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Study of dependence upon the magnetic field and transport current of the magnetoresistive effect in YBCO-based bulk composites

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Abstract

The magnetoresistive properties of bulk YBCO + CuO and YBCO + $BaPb_{0.75}Sn_{0.25}O_3$ composites for different orientations of external magnetic field $\boldsymbol{H}$ and macroscopic transport current $\boldsymbol{j}$ have been measured. These composites exhibit large magnetoresistance in weak magnetic fields ($<$100 Oe), which makes them promising candidates for practical application in magnetic field sensor devices. The difference between $\rho(T)$ dependences, magnetoresistance curves $R(H)$ and current–voltage characteristics measured for $\boldsymbol{H} \parallel \boldsymbol{j}$ and $\boldsymbol{H} \perp \boldsymbol{j}$ is observed indicating the presence of the Lorentz-force-dependent dissipation in the composites. Angular dependences of magnetoresistance $R(\theta)$ (where $\theta = \angle \boldsymbol{H}, \boldsymbol{j}$) of the composites in weak magnetic fields are found to be proportional to $\sin^2\theta$. This fact suggests that the flux flow in the intergrain boundaries is responsible for the large magnetoresistive effect observed in the composites.

1. Introduction

In our previous work [1], the results of the magnetoresistive (MR) effect in the bulk YBCO + CuO and YBCO + $BaPb_{1-x}Sn_xO_3$ ($x = 0, 0.25$) composites were reported. It was found that the composites exhibit the large MR effect in a wide temperature range (~50–90 K) for weak (less than 100 Oe) magnetic fields, and their resistivity is highly sensitive to the external magnetic field $d\rho/dH \sim$ 2–20 mΩ cm Oe^{-1}. In polycrystalline HTSC, the MR effect is observed in a narrow temperature range [2], and the values of $d\rho/dH$ are small [3]. For this reason, HTSC-based composites with the large MR effect are attractive in terms of their potential practical application in magnetic field sensor devices [1]. Later, the large MR effect was found in the bulk Bi2212 + USr_2CaO_6 [4, 5] and Bi2212 + MgO composites [6]. Also, the sufficiently large MR effect was detected in granular YBCO thick films [7] and BSCCO films [8].

In this work, we have determined the MR effect in the YBCO + CuO and YBCO + $BaPb_{0.75}Sn_{0.25}O_3$ composites for different orientations of the external magnetic field $\boldsymbol{H}$ and macroscopic current density $\boldsymbol{j}$. This study is aimed at solving the following two problems. First, to apply the HTSC-based composites in magnetic field sensors, it is necessary to know the MR effect dependence on the mutual orientation of $\boldsymbol{H}$ and $\boldsymbol{j}$ vectors. As far as we know, no experiments on the HTSC-based composites that could help to clarify this dependence have been performed. Second, the character of the angular dependence of magnetoresistance $R(\theta)$, where $\theta = \angle \boldsymbol{H}, \boldsymbol{j}$, might illuminate physical mechanisms responsible for the MR effect observed in these materials. It is well known that, for the flux flow regime, the angular dependence of dissipation (as well as resistance or voltage drop) is proportional to $\sin^2\theta$ [9, 10]. On the other hand, if the pinning force is not negligible as compared to the Lorentz force, an additional term proportional to $\sin\theta$ appears in the angular dependence of magnetoresistance [10]. The $R(\theta)$ dependences

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were studied on granular HTSCs $La_{1.85}Sr_{0.15}CuO_4$ [11–13], $Bi_{1.6}(Pb_{0.3}Sb_{0.1})Sr_2Ca_2Cu_3O_x$ [14] and $YBa_2Cu_3O_7$ [15]. The dependence $R(\theta) \sim R_{is} + R_{anis}\sin^2\theta$, where R_{is} and R_{anis} are the angle-independent and angle-dependent portions of magnetoresistance, respectively, was observed in weak magnetic fields. The existence of an angle-independent term in the $R(\theta)$ dependence of a granular HTSC was explained satisfactorily in [16].

