Averaged effective pinning potential in YBCO single crystals near T_c

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The dynamics of magnetic flux trapped in low dc magnetic fields (of the order of the Earth's field) was for the first time studied experimentally in single-crystal YBCO samples with unidirectional twin boundaries in the temperature range near T_c ($0.8 < T/T_c < 0.99$). Strong pinning in the system of unidirectional planar defects was demonstrated, and a significant deviation from monotonous behavior was established for the averaged effective pinning potential $U_p(T)$ for the trapped flux of low density. In order to compare different methods of J_c determination, the field dependences of the magnetization loop width $M(H)$, which are related to the effective pinning and J_c, were obtained, and resistive measurements on microbridges made from the same single crystals were carried out. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4896727]

1. The literature on the dynamics of magnetic flux in high-temperature superconductors (HTSC) is predominantly focused on clarifying the transformation processes in the vortex lattice and its interactions with the sample crystal structure, which determine the limiting current-carrying characteristics of superconductors in high magnetic fields.[1,2] The region of low dc magnetic fields of the order of the Earth's field and the temperature range near the critical temperature (T_c) remain the least studied. With regard to magnetometric measurements, this is due to a decrease in the response signals, which are proportional to an applied field, and an increase in the noise caused by significant thermal fluctuations in this temperature range. Despite a large amount of theoretical and experimental studies on the structure and dynamics of the magnetic flux in HTSC, to date there is no complete picture of complex and interrelated processes of pinning and creep.[3]

Motion of trapped magnetic fluxes associated with the creep and jumps of single vortices and their bundles depends on the pinning on structural defects of the samples and determined by the thermal activation energy for these metastable processes. The probability of jumps for the magnetic vortices increases exponentially with increasing temperature and decreasing the pinning force, so the microstructure of the HTSC material, which determines the landscape of the pinning potential, plays a crucial role in the dynamics of magnetic flux and the appearance of dissipative processes.

In the present communication we report on studies of the pinning behavior of low-density magnetic fluxes. The studies were carried out using the measurements of the isothermal relaxation of magnetization $M(t)$ in impurity-free single-crystal $YBa_2Cu_3O_{7-x}$ (YBCO) samples near the superconducting phase transition. Using the obtained data and applying well-known model relations, the effective pinning potential (U_p) and its temperature dependence were evaluated. In the region $0.8 < T/T_c < 0.99$, we established a significant non-monotonicity of a decrease in the averaged effective potential with increasing T. This may reflect a competing effect of the processes changing the potential depth of pinning centers and an increase in the creep in HTSC as the temperature approaches T_c.

2. The studies were carried out on oriented YBCO single crystals of optimal oxygenation with the dimensions of the order of 1×1 mm (along the a and b axes) and the thickness (along the c-axis) $\sim$0.02 mm, in which the unidirectional twin boundaries (TB) were oriented parallel to the c-axis of the crystal throughout its thickness. Non-contact SQUID magnetometer method for measuring the magnetic moment, which was employed in this study, provides the necessary sensitivity of $\approx 8 \times 10^{-11}$ A·m^2. At the same time, the stability of the sample temperature set in the experiment was $\approx$5 mK in the range 50–95 K.

The residual magnetic moment arises due to the field trapped in the sample during field cooling (FC). At the same time, the role of the surface energy barriers in the dynamics of magnetic flux is minimal.[1,2] Thermally activated creep of individual vortices and their bundles leads to the redistribution and damping of supercurrents, and the averaged magnetization M of the superconducting sample begins to relax.[2]

Data on the dynamics of magnetic flux in superconductors are used to obtain the most important parameters of vortex pinning in high-temperature superconductors, specifically the averaged effective depth of the pinning potential (U_p). In the simplest case, it can be estimated from the calculation of the normalized rate of isothermal magnetization relaxation S, which, in the linear Anderson-Kim model, is related with U_p through the expression

$$S = 1/M_0(dM/d\ln t) = -kT/U_p. \qquad (1)$$

Most of published studies of the magnetization relaxation in HTSC have been carried out in strong magnetic fields (of the order of several kOe), in which an important role is played by the processes of interaction within a dense, well established lattice of magnetic vortices, and the pinning parameters are determined by inter-vortex interaction.

