Critical Current in the High-$T_c$ Glass model

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The high-$T_c$ glass model can be combined with the repulsive $t't'$-Hubbard model as microscopic description of the striped domains found in the high-$T_c$ materials. In this picture the finite Hubbard clusters are the origin of the $d$-wave pairing. In this paper we show, that the glass model can also explain the critical currents usually observed in the high-$T_c$ materials. We use two different approaches to calculate the critical current densities of the high-$T_c$ glass model. Both lead to a strongly anisotropic critical current. Finally we give an explanation, why we expect nonetheless a nearly perfect isotropic critical current in the high-$T_c$ superconductors.

Keywords: High-$T_c$, Superconductivity, Glass Model, Critical Current, Bean Model

I. INTRODUCTION

The high-$T_c$ glass model was introduced in 1987 to describe superconductivity in the high-$T_c$ cuprates (HTSC). Originally the glass model was designed for $s$-wave symmetry of the superconducting wave functions. Whereas it was first argued, that the glass model is not applicable for $d$-wave symmetry, the experimental result of striped domains in the superconducting CuO-planes inside the high-$T_c$ materials only gives rise to weak disorder. Thus the high-$T_c$ glass model is applicable in this situation, too. It was demonstrated, that the high-$T_c$ glass model including the $t't'$–Hubbard model as a microscopic description of the striped superconducting domains is able to explain e.g. the $d$-wave symmetry of the superconducting phase and the pseudogap above $T_c$ in the density of states (DOS). In the combined high-$T_c$ glass and striped Hubbard model picture the stripes in the HTSC occur at least at the same temperature, at which the pseudogap in the DOS opens, because otherwise the striped Hubbard clusters, which are responsible for these gaps, do not exist.

In this paper we will show, that within the high-$T_c$ glass model the maximum critical currents found in high-$T_c$ materials and their almost perfect isotropy in a-b-direction can be understood. Following two independent paths we calculate in the next section an upper bound for the critical current density $j_c$: first with a direct calculation from the high-$T_c$ glass model and second considering the extended Bean model. Afterwards we offer an intuitive picture for the (observed) isotropy of the critical currents and explain, why the values of $j_c$ usually measured in high-$T_c$ materials are smaller than these upper bounds. From these simple ideas follows a fabrication procedure, which could lead to a possible increase of $j_c$ in the high-$T_c$ materials.

II. CRITICAL CURRENTS IN THE HIGH-$T_C$ GLASS MODEL

In the high-$T_c$ glass model a single superconducting CuO-plane is described as an array of striped domains, figure. The typical dimension of a single striped domain with constant superconducting phase inside the high-$T_c$ glass model can be roughly estimated following e.g. Tsuei and Doderer and Tranquada et. al. We take for our calculation the values $a \approx 100 \, \text{Å}$, $b \approx 10 \, \text{Å}$, (e.g. $b \approx 16 \, \text{Å}$ in LaSrCuO or $b \approx 23 \, \text{Å}$ in YBaCuO) and $z \approx 10 \, \text{Å}$ with the directions of figure. This choice of $a$, $b$, and $z$ is not crucial for our considerations, where only their order of magnitude is important for the conclusions.

In the following calculation we show that the glass-model leads to critical current densities, which are in agreement with the experiments. The starting point is the Hamiltonian for the glass model:

$$\mathcal{H} = -J \sum_{(i,k)} \cos(\phi_i - \phi_k - A_{i,k}) \, .$$

The phase factors $A_{i,k}$ are given by

$$A_{i,k} = \frac{2\pi}{\Phi_0} \int_i^j \bar{A} \, d\bar{l}$$

with $\text{rot} \bar{A} = H \cdot \hat{z}$, where $\hat{z}$ is the unity vector in z-direction, and with $A_{i,k} = a_{i,k} \cdot H$ we get...
\[ a_{i,k} = \frac{2\pi x_i + x_k}{\Phi_0} \frac{y_k - y_i}{2} \]  

(3)

In equation (3) up to (11) \( \Phi_0 \) is the elementary flux quantum, \( \phi_i \) are the phases of the superconducting wave functions, \( J \) is the coupling energy between two clusters, \( \langle i, k \rangle \) is the sum over all nearest neighbors, and \( x_i, x_k, y_i, \) and \( y_k \) are the coordinates of the center of gravity of the domains \( i \) respectively \( k \). Finally \( H \) is the external magnetic field and \( \bar{A} \) the corresponding vector potential [1].

