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Atomic-layer engineering of high-T_c superconductors

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Collaborators:

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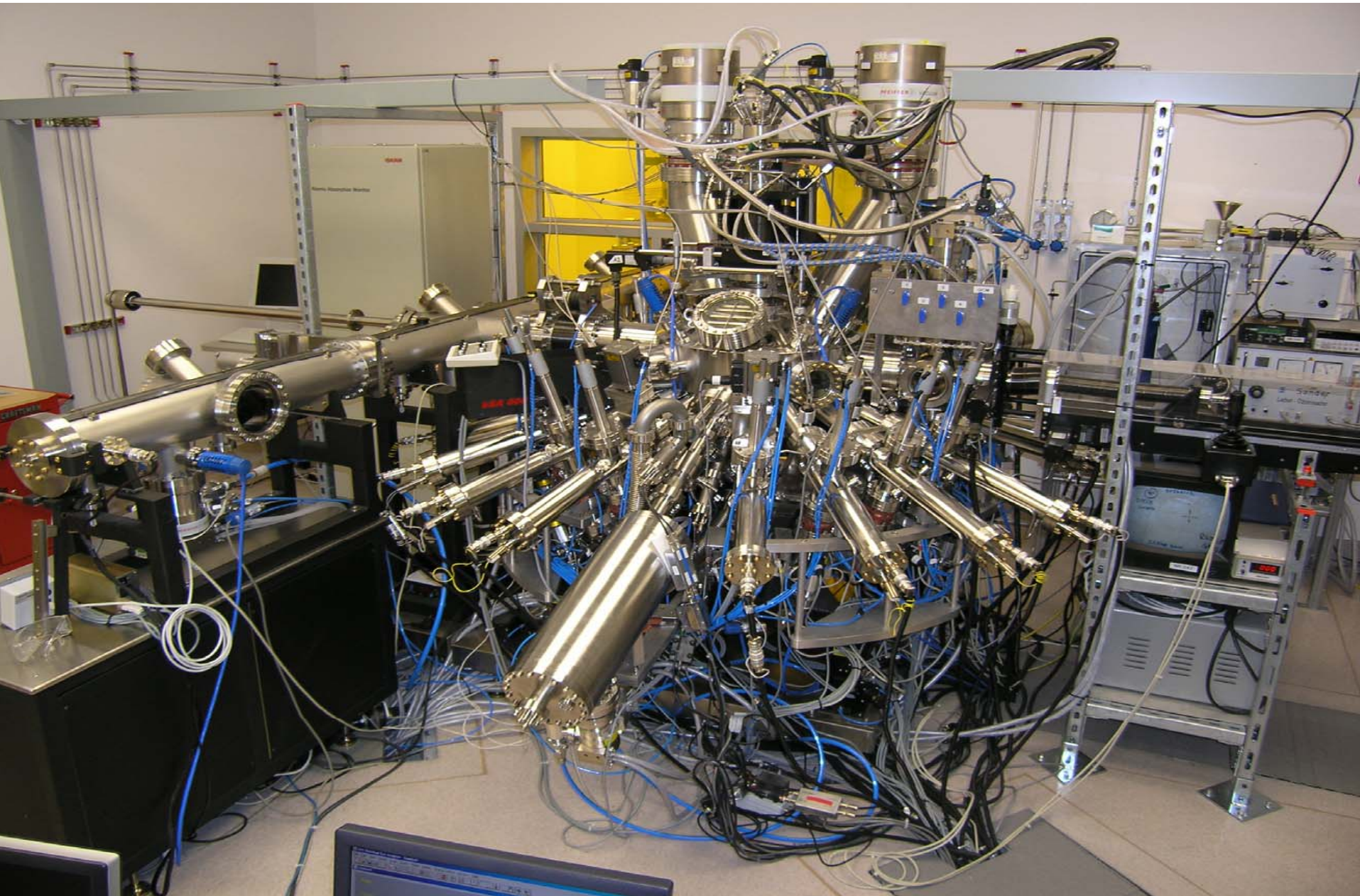
Q: Which of these is possible?

- One-atom-thick HTS
- Non-zero *E* in superconductor
- Broken inversion symmetry
- Triplet superconductivity
- Quantum spin liquid
- Homogeneous cuprate
- Levitating ions

