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Improvement of Tc, Unit Cell Volume, and Meissner Effect in High-Temperature Superconductors

Abdeljabar Aboulkassim[1*], *Said* Kririm[1], *El Hanafi* Arjdal[1], *Rachid* Oualaid[2], *Youssef* El bid[2] *and Kamal* Boujaghama[2]

[1]Materials, Signals, Systems and Physical Modeling Laboratory, Faculty of Sciences, Ibnou Zohr University, Agadir, Morocco
[2]Energies and Sustainable Development Research Team (E2D), Higher School of Technology, Guelmim, Ibnou Zohr University, 81000, Morocco

Abstract. In this paper, experimental research is done on resistivity, AC magnetic susceptibility, and X-ray diffraction. This work examines two heat treatments: [O] and [OA], Oxygen and Oxygen-Argon annealing respectively. [OA] heat treatment raises T_c for x>0.2, the orthorhombicity ε for x varying between 0 and 1 and reduce the d(Ba/Sr-Cu(1)) (interatomic distance) for x>0.2. Under any applied magnetic field and for $T < T_c$, the [OA] samples exhibited a significant enhancement in the shielding effect (Meissner effect), as reflected by the amplitude of $\chi'(T)$. The Meissner factor S(x) decreases for all x values when either T or H_{dc} increases. Correlations were noted between $p_{Sh}(x)$ (the number of holes) and T_c (x), within the superconducting plans Cu(2)-O_2, and the unit cell volume V(x) on the other hand. The observed results could be explained by any of these causes, which include a reduction in d(Ba/Sr-Cu(1)), an improvement in the ordering of cations and chain oxygen, as well as an increase in the in-phase purity of the [OA] samples.

1 Introduction

The magnetic, electric, and crystalline properties of the high-T_c superconductors have been widely studied by several research laboratories globally since their discovery. Superconductivity's Meissner effect is a significant indicator of magnetic characteristics. Within the transition region of these materials, a diamagnetic response arises as magnetic flux is expelled from the inside of the superconducting sample if the outside temperature drops below the critical point (Tc). ReBCO (Re: Rare-earth) huge grain high critical temperature superconductors have the ability to trap stronger magnetic fields at low temperatures, making them useful for permanent magnet applications. [1]. Several engineering applications for such magnets have been identified [2,3], with some already entering commercialization [4].

The superconducting characteristics traits are quite easily changeable by substituting elements in the compounds [5,6] or varying the content of oxygen in these compounds. The influence of substitution on the magnetic, electrical and structural characteristics of YBCO has been in-depth explored [7]. The compound $LnBa_2Cu_3O_{6.95}$ (Single-phase) can be synthesized in bulk form, exhibiting a superconducting transition temperature T_c near 92K. All of these compounds have a triple-perovskite structure that is orthorhombically distorted and oxygen-deficient, with Tc and the degree of orthorhombic distortion being highly sensitive to the oxygen content, denoted as (6+z) [8,9]. Extensive research has been conducted by several authors on the elaboration and investigation of the superconducting and structural properties of $Ba_{2-x}La_{1+x}Cu_3O_y$, where x ranges between 0 and 0.5 [10,11]. These researchers concluded that in order to achieve acceptable superconducting qualities, a tri-perovskite structure with an arranged Ba and La along the c-axis and an oxygen occupation factor at (0, 1/2, 0) and (1/2, 0, 0) near to 1 and 0, respectively, is necessary.

It is intriguing to investigate whether some of the above-described results would change if the rare earth Nd^{3+} (0.995 Å) with a larger ionic radius were to replace Y^{3+}(0.893 Å) in an iso-valent substitution of Ba^{2+}(1.42 Å) with Sr^{2+} (1.12 Å). We examined the impact of heat treatment on the electrical, magnetic and structural properties of $(Y_{1-x}Nd_x)SrBaCu_3O_{6+z}$ (x=1, 0.8, 0.6, 0.5, 0.4, 0.2, 0) in order to investigate the influence of Ba and Y atomic arrangements and determine the factors that influence the superconducting property in these samples.
Subsequently, we discovered that argon heat treatment had a significant impact on these characteristics, was contingent upon the x(Nd) concentration.

2 Experimental techniques

2.1 Preparation of the samples

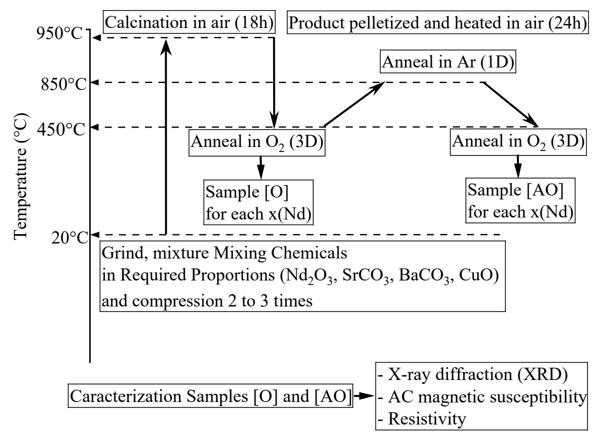

Fig. 1. Diagram illustrates the different preparation steps for the samples $(Y_{1-x}Nd_x)BaSrCu_3O_{6+z}$.

