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Controlled Magnetoresistance in $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$–CuO Composites at 77 K

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Abstract—We have studied the low-temperature magnetoresistance of $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$–CuO composites obtained by fast sintering technique and established a relation between the probing to critical current density ratio j/j_c and the shape of the magnetoresistance curve $\rho(H)$. For $j/j_c < 1$, the electric resistance arises at a threshold value of the magnetic field strength H_c. For $j/j_c \geq 1$, a linear variation of $\rho(H)$ at 77 K in the range from 0 to 14 Oe can be provided by selecting the CuO content (in the 15–30 vol % interval) and the j value (in the 0.003–0.2 A/cm^2 range). In the latter case, the slope $d\rho/dH$ (i.e., the sensitivity of the electric resistivity with respect to the magnetic field) is 1–20 mΩ cm/Oe and the relative field-induced increase in the resistivity $\rho_0 = (\rho(H) - \rho(H = 0))/\rho(H = 0)$ amounts to 1320 and 685% at H = 200 and 35 Oe, respectively. Composites possessing controlled magnetoresistance are promising materials for the active elements of magnetic field sensors capable of operating at a practically convenient liquid nitrogen temperature. *© 2003 MAIK "Nauka/Interperiodica".*

Previously [1], we presented preliminary data on the magnetoresistance of composites based on high-temperature superconductors (HTSCs). The composites, representing a system of artificial Josephson junctions with a non-HTSC component playing the role of barriers between HTSC grains, possess large magnetoresistance in a broad range of temperatures (below the superconducting temperature T_c of the HTSC component) and relatively weak (below 200 Oe) magnetic fields. This property allows such composites to be used in magnetic field sensors capable of operating at a practically convenient liquid nitrogen temperature.

The effect of magnetic field on the resistance of pure HTSC ceramics was studied shortly after the discovery of the phenomenon of high-temperature superconductivity [2–10]. A strong sensitivity of the resistivity ρ of HTSC materials to a weak external magnetic field is observed in a very narrow temperature interval below T_c. To obtain a significant response at T = 77 K, it is necessary to employ high transport currents (~10^2–10^3 A/cm^2), which encounters considerable technical difficulties related to the heat removal from current-carrying leads [3, 5]) and strong magnetic fields (H ~ 10–60 kOe). The magnetic field hysteresis of the electric resistance [4, 6, 7, 9–11] and the nonlinear character of the $\rho(H)$ function [3–7, 11] also restrict the possible applications of magnetoresistive HTSC ceramics.

Below we report the results of a thorough investigation of the magnetoresistance $\rho(H)$ at various transport current densities j in a series of composites based on yttrium ceramics and copper oxide. The parameters of the magnetoresistance observed at 77 K in these HTSC–CuO composites show more optimistic prospects for the practical use of such materials in magnetic field sensors.

The samples of composites were synthesized from an HTSC composition $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ (referred to below as YBCO) and copper oxide CuO by fast sintering technique as described previously [1, 12]. 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 X-ray diffraction measurements confirmed the absence of foreign phases in the final composites. We have synthesized and studied the samples of two different compositions denoted below as YBCO + 15 vol % CuO and YBCO + 30 vol % CuO (with an HTSC component fraction of 85 and 70 vol %, respectively).

The electric resistivity as a function of the temperature, $\rho(T)$, and the magnetic field strength, $\rho(H)$, was studied by a standard four probe technique using samples with typical dimensions of 1 × 2 × 12 mm. The distance between the potential contacts was ~10 mm and the probing (transport) current density was varied in the range from 0.002 to 0.2 A/cm^2 (which corresponds to a total current of ~0.1–10 mA). The superconducting state (R = 0) was detected to within ~10^{-6} Ω cm. The critical current density j_c was determined using the initial part of the current–voltage characteristic according to the conventional criterion of 10^{-6} V/cm [13]. During the magnetoresistance measurements, the magnetic field was applied perpendicularly to the electric current direction. No special measures were taken for shielding the Earth's magnetic field. The magnetization measurements were performed using a vibrating-sample magnetometer [14].

