Functional Materials 11, No.4 (2004) © 2004 — Institute for Single Crystals

Magnetoresistance of granular high-temperature superconductor $YBa_2Cu_3O_{7-\delta}$ in weak magnetic fields

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Received May 7, 2004

The transverse and longitudinal magnetoresistance $\Delta\rho/\rho_{273\ K}(H)$ of ceramic samples of the high-temperature superconductor $YBa_2Cu_3O_{7-\delta}$ was studied experimentally at T = 77.3 K in the magnetic fields $0 \le H \le 500$ Oe. A phenomenon was found of a jumping variation of the magnetoresistance in the magnetic fields $H = H_{jump}$ that was associated with alteration of the vortex structure. The magnetoresistance field dependence is shown to be of hysteresial nature. The presence of an alignment dependence was found of the value of the magnetoresistance and critical fields of the weak links and superconducting granules (H_{c2J}, H_{c1A} and H_{jump}), as well as the dependence of the value of the critical fields H_{c2J}, H_{c1A} and H_{jump}, vs. the transport current density and preceding magnetic history.

Экспериментально изучено поперечное и продольное магнитосопротивление $\Delta\rho/\rho_{273\ K}(H)$ керамических образцов высокотемпературного сверхпроводника $YBa_2Cu_3O_{7-\delta}$ при T = 77.3 K в магнитных полях $0 \le H \le 500$ Oe. Обнаружен эффект скачкообразного изменения магнитосопротивления в магнитных полях $H = H_{jump}$, связанный с перестройкой вихревой структуры. Показано, что полевая зависимость магнитосопротивления носит гистерезисный характер. Обнаружено наличие ориентационной зависимости величины магнитосопротивления и критических полей слабых связей и сверхпроводящих гранул (H_{c2J}, H_{c1A} и H_{jump}) и зависимости величины критических полей H_{c2J}, H_{c1A} и H_{jump} от плотности транспортного тока и магнитной предыстории.

A tremendous number of scientific papers have been written on studies of the kinetic properties (electric resistance, critical current, Hall coefficient and magnetoresistance) of single crystals, thin films and bulk samples of high-temperature superconductors (HTSC) of variable composition across a wide interval of temperatures and applied magnetic fields. One must note that, despite the high potential possibilities of the magnetoresistance measurement method to make studies both on the fundamental parameters of the superconductivity (meaning the lower H_{c1} and upper H_{c2} critical fields, see, for example, the review paper [1]) and the dynamics of magnetic vortices (see, for instance, the review papers [2–4]), this method occupies a relatively modest slot in the research on HTSC properties.

The analysis of measurement-takings of the magnetoresistance ($\Delta\rho/\rho_{273\ K}$) of the HTSC is rather complicated, the alignment dependence $(\Delta\rho/\rho_{273\ K})(H)$ being described by the fourth-rank tensor [5]. With this observation in mind, while interpreting results of studies on the magnetoresistance of granular HTSC, the objects of study are, as a rule, regarded as a certain unbroken medium consisting of a mixture of the superconducting (S) and normal (N) phases [6–11].

It is quite obvious that information on the magnetoresistance of ceramic (granular) HTSC materials *in weak magnetic fields* must be invaluable for studies on the superconductivity parameters and dynamics of magnetic vortices both in HTSC granules and quasi-2D intergrain contacts, the Josephson *weak links*, for which the critical temperatures and fields are considerably lower than for the superconducting granules: $T_{cJ} \le T_{cA}$, $H_{c1J} << H_{c1A}$, $H_{c2J} << H_{c2A}$ (where the subscripts "J" and "A" pertain to the weak links and superconducting granules, i.e. to the Josephson and Abrikosov media).

The aim of this paper is to pursue research into the field relationships of the transverse $(\mathbf{I} \perp \mathbf{H})$ and longitudinal $(\mathbf{I} \parallel \mathbf{H})$ magnetoresistance of the granular superconductor $YBa_2Cu_3O_{7-\delta}$ at the temperature $T = 77.3$ K in such a range of the magnetic field strengths H that embraces the region of the fields H_{c1J}, H_{c2J} and H_{c1A}. An outstanding feature of the present work is such that the value of measuring (transport) current I in the course of taking the V-H characteristics and the "magnetocycling depth" (i.e. the value of the maximum field H_{max}, up to which the measurements of magnetoresistance are taken according to the scheme "$0 \to H_{max} \to 0$", see below) vary across relatively wide limits.

In addition to making study on the general nature of the relationships $\Delta\rho/\rho_{273}(H)$ the paper considers two phenomena:

1. Irreversibility (hysteresis) of the magnetoresistance upon increasing or decreasing of the applied magnetic field strength H,
2. Appearance of jumps on the curves of $\Delta\rho/\rho_{273}(H)$ at certain values of the applied magnetic field H.

Let us note at once that, if the appearance of clockwise hysteresis loops of the magnetoresistance had been observed earlier (see, for instance [6–8, 12]), as well as, by the way, the more-than-once-observed dependence of the critical current I_c on the direction of magnetic field variation (see, for instance [13–18]), then emergence of the jumping variation of magnetoresistance in ceramic HTSC in *weak magnetic fields* is, in all evidence, discovered for the first time in this work.

This work implemented the following research program:

1. Measurement-takings of the transverse magnetoresistance $\Delta\rho_\perp/\rho_{273}(H)$ at $0 \le H \le H_{max}$ ($H_{max} = const \sim 500$ Oe) in accordance with the scheme "$0 \to H_{max} \to 0$" across the range of transport current values $\sim 0.01 \le I/I_c \le \sim 0.99$.
2. Measurement-takings of the longitudinal magnetoresistance $\Delta\rho_\parallel/\rho_{273\ K}(H)$ according to the very same scheme.
3. Measurement-takings of $\Delta\rho_\perp/\rho_{273\ K}(H)$ and $\Delta\rho_\parallel/\rho_{273}(H)$ at $0 \le H \le H_{max}$ according to the scheme "$0 \to H_{max} \to 0$" at $I = const$ ($I/I_c \sim 0.05$) in the range of values of the maximum magnetic field strength $10 \le H_{max} \le 500$ Oe.

