

Mechanism of current limitation in polycrystalline high T_c superconductors

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The transport properties and the nature of the breakdown of superconductivity in oxide ceramics with "strong" intergrain coupling are discussed. As an alternative to the XY-model which is not applicable to these materials, the "limiting interface" model is proposed. The model is used to calculate the texturing dependence of the critical current density in polycrystalline $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ -films. An extension of the limiting interface model allows for the calculation of the current-voltage characteristic which is expected to contain interesting information on the spatial structure of the superconducting-to-normal transition.

1. INTRODUCTION

The macroscopic current flow in polycrystalline oxide superconductors is determined by the presence of weak links introduced into the material by the ceramic processing technique. The superconductivity in these materials is the superposition of a strong intragrain superconductivity and a weak intergrain superconductivity which establishes the coherence in the ceramics and determines the transport and low field magnetic properties of the sample. For the discussion of the mechanism of transport current limitation, the ratio between the average grain size $\langle a \rangle$ and the ceramic London penetration depth λ_{cer} is the critical parameter. This ratio is given by

$$\eta = \frac{\lambda_{\text{cer}}}{\langle a \rangle} = \left(\frac{c\Phi_0}{8\pi^2\mu_{\text{cer}}\langle a \rangle^3\langle j_J \rangle} \right)^{1/2},$$

where Φ_0 denotes the flux quantum, μ_{cer} is the effective permeability of the ceramic [1, 2, 3], and $\langle j_J \rangle$ is the average intergrain critical current density. The phase φ of the superconducting order parameter varies on the scale λ_{cer} . Hence for $\eta \gg 1$, φ can be assumed to be constant over a single grain; this limit is adequately described by the XY-model [4, 5, 6]. The critical current in this case is determined by either the depinning of macro (intergrain) vortices [7], or by the "phase glass" transition [6]. In this article we consider the opposite case of ceramics with strong intergrain coupling ("good ceramics"), *i.e.*, $\eta < 1$. In this case the phase φ varies strongly on the scale of a grain and the XY-model does not apply. The topological excitations are the Josephson vortices fitting into the grain boundaries. Their size is given by the Josephson penetration depth $\lambda_J = (c\Phi_0/16\pi^2\lambda_{j_J})^{1/2}$, where λ is the penetration depth of the grains. The depinning of the Josephson vortices determines the critical current of the ceramic sample. The analysis of experimental data in terms of an improved critical state model shows that present ceramics (at least $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$) indeed belong to this strong intergrain coupling limit [8]. A first attempt to describe this regime is the "limiting interface" (LI) model [9]. The LI-model allows for the calculation of the critical current of the ceramic from the knowledge of the critical current across the single grain boundaries which in turn can be obtained either from a model calculation or from experiments. In section 2 we describe the LI model and apply it to the calculation of the a -axis texturing dependence of the critical current in a c -axis oriented thin $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ -film. In section 3 the LI model is extended to the calculation of the current-voltage (I-V) characteristic which is expected to exhibit interesting features at low temperatures.

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2. THE LIMITING INTERFACE MODEL

The basic question answered by the LI-model is the following. Assume we know the critical currents of the individual grain boundaries (i.e., the currents at which the Josephson vortices are depinned), what is the critical current I_c of the whole sample? The critical current I_c is reached when there is an interface γ_c transverse to the current flow on which all junctions (grain boundaries) are critical [9]. Along γ_c vortices will start to flow across the entire sample, thus creating a finite voltage across γ_c . We call γ_c the *limiting interface*. In order to obtain a mathematically well defined problem we consider a 2-dimensional ceramic sample (thin film) consisting of square shaped grains where the intergrain current i_l across the l -th grain is bounded by the critical current $i_{c,l}$: $-i_{c,l} \leq i_l \leq i_{c,l}$ (see Fig. 1). In order to avoid charging we impose the continuity equation: $\sum_n i_n = 0$ where n denotes the set of four boundaries of a given grain. The maximal current through the sample is then given by $I_c = \max_{\{i_\mu\}} \sum_{\mu \in \gamma} i_\mu$, where γ is an arbitrary interface separating the current feeding contacts. I_c can be calculated exactly in several ways: (i) The above equations and inequalities constitute a linear

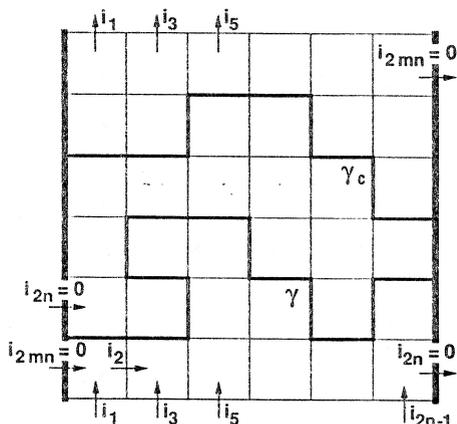


Fig. 1: 2D example for the LI model. The square shaped grains are coupled by random coupling strengths $i_{c,l}$, $l = 1, \dots, 2mn$ such that $-i_{c,l} \leq i_l \leq i_{c,l}$. The current flow is in the vertical direction (periodic boundary conditions). γ denotes a transverse interface. The limiting interface γ_c minimizes the functional $I[\gamma] = \sum_{\mu \in \gamma} i_{c,\mu}$.

