Violation of a logarithmic trend of magnetization relaxation in HTSCs with strong pinning centers

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The dynamics of magnetic fluxes trapped in small constant magnetic fields, of the order of the Earth's field, were experimentally investigated in single crystals of YBCO with strong pinning centers formed in the structure of unidirectional twinning boundaries. A significant deviation of the isothermal magnetization relaxation from the logarithmic behavior observed previously only in strong magnetic fields was found for the first time in the region of strong thermal fluctuations near the superconducting phase transition. Within the Anderson-Kim linear model of the thermally activated creep and using experimental data, an effective pinning potential was estimated. It is shown that at the temperatures close to critical one the inverse logarithmic model of Zeldov describes better the magnetization drop, in particular, at long measurements times. © *2012 American Institute of Physics*.
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INTRODUCTION

In spite of a great number of theoretical and experimental works on studying the structure and dynamics of magnetic fluxes in high-temperature superconductors (HTSCs), up to now there is no full understanding of the pinning mechanisms of the Abrikosov vortices.[1,2] Most investigations are concentrated on the elucidation of main processes of interaction between the vortex lattice and HTSC, determining limiting characteristics of a superconductor in strong magnetic fields. The region of weak fields, of the order of the Earth's magnetic field, which are close to the critical (T_c) in a zero field, remains less studied. To develop highly sensitive HTSC SQUID-sensors, bolometers, microwave resonators and other elements of superconducting electronics operating at the nitrogen temperature, such investigations in weak magnetic fields ($H \approx 1$ Oe) in this temperature range become very topical.

The dynamics of magnetic fluxes related to a creep and jumps of vortices depends on the pinning on structural defects of samples and is determined by the energy of thermal activation of these metastable processes. The jumps of vortices make a considerable contribution to generation of low-frequency magnetic noise. They depend on the presence and efficiency of pinning centers in used HTSC materials. The probability of jumps of magnetic vortices grows exponentially with increasing the temperature and with decreasing the pinning strength, so the microstructure of HTSC material and corresponding activation energies play a crucial role in the dynamics of magnetic fluxes.

In this work, the dynamics of trapped magnetic fluxes of small density in undoped single-crystal samples of $YBa_2Cu_3O_{7-x}$ (in what follows, YBCO) is investigated near the superconducting phase transition. To do this, the isothermal relaxation of the magnetic moment, caused by fluxes trapped in weak stationary magnetic fields (the single Abrikosov vortices and their bundles), were registered. The comparison of samples with different crystal structure revealed the influence of thermally activated transformation of the Josephson weak links on an effective pinning in a system of unidirectional twinning boundaries (TBs).

A contactless magnetometry method used in the experiment provided the necessary sensitivity ($\approx 8 \cdot 10^{-11}$ A·m^2 for a magnetic moment), suitable thermal stabilization in a measuring chamber ($\approx$10 mK), eliminated the preliminary treatments of samples completely, and enabled to retain their initial structure. A highly sensitive HF SQUID used as a magnetometer sensor allowed to widen significantly the range of applied magnetic fields within the region of small intensities (up to ~ 0.1 Oe) and to investigate the dynamics of weak trapped fluxes in a HTSC.

EXPERIMENTAL TECHNIQUE AND CHOICE OF SAMPLES

Undoped single-crystal samples of YBCO were taken as a main object of investigations. The samples under investigation had dimensions of the order of 1×1 mm, the thickness of 0.015–0.02 mm. The main crystallographic axis c is perpendicular to the largest plane (see inset in Fig. 1(b)). The annealing in oxygen flow which is necessary to obtain the maximal value of T_c leads to transformation of the tetragonal structure of crystals into orthorhombic one and, as a consequence, to formation of twinning planes due to removing internal stresses. It is known[1] that a similar transformation of the structure occurs in both polycrystals and thin films of HTSCs. In order to investigate an effect of these plane defects on pinning processes we have selected single-crystal samples of YBCO in which unidirectional twinning boundaries are oriented parallel to the c axis of the crystal over all its thickness and the degree of mosaicity is minimal.

The most prominent HTSC materials belong to type-2 superconductors. A magnetic field can penetrate into them in the form of the Abrikosov vortices which are pinned by various defects of crystal structure (vacancies, dislocations, impurities, intermosaic boundaries, twinning boundaries,

