Вісник Харківського національного університету імені В. Н. Каразіна. Серія «Фізика». Вип. 41, 7–15 (2024)
Journal of V. N. Karazin Kharkiv National University. Series Physics. Iss. 41, 7–15 (2024)
DOI: 10.26565/2222-5617-2024-41 ISSN 2222-5617 (Print)

Original article
In print article
https://doi.org/10.26565/2222-5617-2024-41-01
UDC 537.5, 537.6/.8, 536.4
PACS numbers: 74.70.-b, 75-50.-y, 64.70.Nd

OPTIMIZATION OF CONDITIONS FOR DISSIPATION-FREE TRANSFER OF ELECTRIC CURRENT USING TWO-LEVEL GRANULAR HIGH-TEMPERATURE SUPERCONDUCTORS OF VARIOUS COMPOSITIONS

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Received on August 29, 2024. Reviewed on October 05, 2024.
Accepted for publication on October 15, 2024.

In order to optimize the conditions for dissipative-free electric current transport, the influence of chemical composition, temperature and magnetic field on phase transitions in model HTSC objects – granular high-temperature superconductors $YBa_2Cu_3O_{7-\delta}$ and $DyBa_2Cu_3O_{7-\delta}$ – was studied. The work investigated the peculiarities of magnetic field penetration into granular high-temperature superconductors of the 1:2:3 type, depending on the presence or absence of magnetically active atoms in their crystal lattice.Large-scale measurements of specific electrical resistance were carried out under conditions of continuous temperature change and discrete change in the external perpendicular magnetic field strength at a constant value of the transport current density. The influence of the nature of filling the electron shells of the central atoms (Y or REM) in the 1:2:3 HTSC crystal lattice on the occurrence of phase transitions in superconducting granules and in the Josephson medium was investigated. It is shown that the presence of a magnetoactive Dy atom in the HTSC crystal structure has a weak effect on the critical temperatures of phase transitions in superconducting granules, but leads to a significant decrease in the critical temperatures of phase transitions in the Josephson medium. Thus, it is shown that from a wide class of granular superconductors of the 1:2:3 type, only granular superconductors based on HTSC $YBa_2Cu_3O_{7-\delta}$ can be used as the main material for dissipative-free transfer of electric current at the boiling point of liquid nitrogen.

Keywords: *$YBa_2Cu_3O_{7-\delta}$, phase transitions, two-level granular high-temperature superconductors, HTSCs, Josephson medium, external magnetic field, internal magnetic fields, magnetically active atoms, nature of filling the electron shells, dissipation processes.*

In cites: *M. O. Azarenkov, T. V. Sukhareva, M. S. Sunhurov, Y. M. Shakhov. Optimization of conditions for dissipation-free transfer of electric current using two-level granular high-temperature superconductors of various compositions. Journal of V. N. Karazin Kharkiv National University. Series Physics. Iss. 41, 2024, 7–15.* https://doi.org/10.26565/2222-5617-2024-41-01

1. INTRODUCTION

For modern physics, the twentieth century was marked not only by the discovery of a qualitatively new phenomenon of superconductivity from the point of view of classical electrodynamics in 1911 [1], but also by such important milestones as the emergence and development of the concept of the existence of type II superconductors in 1934 [2, 3] and the discovery of high-temperature superconductivity in 1986 [4]. The development of new ideas and the discovery of new superconductors meant not only a *quantitative* change in the values of the critical parameters of superconductivity – critical temperatures T_c, critical fields H_c and critical currents I_c, but also a *qualitative* change in the nature of the phase *T-H-I* - diagrams. As is known, the phenomenon of high-temperature superconductivity was discovered in 1986 while studying the electrical properties of granular samples of the metal oxide compound $La_{2-x}Ba_xCuO_4$ [4]. This discovery had two important aspects: firstly, a superconductor with a critical temperature T_c twice as high as those previously obtained on metal compounds was synthesized and studied for the first time; secondly, the existence of a previously unknown class of superconductors was discovered – the so-called two-level superconductors (see, for example, [5–8]).

