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THERMAL INFLUENCE ON $J_c - B - T$ SURFACES OF Ag-CLAD Bi-BASED SUPERCONDUCTING TAPES

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This paper is dedicated to Professor A. Bonefačić on the occasion of his 70$^{\text{th}}$ birthday

We have studied $J_c - B - T$ surfaces for high-J_c Ag-clad $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212) and $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+y}$ (Bi2223) tapes in the temperature range 4.5 - 100 K and magnetic field $B \leq 1$ T. In both types of tapes, for temperature $T \geq 0.5\ T_c$, $J_c(T,B)$ and the pinning force density $F_p = J_cB$ exhibit scaling behaviour analogous to that observed in high-T_c single crystals and epitaxial films. The parallel study of the pinning potentials U_0 and of the irreversibility fields B_{irr} (deduced from the resistive transitions in the applied field) for the same tapes, revealed that the activation barrier $U = U_0(1 - T/T_c)/B^m$ determines both the magnitudes and temperature dependency of the scaling fields B^* (defined by $F_p = F_{pmax}$) and B_{irr}. Considerably larger U_0 for Bi2223 tape, compared to that of Bi2212 tape, is probably due to both lower electronic anisotropy of this compound and higher content of defects. However, in both types of tapes, the pinning of vortices is insufficient for the high-B high-T applications.

1. Introduction

The knowledge of the variation of critical current density J_c (defined by the electric field E_c) with temperature T and magnetic field B is important for most applications of superconductivity. The resulting $J_c - B - T$ surface bears sufficient information for the applicative purposes (any point below this surface corresponds to $E < E_c$), and may also indicate the nature of interactions giving rise to the observed behaviour. Since in type II superconductors J_c depends on the pinning of vortices, the main problem is to establish the correlation between the pinning centres (PC), such as the structural imperfections and/or impurities, and the current density J, i.e., to establish a consistent model for the pinning of vortices. Unfortunately, such a unique model is not known. Whereas in the conventional type II superconductors, one of the key problems is whether the interaction between PCs and vortices leads to the plastic or elastic deformations of the flux (vortex) lattice, in the layered high temperature superconductors (HTS) even the proper description of vortices (2D pancakes or 3D rods) presents the problem. The additional problem for HTS are thermal effects on the pinning of vortices, associated with their high superconducting transition temperatures T_c.

According to the above, well below T_c, J_c corresponds to J at which the driving force ($F \sim JB$) overcomes the pinning energy U. Since the work of F depends on the size of the moving flux bundle (V) and its hop distance (x), J_c is not that suitable for the estimation of U. A more convenient way to estimate U is to investigate the onset of the dissipation (resistance R) at low J (hence low F) which should yield directly the size (depth) of the pinning potential [1]. However, for HTS, this method has also been criticized, because it gives the values of U which are considerably larger than those deduced from the magnetization relaxation (reflecting the decay of J_c with time due to the flux creep). At present, it is not clear which of these methods provides more reliable estimate for U. Additionally, in granular (inhomogeneous) HTS, the existence of weak links (visualized as the Josephson junctions) at some grain boundaries makes the origin of the resistance onset rather unclear. However, our previous results have shown [2] that the onset of R in well prepared Ag-clad Bi-Sr-Ca-Cu-O tapes has the same form as that in the corresponding homogeneous samples (epitaxial films and single crystals) and, therefore, has probably the same origin [1]. Furthermore, the onset of the resistance also yields the irreversibility field B_{irr} (the field at which J_c disappears) which is, like U, closely related to the pinning of vortices and is a very important parameter in HTS.

Since the Ag-sheathed Bi-based tapes are the most highly developed high-T_c superconductors for high current application, the knowledge of their $J_c - B - T$ surface is desirable. Recently, the study of $J_c - B$ curves ($4.2 \leq T \leq 77.3$ K) for an Ag-clad $Bi_2Sr_2CaCu_2O_x$ (hereafter Bi2212) tape [3] enabled the construction of $J_c - B - T$ surface for this system. We performed similar measurements on an Ag-clad $(Bi,Pb)_2Sr_2Ca_2Cu_3O_y$ (hereafter Bi2223) tape and compare here the $J_c - B - T$ surfaces for these systems. For both systems, we find the scaling of J_c and the macroscopic pinning force $F_p = J_cB$ with B over a broad temperature range $T > 0.5\ T_c$. This behaviour is analogous to that observed in epitaxial films [4–6] and single crystals [7,8], and shows that at finite fields (bigger than the self-field of J_c) our tapes behave as homogeneous HTS. Furthermore, we compare our $J_c - B - T$ results with those for U and B_{irr} of the same samples. This comparison seems to indicate that within the investigated field range ($B \leq 1$ T), U determines the $J_c - B - T$ variation (via the scaling field B^*) and B_{irr}. In particular, the magnitudes of B^* and B_{irr} seem to be determined with that of U, whereas their temperature dependencies are determined with the thermal effects on the pinning of vortices (the temperature dependence of U).

