Available online at www.sciencedirect.com
ScienceDirect
Physica C 468 (2008) 280–283
PHYSICA C
www.elsevier.com/locate/physc

Oscillatory magnetic relaxation in $Bi_2Sr_2CaCu_2O_{8+\delta}$

D. Barness *, I. Sochnikov, B. Kalisky [1], A. Shaulov, Y. Yeshurun

Department of Physics, Bar-Ilan University, Ramat-Gan 52900, Israel

Accepted 17 August 2007
Available online 21 November 2007

Abstract

Time-resolved magneto optical measurements in $Bi_2Sr_2CaCu_2O_{8+\delta}$ show oscillatory relaxation of the local magnetization. The oscillatory behaviour is observed in a limited range of temperatures and fields below the vortex order–disorder phase transition line. We ascribe this phenomenon to coupled effects of thermally activated flux creep and annealing of transient disordered vortex states injected into the sample during field increase.

PACS: 74.25.Qt; 64.60.Cn; 74.72.Hs

Keywords: Vortex matter; Magneto optical imaging; Magnetic relaxation; Order–disorder transition

1. Introduction

Magnetic relaxation in high temperature superconductors has been the subject of numerous experimental and theoretical studies [1]. In general, the magnetization, M, and the induction, B, change monotonically with a decreasing rate, as expected for a system approaching its equilibrium state. A distinct behaviour was recently observed [2] in local magnetic measurements in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) crystals for inductions below the order–disorder vortex phase transition, B_{od}. Namely, the relaxation of the local magnetization starts at a slow rate, it then accelerates for a short period of time, after which a slow relaxation rate is resumed. The accelerated rate was attributed to annealing of transient disordered vortex states [3–5] injected to the sample through inhomogeneous surface barriers during field increase [6]. The slow relaxation rate, before and after the acceleration, reflects ordinary thermally activated flux creep process in the disordered and quasi-ordered vortex phases, respectively. In this paper we show that under certain conditions, the annealing and the ordinary thermally activated flux creep processes may couple to produce oscillatory behaviour of the local induction B. A similar oscillatory behaviour was recently reported [7] for BSCCO crystals near a stripe-like defect [8] commonly found in BSCCO crystals grown by the floating zone technique [9]. Here we show that the proximity to such a defect is not a necessary condition for the generation of the oscillatory behaviour. Nevertheless, inhomogeneity in B_{od}, as well as certain temperatures and field conditions, are required for the generation of local induction oscillations.

2. Experimental

Flux oscillations were observed in a series of BSCCO single crystals grown by the floating zone method [9]. Here we present new results obtained in a $2 \times 1 \times 0.03\ mm^3$ crystal exhibiting $T_c \approx 92$ K and local vortex order–disorder transition induction B_{od} ranging between 380 and 450 G. The sample was zero-field-cooled (ZFC) to a target temperature and was then subjected to an external field of 100–600 Oe (rise time < 50 ms) applied parallel to the

* Corresponding author. Tel.: +972 3 5318607; fax: +972 3 7384054.
E-mail address: ph88@mail.biu.ac.il (D. Barness).
[1] Present address: Department of Physics and Applied Physics, Stanford University, Stanford, CA 94305, USA.

0921-4534/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.physc.2007.08.030

crystallographic c-axis of the sample. Magneto optical images of the induction distribution were taken using an iron-garnet indicator with in-plane anisotropy and a high speed CCD camera with a maximum frame rate of 25 Hz.

