²) as the Hall structure. Sample and irradiation geometry are sketched in Fig. 1 for the Hall structure with the 1:7 ratio. All samples show sharp resistive zero field transitions (ΔT < 1 K) for both, the irradiated and unirradiated test bridges with critical temperatures of T_c ≈ 91 K. The efficiency of the metal masks in the patterned irradiation was analyzed using glass substrates that were irradiated through the masks with a dose of approximately 3 × 10^{6} Ions/cm². To visualize the defects, the glass substrates were etched with 18% HF for 20 s. A result of this procedure is shown in Fig. 2 for the 1:7 ratio. The width of the weak pinning channels is 110 μm, the periodic length of the irradiation pattern is 820 μm. Higher image resolutions show that the defect concentration has a step-like behavior at the interfaces between strong and weak pinning. Less than 2% of the ions are scattered in a 5 μm wide region of the unirradiated channels in both experimental arrangements.

III. EXPERIMENT

Measurements of the voltage drop across different contacts of the Hall structure were performed for temperatures from 300 K to 70 K and magnetic fields up to 12 T at a constant current density of J = 125 A/cm². The various contacts allow to measure the voltage drop in different directions with respect to the direction of the weak pinning channels and the external current. In addition, the two parts of the test bridge allow to determine in parallel the voltage drop over a completely irradiated and unirradiated part of the sample for all parameters used in the measurement. These results represent the input values for scaled resistor network representations of the periodically irradiated Hall structures with the different arrangements. Based on Kirchhoff’s laws, it is then possible to calculate the potential distribution at the borders of the Hall structures and to compare the calculated with the measured results. Another advantage of this experimental set is the possibility to measure the current-voltage characteristics of both, the unirradiated and irradiated part of the film. Based on this information one can carry out a glass analysis in order to determine the characteristic fields and temperatures of the vortex dynamics for both test bridges.

IV. RESULTS

The resistive transitions of the irradiated Hall structure have been measured for different directions of the voltage drop with respect to the external current direction in zero field. In an unirradiated sample transverse voltages are negligible in zero field and one should observe a monotonously vanishing voltage signal along all contact configurations containing a longitudinal component. Measuring the configurations connecting contacts 1 and 3 (V_{13}) (see Fig. 3) should yield identical results as testing V_{23}, V_{14}, or V_{23}, respectively. In the patterned irradiation geometry the symmetry of the contact configuration is broken. The resistive transition measured using V_{14} shows a maximum at 91.88 K and using V_{23} one even observes a sign reversal. The network calculation reproduces these unusual features for both contact configurations. Figure 3 shows the temperature dependence of V_{14} and V_{23} together with the corresponding calculations. The existence of a sign reversal for V_{23} is obvious from the potential distribution sketched in the inset. It shows the equipotential lines across the 1:7 ratio structure resulting from the network calculation at T = 91.88 K. By measuring the two indicated directions, the number of lines that are crossed differs due to the arrangement of the strong and weak pinning channels. Following the dashed line, i.e. V_{14}, the equipotential lines are only crossed in the positive current direction, whereas this is not the case for the contacts of the solid line (V_{23}).

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If the voltage drop for fixed temperatures is measured during magnetic field sweeps (−12 T < μ0H < 12 T), the consistency between calculation and measurement holds for the longitudinal voltages as well as for the transverse case. The network calculation does not include the asymmetric part of the transverse voltages V_{t\text{odd}} that can be measured for inversion of the magnetic field due to the Hall effect. However, here we are interested in the GVM due to anisotropic pinning forces. This shows up as a transverse voltage, symmetric with respect to the field direction 

\[ V_{t\text{even}} = \frac{V_{12}^t(+H) + V_{12}^t(-H)}{2}. \] (1)