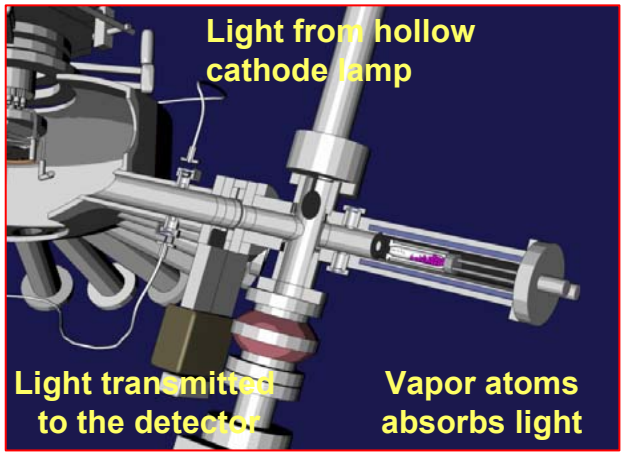
Technique: atomic-layer MBE

Cf. the talks by J. Eckstein, S. Stemmer

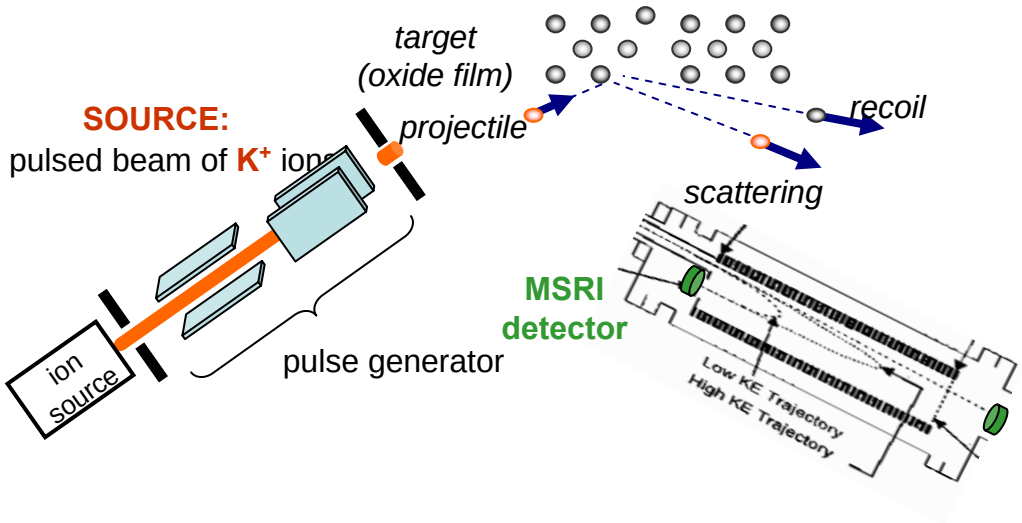
ALL-MBE SYSTEM AT BNL



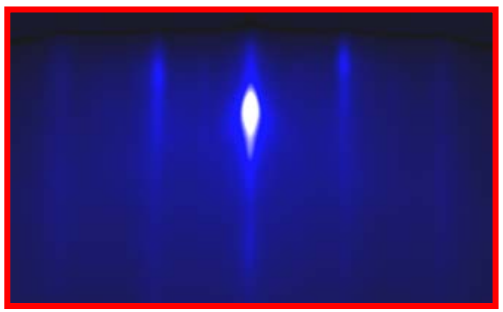
Atomic Absorption Spectroscopy

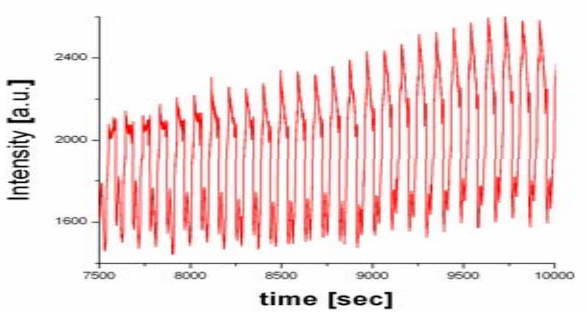


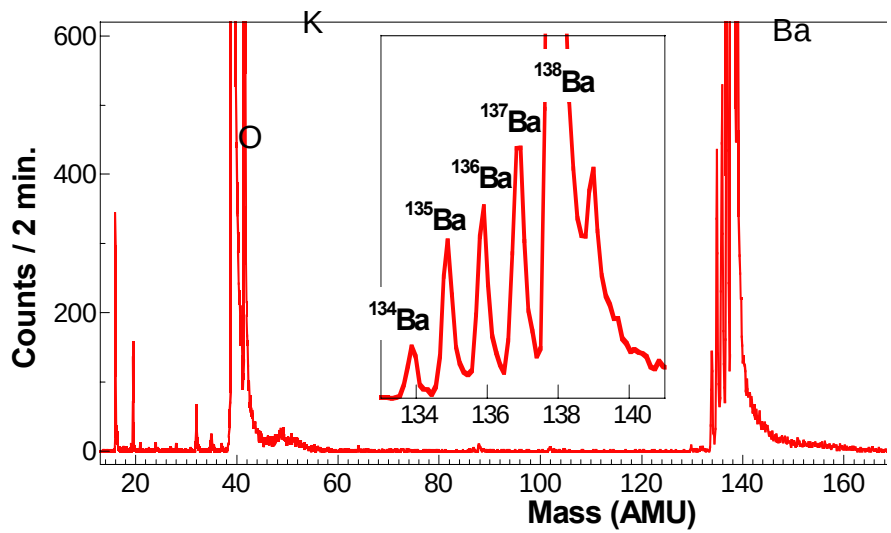
TOF-ISARS



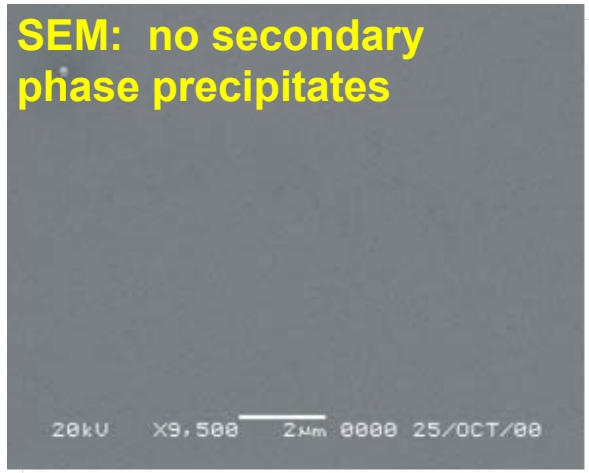
RHEED

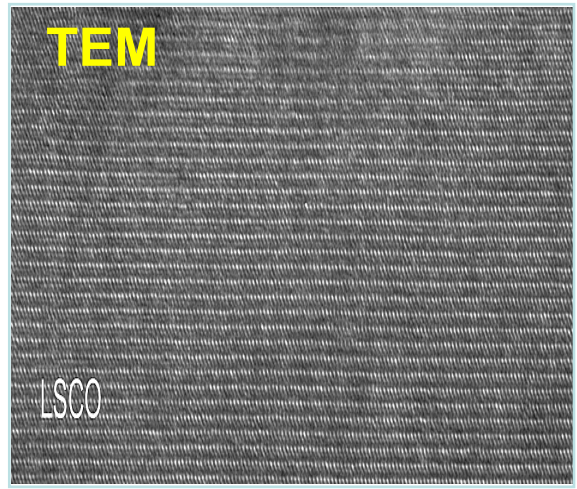


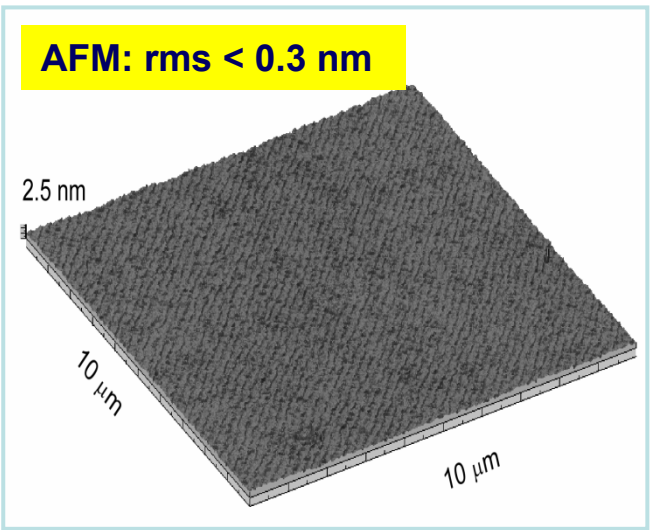


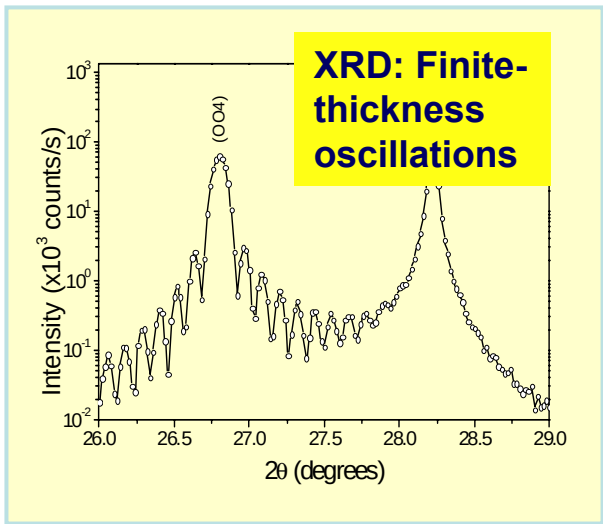


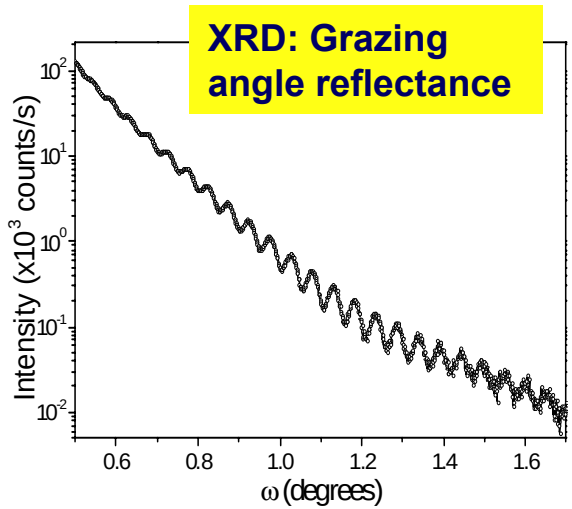
ATOMICALLY SMOOTH CUPRATE FILMS GROWN BY MBE











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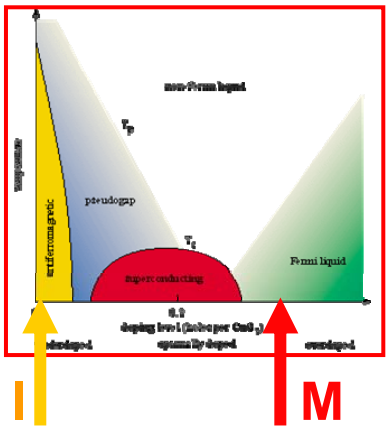
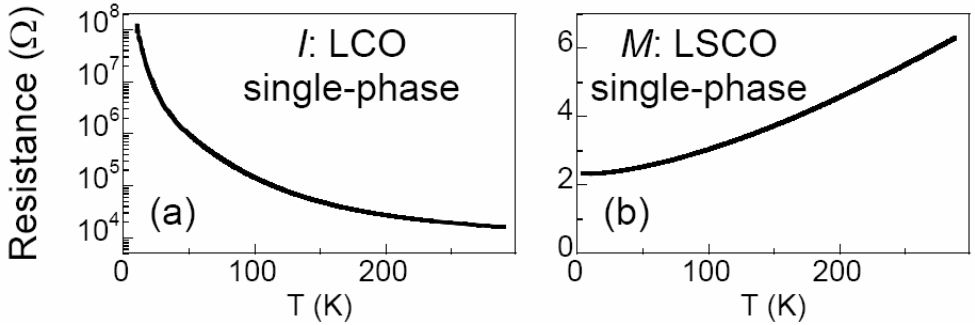
$La_{1.85}Sr_{0.15}CuO_4$ film on $LaSrAlO_4$ substrate

HTS in a single CuO_2 layer

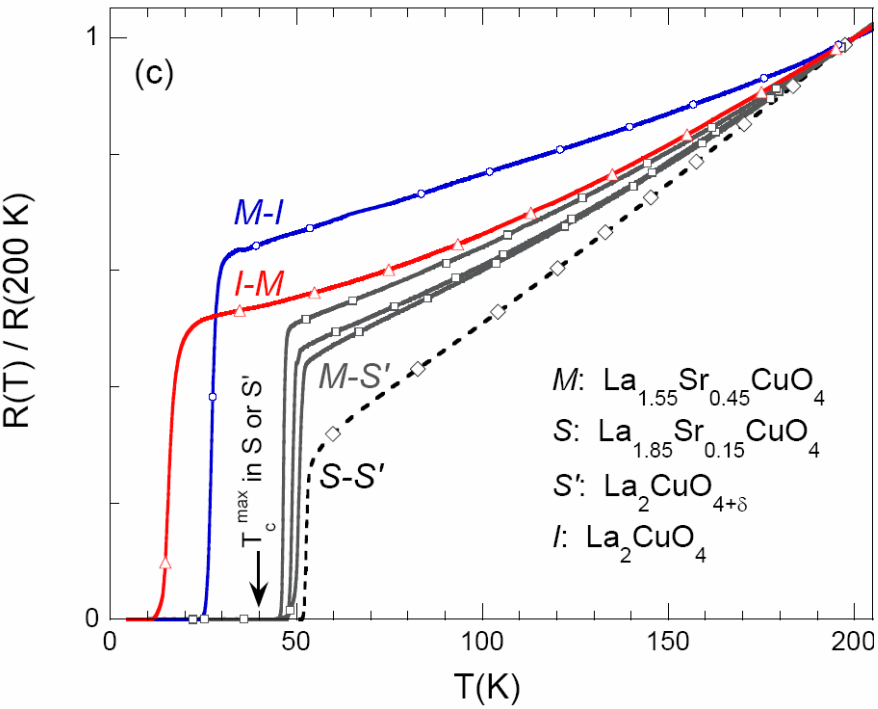
Related talks: J. Mannhart, P. Abbamonte, S. Okamoto, H. Hwang,…

INTERFACE SUPERCONDUCTIVITY IN CUPRATES





R(T) for single-phase layers of *I* and *M*.

