Effect of ion irradiation on the properties of high-temperature oxide superconductors

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$YBa_2Cu_3O_{7-y}$ films fabricated by laser sputtering were irradiated by 6.7-MeV He^{++} ions. The superconducting and structural characteristics of the films were found to change as a result of irradiation. These films are much more sensitive to irradiation than the Nb_3Sn films.

We have fabricated almost absolutely single phase $YBa_2Cu_3O_{7-y}$ films using the method of pulsed laser sputtering. As targets we used annealed ceramic pellets of the necessary composition. A laser with a pulse time of 10 ns, pulse energy ~0.02 J, and repetition frequency 50 Hz was used for the sputtering. The deposition was carried out in an oxgen atmosphere on sapphire and barium titanate substrates heated to 700–850 °C. The lattice constants of the principal phase were: $a = 3.828 \pm 0.001$ Å, $b = 3.887 \pm 0.001$ Å, and $c = 11.699 \pm 0.002$ Å. The film thickness was 1.5–2.0 μm. The best films had a critical temperature $T_c = 83$ K, the onset of the transition occurred at 95 K, and the total superconductivity occurred at $T > 80$ K.

The value of T_c was measured by the inductive method, allowing the T_c to be determined at different points on the film surface. Before and after the irradiation the samples were also studied by the method of x-ray diffractometry.

The samples were irradiated in a vacuum by 6.7-MeV He^{++} ions with a flux of 1.0×10^{15}–7.0×10^{16} ions/cm^2, which was measured within $\pm 5\%$. The sample holder was cooled by water. To control the change in the properties of the films, we irradiated

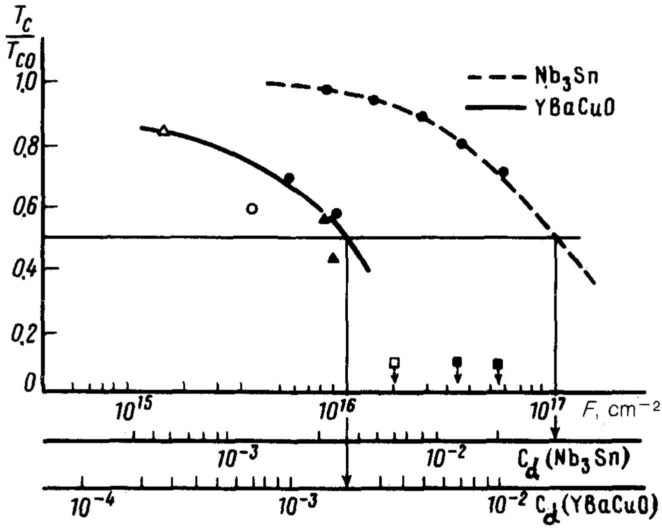

FIG. 1. T_c/T_{c_0} vesus F and C_d for the $YBa_2Cu_3O_7$ system (solid lines) and Nb_3Sn (dashed lines). ▲, △, ○, ●, □, and ■—Results for various samples.

only a part of their surface. The critical temperature of the nonirradiated part of the film in this case decreased only slightly.

Figure 1 shows the experimental results for T_c/T_{c_0} (T_{c_0} is the critical temperature in the initial state) of the films versus the irradiation flux F and the number of displacements per atom C_d. On the basis of the results of the studies the following conclusions may be drawn: when the flux is greater than 2.0×10^{16}, the critical temperature falls below 4.2 K; the width of the superconducting transition (ΔT_c) increases with increasing flux; the parameters and volume of the unit cell increase in irradiated samples (for a flux of 4.0×10^{16} ions/cm^2, for example, the parameters increase: a increases to 3.839 Å, b increases to 3.891 Å, c increases to 11.707 Å, and the volume increases from 174.1 Å^3 to 174.9 Å^3); broadening of the diffraction lines was not detected in the irradiated samples; the ratio of the diffraction line intensities of the principal phase and the impurity phase decreases in the irradiated samples; a transition to the tetragonal phase was not observed in the irradiated samples; superconducting oxide films are much more sensitive to ion irradiation than Nb_3Sn.

The sample which was irradiated before a flux of 4.0×10^{16} ions/cm^2 was applied was annealed in an oxygen atmosphere at a temperature of 90 °C for 2 h. After annealing the critical temperature and volume of the unit cell of the sample returned to the original state.

We calculated the number of displacements per atom when the $YBa_2Cu_3O_{7-y}$ films were irradiated with ions. The calculations were carried out on the basis of the "Ion" program which allowed us to find the electronic and nuclear losses, the ion range profiles, and the damage profile. In describing the nuclear collisions we used the cross sections calculated for the Thomas-Fermi potential or in accordance with Ref. 1;

the electronic losses were determined from the relations in Ref. 2. When thin films were irradiated, a flux of 5.7×10^{18} ions/cm^2 of 6.7-MeV helium ions was found to correspond to a displacement $C_d = 1$. As can be seen from Fig. 1, this value is much lower than a similar value for Nb_3Sn. Accordingly, the critical temperature will be reduced by a factor of two as a result of irradiation if there are twenty times fewer displacements per atom in the ceramic than there are in Nb_3Sn (2.0×10^{-3} and 4.0×10^{-2}, respectively).

Let us consider the possible causes of degradation of the critical temperature of oxide superconductors as a result of irradiation. We should first point out that radiation heating can be ignored in our experiments. Single crystalline sapphire substrates have a high thermal conductivity. As many measurements have shown, the films become overheated by no more than several tens of degrees if the contact with the water-cooled copper holder is good during the irradiation. Furthermore, since the range of the 6.7-MeV helium ions (12 μm) is much greater than the thickness of the films (< 2 μm), the heat is released primarily in the substrate. We have also studied the effect of annealing in a vacuum on the properties of the Y-Ba-Cu-O ceramic. We found that T_c begins to decrease only at temperatures above 300 °C. At these temperatures the ceramic undergoes a transition from the orthorhombic structure to a tegragonal structure (the tetragonal phase is characterized by a smaller oxygen content than the orthorhombic phase). Since a structural transition is not observed after irradiation and since T_c of the nonirradiated part of the film changes only slightly, we can assume that the radiation heating is so small that it has only a slight effect on T_c.

The formation of point defects in the ceramic during the irradiation may account for the change in its properties. Although there is yet no direct proof of this assumption, there are many pieces of evidence which indicate that such a mechanism is possible. Upon introduction into $YBa_2Cu_3O_{7-y}$ of an iron impurity of concentration $\gtrsim 1$ at.%, for example, T_c is found to decrease by a factor of two. As was shown by gamma-resonance measurements, the iron atoms replace copper atoms, i.e., they produce defects in the copper sublattice. If we now assume that the relationship between the number of defects and the number of displacements per atom in barium-yttrium ceramic is the same as that in Nb_3Sn (Ref. 3), the points on the curve for T_c/T_{c_0} versus the iron concentration will be consistent with the curve for $T_c/T_{c_0}(F,C_d)$ in Fig. 1. We can assume, therefore, that ionic irradiation produces defects in the copper sublattice of the $YBa_2Cu_3O_{7-y}$ structure, which accounts for the decrease in the critical temperature of barium-yttrium ceramic. The basic results were reported in a paper published previously.[4]

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