| | Experiment title: | Experiment number: |
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| ESRF | **The effect of lateral confinement on charge order in nano-patterned RBCO superconductor** | HC2703 |
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**Names and affiliations of applicants** (* indicates experimentalists):

**R. Arpaia*, R. Baghdadi*, T. Bauch*, and F. Lombardi***, *Department of Microtechnology and Nanoscience, Chalmers University of Technology, SE-41296 Göteborg, Sweden*
**Y. Y. Peng*, and G. Ghiringhelli***, *Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, I-20133 Milano, Italy*
**G. M. De Luca*, D. Stornaiuolo*, and M. Salluzzo***, *CNR-SPIN, Complesso Monte Sant'Angelo - Via Cinthia, I-80126 Napoli, Italy*


## Report:

In this experiment, we used Cu $L_3$ edge resonant inelastic x-ray scattering (RIXS) to detect the charge order in high-$T_c$ superconducting $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films and nanostructures on MgO (110) substrates. In particular, we have studied the evolution of such order with the dimensionality of the system, in superconducting objects, having a size comparable to that of the charge density wave correlation length $\xi_{CDW}$, with properties unaffected by the nanopatterning [1]. We focused on four different samples corresponding to three different oxygen doping: a slightly overdoped sample, with thickness t = 50 nm and critical temperature $T_C$ = 85.2 K (OD85), a slightly underdoped sample, with t = 50 nm and $T_C$ = 81.1 K (UD81), and two underdoped samples with $T_C$ = 61.8 K, UD62-50 and UD62-8, having respectively t = 50 nm and 8.5 nm. On each chip we have explored an unpatterned area (0.5x3 $mm^2$, the "thin film"), to get a reference signal, and several patterned regions (0.5x3 $mm^2$), with nanodots and nanostripes having lateral dimensions in the range 50 - 200 nm (larger, but comparable with $\xi_{CDW}$) and in the range 10 - 50 µm (much larger than $\xi_{CDW}$).
We have directly observed charge density modulation in the "thin film" regions of the four samples, at momentum transfer $q_{//}$~0.31 r.l.u.. The effect of lateral confinement on charge order looks very strong, since we found no charge order peak in structures below 200 nm. In addition, we have also measured the paramagnon dispersions along the high-symmetry directions, as a function of the object lateral size, for the four samples under investigation. In this brief report, we will mainly present our charge order results including the doping and the temperature dependence, both in unpatterned areas and in nanostructrues, and the effects played on CDW by the strain induced by the substrate and by the thickness confinement.

### -----*Thin films*

Taking advantage of the small beam spot size (4 x 60 $\mu m^2$) at ID32 and of its excellent positioning control and stability, we have explored the RIXS spectra related to the unpatterned regions of our samples, whose size is 0.5x3 $mm^2$. A charge density wave (CDW) order has been revealed at any oxygen doping, proven by the variation of the RIXS intensity of the quasi elastic peak, as a function of the momentum-transfer component parallel to the $CuO_2$ planes $q_{//}$, which is maximum at $q_{//}$~0.31 r.l.u. (see Fig. 1). The intensity of the CDW peak is dependent on the oxygen doping, being much smaller in the slightly overdoped YBCO sample (OD85) than in the three underdoped ones.

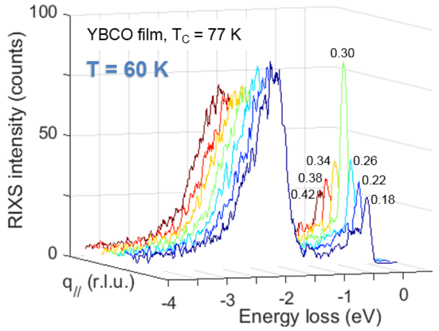


Fig. 1: Energy resolved spectra of the unpatterned area of sample UD81, measured along the YBCO a-axis

We have studied the charge order in the sample UD81 as a function of the temperature: the CDW peak can be seen already at 10 K and becomes sharper and more intense at T approaching the superconducting critical temperature $T_C$; above $T_C$, the intensity of charge order signal decreases (see Fig. 2). At T>140 K a weak and very broad peak, centered at $q_{//}$~0.31 r.l.u., is still present: it persists, with an almost temperature independent intensity, up to T≈250 K, well above the maximum $T_{CDW}$ measured so far on YBCO single crystals and thin films. This feature, which could be a consequence of the strain induced by the substrate on the film, will require further investigation.