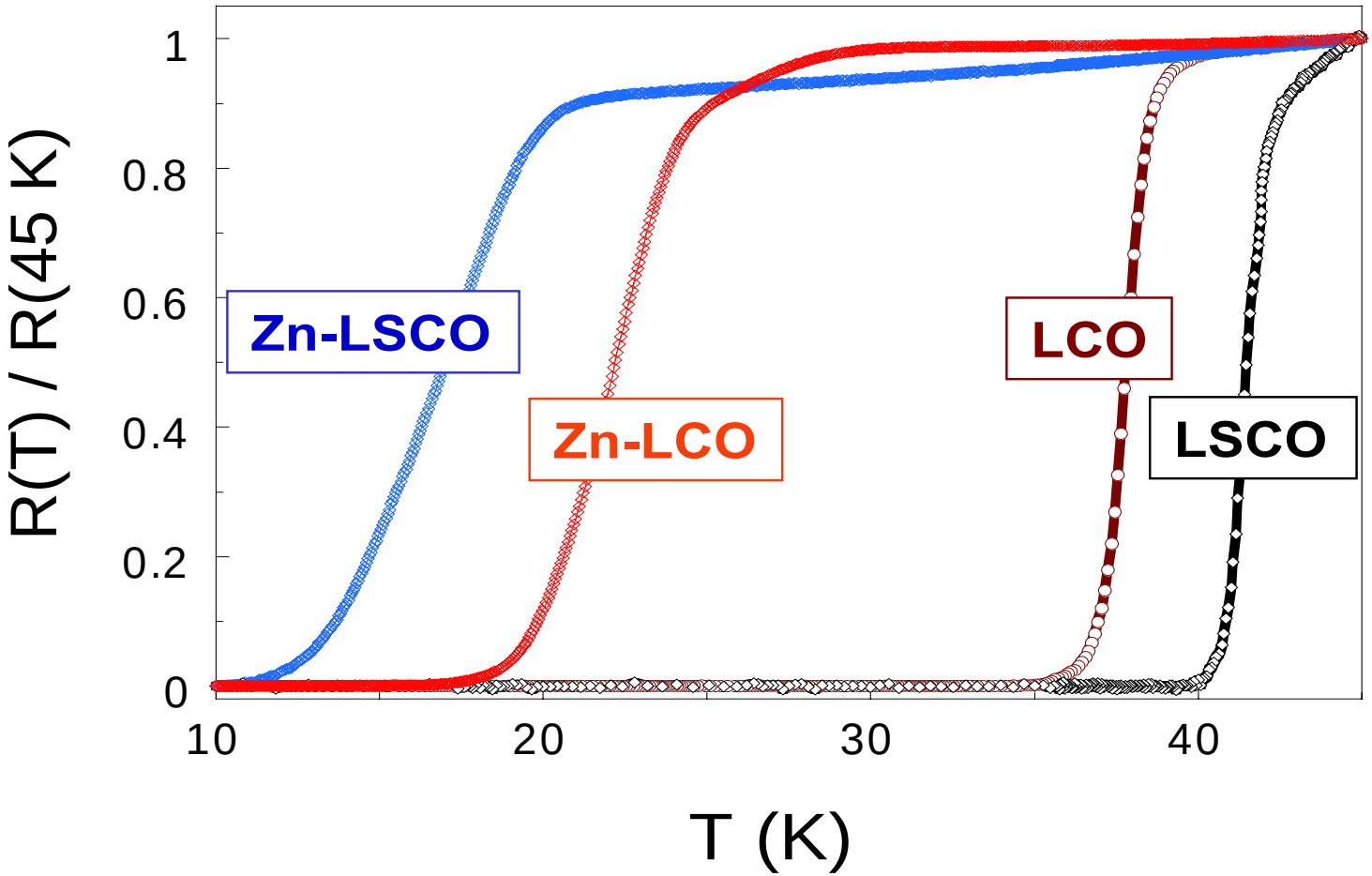


R(T) for various bilayers.

I-M **and** ***M-I*** **bilayers show superconductivity even though neither of the two constituents does.**

In single-phase *S* or *S′* films grown under the same conditions $T_c \leq$ 40 K.

Nature 455, 782 (2008)

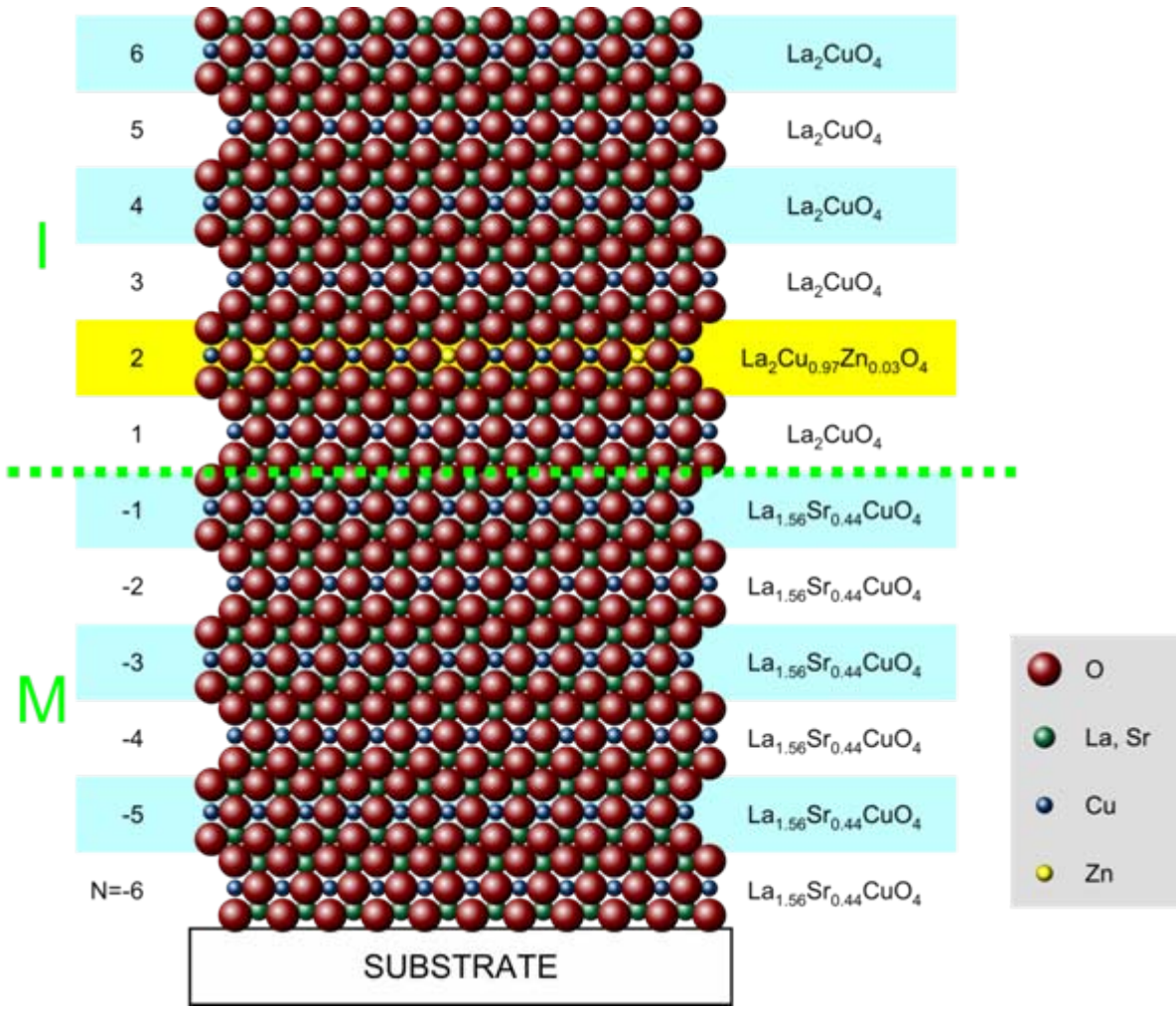


(Isovalent) substitution of 3% Cu by Zn causes pair breaking and reduces T_c

Science 326, 699 (2009)

δ-doping by Zn

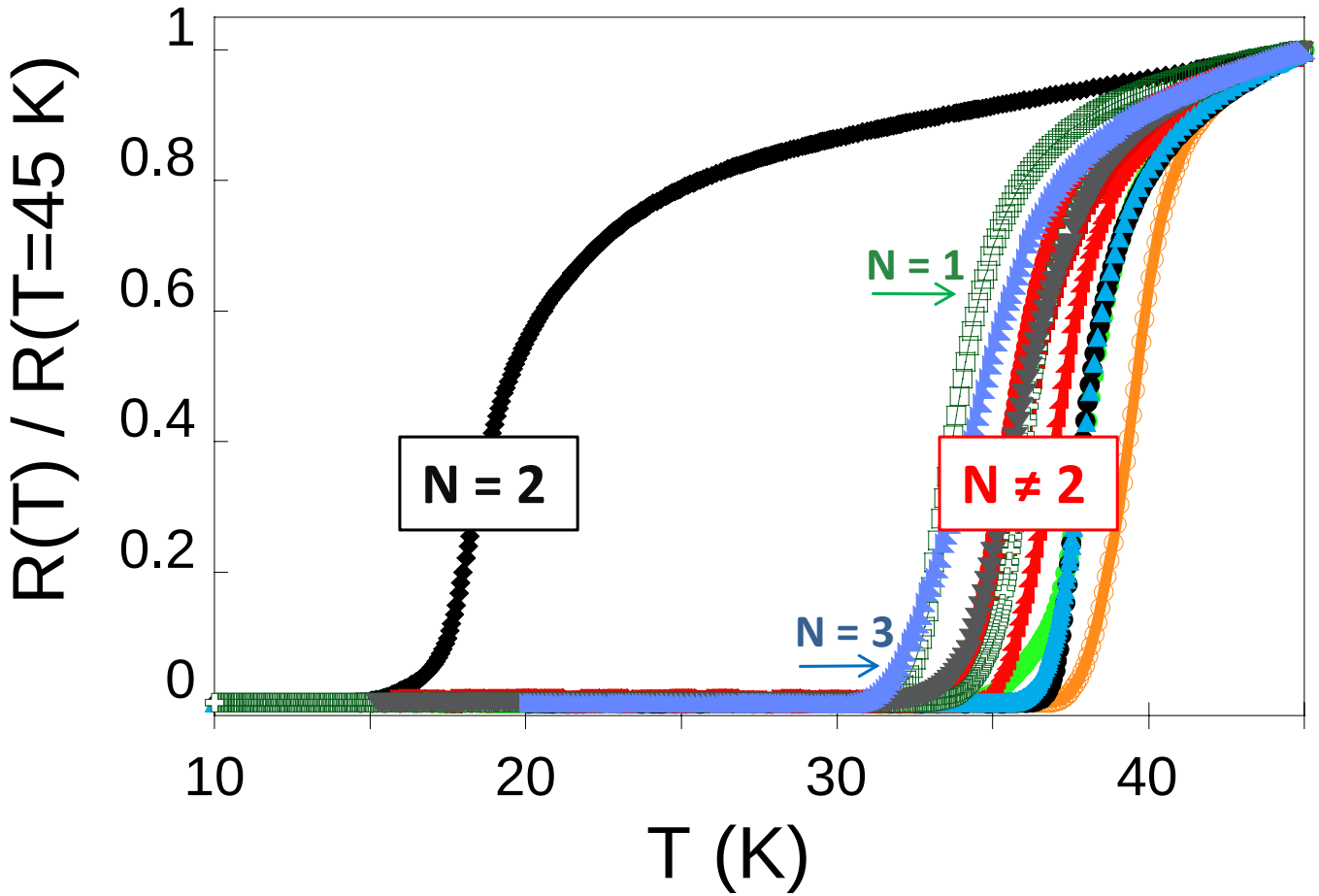
By virtue of digital (atomic-layer-by-layer) synthesis, it is possible to dope selectively at specific atomic sites, e.g., within a single CuO_2 plane.