2. Experimental procedure

The sample preparation and the measurement methods were reported earlier [3,9]. The Bi2223 tape [9] (containing 7.5% of Bi2212 phase) was the same one for which the pinning potential [10] $U_0(B)$ and $J_c(B,T)$ were previously studied for $T \geq 77$ K. We extended these measurements to 4.5 K and performed some new measurements of $J_c(B,T)$ on Bi2212 tape from Ref. 3. In presented measurements, the magnetic field B was applied perpendicular to the tape plane. The advantages of this geometry are simpler vortex structure (parallel to B) and larger change of J_c over the available range of B. As discussed elsewhere [3,9], the reduction of J_c with B for B in the plane of tape depends on the alignment of grains (angle ϕ).

TABLE 1. Data for the tapes: J_c is the critical current density at 4.5 K, U_0 is the pinning potential at $B = 0.9$ T, α is the exponent of the initial $J_c \sim B^{\alpha}$ variation and ϕ is the tilt angle of grains.

Tape	T_c(K)	J_c(kA/cm^2)	$\phi(^\circ)$	U_0(K)	α
Bi2212	90.6	218	8	1250	≈ -0.2
Bi2223	107.4	107	12	4800	≈ -0.5

Critical current I_c was measured with a pulse method by using the single sawtooth pulse of typical duration of 10 ms. The J_c criterion was $E_c = 1\mu$V/cm. The resistive transitions were measured [3,10] with a low frequency AC method with the voltage resolution of 0.5 nV. Some data relevant to our tapes are given in Table 1.

3. Results and discussion

The three-dimensional plot of $J_c(B,T)$ variation for Bi2212 tape is shown in Fig. 1a. It can be seen that $J_c(B,T = const)$ curves show somewhat different behaviour at lower and higher temperatures ($T \geq 39$ K). At low temperatures, J_c decreases with B at low fields ($B < 0.1$ T), but changes a little at higher fields. For $T \geq 39$ K ($t \equiv T/T_c \geq 0.43$, where T_c denotes the zero magnetic field transition temperature, Table 1), J_c exhibits a second rapid decrease with B above some characteristic field which decreases with increasing temperature [3]. The variation of J_c with B in the corresponding epitaxial films [6] is analogous to that for our tape. Figure 1a also shows that the T-dependence of J_c at a fixed B depends on the magnitude of B.

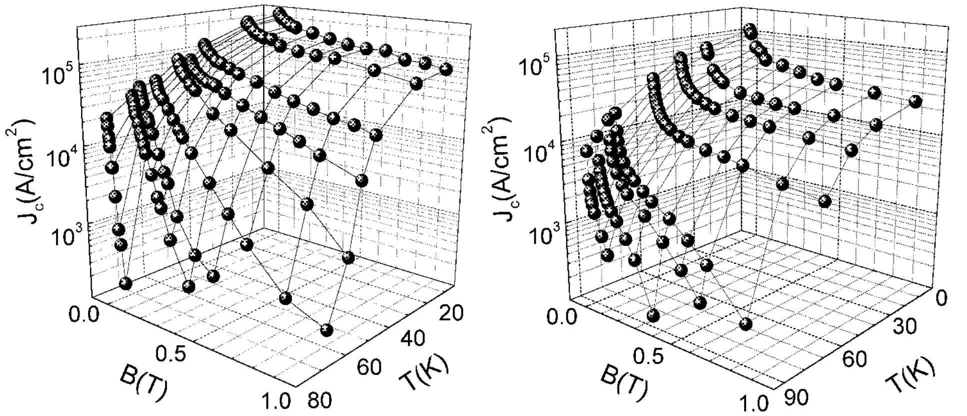

Fig. 1. Variation of critical current density with field and temperature for a) the Bi2212/Ag tape and b) the Bi2223/Ag tape.