The translation of this research program into life, as the authors see it, is bound to allow them to become clear on the nature of the influence of the density of the transport current I and the strength, alignment and variation direction of the applied magnetic field $\mathbf{H}$ on peculiarities in the behavior of the magnetoresistance of the ceramic HTSC $YBa_2Cu_3O_{7-\delta}$.

Experimental technique

Objects of the study were HTSC samples of the composition $YBa_2Cu_3O_{\sim 6.95}$, synthesized according to the standard ceramic technology (see, for instance [19]). The size of the samples was $\sim 20 \times 3 \times 2$ mm^3. The low-ohmic and potential Ag-contacts were deposited using conductive glue. To test out the samples, the techniques were used of XRD, resistive and magnetic measurements of the critical transition temperature T_c and the measurements of the critical currents I_c ($T = 77.3$ K, $H = 0$).

The studied samples were actually single-phase. A relatively faint crystallographic texture was observable that was close to that of the basal plane (001) of the orthorhombic lattice [20, 21] formed obviously at the stage of uniaxial powder pressing preceding the final operation of synthesis, the sintering in the atmosphere of oxygen. For all samples, the mediating transition temperature $T_c^{1/2}$ was 92.6 K, the transition width being $\Delta T_c = 0.4$ K; the critical current value I_c varied across relatively wide limits. Bearing in mind the considerable differences in the critical current values of the samples studied and some differences in their resistance in the normal state ($R_{273\ K}$), relative values of the current and resistance are used throughout this work $I/I_c \equiv j/j_c$ and $\Delta R/R_{273\ K} \equiv \Delta\rho/\rho_{273\ K}$ (typical values: $\rho_{273\ K} \sim 1000\ \mu\Omega \cdot cm$, $j_c \sim 100$ A/cm^2).

The experiments mostly comprised precision measurements of the electrical resistance of $YBa_2Cu_3O_{\sim 6.95}$ at $T = 77.3$ K at unvaried value of the transport current I vs. the value and direction of variation of the magnetic field **H**. The Dewar vessel filled up with liquid nitrogen with a turning device, the sample holder, positioned on it, was placed in the solenoid. Using this device, the angle between the axes of the sample and solenoid could be assigned with the accuracy not less than 2°.

The taking of V-H-characteristics at $I = const$ on the base of a computer of the type PC/AT 386 called for development of a dedicated device [22] that consisted of a control unit of the magnetic field source (solenoid) I_{sol} and a control unit for the measuring (transport) current I_{meas} flowing through the sample. All the measurements were taken in the automatic regime: at the assigned transport current value I_{meas}, the current passing through the solenoid I_{sol} increased smoothly to a certain value that corresponded to the assigned value of the maximum magnetic field strength H_{max}, and then it decreased to $I_{sol} = 0$. All information was recorded as the relationships $R(H)$ at $I = const$ went into the computer memory [the error in the measurements of the relative magnetoresistance $\Delta\rho/\rho_{273\ K}$ did not exceed 10^{-2} %]. Then the sample was heated to $T > T_c$, the next value of I_{meas} was assigned and the cycle of measurements repeated itself.

Results

The curves of the relation of the transverse magnetoresistance $R_{\perp}(H)$ of typical HTSC sample of $YBa_2Cu_3O_{\sim 6.95}$ vs. magnetic field strength is shown in Fig. 1. As one can see, progression of the curves $R_{\perp}(H)$ differs in the case of "weak" ($I/I_c \sim 0.1$, Fig. 1a) and "strong" ($I/I_c \sim 0.5$, Fig. 1b) transport currents. The common trait of the curves $R_{\perp}(H)$ is the presence of clearly observable effects of the hysteresis, — the irreversibility of the curves of magnetoresistance field relationships while the magnetic field strength increases or decreases.

When a relatively weak current passes through sample, the appearance of the magnetoresistance $R_{\perp}$ is observable concurrently with increasing of the magnetic field strength in sufficiently weak fields H_0^+ (Here and further on, the symbol "+" stands for magnetic field strength increasing, while the one "−" does for the decreasing of H). With any further increase, the value of the field of $R_{\perp}$ increases at $H > H_0^+$, all curves of $R_{\perp}(H)$ displaying a faint bend in the fields H_{flex}^+. In the fields $H_{jump}^+ >> H_0^+$ the value of $R_{\perp}$ keeps jumping upward, while at $H > H_{jump}^+$ the curve of $R_{\perp}(H)$ shows a peak. While decreasing the magnetic field strength downward from H_{max}, the value of $R_{\perp}$ decreases as well; a jump is observable on the curves of $R_{\perp}(H)$, although considerably smaller than at increasing H, in the fields $H_{jump}^- < H_{jump}^+$; a bend on the curve of $R_{\perp}(H)$ occurs in the fields $H_{flex}^- > H_{flex}^+$. With any further decrease of H the magnetoresistance keeps falling reverting to zero in the fields $H_0^- > H_0^+$.

