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Intrinsic variation of the intergrain critical current in polycrystalline $YBa_2Cu_3O_{7-x}$

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Systematic investigation of *V-I* curves and ac susceptibility of a monophasic polycrystalline Y-Ba-Cu-O sample with low critical current density (J_c) has been performed. Very similar magnitudes and variations of J_c obtained from transport and ac susceptibility measurements indicate that the effects of the self-field on J_c are greatly reduced in samples with low J_c. The observed variation of J_c with temperature $[\sim(1-T/T_c)^2]$ and magnetic field $(\sim e^{-\alpha H})$ indicates that the intergrain coupling in polycrystalline Y-Ba-Cu-O can be modeled in terms of thick superconductor–normal-metal–superconductor (SNS) junctions. This conclusion is supported by other recent results and is also plausible considering the very short coherence length in this compound.

It has been shown recently[1] that the strong dependence of the critical current (I_c) on magnetic field makes it impossible to deduce the actual zero-field I_c in usual polycrystalline Y-Ba-Cu-O samples via transport measurements. In these samples I_c is limited[2] by the self-field which affects not only the magnitude of I_c obtained from *V-I* curves, but also causes the variations of I_c with temperature and magnetic field that are different from the ones which would be obtained if there were no self-field effects. Although the intrinsic variation of I_c can, in principle, be obtained from high-resolution ac susceptibility measurements,[1,3] it is of interest to find out whether, in the limit of very low critical current density (J_c), the self-field effects become less important.[2] In that case the *V-I* curves could also yield the intrinsic variation of J_c in polycrystalline samples.

In what follows we report the results of the systematic measurements of the *V-I* curves and ac susceptibility of a polycrystalline Y-Ba-Cu-O sample satisfying the above requirement. Within the temperature range studied (79–90 K), both techniques yield the variation of J_c analogous to that observed in thick superconductor–normal-metal–superconductor (SNS) junctions[4] at temperatures close to T_c. The variation of J_c with the applied magnetic field ($H < 30$ Oe) is also consistent with the above finding.

The synthesis of Y-Ba-Cu-O was performed by the usual solid-state reaction and sintering at 940° C for 12 h in flowing oxygen. X-ray diffraction of the resulting pellet revealed a pure 1:2:3 ($YBa_2Cu_3O_{7-x}$) phase. The density of the pellet was 4.8 g/cm^3. The resistance was measured by a standard ac technique. The *V-I* curves (in the current range up to 10 A) were measured in a single-shot half-sinusoidal current pulse with a typical width of 50 ms. I_c was determined by the linear extrapolation of the first few nonzero voltage data down to zero. (The voltage resolution was 1 μV). This ensured that the effective resistivity of the sample remains below that of copper at 77 K even for the lowest I_c values.[5] The *V-I* curves were also measured in a magnetic field ($H < 50$ Oe). Such low field ensured a negligible penetration into the grains of the ceramic sample.[6] The temperatures in the range of 79–90 K were achieved by immersing the sample in the appropriate mixture of liquid nitrogen and oxygen. The ac susceptibility of the same sample was measured at 28.4 Hz with the amplitudes of the ac field varying from 0.01 to 38 Oe. Some data relevant to our sample are given in Table I.

TABLE I. Data relevant to our $YBa_2Cu_3O_{7-x}$ sample: D is the density, ρ is the resistivity at the specified temperature, χ' is the initial susceptibility, and J_c the critical current density at 80 K as determined from the maximum of the imaginary part of the ac susceptibility (χ''), the real part of the ac susceptibility and *V-I* curve, respectively.

	$\rho(T)$ (mΩ cm)		χ'	J_c (A cm^{-2})		
D (g cm^{-3})	95 K	295 K	80 K	χ''	χ'	*V-I*
4.8	1.6	2.7	−0.93	26	23	20

The superconducting transition of the sample observed by both ac susceptibility and resistivity measurements is shown in Fig. 1. There is a foot at the bottom of the resistive transition which somewhat broadens; otherwise it is a very narrow transition. Such a foot is often ob-

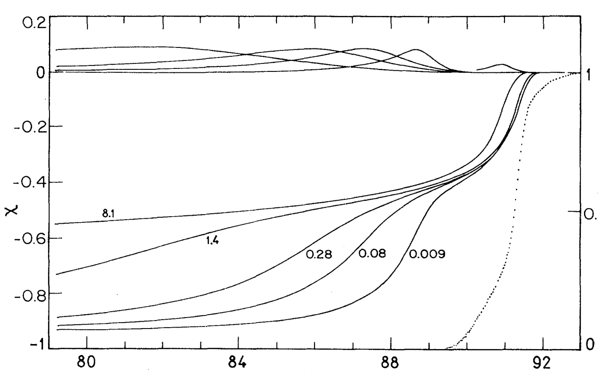

FIG. 1. Resistivity (dotted) and ac susceptibility (real and imaginary part) of $YBa_2Cu_3O_{7-2}$ sample vs temperature. The numbers denote rms values of ac fields (in Oe).

served in ceramic Y-Ba-Cu-O samples and is attributed either to the flux-creep effects or to a weak intergranular coupling. A rather high resistivity and low density of our sample seem to support the second explanation.

