Superconducting $Sr_{0.85}La_{0.15}CuO_2$ bicrystal grain boundary Josephson junctions

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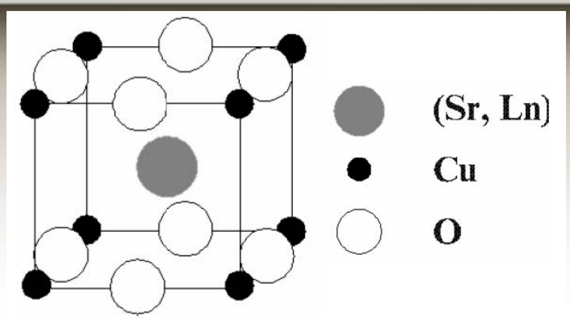
Outline

1. Motivation of the work - the electron-doped infinite-layer type $Sr_{1-x}La_xCuO_2$ high T_c superconductors
2. $Sr_{1-x}La_xCuO_2$ (x=0.125-0.15) thin films: PLD growth by the reduction method and characterization (RHEED, XRD, HRTEM, RBS)
3. Grain boundary $Sr_{1-x}La_xCuO_2$ (x=0.15) Josephson junctions
4. Conclusions

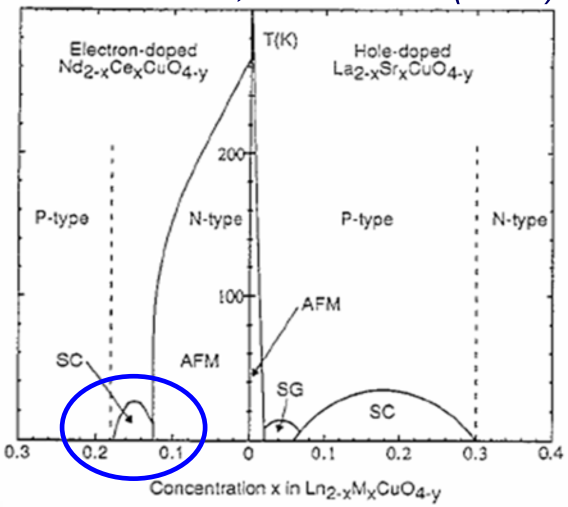
The $Sr_{1-x}La_xCuO_2$ (SLCO) compounds



$Sr_{1-x}Ln_xCuO_2$; $T_{c,max}$ = 43 K

-infinite-layer type structure

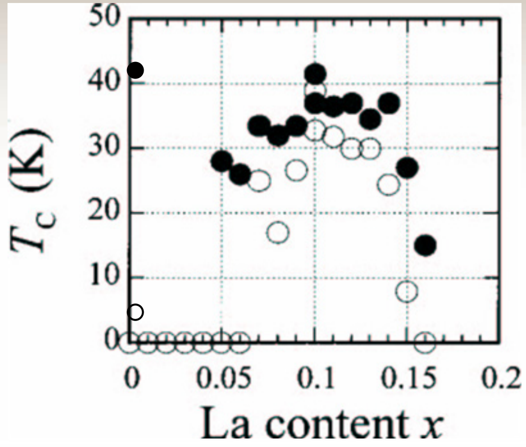
Smith et al., Nature 351 (1991)

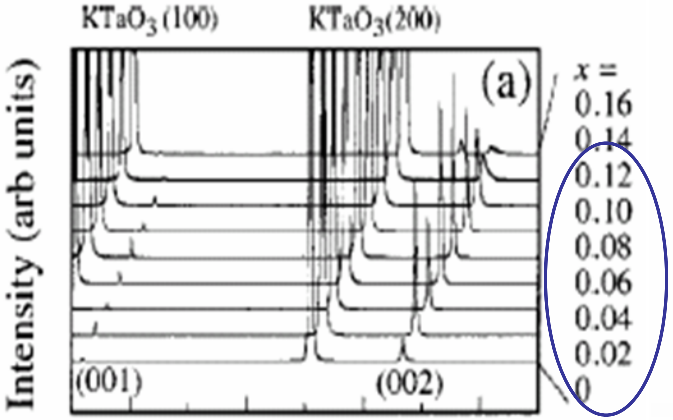


T_c vs. dopant concentration phase diagram for T'-$Ln_{2-x}Me_xCuO_4$

Optimum doping for SLCO?

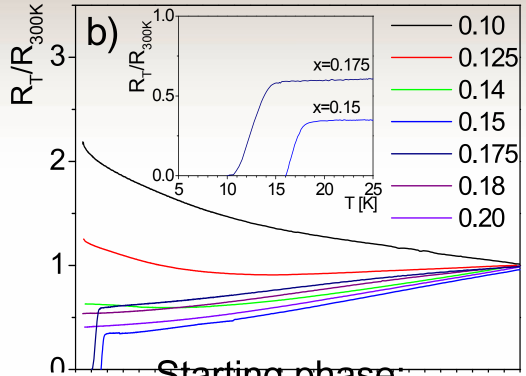
MBE growth on (001) $KTaO_3$
(reduction method)





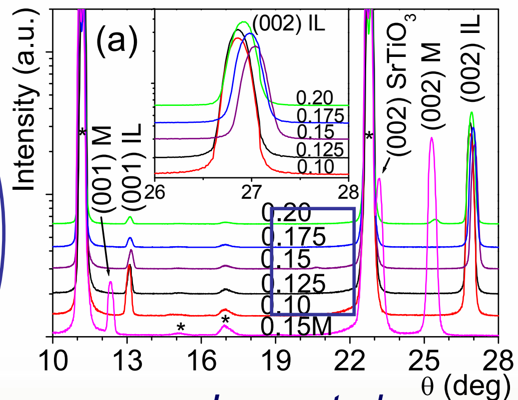
Karimoto et al.
Appl. Phys. Lett. 79 (2001)

PLD growth on (001) $KTaO_3$
(oxidation method)



Starting phase:

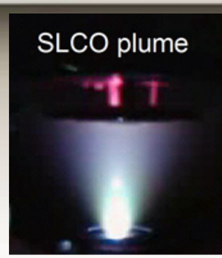
$$2\sqrt{2}a_p \times 2\sqrt{2}a_p \times c \text{ (super)structure}$$



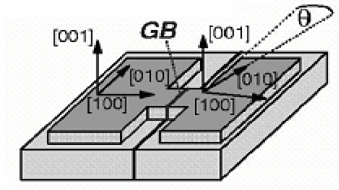
Leca et al.
Appl. Phys. Lett. 89 (2006)

