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Study of current–voltage characteristics of Bi-based high-temperature superconductors with fractal cluster structure

K.A. Shaykhutdinov [a,*], D.A. Balaev [a], D.M. Gokhfeld [a], Yu.I. Kuzmin [b], S.I. Popkov [a], M.I. Petrov [a]

[a] *Kirensky Institute of Physics, 660036 Akademgorodok, Krasnoyarsk, Russia*
[b] *Ioffe Physical-Technical Institute, 194021 Polytechnicheskaya St., 26, St.-Petersburg, Russia*

Abstract

We study the effect of the structure on critical currents and current–voltage characteristics (CVC's) of foamed bismuth-based polycrystalline high-temperature superconductors (HTSC). The fractal cluster structure of superconducting foams has been observed and the fractal dimension of boundaries between superconducting and normal clusters has been determined. Based on the magnetic and transport properties of the foamed polycrystalline superconductors, we have shown that the initial parts of CVC's of the superconducting foams are described well by the model that accounts the magnetic flux trapping in fractal clusters of a normal phase.

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Keywords: Superconducting foam; Pinning; Critical current density; Fractal; Percolation; Cluster

1. Introduction

Recently fabricated superconducting foams [1,2] can be considered as the representatives of a new class of superconducting materials with interesting physical properties [3–5]. A foam structure superconductor represents a percolation system that consists of an infinite superconducting cluster carrying transport current, as well as of interstices with varying geometry. The interstices, which can be opened or closed, also form clusters that support magnetic flux flow. At a certain range of the material density the percolation superconducting cluster can coexists with the non-superconducting cluster of the open interstices. The effect of such topology of the percolation clusters on flux pinning and transport properties of superconducting foams has not been studied before and will be discussed in this paper. Porous superconducting materials are also attractive from the practical point of view. The porous structure of these materials facilitates heat exchange between HTSC crystallites and refrigerating media and prevents the formation of hot-spots, which increases the current-carrying capability. This feature, along with a number of other special characteristics that have not been completely studied yet [4,5], causes high values of magnetization critical currents, making these materials promising candidates for practical applications.

2. Experimental

The samples of bulk polycrystalline $Bi_{1.8}Pb_{0.3}Sr_2Ca_2Cu_3O_x$ (BPSCCO) with low density were prepared by solid-state reaction technique. The sintering time was 400 h [6]. The preparation technique was described in detail previously [7], but we changed the final heat treatment which causes dominant growth of HTSC crystallites in *ab* plane. Due to random orientation of the crystallites, this growth led to an increase in the material volume. Moreover,

* Corresponding author.
E-mail address: smp@iph.kr.asn.ru (K.A. Shaykhutdinov).

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the final decomposition of calcium carbonate occurred during the final heat treatment. The overpressure of carbonic gas at this process also leads to the increase in the material volume. The scanning electron microscopy images (SEM) of three natural chips of foam BPSCCO are shown in Fig. 1. The density of the material obtained was 2.26 g/cm^2 (38% of the theoretical one for bulk BPSCCO). Because of the flatness of BPSCCO crystallites the superconducting foam has a distinctive flaky structure which has significantly more branches than YBCO based superconducting foams [2,4]. The SEM results (Fig. 1) confirm the existence of three-dimensional superconducting percolation cluster in the BPSCCO foam which consists of flat crystallites with the width of 10–20 μm and thickness of 1–2 μm. Possible current trajectories are shown schematically in Fig. 1b. The interstices are clearly seen between the crystallites. The analysis of SEM images shows the fractal cluster structure of the superconducting foam. To determine the fractional dimensions of boundaries of the normal phase clusters we measured the perimeters and areas of the clusters by covering the SEM images (Fig. 1) with square grids of spacing $L \times L$ where L is varied in the range from 75 to 1200 nm. Fractal dimension of boundaries of normal phase clusters was calculated using the following formula [8]:

$$D = \frac{\ln N(L)}{\ln(L_{\max}/L)}, \quad (1)$$

where $N(L)$ is the number of squares of spacing $L \times L$ with boundaries of normal phase and $L_{\max}$ is maximum square length. The obtained value of fractal dimensions of the boundaries of the normal phase clusters is $D = 1.80 \pm 0.06$, which lies between the extreme cases of Euclidean clusters ($D = 1$) and clusters of the most fractality ($D = 2$). This means that the fractal properties of the cluster boundaries play an important role at the study of the transport properties of superconducting foams.

