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Critical fields and the critical current density of $La_{1.85}Sr_{0.15}CuO_4$

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A detailed investigation of the magnetic and transport properties of $La_{1.85}Sr_{0.15}CuO_4$ in the superconducting state is presented. It is concluded that the magnetic and transport behavior is that of a granular type-II superconductor in which strongly superconducting grains are coupled via weak superconducting links. Five characteristic fields are identified. H_{c1}^{w} (≈ 1 Oe at 4 K) is the field at which the first vortex line penetrates the weak links. At $H = H^{w}$ (≈ 11 Oe at 4.2 K) the London penetration depth in the weak links is very large compared to their dimensions. H_{c1}^{g} (≈ 300 Oe at 4.2 K) defines the first flux thread entering the grains themselves. H^{g} is the value above which the magnetic behavior of the grain is thought to be governed by Abrikosov's negative surface energy model. The critical current density measured by the resistivity technique is about 8 A/cm^2 and is imposed by the sample size and compositional inhomogeneities and by H_{c1}^{w}, whereas the bulk (or intragrain) critical density could attain 10^5–10^6 A/cm^2.

Since the discovery of high-T_c superconductivity in La-Ba-Cu-O and Y-Ba-Cu-O oxides, many extensive studies have been started on these materials. However, unambiguous determination of the critical parameters of the superconducting state are still lacking. Very recently, we reported in a short communication,[1] that the critical current densities in these materials, as determined from magnetic data, could attain 10^6 A/cm^2. Here, we report a more extensive magnetic investigation, especially at very low fields, together with some transport measurements on the same sample of $La_{1.85}Sr_{0.15}CuO_4$. The magnetization of a cylindrical specimen (≈ 7 mm long and 2.5 mm in diameter) was measured with a vibrating sample magnetometer, the sensitivity of which was about 10^{-4} emu. The resistance was measured by means of a standard four-probe method using silver-paint contacts.

The set of M-H curves shown in Fig. 1 corresponds to the same $La_{1.85}Sr_{0.15}CuO_4$ sample and all curves were plotted at 4.2 K after zero-field cooling. Note, however, that they differ in the field and magnetization scales. The comparison of these curves reveals that the M-vs-H relationship exhibits a variety of magnetic behaviors as a function of H. First, Fig. 1(a), when the cycle is recorded just after zero-field cooling we find that the variation of M with H is quite linear and reversible up to a first critical field $H_{c1}^{w} = 1 \pm 0.3$ Oe.[2] Note that the small asymmetry with respect to the origin is due to the earth's field. Furthermore, in this field region the relationship $-4\pi M = H$ is well obeyed within our experimental precision ($\sim \pm 8\%$ of the absolute value of M), implying that the screening of the sample is complete to this precision, in agreement with other low-H data.[3] This diamagnetism is obviously associated with persistent macroscopic currents. As H is further increased [$H \gtrsim 1$ Oe, Figs. 1(a) and 1(b)], departure from linearity, together with a regime of weak irreversibilities, sets in up to a second threshold field H^{w} (~ 10 Oe at 4.2 K), beyond which the curve again becomes reversible and linear but with a reduced slope: $-4\pi M/H \approx 68\%$. It is clear that H_{c1}^{w} represents the field at which the first flux lines penetrate the sample through the weak links. The meaning of H^{w} is less clear. However, by analogy with the magnetic behavior of more conventional inhomogeneous superconductors,[4-6] we tentatively suggest that our sample has roughly two phase components and is formed by highly superconducting grains

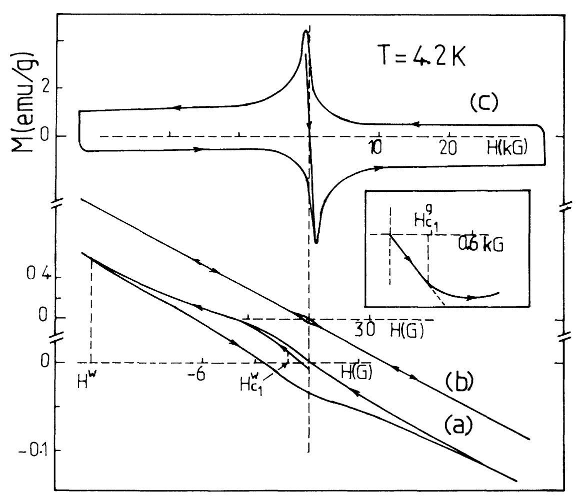

FIG. 1. The isothermal magnetization (4.2 K) as a function of field for three different field scales. Note the presence of two very different regimes of irreversibilities near (a) and (b) $H = 0$ and (c) at much higher fields.

