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Field-effect tuning of carrier density in $Nd_{1.2}Ba_{1.8}Cu_3O_y$ thin films

A. Cassinese, G. M. De Luca, A. Prigiobbo, M. Salluzzo,[a] and R. Vaglio
INFM-COHERENTIA, Dipartimento di Scienze Fisiche, Università di Napoli Federico II, Napoli, Italy

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Using a field effect device we modified the number of holes in the surface layers of 4 to 10 unit cell $Nd_{1.2}Ba_{1.8}Cu_3O_y$ (NBCO) epitaxial films grown on (100) $SrTiO_3$ substrates. The results obtained on a set of 12 devices demonstrate that it is possible to induce reversible changes of the hole density of NBCO films by field effect. It is found that the field effect becomes less pronounced increasing the film thickness. Insulating–superconducting transition was observed in one 8 unit cell NBCO field effect device. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1745103]

Field effect transistor-like devices (FET) based on strongly correlated systems, such as organic conducting compounds, metal transition oxides, or high temperature superconductors (HTS), exhibit many interesting features both for basic physics and electronic applications.[1,2] Recently increasing attention has been devoted to HTS superconducting (and "parent" insulating) compounds, using the field effect to gain insight in the temperature-doping phase diagram, modifying the electronic properties by changing the number of carriers without modification of the composition and/or the structure. In particular the possibility to induce superconductivity in insulating samples has been the subject of extensive work.[1] Moreover these materials are potentially attractive for FET applications, since their transport properties are strongly dependent on the carrier density that is one to two orders of magnitude lower than ordinary metals.

It is generally believed that in HTSs a relevant field effect can be observed only in ultrathin films, since the Thomas–Fermi screening length λ_{TF} is typically of the order of one unit cell (1 nm).[3] Since the film surface properties and the quality of the interfaces are extremely relevant, *ex situ* or photolithographic processes are highly detrimental for the device operation. In this letter we report the realization of field effect devices based on $Nd_{1.2}Ba_{1.8}Cu_3O_7$ (NBCO) films fabricated fully "*in situ*" and characterized by high quality interface properties.

The NBCO films are grown on $10\times10\times0.5\ mm^3$ $SrTiO_3$ (100) (STO) substrates by high oxygen pressure diode sputtering from a single target. The films thickness is measured by x-ray diffraction, with a precision of one unit cell (u.c.), by determining the distance between consecutive Pendellösung fringes around the (001) reflection. Rocking curves on (001) reflection of 100 nm as well as 10 nm thin films exhibit full width at half maximum of 0.03°. The root mean square roughness, measured on $5\times5\ \mu m^2$ area by atomic force microscopy, is below 1 nm for 100-nm-thick films and 0.4 nm for 10-nm-thin films. More details on deposition procedure and on structure and morphology of the films are reported elsewhere.[4]

FET based on optimally doped $Nd_1Ba_2Cu_3O_{7-\delta}$ films have been extensively studied recently.[5,6] These films are superconducting down to very low thickness (2 unit cells), and represent ideal systems to investigate the role of electric field doping on the superconducting transition. On the contrary, our Nd-rich NBCO films are underdoped due to the Nd–Ba substitution and exhibit a superconducting to insulating transition when the film thickness is reduced below 9 unit cells as shown in Fig. 1. Thus these films are suitable for studies of insulating–superconducting transition by field effect doping.

Our device design is sketched in the inset of Fig. 1. A NBCO film is grown on a STO substrate on which 15 nm thin Au contacts, a 150 nm Al_2O_3 insulating film, and the Au gate electrode are sequentially deposited "*in situ*" using suitable stencil-steel masks. The Al_2O_3 film is deposited by dc magnetron reactive sputtering using a pure aluminum target in a mixture of Ar (flux of 50 sccm) and O_2 (4 sccm) gas. The deposition conditions have been adjusted in order to have stoichiometric or oxygen-rich films according to Ref. 7. The resulting breakdown field of our Al_2O_3 is in the range of 7 MV/cm.

Gold layers are grown by a Joule effect evaporator source. The contacts are 50 μm wide, the distance between the current pads (I_{DS} in the inset of Fig. 1) is about 200 μm, and the drain to source channel length (V_{DS} in the inset of Fig. 1) is 25 μm. Resistivity was measured as a function of temperature, at different gate voltages, using a four probe

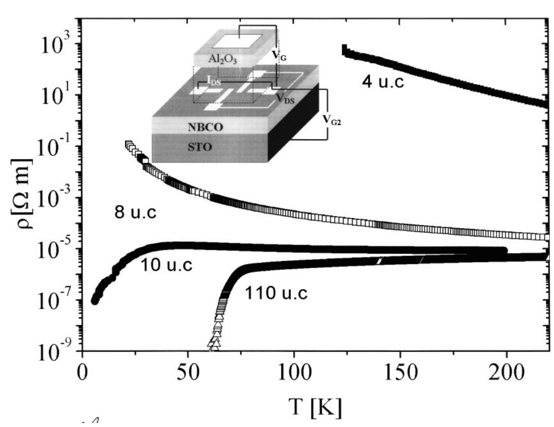

FIG. 1. Temperature dependence of the resistivity of $Nd_{1.2}Ba_{1.8}Cu_3O_y$ films having different thicknesses: 4 u.c. (closed squares), 8 u.c. (open squares), 10 u.c. (closed circles), and 110 cells (open triangles). In the inset a sketch of the field effect device is shown.