As has been established [5, 6], the behavior of a new class of superconducting materials – granular high-temperature superconductors (HTSCs) – can be described within the framework of a two-level critical state model. In this model, granular HTSCs are considered as a combination of two subsystems of type II superconductors [2, 3]: three-dimensional superconducting granules (size ~ 1 μm) with strong superconductivity and two-dimensional intergranular boundaries – Josephson "weak links" (size ~ several nm) with weak superconductivity. In the two-level model for superconducting granules (indices "g") and intergranular boundaries – Josephson "weak links" (indices "J"):

$$\begin{aligned} &H_{c1g}(T) > H_{c1J}(T), \\ &H_{c2g}(T) > H_{c2J}(T), \\ &I_{cg}(T, H_{ext}) \gg I_{cJ}(T, H_{ext}), \end{aligned} \qquad (1)$$

where H_{c1g} and H_{c1J} are the critical fields for starting the process of penetration of a magnetic field into the subsystems of a granular superconductor; H_{c2g} and H_{c2J} are the critical fields of complete penetration of a magnetic field into the subsystems of a granular superconductor; I_{cg}, I_{cJ} are critical currents.

System of equations (1) quite adequately describes the processes of penetration of a magnetic field into both subsystems of a two-level granular superconductor, as well as the destruction of the superconducting state. Penetration of an external magnetic field $\mathbf{H}_{ext}$ into granular high-temperature superconductors is realized, in contrast to "classical" type II superconductors (including HTSC single crystals), due to Abrikosov vortices into granules at $H_{ext} > H_{c1g}$ and Josephson vortices into "weak links" at $H_{ext} > H_{c1J}$. Naturally, the features of the penetration of a magnetic field into granular high-temperature superconductors to a very significant extent determine the behavior of their magnetic, electrophysical (transport and galvanomagnetic), etc. properties in a wide range of temperatures, magnitude and orientation of the magnetic field **H** and other external parameters.

It should be recognized that in the 37 years that have passed since the discovery of the phenomenon of high-temperature superconductivity, two problems of paramount importance have not been fully resolved: the *fundamental* one – establishing the nature of the phenomenon, and the *applied* one - the creation of technical superconductors for high-current technology based on HTSC. And although the macroscopic theory of high-temperature superconductivity has not yet been constructed, high-temperature superconductors (HTSC) are widely used in modern technology. HTSCs are actively used in low-current technology: in microelectronics and computer technology (devices based on Josephson junctions), as detectors of weak magnetic fields for use in medicine (magnetoencephalography, MEG), in geology and geophysics (search for minerals, study of the geological structure of the earth's crust, earthquake forecast), in materials science (non-destructive testing of materials and structures); in high-current technology: creating powerful magnetic fields by passing a strong current through a superconducting coil (this effect is used, for example, in nuclear magnetic resonance (NMR) imaging). The use of HTSC in high-current technology also includes the creation of electrical power devices and systems that generate, transmit and convert electricity on an industrial scale. This direction is based on the high current-carrying capacity of superconductors even in strong magnetic fields at temperatures below critical. On the basis of HTSC, powerful superconducting magnets and superconducting wires have been created, which are used, for example, in the Large Hadron Collider; magnetic levitation trains (electrodynamic suspension, EDS) have been actively used in Japan for quite a long time. Despite the fact that HTSCs have already found their wide application in modern technology, the search for new superconducting materials with higher critical parameters and further research into the applied and fundamental properties previously discovered of oxide HTSCs do not stop. Since the discovery of the phenomenon of high-temperature superconductivity, a large number of different high-temperature superconductors with different crystal lattices have been synthesized: type 214 (for example, La_2CuO_4), type 123 ($YBa_2Cu_3O_{7-\delta}$), type 124 ($YBa_2Cu_4O_{8+\delta}$), type 2212 ($Bi_2Sr_2CaCu_2O_{8+\delta}$), type 2223 ($Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$), as well as $Tl_2Ba_2Ca_{n-1}Cu_nO_{2n+4}$ (n = 2, 3), MgB_2, etc. In terms of potential applications of such superconducting materials (such as high-capacity power cables for modern power lines, generators, superconducting magnets, low-resistance and high-efficiency transformers, electrical energy storage devices, as well as other superconducting electrical equipment operating under liquid nitrogen cooling), HTSC type Re123 ($ReBa_2Cu_3O_{7-\delta}$), where Re is yttrium or trivalent rare earth metal, are most actively used. Comparing with other cuprate superconductors, conductors based on ReBCO are the most promising materials due to their high superconducting current density and the ability to carry current in strong magnetic fields. On the contrary, in BSCCO ($Bi_2Sr_2CaCu_2O_{8+\delta}$) the critical current drops very quickly with increasing external magnetic field strength and, despite the relative ease of manufacture, bismuth-based HTSCs with Bi-2212 and Bi-2223 structures have fairly low irreversibility fields, which imposes significant restrictions on their use in strong magnetic field at the boiling point of liquid nitrogen.