* Corresponding author: abdeljabar.aboulkassim@edu.uiz.ac.ma

The corresponding carbonates and oxides were solid state sintered to elaborate our polycrystalline compounds. The following diagram "Fig. 1" illustrates the different preparation steps for the $(Y_{1-x}Nd_x)BaSrCu_3O_{6+z}$

2.2 Characterization of the samples

Our samples $(Y_{1-x}Nd_x)BaSrCu_3O_{6+z}$ were subjected to X-ray diffraction measurements using a diffractometer (Philips) with a CuKα radiation source and a graphite monochromator for the secondary beam at 40kV and 20 mA. The 2θ angle ranged (π/9 - 2π/3) with increments of π/18000, and each step had a counting time of 10 seconds. Subsequently, the X-ray diffraction spectra were refined using Rietveld refinement techniques.

Measurements of the real and imaginary components of the AC magnetic susceptibility (χ' and χ'') as functions of T under H_{dc} (with 0 Oe < H_{dc} < 150 Oe) superimposed over Hac = 0.11 Oe at a frequency of f=1.5 kHz were used to investigate superconducting transitions.

Resistivity was measured using the Van der Pauw method, denoted as ρ(T). This involved utilizing a cryostat equipped with a temperature regulator (10^{-6}A - 10^{-3}A), a closed helium circuit, a digital voltmeter with a resolution of 1 μV and a cryogenic pump, all fully computer-controlled. The critical temperature T_c was verified by measuring χ'(T) and confirmed by measuring ρ(T).

3 Results

The diamagnetism effect S (Meissner effect) is one of the features of a superconducting material characteristics. The following formula represents the relationship between a magnetic material's magnetization M, applied magnetic field strength H_a, and magnetic flux density B:

$$B = \mu_0(H_a + M) \quad (1)$$

Considering that $B = 0$ within a superconductor, the previous equation gives us:

$$M = -H_a \quad (2)$$

and the magnetic susceptibility is thereby represented by:

$$\chi = dM/(dH_a) = -1 \quad (3)$$

The superconducting transition width ΔT_c for each sample $(Y_{1-x}Nd_x)BaSrCu_3O_{6+z}$ is taken as the midpoint temperature between 0.1 and 0.9 of the transition region. This zone, measured between 10% and 90% of the real part χ' signal's height, exhibited an increase across all samples. Specifically, it ranged from $0.58\,K$ for x=0 [OA] to approximately 3 K (x = 1) [OA], and from 0.94 K (x = 0) [O] to roughly 8 K (x=1) [O]. In "Fig. 3" the alterations witnessed in the imaginary part χ'' signal is also remarkable. The ΔT_p (defined as the width at half-maximum of the of χ'' peak) gradually increased, from about $0.4\,K$ for x=0 [OA] to approximately 2 K for $NdBaSrCu_3O_{6+z}$ [OA], and from around 1 K for $YBaSrCu_3O_{6+z}$ [O] to nearly 7 K for x=1 [O] "Fig. 3". However, in the case of the [OA] samples, there was a significant decrease in ΔT_p (from 1.29 K to 0.51 K) as x decreased (from 1 to 0). Following the [OA] heat treatment, we observed that $\Delta T_{c(max)} \approx 8$ K (and $\Delta T_{p(max)} \approx 7.4$ K), suggesting that the [OA] treatment increase in S (and enhance the intergranular coupling) in this instance.

We focus now on the χ'(T), which give information about several properties of high-T_c superconductors, such as S (Meissner effect) and T_c (superconducting critical temperature) in "Fig. 2 (a-b)".

Using the identical sample for both heat treatments allow for a comparison of the diamagnetic response. It is evident from "Fig. 2 (a-b)" that the screening current of the [OA] sample exhibited a considerable increase in comparison to the [O] at x=1.

The real $\chi'(T)$ and imaginary $\chi''(T)$ parts of the AC susceptibility of the samples are depicted in "Fig. 2 (a-b)" and "Fig. 2 (c-d)" respectively. The critical temperature T_c, of the sample [O] occurred at 68 K "Table 1". The peak of the imaginary part was identified at 67.3 K, with a width spanning half the maximum amplitude (FWHM) of approximately 1.54 K. Our measured value of Tc for the [O] sample is smaller (though Tc for the [OA] sample is higher) in comparison to the value of T_c= 74 K reported in [12]. The sample [OA] showed a critical temperature $T_c(\chi') = 77.2$ K and $T_c(\rho) = 77.2$ K, which was higher by around 9 K for $\chi'(T)$ and $\rho(T)$ compared to that of the sample [O]. Additionally, there was a noticeable shift in T_p to $76.5\,K$, suggesting that the interconnection between grains (superconductors) occurred under higher-temperature conditions when the sample underwent heating in argon followed by oxygen annealing.

We observe that all of the samples' XRD patterns clearly revealed the orthorhombic splitting, indicating an increase in orthorhombicity, and that some faint, unexplained impurity peaks were detected; these were removed in the [OA] samples "Fig. 4". This implies that the [OA] samples' crystallographic quality has improved.

