Electron beam irradiation of $Y_1Ba_2Cu_3O_{7-x}$ grain boundary Josephson junctions

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The properties of the $Y_1Ba_2Cu_3O_{7-x}$ biepitaxial Josephson junctions were reproducibly modified by a focused electron beam irradiation of the interface region. The junctions were fabricated by depositing $Y_1Ba_2Cu_3O_{7-x}$ thin film by cylindrical magnetron sputtering technique on the (110) SrTiO$_3$ substrate, partially covered by a pregrown MgO seed layer. The junction parameters can be adjusted controllably by applying an appropriate dose. Electron irradiation decreased the critical current of the junctions $I_C$ and increased the normal state resistance times area to values of the order of $1 (\mu \Omega \text{ cm}^2)$. Some other effects, such as the disappearance of the excess current, were also observed. The original properties of the junctions could be partly restored by isothermal annealing. We also speculate that some aspects of the nature of the grain boundary barriers can be better understood from the study of the properties of irradiated junctions. © 1997 American Institute of Physics. [S0003-6951(97)03127-6]

Josephson junctions, the backbone of superconducting electronics, can also be used as a powerful tool to explore the fundamental properties of superconductors. In the last few years, significant progress has been made in the development of high-$T_C$ Josephson junctions (HTS-JJ), superconducting quantum interferometer devices, and digital devices. Nevertheless, the problems of reproducibility and uniformity of the existing technologies still impose severe restrictions on practical applications, especially in the area of digital multijunctions HTS circuits. The peculiar properties of HTS, such as short coherence length, symmetry of the order parameter, and the actual structure of the junction interfaces, only add to the puzzling and often contradictory phenomenology. This justifies the efforts presently devoted to understanding the nature of the transport mechanisms across the junction interface in order to improve the Josephson junction technology.

In this letter, we present a study of the properties of biepitaxial YBA$_2$Cu$_3$O$_7$ (YBCO) Josephson junctions modified by electron beam irradiation. The aim of this work is to controllably change the properties of HTS Josephson junctions and to characterize their barrier, by considering the junction response to irradiation. This is achieved by disordering oxygen in the region of the junction interface by an electron beam and by studying the induced change in the current–voltage characteristics. This novel technique makes it possible to adjust controllably the properties of a single junction, which may be a part of a more complex multijunction circuit. The procedure can be used in circuit design and testing to modify the parameters of one or a few selected junctions (one or several times sequentially), in order to achieve the desired device performance.

In order to fabricate the biepitaxial junctions, a (110) oriented MgO film was deposited on a (110) SrTiO$_3$ substrate. It served as a seed layer to modify the crystal orientation of YBCO on SrTiO$_3$. In the junctions studied in this work, YBCO grows predominantly (103) oriented on the SrTiO$_3$ substrate and (001) oriented on the MgO layer, respectively. These junctions are characterized by high $I_C R_J$ values, low critical current densities ($J_C$), high normal state resistivities ($\rho_N$), and exhibit a Josephson behavior over the entire working temperature range.

Details of the fabrication procedure for biepitaxial junctions and of the electron beam technique were described elsewhere; here we only briefly outline the major processing steps. A 20-nm-thick MgO film was deposited by magnetron sputtering from a stoichiometric oxide target on (110) SrTiO$_3$ at a temperature of 600 °C. A 120-nm-thick YBCO film...
A typical I–V curve as a function of temperature before and after irradiation are shown in Figs. 1 and 2, respectively. The critical current of this junction and after irradiation are shown in Figs. 1 and 2, respectively. The change in the critical current density \( J_C \) of the (103) oriented YBCO films after irradiation is on average smaller than the one found for the c-axis defined microbridges. These results are not surprising since a highly anisotropic material, such as YBCO, should have a strong dependence of the scattering cross section on the irradiation angle.

We believe that the substantial increase of \( R_N \) can be explained in terms of modifications of the properties of the barrier after the electron beam irradiation. In order to understand this, it is necessary to compare variations of the specific conductance \( \sigma_N \) with the data on the critical conductance. The electron irradiation of c-axis YBCO films causes a maximum variation of \( \sigma_N \) of the order of \( 10^3 \left( \mu \Omega \text{ cm}^2 \right)^{-1} \). The actual variation to this change of \( \sigma_N \) can be partly restored by isothermal annealing in the He atmosphere of the cryostat.9

The typical I–V curves as a function of temperature before and after irradiation are shown in Figs. 1 and 2, respectively. The critical current of this junction (biep#20) decreases by a factor of \( \approx 20 \) at \( T = 8 \) K, while the maximum working temperature of the junction \( T_C \) decreases from 70 to about 40 K. A significant increase of \( R_N \) was also observed (from 70 to 220 \( \Omega \)). It is interesting to note that the excess current observed in the original junctions (see Fig. 1) disappears after the electron irradiation, so that the I–V characteristics of the irradiated junction can be properly described by the resistively shunted junction (RSJ) model. The properties of the original junctions can be partly restored by isothermal annealing (see also inset in Fig. 2). In the course of these annealings, \( I_C \) and \( T_C \) increase, while no significant change of \( R_N \) was observed. The summary of the junction parameters for two typical samples is given in Table I. The original \( I_C R_N \) value decreases after electron irradiation, but then increases controllably as a function of annealing time.

