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Fractal Structure Near the Percolation Threshold for $\text{YBa}_2\text{Cu}_3\text{O}_7$ Epitaxial Films

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Abstract. Inhomogeneity of the properties of $\text{YBa}_2\text{Cu}_3\text{O}_7$ epitaxial c -oriented films has been investigated. Using a low - temperature SEM the lateral distribution of local critical temperature has been determined with spatial resolution of 2 μm . The technique provides a direct observation of the percolative character of the superconducting transition on a microbridge scale. It is shown for the first time that near the percolation threshold the current channel has a very rough, irregular configuration and the fractal dimensionality of the superconducting cluster is estimated as 1.55. The magnetic field imaging of samples is carried out and a quantitative correlation between T_c -map and the map of critical density of shielding currents is observed. The transition curves $R(T)$ over a wide range of resistances and bias currents are described in terms of the network model. The model takes into account both the spatial distribution of T_c and the presence of random weak links with a wide distribution of their critical currents.

1. INTRODUCTION

Due to their complicated structure and short coherence length high- T_c superconductors (HTSC) are known to be strongly inhomogeneous. This inhomogeneity has a profound effect on various properties of HTSC films and devices. In particular, spatially resolved investigations carried out by Gross et al. [1] showed that the critical current density of the whole film was limited by critical current density in the most weak cross section. Such a cross section behaves as a bottleneck for the current flow. For the interpretation of experimental dependences of the paraconductivity and fluctuation magnetoconductivity, Lang [2] introduced the critical temperature distribution over the sample. The analysis of the HTSC behaviour in the mixed state suggests the existence of random pinning potential [3]. Thus, the investigation of inhomogeneity provides valuable information for the understanding of HTSC properties. However, up to now, there has been lack of experimental data on T_c -spatial distribution in HTSC films.

In the paper [4] we investigated T_c -inhomogeneity of $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO) film considering it as a two-phase system containing regions with different critical temperatures T_{c1} and T_{c2} . In this paper we do not restrict ourselves to this limitation. A method using low - temperature SEM (LTSEM) has been developed that allows the determination of the lateral distribution of critical temperature over the superconducting film with spatial resolution of 2 μm and accuracy of T_c up to 0.2 K. The technique provides a direct observation of the percolative character of the superconducting transition on a microbridge scale. The percolation theory is often used to describe the behaviour of various characteristics of HTSC films, such as flicker noise [4-6] and magnetic penetration depth [7] near the critical point. The knowledge of T_c -distribution over the film enables us to test the applicability of the percolation approach.

In this work the fractal dimensionality of the superconducting (SC) cluster is estimated and the resistance dependence on the SC fraction are analyzed in terms of the percolation theory. It is shown that the low-temperature tail of transition curve $R(T)$ can not be explained by T_c -distribution alone. The network model taking into account both the T_c -distribution and the presence of random weak links with a wide distribution of their critical currents has been developed and accounts for $R(T)$ dependences in a wide range of temperatures and bias currents. The results of SEM experiment are compared to magneto-optical visualization of magnetic field distribution. A correlation of regions with low T_c and regions of easy flux penetration is demonstrated for the first time.

2. SAMPLES AND EXPERIMENTAL METHODS

$YBa_2Cu_3O_7$ films with thickness of 0.25 μm were grown by dc magnetron sputtering [8]. Preliminary characterization by X-ray diffractometry has shown the presence of only (00l) reflexes which confirms c -orientation of the films. The Raman spectroscopy analysis has revealed their high epitaxiality. Microbridges of 500-50 μm size were formed by a standard photolithography procedure. Three samples were studied. They will be referred to as sample A, B and C. Samples A and B were formed on the YBCO/NdGaO₃ film, while sample C was formed on YBCO/MgO film.

T_c -inhomogeneity of the samples was studied by LTSEM [9]. Firstly, the temperature dependence of the voltage resulting from a local heating of the film by an electron beam was measured at fixed points. By the maximum of this dependence the local T_c was determined. A numerical deconvolution method was used to remove the distorting effects associated with thermal diffusion. As a result, the spatial distribution of critical temperature T_c (T_c -map) accurate to 0.2 K with resolution of 2 μm has been obtained.