Figure 1 shows the experimental ρ(*T*) curves of the YBCO + 15 vol % CuO and YBCO + 30 vol % CuO composites measured at 77 K using different values of the probing transport current. All variants of the observed ρ(*T*) curves can be divided into three types depending on the probing current density (at a given temperature). When the current density is below the critical value, $j < j_c$, there is an interval in which $\rho \leq 10^{-6}$ Ω cm. Only beginning with a certain H_c ($H_c \approx$ 10 Oe for YBCO + 15 vol % CuO at j = 0.12 A/cm^2 and T = 77 K), for which the given current density is critical, does the resistivity exhibit a nonlinear growth with the magnetic field strength (Fig. 1a, curve *1*). For $j \approx j_c$, the growth of ρ(*H*) begins at the origin of coordinates (Fig. 1a, curve *2*). Finally, for $j > j_c$, the resistivity varies from a certain zero-field value ρ(*H* = 0) (Fig. 1, curve *3*) and ρ(*H*) is a linear function of the field strength in the interval from 0 to 14 Oe with a slope of $d\rho/dH \approx$ 2.5 mΩ cm/Oe.

For the YBCO + 30 vol % CuO composition, the critical current j_c (77 K) is below 0.001 A/cm^2 and all the ρ(*H*) curves measured in the entire interval of probing currents *j* (Fig. 1b) are similar to curve *3* in Fig. 1a. These ρ(*H*) plots are also linear in the interval from 0 to 14 Oe, but the slope is $d\rho/dH \approx$ 17.5 mΩ cm/Oe.

In the magnetic fields with $|H| \leq$ 37 Oe, both composites were characterized by coinciding ρ(*H*) curves measured when increasing and decreasing the absolute value of the field strength. For greater magnetic field amplitudes, the ρ(*H*) curves exhibit a hysteresis. Figure 2 shows the pattern of ρ(*H*) and the corresponding magnetization curve *M*(*H*) measured for the same specimen of YBCO + 30 vol % CuO with the field varied in the interval –210 Oe $\leq H \leq$ 210 Oe. Note that the behavior of *M*(*H*) is typical of HTSC ceramics [11]. The ρ(*H*) loops are well reproduced in the course of multiply repeated field cycling. The thermomagnetic history can be reset by heating a sample above T_c followed by cooling in a zero field. A comparison of the ρ(*H*) and *M*(*H*) curves shows that the sample resistance is a complicated function of the magnetization.

The results of ρ(*H*, *j*) measurements at other temperatures were similar to those presented in Figs. 1 and 2. The ratio of the probing to critical current density, j/j_c, is the main parameter determining the type of the ρ(*H*) curve. Figure 3 shows the temperature dependence of the critical current density $j_c(T)$ in the vicinity of T_c. Using these data and selecting the probing current density, it is possible to predict the shape of the ρ(*H*) characteristic of a given magnetic field sensor for any temperature in the range studied. In ceramics with natural grain boundaries, the values of j_c(77 K) range within 10–250 A/cm^2 [5, 6, 15]. For this reason, ρ(*H*) curves of various types such as *1*–*3* in Fig. 1a are more difficult to obtain in pure ceramics than in composites.

