

## Alternative approach to the hysteresis of transport current in Bi-based tapes

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**ABSTRACT:** The induced critical currents and the reversible (equilibrium) magnetic moment were studied in Bi-based samples prepared by different technologies, in a wide range of temperatures and external magnetic fields. A hysteresis of intergranular (transport) currents appears in the Bi-2212 and Bi-2223 tapes together with an anomaly of reversible moment. We conclude that the effect of intragranular stray fields on the field at grain boundaries cannot explain the observed behavior. The data indicate that the transport currents might be due to opposite field gradients in the intergranular space to those inside the grains.

### 1. INTRODUCTION

Due to vortex pinning, the critical current density,  $j_c$ , in type-II superconductors exhibits hysteresis. Surface and/or geometrical barriers can also contribute to the critical current hysteresis manifested by a vertical asymmetry of the magnetic hysteresis loops. Both surface and geometrical barriers seek to enhance the critical currents in *increasing* fields with respect to those in decreasing fields. The lagging of the effective internal field behind the applied field and the shift due to reversible (equilibrium) moment also contribute in the same manner.

In polycrystalline Tl- and Bi-based tapes just the opposite behavior has been observed, i.e.  $j_c$  being higher in decreasing applied field than in increasing one. At the same time an anomalous shift of the central peak maximum to positive fields on the descending field branch appears. Both these effects are particularly enhanced in Bi-2223 tapes. A number of models have been developed to explain these anomalies on the basis of original idea of Evetts and Glowacki (1988) who pointed out that stray fields originating from critical currents inside individual grains could affect intergranular (transport) current flow through grain boundaries. Dyachenko (1992) proposed a mechanism explaining the anomalous transport current flow in terms of Bean-Livingston surface barriers at grain boundaries. The bending experiments proposed by Müller et al (1994) with the aim to separate contributions of intra- and intergranular currents proved that in Bi-2223 tapes the intergranular (transport) currents is the main source of both anomalies.

In this paper, we present new experimental data measured on four Bi-based samples prepared by different technologies and propose a novel description of the transport current hysteresis.

### 2. EXPERIMENTAL

Four different Bi-based polycrystalline samples were investigated:

- (i) Bi-2212 tape, dip-coated, made at University of Oxford, UK,

- (ii) Bi-2212 partially melted ceramics prepared at NTNU Trondheim,
- (iii) Bi-2212 single crystal from the Institute for Metal Physics, Kiev, and
- (iv) Bi-2223 monocore tape produced by conventional powder-in-tube technique in NST, Denmark.

The magnetic hysteresis and the field-cooled equilibrium moments were measured on all samples by means of a SQUID magnetometer. Temperatures ranged between 5 K and 120 K. The dip-coated Bi-2212 and the Bi-2223 tape were tested by means of the bending procedure (Müller et al 1994).

### 3. RESULTS AND DISCUSSION

In the Bi-2223 tape a pronounced anomalous hysteresis of the total magnetic moment (before sample bending) was observed, being manifested by both the anomalous position of the central peak at *positive* decreasing applied fields and the MHL asymmetry in favor of the descending field branch (see Fig. 1 (b)). In the original Bi-2212 tape we observed the MHL curve nearly symmetrical with respect to field axis (Fig. 1 (a)). In both samples after the bending to a diameter  $\approx 1.3$  mm, the MHLs had conventional shapes (Figs. 1 (a) and (b)). After the subtraction of the latter curves from the original ones the resulting net „intergranular“ component had an anomalous behavior not only in Bi-2223 but also in the Bi-2212 tape (Fig. 1 (b)). This proved that the anomaly is closely related to intergranular current properties. The anomalous behavior was observed in the temperature range between 5 K and 60 K in Bi-2223, and in a narrower range between 5 K and 25 K in Bi-2212. The effect in the Bi-2212 tape is not so pronounced as in the Bi-2223 tapes, and it is completely absent in the Bi-2212 single crystal and in the Bi-2212 partial-melted ceramics. These observations confirm that both anomalies are due to transport currents in well-grain-aligned polycrystalline samples. The reason for the lack of the anomaly in the partial-melted ceramics is not clear. Some role the different mechanical and thermal treatment can play, which results in not so good grain alignment and produces a different intergranular medium to that in tapes.

