# Defects network and transport properties in electron-doped $Sr_{1-x}La_xCuO_2$ thin films grown by laser ablation


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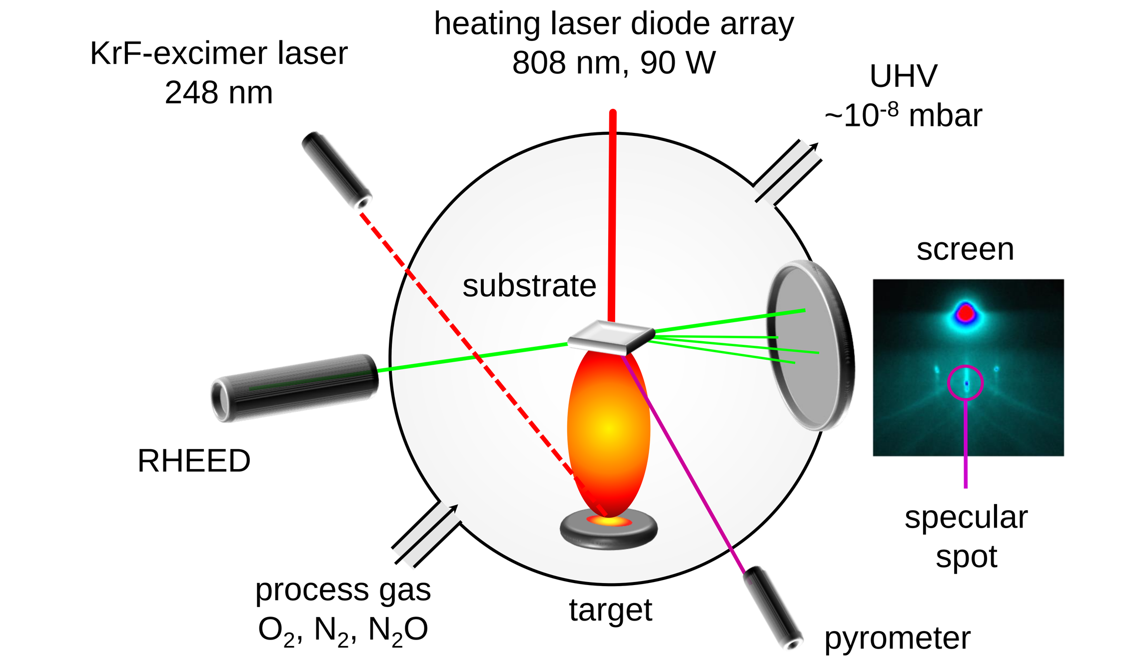
## I. Motivation

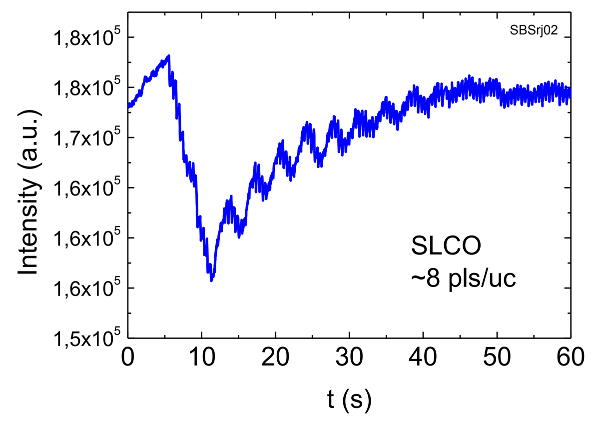
The electron-doped infinite-layer (IL) compounds $Sr_{1-x}Ln_xCuO_2$ (*Ln* = La, Pr, Nd, Sm, Gd) have the highest $T_c$ among electron-doped cuprate superconductors and the simplest crystal structure of any cuprate superconductor [1], but dificulties in fabricating single-phase thin films hampered the investigation of their basic properties, such as the order parameter symmetry.

