Proximity effect in bilayer films of $YBa_2Cu_{2.7}Fe_{0.3}O_y$ and $YBa_2Cu_3O_{7-\delta}$

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We studied the proximity effect in a series of $YBa_2Cu_{2.7}Fe_{0.3}O_y/YBa_2Cu_3O_{7-\delta}$ bilayer film with varying $YBa_2Cu_3O_{7-\delta}$ thickness. In a bilayer of isolated YBCO islands, a T_c of 72 K was observed, much higher than T_c of 32 K of the $YBa_2Cu_{2.7}Fe_{0.3}O_y$ film. T_c and J_c of thicker bilayers of continuous $YBa_2Cu_3O_{7-\delta}$ films were found to decrease with decreasing YBCO thickness. This behavior of T_c and J_c can be explained by the Deutscher de Gennes theory for the proximity effect, provided one models the film as a series of grains whose lateral dimensions scale with the average film thickness. © *1998 American Institute of Physics.* [S0003-6951(98)02914-3]

To understand the behavior of $YBa_2Cu_3O_{7-\delta}$ (YBCO) based junctions having doped YBCO derivatives with $T_c < 50$ K as a barrier, one has to study both the properties of the individual materials and the proximity effect between them. Doped YBCO compounds have a small interface resistance with YBCO (smaller than $10^{-10}\Omega$ cm^2), minimal interface stress, good lattice match with close thermal expansion coefficients, and almost no interdiffusion.[1–4] If the conductance in junctions having these barriers is due to the proximity effect,[5] one expects an exponential decay of the critical current J_c with increasing thickness d_N of the normal metal barrier in SNS structures,[6] and a depression of T_c in NS bilayers which becomes larger with decreasing thickness d_S of the superconductor.[7] In the present study we investigate the proximity effect by using SN bilayers of YBCO (S) and doped YBCO (N) that are prepared *in situ* in a single deposition run. a-b coupling of the bilayers is obtained via the interface roughness of these films. Two separate experiments are described in which a proximity effect in both N and S is observed. We show that our results are consistent with the Deutscher de Gennes theory for the proximity effect.

YBCO and $YBa_2Cu_{2.7}Fe_{0.3}O_y$ (YBCFeO) films and the YBCFeO/YBCO bilayers were prepared on (100)$SrTiO_3$ wafers by laser ablation using our standard deposition conditions.[8] X-ray diffraction of the YBCFeO/YBCO bilayers showed c-axis orientation with good crystallinity and oxygenation of both layers. The existence of a proximity effect in YBCFeO was investigated in a bilayer made of isolated YBCO islands covered by a continuous overlaying YBCFeO film. First, an ultrathin YBCO film of nominally 6 nm thickness was prepared on (100) $SrTiO_3$ substrate. Then, 150 nm thick YBCO electrodes for the contacts (banks) were deposited on both of its sides. An atomic force microscope (AFM) image of this film, with a typical cross-section profile are shown in Fig. 1. This image shows clearly that the film is made of loosely connected islands of ~30–50 nm lateral size, and the cross-section profile shows that these islands are almost fully separated. To avoid degradation of this delicate film it was taken out of the deposition chamber in dry ambient and its transport properties were measured immediately in He atmosphere. The resistivity of this film versus temperature is shown in the inset of Fig. 2. An insulating behavior down to 100 K is clearly seen. Below 100 K the resistivity becomes too high to be measured in our measurement setup, but no superconducting transition was observed down to 4.2 K. To further test that this result is not due to a degradation of the islands film after deposition, we repeated this experiment with a protective cap layer of $SrTiO_3$ deposited on top of the ultrathin YBCO islands and obtained similar results. The AFM image and the transport results indicate that the conductance of this film is based on percolation between the superconducting islands, with hopping conductivity through the coupling zones. As a result, no superconducting transition was observed.

Next a reference YBCFeO film of 30 nm thickness was deposited on one half of the wafer while the bilayer of 30 nm thick YBCFeO film on top of the 6 nm thick YBCO islands was prepared on the other half of the wafer. Transport measurement in the bilayer and the reference film are shown in Fig. 2. T_c of the NS bilayer is 72 K, while T_{cN} of the reference YBCFeO film is only 32 K. This indicates that the superconducting YBCO islands are now having a superconducting coupling along the a-b plane induced in the normal YBCFeO metal. Another experiment shows that YBCO layers of 8 nm thickness and c-axis orientation prepared under similar conditions have a $T_c > 85$ K.[9] Therefore, the observed T_c of 72 K is the T_c induced in the YBCFeO by the YBCO islands. The observed 2.5 fold increase of T_c of the bilayer demonstrates unequivocally the existence of a proximity effect in the normal metal film N.