3. Results

Induction oscillations were observed in a small area located approximately 350 and 450 μm from the long and short edges of the sample, respectively as portrayed in Fig. 1. We note that the oscillations were measured in a vicinity of a small (approximately $150 \times 20\ \mu m^2$) stripe defect, stretched from the sample edge inward, also shown in Fig. 1. This defect was detected magneto optically but could not be observed visually. Local magneto optical measurements reveal inhomogeneous distribution of B_{od}, with values close to 400 G in the immediate vicinity of the defect, lower by approximately 50 G than in the region where the oscillations are observed. Fig. 2 depicts the time dependence of the local induction for various external fields between 375 and 532 Oe, measured at 22 K. While the $B(t)$ curves above 495 Oe and below 375 Oe exhibit the conventional, monotonic relaxation, the intermediate curves exhibit oscillatory behaviour. Note that the oscillations set in only ~0.5 s after the field is applied, allowing a certain induction level to be reached. The period of oscillations increases with time while the amplitude exhibits a non-monotonic behaviour, decaying at long times.

Fig. 3 exhibits the time dependence of the local induction for various temperatures, measured at the same location, for an external field of 457 Oe. Evidently, the oscillations are limited to temperatures above 19 K and below 22.5 K. A time delay is observed between the moment that the external field is applied and the onset of the oscillatory behaviour, in accordance with the data of Fig. 2. Also, the oscillation amplitude exhibits non-monotonic behaviour while the period increases with time.

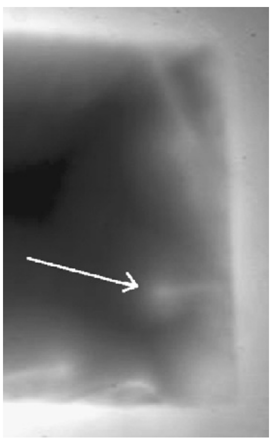

Fig. 1. Magneto optical image showing a $0.6 \times 1\ mm^2$ part of the sample, focusing on the region where vortex density oscillations are observed. Note the defect, indicated by an arrow and visible only magneto optically, that is stretched from the right edge. The oscillatory behaviour is obsereved in the area left to the defect.

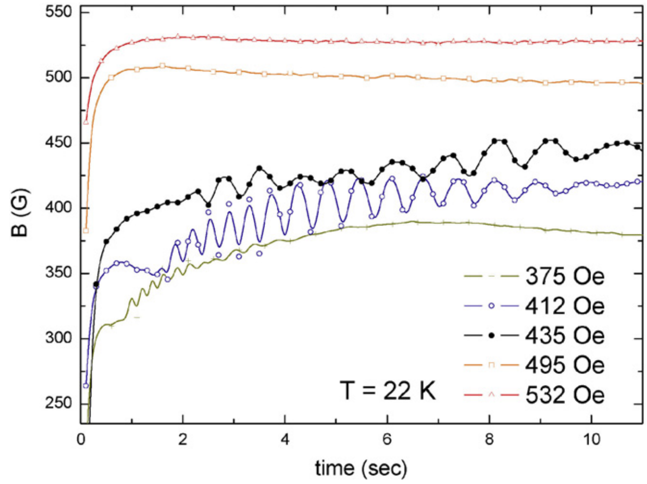

Fig. 2. Time dependence of the local induction for the indicated external fields, measured at 22 K. (For interpretation of the references to colors, the reader is referred to the web version of this paper.)

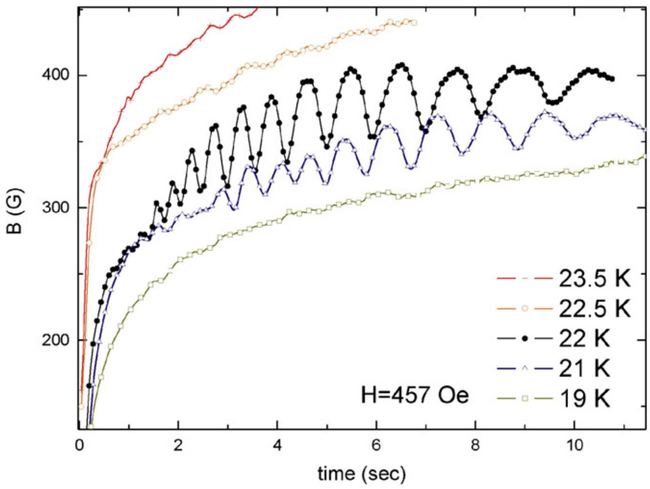

Fig. 3. Time dependence of the local induction for the indicated temperatures, measured for external field of 457 Oe. (For interpretation of the references to colors, the reader is referred to the web version of this paper.)

