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ORIGINAL PAPER

Correlation Between Magnetoresistance and Magnetization Hysteresis in a Granular High-T_C Superconductor: Impact of Flux Compression in the Intergrain Medium

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Abstract The correlation between experimental magnetic field dependences of magnetoresistance and magnetization hysteresis in granular $YBa_2Cu_3O_7$ is established. Within the proposed approach, magnetoresistance is assumed to be determined by the effective field in the intergrain boundaries the ensemble of which is considered to be a Josephson medium. The effective field in the intergrain medium can be written in the form $B_{\mathrm{eff}}(H) = H - 4\pi M(H) \times \alpha$, where α is the parameter of averaged demagnetizing factors of grains and the degree of flux compression. A comparison of experimental magnetoresistance $R(H)$ and magnetization $M(H)$ hysteresis dependences obtained at different external magnetic field sweep rates yields the value $\alpha \sim 10$, which is caused by the flux compression between grains. The proposed model describes well most of the features of the magnetoresistance hysteresis in granular high-T_C superconductors.

Keywords Granular superconductor · Josephson medium · Effective field · Magnetoresistance · Magnetization hysteresis

1 Introduction

Since the discovery of high-temperature superconductivity, the magnetoresistive effect in granular high-T_C superconductors (HTS) has been in focus of researches. Bulk HTS materials are interesting for both application and fundamental research due to the possibility of implementation of Josephson junction networks. In granular HTS materials, an intergrain boundary length is a few nanometers, which is comparable with the superconducting coherence length. This favors the formation of the Josephson coupling between superconducting grains. The ensemble of grain boundaries in granular HTS materials can be considered as a Josephson medium [1]. Specifically, a granular HTS is considered as a two-level superconducting system [2] consisting of superconducting grains and a Josephson medium. Both subsystems contribute to the magnetic and magnetoresistive properties of a material. The magnetic contribution of the Josephson medium subsystem is observed as a weak $M(H)$ hysteresis against the background of a large diamagnetic response of HTS grains. This behavior usually takes place in very weak magnetic fields.[1] In the field dependence of magnetoresistance $R(H)$, the dissipation (the voltage drop in an external magnetic field) is governed mainly by processes occurring in the Josephson medium subsystem. The contribution of HTS grains to the magnetoresistance is visualized in the $R(H)$ dependence as the curvature variation in strong magnetic fields.[2]

As is known, the magnetic field dependence of magnetoresistance $R(H)$ in granular HTS materials is a hysteresis function [6–24]. After pioneering reports [6, 7], a number of studies on the magnetoresistance hysteresis in granular HTS systems have been published [11–24] aimed mainly at clarification of the hysteretic behavior of magnetoresistance. Today, one may conclude that the hysteresis of the $R(H)$

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[1] Typically, a few Oersteds at the liquid helium temperature and about the Earth's magnetic field or lower in the vicinity of the liquid nitrogen temperature [3, 4].

[2] For example, for optimally doped Y–Ba–Cu–O with $T_C \sim 90$ K, the field of the dissipation onset in grains is about $\sim 10^5$ Oe at the liquid nitrogen temperature [5].

dependence is caused by the effect of magnetic moments of HTS grains on the total magnetic induction in the intergrain medium. If an external field exceeds the first critical field of the Josephson medium, the total magnetic induction in the intergrain medium is a vector sum of the external field $\boldsymbol{H}$ and the field induced by HTS grains.

Surprisingly, the effect of the magnetic moments of HTS grains on the total field in the intergrain medium appeared much larger than that estimated using the conventional $M(H)$ data [22, 24]. Therefore, to obtain the parameters of the $R(H)$ hysteresis, one should assume that the magnetic flux is compressed in the intergrain medium. In this study, based on the $R(H)$ dependences for bulk $YBa_2Cu_3O_7$ measured at different rates of the external field sweep (dH/dt), we experimentally confirm the existence of flux compression in the intergrain medium of a granular HTS material. We demonstrate that it is the flux compression that ensures the strong correlation of the magnetic and magnetoresistive properties of granular HTS materials.

