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Physica C 408–410 (2004) 384–385
PHYSICA C
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Accelerated magnetic relaxation of transient disordered vortex states in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Abstract

Time relaxation of the local persistent current in a $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystal was magneto-optically recorded after suddenly exposing the crystal to a constant magnetic field between 140 and 840 G. A remarkable behavior of the relaxation is revealed for fields below the order–disorder vortex phase transition: The relaxation starts at a slow rate, it then accelerates for a short period of time, after which a slow relaxation rate is resumed. We show that this acceleration marks a local transition of a transient disordered vortex state to a thermodynamically favored quasi-ordered vortex phase. The slow relaxation rates, before and after the transition, reflect ordinary thermally activated flux creep process in the disordered and quasi-ordered vortex phases, respectively.

Keywords: Vortex matter; Vortex phase transitions; Vortex transient states

Magnetic relaxation in high temperature superconductors has been the subject of numerous experimental studies [1]. In general, an approximately logarithmic time decay of the magnetization, M, is observed, and the relaxation rate, $dM/d\ln t$, decreases with time, as expected for a system approaching its equilibrium state. In this manuscript we report on an unusual phenomenon, namely an *increase* of the relaxation rate with time, observed in $Bi_2Sr_2CaCu_2O_{8+\delta}$ in a limited field range below the order–disorder vortex phase transition.

Measurements were preformed on a $1.55\times1.25\times0.05$ mm^3 $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal ($T_c \sim 92$ K), grown by the traveling solvent floating zone method. The crystal, at $T = 21$ K, was suddenly (rise-time <50 ms) exposed to an external magnetic field, H, between 140 and 840 G. Immediately after reaching the target field, magneto-optical (MO) snapshots of the induction distribution across the sample surface were recorded at time intervals of 40 ms for 4 s, and 300 ms for additional 26 s. The magneto-optical system incorporated an iron-garnet MO indicator with in-plane anisotropy and a high speed CCD camera. Induction profiles across the sample width were extracted from the 2D MO images.

Fig. 1 shows the time evolution of induction profiles after a step increase of the external field to 465 G. Note the sharp change (“break”) in the slope of the induction profiles at a location (marked by a circle) moving towards the sample edge. The moving break in the profiles has been interpreted as indicating dynamic coexistence of two distinct vortex states: a transient disordered and a quasi-ordered states, characterized by high and low persistent current, respectively [2]. The absence of a break at short times, following the application of the field, indicates a transient disorder vortex state throughout the entire sample, resulting from rapid injection of vortices into the sample through inhomogeneous surface barriers [2,3]. The appearance and movement of the break indicate nucleation and growth of the thermodynamically favored quasi-ordered vortex state.

From the induction profiles illustrated in Fig. 1, the time dependence of $j \sim dB/dx$ was extracted at different locations x measured from the sample center ($x = 0$). In calculating dB/dx, we averaged over a “probed segment” $dx = 23$ μm (marked in Fig. 1 by the grey area

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doi:10.1016/j.physc.2004.02.120

around $x = -514$ μm). Fig. 2 shows typical results of dB/dx versus log time at $x = -514$ μm, measured for external field steps to 370 (squares), 465 (bold circles) and 610 G (triangles). Note that the relaxation rate for external fields of 370 and 610 G behave in a conventional manner, i.e. the relaxation rate continuously decreases with time. However, for $H = 465$ G the relaxation curve exhibits remarkable accelerated rate between 1.1 and 4.8 s. Tracing the annealing process of the initially injected transient disordered state provides a clear explanation to this phenomenon. The key observation is that the quasi-ordered vortex state propagates (and thus the transient disordered state retreats) in a front like manner. Returning to Fig. 1, we find that the front of the expanding quasi-ordered vortex phase (marked by the break in the induction profile) reaches