[a]Author to whom correspondence should be addressed; electronic mail: salluzzo@na.infn.it

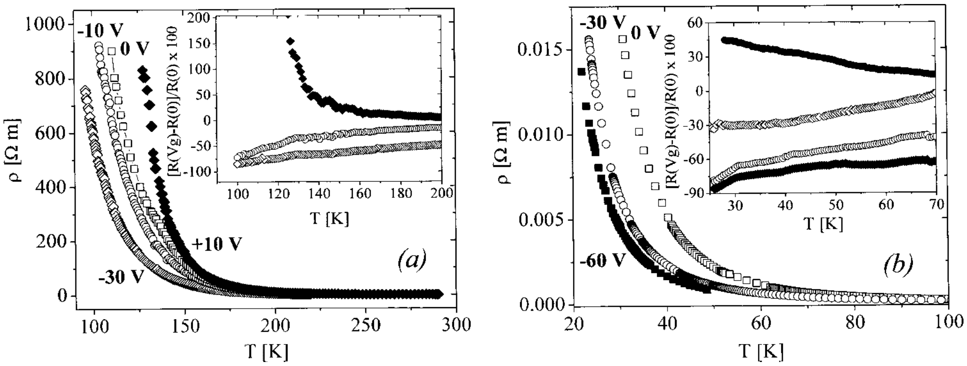

FIG. 2. Resistive measurements as a function of temperature measured for different values of the gate voltage: (a) 4 u.c. FET at $V_g = 0$ V (open squares), $V_g = +10$ V (closed diamond), $V_g = -10$ V (open circles), $V_g = -30$ V (open diamonds); (b) 8 u.c. FET at $V_g = 0$ V (open squares), $V_g = -30$ V (open circles), $V_g = -60$ V (closed squares). In the insets the relative change of the channel resistance is shown. In the inset of (b) the relative change of the channel resistance with a gate voltage applied on the back of the $SrTiO_3$ substrate is also shown for comparison ($V_g = -500$ V, open diamonds; $V_g = +500$ V, closed diamonds).

technique, where a constant current is injected between the current pads and the drain–source voltage drop is recorded. Only in the case of 4 u.c. films have the measurements been performed with a two-probe technique, by applying a voltage difference between drain and source ($\geqslant 15$ V) and measuring the current by using a Keitley 487 picoammeter. In some devices a gate is deposited on the back side of the STO substrate in order to study the field effect doping through the STO single crystal.

NBCO films between 4 and 8 u.c. show a typical ''Mott-insulating'' behavior that can be fitted by a variable range hopping mechanism (VRH) with a temperature dependence of the resistivity described by

$$\rho(T) = \rho_0' \left(\frac{T}{T_0} \right)^{2p} \exp\left[\left(\frac{T_0}{T} \right)^{p} \right], \tag{1}$$

where T_0 is a characteristic temperature related to the localization length and p is an exponent dependent on the model.[8] A discussion of the fitting procedure and results is beyond the scope of this letter and will be reported elsewhere.

During each measurement the leakage current through the Al_2O_3 layer was always at least two orders of magnitude lower than the current between source and drain (typically 1 μA), and in any case at low temperature ($T < 100$ K) it was never found to be higher than 10 nA. In Fig. 2 typical resistivity curves as a function of temperature at different gate voltages are reported for 4 and 8 u.c. films. In this geometry, a gate voltage of 10 V corresponds to an electric field of about 0.7 MV/cm. The corresponding injected surface carrier density is expected to be in the range of 4×10^{12} cm^{-2}. Applying a negative potential to the gate, a decrease of the resistivity was observed for all devices, suggesting that the charge carriers of these NBCO thin films are holes, as expected. All the measurements are reversible upon changes of the value and sign of the applied gate voltage. A change of the resistivity of 4 unit cell films up to 150% at 120 K is obtained. There is a clear evidence that the change of resistivity by field effect in these samples is temperature dependent. As shown in the inset of Fig. 2(a), the relative variation of the drain–source channel resistance, measured at different gate voltages, increases significantly at low temperature. In the framework of a VRH transport mechanism, this effect can be explained with a change of the characteristic temperature T_0, that is found to decrease by increasing the density of holes injected, in agreement with experiments performed on $R_{1+x}Ba_{2-x}Cu_3O_y$ films at different doping levels.[9]

The field modulation is less effective when the film thickness is increased from 4 to 8 u.c. Indeed in the case of 8 u.c. FET a higher gate voltage and/or a lower temperature is needed to see a substantial change in the resistivity. Finally, measurements performed on superconducting 10 u.c. NBCO devices (not shown) reveal only a small variation of the normal state resistance (1%–2%), while no appreciable changes have been observed on the value of the superconducting transition temperature.

