Networks of superconducting nano-puddles in 1/8 doped YBa$_2$Cu$_3$O$_{6.5+y}$ controlled by thermal manipulation

Alessandro Ricci$^{1,2}$, Nicola Poccia$^{2,3}$, Gaetano Campi$^4$, Francesco Coneri$^3$, Luisa Barba$^5$, Gianmichele Arrighetti$^5$, Maurizio Polentarutti$^5$, Manfred Burghammer$^{6,7}$, Michael Sprung$^1$, Martin v Zimmermann$^1$ and Antonio Bianconi$^{2,4}$

$^1$ Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, D-22607 Hamburg, Germany
$^2$ Rome International Center for Materials Science Superstripes RICMASS, via dei Sabelli 119A, I-00185 Roma, Italy
$^3$ MESA+ Institute for Nanotechnology, University of Twente, PO Box 217, 7500AE Enschede, Netherlands
$^4$ Institute of Crystallography, CNR, via Salaria Km 29.300, Monterotondo Roma, I-00015, Italy
$^5$ Elettra Sincrotrone Trieste. Strada Statale 14 - km 163; 5, AREA Science Park, I-34149 Basovizza, Trieste, Italy
$^6$ European Synchrotron Radiation Facility, B. P. 220, F-38043 Grenoble Cedex, France
$^7$ Department of Analytical Chemistry, Ghent University, Krijgslaan 281, S12 B-9000 Ghent, Belgium

E-mail: phd.alessandro.ricci@gmail.com

Received 11 December 2013, revised 28 February 2014
Accepted for publication 1 April 2014
Published 14 May 2014

New Journal of Physics 16 (2014) 053030
doi:10.1088/1367-2630/16/5/053030

Abstract

While it is known that the nature and the arrangement of defects in complex oxides have an impact on the material functionalities, little is known about control of superconductivity by oxygen interstitial organization in cuprates. Here we report direct compelling evidence for the control of $T_c$ by manipulation of the superconducting granular networks of nanoscale puddles, made of ordered oxygen stripes, in a single crystal of YBa$_2$Cu$_3$O$_{6.5+y}$ with average formal hole doping $p$ close to 1/8. Upon thermal treatments we were able to switch from a first network of oxygen defect striped puddles with OVIII modulation ($q_{OVIII}(a^*) = (h + 3/8, k, 0)$ and $q_{OVIII}(a^*) = (h + 5/8, k, 0)$) to a second network characterized by OXVI modulation ($q_{OXVI}(a^*) = (h + 7/16, k, 0)$ and $q_{OXVI}$-VI...
(a*) = (h + 9/16, k, 0)) and finally to a third network with puddles of OV periodicity \( q_{OV}(a*) = (4/10, 1, 0) \) and \( q_{OV}(a*) = (6/10, 1, 0) \). We map the microscopic spatial evolution of the out of plane OVIII, OXVI and OV puddle nanosize distribution via scanning micro-diffraction measurements. In particular, we calculated the number of oxygen chains \( n \) and the charge density (hole concentration \( p \)) inside each puddle, analyzing areas of 160 \( \times \) 80 \( \mu \)m\(^2\), and recording 12 800 diffraction patterns to reconstruct each spatial map. The high spatial inhomogeneity shown by all the reconstructed spatial maps reflects the intrinsic granular structure that characterizes cuprates and iron chalcogenides, disclosing the presence of several complex networks of coexisting superconducting domains with different lattice modulations, charge densities and gaps as in the proposed multi-gap scenario called superstripes.

Keywords: phase separation, inhomogeneity, cuprates, high temperature superconductivity, complex materials

