ISSN 1063-7850, Technical Physics Letters, 2006, Vol. 32, No. 8, pp. 677–679. © Pleiades Publishing, Inc., 2006.
Original Russian Text © D.A. Balaev, A.G. Prus, K.A. Shaikhutdinov, M.I. Petrov, 2006, published in Pis'ma v Zhurnal Tekhnicheskoĭ Fiziki, 2006, Vol. 32, No. 15, pp. 67–73.

Angular Dependence of the Magnetoresistance in $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$–CuO Composites at 77 K

D. A. Balaev*, A. G. Prus, K. A. Shaikhutdinov, and M. I. Petrov
Kirensky Institute of Physics, Siberian Division, Russian Academy of Sciences, Krasnoyarsk, Russia
** e-mail: smp@iph.krasnoyarsk.ru*
Received February 13, 2006

Abstract—The angular dependence of the magnetoresistance of polycrystalline $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$–CuO composites has been studied. These composites represent a system of Josephson junctions and exhibit a large magnetoresistance at 77 K. In addition to the isotropic component, there is the angle-dependent component proportional to $\sin^2\theta$, where θ is the angle between the directions of current and magnetic field. This behavior is unambiguous evidence for the process of flux flow in the Josephson medium realized in the composites.

PACS numbers: 74.50.+r, 74.60, 74.80.Bj
DOI: 10.1134/S1063785006080128

Previously [1, 2], we presented the results of experimental investigations into the magnetoresistance (MR) of composites based on high-temperature superconductors (HTSCs). Prepared using the method of fast sintering [3], these composites possess large MR at liquid nitrogen boiling temperature. The values of the resistivity response $\Delta\rho(H) = \rho(H) - \rho(H = 0)$ and the sensitivity $d\rho/dH$ to magnetic field, which were observed for the composites of $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ (referred to below as YBCO) with copper oxide (CuO), have proven to be several orders of magnitude higher (e.g., $\Delta\rho$(37 Oe) ≈ 0.08–0.5 Ω cm; $d\rho/dH \approx$ 2–20 (mΩ cm)/Oe) than those for pure HTSCs of the YBCO system [2, 3]. The relative MR, defined as $\rho_0(H) = [\rho(H) - \rho(H = 0)]/\rho(H = 0)$, can reach thousands of percent (in a field of several dozen oersteds) [1–3], which is comparable with the analogous effect observed in lanthanum manganites in much greater fields. These results are indicative of good prospects for using YBCO–CuO composites as highly sensitive cryogenic detectors of weak magnetic fields. Therefore, further experimental investigations aimed at elucidating the physical mechanisms responsible for MR of such composites are necessary.

This Letter reports the results of measurements of the angular dependence of the MR in YBCO–CuO composites. Using these data, it is possible to judge the Lorentz force acting upon magnetic vortices. The MR and electric resistance of polycrystalline HTSCs and related composites are largely determined by the well-developed network of Josephson junctions, which are formed at the boundaries between HTSC grains through which the charge carrier transport unavoidably proceeds. In the composites, the role of intergrain spacers is played by the non-HTSC component [1–3]. The network of contacts formed in such systems may be called a Josephson medium [4].

The MR measurements were performed for an YBCO–CuO composite containing 70 vol % YBCO and 30 vol % CuO, which was prepared by the fast sintering method [3]. The samples were annealed according to the following schedule: 2 min at 910°C, 3 h at 350°C, and cooling down to room temperature with the furnace.

The electrical measurements were performed according to the standard four-point-probe scheme. The sample had the dimensions 1 × 1 × 9 mm, and the distance between the potential contacts was ~5 mm. The magnetic field was generated using Helmholtz coils. The voltage drop between the contacts was measured both in the absence of magnetic field and in a constant field at various angles θ between the directions of electric current (along the sample) and magnetic field. The whole system was immersed in liquid nitrogen. No special measures were taken to shield the Earth's magnetic field.

