Effect of $\gamma$-irradiation on superconducting transition temperature and resistive transition in polycrystalline YBa$_2$Cu$_3$O$_{(7-\delta)}$

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A bulk polycrystalline sample of YBa$_2$Cu$_3$O$_{(7-\delta)}$ ($\delta \approx 0.1$) has been irradiated by $\gamma$-rays with $^{60}$Co source. Non-monotonic behavior of $T_c$ with increasing irradiation dose $\Phi$ (up to about 220 MR) is observed: $T_c$ decreases at low doses ($\Phi \leq 50$ MR) from initial value ($\approx 93$ K) by about 2 K and then rises, forming a minimum. At higher doses ($\Phi \geq 120$ MR) $T_c$ goes down again. The temperature width of resistive transition increases rather sharply with dose below 75 MR and drops somewhat at higher dose. The results observed are discussed, taking into account the granular structure of sample studied and the influence of $\gamma$-rays on intergrain Josephson coupling.

The influence of crystal-lattice disorder on superconductivity is one of the key points in understanding fundamental properties of high-$T_c$ superconductors (HTSCs). To a good approximation, the two main types of disorder, which are essential for superconductivity, can be distinguished [1]. The first is microscopic disorder associated with perturbations of the crystal lattice on the atomic scale (e.g., impurities, vacancies). It is responsible for electron localization and other phenomena which can affect the superconducting order parameter. The second type of disorder is associated with structural inhomogeneity of superconductors (granular structure, phase separation etc.). The disorder scale in this case is far larger than interatomic distances, and, hence, this disorder is called macroscopic. The macroscopic disorder affects mainly the superconducting phase coherence. In experimental studies it is desirable to separate the effects of these types of disorder. Ignoring this point could lead to serious errors in interpretation of results.

The disordering of HTSC can be produced with $\gamma$-rays. Attenuation distances of $\gamma$-ray with energies of a few MeV are of order of a few centimeters that enables one to investigate bulk samples. The known works in this field are mostly relevant to polycrystalline YBa$_2$Cu$_3$O$_{(7-\delta)}$ (YBCO) (see [2–5] and refs. therein). They are quite contradictory. In some of them [3] no influence of $\gamma$-rays on $T_c$ and resistivity, $\rho$, was found up to dose $\Phi \approx 1000$ MR; whereas in others [2,4,5] a marked decrease in $T_c$ and increase in $\rho$ were observed at quite low doses.

In this report, we present a study of the effect of $\gamma$-rays on $T_c$ and the superconducting transition in bulk polycrystalline sample (with grains about 12 $\mu$m of YBCO with $\delta \approx 0.1$). Irradiation was accomplished with a $^{60}$Co source at room temperature in air up to a dose $\Phi \approx 220$ MR. The temperature dependence $\rho(T)$ is found to be linear above $T_c$ up to 300 K, which is the usual behavior for optimally doped YBCO. We have defined the experimental $T_c$ to be the temperature at which normal resistance is halved. Before irradiation $T_c$ was about 93 K. The temperature $T_{cz}$, at which the resistance goes to zero, was used as a second characteristic of the resistive transition. The difference in $T_c$ and $T_{cz}$, $\delta T_c = T_c - T_{cz}$, is a quite definite measure of the width of the resistive transition. Sometimes, the temperature $T_{cb}$ at the onset of the superconducting tran-
tion is used for characterization of HTSCs. But this temperature can be evaluated with much less precision than $T_c$ or $T_{cz}$.

The changes in $T_c$ and $T_{cz}$ with $\gamma$-ray dose are shown in Fig. 1. It can be seen that that $T_c$ decreases at low dose ($\Phi \leq 50$ MR) by $\approx 2$ K and then rises again, forming a minimum. At higher dose ($\Phi \geq 120$ MR) $T_c$ clearly goes down again. The zero-resistance temperature $T_{cz}$ varies with $\gamma$-ray dose in a nearly same way as $T_c$, but with greater amplitude: the initial decrease is about 4 K. This means that $\delta T_c$ (which is a measure of sample inhomogeneity) increases with dose up to $\Phi \approx 75$ MR. At higher doses $\delta T_c$ stops increasing and even drops somewhat. The effect of $\gamma$-rays on the resistivity was found only for temperatures close to $T_c$. No radiation effect in resistivity was detected above 200 K.

Granularity of the sample should be taken into account in evaluating the results. The sample resistivity at room temperature ($\approx 3.2$ m$\Omega$ cm) is larger than that of the YBCO single-crystals by at least by a factor 10. The increased value comes from grain boundaries, which can be poorly conductive or even dielectric in HTSCs. At the same time the measured $T_c$ ($\approx 93$ K) corresponds to the highest $T_c$ in YBCO single crystals. This means the occurrence of optimal current-carrying chains of grains with strong Josephson coupling.

Our calculations of the cross sections for displacement of lattice atoms in YBCO by $\gamma$-rays due to the Compton process have shown that with commonly used $\gamma$-ray doses (up to 1000 MR) one should not expect any detectable variations in $\rho$ and $T_c$ in homogeneous crystals of YBCO. The effects observed in this work (as well as in the previous studies [2,4,5]) are therefore undoubtedly connected with influence of $\gamma$-rays on the regions of grain boundaries. In HTSCs, the regions and their environment are strongly depleted of charge carriers and thus can be very sensitive to $\gamma$-rays or particle irradiation.

The initial decrease in $T_c$ and $T_{cz}$ combined with the simultaneous increase in width of the resistive transition at low dose (Fig. 1) is quite expected for a percolating granular system. Optimal percolation current paths, which have ensured the high $T_c$ value before irradiation, surely have some “weak” links. These are grain boundaries, which are strongly enough depleted with charge carriers and, therefore, are sensitive even to small radiation doses. Displacement of atoms from these areas can lead to carrier removal and, therefore, to deterioration of Josephson coupling in “weak” links. This can explain the observed decrease in $T_c$ and increase in $\delta T_c$ at low doses (Fig. 1).

Although the initial $T_c$ drop appears to be explicable, the general non-monotonic picture in Fig. 1 is fairly surprising. To our knowledge, such behavior has not been reported previously. It is likely that a second, independent mechanism of the $\gamma$-ray influence (maybe unrelated to radiation damage) operates concurrently with the above-mentioned one. This mechanism enhances the Josephson coupling and causes the increase in $T_c$ at higher doses. It can be connected with the ionizing influence of $\gamma$-rays. We will consider this hypothesis thoroughly in an extended paper.

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