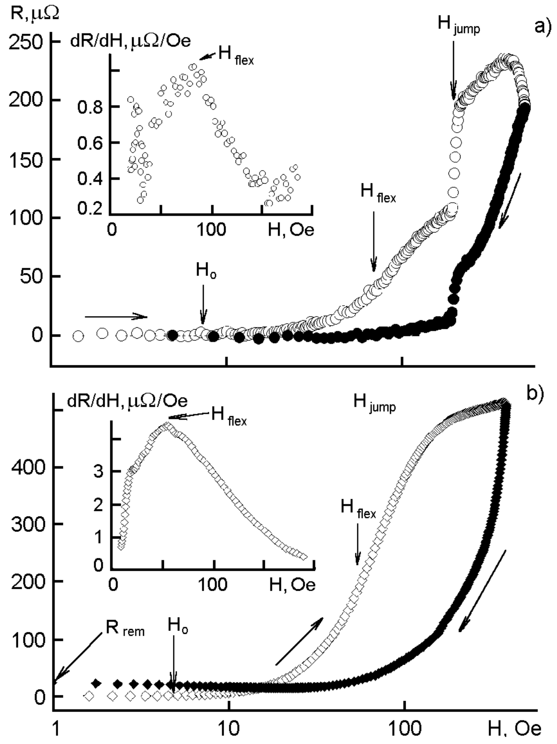

Fig. 1. Transverse magnetoresistance of HTSC $YBa_2Cu_3O_{\sim 6.95}$. The light dots stand for increasing of strength of the magnetic field H, the dark ones, for decreasing of H. The insets show the field relationships of the derivatives dR/dH in the vicinity of the field H_{flex}. Measuring current $I = 50$ mA (a). Measuring current $I = 250$ mA (b).

One must point out that at $H = H_{jump}$, $I/I_c = const$ the value of resistivity ρ of the samples of $YBa_2Cu_3O_{\sim 6.95}$ sways across relatively broad limits vs. a certain average value $\rho_{average}$ (Fig. 2). The distribution over frequencies $\rho/\rho_{average}$ (see, inset on Fig. 2)

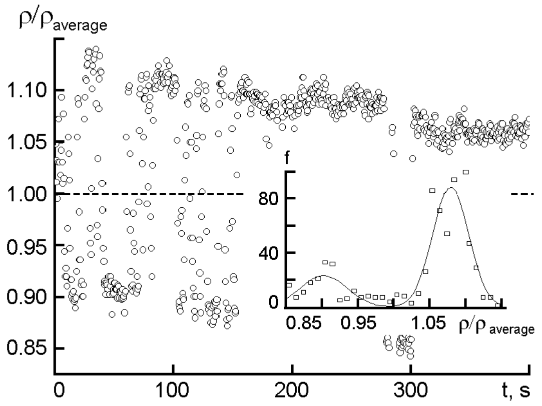

Fig. 2. Temporal dependence of transverse magnetoresistance of HTSC $YBa_2Cu_3O_{\sim 6.95}$ ($I \sim 0.1 \cdot I_c$, $H = H_{jump} = 201.5$ Oe). The inset shows frequency distribution of the value of $\rho/\rho_{average}$.

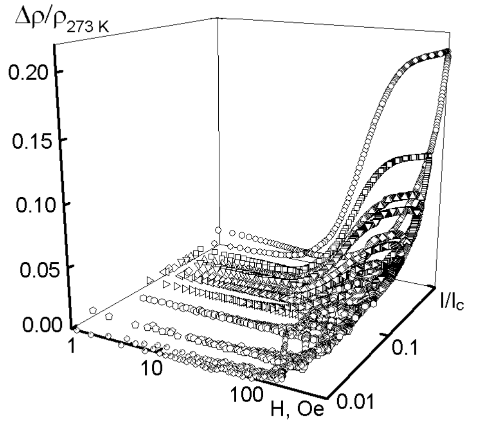

Fig. 3. Dependence of transverse magnetoresistance of HTSC sample $YBa_2Cu_3O_{\sim 6.95}$ on transport current.

turns out to have two clear-cut peaks corresponding to the "upper" and "lower" values of the resistance.

The differences in progression of the curves of $R_\perp(H)$ between the "strong" transport currents and "weak" currents are as follows:

— At the half-cycle "$0 \to H_{max}$", no magnetoresistance jumps are observable, yet, there is a tendency toward jumps appearing at the half-cycle "$H_{max} \to 0$",

— No peaks are observable on the curves of $R_\perp(H)$,

— While the magnetic field strength is falling, the resistance does not revert to zero, the curve of $R_\perp(H)$ displaying a peak and the zero field retaining the remnant resistance (R_{rem}) (the relaxation effects of R_{rem} are observable with the characteristic times 10^3–10^4 s).

The evolution of progression of the curves of the transverse magnetoresistance field relationships of HTSC $YBa_2Cu_3O_{\sim 6.95}$ is shown in Fig. 3 during variation of the transport current I in the given coordinates "$H - I/I_c - \Delta\rho/\rho_{273\ K}$". As the current I grows, the following tendencies are observed:

— Growth of the total magnetoresistance;

— Decreasing of the critical fields H_0^+, H_0^-, H_{flex}^+, H_{flex}^-;

— A very faint growth of the fields H_{jump}^+ and decreasing of the fields H_{jump}^-;

— A decreasing, followed actually by the total disappearance, occurs of the magnetoresistance jump on the curves $\Delta\rho_\perp/\rho_{273\ K}(H)$, while at the half-cycle "$H_{max} \to 0$",

— the magnetoresistance jumps are drastically shorter than at the half-cycle "$0 \to H_{max}$";

— Emergence and growth of the remnant resistance R_{rem}.

The dependence of the critical fields H_0, H_{flex}, H_{jump} and magnetoresistance jump in the field H_{jump} ($\delta\rho_{jump}/\rho_{273\ K}$) on I/I_c during increasing or decreasing of the magnetic field strength are shown in Fig. 4.

The evolution of progression of the longitudinal magnetoresistance curves of the HTSC $YBa_2Cu_3O_{\sim 6.95}$ during variation of the transport current I is given in Fig. 5 in the coordinates "$H - I/I_c - \Delta\rho/\rho_{273\ K}$". The relations of the critical fields H_0, H_{flex}, H_{jump} and magnetoresistance jumps $\delta\rho_{jump}/\rho_{273\ K}$ vs. I/I_c during increasing or decreasing of the magnetic field strength are shown in Fig. 6.

