

Galvanomagnetic properties of superconducting granules and grain boundaries in ceramic $YBa_2Cu_3O_{7-\delta}$ high-temperature superconductor

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The objective of the work is to reveal the contribution of superconductive granules and grain boundaries (weak links) in magnetoresistance ρ value of $YBa_2Cu_3O_{7-\delta}$ granular high-temperature superconductor (HTS) at $T < T_c$. The current-voltage characteristics (CVCs) $E(j)_{Hext=\mathrm{const}}$ of $YBa_2Cu_3O_{6.95}$ ceramic samples were measured in $\mathbf{H}_{ext}$ ($0 \le H_{ext} \lessapprox 500$ Oe) magnetic fields. The CVCs $E(j)_{Htrap=\mathrm{const}}$ of the samples magnetized in $\mathbf{H}_{treat}$ magnetic fields were measured at $H_{ext} = 0$. Based on the CVCs, $\rho(j)_{Hext=\mathrm{const}}$, $\rho(H_{ext})_{j=const}$ and $\rho(j)_{Htreat=\mathrm{const}}$ dependences were reestablished. The comparative analysis of $\rho(j)_{Hext=\mathrm{const}}$ and $\rho(H_{ext})_{j=const}$ dependences indicates the magnetic field redistribution between grain boundaries and superconductive granules influence on transport and galvanomagnetic properties of granular HTS. The superconductive grain magnetoresistance ρ_g was established to be significantly lower than ρ_J value of Josephson medium.

Исследован вклад сверхпроводящих гранул и межзеренных границ — слабых связей в магнитосопротивление ρ гранулярного высокотемпературного сверхпроводника (ВТСП) $YBa_2Cu_3O_{7-\delta}$ при $T < T_c$. Вольтамперные характеристики (ВАХ) $E(j)_{Hext=\mathrm{const}}$ керамических образцов $YBa_2Cu_3O_{6.95}$ измерены в магнитных полях $\mathbf{H}_{ext}$ ($0 \le H_{ext} \lessapprox 500$ Oe). При $H_{ext} = 0$ измерены ВАХ $E(j)_{Htrap=\mathrm{const}}$ образцов, намагниченных в магнитных полях $\mathbf{H}_{treat}$ ($0 \le H_{trap} \le H_{c2J}$, где H_{c2J} — верхнее критическое поле джозефсоновских слабых связей). На основании ВАХ восстановлены зависимости $\rho(j)_{Hext=\mathrm{const}}$, $\rho(H_{ext})_{j=const}$ и $\rho(j)_{Htrap=\mathrm{const}}$. Сравнительный анализ зависимостей $\rho(j)_{Hext=\mathrm{const}}$ и $\rho(H_{ext})_{j=const}$ свидетельствует о влиянии процесса перераспределения магнитного поля между границами зерен и сверхпроводящими гранулами на транспортные и гальваномагнитные свойства гранулярных ВТСП. Установлено, что магнитосопротивление ρ_g сверхпроводящих зерен значительно меньше, чем магнитосопротивление ρ_J джозефсоновской среды ρ_J.

1. Introduction

It is well known that transport and galvanomagnetic properties of granular high-temperature superconductors (HTS) can be adequately described in the framework of the critical state two-level model [1, 2]. In this model, the granular HTS is considered as an assembly of granules with strong superconductivity and intergranular boundaries forming Josephson weak links. The superconductivity parameters of granules (g) and weak links (J), namely, critical temperature T_c, lower H_{c1} and upper H_{c2} critical fields, and critical currents j_c, are different: $T_{cJ} \le T_{cg}$, $H_{c1J} << H_{c1g}$, $H_{c2J} << H_{c2g}$, $j_{cJ} << j_{cg}$.