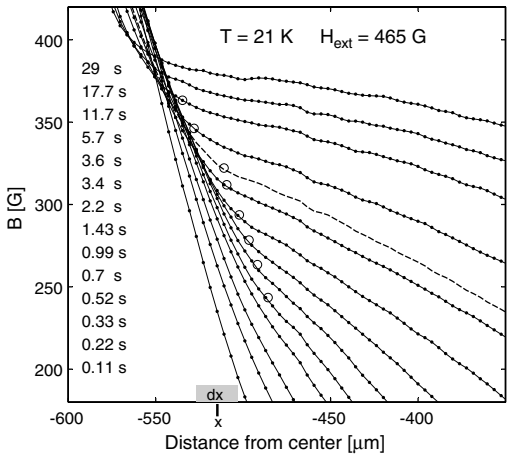

Fig. 1. Time evolution of induction profiles after a step increase of the external field to 465 G. Circles mark the break on the induction profiles. The grey area denotes the "probed region" dx around $x = -514$ μm where the data of Fig. 2 was derived.

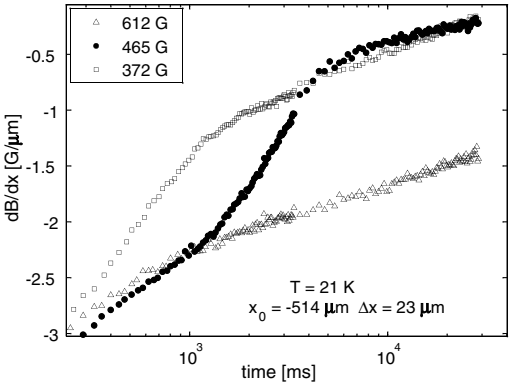

Fig. 2. dB/dx versus log time at $x = -514$ μm, measured for external field steps to 370 (squares), 465 (bold circles) and 610 G (triangles).

the right edge, $x + dx$, of the probed area at $t = 1.1$ s, and at 4.8 s this front crosses the left edge, $x - dx$, of this area [4]. This means that the entire probed segment was in a transient disordered state until 1.1 s, and in a quasi-ordered state after 4.8 s. Thus, the accelerated relaxation rate, between 1.1 and 4.8 s, occurs when the transient disordered vortex state in the probed segment transforms into a quasi-ordered phase.

We conclude that the annealing of transient disordered vortex state proceeds via two mechanisms: a slow thermally activated flux creep and a fast process related to the interaction between disordered fluxons and the neighboring quasi-ordered fluxons residing on the front of the quasi-ordered phase. In the latter mechanism, the disordered fluxons at the interface rapidly relax to the thermodynamically favored quasi-ordered phase, creating a new front. Thus, the annealing at short and long times is due to thermally activated creep whereas at intermediate times, when the front enters the probed region, it is controlled by the second mechanism. The sharpness of the effect is determined by the length dx of the probed region and velocity of the front.

The normal behavior of the other two relaxation curves, corresponding to 370 G (squares), and 610 G (triangles), is explained as follows: For low external fields (e.g. 370 G), the low inductions result in extremely short annealing times, so that annealing process cannot be traced with our system. As a result, we measure, in fact, the relaxation of the quasi-ordered state. The relaxation curve corresponding to 610 G represents a case where the annealing times are extremely large, so that flux creep increases the induction at the measured location x above the phase transition induction (approximately 410 G) before the front reaches this location. As a result the vortices at the measured location always remain in a disordered state, and the measured relaxation curve reflects ordinary thermally activated flux creep.

Acknowledgements

This manuscript is a part of B.K. Ph.D. thesis. We acknowledge support from the German–Israel Foundation (GIF). Y.Y. acknowledges support from the ISF Center of Excellence Program, and by the Heinrich Hertz Minerva Center for High Temperature Superconductivity.

References

[1] Yeshurun et al., Rev. Mod. Phys. 68 (1996) 911.
[2] D. Giller et al., Phys. Rev. Lett. 84 (2000) 3698.
[3] Y. Paltiel et al., Nature 403 (2000) 398.
[4] M. Konczykowski et al., Physica C 332 (2000) 219; Physica C 341–348 (2000) 1317.