Transport hysteresis of the oxide superconductor $YBa_2Cu_3O_{7-x}$ in applied fields

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The results of transport measurements on the oxide superconductor $YBa_2Cu_3O_{7-x}$ in the presence of an external magnetic field with various dc currents are reported. The observed highly irreversible behavior and other peculiar features are analyzed considering the granularity and weak-link nature of the bulk oxide superconductors. This study confirms the nonideal type-II superconducting nature of the compound.

The discovery of oxide superconductors with transition temperatures above 90 K offers the possibility of extending the applications of superconducting technology. However, the zero-field critical current density of sintered bulk samples, such as $YBa_2Cu_3O_{7-x}$, at liquid-N_2 temperature only reach $\sim 10^3$ A/cm^2 (Ref. 1), much lower than that required by most practical applications. Furthermore, most applications, for example, superconducting magnets, usually require that the material be able to carry large nondissipative current at high field. Certainly, the properties of oxide superconductors relevant to these requirements should be well studied either for ways to enhance the critical value or to gain more information for understanding the micromechanisms of these new oxide superconductors. We have reported some results of *I-V* characteristic measurements in the presence of applied fields on the Y-Ba-Cu-O compound.[2] It was found that the critical current drops drastically at weak applied field (10^{-3} T). A Josephson weak-link network model has been proposed to interpret the observed phenomena. In this report, we present the primary results of transport measurements under external fields up to 3 T. A qualitative interpretation based on the granularity and weak-line features of the oxide compound is given.

The samples studied in this measurement were from two sources, one was made in this lab[3] and another was prepared by the Baoji Institute for Nonferrous Metal Research (Shanxi, China).[4] Both samples are single phase, analyzed by means of x-ray diffraction patterns, and have a T_c around 90 K as determined with the four-probe technique as well as the ac susceptibility measurement. The zero-field (earth-field) critical current density at 77 K ranged from 30 to 150 A/cm^2 for the former samples while a value of 300 A/cm^2 was obtained for the latter ones. The specimens were cut out from sintered pellets to form bars of a cross sectional area of 1×2 mm^2 and 10 mm in length. Four pads of silver film were deposited on the bars and the leads were then pasted on with conductive epoxy. The specimen being measured was placed in a superconducting magnet which could produce a 3-T field. The field could be applied either parallel or perpendicular to the direction of the current flowing in the sample. The results of these two configurations showed only the difference due to the diamagnetization factor, as expected. Therefore, only the perpendicular case was chosen to be presented in this report. The applied fields were recorded by means of a Hall probe (Model 5200 Oxford Instruments) and the temperature of the sample could be regulated from 4.2 K to temperatures above T_c and was monitored by a calibrated diode thermometer (Lake Shore Cryogenics).

Figure 1 shows the variations of the voltage produced by various constant dc currents under an applied field. Several distinct features can be immediately seen. The output voltage, i.e., the resistance of the specimen, behaves very differently depending on whether the field is ramped up or down. In the case of increasing field, the specimen enters the resistive state at quite low applied fields H_u. The zero-resistance state can hardly be seen on the scale of Fig. 1. In the case of decreasing field the specimen recovers to the zero-resistive state at fields H_d which are obviously higher than H_u. The resistance at the dissipative state in the situation of decreasing field is always lower than the case for increasing field. There is a resistance peak and valley, or equivalently, a negative dynamic magnetoresistance region, on all the curves shown in Fig. 1. The location of the peak moves to a higher field with the decrease in the transport current. The valley moves too and becomes so shallow that it can hardly be observed at small currents. The measurements at other temperatures and on the samples from different batches show similar results. Alternating the sweeping rate from

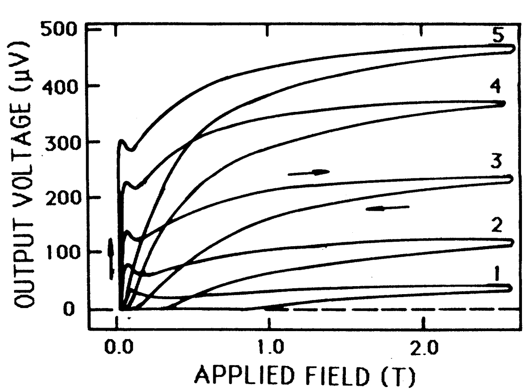

FIG. 1. The variation of the voltage produced by dc currents for a Y-Ba-Cu-O sample (Ref. 4) under applied field at 4.2 K. The curves shown are corresponding to the current density of 1.40, 2.50, 3.60, 4.70, 5.81.4 A/cm^2, respectively. The arrows show the direction of the field sweeping.

0.05 to 0.3 T/min did not cause any visible deviations from the curves shown in Fig. 1.