The relationships $\Delta\rho_{\parallel}/\rho_{273\ K}$ (H, I/I_c), as given in Fig. 5, are qualitatively similar to those for $\Delta\rho_\perp/\rho_{273\ K}$ (H, I/I_c), (see, Fig. 3.). As it is the case with $\mathbf{I}\perp\mathbf{H}$, $H_0^- >> H_0^+$, $H_{flex}^- > H_{flex}^+$, $\delta\rho_{jump}^+/\ \rho_{273\ K} > \delta\rho_{jump}^-/\rho_{273\ K}$. However, some *quantitative* variations take place:

— The total magnetoresistance level $\Delta\rho/\rho_{273\ K}$ at $\mathbf{I}\|\mathbf{H}$ is somewhat lower than at $\mathbf{I}\perp H$;

— The critical fields H_0 and H_{flex} are noticeably higher at $\mathbf{I}\|H$ than at $\mathbf{I}\perp H$;

— The magnetoresistance jumps in H_{jump} in the longitudinal magnetic fields

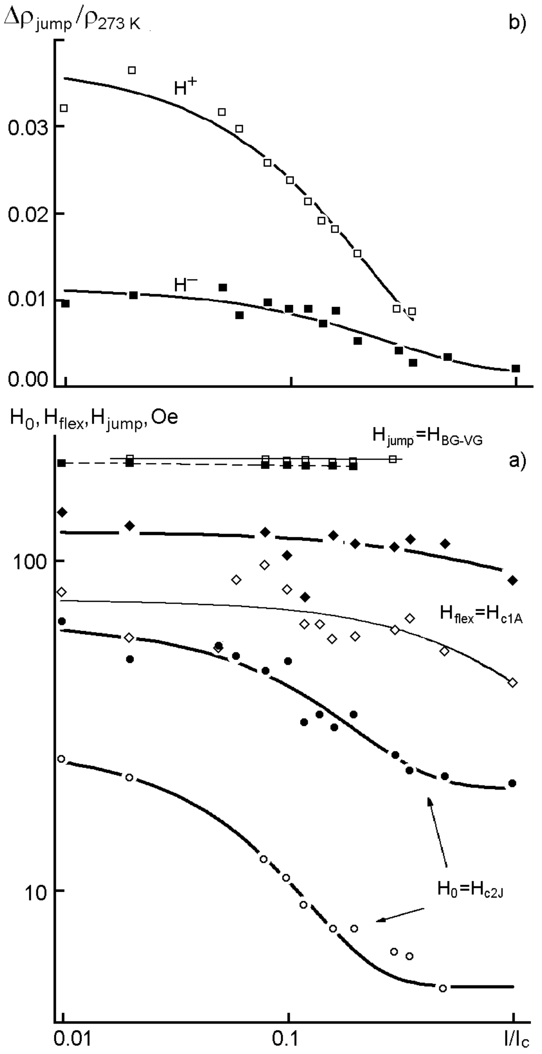

Fig. 4. Dependences of the critical fields H_0, H_{flex} and H_{jump} (a) and magnetoresistance jump $\delta\rho_{jump}/\rho_{273\ K}$ (b) on transport current. Transverse magnetoresistance. The light symbols stand for increasing H, the dark ones, for decreasing H.

are substantially shorter than they are in the transverse fields;

— As distinct from the situation with **I**⊥**H**, at **I**||**H**, the values of $\delta\rho_{jump}/\rho_{273\ K}$ keep growing during increasing of the transport current, they do not fall.

The results of measurement-takings of the transverse magnetoresistance $\rho_{\perp}/\rho_{273\ K}(H)$ for the HTSC $YBa_2Cu_3O_{\sim 6.95}$ are shown in Fig. 7 at the constant transport current value ($I/I_c \sim 0.05$) and variable values of the maximum magnetic field H_{max} in the coordinates "$H - H_{max} - \Delta\rho/\rho_{273\ K}$". In progression of the curves of $\Delta\rho_{\perp}/\rho_{273\ K}(H)$, depending on the value of H_{max}, the following regularities are observable:

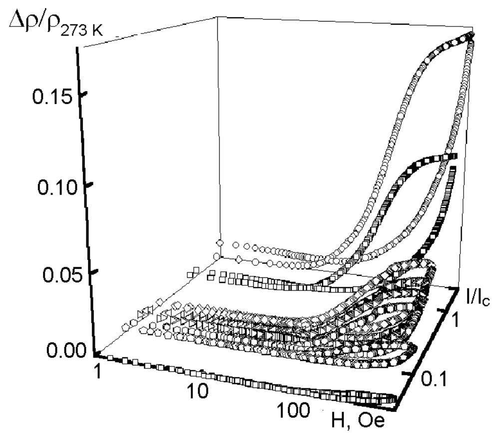

Fig. 5. Dependences of longitudinal magnetoresistance of HTSC $YBa_2Cu_3O_{\sim 6.95}$ vs. transport current.

— The hysteresis on the curves of $\rho_{\perp}/\rho_{273\ K}(H)$ appears at $H_{max} \geq \sim H^+_{flex}$, it is exactly at that moment that the distinctions between H^+_0 and H^-_0 appear;

— Upon achievement of the field $H_{max} \sim H^+_{jump}$ the curves of $\Delta\rho_{\perp}/\rho_{273\ K}(H)$ display jumps in the magnetoresistance during both increasing and decreasing of H.