connected together by weak-link superconductors (Josephson junction, proximity effect, etc.).[7] Then, in this picture H^w could mean that the number of flux lines threading the weak links has become very large and attained the limit[4] imposed by Abrikosov's negative surface energy concept. The sharp drop of the effective screening volume (as defined by the ratio $-4\pi M/H$) from ~ 1 (perfect screening) to ~ 0.68 for $H > H^w$ suggests a large London penetration depth (for $H > H^w$) through the weak links probably comparable to the sample radius.[4] The examination of Fig. 1(c) and the inset of the same figure show that the linear and reversible behavior discussed just above ($H > H^w$) continues right up to a third critical field H^g_{c1} (≈ 300 Oe at 4 K) which marks the onset of a regime of strong irreversibilities. (These irreversibilities are illustrated by the inset of Fig. 2 where we have cycled the field several times in steps of about ± 100 Oe). For still higher fields [Fig. 1(c)] the magnetization goes through a maximum at field $H_m \approx 650$ Oe and then decreases gradually and monotonically with H. We emphasize that the same characteristic behavior (with several critical fields) is observed at higher temperatures. In addition, we find (Fig. 2) that at high enough field and temperature (near T_c) the M-H curve again becomes reversible above a fourth threshold field $H^g(T) \gg H_m(T)$. The field H^g could represent a de Almeida–Thouless spin-glass-like line of the sort reported by Müller *et al.*[8] We propose here an alternative interpretation (4) according to which $H^g(T)$ is the field above which the M-vs-H law is governed by the Abrikosov negative surface energy model. Consequently, the magnetization loop, for $H > H^g$, would rather represent an intrinsic bulk (or single-grain) property. Finally, in addition to the critical fields defined above we must have the usual upper critical field H_{c2} [$H_{c2}(0) \approx 500$ kG] where the superconductivity of the grain vanishes.

A sequence of low-field M-H curves at different temperatures is presented in Fig. 3. We note a global but gradual diminution of the hysteresis effects with increasing temperatures and the disappearance (within our precision) of the low cycle at ~ 33.5 K (i.e., slightly below $T_c \approx 36$ K). This suggests that most of the weak links become nonsuperconducting above 33.5 K. It is possible that the vanishing of the low-H cycle is correlated with the beginning of the increase of the resistivity curve (Fig. 4) so that both phenomena would have the same origin. To give more support to our hypothesis that the superconducting behavior is that of weak links connecting more strongly superconducting grains, we have measured (Fig. 5) the critical-current density j_c of our sample at liquid-helium temperature and found $I_c \approx 0.4$ A and $j_c \approx 8$ A/cm^2. As can be seen, the I-V characteristic has a rich structure which is more typical of a Josephson junction rather than a homogeneous superconducting material. This suggests that the critical current and the low-field structure of the magnetization curves are controlled by the same weak links. This is also consistent with the analysis of the data in the framework of the Bean model[9] which we want to consider now.

Let us first concentrate on the low-H cycles [Figs. 1(a) and 1(b)]. Since the magnetic screening is quasicomplete, at sufficiently low H, we can accept that, to a first approximation, the whole sample behaves as a single filament of radius $R \approx 1.25$ mm (i.e., the sample radius). This allows

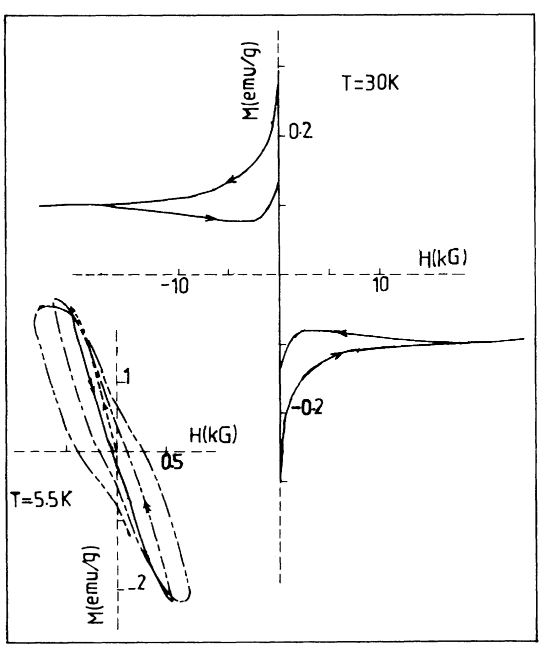

FIG. 2. The magnetization as a function of field at 30 K. The inset shows an example of magnetic irreversibilities at 5.5 K.