Further measurements showed that H_d is unique if only the applied field was swept up over a certain value, otherwise there is no well-defined value of H_d as shown in Fig. 2 in which the direction of the field sweeping was reversed at three values of applied field. It was found that the sample returns to the zero-resistive state just after the turning points for all three cases. A similar phenomenon was also observed for the situation of H_u. In Fig. 3 a set of output voltages produced by a dc current versus applied field is shown. Depending on the field value H_i at which the direction of field sweeping reverses from down to up, H_u varied such that the higher H_i, the higher H_u, as well as the smaller the difference between H_u and H_i.

To our knowledge, such distinct hysteresis has not been experimentally observed in the ordinary helium-temperature superconductors. It must be connected with the special features of the oxide superconductors, at least in their bulk form. Based on a number of investigations, it is now a generally accepted aspect that a bulk oxide superconducting sample can be described as an assembly of type-II superconducting grains with weak-coupling correlating them to each other. The granularity and short coherence length are believed to be responsible for this aspect. The weak coupling between grains (or superconducting domains as one cannot rule out the presence of the weak couplings within structure grains) can be the Josephson weak-link nature as proposed by several authors including ourselves.[2,5-7] They can also be the proximity effect[8] or weak-pinning center.[9] For a qualitative understanding of the observed phenomena in this study, one need only recognize the following hypothesis. The weak links between grains (domains) form a complicated network. The critical current of the sample is dominated by the effective critical current of the network. Once the current in the sample reaches the value at which there is no continuous zero-resistance path existing in the network, the sample enters the dissipative state. This value of the current is usually defined as the critical current of the sample. Certainly, the zero-voltage current of the individual weak link must be in some sort of distribution due to the variation in the thickness of the nonsuperconducting phases at the boundaries and in the contact area between grains. Thus, there are weak links at their zero-resistance state even though the sample is in the dissipative (non-zero-resistance) state. The residual superconducting weak links gradually escape from the zero-resistance state upon further increase in the transport current. This feature is reflected by the nonlinearity commonly observed in the I-V characteristic measurements. The dynamic resistance at a relatively small current (certainly higher than the critical current conventionally defined) less than the normal one is additional proof of the presence of these residual zero-resistance weak links. Owing to this statistic property of the network, the structures on the single Josephson diffraction pattern $[I_c = I_{c0} \times \sin(B/B_0)/(B/B_0)]$ is averaged out and a smooth curve of zero-voltage current versus applied field presented.[2] For a given transport current, there is a threshold magnetic field at which the sample shifts into or from the zero-resistance state depending upon the direction of the field sweeping. Similarly, there are residual zero-resistance weak links in the magnetically induced dissipative state and they gradually lose their zero resistance upon the increase in the applied field. The sharp variation of the sample resistance in the dissipative state with the external field reflects this feature. In contrast with the weak-link network, the superconducting grains (domains) remain in their zero-resistance state (Meissner or mixed state depending on the value of the field) in the relative small transport current and field for a given temperature as reached in this measurement. The grains made no contribution of the resistance measured at all. But, importantly, the presence of these superconductive grains and especially their magnetic properties are optimum for the observed hysteresis in this study. The pinning effect of the grains results in the local field distribution inside the sample being different from the applied one and certainly different in the case of the field being ramped up and down. Let β be the portions of the weak-link area (including the porosity), then one can write down the following equation based on the flux conservation

$$H_e = \beta H_w + (1-\beta)B \quad (1)$$

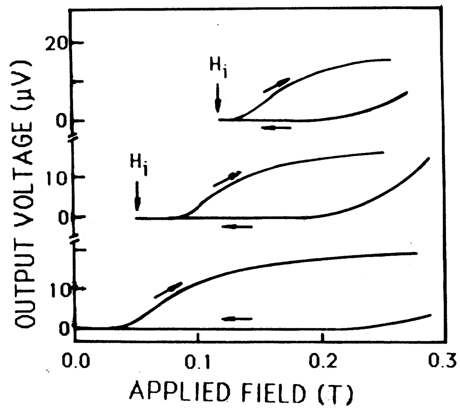

FIG. 3. Three recorded curves of the voltage produced by a dc current of 16 A/cm^2 on a Y-Ba-Cu-O sample (Ref. 5) for different field H_i (explained in the text). The arrows show the order of field sweeping. The zero-voltage line was shifted for seeing the difference clearly.