A significant effect of argon annealing on T_c was observed. The temperature indicating the onset of diamagnetic behavior, denoted as T_c, was observed to be contingent on both x and the specific heat treatment utilized, as indicated in "Table 2".

As observed in "Table 2", as x increases (0 to 1), the ε decreases and reaches 0, signifying the changing in

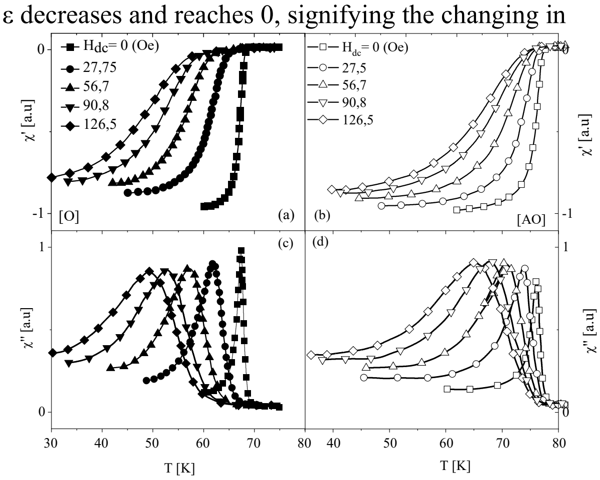

Fig. 2. χ''(T) (c,d) and χ'(T) (a,b) of $NdSrBaCu_3O_{(6+z)}$ at H_{dc} ($0 \leq H_{dc} \leq 126.5$ Oe) under [OA] and [O] heat treatment

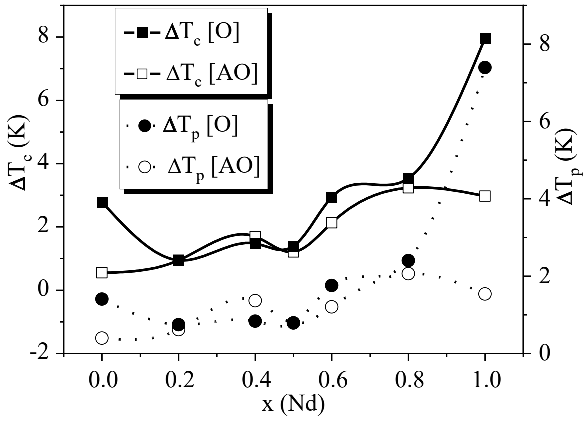

Fig. 3. Variation of the $\Delta T_c(x)$ and $\Delta T_p(x)$ for [OA] and [O] compounds

structure (orthorhombic to quadratic). The T_c [O] diminishes with orthorhombicity ε[O]. Despite this, ε[OA] decreases with T_c [OA] up to x = 0.2, then increases at x = 0.4, and subsequently drops by 9.80 K to 77.22 K for x = 1 [OA].

The upper part of "Fig. 8" shows that for any value of x, in [OA] compound, T_c increases for x greater than 0.2 and reduces it to x less than or equal to 0.2. For x = 1 [OA], a total increase in T_c of 10 K was noted.

Moreover, the [OA] treatment enhanced ε for all values of x in the range $0 \leq x < 1$.

For x=0.6, the largest increase in ε was noted, going from 2.23 10^{-3} to 5.81 10^{-3}, while its value becomes zero for x=1, like that found by Thompson et al. [14]. Compared to 10.10^{-3} reported by R.J. Cava et al. for $YBa_2Cu_3O_{6+z}$ [15], all these values are substantially smaller.

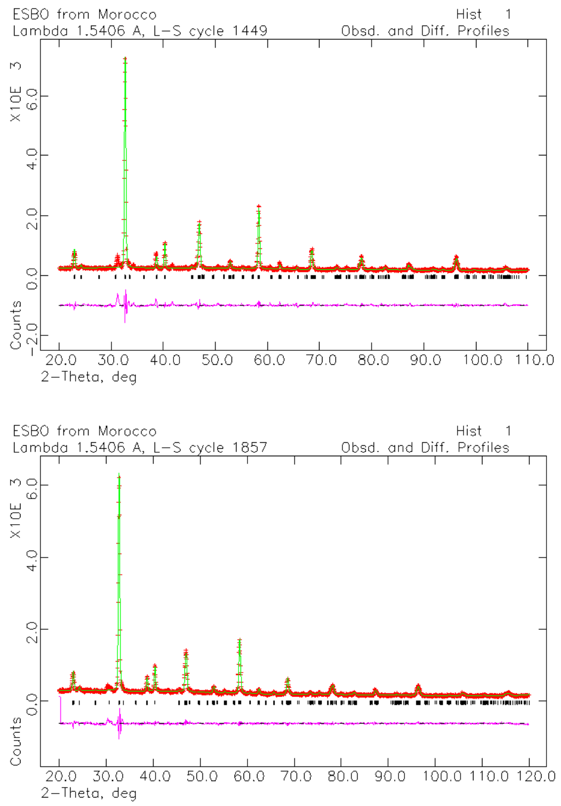

Fig. 4. XRD (Cu Kα) patterns of NdSrBaCuO. (top) Sample [O], (bottom) sample [OA]

Hence, we posit that the characteristic of the resistivity curves indicates the absence of a superconducting phase within the grain boundaries, serving as weak links, and consequently diminishing the intergranular coupling.