Against the backdrop of today's threats facing humanity, it is necessary to solve the problem of minimizing the use of hydrocarbons in the energy sector. One of the most important elements of energy security is the transfer of electricity from producer to consumer without loss. High-temperature superconductors can carry out just such dissipative-free transmission, which makes their use effective in high-current technology, for example, in the architecture of second-generation high-temperature superconductors (2G HTS). Therefore, the analysis of HTSC properties, which are critical for application purposes, is relevant and necessary in this context.

In fact, our work is a fundamental study, but it is aimed primarily at optimizing the conditions for non-dissipative transfer of electric current using two-level granular HTSCs of various compositions. The concept of "optimization" in this case is quite broad. This refers to both environmental protection and the simplicity and relative cheapness of manufacture and use. As for environmental protection, this is associated not only with the reducing to use hydrocarbons in the energy sector and, for example, in steel production, but also with the reduction of helium production in the world, due to the depletion of its reserves. In this regard, the most accessible, safe to use and environmentally friendly cryogenic liquid is liquid nitrogen. Large-size granular superconductors are excellent current leads and can displace blast furnaces operating on solid fuel. Polycrystalline superconducting films, which have the same properties as bulk granular HTSCs, are much easier to manufacture than single-crystalline ones, and therefore their use in the architecture of second-generation high-temperature superconductors (2G HTS) is also an element of optimization.

In this regard*, the goal of this work is to optimize the conditions for the non-dissipative transfer of electric current from producer to consumer using two-level granular HTSCs of various compositions*.

Specifically, we are talking about establishing the influence of magnetically neutral yttrium atoms and magnetically active rare-earth atoms in the structure of 1:2:3 HTSC on the occurrence of phase transitions in two-level granular high-temperature superconductors, using the example of HTSC $YBa_2Cu_3O_{7-\delta}$ and $DyBa_2Cu_3O_{7-\delta}$ under the influence of an external magnetic field and transport current when the temperature changes. To achieve the goal of this work, large-scale studies of the influence of the chemical composition, temperature and external magnetic field strength on the crystal structure, electrophysical and magnetic properties of two-level granular high-temperature superconductors $YBa_2Cu_3O_{7-\delta}$ and $DyBa_2Cu_3O_{7-\delta}$ are needed.

One of the objects of study is the high-temperature superconductor $YBa_2Cu_3O_{7-\delta}$. An essential fact is that the filling of the electronic shells of the central yttrium atom ($\mathbf{1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 5s^2 4d^1}$) is fundamentally different from the filling of the electronic shells of rare earth atoms, since in Y the "magnetic" **4f** shell is vacant. This means that in the case of HTSC $YBa_2Cu_3O_{7-\delta}$, there are no sources of internal magnetic field, $H_{int} \equiv 0$. The second object of study is $DyBa_2Cu_3O_{7-\delta}$, in which the central rare earth atom Dy has a filled **4f** shell ($\mathbf{1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 5s^2 4d^{10} 5p^6 6s^2 \underline{4f^{10}}}$) and $H_{int} > 0$. Note that quite numerous studies of the crystal structure and electromagnetic properties of HTSC $DyBa_2Cu_3O_{7-\delta}$ were started back in the late 80s of the twentieth century (see, for example, [9–20]), but were limited mainly to establishing the influence of the crystal structure on macroscopic superconductivity parameters. However, the question of the influence of filling the electronic shells of central atoms (Y or REM) in the 1:2:3 HTSC crystal lattice on the phase transitions in superconducting granules and in a Josephson medium has still remained open.

Obviously, the most effective way to study phase transitions (PTs) in a magnetic field is to conduct experiments in a wide range of temperatures at several fixed values of the external magnetic field strength. To establish the thermodynamic features of the phase transition caused by the interaction of the magnetic field with both subsystems of granular HTSC, electrical resistance was measured at fixed values of the magnetic field with increasing temperature.

2. METHODOLOGICAL ASPECTS OF RESEARCH

2.1 Samples for research

The objects of study were samples of granular high-temperature superconductor of the 1:2:3 type – $YBa_2Cu_3O_{7-\delta}$ and $DyBa_2Cu_3O_{7-\delta}$. The choice of research objects was determined by several circumstances. Firstly, $YBa_2Cu_3O_{7-\delta}$ is a typical representative of metal oxide granular HTSCs and is often a model object of research; secondly, $YBa_2Cu_3O_{7-\delta}$ and $DyBa_2Cu_3O_{7-\delta}$ have the same orthorhombic structure and similar crystal lattice parameters; their critical superconducting transition temperatures differ slightly; and thirdly, despite all the similarities, the objects of study have a fundamental difference: the absence of a magnetically active atom in the structure of $YBa_2Cu_3O_{7-\delta}$ and its presence in $DyBa_2Cu_3O_{7-\delta}$.