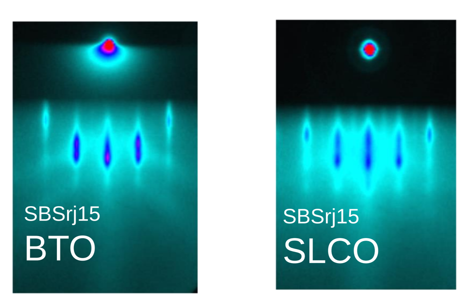
Superconducting single-crystalline $Sr_{1-x}La_xCuO_2$ (x=0.125-0.15) thin films, with a tetragonal, infinite-layer type structure, were grown by means of pulsed laser deposition (PLD) on $BaTiO_3$-buffered $SrTiO_3$(100) and on $KTaO_3$(100) substrates.

## II. Pulsed Laser Deposition




Damped RHEED oscillations of the specular spot during deposition of BTO and SLCO indicate a Stranski-Krastanov growth mode.



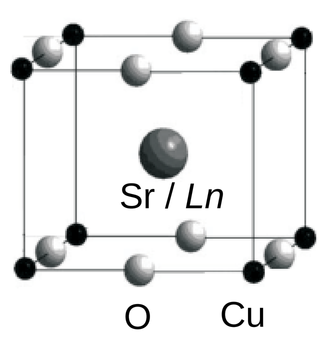

streaky RHEED patterns indicating 2D growth mode

### Deposition parameters:

| | $T_d$ (°C) | $P_{d,O2}$ (mbar) | $E_L$ (mJ) | $d_{TS}$ (mm) | f (Hz) |
|---|---|---|---|---|---|
| $BaTiO_3$ | 650-750 | $1 \times 10^{-1}$ | 110(*) | 65 | 2 |
| $Sr_{0.875}La_{0.125}CuO_2$ | 550-600 | $4 \times 10^{-1}$ | 110 - 130 | 60 | 2 |

(*) ~ 2 J/cm²

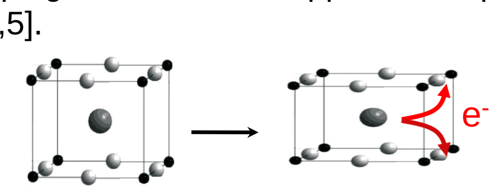
## III. Crystal structure

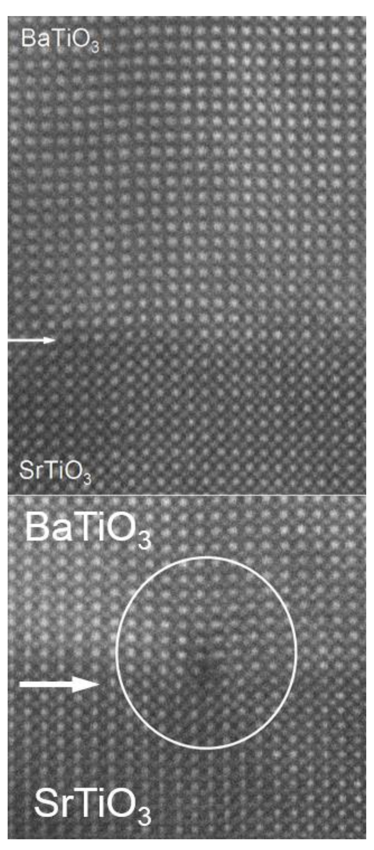



| | symmetry | a (A) | c (A) |
|---|---|---|---|
| $Sr_{0.9}La_{0.1}CuO_2$ (bulk) [2] | tetragonal | 3.949 | 3.415 |
| $Sr_{0.9}La_{0.1}CuO_2$ (on $KTaO_3$) [3] | tetragonal | 3.976 | 3.397 |
| $KTaO_3$ | cubic | 3.988 | 3.988 |
| $SrTiO_3$ | cubic | 3.905 | 3.905 |
| $BaTiO_3$ | tetragonal | 3.996 | 4.029 |

