Proximity effect in bilayer films of YBa$_2$Cu$_{2.7}$Fe$_{0.3}$O$_y$ and YBa$_2$Cu$_3$O$_{7-\delta}$

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We studied the proximity effect in a series of YBa$_2$Cu$_{2.7}$Fe$_{0.3}$O$_y$/YBa$_2$Cu$_3$O$_{7-\delta}$ bilayer film with varying YBa$_2$Cu$_3$O$_{7-\delta}$ 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$_2$Cu$_{2.7}$Fe$_{0.3}$O$_y$ film. $T_c$ and $J_c$ of thicker bilayers of continuous YBa$_2$Cu$_3$O$_{7-\delta}$ 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$_2$Cu$_3$O$_{7-\delta}$ (YBCO) based junctions having doped YBCO derivatives with $T_c \sim 50$ 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 $10^{-10}$ Ω 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 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$_2$Cu$_{2.7}$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 $\sim 30–50$ 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 $T_c$ 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 $13 < d_N < 110$ 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-
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 \( (T_c \approx 91 \text{ K}) \). 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 \( W_g \) of each of the different films was measured, from the AFM micrographs on areas of \( 1 \times 1 \, \mu \text{m}^2 \). \( W_g \) was found to be linear in the film thickness \( d_s \), in the range \( 13 \leq d_s \leq 66 \, \text{nm} \) [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 \( \Delta T_c \) on \( W_g \), and found as shown in Fig. 5(a) that \( \Delta T_c \) is proportional to \( 1/(W_g)^2 \) for \( 13 \leq d_s \leq 56 \, \text{nm} \). We also measured the critical current density \( J_c \) of the bilayers, and found that \( J_c \) increases with \( W_g \). Figure 5(b) shows an exponential dependence of \( J_c \) on \( W_g \) at constant reduced temperature \( 1 - T/T_c = 0.275 \), for \( 13 \leq d_s \leq 56 \, \text{nm} \).

We try to explain these results (for \( 13 \leq d_s \leq 56 \, \text{nm} \)) 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 \( \ldots \) SNSNSNSN \ldots in the \( a-b \) plane, with thicknesses of \( W_g \) for the S and \( W_N \) for the N. Figure 3(b) shows that \( W_N = 155 - W_g \, \text{nm} \). The exponential increase of \( J_c \) with \( W_g \) thus gives an exponential decay of \( J_c \) with \( W_N \). 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 \( \sim \) 30 nm in \( a \)-axis SNS junctions with Pr\(_{1-x}\)Y\(_2\)Ba\(_2\)Cu\(_3\)O\(_7\)-\( d \) as a normal metal barrier.\(^7\)

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:\(^7\)

\[
\Delta T_c = T_{c0} \frac{\xi_0^2}{2} \left( \frac{0.74\pi}{2} \right)^2 \frac{1}{(d_s+b)^2},
\]

where \( \Delta T_{c0} \) is the difference in \( T_c \) between bulk YBCO \( (T_{c0} \approx 91 \text{ K}) \) and the bilayer, \( \xi_0 \) 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-

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**FIG. 1.** AFM image of a nominally 6 nm thick YBa\(_2\)Cu\(_3\)O\(_7\) film on (100) SrTiO\(_3\) with a typical cross-section of a line profile.

**FIG. 2.** Resistivity of a 30 nm thick YBa\(_2\)Cu\(_2\)-Fe\(_{0.3}\)O\(_7\) film, and a bilayer made of a 30 nm thick YBa\(_2\)Cu\(_2\)-Fe\(_{0.3}\)O\(_7\) film on top of a 6 nm YBa\(_2\)Cu\(_3\)O\(_7\)-\( d \) film. Inset: resistivity of a 6 nm thick YBa\(_2\)Cu\(_3\)O\(_7\)-\( d \) film on (100) SrTiO\(_3\) substrate.

**FIG. 3.** (a) \( T_c \) of a bilayer consisting of a 150 nm thick YBa\(_2\)Cu\(_2\)-Fe\(_{0.3}\)O\(_7\) film on top of YBa\(_2\)Cu\(_3\)O\(_7\)-\( d \), as a function of the YBa\(_2\)Cu\(_2\)-Fe\(_{0.3}\)O\(_7\)-\( d \) film thickness \( d_s \), (solid squares). \( T_c \) of YBa\(_2\)Cu\(_3\)O\(_7\)-\( d \) single layer films as a function of the YBa\(_2\)Cu\(_3\)O\(_7\)-\( d \) film thickness \( d_s \) (open squares). In the inset, the nano-holes 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\(_2\)Cu\(_3\)O\(_7\)-\( d \) grains \( W_g \) as a function of the film thickness \( d_s \). The open square was measured in the 6 nm thick YBa\(_2\)Cu\(_3\)O\(_7\)-\( d \) film.
perconductors with rough surface such as our YBCO films, and found to be $\sim \xi_0$, which is negligible in our materials compared to $\bar{W}_g$ and $d_s$. By substituting our results from Fig. 3(a) in Eq. (1), and using $\xi_0 = \xi_{a-b} = 2\text{ nm}$ 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 $13 < d_s < 56$ nm. We note that in this range, $d_s^{a-b}$ is almost identical with $\bar{W}_g$ which is equal to $47 + 1.5d_s$ nm, as seen from Fig. 3(b). Thus $d_s^{a-b}$ and $\bar{W}_g$ 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 $T_c$ of $a$ and $b$ grains around these regions. If these lower $T_c$ regions 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 $\bar{W}_g$ 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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