In the high-\( T_c \) glass model only weak, "correlated" disorder was chosen in the framework of the square lattice [1]. We should note, that this weak disorder in the high-\( T_c \) glass model can be described as \( x_i \approx i \cdot a \) and \( y_i \approx i \cdot b \) with the lattice constants \( a \) in x-direction and \( b \) correspondingly in y-direction [16,17,18].

Next we assume a constant increase of the internal magnetic field analogous to the assumptions of the Bean model [16,17,18]:

\[ \text{rot} \ H_{i,k} = j_{i,k} \]  

(4)

The free energy \( F \) is given as \( F = -k_B T \ln Z \), where the partition function \( Z = \sum_{\{\Phi\}} \exp (-\beta H(\Phi)) \) with the inverse temperature \( \beta \equiv 1/(k_B T) \) and the sum \( \{\Phi\} \) is over all possible configurations of the phases \( \Phi = (\phi_1, \ldots, \phi_{L^2}) \) for a lattice with \( L \times L \) sites (\( k_B \) is the Boltzmann constant). The magnetization \( M \) of a sample is given by \( M = -1/V \cdot \partial F/\partial H \), where \( V \) is the volume of the sample. For the external magnetic field \( H = 0 \) we obtain:

\[ M = \frac{1}{V} 2\pi J \sum_{\langle i,k \rangle} \frac{x_i + x_k}{2} (y_k - y_i) \langle \sin (\phi_i - \phi_k) \rangle \]  

(6)

where \( \langle \ldots \rangle \) denotes the thermal expectation value.

The magnetization can be expressed in terms of the internal magnetic fields \( H_{i,k} \):

\[ M = \frac{1}{2L^2} \sum_{\langle i,k \rangle} H_{i,k} \]  

(7)

Inserting equation (3) into equation (7), using the abbreviation \( I = J 2\pi / \Phi_0 \) and the volume \( V = L a \cdot b \cdot z \) (geometries of a striped domain, figure 2), it follows

\[ H_{i,k} = \frac{1}{abz} 2I \frac{x_i + x_k}{2} (y_k - y_i) \langle \sin (\phi_i - \phi_k) \rangle \]  

(8)

Using the equations (3), (8), and (8) we get for the critical current density of the domains \( i \) and \( k \):

\[ j_{i,k} = \frac{I}{az} \langle \sin (\phi_i - \phi_k) \rangle \]  

(9)

Here we made also use of \( y_k - y_i \approx b \), if \( i \) and \( k \) are nearest neighbors (n.n.) in y-direction and \( y_k - y_i \approx 0 \) in the other cases.

Now we average over all \( 2L^2 \) bonds between n.n. in the lattice and introduce \( j_0 \equiv I/az \), where \( az \) is the area "used" by a single junction between two domains. We obtain:

\[ j = \frac{1}{2L^2} \sum_{\langle i,k \rangle} j_{i,k} = j_0 \frac{1}{2L^2} \sum_{\langle i,k \rangle} \langle \sin (\phi_i - \phi_k) \rangle \]  

(10)

The average of the sinuses:

\[ \langle \sin (\phi_i - \phi_k) \rangle = \frac{1}{2L^2} \sum_{\langle i,k \rangle} (\sin (\phi_i - \phi_k)) \]  

(11)

can be obtained from the simulation (index sim) with
\[ M_{\text{sim}} = \frac{1}{2L^2} \sum_{(i,k)} x_{i,\text{sim}} + x_{k,\text{sim}} \left( \frac{1}{2} (y_{k,\text{sim}} - y_{i,\text{sim}}) \sin (\phi_i - \phi_k) \right) . \]  

(12)

We now make following approximations: \( y_{k,\text{sim}} - y_{i,\text{sim}} = 1 \), if \( i \) and \( k \) are n.n. in y-direction, \( y_{k,\text{sim}} - y_{i,\text{sim}} = 0 \), if \( i \) and \( k \) are n.n. in x-direction, and \( x_{i,\text{sim}} + x_{k,\text{sim}} \approx 2i \) neglecting the random placement of the domains in the glass model [1].