The critical temperature T_c of our samples was also determined from resistivity measurements. For instance, the resistivity (ρ) data points for the $NdSrBaCu_3O_{6+z}$ [OA] sample clearly lower than those of the [O] sample in "Fig. 5 (a)". It's noteworthy that for a given heat treatment, $T_c(\chi')$ surpasses T_c ($\rho = 0$) by 1 to 2 K, with T_c ($\rho = 0$) approximately equal to $T_p(\chi'')$. In the normal state of the granular superconducting sample, the resistivity is denoted by ρ(T). The relationship between ρ(T) and temperature (T) is expressed as:

$$\rho = \rho_0 + \alpha . T \quad (4)$$

Arising from both grains and grain boundaries, the resistivity is contributed by two components, the resistivity from the grains is temperature-dependent, whereas that from the grain boundaries remains temperature-independent. Consequently, the inter-grain

Table 1. Results of resistivity and susceptibility measurements of $NdBaSrCu_3O_{6+z}$ for [OA] and [O] samples

	Sample [OA]	Sample [O]
T_p (χ")(K)	76.50	67.30
T_c (χ')(K)	77.18	68.02
T_c (ρ)(K)	77.20	67.32
ΔT_c (K)	2.97	7.96
ΔT_p (K)	1.53	7.39
ρ_0(μΩcm)	468	1011
ρ_{294}(μΩcm)	970	2053
α (μΩcm/K)	1.43	2.93

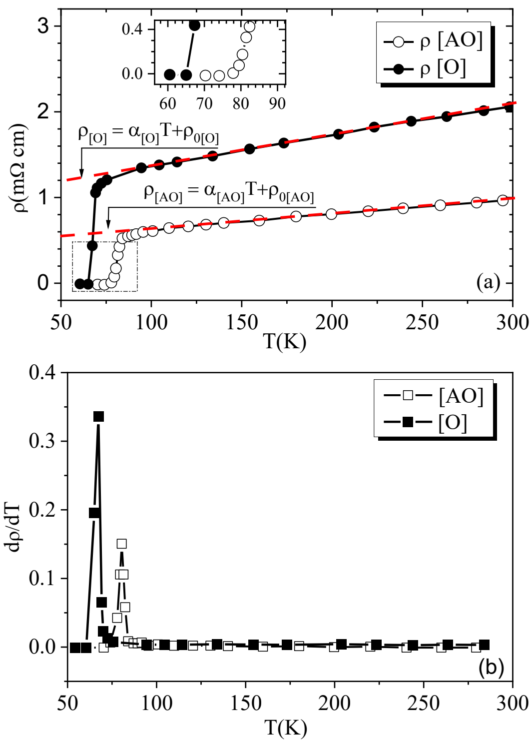

Fig. 5. (a) Variation of the **resistivity** $\rho(\boldsymbol{T})$ and (b) Temperature dependency of resistivity derivative of (YNd)$SrBaCu_3O_{6+z}$ as a function of [OA] and [O] heat treatment.

coupling parameter at absolute zero temperature is determined by the intercept ρ_0 of "Eq. (4)" on the Y-axis, as illustrated in "Fig. 5 (a)".

Here, ρ_0 represents the residual resistivity extrapolated to T=0 K, and α denotes the incline $d\rho\ /\ dT$.

For example, $NdSrBaCu_3O_{6+z}$ [O] has $\alpha[O] = 2.93(\mu\Omega cm/K)$, $\rho_0[O] = 1011(\mu\Omega cm)$ and $\rho_{294}[O] = 2053(\mu\Omega cm)$. The [OA] treatment significantly reduced these parameters specifically, $\alpha[OA] = 1.43\ (\mu\Omega cm/K)$, $\rho_0[OA] = 468\ (\mu\Omega cm)$ and $\rho_{294}[OA] = 970(\mu\Omega cm)$. This suggests an enhancement in inter-grain connectivity and a decrease in the carrier-phonon interactions. The latter value should be compared with $\rho_{300} = 3000(\mu\Omega cm)$ and $\alpha = 5.4\ (\mu\Omega cm/K)$ as reported in [14] for the sample NdSrBaCu3O6+z. All these values are significantly bigger compared to 600-700 (μΩcm) at room temperature and decreases to 200-250 (μΩcm) at 100K as reported in [15] for the conventionally oxidized sample $YBa_2Cu_3O_{6+z}$.

A two-step resistive transition ρ(T) is found for high critical temperature superconductors, which are distinguished by a unique superconducting transition temperature. Due to this, a tail and a peak appear on the low-temperature region of the derivative of ρ(T) [16]. The tail corresponds to intergranular coupling, while the peak signifies the superconducting transition within the grains. In "Fig. 5 (a)", the resistivity transition behavior of [OA] and [O] compounds appears. In the normal state, metallic behavior and a superconducting transition to zero resistance are exhibited by every sample. Additionally, these curves demonstrate a continuous increase in the resistivity in the normal state from [OA] to [O] compounds. Further information can be obtained via plotting the resistivity curve derivative for samples [OA] and [O],, as "Fig. 5 (b)" illustrates.

