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Relaxation of the Remanent Resistance of Granular HTSC Y–Ba–Cu–O + CuO Composites after Magnetic Field Treatment

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Abstract—The hysteresis of magnetoresistance $R(H)$ and relaxation of the remanent resistance R_{rem} with time after magnetic field treatment of HTSC (Y–Ba–Cu–O) + CuO composites are studied. Such a composite constitutes a network of Josephson junctions wherein the nonsuperconducting component (CuO) forms Josephson barriers between HTSC grains. By comparing the experimental $R_{rem}(t)$ and $R(H)$ dependences, it is shown that the relaxation of the remanent resistance is caused by the decreased magnetic field in the intergrain medium due to relaxation of magnetization. The reason is uncovered for the differences between the published values of pinning potentials determined by measuring the relaxation of magnetization or resistance and fitting them by the Anderson law.

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1. INTRODUCTION

The relaxation of remanent electrical resistance R_{rem} of granular high-temperature superconductors (HTSC) after magnetic field treatment has been studied in a number of papers [1–7]. It is known that R_{rem} decreases with time following a logarithmic law $R_{rem} \sim 1 - \alpha\ln(t)$ [1–5, 7], which is typical of the Anderson flux creep theory [8, 9]. The relaxation of R_{rem} is related to a trapped magnetic flux and well-known relaxation of magnetization [9], for which

$$M(t)/M(t_0) = 1 - (k_B T/U_p)\ln(t). \qquad (1)$$

Here, U_p is the activation energy, i.e., the magnitude of the vortex pinning potential [9]. However, some questions remain unanswered. In [1–4], using an expression like Eq. (1) for the relaxation of remanent resistance

$$R_{rem}(t)/R_{rem}(t_0) = 1 - (k_B T/U_p^*)\ln(t). \qquad (2)$$

the pinning potential U_p^* was determined. It turned out that the values of U_p^* are substantially different for similar HTSC systems [1, 2] and do not correlate with the magnitudes of U_p determined using Eq. (1) for the relaxation of magnetization in otherwise identical external conditions. For example, for the La–Sr–Cu–O system, as shown in [3], the activation energies as derived from the relaxation of resistance are an order of magnitude greater than the activation energies obtained from the relaxation of magnetization at the corresponding temperatures. It is not completely clear which subsystem (HTSC grains or the intergrain medium) is responsible for the vortex pinning potential derived from the resistive measurements using Eq. (2) [1–5, 7, 10].

In order to clarify these questions, it is expedient to compare measurements of magnetization and resistance relaxation using the same samples under identical external conditions and perform resistance relaxation measurements in different modes, namely, for the transport current density j being much less than the critical current j_c and for $j > j_c$. These conditions are difficult to satisfy in experiments on polycrystalline HTSCs because of small voltage drops and because of heat dissipation on current terminals when a high-density transport current is passed through a HTSC. In a granular HTSC, intercrystalline boundaries are Josephson weak links and determine the resistive state of the entire sample, because the critical parameters (j_c, critical fields) are much smaller in intergrain boundaries than in HTSC crystallites. The critical current of a granular HTSC can be purposefully decreased by worsening the transparency of the intergrain boundaries for current carriers. In HTSC-based composites [11–14], the nonsuperconducting component forms intercrystallite boundaries and, as a result, the Josephson energy of the links is diminished further [14] and the current j_c decreases with increasing content of the nonsuperconducting component [11, 13, 14]. If the superconducting properties of HTSC grains in a composite remain the same as those of the original polycrystal in the absence of nonsuperconducting additives, then the composite can be considered a sample case of a granular HTSC with controllable Josephson junction properties.

In the present work, we study relaxation of remanent resistance of a composite consisting of the Y–Ba–

Cu–O HTSC and CuO. As demonstrated earlier [13, 14], composites of this kind contain a tunnel Josephson junction network. The results of investigations of magnetoresistance in these composites ($R(H, T)$ dependences for various orientations of **H** and **j**) are given in [14–16]. The objective of this work is to find out the mechanism of relaxation of remanent resistance in granular HTSC composites of this kind and to establish the relation between the values of the pinning potential derived from measurements of magnetization and resistance relaxation.

2. EXPERIMENTAL

The composites consisting of the $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ HTSC and copper oxide CuO are made by rapid sintering [13–15] at 910°C for 2 min and then at 350°C for 3 h. We denote the composites as YBCO + V CuO, where V is the volume percentage of CuO in the composite and the percentage of the superconductor YBCO is $(100 - V)$%. In this paper, we use experimental data for samples with $V = 40$ and 15 vol %.

