Enhancement of the superconducting transition temperature in La$_{2-x}$Sr$_x$CuO$_4$ bilayers: Role of pairing and phase stiffness

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The superconducting transition temperature, $T_c$, of bilayers comprising underdoped La$_{2-x}$Sr$_x$CuO$_4$ films capped by a thin heavily overdoped metallic La$_{1.65}$Sr$_{0.35}$CuO$_4$ layer, is found to increase with respect to $T_c$ of the bare underdoped films. The highest $T_c$ is achieved for $x = 0.12$, close to the 'anomalous' 1/8 doping level, and exceeds that of the optimally-doped bare film. Our data suggest that the enhanced superconductivity is confined to the interface between the layers. We attribute the effect to a combination of the high pairing scale in the underdoped layer with an enhanced phase stiffness induced by the overdoped film.

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There is considerable evidence that $T_c$ in the underdoped (UD) regime of the cuprate high-temperature superconductors is governed by phase fluctuations while some sort of pairing occurs at considerably higher temperatures $1, 2, 3, 4, 5, 6$, akin to the case of granular superconductors $7$. In contrast, the overdoped (OD) region is more conventional in the sense that pairing and phase order take place simultaneously. Consequently, systems which are composed of layers of UD and OD cuprates constitute a unique laboratory for studying the interplay between superconductivity’s two necessary ingredients: pairing and phase coherence. Such systems may also serve as models of the naturally occurring multi-layered cuprate compounds, such as the Hg series, where measurements of the $^{63}$Cu Knight shift have demonstrated that in every unit cell the outer planes tend to become OD, while the inner planes become UD $8, 9$. From a practical point of view, the UD-OD multilayers offer the enticing prospect of raising $T_c$ above that of both components, by combining the high pairing scale of the UD layers with the large phase stiffness of the OD layers $10, 11$.

In this letter we present a systematic study of La$_{1.65}$Sr$_{0.35}$CuO$_4$ – La$_{2-x}$Sr$_x$CuO$_4$ [LSCO(0.35) – LSCO($x$)] bilayers, where $x$ varies from the UD to the OD regime. Our most significant finding is an enhancement of $T_c$ in bilayers containing an UD ($x < 0.15$) layer. The highest $T_c$, well above that of the optimally-doped bare film, was achieved for bilayers with $x = 0.12$, close to the 'anomalous' $x = 1/8$ doping level. $T_c$ did not change when the bottom layer was overdoped. Our magnetization measurements, tunneling spectra, temperature-dependent resistance data and non-linear $V(I)$ characteristics suggest that the enhanced superconductivity occurs at the interface between the layers. We attribute the $T_c$ enhancement (beyond strain effects that cannot fully account for our observations), to an effective combination of the high pairing scale of the UD layer with an increased phase stiffness at the interface, induced by pair-propagation through the OD component. We also point out that the fact that the maximal $T_c$ enhancement occurs at $x = 0.12$ may reflect on the role of stripes in the high-temperature superconductors.

LSCO($x$) films and LSCO(0.35)–LSCO($x$) bilayers with $x = 0.06, 0.08, 0.10, 0.12$ (UD), $x = 0.15$ (optimally doped) and $x = 0.18$ (OD) were epitaxially grown on (100) SrTiO$_3$ (STO) wafers by laser ablation deposition [see schematic illustration in Figs. 1(a) and 1(c)]. The LSCO($x$) films were 90 nm thick, and the LSCO(0.35) overlayer, grown in situ without breaking the vacuum, was 10 nm thick. X-ray measurements confirmed a c-axis orientation perpendicular to the substrate. Temperature-dependent resistance, $R(T)$, measurements were performed using the standard 4-probe technique. Special care was taken to stabilize the temper-
sponding bare film data. The relatively low 

\( T_c \) values of the corresponding bare LSCO films grown on LaSrAlO_4 (open symbols) and on STO (solid symbols), as compiled from Refs. 12 and 13, are presented in Fig. 1(b-d) along with the corresponding bare LSCO(0.35) – LSCO(0.10) bilayers. Moreover, the 

\( T_c \) enhancement was observed for all the UD bilayers. However, a clear diamagnetic response was observed when each bilayer was cooled through the transition temperature of the corresponding bare LSCO(x) film. This behavior points to the fact that the enhancement does not occur in the bulk of the sample, but is likely an interface phenomenon. We find further support for this conclusion in our STM data.

