Magnetic field dependence of the critical current of tridimensional YBa$_2$Cu$_3$O$_{7−δ}$ Josephson junction arrays

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Abstract

In this paper we determine the magnetic field dependence of the critical current of a tridimensional disordered Josephson junction array (3D-DJJA). A contactless configuration, employing measurements of the AC-susceptibility, is used to evaluate the average critical current of an array of YBa$_2$Cu$_3$O$_{7−δ}$. The critical field necessary to switch off supercurrents through the weak links at the working temperature is also obtained.

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Tridimensional disordered Josephson junction arrays (3D-DJJA) can be produced in a controlled manner, as we have recently demonstrated. Arrays of conventional superconductors (LTS), fabricated from classified powder, and from ceramic high-temperature (HTS) superconductors, prepared using a Sol-Gel route, have proved to exhibit all relevant signatures of a JJA. Those include the typical Fraunhofer dependence of the critical current with the applied magnetic field, $J_c(H)$, the magnetic remanence, and the Wohlleben effect (WE). In fact, these features are controlled by the McCumber parameter, $β_L = 2πJ_c(T)L/φ_0$ -where $L$ is the plaquette inductance, and appear only if $β_L >> 1$. This strong agreement brings
us to believe that average $\beta_L$ is in the range, in the case of our samples. But, it is difficult to infer the actual value of $\beta_L$ because the irregularity of our 3D-DJJA.

Even though behaving as genuine Josephson junction arrays, these 3D-DJJAs can also be envisaged as especially assembled specimens of granular superconductors, so that their transport and magnetic properties can be studied by the commonly employed approaches based on critical state models$^{5,6}$. A particularly effective experiment to determine the average critical current density, $< J_c >$, of multileveled granular structures$^{7-9}$, consists of measuring the isothermal AC susceptibility, $\chi_{AC}(h)$, as a function of the magnetic field amplitude, $h$. The imaginary component, $\chi''$, related to energy losses, peaks at a field $h_p$ which, in turn, is an indirect measure$^7$ of $< J_c >$, i.e., $h_p = a < J_c >$ for a sample of cylindrical shape of radius $a$. This contribution contains results of a systematic study of the isothermal $\chi_{AC}(h)$ for a 3D-DJJA fabricated from YBa$_2$Cu$_3$O$_{7-\delta}$. The experiments were carried out for different values of the applied magnetic field $H$, and the intergranular peak of $\chi''$, at $h = h_p$, was used to determine the average $< J_c(H) >$. The present approach is a practical alternative - employing $\chi''(H)$ instead of $\chi'(H)$ - to the method used by Araujo-Moreira and coworkers$^4$ to determine $J_c(H)$ for JJAs. It proved to be particularly useful for high temperatures in the $h$-parallel-to-$H$ configuration, where the static flux imposed to the array affects $\chi'(H)$, as a background to be subtracted, but not $\chi''(H)$.

Granular YBCO material used to fabricate the arrays was prepared employing a modified method of polymeric precursors$^{10}$. This route consists of mixing oxides and carbonates in stoichiometric amounts dissolved in HNO$_3$, and then to an aqueous citric acid solution. A metallic citrate solution is then formed, to which ethylene glycol is added, resulting in a blue solution which was neutralized to pH~7 with ethylenediamine. This solution was turned into a gel and subsequently decomposed to a solid by heating at 400 °C. The sample was heat-treated at 850 °C for 12 h in air with several intermediary grindings, in order to prevent undesirable phase formations. Then, it was pressed into a pellet using controlled uniaxial (5,000 kgf/cm$^2$) pressure and sintered at 9500 °C for 6 h in O$_2$. This pellet is a 3D-DJJA, in which the junctions are weakly coupled grains with 5 µm of average diameter,
i.e., weak-links (WLs) formed by sandwiches of YBCO grains and intergrain material. As a consequence of the uniaxial pressure, samples produced in this way are anisotropic, a feature that can be either enhanced, by using higher pressures, or reduced, by applying isostatic pressures. Also, thermal treatment plays a fundamental role on creation and control of WLs and anisotropy, as is thoroughly discussed elsewhere.