2. Experimental details

To prepare the $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7 + CuO$ and $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7 + BaPb_{0.75}Sn_{0.25}O_3$ composites, the fast backing technique described in detail in [1] was used. Hereafter we will designate the composite samples as YBCO + VCuO, YBCO + VBaPb$_{0.75}$Sn$_{0.25}$O$_3$, where V is the volume content of CuO ($BaPb_{0.75}Sn_{0.25}O_3$); the volume content of $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ is equal to $100 - V$. XRD patterns confirmed the presence of both phases without any additional reflections in the composites. An average YBCO grain size, estimated from the SEM image, is $\sim$1.5 μm. Magnetic measurements carried out on the samples revealed a single superconducting phase with the critical temperature $T_C = 93.5$ K, which is similar to pure $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$.

Dependences of the transport properties ($R(T)$, $R(H)$ and current–voltage characteristics (CVCs) were measured by the standard four-probe technique. The samples were $1 \times 1 \times 9$ mm^3 in size; a fixed current $\boldsymbol{I}$ was applied along the longest direction of a sample. The distance between potential contacts was $\sim$5 mm. The samples were cooled in zero magnetic field with no screening of the Earth's magnetic field. Temperature dependences of resistance were measured for two orientations of the external magnetic field $\boldsymbol{H}$ and macroscopic critical current density $\boldsymbol{j}$: $\boldsymbol{H} \perp \boldsymbol{j}$ and $\boldsymbol{H} \parallel \boldsymbol{j}$. Angular dependences of magnetoresistance and CVCs were determined for different angles θ between $\boldsymbol{H}$ and $\boldsymbol{j}$, $0° \leqslant \theta \leqslant 360°$. In these measurements the Helmholtz split coil, generating magnetic fields up to 50 Oe, was rotated relative to the direction of transport current through a sample. The whole system 'sample + Helmholtz split coil' was immersed into a bath with liquid nitrogen at ambient pressure.

3. Results and discussion

Figure 1 shows a resistive transition of the YBCO + 15CuO composite in zero magnetic field and different fields applied parallel and perpendicular to the current. The $R(T)$ dependences are typical for weakly coupled granular superconductors [2, 13, 16–20]. A sharp drop of resistance at $T = 93.5$ K is related to the superconducting transition in the HTSC crystallites. External magnetic fields up to several kilo-oersteds just slightly affect this specific feature. The critical temperature of the resistive transition $T_C = 93.5$ K coincides with that determined by magnetic measurements. A broad foot structure results from a transition of the network of Josephson junctions in the composites. In the HTSC-based composites this smooth part of the $R(T)$ dependence lies within a much broader temperature region as compared to pure polycrystalline HSTC [2, 17, 18]. Broadening of the resistive transition is caused by weakening of the Josephson coupling between YBCO crystallites in the composites, because a non-superconducting component forms grain boundaries [1, 21]. The electrical resistance of the Josephson junctions is highly sensitive to the external magnetic field [22], which gives rise to the large magnetoresistive effect in the HTSC-based composites at temperatures below T_C (93.5 K).

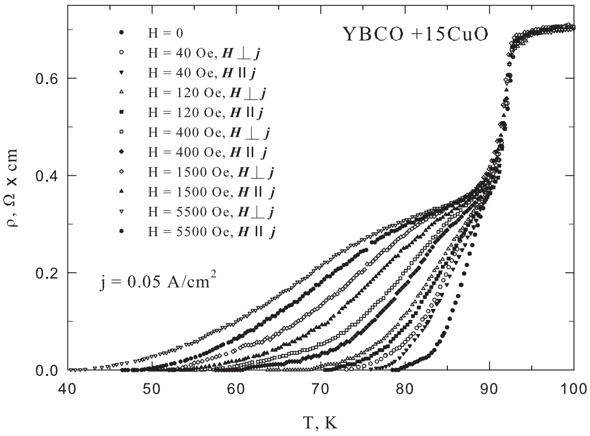

Figure 1. Temperature dependences of resistivity for the YBCO + 15CuO composite measured at different magnetic fields H for orientations $\boldsymbol{H} \perp \boldsymbol{j}$ and $\boldsymbol{H} \parallel \boldsymbol{j}$. For this sample, j_C (4.2 K) is about 8 A cm^{-2}.