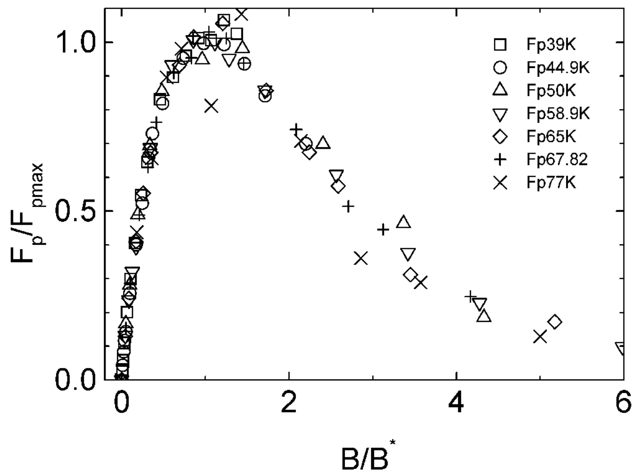

Fig. 2. The variation of pinning force density F_p (normalized to its maximum value F_{pmax}) for Bi2212 tape with magnetic field B (normalized to the field B^* at which $F_p = F_{pmax}$), for different temperatures marked on the graph.

Whereas the $J_c(T, B = 0)$ shows a $(1-t)^n$ variation with $n \approx 1.4$ at higher B, $J_c(T, B = const)$ curves decrease more rapidly with T, and cannot be fitted with the same law [3]. The $J_c - B - T$ surface for Bi2223 tape, shown in Fig. 1b, is quite similar to that for Bi2212 tape (Fig. 1a). However, the "crossover" to high temperature variation of J_c occurs in Bi2223 tape around $t = 0.55$ ($T = 59$ K). As illustrated in Figs. 2 and 3 for both tapes, the corresponding pinning force densities $F_p(= J_c B)$ show clear scaling with B when B is normalized to the value $B^*(T)$ at which F_p reaches its maximum F_{pmax} and F_p is normalized to F_{pmax}. Clearly, the same $B^*(T)$ leads to a scaling of the corresponding J_c vs. B curves (Fig. 4).

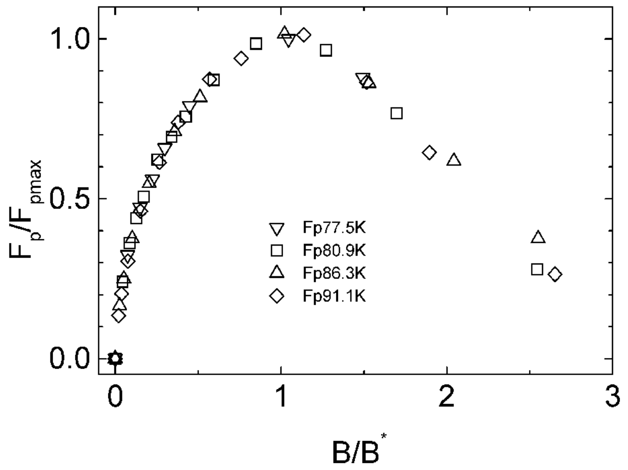

Fig. 3. F_p/F_{pmax} vs. B/B^* for Bi2223 tape for different temperatures denoted on the graph.

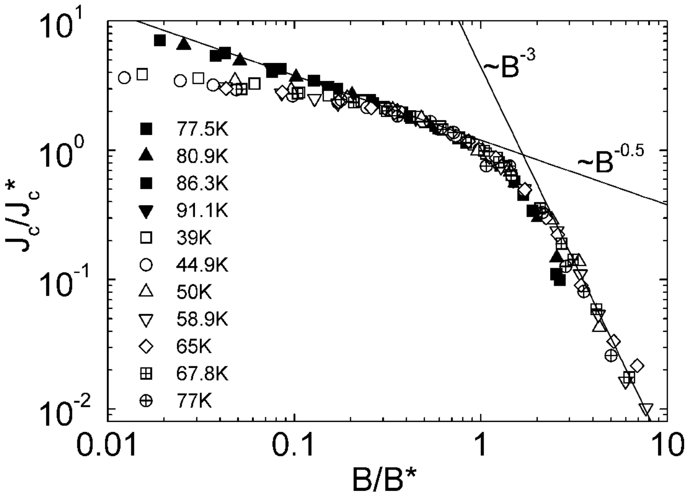

Fig. 4. Critical current density normalized to its value J_c^* at B^* (the field at which $F_p = F_{pmax}$) vs. B/B^* for the Bi2212/Ag (empty symbols) and Bi2223/Ag (full symbols) tape. Different symbols denote different temperatures. Lines illustrate B^α variations with $\alpha \approx -0.5$ and $\alpha \approx -3$ at low and high B, respectively.