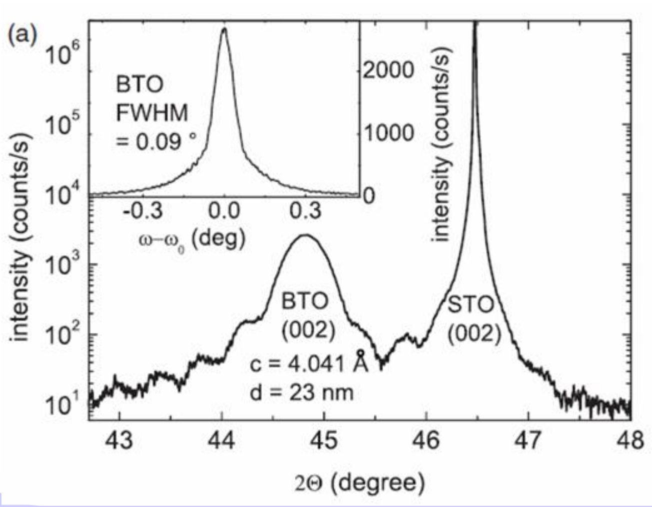
## IV. $BaTiO_3$ buffer layer

BTO buffer layers are deposited on STO substrates in order to enhance the electron-doping effect of the copper oxide planes of $Sr_{1-x}La_xCuO_2$ by tensile strain [4,5].

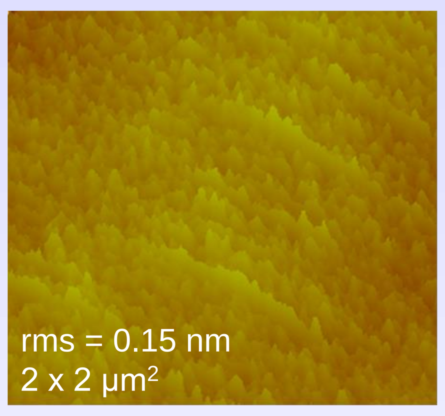


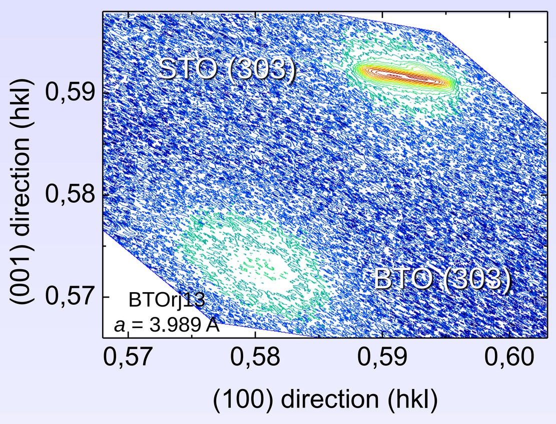



Narrow rocking curves with typical widths (FWHM) smaller than 0.1° and interference fringes around the (001) and (002) reflections were measured, indicating high crystallographic quality of the BTO films.

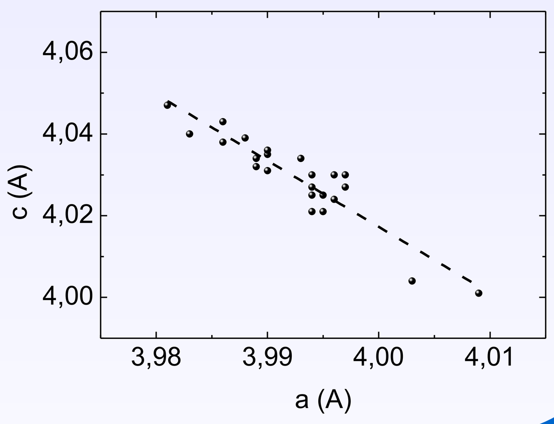



To improve the morphology and to fully relax the BTO film, they were annealed in-situ at 900 – 950 °C and $10^{-7}$ mbar, for 30 min [7].




From run-to-run variations (e.g. deposition temperature and pressure), the unit cell of BTO revealed a linear dependence of the lattice parameters a and c.