It was previously established [1] that the temperature dependence of the electric resistance of YBCO–CuO composites at $H = 0$ has a two-step shape. The first sharp jump at $T_C = 93.5$ K corresponds to the transition of HTSC grains into a superconducting state. The second, smooth and delayed transition at T_{C0} ($T_{C0} < T_C$ for $\rho < 10^{-6}$ Ω cm) corresponds to the transition of weak bonds (Josephson junctions) to the superconducting state. The angular dependence of MR was measured on a sample with $T_{C0} < 77$ K, which was selected from a series studied previously [1, 2]. Accordingly, at 77 K, this sample had $\rho(H = 0) > 10^{-5}$ Ω cm (at this temperature, the current–voltage characteristic is nonlinear [2]). It was also established [2] that the resistivity $\rho(H)$ at

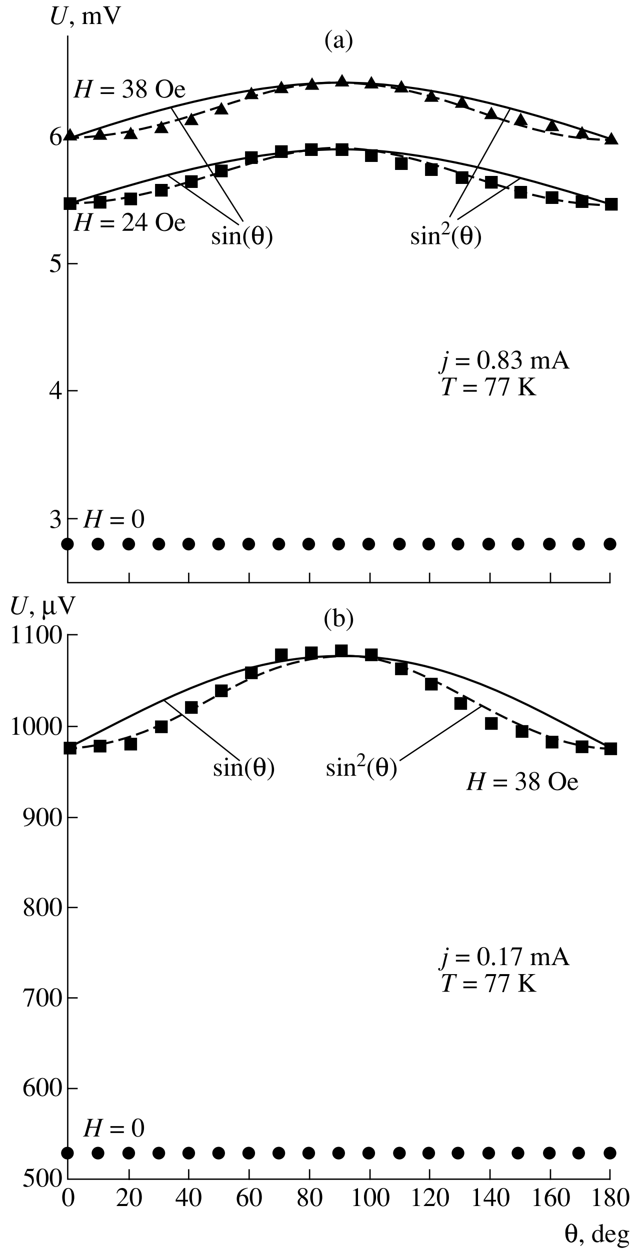

Fig. 1. Plots of the voltage drop U versus angle θ between the transport current j and the magnetic field H for an YBCO–CuO composite sample at 77 K and various values of the field H (0, 24, and 38 Oe, as indicated in the figure) and probing current $j = 0.83$ mA (a) and 0.17 mA (b). Points present the experimental data; curves show the results of fitting to the functions $U(\theta) = U_{is} + (U_{max} - U_{is})\sin^2\theta$ and $U(\theta) = U_{is} + (U_{max} - U_{is})\sin\theta$.

77 K exhibited reversible variation for $H = 0$–38 Oe. In greater fields, the MR exhibits a hysteresis that is related to the hysteresis of magnetization. In order to eliminate the influence of the hysteresis in $\rho(H)$ on the angular dependence $\rho(H)$, the MR measurements in this study were restricted to weak fields (below 38 Oe), where the magnetic field effect on the resistivity is most pronounced [1, 2].

Figures 1a and 1b show plots of the voltage drop on the sample versus angle θ between the field and current, which were obtained for $H = 0$, 24, and 38 Oe at two values of the transport current j. There are two important features in these experimental results. First, a large component of the MR is independent of the field direction. Second, there is an angle-dependent MR component, which is well described by the relation

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

where U_{is} is the isotropic part of the MR (or $U(H)$ at $H \parallel j$) and U_{max} is the voltage drop at $j \perp H$. Analogous shapes of the $U(\theta)$ curves were observed for all transport currents within 1–10 mA and for the other values of magnetic field (12 and 18 Oe) in the range studied.

