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The effect of ferrimagnetic ordering in insulating component of composites HTSC + Yttrium Iron Garnet on its transport properties

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Abstract

Composites $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7 + Y_3Fe_5O_{12}$ modeling random network superconductor–ferrimagnetic–superconductor have been prepared and their transport properties (temperature dependences of resistivity ρ and critical current density j_c, current–voltage characteristics) have been studied. Below the superconducting transition temperature T_c, the $\rho(T)$ dependences exhibit a kink at some temperature T_m. The crossover of current–voltage characteristics from ohmic-like behavior in range T_m/T_c to non-linear one below T_m is observed. Transport properties of the 'benchmark' composites $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7 + Y_3Al_5O_{12}$ are typical for network superconductor–insulator–superconductor Josephson junction. The behavior observed for $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7 + Y_3Fe_5O_{12}$ composites is attributed to peculiarities of supercurrent carriers tunnelling through ferrimagnetic barriers.

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1. Introduction

Two phases high-T_c superconductor (HTSC)-based composites, besides potential practical applications [1–8], have important fundamental interest [2,3,5,6,9–14] connected with their consideration as a random Josephson junction network. Non-superconducting ingredients of such kind of composites play the role of artificially created barriers or weak links between the HTSC crystallites (non-superconducting phase is insulator or metal or degenerated semiconductor). Transport properties of HTSC + normal metal [1–3,5,7–9,12–14], HTSC + insulator [3–5,10] composites are widely investigated by a number of groups up to date. Recently we have reported the study of composites with magnetic impurities in non-superconducting ingredients: YBCO + $Cu_{1-x}Ni_xO (0 \le x \le 0.6)$ [15], YBCO + $BaPb_{0.9}Fe_{0.1}O_3$, YBCO + $BaPb_{0.9}Ni_{0.1}O_3$ [16]. Strong pair breaking effect appeared in suppression of transport properties due to interaction of magnetic moments in the barriers with spins of carriers has been observed. The study of composites HTSC + paramagnetic insulator $NiTiO_3$ [17,18], aside from suppression of superconducting transport properties, have shown the anomalous behavior of resistivity below critical temperature T_c of HTSC crystallites. In a temperature range from T_c down to some temperature T_m the dissipation is ohmic-like while bellow T_m the current–voltage characteristics (CVCs) are strongly non-linear. One of the possible explanations of this feature is attributed to forming and flowing of Abrikosov vortices. Investigation of composites HTSC + insulator with ferro- or ferrimagnetic ordering will be the reasonable next step in this study because SFS (where S is superconductor, F is ferro- or ferrimagnet) structures are under undiverted theoretical [19–26] and experimental attention [27–29]. In this report we choose classic yttrium iron garnet (YIG) playing the role of the second component of the composites so far as it satisfy the necessary condition of chemical non-interaction with HTSC of 1-2-3 structure (which is always

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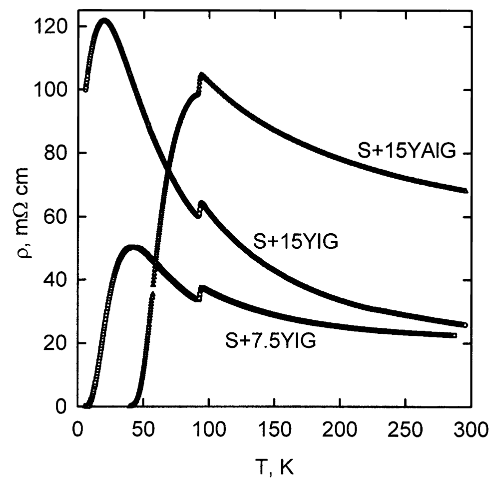

Fig. 1. Experimental dependences $\rho(T)$ for composite samples with YIG and YAlG in a range 4.2–300 K.

checked by XRD analysis). Also we studied HTSC-based composites with yttrium aluminum garnet (YAlG) to separate the 'magnetic' effect on transport properties of the composites, because it has the same structure with iron garnet and reveals no strong magnetic properties.

2. Experimental

The HTSC ($Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$) was synthesized using the standard procedure. $Y_3Fe_5O_{12}$ and $Y_3Al_5O_{12}$ were prepared from Y_2O_3, Fe_3O_4 and $Al(OH)_3$ at 1250 °C for 48 h with three intermediate grindings. The composites were prepared as follows. The components of a composite were thoroughly mixed with additional milling of the of the powders in an agate mortar and then pressed into the pellets. The pellets were placed in preheated boats and then placed in furnace heated to 910 °C. The pellets were kept at this temperature for 2 min and then placed in another furnace for 3 h at 350 °C, which was followed by furnace-cooling to room temperature. Henceforth we designate the samples as S + VYIG, S + VYAlG, where V is the volume content of the YIG or YAlG in a composite.