2 Experimental

A sample to investigate is the classical $YBa_2Cu_3O_7$ obtained by a standard solid-state reaction technique. The parameters of the sample are typical of this composition: the critical temperature $T_C \approx 92$ K; the resistivity 1.8 mΩ cm and 1 mΩ cm at 300 K and 100 K, respectively; and the critical current density ∼50 A/cm^2 at 77.4 K. The physical density is about 87 % of the theoretical value.

Transport measurements were performed by a standard four-probe method. The sample was ∼$0.8 \times 0.8 \times 7$ mm^3 in size. In measuring the $R(H)$ dependence, the sample was placed inside a copper solenoid in the liquid nitrogen medium to exclude the Joule heating effect and stabilize the transport current $I = 150$ mA. A magnetic field was applied parallel to the transport current direction, i.e., along the largest dimension of the sample.

Magnetic measurements were performed on a vibrating sample magnetometer on the sample used for magnetoresistance measurements to ensure the same demagnetizing factor of the entire sample in the $R(H)$ and $M(H)$ measurements. The conditions for the magnetoresistive and magnetic measurements (zero field cooling and magnetic field sweep rate dH/dt) were identical.

3 Results and Discussion

Figure 1 shows the hysteresis dependence of magnetization for the investigated sample for two measurement types. In the measurements of type (i), the entire hysteresis loop was obtained in the fields varying from $H = 0$ to $H_{max} = 500$ Oe

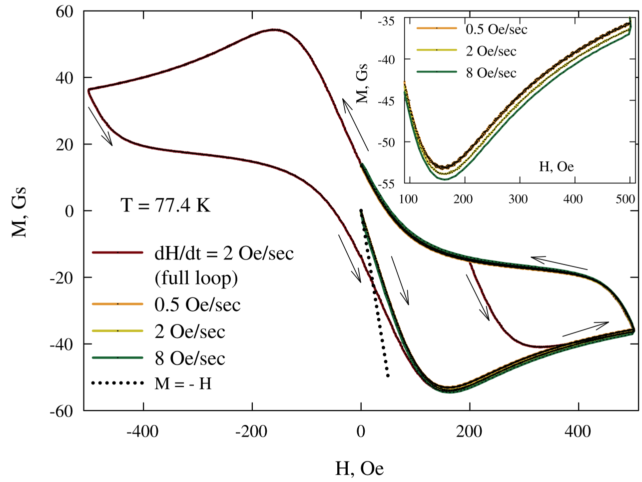

Fig. 1 Hysteresis field dependences of magnetization for different magnetic field sweep rates dH/dt. *Arrows* show the field scanning directions. The *inset* shows the details of the field sweep rate effect

and then cycling within ±500 Oe at the field sweep rate $dH/dt = 2$ Oe/s. In addition, this measurement type includes a subloop, in which the field in the descending branch increases again to H_{max} at $H = 200$ Oe. In the measurements of type (ii), the hysteresis loop portions were obtained at the field varying from $H = 0$ to $H_{max} = 500$ Oe and back at different field sweep rates dH/dt.

Asymmetry of the $M(H)$ loop relative to the abscissa axis (Fig. 1) is typical of a bulk HTS in the high-temperature region [25, 26]. The effect of the magnetic field sweep rate on the $M(H)$ dependence of HTS materials is well-known. As the sweep rate is increased, the absolute value of the total magnetization grows due to the features of the intragrain relaxation processes [25]. The effect of the sweep rate on the $R(H)$ hysteresis is discussed below.

Figure 2(a) shows the hysteresis dependence of magnetoresistance $R(H)$ for the investigated sample. The magnetic prehistory of the presented data corresponds to the results of the magnetic measurements of type (i). The shape and main features of the hysteresis dependence $R(H)$, including the existence of the minimum at field H_{min} in the descending branch of the dependence are typical of granular HTS materials [10, 19]. To describe the magnetoresistance hysteresis, let us briefly consider the model of a granular HTS in an external magnetic field [19, 20].

The complex distribution of magnetic induction lines in the intergrain medium can be simplified by introducing effective field B_{eff} in it. A variety of grain boundaries are in the same effective field, which is the superposition of an external field and the field induced by magnetic moments of grains B_{ind}. The induced field $\boldsymbol{B}_{ind}$ is co-directed with $\boldsymbol{H}$ at $M < 0$ and antiparallel to $\boldsymbol{H}$ at $M > 0$ (for more details, see the schematic of magnetic induction lines in the intergrain medium in Fig. 2(a) and the figures in [19, 21, 24]).