1. Introduction

An essential step towards the understanding of modern materials and their implementation in novel nano-electronic devices is the control and manipulation of their microscopic behavior [1–3]. Recently, the interrelationship between spin, charge, and lattice orders in high temperature superconductors (HTSs) has been at the center of a very animated discussion [4–15]. Novel results obtained in YBa\(_2\)Cu\(_3\)O\(_{6+y}\) (YBCO) provide compelling evidence for charge density waves (CDWs), and static magnetic stripes are intertwined and aggregated in nanoscale puddles [16–21]. These domains are spatially separated by superconducting regions composed by ordered lattice stripes [22–26] forming an intrinsically complex lattice of striped puddles called the ‘superstripe’ scenario [13]. In this scenario the local lattice modulations determine multiple subbands crossing the Fermi level and therefore multi-gap superconductivity below the critical temperature [27, 28]. This theoretical proposal has been recently supported by the prediction of the anomalous isotope coefficient at 1/8 doping [29]. Since the nature and distribution of defects becomes the driving force, their control by thermal annealing is of high relevance. Therefore, a primary task for both fundamental physics and novel nano-electronics is the careful visualization of the effects of a thermal treatment on the system, via imaging the quasi-two-dimensional puddles of oxygen chains in YBCO. Unfortunately, due to the lack of proper local bulk-sensitive probes, the microscopic scenario is still not clear and the real-space and real-time observation of thermally induced rearrangements of superconducting micro-regions in HTS is a difficult experimental task.

The development of a technique for imaging the nanoscale intrinsic inhomogeneity of oxygen chain organization is the first step to open new opportunities for their manipulation. Here we explore the nanoscale granular patterns arising in a YBa\(_2\)Cu\(_3\)O\(_{6.67}\) single crystal with doping close to 1/8 hole content per Cu site in the Y(CuO\(_2\))\(_2\) bilayer. The YBa\(_2\)Cu\(_3\)O\(_{6.67}\) crystal is an ideal system for investigation of inhomogeneity due to the short range ordering of oxygen ions [30] at 1/8 doping. Indeed, it exhibits an incommensurate superlattice of (OVIII) chains indicated by the lattice superstructure modulation at \( q_{OVIII}(a*) = (h + 3/8, k, 0) \) and \( q_{OVIII}(a*) = (h + 5/8, k, 0) \). Although the oxygen tendency to form O–Cu–O fragments in the
basal plane has been widely investigated [31, 32], to date there is little information on the spatial distribution of these fragments, and on their inclination towards aggregation in domains. In the first part of our paper we report the temperature evolution in YBa$_2$Cu$_3$O$_{6.67}$ using standard synchrotron x-ray diffraction of the OVIII puddles of oxygen chains. Using the heat treatment we show the formation of a second network of puddles characterized by OXVI superstructure modulation at $q_{\text{OXVI}}(a^*) = (h + 7/16, k, 0)$ and $q_{\text{OXVI}}(a^*) = (h + 9/16, k, 0)$, and finally a third network of OV puddles characterized by the superstructure wavevectors $q_{\text{OV}}(a^*) = (4/10, 1, 0)$ and $q_{\text{OV}}(a^*) = (6/10, 1, 0)$. The measurements provide us with information about the average order of oxygen chains in the sample. In the following, we investigate the dynamics and spatial distribution of OVIII, OXVI and OV domains upon thermal cycling via micro-x-ray diffraction ($\mu$XRD). By scanning microscopic areas, this technique provides mixed information of the reciprocal and real-space the bulk structure inhomogeneities, and it has never been applied on a YBa$_2$Cu$_3$O$_{6.67}$ single crystal before. Finally, we show how through thermal treatment it is possible to control the puddle size distribution, the number of oxygen chains and their charge density. Indeed using the novel experimental method $\mu$XRD it has been possible to directly visualize how the thermal treatment affects the intrinsic nanoscale phase heterogeneity in this cuprate superconductor. We relate these changes to the onset variation of the superconducting temperature, that we readily can control over a range of 2 K.

2. Materials and methods

Starting reagents with ultra-high purity (CuO and Y$_2$O$_3$ 99.999%, BaCO$_3$ 99.997%) have been employed to grow extremely good single crystals of YBa$_2$Cu$_3$O$_{6.67}$ in barium zirconate crucibles by the self-flux technique [33]. Inductively coupled plasma mass spectroscopy indicates a purity of the crystals higher than 99.99 at.%. The oxygen content of the crystal was set to 6.67 by annealing in flowing oxygen at 914°C, followed by quenching to room temperature under flowing nitrogen gas. The macroscopic oxygen content inhomogeneity was removed by annealing the crystal at 570°C in a sealed quartz capsule, followed by quenching in an ice–water bath. The crystal was then kept at room temperature to let the short range oxygen order establish. Average structure characterization shows a unit cell described by a $P4/m$ spatial symmetry and lattice dimensions $a = 3.807(11)$ Å, $b = 3.864(12)$ Å and $c = 11.52(2)$ Å, with a unit cell volume of 169.5(8) Å$^3$.