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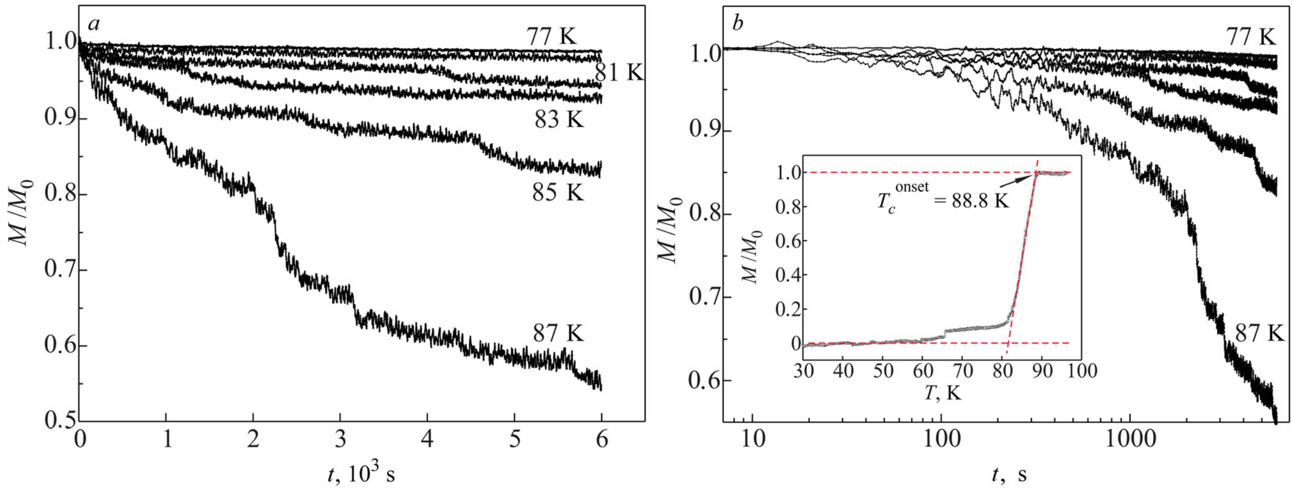

FIG. 1. Isothermal relaxation of magnetization $M(t)$, normalized by its initial value M_0, in one of the investigated YBCO single crystals with unidirectional twinning boundaries (a). Experimental data of $M(t)/M_0$, plotted in a semilog scale (b). Inset shows the superconducting phase transition of the investigated sample.

etc.)—pinning centers. Under action of the Lorentz force caused, for instance, by a gradient of vortices density or by a transport current, as well as due to an effect of thermal activation occurring with the probability $\sim\exp(-U/kT)$, the vortices start to jump quantumly from one pinning center to the nearest neighbors, the dissipation appears, and the superconductor goes to the resistive state. Here, U is the effective activation energy of jumps, actually equal to an averaged depth of the pinning potential; k is the Boltzmann constant; T is the sample temperature. These processes, related to motion of the Abrikosov vortices and their bundles, determine the critical-current density of the sample (J_c), the maximal dissipationless current in the superconducting material under investigation.

In order to study the dynamics of magnetic fluxes associated with the influence of bulk pinning centers in YBCO single crystals, the measurements were performed in the regime of cooling the sample under a specified homogeneous magnetic field of a solenoid (the field cooling (FC) regime). Upon removing the field (or decreasing it) the Abrikosov vortices are trapped by various defects over all the crystal. A role of surface energy barriers is minimal in the dynamics of magnetic fluxes. The thermally activated creep of single vortices and their bundles leads to redistribution and decay of supercurrents. An integral dipole momentum decreases, and an averaged magnetization M of the superconducting sample starts to relax.[4]

The data on investigation of dynamics of magnetic fluxes in superconductors is used to obtain most important parameters of vortices pinning mechanism in HTSCs. Moreover, in the simplest case, an effective depth of the pinning potential can be estimated by measuring a normalized rate of isothermal relaxation of magnetization in time t,

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

where M_0 is the initial magnetization which is usually considered in a theory as the magnetization in the Bean critical state. However, almost all published investigations on the magnetization relaxation in HTSCs with different crystal structures have been performed in strong magnetic fields (of the order of several kOe) when the considerable role is played by interaction processes in a rigid well-formed lattice of magnetic vortices. The obtained experimental results are very sensitive to the field orientation with respect to crystallographic planes of a sample under investigation, to its linear and plane defects.

As shown in Ref. 5, in terms of collective pinning a creep of non-interacting vortices is realized in weak magnetic fields. In this case, the velocity of motion of magnetic flux, the correlation length L_0 and the pinning potential U_0 do not depend on intensity of magnetic field, and the measurements results are weakly sensitive to deviation of the magnetic field H from the c axis of the YBCO single crystal. Furthermore, the value of the critical current density determined by an equality of specific pinning forces and the Lorentz force, $J_c = U_0 c/\Phi_0 L_0$, is also insensitive to the slope of H.

