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Fractal Boundaries of Vortex Pinning Clusters in Copper-oxide Superconductors in Magnetic Field

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The influence of fractal boundaries of a normal phase clusters on the flux creep in the copper-oxide high-temperature superconductors YBCO was investigated. A model of the magnetic-field dependence of the voltage due to flux creep for different transport currents was developed. To describe the experimental curves is proposed to use an exponential-hyperbolic function in which the argument is direct current. Empirical dependence of the fractal dimension of the cluster boundaries on the magnetic field strength was determined. The characteristic values of the magnetic field were found. The index of connectivity of the flux creep paths at the percolation threshold was calculated.

Keywords: superconductivity, normal phase clusters, fractal boundaries, flux creep.

The boundaries of different areas in samples of weakly coupled superconductors play an important role, resulting in both a decrease and an increase of the critical current. The network of weak links has a fractal structure as in the whole volume of the sample and on the boundaries of various defects or inclusions. Fractal properties have been found in many copper-oxide high-temperature superconductors (HTSC) experimentally based on resistive measurements [1, 2] and the direct supervision of using a magneto-optical technique [3–5]. Modeling of properties copper-oxide HTSC is also possible with the help consideration of their fractal features [6–8].

Magnetic field parameters peculiarities the copper-oxide HTSC depend on at least of three factors: 1) distribution of inhomogeneities on the areas, 2) changes in the boundaries of these inhomogeneities, 3) changes in the network of weak links throughout the sample. All of these factors significantly associated with the fractal properties of the boundaries of the normal phase clusters. Such clusters are formed as by irradiating the samples with heavy ions, and during film growth or sintering of polycrystalline bulk samples [8–11].

The peculiarities of the normal phase clusters were considered in detail in papers [12–15]. In the article [8] it was found that the DC magnetic field strongly influences on the fractal dimension of the boundaries of the normal phase clusters. This is due to the formation of weak links and structural defects generated easily in HTSC because of the short coherence length in these materials. With increasing field strength from ≈ 50 Oe to ≈ 200 Oe fractal dimension increased from 1.2 to 1.9. Determination of the fractal dimension was done by fitting of the

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experimental dependences of the first harmonic voltage from DC (proportional to the differential resistance at low currents) with help exponential-hyperbolic function. Parameter of this function was the fractal dimension.

In this paper we investigate the magnetic field dependence of the first harmonic of the voltage at different currents. Here direct current uses as a parameter, and the magnetic field dependence is mediated by fractal dimension of the boundaries of the normal phase clusters.

Samples of the copper-oxide HTSC $YBa_2Cu_3O_{7-x}$ (YBCO) were prepared by the standard method of solid-phase synthesis of initial oxides. The density of polycrystalline samples was 4.18 g/cm^3. The temperature of the superconducting transition was $T_c \approx 92.0$ K. The transition width was $\Delta T \approx 1.5$ K. Investigations were carried out at a temperature T ≈ 77 K with help of four-contacts method. Contact resistance was less than 3 mΩ. Through the current contacts are skipped DC and AC currents. From potential contacts was measured voltage. The first voltage harmonic was allocated by selective amplifier. More measurement technique in paper [16] is described.

Fig. 1 shows the dependence of the fractal dimension of the boundaries of the normal phase clusters D on strength of DC magnetic field H. The dependence D(H), obtained in [8] (black circles), was approximated by the function (solid line):

$$D = 2/[\exp(-(H - H_1)/H_0) + 1], \tag{1}$$

where $H_0 = 40$ Oe and $H_1 = 36$ Oe are the field strengths, is the characteristic of the given sample.
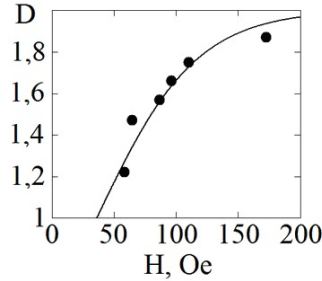

Fig. 1. The dependence of the fractal dimension of the normal phase clusters on the magnetic field strength. Black circles are the data obtained in paper [8], solid line is empirical dependence (equation (1))