Samples of the granular high-temperature superconductor $YBa_2Cu_3O_{7-\delta}$ were synthesized using standard "ceramic technology" [21, 22] from powders produced at the STC ISC of the NAS of Ukraine, Kharkov. The dimensions of the samples were ≈ 2 × 2 × 20 mm^3. Current and potential contacts were made by deposition of silver vapor in a vacuum. The final annealing of the samples in an oxidizing environment at 500 °C followed by slow cooling was carried out after the deposition of Ag contacts, which led to a significant decrease in the contact resistance at the $YBa_2Cu_3O_{7-\delta}$/Ag interface.

The synthesis of $DyBa_2Cu_3O_{7-\delta}$ samples was carried out according to the following scheme: the initial components – Dy_2O_3, $BaCO_3$ and CuO taken in a stoichiometric ratio, are carefully ground in an alcoholic environment. The alcohol is then evaporated and the composition is placed in a muffle furnace for synthesis. Synthesis is carried out at a temperature of T = 950 ºC. Synthesis time t = 24 hours from the moment the temperature is reached. Upon completion, the composition cools down with the oven to room temperature. The heating/cooling rate was ~ 5 ºC/min. The resulting mixture is again ground in an alcoholic environment; then the alcohol evaporated.

Next, samples of the required shape and size are pressed from the mixture under a pressure of 650 kg/mm^2. The dimensions of the samples were ≈ 2 × 2 × 20 mm^3. Current and potential contacts were made by deposition of silver vapor in a vacuum. The final annealing of the samples in an oxidizing environment at 500 °C followed by slow cooling was carried out after the deposition of Ag contacts, which led to a significant decrease in the contact resistance at the $DyBa_2Cu_3O_{7-\delta}$/Ag interface.

To certify HTSC samples, methods of X-ray diffraction analysis, resistive and magnetic measurements of the critical temperature T_c were used. To carry out X-ray diffraction studies, the obtained samples of granular high-temperature superconductors $YBa_2Cu_3O_{7-\delta}$ and $DyBa_2Cu_3O_{7-\delta}$ were crushed into powder. X-ray studies were carried out using a stationary X-ray instrument DRON UM-1 in the Bregg-Brentano focusing scheme; CuKα radiation was used. Diffraction patterns were recorded in the angle range 2θ = 15–75 degrees, with an accuracy of 10^{-1} degrees. To determine the parameters of the crystal lattice, the positions of the triplet of diffraction lines (006), (200), (020) were recorded with an accuracy of Δ2θ ~ 10–2 deg. To resolve the triplet components, the diffraction profile components were analyzed using the Gaussian function. The accuracy of determining crystal lattice parameters is 10^{-4} Å.

In the diffraction patterns of YBCO and DyBCO powder samples, characteristic systems of diffraction lines $YBa_2Cu_3O_{7-\delta}$ (Y-123) and $DyBa_2Cu_3O_{7-\delta}$ (Dy-123) corresponding to the orthorhombic structure of perovskite, space group *Pmmm*, are observed. There are practically no lines of extraneous phases.

Table 1 presents the crystal lattice parameters (which are close to the data of other authors, [23, 24]), the volumes of the unit cell, and the degree of rhombicity of the samples $\Delta = 2 \times (b - a) / (b + a)$, where a, b are the lattice parameters in the basal plane. As can be seen, the parameter Δ for Dy-123 is less than for Y-123. The change in Δ can be explained by the removal of oxygen atoms from the Cu–O chains, which are located along the b axis of the orthorhombic $DyBa_2Cu_3O_{7-\delta}$ lattice [25–27].

Table 1

Lattice parameters, unit cell volume, degree of rhombicity of YBCO and DyBCO samples after annealing in an oxidizing environment

ReBCO(Re=Y,Dy)	a, Å	b, Å	c, Å	V, $Å^3$	Δ, arb. units
Y-123	3.828	3.894	11.728	174.86	0.0172
D-123	3.834	3.898	11.721	175.17	0.0165

2.2. Experimental setup and determination of the critical temperature of the superconducting transition

As mentioned above, methods of resistive and magnetic measurements of the critical temperature T_c were used to certify the samples. The temperature of the middle of the superconducting transition, determined from the maximum derivative $d\rho/dT(T)$, was 92.6 ± 0.01 K for $YBa_2Cu_3O_{7-\delta}$ and 90.5 ± 0.01 K for $DyBa_2Cu_3O_{7-\delta}$. As can be seen, in the absence of an external magnetic field, the resistivity curve $[\rho(T)_{Hext=0}]$ has a classical σ-type character, described with high accuracy by the Boltzmann function, widely used in the theory of phase transitions accompanied by jumps in the corresponding physical quantities [28, 29]. For a jump in electrical resistance during a superconducting transition, the Boltzmann equation takes the form:

$$\Delta R(T) = \frac{\Delta R_N}{1 + e^{T_c - \Delta T_c}} \qquad (2)$$

where ΔR is the resistance in the normal state near T_c.