optimization problem which can be solved by the simplex method [9]. Much more suitable for the efficient treatment of large samples (up to $\sim 200 \times 200$ grains) is the direct determination of the limiting interface γ_c , which is given by the minimization of the functional $I[\gamma] = \sum_{l \in \gamma} i_{c,l}$, where γ runs over all transverse interfaces. The variational problem is highly non-trivial due to its rich structure of local minima; this renders any variational equation useless, since it would have many solutions, each corresponding to a particular local minimum of $I[\gamma]$. There are two ways out of this problem: First, an efficient transfer operator method has been developed for the exact calculation of γ_c and $I[\gamma_c]$ in the two-dimensional case [10, 11]. Second, although a variational equation is of little help, a boundary value problem can be formulated, the (unique) solution of which provides the limiting interface γ_c and the critical current $I[\gamma_c]$ [11]. This second approach is applicable to 3D problems, i.e., the calculation of 2D interfaces in bulk ceramics.

What is the physical nature of the limiting interface γ_c ? As the current through the sample is driven beyond its critical value $I_c = I[\gamma_c]$, vortices begin to flow along γ_c and a finite voltage $V_c = 2\Delta/e$ ($\Delta = \text{gap}$) appears across γ_c , whereas the regions on both sides of γ_c remain fully superconducting. This means that γ_c is nothing but

a long inhomogeneous (and curved) Josephson junction characterized by the critical current I_c .

The quenching of the supercurrent by an external magnetic field B_{ext} can be described within the framework of the LI model just by introducing field dependent intergrain critical currents $i_{c,l}(B_{\text{ext}})$. The incorporation of *self-field* effects is more involved and will be discussed elsewhere [12]. In thin films, however, self-field effects are not important and the LI model in the form presented above is applicable.

As an application of the LI model we will discuss the a -axis texturing dependence of the critical current density in a c -axis oriented thin $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ -film. With the c -axes orthogonal to the film plane, the orientation of the grains is completely characterized by the angle ϕ of their a -axis with respect to a given reference direction. The texturing is then described by a Gaussian probability distribution $\mathcal{P}_{\phi_0}(\phi) \sim \exp[-(\phi/\phi_0)^2]$ for the angle ϕ . $\phi_0 = 0$ describes perfect texturing, $\phi_0 = \infty$ completely untextured material.

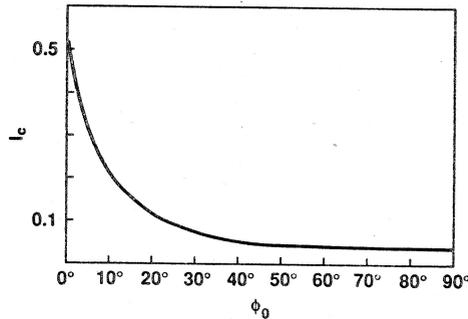


Fig. 2: The a -axis texturing dependence in a c -axis oriented polycrystalline $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ -film, calculated by the LI-model. The intergrain critical currents $i_{c,l}$ are taken from the experiments of Dimos *et al.* [13]. The current is normalized to the intragrain critical current.

The critical currents $i_{c,l}$ are taken from measurements at bicrystals by Dimos *et al.* [13]. Their results imply that the intergrain critical currents depend on the relative orientational misfit of two neighboring grains ν and ν' : $i_{c,\nu,\nu'} = i_{c,\nu,\nu'}(|\phi_\nu - \phi_{\nu'}|)$. For a given realization of $\{\phi_\nu\}$ we obtain the critical currents $i_{c,l}$ allowing us to determine the limiting path γ_c and the critical current I_c of the film. The numerical result for the function $I_c(\phi_0)$ is shown in Fig. 2. We find that the critical current in films with randomly oriented a -axes is suppressed by a factor of $\simeq 1/30$ as compared with the single crystal value. Only very strong texturing with $\phi_0 \sim 10^\circ$ leads to a considerable improvement of I_c .

