Increase in the critical current of a metal-oxide ceramic under pressure

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(Submitted 28 May 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 9, 457–459 (10 May 1988)

A significant increase in the critical current density of $YBa_2Cu_3O_{7-\delta}$ samples has been observed under pressure: $d\ln j_c/dP \sim 0.1\ \text{kbar}^{-1}$. When there is a substantial decrease in the width (ΔT_c) of the resistive $R(T)$ transition to the superconducting state ($d\ln\Delta T_c/dP = -0.06\ \text{kbar}^{-1}$), the critical temperature T_c increases considerably more slowly ($d\ln T_c/dP = 0.003\ \text{kbar}^{-1}$, $P \lesssim 10$ kbar).

Determining the topology of the current-conduction paths in metal ceramics is of fundamental importance for determining the nature of high-temperature superconductivity. In the present study we have used hydrostatic pressure for this purpose. This approach makes it possible to reach a definite conclusion regarding the nature of the arrangement of the superconducting phase, on the basis of the response of various current-flow mechanisms to a change in the volume of the sample.

For the experiments we used thin wafers with dimensions of $0.08\times0.5\times6$ mm and a density of 5.95 g/cm^3 synthesized by pressing powdered $YBa_2Cu_3O_{7-\delta}$. The samples, annealed at 900 °C, consisted of close-packed single-crystal wafers $\sim 20\ \mu$m in size. Copper current contacts and potential contacts were vacuum-deposited on the surfaces of the samples. The contact resistance did not exceed $10^{-12}\ \Omega/\text{mm}^2$. This approach made it possible to avoid heating effects during the recording of the current-voltage characteristics in the pressure chamber at currents up to an absolute value[1)] $I \sim 100$ mA. The resistance was measured by the standard four-probe method with an ac bridge. The working current did not exceed 50 mkA. It was noted that currents up to 100 mkA did not affect the width or shape of the $R(T)$ transition. A hydrostatic pressure $P \lesssim 10$ kbar was produced with a kerosene-oil mixture in the pressure chamber. The pressure was measured by a gauge made of an alloy equivalent to Manganin (at room temperature); at liquid helium temperature, the pressure was determined from the known dT_c/dP dependence for indium. The pressure drop at low temperatures with respect to room temperature was ~ 4 kbar. The error in the determination of the pressure was ± 0.5 kbar. The temperature was measured with a thermocouple made of copper and an alloy equivalent to Constantan embedded in the outer wall of the vessel. The external magnetic field was screened to within 0.01 Oe. The critical current was determined at a voltage $U = 1\ \mu$V.

Figure 1 shows the effect of the pressure on the critical current of three $YBa_2Cu_3O_{7-\delta}$ samples with various electrical conductivities. The primary result here is that the critical current nearly doubles upon a pressure change $\Delta P = 7.0$ kbar. The resistance of the sample changes by 5–10% (Fig. 2). Experiments in which the pres-

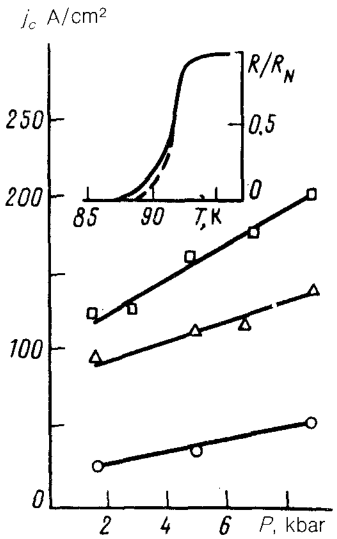

FIG. 1. Pressure dependence of the critical current density, $j_c(P)$, of $YBa_2Cu_3O_{7-\delta}$. The inset shows the narrowing of the $R(T)$ transition under a pressure $P \sim 9$ kbar.

sure was applied and removed in succession demonstrated that the effect was completely reversible.

According to the present theoretical understanding,[2] the change in the critical pinning current (like that in the depairing current) with the pressure is insignificant in ordinary superconductors, if the changes in the electrical conductivity ρ and the critical temperature T_c are small ($\delta j_c/j_c^{\max}$ is on the order of $\delta T_c/T_c$ and $\delta\rho/\rho$). The observed doubling of j_c under pressure with $\delta\rho/\rho = 5$–10% cannot be explained in any simple way in the model of a superconducting network (sponge).

