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Pinning features of the magnetic flux trapped by YBCO single crystals in weak constant magnetic fields

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The dynamics of Abrikosov vortices and their bundles was experimentally investigated in weak constant magnetic fields, in the range of Earth's magnetic field. Characteristics of the isothermal magnetization relaxation in YBCO single-crystal samples with strong pinning centers were studied for different sample-field orientation. The obtained values of normalized relaxation rate S allowed us to estimate the effective pinning potential U in the bulk of the YBCO sample and its temperature dependence, as well as the critical current density J_c. A comparison between the data obtained and the results of similar measurements in significantly higher magnetic fields was performed. To compare different techniques for evaluation of J_c, the magnetization loop measurements $M(H)$, which relate the loop width to the critical current, were carried out. These measurements provided important parameters of the samples under study (penetration field H_p and first critical field H_{c1}), which involve the geometrical configuration of the samples. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4791772]

1. Introduction

Experimental studies of the magnetic flux dynamics in high-T_c superconductors (HTSC) in the wide range of temperatures and magnetic fields are essential for understanding the main mechanisms of the vortex pinning and creep as well as for application-oriented development of superconducting electronics. Currently, the range of weak constant magnetic fields with the magnitude in the range of Earth's magnetic field ($H \approx 1$ Oe) and temperatures close to T_c remains least studied.[1] The motion of magnetic fluxes, which is related to the creep and jumps of the Abrikosov vortices and their bundles, is governed by pinning on the sample structure defects and is determined by the thermal activation energy of the aforementioned metastable processes. The probability of the vortex jumps grows exponentially with increasing temperature T and reducing the depth of effective pinning potential U. Therefore the micro-structure of a HTCS material and the corresponding activation energies play a crucial role in magnetic flux dynamics.[2]

The vortex jumps contribute significantly to the generation of low-frequency magnetic noise in HTCS and the devices based upon them and depend on the presence and efficiency of the pinning centres in the employed superconducting materials. For the development of HTSC-based SQUID-sensors, detectors, bolometers, microwave resonators, as well as other superconducting electronics elements operating under liquid nitrogen cooling, such investigations are of particular importance since they indicate the ways of improving the sensitivity of this type of devices.

In the present work, we report the results on the dynamics of trapped low-density magnetic flux in impurity-free single-crystal $YBa_2Cu_3O_{7-x}$ (YBCO) samples. The studies were carried out in the high-temperature region, mainly in the vicinity of the superconducting phase transition ($0.5 \le T/T_c < 0.99$). The isothermal magnetization relaxation $M(t)$ was measured and the averaged effective pinning potential U was estimated using the linear Anderson-Kim model of thermally activated flux creep. The influence of thermally activated transformation of weak Josephson links in the system of aligned twin boundaries (TB) on the effective pinning in the samples of different crystalline structures was found. The comparative studies of the magnetization loops $M(H)$ in single-crystal samples in relatively weak magnetic fields ($H \le 300$ Oe) were performed.

2. Experimental

Impurity-free oriented single-crystal samples of YBCO with the typical size of 1×1 mm and thickness along the crystallographic c-axis of about 0.015–0.02 mm were chosen for the experiment. The annealing in oxygen stream, which is required to achieve the maximal values of T_c, leads to the transition from orthorhombic to tetragonal crystal structure and, as a result, to the formation of twin boundary planes. It is known[3] that such transition also occurs in polycrystalline and thin-film HTSC. To investigate the influence of such plane defects on the dynamics of magnetic fluxes and pinning processes, we chose single-crystal YBCO samples which had uniformly oriented twin boundaries aligned parallel to the c-axis of the crystal throughout the whole thickness of the crystal and the minimal degree of mosaicity, i.e., regions with different orientations of TB.

Contactless SQUID-magnetometry employed for magnetization measurements of the single-crystal samples provided the required magnetic moment sensitivity ($\Delta m \approx 8 \cdot 10^{-8}$ emu or $8 \cdot 10^{-11}$ A m^2), acceptable thermal stability of the measurement chamber ($\Delta T \approx 20$ mK), did not require any sample preparation and allowed to keep their initial structure.