To measure the temperature dependences of the electrical resistivity of granular HTSCs $YBa_2Cu_3O_{7-\delta}$ and $DyBa_2Cu_3O_{7-\delta}$ in a transverse magnetic field, we used a previously developed setup [30, 31, 32], in which a system of pairs of permanent magnets made of a high-coercivity $Nd_2Fe_{14}B$ alloy was used to create a magnetic field. The *FC* mode of applying a magnetic field (cooling in a magnetic field) was used. This regime, as we showed earlier [30], ensures the achieving maximum equilibrium between the granular HTSC under study and an external magnetic field; the achievement of the equilibrium was also facilitated by the use of very low cooling and heating rates of the samples (≈ 0.002–0.004 deg/s). All measurements were carried out at a constant transport current density (j = 2 A/cm^2), which corresponded to a transport current value of I = 10 mA.

3. RESULTS

3.1. Temperature dependences of the electrical resistivity of granular HTSC $YBa_2Cu_3O_{7-\delta}$ in external magnetic fields

The temperature dependencies of electrical resistivity for one of the series of measurements under heating conditions for samples of granular HTSC $YBa_2Cu_3O_{7-\delta}$ are presented in Fig.1.

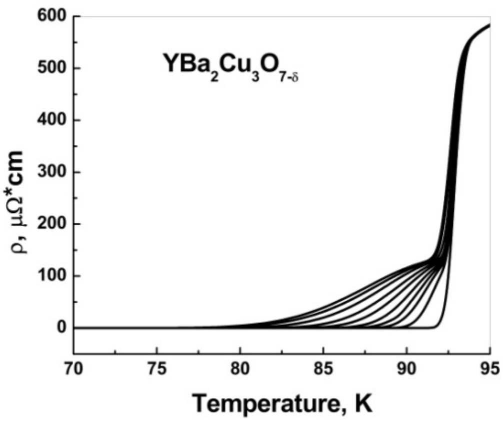


Fig. 1. Temperature dependences of electrical resistivity in external perpendicular magnetic fields H_{ext}: (from bottom to top): 0; 10; 25; 50; 100; 250; 500; 1000; 1400; 1900 Oe.

As can be seen, with increasing H_{ext}, the $\rho(T)_{Hext=\mathrm{const}}$ curves regularly shift towards higher values of electrical resistivity. In the absence of an external magnetic field, the resistivity curve has a classical σ-type character. When an external magnetic field H_{ext} is applied, the behavior of the electrical resistivity curves changes significantly: the curves "swell" towards low temperatures; the temperature of zero resistivity noticeably decreases with increasing field; at $H_{ext} > \approx 100$ Oe, a characteristic feature appears on the ρ(T) curves – a "bend" containing an *inflection point* which turns into a clearly defined maximum as the field grows. As an example, Fig. 2 shows a typical temperature dependence of the electrical resistivity of a granular HTSC $YBa_2Cu_3O_{7-\delta}$ in an external magnetic field H_{ext} = 250 Oe; on the resistivity curve, arrows indicate special points corresponding to three phase transitions (the inset shows the $d\rho/dT(T)$ curve in the vicinity of the phase transition temperature T_{c1g}).

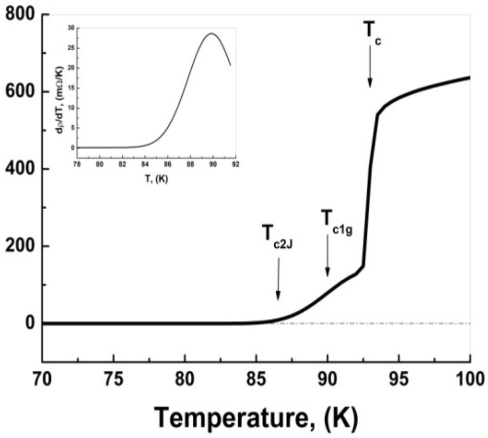


Fig. 2. Temperature dependence of electrical resistivity at H_{ext} = 250 Oe. The inset shows a jump in the derivative $d\rho/dT$ in the vicinity of the phase transition temperature T_{c1g}.