3. T_c -MAPS AND THE PERCOLATION THEORY

Fig. 1 shows the lateral distribution of critical temperature T_c for sample A. It also shows the distributions of the superconducting ($T_c > T$) and normal ($T_c < T$) regions for three different temperatures within the SC transition. One can see that the transition proceeds by the percolation scenario. First, some regions turn into SC state, then the fraction p of the SC regions increases, they combine in clusters and at certain $p = p_c$ a SC cluster connecting two sides of the bridge is formed.

Fig. 1. T_c -map for sample A and distribution of superconducting (white) and normal (black) regions for three temperatures in the vicinity of the transition.

Near the percolation threshold the SC cluster has a very rough, irregular configuration. We estimated the fractal dimensionality D of the system using the relation $s \propto R_g^D$, where s is the cluster size (cluster mass) and R_g is the radius of gyration of the cluster that is average distance between two cluster sites [13] (see Fig. 2). Near the percolation threshold the fractal dimensionality D was in the range 1.53-1.58 for all samples. This is somewhat less than the value $D=1.89$ for infinite random square network at $p=p_c$.

Fig. 2 Cluster size s versus radius of gyration R_g near the percolation threshold for sample B. The slope of the solid line gives the fractal dimensionality $D=1.55$.

Fig.3 The correlation function $G(r)$ of $T_c(x,y)$ distribution defined by formula (1) for sample C. The line is guide to the eye.

When T_c -map is given, one can estimate the correlation length of T_c -inhomogeneity. Note that the scatter of T_c over 2 μm fragments of T_c -map is only in part responsible for the broadening of the global SC transition. Indeed, for sample A the width of global transition estimated by $0.1R_N - 0.9R_N$ levels (R_N is resistance just above transition) turns out to be 1.6 K, while 90% of all fragments of T_c -map have T_c within 0.8 K interval. This suggests the presence of T_c -inhomogeneity inside each fragment of 2 μm size. On the other hand, there exists a large-scale correlation of T_c which can be observed from a detailed analysis of T_c -map. Fig.3 presents the correlation function $G(r)$ of $T_c(x,y)$ -spatial distribution for sample C. It is defined as

$$G(r) = \frac{\overline{T_c(R+r) T_c(R)} - \overline{T_c}^2}{\overline{T_c^2} - \overline{T_c}^2}, \quad (1)$$

where averaging is performed over all R within microbridge. The value $G=1$ corresponds to full correlation, $G=0$ to the absence of correlation and negative G to anticorrelation. It can be seen from Fig. 3 that T_c is somewhat correlated on the scale of tens of microns. The shape of the correlation function $G(r)$ is different for different samples and probably determined by peculiarities of growth process or substrate quality. The existence of correlation on small distances can be responsible for the deviation of the value of fractal dimensionality D from that for random network.

The percolation theory is very convenient for the analysis of SC film properties near the transition point. According to the percolation theory, the resistance of random network of SC and normal resistors depends on the SC fraction p at $p \approx p_c$ as

$$R \sim (p_c - p)^t \quad (2)$$

where t is the critical exponent, $t \approx 1.3$ for 2D square network [10]. Now we analyze the applicability of this approach for a real film using experimental $R(T)$ curve and $p(T)$ dependence obtained from T_c -map. The

expression (2) is valid for infinite systems and therefore we can use it only when the correlation length ξ of the SC cluster is less than the bridge width w . At $\xi > w$ one has to consider one dimensional system where each site of $\xi \times w$ size is SC with some probability p_0 . Dependence $p_0(p)$ can be estimated using a renormalization group procedure. We use the simplest one where each 2×2 square is replaced by one supersite which is SC with probability $p' = p^4 + 4p^3(1-p) + 2p^2(1-p)^2$, where p is the probability for initial network. For the geometry of microbridge under study the $R(p)$ dependence was calculated and the transition curve $R(T) = R(p(T))$ is shown in Fig. 4. It can be seen that the percolative dependence $R(T)$ fails to describe experimental one. Significantly better agreement was achieved using a network model described in section 5.