Current–voltage characteristics (CVC's) of bulk polycrystalline $Bi_{1.8}Pb_{0.3}Sr_2Ca_2Cu_3O_x$ (BPSCCO) with low density were measured by the standard four-probe technique at fixed current conditions; cross section of the central part of the samples was $\sim 1 \times 1.5$ mm^2; the length of the sample was $\sim$10 mm. To avoid the self-heating effects the cell with the sample was dipped into the liquid helium or nitrogen bath. To obtain the low-resistance current and potential contacts we burnt the superdispersed silver into contact pads area. The contact resistance obtained was less than 10^{-4} Ω cm^2. Magnetic measurements were performed using the vibrating sample magnetometer with a superconducting solenoid.

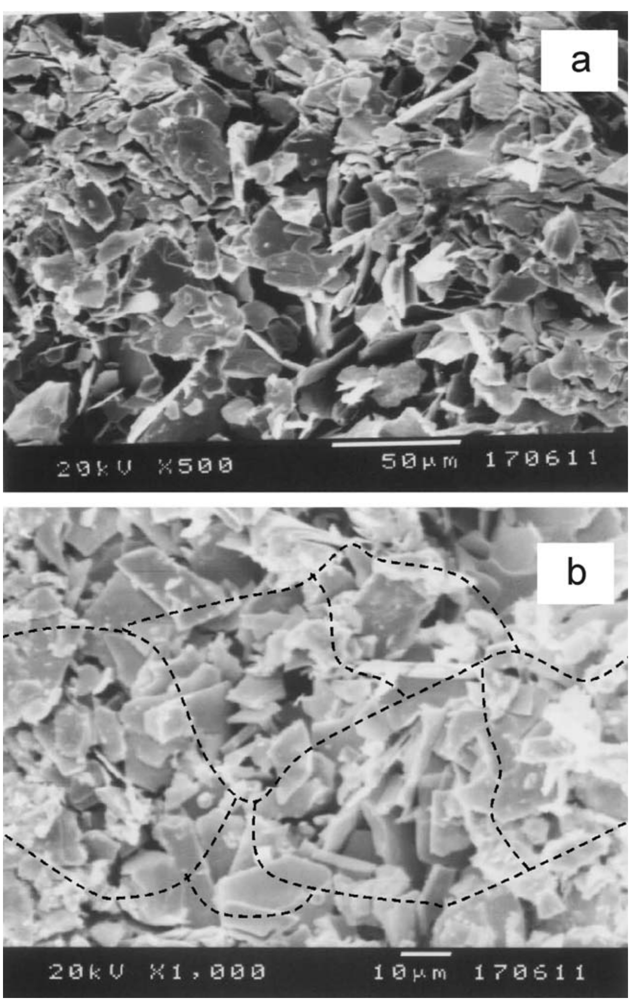

Fig. 1. SEM images of two different natural chips of superconducting foam BPSCCO with different magnifications 500× (a) and 1000× (b). A possible current trajectories by superconducting percolation cluster is shown in (b) also.