3.2. Temperature dependences of the electrical resistivity of granular $DyBa_2Cu_3O_{7-\delta}$ in external magnetic fields

The temperature dependences of electrical resistivity for one of the series of measurements under heating conditions for samples of granular HTSC $DyBa_2Cu_3O_{7-\delta}$ are presented in Fig. 3.

First of all, attention is drawn to the noticeable expansion of the region of existence of the Josephson medium $T_{c2J}(T_{\rho=0}) - T_{c1g}$ and a noticeable shift in the temperature of appearance of resistivity $T_{\rho=0}$ to the region of lower temperatures in the granular HTSC $DyBa_2Cu_3O_{7-\delta}$ compared to $YBa_2Cu_3O_{7-\delta}$ (see Fig. 1) with a slight increasing the external magnetic field strength H_{ext}. When the field value $H_{ext} > \approx 50$ Oe, a characteristic feature appears on the ρ(T) curves – a "bend" containing an inflection point, which turns into a clearly expressed maximum as the field grows.

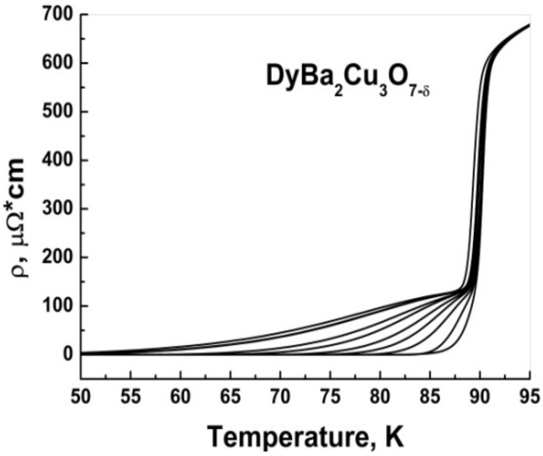


Fig. 3. Temperature dependences of electrical resistivity in external perpendicular magnetic fields H_{ext}: (from bottom to top): 0; 10; 25; 50; 100; 250; 500; 1000; 1400; 1900 Oe.

3.3. Phase transitions in granular HTSCSemperature dependences of the electrical resistivity of granular $YBa_2Cu_3O_{7-\delta}$ and $DyBa_2Cu_3O_{7-\delta}$ in external magnetic fields

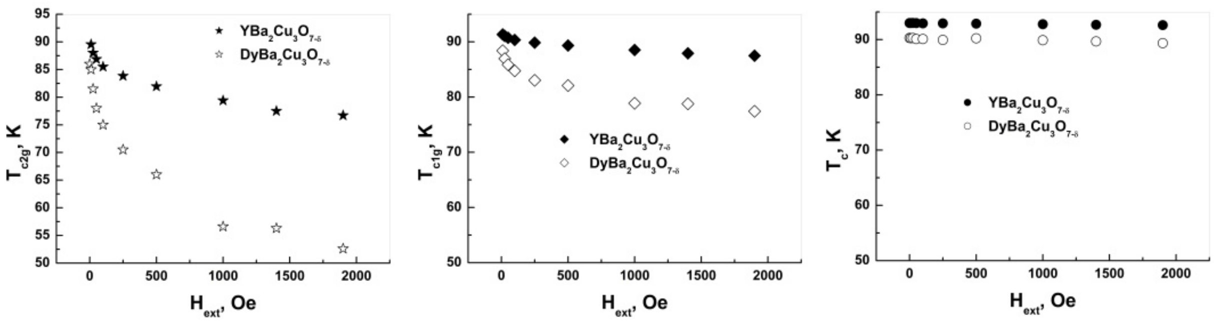
Based on the temperature dependences of electrical resistivity in various external perpendicular magnetic fields (see Fig. 1 and Fig. 3), the field dependences of the critical temperatures of phase transitions (Fig. 4) were determined in both subsystems of two-level granular $YBa_2Cu_3O_{7-\delta}$ and $DyBa_2Cu_3O_{7-\delta}$ HTSCs.