Temperature dependent x-ray diffraction measurements were made on the XRD1 beamline at the ELETTRA synchrotron storage ring, Trieste. The beamline is placed on a multipole wiggler insertion device operating under the current ELETTRA conditions of 2 GeV ring energy and 400 mA injection current (see figure S1). The samples were oriented on a kappa diffractometer equipped with a motorized goniometric X–Y stage head and a Mar-Research 165 mm CCD camera as detector. The data were collected in transmission mode with a photon energy of 20 keV ($\lambda = 0.619 \text{ 92 Å}$), selected from the source by a double-crystal Si(111) monochromator and using a beam of 200 × 200 μm$^2$. The 2D CCD detector (MAR-Research) was placed at a distance of 70 mm from the sample. Data from a LaB$_6$ standard were collected for calibration. Measurements were conducted between 300 and 400 K with a temperature step of 2 K for both the heating (300–400 K) and the cooling (400–300 K) cycles. Temperature was varied and controlled by means of a 700 series Oxford Cryosystems cryo-cooler that allows
working in a range of 90–400 K, guaranteeing accuracy better than ±1 K. All the images measured by single-crystal x-ray diffraction were processed using the FIT2D program jointly with a MATLAB® based software package developed in house. Second, the microscopic behavior of the sample under the thermal treatments has been investigated using scanning μXRD in reflection geometry (in the a–c plane).

The ID13 beamline of the European Synchrotron Radiation Facility (ESRF) is specialized in the delivery of micro-focused x-ray beams for x-ray diffraction experiments. The photon source, in the range 12–13 keV, is an 18 mm period in-vacuum undulator at the ESRF 6.03 GeV storage ring operated in multi-bunch mode with a current of 200 mA. The optics of the micro-focus beamline include compound refractive lenses, Kirkpatrick Baez (KB) mirrors, crossed Fresnel zone plates or waveguides. The ellipsoidal mirror is the main focusing element, demagnifying the source by a factor of 10 (about 40 μm in diameter). The focused beam is defined by a pinhole of 5 μm diameter. The beam is focused by a tapered glass capillary to 1 μm in diameter. The beamline uses two monochromators positioned in series: the first is a liquid N2 cooled Si-111 double crystal or Si-111 (bounce); the second is a channel cut monochromator employing a single liquid nitrogen cooled Si crystal. The detector of x-ray diffraction images is a high resolution CCD camera (Mar CCD) with point spread function 0.1 mm, 130 mm entrance window and 16 bit readout placed at a distance of about 90 mm from the sample. To scan the sample area it has been moved using two piezoelectric stages in x–y directions and data have been collected in the θ–2θ reflection geometry (see figure S2). The huge number of diffraction patterns collected by μXRD (more than 12 800 for each map) have been processed using a MATLAB® based software package developed in house.

The magnetic behavior versus temperature of our YBCO sample at 1/8 has been characterized by means of the vibrating sample magnetometer (VSM) option in a Physical Property Measurement System (PPMS 6000) from Quantum Design. Here a linear motor vibrates the sample with a frequency of 40 Hz and amplitude of 2 mm at the center of a pick-up coil, and the induced voltage is measured synchronically with the oscillation. A magnetization measurement has been chosen to consist of the averaged value over 40 data points, that is, over a period of 1 s of oscillation. These parameters guarantee a good signal to noise ratio.

3. Results and discussion

The ordering process of the oxygen ions in chain domains has been studied using transmission XRD. The diffraction pattern due to the superlattice reflections was recorded at room temperature and is shown in figure 1(a).