Science 326, 699 (2009)

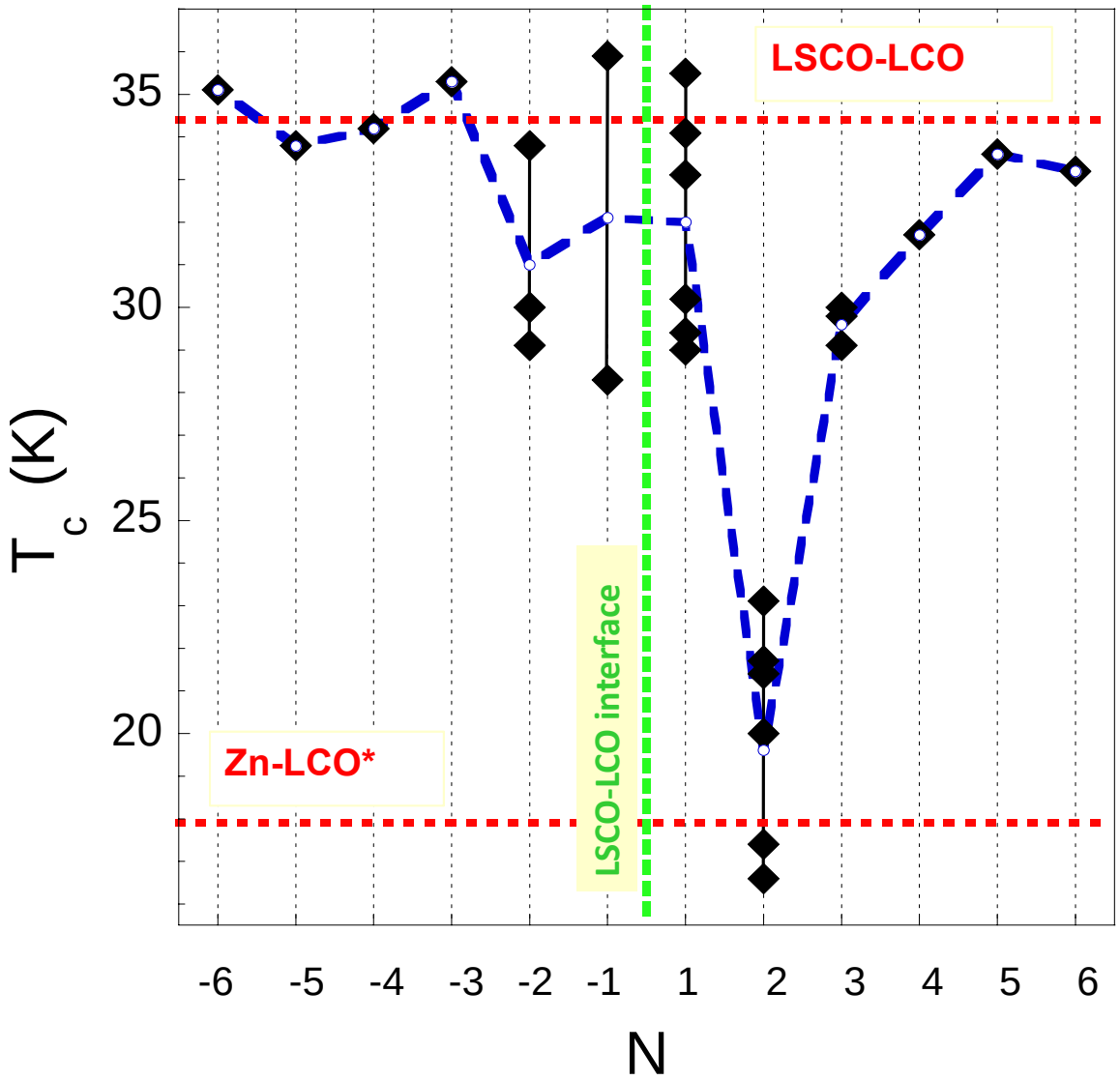
Varying the selected CuO_2 plane: Zn δ- doping "tomography"

δ- doping tomography of M-I bilayers



Only Zn doping in the second CuO_2 layer affects T_c!

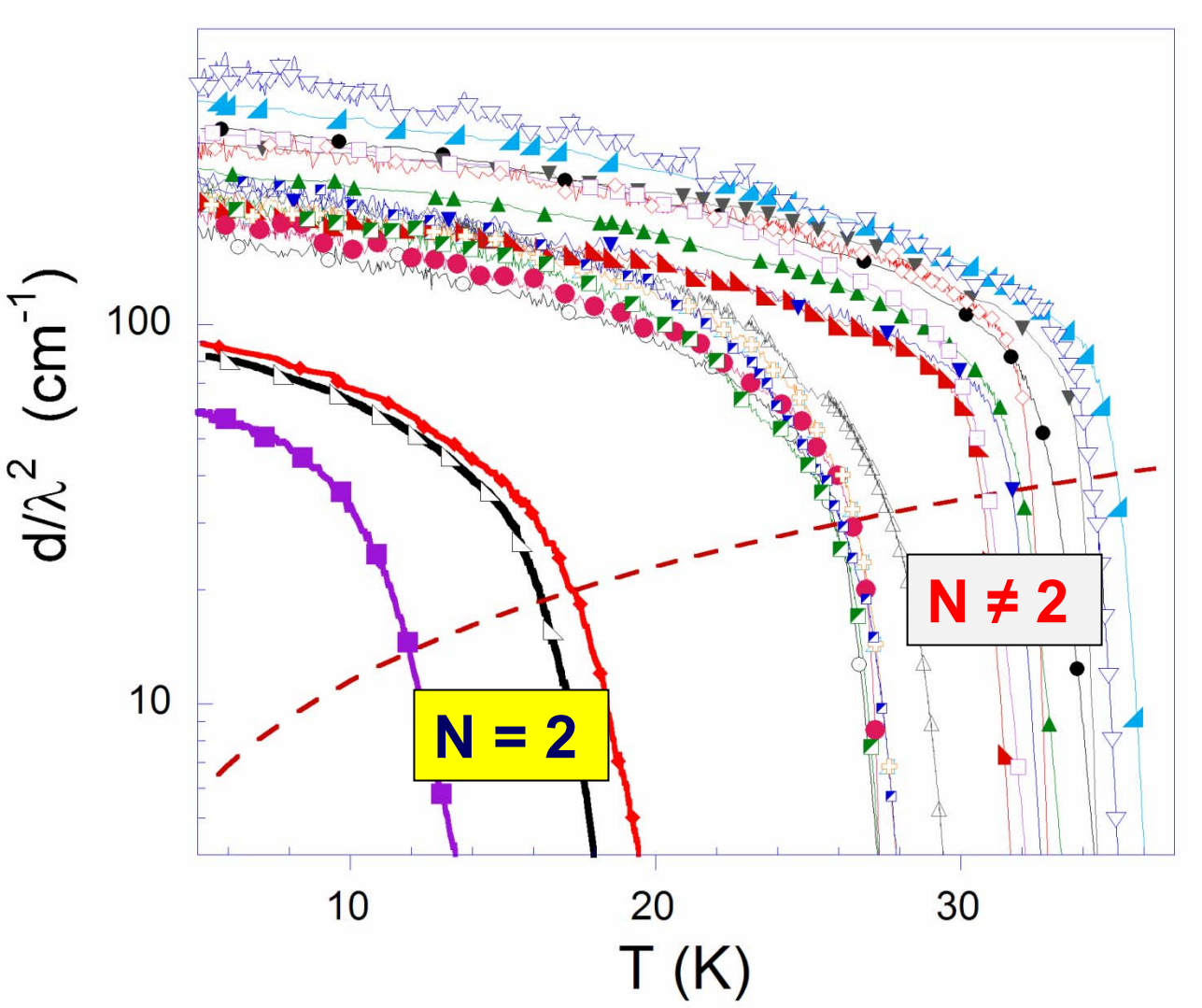
Science 326, 699 (2009)



HTS with T_c = 36 K is confined to a single CuO_2 plane!

