# Magnetic flux distribution in a superconducting core of Bi-2223 tape

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**Abstract**

Local magnetic flux distribution in the superconducting core of a Bi-2223 tape is investigated above and below a characteristic field $B^*$, which is defined by global critical current density $J_c$ measurements. Below this field, $J_c$ as a function of applied magnetic field $B_a$ exhibits a $B_a$-independent plateau often referred to the single vortex pinning regime. We show that below $B^*$ the flux distribution within the core does not change. Furthermore, the strong $B^*(T)$ dependence is suggested to be due to thermally activated depinning of individual vortices.

*Key words:* high-$T_c$ superconductivity; magnetic flux distribution; single vortex pinning; thermally activated depinning

It has been long known that the critical current density $J_c$ of Bi-based superconductors is very sensitive to the externally applied magnetic field $B_a$: $J_c$ decreases rapidly with increasing field [1,2]. However, low field vortex behavior has been poorly investigated so far. During last few years however, considerable attention has been given to the low field behavior of $J_c$ in $YBa_2Cu_3O_7$ samples [3]. It has been found that some peculiar pinning mechanisms lead to a $B_a$-independent plateau in $J_c$ at rather low fields [3]. In this work, by employing a combination of local magneto-optical (MO) imaging and global magnetization measurements we have investigated the low field region of the Bi-2223 ($Bi_2Sr_2Ca_2Cu_3O_{10}$) superconducting core of an Ag-sheathed tape.

The superconducting Bi-2223 Ag-sheathed tape was manufactured by the standard powder-in-tube method. The silver sheath was chemically removed in order to facilitate maximal sensitivity during the MO imaging. An epitaxial ferrite-garnet magneto-optical indicator film with in-plane magnetization was used for the imaging. The global magnetization measurements were carried out with a Quantum Design MPMS SQUID magnetometer. Both types of measurements were performed with the same field orientation: $B_a$ was applied perpendicular to the plane of the core, *i.e.*, parallel to the $c$-axis of the aligned Bi-2223 grains of the core. The core has the critical temperature $T_c \simeq$ 109.7 K measured by the magnetometer at $B_a = 2$ mT.

In Fig. 1(a) a set of $J_c(B_a)$ curves taken at different temperatures is shown. As can be clearly seen, the critical current density has a field independent plateau below a characteristic field $B^*(T)$. The temperature dependence of $B^*$ is plotted in Fig. 1(b). $B^*$ is defined as a 0.5% deviation from a corresponding plateau value of $J_c \simeq J_c(B_a = 0)$. $B^*(T)$ can readily be fitted either by $B^*(T) = B^*(0)(1-t)^x$, where $t = T/T_c$ is the reduced temperature, $B^*(0) \simeq 0.049$ T and $x \simeq 4.36$ (dotted line); or by $B^*(T) = B^*(0)\exp(-qt)$ with $q =$ 5.3 (solid line). Both formulas were found to well describe thermally activated depinning processes in different high-$T_c$ superconductors [4–7]. The power-law formula having $x = 1.5$ was found to satisfactorily describe the behavior of the irreversibility (depinning) line $B_{\rm irr}$ in some high-$T_c$ superconductors [4]. However, the exponential formula has been shown to be more suitable for describing depinning in Bi-based materials [5,6], which have significantly different vortex pinning mechanisms governed by the high anisotropy inherent to these systems. It was also shown [6,7] that thermally activated processes influence vortex behavior not only in the vicinity of the irreversibility $B_{\rm irr}$,

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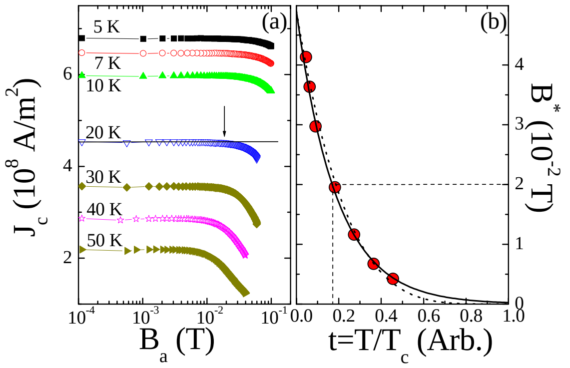


Fig. 1. Critical current density as a function of $B_a$ (a) and characteristic field $B^*$ dependence on $T$(b). The arrow in (a) shows the $B^*$ definition.