Our maximum field $B = 1$ T limited the temperature range over which the scaling behaviour could be verified to $t \geq 0.55$ and 0.43 for the Bi2223 and Bi2212 tape, respectively. We note that any field proportional to $B^*(T)$ can also be used as the scaling field, for instance, a field B_0 at which F_p extrapolates (linearly) to zero [4] ($B_0 \approx (4-5)B^*$ for our tapes). The field B_0 can than be taken to approximate B_{irr}. The data in Fig. 4 indicate that, both well below and above B^*, $J_c(B)$ exhibits the asymptotic power law of $\sim B^\alpha$ variations with different exponents α for $B < B^*$ and $B > B^*$. In particular, for Bi2223 tape,

$\alpha \approx -0.5$ for $B < B^*$, and $\alpha \approx -3$ for $B > B^*$ was found. For Bi2212 tape and $B > B^*$, we found roughly the same α, but at low-field, power-law variation was less convincing (average $\alpha \approx -0.2$). The exponents α for our Bi2223 tape are the same as those obtained for high-J_c $YBa_2Cu_3O_{7-\delta}$ (hereafter YBCO) thin films [4,11] for $T \geq 40$ K. The epitaxial Bi2223 films [5] also exhibit the initial $J_c \sim B^{-0.5}$ variation, whereas the high-B high-T $J_c \sim B^{-3}$ variation seems common to HTS single crystals [7,12]. The B^{-3} variation is reminiscent of the large flux bundle regime in the weak collective pinning (WCP) theory [13]. For somewhat lower fields (small bundles), this theory predicts an approximate $\exp(-B^{3/2})$ variation of J_c, and finally, at low fields (pinning of single vortices), the field-independent J_c. Although at the intermediate fields ($0.5 \leq B/B^* < 3$) our data can be fitted to $\exp(-B^{3/2})$, at lower fields they show stronger instead of the expected [13] weaker field dependence. This discrepancy may arise due to the presence of some strong pinning centres (not included in the WCP model) and/or the granularity (weak links) of our samples.

Usually, the power-law increase of J_c for $B < B^*$ in tapes is attributed to weak links at the grain boundaries [14]. However, the presence of a similar upturn of J_c for $B < B^*$ in epitaxial films of HTS (which exhibit strong flux pinning [4]) seems to question this conjecture. Accordingly, there is no evidence that the power-law upturn of J_c below B^* is the consequence of the weak links only. Also, there is no evidence that the absence of such an upturn below B^* (the saturation of J_c) indicates the absence of weak links in the given material. In particular, since J_c is defined with some specified electric field value (E_c), its variation with B may only indicate whether the dissipation around E_c is dominated with depinning of vortices (flux creep) or with weak links (phase slips within the junctions and/or their transitions to the normal state). Clearly, rather low $J_c(B = 0)$ in tapes (as compared with those in the corresponding epitaxial films which are some ten to hundred times higher) indicates a rather poor coupling between the grains and, hence, the presence of weak links. However, at sufficiently low E_c, the current probably flows along the strongly coupled (percolative) path within the tapes, and the field dependence of J_c is likely to reflect the flux creep. Leaving aside this as yet unsolved problem of the low field variation of J_c in HTS tapes and epitaxial films, we will concentrate in the following on the observed scaling of J_c and F_p with B which is the central result of our study.

It seems unclear [15] whether the collective creep and vortex glass models [13] can explain the scaling of J_c with B^* or not. Also, the models explaining the scaling of F_p in the conventional type II superconductors [15] cannot be applied to HTS, since they ignore thermal effects. Accordingly, the scaling of F_p in HTSs is usually described in terms of phenomenological models, taking into account the thermal effects [4,5,11,15]. Without going into details of these approaches, we note that they predict the scaling field (usually taken to be B_{irr}) that increases with the pinning potential U_0. The comparison of U_0 values for our tapes (Table 1) with the corresponding fields B^* (Fig. 5) seems to support these predictions. In particular,