It is possible to distinguish superlattice peaks due to the OVIII (6/16, 1, 0) and (10/16, 1, 0) reflections in the a*–b* plane at 300 K, in agreement with previous data [21], which confirms the high quality of our single crystal. We monitored the x-ray diffraction patterns during a thermal cycle from 300 to 400 K, and then back to 300 K, using a slow rate of 0.5 K min⁻¹. The continuous evolution of the superlattice profiles from OVIII to OV through OXVI modulation is shown in figure 1(b). The OVIII (6/16, 1, 0) and (10/16, 1, 0) reflections in the a*–b* plane at 300 K evolve into the OXVI (7/16, 1, 0) and (9/16, 1, 0) modulation upon heating to 400 K.

During the subsequent cool-down to 300 K the original OVIII modulation is not restored and a new OXVI phase, identified by the superlattice peaks (7/16, 1, 0) and (9/16, 1, 0), sets in. In figures 1(b)–(e) we report respectively the temperature dependence of the superlattice peak
position, the intensity and the average domain size along $a^*$ and $b^*$. The average domain size along the in-plane $a^*$ and $b^*$ directions has been calculated by fitting the superlattice reflections with a two-Lorentzian model. In addition, above 380 K the system crosses a OXVI phase with wavevector $q_{\text{OXVI}}(a^*) = (h \pm 9/16, k, 0)$. The average size of the OXVIII domain along $a^*$ is about 7.5 (5) nm, but approaching the OV it decreases to 4.5(5) nm. The average size is larger along $b^*$, showing OXVIII and OV domains of about 23.5(5) and 11.5(5) nm, respectively. This phenomenology shows that the in-plane average domain size of oxygen chains can be controlled and manipulated by tuning the temperature in a quasi-irreversible manner. Leaving the sample under vacuum at room temperature, more than one month is needed for the OV phase to spontaneously drive itself back to a new reconstructed OXVIII phase.
This aspect shows relevant analogies with the oxygens and local lattice distortions ordering in La$_2$CuO$_{4+y}$, where the Q2-i0 phase (due to interstitial oxygen ordering) and the Q3-LLT (due to local lattice distortion ordering) can be changed by thermal treatments and restored by waiting a long time or by the use of x-ray continuous illumination [34–39].

In order to monitor the microscopic evolution of OVIII domains into OXVI and OV during the thermal manipulation, we used μXRD as already successfully done to investigate phase separation appearing in other cuprates [34–39] and iron-based superconductors [40–43]. We made our measurements using a beam about 1 μm in diameter. The sample has been scanned over an area of 160 × 80 μm$^2$ collecting 12 800 micro-diffraction patterns showing superlattices at $q_{OVII}(a^*) = (3/8, 0, 4)$ and $q_{OVIII}(a^*) = (5/8, 0, 4)$ due to OVIII puddles of ordered oxygen chains. The superlattice peak profiles have been fitted using a two-Lorentzian model, and the satellite position $h_{XY}$ along $a^*$ and the FWHM $XY$ along $a^*$ and $c^*$ have been extracted for every micro-diffraction pattern at the $X$–$Y$ position.

From the FWHM $XY$ along $c^*$ we calculated the out of plane domain size for every spot of the scanned map. Figures 2(a)–(c) show the real space map of the out of plane domain size (along $c^*$), before the heating (OVIII), at 390 K (OXVI) and after the cooling cycle (OV), respectively. These maps show the presence of clear intrinsic nanoscale heterogeneity in this cuprate superconductor, as has been observed in iron chalcogenides [40, 42].

The OVIII probability density functions for the domain size distribution along $c^*$ is relatively sharp, and varies from 7 to 9 nm. Upon heating, the OXVI phase shows instead a very broad distribution, that spans the 1–6 nm range. After the cooling cycle, the size distribution in the OV phase sharpens again, around the decreased average value of 3 nm, therefore indicating a certain recovered order. The overall behavior indicates a sensible response of the granular network to thermal treatment.

Starting from the FWHM$_{XY}$ and the $h_{XY}$ along $a^*$, measured at each $X$–$Y$ spatial position, we reconstructed the spatial maps of the number of oxygen chains ($n$) inside the puddles. Using the expression $n_{XY} = (1 - h_{XY})/FWHM_{XY}$, we calculate this quantity for OVIII (figure 3(a)), OXVI (figure 3(b)) and the annealed OV puddles (figure 3(c)).