To study the proximity effect in S, we prepared a 150 nm thick YBCFeO film on top of continuous YBCO films of eight different thicknesses in the range $13 \leqslant d_s \leqslant 110$ nm. In these bilayers the very thin YBCO films were protected from degradation by the thick YBCFeO cap layer, and since all bilayers were prepared in the same deposition run by the use of a shadow mask they were grown under the same condi-

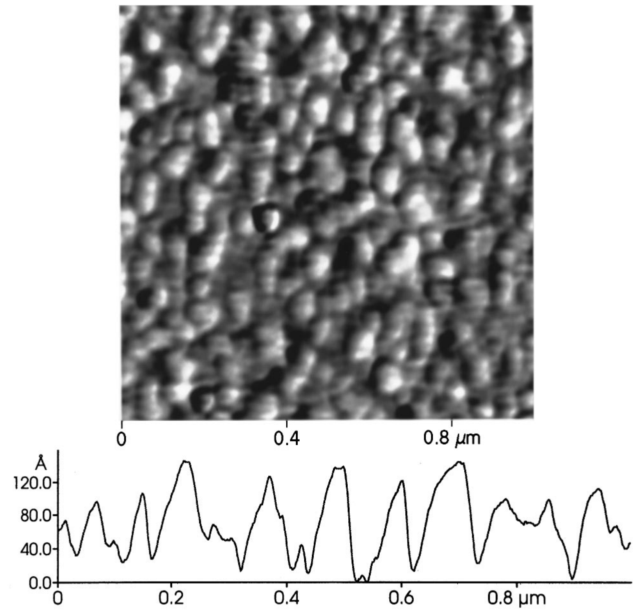

FIG. 1. AFM image of a nominally 6 nm thick $YBa_2Cu_3O_{7-\delta}$ film on (100) $SrTiO_3$ with a typical cross-section of a line profile.

tions. Figure 3(a) shows that the T_c of these bilayers decreases with decreasing thickness d_s of the YBCO layers. Bare YBCO films with the same thicknesses ($13\leq d_s \leq 110$) but without a cap layer showed almost no variation in T_c as compared to that of the thickest YBCO film ($T_c \sim 91$ K). We studied the surface morphology of these films with the aid of an AFM and the result are shown in Fig. 4. One can see that the YBCO films consist of connected grains which increase in size with the film thickness. A constant roughness of 6 nm rms, independent of d_s, was observed in these films. The mean width of the grains $\overline{W}_g$ of each of the different films was measured, from the AFM micrographs on areas of $1\times 1\ \mu m^2$. $\overline{W}_g$ was found to be linear in the film thickness d_s, in the range $13\leq d_s \leq 66$ nm [see Fig. 3(b)]. To study if the results in Fig. 3(a) are due to the proximity effect along the a-b plane we checked the dependence of ΔT_c on $\overline{W}_g$, and found as shown in Fig. 5(a) that ΔT_c is proportional to $1/(\overline{W}_g)^2$ for $13\leq d_s \leq 56$ nm. We also measured the critical current density J_c of the bilayers, and found that J_c increases with $\overline{W}_g$. Figure 5(b) shows an exponential dependence of J_c on $\overline{W}_g$ at *constant* reduced temperature $1-T/T_c=0.275$, for $13\leq d_s \leq 56$ nm.