3. Figure 1(a) shows the curves of isothermal magnetization relaxation for the single crystal under study. The curves are normalized to the initial value M_0 obtained near the superconducting phase transition ($T_c^{\text{onset}} = 92.8$ K). When $T \to T_c$, strong thermal fluctuations cause a giant creep of vortices and their bundles, and, in fact, the state of vortex liquid is observed. In the studied sample, the decline of residual

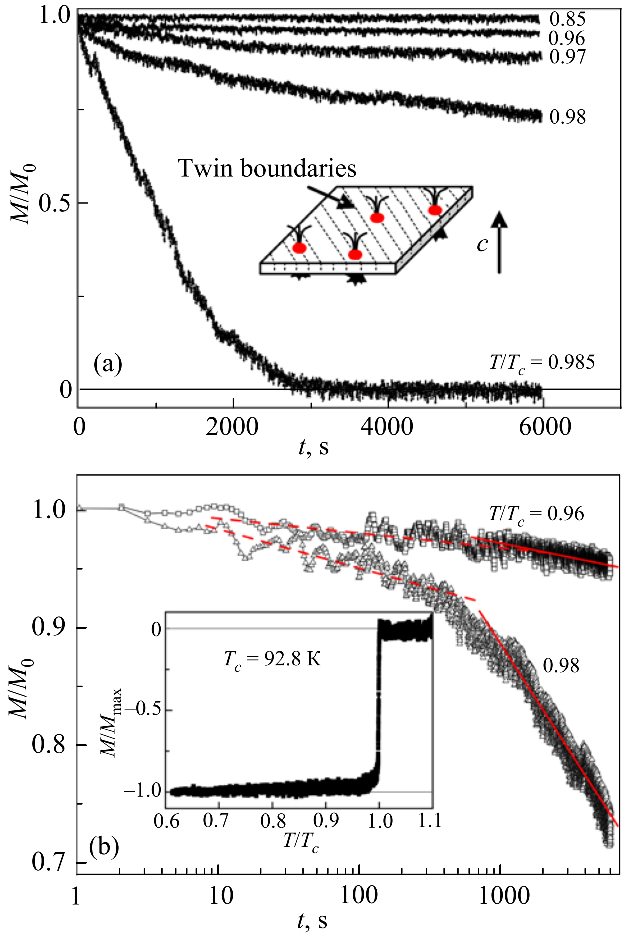

FIG. 1. (a) Typical isothermal relaxation curves of the normalized magnetization $M(t)/M_0$ for one of the studied YBCO single crystals with unidirectional twin boundaries at several temperatures. The inset shows schematically the sample geometry and trapped vortices. (b) Experimental data $M(t)/M_0$, plotted in a semilogarithmic scale, and a method for estimating U_p using a linear model. For illustration purposes, the inset shows the superconducting phase transition for the sample studied.

magnetization to zero, i.e., the complete escape of trapped flux, was observed at a temperature of 91.4 K. The magnetic field of the solenoid in the experiment was directed along the *c*-axis of the single crystal and was equal to 160 A/m (≈2 Oe). In this orientation, the field is parallel to the twin boundary (TB) planes of the crystal, and the pinning of Abrikosov vortices occurs most effectively. The inset in Fig. 1 shows schematically and not to scale the geometry and characteristics of the crystal structure of a typical sample containing Abrikosov vortices pinned on TB. Fig. 1(b) shows the experimental data obtained for two different temperatures and plotted in semi-logarithmic coordinates. The dashed lines overlaid with the curves demonstrate the technique for calculating S using Eq. (1) in two different time-ranges. The inset shows the normalized temperature dependence M/M_{max}—the diamagnetic response of the single crystalline sample in the vicinity of superconducting phase transition.

