Magnetic flux dynamics in a hexagonal network of superconducting islands

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Abstract

Honeycomb arrays (cells \( \approx 50 \mu m \) in size) were patterned in a YBa Cu O thin film in order to model magnetization and transport current processes in granular materials. The samples were studied magnetically and magneto-optically (MO). The induced inter-granular currents exhibited an anomaly similar to that observed in Bi-based tapes. The magneto-optical observation showed a flux penetration/reversal process consisting of two Bean critical states, of inter- and intra-granular screening currents. The rate of flux penetration into the inter-granular space was an inverse function of the bridge width and was significantly faster than penetration into the grains. The grain magnetization was non-uniform and asymmetrical. Although grains stood up to maximum field of 57.7 mT incompletely penetrated, after the field reversal the opposite magnetic flux fully penetrated the grains far before reaching remnant state.

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1. Introduction

In granular superconductors two types of currents screen applied field, namely inter- and intra-granular ones. While the density of latter ones is usually high, their perimeter, limited by the grain size, is rather small. The inter-granular currents have usually relatively low densities but perimeter of their paths is large, related to the whole sample dimensions. As a result, the contributions of both types of currents to the total magnetic moment are comparable. In Bi-based tapes the induced inter-granular currents exhibit an anomalous magnetic hysteresis loop (MHL) [1–3], with the central peak shifted to a distinct positive descending magnetic field from the ordinary negative position typical for compact, e.g. single-crystalline samples. Moreover, the whole curve is usually shifted upwards, to paramagnetic moments [1,2,4] and even the reversible moment detected by field-cooling method can be positive [3].

In order to simplify the complexity of granular matter in tapes, a model thin-film sample
composed of a hexagonal system of tightly packed disks was studied [4]. The results imply that the applied field in the granular medium might drive some local currents in paramagnetic direction.

In the present work we studied magnetically and magneto-optically properties of a series of new model samples consisting of hexagonal grain arrays in a honeycomb configuration. The grains were in one sample isolated, in other two samples inter-connected by superconducting bridges 2 and 4 \( \mu \text{m} \) wide.

2. Details of the experiment

The pattern shown in Fig. 1 was created in a YBa\(_2\)Cu\(_3\)O\(_y\) thin film 200 nm thick. The overall dimensions of the pattern were 4\( \times \)4 mm\(^2\). Each hexagonal superconducting grain of 48 \( \mu \text{m} \) size was surrounded by 2 \( \mu \text{m} \) wide space. Thus each sample consisted of about 6500 grains. In one sample the grains were left isolated, in other two samples the grains were inter-connected by superconducting bridges 2 and 4 \( \mu \text{m} \) wide. The samples were studied magnetically by means of a vibrating sample magnetometer (VSM) and magneto-optically.

3. Experimental

Magnetic hysteresis loops of all three samples measured by VSM at 5 K are presented in Fig. 2(a). Significant is the small intra-granular contribution (sample with no bridges) with respect to that of inter-granular currents (samples with bridges). Rather striking is the appearance of the deep dip at low applied fields (Fig. 2(a) and (b)). The dip depth practically did not depend on the bridge width, which indicated that it was associated with intra-granular currents. After subtraction of the corresponding contribution from MHLs of the samples with bridges, the dip on the resulting MHLs nearly disappeared (Fig. 2(c)). The inter-granular current contribution exhibited a similar anomaly like Bi-based tapes [1,2]: maximum moment appeared at a positive descending field instead of negative one. In contrast to Bi-based tapes, the bridges in the present samples were strong inter-grain links. This shows that the anomaly is associated with the granular character of the sample irrespective of conductivity of inter-granular contacts.

To get better insight into the magnetic flux dynamics in the samples, magneto-optical study was made. First, the sample with isolated grains was investigated. In this case magnetic field freely penetrated the inter-granular space without any sign of screening (Fig. 3(a)). The grains were screened by induced intra-granular currents uniformly throughout the sample. The maximum available field, 577 Oe, was not able to fully penetrate the grains. However, soon after the field reversal the screened grain centers filled with...
magnetic flux of opposite sign and the grains became completely penetrated far before remnant state (Fig. 3(b)).