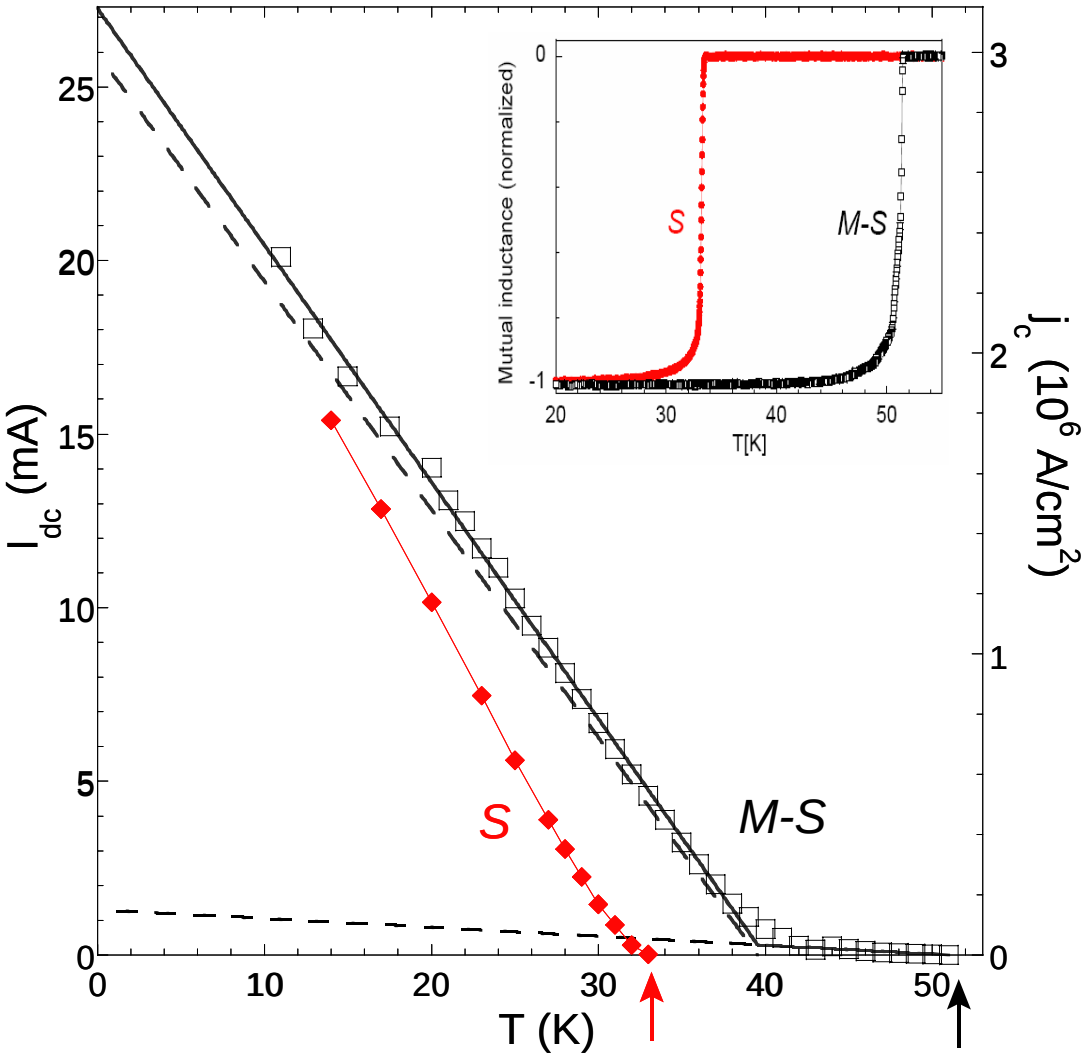
Science 326, 699 (2009)

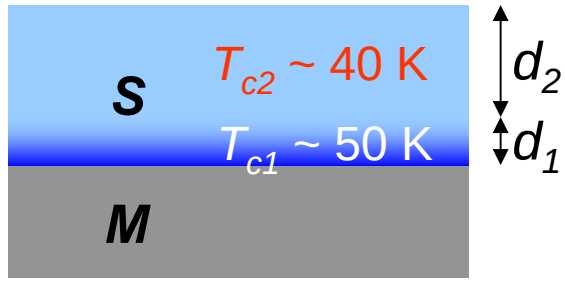
Magnetic measurements also show HTS in N=2 layer



Science 326, 699 (2009)

INTERFACE-ENHANCED SUPERCONDUCTIVITY





d_1 ~ 1-2 UC (~2 nm)

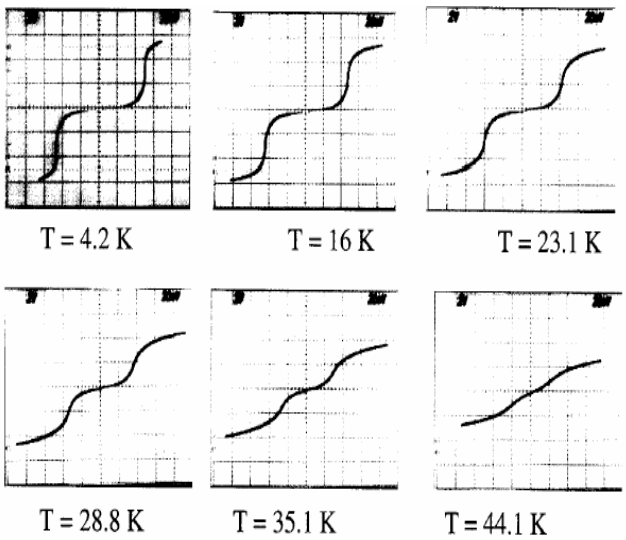
the 25% enhancement in T_c is an interface effect

[Nature 455, 782 (2008)]

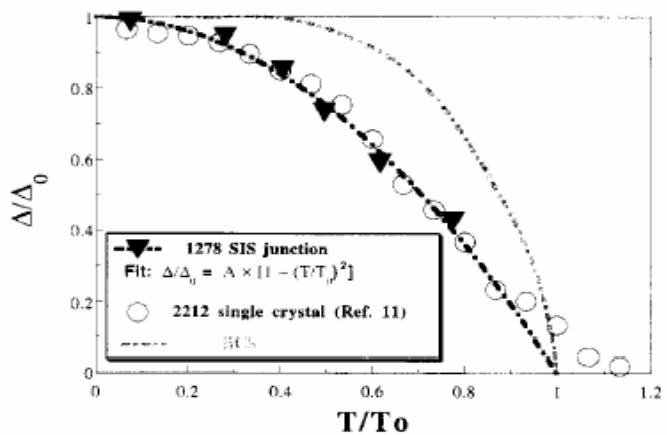
Can HTS cuprates be homogeneous?

Related talks: J. C. Davis, D. Basov, S. Okamoto, L. Teilleffer,…

ARTIFICIAL HTS SIS TUNNEL JUNCTION



Vertical scale: 20 mA/div; horizontal scale: 20 mV/div



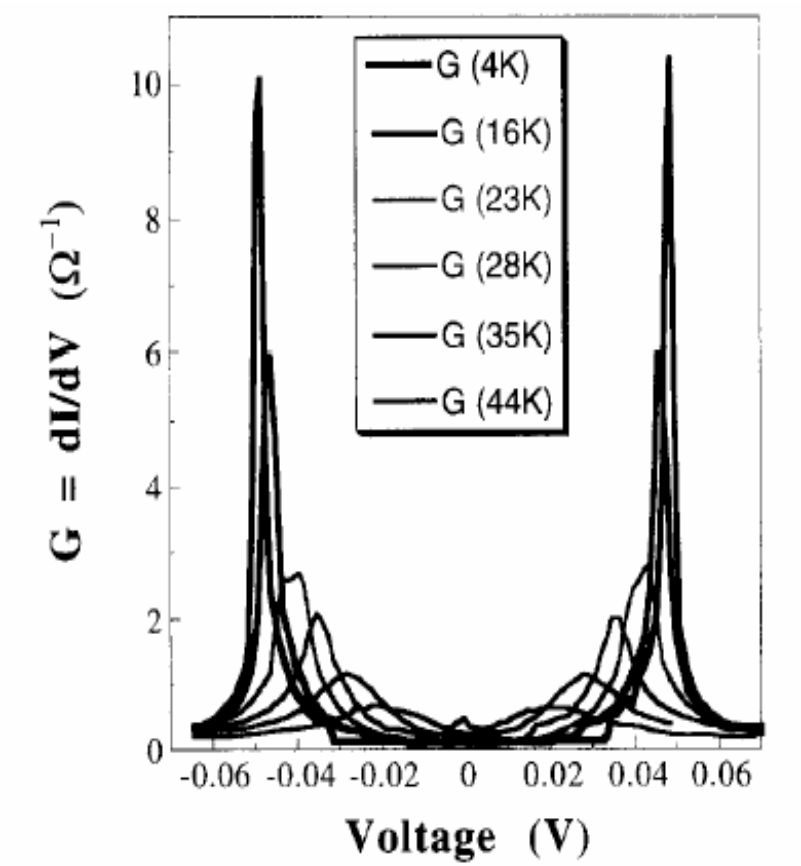
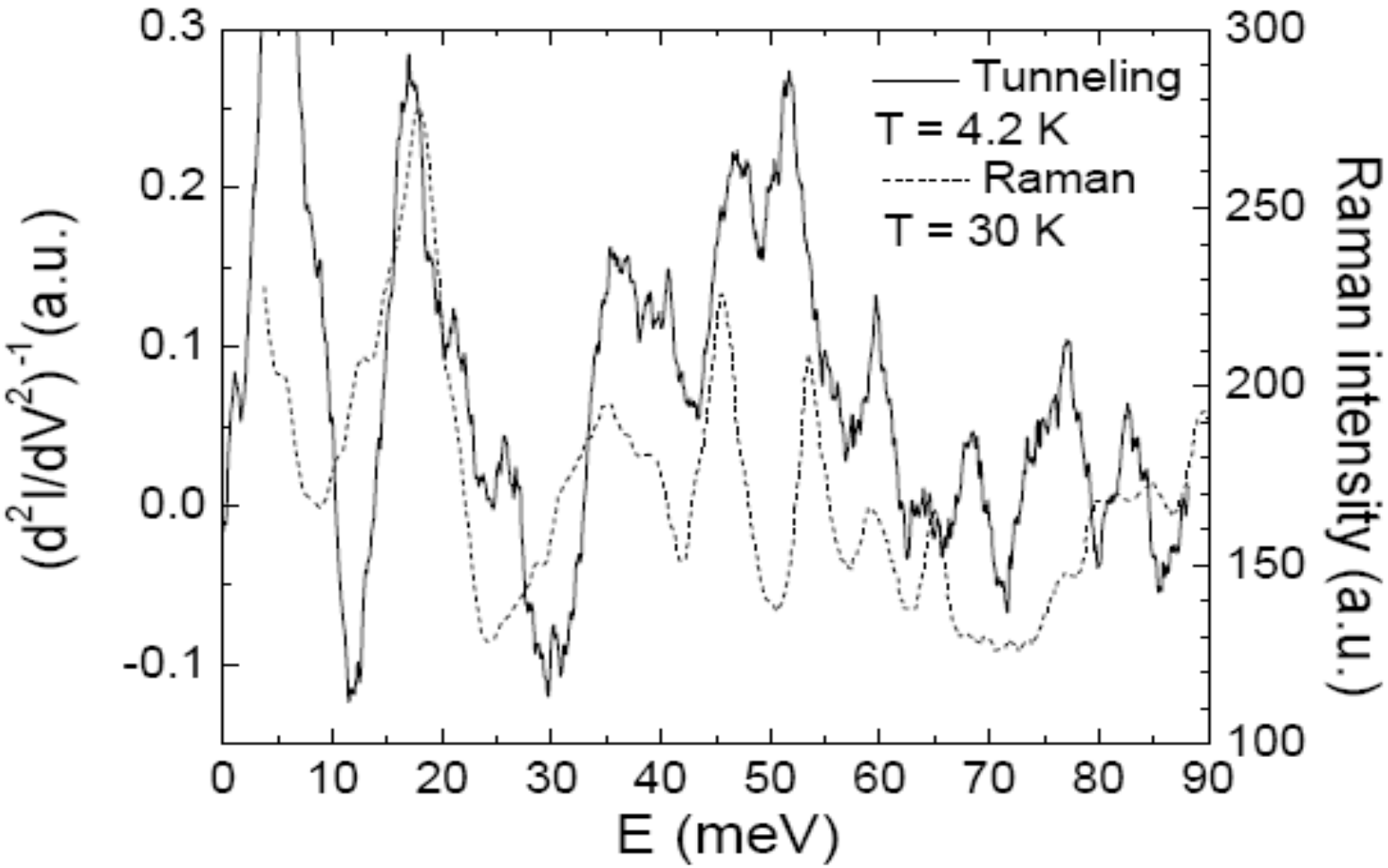