With \( i = 0, 1, \ldots, L - 1 \) this leads to the magnetization

\[ M_{\text{sim}} = \frac{L - 1}{2} \frac{1}{2} \langle \sin (\phi_i - \phi_k) \rangle . \]  

(13)

With \( M_{\text{sim}} = 0.5\Delta M_{\text{sim}} \) from figure [3] it follows

\[ \langle \sin (\phi_i - \phi_k) \rangle = \frac{1}{L - 1} \Delta M_{\text{sim}} . \]  

(14)

Here also as in the Bean model \( j \to j_c \) leads to the critical state and the critical current density is given by:

\[ j_c = j_0 \frac{1}{L - 1} \Delta M_{\text{sim}} . \]  

(15)

with \( j_0 = 2\pi J/(a\pi\Phi_0) \).

Now we calculate the critical current density in a second way. Applying Bean’s formula [16,18] in the anisotropic case [13] is justified as we have periodic boundary conditions in y-direction leading to a very long sample in y-direction. Concerning the internal magnetic fields in the critical state we have the situation illustrated in figure [4]. Therefore we have in the simulation in x-direction a sample size of double length. Thus the experimentally found magnetization \( M_{\text{exp}} \) is the magnetization corresponding to the triangle of figure [4].

With the Bean formula of the anisotropic case [13]:

\[ M_{\text{exp}} = \frac{j_c l}{20} . \]  

(16)

and therefore with the length of the sample \( l = 2(L - 1)a \) (figure [4]) we have

\[ j_c = \frac{20M_{\text{exp}}}{2(L - 1)a} . \]  

(17)

Now we calculate the value of the “experimental” magnetization \( M_{\text{exp}} \) from \( M_{\text{sim}} \):

\[ M_{\text{exp}} = \frac{1}{V} \frac{2\pi J_0}{\Phi_0} \sum_{(i,k)} x_{i,\text{sim}} + x_{k,\text{sim}} \left( \frac{1}{2} (y_{k,\text{sim}} - y_{i,\text{sim}}) \sin (\phi_i - \phi_k) \right) . \]  

(18)

with \( x_i = a \cdot x_{i,\text{sim}} \) (\( x_{i,\text{sim}} = 0, 1, L - 1 \)) and \( y_i = b \cdot y_{i,\text{sim}} \) (\( y_{i,\text{sim}} = 0, 1, L - 1 \)) we have

\[ M_{\text{exp}} = \frac{1}{L^2 a b \Phi_0} \cdot \frac{2\pi J_0}{\Phi_0} \sum_{(i,k)} x_{i,\text{sim}} + x_{k,\text{sim}} \left( \frac{1}{2} (y_{k,\text{sim}} - y_{i,\text{sim}}) \sin (\phi_i - \phi_k) \right) . \]  

(19)

Therefore with \( I \) from equation (8) and \( M_{\text{sim}} \) from equation (12) and with \( \Delta M_{\text{sim}} = 2M_{\text{sim}} \) (figure [3] equation (13) leads to

\[ M_{\text{exp}} = \frac{1}{2} I \Delta M_{\text{sim}} , \]  

(20)

which leads (with equation (17)) to the critical current density

\[ j_c = \frac{I}{a \pi L - 1} \Delta M_{\text{sim}} . \]  

(21)

Using the abbreviation \( j_0 = I/(a\pi) \) and measuring \( j_c \) in A/cm\(^2\) [10] we have finally

\[ j_c = j_0 \frac{1}{L - 1} \Delta M_{\text{sim}} . \]  

(22)
as in our first calculation (equation (13)) of the critical current density using Bean’s assumption (equation (8)) in the high-$T_c$ glass model directly.

Using the numerical values $\Delta M_{\text{sim}} \approx 6$ and $L-1 = 15$ from figure 3 and the experimental values $a = 100 \, \text{Å} = 10^{-8} \, \text{m}$ and $z = 10 \, \text{Å} = 10^{-9} \, \text{m}$ for the stripes in the HTSC [13,5] we get $I \approx 4.2 \cdot 10^{-6} \, \text{A}$. And therefore we have for the critical current density

$$j_c = \frac{I}{az} \Delta M_{\text{sim}} \approx 1.7 \cdot 10^7 \, \text{A/cm}^2,$$

(23)

which is surprisingly close to the experimental values $j_c \approx 5 \cdot 10^7 \, \text{A/cm}^2$ at 4 K and zero field for the best films [19] and higher than $j_c$ in wires ($j_c < 10^8 \, \text{A/cm}^2$, e.g. [26,28]). We want to note, that in figure 3 the $\Delta M_{\text{sim}}$ was measured at $T = 0.2 \, \text{J}$ which corresponds to 20 K for $T_c = 100 \, \text{K}$.