The T_c is obtained from the highest possible value of the dρ(T)/dT curves, remains nearly consistent across all samples [O] and [OA] (refer to "Table 1"). Each sample exhibits a single peak, indicating a single superconducting transition. The peak T_p in χ''(T) indicates the AC losses, and the fall in the real part χ'(T) below T_c indicates diamagnetic Meissner.

Let's investigate the amplitude of the χ'(T) for $NdSrBaCu_3O_{(6+z)}$ in "Fig. 2 (a,b)" in relation to the heat treatment and applied magnetic field H_{dc} (0Oe< H_{dc} < 126.5Oe). This amplitude represents the Meissner effect, denoted as S [17]. In "Fig. 6", S was arbitrarily set equal to 1 for $H_{dc} = 0$ Oe. These measurements were conducted at three temperatures: 60 K, 63 K, and 66 K for $x = 1$ and 0.8, and at 71 K, 73 K, and 75 K for x=0.5,

Table 2. Results of ε and T_c of $(Y_{1-x}Nd_x)SrBaCu_3O_{6+z}$. for [OA] and [O] samples

x(Nd)	Tc[O]	Tc[OA]	ε [O]	ε [OA]
0	83.06	81.80	9.19	10.09
0.2	79.87	80.13	6.91	8.12
0.4	78.95	80.96	5.09	7.04
0.5	78.86	80.54	4.04	6.66
0.6	78.11	79.62	2.23	5.81
0.8	72.64	79.36	0.89	2.23
1	68.02(58 [9])	77.18	0 (0[9])	0

with an externally applied magnetic field H_{dc}. S is the sample's exclusion of magnetic flux in a different dynamic mode. Moreover, regarding the applied field, the reduction in S was significantly slower for the [OA] sample. In particular, at $T = 66K$, the [OA] compound exhibited a reduction in (S) of approximately 35% with the field increasing from 0 to 126.5 Oe, whereas the [O] compound exhibited a reduction of approximately 95%. In the [OA] samples, an augmentation in S has been seen for any practical magnetic field H_{dc} and for all temperatures below T_c. For example, the Meissner effect S at a field of 126.5 Oe in $NdSrBaCu_3\ O_{(6+z)}$ with x=1 at T = 66 K was nearly six times larger in the [OA] compound compared to the [O] compound. Furthermore, in the case of the [OA] compound, the decrease in S with respect to the field was considerably slower. For example, when the field varying from 0 to

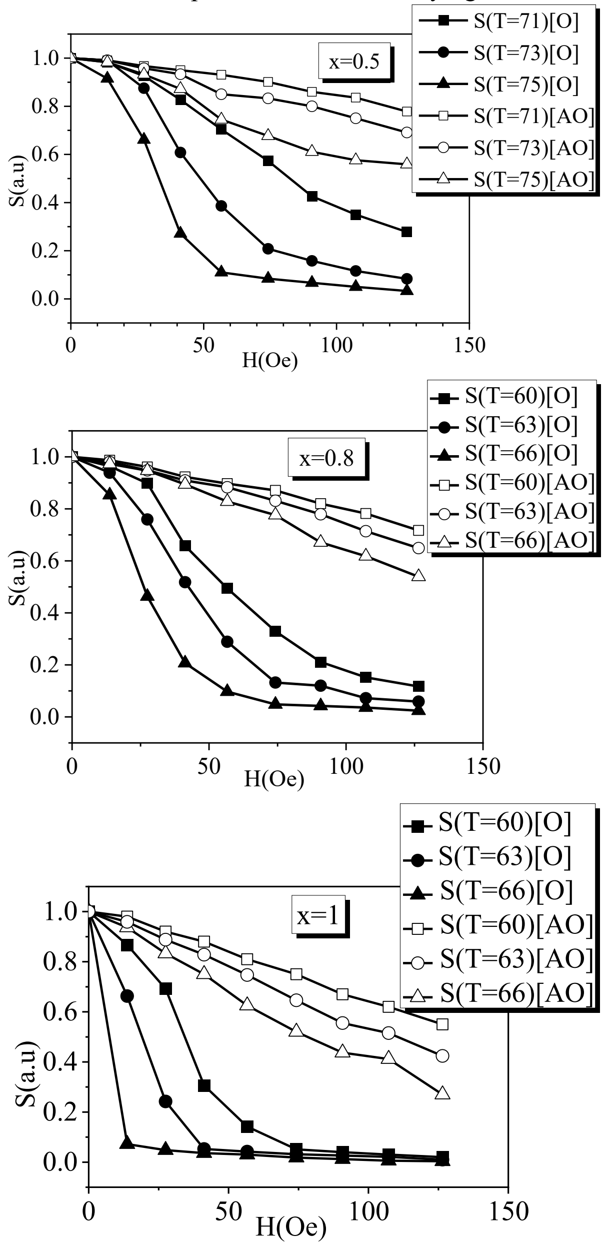

Fig. 6. Evolution of the Meissner effect S as a function of H_{dc}, [OA] and [O] at (x=1, 0.8 : T=60 K, 63 K, 66 K) and (x=0.5 : T=71K, 73K, 75K)

126.5 Oe at T=66K, the [OA] compound exhibited a reduction in S of about 35%, whereas the [O] compound exhibited a reduction of over 95%. This obviously indicates an enhancement shows that the [OA] samples' grain quality and intergranular interaction have improved.