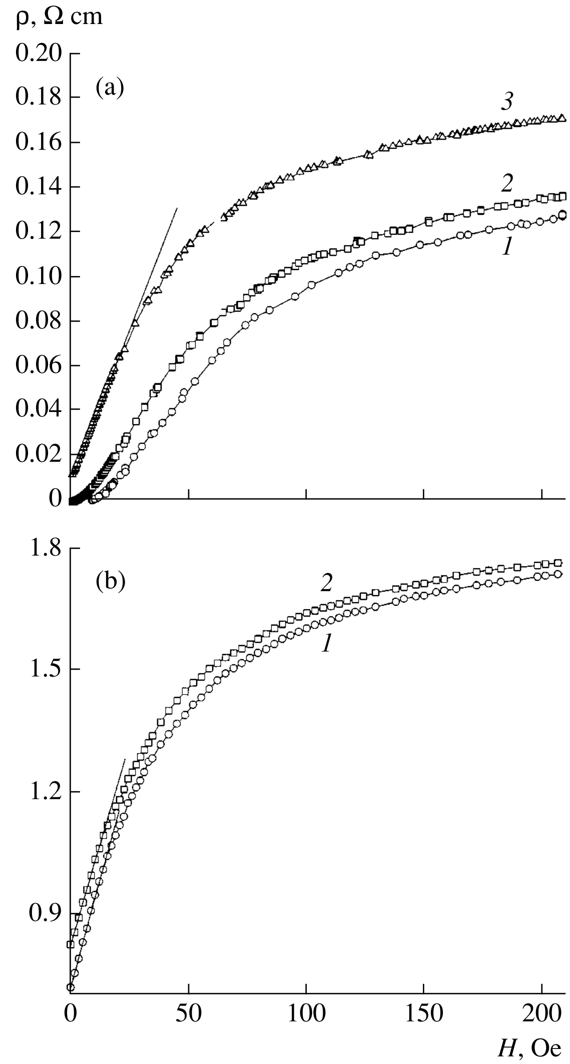

Fig. 1. Plots of the resistivity ρ versus magnetic field strength *H* at *T* = 77 K: (a) YBCO + 15 vol % CuO composite, j = 0.037 A/cm^2 < j_c (*1*), j = 0.12 A/cm^2 ≈ j_c (*2*), and j = 0.37 A/cm^2 > j_c (*3*); (b) YBCO + 30 vol % CuO composite, j = 0.0032 (*1*) and 0.032 A/cm^2 (*2*).

The phenomenon of magnetoresistance observed in polycrystalline HTSCs (including composites) is explained by the fact that these materials represent a system of Josephson junctions. The boundaries between the HTSC grains are weak bonds of the Josephson type, the electric resistance of which is highly sensitive to external magnetic fields [13]. The number of weak bonds per unit length is very large, on the order of 10^3 per mm for a typical size of superconducting granules reaching ~1.5 μm (according to scanning electron microscopy data). Accordingly, the response of one HTSC–grain boundary–HTSC junction has to be multiplied by this number. In the YBCO–CuO composites studied, copper oxide forms dielectric layers between HTSC grains [12]. By selecting the volume content of components, it is possible to control the

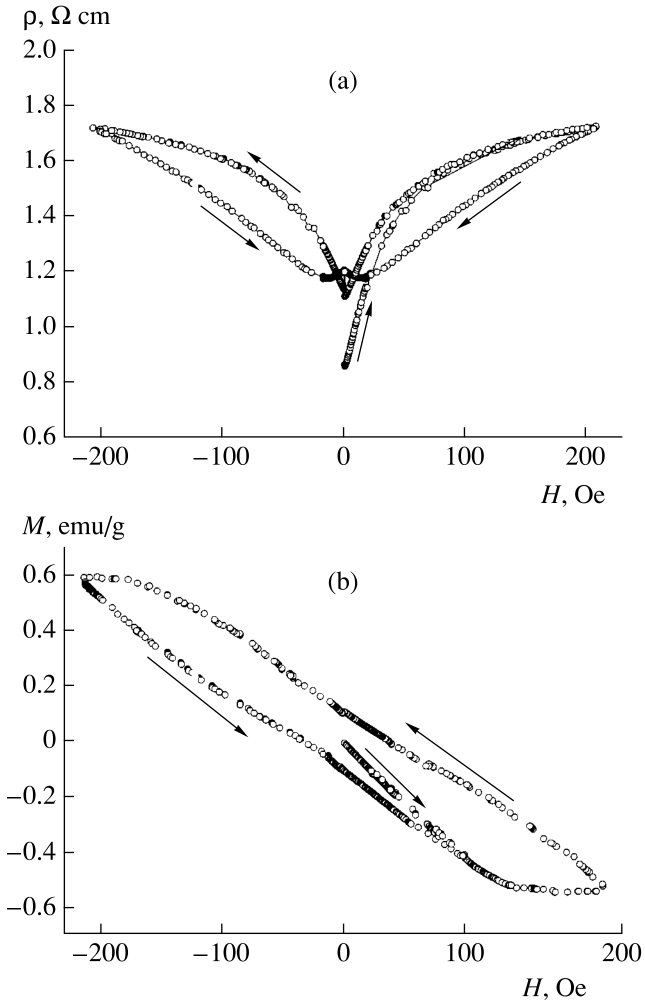

Fig. 2. Plots of (a) the resistivity ρ (j = 0.0032 A/cm^2) and (b) magnetization M versus magnetic field strength H for an YBCO + 30 vol % CuO composite at T = 77 K. Arrows indicate the direction of field variation.