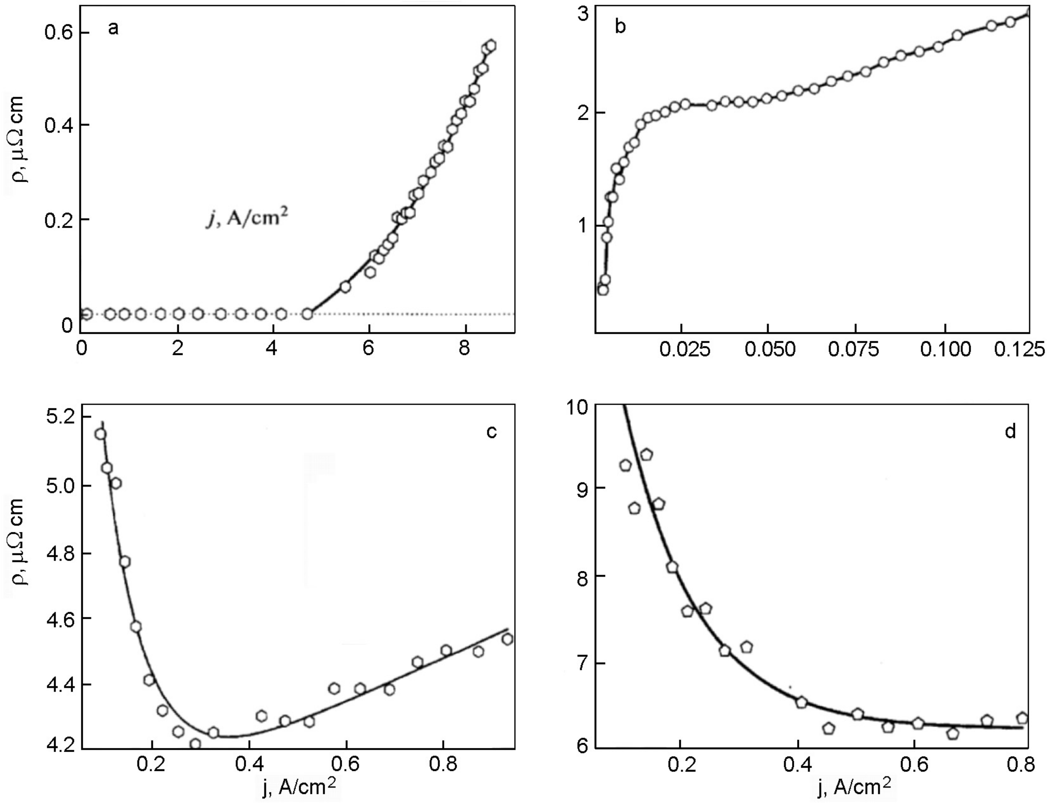

Fig. 1. Dependences of the magnetoresistance of the granular $YBa_2Cu_3O_{6.95}$ high-temperature superconductor sample on the transport current density at T = 77.3 K. a) $0 < H_{ext} = 10.41$ Oe $< H_{c2J}$; b) $H_{c2J} < H_{ext} = 55.24$ Oe $< H_{c1g}$; c) $H_{ext} = 107.39$ Oe $\approx H_{c1g}$; d) $H_{ext} = 153.81$ Oe $> H_{c1g}$.

Experimental studying of the galvanomagnetic properties of granular HTS, i. e., magnetoresistance $\rho(H_{ext})_{j=const}$ and current-voltage characteristics (CVCs) in an external magnetic field, $\mathbf{H}_{ext}$ $E(j)_{Hext=\mathrm{const}}$, where E is electrical field value applied to a sample, contributes much into HTS electrodynamics development. A lot of works were devoted to galvanomagnetic properties of granular HTS, in particular, $YBa_2Cu_3O_{7-\delta}$ (see, for example, [3–19]). The following characteristic peculiarities were observed in the $E(j)_{Hext=\mathrm{const}}$ [$\rho(H_{ext})_{j=const}$] curves [20–23]:

— existence of the beginning parts with zero resistance [$E = 0$ ($\rho = 0$)];

— appearance of resistance [$E \neq 0$ ($\rho \neq 0$)] at $j > j_{cJ}(H_{ext})$ or $H_{ext} > H_{c2J}(j)$;

— changing the curvature at $H_{ext} >> H_{c2J}(j)$.

The objective of the current work is to reveal the contribution of superconductive granules and weak links into magnetoresistance of $YBa_2Cu_3O_{7-\delta}$ granular HTS in low magnetic fields. To achieve the objective, galvanomagnetic properties were studied at $T < T_c$ according to the two following algorithms:

1. In *external* transversal magnetic fields $\mathbf{H}_{ext}$ ($0 \leq H_{ext} \lesssim 500$ Oe), the $E(j)_{Hext=\ \mathrm{const}}$ (T = 77.3 K) CVCs were measured, on which base the dependences $\rho(j)_{Hext}$=const and $\rho(H_{ext})_{j=const}$ were reestablished.