Transport measurements have been performed using standard four-probe technique. The value of critical current density has been obtained from experimental CVCs using the standard criterion 1 μV/cm [30]. Copper solenoid has been used for measurements in magnetic fields less than 500 Oe. Measurements in fields higher than 500 Oe have been performed using a superconducting solenoid. Transport current was perpendicular to the applied field.

3. Results and discussion

Fig. 1 shows temperature dependences of resistivity $\rho(T)$

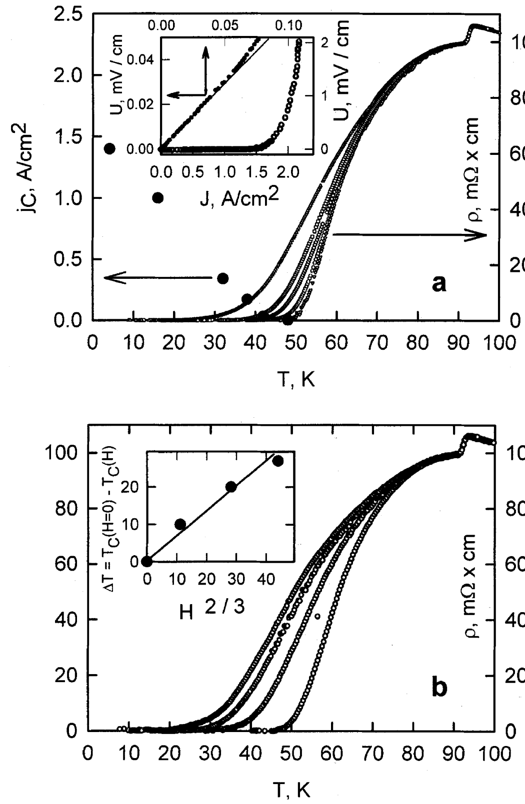

Fig. 2. (a) $j_c(T)$ dependence, closed circles (left scale); experimental dependences of resistance $\rho(T)$ for composite S + 15YAlG measured at various current densities j (right scale), $j = 3.4$, 34, 170, 340, 1000 mA/cm^2 ($H = 0$)—from right to left. (a, inset) Experimental CVCs for composite S + 15YAlG at $T = 4.2$ K (closed circles, right scale), and at 77 K (open circles, left scale). (b) Experimental dependences of resistance $\rho(T)$ for composite S + 15YAlG measured at $j = 34$ mA/cm^2 and various magnetic field strengths H, $H = 0$, 37, 150, 292 Oe—from right to left. (b, inset) Experimental dependence of resistive width $\Delta T_{c0} = T_{c0}$-$(H = 0,\ R = 0) - T_{c0}(H,\ R = 0)$ versus $H^{2/3}$ for composite S + 15YAlG.

for some composite samples. A drop of ρ at $T_c = 93.5$ K is caused by the transition of HTSC crystallites into the superconducting state. Above T_c the $\rho(T)$ dependences have semiconducting-like character similar to that for previously studied HTSC + insulator composites [10,11,18]. This behavior manifest transport current to flow both the HTSC and the non-superconductor grains. Below T_c the $\rho(T)$ is determined by the transition of Josephson junction network [5,7,10,11,15–18]. This part of $\rho(T)$ is strongly dependent on transport current j and weak external magnetic fields. Fig. 2 illustrates this behavior for sample S + 15YAlG. CVCs are nonlinear in the whole range up to T_c, see inset in Fig. 2a. The $j_c(T)$ dependence (points in Fig. 2a) is similar to that obtained previously on HTSC + insulator composites YBCO + CuO [10], YBCO + $MgTiO_3$ [18]. The $\rho(T)$ dependences of the mentioned samples are successfully