The tunneling spectra of our bilayers, measured by an STM on the surface of the LSCO(0.35) top layer, exhibited a predominantly Ohmic (gapless) behavior similar to that of the bare LSCO(0.35) film shown in Fig. 1(a). However, when the thickness of the top LSCO(0.35) layer was reduced from 10 nm to 5 nm, the differential conductance revealed a gap in the low-energy density of states over large parts of the sample surface, as depicted in Fig. 3. It is possible that the STM tip is coupled to a superconducting region at the interface [assuming that the LSCO(0.35) is in the ballistic regime], or alternatively, that the gap is a consequence of a proximity effect in the metallic layer due to such a region. The latter interpretation seems more convincing in light of the absence of coherence peaks from the bilayer data, and the fact that the zero-bias conductance is rather high, about 75% of its normal state value. This should be compared with the spectra measured on the bare LSCO(0.10) film, shown in the inset of Fig. 3, where the normalized zero-bias conductance is about 3 times smaller and the coherence peaks from the bilayer data, and the fact that the gap is a consequence of a proximity effect in the metallic layer due to such a region. The latter interpretation seems more convincing in light of the absence of coherence peaks from the bilayer data, and the fact that the zero-bias conductance is rather high, about 75% of its normal state value. This should be compared with the spectra measured on the bare LSCO(0.10) film, shown in the inset of Fig. 3, where the normalized zero-bias conductance is about 3 times smaller and the coherence peaks are well developed. Regardless of the mechanism responsible for the appearance of the gap, this behavior further suggest that the 

\( T_c \) enhancement effect does not occur in the bulk of LSCO(0.35) layer, but is apparently

![FIG. 2: (color online). (a) \( T_c \) vs. \( x \) of the bilayers (open symbols) and bare films (solid symbols) measured in this work. (b) \( T_c \) of LSCO films grown on LaSrAlO_4 (open symbols) and on STO (solid symbols), as compiled from Refs. 12 and 13. The dotted line depicts the \( T_c \) of bulk LSCO.](image)

![FIG. 3: (color online). Tunneling spectra of a bilayer composed of a 5 nm LSCO(0.35) film on top of a 90 nm LSCO(0.10) layer. The data were taken at 4.2 K and at equidistant steps along a 31 nm long line. Inset: A spectrum of the bare LSCO(0.10) film (red curve) and of the bilayer (black curve).](image)
confined to the interface region. We note that superconductivity in metal-insulator LSCO multilayers was also reported in Ref. [12] yet the doping dependence and corresponding theoretical implications were not addressed.

Superconductivity in a two-dimensional system disappears via a Berezinskii-Kosterlitz-Thouless (BKT) transition [16, 17], where it is destroyed by phase fluctuations due to the unbinding of thermally-excited vortex-antivortex pairs. Consequently, we have looked for the tell-tale signatures of a BKT transition in our data, and found them exclusively in bilayers showing enhancement of $T_c$, as demonstrated in Fig. 4 for the LSCO(0.35) – LSCO(0.12) bilayer. Specifically, we have fitted the measured temperature-dependent resistance to the predicted BKT form $R(T) = R_0 \exp(-bT^{-1/2})$, valid just above the transition temperature $T_{BKT}$. Here $R_0$ and $b$ are material parameters and $t = T/T_{BKT} - 1$. The best fit yields $T_{BKT} \approx 32.2K$, slightly below the value extracted from the resistance derivative, $T_{BKT} \approx 32.6K$, as shown in Fig. 4(a). We note that the fit is in very good agreement with data in the temperature range of the transition. At higher temperatures the fit deviates from the data since the resistance of the LSCO(x) layer exceeds that of the LSCO(0.35) layer and the current flows primarily through the latter. The $V(I)$ characteristics are consistent with a BKT transition as well, where one expects $V \propto I^3$, with $a = 3$ just below $T_{BKT}$ and growing with decreasing temperature. Fig. 4(b) exhibits such a behavior and provides the estimate $T_{BKT} \approx 32.5K$, close to the values stated above. Such signatures, indicative of a BKT transition, were not observed for the LSCO(0.35) – LSCO(0.18) bilayer (that did not exhibit a $T_c$ enhancement), nor on the LSCO bare films.