Fig. 2 shows the experimental dependence of the amplitudes of the first voltage harmonic V_1 for YBCO sample on the magnetic field strength (black circles) for different values of DC. The approximation V_1(H) is made by using an exponential-hyperbolic function found for V_1(i) of the same sample in paper [8]:

$$V_1 = R_d I_a = I_a[R_{d1} \exp(-C_1 C_0 i^{-\mu}) + R_{d2} \exp(-C_2 C_0 i^{-\mu})], \tag{2}$$

where i $= I_d/I_c$ is the relative current, I_d is the d$_c$ current, $I_c = 316$ mA is the critical current at H $= 0$, $R_d = (dV/dI_d)$ is the differential resistance, $I_a = 27$ mA is the amplitude of the alternating current, $C_0 = (1+1/\mu)^{\mu+1}$, $\mu = 2/D(H)$ is the glassy state index [15], $C_1 = 0.02$, $C_2 = 0.14$, $R_{d1} = 0.012$ mΩ, $R_{d2} = 0.78$ mΩ.
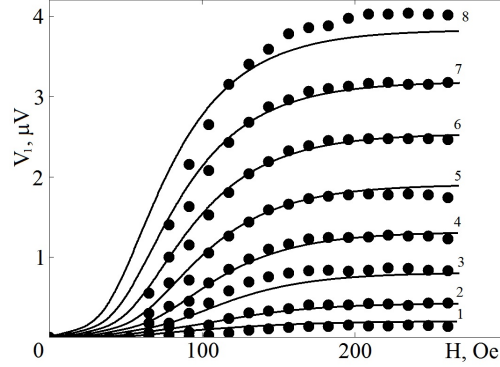
Fig. 2. Dependence of the amplitudes of the first voltage harmonic on magnetic field for different values of DC. Black circles are the experimental dependences, solid lines are the theoretical curves calculated by the formula (2). The numerals represent different values DC: $I_d = 30$ mA (1), $I_d = 40$ mA (2), $I_d = 50$ mA (3), $I_d = 60$ mA (4), $I_d = 70$ mA (5), $I_d = 80$ mA (6), $I_d = 90$ mA (7), $I_d = 100$ mA (8). Measurement error is equal to the diameter of the circle

The function $V_1(H)$ is caused by the magnetic field dependence of the fractal dimension $D(H)$, and thus the glassy state index μ, the value of which in this case ranges from 1 to 2. This corresponds to a creep bundles of vortices in the sample [15].

Two terms in formula (2) are necessary due to quantitative differences intragranular and intergranular differential resistance of the polycrystal. Distribution functions of defects on the areas and fractal dimension of their boundaries do not depend on whether they are inside of granules or between them.

The value $R_{d1} = 0.012$ mΩ in this approximation was reduced when compared to the value found in paper [8]. This is due to the lack of resistance for the values of the field strength of less than 50 Oe. Zero resistance in the beginning of the dependence $V_1(H)$ is caused largely due to the formation of the hypervortices in the sample [17]. Therefore, the beginning of the increasing of voltage is determined by two processes: hypervortices decay into individual Josephson vortices and increase of fractality clusters of the normal phase with increasing field.

For the analysis of nonlinear dynamic systems can use the concept of nonequilibrium (quasi)stationary states with the topology of a percolating fractal set [18]. In this case, one of the main characteristics of the system is connectivity index θ. At the percolation threshold connectivity index of the fractal can be identified by its fractal dimension:

$$\theta = 2(D/d_s - 1), \tag{3}$$

where d_s is the spectral fractal dimension.

Since at the percolation threshold $d_s = C \approx 1.327$ [18], it follows from (3) we can determine the values of the connectivity index for different values of the fractal dimension. In this case (Fig. 1) D varies from 1.2 to 1.9, which corresponds to a change of the connectivity index θ from -0.2 to 1.43. If $D = C \approx 1.327$, then θ changes sign from minus to plus, which means the transition from disconnected to connected systems, ie beginning of percolation. This value of the fractal dimension corresponds to the magnetic field strength ≈ 60–70 Oe. This corresponds to the beginning vortex penetration into granules of polycrystalline YBCO.

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Фрактальные границы кластеров пиннинга вихрей в меднооксидных сверхпроводниках в магнитном поле

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Исследовано влияние фрактальных границ кластеров нормальной фазы на крип потока в меднооксидном высокотемпературном сверхпроводнике YBCO. Разработана модель магнитополевой зависимости напряжения, обусловленного крипом потока, для разных транспортных токов. Для описания экспериментальных зависимостей предложено использовать экспоненциально-гиперболическую функцию, в которой параметром является ток. Определена эмпирическая зависимость фрактальной размерности границ кластеров от напряжённости магнитного поля. Найдены характерные значения напряженности магнитного поля. Вычислен индекс связности путей срыва вихрей на пороге перколяции.

Ключевые слова: сверхпроводимость, кластеры нормальной фазы, фрактальные границы, крип потока.