Magnetic field penetrates into cuprate HTSC and is trapped there in the form of the Abrikosov and Josephson vortices, which are anchored on different pinning centres. Under thermal activation, which occurs with the probability of $\sim\exp(-U/kT)$, the vortices start to move. The creep of magnetic fluxes from the initial pinning centres to their nearest neighbours begins, and the dissipation appears. It is the processes related to the motion of Abrikosov vortices and their bundles, not the pair-breaking current, that determine the critical current density J_c in the sample.

To study the dynamics of magnetic fluxes related to the influence of the bulk pinning centres in YBCO single crystals, the measurements were carried out in the regime of field cooling (FC)—sample cooling in constant uniform magnetic field of the solenoid. Upon the superconducting transition of the sample, most of the magnetic field is expelled from the sample, while some fraction of it in the form of Abrikosov vortices and their bundles is trapped by various defects throughout the single crystal and anchored at the deepest pinning centres. Upon removal (or abrupt reducing) of the magnetic field, the Meissner screening currents can be compensated and the remanent magnetization of HTSC is defined by the vortices trapped in the bulk of the superconductor. In this case, the role of surface energy barriers (e.g., Bean-Livingstone barrier) in the dynamics of magnetic fluxes is minimal. Thermally activated creep of vortices and their bundles leads to redistribution and decay of bulk superconducting currents. The integral dipole moment starts to decrease and the average magnetization M of the superconducting sample relaxes.[1] In the simplest case, using the linear Anderson-Kim model, the effective depth U of the pinning potential can be estimated from the measurements of the normalized isothermal magnetization relaxation rate

$$S = 1/M_0(dM/d\ln t) = -kT/U,$$

where M_0 is the initial value of the magnetization, which is commonly taken in theoretical estimates as the magnetization in the Bean critical state, k is the Boltzmann constant, and t is the time. Most of the published studies of pinning mechanisms and magnetization relaxation in HTSC of different crystalline structures have been carried out in strong magnetic fields (of the order of tens kilooersted), in which the interaction processes in a well-established rigid vortex lattice play a significant role. In that case, the weak Josephson links are suppressed, while the experimental data are very sensitive to the magnetic fields orientation relatively to the principal crystallographic axes of the sample (a, b, c) as well as the presence of linear and planar defects. The region of weak constant magnetic fields and the initial sections of magnetization curves remain least studied, which is related to a reduced magnetic response in these ranges of H and strong influence of electromagnetic interference.

As was shown in Ref. 4, from the perspective of the collective pinning theory, the creep of non-interacting vortices is realized in weak magnetic fields. In this case, the velocity of the magnetic flux, correlation length L_0 and pinning potential U are independent on the magnetic field strength, while the measurement results are only weakly sensitive to the magnetic field deviation from the principal crystallographic axis of YBCO single crystal. Besides that, the value of the critical current density, which is defined by the balance of specific pinning force and Lorentz force $J_c = Uc/\Phi_0 L_0$ (Φ_0 is the magnetic flux quantum), is also not sensitive to the angle between the crystallographic axis, TB plane and magnetic field H.

3. Results and discussion

The standard magnetization measurement technique using an RF-SQUID gradiometer was employed in the experimental studies.[2] During the $M(T)$ measurements, the samples were cooled down (from $T \approx 150$ K down to the minimal temperature $T_{\min} \approx 30$–50 K) in a constant weak magnetic field according to the FC method. Afterwards, the field was switched off and the single crystal was warmed up (with the rate $dT/dt \approx 0.2$ K/min) while the temperature dependence of the magnetization $M(T)$, caused by the trapped fluxes, was registered (field cooled warming (FCW) regime).

Then, the isothermal relaxation of the magnetization $M(t)$ in the temperature range of interest was measured. For this purpose, the solenoid magnetic field was switched on ($H \approx 1$ Oe), sample cooling at a moderate rate in the FC-regime started, the required temperature of the measurement chamber was set and stabilized. Afterwards, the solenoid current was switched off ($H = 0$) and the registration of the magnetization decrease $M(t)$ due to the creep of trapped fluxes immediately started.