Now, let us focus on the effect of magnetic field orientation relative to the current flow through a composite sample in the $R(T)$ curves. In figure 1 one can see that broadening of the resistive transition for the case $\boldsymbol{H} \parallel \boldsymbol{j}$ is less than that for the case $\boldsymbol{H} \perp \boldsymbol{j}$. At constant temperature, $R_{H\perp j}$ is larger than $R_{H\parallel j}$. Nevertheless, anisotropy of resistance measured at different $\boldsymbol{H}$ and $\boldsymbol{j}$ orientations is not sufficiently large. Similar behaviour was observed on single crystals and single-crystalline thin films of HTSCs [9, 23]. This fact was discussed in the literature, as these experiments demonstrated a minor role of the Lorentz force [24]. However, for the case of granular superconductors, local fields with random orientation in the intergrain boundaries (Josephson junctions) caused by the Meissner currents in the HTSC crystallites must be taken into account. Theoretical consideration of the resistive transition of Josephson junctions in granular HTSC under the external magnetic field explains large magnetoresistance in the case $\boldsymbol{H} \parallel \boldsymbol{j}$ [16].

For data presented in figure 1 (YBCO + 15CuO sample), the transport current density j (0.05 A cm^{-2}) is more than two orders of magnitude less than the critical current density j_C at 4.2 K ($\approx$8 A cm^{-2}). The strength of the magnetic field has no pronounced effect on the difference $R_{H\perp j} - R_{H\parallel j}$. With an increase in the ratio j/j_C (4.2 K), the difference $R_{H\perp j} - R_{H\parallel j}$ at high fields (5.5 kOe) becomes less than that at fields of 50 and 150 Oe. This is seen from figure 2, which shows anisotropy of $\rho(T)$ dependences of the YBCO + 15BaPb$_{0.75}$Sn$_{0.25}$O$_3$ composite for $\boldsymbol{H} \parallel \boldsymbol{j}$ and $\boldsymbol{H} \perp \boldsymbol{j}$ configurations. For data given in figures 2(a) and (b), the conditions j/j_C (4.2 K) $\sim$ 0.1 and j/j_C (4.2 K) $\sim$ 1 (j_C (4.2 K) $\approx$ 1.6 A cm^{-2}) are met. Apparently, large transport currents result in small-angle-dependent magnetoresistance. In [16], to characterize electrical anisotropy of granular HTSCs, the parameter $R_{H\parallel j}/R_{H\perp j}$ was proposed. The analysis of data

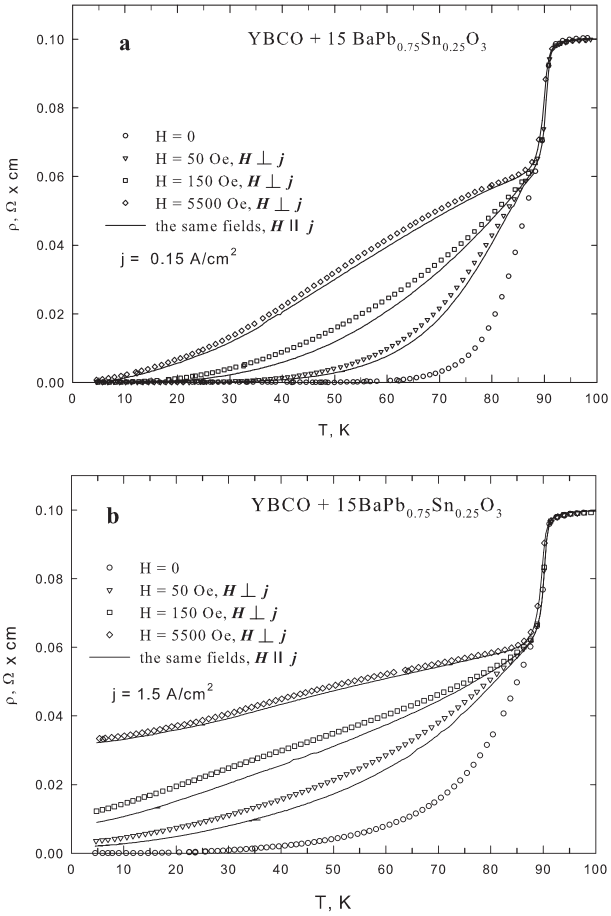

Figure 2. Temperature dependences of resistivity for the $YBCO + 15BaPb_{0.75}Sn_{0.25}O_3$ composite measured at different magnetic fields H and transport current densities ($j = 0.15$ A cm^{-2} (a) and $j = 1.5$ A cm^{-2} (b)) for orientations $\boldsymbol{H} \perp \boldsymbol{j}$ and $\boldsymbol{H} \parallel \boldsymbol{j}$. For this sample, j_C (4.2 K) is about 1.6 A cm^{-2}.