3. CURRENT-VOLTAGE CHARACTERISTIC

In this section the LI model is extended to describe the full I - V characteristic of the ceramic. The LI model as it has been formulated in the last section, allows for the calculation of the critical current of a macroscopic sample from the knowledge of the critical currents of the individual grain boundaries. We now discuss the following, more general question: Given the I - V characteristic of the individual grain boundaries, what is the I - V characteristic of the whole sample? To solve this problem we adopt a random resistor network (RRN) description of the ceramic superconductor. The grain boundaries are Josephson weak links with the (idealized) characteristic given by

$$\Delta V_l(i_l) = \begin{cases} 0, & \text{if } |i_l| < i_{c,l}, \\ \sigma_{n,l}^{-1} \cdot i_l, & \text{if } |i_l| \geq i_{c,l}, \end{cases} \quad (1)$$

where ΔV_l is the voltage difference between the two grains separated by the l -th grain boundary, and the normal conductivity $\sigma_{n,l}$ of the l -th grain boundary is related to the critical current $i_{c,l}$ via the Ambegaokar-Baratoff formula [14]: $i_{c,l} = \frac{\pi \Delta(T) \sigma_n}{2e} \tanh \frac{\Delta(T)}{2k_B T}$. Unfortunately the I - V characteristic (1) cannot be incorporated into a RRN because of the infinite conductivity for $|i_l| < i_{c,l}$. This problem can be circumvented by introducing a *fictitious* finite but very large "superconductivity" σ_s , where "very large" means $\sigma_s \gg \max_l \{\sigma_{n,l}\}$. The characteristic of the l -th grain boundary is then given as follows:

$$\Delta V_l(i_l) = \begin{cases} \sigma_s^{-1} \cdot i_l & \text{if } |i_l| < i_{c,l}, \\ \sigma_{n,l}^{-1} \cdot i_l & \text{if } |i_l| \geq i_{c,l}. \end{cases} \quad (2)$$

As in the LI model we impose the continuity equation $\sum_n i_n (\Delta V_n) = 0$, and, in addition, the boundary condition $V = 0$ at the bottom of the network and $V = V_{\text{top}}$ at the top of the network (the current flows from the bottom to the top). This defines an RRN problem. The I - V curve can be calculated by standard techniques. The result is shown in Fig. 3. The most prominent feature of the I - V characteristic is its step like structure (voltage jumps). Their physical interpretation is the following: The step starting from zero-voltage occurs when vortices begin to move along the limiting interface γ_c as the current has reached its critical value. Increasing the current further,

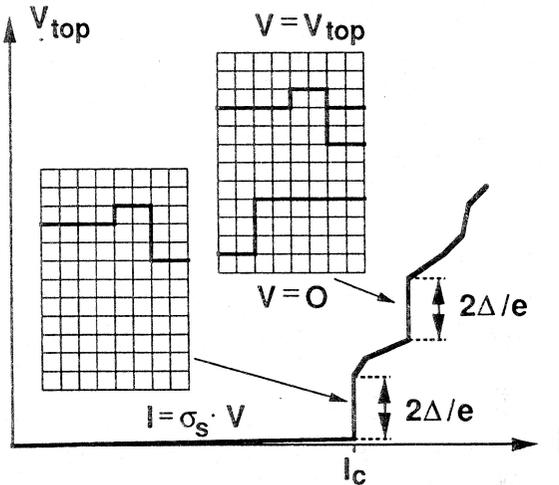


Fig. 3: The current-voltage characteristic of a strongly coupled oxide ceramic, calculated by the extended LI-model for an 8×12 -lattice. Voltage steps of the size $2\Delta/e$ occur whenever a new "flux flow sheet" appears which is completely disconnected from those which already exist. The flux flow sheet configuration corresponding to two of the voltage steps are shown. The intergrain critical currents $i_{c,l}$ are chosen according to the data in Ref. [13] for a completely untextured sample. In our arbitrary units we put $\sigma_{n,l} = i_{c,l}$, $l = 1, \dots, 192$ (Ambegaokar-Baratoff), and the fictitious large "superconductivity" σ_s is 20 times the maximal $\sigma_{n,l}$.

more and more interfaces for vortex flow open. We will call them "flux flow sheets". The coherence across the flux flow sheets is "broken up" into several coherent subdomains bounded by the flux flow sheets. It can be shown that a voltage step in the I - V curve occurs only when a new flux flow sheet is formed which is completely disconnected from those

which already exist. If a new sheet shares at least one grain boundary, it leads only to a change in the *slope* of the I - V curve. Hence the I - V curve contains information on the spatial structure of the breakdown of superconductivity in the ceramic.

Experimentally the steps are not observed at $T=77$ K [3]. This is probably due to strong flux creep at these high temperatures, which are smoothening the step structure. The steps have been observed, however, in "classical" granular Al and In films at $T=4.2$ K and have been observed to smooth out with raising temperature [15]. It would therefore be very interesting to measure the I - V characteristics of the oxide ceramics at low temperatures.

In summary, we have presented the limiting interface (LI) model for oxide ceramics with strong intergrain coupling, for which the XY -type models are not applicable. The extension of the LI-model to finite voltages shows that the current-voltage characteristic contains interesting information on the structure of the S-N transition.

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