The number of oxygen chains decreases after the thermal heating cycle from OVIII to OXVI and increases again after the cooling in the OV puddles (but remains lower than in the OVIII phase).

Figures 4(a)–(c) show the spatial map of the charge density (or hole concentration $p$) inside the puddles of oxygen chains, onto the same area as described in figure 3, before heating (OVIII phase), at 390 K (OXVI phase) and after cool-down (OV phase). The charge density has been calculated considering the difference of the superlattice position along $a^*$ ($h_{XY}$) with respect to the ortho-II (OII) phase following the relationship $p_{XY} = h_{XY} - 0.5$, where the OII modulation corresponds to a periodicity of a filled CuO chain intercalated by one empty chain. During the thermal annealing process the charge density changed on the microscopic scale and its distribution in the OXVI and OV puddles gets broader, demonstrating the strong granularity of the system. Figure 5(a) shows the spot to spot charge density ($p_{XY}$) as a function of the number of oxygen chains ($n_{XY}$), inside the OVIII, OXVI and OV puddles. The behavior has been fitted using an exponential model: $p_{XY} = 1 - \exp\{ -[(n_{XY} - n_0)/\xi_p]\}/\xi_p$. Here $n_0$ and $\xi_p$ are the minimum and the maximum number of chains present in the average puddle. In order to understand how the microscopic reduction of the effective hole doping affects the superconducting properties, we studied the magnetic response of our sample across the superconducting transition before
and after the thermal annealing, i.e. in the OVIII and in the OV phase, by means of the VSM option in a PPMS 6000 from Quantum Design. The results are shown in figure 5(b). A first measurement is made before any annealing procedure is carried out (OVIII phase), and shows the onset temperature of the diamagnetic screening ($T_c$) to be about 66 K. The subsequent measurements are made upon thermal annealing at 380 K (OV phase), with increasing dwell time of 30, 60, 90 and 150 min. In all these cases $T_c$ decreases by about 2 K. This effect is irrespective of the annealing time, and we associate such a reduction with the lower effective charge density we point out in figures 4 and 5(a).
4. Conclusion

In conclusion, we have investigated how thermal treatments allow us to microscopically manipulate and control the functional properties of YBa$_2$Cu$_3$O$_{6.67}$ ($p \approx 1/8$). We used an x-ray diffraction approach, combining standard synchrotron XRD measurements (200 × 200 $\mu$m$^2$ beam size) with scanning $\mu$XRD (1 × 1 $\mu$m$^2$) and VSM. Using thermal annealing we induced a continuous phase transition that led to a different final arrangement of Cu–O chains in the sample. In particular we monitored a transition from the OVIII to the OV modulation for the oxygen chain domains, by cycling between 300 and 400 K. The microscopic dynamics of the domains have been investigated by scanning $\mu$XRD. We mapped with micrometric resolution the out of plane domain size, the number of oxygen chains and the charge density inside each domain, covering a total area of 160 × 80 $\mu$m$^2$. We recorded 12 800 diffraction patterns for each spatial map, showing a high nanoscale inhomogeneity and the presence of a complex network-like organization of competing superconducting puddles that are characterized by different numbers of oxygen chains and charge densities. Reductions in the out of plane domain size, in

![Figure 3.](image)
the number of oxygen chains and in the microscopic distribution of charge density have been observed in the OV phase. These reductions have been connected to a decrease of the number of holes in the active layer. As a consequence, magnetization measurements show that the modification of the network structure of superconducting grains is responsible for a drop of \( T_c \) of about 2 K. This can open the way to a possible \( T_c \) tuning by microscopic thermal manipulation of the oxygen chain distribution in HTSs. This work shows the presence of a microscale phase separation in YBa\(_2\)Cu\(_3\)O\(_{6.67}\) with a hole doping close to 1/8, where the lattice misfit strain [43] in these heterostructures at atomic limit and the proximity of the Fermi level to a 2.5 Lifshitz transition near a band edge of the subbands [44, 45, 27–29] induce the observed nanoscale phase separation predicted by the multiband Hubbard model [46]. Finally, in this experiment we observe a superstripe [13] lattice scenario in YBa\(_2\)Cu\(_3\)O\(_{6.67}\) made of different striped nanoscale puddles of locally ordered interstitials with well defined hole doping density. The unique information that our experiment provides on the density distribution of the nanoscale striped puddles shows complex networks of superconducting units, that supports the statistical physics theories of percolative superconductivity in complex networks as an essential feature for understanding the emerging high temperature superconductivity [47–51]. In fact, the reconstructed spatial maps shown here provide compelling evidence for the generic granular