In the samples with inter-grain bridges the situation was different. At low applied fields the whole sample was perfectly screened by inter-granular currents flowing through the system of bridges. Magnetic field entered the inter-granular space gradually. In the sample with narrower bridges the flux front penetrated about twice as fast as in the sample with broader bridges (Fig. 4). Magnetic field penetrated the inter-granular space in the dome-like manner reflecting thus the rectangular geometry of the sample. The flux penetration into the inter-granular space was in both samples significantly faster than that into the grains. In other words, a part of the flux penetrated the inter-granular space not across the bridges but along the sample normal. This additional flux had to be screened in the superconductor by extra currents flowing around the penetrated inter-grain “cells”, including the relevant bridges. We note that these extra screening currents, flowing at inner sides of the bridges, are opposite to those flowing at outer sides (with respect to the sample center). Thus, the bridges are two-way paths for the screening currents. During flux entrance the “inner” screening currents are always less in magnitude than the “outer” ones, after the field reversal the situation flips over. Each cell, surrounded by three neighbouring grains and three bridges (Fig. 1), can be understood as a giant vortex. The currents screening such a giant vortex close through the neighbouring grains, where they represent a part of the intra-granular currents.

Fig. 3. Magneto-optical images of the sample without bridges in ascending applied field 350 Oe (top) and the same descending one (bottom) after reaching 577 Oe. No (dark) screened grain centers remained in the bottom figure. The grains became fully penetrated. In both regimes magnetic field uniformly penetrated the inter-granular space (the slight light gradient is an apparatus artefact) and no $d^+$ lines [3] appeared in the image.

Fig. 4. Magneto-optical images of two samples with different bridge widths (2 $\mu$m top and 4 $\mu$m bottom) in ascending field 17.5 Oe. The gradual flux penetration into inter-granular space is about double for narrow bridges due to the less field screening by inter-granular currents. Bean dome-like penetration and $d^+$ lines [3] appear.
Note that these screening currents flow in “paramagnetic” sense with respect to the external field.

In the samples with bridges, the inter-granular field at opposite sides of grains is different. Therefore, the flux penetration into the grains is anisotropic. This is a distinct difference from the sample without bridges, where the flux penetration into both inter- and intra-granular space was isotropic.

In the samples with bridges, magnetic flux propagates into the inter-granular space in the dome-like manner, forming an inhomogeneous inter-granular flux distribution (Fig. 4). Therefore, magnetic flux penetration into the grains depends on the grain position in the sample. In the present MO experiment the maximum field of 57.7 mT did not allow to saturate the grains even at the highest local field. After the field reversal, the flux in the grains of all the samples reversed much faster than it previously penetrated, moreover the flux front reached the grains centers long before remnant state. Fig. 5 shows in detail the magnetic field distribution in the sample with wide bridges after its magnetization up to the maximum of 57.7 mT and the following field reduction to 15.6 mT (top figure). The mathematical analysis of the magnetic flux in a series of grains along the white line in the top image is show in the bottom graph. A slight inter-granular field gradient (corresponding to inter-granular screening current of 3.4 kA/cm²) is seen, together with strong field gradients (indicating intra-granular current density \(\approx 47 \text{ kA/cm}^2\)) close to grain edges. These critical currents have reasonable magnitudes and indicate that magnetic moment from inter-granular currents is about 14 times higher than that from intra-granular ones. This is in a qualitative agreement with Fig. 2 if we take into account the incomplete sample magnetization. In the grain centers the field was surprisingly nearly constant.

The maximum field of the MO set-up was too low to fully penetrate the sample at low temperatures, where the magnetic anomalies were most pronounced. Therefore, at the present stage of study, we could not recognize origin of the anomalous behavior of inter- and intra-granular currents.

4. Summary

Arrays of hexagonal microscopic thin film superconducting islands, in one sample isolated and in other two samples inter-connected by tiny superconducting bridges of different widths, were studied magnetically and magneto-optically. The total magnetic moment was nearly proportional to the bridge width, which indicated that the principal role belongs to inter-granular currents. A dip of a constant depth, observed on MHLs of all samples around zero field, was attributed to intra-granular currents. In the system with isolated grains no sign of magnetic flux screening in the inter-granular space was observed and flux penetrated all the space immediately after field application. In the samples with bridges, magnetic field propagated among the grains gradually and magnetization of grains was anisotropic. It also strongly depended on the grain position in the rectangular sample. The grains of all samples...
remained incompletely magnetized up to maximum field 57.7 mT. After the field reversal the flux inside grains did not only reverse but penetrated up to the grains centers at fields far before remnant state. The limited maximum field of the MO set-up did not allow for a recognition of the origin of anomalous magnetization process. On the other hand, several specific features of the magnetization process in granular medium was manifested.

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References