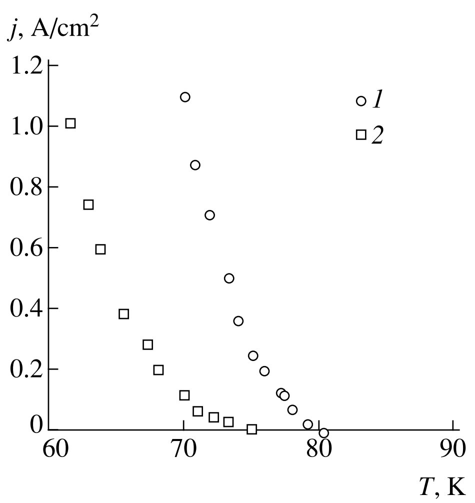

Fig. 3. Plots of the critical current density j_c versus temperature for (*1*) YBCO + 15 vol % CuO and (*2*) YBCO + 30 vol % CuO composites.

"strength" of the Josephson bonds so as to provide that the overall superconducting transition takes place at a preset temperature (in our case, ~80 K for YBCO + 15 vol % CuO and ~76 K for YBCO + 30 vol % CuO). Then, a significant magnetoresistance at 77 K can be observed for relatively weak magnetic fields and low probing current densities. In addition, CuO can be considered as an insulator at low (<100 K) temperatures [16]. This leads to an increase in the resistivity of YBCO–CuO composites in the normal state as compared to that of the pure HTSC ceramics [12]. For this reason, the slope $d\rho/dH$ (i.e., the sensitivity with respect to the magnetic field) obtained in the composites (2–20 mΩ cm/Oe) is greater by at least two orders of magnitude than that in polycrystalline HTSCs (0.01–0.15 mΩ cm/Oe, as estimated from the data reported in [2, 3, 5, 6]).

Another important parameter characterizing the magnetoresistance is the relative field-induced increase in the resistivity $\rho_0 = (\rho(H) - \rho(H = 0))/\rho(H = 0)$, which is the factor by which the resistivity grows upon application of the magnetic field H. Of course, the growth in the resistivity relative to that in the superconducting state (R = 0) is always very large. In practice, it is more important to estimate the resistivity growth relative to a certain finite value of $\rho(H = 0)$. In YBCO + 15 vol % CuO, the value of ρ_0 for $j > j_c$ (Fig. 1a, curve *3*) amounts to 1320% at H = 200 and 685% at 35 Oe (i.e., in the region of reversibility). The zero-field resistivity $\rho(H = 0, T = 77$ K) at j = 0.37 A/cm^2 is 8 mΩ cm. In YBCO + 30 vol % CuO, the value of ρ_0 for j = 0.0032 A/cm^2 amounts to 140 and 78% at H = 200 and 35 Oe, respectively, and $\rho(H = 0, T = 77$ K) is 725 mΩ cm.

The behavior of $\rho(H)$ such as that depicted in Fig. 1a can be used in devices intended to signal in response to a threshold magnetic field strength H_c. HTSCs materials operating in this regime are called supermagnetoresistors [5]. In out composites, the required H_c value can be adjusted by selecting the volume content of a non-HTSC component and the transport current density.

Thus, the behavior of $\rho(H)$ in the composites under study is determined by the probing (transport) to critical current density ratio j/j_c. For j/j_c, the electric resistance arises at a threshold value of the magnetic field strength H_c. For $j/j_c \geq 1$, there is a region in which $\rho(H)$ is a linear function with a high value of the sensitivity with respect to the field strength: $d\rho/dH$ ~ 1–20 mΩ cm/Oe. The relative increase in the resistivity ρ_0 in the region of reversibility at T = 77 K reaches several hundred percent. The resistivity response to magnetic field in the $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$–CuO composites studied (at relatively low values of the probing current, j ~ 1 mA/cm^2) is two orders of magnitude greater than that in pure polycrystalline HTSC ceramics. All these results are indicative of good prospects for using these composites in the active elements of magnetic field sensors capable of operating at a practically convenient liquid nitrogen temperature. In the region of reversible magnetoresistance ($|H| \leq 37$ Oe), the characteristics of such sensors (ρ_0, $d\rho/dH$, $\rho(H)$) are comparable with those of the best devices based on magnesium oxide [17].

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