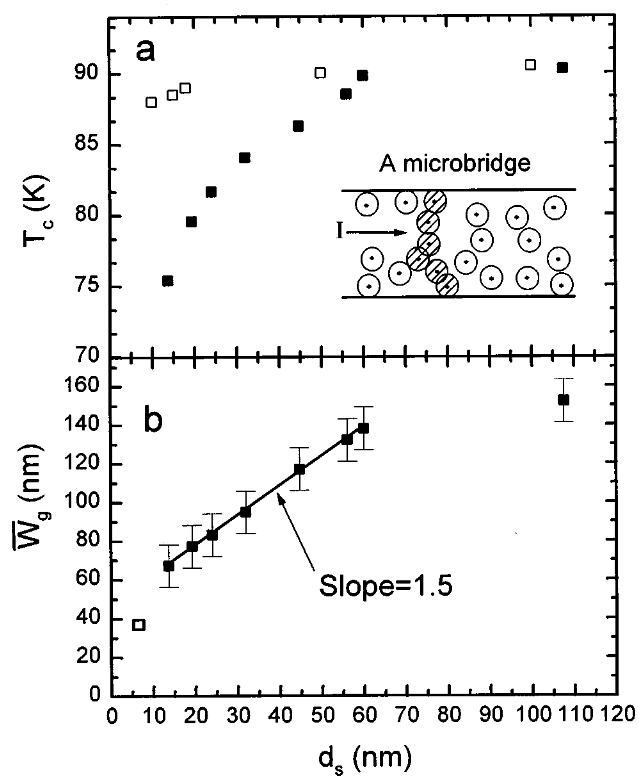

FIG. 3. (a) T_c of a bilayer consisting of a 150 nm thick $YBa_2Cu_{2.7}Fe_{0.3}O_y$ film on top of $YBa_2Cu_3O_{7-\delta}$, as a function of the $YBa_2Cu_3O_{7-\delta}$ film thickness d_s (solid squares). T_c of $YBa_2Cu_3O_{7-\delta}$ single layer films as a function of the $YBa_2Cu_3O_{7-\delta}$ film thickness d_s (open squares). In the inset, the nanoholes are marked schematically by black dots, and the affected lower T_c zones by circles around them. A percolation path of these zones that crosses the microbridge (hatched circles). (b) Mean width of the $YBa_2Cu_3O_{7-\delta}$ grains $\overline{W}_g$ as a function of the film thickness d_s. The open square was measured in the 6 nm thick $YBa_2Cu_3O_{7-\delta}$ film.

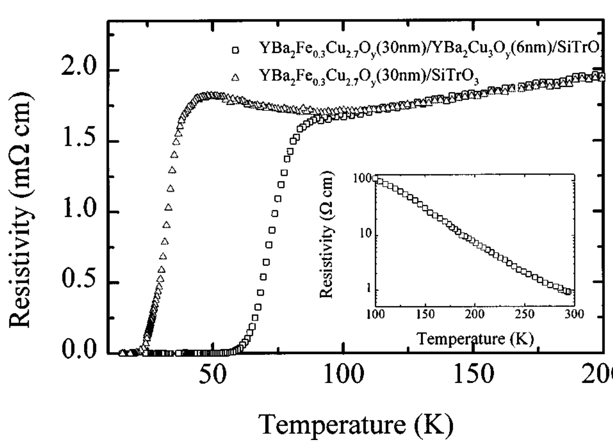

FIG. 2. Resistivity of a 30 nm thick $YBa_2Cu_{2.7}Fe_{0.3}O_y$ film, and a bilayer made of a 30 nm thick $YBa_2Cu_{2.7}Fe_{0.3}O_y$ film on top of a 6 nm $YBa_2Cu_3O_{7-\delta}$. Inset: resistivity of a 6 nm thick $YBa_2Cu_3O_{7-\delta}$ film on (100) $SrTiO_3$ substrate.

We try to explain these results (for $13\leq d_s \leq 56$ nm) by using a schematic model [in the inset to Fig. 5(b)] which describes the interface between the YBCO (S) and the YBCFeO (N) as a series array of ...SNSNSN... in the a-b plane, with thicknesses of $\overline{W}_g$ for the S and $\overline{W}_N$ for the N. Figure 3(b) shows that $\overline{W}_N = 155 - \overline{W}_g$ nm. The exponential increase of J_c with $\overline{W}_g$ thus gives an exponential decay of J_c with $\overline{W}_N$. This is in agreement with the prediction for SNS junctions,[6] and gives a decay length of 31 nm. Other groups also found similar decay length (~30 nm) in a-axis SNS junctions with $Pr_{1-x}Y_xB_2C_3O_{7-\delta}$ as a normal metal barrier.[10] To examine if our results can be explained in the framework of a proximity effect, we used the formula given by Deutscher and de Gennes for an ideal SN sandwich, in the clean limit:[7]

$$\Delta T_c = T_{c0}\xi_{0s}^2\left(\frac{0.74\pi}{2}\right)^2 \frac{1}{(d_s+b)^2}, \tag{1}$$

where ΔT_c is the difference in T_c between bulk YBCO ($T_{c0}=91$ K) and the bilayer, ξ_{0s} is the coherence length of S, d_s is the thickness of the YBCO film, and b is the extrapolation length. Recently, b was calculated for anisotropic su-