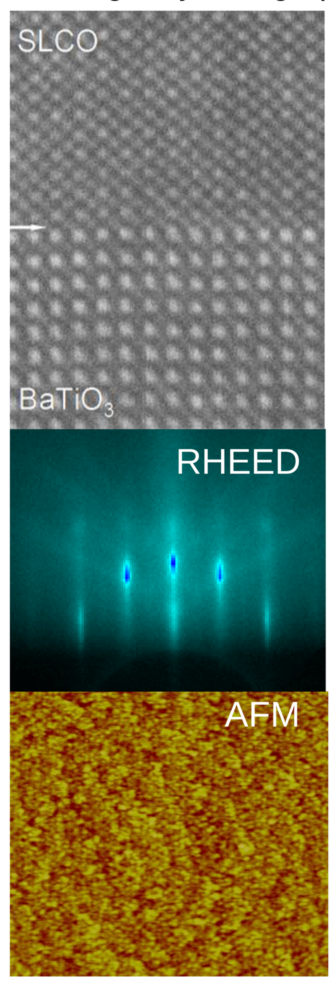


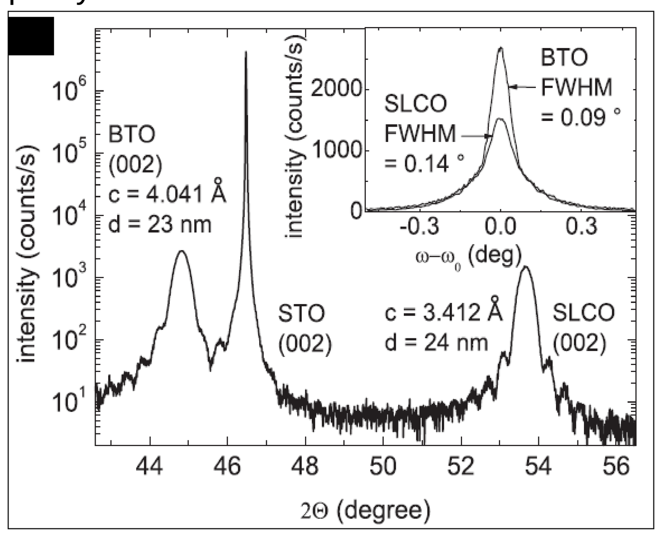

Sufficient tensile strain for SLCO was provided by all BTO films.

## V. $Sr_{0.875}La_{0.125}CuO_2$ films grown on BTO-buffered STO

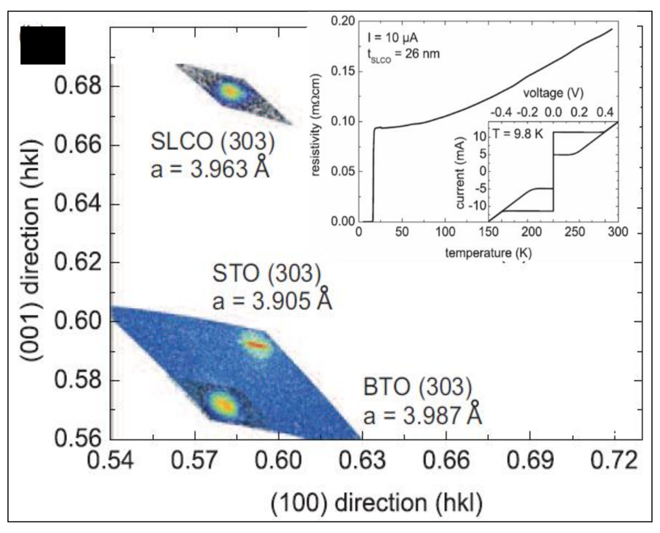
### Crystal structure & morphology:

As for BTO, narrow rocking curves (FWHM ~ 0.15°) and interference fringes indicate high crystallographic quality of the films.