3. Results and discussion

Fig. 2 shows temperature dependence of resistivity $\rho(T)$ of the foam BPSCCO in temperature range of 77–300 K. The transition temperature of the foam BPSCCO is 107 K (see the insert in Fig. 2). Fig. 3 presents hysteretic loops (magnetization vs. magnetic field $M(H)$) of the foam $Bi_{1.8}Pb_{0.3}Sr_2Ca_2Cu_3O_x$ (a) and $M(H)$ dependence of bulk

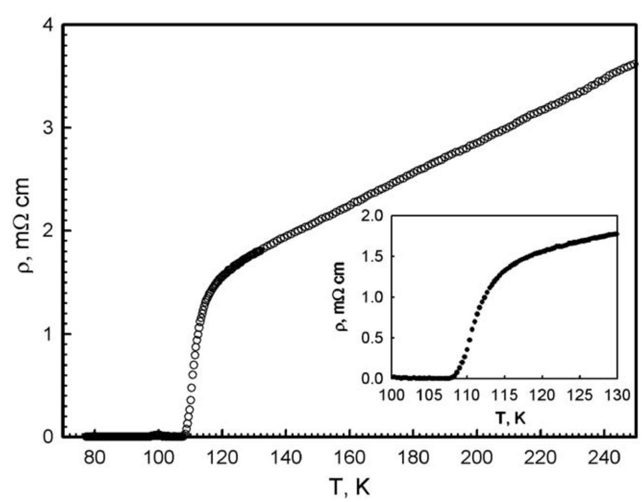

Fig. 2. Temperature dependence of resistivity $\rho(T)$ of the foam BPSCCO.

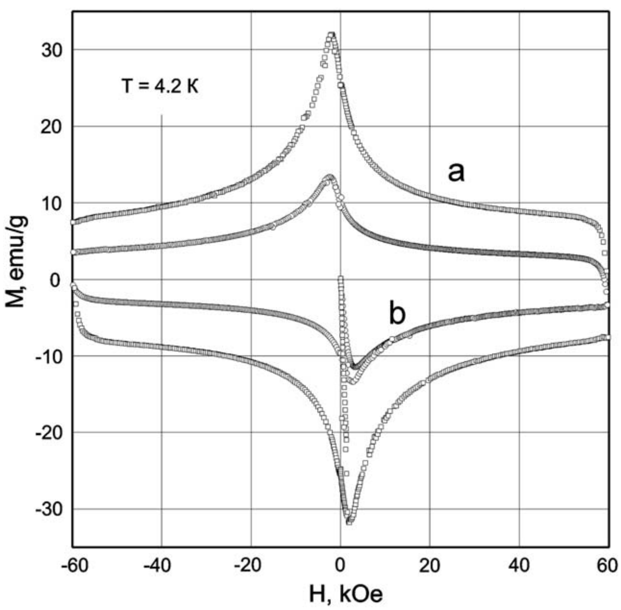

Fig. 3. Hysteretic loops $M(H)$ of the foam $Bi_{1.8}Pb_{0.3}Sr_2Ca_2Cu_3O_x$ (a) and $M(H)$ dependence of bulk polycrystalline $Bi_{1.8}Pb_{0.3}Sr_2Ca_2Cu_3O_x$ with nominal density (b).

polycrystalline $Bi_{1.8}Pb_{0.3}Sr_2Ca_2Cu_3O_x$ with nominal density (5.83 g/cm^3) (b) measured at $T = 4.2$ K.

The polycrystalline bulk $Bi_{1.8}Pb_{0.3}Sr_2Ca_2Cu_3O_x$ with nominal density was prepared from the foamed superconductor in order to compare their transport and magnetic properties. The $Bi_{1.8}Pb_{0.3}Sr_2Ca_2Cu_3O_x$ with low density was milled, pressed as a pellet and annealed at 930 °C for 12 h. The density of the material obtained was 5.83 g/cm^3 which is 98% from the theoretical density of $Bi_{1.8}Pb_{0.3}Sr_2Ca_2Cu_3O_x$. The form of the $M(H)$ curves (Fig. 3) is the same whereas the value of diamagnetic response (in units of emu/g) of foam BPSCCO is 2.4 times higher than that of the bulk BPSCCO. Equivalent magnetization critical current density of the foam superconductor derived according to Bean model is appeared to be 340 kA/cm^2 at $T = 4.2$ K which is 1.6 times higher than critical current density of the bulk BPSCCO superconductor due to more effective pinning in superconductors with fractal cluster structure of the normal phase clusters.