Motivation of the work

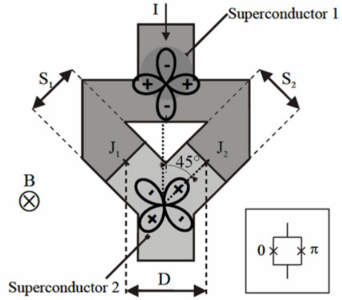
1. Studies on the $Sr_{1-x}La_xCuO_2$ (x=0.10-0.175) thin films - *role of the epitaxial strain on structural and transport properties* for PLD grown films on different substrates: (001) $SrTiO_3$, (001) $KTaO_3$, and (110) $DyScO_3$



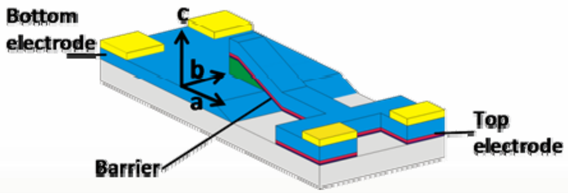
2. Transport properties of $Sr_{1-x}La_xCuO_2$ *grain-boundary Josephson junctions*



3. Studies on the *order parameter symmetry* – based on grain boundary Josephson junctions and phase sensitive experiments (on tetracrystals, using 0- and π-SQUIDs) for different La doping levels (x=0.10-0.175) and temperatures (2 K-T_c)



4. *Physics at the interface* between p- and n-type HTSc superconductors (based on ramp-type Josephson junction technology)



$Sr_{1-x}La_xCuO_2$ (0.125-0.15) growth parameters

On (001) $KTaO_3$ and (110) $DyScO_3$

$Sr_{1-x}La_xCuO_2$:
T_d = 500-575 ^oC
P_d = 0.20-0.40 mbar O_2
Post-deposition vacuum annealing (reduction) @ 10^{-7} mbar:
- 15-20 min ($KTaO_3$ case)
- 20-30 min ($DyScO_3$ case)

T_c: up to 24 K, on $KTaO_3$
up to 18 K, on $DyScO_3$

Film's composition (x_t=0.15 target), from RBS data:
- x_f = 0.145, films grown on $KTaO_3$
- x_f = 0.135, films grown on $DyScO_3$

On $BaTiO_3$- buffered (001) $SrTiO_3$

$BaTiO_3$:
T_d = 700-850 ^oC
P_d = 0.10 mbar O_2
Post-deposition annealing:
-15 min @ 950^{o}C, under 0.10 mbar O_2, and 30 min @ 950^{o}C, in vacuum (10^{-7} mbar)

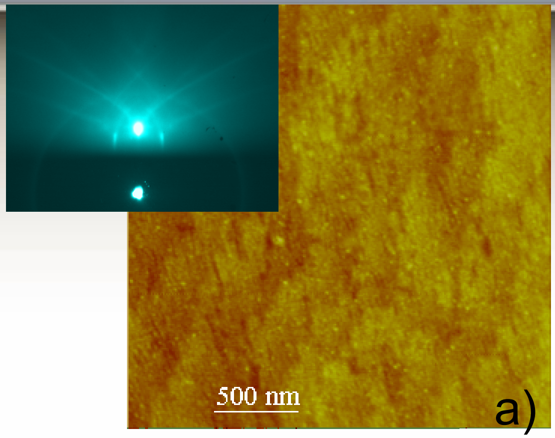
$Sr_{1-x}La_xCuO_2$:
T_d = 550-600 ^oC
P_d = 0.20 mbar O_2
Post-deposition annealing (reduction):
45-60 min @ 550 ^oC, in vacuum (10^{-7} mbar)

Film's composition (x_t = 0.15 target), from RBS data: x_f = 0.145
T_c: up to 21 K

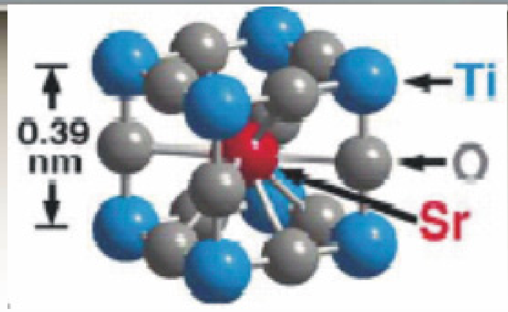
Highest reported T_c values for PLD grown SLCO films!

Tomaschko, Leca, Selistrovski, Diebold, Jochum, Kleiner, Koelle, Phys. Rev. B 85 (2012)

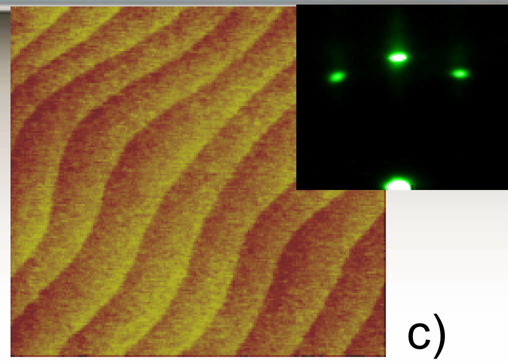
Substrate morphology – $SrTiO_3$



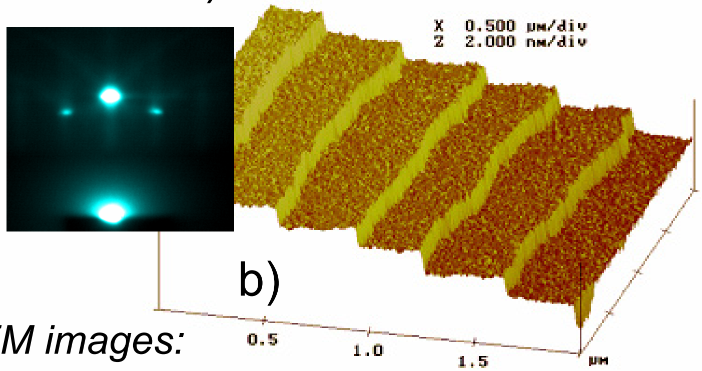
a)



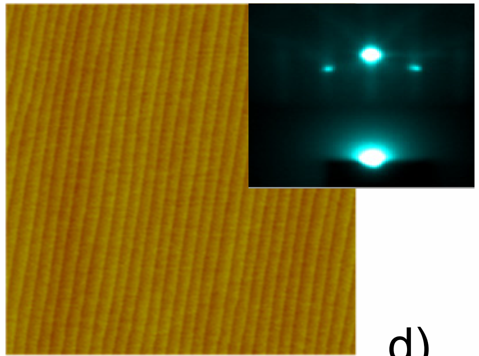
$SrTiO_3$ structure



c)



b)



d)

RHEED and AFM images:

a) of an as-received substrate

b) after chemical treatment (BHF) and subsequent annealing (950°C/1h/O_2) ⇒ TiO_2 termination