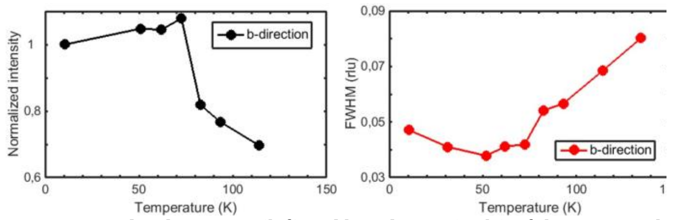

Fig. 2: Normalised intensity (*left*) and broadening (*right*) of the CDW peak as a function of T on the unpatterned area of sample UD81.

We investigated the charge order in our samples both along the a- and the b- axis of YBCO. A difference is clearly visible, independent of temperature and oxygen doping: we observe a splitting in $q_{//}$ of the CDW peak along the YBCO b-axis direction (see Fig. 3). This is a consequence of the buckling of the atomic planes of YBCO along the b-axis, when grown on MgO (110) (see inset of Fig. 3). This confirms the strong intertwining between strain and charge order in our films.

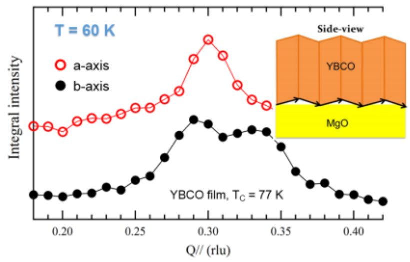

Fig. 3: RIXS intensity vs q along the a- and b-axis (unpatterned area of sample UD81). The buckling of the atomic planes is sketched in the inset.

We have also investigated the effect of the film thickness on the charge order, at a fixed oxygen doping (see Fig. 4). In particular, we have measured the CDW peak both along the [1 0] (a-axis) and the [0 1] (b-axis) YBCO direction, to check if there is any relative variation of intensity, which could be compatible with the observed depression of the pseudogap temperature T* in ultrathin films along b-axis. The understanding of these measurements is currently in progress.

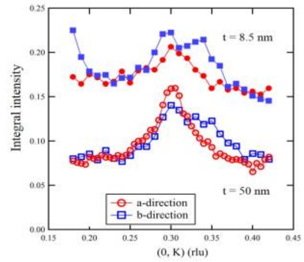

Fig. 4: RIXS intensity vs q along the a- and b-axis (unpatterned area of samples UD62-8 and UD62-50).

-----*Nanostructures*

All the nanostructures are protected by an amorphous carbon capping layer, which leaves unaltered the signal coming from the CDW. The effects of in-plane confinement are indeed extremely strong at any investigated oxygen doping: while on 10 µm wide wires the peak at (0.31,0,*l*) is still as strong as on the unpatterned areas, in the case of the 50 nm and 200 nm wide structures there is no hint of CDW peak (see Fig. 5), even though the intensity of the quasi-elastic peak, from whose modulation in *q* the CDW peak is determined, is still very strong. We are currently scrutinizing among different models, to understand the reason of the disappearance of the CDW peak in very small structures, with the aim of writing soon a manuscript about these surprising results. More beam time will be needed to estimate the critical dimension at which such transition occurr.

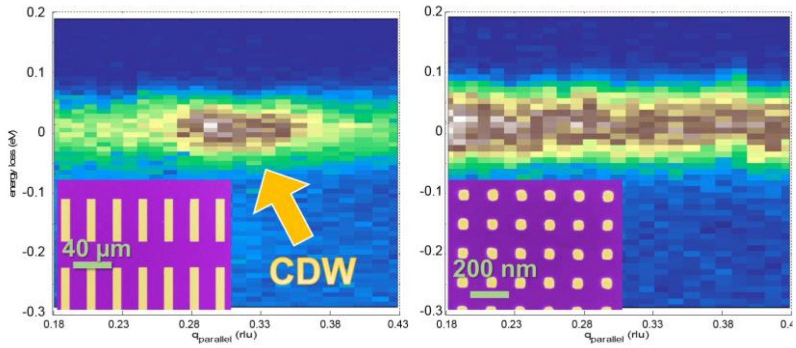

Fig. 5: E vs q maps on 10 µm wide wires (*left*) and 50 nm wide dots (*right*) patterned on the underdoped swample UD62-50. In the two insets, Scanning Electron Microscopy pictures of the investigated patterned structures are shown.

**References:**

[1] S. Nawaz, R. Arpaia, F. Lombardi and T. Bauch, Phys. Rev. Lett. 110, 167004 (2013).