Fig. 5. Differential conductance ($G = dI/dV$) as a function of voltage, at different temperatures, for an intra-cell junction based on Dy-doped Bi-1278.

JAC **251**, 201 (1997).

Sharp gap in >1,000 μm² device!

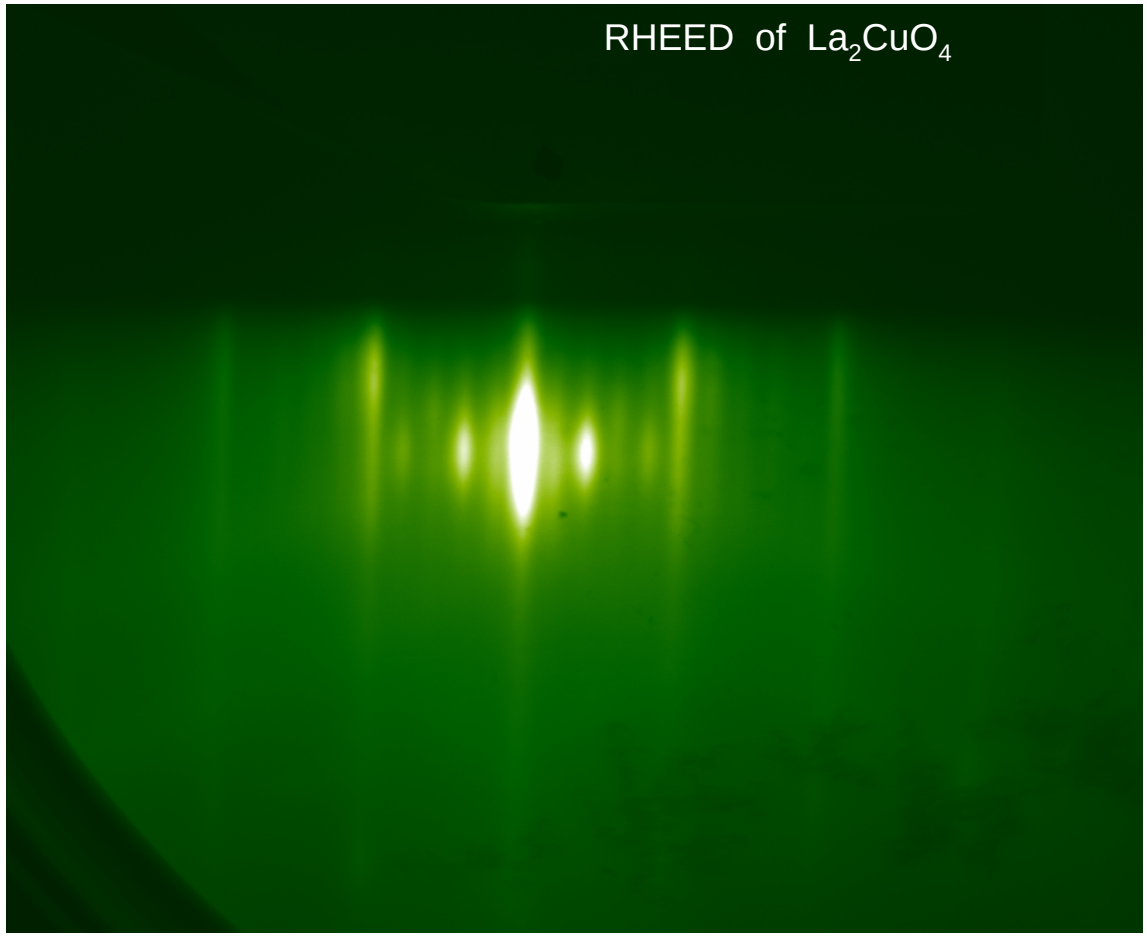
Tunneling data for SIS junction (LSCO grown on $SrTiO_3$ bicrystal)



Tunneling: Shim et al., PRL 2008

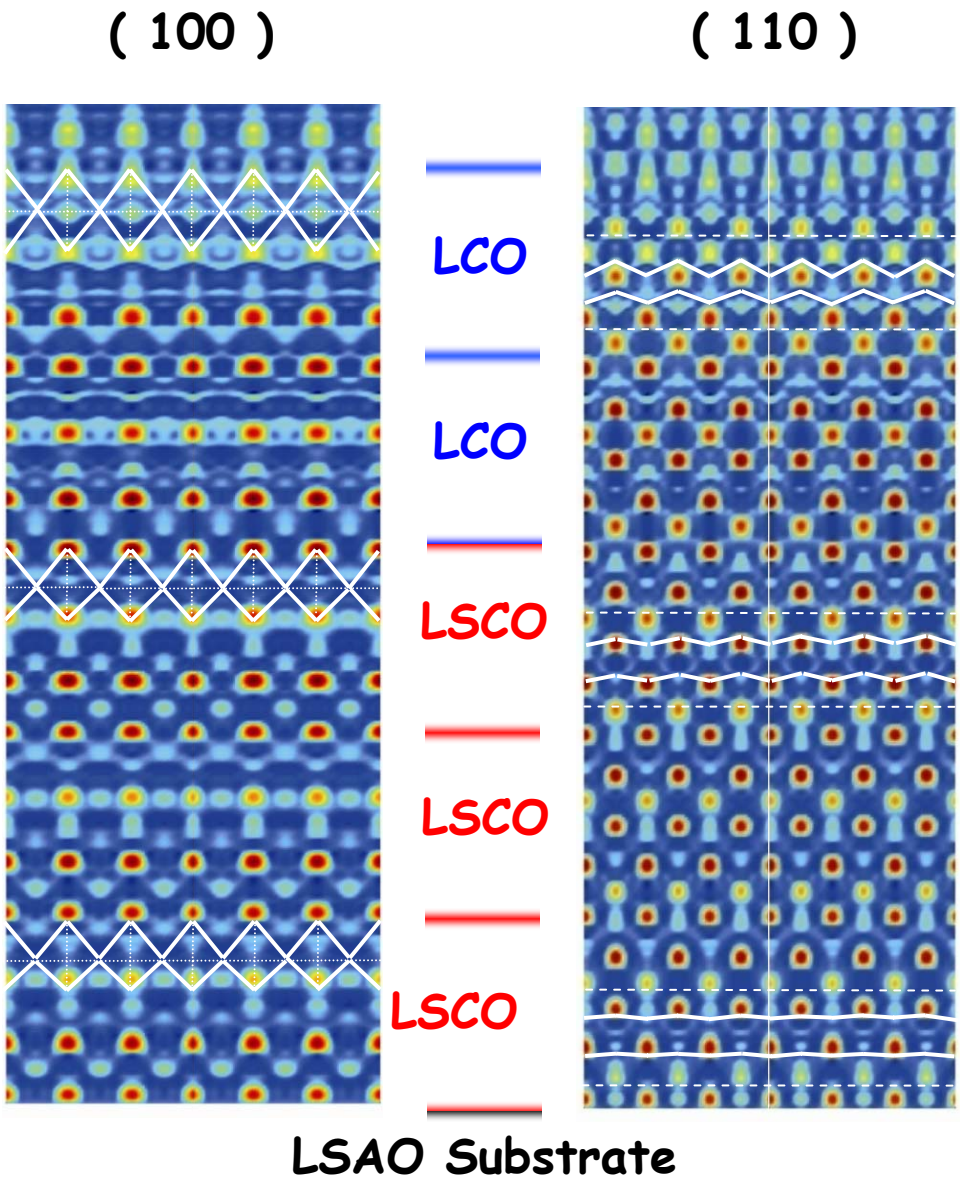
Raman: Sugai et al., SSC 1990

Surface ≠ bulk



Surface reconstruction is expected to occur in ionic crystals!

NEAR THE SURFACE, APICAL OXYGEN SHIFTS BY 0.45 Å!



Cross-sections through the **measured** 3D electron density map.