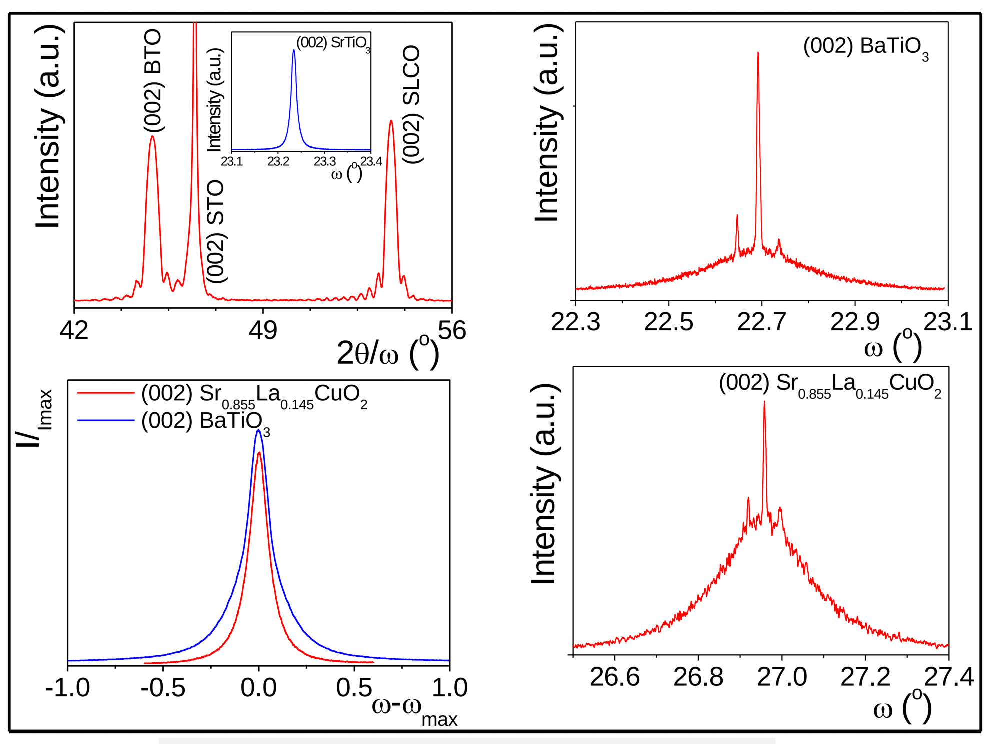




Singly-crystallinity is proven by the XRD scans.




AFM reveals smooth surfaces with a peak-to-valley roughness smaller than 0.7 nm = 2 uc.

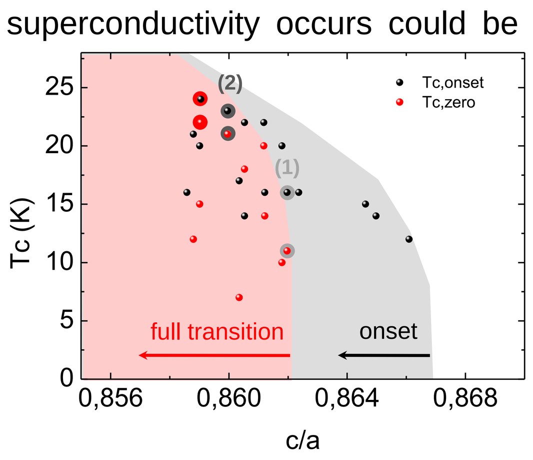
### Microstructure – role of XRD setup:




➢XRD double-axis and triple-axis data

An upper limit for the ratio *c*/*a* where superconductivity occurs could be identified empirically (*c*/*a* ≤ 0.862 ):

| | a (A) | c (A) | c/a |
|---|---|---|---|
| SBSrj08 | 3.963 | 3.416 | 0.862 |
| SBSrj08a | 3.964 | 3.408 | 0.860 |
| SBSrj13 | 3.966 | 3.407 | 0.859 |