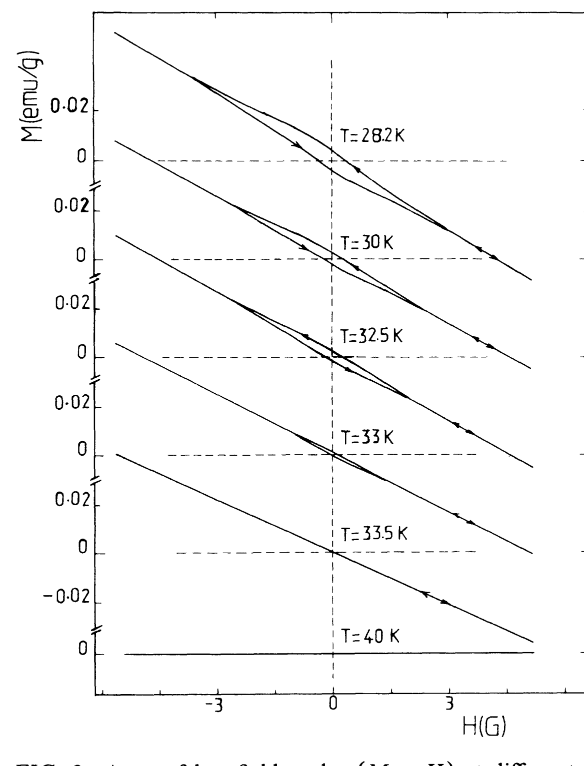

FIG. 3. A set of low-field cycles (M vs H) at different temperatures. Here, the curves have been corrected for the earth field.

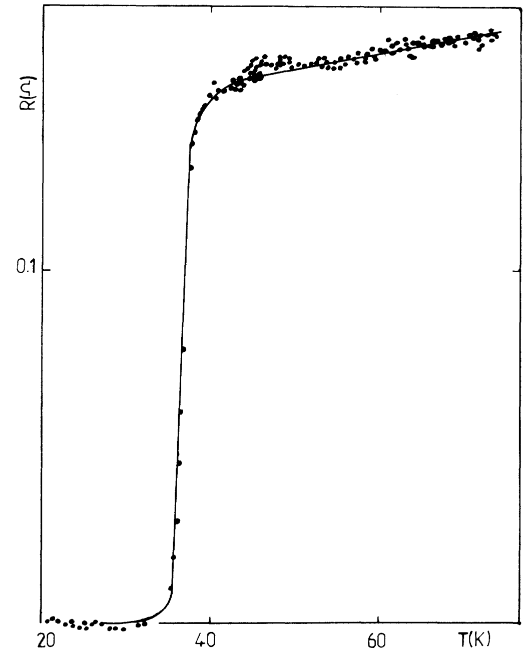

FIG. 4. The temperature dependence of the resistance of the sample as in Figs. 1–3.

us to apply Bean's model[9] according to which the magnetization M, the critical current density J_c, and the filament's radius R are related together by the relationship

$$J_c = -30M/R \ . \tag{1}$$

Equation (1) above would be valid in the field region such that

$$H_{c1}^{w} \lesssim H^B \lesssim H \lesssim H^w \ ,$$

where

$$H^B = 4\pi J_c R/10 \tag{2}$$

is a field parameter introduced by Bean. Note that the

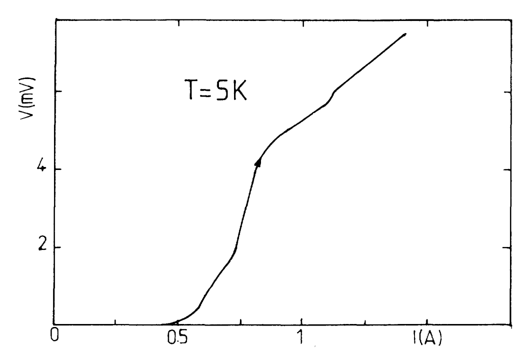

FIG. 5. The voltage-current characteristic at about 5 K. Note that the samples corresponding to Figs. 4 and 5 have been cut from the same ingot but have different geometrical factors.