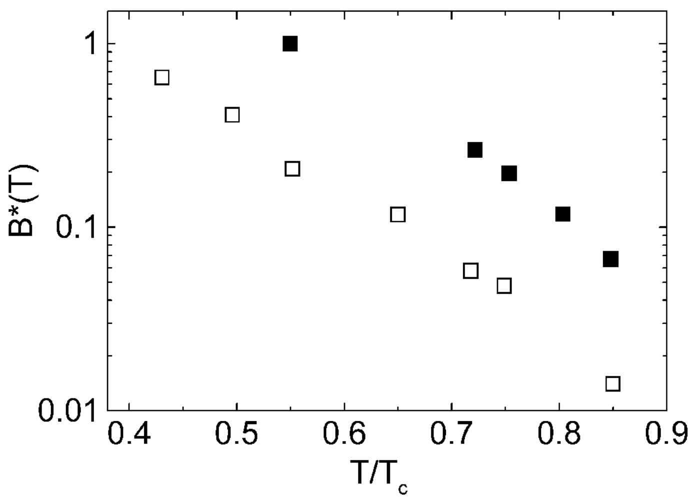

Fig. 5. The field B^* (at which $F_p = F_{pmax}$) vs. T/T_c for the Bi2212/Ag (□) and Bi2223/Ag (□) tape.

at the same value of t, the magnitude of B^* for the Bi2223 tape is about four times larger than that of the Bi2212 sample. The magnitudes of B^* for B in the plane of the tape were four (Bi2223) and seven (Bi2212) times larger than those for B perpendicular to the plane at the same t, what is consistent with better alignment of grains (smaller angle ϕ) in the Bi2212 sample than that in the Bi2223 tape (Table 1). The irreversibility fields B_{irr} of our tapes (determined from the resistive transitions by using the criterion $R/R_n = 0.005$, where R_n is the respective resistance in the normal state), behaved similarly to the corresponding B^*s (Fig. 5). Close to T_c, B^* for both tapes seems to follow a $(1-t)^n$ variation with $n \approx 2.3$. This is nearly the same dependence as that of the vortex-glass melting field B_g deduced from the $E - J$ curves for a Bi2223 tape [16]. Moreover, the reported values for B_g are roughly the same as B^* for our tape. In spite of this, it is not quite clear whether B^* is B_g or not. In particular, in these granular samples, a broad distribution of critical currents [17] makes the analysis of $E - J$ curves rather complex. Moreover, even the actual meaning of J (obtained by dividing measured I with the average cross-section area of the core) is rather uncertain if one considers the percolative current path, meandering along the well connected grains. Furthermore, B^* is not a crossover field, since J_c follows the same $\exp(-B^{3/2})$ variation both below and above B^* (Fig. 4). Therefore, it seems unlikely that the vortex glass melts at B^* in our tapes. The high-accuracy measurements of $V - I$ curves, and the extension of $J_c(B,T)$ measurements to higher fields, may help to elucidate this question. The observation that B_{irr} seems to follow the same temperature dependence as B^* allows to check whether the thermal activation of vortices over the energy barrier U can explain their variations or not. We note that our B_{irr} is determined from the resistance region where $R \sim \exp(-U/kT)$. Therefore, fixed R means $U/kT = const$. Inserting $U = U_0(1-t)/B^m$, which is appropriate both for our tapes [3,10] and the corresponding epitaxial films [5,6], we obtain $B_{irr} \sim ((1/t) - 1)^{1/m}$. Fig. 6 shows that both B^* and B_{irr} of Bi2212 tape follow quite well a $((1/t) - 1)^p$ variation with $p \approx 1/m$, where $m \approx 0.5$ is deduced from the variation of U_0 with B shown in the inset in Fig. 6. Since B^* and B_{irr} of our Bi2223 tape and the same t are considerably higher than those of Bi2212 tape (the corresponding U_0 is larger, Table 1), these data cover a smaller temperature range than those shown in Fig. 6. However, within this limited temperature range, they also seem to show a $((1/t)-1)^{1/m}$ variation.

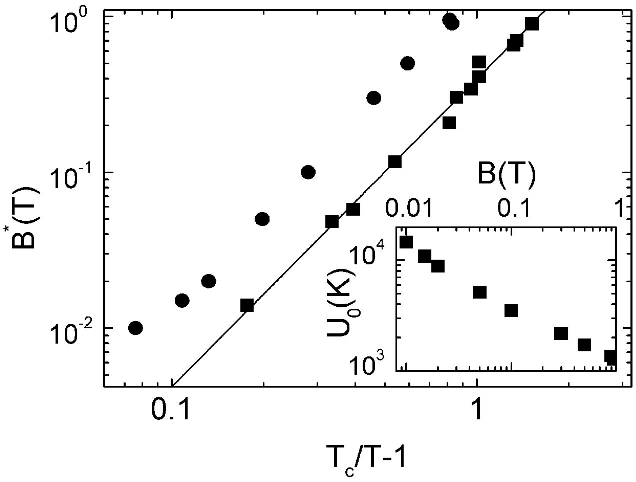

Fig. 6. Variation of scaling field B_{irr} (empty symbols) and B^* (at which $F_p = F_{pmax}$, full symbols) with $T_c/T - 1$ for Bi2212 tape. The inset: variation of pinning potential U_0 with field for the same tape.