Critical temperatures of phase transitions (Fig. 2 and Fig. 4):

a. $T_{c2J} = T_{\rho=0}$ (the criterion – is the appearance of resistance with increasing temperature) is the critical temperature of the beginning of magnetic field penetration into the "weak links" subsystem. There is a tendency for T_{c2J} to decrease with increasing external magnetic field strength H_{ext}.

b. T_{c1g} (the criterion – is the appearance of a maximum of the derivative $d\rho/dT$) is the critical temperature of the beginning of magnetic field penetration into the subsystem of superconducting granules. T_{c1g} slightly decreases with increasing H_{ext}.

c. T_c is the critical temperature of the superconducting transition, which is practically independent on H_{ext}.



a b c

Fig. 4. Dependencies of critical temperatures of phase transitions (a) $T_{c2J}(T_{\rho=0})$, (b) T_{c1g} and (c) T_c at $0 \le H_{ext} \le 1900$ Oe in granular HTSC $YBa_2Cu_3O_{7-\delta}$ and $DyBa_2Cu_3O_{7-\delta}$.

4. DISCUSSION

As is known, (see Introduction) a description of the behavior of granular high-temperature superconductors is possible within the framework of a two-level critical state model, when granular HTSCs are considered as a combination of two subsystems of type II superconductors: three-dimensional superconducting granules with strong superconductivity and two-dimensional intergranular boundaries – Josephson "weak links" with weak superconductivity. In accordance with existing concepts, at temperatures below T_c:

1. In the range of $0 < H_{ext} < H_{c1J}$, both subsystems of a two-level granular superconductor are in a superconducting state.
2. In the range of $H_{c1J} < H_{ext} < H_{c2J}$, Josephson vortices begin to penetrate into the "weak links" subsystem (in this case, the appearance of resistance is not observed [33, 34]).
3. In the range of $H_{c2J} < H_{ext} < H_{c1g}$, resistance appears. For granular HTSCs, the effect of the appearance of non-zero electrical resistance at $H_{ext} > H_{c2J}$ can be due to various mechanisms: this may be associated with the formation of an extended Josephson junction of one type in the "weak links" subsystem, i.e. at $H_{ext} \sim H_{c2J}$, there is no final transition of all "weak links" to the resistive state, but the process of breaking all percolation paths for the flow of superconducting current is completed [35–37]. The appearance of resistance is a consequence of a "classical" second-order phase transition in a system of

"weak links" at $H_{ext} = H_{c2J}$. The main argument in favor of this point of view is the appearance of a maximum in the dependence of the complex magnetic susceptibility [38] – the second derivative of thermodynamic potentials. The appearance of resistance is due to the destruction of the coherent connection between superconducting granules and thermally activated phase slip in the resulting Josephson junctions [39–41].

4. In the range of $H_{c1g} < H_{ext} < H_{c2g}$, Abrikosov vortices penetrate into the subsystem of superconducting granules.
5. At $H_{ext} > H_{c2g}$, the granular superconductor completely transforms into the normal state.

As already noted in the Introduction, the peculiarities of the penetration of a magnetic field into granular high-temperature superconductors to a very significant extent determine the behavior of their magnetic, electrophysical, galvanomagnetic and other properties in a wide range of temperatures, the magnitude and orientation of the magnetic field **H** and other external parameters. From a purely applied point of view, the influence of an external magnetic field on critical temperatures and currents comes down to a relatively weak decrease in the critical temperature T_c and a fairly strong decrease in the values of critical currents I_c with an increase in the external magnetic field strength H_{ext} (see, for example, [42]). As was shown earlier [37], the main contribution to the electrical resistance of two-level HTSCs is made by dissipation processes at Josephson "weak links". A necessary condition for turning on the dissipation mechanism, naturally, is the presence of an external magnetic field [42].

As can be seen (Fig. 4), with an increase in the external magnetic field strength H_{ext}, the critical temperature T_{c2J} of the phase transition, when the external magnetic field begins to penetrate into the "weak links" subsystem, noticeably shifts to the region of low temperatures.

Moreover, if in the HTSC $YBa_2Cu_3O_{7-\delta}$, the critical phase transition temperature T_{c2J} (the temperature at which the resistivity of the Josephson medium appears) is higher than the liquid nitrogen boiling point even at the maximum strength of the external magnetic field H_{ext} = 1900 Oe (Fig.4a), then for HTSC $DyBa_2Cu_3O_{7-\delta}$, the critical temperature T_{c2J} becomes 70.5 K, i.e. lower than the boiling point of liquid nitrogen already at H_{ext} = 250 Oe. That is, the presence of sources of internal magnetic field in the structure of granular HTSC $DyBa_2Cu_3O_{7-\delta}$ enhances dissipation processes and thereby leads to a significant decrease in the critical temperatures of phase transitions in the region of existence of the Josephson medium. Thus, since there are no sources of internal magnetic field in the crystal structure of granular HTSC $YBa_2Cu_3O_{7-\delta}$, dissipation processes are caused exclusively by the influence of the *external* magnetic field. For $DyBa_2Cu_3O_{7-\delta}$, which has a magnetically active Dy atom as a source of internal magnetic field, the effects of a significant expansion of the "transition region" $T_{\rho=0} - T_c$ and a noticeable increase in electrical resistance with increasing H_{ext} may mean the combined influence of *external and internal* magnetic fields on dissipation processes in both subsystems.