According to x-ray diffraction data, the composites consist solely of the initial components $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ and CuO. According to electron microscopy data, the average size of YBCO grains is ~1.5 μm. Magnetic measurements of the composites show that all samples have the same superconducting transition temperature T_c = 93.5 K, which coincides with the critical temperature of the initial HTSC. At this temperature, a sharp drop in electrical resistance is observed, which is related to the transition of HTSC grains to the superconducting state. As the temperature is decreased further, the $R(T)$ dependences pass gradually to the "$R = 0$" state, which is related to the transition of the Josephson junction network to the superconducting state. With increasing volume fraction of the nonsuperconducting component, the temperature of the $R = 0$ state decreases. Data on $R(T)$ for YBCO + CuO with different CuO contents are given in [13, 14]. For small measuring current densities, the temperature of the $R = 0$ state is ~80 K for the YBCO + 15 CuO sample and ~20 K for YBCO + 40 CuO. The critical current density j_c at 4.2 K for these composites is ~5.3 A/cm^2 (YBCO + 15 CuO) and ~0.1 A/cm^2 (YBCO + 40 CuO). For sample dimensions 9 × 1.5 × 1mm, the instrumental critical current I_c is found to be ≈80 and ≈1.5 mA, respectively, using the standard condition 1 μV/cm. The "normal-state" resistivity (at T = 95 K) of the composites is ≈22 mΩ cm (R of the sample, ≈0.75 Ω) and ≈0.52 Ω cm (R of the sample, ≈17.3 Ω) for YBCO + 15 CuO and YBCO + 40 CuO, respectively.

The magnetoresistance $R(H) = U(H)/I$ (U is the voltage drop) is measured by the usual four-probe method at a constant current I. The magnetic field H is applied perpendicular to the current direction. The magnetic field sweep rate is ≈300 Oe/min. We did not find any effect of the field sweep rate on the $R(H)$ dependence in the range 50–800 Oe/min. After the external field is increased from $H = 0$ to a fixed value H_{max}, it is decreased to zero at the same rate. We denote the external magnetic field as $H\uparrow$ if it increases ($dH/dt > 0$) and as $H\downarrow$ if it decreases ($dH/dt < 0$). After an increase (to 5 kOe) and subsequent decrease of the external magnetic field to zero, the evolution of the remanent voltage $U_{rem}(t)$ with time is recorded for a given current. After each measurement of $R(H)$ and $U_{rem}(t)$, the sample is heated above T_c and then cooled in a zero external magnetic field (no special measures are taken to screen out the magnetic field of the Earth).

Measurements of magnetization curves $M(H)$ and relaxation of magnetization $M_{rem}(t)$ are performed using an automatic vibrating-sample magnetometer [17]. The field sweep rate is the same as in the measurements of $R(H)$.

3. RESULTS AND DISCUSSION

Figure 1 shows the $R(H)$ dependences for YBCO + 40 CuO and YBCO+15 CuO at 4.2 K measured with a maximum field H_{max} = 5 kOe. The dependences manifest hysteresis; indeed, the resistance in the direct branch is higher than R in the backward branch, $R(H\uparrow) > R(H\downarrow)$, except in the range of small fields, where $R(H\downarrow)$ passes through a minimum and increases. After an increase and subsequent decrease of the external magnetic field to zero, the sample has remanent resistance R_{rem}. Its magnitude decreases in time.

Let us first dwell on the hysteretic behavior of $R(H)$ in the quasistatic mode. The external magnetic field penetrates into the granular HTSC predominantly through intergrain boundaries (Josephson junctions), with the first critical field of the Josephson medium H_{c1J} being very small in magnitude (a fraction of one oersted) [10, 18–20]. The total magnetic induction in the intergrain medium $\mathbf{B}_{ind}$ is the sum of the external field **H** and the field $\mathbf{B}_{M-A}$ generated by the dipole moments of superconducting grains [21, 22]. The diamagnetic response of the Josephson medium can be neglected for external fields much larger than H_{c1J}. Also, to begin with, we assume that pinning of vortices in the intergrain medium (Josephson vortices) is also inessential. Figure 2 schematically shows the directions of the external field **H** and the magnetic induction produced by Meissner currents flowing on the grain surfaces and by Abrikosov vortices pinned in the grains. The field of the first penetration of Abrikosov vortices into the grains H_{c1G} is 100–200 Oe at 4.2 K [23], which is smaller than H_{max} in our experiment (Fig. 1). Figure 2a corresponds to the direct branch of the $R(H)$ dependence at an external field **H** larger than H_{c1G}. Figure 2b shows the case corresponding to the decreasing field. As the external field increases to H_{max}, a sufficiently large number of Abrikosov vortices penetrate into the grains. As a result, when the external field decreases,