AC-susceptibility measurements, $\chi_{AC}(h)$, were carried out using the AC-module of a Quantum Design SQUID magnetometer, for the excitation field $0.01 \leq h \leq 3.8$ Oe and frequency of 100 Hz, at temperatures ranging from $T = 2$ K up to 100 K. In this paper we focus on the field dependence for $T = 78$ K, close enough to $T_c$ to ensure that $h_p$ is below 3.8 Oe, the upper AC field achievable in the experimental apparatus employed. Fig.1 shows the real ($\chi'$) and imaginary ($\chi''$) parts of $\chi_{AC}(h)$ for some values of $H$. As mentioned above, $h_p$ is an indirect measure of $< J_c >$ which, in the present case, is the average critical current density of the 3D-DJJA. In Fig.2, the average $J_c(H)$ for $T = 78$ K is shown. The line connecting the experimental points for the average $J_c(H)$ is a fit of the form $J_c(H, T) = J_{c0}[A + B(H^2 + C^2)^{-1}](1 - T/T_c)^{2.38}$, introduced by Wright and coworkers for a matrix formed by grains linked by Josephson couplings. The fitting parameters appear in the inset table. It is worth mentioning that $T_c$ is not the grain’s critical temperature, but the array’s instead, reported previously for this same sample as $T^* = 83$ K. Also, from the values arising from the fitting one concludes that a critical field $H_c = 35$ Oe is sufficient to suppress superconductivity through the 3D-DJJA at any temperature, as the superconducting current across the weak-links vanishes for fields above $H_c$.

To summarize, we recall that, besides current transport across the sample, which would be infeasible here, two other methods could be employed to determine the magnetic field dependence of the critical current of 3D-DJJAs: (i) measure of $\chi'(H)$ with $H$ parallel to the plaquettes, and (ii) measure of $\chi'(H)$ with $H$ perpendicular to the plaquettes. Method (i) would require static and sinusoidal fields perpendicular to each other, what is unattainable in our experimental apparatus, as well as in most of the existing laboratory setups. Method (ii) imposes static flux into the array, affecting $\chi'(H)$, so that a background
has to be subtracted. Using the present method, however, the average critical current density
is obtained in a straightforward manner, since $\chi''(H)$ is not affected by the static flux.

Financial support was partially provided by Brazilian agencies FAPESP, CAPES, PRONEX and CNPq.
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FIGURES

Fig. 1. Real ($\chi'$) and imaginary ($\chi''$) parts of $\chi_{AC}(h)$ for three values of the static applied field, $H = 5, 10$ and $15$ Oe. The excitation field at which $\chi''$ peaks is an indirect measure of the average critical current density of the array.

Fig. 2. Average $J_c(H)$ for $T = 78$ K. The line connecting the experimental points is a fit of the form $J_c(H, T) = J_{c0}[A + B(H^2 + C^2)^{-1}](1 - T/T_c)^2$. $T_c$ is the array critical temperature. The appropriate combination of the fitting parameters lead to $H_c = 35$ Oe, above which the WLs in the array do not superconduct at this temperature.
$\chi'$ and $\chi''$ (10^4 emu/Oe) vs. $h$ (A/m) for $T = 78$ K and $YBa_2Cu_3O_{7-\delta}$ at different fields:

- Square marker: 5 Oe
- Circle marker: 10 Oe
- Triangle marker: 15 Oe
$J_c = J_{c0} \times (A + B(H^2 + C^2)^{-1}) \times (1 - 78/83)^{2.38}$

$A = -60.7$
$B = 9.05 \times 10^4$
$C = 16.2$
$T_c = 83 \text{ K}$

$H_c = 35.07$

$T = 78 \text{ K}$