The same type of variation of B_{irr} with t has also been observed in Bi2223 epitaxial films [18] and tapes [19]. Therefore, it seems likely that the thermal activation of the vortices over the barrier U determines the temperature variations of both B^* and B_{irr} in our tapes for $B \leq 1$ T and $t > 0.4$. Since J_c and F_p are unique functions of B/B^*, this implies that the same mechanism determines also the variations of these quantities at temperatures $T \geq 0.5\ T_c$. Although J_c is the unique function of B/B^*, this function is not quite the same for $B < B^*$ in the two tapes (Fig. 4). This results in different dependence of J_c and F_{pmax} with B^* in the two tapes. In particular, $F_{pmax} \sim (B^*)^k$, with $k \approx 1.5$ and 1.2 for the Bi2223 and Bi2212 tapes, respectively. As discussed earlier, it is not clear whether weak links or different pinning of vortices cause this difference in the low field variation of J_c in two tapes. The electron microscopy has indicated considerably larger defect density in Bi2223 tapes [20] than that in Bi2212 tape [21]. This finding together with the lower superconductivity anisotropy may explain higher U_0 in Bi2223 tape, but is unclear whether it can explain the difference in J_c vs. B variation for $B < B^*$ between the two tapes.

4. Conclusion

The systematic measurements of the variations of J_c with B and T for Bi-based Ag-sheathed tapes yield the $J_c - B - T$ surfaces which bear all the information required for their practical applications. Over a broad temperature range $T/T_c \geq 0.5$, J_c and F_p in these materials show clear scaling with B. Since the temperature variation of the scaling fields B^* and B_{irr} seems determined with the thermal activation of vortices, the same probably applies to J_c and F_p of these materials. Rather strong thermal reduction of these quantities is consistent with a high anisotropy of these compounds, and rules out the high-B high-T applications of these tapes (unless the extrinsic strong pinning centres are introduced). Since the homogeneous HTS show a similar scaling of J_c with B, the well prepared tapes can be used for the high-accuracy transport studies of the vortex states and pinning in HTS. Since at lower temperatures the thermal activation of vortices should become less important, the extension of these measurements to higher fields (lower temperatures) is very important for the understanding of the pinning mechanisms(s) in Bi2212 and Bi2223 tapes. Furthermore, the accurate studies of the critical current distributions within the tapes are required in order to understand the effects of microstructure (grain connectivity) on $J_c - B - T$ surfaces of these materials.

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TERMIČKI UTJECAJ NA $J_C - B - T$ PLOHE SREBROM OBLOŽENIH SUPRAVODLJIVIH VRPCI NA OSNOVI BIZMUTA

Proučavane su $J_c - B - T$ plohe srebrom obloženih $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212) i $(Bi, Pb)_2Sr_2Ca_2Cu_3O_{10+x}$ (Bi2223) vrpci u području temperatura 4.5 – 100 K i magnetskog polja $B \leq 1$ T. $J_c(T,B)$ i gustoća sile zapinjanja $F_p = J_cB$, u obje vrste vrpci, pokazuju normiranje slično onom u monokristalima i epitaksijalnim slojevima visokotemperaturnih supravodiča, za temperature $T \leq 0.5$ T_c. Paralelno istraživanje potencijala zapinjanja U_0 i ireverzibilnih polja B_{irr} (odredenih iz otpornih prijelaza u magnetskom polju) pokazuju da aktivacijske barijere $U = U_0(1 - T/T_c)/B^m$ odreduju veličine i temperaturne ovisnosti normirajućih polja B^* (definiranih s $F_p = F_{pmax}$) i B_{irr}. Znatno veći U_0 za Bi2223 traku u usporedbi s onim Bi2212 trake, pripisuje se nižoj anizotropiji tog spoja i višem stupnju strukturnih nesavršenosti. Medutim, u obje vrste vrpci zapinjanje magnetskih vrtloga nije dovoljno za njihove primjene u jakim poljima i pri visokim temperaturama.