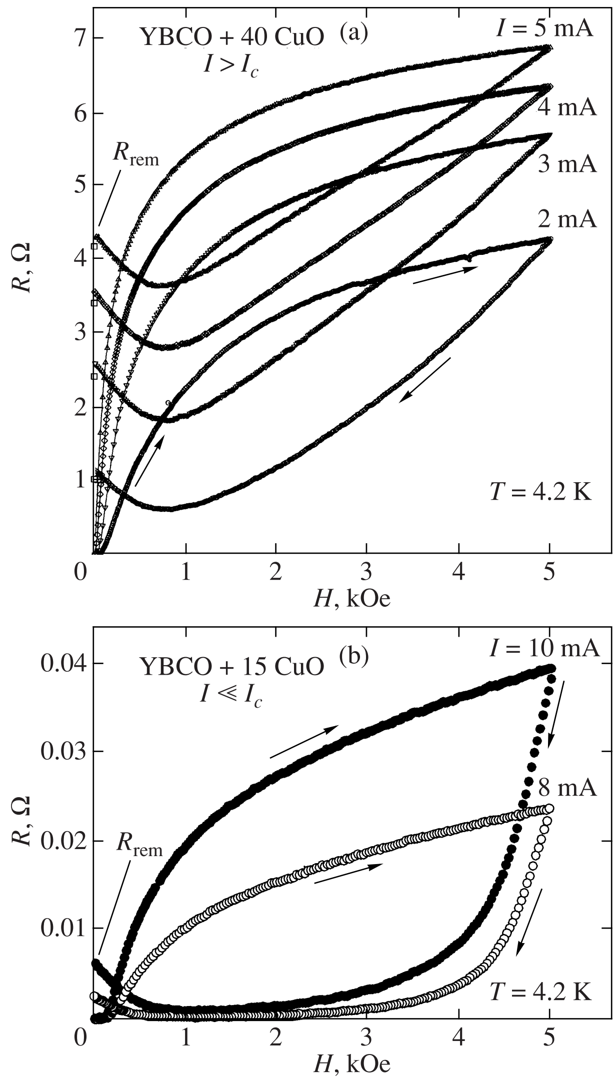


Fig. 1. Hysteretic field dependences of the magnetoresistance of (a) the YBCO + 40 CuO and (b) YBCO + 15 CuO composites measured for various transport current values at T = 4.2 K. Arrows show the sweep direction of the external magnetic field H. R_{rem} is the remanent resistance of the samples measured after the magnetic field is applied and then decreased to zero.

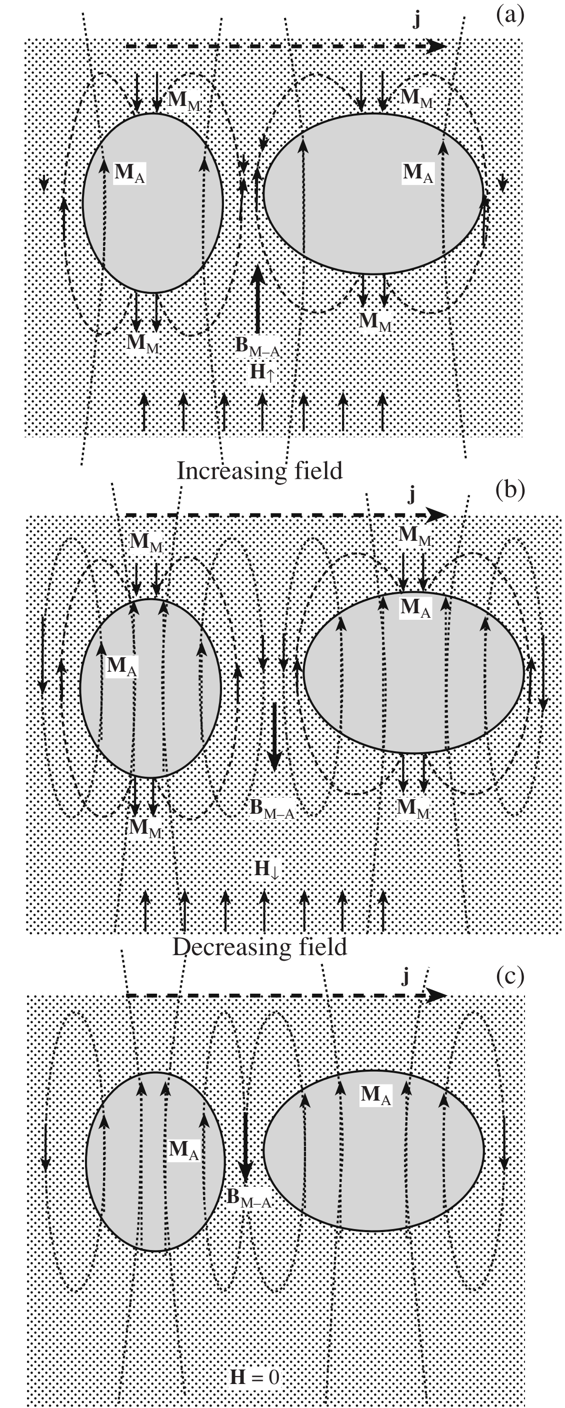


Fig. 2. Magnetic induction lines in the intergrain medium of a granular HTSC (schematic). HTSC grains are shown in gray, and the background is the Josephson medium (intergrain boundary). $\mathbf{M}_M$ is the dipole moment created by Meissner currents in the grains, dotted lines are magnetic induction lines of Meissner currents, and $\mathbf{M}_A$ are Abrikosov vortices. The external field (a) increases ($H = H_\uparrow$), (b) decreases ($H = H_\downarrow$), or (c) is zero after the field was increased to H_{max} and then decreased to zero. Thick arrows show the prevailing direction of the field $\mathbf{B}_{M-A}$ induced in the intergrain boundary by Meissner currents and vortices in adjacent grains. The total magnetic field in the intergrain medium $\mathbf{B}_{ind}$ is the sum of $\mathbf{B}_{M-A}$ and H.