What is the reason for the enhancement? Previous reports of $T_c$ enhancement in LSCO thin films, attributed the effect either to epitaxial compressive strain exerted by the substrate [13, 18, 19], or to excess oxygenation of the film [19, 20]. Our samples were annealed in standard oxygen environment at moderate temperatures which generally yield a stoichiometric oxygen content [19], thus making it highly unlikely that over-oxygenation plays a role in the enhancement reported here. The effect of compressive strain is depicted in Fig. 2(b), where we plot $T_c$ data [19], for LSCO films grown on LaSrAlO$_4$, whose lattice constant mismatch with our LSCO(x) layers is somewhat larger than that of LSCO(0.35) [18]. Apparently, compressive strain increases $T_c$ for every x within the superconducting region of the phase diagram. Moreover, the original dome structure of this region is preserved, and in particular, maintains its maximum at $x = 0.15$. The $T_c$ enhancement in our bilayers presents a markedly different behavior, as seen in Fig. 2(a). First, it occurs only for UD bilayers. Secondly, the original peak in $T_c$ is shifted from $x = 0.15$ to the vicinity of $x = 0.12$, where a dip or flattening occurs in the $T_c$ curve of the bare films. Thus, strain alone cannot account for the enhancement found in the bilayer systems. Finally, since the maximal enhanced $T_c$ is far larger than the optimal $T_c$ of the bare films, we can rule out migration of cations across the interface as the source of the effect.

A previous study [7] of an analogous system to the bilayers discussed here, may shed light on our findings. There, $T_c$ of a granular Pb film covered by a silver overlayer, was found to initially increase with Ag thickness. Despite being insulating, tunneling into the bare lead film demonstrated well-developed superconductivity on each grain below the bulk $T_c$ of lead. Strong phase fluctuations between the grains denied the system of establishing global superconductivity. Apparently, the silver enhanced the inter-grain Josephson coupling, leading to a larger phase stiffness and higher $T_c$. The parallels with our bilayers are compelling. Like in the granular lead film, $T_c$ of UD cuprates is governed by their small superfluid stiffness, while there are indications for pairing above $T_c$ (the analogy may go even further in view of the evidence for electronic inhomogeneities in these systems [21]). We suggest that pair tunneling through the metallic LSCO(0.35) overlayer strengthens the phase coupling between locally superconducting regions of the LSCO(x) layer in the vicinity of the interface, thereby enhancing $T_c$ in this portion of the sample. Such coupling is possible since the coherence length in the LSCO(0.35) layer, at the relevant temperatures (estimated from data presented in Ref. [22]), is larger than the typical spatial scale, $\sim 2 - 3$ nm, of the superconducting-gap inhomogeneities in the cuprates [6, 21]. When the bottom layer is overdoped, phase stiffness ceases to be a limiting factor and the enhancement disappears. On the other hand, the decrease in the enhancement towards the UD boundary of the superconducting region may reflect the reduction of the excitation gap in this limit, as measured by angle resolved photoemission spectroscopy (ARPES) [23], and by STM [24].
In view of this proposed scenario we need to recall that no enhancement of $T_c$ was observed in our Au–LSCO(0.10) bilayer. Such a negative result may stem from the differences in both the Fermi wavevectors and lattice structures of the two layers, which could significantly reduce the tunneling amplitude through the interface. Additionally, since the induced phase couplings in the bottom layer depend on the pair propagation amplitude through the top metallic film, it is possible that vestiges of pairing in the LSCO(0.35) layer play a role in establishing the enhancement in the LSCO(0.35)–LSCO($x$) systems. Finally, we note that the lack of enhancement in the Au–LSCO(0.10) sample implies that screening due to the top metallic layer is not responsible for the effect which we measure, in contrast to Ref. [25].

Another distinctive feature of our data deserves attention. The maximal enhanced $T_c$ is achieved when the UD layer is approximately 1/8 doped. At the same doping level the lanthanum based cuprates exhibit the same doping level [4]. In light of these facts it appears that the maximal signal is attained at the same doping level [125, and measurements of the vortex-Nernst effect, which is indicative of a phase-disordered superconducting state, find that in LSCO the maximal signal is attained at the same doping level [434 (1995)].

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