Relevant changes of the resistivity have also been observed on 8 u.c. films by applying high voltages (up to 500 V) to the gate electrode on the back side of the $SrTiO_3$ substrate. As shown in the inset of Fig. 2(b) the relative change of resistance is somewhat lower compared with the field effect through the Al_2O_3 insulator. Though the effect appears to be of the same order of magnitude, a direct comparison is difficult due to the lower maximum electric field achievable and to the temperature and field dependence of the dielectric constant of STO.

According to the results reported on films having similar properties,[5,6,10] we assume that free carriers are present even in the Mott-insulating 8 u.c. samples. Therefore, only the surface layer of the NBCO films is interested by the modulation of the carriers ($\lambda_{TF} \approx 1$ nm). In other strongly correlated systems, such as manganites, the screening length λ_{TF} is reported to be extended to the whole film thickness[11] because of the role of localization. It cannot be excluded that localization has a role in our films as well. However, assuming that free carriers are present, many of our observations can be explained. Even if it is reasonable to suppose that the carrier density increases with thickness in $Nd_{1.2}Ba_{1.8}Cu_3O_y$ films (affecting the relative change of the field effect), to a large extent the resistivity modulation can be explained by supposing that only a surface layer is interested by the carrier buildup (depletion). Thus, it is not easy to observe, on these films, a transition from ''Mott-insulating'' to ''metallic'' behavior since, even if a metallic percolating path is created by applying an electric field on the surface layer, the resistance of this path can still be higher than the overall resistance of the remaining layers. On the contrary, at low temperature, a

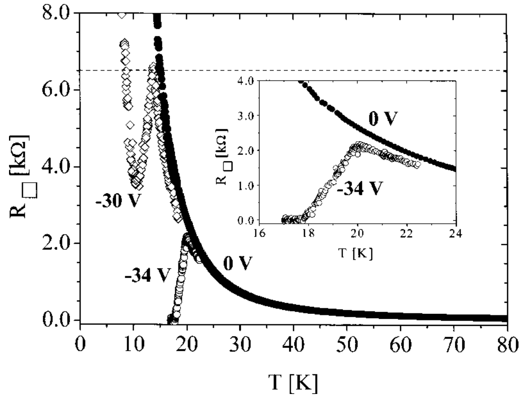

FIG. 3. Sheet resistance measured as a function of temperature on an 8 u.c. FET for $V_g = 0$ (closed circles), $V_g = -30$ V (open diamonds), and $V_g = -34$ V (open circles). The dashed line indicates the value of the quantum resistance $R_Q = 6.45$ kΩ. In the inset the insulating–superconducting transition is shown.

superconducting percolating path is able to short circuit the drain to source channel, which may result in an insulating–superconducting transition. We observed such transition in only one of the six nominal 8 u.c. FET devices fabricated, characterized by a resistivity that was slightly lower than other equivalent devices. The insulating–superconducting transition is shown in Fig. 3 where we represented the sheet resistance versus temperature for different negative gate voltages. The measurements have been carried out with the four probe technique by feeding a constant current of 1 μA in the sample and switching regularly the polarity. As in the case of the other measured 8 u.c. FET, the field effect is negligible at temperature higher than 50 K and low gate voltages. At $V_g = -30$ V a resistive drop is observed at $T = 13.6$ K, but below 10 K the resistance increases again. Note that the sheet resistance is lower than the quantum resistance $R_Q = 6.45$ kΩ. The effect was fully reproducible and by reducing to zero the gate voltage the original R versus T curve was retained. By applying a gate voltage of -34 V a complete superconducting transition with $T_c = 18$ K is obtained. A transition to the insulating state is reversibly obtained by switching off the gate voltage. Superconductivity was observed up to bias currents of 4–5 μA. This current induced transition was also reversibly reproduced. The transition to the normal state in this case is likely due to overcoming of the critical current density value in a surface percolating path.

It is worth noting that a similar transition was observed and discussed by Ahn *et al.*[10] on ultrathin $GdBa_2Cu_3O_7$ films in the presence of a magnetic field. However the occurrence of the electric field induced superconducting transition appears to be very critical and was not observed in other nominally equivalent 8 u.c. devices possibly due to a slight degradation of the surface layer which avoids the formation of a superconducting path.

In conclusion, we reported on the realization and characterization of field effect devices based on underdoped Nd-rich $Nd_{1.2}Ba_{1.8}Cu_3O_y$ films with different thicknesses. The devices are realized fully *in situ* in order to avoid degradation of the interfaces. The results obtained on a series of devices characterized by different film thickness demonstrate that, using the field effect, it is possible to increase the conductivity of $Nd_{1.2}Ba_{1.8}Cu_3O_y$ thin ($\leqslant$8 unit cells) films by injecting holes, while a decrease is observed by reversing the field. No relevant field effect was observed on the superconducting transition of 10 unit cells films. The possibility to induce, in underdoped $Nd_{1.2}Ba_{1.8}Cu_3O_y$ films, insulating–superconducting transition by varying the number of carriers without modification of the chemical composition or structure, was clearly demonstrated in one sample. The overall data support a free carrier scenario.

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