5. CONCLUSION

Studies of phase transitions in two-level granular HTSCs with different the chemical composition in an external magnetic field with a change in temperature allowed us to conclude that the presence or absence of magnetically active atoms in the crystal structure is critically important for the practical application of HTSC in high-current technology, in particular, in the architecture of second-generation high-temperature superconductors (2G HTS) and the use of large-sized granular superconductors as current leads, which can displace solid fuel blast furnaces in the steel industry. It has been shown that the nature of filling the electron shells of central atoms in the crystal structure of 1:2:3 type HTSC has the strongest influence on the occurrence of phase transitions in the Josephson medium of granular high-temperature superconductors. It has been established that for $DyBa_2Cu_3O_{7-\delta}$, which has a magnetically active Dy atom as a source of internal magnetic field in its crystal structure, dissipation processes in both subsystems are caused by the combined influence of external and internal magnetic fields; this leads to a significant decrease in the critical temperatures of phase transitions in a Josephson medium. In contrast, there are no magnetically active atoms in granular $YBa_2Cu_3O_{7-\delta}$; therefore, the influence of an external magnetic field on the occurrence of phase transitions in both subsystems does not lead to a significant change in the critical temperatures of phase transitions.

Based on fundamental studies of phase transitions in two-level granular high-temperature superconductors of various compositions, the main result of this work from an applied point of view is following: as the main material for the dissipation-free transfer of electricity from producer to consumer at the boiling point of liquid nitrogen, conductors *predominantly* based on HTSC $YBa_2Cu_3O_{7-\delta}$ can be used.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interests.

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ОПТИМІЗАЦІЯ УМОВ БЕЗДИСИПАТИВНОГО ТРАНСПОРТУВАННЯ ЕЛЕКТРИЧНОГО СТРУМУ ЗА ДОПОМОГОЮ ДВОРІВНЕВИХ ГРАНУЛЬОВАНИХ ВИСОКОТЕМПЕРАТУРНИХ НАДПРОВІДНИКІВ РІЗНОГО СКЛАДУ

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Надійшла до редакції 29 серпня 2024 р. Переглянуто 05 жовтня 2024 р.
Прийнято до друку 15 жовтня 2024 р.

З метою оптимізації умов бездисипативного транспортування електричного струму досліджено вплив хімічного складу, температури та магнітного поля на фазові переходи в модельних ВТНП об’єктах – гранулярних високотемпературних надпровідниках $YBa_2Cu_3O_{7-\delta}$ та $DyBa_2Cu_3O_{7-\delta}$. У роботі досліджено особливості проникнення магнітного поля в гранулярні високотемпературні надпровідники типу 1:2:3 залежно від наявності або відсутності в їх кристалічній решітці магнітно-активних атомів. Проведено масштабні вимірювання питомого електричного опору в умовах безперервної зміни температури та дискретної зміни напруженості зовнішнього перпендикулярного магнітного поля при постійному значенні густини транспортного струму. Досліджено вплив характеру заповнення електронних оболонок центральних атомів (Y або РЗМ) у кристалічній ґратці ВТСП 1:2:3 на протікання фазових переходів у надпровідних гранулах та джозефсонівському середовищі. Показано, що наявність магнітоактивного атома Dy у кристалічній структурі ВТНП слабо впливає на критичні температури фазових переходів у надпровідних гранулах, але призводить до значного зниження критичних температур фазових переходів у джозефсонівському середовищі. Таким чином, показано, що з широкого класу гранулярних надпровідників типу 1:2:3 лише гранулярні надпровідники на основі ВТНП $YBa_2Cu_3O_{7-\delta}$ можуть бути використані як основний матеріал для бездисипативного перенесення електричного струму при температурі кипіння рідкого азоту.

Ключові слова: *$YBa_2Cu_3O_{7-\delta}$, фазові переходи, дворівневі гранулярні високотемпературні надпровідники, ВТНП, джозефсонівське середовище, зовнішнє магнітне поле, внутрішні магнітні поля, магнітно-активні атоми, характер заповнення електронних оболонок, процеси дисипації.*