Fig. 1(a) shows a typical example of dynamics of the normalized isothermal magnetization relaxation $M(t)$ in one of the studied samples at different temperatures, including those acquired in the vicinity of superconducting transition ($T_c^{onset} = 90.2$ K). Similar dependences with a good degree of reproducibility were obtained for several other YBCO single crystals with the optimal level of oxygen saturation. In this case, the magnetic field was oriented parallel to the crystalline planes ($H \parallel a, b$ or $H \parallel c$). In the sample temperature range $T/T_c \leq 0.8$, the isothermal magnetization relaxation exhibits initial move with weak dynamics which is then

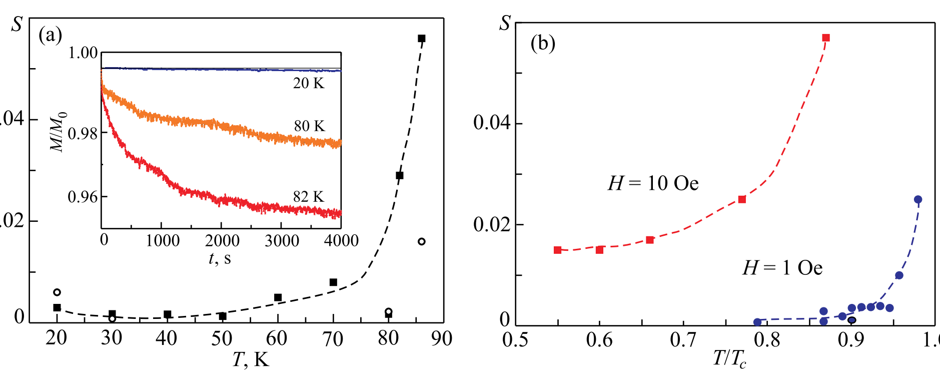

FIG. 1. Temperature dependence of the averaged normalized isothermal magnetization relaxation rate S for one of the investigated YBCO single crystals ($H \parallel a, b$). The inset shows the relaxation curves $M(t)$ normalized by its initial value M_0 obtained at several temperatures (a); experimental data $S(T/T_c)$ obtained at magnetic fields of 10 Oe (Ref. 5) and 1 Oe ($H \parallel c$) (b).

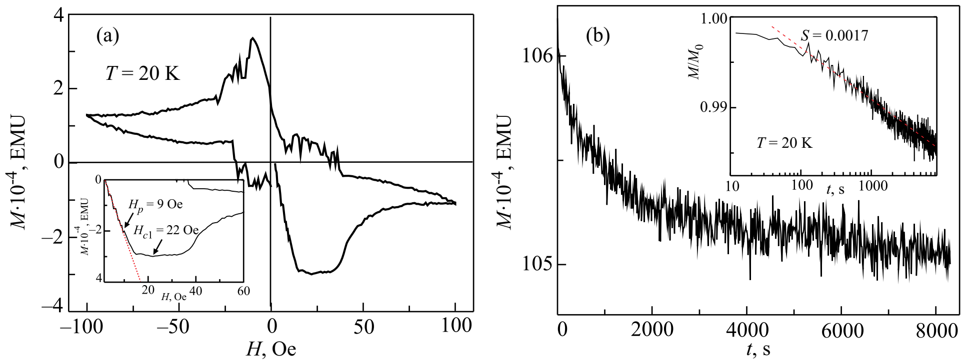

FIG. 2. Typical dependence $M(H)$ in one of the investigated YBCO single crystals for $T/Tc = 0.22$. The inset shows the initial segment of the sample magnetization (a); isothermal magnetization relaxation obtained at the same temperature ($H = 10$ Oe). The inset shows the estimate of the value of S according to the linear Anderson-Kim model (b).