The twin boundaries contain CuO_x layers with oxygen vacancies, and the dislocations located along their planes locally suppress the superconducting order parameter, leading to the appearance of effective pinning centers. From the measurement data of the isothermal magnetization relaxation, using Eq. (1), we evaluated the effective pinning potential averaged over the sample volume and its dependence on temperature (see Fig. 2(a)). In comparison with previously available data, for example, those published in Refs. 2 and 4, this temperature range was investigated for the first time in such detail and new types of behaviour were established. First, a significant increase in the absolute value of the effective pinning potential was observed, reaching tens of eV in the initial part of the investigated temperature range. Second, a significantly non-monotonic dependence $U_p(T)$ was observed, which cannot be attributed to a structural rearrangement of the vortex lattice.[5]

An increase in the absolute value of U_p which was registered in our experiments can be attributed to the poorly studied dependence of the pinning potential on the magnetic field and induced currents in the sample.[6] Small dc fields and hence a low density of the trapped magnetic flux allowed us to explore the initial segment of the $U_p(H,J)$ dependence, where the presence of a maximum is expected in the non-linear model.[1,2] The observed non-monotonic decrease in the effective pinning as temperature approaches T_c can be attributed, on the one hand, to the competing processes increasing the thermal activation energy of creep, and, on the other hand, to the increasing depth of the pinning center potential at crystallographic defects in HTSC and the possible emergence of local normal phases on twinning boundaries.

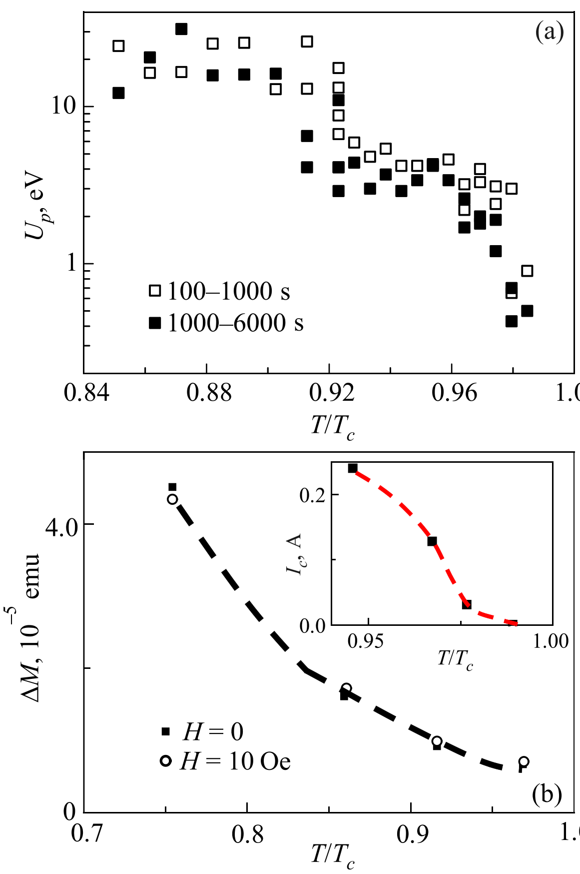

FIG. 2. (a) Temperature behavior of the averaged effective pinning potential (the experimental points corresponding to different time windows within which U_p was evaluated, are shown with empty and filled squares). (b) Dependence of the magnetization loop width ΔM, which is proportional to the average pinning force, on the normalized temperature near the low-field region. The inset shows the critical current data obtained by resistivity measurements on the same YBCO single-crystal.

The critical current density J_c, which is related to the averaged value of the pinning potential U_p, is an important parameter of an HTSC material. J_c can be evaluated by either contact resistivity or contactless magnetometric methods. To compare the $U_p(T)$ dependences established from the data on isothermal relaxation of the magnetization, the width of the magnetization loops $M(H)$, which is proportional to the effective pinning force, was measured for the investigated sample.[2] Fig. 2(b) shows the comparison of the obtained data on the loop width $\Delta M(T/T_c)$ with the data from resistive measurements of the critical current of a microbridge cut from the same single crystal. As can be seen in Fig. 2, in the temperature range studied, the temperature behavior of the critical current in an YBCO single crystal, assessed by three different methods, is qualitatively the same.

Conclusion

For the first time, the dynamics of magnetic flux trapped in low dc magnetic fields in single-crystal YBCO samples with unidirectional twin boundaries was studied in the temperature region near T_c. The presence of strong pinning on a system of unidirectional planar defects associated with twin boundaries was demonstrated, and significant nonmonotonicity of the behavior of the averaged effective pinning potential $U_p(T)$ was established for low-density magnetic fluxes.

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