Tailoring the Mesoscopic Structure of Superconductors to Boost T_c beyond the Present Limits

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Loen, June 20, 2007

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Pohang University
S.I. Lee

The Road to Room-Temperature Superconductivity

For Fame:

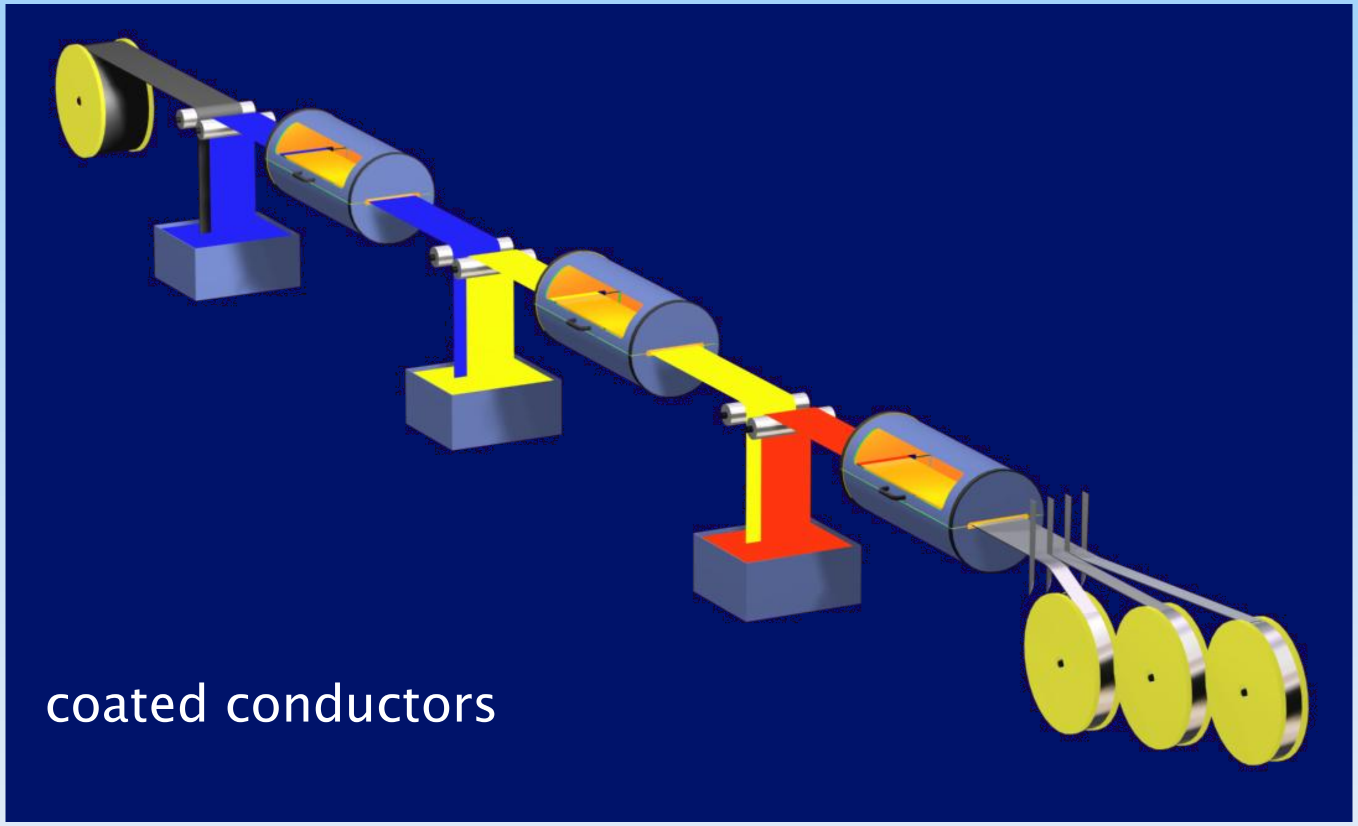
- T_c = 300 K
- no layered cuprate

For Fortune:

- T_c > 500 K
- J_e (350 K) > 10^4 A/cm^2 in 5 T
- ductile, robust, good thermal properties
- good Josephson junctions
- environmentally friendly compound
- available in large quantities
- < 20 € kA/m