The results of determination of the critical fields H^+_0, H^-_0, H^+_{flex}, H^-_{flex}, H^+_{jump} and H^-_{jump} and jumps of the transverse magnetoresistance $\delta\rho^+_{jump}/\rho_{273\ K}$, $\delta\rho^-_{jump}/\rho_{273\ K}$ in the fields H^+_{jump} and H^-_{jump} vs. H_{max} are shown in Fig. 8.

The values H^+_0, H^+_{flex}, H^+_{jump} and $\delta\rho^+_{jump}/\rho_{273\ K}$ are, quite naturally, independent of the field H_{max}. At the half cycle "$H_{max} \to 0$", the critical field H^-_0 increases with increasing H_{max} (at $H_{max} \geq \sim H^+_{flex}$), while the jump of magnetoresistance in the field H^-_{jump} ($\delta\rho^+_{jump}/\rho_{273\ K}$) drops off. The critical field $H^+_{jump} > H^-_{jump}$.

On the whole, similar data was obtained for the longitudinal magnetoresistance, as well $\Delta\rho_{||}/\rho_{273\ K}(H)$.

Discussion

Evidently, the following results must be the subject-matter for discussion:

1. The presence of major differences in the magnetoresistance value of the granular

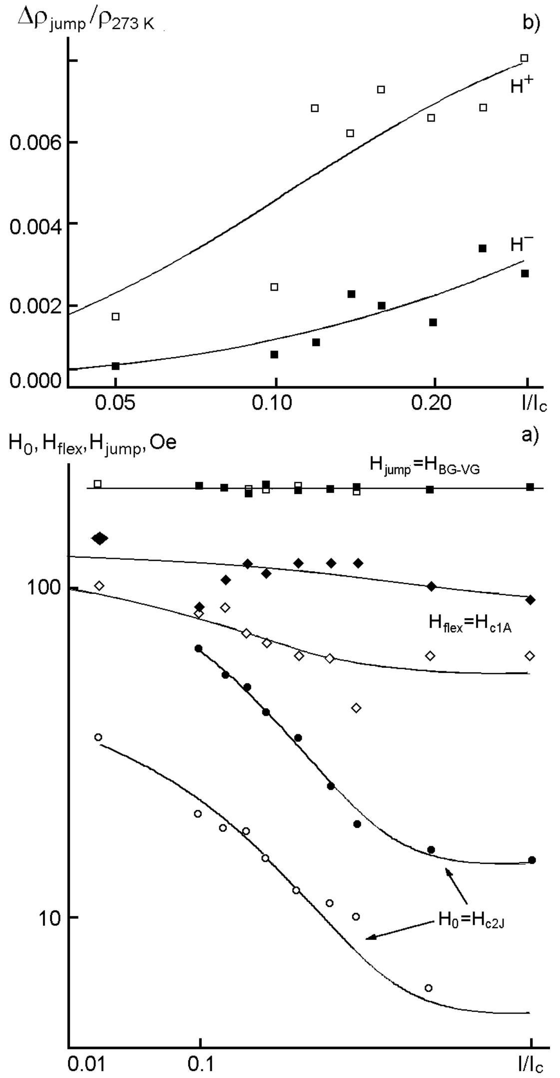

Fig. 6. Dependences of the critical fields H_0, H_{flex} and H_{jump} (a) and magnetoresistance jump $\delta\rho_{jump}/\rho_{273\ K}$ (b) vs. transport current. Longitudinal magnetoresistance. The light symbols stand for increasing H, the dark ones, for decreasing H.

HTSC $YBa_2Cu_3O_{7-\delta}$ between increasing and decreasing of the applied magnetic field strength, the hysteresis of magnetoresistance;

2. Appearance of the off-zero magnetoresistance in the vicinity of the critical fields H_0;

3. Presence of the dependence of the value of the critical fields H_0 on transport current density and preceding magnetic history;

4. Anisotropy of magnetoresistance and alignment dependence of the critical field value;

5. Appearance of anomalies in the field relations of magnetoresistance in the vicinity of the critical fields H_{flex};

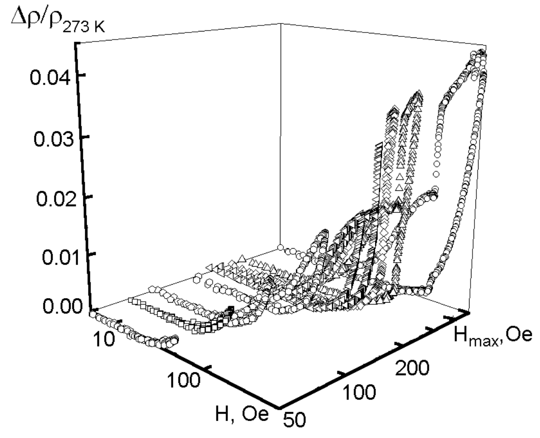

Fig. 7. Dependence of transverse magnetoresistance of HTSC $YBa_2Cu_3O_{\sim 6.95}$ at $I/I_c \sim 0.05$ vs. maximum magnetic field strength H_{max}.

6. Appearance of the magnetoresistance jumps in the magnetic fields H_{jump}, the dependence of the value of the magnetoresistance jumps on transport current density, cross-orientation of the vectors **H** and **I** and preceding magnetic history.

Before broaching the subject of the nature of the phenomenon of appearance of the hysteresis of magnetoresistance of the HTSC $YBa_2Cu_3O_{7-\delta}$ [hysteresis of magnetoresistance is observable only in the applied magnetic fields $H \geq H^+_{flex}$; the nature of the critical fields H_{flex} will be considered below (Article 4.5)], let us note that each cycle of the measurements taken according to the scheme "$0 \to H_{max} \to 0$" included actually two types of samples:

— At the half-cycle "$0 \to H_{max}$", the samples that are cooled down in the absence of the magnetic field (ZFC) can capture the magnetic flow during increasing of the applied magnetic field strength $H(H^+)$;

— At the half-cycle "$H_{max} \to 0$", the samples carry the magnetic flow captured by the weak links (at $H_{max} > H_{c1J}$) and/or by superconducting granules (at $H_{max} > H_{c1A}$).