4 Discussion

The linear resistivity characteristics were significantly decreased in the usual state by the [OA], suggesting improved inter-grain connection and a decrease in the interaction between phonons and carrier charges. Below T_c, the reduction in $\chi'(T)$ is indicative of Meissner effect S (amplitude of $\chi'(T)$). A notable enhancement in S was observed in the [OA] samples at any applied magnetic field H_{dc} and for all temperatures below T_c. For each heat treatment and value of x, the Meissner effect S(x) decreases as both the applied magnetic field H_{dc} and temperature increase. This phenomenon occurs due to the weakening of the connections between granules caused by H_{dc} applied and elevated temperature. Below the inflection point $I(\chi'(T))$, the grains are connected, and the current generated by the external magnetic field leads to the formation of diamagnetic zone along the outermost layer of the sample surface. For T>T(I), when considering a constant field, the grains become disconnected. Our Rietveld-refined XRD spectra supports these conclusions, this revealed an improvement in the [OA] samples' crystallographic quality. This enhancement signifies an improvement in the grains' quality and inter-grain contacts, including

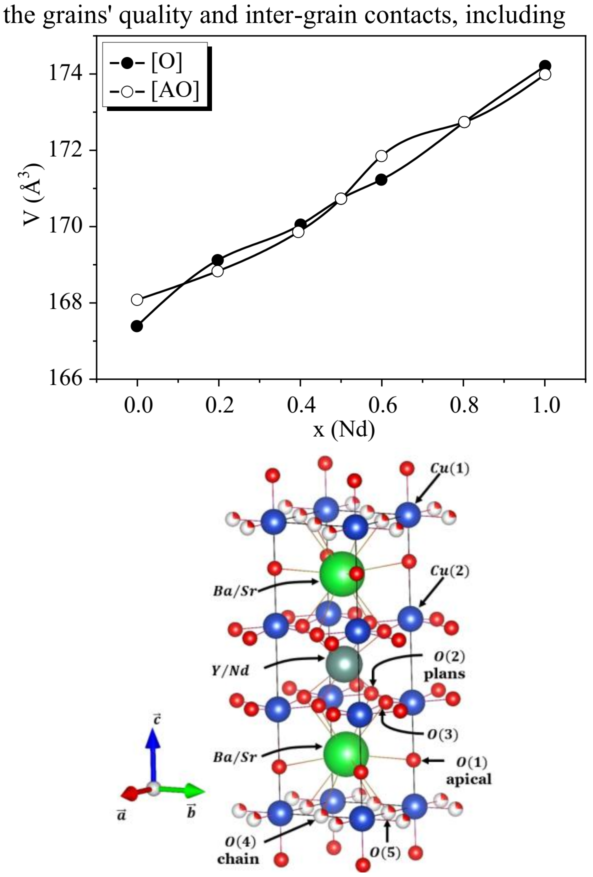

Fig. 7. Volume V(x) (top) and unit-cell volume (bottom) of $(Y_{1-x}Nd_x)SrBaCu_3O_{6+z}$

Josephson-junction coupling. This assertion is corroborated by the observation that the disparity separating inter-grain and intra-grain currents diminishes, leading to the merging of the two steps in $\chi'(T)$ (and $\chi''(T)$ peaks), as depicted in "Fig. 2".

Annealing in argon at 850 °C enhances oxygen extraction from the structure, hence boosting atomic diffusion inside the lattice, as we previously suggested for $LnSrBaCu_3O_{6+z}$ (Ln = Eu, Nd, Sm) [18]. Consequently, the starting point from the reduced (6+z) state, following the [OA] treatment, reduces the disorder of Nd/Y on the Ba/Sr site and promotes Nd/Y-Ba/Sr-Nd/Y ordering along the c-axis. This enhances anionic ordering in the basal plane and increases the number of oxygen atoms along the Cu(1)-O chains (NOC), thereby facilitating hole transfer to the Cu(2)–O_2 via the apical oxygen O(1) located between Cu(1) and Cu(2), consequently resulting in an increase in T_c, as depicted in "Fig. 8".

The lattice parameters a and c increase [13], while parameter b remains nearly constant, suggesting an increased oxygen occupancy in the chains (NOC) along the a-axis. For x = 1 [O], this reduction in ε for the [O] sample suggests a transition from the orthorhombic phase to the tetragonal phase.

The variation of V(x) as a function of heat treatment is illustrated in "Fig. 7", it's notable that the volume V increases with x, which aligns with the understanding that the ionic radius of $r(Nd^{3+}) = (0.98\ \text{Å}) > r(Y^{3+}) = (0.90\ \text{Å})$. The [OA] heat treatment increases T_c for x > 0.2 and decreases d[Cu(1)-(Ba/Sr)] (interatomic distance) for x > 0.2, but for each value of x it improves ε for x varying between 0 and 1 [13]. Along the c-axis through the apical oxygen O(1), this enhancement makes it easier for holes to get to Cu(2)-O_2 by going from chains along the b-axis, improving T_c.

