Flux creep in the Josephson mixed state of granular-oriented $YBa_2Cu_3O_{7-x}$ thin films

E. C. Jones
Department of Physics, University of Tennessee, Knoxville, Tennessee 37996-1200

D. K. Christen and C. E. Klabunde
Solid State Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6061

J. R. Thompson
Department of Physics, University of Tennessee, Knoxville, Tennessee 37996-1200 and Solid State Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6061

D. P. Norton, R. Feenstra, D. H. Lowndes, and J. D. Budai
Solid State Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6061

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A self-consistent critical current model in the Josephson mixed state is proposed for a series of *c*-oriented, polycrystalline and for a series of epitaxial triaxially oriented YBCO thin films. The flux pinning activation energies were experimentally determined from electrical transport measurements over a wide range of temperatures and were found to behave quite differently for the two types of granular film. With these activation energies applied to a superconductor-normal metal-superconductor weak-link system, thermally activated flux motion is shown to reproduce the experimentally measured critical current densities.

Oriented, deposited conductors hold potential for the fabrication of high-T_c superconducting tapes, thereby prompting the desire to understand the physical properties of such systems. This work investigates the mechanism limiting the transport critical current density J_c for two types of granular $YBa_2Cu_3O_{7-x}$ thin films: (1) *c*-oriented, but granular films grown on polycrystalline yttria-stabilized zirconia (YSZ) by pulsed laser ablation[1,2] and (2) triaxial epitaxial films [composed of small grains having either the (110) or (103) orientation] grown on (110) $SrTiO_3$ by coevaporation and post annealing.[3] Dimos *et al.* found relatively large J_c values ($\sim 4\times 10^6$ MA/cm^2 at 4.2 K) at low angle grain boundaries (less than 10°) of $YBa_2Cu_3O_{7-x}$ (Ref. 4) suggesting the possible existence of percolation paths of high J_c material in granular films. This implies a "scaled down," but otherwise similar $J_c(T,H)$ behavior as those seen in totally epitaxially films. On the contrary, the granular films presented in this work were found to behave as weak-link systems in the presence of giant Josephson vortices described in some detail elsewhere.[5,6] Typical values for zero resistance transition temperatures T_c were near 88 and 67 K, respectively, and $J_c(T=0)$ values were near 130 and 245 kA/cm^2, respectively.

In this study, *I–V* curves were acquired for a set of temperatures and applied magnetic fields, and all curves displayed behavior indicative of flux-creep-limited superconductors ($E\propto J$ in fields $H \ll H_{c2}$). The temperature dependence of $J_c(H=0)$ for either type of thin film was found to fit neither the superconductor–insulator–superconductor (SIS) model,[7] nor any one of the superconductor-normal metal-superconductor (SNS) family of curves, parametrized by the ratio of barrier thickness to normal state coherence length $L/\xi_N(T_c)$.[8] However, critical current densities typically were two orders of magnitude below those of totally epitaxial films, and showed a strong dependence on the applied magnetic field history, indicative of a weak-link system. For *c*-oriented films grown under the same conditions on both polycrystalline and single crystal YSZ (100) substrates, subtraction of the resulting polycrystal and single crystal resistivity curves $\rho(T)$, yield grain boundary resistivity curves which increase with temperature in a way consistent with dirty metals. In addition, using the measured grain size[2] (0.2–1.0 μm), I_cR_N products were determined to fall between 0.3 and 2.1 mV, which are well below those expected for SIS barriers, i.e., approximately 20 mV at $T=0$.[9] Rather, we show in the following that these granular thin films behave as SNS systems for which the critical current densities are further limited by thermal activation of self-field created Josephson vortices at the grain boundaries.[5]

From the Anderson–Kim thermally activated flux creep model,[10,11] in the limit of weak pinning barriers (e.g., at large applied magnetic fields), one expects a thermally activated creep resistivity $\rho=(dE/dJ)$ at $J=0$ given by,[12]

$$\rho=\rho_0 \exp(-U_0/kT),$$

where U_0 is the activation energy and ρ_0 is at most a slowly varying function of T involving the flux lattice response. Thus, the systematic determinations of ρ as a function of field and temperature yield activation energies[13] with the temperature dependencies shown in Fig. 1. The field dependencies of the activation energies could be described by

$U_0(T,B)\propto 1/(B+B_0)^{0.15}$, for the *c*-oriented films and

$U_0(T,B)\propto 1/(B+B_0)$, for the triaxial films.

