Initial dissipation and current-voltage characteristics of superconductors containing fractal clusters of a normal phase

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The influence of fractal clusters of a normal phase on distinctive features of current-voltage (U-I) characteristic of percolative type-II superconductors is considered. The results of high-resolution measurements of the differential resistance of BPSCCO/Ag composites are discussed in the context of magnetic flux dynamics. The region of initial dissipation is observed on U-I characteristics in the neighborhood of the transition into a resistive state. In the course of this stage of resistive transition the vortices start to break away from the normal-phase clusters, which act as pinning centers. The effect of transport current on vortex depinning is investigated. A broad current range of initial dissipation is considered as an evidence of fractal nature of the normal-phase clusters.

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I. INTRODUCTION

Superconductors containing fractal clusters of a normal phase have specific magnetic and transport properties. The study of their U-I characteristics enable to get new information on the electromagnetic properties as well as on the nature of a vortex state in such materials. The neighborhood of resistive transition, especially its initial stage where the energy dissipation sets-in, is of special interest. In this region the process of vortex depinning gradually accrues resulting finally with the destruction of a superconducting state.

The problem of initial dissipation in high-temperature superconductors (HTS’s) has been studied by many authors. The residual resistance of bismuth-based HTS’s [Bi2Sr2CaCu2O8+y (BSCCO-2223) and Bi2Sr2CaCu2O10+y (BSCCO-2212)] at small currents has been explained by deterioration of grain boundaries, by initiation of micro-cracks which can act as chains of weak links as well as by the grain-to-grain misalignment or by degradation of the grains themselves. A strong influence of transfer resistance between superconducting and normal metal on U-I characteristics of silver-sheathed BSCCO-2223 tapes has been found. The ohmic behavior of U-I curve on the initial stage of resistive transition in BSCCO-2223 and BSCCO-2212 has been attributed to the local transfer of excess current into the normal metal inclusions. The fractal regime in the initial stage of dissipation has been observed in BSCCO-2223, YBa2Cu3O7−x and GdBa2Cu3O7−x. The fractal nature of the normal-phase clusters contained in YBa2Cu3O7−x thin films has been found and the effect of such clusters on vortex dynamics has been analyzed. In the present work we consider the influence of the fractal clusters of a normal phase on the initial part of U-I characteristic near the resistive transition.

II. STATEMENT OF A PROBLEM

Let us consider a superconductor containing inclusions of a normal phase, which are out of contact with one another. We will suppose that the characteristic sizes of these inclusions far exceed both the superconducting coherence length and the penetration depth. A prototype of such a structure is the superconducting wire or tape armored by normal metal for giving the necessary electrical and mechanical properties. Concrete example is the silver-sheathed HTS bismuth-based composites, which are of practical interest for energy transport and storage.

When electric current is passed through such a material, it flows through a superconducting percolative cluster. A specificity of the problem is that the percolative cluster consists of mesoscopic superconducting islands joined by weak links. As the transport current is increased, the local currents flowing through ones or other weak links begin to exceed the critical values, some part of them become resistive. Thus, the number of weak links involved in the superconducting cluster is randomly reduced so the transition of a superconductor into a resistive state corresponds to breaking of the percolation through a superconducting cluster. The transport current acts as a random generator that changes the relative fractions of conducting components in classical percolative medium, hence the resistive transition can be treated as a current-induced critical phenomenon.

On the other hand, the dissipation of energy in a superconductor is linked with the vortex dynamics as any motion of a magnetic flux induces an electric field. In HTS’s the vortex motion is of special importance because of large thermal fluctuations existing at high temperatures and small pinning energies. The magnetic flux can move only after the vortices will be broken away from the pinning centers. Until the moment when the Lorentz force...
created by a transport current will exceed the pinning force the magnetic flux remains trapped in normal-phase clusters. These clusters present the sets of normal-phase inclusions, united by the common trapped flux and surrounded by the superconducting phase. In such a system depinning has a percolative character because vortex transport can be created by weak links which form readily in HTS’s due to the intrinsically short coherence length. Depending on the specific weak link configuration each normal-phase cluster has its own current of depinning, which contributes to the total statistical distribution of critical currents. Thus, the weak links do not only connect superconducting clusters between themselves, maintaining the electrical current percolation, but they also form the channels for vortex transport so providing for the percolation of magnetic flux.