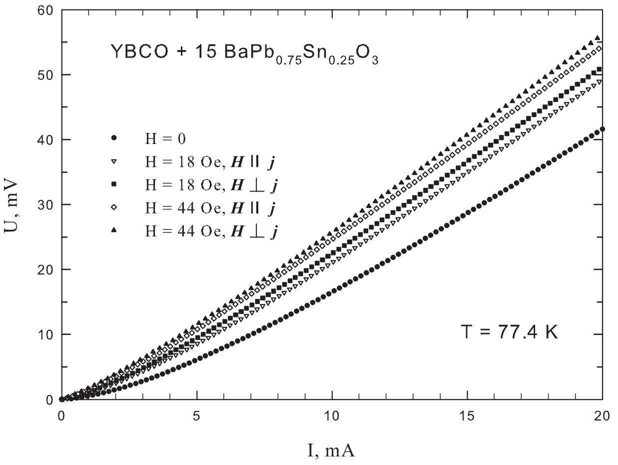

Figure 3. Current–voltage characteristics of the $YBCO + 15BaPb_{0.75}Sn_{0.25}O_3$ composite at 77 K measured at $H = 18$ and 44 Oe, and $\boldsymbol{H} \perp \boldsymbol{j}$ and $\boldsymbol{H} \parallel \boldsymbol{j}$.

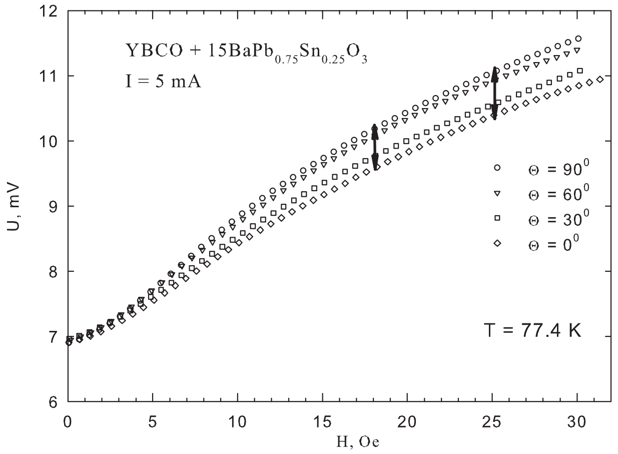

Figure 4. The dependence of voltage drop on the external magnetic field $U(H)$ ($R(H) = U(H)/I$) for the $YBCO + 15BaPb_{0.75}Sn_{0.25}O_3$ composite at 77 K measured for different angles θ ($\theta = \angle \boldsymbol{H}, \boldsymbol{j}$). Double arrows indicate an amplitude of the angle-dependent voltage drop at $H = 18$ and 25 Oe for data shown in figure 5(b).

presented in figure 2 shows that the parameter $R_{H\parallel j}/R_{H\perp j}$ grows with an increase in current and magnetic field. These results were verified in [16].

The presence of electrical anisotropy can be demonstrated also by means of the CVCs and $R(H)$ measurements performed at different $\boldsymbol{H}$ and $\boldsymbol{j}$ orientations. Figure 3 shows CVCs of the $YBCO + 15BaPb_{0.75}Sn_{0.25}O_3$ sample at 77 K in magnetic fields $H = 0$, 18 and 44 Oe for $\boldsymbol{H} \parallel \boldsymbol{j}$ and $\boldsymbol{H} \perp \boldsymbol{j}$ configurations. The $R(H)$ dependences for this sample measured at $\theta = \angle \boldsymbol{H}, \boldsymbol{j} = 0°, 30°, 60°, 90°$ are shown in figure 4. It should be noted that the critical current density at 77 K is sufficiently small for this sample, j_C (77 K) $\sim$0.01 A cm^{-2} at $H = 0$. For this reason, at a transport current $j = 0.15$ A cm^{-2} ($j > j_C$) the $R(H)$ dependences start from some nonzero value $R(H = 0)$. The effect of orientation of $\boldsymbol{H}$ and $\boldsymbol{j}$ vectors on the CVCs and $R(H)$ dependences is clearly seen in figures 3 and 4.