This procedure eliminates the asymmetric Hall contributions. The magnetic field dependence of V_{t\text{even}} at different temperatures is shown in Fig. 3 for the 1:7 ratio structure and in Fig. 4 for the 1:4 ratio structure, respectively. Both samples show the same behavior, except for the fact that the angle θ describing the direction of the weak pinning channels is +45° in one and −45° in the other case. This results in negative and positive values for V_{t\text{even}} as can be directly seen from the calculation of the potential distribution (e.g. inset of Fig. 2) for the case of θ = ±45°. For magnetic fields μ0H > 3 T, the absolute value decreases with decreasing field. For smaller fields, an increase of |V_{t\text{even}}| which has a maximum at μ0Hm followed by a sharp transition to V_{t\text{even}} = 0 at μ0H0 can be observed. The characteristic field μ0Hm increases and |V_{t\text{even}}(μ0Hm)| decreases with decreasing temperature. This behavior is exactly the same as observed in YBCO single crystals with unidirected twin boundaries. Thus, these results are a first indication for GVM in periodically irradiated YBCO films. Compared to YBCO single crystals one should note that the length scale of both experiments is very different. The usual periodic length in TB experiments is about 1 μm to 10 μm whereas the experiment here was performed on a length scale that is two orders of magnitude larger. In spite of this huge difference the results obtained in both cases are comparable. At high field values in our experiment the resistivity of the unirradiated regions of the film is close to the normal state resistivity, which is nearly the same for both regions and therefore no transverse voltage should occur. For single crystals in the normal state the twin boundaries only marginally influence the total resistivity and accordingly the transverse voltage vanishes. Experimentally small values of V_{t\text{even}} are observed in both cases which are attributed to a small longitudinal contribution. For temperatures below Tc and low magnetic fields again no transverse voltage is observed in both experiments. Clearly in this temperature and field range the vortex system becomes rigid and the longitudinal resistivity vanishes in the whole sample enforcing zero transverse voltage.

Therefore, we focus in the following on the intermediate field range where a pronounced maximum of V_{t\text{even}} is observed. Our calculation reproduces quantitatively the maximum in the magnetic field dependence of V_{t\text{even}} as shown in Fig. 4. The existence of this maximum was already verified in an analytical approach by Shklovskij et al. They used an effective medium approach to calculate the averaged resistivity of YBCO crystals containing dense arrays of unidirected twin planes. However, in our case we only have a small number of weak pinning channels and an effective medium theory is not appropriate. A second point to mention is that possible nonlinearities of the current-voltage characteristics (CVCs) have to be taken into account. This is done by using identical current densities for the reference bridges and the Hall structures. In this case the continuity condition for the current eliminates nonlinear effects in first approximation. Compared to the calculated values for V_{t\text{even}} the experimentally determined values show deviations for high and low fields. At high fields, the influence of the limited lateral resolution of the photolithographically patterned voltage probes leads to a residual longitudinal voltage. This can be included in the network calculations and one can show that this contribution is negligible at fields below μ0Hm. More interesting are the deviations for H < H0 where the transition to V_{t\text{even}} = 0 appears. The logarithmic illustration of Fig. 5 indicates that the measured value is nearly one order of magnitude smaller than the corresponding calculated value expected from the longitudinal resistivities of the reference bridges. We believe that this discrepancy is due to the interaction between pinned flux lines in the irradiated channels and vortices in the weak pinning channels as will be discussed below.

A further interpretation of these results requires a detailed analysis of the different vortex states in the irradiated Hall structure. A straightforward access to this problem is the analysis of the current-voltage characteristics of the test bridges. Figure 5 shows such a set of curves for the irradiated part of the test bridge and a magnetic field of μ0H = 1 T. The Bose-glass temperature TBG of the irradiated and the vortex glass temperature TVG of the unirradiated test bridge were determined using scaling analysis.

While vortex-glass and Bose-glass represent two distinct physical phenomena the scaling relations are mathematically equivalent but differ in the critical exponents. In both cases the T − V curve that separates the glassy from the fluid regime gives a power law dependence over the whole current range. For the Bose-glass case this relation between electric field E and current density J is given by

\[ E \propto J^{(z'+1)/3}, \] (2)\

where z′ is the dynamic exponent of the Bose-glass transition. Starting with a scaling ansatz

\[ E \propto l_\perp^{(z'+1)} J l_\parallel (J l_\perp l_\parallel) \] (3)
and supposing that the parallel glass correlation length $l_\parallel$ is proportional to $l_\parallel^2$ (three-dimensional case), one can plot all the $I - V$ curves lying below the dashed lines in Fig. 3. Such a scaling is shown in Fig. 5 for the irradiated test bridge at $\mu_0H = 1$ T. For $\nu' = 7.5(2)$ and $\nu'_\perp = 0.94(2)$, all $I - V$ curves in question collapse onto two branches that are separated by $T_{BG} = 89.8(3)$ K.

