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NONLINEAR CVC AND CRITICAL CURRENT OF SUPERCONDUCTIVE GLASS MODEL

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1. Introduction

Up to date there is a number of experimental papers dealing with the investigation of the current-voltage characteristics(CVC) of the high-T_c oxides /1-6,15-19/. The most interesting of them have a power-law behaviour $V \sim (I-I_c)^a$ with specific temperature and magnetic field dependences of the exponent a and critical current I_c (see e.g. /1-6/). To treat these peculiarities some explanations, namely: i) 2D Kosterlitz-Thouless (KT) transition /2/, ii) collective fluxoid motion /3-5/, iii) 3D Josephson medium /1,6/ have been suggested.

On the other hand, in the frame of the superconductive glass (SG) model, pioneered in /7/ and then advanced in /8-12/, a rather successful description of the nonequilibrium (nonergodic) properties of high-T_c superconductors was achieved. In a somewhat program paper /12/ the connection between the SG model and the phenomenological critical state model(including the flux creep) is discussed. It is stressed in /12/ that the glassy picture of high-T_c oxides is restricted to a near T_c temperature region.

In the present paper we consider via the SG model a nonlinear power-law CVC as well as temperature-field dependences of a critical supercurrent. As it will be shown these dependences behave rather like 3D intergranular systems /6/ than 2D systems with a topological KT transition /2/. In conclusion we discuss possible relations of the long-time (low-frequency) behaviour of the Josephson spin correlator (in the SG model) with the type of a nonlinear CVC for systems containing intragranular weak links.

2. Power-law CVC of the SG model

As is well known /8,9/ the Hamiltonian of the SG model in the pseudospin representation has a form

$$\hat{H} = -\mathrm{Re} \sum_{ij} J_{ij} S_i^* S_j \,, \qquad (1)$$

where

$$J_{ij} = J(T)\exp(iA_{ij}),\ S_i = \exp(if_i),$$

$$A_{ij} = \pi H(x_i+x_j)(y_i-y_j)/\phi_0, \quad \phi_0 = \hbar c/2e. \qquad (2)$$

The model (1) describes the interaction between superconductive clusters (with phases f_i) via Josephson junctions (with an energy J(T)) on a 2-D disordered lattice (with cluster coordinates (x_i, y_j)) in a frustrated external magnetic field **H** = (0,0,H). So, as usually (see, however, /10/), we have neglected the shielding current effects. The field is normal to the ab-plane where a glass-like picture of high-T_c oxides is established. Since the Hamiltonian (1) contains only the tunneling of the Cooper pairs , the linear (Ohmic) contribution to the CVC is absent. So, as in paper /13/ we shall use the supercurrent $I_S \sim I - V/R_N$ and not the total current I (this distinction is inessential, however, when $I_S \gg I_N$), and the critical current I_c (we are dealing with) is a decoupling current ,built up from the maximum Josephson current of individual junctions.

Following /13/ for the supercurrent density operator (on the square lattice with a side d) we have

$$j_S = 2ie \sum_{i,j} J_{ij} S_i^* S_j \mathbf{r}_{ij} / \hbar d^2 \quad , \qquad (3)$$

where $\mathbf{r}_{ij} = \mathbf{r}_i - \mathbf{r}_j$ is the distance between clusters. In our case $\mathbf{r}_i$ = (x_i, y_i, 0).

When an electric field **E** is applied to the system (1) , the coupling energy $J_{ij}(T,H)$ is renormalized in a way : J_{ij} $J_{ij}\exp(i\omega_{ij}t)$, where $\omega_{ij} = 2e\mathbf{E}\mathbf{r}_{ij}/\hbar$.

According to the linear response theory /14/ the thermal averaging of the Fourier transform of the supercurrent density $j_S(\omega)$ has a form

$$\langle j_S(\omega)\rangle = 4e^2\int_0^\infty dt\cos(\omega t)\sum_{i,j} J_{ij}e^{i\omega_{ij}t}\langle S_i^*(t)S_j(0)\rangle(r_{ij}E)r_{ij}/\hbar^2 d^2. \qquad (4)$$