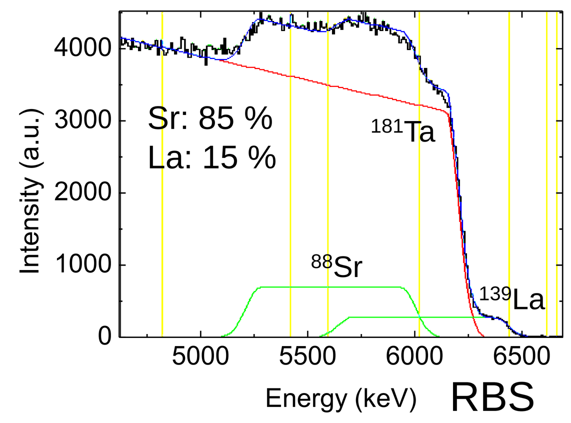



*Results:*

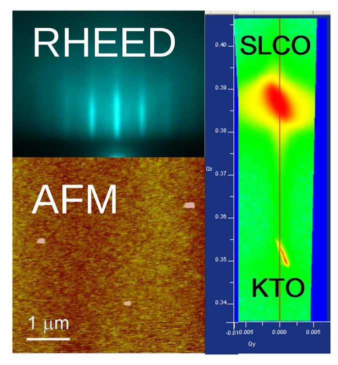
- ➢ Removal of excess oxygen leads to decrease of *c*-axis and slight increase of *a*-axis.
- ➢ Highest reported $T_c$ of 22 K for PLD-grown SLCO was obtained [8].
- ➢ For a full transition, *c*/*a* has to be smaller than 0.862.
- ➢ Problem: too small values for *a*-axis (inferior epitaxial tensile strain), due to incomplete relaxation.

## VI. $Sr_{0.875}La_{0.125}CuO_2$ films grown on KTO substrates

### Stoichiometry and morphology:



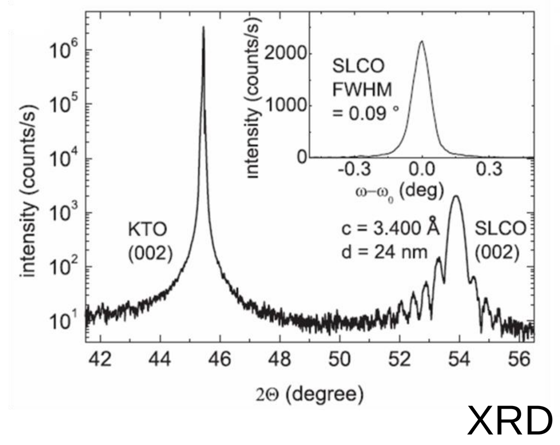

RBS

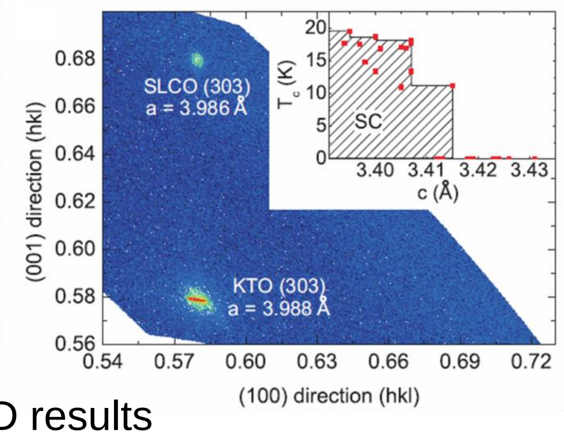



RHEED, AFM, and XRD

### Crystal structure:

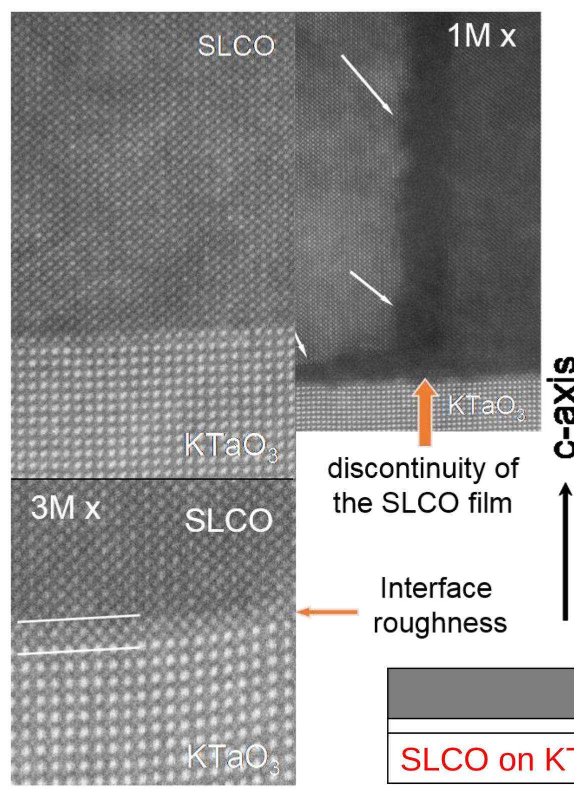
As on BTO-buffered STO substrates, single-crystalline films with high crystallographic quality have been grown on as-received KTO-substrates.