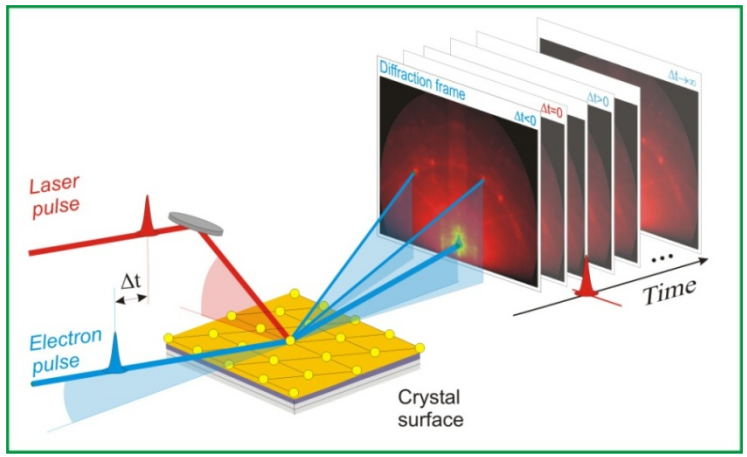
Left: atomic positions in the (100) plane. The CuO octahedra, outlined by the white lines, are significantly elongated near the surface.

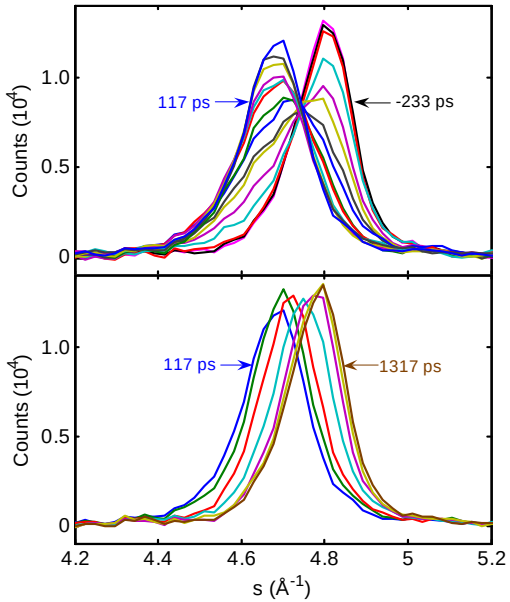
R*ight:* atomic positions in the (110) plane. The corrugation of La(Sr)-apical O planes, outlined by white lines, increases toward the surface.

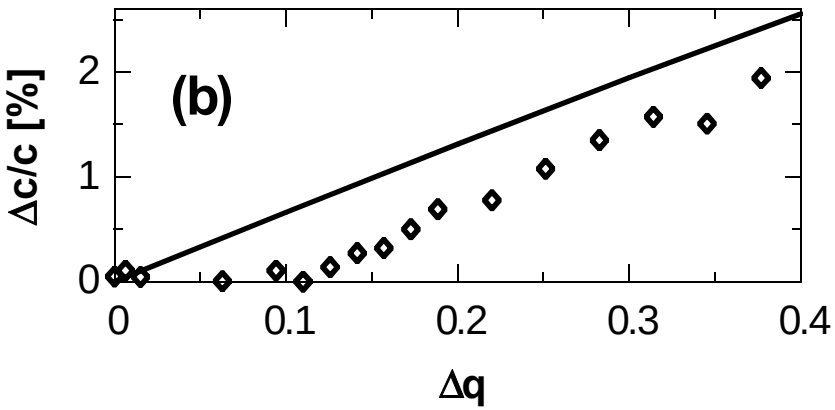
[Zhou et al., subm. to PNAS]

Electron-lattice interaction in cuprates

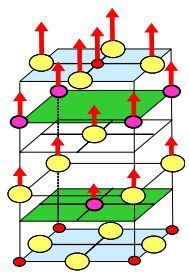
COLOSSAL PHOTO-INDUCED EXPANSION







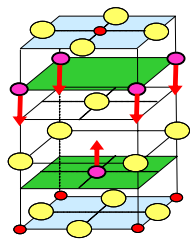
Science 316, 425 (2007); PRB 77, 092508 (2008)



Q_1

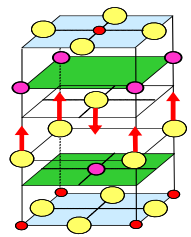
c-axis LAPs

$k << 2\pi/d_f$



Q_2

k = 0, A_{1g} RA mode, hν = 230 cm^{-1}

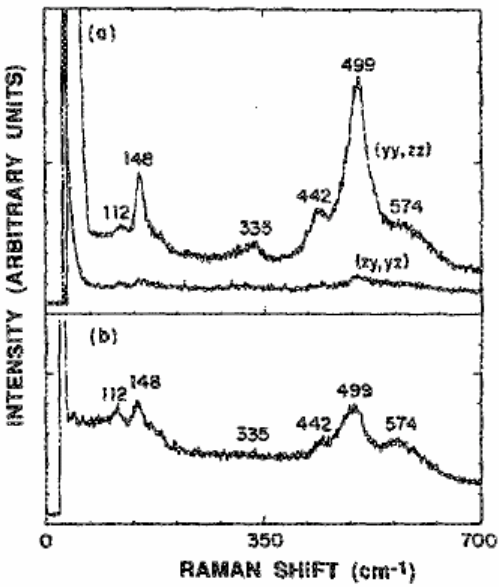


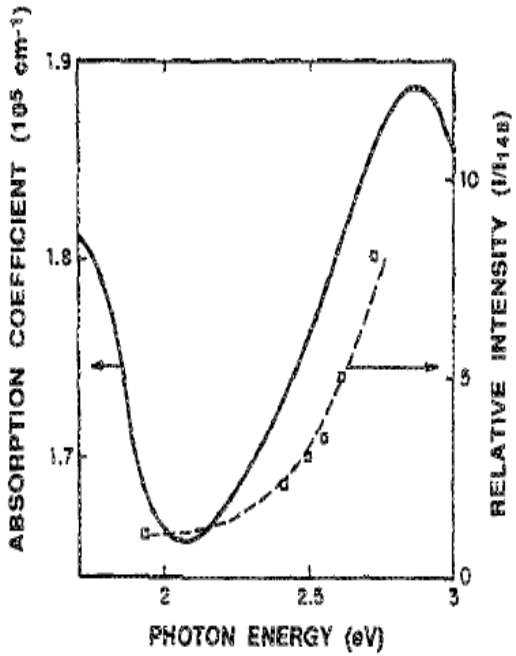
Q_3

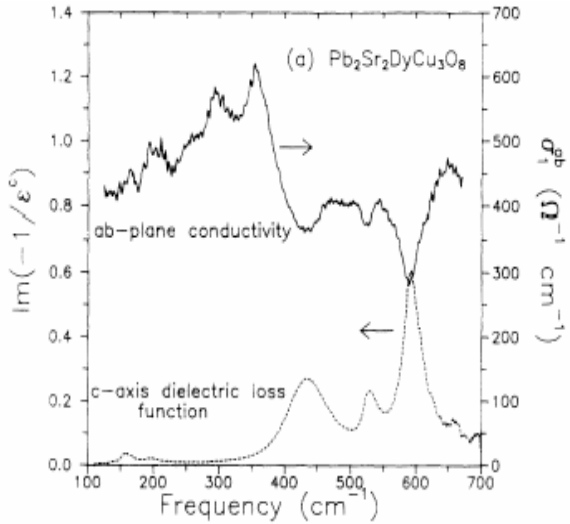
k = 0, A_{1g} RA mode, hν = 440 cm^{-1}

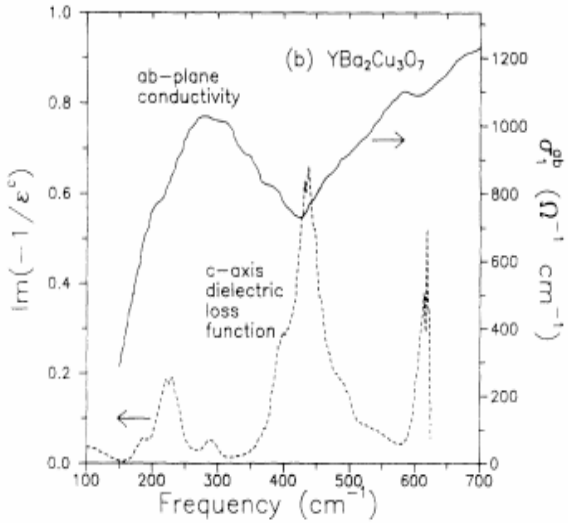
→ CHARGE-LATTICE COUPLING IS VERY STRONG!

Resonant Raman: E ll ab, ions move along c-axis







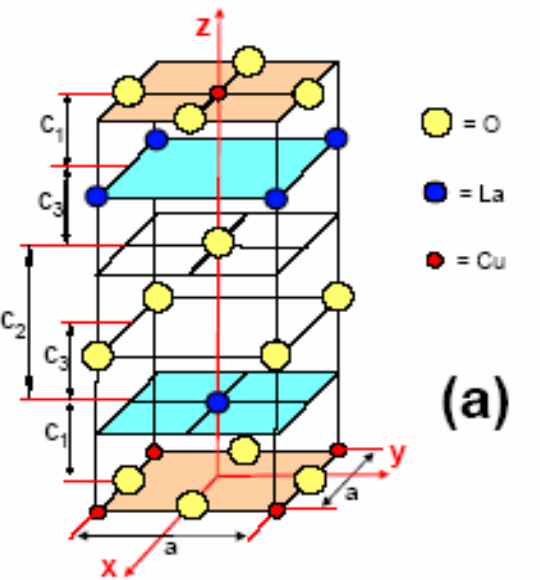


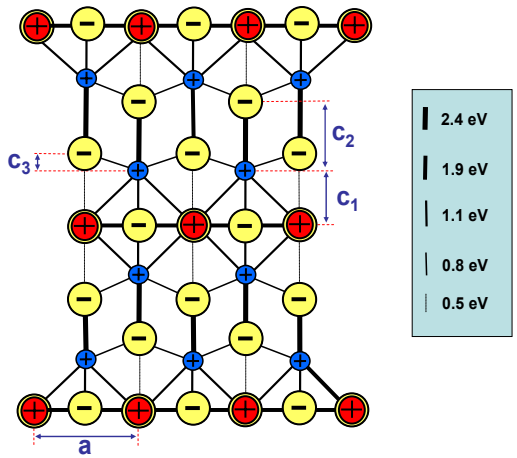
[J. Appl. Phys. 66, 977 (1989)]