the magnetic moment becomes positive (see Fig. 3, showing part of the hysteresis loop of a YBCO + 40 CuO sample). From comparing Figs. 2a and 2b, it follows that the induced field $\mathbf{B}_{M-A}$ is directed parallel (antiparallel) to the external field when $\mathbf{H}$ increases (decreases). For $H_\uparrow = H_\downarrow$, the total magnetic induction in the intergrain medium $\mathbf{B}_{ind} = \mathbf{H} + \mathbf{B}_{M-A}$ is larger in the case where the field increases. Since the resistive state of a granular HTSC is defined predominantly by intergrain boundaries (for which the larger $\mathbf{B}_{ind}$, the higher the resistance), we have $R(H_\uparrow) > R(H_\downarrow)$. As the external field decreases, the contribution from pinned vortices to $\mathbf{B}_{ind}$ becomes dominant. The minimum in the $R(H_\downarrow)$ dependence appears when the external field is compen-

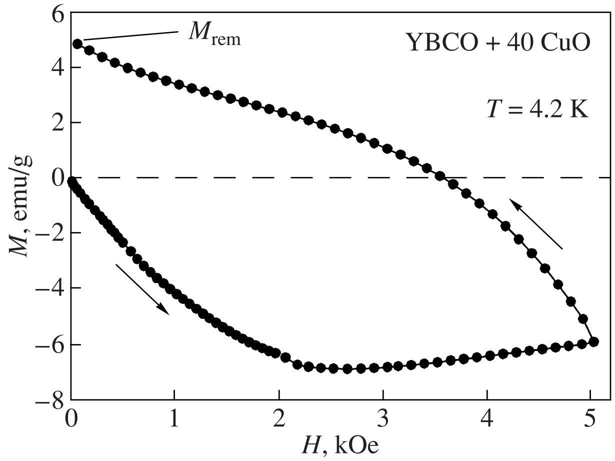


Fig. 3. Part of a magnetization hysteresis loop of a YBCO + 40 CuO sample at T = 4.2 K (H_{max} = 5 kOe). M_{rem} is the remanent magnetization measured after a magnetic field was applied and then decreased to zero.

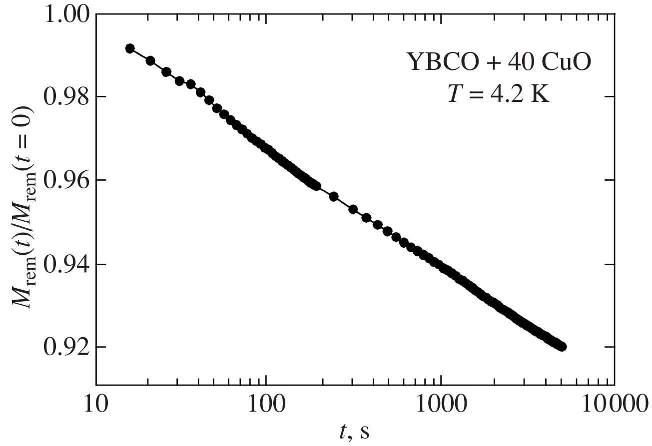


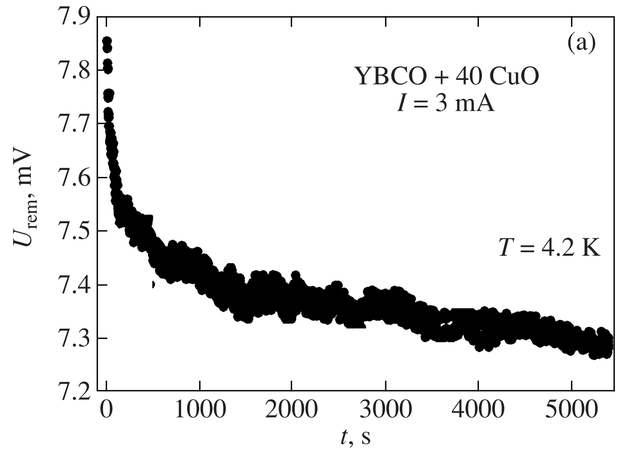
Fig. 4. Semilogarithmic plot of the time dependence of the remanent magnetization $M_{rem}/M_{rem}(t = 0)$ of a YBCO + 40 CuO sample measured after a field H_{max} = 5 kOe was applied and then removed. T = 4.2 K.

sated by the field of the grains to the maximum extent. Figure 2c shows the case of a zero external magnetic field which occurs after the field is increased to $H_{max} > H_{c1G}$ and then decreased to zero. In this case, $\mathbf{B}_{ind}$ is the field induced in the intergrain medium by Abrikosov vortices pinned inside superconducting grains ($\mathbf{B}_{ind} = \mathbf{B}_{M\text{–}A}$). Evidently, the resistive response of the granular HTSC is determined by the magnetic induction $\mathbf{B}_{ind}$ averaged over all intergrain boundaries through which a current passes inside the sample, i.e., by $\langle\mathbf{B}_{ind}\rangle$. So, in this case, a nonzero magnetic induction remains in the intergrain medium at $H_{\downarrow} = 0$, which leads to a remanent electrical resistance R_{rem}.

Over the course of time, the pinned vortices break away from pinning centers and disintegrate on the grain surfaces. This is reflected in well-known relaxation of the remanent magnetization M_{rem} in time. Figure 4 shows the dependence of the normalized M_{rem} on the logarithm of time for the YBCO + 40 CuO sample for which $R(H)$ and $R_{rem}(t)$ were measured after a field H_{max} = 5 kOe was applied (Fig. 3, $M(H)$ curve). The experimental data fit well a straight line. Using Eq.(1), we get a pinning potential $U_p \approx 28$ meV, which is in agreement with analogous measurements in the yttrium HTSC [24].