To calculate critical current densities with equation (15) resp. (22) we made use of Bean’s assumption of a constant $J_c$ with $J = k_B T_c$, $J_c = 2 e k_B T_c / h \approx 0.667 \cdot 10^8 \, \text{A/cm}^2$.

This is indeed an upper bound to $j_c$ in the glass model [21]. To determine the critical current density $j_c$ in a-direction we consider in a single domain (in figure 1) the area $A$ in b-z-direction, through which the current flows, figure 2. With $A \approx b \cdot z \approx 10^{-18} \, \text{m}^2$ we obtain the critical current density

$$j_c = \frac{J_c}{A} = \frac{2 e k_B T_c}{h b z} = 0.667 \cdot 10^8 \, \text{A/cm}^2.$$

(25)

This is indeed an upper bound to $j_c$ in equation (23). Thus both calculations (equation (15) and (22)) of $j_c$ give the same formula for $j_c$, which is lower than the upper bound for the high-$T_c$ glass model in equation (25).

### III. (AN)ISOTROPY OF THE CRITICAL CURRENT

Next we consider the critical currents in the b-direction instead of the a-direction. First we determine the magnetization (with $I = (2 \pi / \Phi_0) J$)

$$M = \frac{I}{z} \Delta M_{\text{sim}} \approx 260 \, \text{A/cm},$$

(26)

which is in good agreement with the experiments [33], too. Note, that $M$ is independent of the size of the domains in the a-b-plane. Repeating the above calculations we have for the critical current density in b-direction:

$$j_{c b} = \frac{j_0}{L-1} \Delta M_{\text{sim}}.$$

(27)

This is analogous to equation (15) with a different $j_0 = I / (b z)$, in which $a$ is replaced by $b$. Inserting the experimental values $b \approx a / 10 = 10 \, \text{Å}$ and $z \approx 10 \, \text{Å}$ [13,5] we obtain

$$j_{c b} \approx 10 \cdot j_{c a} = 1.7 \cdot 10^8 \, \text{A/cm}^2.$$

(28)

In b-direction the upper bound analogous to equation (23) also exists. Of course this upper bound is now also about ten times larger than in a-direction.

Thus the consideration of stripes in the high-$T_c$ glass model leads to a strong anisotropy of about the factor ten for the critical current densities between a- and b-direction depending on the ratio $a/b$ of the striped domains. But this relatively large factor was never reported in the experimental literature.
We want to note, that on the one hand the size of the stripes enters the calculation of \( j_c \) reciprocally, but on the other hand the number of domains in one spatial direction influences \( j_c \), too. Thus a better knowledge of the size of the domains is desirable. Additionally a finite size scaling (or the simulation of different system sizes \( L \)) for the magnetization \( \Delta M_{\text{sim}} \) of the high-\( T_c \) glass model is necessary to calculate the critical current densities more accurately.

Now we have two features (anisotropy of \( j_c \) in a- and b-direction and a \( j_c \), which is in the order of magnitude of the largest experimentally found \( j_c \) in HTSC) of the high-\( T_c \) glass model, which do not agree with the experiment. In our opinion there are two possible mechanisms, which can lead to a small or vanishing anisotropy. The first one is an anisotropic coupling constant \( J (J_a \neq J_b) \) in the high-\( T_c \) glass model, which may be different in a- and b-direction. But this probably only reduces the anisotropy. And it is unlikely, that these anisotropic coupling constants will lead to an isotropic critical current density \( j_c \).

We postulate therefore the existence of Weiss-type domains in the planes with the stripes, which are dominantly either pointing in a- or b-direction, figure 5. The existence of the Weiss-domains on the other hand explains the relatively lower critical current densities \( j_c \) found in experiments for single crystals and thin films and in particular their differences.

The resulting weak links between the Weiss-domains (figure 5), which have to be assumed to be (much) "weaker", than the weak links of the high-\( T_c \) glass model, restrict \( j_c \) to lower values. Thus equation (23) and (28) are only upper bounds of \( j_c \), too.