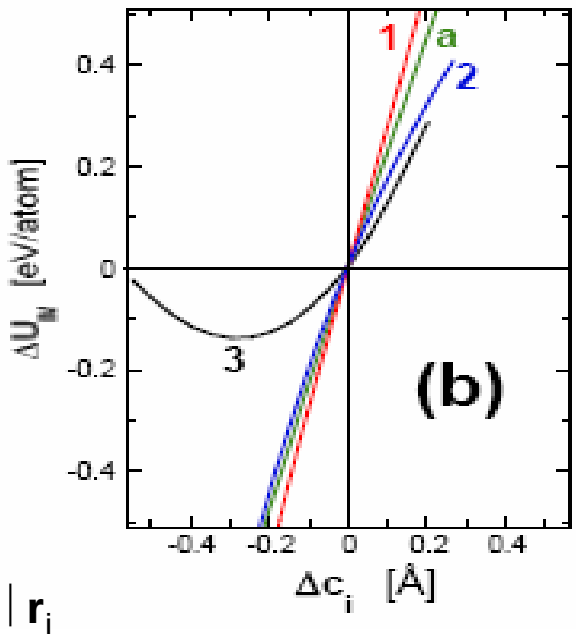
The same seen in Infrared spectra

Reedyk & Timusk PRL **69**, 2705 (1992)

Madelung surprises







The model: $U = (e^2/2)\Sigma\, q_i q_j / |\mathbf{r}_i - \mathbf{r}j| + (1/2)\Sigma\, A_{ij}*\exp(-B_{ij}|\mathbf{r}_i - \mathbf{r}_j|)$

A, B are chosen to reproduce the structure and fixed.

La–O is not flat – the corrugation is huge, 0.6 Å.

This is a purely electrostatic effect – Madelung levitation – **not JTE**.

[Phys. Rev. B. 77, 092508 (2008)]

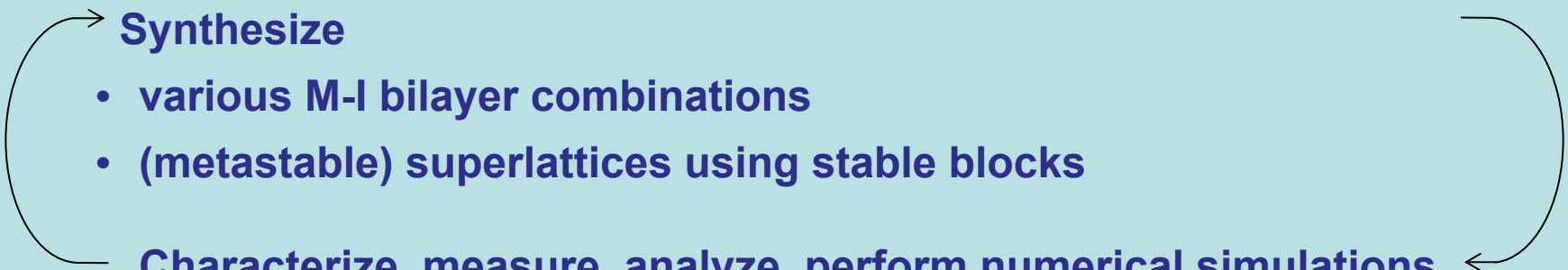
ALL-MBE engineering of novel superconductors

Related talks: J. Mannhart, J. Eckstein, M. Greenbaltt, C. Varma, …

ALL-MBE toolbox

- Epitaxial strain
- Epitaxial stabilization; Madelung strain; interface compounds
- Doping without disorder
- Interface-enhanced superconductivity
- Controlling displacements of apical oxygen
- Tuning charge-lattice coupling

ALL-MBE game plan

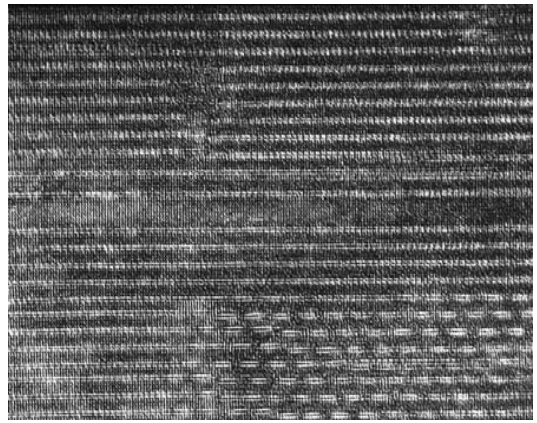


Epitaxial stabilization and Madelung strain

Artificial metastable superconductors synthesized by ALL-MBE

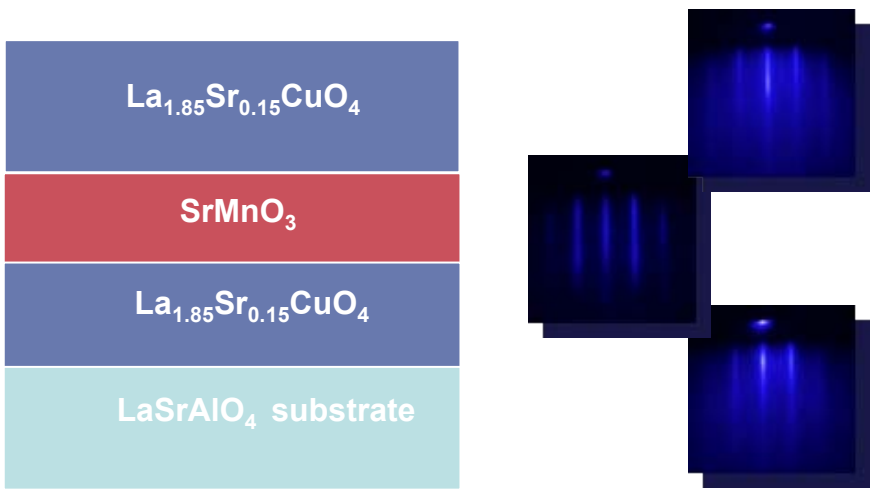
Bi-2278 (T_c = 60 K)

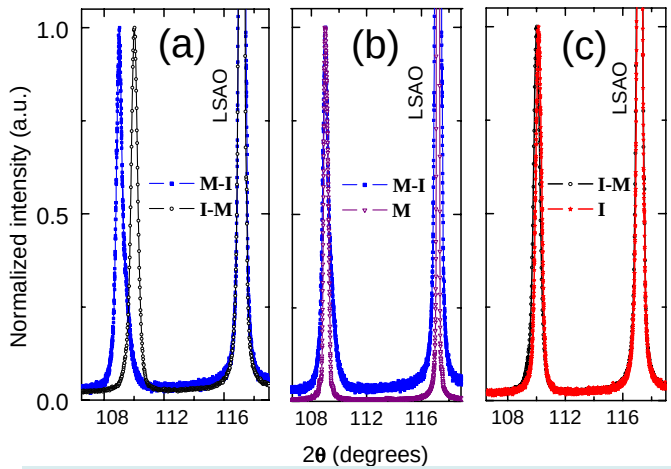
Bi-1278 (T_c = 75 K)



J. Supercond. 7, 187 (1994)

$SrMnO_3$ in perovskite structure





I-M ≠ M-I (b) M-I = M (c) I-M = I

[Bulk $SrMnO_3$: a = 5.454(1) Å, c = 9.092(2) Å, SG: $P6_3/mmc$]

Adv. Mater. 21, 1 (2009)

DIGITAL SYNTHESIS OF ARTIFICIAL HTS MATERIALS

La_3NiCuO_7

-- LaO --
-- NiO_2 --
-- LaO --
-- CuO_2 --
-- LaO --

NB: Artificially broken inversion symmetry!

Also, replace Ni with M = Ti, Mn, Co, Fe,…

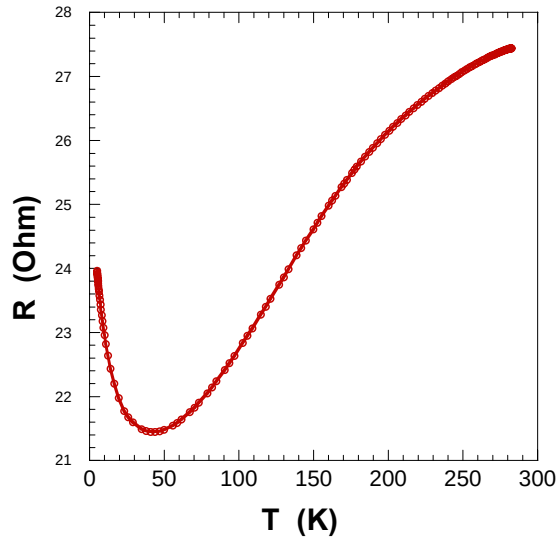
3xLa^{3+}, M^{3+}, Cu^{2+}: 14 electrons donated to 14 oxygen 2p states. This could be an (AF?) ionic insulator. However, some electrons could flow from MO_2 layer to CuO_2 layer because of the electro-chemical potential difference. This could make the MO_2 layer metallic, and CuO_2 layer superconducting.

One can also try oxygen or Sr→La doping, as well as photo-doping. Photo-generated electrons and holes could migrate to separate layers.
=> Long lived excitons? Photo-induced HTS?

DIGITAL SYNTHESIS OF ARTIFICIAL HTS MATERIALS

Ba_3LaBiO_9

-- BaO --
-- BiO_2 --
-- BaO --
-- LaO_2 --
-- BaO ----
-- BiO_2 –



NB: Artificially broken inversion symmetry!

This should be a realization of hole-doped, artificially-layered, quasi-2D $BaBiO_3$.

We have also experimented with ILC, Sr_2CuO_{4-d}, $LaAlO_3$, $LaSrAlO_4$, $LaNiO_3$, $La_{2-x}Sr_xNiO_4$, titanates, manganites, etc.

ALL-MBE → evidence for:

- One-atom-thick HTS
- Non-zero *E* in superconductor
- Broken inversion symmetry
- Quantum spin liquid
- Homogeneous HTS
- Strong electron-lattice interaction in HTS
- … and more to come.