The relaxation of the magnetization decreases the magnetic field induced in the intergrain medium. Since all dissipation takes place in the intergrain boundaries, the boundaries (Josephson junctions) respond to the decrease in the induced magnetic field and the remanent resistance also relaxes with time. Figure 5 shows the time dependence of U_{rem} (the remanent voltage for a given current, $R_{rem} = U_{rem}/I$) measured for a YBCO + 40 CuO sample after the external field is increased to H_{max} = 5 kOe and then decreased to zero. The $R(H)$ dependences for this sample measured in an increasing and then decreasing magnetic field are shown in Fig. 1a. The $U_{rem}(t)$ dependences for a YBCO + 15 CuO sample are shown in Fig. 6 (the corresponding $R(H)$ dependences are shown in Fig. 1b). For a YBCO + 40 CuO sample, which has a relatively large resistance in the "normal" state (17.3 Ω, see Section 2), the remanent voltage decreases in time t = 3600 s by ≈530 μV for a current I = 3mA and by ≈750 μV for a current I = 5 mA (Fig. 5). In the YBCO + 15 CuO composite, Josephson links are weakened to a lesser extent (the resistance in the normal state is 0.75 Ω) and U_{rem} decreases over an hour by just ≈8 μV for I = 8mA and by ≈22 μV at I = 10 mA (Fig. 6). In "pure" (non-composite) granular HTSCs, the voltage drop in this time is also a few microvolts to several tens of microvolts but at much larger transport current values [1, 2, 4] and a temperature of 77.4 K. In a composite, the Josephson junctions are weakened and this leads to a higher sensitivity of its electrical resistance and of its remanent resistance to a magnetic field (Fig. 1). Therefore, a composite HTSC is a more convenient object for investing magnetoresistance and relaxation of R_{rem} than are pure HTSC polycrystals.

In order to explain the data on relaxation of the remanent electrical resistance, it is instructive to confront R_{rem} with the equal resistance value in the direct branch of the $R(H)$ dependence. Indeed, the equality of R_{rem} and $R(H_{\uparrow} = H^*)$ means that the value of the magnetic induction averaged over all intergrain boundaries, $\langle\mathbf{B}_{ind}\rangle$, is the same at $H_{\downarrow} = 0$ (after a field H_{max} is applied) and $H_{\uparrow} = H^*$. At $H_{\downarrow} = 0$, the field $\langle\mathbf{B}_{ind}\rangle$ is determined only by the flux trapped by the superconducting grains (Fig. 2c), whereas at $H_{\uparrow} = H^*$ it is the sum of the external and induced fields (Fig. 2b). The field H^* is determined as the abscissa of the intersection of the straight



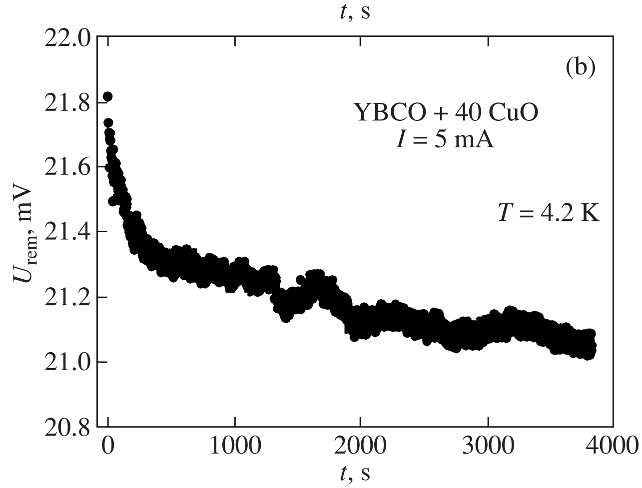


Fig. 5. Time dependence of the remanent voltage for a YBCO + 40 CuO sample measured for the transport current I equal to (a) 3 and (b) 5 mA after a field H_{max} = 5 kOe was applied and then removed. T = 4.2 K.

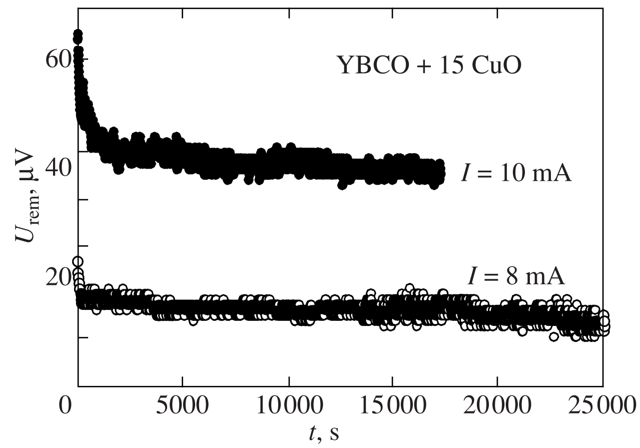


Fig. 6. Remanent voltage as a function of time for a YBCO + 15 CuO sample measured at a transport current I = 8 and 10 mA after a field H_{max} = 5 kOe was applied and then removed. T = 4.2 K.