2. For the samples magnetized at T = 77.3 K in magnetic fields $\mathbf{H}_{treat}$ ($0 \leq H_{treat} \lesssim 500$ Oe) the $E(j)_{Htheat=\mathrm{const}}$ CVCs were measured at $H_{ext} = 0$, on which base the dependences $\rho(j)_{Htreat=\mathrm{const}}$ and $\rho(H_{treat})_{j=const}$ were reestablished in the range $0 \leq H_{trap} \leq H_{c2J}$, where $\mathbf{H}_{trap}$ is the trapped magnetic field.

2. Samples, experimental technique, and results treatment

HTS samples of $YBa_2Cu_3O_{6.95}$ composition, synthesized by routine ceramic technology [24] were the objects of the study. Superconductivity transition mid-point temperature, $T_c^{1/2}$, was 92.5±0.1 K, the transition width, $\Delta T_c \approx 0.4$ K, and electrical resistivity, $\rho_{273\ K} \approx 4\ 000$ μΩcm.

The measurement technique using both algorithms was described earlier [15–18, 20–25].

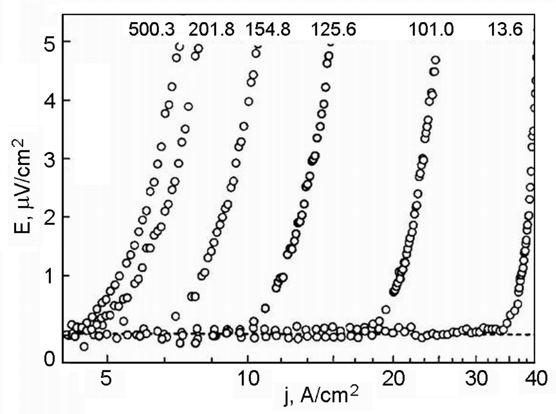

Fig. 2. Current-voltage characteristics $E(j)_{Htreat=\mathrm{const}}$ for the granular $YBa_2Cu_3O_{6.95}$ high-temperature superconductor sample preliminarily magnetized at T = 77.3 K in the transverse magnetic field $\mathbf{H}_{treat}$ of variable strength. Numbers near the current-voltage curves are the values of the field H_{treat} (given in oersteds).

As it is known (see, for example, [26, 27]), for granular HTS with random distribution of inter-granular critical currents in relatively low magnetic fields, $\rho(j)_{H=const}$ dependence shows exponential character

$$\rho(j)_{H_{ext}=const} = \rho_0 + a \cdot e^{-(j - j_c)/t}. \quad (1)$$

The measurements results of $\rho(j)_{H=const}$ in external magnetic fields, $\mathbf{H}_{ext}$, were treated by the following scheme:

— on the basis of $\rho(j)_{Hext=\mathrm{const}}$ dependences, approximate j_c values were found according to $\rho = 0$ criterion;

— the values of ρ_0, a, and t parameters for Eq. (1) were calculated;

— by the method of functional minimization, ρ_0, a, and t parameters for Eq. (1) were refined;

— on the basis of $\rho(j)_{Hext}$=const data file obtained, the curves of magnetoresistance versus external magnetic field $\rho(H_{ext})_{j=const}$ were reestablished.

The treatment procedure of CVCs obtained at $H_{ext} = 0$ for the samples pre-magnetized in $\mathbf{H}_{treat}$ magnetic fields does not differ in principle from the one described above.

3. Experimental results

3.1. Magnetoresistance in external magnetic fields H_{ext}

In Fig. 1 $\rho(j)_{Hext=\mathrm{const}}$ curves obtained at $0.1 \le j \le 0.6$ A/cm^2 are shown. As it can be seen, the curves are qualitatively different in different ranges of H_{ext}–j_c phase diagram:

In the range of $0 < H_{ext} < H_{c2J}$ (see Fig. 1a), an extended part with $\rho = 0$ and the part of ρ exponential rise with j increasing are observed. The results are described adequately by Eq. (1) with a correlation coefficient $r^2 \to 1$.

In the range of $H_{c2J} < H_{ext} < H_{c1g}$ (see Fig. 1b), only a "virtual" part with $\rho = 0$ at $j \approx 0$ is observed, followed by a smeared resistance jump. The following $\rho(j)$ curve behavior is described satisfactory by Eq. (1).

In the vicinity of H_{c1g} (see Fig. 1c), the $\rho(j)_{Hext=\mathrm{const}}$ curve consists of two branches — a "normal" one where ρ increases with j rising, and "anomalous" one, where ρ drops with j growth.