On the other hand, we would expect a substantial increase in the critical current

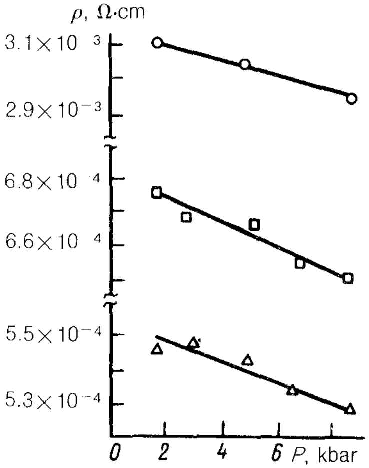

FIG. 2. Pressure dependence of the resistivity, $\rho(P)$, for the same $YBa_2Cu_3O_{7-\delta}$ samples.

during a bulk compression of weak-link granular structures with tunnel *S–I–S* or *S–N–S* junctions, whose critical current I_c is exponentially sensitive to changes in the parameters of the weak link [the width d and height φ of the barrier at *S–I–S* junctions; the coherence length ξ_N and the thickness t of the the normal (N) region at *S–N–S* junctions]. For tunnel junctions we would have $I_c \sim \Delta^2/eR_0$, where R_0 is the resistance of the junctions, which is an exponential function of the product $d \cdot \varphi^{1/2}$. A decrease in $d \cdot \varphi^{1/2}$ with the pressure should therefore lead to a rapid decay of the resistance R_0 and—a very important point—an equally rapid increase in the critical current I_c. In our case, on the other hand, the resistance of the interlayers between granules changes by no more than 10% when the pressure is applied, so it would be difficult to explain the observed increase in j_c on the basis of a realization of a structure with tunnel *S–I–S* links in the metal ceramic. At *S–N–S* junctions the critical current is

$$I_c(T) \sim \frac{1}{R_0}\left(\frac{T_c - T}{T_c}\right)^n \exp(-\zeta) \qquad \zeta(T) = t/\xi_N \qquad 1 \leqslant n \leqslant 2, \tag{1}$$

where R_0 is the resistance of the contact in the N state, but in contrast with *S–I–S* contacts there is an additional exponential factor $\exp(-\zeta)$. The bulk compression in this case leads to a change in R_0 and also a change in the exponent ζ. The latter effect will be dominant if the ratio t/ξ_N is large. At $\zeta \sim 10$, for example, a 10% change in ζ leads to an increase in the current by a factor of e. Large values of ζ are typical of a network of contacts with random parameters.[3]

In summary, a weak-link structure of *S–N–S* contacts is realized in this metal ceramic. It is quite possible that twinning planes play the role of such contacts.[4] From the experimental dependence $j_c(P)$ and expression (1) we find $\zeta' = d\zeta/dP = -0.1 \pm 0.01$ kbar^{-1} (we are ignoring the change in R_0 with the pressure). Consequently, if the model proposed here is justified, then we would have $j_c(P) \approx j_c(0)\exp(-\zeta' P)$, and we would expect an increase in the critical current of the metal oxides by two orders of magnitude at pressures $P \sim 40$–50 kbar.

Working from the condition for the establishment of a phase coherence in a weak-link medium,[3] $k_B T_{c0} \sim \hbar I_c(T_{c0})/2e$, and expression (1), we find that the fluctuation-induced width (ΔT_c) of the $R(T)$ transition should decrease with the pressure: $\Delta T_c(P)/\Delta T_c(0) \approx [j_c(0)/j_c(P)]^\beta$, $\beta = [\xi_N(T)/\xi_N(T_{c0})]^n$. This result agrees with the experimental data (see the inset in Fig. 1) with $n \approx 1.3 \pm 0.2$; here $\xi_N(T)/\xi_N(T_{c0}) = (T_{c0}/T)^{1/2}$ and $\Delta T_c = T_c(R/R_N = 0.5) - T_{c0}(R/R_N = 0.01)$.

1) In some published studies (see the review by Griessen[1]) of the effect of pressure on the superconductivity of $YBa_2Cu_3O_{7-\delta}$, it has been found possible to measure only the dependence $T_c(P)$. It has been found that the transition broadens with increasing pressure,[1] in contrast with our own result. We believe that the other result was a consequence of an inadequate homogeneity of the sample or a nonuniformity of the applied pressure.

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Translated by Dave Parsons