We have measured the angular dependences of magnetoresistance $R(\theta) = U(\theta)/I$ of the composites for different transport currents in weak magnetic fields at 77 K. Figure 5 shows the angular dependences of voltage drop $U(\theta)$ for the $YBCO + 15BaPb_{0.75}Sn_{0.25}O_3$ sample at $H = 37$ Oe, $I = 0.5$ mA (figure 5(a)) and $H = 18$, 25 Oe at $I = 5$ mA (figure 5(b)). Figure 6 shows the $U(\theta)$ dependences for the YBCO + 30 sample CuO at $H = 24$ Oe and 37 Oe ($I = 0.83$ mA). In these measurements the external magnetic field is not higher than the field of irreversible behaviour of magnetoresistance for these composites. The $R(H)$ dependences are reversible in the magnetic field range -37 Oe $\leqslant H \leqslant 37$ Oe at 77 K, with a field of 37 Oe being independent of the type of non-superconducting component (CuO or Ba(Pb, Sn)O$_3$) [1]. The curves have maxima at $\theta = 90°$ and 270° ($\boldsymbol{H} \perp \boldsymbol{j}$), and minima when $\boldsymbol{H} \parallel \boldsymbol{j}$. All the $U(\theta)$ data obtained for the composites in weak magnetic fields are well described by the function

$$U(\theta) = U_{\mathrm{is}} + U_{\mathrm{anis}} \sin^2\theta, \qquad (1)$$

where U_{is} is the isotropic part of magnetoresistance, which was discussed above, and $U_{\mathrm{anis}} = (U_{H\perp j} - U_{H\parallel j}) \times I$ (see figures 5 and 6). The dependence $R \sim \sin^2\theta$ follows from the Bardeen–Stephen model [25] of the flux flow. The transport current densities and external magnetic fields used