At $H_{ext} > H_{c1g}$ (see Fig. 1d), $\rho(j)_{Hext=\mathrm{const}}$ curve gets the distinctly expressed anomalous character — the resistance decreases with growing j.

3.2. Magnetoresistance under entrapped fields, H_{trap}

In Fig. 2, typical $E(j)_{Htreat=\mathrm{const}}$ CVCs are shown for $YBa_2Cu_3O_{6.95}$ HTS samples magnetized under $\mathbf{H}_{treat}$ fields. All the curves have a similar character — there are initial parts with $E = 0$ and the parts of exponential E increase with j rise. As H_{treat} increases, $E(j)_{Htreat=\mathrm{const}}$ curves shift to lower j values, while the curve non-linearity substantially increases.

The obtained $E(j)_{Htreat=\mathrm{const}}$ CVCs were "transformed" into $\rho(j)_{Htreat=\mathrm{const}}$ curves (Fig. 3). The curves were described satisfactory by exponential Eq. (1) for $r^2 \ge 0.95$.

4. Discussion

4.1. Dissipation processes in weak links

The results of $\rho(j)_{Hext=\mathrm{const}}$ curves evolution described in 3.1 indicate a possibility of various dissipation mechanisms to exist. In Fig. 4, the field dependences of ρ_0, a, and t parameters from Eq. (1) are shown. On the basis of these results, the following conclusions can be done:

1. The high non-linearity degree of $\rho(j)_{Hext=\mathrm{const}}$ curves ($t >> 0$) at $0 \le H_{ext} < H_{c1g}$ is an obvious feature of magnetic field penetration as Josephson vortices into weak links system [28].

2. Magnetoresistance occurrence at $H_{c2J} < H_{ext} < H_{c1g}$ ($\rho_0 > 0$, $a > 0$) is connected

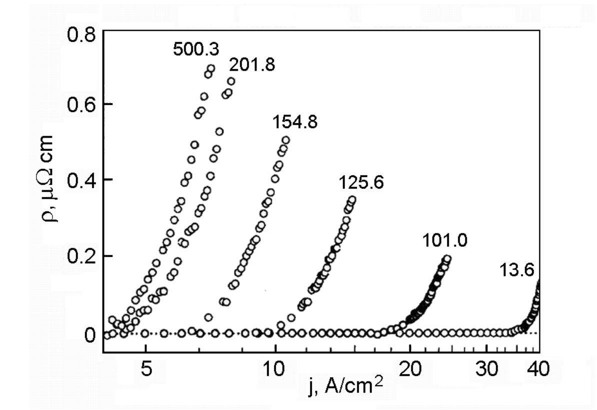

Fig. 3. Dependences $\rho(j)_{Htreat=\mathrm{const}}$ for the granular $YBa_2Cu_3O_{6.95}$ high-temperature superconductor sample preliminarily magnetized at T = 77.3 K in the transverse magnetic field $\mathbf{H}_{treat}$ of variable strength. Numbers near the curves are the values of the field H_{treat} (given in oesterds).

exclusively with dissipation processes in Josephson medium. The fact, the "nonlinearity parameter" $t \neq 0$, indirectly supports the suggestion, that at $H_{ext} = H_{c2J}$ not all the weak links transfer into resistive state, but only there comes to end the process of breaking-up all percolation paths for superconductive current passage.

3. The drastic change of $\rho_0(H_{ext})$, $a(H_{ext})$, and $t(H_{ext})$ curves behavior at $H_{ext} \approx H_{c1g}$ ($\rho_0 > 0$, $a > 0$, $t \approx 0$) indicates that due to beginning Abrikosov vortices penetration into the superconductive granules the magnetic flux re-distribution begins between weak links and superconductive granules [12–14, 29], resulting in decreasing the effective magnetic field in inter-granular boundaries with j increasing.

4. The anomalous character of $\rho(j)_{Hext=\mathrm{const}}$ curves at $H_{ext} > H_{c1g}$ (see Fig. 1d) is obviously caused by following decreasing the intergranular field density and penetrating Abrikosov vortices into superconductive granules.

4.2. Dissipation processes in superconductive granules

On the basis of $\rho(j)_{Htreat=\mathrm{const}}$ curves (see Fig. 3) for $YBa_2Cu_3O_{7-\delta}$ HTS samples, the magnetoresistance field $\rho(H_{treat})_{j=const}$ dependences were calculated (Fig. 5).