line $R(H) = R_{rem}$ and the direct brunch of the $R(H)$ dependence. Figure 7 shows in detail the initial segments of the direct $R(H)$ brunch for the YBCO + 40 CuO composite and the crossing points of these dependences with $R(H) = R_{rem}$ straight lines correspond to the given transport current. It turns out that the field H^* is the same for all transport current values and is ≈440 Oe (at H_{max} = 5 kOe). Figure 7 also shows the values of $R_{rem}(t = 3000$ s), i.e., the resistance measured 3000 s after the field is removed. We equate the value of $R_{rem}(t = 3000$ s) to the resistance in the $R(H_\uparrow)$ dependence as is done for $R_{rem}(t = 0)$. It can be seen in Fig. 7 that the field $H^*(t = 3000$ s), i.e., the abscissa of the crossing point of the straight line $R(H) = R_{rem}(t = 3000$ s) with the $R(H_\uparrow)$ curve, is also the same for all transport currents and is ≈385 Oe. For other values of t, the situation is similar. Low transport currents cannot induce in the sample a field comparable to the external field. Therefore, the field $\langle \mathbf{B}_{ind} \rangle$ for the same magnetic history is identical for different currents.

A similar behavior is also observed for the YBCO + 15 CuO sample (Fig. 8). However, in the former sample (YBCO + 40 CuO), the transport currents are larger than the critical current ($I > I_c(H_\uparrow = 0)$), whereas for the YBCO + 15 CuO sample we have $I \ll I_c(H_\uparrow = 0) \approx 80$ mA. Our measurements for the composite with metal oxide $BaPbO_3$ give similar results.

If we take into account vortex pinning in the intergrain boundaries, the pattern of the field penetration into the granular superconductor (Fig. 2) becomes more complicated and $\langle \mathbf{B}_{ind} \rangle$ at $H_\downarrow = 0$ is the sum of the fields induced by Abrikosov vortices and Josephson vortices in the intergrain medium [10, 12, 18]. However, a transport current larger than the critical current of the Josephson junctions would favor additional depinning of vortices in the intergrain medium, which should lead to a decrease in $\langle \mathbf{B}_{ind} \rangle$ with increasing current and, therefore, to an I dependence of H^*. Since we did not observe such a dependence in experiment, it can be concluded that the relaxation of the electrical resistance of the HTSC composites studied is due solely to relaxation of the magnetic flux trapped by the superconducting grains. The decrease of the field H^* with time (by ~55 Oe over ~3000 s) is the same for various transport current densities. In our opinion, this is convincing evidence that the relaxation of the remanent resistance (at least in the composite samples under study) is caused by the decreased magnetic induction $\langle \mathbf{B}_{ind} \rangle$ in the intergrain medium, which, in turn, is related to vortices leaving the HTSC grains. The conclusion that the influence of the flux trapping in the Josephson medium on the sample resistive response is insignificant in fields of up to ~1 kOe at T = 77.4 K was also drawn in [20] from analyzing current–voltage characteristics of granular $YBa_2Cu_3O_7$.

The experimental data on resistance relaxation fit well straight lines when plotted in $R_{rem}/R_{rem}(t = t_0)$ ver-

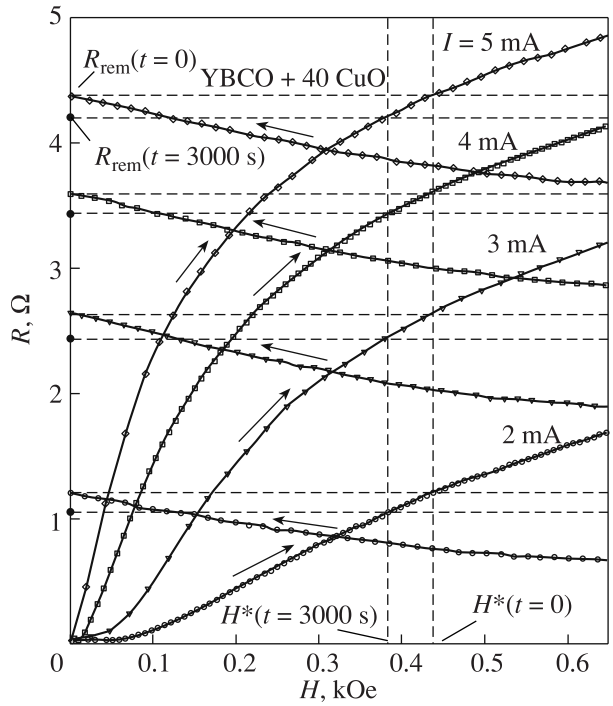


Fig. 7. Hysteretic field dependences of the magnetoresistance for a YBCO + 40 CuO sample measured at $T = 4.2$ K in fields of up to 0.65 kOe. Arrows indicate the sweep direction of the external magnetic field H. Shown are the remanent resistances $R_{rem}(t = 0)$ and R_{rem} at $t = 3000$ s (solid circles located under the values of $R_{rem}(t = 0)$ corresponding the given transport current) measured after a field $H_{max} = 5$ kOe was applied and then decreased to zero. Dashed lines illustrate the definition of the fields $H^*(t = 0)$ and $H^*(t = 3000\text{ s})$ at which $R_{rem} = R(H\uparrow)$ for the given current (see text).