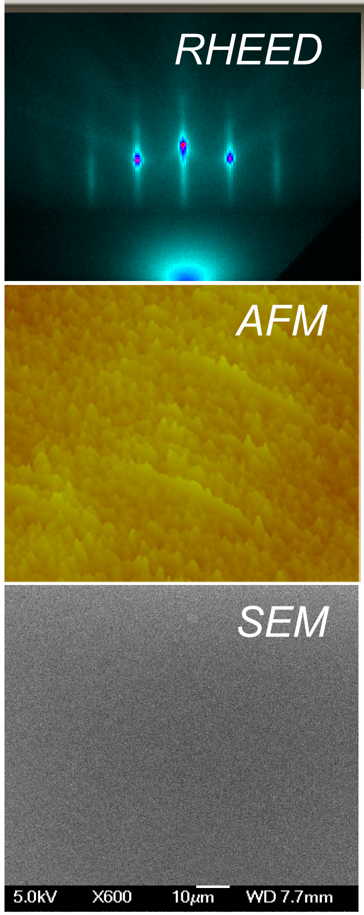
c) after annealing (950°C/1h/O_2) ⇒ SrO termination

d) after chemical treatment (BHCl) and subsequent annealing (950°C/1h/O_2) ⇒ TiO_2 termination (high miscut angle case)

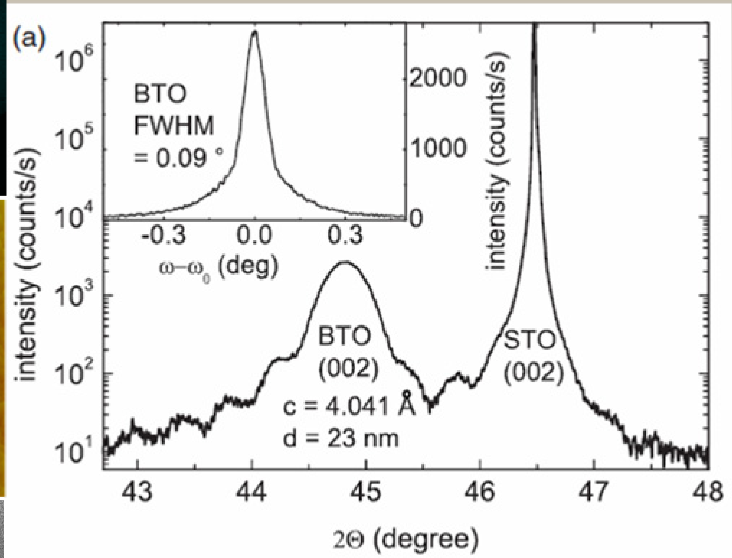
Control of the surface termination by selective removal of one of the surface oxides.

Kawasaki et al. Science 226 (1994)
Koster et al. Appl. Phys. Lett 73 (1998)
Leca, PhD thesis (2003)

$Sr_{1-x}La_xCuO_2$ (x=0.15) grown on $BaTiO_3/SrTiO_3$ (001)



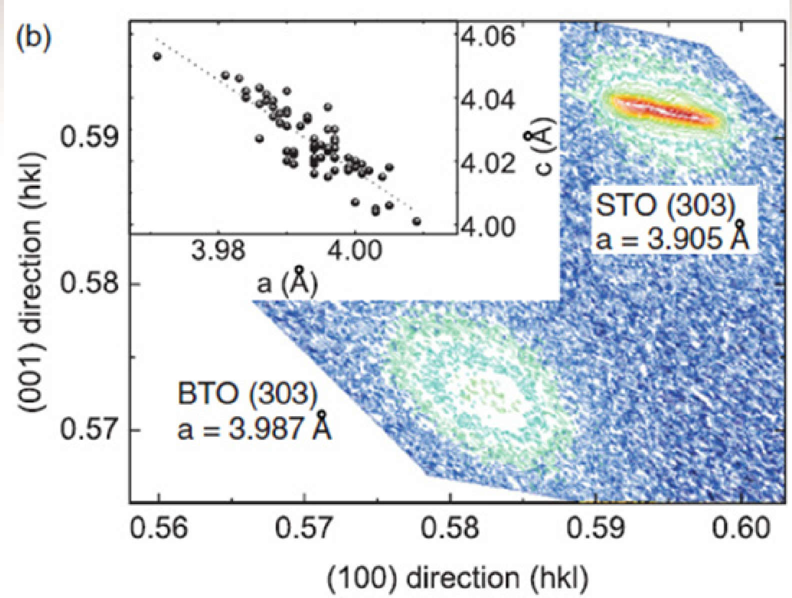
Smooth surface
for sharp interface



2θ/ω XRD scan of (002) BTO/STO

- *single phase;*
- *epitaxial, c-axis oriented;*
- *tetragonal symmetry*

The $BaTiO_3$ buffer layer

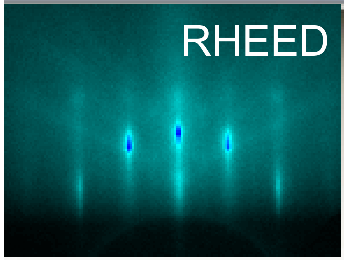


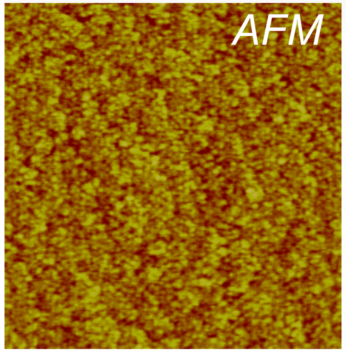
XRD rsm of (303) BTO/STO

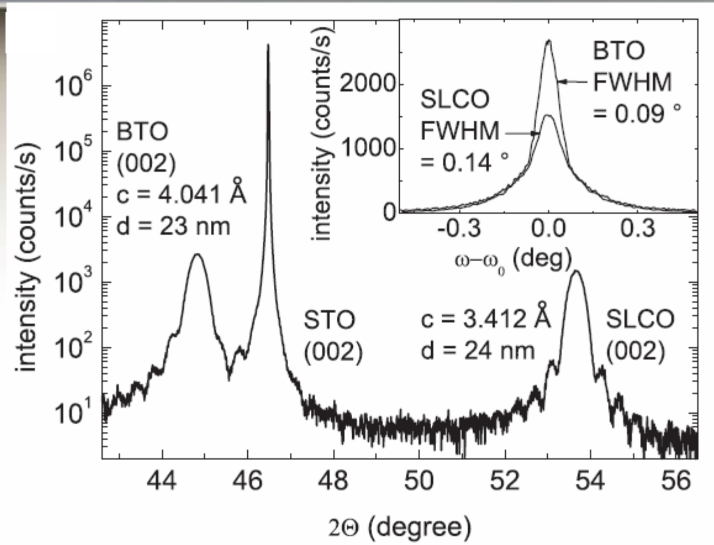
Deposition conditions for $BaTiO_3$:
T_d=750°C, P_d=0.10 mbar O_2, E_d=1.75 J/cm^2;
annealing 15 min/950°C/0.10 mbar O_2 and 30 min/950°C/10^{-7} mbar