Additionally, for each value of x, the [OA] heat treatment causes an increase in the parameter b and decrease in the parameter a. This effect results in an increase in anionic order in the basal plane and a decrease in the cationic disorder of (Nd/Y) on the (Ba/Sr) site along the c-axis. It also enhances the number of oxygen atoms in the chains (NOC) along the b-axis. Consequently, there is an increase in $p_{Sh}(x)$ (the number of holes per $Cu(2)O_2$ plane) derived from the undersaturation region of the universal relation T_c/T_{cmax} [19] and an increase in T_c for $x > 0.2$, as illustrated in "Fig. 8". The decrease in d[(Ba/Sr)-Cu(1)] for x > 0.2 can be regarded as evidence supporting the increase in Cooper pair formation and the increase in p_{Sh} and T_c, as depicted in "Fig. 8".

Two arguments regarding the disorders underlying anionic and cationic are substantiated by two notable correlations between $p_{Sh}(x)$ (number of hole) and $T_c(x)$ "Fig. 8", and between V and x in "Fig. 7". The latter shows that the unit cell volume, which determines T_c, has been rearranged. As a result, the impact of [OA] heat treatment is connected with the electrical, magnetic and structural characteristics.

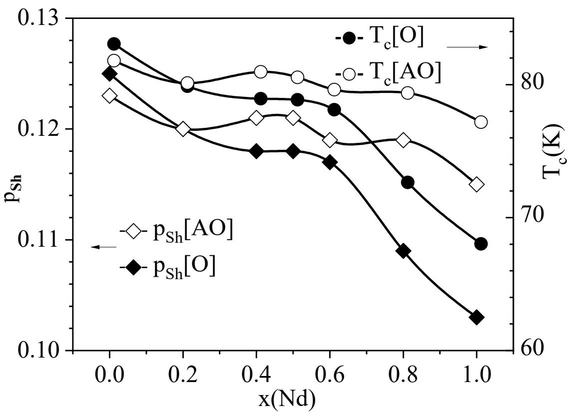

Fig. 8. Correlation between $p_{Sh}(x)$ and $T_c(x)$ for [OA] and [O] heat treatment

5 Conclusion

In summary, the significant increase in S observed in the [OA] samples can be attributed to the enhancement of intergranular coupling, resulting from the improvement in the crystallographic quality of these compounds. Moreover, in the normal state, the [OA] treatment led to a reduction in the linear resistivity parameters, indicating a decrease in the interaction between phonons and carrier charges. A shift from an orthorhombic to a quadratic structure is indicated by the orthorhombicity ε decreasing to zero as x climbs from 0 to 1. Additionally, for every x value, the [OA] heat treatment changes the d[(Sr/Ba)-Cu(1)], improves T_c (for $x > 0.2$) and increase ε (for $0 < x \leq 1$). This distance decreases x greater than 0.2, leading to an increase in T_c, while it increases for $x < 0.25$, resulting in a decrease in T_c. The argon heat treatment encourages (Nd/Y)-(Ba/Sr)-(Nd/Y)… ordering along the c-axis and lessens the disorder of Nd/Y on the Ba/Sr site. As a result, there are more oxygen atoms in the Cu(1)-O chains (NOC), increasing the anionic order in the basal plane. As a result, the apical oxygen Cu(1)-O(1)-Cu(2) facilitates an enhanced hole transfer to Cu(2)-O_2, increasing T_c. The charge-transfer model is in agreement with this observation. The electrical, magnetic, and structural properties correlate with the effect of [OA] heat treatment by Argon. These outcomes result from the interplay between cation disorder along the c-axis and oxygen disorder in the basal plane. The $p_{Sh}(x)$ hole concentration in the Cu(2)-O_2 superconducting planes, the ordering of chain oxygen and increase in cationic, the reduction in d[(Ba/Sr)-Cu(1)] for $x > 0.2$, and the in-phase purity found in the [OA] compounds are some of the explanations for these discoveries. These combined factors most likely account for the found results.