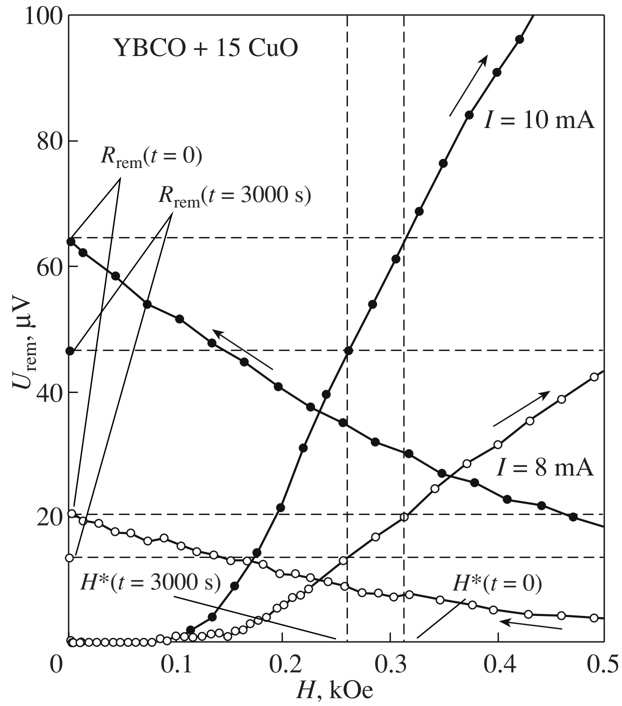


Fig. 8. Hysteretic dependences of the voltage across a YBCO + 15 CuO sample on external field H for the transport current $I = 8$ and 10 mA at $T = 4.2$ K measured in fields of up to 0.5 kOe. Arrows indicate the sweep direction of the external field H. Shown are the remanent resistance R_{rem} and the values of R_{rem} at $t = 3000$ s after a field $H_{max} = 5$ kOe was applied and then decreased to zero. Dashed lines illustrate the definition of the fields $H^*(t = 0)$ and $H^*(t = 3000\text{ s})$ at which $R_{rem} = R(H\uparrow)$ for the given current (see text).

sus ln(t) coordinates (Fig. 9). Let us discuss this fact in more detail. The remanent magnetization decreases in time following a logarithmic law (Fig. 4), and the magnetic induction in the intergrain medium $\langle \mathbf{B}_{ind} \rangle$ is proportional to the magnetization, $\langle \mathbf{B}_{ind} \rangle \sim \mathbf{M}$. The sample resistance (i.e., the resistive response of the intergrain boundaries) reacts on the variation of $\langle \mathbf{B}_{ind} \rangle$ with time. Indeed, the resistance of intergrain boundaries is dependent on $\langle \mathbf{B}_{ind} \rangle$, $R(\langle \mathbf{B}_{ind} \rangle)$, which is manifested by the experimental $R(H)$ dependence. The change in $\langle \mathbf{B}_{ind} \rangle$ in several hours (the period of measurements of $R_{rem}(t)$) is relatively small (the magnetization decreases by ≈8% in a time $t = 5000$ s (Fig. 3)). Probably, the $R(\langle \mathbf{B}_{ind} \rangle)$ dependence in this case can be approximated by a linear function. This assumption is supported by the approximately linear behavior of the $R(H_\uparrow)$ dependence over the range from $H^*(t = 0)$ to $H^*(t = 3000\text{ s})$ (Figs. 7, 8). So, $R_{rem} \sim |\langle \mathbf{B}_{ind} \rangle| \sim M$. Therefore, $R_{rem}(t) \sim M_{rem}(t)$, and, consequently, if $M_{rem}(t) \sim -\ln(t)$, then $R_{rem}(t) \sim -\ln(t)$. In principle, one might expect the $R_{rem}(t)$ dependence to deviate from the logarithmic law during longer measurements and for smaller values of H_{max}, because the magnetoresistance curve is not linear over a range wider than the range from $H^*(t = 0)$ to $H^*(t = 3000\text{ s})$; however, we did not observe such effects up to $t = 25\,000$ s.

In [1–4], the experimental data on the relaxation of R_{rem} were used to calculate the pinning energy from the Anderson dependence (2). Let us consider the effect of a transport current on the $R_{rem}(t)/R_{rem}(t = 0)$ dependence. An increase in the transport current leads to increased values of R_{rem} (Figs. 1, 7, 8) and to increased variations in R_{rem} with time (Figs. 5, 6). However, the variation in the relative resistance $R_{rem}(t)/R_{rem}(t = 0)$ for identical time periods decreases with increasing I, as can be seen in Fig. 9. Using the data obtained for the YBCO + 40 CuO sample, we found that the slope of $R_{rem}(t)/R_{rem}(t = 0)$ versus ln(t) plots decreases threefold when the transport current increases from 2 to 5 mA. A similar pattern is observed for the YBCO + 15 CuO sample. It is due to the fact that $R(H_\uparrow)$ depends on current. As demonstrated above, the behavior of $R_{rem}(t)$ is equivalent to the behavior of $R(H_\uparrow)$ with decreasing $H_\uparrow$. If we normalize the $R(H_\uparrow)$ dependences by $R_{rem}(t = 0)$, i.e., by the value $R(H_\uparrow = H^*(t = 0))$ (Figs. 7, 8), then the slope of the normalized dependences $R(H_\uparrow)/R(H_\uparrow =$