but also at the first vortex penetration in superconductors. Therefore, the $B^*(T)$ dependence can also be attributed to the onset of thermally activated depinning. Rather high values of the pinning dependent parameter $x$ and the prefactor $q$ are likely to be due to differences in the pinning of individual vortices (in the vicinity of $B^*(T)$) and collective pinning (close to $B_{\rm irr}(T)$). As soon as vortex-vortex interactions become important near $B^*$ [3], the pinning of individual vortices weakens to allow a crossover to a collective regime [7], and vortices become very sensitive to a thermally activated environment. Indeed, the intervortex spacing $a_0 \simeq 1.07(\Phi_0/B_a)^{1/2}$ in the vicinity of $B^*(T = 19\text{K}) \simeq 0.02$ T is $a_0 \simeq 350\,\text{nm} < 2\lambda(T) \sim 500$ nm [8], which is within the range where vortices start to interact.

The local magnetic behavior in the vicinity of the $B^*(T)$ line, as observed by the MO imaging technique, can be described as follows. The observations were carried out in a field cooled state, in order to imitate the magnetic state within which the above-described global $J_c(B_a)$ measurements were done. An identical magnetic prehistory for both global and local measurements could not be fulfilled due to the external field value limitation in our MO setup: the highest achievable field is about 0.2 T. In Fig. 2, one can see two images taken at $T = 19$ K and (a) $B_a \simeq 37$ mT, (b) 20 mT. $B_a \simeq 37$ mT is higher than $B^*(T = 19\text{ K}) \simeq 20$ mT (shown by dashed lines in Fig. 1(b)) almost by a factor of 2. In both images the frozen magnetic flux inside the core is highly inhomogeneously distributed (the brighter the color, the higher the induced field). This is simply due to large-scale cracks most likely introduced either by the manufacturing procedure or by the subsequent handling of the sample, in particular, during the sheath removal. However, one can clearly see the difference between these two images: although the high induced field areas far from the core edges (shown by solid lines) and cracks (shown by dashed lines) remain almost unchanged, the "boundary" regions (close to the edges and cracks) became much darker at $B_a = 20$ mT (despite of a longer exposure time, maximizing sensitivity, and correspondingly the brighter image). This is due to the fact that the magnetic flux near the edges leaves the superconductor in agreement with the critical state model. Further reducing the field down to $B_a = 0$ T, we could not detect any change in the flux distribution over the core. This implies that the critical state achieved at $B^*$ does not change within the sample below this field: vortices neither move nor leave the core. A similar connection between the globally measured $J_c$-plateau below $B^*(T)$ and the local magnetic flux distribution was observed for $T = 25$ and 40 K.

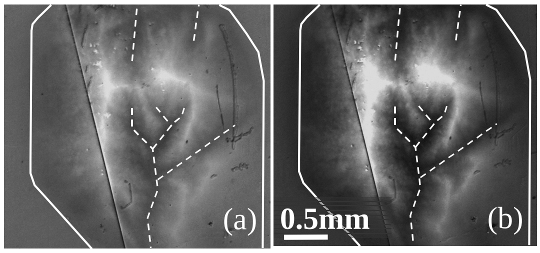


Fig. 2. MO images of frozen magnetic flux distributions in the core at $T = 19$ K in $B_a = 37$ (a) and 20 mT (b). The solid lines show the sample edges; the dashed lines mark the largest cracks.

In summary, thermally activated depinning of *individual vortices* is proposed as the origin of the temperature dependence of $B^*(T)$. A comparison between global and local magnetic measurements shows that within the available resolution of our MO technique, the frozen magnetic flux distribution does not change at $B_a \leq B^*(T)$, indicating that no vortex movement takes place in this field range.

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## References


[1] R. L. Peterson, J. W. Ekin, Physica C **157** (1989) 325; K. Shibutani, *et al.*, Appl. Phys. Lett. **63** (1993) 3515.

[2] J. Horvat, *et al.*, Physica C **271** (1996) 51.

[3] F.C. Klaassen, *et al.*, Phys. Rev. B **64** (2001) 184523; V. M. Pan, A. V. Pan, Low Temp. Phys. **27** (2001) 732 [Fiz. Niz. Temp. **27** (2001) 991].

[4] K. A. Müller, *et al.*, Phys. Rev. Lett. **58** (1987) 1143.

[5] L. Miu, Phys. Rev. B **46** (1992) 1172 and references therein.

[6] L. Burlachov, *et al.*, Phys. Rev. B **50** (1994) 16770.

[7] M. V. Fiegel'man, V. M. Vinokur, Phys. Rev. B **41** (1990) 8986.

[8] See for example A. M. Suvarna, C. S. Sunandana, Solid State Commun. **95** (1995) 11.