Tomaschko, Leca, Selistrovski, Diebold,
Jochum, Kleiner, Koelle, Phys. Rev. B 85 (2012)

$Sr_{1-x}La_xCuO_2$ (x=0.15) grown on $BaTiO_3/SrTiO_3$ (001)

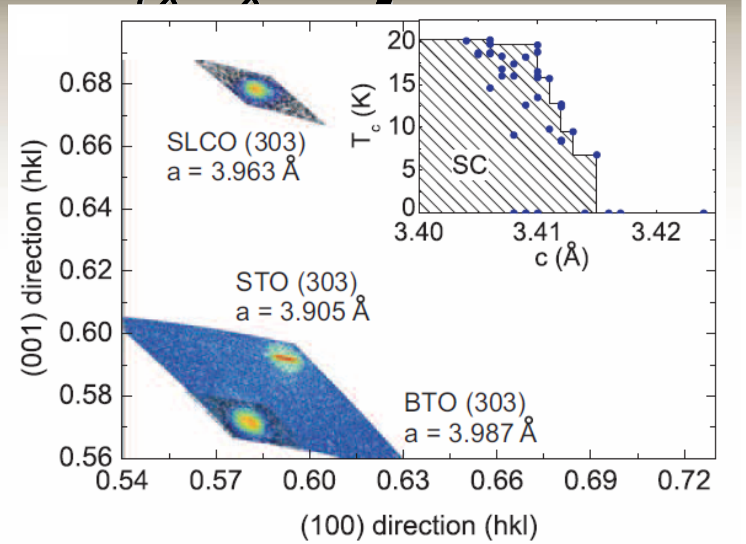




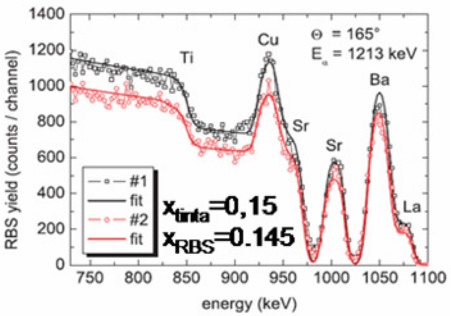


2θ/ω XRD scan of (002) planes

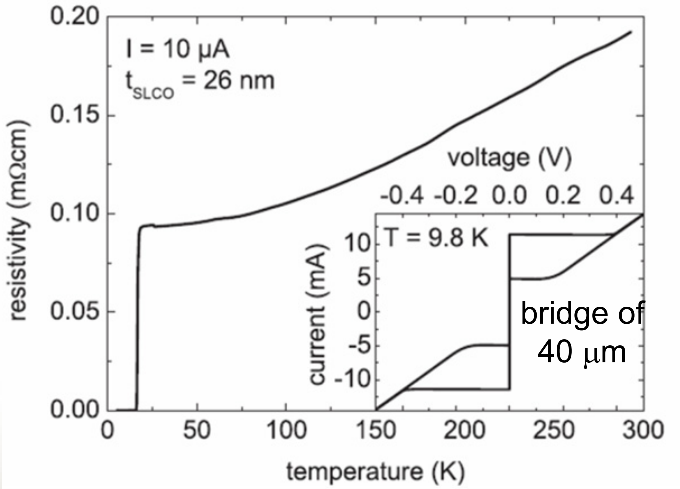
$Sr_{1-x}La_xCuO_2$ films



XRD rsm of (303) SLCO/BTO/STO



RBS data



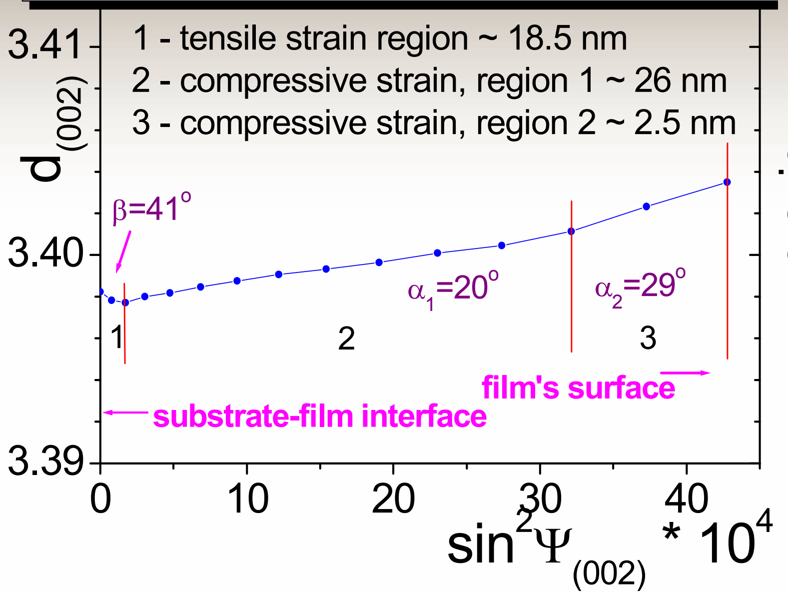
ρ vs. T and I_c vs. V

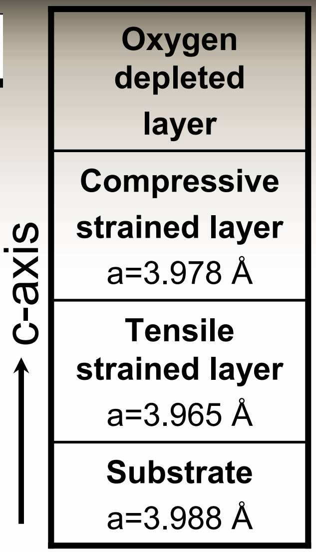
Deposition conditions:
T_d=550°C, 0.20 mbar O_2;
50 min/550°C/10^{-7} mbar
$T_{c,0}$=12-21 K
$J_{c@4.2K}$=2.1×10^6 A/cm^2

Tomaschko, Leca, Selistrovski, Diebold, Jochum, Kleiner, Koelle, Phys. Rev. B 85 (2012)