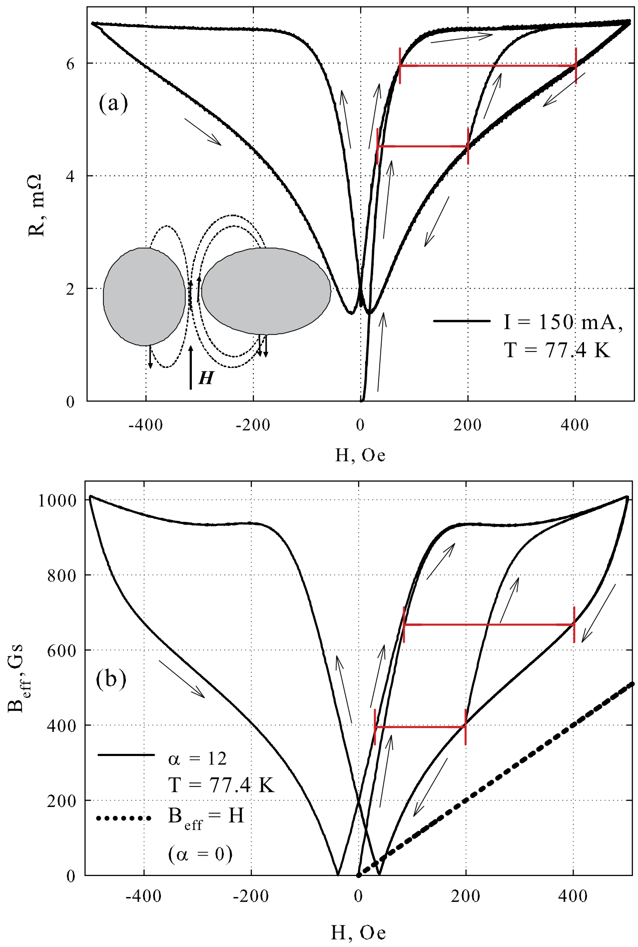

Fig. 2 Hysteresis field dependences of (**a**) magnetoresistance and (**b**) effective field $B_{\mathrm{eff}}(H)$ calculated using Eq. (2) from the data presented in Fig. 1. (**a**) Schematic of magnetic induction lines in the intergrain medium of the granular superconductor: *ovals* correspond to the superconducting grains, $\boldsymbol{H}$ is the external field. *Horizontal lines* are examples of determination of field hysteresis width ΔH at $H_{\downarrow} = 200$ and 400 Oe, *arrows* show the field scanning directions. (**b**) The *straight line* $B_{\mathrm{eff}} = H$ is shown to clarify the effect of parameter α on the $B_{\mathrm{eff}}(H)$ dependence

To relate field B_{ind} induced by superconducting grains to the macroscopic magnetic moment obtained by the magnetic measurements, a parameter α is introduced:

$$B_{\mathrm{ind}} = 4\pi M \times \alpha. \tag{1}$$

This parameter includes averaged demagnetizing factors of superconducting grains and the degree of flux compression in the intergrain medium due to the interference of neighboring grains [10, 19, 24]. Relation (1) is applicable in a wide magnetization range, except the region near $M \approx 0$ in the descending branches of the hysteresis dependence $M(H)$ (Fig. 1). Indeed, the zero total magnetization results from the equality of the magnetic contributions from the screening (Meissner) currents and Abrikosov vortices averaged over the entire sample. These contributions, however, can yield the nonzero magnetic induction in the intergrain medium.

Thus, the effective field in the intergrain medium can be written as

$$B_{\mathrm{eff}}(H) = H - 4\pi M(H) \times \alpha. \tag{2}$$

Equation (2) takes into account the mutual orientation of $\boldsymbol{H}$ and $\boldsymbol{B}_{\mathrm{ind}}$. In the first approximation, parameter α is assumed to be field-independent. Regarding the magnetoresistance, we should consider the absolute values of the effective field $|B_{\mathrm{eff}}(H)|$.