Since the region damaged by the electron beam is wider than the nominal spot size,9,10 the effect of the irradiation extends to the areas of the film close to the interface. Therefore, in order to draw meaningful conclusions from the modification of the junction properties, it is necessary to know the effects of irradiation on (103) oriented YBCO microbridges and to recall some established9,10 results on (001) YBCO films. In contrast to the irradiation of the c-axis films, the electron beam in the microbridges made out of (103) YBCO film was scanned almost perpendicular to the c-axis of the film, as shown in the inset in Fig. 3. The \( T_C \) of the (103)-oriented microbridges typically decreases from 87 down to 72–78 K. The critical current density \( J_C \) dependence on the temperature is shown in Fig. 3 before irradiation, after irradiation, and after a 10 min annealing at 330 K, respectively. The change in the \( T_C \) and \( J_C \) of (103) YBCO films after irradiation is on average smaller than the one found for the c-axis defined microbridges. These results are not surprising since a highly anisotropic material, such as YBCO, should have a strong dependence of the scattering cross section on the irradiation angle.

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variation of $\sigma_N$ of the irradiated junctions is much smaller, of the order of $1(\mu \Omega \text{ cm}^2)^{-1}$. This effect is probably due to the oxygen exchange between the barrier and the adjacent regions.

Other features in I–V curves which are affected by the electron irradiation are the Fiske steps observed at 200–300 $\mu$V. The shift of their position (induced by electron irradiation) (of the order of 50 $\mu$V) was observed in I–V characteristics of biep36. This would be directly related to changes in the barrier structure. The disappearance of the excess current $I_{\text{exc}}$ after irradiation, corresponding to the $I_C$ decrease, must also be connected to the nature of the barrier and the adjacent regions. According to Clarke, the $I_{\text{exc}}$ could be directly related to dc supercurrents with a nonzero time average. For high currents (in our case 40–50 $\mu$A), the junction is long, when we decrease the critical current to 2–5 $\mu$A by irradiating the junction, it becomes short and the $I_{\text{exc}}$ disappears. A different explanation of the $I_{\text{exc}}$ can be given in terms of the proximity effect in the barrier region and nonequilibrium state of quasiparticles in the superconducting electrode. In this scenario, the irradiation would reduce the effects due to proximity.

In Fig. 4, the critical current $I_C$ of junction biep36 is shown as a function of temperature before irradiation (filled squares), after irradiation (filled circles) and after an annealing of 34 h (open squares), respectively. As a comparison theoretical curves (Ref. 15) are reported for values of the ratio $L/\xi_N^c=3$ (crosses) and 5 (diamonds). The gap value of the superconducting electrodes to which theoretical curves are usually normalized is $\approx 0.8$ meV. In the inset (a), the Josephson current, normalized to the corresponding value at $T=0.2 T_C$, is reported vs the reduced temperature $T/T_C$. In the inset (b), a possible profile of $\Delta(\gamma)$ before and after irradiation is shown: $\gamma_{B12}$ is proportional to the specific resistance of the S/N boundary (Ref. 17).

In summary, we have shown that the properties of a HTS Josephson junction can be modified by electron beam irradiation of the grain boundary. The change in the microbridge properties seems to be characteristic of the junction configuration and dominated by the modifications induced by irradiating the barrier. Although we have only studied the effect in a particular type of junction, the ease of oxygen desorption from the grain boundary indicates that the electron beam technique may be applied to modify other types of grain boundary and possibly step-edge junctions. This technology allows controllable modification of the parameters of a single junction, which may be used in testing and optimizing characteristics of HTS Josephson devices.

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**FIG. 4.** The critical current $I_C$ of the samples biep36 is shown as a function of the temperature before irradiation (filled squares), after irradiation (filled circles) and after annealing for 34 h (open squares), respectively. As a comparison theoretical curves (Ref. 15) are reported for values of the ratio $L/\xi_N^c=3$ (crosses) and 5 (diamonds). The gap value of the superconducting electrodes to which theoretical curves are usually normalized is $\approx 0.8$ meV. In the inset (a), the Josephson current, normalized to the corresponding value at $T=0.2 T_C$, is reported vs the reduced temperature $T/T_C$. In the inset (b), a possible profile of $\Delta(\gamma)$ before and after irradiation is shown: $\gamma_{B12}$ is proportional to the specific resistance of the S/N boundary (Ref. 17).

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