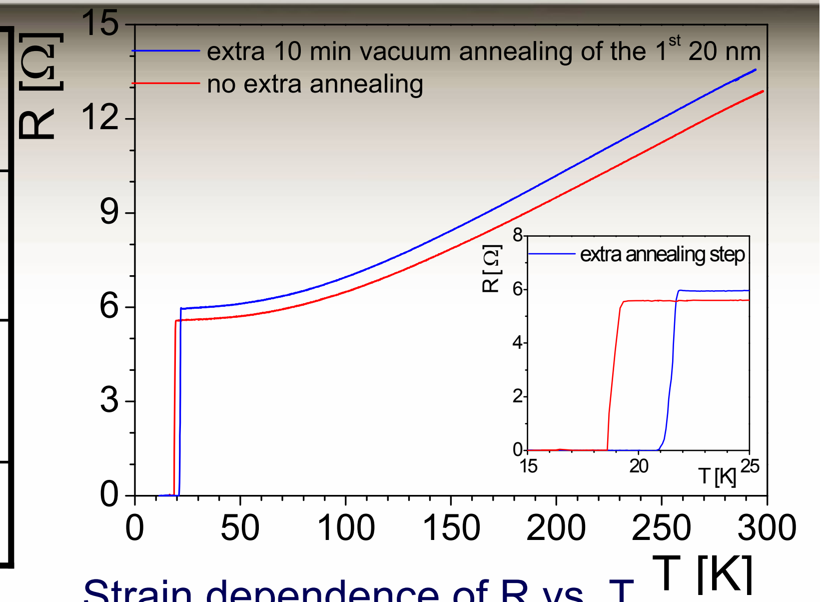
Role of the epitaxial strain

strain evolution in in-plane direction

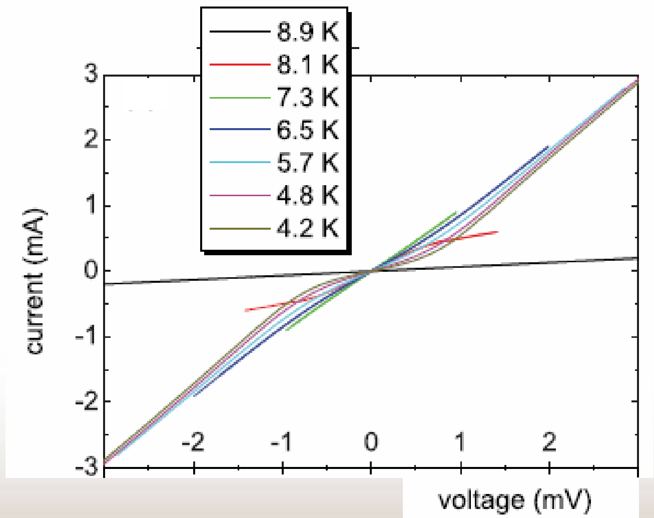




SLCO on $KTaO_3$
(similar on $SrTiO_3$)



Strain dependence of R vs. T



Tomaschko et al., PRB 84 (2011)

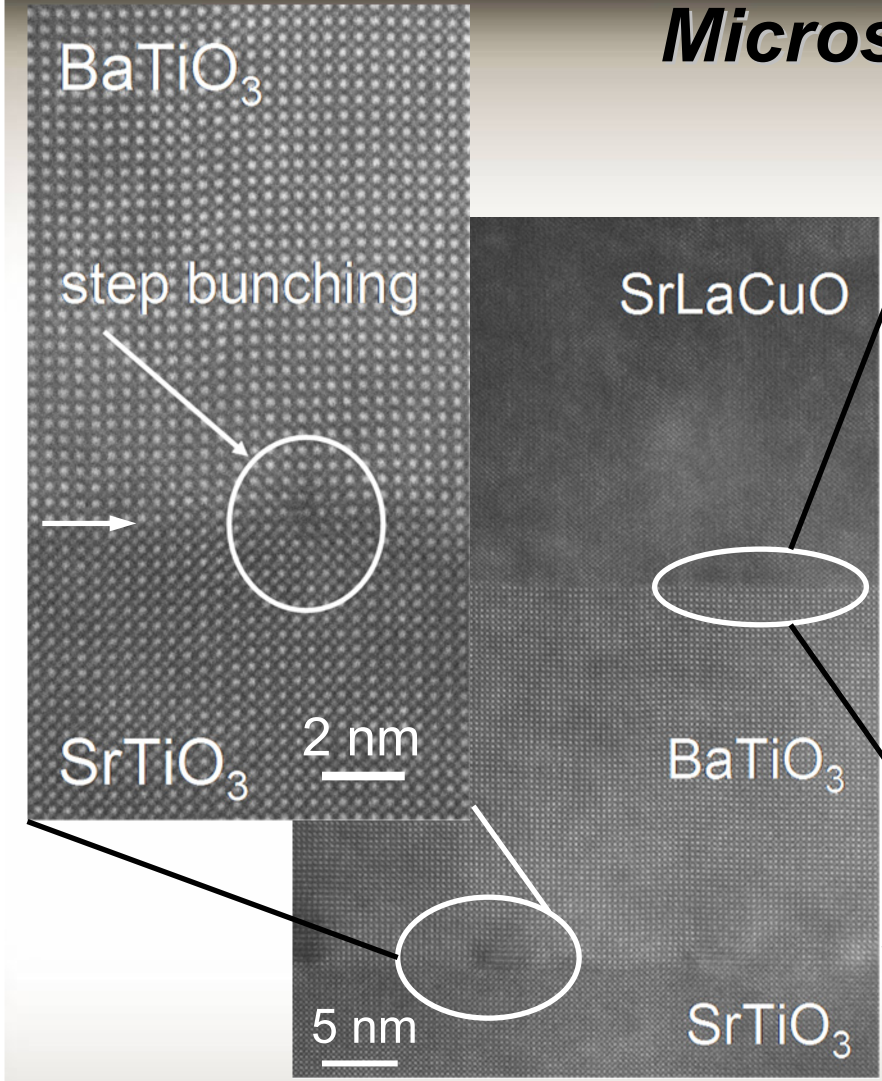
***XRD and XPS**: existence of an oxygen depleted top layer;*

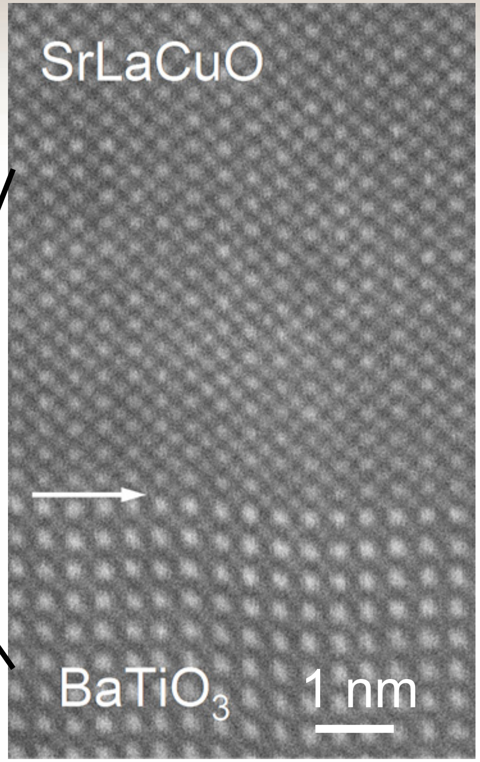
***Implications:** no Copper pair tunneling in planar SLCO/Au/Nb junctions*