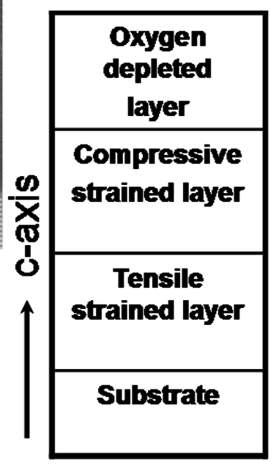



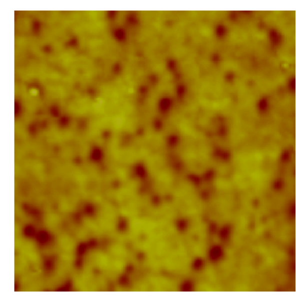

XRD results

### Microstructure




HRTEM:
Interface roughness (due to substrate morphology) results in structural defects.



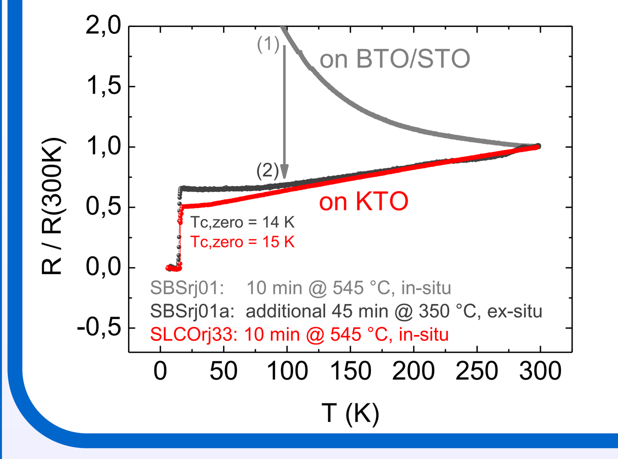
KTO as-received

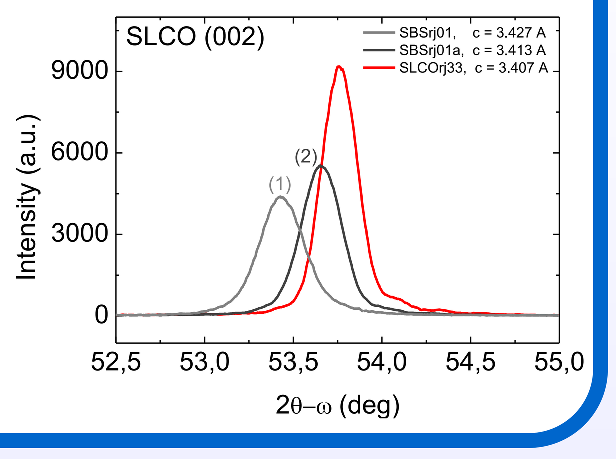
Strain evolution

| | a (A) | c (A) | c/a |
|---|---|---|---|
| SLCO on KTO | 3.979 | 3.407 | 0.856 |

### Comparison BTO/STO- KTO-substrates:

SLCO films on BTO-buffered STO substrates need additional annealing time to remove the excess oxygen compared to films on KTO:




## VII. Conclusions and outlook

- The major challenge in growing superconducting SLCO films is to achieve simultaneously full oxidation of the copper oxide planes and absence of interstitial oxygen in the $Sr_{1-x}La_x$ interlayers. Therefore, different post-deposition vacuum annealing steps (in-situ, ex-situ) have been successfully used.
- For SLCO films on BTO/STO, one main problem to be solved is the inferior epitaxial strain.
- Further investigations are necessary to improve $T_c$ ($T_{c,max}$ = 43 K [2]), e.g. different deposition temperature, pressure, target-substrate distance, laser energy.
- Use different doping levels (*x* = 0.10, 0.15).
- Use different materials as buffer layer (e.g. KTO on STO) to maintain enhanced epitaxial strain.
- TEM analysis to identify oxygen vacancies and excess oxygen.

## VIII. References


[1] M. G. Smith *et al.*, Nature **351**, 549 (1991)
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