4. Discussion

Figs. 2 and 3 demonstrate that the oscillatory behaviour is observed in a limited range of temperatures and fields. Based on similar data for a wide range of temperatures and fields, we conclude that the range of existence of oscillation is a narrow strip in the B–T plane, slightly below the order–disorder vortex phase transition line and it is included in the region of existence of transient disordered vortex states (see e.g. Fig. 1 in Ref. [5]). In the following we argue that the oscillatory relaxation involves ordinary flux creep and annealing of transient vortex states.

The relaxation process is governed by the equation [10], $\partial B/\partial t = -c\partial E/\partial x = (c^2/4\pi)[\partial/\partial x(D_f \partial B/\partial x)]$, where the diffusion coefficient, $D_f = R_f(J/J_c)^{U_0/T}$, is inversely proportional to the critical current J_c and R_f is the flux flow resistance. For a homogeneous vortex state (ordered or disordered), the electric field E is a monotonic function of time and location giving rise to a monotonic increase of the local induction B with a decreasing rate. Thus, the oscillatory behaviour of B with time must be associated with a periodic transformation in the vortex state, from ordered to disordered state and vice versa. This transformation results in an oscillatory behaviour of J_c (from a low to high value, respectively) and D_f, and consequently $\partial E/\partial x$ changes sign periodically. Such phase oscillations can occur in a certain region of the sample characterized by a higher B_{od} relative to its surrounding. A transient disordered vortex state initially injected into this region anneals faster, drawing vortices from its surrounding. (The ordered state is characterized by lower current density, i.e. shallower induction profiles and thus higher average induction.) This accelerates the relaxation process resulting in a faster increase in B. The accumulation of vortices in this region continues until the induction gradient $\partial B/\partial x$ changes sign (when the annealed area becomes ordered relatively to surrounding), resulting in an expulsion of the vortices from this region to the surrounding and the vortex state is again disordered. This disordered state starts annealing once again, and the process repeats itself. The time period of the oscillations increases because as the average B increases, approaching B_{od}, the annealing and the relaxation processes slow down.

The above scenario of oscillations between ordered and disordered vortex states is supported by the phase relationship between the waveforms of B and $j \sim \partial B/\partial x$ shown in Fig. 4. This figure presents the time dependence of B and $\partial B/\partial x$ for $T = 22$ K and $H = 457$ Oe. While the oscillations period of both $j \sim \partial B/\partial x$ and B are correlated, B and $\partial B/\partial x$ are in anti-phase, indicating that high and low current density states correspond to low and high level of local induction. As low (high) j characterize the ordered (disordered) state, this observation indicates that the oscillations between low and high B correspond to oscillations between disordered and ordered states.

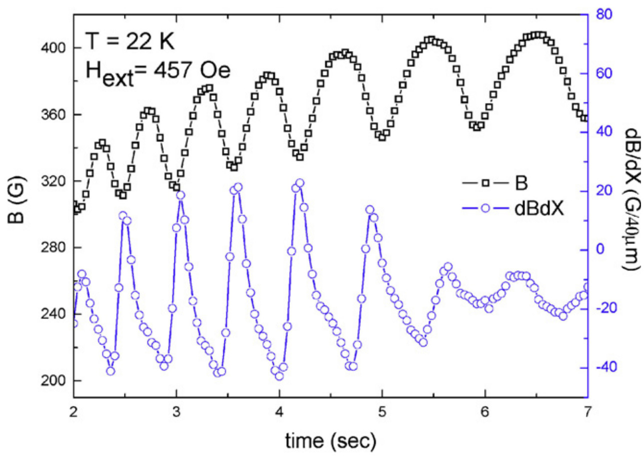

Fig. 4. Time dependence of the induction B (squares) and the induction gradient $\partial B/\partial x$ (circles) for $T = 22$ K and $H = 457$ Oe. (For interpretation of the references to colors, the reader is referred to the web version of this paper.)