The diamagnetic transition of ac susceptibility is considerably broader and shows two characteristic steps associated with intragrain and bulk shielding effects, respectively.[7,8] In spite of rather broad transition (indicating a weak intergrain coupling), there is an almost perfect diamagnetism at 80 K in lower ac fields. The measurements of the real (χ') and imaginary parts (χ'') of the ac susceptibility at different amplitudes of the ac field (Fig. 1) enable, in principle, two independent determinations of the temperature dependence of J_c. The maximum of χ'' (loss) occurs when the magnetic field fully penetrates the sample. For a superconductor in the form of a long cylinder of radius R placed in magnetic field H along its axis, this occurs when $H \cong H_p \cong RJ_c(H_p)$. Hence, if the field dependence of J_c within the explored range of H_p is sufficiently weak [i.e., if $J_c(T,H_p) \approx J_c(T,0)$], these measurements can yield $J_c(T)$. However, the assumption that $J_c(T,H_p) \approx J_c(T,0)$ has to be checked out by an independent determination of $J_c(T,0)$. This can be achieved by the high-resolution measurements of the change of χ' at the given temperature due to an increase of the amplitude of the ac field at low fields.[3] (Note that the separation of the contributions of the superconducting grains to the measured χ' is required in order to obtain the correct magnitude of J_c.) The values of J_c at 80 K obtained from the V-I curve, the maximum of χ'' and a change of χ', respectively, are given in Table I. We note a rather good agreement between these values, which is not the case if J_c is field limited.[1]

The temperature variation of J_c determined from the V-I curves and the maxima of χ'' are shown in Fig. 2. In contrast to the results for the self-field limited samples in which the transport J_c exhibits quasilinear or concave-upward variation with temperature,[1,9] present results show a strong concave-downward variation similar to that obtained from the high-resolution ac susceptibility measurements on the self-field limited samples.[1] Furthermore, the variations of J_c, as determined from the V-I curves, and maxima of χ'' are practically the same and are rather well described by $J_c \simeq (1-T/T_c)^2$, as shown in the inset to Fig. 2. We note that the same variation of J_c was obtained from high-resolution measurements of χ' on samples[1] in which the transport J_c was self-field limited. The same temperature dependence of J_c at temperatures close to T_c has also been deduced from the recent investigation of the intergrain current in the epitaxial thin films.[10] As proposed earlier,[1] such a (intrinsic) variation of J_c seems to indicate that the intergrain coupling in the polycrystalline Y-Ba-Cu-O can be modeled in terms of thick SNS junctions.[4] Such a proposal seems plausible considering the very short coherence length in this material.

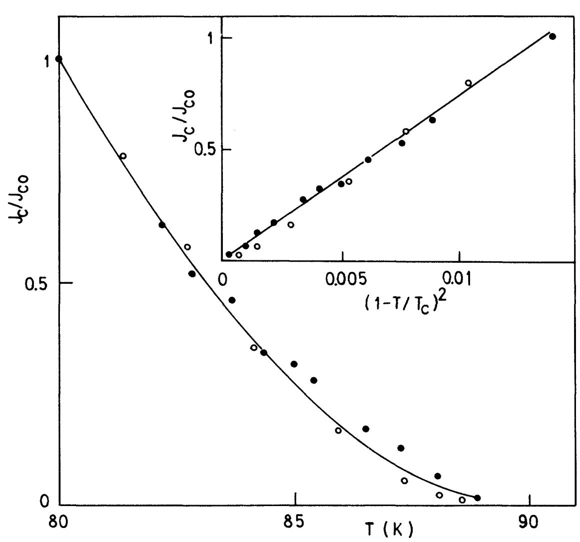

FIG. 2. Variation of critical current density (normalized to its value at 80 K) with temperature as determined from V-I curves (●) and the maxima of the imaginary part of the ac susceptibility (○). The inset: J_c/J_{c0} vs $(1-T/T_c)$ (Ref. 2).

Further support to the above proposal is provided by the comparison of the differential resistance R_f (its magnitude, temperature, and magnetic field dependence) in Y-Ba-Cu-O (Refs. 1, 11, and 12) to that in dilute normal metal-superconductor composites.[13]

A detailed investigation of V-I curves and the critical current distributions for the present sample[14] has confirmed the previous findings[1,11,12]. In particular, R_f of our present sample was independent of temperature ($T < 89$ K) and magnetic field as is the case in dilute normal metal-superconductor composites.[13] The main difference between the results for present sample and the earlier ones[1,12] is in the maximum attainable critical current density ($J_{c\,\max}$) deduced from the critical current distribution curves.[15] Whereas, in the previous samples, $J_{c\,\max}$ has been about 800 A/cm^2, and practically independent of the measured J_c of a given sample,[1,12] here $J_{c\,\max}$ is only about 200 A/cm^2, consistent with a very weak intergrain coupling in the present sample. Furthermore, the critical current distribution is extremely asymmetric with the most probable critical current density (J_{cp}) much lower than $J_{c\,\max}$.