Obviously, $\rho(H_{treat})_{j=const}$ curve behavior should be defined by the character of the entrapped field effect onto the current passage through superconductive granules. In this connection, first of all the following three effects should be subject of the discussion:

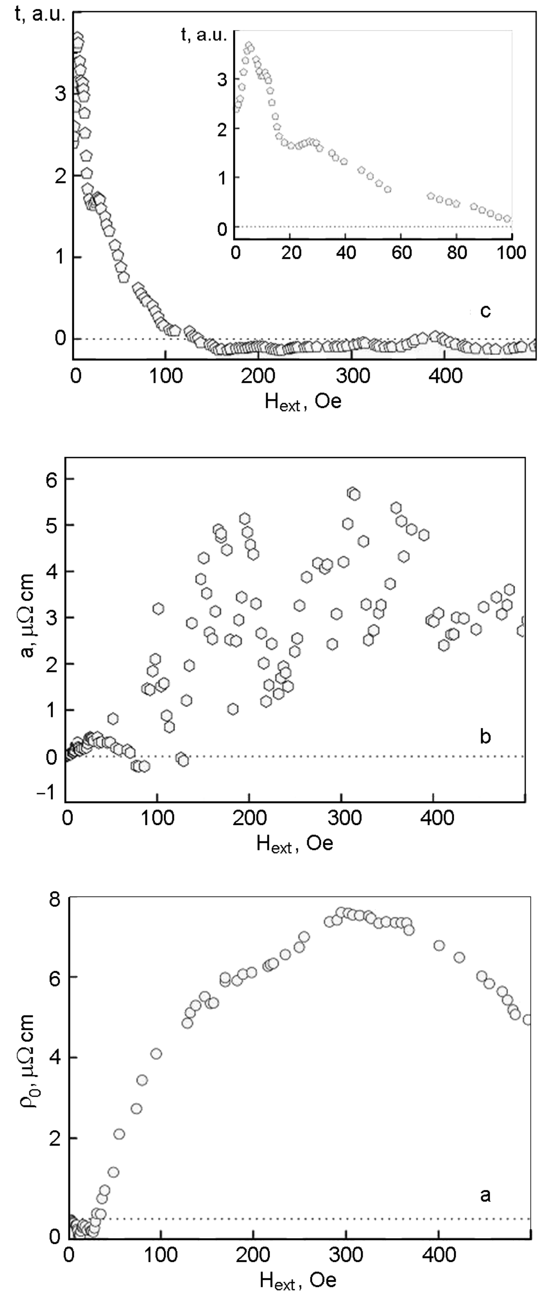

Fig. 4. Dependences of the parameters (a) ρ_0, (b) a, and (c) t in Eq. (3) on the external magnetic field strange $\mathbf{H}_{ext}$ for the granular $YBa_2Cu_3O_{6.95}$ high-temperature superconductor sample at T = 77.3 K. The inset shows the dependences t (H_{ext}) in the range of weak magnetic fields.

1. Extremely low magnetoresistance values of superconductive granules. The effect is caused by very low entrapped magnetic field, H_{trap}, values.

2. Existing a trend of granule magnetoresistance field dependences, $\rho_g(H_{treat})_{j=const}$ to

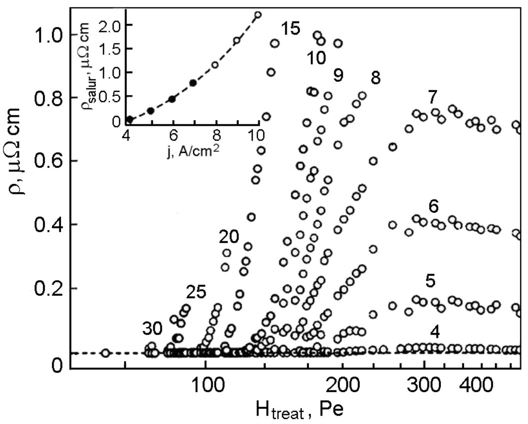

Fig. 5. Dependences $\rho(H_{treat})_{j=const}$ for the granular $YBa_2Cu_3O_{6.95}$ high-temperature superconductor sample preliminarily magnetized at T = 77.3 K in the transverse magnetic field $\mathbf{H}_{treat}$. Numbers near the curves are the values of the density j (given in A/cm^2). The inset shows the dependences $\rho_{satur}(j)$ (closed circles are experimental data, and open circles represent the results of extrapolation of the dependences $\rho(H_{treat})_{j=const}$ toward high values of H_{treat}.

saturation and ρ_{satur} growth with j increase. The effect is a direct consequence of Lorentz force $\mathbf{F}_L = \mathbf{j} \times \mathbf{H}_{ext}$ increase with H_{treat} and j_c rising.

