J Supercond Nov Magn (2013) 26:491–493
DOI 10.1007/s10948-012-1796-6

LETTER

Dielectricly Enhanced T_c in Underdoped Cuprates

K.A. Müller · A. Shengelaya

Received: 26 October 2012 / Accepted: 28 October 2012 / Published online: 17 January 2013

Abstract It is proposed to create a multilayer structure in which an underdoped copper-oxide high-temperature superconductor is sandwiched between high-dielectric-constant insulator layers such as ferro- or ferri-electrics, thereby reducing the Coulomb repulsion between the intrinsically present clusters or stripes in the CuO_2 layers of the pseudogap phase. This should lead to an increase in the size of such clusters, resulting in smaller distances between them and coherence at higher temperature, i.e., a higher T_c with a smaller pseudogap $(T^* - T_c)$.

Keywords Dielectric enhancement · Superconducting transition temperature · Superconductivity · Cuprates · Dielectric T_c enhancement

Superconductivity in copper oxides sets in at about 6 % hole doping. As a function of doping, $T_c(n)$ is dome-like with a maximum at $n_{\max}$. One of the unique properties found in the cuprates is the existence of a pseudogap. It occurs for n below $n_{\max}$ for all cuprates and is thus generic. Upon cooling, it sets in at a temperature designated by T^* [1].

It is largest at minimum doping n, and decreases near linearly as a function of n, *without touching the dome of* $T_c(n)$ (see Fig. 1). This phase occurs because the Jahn–Teller intersite bipolarons aggregate to form metallic clusters or stripes (note that also various other models have been proposed) [2]. This quasiparticle scenario is increasingly supported by experimental observations, such as the oxygen isotope effects at T^* and T_c, the susceptibility $\chi(T)$, tunnelling, etc. As a function of doping, this model yields the onset of superconductivity at 6 % as well as the maximum of $T_c(n)$ near 15 % [3]. In the words of Mihailovic: "Upon cooling, bipolarons are formed at $kT^* = 2\Delta$. They lead to a charge-inhomogeneous state. These objects form and dissociate according to thermal fluctuations, leading to a state which is *dynamically inhomogeneous*" [4]. Indeed, Monte Carlo simulations showed the existence of clusters and stripes in either the [01] or [11] crystallographic directions depending on the interplay between long-range Coulomb repulsion and short-range elastic attraction. In the latter, the compatibility criterion for the lattice of Saint Venant was included. These simulations clearly showed growing dynamic clusters as the elastic forces are being opposed by the electrostatic repulsion of these charged entities [4].

Based on the above understanding for the occurrence of $T^*(n) \gg T_c(n)$ for small n, Wolf and Kresin [5] recently made a proposition by considering that the cause for the pseudogap are the dopants nucleating the clusters. Accordingly, they proposed to dope the AFM CuO_2 planes with oxygen in periodic stripes (called columns by them), with neighbouring columns remaining undoped [5]. The holes present in the doped columns would diffuse into the undoped ones, generating the pseudogap phase with large $T^*(n)$ in them. $T_c(n)$ would then approach it from below because it is expected that the clusters occurring there are larger than those in the doped regions. Here we rather assume that the clustering is an intrinsic property of the cuprates, as outlined in the previous paragraph. Like in the Wolf–Kresin proposal, the aim is to increase the size of the metallic clusters present such that the percolation towards 3D superconductivity oc-

K.A. Müller (✉)
Physik Institut, Universität Zürich, Winterthurerstr. 190,
8057 Zürich, Switzerland
e-mail: irmamf@bluewin.ch