***XRD**: two types of strain: tensile (@ substrate-film interface) and compressive, on top*

$Sr_{1-x}La_xCuO_2$ (x=0.15) grown on $BaTiO_3/SrTiO_3$ (001)

Microstructure

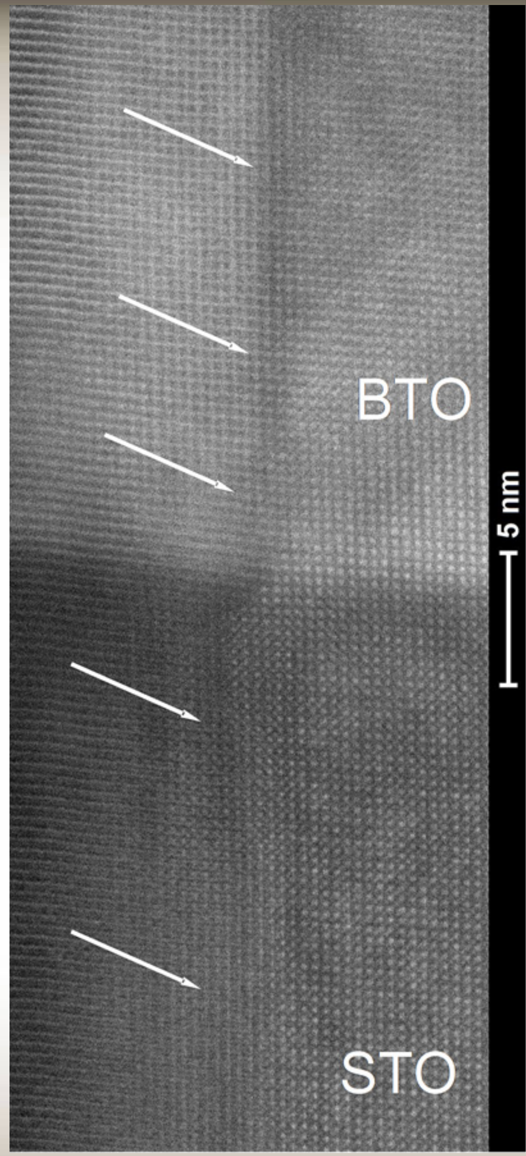




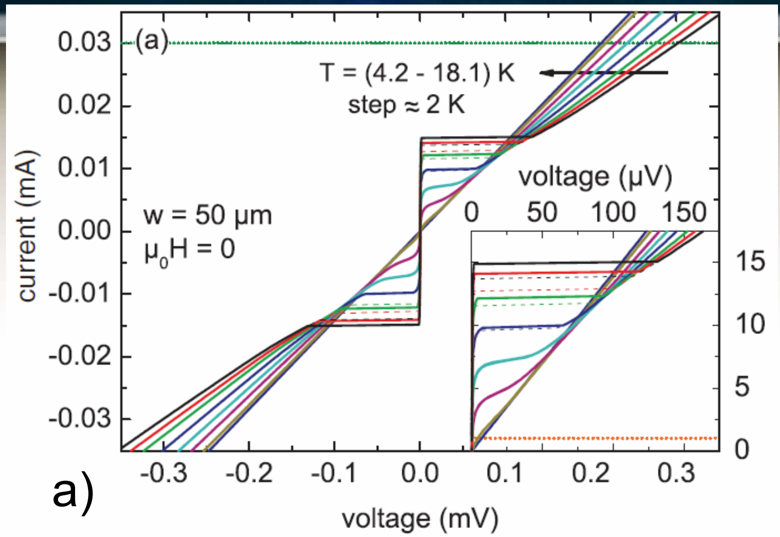
HRTEM data
$Sr_{0.85}La_{0.15}CuO_2$
on $BaTiO_3/SrTiO_3$