If the dissipation (the voltage drop in an external field) occurs in the intergrain medium only, the value of $|B_{\mathrm{eff}}|$ eventually determines the magnetoresistance. The $R(B_{\mathrm{eff}})$ dependence is assumed to be non-hysteretic, while the $M(H)$ hysteresis (Fig. 1) results in the $B_{\mathrm{eff}}(H)$ hysteresis and, consequently, the $R(H)$ hysteresis. For any two points in the $R(H)$ hysteretic dependence where $R = \mathrm{const}$, the effective fields are assumed to be equal. This hypothesis was confirmed by the studies of the $R(H)$ hysteresis at different transport currents [19, 20, 23, 27]. Indeed, if for certain increasing ($H_{\uparrow}$) and decreasing ($H_{\downarrow}$) fields, the equality $R(H_{\uparrow}) = R(H_{\downarrow})$ is valid, this equality holds in a wide transport current range ($R(H) = V(H)/I$) despite the strongly nonlinear behavior of the (I–V) characteristics. Therefore, it would be reasonable to introduce a current-independent parameter of the hysteresis dependence $R(H)$, specifically the field hysteresis width $\Delta H = H_{\downarrow} - H_{\uparrow}$ obtained at $R = \mathrm{const}$ and $B_{\mathrm{eff}} = \mathrm{const}$. This parameter is convenient for comparison of the hysteresis dependences $R(H)$ and $B_{\mathrm{eff}}(H)$ [19, 20, 23]. From Eq. (2), we obtain

$$\Delta H = H_{\downarrow} - H_{\uparrow} = \alpha \times 4\pi\big(M(H_{\downarrow}) - M(H_{\uparrow})\big). \tag{3}$$

Figure 2(a) shows the examples of determination of field hysteresis width ΔH for the $R(H)$ dependence (horizontal lines). Figure 2(b) demonstrates the absolute value of the $B_{\mathrm{eff}}(H)$ dependence obtained by Eq. (2) using the magnetic data presented in Fig. 1. Horizontal lines in Fig. 2(b) correspond to field hysteresis width ΔH for the $B_{\mathrm{eff}}(H)$ dependence. At $\alpha \approx 12$, the values of ΔH for the $R(H)$ and $B_{\mathrm{eff}}(H)$ dependences from Figs. 2(a) and 2(b) are in good agreement.

Regarding the shape of the $R(H)$ dependence, the magnetoresistance is a function of the absolute value of the effective field. As follows from the conventional description of dissipation processes in type II superconductors, the $R(|B_{\mathrm{eff}}|)$ dependence should be an S-shaped curve tending to saturation at relatively high B_{eff}. A pronounced plateau on the $R(H_{\uparrow})$ dependence corresponds to the behavior of the $B_{\mathrm{eff}}(H)$ dependence. With a further increase in an external field (up to $\sim 10^4$ Oe), the resistance slowly grows. According to our estimations based on the $R(T, H)$ data (not