The depinning current of each cluster is related to the cluster size, because the larger cluster has more weak links over its boundary with the surrounding superconducting space, and thus the smaller current of depinning. As a measure of the cluster size we will take the area of its cross-section, and in the subsequent text we will call this value simply “the cluster area”. In the general case the distribution of the cluster areas may be described by gamma distribution with the probability density

\[ w(a) = \frac{(g + 1) g^{g+1}}{\Gamma(g + 1)} a^g \exp[-(g + 1) a] \tag{1} \]

where \( \Gamma(\nu) \) is Euler gamma function, \( a \equiv A/\bar{A} \) is the dimensionless area of the cluster, \( A \) is the area of the cross-section of the cluster by the plane, transversally to which the vortices are moving, \( A_0 > 0 \) and \( g > -1 \) are the parameters of gamma distribution that control the mean area of the cluster \( \bar{A} = (g + 1) A_0 \) and its variance \( \sigma_\bar{A}^2 = (g + 1) A_0^2 \). The mean dimensionless area of the cluster is equal to unity, whereas the variance is determined by \( g \)-parameter only: \( \sigma_\bar{A}^2 = 1/(g + 1) \).

In order to use the formulas for \( U-I \) characteristics obtained in Refs. 13,14 for the case of thin films with clusters of columnar defects, it is necessary to assume that all the entry points into weak links are distributed uniformly along extended parts of the normal-phase inclusions. The problem setting for armored superconducting wires has some distinctive features: (i) the fragments of a normal phase has the form of extended inclusions oriented along an axis of the wire; (ii) the magnetic flux is created by the transport current itself and is concentrated along irregular-shaped rings, which are deformed in such a way that the normal-phase clusters would be most captured; (iii) the vortices are transferred through the weak links connecting long parts of the normal-phase inclusions between themselves.

Gamma distribution of the cluster area of Eq. 1 gives rise to exponential-hyperbolic distribution of depinning currents, for which \( U-I \) characteristic has the form.

\[ U = \frac{r_f}{\Gamma(g + 1)} \left[ i \Gamma \left( g + 1, G i^{-2/D} \right) - G^{D/2} \Gamma \left( g + 1 - \frac{D}{2}, G i^{-2/D} \right) \right] \tag{2} \]

where

\[ G \equiv \left[ \theta^{\theta+1} - (D/2) \exp(\theta) \Gamma(g + 1, 1, \theta) \right]^{\frac{1}{\theta}} \]

\( \theta \equiv g + 1 + D/2, i \equiv I/I_c \) is the dimensionless electrical current normalized to the critical current of the transition into a resistive state \( I_c = \alpha (A_0 G)^{-D/2} \), \( \alpha \) is the form factor, \( D \) is the fractal dimension of the cluster boundary, \( \Gamma(\nu, z) \) is the complementary incomplete gamma function. The voltage across a sample \( U \) and flux flow resistance \( R_f \) are linked to the corresponding dimensionless quantities \( u \) and \( r_f \) by the formula: \( U/R_f = I_c (u/r_f) \).

The \( U-I \) characteristics in the simplest case of \( g = 0 \), when gamma distribution of Eq. 1 is reduced to the exponential one, \( w(a) = \exp(-a) \), are shown in Fig. 1. This figure demonstrates that in the range of the currents \( i > 1 \) the fractality of the clusters reduces the voltage arising from magnetic flux motion. Meanwhile, the situation is different below the critical current. When \( i < 1 \), the higher the fractal dimension of the normal phase cluster is, the larger is the voltage across a sample and the more stretched is the region of initial dissipation on \( U-I \).
III. EXPERIMENT

For experimental study of initial dissipation the high-resolution measurements of differential resistance of HTS composites (BiPb)$_2$Sr$_2$Ca$_2$Cu$_2$O$_{10+y}$ containing inclusions of silver (BPSCCO/Ag) were carried out. The samples had the form of silver-sheathed tapes with superconducting core. These tapes were prepared following a conventional “powder-in-tube” technique. Magneto-optical micrographs of such tapes are given in Refs. [13] [14] [15]. The superconducting core inevitably contains the normal-phase inclusions of Ag as well as different secondary phases (the degraded non-stoichiometric material, grain boundaries, voids, cracks, impurities, etc.). The volume content of the normal phase in the core was far below the percolation threshold so the percolative superconducting cluster was dense enough. Comprehensive characterization of structural (XRD, EDX, SEM, and TEM data), mechanical (microhardness) and electrical properties (transport critical current) of the samples can be found in Ref. [21]