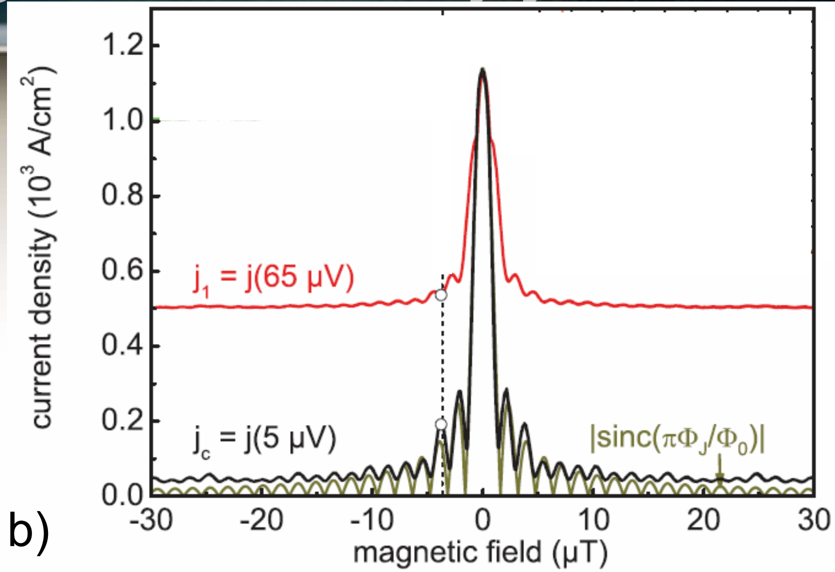
Sharp interfaces

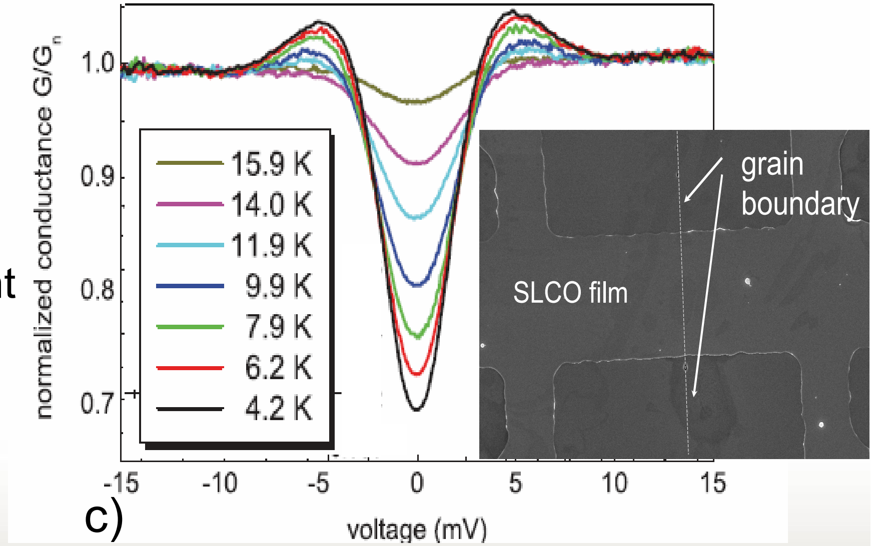
24º grain boundary



$Sr_{1-x}La_xCuO_2$ 24º symmetric grain boundary junctions







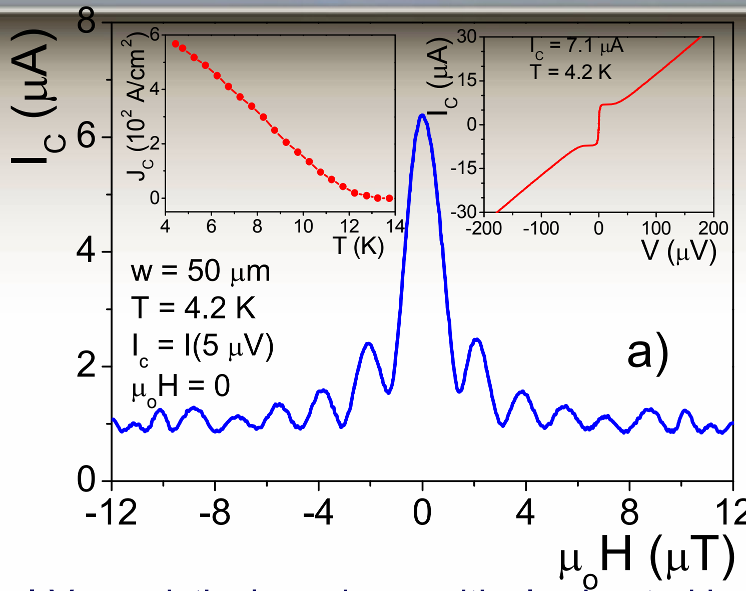
a) I_cVs: resistively and capacitively shunted junction (RCSJ)-like, with no significant excess current;
- J_c @ 4.2 K ~ 1.2 kA/cm² – 1-2 orders of magnitude above J_c of 24º GB based on T' e-doped HTSc (NdCeCuO and LaCeCuO compounds)

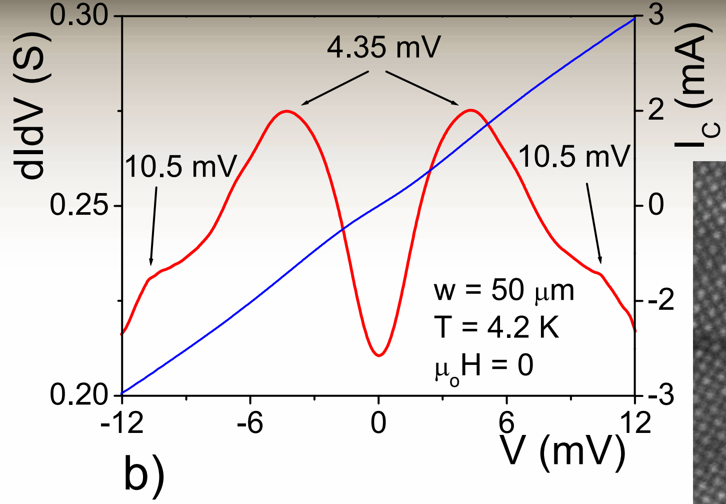
b) highly regular Fraunhofer-like patterns for different voltage criterion

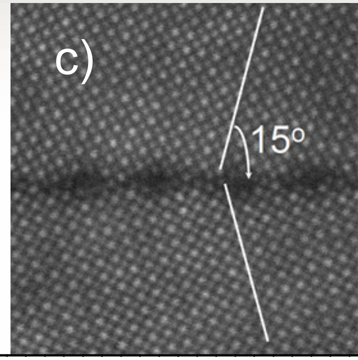
c) conductance spectra did not show a zero-bias conductance peak. s-wave symmetry?
however, the V-shaped of the spectra in the subgap regime may indicate an order parameter with nodes

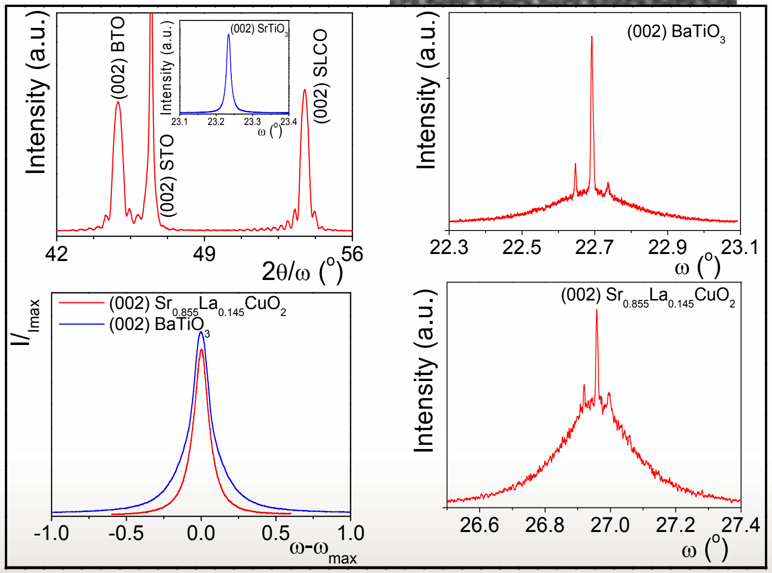
Tomaschko, Leca, Selistrovski, Kleiner, Koelle, Phys. Rev. B 84 (2011)

$Sr_{1-x}La_xCuO_2$ 30º symmetric grain boundary junctions









d) *Double axis* *Triple axis*

a) - I_cVs: resistively and capacitively shunted junction (RCSJ)-like;
- highly regular Fraunhofer-like patterns;
- high J_c @ 4.2 K of ~ 0.55 kA/cm²; I_cR_n of ~ 50 µV

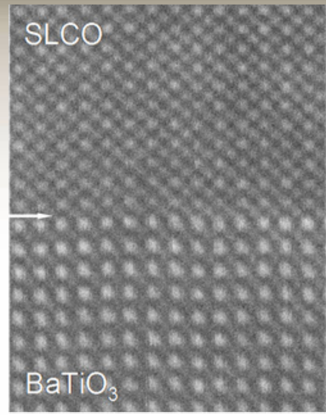
b) conductance spectra did not show a zero-bias conductance peak (but a V-shaped subgap spectra, as for the 24º grain boundary junctions) ***and*** extra peaks above the coherence peaks; microscopic roughness?

c) plain view HRTEM of the substrate (30º) grain boundary;

d) XRD scans in double (one monochromator) and triple (two monochromators) axis configuration showing the presence of dislocations in the (buffer) $BaTiO_3$ and SLCO layers.