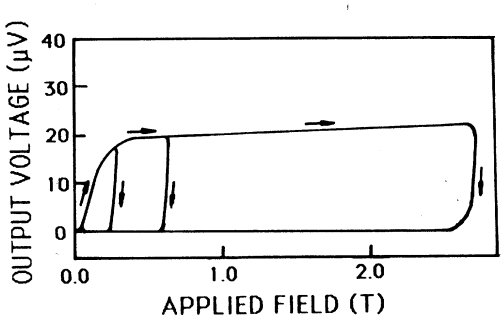

FIG. 2. The output voltage traces of a Y-Ba-Cu-O sample for the cases of field swept up and down. The field sweeping direction (shown by arrows) turned at values of 0.27, 0.63, and 2.8 T. The transport dc current density is 2.3 A/cm^2 and the measurement temperature is 4.2 K.

where H_e and H_w are the external field and the local field at the weak-coupling area, respectively, and B should be described by the standard formula $B = H_w + M$ for the superconductive grains. Thus, Eq. (1) is easily reduced to

$$H_e = H_w + (1-\beta)M(H_w) \tag{2}$$

where M is the magnetization of the grains emphasized to be a function of the local field in the formula. For a given transport current and the field at which the sample enters the dissipative state, one may write down the following equations:

$$H_u = H_t + (1-\beta)M(H_{t\uparrow}) , \tag{3a}$$

$$H_d = H_t + (1-\beta)M(H_{t\downarrow}) , \tag{3b}$$

for the cases of the field swept up and down, respectively, where H_u and H_d are the recorded threshold field with the external field in two cases and $M(H_t)$ is the magnetization of grains at the local field H_t, which is the real threshold field of the network. The arrows in the equations indicate the directions of the field sweeping, ↑ for the up and ↓ for the down. Naturally, the following equation is obtained from Eqs. (3a) and (3b):

$$H_d - H_u = (1-\beta)(M(H_{t\downarrow}) - M(H_{t\uparrow})) . \tag{4}$$

According to Eq. (4), no hysteresis would be expected if $M(H_{t\downarrow})$ equals $M(H_{t\uparrow})$. This condition can be satisfied when the applied field is swept only to values such that the local field H_w is smaller than H_{c1}, the lower critical field of the superconductive grain, where $M(H_{t\downarrow}) = M(H_{t\uparrow})$. The condition of $H_t < H_{c1}$ can be satisfied at relatively high current. Measurement of the quantity of $H_d - H_u$ as a function of current may offer a way to obtain unambiguously the value of H_{c1}. With the condition of $H_w > H_t > H_{c1}$ satisfied, $M(H_{t\downarrow})$ no longer equals $M(H_{t\uparrow})$ as proved by magnetization measurements on single crystals of Y-Ba-Cu-O.[10] Depending on the degree of the hysteresis of the magnetization curve, the threshold magnetic field of the network recorded with the external field have a similar degree of hysteresis. According to Eq. (4), the hysteresis of the threshold field depends on both the magnetic properties as well as the morphology (β) of the sample. The observed great hysteresis indicates that the superconductive oxide crystal itself is a very nonideal type-II superconductor. As indicated by Eq. (2), the trapped flux inside of grains results in a lower local field when the field is swept down rather than up. The resistance of the sample in its dissipative state is a function of the field exerted on the weak links, the stronger the field, the higher the resistance, as stated in the previous paragraph. Then the observed resistance hysteresis, i.e., lower resistance for the field swept down than that for up, is easy to understand.

There is no conclusive explanation for the observed negative dynamic magnetoresistance shown in Fig. 1 at the present time. A tentative interpretation is that, upon the increase in field, the loops comprised by grains and weak links break down due to the escape of the weak links from the zero-resistance state for a given constant current. The penetration of the field into the loop area lowers the local field. Some of the weak links, which were previously in the dissipative state, recover to the zero-resistance state again, lowering the total resistance of the sample and the negative dynamic resistance is obtained.

The results shown in Figs. 2 and 3 can be understood in the same sense. According to Eq. (2), the local field H_w is higher than H_e in the case of the field swept up, while in the situation of the field swept down, H_w is smaller than H_e since there is an abrupt change in the sign of the magnetization M of the grains. Thus, the sample recovers to the zero-resistance state immediately after the direction of the field sweeping is reversed provided H_w is smaller than H_d defined uniquely by Eq. (3b). The trapped field inside the grains could even result in a field, the direction of which is opposite to the applied one. It may be responsible for the delayed appearance of the resistance, i.e., the higher H_u as shown in Fig. 3.

In summary, very peculiar hysteresis has been observed in the transport measurements in the presence of the external field. The observed phenomena can be qualitatively understood on the basis of the granularity and weak-link aspect of the sintered bulk oxide superconductors. The results of this study confirm the nonideal type-II superconducting nature of the oxide compounds. More careful measurements, now underway in this lab, may provide information about superconducting oxide crystals before single crystals large enough for the transport measurement are available.

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