Electrical properties of Ag-$YBa_2Cu_3O_7$ system

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When silver is added to a $YBa_2Cu_3O_7$ matrix, the critical current I_c increases significantly. The effect is linked with a shunting of grain boundaries by high-conductivity, finely divided inclusions of silver ($\sim 0.1\ \mu$m in diameter). The effect is to attenuate the flux creep.

It has been established that although a Josephson medium is quite different from an ordinary type-II superconductor, the basic aspects of the appearance of a resistive state are the same, and at low stress levels the driving force is a flux creep. Convenient systems for observing this process are metal-ceramic superconductors, in which the low current densities are known to be a consequence of grain boundaries.[1-4] The analogy between the resistive properties of Josephson media and those of type-II superconductors raises the hope that high-conductivity inclusions in a metal oxide would be able to slow the flux diffusion and thus substantially reduce the dissipation level.

For a correct study of the current-voltage characteristics of the metal-oxide samples, we developed a procedure which keeps the contact resistance of the areas in which contact is made at the level of $5\times 10^{-8}\ \Omega\cdot\text{cm}^2$. The contacts were fabricated by brazing silver into the surface of wafers with dimensions of $10\times 1\times 0.04$ mm, synthesized by pressing a powder of the yttrium ceramic under high pressure. The specific gravity of the samples was 6.2 g/cm^3, and the superconducting transition temperature was 92 K with $\Delta T_c = 2K(R/R_N = 0.9\text{–}0.01)$. The finely divided metallic silver which was added was mixed with the metal-oxide powder before the samples were synthesized. Silver was selected because this metal does not chemically react with the ceramic during the sintering; it furthermore makes good ohmic contact with the grains. Evidence for this conclusion comes from the decrease in the resistivity of the samples upon the addition of silver, from $(4\text{–}6)\times 10^{-4}$ to $(3\text{–}4)\times 10^{-5}\ \Omega\cdot$cm. A small silver impurity, up to 10% by volume, does not alter T_c or the width of the superconducting $R(T)$ transition. Furthermore, it does not alter the temperature dependence of the critical current, $I_c(T)$ (Fig. 1). These results demonstrate that the silver does not directly affect the critical current I_c^0 of the individual weak links between grains; the magnitude of this current is associated with the width of the $R(T)$ transition[5] (Tsuchida *et al.*[4] have attributed the increase in the critical current upon the addition of silver to the ceramic to an acceleration of technological processes). On the other hand, the magnitude of the critical current increases substantially (Fig. 2). At high Ag concentrations ($\approx 20\%$), the $R(T)$ transition broadens significantly, probably because of the rupture of natural bridges between grains and their replacement by silver interlayers. A similar broadening of the $R(T)$ transition has been observed upon the addition of gold to a ceramic.[6] For these samples, the critical current density is lower than that of the control samples by a factor of several units.

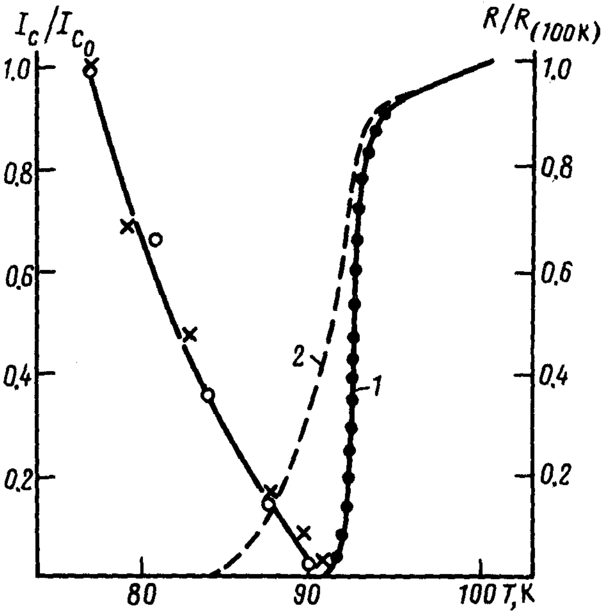

FIG. 1. 1—Resistive $R(T)$ transition of $YBa_2Cu_3O_7$ [(filled circles) sample without admixture; (solid line) sample with a 10% Ag admixture]; 2—$R(T)$ transition of $YBa_2Cu_3O_7 + Ag(20\%)$. The scale at the left shows the temperature dependence of the critical current of a doped sample (×) and a control sample (O).

We turn now to the analysis of the current-voltage characteristics. Since the power dissipation in a unit area s is small, $p = IU/s \approx 10^{-4}$ W/cm^2, we can ignore the effects of the heating of the sample in liquid nitrogen, in which heat removal at the given level of p keeps the heating to a level of $\Delta T \sim 10^{-3}$ K over the entire range of working currents. A significant heating and an accompanying hysteresis on the current-voltage characteristics are observed only at current densities of $(1.2\text{–}1.5) \times 10^4$ A/cm^2 (the metal-ceramic) or $(4\text{–}6) \times 10^4$ A/cm^2 (the metal-ceramic plus silver at $U \sim 10$ mV). Measurements taken in electric fields of magnitude $E \leqslant 100$ μV/cm for these samples correspond to voltages $U \sim 100\,\mu V/n \sim 100$ nV across an individual link of the metal-ceramic, where $n \sim l/a \sim 10^3$ is the number of grains per unit length l of the sample, and $\alpha_0 \approx 10$ μm is the percolation length. At such a low voltage level across a contact ($U \ll V_c = I_c^0 R_k = 10\text{–}100$ μV, where I_c^0 is the critical current of the link, and R_k is the resistance), the influence of thermal fluctuations$^{1)}$ on the shape of the current-voltage characteristic becomes important, even at a low ratio $\gamma = I_f/I_c^0 \sim 0.1$. The role of flux creep thus becomes important.