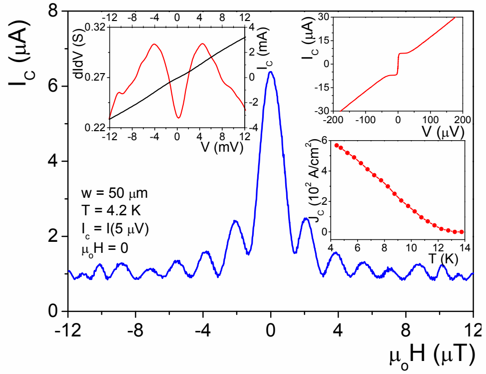
Conclusions

- the superconducting properties of the PLD grown electron-doped $Sr_{1-x}La_xCuO_2$ thin films are still far of those of the bulk or of the MBE grown films; however, higher phase stability could be achieved by PLD compared with other deposition techniques;



- epitaxial strain controls the structural and transport properties of the films; see the role of the substrate;

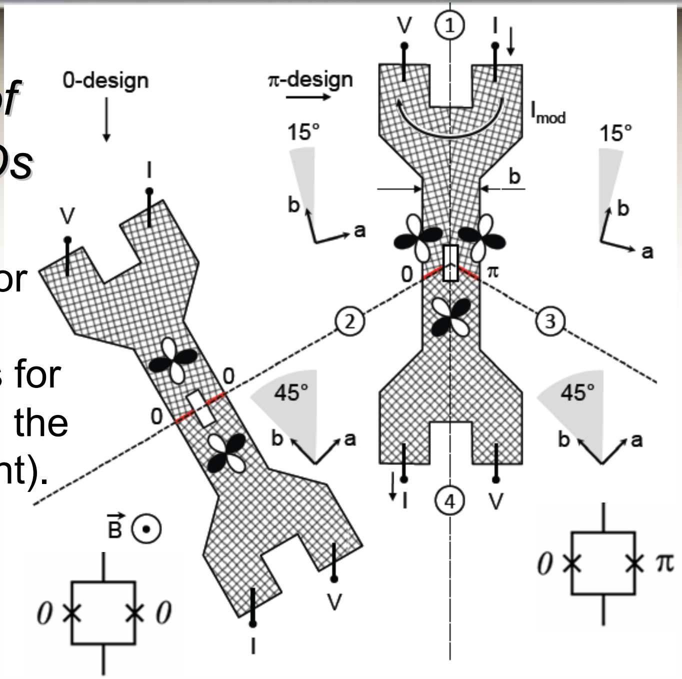
- first 24° and 30° [001] tilt grain boundary junctions were fabricated and their transport properties studied; no zero bias conductance peak was observed, probably due to strong disorder at the barrier (oxygen vacancies, etc).



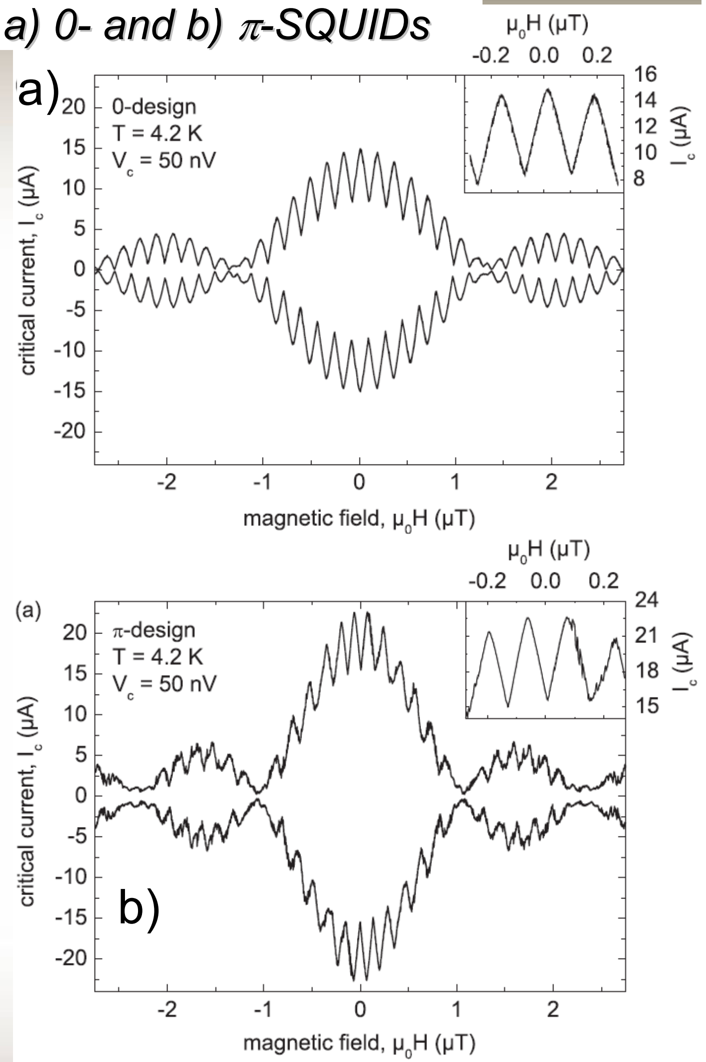
Pairing symmetry from phase sensitive experiments

Schematic layout of the 0- and π-SQUIDs

- one grain boundary for the 0-SQUID;
- four grain boundaries for the π-SQUID (crossing the tetracrystal central point).



I_c vs magnetic field for a) 0- and b) π-SQUIDs



For $d_{x^2-y^2}$-wave symmetry: the π-SQUID consists of one 0-Josephson junction and one π Josephson junction (π-phase shift inside the SQUID loop).

Predominantly $d_{x^2-y^2}$ pairing symmetry

Tomaschko, Scharinger, Leca, Nagel, Kemmler, Selistrovski, Koelle, Kleiner, Phys. Rev. B 86 (2012)

Chesca et al., PRL 90 (2003)
Schulz et al., APL 76 (2000)