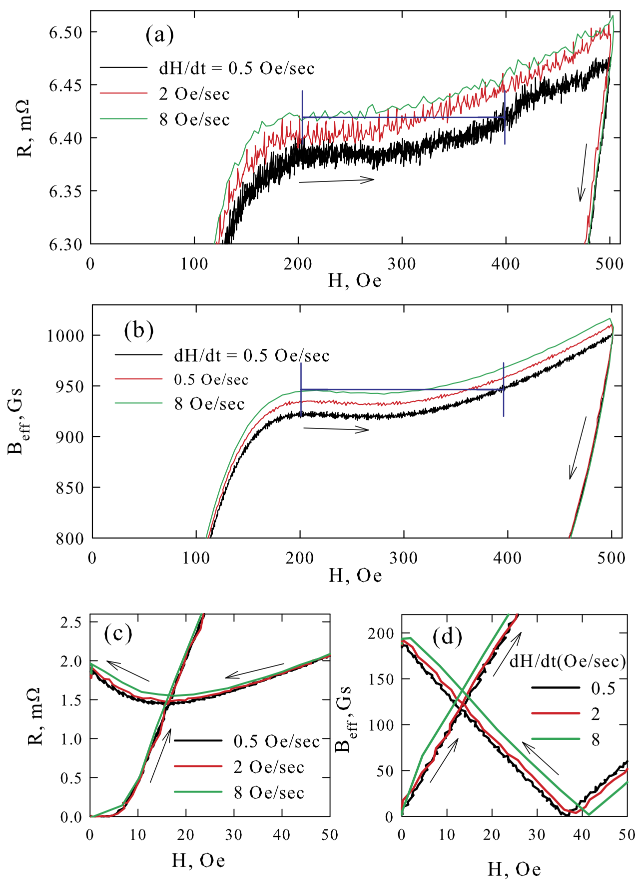

Fig. 3 Details of the hysteresis (**a**, **c**) $R(H)$ and (**b**, **d**) $B_{\text{eff}}(H)$ (calculated by Eq. (2) from the data presented in Fig. 1) dependences obtained at different field sweep rates dH/dt. (**a**, **b**) *Horizontal lines* show the values identical to ΔH for the $R(H)$ and $B_{\text{eff}}(H)$ dependences obtained using relation (4)

shown), the value $R(H_\uparrow = 500\ \text{Oe},\ T = 77.4\ \text{K})$ is about 70 % of the maximal contribution of intergrain boundaries to the total resistance

Thus, the consideration of the effective field $B_{\text{eff}}(H)$ allows explaining the following features of the hysteresis dependence $R(H)$: (i) the sharp growth of the resistance in weak magnetic fields (up to 10^2 Oe), (ii) the plateau-like behavior in fields over 10^2 Oe, (iii) the specific shape of the descending $R(H_\downarrow)$ branch (the change of the curvature sign at $H_\downarrow \approx 400$ Oe), (iv) the subloop behavior at $H \geq 200$ Oe, and (v) the relative position of the virgin $R(H)$ curve and the $R(H_\uparrow, H_\downarrow)$ branches in the fields from $H = 0$ to $H_{\max} = \pm 500$ Oe.

Figure 3(a) shows the portions of the $R(H)$ dependences obtained at different field sweep rates dH/dt (measurements of type (ii)). It can be seen that at a certain field value the growth of dH/dt results in the growth of magnetoresistance. This effect is explained well within the model discussed above. The $M(H)$ dependences measured at the same values of dH/dt as the $R(H)$ dependences are shown in Fig. 1. Figure 3(b) presents the portions of the $B_{\text{eff}}(H)$ dependences obtained by Eq. (2) using the $M(H)$ data and the value $\alpha = 12$ at different field sweep rates. One can see the qualitative consistency with the data in Figs. 3(a) and 3(b). The quantitative agreement can be seen from parameters ΔH of these dependences shown by horizontal lines in Figs. 3(a) and 3(b). Indeed, if $R = \text{const}$ for certain fields H_1 and H_2 of the $R(H)$ dependences for different sweep rates, then the condition $B_{\text{eff}}(H_1) = B_{\text{eff}}(H_2)$ can be valid. In this case, instead of expression (3), we obtain

$$\Delta H = H_{2\uparrow} - H_{1\uparrow} = \alpha \times 4\pi \left(M_{\text{SR2}}(H_{2\uparrow}) - M_{\text{SR1}}(H_{1\uparrow}) \right), \tag{4}$$

where M_{SR1} and M_{SR2} are the magnetizations measured at different sweep rates. As can be seen from Figs. 3(a) and 3(b), the values of ΔH (horizontal lines) obtained using relation (4) are similar.

Note that the $B_{\text{eff}}(H)$ data obtained at $dH/dt = 0.5$ and 8 Oe/s differ by about 20 Gs for the same values of H, while the difference in the $M(H)$ data obtained at the same sweep rates is merely about 1.5 Gs. The larger difference in the $B_{\text{eff}}(H)$ data is caused by the factor $\alpha = 12$ used in the calculation of the effective field. Thus, the effect of the field sweep rate on the $R(H)$ dependence is clear, assuming $\alpha \sim 10$.