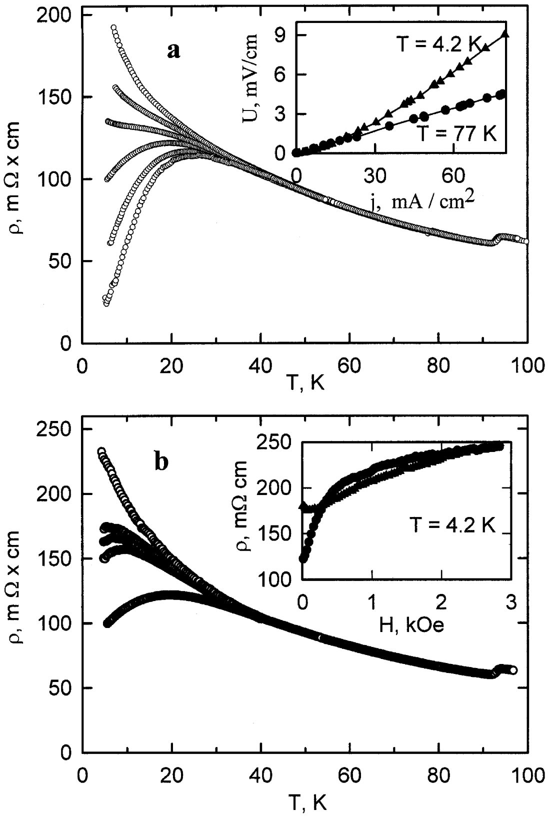

Fig. 3. (a) Experimental dependences of resistance $\rho(T)$ for composite S + 15YIG measured at various current densities j, $j = 15$, 7.7, 15, 77, 150, 600 mA/cm^2 ($H = 0$)—from right to left. (a, inset) Experimental CVCs for composite S + 15YIG at $T = 4.2$ and 77 K. (b) experimental dependences of resistance $\rho(T)$ for composite S + 15YIG measured at $j = 15$ mA/cm^2, and various magnetic field strengths H, $H = 0$, 40, 80, 150, 1900 Oe—from right to left. (b, inset) Experimental dependence of magnetoresistance $\rho(H)$ for composite S + 15YIG at $T = 4.2$ K.

described by the thermally activated phase slippage (TAPS) mechanism [31] developed for tunnel Josephson junctions. Note, that TAPS mechanism [31] explains experimentally observed 'zero' critical currents at high temperature range [10]. There is no doubt that the $\rho(T, j)$ curves will be described by TAPS. Treatment of experimental $\rho(T, j)$ for composites with aluminum garnet within the TAPS theory is out of scope of the present paper and will be presented elsewhere.

Similar to $\rho(T, j)$ dependences, experimental $\rho(T, H)$ ones for S + 15YAlG are also characterized by 'zero resistivity' critical temperature ($\rho \leq 10^{-6}$ Ω cm) T_{c0} which magnitude depends on magnetic field H. To describe experimentally observed resistive transition width of HTSC materials in a magnetic field Tinkham proposed a model of thermally activated flux flow [32]. One of the theoretical result of the work [32] is magnetic field dependence of resistive width $\Delta T_{c0} = T_{c0}(H = 0, R = 0) - T_{c0}(H, R = 0) = H^{2/3}$. This dependence has been observed experimentally on polycrystalline HTSC samples [32] and HTSC + CuO composites [7]. Inset in Fig. 2b shows experimental dependence of $\Delta T_{c0} = T_{c0}(H = 0, R = 0) - T_{c0}(H, R = 0)$ as function of $H^{2/3}$ for sample S + 15YAlG. It is seen that this dependence is close to linear. The same dependence of ΔT_{c0} vs. $H^{2/3}$ is observed for sample S + 7.5YAlG. So magneto-resistive properties of composites HTSC + $Y_3Al_5O_{12}$ have the same character as previously studied HTSC + insulator composites [7,10, 18] and polycrystalline samples [32].

Dramatically differ $\rho(T)$ behavior is observed for HTSC composites with YIG, see Fig. 3. There is an interval of $\rho(T)$ below T_c where $\rho(T)$ has semiconducting-like character similar to that above T_c. Strong $\rho(j, H)$ dependence, characteristic for Josephson network, takes place only below well pronounced temperature T_m, see Fig. 3. In the range T_m/T_c CVC are linear. Sample S + 15YIG has no critical current at 4.2 K. For S + 7.5YIG $j_c(4.2\ K) = 0.025$ A/cm^2, for S + 4.5YIG $j_c(4.2\ K) = 1.12$ A/cm^2. Superconducting transport properties of composites HTSC + ferrimagnetic are strongly suppressed by, respectively, small values of measuring current j and external magnetic fields. As it is seen from Fig. 3 at some critical current density value $j_{cr} = 0.6$ A/cm^2 ($H = 0$) and critical external field $H_{cr} = 1900$ Oe (value of measuring current $j = 0.015$ A/cm^2) $\rho(T)$ curve prolongs semiconducting-like behavior which takes place above T_m and T_c. At $j \geq j_{cr}$ CVC transits to linear part, and at $H \geq H_{cr}$ $\rho(H)$ curve becomes weakly field dependent, see inset in Fig. 3b. For samples with YIG content less than 15 vol.%, the j_{cr} and H_{cr} values are sufficiently higher: $H_{cr} \approx 30$ kOe, $j_{cr} \approx 10$ A/cm^2 ($H = 0$) for S + 7.5YIG, and $H_{cr} \geq 70$ kOe, $j_{cr} \geq 50$ A/cm^2 (H = 0) for S + 3.75YIG.