Fig. 4 shows CVC's of the foam BPSCCO measured at temperatures $T = 4.2$ K and $T = 77$ K, which have non-linear form typical for polycrystalline HTSC. The initial part of the CVC's curves, where the non-zero voltage drop appears, is of particular interest. Starting from this part, the vortices break away from pinning centers by Lorenz force, which finally causes the full destruction of superconductivity. Superconductors with isolated clusters of the normal phase provide the effective pinning due to magnetic flux flow trapped in this clusters, and vortices can not leave this clusters omitting the superconducting space. When transport current increases, the vortices break away from the clusters with pinning force less than Lorenz force. Thus, the depinning has the percolation character with vortices moving out by random transport channels [9–11]. The clusters of the normal phase provide significant effect on the dynamics of trapped magnetic flux flow in case if they have fractal boundaries [12,13]. This effect is caused by structural irregularity of fractal clusters having very huge dispersion of geometrical sizes where the vortices pins on. This provides strong interaction of the vortices with such clusters effectively trapping magnetic flow.

The analysis of the effect of fractal clusters of the normal phase on magnetic and transport properties of the percolation superconductors described in detail lately [12–15]. It have been shown that the pinning enhances with increase of the dimension of the normal phase clusters boundaries. In case of the exponential–hyperbolic distribution of the critical currents the CVC's of the superconductors with fractal clusters of the normal phase can be written as [15]:

$$u = r_f \left[i \exp\left(-\left(\frac{2+D}{D}\right)^{2/D+1} i^{-2/D} \right) - \left(\frac{2+D}{D}\right)^{(2+D)/2} \Gamma\left(1 - \frac{D}{2}, \left(\frac{2+D}{D}\right)^{2/D+1} i^{-2/D}\right) \right], \quad (2)$$

where u is dimensionless voltage, r_f is dimensionless flux flow resistance, $i \equiv I/I_c$ is the dimensionless current normalized on the critical current of the transition into resistive state I_c and $\Gamma(v,z)$ is the complementary incomplete gamma function. The value of the critical current of the transition into resistive state I_c is defined by the intersection of the abscissa and the tangent which traced through the inflection point of the differential resistivity vs. current curve. The value of the critical current I_c defined in such a way exceeds the critical current defined by the voltage criterion. The dimensionless voltage u and dimensionless flux flow resistance r_f are in agreement with dimension values U and R_f by the relation $U/R_f = I_c(u/r_f)$.

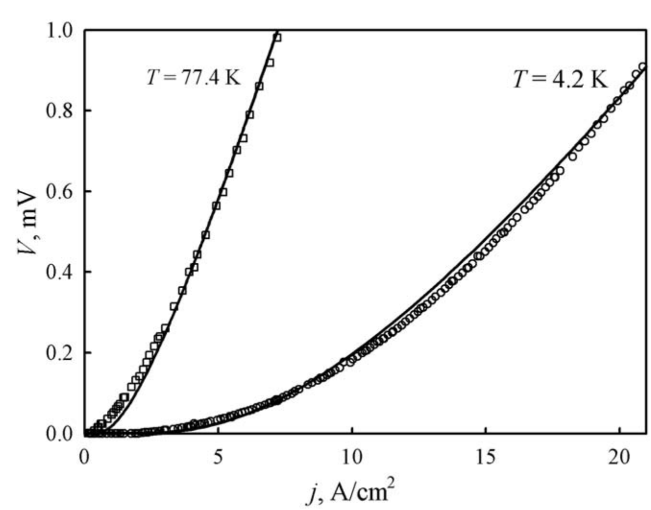

Fig. 4. CVC's of superconducting foam BPSCCO. Circles—experimental data, solid lines—the theoretical dependences obtained according to Eq. (2) at fractal dimension of clusters of the normal phase $D = 1.8$.