First, let us make some remarks concerning the isotropic part of the MR. This component is frequently observed for single crystals of HTSCs (see, e.g., [5, 6]) and practically always for polycrystalline HTSCs [7–11]. In the latter case, one possible explanation is related to the chaotic orientation of Josephson junctions in polycrystalline samples, since the direction of microscopic current is not parallel to the field even when the total transport current is $j \parallel H$. Moreover, it was recently demonstrated [12] that the joint action of an external magnetic field and the field generated by screening current in grains of the Josephson medium results in the direction of a local magnetic field not coinciding in the general case with that of the external field. According to the theory proposed in [12], the anisotropy parameter U_{is}/U_{max} increases with the magnetic field. The same conclusion follows from the results of our measurements. A quantitative comparison of the experimental data and theory [12] will be presented in a forthcoming paper.

The second important result of this study is related to the angle-dependent part of the MR. The law $R \sim \sin^2\theta$ was originally predicted in the Bardeen–Stephen theory [13] for type-II superconductors (including YBCO-based HTSCs). According to this theory, the rate of energy dissipation per vortex length depends on the product $F_L v_L$, where F_L of the Lorentz force and the v_L is vortex velocity [13, 5]. Since the vortex motion is caused by the Lorentz force, v_L is proportional to $\sin\theta$ and, hence, the energy dissipation rate and the R value are proportional to $\sin^2\theta$. At the same time, it was pointed out [8, 10, 14] that, if the vortex pinning force is comparable with the Lorentz force, an additional term proportional to $\sin\theta$ appears in the angular dependence of the MR:

$$U = A_1\sin^2\theta + A_2\sin\theta. \qquad (2)$$

Thus, the ratio A_1/A_2 in relation (2) is proportional to the ratio of the Lorentz force to the vortex pinning force [8, 10, 14].

As can be seen from Fig. 1, relation (1) described our experimental results well. An attempt to describe these data using Eq. (2) with two angle-dependent terms does not improve the fit of experimental points to theoretical curves, which indicates that the contribution of the term proportional to $\sin\theta$ is rather insignificant. Therefore, in our system at 77 K, the pinning force is much smaller than the Lorentz force and, hence, the over-barrier flow of vortices (flux flow) must take place [13]. This situation is quite possible in the composite under study, since the introduction of a non-HTSC component (CuO) into the HTSC matrix (YBCO) decreases the Josephson bonds between superconducting granules. The composite sample used for the MR measurements occurs in the resistive state even in a zero magnetic field, because the temperature (77 K) is above T_{C0} for this sample ($T_{C0} \approx 70$ K). For all values of the probing current in the interval studied, this current exceeds the critical value. The magnetic field penetrates into the system of grain boundaries of the polycrystalline sample primarily in the form of Josephson vortices, since the first critical field for the Josephson medium at 77 K can be on the order of a fraction of an oersted or lower [4, 15]. On the other hand, the probing current density (~1 A/cm^2) is several orders of magnitude smaller than the critical values for HTSC granules (~10^3–10^4 A/cm^2 [16]), for which the first critical field is on the order of several dozen oersteds [12]. For this reason, the MR under these experimental conditions is determined entirely by the process of energy dissipation in the network of Josephson junctions (YBCO–CuO–YBCO) realized in the composite. Therefore, in the presence of an external magnetic field, the Josephson vortices move over the Josephson medium in accordance with the flux flow model (not being retarded on the pinning centers), and this circumstance determines the observed angular dependence of the MR.

It should be noted that an analogous angular dependence of the anisotropic part of the MR ($R \sim \sin^2\theta$) was previously observed for polycrystalline HTSCs of the compositions $La_{1.85}Sr_{0.15}CuO_4$ (at T = 10–30 K in the magnetic fields H = 2–15 Oe) [7–9], $Bi_{1.6}(Pb_{0.3}Sb_{0.1})Sr_2Ca_2Cu_3O_x$ (T = 77 K, H = 250 Oe) [10], and $YBa_2Cu_3O_7$ (T = 77 K, H ~ 11 Oe) [11]. In this study, the MR anisotropy has been measured for the first time in YBCO-based HTSC composites. For an artificial Josephson medium realized in such composites, the mechanism of energy dissipation, at least in the presence of a magnetic field, is apparently the same as that in the pure HTSCs where the Josephson medium involves the natural grain boundaries. The results of our experiments are of practical significance, since the knowledge of the angular dependence of the MR in active HTSC elements is important for the use of magnetic field sensors.

Acknowledgments. The authors are grateful to A.D. Balaev for fruitful discussions. One of the authors (D.A.B.) is grateful to A.V. Mitin and L.P. Ichkitidze for fruitful discussions of the MR phenomenon in polycrystalline HTSCs.

This study was supported in part within the framework of the program for winners of the Lavrentiev Competition of Young Scientists Projects (project no. 52).

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Translated by P. Pozdeev