This possibility was first brought to our attention in private discussions with Tsuei and Doderer. In the light of the above estimated factor of \( a/b \approx 10 \) this picture is in our view one possible explanation for the experimental situation. Crystals or thin films with a predominant direction of the stripes are therefore predicted to show this anisotropy. But the main problem are the weak links between the Weiss-domains. These obviously govern the final experimental measurement of the critical current density. This picture could also explain the differences from sample to sample. While \( T_c \) is for all samples (nearly) identical, \( j_c \) is quite different. But in our theoretical calculations for the high-\( T_c \) glass model both \( T_c \) and \( j_c \) only depend on the coupling \( J \).

Considering this picture it is clear, that improvements of \( j_c \) rise in general the quality of the samples. Especially in the light of the possible coupling of electronic devices, better high-\( T_c \) samples have to be obtained by removing the Weiss-domains and the weak links between these domains. Therefore it would be extremely fruitfully to avoid the Weiss-domains or to restrict the influence of the resulting weak links. In this spirit we propose a receipt following from the fabrication of magnets. The magnets are cooled down in a strong magnetic field. For high-\( T_c \)-materials we propose a similar procedure. The cooling process should use the cooling schedule known from simulations. This schedule has been subject to extensive research in the field of (physical) optimization in particular the "simulated annealing" method.

Procedures developed in the optimization theory may be directly transferred to the annealing of the high-\( T_c \)-materials. Furthermore the annealing has to be carried out in an electric field and/or while an electric current is flowing through the sample.

We expect from these procedures a substantial increase of the quality of the high-\( T_c \)-materials. In particular the fabrication of electronic devices as e.g. transistors should benefit greatly from these ideas. In the fabrication of wires or polycrystals additionally the weak links between the superconducting grains limit the critical current densities and should be removed, too.

**IV. SUMMARY AND CONCLUSIONS**

In the high-\( T_c \) glass model the striped superconducting domains of the high-\( T_c \) materials are the domains of constant superconducting phases. The size of the striped domains may be deduced by mainly theoretical considerations and magnetic measurements. These measurements and the corresponding theoretical framework were already known shortly after the discovery of the HTSC. Already there the size of the domains could be estimated correctly to be approximately \( 10^4 \text{ Å}^2 \). This leads to the conclusion, that the glass behavior is not related to the early ceramic structure of the grains, that many but not all samples exhibit.

From the high-\( T_c \) glass model the critical current density can be calculated following two different paths: first using the extended Bean model and hysteresis measurements of the high-\( T_c \) glass model and second directly from the definition of the glass model using Bean’s assumption of the critical state model. Both approaches lead consistently to the same critical current densities \( j_c \) and to a strong anisotropic critical current density for the a- resp. b-direction of \( j_c \), which is much larger than the anisotropy found experimentally. But they are close to the highest
measured critical current densities in thin films. This strong anisotropy follows from the underlying striped shape of the domains.

Taking the same type of approximation (following the Bean model) we obtain the same value of \( j_c \) in the simulation as in the experiments. This is in our opinion a strong evidence in favor of the high-\( T_c \) glass model.

Nonetheless it is puzzling, why this anisotropy in the a-b-plane was never reported for \( j_c \). We propose two extensions of the high-\( T_c \) glass model: first an anisotropic coupling \( J_a \neq J_b \), which in our opinion can only reduce the anisotropy, and second the existence of Weiss-type domains, in which the predominant direction of the stripes is turned by 90°. The latter leads to nearly isotropic critical current densities and lowers \( j_c \) on account of the "new" weak links between these areas with the same direction of the stripes. This explains, too, why \( T_c \) is nearly constant between different samples whereas \( j_c \) is quite different. Removing these Weiss-type domains should lead to higher critical current densities \( j_c \), which may be done by simulated annealing of the HTSC (eventual in electric fields).

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FIG. 1. Superconducting (SC) domains (stripes) in the CuO-planes described microscopically with the Hubbard model (HM).

FIG. 2. Geometry and size of a single striped domain in the high-$T_c$ glass model.

FIG. 3. Hysteresis measurement of the high-$T_c$ glass model. (analogous to figure 12 in [1])

FIG. 4. Critical state in a single striped domain in the high-$T_c$ glass model.
FIG. 5. Weak links between Weiss-domains.