A. Shengelaya
Department of Physics, Tbilisi State University,
Chavchavadze Ave. 3, 0128 Tbilisi, Georgia

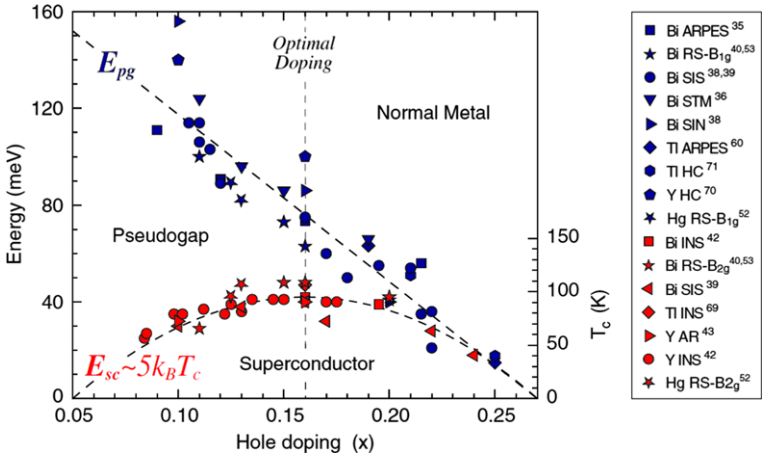

Fig. 1 Pseudogap and superconducting energy scale as a function of hole doping in different high-temperature superconductors (HTSs). From Ref. [1]

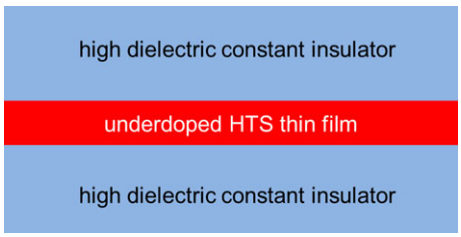

Fig. 2 Schematic drawing of the proposed structure in which an underdoped copper-oxide high-temperature superconductor is sandwiched between high-dielectric-constant insulator layers

curs at higher temperature, hopefully near $T^*(n)$. To obtain larger clusters and therefore, owing to the percolative character of the superconducting transition, higher T_c's requires a reduction of the electrostatic cluster/stripe repulsion. This can be obtained by having a material with a larger effective dielectric constant present between the clusters.

To increase the effective dielectric constant in copper-oxide HTSs, we propose to create multilayer structures in which an underdoped copper-oxide HTS is sandwiched between high-dielectric-constant insulator layers such as ferro- or ferri-electrics, thereby reducing the Coulomb repulsion between the intrinsically present clusters or stripes in the CuO_2 layers of the pseudogap phase. Such an effect is well known in semiconductor physics. The possibility to modify the Coulomb interaction in a thin semiconducting layer sandwiched by insulators with a different dielectric constant was pointed out for the first time by Keldysh [6]. He called this method "Coulomb interaction engineering". This effect is caused by the effective change of the dielectric constant of the semiconductor due to the penetration of the electric field into the surrounding insulators with a different dielectric constant, and is called the dielectric confinement effect by analogy to the quantum confinement effect. We propose to create such a multilayer structure as schematically shown in Fig. 2.

As we deal with superconducting oxides, it is appropriate to look for dielectric oxides with a high dielectric constant. In fact, transition-metal perovskites are known to have the highest ferroelectric transition temperatures, and mixtures of them exhibiting ferrielectric properties have been synthesized that show large, nearly temperature-independent dielectric constants. The choice among them has to be such that it matches the lattice constant of the HTS compound. One possibility would be $SrTiO_3$, which is a quantum paraelectric below 4 K [7]. In that region, it reaches ε values over 10,000; but in the region of interest here, near 100 K, $\varepsilon = 300$ are found. Regarding the matching of its lattice, the epitaxial growth of YBCO on $SrTiO_3$ substrates using pulsed laser deposition has been reported by many groups. Instead of $SrTiO_3$, one can also use other perovskites, e.g., $Sr_{1-x}Ba_xTiO_3$ and $Pb(Zr_xTi_{1-x})O_3$ with dielectric constants above 300 [8]. Cuprate superconductors have dielectric constants of about 30 [9]. Therefore the dielectric confinement effect is expected to be significant. Another possible compound with high dielectric constant could be a mixed perovskite with ferri- or ferro-electric properties such as $KTa_{0.9}Nb_{0.1}O_3$ with an ε of 160,000 near its ferroelectric phase transition, the highest ever reported [10].

According to the theoretical model, in order to achieve a significant dielectric confinement effect, the thickness of the superconducting layer should be on the order of the Bohr radius [11]. The Bohr radius in cuprates is about 1 nm [9]. Therefore the thickness of the cuprate layer should be in the range of 1–10 nm. In addition, the cuprate HTS must be underdoped.