U-I characteristics were obtained by integration of experimental dependencies of the differential resistance on a current. Such a measurement technique was chosen for the following reasons: (i) the differential resistance presents a small-signal parameter suitable for description of the nonlinear U-I characteristic; (ii) the lock-in ac technique provides the high resolution necessary to observe peculiarities of the resistive transition. In our experiments the differential resistance resolution was equal to 1 μV that corresponds to the equivalent voltage resolution of 1.5 nV at ac current component of 1.5 mA. The measured differential resistance $R_d$ is proportional to density of vortices, $n$, broken away from the pinning centers: $R_d = nR_f\Phi_0/B$, where $B$ is the magnetic field, $\Phi_0 \equiv hc/(2e)$ is the magnetic flux quantum, $h$ is Planck constant, $c$ is the velocity of light, and $e$ is the electron charge. It is just a motion of these vortices induces electrical field in a sample and thus causes the dissipation.

The obvious region of initial dissipation was observed in ten samples taken from different batches. The U-I characteristic of one of the samples, where this region was more clearly defined, is presented in Fig. 2. The parameters of this sample were as follows: cross-section area of the superconducting core was equal to 0.068 mm$^2$ at the thickness of 30 μm while the width of the tape was 4 mm at the thickness of 0.2 mm, transition temperature was $T_c=107.3$ K, normal state resistance just above the transition (at $T=110$ K) was equal to 545 μΩ, critical current density at $T=77$ K (criterion 1 μV/cm, self-field) was equal to 3.1 kA/cm$^2$. The measurements were also performed in the temperature range 90 K < $T$ < 105 K, and in applied magnetic field up to 100 Oe, but obtained results were similar. The flux flow resistance, which gives the asymptotic slope of U-I characteristic of a superconductor in a resistive state, was equal to $R_f = 560$ μΩ. The corresponding curve in the limiting case of flux flow is shown by the dash-dot line in the upper inset of Fig. [2]. The value of the critical current of resistive transition $I_c=0.8$ A was found by the point of intersection of abscissa axis and the tangent line drawn through the inflection point of the curve of dependence of the differential resistance on the current. Theoretical U-I characteristic, found from equation [24], is shown in Fig. [2] by a solid line. In order to highlight the effects associated with the fractal properties of clusters,
the greatest possible value of fractal dimension $D = 2$ was taken (such a fractal dimension is inherent, for example, in Peano curves). In this case the onset current, calculated on the level of $10^{-5}u/r_f$, is equal to $I_{on} \approx 0.38$ A (see also inset of Fig. 1). The only one free parameter of the theoretical model is $g$-parameter of gamma distribution. Inasmuch as there is no experimental information about statistical distribution of normal-phase cluster areas, we have taken the simplest case of exponential distribution ($g = 0$). The insets of Fig. 2 show how the distribution of the cluster sizes (lower inset) can affect the $U-I$ characteristics (upper inset). The theoretical curve agrees with experimental data in the main point: the $U-I$ characteristic does not start exactly from the critical current $I_c$, but there is a well-defined initial region that begins with the onset current $I_{on}$, with the perfect coincidence between the calculated and measured magnitudes of latter parameter. At the same time, the theoretical curve passes below the experimental points at small currents and has no bend near $I_c$. This feature may be explained by that the theoretical curve was calculated for the case of the constant value of fractal dimension, whereas the experimental data relate to the situation where the fractal dimension is not the same for the different parts of $U-I$ characteristic because its value is governed by the transport current. Indeed, on the current-induced resistive transition the cluster topology varies as the transport current increases. As more and more weak links turn resistive, the superconducting cluster becomes less and less ranified. This can result in changing in fractal dimension of the normal-phase clusters as the boundary between superconducting and normal phases becomes less indented. Thus it is necessary to take into account that the interface sweeps through the area of reduced value of a superconducting order parameter that surrounds the normal-phase inclusions, so its position depends on the magnitude of transport current. Therefore dependence of the fractal dimension on the current can be very complicated. In addition to that, the differences observed may be ascribed to the peculiarities of flux creep in the initial stage of resistive transition, which are not taken into account within the used theoretical model.

In conclusion, we have shown in this paper that the initial region of dissipation in HTS's can be considered as vortex dynamics phenomenon, which demonstrates the fractal properties of the normal-phase clusters.

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