Figure 4. (a)–(c) The spatial map of the charge density (hole concentration \( p \)) of the OVIII, OXVI and OV puddles. (d) Distribution of the charge density in the OVIII (blue filled circles), OXVI (black filled squares) and OV (red empty crosses) puddles. During the thermal annealing process the charge density changes and its distribution in the OXVI and OV puddles gets broader.
structure that characterizes cuprates and iron chalcogenides. We disclose practical multiple realizations of complex networks of dopant self-organization at the nanoscale with striped puddles characterized by different modulations, local charge densities and superconducting condensates, which share the common features for the emergence of high $T_c$ superconductivity.

**Acknowledgments**

We thank Ruixing Liang, D A Bonn, and Walter N Hardy of the Department of Physics of the University of British Columbia for providing us with the crystals and for helpful discussions. We thank the ID13 beamline staff of ESRF and the XRD1 beamline staff of ELETTRA, especially G Bais N P acknowledges the Marie Curie Intra-European Fellowship for financial support.
References

[1] Hwang H Y, Iwasa Y, Kawasaki M, Keimer B, Nagaosa N and Tokura Y 2012 Emergent phenomena at oxide interfaces Nat. Mater. 11 103–13
[2] Huijben M, Brinkman A, Koster G, Rijnders G, Hilgenkamp H and Blank D H A 2009 Structure–property relation of SrTiO3/LaAlO3 interfaces Adv. Mater. 21 1665–77
[3] Mannhart J and Schlom D G 2010 Oxide interfaces—an opportunity for electronics Science 327 1607–11
[4] Dagotto E 2005 Complexity in strongly correlated electronic systems Science 309 257–62
[5] Littlewood P 2011 Superconductivity: an x-ray oxygen regulator Nat. Mater. 10 726–7
[6] Zaanen J 2010 High-temperature superconductivity: the benefit of fractal dirt Nature 466 825–7
[7] Zeljkovic L and Hoffman J E 2013 Interplay of chemical disorder and electronic inhomogeneity in unconventional superconductors Phys. Chem. Chem. Phys. 15 13462
[8] Bishop A R, Shenoy S R and Sridhar S (ed) 2003 Intrinsic Multiscale Structure and Dynamics in Complex Electronic Oxides (New Jersey: Word Scientific)
[9] Kalinin S V and Spaldin N A 2013 Functional ion defects in transition metal oxides Science 341 858–9
[10] Borisenko S 2013 Superconductivity: fewer atoms, more information Nat. Mater. 12 600–1
[11] Saini N L 2013 Nanoscale structure and atomic disorder in the iron-based chalcogenides Sci. Technol. Adv. Mater. 14 014401
[12] Giraldo-Gallo P et al 2013 Inhomogeneous superconductivity in BaPb1−xBixO3 J. Supercond. Novel Magn. 26 2575
[13] Bianco-Canosa S et al 2012 Distinct charge orders in the planes and chains of ortho-iii-ordered YBa2Cu3O6+y superconductors identified by resonant elastic x-ray scattering Phys. Rev. Lett. 109 167001
[14] Campi G et al 2013 Scanning micro-x-ray diffraction unveils the distribution of oxygen chain nanoscale puddles in YBa2Cu3O6.33 Phys. Rev. B 87 014517
[15] Ricci A et al 2013 Multiscale distribution of oxygen puddles in 1/8 doped YBa2Cu3O6.67 Sci. Rep. 3 2383
[16] Bianconi A et al 1996 Stripe structure in the CuO2 plane of perovskite superconductors Phys. Rev. B 54 12018
[17] Perali A et al 1996 The gap amplification at a shape resonance in a superlattice of quantum stripes: A mechanism for high Tc, Solid State Commun. 100 181
[18] Perali A et al 2012 Anomalous isotope effect near a 2.5 Lifshitz transition in a multi-band multi-condensate superconductor made of a superlattice of stripes Superconducting Sci. Technol. 25 124002