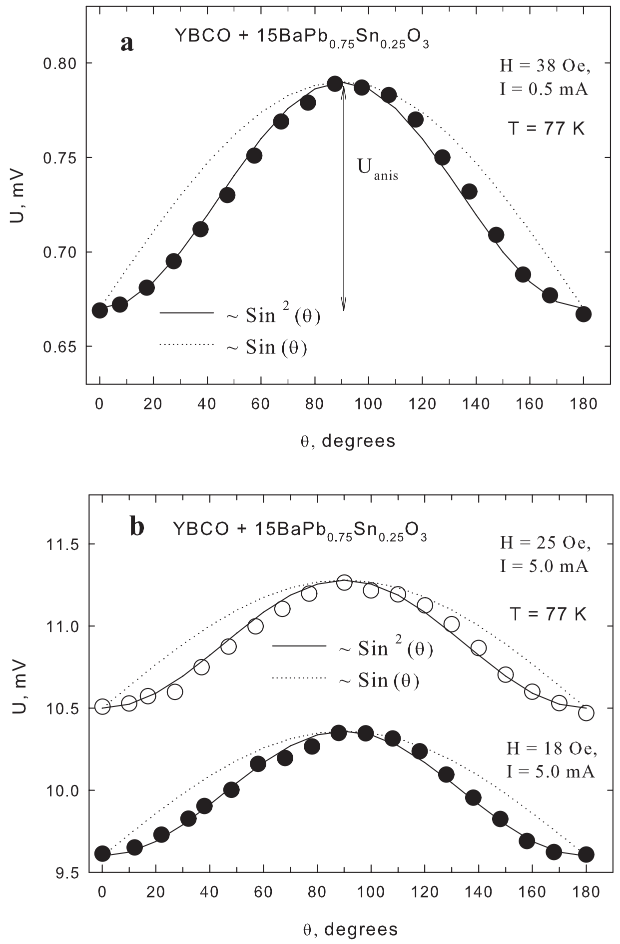

Figure 5. Angular dependences of voltage drop $U(\theta)$ ($R(\theta) = U(H)/I$), $\theta = \angle \boldsymbol{H}, \boldsymbol{j}$ for the YBCO + $15BaPb_{0.75}Sn_{0.25}O_3$ composite at 77 K measured at $I = 0.5$ mA ($j = 0.15$ A cm^{-2}), $H = 38$ Oe (a) and $I = 5$ mA ($j = 1.5$ A cm^{-2}), $H = 18$ Oe, 25 Oe (b). The critical current density value $j_C(77\text{ K})$ is about 0.01 A cm^{-2}. The values of $U(H = 0)$ are ≈0.26 mV for $I = 0.5$ mA and $U(H = 0) \approx 0.7$ mV for $I = 5$ mA. The fits of the experimental data by $\sim \sin^2\theta$ and $\sim \sin\theta$ functions are shown.

in this experiment are much less than j_C and H_{C2} of YBCO grains at 77 K. Therefore, the entire dissipation occurs in the Josephson junctions and the flow of Josephson vortices takes place in the intergrain boundaries. On the other hand, the account of the pinning of vortices results in the appearance of an additional term $\sin\theta$ in the angular dependence of magnetoresistance [10]:

$$R(\theta) = R_{is} + R_1 \sin\theta + R_2 \sin^2\theta. \qquad (2)$$

The ratio R_1/R_2 in equation (2) is proportional to the ratio of the Lorentz force to the pinning force [10]. When using equation (2), we failed to obtain better agreement of the experimental data presented in figures 5 and 6, as compared to using equation (1). This makes us assume that the pinning force is much less than the Lorentz force. One can conclude that the flux flow process of Josephson vortices in the grain boundaries accounts for anisotropic magnetoresistance of the HTSC-based composites. This result is not surprising because the transport current density is larger than the critical current density in our $R(\theta)$ measurements. For the YBCO + $15BaPb_{0.75}Sn_{0.25}O_3$ sample, $j_C(77\text{ K}) \sim 0.01$ A cm^{-2}, while $j \approx 0.15$–1.5 A cm^{-2} (figure 5). For the YBCO + 30 CuO sample the temperature of resistive transition into the superconductive state $R = 0$ is ∼70 K [1]. For this reason, this composite has no critical current at 77 K and the condition $j > j_C$ is also met (figure 6). According to the classical consideration of pinning processes in superconductors, when the transport current exceeds the critical current, the profile of a coordinate function of the pinning potential changes dramatically [24]. Pinning of vortices becomes inessential for this case.

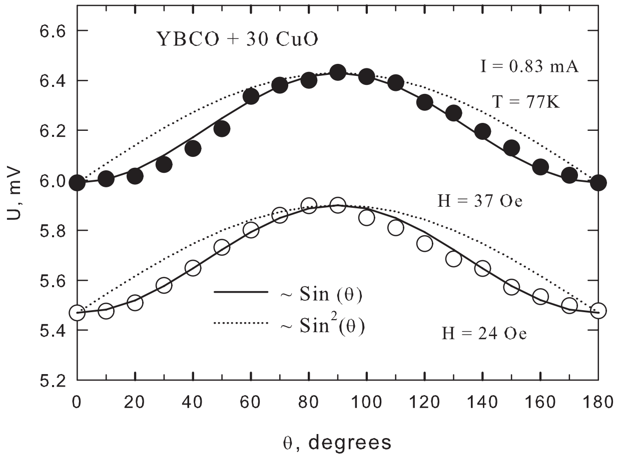

Figure 6. Angular dependences of voltage drop $U(\theta)(R(\theta) = U(H)/I)$, $\theta = \angle \boldsymbol{H}, \boldsymbol{j}$ for the YBCO + 15CuO composite at 77 K measured for $I = 0.83$ mA, $H = 24$ Oe, 37 Oe. The value $U(H = 0)$ is ≈2.8 mV. The fits of the experimental data by $\sim \sin^2\theta$ and $\sim \sin\theta$ functions are shown.