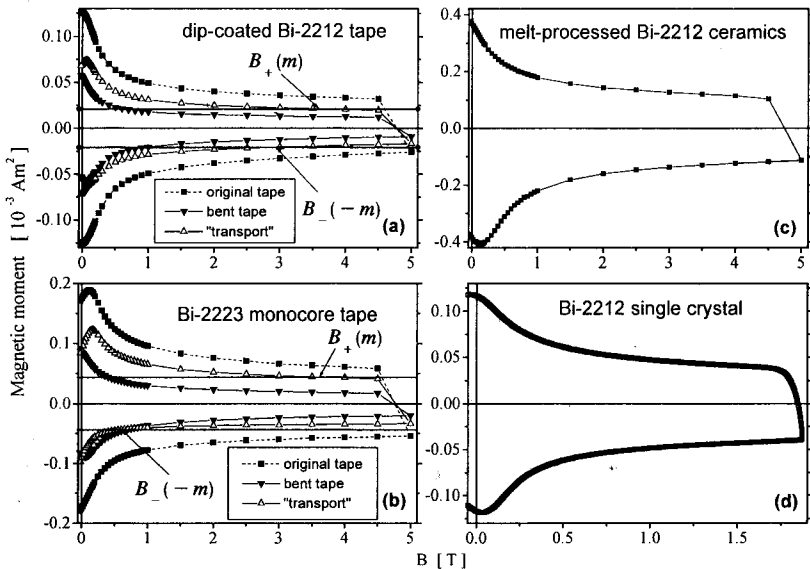


Fig. 1 Magnetic hysteresis measured at  $T = 5$  K on four Bi-based samples prepared by different methods, as indicated in the figures. (a) Magnetic moments measured before and after bending of the Bi-2212 tape and the corresponding "transport" magnetic moment. The horizontal lines at  $\pm m$  are used to define  $B_+$  and  $B_-$ . (b) The same for the Bi-2223 tape. (c) and (d) MHLs measured on the Bi-2212 ceramics and the Bi-2212 single crystal. Note the difference in positions of the central peaks and of the symmetry with respect to x-axis.

To describe the hysteresis of transport currents more precisely, we used an alternative description of the phenomenon. We adopted two natural assumptions: (i) the transport current flow is unambiguously determined by the actual magnetic field  $B_{gb}$  at the grain boundaries and (ii) the intergranular current is a decreasing function of  $|B_{gb}|$ . These two assumptions lead to the conclusion that the value of  $|B_{gb}|$  has to be the same at the two external fields  $B_+$  and  $B_-$ , where the intergranular current (or the associated magnetic moment  $m$  on one of the MHL branches) reaches the same value. This gives us the possibility to reconstruct the conditions at the grain boundaries: For any value of  $m$  we find the fields  $B_+$  and  $B_-$  (on one MHL branch). Due to MHL symmetry  $B_+(m) = -B_+(-m)$  and  $B_-(m) = -B_-(-m)$ . Then, for a given  $m$ , it applies

$$B_{gb} = B_+ + B_{stray+} = -B_- - B_{stray-}, \quad (1)$$

where  $B_{stray+}$  and  $B_{stray-}$  are the stray fields at  $B_+$  and  $B_-$ , respectively. As, in general,  $B_+ \neq -B_-$ , also  $B_{stray+} \neq -B_{stray-}$ . By substitution, we obtain

$$(B_+ - B_-)/2 = B_{gb} + (B_{stray+} - B_{stray-})/2, \quad (2)$$

$$(B_+ + B_-)/2 = (B_{stray+} + B_{stray-})/2. \quad (3)$$

We see that  $(B_+ + B_-)/2$  can serve as a measure of the magnitude of averaged stray fields for a given  $B_{gb}$ . The stray fields  $B_{stray-}$  and  $B_{stray+}$  are expected to be proportional to the intragranular currents and should have therefore the same sign on the same MHL branch. Consequently, they partially cancel each other and  $(B_+ - B_-)/2$  gives an approximation of  $B_{gb}$ . In Fig. 2 we plot the average

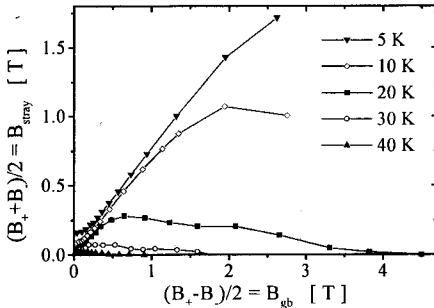


Fig. 2 Stray fields in the Bi-2223 tape arising from intra-granular currents plotted as a function of the field at grain boundary.