In Josephson media, flux creep may set in long before the critical currents of the contacts, I_c^0, are reached. The reason is a significant scatter in the values of the properties of a percolation cluster. As a result, the local critical density $j_c(\mathbf{r})$ differs from region to region in the sample. The flux may begin its motion in a region with $j > j_c(\mathbf{r})$, while in regions with $j < j_c(\mathbf{r})$ the field lines remain immobile. A dissipation arises upon the appearance of continuous channels with $j > j_c(\mathbf{r})$, along which there is a

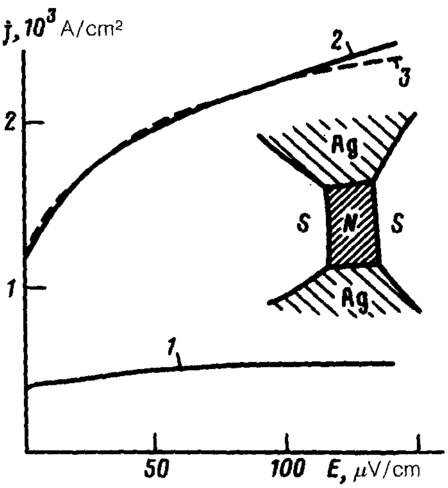

FIG. 2. Experimental (solid lines) and theoretical (dashed line) current-voltage characteristics. 1—$YBa_2Cu_3O_7$; 2,3—$YBa_2Cu_3O_7$ + Ag(10%).

diffusion of magnetic flux, which begins and ends at the walls of the sample. The average I-V characteristics describing flux creep in a Josephson medium are therefore similar to the corresponding characteristics in hard type-II superconductors[7] and are described by

$$E = \int_0^j E_{loc}(j'_c, j)\, W(j_1, j'_c)\, dj'_c, \tag{1}$$

where $E_{\text{loc}}(j'_c, j)$ is the current-voltage characteristic of a homogeneous region of the Josephson medium with critical current j'_c, $W(j_1, j'_c)$ is the probability density for the realization of a region with a critical current j'_c, in a unit volume, and the parameter j_1 is a measure of the scatter in the local current densities. Finding the functions $E_{\text{loc}}(j_c, j)$ and $W(j_1, j_c)$ is a problem for an elementary theory incorporating the structure of a percolation cluster. However, it is clear from the picture of the flux creep drawn above that the function W is related to the probability of sums of a large number of random quantities and should accordingly be bell-shaped with a half-width j_1. A numerical simulation has shown that in this case the shape of the resulting current-voltage characteristics (1) can be described by the following simple expression under various reasonable assumptions regarding the function E_{loc}:

$$j = j_c + j_1 \ln(E/E_0), \tag{2}$$

where E_0 is the particular electric field at which the critical current density j_c is determined. Figure 2 demonstrates the analysis of the experimental data with the help of expression (2).

In ordinary type-II superconductors[7] we would have $j_1 \sim (10^{-2}\text{–}10^{-3}) j_c$, so measurements of the critical current would be insensitive to the choice of the parameter

E_0. In a metal-ceramic we would have a situation with $j_1 \gtrsim 0.1j_c$ (Fig. 2), so the result of a determination of j_c would depend strongly on the voltage level at which this current is adopted as the critical current.

The good agreement between expression (2) and the current-voltage characteristics of a series of samples (including samples with metallic inclusions) means that this expression can be used to analyze the increase in the critical current density in Ag-YBaCuO composites. The silver admixture which penetrates into interlayers between grains (Fig. 2) forms a good electrical contact with the grains, as is demonstrated by the significant increase in the electrical conductivity of the sample. The electrical resistance of the contacts, R_k, is replaced by the resistance (R_e) of the shunting silver interlayer.[2] As a result, there is a decrease in the field associated with the flux creep, $E_0(j)$; this field, like $E_{\rm loc}(j)$, is proportional to the average resistance of the contacts. Equivalently, we are replacing the parameter E_0 in (2) by $E'_0 = E_0R_e/R_k$; i.e., the effective increase in the critical current density is $\Delta j_c = j_1 \ln(R_k/R_e)$. With $j_1 \sim 0.3j_c$ and $R_k/R_e \sim 10^2$ we find $\Delta j_e \approx j_c$, as is observed experimentally.

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[1] Here $I_f = 0.084T$ [μA] is the current of thermal fluctuations at the temperature T. The value of I_c^0 can be estimated from $I_c^0(T) = ((T_c - T)/\Delta T_c)^n.I_f$, where ΔT_c is the width of the $R(T)$ transition, and the exponent is $n = 1.5$–2 (Ref. 5). The resistance R_k can be estimated from the resistance R in fields $H > 100$ Oe, in which the links are destroyed: $R_k \sim sR/la_0$, where s is the cross-sectional area of the sample.

[2] This is possible if the inductive reactance (L_e) of the shunt which is introduced is small, $L_e\omega \ll R_e$, at all characteristic frequencies ω (Ref. 8). During flux creep, the typical frequencies are $\omega \sim \omega_c = (\phi_0/2\pi)V_c$, so the necessary condition becomes $L_e \ll L_c \equiv \phi_0/(2\pi I_c)$. If d is the thickness of the silver shunting layer, and r a characteristic radius, then we have $L_e \sim \mu_0 d^2(4\pi r)^{-1}$. With $r \sim 1\ \mu$m, $d \sim 0.1\ \mu$m, and $I_c^0 \approx 100\ \mu$A, we find the estimates $L_e \sim 10^{15}$ H and $L_c \sim 10^{-12}$ H, i.e., $L_e \ll L_c$.

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