EXPERIMENTAL RESULTS AND THEIR DISCUSSION

During investigations we used a standard magnetization measurement technique via registration of radio-frequency response of a SQUID-gradiometer on a magnetic moment of the sample, induced in a homogeneous constant magnetic field (H_z).[6] When investigating the features of the superconducting phase transitions and the isothermal relaxation of magnetization, the samples under study were cooled down (from the temperature $\approx$150 K down to minimal $\approx$30–50 K) in a specified small magnetic field using the FC (field cooling) method. Then the field was removed, the single crystal was warmed up (with the rate $\approx$0.2 K/min) and the magnetization, caused by trapped fluxes, as a function of the temperature $M(T)$, i.e., the superconducting phase transition of the sample, was registered. The single crystal was warmed up to the maximal temperature $T \approx 150$ K.

After that, the isothermal relaxation of magnetization $M(t)$ was measured. To do this, the solenoid field was turned on, the sample was cooled down with a moderate rate, and a necessary specified temperature of a measuring chamber was set and stabilized. Then the solenoid current was turned off

($H = 0$) and at once the decrease in time of magnetization $M(t)$ caused by a creep of trapped fluxes was registered.

Fig. 1(a) shows a dynamics of the isothermal relaxation of magnetization $M(t)$, normalized by its initial value M_0, in one of the investigated single crystals with unidirectional twinning planes at different temperatures in the vicinity of the superconducting phase transition ($T_c^{\rm onset} = 88.8$ K). The solenoid magnetic field during the sample cooling was oriented along the c axis of the single crystal and equal to 80 A/m ($\approx$1 Oe). In such a configuration the field is parallel to planes of the crystal TBs, and the pinning of the Abrikosov vortices is accomplished more efficiently. Similar dependences with good reproducibility were obtained for a series of other single crystals of YBCO with optimal level of saturation by oxygen. Fig. 1(b) demonstrates experimental data for the same temperatures but in a semilog scale. It is seen that the Anderson-Kim linear model cannot describe the behavior of $M(t)$ in a wide time range and at all temperatures. In the inset, the normalized dependence $M(T)/M_0$, the superconducting phase transition of this single crystal, is shown as an illustration.

In the case of low temperature range of the sample ($T/T_c \leq 0.8$) the isothermal relaxation of magnetization has an initial trend with an ill-defined dynamics followed by a quasi-logarithmic behavior, described by the Anderson-Kim linear model.[4] However, at much higher temperatures and for longer registration time, a character of the behavior of $M(t)$ changes considerably. In the vicinity of the phase transition ($T \to T_c$), when the strong thermal fluctuations are present, the dynamics of vortices becomes to be similar to the regime of thermally activated flux flow (TAFF—thermally assisted flux flow).[1] Previously, a similar behavior of $M(t)$ in such weak magnetic fields has not been observed.

As seen in the figure, at short initial observation times the magnetization does not change, or drops very slowly. At relatively low temperatures this can be explained by an exponential decrease of thermal creep of magnetic flux and by the presence of random Josephson links, not suppressed by the magnetic field, in regions of twinning boundaries.[6] As the temperature increases, the probability of the creep of trapped fluxes increases, the relaxation of $M(t)$ becomes noticeable in the time range of the order of a few hundreds of seconds from the beginning of the registration. At $T \to T_c$ strong thermal fluctuations cause a giant creep of vortices and their bundles, the dynamics of trapped fluxes akin to the TAFF regime is observed.

The boundaries of twins include the CuO_x layers containing the oxygen vacancies located along their planes and locally strongly affecting the suppression of the superconducting ordering parameter, leading to lowering the activation energy of the creep of trapped vortices. So the density of vortex filaments is higher on twins rather than in the rest of the crystal. Taking into account that in the field $\approx$ 1 Oe the intervortex distance ($\approx 10^3$ nm) is comparable with the period of TBs ($\approx 10^4$ nm) and with the field penetration depth in a specified temperature range ($\approx 10^4$–10^5 nm), the localization of all vortices on twins can be expected. At long observation times the existence of the region of strong thermal fluctuations following the quasi-logarithmic decrease of magnetization was registered. This agrees with the previously preformed analysis,[1] according to which the thermal fluctuations nearby the phase transition can play significant roles as opposed to classical low-temperature superconductors. In this case the Ginzburg parameter reaches the value $Gi \approx 0.01$.

Using the measurements results for the isothermal relaxation of magnetization, its averaged normalized velocity S was estimated in the temperature range $70\,{\rm K} \leq T \leq 87\,{\rm K}$ (see Fig. 2(a)) by the expression (1). The made estimate of the S value is consistent with experimental data obtained by other authors in similar HTSC samples but in strong magnetic fields.[3,4] However, for the upper temperature range, because of a significant deviation from the logarithmic trend (most pronounced for long observation times, $t \geq 1000$ s), the Anderson-Kim linear model, for which the normalized activation energy of the creep is related to the current by the relation $U/U_0 = (1–J/J_c)$, becomes purely applicable. In the expression, the U_0 is the averaged depth of the energy potential of pinning centers in the absence of the current and thermal fluctuations. In order to describe the experimental data