This stands to mean that the internal magnetic field of the sample (H_i) for applied fields H^+ and H^- can be different. In other words, the measurable cycle "$0 \to H_{max} \to 0$" has variation occurring in it of the density and geometry of the distribution of the Josephson and/or Abrikosov vortices, as regards the HTSC sample.

The sufficiently correct calculation of the internal fields H_i is known to be possible in two ultimate cases:

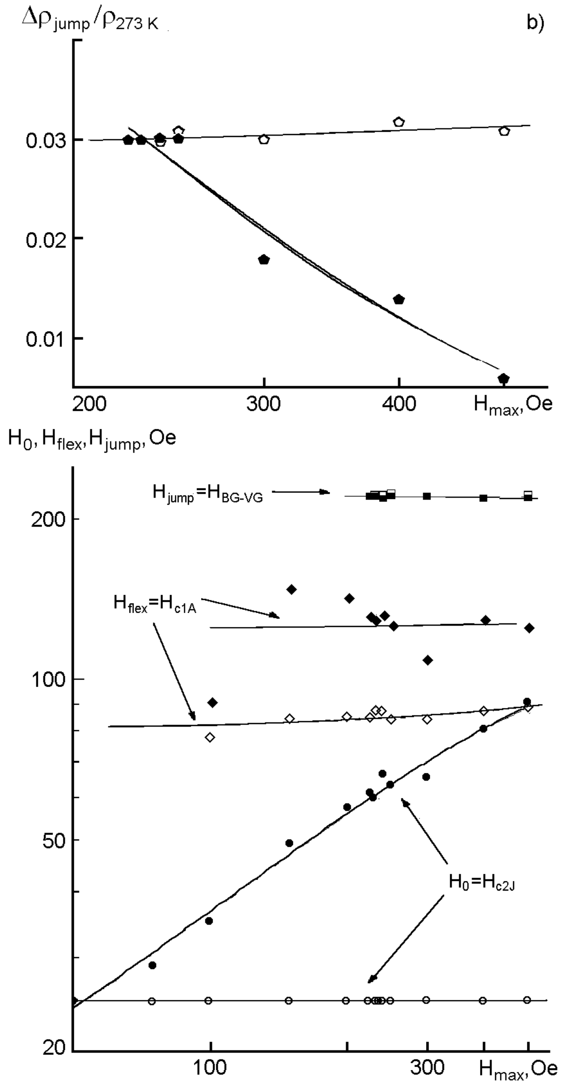

Fig. 8. Dependences of the critical fields H_0, H_{flex} and H_{jump} (a) and magnetoresistance $\delta\rho_{jump}/\rho_{273\ K}$ at $I/I_c \sim 0.05$ (b) vs. strength of maximum magnetic field H_{max}. Transverse magnetoresistance. The light symbols stand for increasing H, the dark ones, for decreasing H.

1. The material is in the Meissner state (the magnetic susceptibility $\chi = const = -1/4\pi$):

$$H_i = \frac{H^+}{1 - D^+}, \quad (1)$$

where D^+ — the effective de-magnetizing factor for the field H^+;

2. The granules of ceramic HTSC are permeated inside out with magnetic vortices making the determination of the superconductor magnetization M feasible within the framework of the critical state model (see, for example, [23–25]):

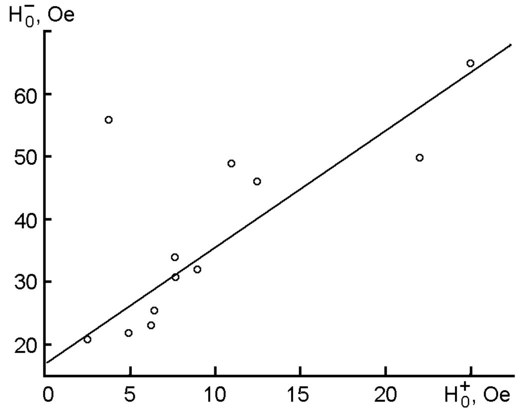

Fig. 9. Dependence of fields $H_0^-(H_{c2J}^-)$ on fields $H_0^+(H_{c2J}^+)$.

$$H_i = H^- - D^- \cdot 4\pi \cdot M, \quad (2)$$

where D^- — the effective demagnetizing factor for the field H^-.

As it is known [18], the values of applied growing (H^+) and diminishing (H^-) magnetic fields that correspond to the internal (summed-up) magnetic fields H_i are interconnected via linear relationships of the type

$$H^- = (-D^+H_{c1} + AD^-) + \frac{1}{1 - D^+}H^+, \quad (3)$$

where H_{c1} — the lower critical field (H_{c1J} or H_{c1A}), A — the constant.

Quite obviously, the presence of such correlation between the applied fields H^+ and H^- must result in the appearance, as well, of a certain correlation among the critical fields H_0^+ and H_0^-, H_{flex}^+ and H_{flex}^-, H_{jump}^+ and H_{jump}^-, respectively. This kind of correlation really occurs: considering the example in Fig. 9, there is the presence of explicit linear connection of the fields H_0^+ and H_0^-, as obtained during measurement-takings of the transverse magnetoresistance.

Judging by the values of the critical fields H_0 at minimal values of the transport current density ($H_0 \sim$ 20–40 Oe), the emergence of the off-zero magnetoresistance in the granular HTSC $YBa_2Cu_3O_{7-\delta}$ cannot be associated with the onset of the process of magnetic field penetration into the weak links, the respective critical fields H_{c1J} being extremely low at the liquid nitrogen temperature (see, for example [26, 27]). On the other hand, the values of H_0 obtained in this work at low values of the currents (I/I_c) are relatively close to the known values of fields of the total magnetic flow penetration into the weak links (H_{c2J}) of the HTSC $YBa_2Cu_3O_{7-\delta}$, which were determined using the magnetic and other techniques (see, for example [14, 26, 28]). All of this gives ample ground to believe that the critical field $H_0 \equiv H_{c2J}$.