Fig.4. Experimental transition curve (circles) for sample A, transition curve in the percolation approach (dashed line) and transition curve calculated in the network model using T_c -map data (solid line).

4. MAGNETIC FIELD IMAGING

The samples were also investigated by magnetic field imaging using magneto-optical Faraday effect. This provides instantaneous global visualization of flux distribution in a plane adjacent to the surface of the superconductor. Flux penetration in the SC film appeared to be highly inhomogeneous implying the inhomogeneity of the critical density of shielding currents.

Fig. 5. Flux distribution for sample B at $T=18$ K and magnetic field 5 mT. The lines indicate the position of the superconducting bridge.

Fig. 5 presents image measured at $T=18$ K for sample B. A qualitative analysis shows correlation between positions with relatively low T_c and the ones with easy penetration. This means that the critical current density is low in regions with low T_c . This leads us to the conclusion that regions of "bad" quality (low T_c) contains high concentration of weak links on grain boundaries which limit the critical current. This is in contradiction with conclusions of Refs. [11,12] where the weak vortex pinning was supposed to be the limiting factor. Fig. 6 presents quantitative correlation between the local value of critical density of shielding current J_c and local critical temperature. The local value of J_c was estimated as average absolute of the magnetic field gradient over given area. It can be clearly seen that higher T_c corresponds to higher J_c values.

Fig.6. Correlation between local values of critical temperature T_c and critical density of shielding current J_c . The line is guide to the eye.

5. CALCULATION OF THE TRANSITION CURVE

On the basis of T_c -map and flux distribution data the transition curves $R(T)$ for different bias currents were calculated. For this purpose a network model was developed. The model assumes the presence of random weak links in the film. Therefore each bond of square network was supposed to be resistor with nonlinear I - V characteristic given by the following expression:

$$\begin{aligned} V &= RI, & T > T_c \\ V &= R_n (I^2 - I_c^2)^{1/2} + V_{AH}, & T < T_c \end{aligned}$$

where V and I are voltage on and current through the bond, R is the resistance of the bond which is a step-like function of temperature, R_n and I_c are the normal resistance and critical current of the weak link.

Fig. 7. Experimental and calculated in terms of the network model transition curves for bias currents 1mA, 1μA and 5 mA for sample C.

Below T_c voltage is given by the resistance shunted junction model [14] taking into account thermal noise voltage V_{AH} according to Ambegaokar and Halperin model [15]. The critical temperature for each element of the network was determined from the T_c -map. The normal resistance R_n was supposed to be the same for all weak links. The critical current was assumed to follow temperature dependence $I_c = I_{c0} (1 - T/T_c)$. The values of I_{c0} were distributed in correlation with T_c value according to the results depicted in Fig. 6.

The results of calculation over three orders of resistances and bias currents are presented in Fig. 7. A good agreement with experiment is obtained for bias currents I_{bias} less than 1 mA. At higher I_{bias} there is a clear deviation from the

experimental curve. This is because in this case the local value of critical temperature is strongly affected by the local value of current density [4]. From the fitting we determined the value of the normal resistance of random weak links R_n . Assuming that the weak link separates two superconducting grains, R_n of a weak link is equal to 1/100 of the normal resistance of the bulk of the grains.

6. RESISTANCE NOISE

Fig. 8. Temperature dependences of voltage noise for bias current $I=10$ mA and resistance for $I=1$ mA and 5 mA for sample A.

Voltage flicker noise measurements in the transition region have been carried out for all samples. Fig. 8 shows a wide peak of voltage noise S_V at the tail of the transition. We explain such a behavior as related to the fluctuations of critical current of weak links with very sharp peaks associated with single most unstable weak links located at the bottleneck of the current channel. Analysis based on T_c -map data shows that a sharp increase of noise occurs at the percolation threshold, when the global superconducting cluster is formed and the film resistance is determined by weak links only.

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