intragranular stray field as a function of the grain boundary field for the Bi-2223 tape at various temperatures. We see that at low temperatures the average  $B_{stray}$  is approximately directly proportional to the grain boundary field. This is rather surprising, as the stray fields should be proportional to the intragranular currents, which in turn should decrease with increasing applied field (Müller et al 1997). The stray fields should therefore decrease with increasing field and the anomaly should disappear. Neither the concept of Evetts and Glowacki (1988), nor any of the related models can explain this controversy.

For a correct estimation of the transport current anomaly we need to know the equilibrium magnetic moment  $m_{eq}$ , i.e. the reversible moment, to which the irreversible moments on both MHL branches are related. We measured the equilibrium moment by field cooling using SQUID magnetometer. From the  $m_{eq}(T)$  curves measured for a series of applied fields (Fig. 3 (a)), the  $m_{eq}(B)$  dependencies (Fig. 3 (b)) were reconstructed. At the first glance the behavior of the equilibrium moment is rather complex. Above 65 K,  $m_{eq}(B) \approx \ln B$  and with increasing temperature  $m_{eq}$  gradually decreases, as expected. Below 60 K this tendency breaks and the  $m_{eq}(B)$  curves gradually shift with decreasing temperature towards zero. The temperature dependence in Fig. 3 (a) exhibits a bound towards zero instead of saturation at an appropriate level at low temperatures. Comparison of Figs. 2, 3 (a) and (b) with the set of MHLs measured at different temperatures showed that the regular behavior of the equilibrium moment fits in the vortex phase diagram into the range of the melted vortex lattice. Coming close to the irreversibility line the anomaly of the reversible (equilibrium) moment starts to develop. This points to the existence of two vortex media in the Bi-based tapes. The character of curves in Figs 3 (a),(b) implies that besides the regularly behaving reversible moment, corresponding to the vortices inside the grains, the intergranular

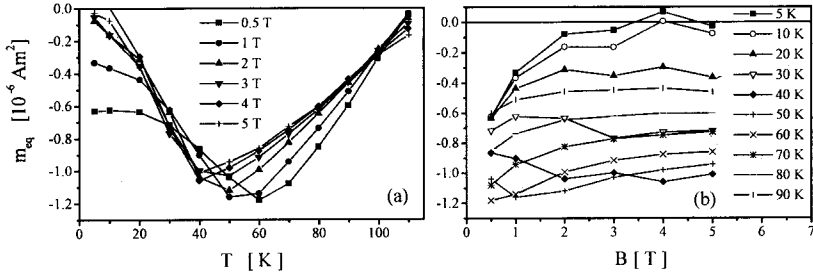


Fig. 3 Equilibrium magnetic moment measured on the unburnt Bi-2223 tape by field-cooled method using SQUID magnetometer. (a)  $m_{eq}$  as a function of temperature, (b)  $m_{eq}$  as a function of applied field.

superconducting medium develops a reversible moment of opposite polarity, which competes with the former one. This results in the anomaly of the total reversible moment. For the observed suppression of the total reversible moment at low temperatures, the reversible moment corresponding to the irreversible currents has to be of a comparable magnitude to that of intragranular currents. This magnitude is, however, too low to account for the transport current hysteresis. We believe that the positive reversible moment corresponding to the intergranular medium is a sign of an opposite orientation of the field gradients in the intergranular space to the gradients in the grains. In such a case the transport current hysteresis would be easy to understand. However, this hypothesis needs a further experimental and theoretical check.

#### 4. SUMMARY

In conclusion, we measured and analyzed magnetic hysteresis loops on different Bi-based samples. On the Bi-2223 and Bi-2212 tapes we observed hysteresis of intergranular (transport) currents and also an anomaly of the total equilibrium (reversible) moment in the field-temperature range coinciding with the region of irreversibility. We conclude that only the intragranular stray fields cannot explain the observed behavior. The observed anomaly of the total equilibrium moment indicates that the field gradients in the intergranular space, responsible for the transport currents, might have the opposite direction to those inside the grains. Then the anomaly of the transport currents would be easy to understand. Further experiments are in the course to check this hypothesis.

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