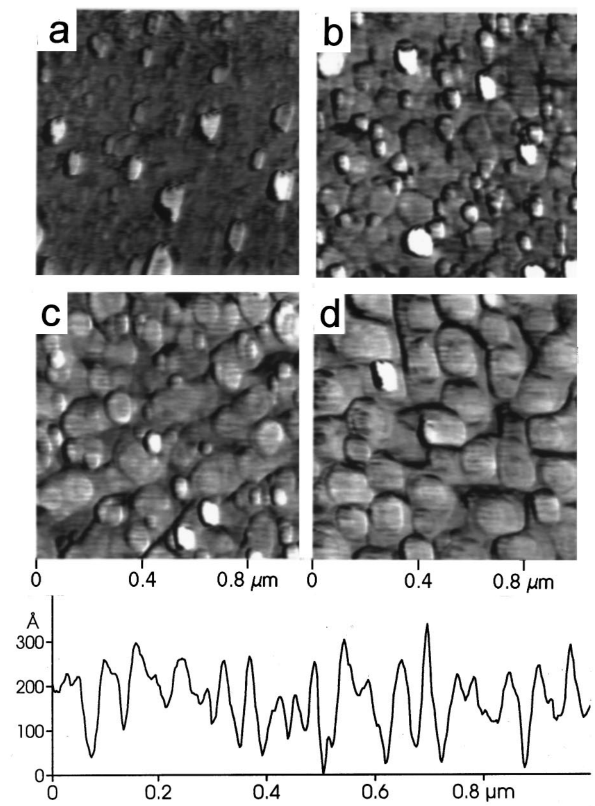

FIG. 4. AFM images of four representative $YBa_2Cu_3O_{7-\delta}$ films with different thicknesses, (a) 13 nm, (b) 24 nm, (c) 56 nm, (d) 110 nm. Also shown is a typical cross-section of a line profile of a 20 nm thick $YBa_2Cu_3O_{7-\delta}$ film, showing the presence of nano-holes.

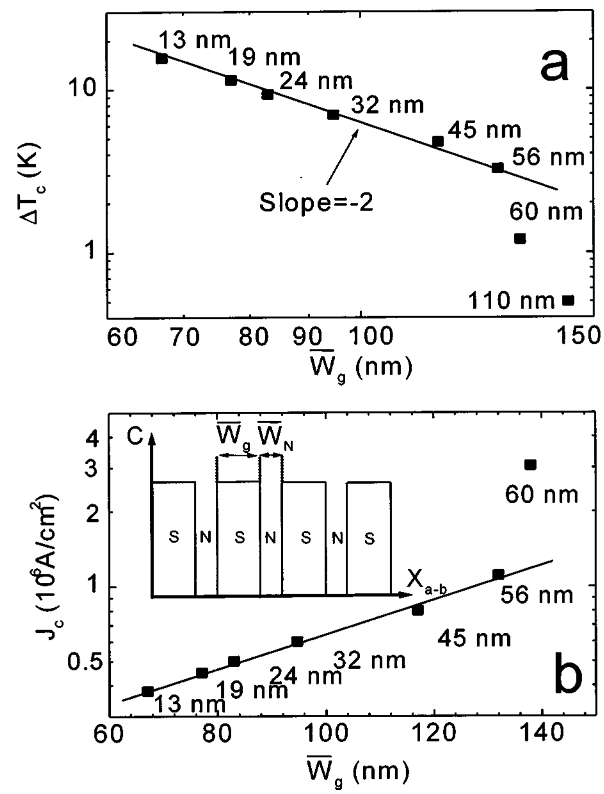

FIG. 5. (a) ΔT_c as a function of the mean width of the $YBa_2Cu_3O_{7-\delta}$ grains $\overline{W}_g$. (b) J_c as a function of the mean width of the $YBa_2Cu_3O_{7-\delta}$ grains $\overline{W}_g$ at $1-T/T_c=0.275$. Inset: a schematic model of the interface between the $YBa_2Cu_3O_{7-\delta}$ (S) and the $YBa_2Cu_{2.7}Fe_{0.3}O_y$ (N).

perconductors with rough surface such as our YBCO films, and found to be $\sim\xi_0$, which is negligible in our materials compared to $\overline{W}_g$ and d_s.[11] By substituting our results from Fig. 3(a) in Eq. (1), and using $\xi_{0s}=\xi_{a-b}=2$ nm of YBCO, we obtain a modified film thickness in the a-b plane d_s^{a-b}, which is related to d_s by $d_s^{a-b}=35+1.5d_s$ nm, in the range $13\leqslant d_s\leqslant 56$ nm. We note that in this range, d_s^{a-b} is almost identical with $\overline{W}_g$ which is equal to $47+1.5d_s$ nm, as seen from Fig. 3(b). Thus d_s^{a-b} and $\overline{W}_g$ have the same physical meaning. We attribute the strong reduction in T_c and exponential decay of J_c as seen in Fig. 5 to the fact that in YBCO films of $d_s<56$ nm there are a few holes in between the grains where the substrate is exposed. In the bilayers these holes are filled with normal YBCFeO which suppresses T_c around these regions. If these lower T_c zones are connected and cross the current path, the whole bilayer is affected by the proximity effect and thus it has a lower T_c [see the inset to Fig. 3(a)]. When $d_s>56$ nm, these connected areas of lower T_c are not crossing the current path and therefore T_c of the bilayers is not affected by the proximity effect. When $d_s<13$ nm one can see from Fig. 3(b) that the dependence of $\overline{W}_g$ on d_s is not linear, and therefore our model is not valid in this regime.

In conclusions, we demonstrated the existence of the proximity effect in bilayers of YBCO and YBCFeO in two complementary experiments. Our results are consistent with a model in which the interface between the YBCO (S) and the YBCFeO (N) is described as a series array of many SNS junctions.

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