At small doping, the T^* in the Bi-2212 compounds is between 200 and 250 K, considerably higher than the T_c at optimum doping of 110 K [12]. Thus, by creating structures as shown in Fig. 2 which combine high-dielectric-constant materials and underdoped CuO_2 layers, one may expect superconducting transition temperatures well above 100 K to occur. An indication that the proposed mechanism can be operative comes from research of FET-type transistors in which

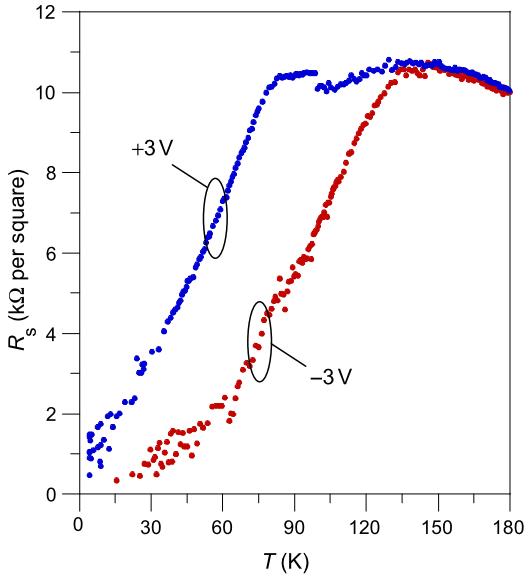

Fig. 3 Sheet resistance versus temperature of the underdoped YBCO thin film in the field-effect transistor (FET) configuration using a polymer electrolyte as gate dielectric at $V_g = 3$ V (*blue*) and $V_g = -3$ V (*red*). From Ref. [13], © 2010 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

the gate material used was an electrolyte [13]. In one run with an oxygen-deficient, i.e. an underdoped, device, upon application of a negative 3 V gate voltage (inducing holes) a T_c of 138 K was observed, *much higher* than the $T_c \approx 92$ K of optimally doped YBCO (see Fig. 3).

The authors of [13] discuss their research in terms of carrier modulation of the FET gate by the electrolyte without considering the effect of the high-dielectric-constant behaviour of the adsorbed electrolytic ions on the surface of the YBCO, which according to the mechanism proposed above enhances the size of the metallic clusters in the CuO_2 layers.

Acknowledgement The authors thank A. Bussmann-Holder for her interest in the subject.

References

1. Hüfner, S., Hossain, M.A., Damascelli, A., Sawatzky, G.A.: Rep. Prog. Phys. **71**, 062501 (2008)
2. Müller, K.A.: J. Phys. Condens. Matter **19**, 251002 (2007)
3. Mihailovic, D., Kabanov, V.V., Müller, K.A.: Europhys. Lett. **57**, 254 (2002)
4. Mertelj, T., Kabanov, V.V., Mihailovic, D.: Phys. Rev. Lett. **94**, 147003 (2005)
5. Wolf, S.A., Kresin, V.Z.: J. Supercond. Nov. Magn. **25**, 165 (2012)
6. Keldysh, L.V.: Pis'ma Zh. Eksp. Teor. Fiz. **29**, 716 (1979). JETP Lett. **29**, 658, 1979
7. Müller, K.A., Burkard, H.: Phys. Rev. B **19**, 3593 (1979)
8. Lines, M.E., Glass, A.M.: Principles and Applications of Ferroelectrics and Related Materials, pp. 285–292. Oxford University Press, London (1979)
9. Kastner, M.A., et al.: Rev. Mod. Phys. **70**, 897 (1998)
10. Kind, R., Müller, K.A.: Commun. Phys. **1**, 223 (1976)
11. Keldysh, L.V.: Phys. Status Solidi A **164**, 3 (1997)
12. Kresin, V.Z., Wolf, S.A.: J. Supercond. Nov. Magn. **25**, 175 (2012)
13. Dhoot, A.S., Wimbush, S.C., Benseman, T., MacManus-Driscoll, J.L., Cooper, J.R., Friend, R.H.: Adv. Mater. **22**, 2529 (2010)