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References

1. Subhasis Shit; Devendra K. Namburi; S. D. Das; T. K. Nath, "Revealing the vortex phases and second magnetization peaks in SmBCO superconductors", J. Appl. Phys. 136, 173904 (2024), https://doi.org/10.1063/5.0235000.
2. Le Xu, Jun Zheng, Yonghai Zhao, Peng Pang, Li Wang, Jukun Wang, "Motion and thermal stability for high-temperature superconducting maglev vehicle under extreme crosswind conditions", Physica C: Superconductivity and its Applications, Volume 628, 2025, 1354620, ISSN 0921-4534, https://doi.org/10.1016/j.physc.2024.1354620.
3. Zili Zhang, Benzhe Zhou, Lei Wang, Jianhua Liu, Qiuliang Wang, "Research progress on the properties of REBCO superconductor tapes for the application of superconducting magnet", Renewable Energy System and Equipment, Volume 1, Issue 1, 2025, Pages 50-60, ISSN 2950-208X, https://doi.org/10.1016/j.rese.2024.10.001.
4. Kévin Berger, Santiago Guijosa, Frederic Trillaud, Bruno Douine, Jean Lévêque, "Fast Field Mapping of Large Size Bulk Superconductors at Variable Temperatures and Magnetic Fields" IEEE Transactions on Applied Superconductivity, DOI : 10.1109/TASC.2026.3663128
5. G.Ya. Khadzhai, I. Goulatis, A. Chroneos, V.M.P. Simoes, R.V. Vovk, "Resistive investigation of pressure effect on the temperature dependence of the pseudogap in $Y_{0.66}Pr_{0.34}Ba_2Cu_3O_{7-δ}$ single crystals accounting for the BCS - BEC crossover" Functional Materials, doi:https://doi.org/10.15407/fm32.02.190 (2025).
6. R.V. Vovk, N.R. Vovk, G.Y. Khadzhai, I.L. Goulatis, A. Chroneos, Effect of praseodymium on the electrical resistance of $YBa_2Cu_3O_{7-δ}$ single crystals", Solid State Communications. **190** (2014) 18–22. doi:10.1016/j.ssc.2014.04.004.
7. R.J. Cava, Structural chemistry and the local charge picture of copper oxide superconductors, Science. **247** (1990) 656–62. doi: 10.1126/science.247.4943.656.
8. R.J. Cava, B. Batlogg, C.H. Chen, E.A. Rietman, S.M. Zahurak, D. Werder, Oxygen stoichiometry, superconductivity and normal-state properties of $YBa_2Cu_3O_{7-δ}$, Nature. **329** (1987) 423–425. doi:10.1038/329423a0.
9. R. V. Vovk, N.R. Vovk, O. V. Dobrovolskiy, Effect of Structural Relaxation on the In-Plane Electrical Resistance of Oxygen-Underdoped $ReBa_2Cu_3O_{7-δ}$)(Re = Y, Ho) Single Crystals, Journal of Low Temperature Physics. **175** (2014) 614–630. doi:10.1007/s10909-014-1121-9.
10. T. Wada, N. Suzuki, A. Maeda, T. Yabe, K. Uchinokura, S. Uchida, and S. Tanaka, "Preparation and properties of superconducting $La_{1+x}Ba_{2-x}Cu_3O_y$ (with $0 < x < 0.5$) ceramics sintered in N_2 gas atmosphere," Phys. Rev. B, vol. 39, no. 13, pp 9126-9138 May 1, 1989. doi: https://doi.org/10.1103/PhysRevB.39.9126
11. M. Izumi, T. Yabe, T. Wada, A. Maeda, K. Uchinokura, S. Tanaka, and H. Asano, Structural properties of the superconductor $LaBa_2Cu_{3-y}O_{7-z}$ in the solid solution system $La_{1+x}Ba_{2-x}Cu_{3-y}O_{7-z}$ Phys. Rev. B, vol. 40, no. 10, pp. 6771–6786, October 1, 1989. doi: https://doi.org/10.1103/PhysRevB.40.6771
12. X.Z. Wang, B. Hellebrand, D. Bauerle, "Crystal structure and superconductivity in $REBaSrCu_3O_x$, **200** (1992) 12–16. doi: 10.1016/0921-4534(92)90316-5.
13. A. Aboulkassim, A. Nafidi, H. Chaib, J. Hemine, A. Ramzi, A. Tirbiyine, A. Taoufik, E.Y. El Yakoubi, H. Sahsah, M. Massaq, T. El Gouti, Correlation Between Enhanced T_c, Orthorhombicity and the Volume of the Unit Cell in Argon Preheated $(Y_{1-x}Nd_x)SrBaCu_3O_{6+z}$, IEEE transactions on applied superconductivity. **23** (2013) 3–6. doi: 10.1109/TASC.2013.2237735.
14. J. D. Thompson, G. Sparn, K. Holczer, O. Klein, G. Gruner, R. B. Kaner, R. Diederich, and R. L. Whetten, Physical and Material

Properties of High Temperature Superconductors, edited by S. K. Malic and S. S. Shah (Nova Science, Commack, NY, 1994), p. 139.

15. R.J. Cava, B. Batlogg, R.B.van Dover, D.W. Murphy, S. Sunshine, T. Siegrist, J.P. Remeika, E.A.Rietman, S. Zahurak and G.P. Espinosa, Phys. Rev. Lett. 58 (1987) 1676. doi: https://doi.org/10.1103/PhysRevLett.58.1676
16. A.R. Jurelo, I.A. Castillo, J. Roa-Rojas, L.M. Ferreira, L. Ghivelder, P. Pureue, P. Rodrigues, Coherence transition in granular high temperature superconductors, Physica C. **311** (1999) 133–139. doi:10.1016/S0921-4534(98)00617-0.
17. R. Hein, T. Francavilla, D. Liebenberg, Magnetic Susceptibility of Superconductors and Other Spin Systems, 1991. doi:10.1007/978-1-4899-2379-0.
18. Keltoum Khallouq, Abdelhakim Nafidi, Abdeljabar Aboulkassim, Essediq Youssef El Yakoubi, Es-saïd Es-Salhi, Effects of isovalent substitutions and heat treatment on structural and superconducting properties of high-critical temperature superconductors, Materials Today: Proceedings, Volume 22, Part 1, 2020, Pages 140-145, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2019.08.180.
19. H. Sato, H. Zhang, Comment on "Universal relationship between T_c and the hole content in p-type cuprate superconductors, Physical Review Letters. **71** (1993) 303. doi: 10.1103/PhysRevLett.71.303.