In order to obtain from (4) the mean value of the supercurrent density in the SG model (1), one needs to perform averaging over random cluster coordinates (x_i, y_j) (by the Gaussian $P(x_i, y_j)=\exp(-x_i^2/2\sigma-y_j^2/2\sigma)/2\pi\sigma$, where σ is the projected area of superconductive loops with a uniform phase)/8/. Choosing, for simplicity, $\mathbf{E}$ = (E,0,0), after the configurational averaging one gets for the supercurrent

$$I_S\equiv d\overline{\langle j_S^X(\omega)\rangle}=A\int_0^\infty dt\cos(\omega t)\exp(-4e^2E^2\sigma t^2/\hbar^2)D(t)E\ , \qquad (5)$$

where

$$J(T,H)=J(T)/(1+H^2/H_o^2)^{1/2},\ A=8e^2\sigma J(T,H)N/\hbar^2 d,\ H_o=\phi_o/2\sigma,$$

$$D(t)=\sum_{i,j}\overline{\langle S_i^*(t)S_j(0)\rangle}/N\ .$$

So, the form of CVC (5) (as well as the magnetization in the SG model /8/) is determined by the behaviour of the correlator D(t). As is shown in /9,11/ the long-time (low-frequency) singularities of the correlator D(t) define glassy properties of the SG model and observable experimental peculiarities. In the present paper we restrict ourselves to the simplest Ansatz of this kind . Namely , we take a power-like relaxation law /9/

$$D(t)=L+D_o(t/\tau)^{-\alpha}\ , \qquad (6)$$

where

$\alpha = 1/2 - 3L/2D_o$, $\tau = \hbar^2 N/4e^2 RT$.

Here, L(T,H) is the order parameter in the SG model (1) (studied in detail in /8,9,11/) , N is the number of superconducting clusters, and R is the normal state resistance between two grains. Remember /9/ that the order parameter L(T,H) is the solution of the equation : $L^3-L^2+L-(1-T^2/T_c^2(H))=0$, where the phase boundary $T_c(H)$ (separating the nonergodic state from the ergodic one) was described in detail in /8/ . Thus , the field dependence of the L(T,H) is governed by the function $T_c(H)$. In the range of validity of the glass-like picture /12/ we have $D_o \sim 1$, $L \sim 1-T/T_c$, and $0<\alpha\leq 1/2$ (see /9/). According to (6) and (5) one gets a power-law CVC

$$V/V_o = (I_s - I_c)^a / I_o \ , \qquad (7)$$

where

$$a = 1/\alpha \ , \ V = Ed \ , \ V_o = \hbar d/2e\sigma^{1/2}\tau \ , \ I_o = AD_o F(\alpha)\hbar/2e\sigma^{1/2} \ ,$$

$$I_c = I_o F(0) L/F(\alpha) D_o \ , \ F(\alpha) = \int_0^\infty dx\ x^{-\alpha} \exp(-x^2) \ . \qquad (8)$$

So, in view of (7) and (8) the temperature and field dependences of the exponent a(T,H) and the critical current $I_c(T,H)$ are governed by the order parameter L(T,H) (and via the Josephson energy J(T,H) (5)). Figure 1 shows the calculated by (6)-(8) behaviour of a(T) versus T/T_c at H=0. It is seen that $a(T_c)=2$ (in agreement with the critical long-time behaviour of the correlator D(t) /9/) and increases linearly when the reduced temperature $t=T/T_c$ decreases (cf. with a similar behaviour reported for high-T_c oxides/1,5,6/) . As is shown in /9/ , the nonergodicity parameter L decreases with increasing magnetic field H . In

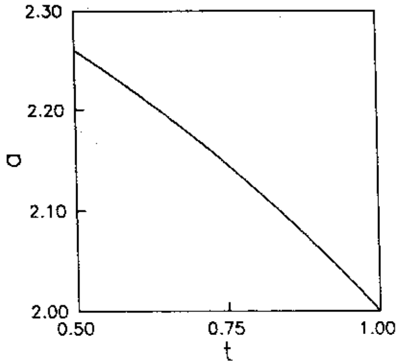

Fig. 1: The temperature dependence of the CVC exponent a(T) versus $t=T/T_c$.

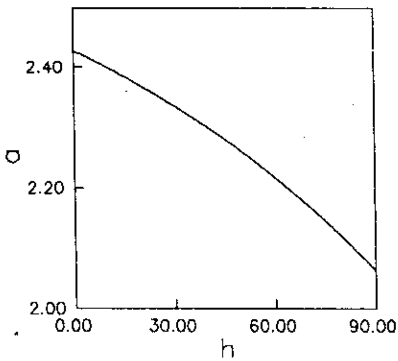

Fig. 2: The magnetic field dependence of the CVC exponent a(H) versus $h=H/H_o$ at $t=T/T_c=0.6$.