The theoretical CVC's calculated for investigated samples using Eq. (2) are presented in the Fig. 4 (solid curves). We used the obtained value of the fractal dimension of the boundaries of the clusters of the normal phase. The values of the critical current density of the resistive transition and the flux flow resistance were the fitting parameters. Good agreement with experimental CVC's achieves at the following parameters: $D = 1.8$, J_c (4.2 K) = 2.5 A/cm^2, R_f (4.2 K) = 0.11 mΩ cm^2, J_c (77 K) = 0.4 A/cm^2, R_f (77 K) = 0.228 mΩ cm^2. We used the temperature dependence of flux flow resistance $R_f(T) = R_{f0}/(1 - (T/T_c)^2)$ [16] during fitting procedure. The value R_f indicated in units mΩ cm^2 due to the current density j (see Fig. 4) showing in units A/cm^2. A satisfactory agreement between the initial part of the experimental CVC's curves for the foam BPSCCO and theoretical ones is clearly seen. At higher values of the current the discrepancy between the experimental and the theoretical curves is observed. The possible reason of this difference can be modification of the fractal dimension of the cluster boundaries with increase of transport current.

In conclusion, it should be noted that the experimental current–voltage characteristics of polycrystalline HTSCs can be described by other models [16–18]. However, on author's opinion, the application of the model of the superconductors with the fractal clusters of the normal phase is more correct because this model reflects the effect of real structure of the superconducting foams on the critical currents of depinning and on the form of CVC's.

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References

[1] E.S. Reddy, G.J. Schmitz, Supercond. Sci. Technol. 15 (2002) 21.
[2] E.S. Reddy, M. Herweg, G.J. Schmitz, Supercond. Sci. Technol. 16 (2003) 608.
[3] M.I. Petrov, T.N. Tetuyeva, L.I. Kveglis, et al., Tech. Phys. Lett. 29 (2003) 986.
[4] E. Bartolomé, X. Granados, T. Puig, X. Obradors, E.S. Reddy, G.J. Schmitz, Phys. Rev. B 70 (2004) 144514.
[5] E. Bartolomé, X. Granados, T. Puig, X. Obradors, S. Reddy, J. Noudem, Critical state of YBCO superconductors with artificially patterned hole structures, in: Proc. 2004 Int. Applied Superconductivity Conf., ASC'2004, Jacksonville, FL, USA, 3–8 October 2004, Material Session, p. 52.
[6] M.I. Petrov, D.A. Balaev, K.A. Shaykhutdinov, et al. Patent of Russian Federation, RU N2004104966/03(005126).
[7] V.S. Kravchenko, M.A. Zuravleva, E.M. Uskov, P.P. Bezverkhii, N.A. Bogolybov, O.G. Potapova, Neorganicheskie Mater. 34 (1998) 1274 (in Russian).
[8] B.B. Mandelbrot, Fractals: Form, Chance, and Dimension, Freeman, San Francisco, 1977.
[9] K. Yamafuji, T. Kiss, Physica C 258 (1996) 197.
[10] M. Ziese, Physica C 269 (1996) 35.
[11] M. Ziese, Phys. Rev. B 53 (1996) 12422.
[12] Yu.I. Kuzmin, Phys. Rev. B 64 (2001) 094519.
[13] Yu.I. Kuzmin, Phys. Lett. A 281 (2001) 39.
[14] Yu.I. Kuzmin, Phys. Lett. A 300 (2002) 510.
[15] Yu.I. Kuzmin, J. Low Temp. Phys. 130 (2003) 261.
[16] A. Kilic, Supercond. Sci. Technol. 8 (1995) 497.
[17] R. Kümmel, U. Gunsenheimer, R. Nicolsky, Phys. Rev. B 42 (1990) 3992.
[18] M.I. Petrov, D.M. Gokhfeld, D.A. Balaev, K.A. Shaihutdinov, R. Kümmel, Physica C 408 (2004) 620.