Analyzing the Bose-glass transition for different magnetic fields, one obtains the irreversibility line defined by $T_{BG}(B)$. The temperature dependence of the characteristic field $B_{BG}(T)$ is shown in Fig. 6 (open squares) together with the $B_{VG}(T)$-behavior of the unirradiated test bridge (open circles). It is in qualitative accordance with $H(T)$ diagrams obtained in experiments that reveal the influence of correlated defects on the vortex system.

In addition, the characteristic points of $V'_{\text{even}}(B)$ for different temperatures shown in Fig. 3 are plotted. The magnetic fields $B_{\text{max}}$ at which $V'_{\text{even}}$ reaches its maximum (filled up triangles) and $B_0$ where $V'_{\text{even}}$ disappears (filled down triangles) are two important features.

The first information one can extract from this diagram is that the maximum of $V'_{\text{even}}$ appears for fields and temperatures above the irreversibility line of the irradiated test bridge. A comparison between the 1:4-ratio and the 1:7-ratio structure shows that the temperature dependence of $B_{\text{max}}$ is proportional to $T/T_{\text{crit}}^\ast$, where $T_{\text{crit}}^\ast$ is the critical temperature of the irradiated test bridge in zero field. Thus, the peaks in the field dependence of $V'_{\text{even}}$ appear in the flux flow regime as shown in Fig. 3 and Fig. 2.

The analysis of the temperature and magnetic field behavior of $V'_{\text{even}} = 0$ is the second point to be discussed in this context. In the phase diagram the obtained data points for $B_0(T)$ can be found between the irreversibility lines of irradiated and unirradiated test bridges. However, the position of the $(B_0(T))$-line with respect to the test bridge results depends on the ratio between the widths of both, strong and weak pinning channels. For the 1:7 ratio structure the irradiated channels are dominant and the $(B_0(T))$-line coincides with the irreversibility line of the irradiated test bridge. The situation is different for the Hall structure with the 1:4 ratio. In this case, the $(B_0(T))$-line is shifted towards lower fields and lower temperatures.

To explain these results, a hydrodynamic approach at the vortex Bose-glass transition as proposed by Marchetti and Nelson is considered. This approach is based on two heavily irradiated Bose-glass contacts that sandwich a weak pinning channel. Viewing on the potential distribution sketched in the inset of Fig. 3 shows that our experiment represents this scenario. The different glass temperatures lead to a vortex motion in the weak pinning channel whereas the vortices in the strong pinning regions are trapped, acting like a barrier for the free vortices. The influence of the Bose-glass contacts can be described by a viscous length $\delta$, depending on the flux liquid viscosity $\mu$. A further analysis shows that $\delta$ is the Bose-glass correlation length $l_\perp$ (Ref. 4). Therefore, the borders of a weak pinning channel can be understood as a Bose-glass contact and we interpret the results of Fig. 3 and Fig. 4 in this sense. The vanishing transverse resistivity at $B_0(T)$ indicates the transition into a glass phase in the weak pinning channels at fields well above $B_{VG}$. This is underlined by the comparison between the measured and calculated magnetic field dependence of $V'_{\text{even}}$. The transition to $V'_{\text{even}} = 0$ is measured for higher fields than the calculated transition, indicating that the divergence of the shear viscosity $\eta$ depends on whether strong and weak pinning regions are independent or, as in the case of the Hall structures and Bose-glass contacts, depends on the interaction between vortices in both regions. The length scale set by this interaction can be macroscopic and is described by the viscous length $\delta$.

This result is consistent with other experiments carried out on this field of research. The diverging correlation length of the vortex system near the melting transition was already predicted by Nelson and Halperin for $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystals being irradiated similarly to the samples used in this experiment. Pastoriza et al. pointed out that the characteristic features of the melting transition can be observed when the correlation length is comparable to the dimensions of the width of the unirradiated channel (in this case $\approx 10 \mu m$). Experiments in the Corbino disk geometry give an estimation of the order of magnitude of the dynamic correlations between vortices in YBCO single crystals. López and co-workers report of a correlation length with macroscopic dimensions. The voltage probes they used to obtain these results have distances of $60 \mu m$ which is in good agreement to the dimensions of the unirradiated channels in the experiment described above.