The composites S + 15YIG, besides strong suppression of transport properties in comparison with S + 15YAlG composites, have entirely different transport properties. Experimental data on Figs. 1 and 3 point out indirectly that in percolation network of composites S + 15YIG the Josephson effect takes place only in a range below T_m in contrast to composites with HTSC + 'non-magnetic' insulator S + 15YAlG where non-linearity of CVCs remains up to T_c. The T_m value depends on volume content of ferrite, i.e. on effective barrier length [10,11,14]. For S + 15YIG $T_m \approx 40$ K, for S + 7.5YIG $T_m \approx 55$ K, for S + 3.75YIG $T_m \approx 65$ K.

This effect, on author opinion, arises not due to influence of barrier distribution function and preparation technique because the bench-mark composites $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ + $Y_3Al_5O_{12}$ exhibit usual behavior which describes by theories for tunnel Josephson junctions [31,32]. Moreover, we point out identity of our experimental data with data obtained on single S–F–S structures with ferromagnetic Gd barrier. The $\rho(T)$ curves of Nb/Al/Gd/Al/Nb junctions studied in Ref. [27] have also two distinctive parts below the transition temperature (≈7.6 K). In a range $T < T_m^*$ CVC are strongly nonlinear, in a range $T_m^* - T_c$ $\rho(T)$ curves do not depend on transport current. Values of T_m^* are ≈5.2 K for 4 nm Gd layer and ≈4 K for 8 nm Gd layer. The impact of the ferromagnetic character of Gd on the barrier potential, however, has not been discussed in the cited work. In present paper, we suggest two possible explanations of the behavior observed for composites HTSC + YIG.

(1) In Refs. [17,18] $\rho(T)$ behavior of composites HTSC + paramagnetic $NiTiO_3$ has been explained by the hypothesis based on Abrikosov vortex lattice formation in HTSC grains. Really, magneto-active component of the composites can induce some field penetrating inside the HTSC crystallites as Abricosov vortices in the depth of order Josephson penetration depth (~1000 Å). The value of this field is of order of molecular field (10^6 Oe for $Y_3Fe_5O_{12}$ [33]) on interface $Y_3Fe_5O_{12}$/YBCO. The property of Abrikosov vortex lattice is ohmic-like dissipation above the melting temperature [34]. So far the transport current necessarily flows through barriers between HTSC crystallites, therefore, it flows also through adjacent grains with magnetic flux. The hypothesis proposed explains two distinctive parts on $\rho(T,j)$ curves assuming T_m is Abrikosov vortex lattice melting temperature. Experimentally observed decreasing of T_m values with growth of $Y_3Fe_5O_{12}$ content seems to be due to enhancement of interface $Y_3Fe_5O_{12}$/YBCO.

(2) In Ref. [22] stationary Josephson effect in a system with ordered localized magnetic impurities at the barrier has been studied theoretically. Zero Josephson current due to Cooper pair scattering from magnetic impurities has been predicted at some critical effective junction thickness. From the other hand, the TAPS mechanism [31] explains the disappearance of experimentally observed critical currents at high temperatures [10] due to thermal noise. Substitution $I_1 = 0$ (I_1 is the current in absence of thermal fluctuations in model [31]) into general CVC expression for TAPS result in linear CVC. Disappearance of fluctuation-free critical current in a Josephson network YBCO–$Y_3Fe_5O_{12}$–YBCO (predicted theoretically [22] for single contact) in composites HTSC + $Y_3Fe_5O_{12}$ lead to CVC crossover from nonlinear to ohmic at temperature T_m. Theory [22] and TAPS mechanism may explain the general behavior of resistive state observed on HTSC + $Y_3Fe_5O_{12}$ composites. Estimation T_m in the frames of work [22], however, seems to give too rough value because the case of ferrimagnetic ordering has not been considered therein. Moreover, the results for HTSC may be quite different than for conventional superconductors [25]. So, it is advisable to consider theoretically S–F–S structures not only from the point of view of π-states [19–21,24–26] but regarding destroying of the Josephson effect due to spin–flip scattering processes.

Thus, transport properties of $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7 + Y_3Fe_5O_{12}$ composites modeling Josephson network of superconductor–ferrite–superconductor junctions have been studied. Aside from strong suppression of critical current density, as compared with HTSC + 'nonmagnetic' insulator ($Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7 + Y_3Al_5O_{12}$) composites, unusual peculiarity of transport properties for HTSC + ferrimagnetic composites at some temperature T_m ($T_m < T_c$) is observed. In the range below T_m the CVC's for HTSC + $Y_3Fe_5O_{12}$ composites are non-linear, which is characteristic for Josephson junction network; in the range $T_m - T_c$ the dissipation is ohmic-like. Resistive behavior of the 'bench-mark' composites HTSC + $Y_3Al_5O_{12}$ can be explained in terms of thermal fluctuations in Josephson junction network [31].

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