The observable effects of a steep fall of the upper critical fields of the weak links H_{c2J} and increasing of magnetoresistance during increasing of the transport current I (see, Fig. 5, 7) must be accounted for by a partial transition of the weak links into the resistive state under the impact of the electric field [29]. In view of the existent representations [30], the conditions for transition of individual weak link into the resistive state are altogether determined by the local magnetic field values H_{local} (the field H_{local} is superposition of the applied magnetic field H_{ext} and demagnetization fields H_{demagn}, as they are created by adjacent superconducting grains) and local current density j_{local}.

The dependence of local current density vs. local magnetic field strength comes out as follows [30]:

$$j_{local} = j_{local,0} \cdot \frac{H^*}{\pi \cdot H_{local}}, \qquad (4)$$

where $j_{local,0}$ — the value of local current density in the absence of magnetic field, H^* — the parameter that is dependent on the granular superconductor microstructure.

The critical local magnetic field value must be as follows $H_{local} = H_{c2J}$. In this case, it follows from the equation (4) that:

$$H_{c2J}(j_{local}) = H^* \cdot \frac{J_{local,0}}{\pi \cdot j_{local}}. \qquad (5)$$

The general nature of the relationships $H_{c2J}(I)$, — a downward leap of the critical field during transport current growth, — agrees, on the whole, with the equation (5). The deviations from hyperbolic nature of the curve $H_{c2J}(I)$ may well have to do with such circumstance that the condition $I \sim j_{local}$ that provides for fulfillment of the equation (5) is true only with the normal distribution of the local current densities in ceramic HTS samples of $YBa_2Cu_3O_{7-\delta}$; the function of local current distribution in the ceramics, as it is believed, does have the exponential character [31].

The dependence of the critical current H_{c2J} on "magnetocycling depth" (H_{max}), i.e. in essence on the value of applied magnetic field at $I = const$, is without a shade of doubt accounted for by the same cause, destruction of the "weak links" under the impact of magnetic fields. However, we deal here with the *direct* action of applied magnetic field, not a field created by transport currents.

As stated above (see, Article 3.b.), the magnetoresistance field relationship curves of the HTSC $YBa_2Cu_3O_{7-\delta}$ in the transverse and longitudinal applied magnetic fields are distinctly different. It is known that in accordance with the existent representation [32] that goes down to the Bardeen-Stephen model [33], the dependence of magnetoresistance on the transport current I, applied magnetic field strength H and angle θ between the vectors **I** and **H** looks like as follows:

$$\frac{\Delta\rho}{\rho} = A + B \cdot I + C \cdot H \cdot \sin^2\theta, \qquad (6)$$

where A, B and C — the constants.

As noted above, the total level of magnetoresistance in the transverse magnetic fields is, considering that all the other conditions are equal, higher than in the longitudinal fields, which agrees with theory qualitatively. The basic differences, although, concern not so much the progression of the curves $\Delta\rho/\rho_{273\ K}(H)$, as the appearance of the anisotropy of the critical fields H_0, H_{flex} and H_{jump}. The most prominent effects are those of the anisotropy of the critical fields of the weak links H_0 (H_{c2J}).

The emergence of the alignment dependence of the critical fields H_{c2J} [$H_{c2J}(\mathbf{I} \perp \mathbf{H}) \neq H_{c2J}(\mathbf{I} \| \mathbf{H})$] can be explained by a number of factors: essential differences in the demagnetization fields H_{demagn} with variable geometry of the experiment, considerable differences of granule sizes along and across the ceramic samples of the HTSC $YBa_2Cu_3O_{7-\delta}$, presence of the texture of the basal plane (see above), etc.

It is quite possible that the main cause for the anisotropy of the critical field weak links H_{c2J} is the presence of the crystallographic texture of samples, i.e. as regards the situation considered:

— Different orientation of the applied magnetic field strength vector **H** vs. intergrain contacts, "weak links",

— Differences in the critical parameters of the weak links themselves depending on its alignment relative to the crystallographic axes of superconducting granules ("weak link hierarchy" [26]),

— Presence of an alignment dependence j_{local} [30], etc.

The variation of the nature of the relationships $\Delta\rho/\rho_{273\ \mathrm{K}}(H)$ near the critical values H_{flex}, appearance of bends on the curves, all is indicative of appearance of a new (strong enough) magnetoresistance mechanism. It is obvious that this mechanism is associated with the onset of magnetic flow penetration in the superconducting granules of HTSC $\mathrm{YBa_2Cu_3O_{7-\delta}}$, i.e. with appearance in the superconductor of the Abrikosov vortices.

Another way around, all the reasons are there to believe that the critical field $H_{flex} \equiv H_{c1A}$.

Of no less significance is the following circumstance: the obtained values of the field $H_{flex}(H_{c1A})$ (especially at the half-cycle "$H_{max} \to 0$") have relatively weak dependence on the transport current I and cross-orientation of the vectors **H** and **I**. At the same time, it is known well that the direct measurements of the field H_{c1A} on single crystals of $\mathrm{YBa_2Cu_3O_{7-\delta}}$ indicate the presence of a relatively strong anisotropy (see, for example [34–37]). Obviously, during the measurement-takings of magnetoresistance, the bends on the curves of $\Delta\rho/\rho_{273\ \mathrm{K}}(H)$ correspond to the *minimal value* of the field H_{c1A}, i.e. the lower critical field of the superconducting granules on the basal plane **ab** of the orthorhombic lattice H_{c1A}^{ab}.