**V. CONCLUSION**

In summary, we have investigated the vortex dynamics in periodically irradiated YBCO thin films for $100 \mu m$ wide unirradiated channels forming an angle of $\pm 45^\circ$ with the direction of an external current. Compared to experiments on single crystals with unidirected TB this method is not limited on YBCO and can also be applied to other HTSC thin films and single crystals. Another important advantage of the described method is that there are no restrictions to the geometry of the heavy ion irradiation pattern. The even transverse voltage gives clear indications for a guided motion of the vortices in such systems as it was observed in recent experiments on YBCO single crystals with unidirected twin boundaries.

With the aid of an irradiated and an unirradiated test bridge it was possible to gain input parameters for a numerical simulation of the potential distribution and to analyze the current-voltage characteristics of both the strong and weak pinning parts, respectively. Based on these results, the existence of a Bose-glass contact in the periodically irradiated samples was assumed and the ob-
tained $B - T$ phase diagram was interpreted in a hydro-
dynamical approach near the Bose-glass transition.

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FIG. 1. Sample and irradiation geometry of the 1:7 ratio structure. The upper part shows the two test bridges. Grey regions are irradiated.
FIG. 2. Image of an irradiated glass substrate that was etched in 18% HF for 20 s. For the structure with the 1:7 ratio that is shown here, the channel width is 110 µm for the unirradiated and 710 µm for the irradiated regions.

![Image of an irradiated glass substrate]

FIG. 3. Voltage drop between two contact pairs of different direction with respect to the applied current density for the structure with the 1:7 ratio. The solid line (calculated data) corresponds to the open circles (measured results), the dashed line to open squares. Measured and calculated data are normalized to its corresponding value at $T = 95$ K. The position of the contacts is sketched schematically in the inset. In this sample $T_c$ differs by 0.14 K between test bridges and Hall structure, visible as a shift in the local extrema between calculated and measured curves. The inset shows the measurement geometry as well as the equipotential lines for $T = 91.88$ K.

![Graph of voltage drop vs. temperature]

FIG. 4. Even transverse voltage for temperatures below $T_c$ in the case of the 1:7 ratio structure. The curve is characteristic for the GVM and was also observed for YBCO single crystals with unidirected TB. The characteristic fields are considered to be $\mu_0 H_m$ where $V_{\text{even}}^\alpha$ reaches its maximum and $\mu_0 H_0$ where it vanishes.

![Graph of even transverse voltage vs. magnetic field]

FIG. 5. Even transverse voltage of the Hall-structure with 1:4 ratio at a temperature of 88 K. Near the transition to $V_{\text{even}}^\alpha = 0$ calculated and measured values differ by one order of magnitude. The inset shows a linear plot of the transition. The deviation for high magnetic fields is discussed in the text.

![Graph of even transverse voltage vs. current]

FIG. 6. Current-voltage characteristics of the irradiated test bridge for a magnetic field $\mu_0 H = 1$ T and temperatures between 91 K and 80 K. The dashed lines border the region that was used for the Bose-glass scaling shown in Fig. 7.

![Graph of current-voltage characteristics]

**Equation**: 

$\log \frac{E}{J} \bigg|_{T_B G - T}^{-3\gamma} = \log J \bigg|_{T_B G - T}^{-3\gamma}$
FIG. 7. Bose-glass scaling of the $I - V$ curves of Fig. 6 in accordance with Eq. 3. Good scaling is achieved with $T_{BG} = 89.8(3)$ K, $\nu \parallel = 0.94(2)$ and $z' = 7.5(2)$ and the determined critical exponents are in agreement with theoretical predictions.

FIG. 8. Temperature dependent characteristic fields of the irradiated (open squares, $B_{BG}(T)$) and unirradiated (open circles, $B_{VG}(T)$) test bridge. In addition, $B_0(T)$ revealing from the magnetoresistive measurements of $V_{even}$ for the 1:4 ratio structure is plotted (filled down triangles) together with the $B_{max}(T)$ dependence (filled up triangles). The position and the behavior of the $B_0(T)$ curve in the phase diagram corresponds to predictions that were made for a Bose-glass contact.