[30] Zimmermann V et al 2003 Oxygen-ordering superstructures in underdoped YBa2Cu3O6+x studied by hard x-ray diffraction Phys. Rev. B 68 104515
[31] Jorgensen J D et al 1987 Oxygen ordering and the orthorhombic-to-tetragonal phase transition in YBa2Cu3O7-x Phys. Rev. B 36 3608
[32] Jorgensen J D et al 1990 Structural properties of oxygen-deficient YBa2Cu3O7-δ Phys. Rev. B 41 1863
[33] Liang R, Bonn D A and Hardy W N 2012 Growth of YBCO single crystals by the self-flux technique Phil. Mag. 92 2356
[34] Bianconi A, Di Castro D, Bianconi G, Pifferi A, Saini N L, Chou F C et al 2000 Coexistence of stripes and superconductivity: Tc amplification in a superlattice of superconducting stripes Physica C 341 1719–22
[35] Poccia N et al 2011 Evolution and control of oxygen order in a cuprate superconductor Nat. Mater. 10 733–6
[36] Poccia N, Bianconi A, Campi G, Fratini M and Ricci A 2012 Size evolution of the oxygen interstitial nanowires in La2CuO4+y by thermal treatments and x-ray continuous illumination Superconductor Sci. Technol. 25 124004
[37] Fratini M et al 2010 Scale-free structural organization of oxygen interstitials in La2CuO4+y Nature 466 841–4
[38] Poccia N et al 2012 Optimum inhomogeneity of local lattice distortions in La2CuO4+y Proc. Natl Acad. Sci. 109 15685–90
[39] Poccia N et al 2011 Spatial inhomogeneity and planar symmetry breaking of the lattice incommensurate supermodulation in the high-temperature superconductor Bi2Sr2CaCu2O8+δ Supercond. Sci. Technol. 24 082002
[40] Ricci A et al 2011 Nanoscale phase separation in the iron chalcogenide superconductor K0.8Fe1.6Se2 as seen via scanning nanofocused x-ray diffraction Phys. Rev. B 84 060511
[41] Fratini M, Caivano R, Puri A et al 2008 The effect of internal pressure on the tetragonal to monoclinic structural phase transition in ReOFeAs: the case of NdOFeAs Supercond. Sci. Technol. 21 092002
[42] Ricci A, Poccia N, Joseph B et al 2011 Intrinsic phase separation in superconducting K0.8Fe1.6Se2 (Tc = 31.8 K) single crystals Supercond. Sci. Technol. 24 082002
[43] Poccia N, Ricci A and Bianconi A 2010 Misfit strain in superlattices controlling the electron-lattice interaction via microstrain in active layers Adv. Condens. Matter Phys. 2010 261849
[44] Bianconi A, Valletta A, Perali A et al 1997 High Tc superconductivity in a superlattice of quantum stripes Sol. State Commun. 102 369–74
[45] Romero-Bermúdez A and García-Garcia A M 2014 Shape resonances and shell effects in thin-film multiband superconductors Phys. Rev. B 89 024510
[46] Kugel K I et al 2008 Model for phase separation controlled by doping and the internal chemical pressure in different cuprate superconductors Phys. Rev. B 78 165124
[47] de Mello E V L 2012 Describing how the superconducting transition in La2CuO4+y, is related to the iO phase separation J. Supercond. Novel Magn. 25 1347–50
[48] Bianconi G 2012 Superconductor-insulator transition on annealed complex networks Phys. Rev. E 85 061113
[49] Bianconi G E P L 2013 Superconductor-insulator transition in a network of 2d percolation clusters Europhys. Lett. 101 26003
[50] Gor’kov L P and Teitel’baum G B 2008 The two-component physics in cuprates in the real space and in the momentum representation J. Phys.: Conf. Ser. 108 012009
[51] Yukalov V I and Yukalova E P 2014 Statistical theory of materials with nanoscale phase separation J. Supercond. Novel Magn. 27 919–24