3. Existing a strong j dependence of H_{kink} field at which $\rho_g \neq 0$ (Fig. 6). The effect indicates, that H_{kink} field is identical to H_{c1g}. The nature of $H_{kink}(j) \equiv H_{c1g}(j)$ dependence is clear, if to consider the physically equivalent effect of critical current versus magnetic field dependence (insert in Fig. 6).

5. Conclusions

As it was mentioned in the Introduction, the aim of the work was to reveal the contribution of superconductive granules and weak links into magnetoresistance of granular samples of $YBa_2Cu_3O_{7-\delta}$ high-temperature superconductor at $T < T_c$.

It was found, that for CVCs measured in rather high external magnetic fields, $\mathbf{H}_{ext}$, and at relatively low transport current densities, j, in the range $0 < H_{ext} < H_{c1g}$ the dissipation is related exclusively with processes of Josephson vortices penetration into intergranular boundaries — weak links.

The treatment of HTS granular samples at $T < T_c$ with rather external magnetic field $\mathbf{H}_{treat}$ results in trapping the magnetic

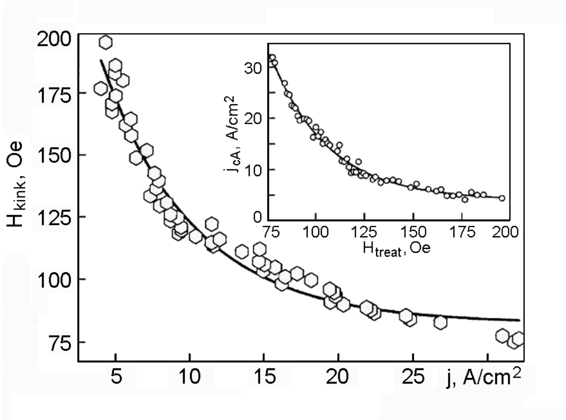

Fig. 6. Dependences of the critical field H_{kink} on the transport current density j for the granular $YBa_2Cu_3O_{6.95}$ high-temperature superconductor sample preliminarily magnetized at T = 77.3 K in the transverse magnetic field $\mathbf{H}_{treat}$. The inset shows the dependence of the critical intracranial current density j_{cg} on the field $\mathbf{H}_{treat}$.

field $\mathbf{H}_{trap}$ by superconductive granules, at this $H_{trap} < H_{c2J}$.

Thus, using the magnetically pretreated granular samples, during CVCs measurements carried out in *zero* magnetic fields, a unique possibility appears to study the dissipation processes in superconductive granules.

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Гальваномагнітні властивості надпровідних гранул та меж зерен у керамічному високотемпературному надпровіднику $YBa_2Cu_3O_{7-\delta}$

Т.В.Сухарева

Встановлено внесок надпровідних гранул та міжгранульних меж — слабких зв'язків у магнітоопір ρ гранулярного високотемпературного надпровідника (ВТНП) $YBa_2Cu_3O_{7-\delta}$ при $T < T_c$. Вольтамперні характеристики (ВАХ) $E(j)_{Hext=\mathrm{const}}$ керамічних зразків $YBa_2Cu_3O_{6.95}$ виміряно у магнітних полях $\mathbf{H}_{ext}$ ($0 \le H_{ext} \le \approx 500$ Oe). При $H_{ext} = 0$ виміряно ВАХ $E(j)_{Htrap=\mathrm{const}}$ зразків, які намагнічено у магнітних полях $\mathbf{H}_{treat}$ ($0 \le H_{trap} \le H_{c2J}$, де H_{c2J} — верхнє критичне поле джозефсонівських слабких зв'язків). На підставі ВАХ відбудовані залежності $\rho(j)_{Hext=\mathrm{const}}$, $\rho(H_{ext})_{j=const}$ та $\rho(j)_{Htrap=\mathrm{const}}$. Порівняльний аналіз залежностей $\rho(j)_{Hext=\mathrm{const}}$ та $\rho(H_{ext})_{j=const}$ свідчить про вплив процесу перерозподілу магнітного поля між межами зерен і надпровідними гранулами на транспортні та гальваномагнітні властивості гранулярних ВТНП. Встановлено, що магнітоопір ρ_g надпровідних зерен значно менший, ніж магнітоопір ρ_J джозефсонівського середовища ρ_J.