Discovered, probably, for the first time in this work were plain anomalies on the curves of the field relationship of the magnetoresistance $\Delta\rho/\rho_{273\ \mathrm{K}}(H)$ of the HTSC ceramic materials $\mathrm{YBa_2Cu_3O_{7-\delta}}$ at $H_{jump} > H_{c1A}$, i.e. jumping variation of the transport properties in the magnetic field (we deal with a jump of resistance in weak magnetic fields; similar phenomena had earlier been observable in single crystals of $\mathrm{YBa_2Cu_3O_{7-\delta}}$ near T_c in the fields **H**||**c** with the strength $H \sim 2–6$ T and were attributed to fusion of the vortex lattice [38]), which attests, above all, to the phase transition of the first kind "over magnetic field" [the most solid arguments in favor of this kind of transition is appearance of the *hysteresis* of the phase transition "over magnetic field" ($H^{+}_{jump} > H^{-}_{jump}$) and presence of the phenomenon of *coexistence* of the high- and low-field phases at $H = H_{jump}$, $I = const$].

Note that in the interval I/I_c, in which these jumps were observable, in any case at **I**⊥**H**, with $H > H_{jump}$, peaks appeared on the relationships $\Delta\rho/\rho_{273\ \mathrm{K}}(H)$. Obviously, those two phenomena were associated with the character of the vortex structure in the superconducting granules. With that, it should be borne in mind that the phenomena are observable on granular (ceramic) samples of the HTSC, i.e. on objects with defective crystal lattice, while at $H_{jump} > H_{c1A}$ they are so with the known imperfect vortex lattice (state of the Bragg glass [39]).

An assumption can be made that the jumps of magnetoresistance of the ceramic HTSC $\mathrm{YBa_2Cu_3O_{7-\delta}}$ in weak magnetic fields are associated with variation of the vortex structure, i.e. with the theoretically predicted [39–41] phase transition of the first kind "Bragg glass-vortex glass (BG-VG). A characteristic feature of the BG-VG phase transition is a jumping decreasing of the critical current I_c along the axis **c** and increasing of I_c on the basal plane **ab** [42]. The phenomenon of jumping growth of $\Delta\rho/\rho_{273\ \mathrm{K}}$ found in this paper with increasing of H is indicative of a decreasing of the critical current (decreasing by jumps of I_c by several times at $H \sim H_{jump}$ was observed experimentally while taking measurements of $I_c(H)$).

The tendency toward appearance of the magnetoresistance peak at $H > H_{jump}$ that is transformed into a "plateau" on the relationships $\Delta\rho/\rho_{273\ \mathrm{K}}(H)$ at high transport current densities can be associated with decreasing of the pinning force as a result of the creation of the vortex glass phase.

In this way, there are sound reasons to believe that the field $H_{jump} \equiv H_{BG\text{-}VG}$.

The very fact that the lines of the BG-VG phase transitions in I-H-diagrams drop off at $I/I_c > \sim 0.3–0.4$, while the magnetoresistance jumps diminish noticeably at **I**⊥**H** with increasing of I/I_c or H_{max}, is indicative of the fact that the difference between BG- and VG-phases are smoothed out with increasing current, the phase transition BG-VG being terminated at the critical point.

Note that both the value of magnetoresistance jumps in H_{jump} ($H_{\mathrm{BG\text{-}VG}}$) and character of the dependence of this value vs. current (I/I_c) and "magnetocycling depth" (i.e. the field H_{max}) depend considerably on the cross-orientation of the vectors **I** and **H**, and in the case of **I** || **H**, the magnetoresistance jumps are several times as small as in the case of $\mathbf{I} \perp \mathrm{H}$, their value increasing, not vice versa, at the growth of I/I_c; the magnitude of the jumps does not depend on the field H_{max}, not increasing at the growth of this field. The underlying nature of these phenomena is still obscure.

Conclusions

The major results of the experimental study of the transverse and longitudinal magnetoresistance of ceramic HTSC samples of $\mathrm{YBa_2Cu_3O_{7-\delta}}$ in weak magnetic fields should be considered as follows:

— Discovery of jumping variation of magnetoresistance in magnetic fields H_{jump};

— Establishment of the nature of hysteresis of magnetoresistance: the differences in progression of the relation of $\Delta\rho/\rho(H)$ at increasing or decreasing of the applied magnetic field strength;

— Discovery of the presence of an alignment dependence of the value of magnetoresistance and critical fields of weak links and superconducting granules (H_{c2J}, H_{c1A} and H_{jump});

— Discovery of the presence of a dependence of the value of the critical fields of weak links and superconducting granules H_{c2J}, H_{c1A} and H_{jump} vs. transport current density and preceding magnetic history.

The authors express their gratitude to Prof. V.A. Shklovskij for his invaluable discussions.

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Магнітоопір гранульованого високотемпературного надпровідника $YBa_2Cu_3O_{7-\delta}$ у слабких магнітних полях

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Експериментально вивчено поперечний і подовжній магнітоопір $\Delta\rho/\rho_{273\ K}(H)$ керамічних зразків високотемпературного надпровідника $YBa_2Cu_3O_{7-\delta}$ при $T = 77.3$ K у магнітних полях $0 \le H \le 500$ Oe. Виявлено ефект стрибкоподібної зміни магнітоопору у магнітних полях $H = H_{jump}$, пов'язаний з перебудовою вихрової структури. Показано, що польова залежність магнітоопору носить гістерезисний характер. Виявлено наявність орієнтаційної залежності величини магнітоопору і критичних полів слабких зв'язків і надпровідних гранул (H_{c2J}, H_{c1A} і H_{jump}) і залежності величини критичних полів H_{c2J}, H_{c1A} і H_{jump} від щільності транспортного струму і магнітної передісторії.