changes over to quasi-logarithmic behavior. At relatively low temperatures this can be explained by the exponential decrease of the thermal creep of magnetic flux and the presence of random Josephson links in the TB regions which were not suppressed by magnetic field.[2] However, at higher temperatures and longer registration times, the behavior of $M(t)$ changes. In the vicinity of the phase transition ($T \rightarrow T_c$) in the presence of strong thermal fluctuations, the vortex creep increases dramatically and begins to cross over into the regime of thermally-assisted flux flow (TAFF).[4] Fig. 1(b) shows the comparison of the normalized isothermal relaxation rate obtained in our experiments with the data from Ref. 5 measured in a higher magnetic field ($H = 10$ kOe), which strongly influenced the pinning potential. At the orientation $H \parallel c$, the magnetic field is parallel to the TB planes of the crystal and the pinning of non-interacting Abrikosov vortices is most efficient.

The magnetization curve $M(H)$ of ideal type-II superconductors, which do not contain any impurities, defects, or other pinning centres, is reversible, exhibits a peak at $H \approx H_{c1}$ and smoothly decreases at higher magnetic fields reaching zero at H_{c2} (H_{c1} and H_{c2} are the first and second critical fields, respectively). However, in the presence of the defects of HTSC crystalline structure, the $M(H)$ dependence becomes irreversible and a hysteresis appears. In typical single-crystal YBCO samples, the presence of pinning centres for Abrikosov vortices transforms the $M(H)$ curve into a magnetization loop.

The width of the HTSC magnetization loop ΔM is proportional to the effective depth of the pinning potential U averaged over the sample volume. According to the Bean model of critical states, the value of the superconductor critical current density J_c is related to the geometrical parameters of the investigated sample and ΔM. The value of J_c can be estimated, e.g., by relation $J_c = 15\,\Delta M/R$, where R is the function of the sample geometry, which takes into account the demagnetization factor and the magnetic field dependence of the critical current.[6] A similar expression $J_c = 20\,\Delta M/[a(1 - a/3b)]$, where a, b ($a < b$) are the dimensions of the sample cross-section, has been obtained in Ref. 7.

To perform comparative experiments using two different methods for the investigation of magnetic fluxes dynamics in HTSC, we measured magnetic properties of single-crystal YBCO samples using a commercial MPMS setup (Quantum Design).

Fig. 2(a) shows a typical $M(H)$ dependence obtained in one of the investigated YBCO single crystals at $T = 20$ K. The initial segment of the magnetization curve, shown in the insert, allows us to estimate the onset of field penetration H_p and first critical field H_{c1}, which are difficult to calculate taking a rigorous account of all geometrical sample parameters and edge effects. The magnetization loop $M(H)$ is asymmetric with respect to the abscissa (H–axis) indicating a strong influence of the Bean-Livingstone surface barrier and thermally assisted collective creep of the Abrikosov vortices and their bundles.[8] It is not possible to apply the Bean critical state model for the estimation of J_c using the $M(H)$ data acquired in weak magnetic fields in the chosen temperature range. Therefore, the estimates of the effective pinning potential made above from $M(t)$ measurements has to be taken as the defining method. Fig. 2(b) illustrates the influence of the magnetization relaxation, which is caused by the vortices trapped upon sample cooling in magnetic field of 10 Oe. This condition corresponds to the initial segment of the hysteresis loop and, as follows from literature, is largely unexplored.

4. Conclusion

For the first time, the significant influence of the crystalline structure (including uniformly aligned twin boundaries) of YBCO single crystal on the magnetization relaxation rate, governed by the trapped magnetic fluxes, was demonstrated in weak constant magnetic fields (1 Oe $\leq H \leq$ 10 Oe) in the vicinity of critical temperature over extended time interval.

The obtained results allow re-evaluating in a new light the dynamics of magnetic fluxes trapped in FC regime due to significant increase of the effective pinning potential at such low flux densities. The obtained results can be beneficial for research on improving the sensitivity of the reception equipment which operates at liquid nitrogen temperatures and is cooled down in Earth's magnetic field.

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