units for H^B are Oe, for J_c are A/cm^2, and for M are emu/cm^3. Then assuming as in Ref. 9, that $H_{c1}^{w} \lesssim H^B \lesssim H^w$ and using our low-H data of Fig. 1(a), we get the current density limit imposed by the weak links:

$$15 \text{ A/cm}^2 \lesssim J_c < 150 \text{ A/cm}^2 \ . \tag{3}$$

This is to be compared with the measured J_c (Fig. 5) of our sample in liquid helium: $J_c \approx 8$ A/cm^2. It is to be emphasized, however, that the real macroscopic-current density at 4.2 K is certainly somewhat higher than the above measured value because of the earth's field. More fundamentally, we feel that sample inhomogeneities[10] would have more drastic effects on the critical-current density than on the magnetic properties. The reason is that, when the first weak-link is broken, (assuming the electrical current imposed by an external source), the current density automatically increases in the neighboring area of the sample, thus disrupting other weak links, and so on. Obviously, no such cooperative phenomena could exist for magnetic measurements. In view of the above results we can consider that the agreement between the measured and the calculated current densities, assuming the sample as a single superconducting filament (near $H=0$) and Bean's model, is quite reasonable. At this point, we stress that since J_c is a volume parameter (dc current), the above arguments also imply that the low-H structure of the magnetic loop is a volume effect too.

Finally, it is interesting to note that the field $H(I_c)$ produced by the critical current itself at the surface of the sample, as calculated naively by Ampère's theorem, is about 0.6 Oe. This value is very close to that of the first critical field H_{c1}^{w} determined by magnetic measurements. The difference can be ascribed to the uncertainties on H_{c1}^{w} and to the more basic reasons discussed above [i.e., the extreme sensitivity of I_c and thus of $H(I_c)$ to any disturbance of the weak links].

The above analysis suggests that the critical current measured by the resistivity technique does not represent the bulk or intragrain critical current, but is first of all a shape-dependent parameter imposed by the physical dimension and the inhomogeneities in the sample. This could explain why the critical-current density values taken from different sources of the literature[11–13] are so incoherent and vary from 0.1 to more than 10^3 A/cm^2.

We now turn to our high-field data. As already mentioned, these are strikingly similar to older measurements on granular superconductors[4–6] and can be analyzed in the same picture. It is then reasonable to assume that, for $H \gg H^w$, the sample can no longer be considered as a single filament and that our high-field curves are related to the granular structure of our sample. X-ray studies,[14] together with scanning electron microscopy (as well as optical microscopy) observation show that the material is granular with grain size of the order of 1 to 10 μm. By analogy with Swartz,[4] whose older interpretation of magnetic data is very similar to ours, we consider that the high-field magnetization curve is the sum of two contributions: one intrinsic contribution which is independent of the size of the grains until the London penetration depth effects (in the grain) becomes important and one which depends on the size and the current density within the grains. The former contribution would be that predicted by the negative surface energy model of superconductivity and would be predominant for $H > H^g(T)$ (Fig. 2), whereas the latter would correspond to the curve deduced from Bean's model.[9] The relative contribution of the second curve increases with the size of the grain and is much more important at intermediate fields such as $H^g_{c1} < H < H^g$ where the variation of M with H is very slow.

Assuming that to a first approximation the M-H relationship for $H^g_{c1} < H < H^g$ is that inferred from formula (1) in which we now take $M \approx 10$ emu/cm^3 [the value given by the high-field upper branch of Fig. 1(c)], we get $J_c \approx 3.10^5$ to 3.10^6 A/cm^2 for a grain radius of 10 or 1 μm, respectively. Alternatively, using the above $M = 10$ emu/cm^3 value and assuming (as for the low-H limit) the sample as a single homogeneous grain with $R = 0.1$ cm, we obtain the lowest possible limit (inferred from Bean's model) for the critical-current density ($J_c \approx 300$ A/cm^2) associated with the high-field cycle at 4.2 K [Fig. 1(c)].

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