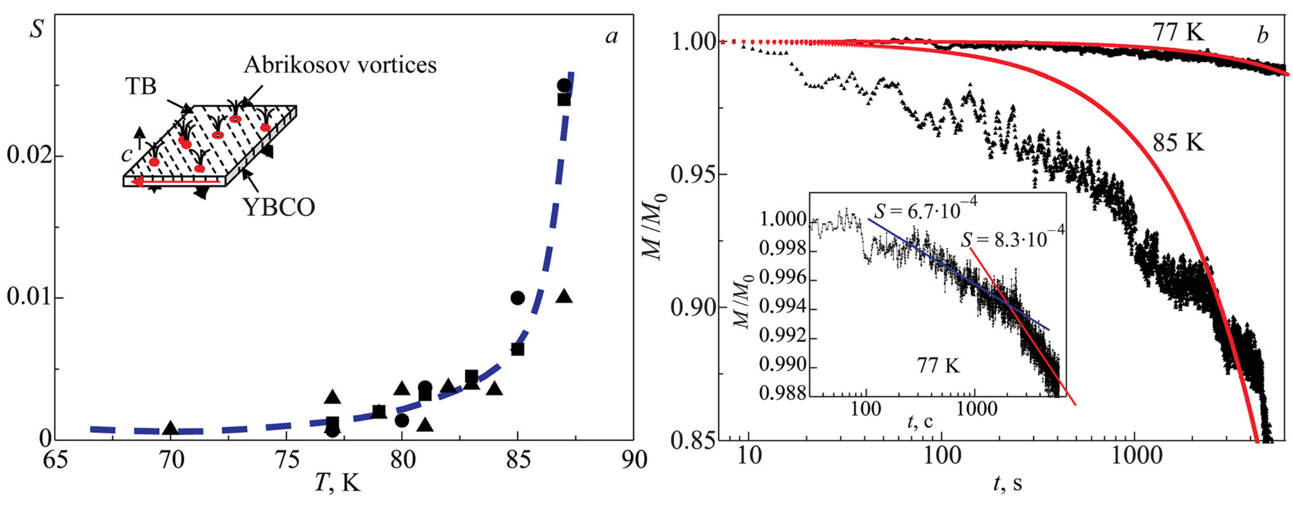

FIG. 2. Normalized isothermal relaxation rate of magnetization S estimated by using the Anderson-Kim model linear in current. Inset shows schematically features of the structure of used samples and the pinning picture of the Abrikosov vortices (a). Typical dependences $M(t)/M_0$ for two specified temperatures with the curves calculated by Eq. (2). For $T = 77$ K the constants of the Zeldov model: $kT/U_0 = 1.1 \cdot 10^{-3}$ and $t_0 = 80$ s. For $T = 85$ K: $kT/U_0 = 8 \cdot 10^{-3}$ and $t_0 = 300$ s. Inset shows the possible estimate of S made by the simplest linear model (b).

in the regimes under consideration, we attempted to use the inverse logarithmic model of Zeldov, $U/U_0 = \ln(J_c/J)$.[4,7] According to this model, the current in a superconductor is related to U_0 and to the macroscopic time parameter t_0 by the expression,

$$J/J_c = \exp\{-(kT/U_0)\ \ln\ (t/t_0)\}. \tag{2}$$

And because M is defined by currents induced in the sample, then $S = -kT/U_0$.

As an illustration, Fig. 2(b) shows the experimental points obtained from measurements of the magnetization relaxation in the single crystal at two very different temperatures (77 and 85 K), and the curves describing these data in accordance with the inverse logarithmic model of Zeldov. As seen in the figure, for the low range of investigated temperatures the behavior of $M(t)$ agrees well with this model over all the temperature range of performed measurements. For $T \to T_c$ the taken model describes the trend of the experimental curve with a reasonable accuracy in the case of long observation times.

CONCLUSION

The dynamics of magnetic fluxes trapped in weak magnetic fields ($H \approx 1$ Oe) was investigated for the first time in single-crystal samples of YBCO with the ordered crystal structure of twinning boundaries at the temperatures close to the critical temperature. A significant effect of the crystal structure (first of all, TBs) of the single crystal on the relaxation rate of magnetization, S, was demonstrated. A possibility of considerably non-logarithmic trend of the isothermal relaxation of $M(t)$ was found. Within the framework of model of the thermally activated creep, an effective pinning potential at these conditions was estimated. It was shown that the inverse logarithmic model of the thermally activated creep of Zeldov describes well a behavior of magnetization in single-crystal samples of YBCO in a wide time range at these temperatures.

The results obtained are useful and relevant for understanding of pinning mechanisms in HTSCs. They can be used in practice for designing of high-temperature superconducting receivers to reduce intrinsic magnetic noise of HTSC sensors and to increase sensitivity of a receiving device with the nitrogen-cooling.

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