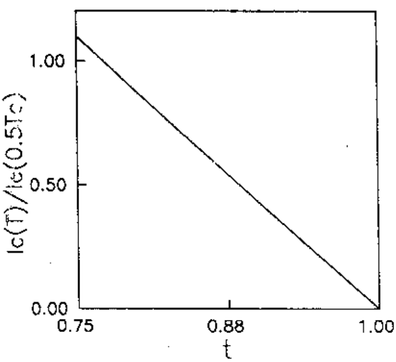

Fig. 3: The behaviour of reduced critical current $I_c(T)/I_c(0.5T_c)$ versus reduced temperature $t=T/T_c$.

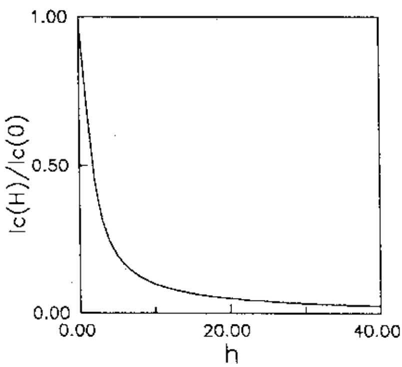

Fig. 4: The behaviour of reduced critical current $I_c(H)/I_c(0)$ versus reduced magnetic field $h=H/H_o$.

particular , in the region of strong frustration ($H \gg H_o$) this leads to the following behaviour of the exponent $a(H)-2 \simeq (H_o/H)^2$. Figure 2 shows the behaviour of the a(H) versus reduced field $h=H/H_o$ at the reduced temperature $t=T/T_c=0.6$. Such a behaviour really correlates with some observations /3,4/ .

Let us now turn to the critical current $I_c(T,H)$. As it follows from (8) the temperature behaviour of the I_c near T_c is determined by the critical behaviour of the parameter L(T,H) and has an asymptotic form $I_c \sim (1-T/T_c)$ (see Fig.3). A similar dependence of the critical current for high-T_c oxides is discussed in /5,6,13,16-19/ . The magnetic field dependence of the critical current is influenced by two factors . They are : i) the coupling energy J(T,H) (5) , and ii) the nonergodicity parameter L(T,H) /9/. The main contributer is the Josephson energy . In the case of weak fields ($H \ll H_o$) from (5) and (8) it follows that :

$$I_c(H) = I_c(0)(1-H^2/H_o^2). \tag{9}$$

In the opposite case of strong fields ($H \gg H_o$) one gets :

$$I_c(H) = I_c(0)H_o/H. \tag{10}$$

The behaviour of the reduced critical current $I_c(H)/I_c(0)$ versus reduced applied field $h=H/H_o$ is illustrated in Fig.4 . It is seen that the observable forms of the $I_c(H)$ /4,5,17,18,20/ are in qualitative agreement with the predictions of the SG model (1) .

3. Discussion

To better understand the described above features in the behaviour of the CVC in the real experimental situations , let us make some estimates for typical values of the current I_o and the voltage V_o . In view of $D_o \sim 1$, $F(\alpha) \sim 1$, and $d \sim N\sigma^{1/2}$ for $J \sim 50K$ and $R \sim 5\ \Omega$, from (6) and (8) one gets :

$$I_o \sim 4eJ/\hbar \sim 10^{-5}A \quad , \quad V_o \sim 2eRT_c/\hbar \sim 10^{-3}V . \qquad (11)$$

Following the experimental data /1-6,15-19/ , this is the range of parameters where the obtained above peculiarities in a power-law CVC behaviour were registered .

It is known , however , that there are more complex than a power-like one types of CVC (e.g. logarithmic-like /21/) . Not pretending to give a unique description of all the observable laws, we would like to emphasize the following circumstances. As is well-known /7-9,11,12/ , the most prominent feature of the glassy behaviour is the existence of a hierarchy of long-time relaxation laws (including the aging effects /22/). If , for instance , instead of the power-law Ansatz (6) for the correlator D(t) (used in the present paper) we took a logarithmic one /9/, the above described procedure would lead us to the logarithmic CVC /21/. So , it is possible that the existence of different types of CVC reflects complex dynamical (low-frequency) processes of relaxation in these materials . To verify such a hypothesis one needs to make the measurements of both the long-time relaxation law (e.g. of the remanent magnetization) and the corresponding CVC for the same sample but at different initial conditions (e.g. for different waiting times) .

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