A commonly observed Fraunhofer diffraction-like variation of J_c with the applied field (H) in ceramic Y-Ba-Cu-O samples[16] is often attributed[2] to the array of thin SNS and/or superconductor-insulator-superconductor (SIS) junctions within the sample.[17] However, as explained in previous papers,[1,12] such a variation in low applied fields stems from the self-field (in the case of transport measurements) or trapped field (for magnetization measurements). More precisely, the measured J_c tends to saturate for the applied field lower than the self- or trapped field. This decreases the value of J_c measured in zero applied field below that which would be obtained in a true zero field within the sample and, more importantly, masks the intrinsic $J_c(H)$ variation.

In thick SNS junctions, at not too high fields, an exponential decay of J_c with H is both expected and observed.[4] Therefore, if the temperature dependence of J_c of our sample is indeed associated with thick SNS junctions, it should follow that $J_c \simeq \exp(-\alpha H)$. As shown in

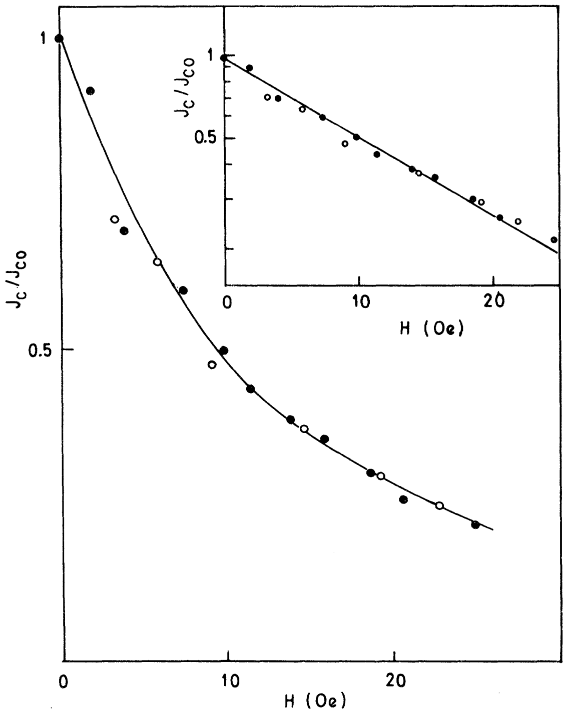

FIG. 3. Variation of normalized critical current density $[J_c(H)/J_c(H=0)]$ with the applied magnetic field at 80 K (○) and 79 K (●). The inset: J_c/J_{c0} (logarithmic scale) vs H plot (showing an $e^{-\alpha H}$ variation).

Fig. 3 and in the inset, the experimental results for transport J_c of our sample obey rather well such a variation. The decay constant $\alpha \approx 0.08$ Oe^{-1} obtained from the present results agrees quite well with those deduced from the variation of J_c with H determined from magnetization measurements at somewhat higher applied fields.[6] (We note that, for H larger than the trapped field, the effects of the trapped field on J_c are greatly reduced.) Furthermore, except for the lowest fields ($H < 3$ Oe), the transport measurements of the critical current between two grains in an epitaxial thin film[18] can also be fitted to exp $(-\alpha H)$ with a similar value of α. Finally, we note that the decay constant of thick SNS junctions depends[4] on the thickness (d_N) and properties (the diffusion length and Fermi velocity) of the normal layer. Therefore, a systematic investigation of the intrinsic variation of J_c with H in polycrystalline Y-Ba-Cu-O samples (both bulk and thin films) may be of particular interest to understand the nature of the weak intergrain coupling in high-temperature superconductors.

Summarizing the above, we note that the polycrystalline Y-Ba-Cu-O sample with a rather high normal-state resistivity and a low transport critical current density (Table I) exhibits the variations of J_c with temperature and magnetic field that are different from those observed for polycrystalline samples with higher J_c. The simplest explanation of this phenomenon is that, in the case of very weak intergrain coupling, the effects[2] of the self-field on J_c are greatly reduced and hence the nature of weak links determines the variation of the transport critical current. The results presented in this work, as well as previous findings,[1,10,12,18] indicate that the intergrain junctions in polycrystalline Y-Ba-Cu-O can be modeled in terms of thick SNS junctions.[4] Such a conclusion seems plausible considering the very short coherence lengths in these materials. Systematic study of the intrinsic variations of J_c with the magnetic field and temperature may provide more detailed insight in the nature of the critical current limitation in polycrystalline high-temperature superconductors.

Since the nature of the intergrain coupling in grain-oriented high-J_c Y-Ba-Cu-O samples may be quite different, comparative studies of the intrinsic variations of J_c in these samples would be of particular interest.

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