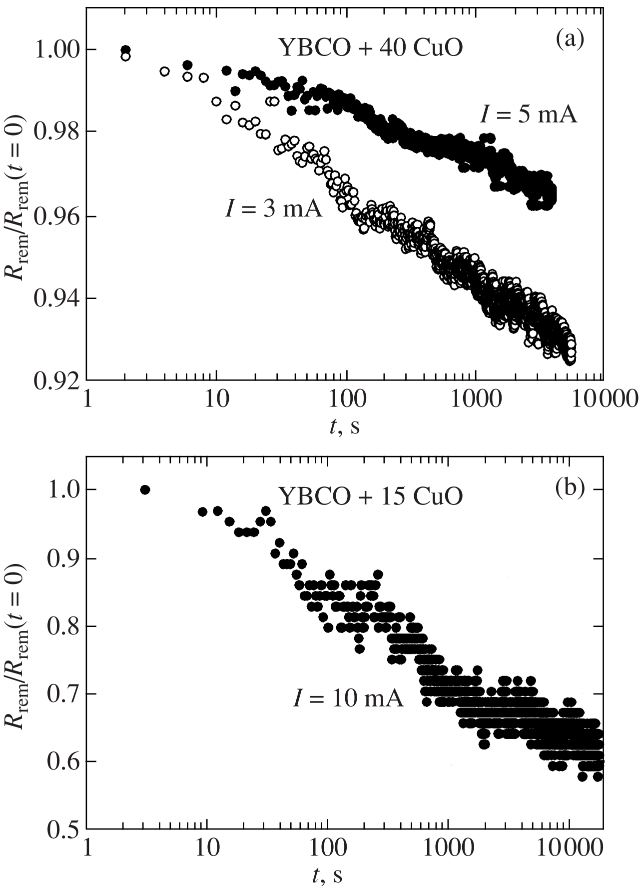


Fig. 9. Semilogarithmic plots of the remanent resistance as a function of time for (a) YBCO + 40 CuO (I = 3 and 5 mA) and (b) YBCO + 15 CuO (I = 10 mA).

$H^*(t = 0)$)) in the range from $H^*(t = 0)$ to $H^*(t = 3000$ s) will decrease with increasing current. Therefore, as the current increases, the sensitivity of the relative resistance to changes in $\langle \mathbf{B}_{ind} \rangle$ decreases and, accordingly, the slope of $R_{rem}(t)/R_{rem}(t = 0)$ versus ln(t) plots (which defines the pinning potential) also decreases. Thus, it is not surprising that the values of U_p^* as determined from Eq. (2) for YBCO + 40 CuO increase from ≈19 to ≈60 meV as the current I increases from 2 to 5 mA; for YBCO + 15 CuO, these values are 7.5 and 8.5 meV at I = 8 and 10 mA, respectively. Naturally, this result cannot be explained in terms of usual processes of flux creep and flux flow, because an increase in the transport current should lead to a decrease in the effective pinning potential [9]. The above result explains the wide range of values of the "activation energy" obtained from measurements of the relaxation of remanent resistance [1, 2, 4] and the disparity between the values of the "pinning potential" obtained from measurements of the resistance and magnetization relaxation [3], which is also found in this work. So, though the vortex pinning energy determined from the experimental time dependences of the remanent electrical resistance using the Anderson equation (2) can have the same order of magnitude as that determined from measurements of the relaxation of magnetization, the former method is incorrect because of the $R(I)$ dependence, a fact demonstrated for the first time experimentally in this paper.

4. CONCLUSIONS

Let us formulate the main results obtained in this study of magnetoresistance and relaxation of the remanent electrical resistance of the $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ + CuO composites, which can be treated as a network of Josephson junctions with an artificially reduced Josephson coupling energy between HTSC grains. We have demonstrated experimentally that the remanent resistance is determined by the magnetic induction in the intergrain medium induced by the flux trapped in the superconductor. The intergrain medium is a "resistive sensor" reacting on the magnetic induction. The relaxation of the remanent resistance is caused solely by relaxation of the magnetic flux in HTSC grains, and vortex pinning in the intergrain medium does not have a significant effect on the resistance relaxation. Since this behavior is observed both for $I > I_c$ (I_c in the absence of an external field) and for $I \ll I_c$, the effect of vortex pinning in the intergrain medium on the relaxation of R_{rem} is apparently also insignificant in "pure" (non-composite) granular HTSCs, which were studied previously for $I < I_c$ [1–5]. The transport current can be used to vary the "sensitivity" of the response of the electrical resistance and remanent resistance to a change in the magnitude of the magnetic induction in the intergrain medium. An increase in the transport current leads to increased values of R_{rem} and $R_{rem}(t) - R_{rem}(t = 0)$ but causes a decrease in the relative resistance $R_{rem}(t)/R_{rem}(t = 0)$. Therefore, the determination of the pinning potential inside grains from the experimental $R_{rem}(t)$ dependence and the Anderson formula (2), as it was performed in [1–4], is incorrect.

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