The constant B_0, taken to be approximately 10 G, is included to prevent $U_0(T,B)$ from diverging under self-fields near T_c. The prefactor ρ_0 is explicitly given by[13]

$$\rho_0=(E_0/J_{c0})(U_0/kT),$$

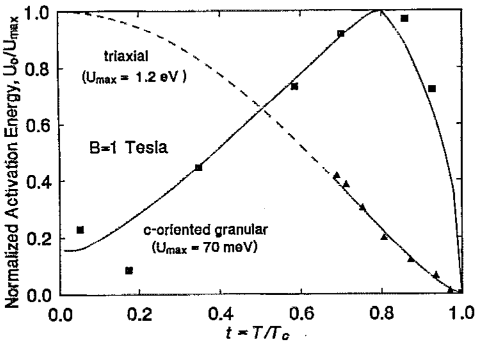

FIG. 1. Temperature dependence of the activation energy at an applied field of 1 T for triaxial and c-oriented granular thin films of $YBa_2Cu_3O_7$. The curves are empirical fits to the experimental data (symbols) for use in the flux creep models.

where in the present case J_{c0} is taken as an SNS critical current density in the absence of flux creep. The parameter E_0, which is proportional to the elementary "attempt" frequency for flux hops, can be estimated by scaling the experimental I–V curves to the Anderson–Kim expression,[10,11]

$$E=E_0 \exp(-U_0/kT)\sinh[(J/J_{c0})(U_0/kT)].$$

For the granular films studied, the E_0 values were found to have temperature dependencies somewhat similar to the respective activation energies. Interestingly, these E_0 dependencies are in qualitative agreement with the prediction of Feigel'man *et al.* for collective thermally activated processes in the vortex state:[14]

$$E_0 \propto \rho_{\text{flow}} U_0/T.$$

Self-consistency of this model is shown for both types of granular films by substituting the U_0 and E_0 parameters, determined in the dissipative state, into the relationship for a creep-limited J_c:[11]

$$J_c=J_{c0}[kT/U_0(T,B)] \times \sinh^{-1}\{(E_c/E_0)\exp[U_0(T,B)/kT]\},$$

where E_c is the electric field criterion of 1 μV/cm. Here, the self-fields B are assumed to be proportional to the current density[15] and are on the order of 100 G at 4.2 K, estimated from the $J_c(H)$ data. In Figs. 2(a) and 2(b), best fits to the experimental data, for both types of film, are found by choosing the J_{c0} function as the Likharev SNS curve[8] for which $L = 3.5\ \xi_N(T_c)$. Even though the activation energies differ markedly, this model provides a good description of the experimental J_c data in both cases. The slight discrepancies which occur above $t \approx 0.7T_c$ could be ascribed to a number of effects, including high-temperature fluctuations, or simply errors in extrapolating high-field U_0 values to the limit of self fields.

In conclusion, a self-consistent model for $J_c(T,H=0)$ was shown for two types of granular-oriented $YBa_2Cu_3O_{7-x}$ thin films. In both cases, the self-field was found to penetrate along the grain boundaries producing a Josephson mixed state.[5] The thermal activation energies of

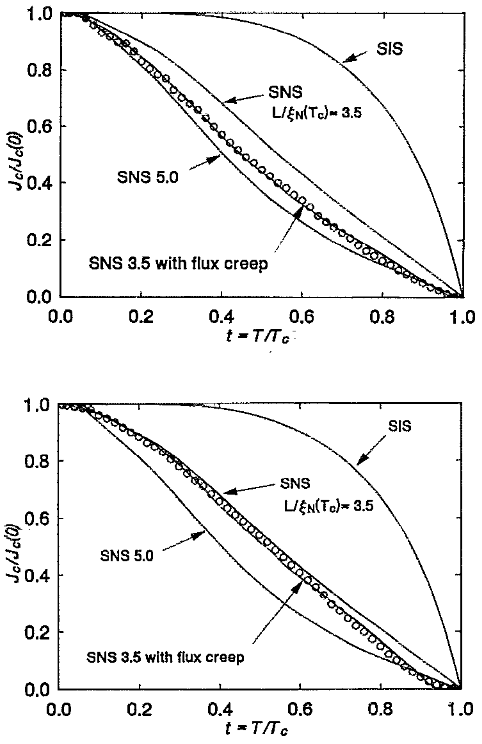

FIG. 2. Reduced critical current density $J_c(T)/J_c(0)$ vs reduced temperature. Symbols show experimental results for granular $YBa_2Cu_3O_7$ films: (A) c-axis oriented and (B) triaxial. Curves show the conventional SIS and SNS weak-link models and the SNS model with flux creep dissipation.

the resulting Josephson vortices, determined in the limit of large magnetic fields, were found in the triaxial films to behave as those seen in totally epitaxial films but scaled down by one order of magnitude. Unlike the triaxial films which contain only special grain boundaries, the c-oriented granular films having random ab-plane grain boundaries were found to have even lower activation energies which exhibit maximums at temperatures near $0.8T_c$. Finally, thermally activated flux creep of the Josephson vortices applied to an SNS weak-link system[8] was shown to reproduce the experimentally measured critical current densities.

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