In addition, the approach used explains the relative positions of the $R(H)$ curves at different sweep rates in the field range 0–50 Oe (Figs. 3(c) and 3(d)). The minima in the $B_{\text{eff}}(H_\downarrow)$ and, consequently, $R(H_\downarrow)$ dependences result from the maximum cancellation of the external field and induced field B_{ind}.[3] As can be seen in Figs. 3(c) and 3(d), an increase in the sweep rate results in the shift of $H_{\min}$ toward higher fields both for the $R(H_\downarrow)$ and $B_{\text{eff}}(H_\downarrow)$ dependences.

Analogously, the effect of the field sweep rate on the $R(H)$ dependence is explained. Figure 4 shows portions of the hysteresis $R(H)$ dependences measured in the following way. The field was increased from $H = 0$ with the sweep rate $dH/dt = 0.5$ Oe/s; then, at $H = 250$ Oe the sweep rate was changed for 8 Oe/s ($H_{\max} = 500$ Oe). In the other experiment, the sweep rate was changed from 8 to 0.5 Oe/s at $H = 250$ Oe. It can be seen that the $R(H)$ dependences measured under these conditions intersect near $H \approx 250$ Oe. The $B_{\text{eff}}(H)$ dependences calculated from the $M(H)$ data obtained under the same experimental conditions at $\alpha = 12$ behave similar to the $R(H)$ dependences.

[3]Some discrepancy between the values of $H_{\min}$ for the $B_{\text{eff}}(H)$ and $R(H)$ data in Figs. 3(c) and 3(d) originates from the fact that relation (1) is not quite applicable in the vicinity of zero magnetization ($M \approx 0$ at $H_\downarrow \approx \pm 50$ Oe), as was discussed above.

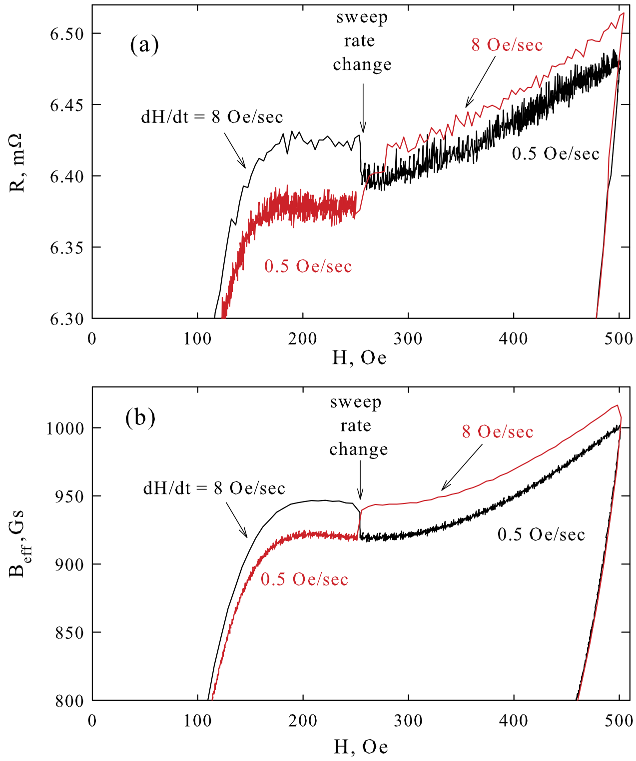

Fig. 4 Details of the hysteresis (**a**) $R(H)$ and (**b**) $B_{\mathrm{eff}}(H)$ (calculated by Eq. (2)) dependences. At $H_{\uparrow} = 250$ Oe, the magnetic field sweep rate was changed as shown

4 Conclusions

Thus, the consideration of the effective field in the intergrain medium of a granular HTS material in the form of Eq. (2) accounts for the observed magnetoresistance hysteresis and the effect of a magnetic field sweep rate on the $R(H)$ dependence. The description involves the important phenomenon of flux compression in the intergrain medium. The flux compression results in the strong effect of magnetization of superconducting grains on the effective field and eventually on the magneto-resistive effect in the granular HTS in weak magnetic fields (up to 10^3 Oe).

The observed effects are inherent to bulk HTS materials since the sample under study has standard characteristics. Different preparation techniques, chemical substitution, or addition of non-superconducting components can affect the magnetic and transport properties of HTS materials. Nevertheless, the main features of the $R(H)$ hysteresis are explained within the approach based on the correlation between magnetoresistance and magnetization.

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