We turn now to explain the limited region of existence of oscillations in the B–T plane. The range of existence of transient states [3–5] extends to much lower inductions and much higher temperatures. As the coupled effects of the annealing and the thermally activated creep processes generates the oscillatory behaviour, a necessary condition for the observation of oscillations is that both proceed in a comparable rate. Too close to B_{od}, the annealing process slows down and the thermally activated creep dominates. At low inductions the annealing is much faster than the conventional creep and it dominates the behaviour. Similarly, at low (high) temperatures, the annealing (creep) rate is larger. Oscillations are observed only in a narrow temperature region where these rates are comparable.

5. Conclusion

In the presence of transient disordered vortex states, magnetic relaxation proceeds via two mechanism: The conventional thermally activated flux creep and annealing of the disordered states. Coupling of these two processes through the critical current may produce time oscillations in the local vortex density. Such oscillations may be ignited in a region characterized by a higher transition induction B_{od}, relative to that of the surrounding. The oscillations are limited to temperatures and inductions where the thermally activated creep and the annealing rates are comparable.

Acknowledgements

This research is supported in part by the Israel Science Foundation (ISF Grant no. 499/07) and by the Heinrich Hertz Minerva Center for High-Temperature Superconductivity.

References

[1] Y. Yeshurun, A.P. Malozemoff, A. Shaulov, Rev. Mod. Phys. 68 (1996) 911.
[2] B. Kalisky, A. Shaulov, T. Tamegai, Y. Yeshurun, Physica C 408 (2004) 382.
[3] B. Kalisky, A. Shaulov, Y. Yeshurun, Phys. Rev. B 68 (2003) 012502.
[4] B. Kalisky, Y. Bruckental, A. Shaulov, Y. Yeshurun, Phys. Rev. B 68 (2003) 224515.
[5] Kalisky, Y. Bruckental, A. Shaulov, Y. Yeshurun, Phys. Rev. B 73 (2006) 014501.
[6] E. Zeldov, A.I. Larkin, V.B. Geshkenbein, M. Konczykowski, D. Majer, B. Khaykovich, V.M. Vinokur, H. Shtrikman, Phys. Rev. Lett. 73 (1994) 1428.
[7] B. Kalisky, M. Gitterman, B. Ya. Shapiro, I. Shapiro, A. Shaulov, T. Tamegai, Y. Yeshurun, Phys. Rev. Lett. 98 (2007) 017001.
[8] M. Yasugaki, M. Tokunaga, N. Kameda, T. Tamegai, Phys. Rev. B 67 (2003) 104504;
I.F. Tsu, J.L. Wang, S.E. Babcock, A.A. Polyanskii, D.C. Larbalestier, K.E. Sickafus, Physica C 349 (2001) 8;
R. Gerbaldo, R. Cherubini, A. Chiodoni, R. Fastampa, G. Ghigo, L. Gozzelino, F. Laviano, E. Mezzetti, B. Minetti, Physica C 354 (2001) 173;

L. Gozzelino, D. Botta, R. Gerbaldo, G. Ghigo, F. Laviano, E. Mezzetti, R. Fastampa, Int. J. Mod. Phys. B 17 (2003) 879;
M. Li, P.H. Kes, S.F.W.R. Rycroft, C.J. van der Beek, M. Konczykowski, Physica C 408 (2004) 25.
[9] N. Motohira, T. Hasegawa, K. Kishio, K. Kitazawa, J. Ceram. Soc. Jpn. 97 (1989) 1009.
[10] G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, V.M. Vinokur, Rev. Mod. Phys. 66 (1994) 1125.