4. Conclusions

Thus, we have studied the magnetoresistive effect in the YBCO + CuO and YBCO + $BaPb_{0.75}Sn_{0.25}O_3$ composites for different orientations of magnetic field relative to the direction of macroscopic transport current flowing through a sample. There are two parts of magnetoresistance $R(H)$, namely magnetoresistance R_{is} independent of the angle between $\boldsymbol{H}$ and $\boldsymbol{j}$, and anisotropic magnetoresistance R_{anis}. Contributions of these two parts to the total magnetoresistance depend on a transport current value and magnetic field strength. With an increase in magnetic field and transport current, the anisotropic part contribution decreases. It has been found that this part of the magnetoresistance at $j > j_C$ in weak magnetic fields (tens of oersteds) follows the $\sin^2\theta$ law. This suggests that the flux flow mechanism is responsible for the large magnetoresistive effect observed in the composites under the above-mentioned conditions. This result is of high practical significance, because magnetoresistive sensors on the basis of the investigated composites can register a magnetic field vector.

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References

[1] Balaev D A, Shaihutdinov K A, Popkov S I, Gokhfeld D M and Petrov M I 2004 *Supercond. Sci. Technol.* **17** 175
[2] Dubson M A, Herbet S T, Calabrese J J, Harris D C, Patton B R and Garland J C 1988 *Phys. Rev. Lett.* **60** 1061
[3] Nojima H, Tsuchimoto S and Kataoka S 1988 *Japan. J. Appl. Phys.* **27** 746
[4] Ionesku M, Winton B, Silver T, Dou S X and Ramer R 2004 *J. Phys. D: Appl. Phys.* **37** 1727
[5] Ionesku M, Winton B, Silver T, Dou S X and Ramer R 2004 *Appl. Phys. Lett.* **84** 5335
[6] Winton B, Ionesku M, Silver T and Dou S X 2005 *J. Phys. D: Appl. Phys.* **38** 2337
[7] Albiss B A 2005 *Supercond. Sci. Technol.* **18** 1222
[8] Ichkitidze L P 2006 *Physica* C **435** 136
[9] Kwok W K, Welp U, Crabtree G W, Vandervoot K G, Hulscher R and Liu J Z 1990 *Phys. Rev. Lett.* **64** 966
[10] Kilic A, Kilic K, Senoussi S and Demir K 1998 *Physica* C **294** 203
[11] Lopez D and de la Cruz F 1991 *Phys. Rev.* B **43** 11478
[12] Lopez D, Decca R and de la Cruz F 1991 *Solid State Commun.* **79** 959
[13] Lopez D, Decca R and de la Cruz F 1992 *Supercond. Sci. Technol.* **5** 276
[14] Asim M M and Hasanin S K 1991 *Solid State Commun.* **80** 719
[15] Ginzburg S L, Gerashchenko O V and Sibilev A I 1997 *Supercond. Sci. Technol.* **10** 395
[16] Daghero D, Mazzetti P, Stepanescu A and Tura P 2002 *Phys. Rev.* B **66** 11478
[17] Wright A C, Zhang K and Erbil A 1991 *Phys. Rev.* B **44** 863
[18] Gaffney C, Petersen H and Bednar R 1993 *Phys. Rev.* B **48** 3388
[19] Mitin A V 1994 *Physica* C **235–240** 3311
[20] Petrov M I, Balaev D A, Ospishchev S V, Shaihutdinov K A, Khrustalev B P and Aleksandrov K S 1997 *Phys. Lett.* A **237** 85
[21] Balaev D A, Popkov S I, Shaikhutdinov K A and Petrov M I 2006 *Physica* C **435** 12
[22] Barone A and Paterno J 1982 *Physics and Application of the Josephson Effect* (New York: Wiley)
[23] Kim D H, Miller D J, Smith J C, Holoboff R A, Kang J H and Talvacchio J 1991 *Phys. Rev.* B **44** 7607
[24] Kadowaki K, Songliu Y and Kitazawa K 1994 *Supercond. Sci. Technol.* **7** 519
[25] Barden J and Stephen M J 1965 *Phys. Rev.* **140** A1197