Two Breakthrough Developments in Materials Fabrication

1) Bulk can be fabricated with film techniques



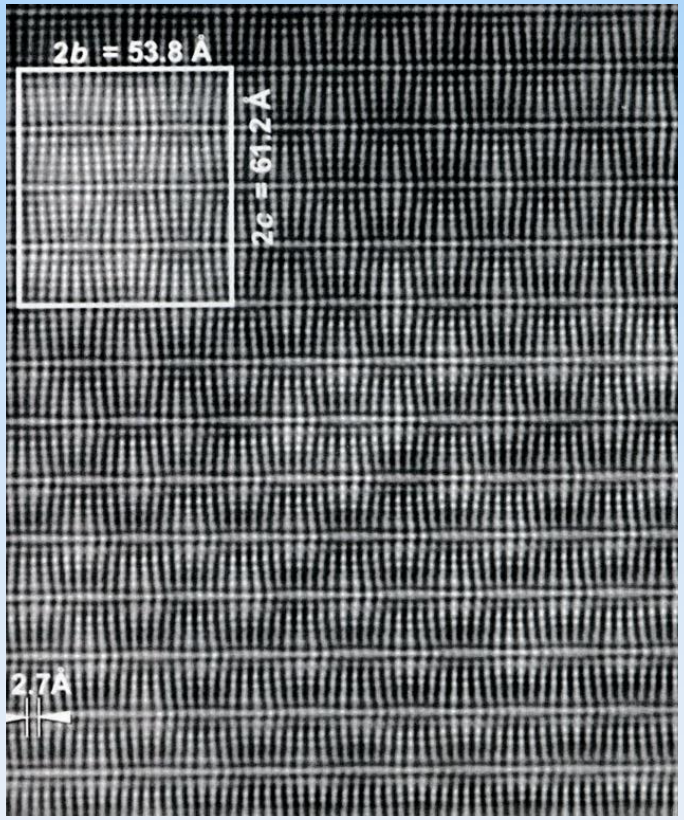
link to Gurevich, Grant

Two Breakthrough Developments in Materials Fabrication

1) Bulk can be fabricated with film techniques

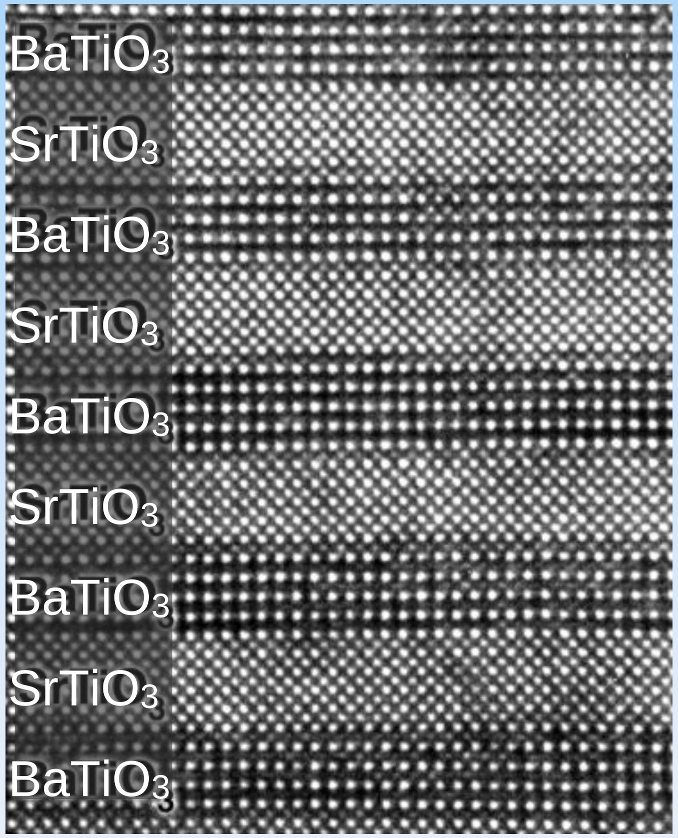
2) Fabrication of new materials that are designed on the unit cell level

$Bi_2Sr_2CaCu_2O_8$



Y. Zhu (2000)

$BaTiO_3$ / $SrTiO_3$ - superlattice



D.G. Schlom *et al.*, (2001)

link to Bozovich

Models and theories usually focus on single phase materials

the limits and problems that have been identified predominantly refer to single phases

Design and Fabrication of New Superconducting Materials

I) New phases

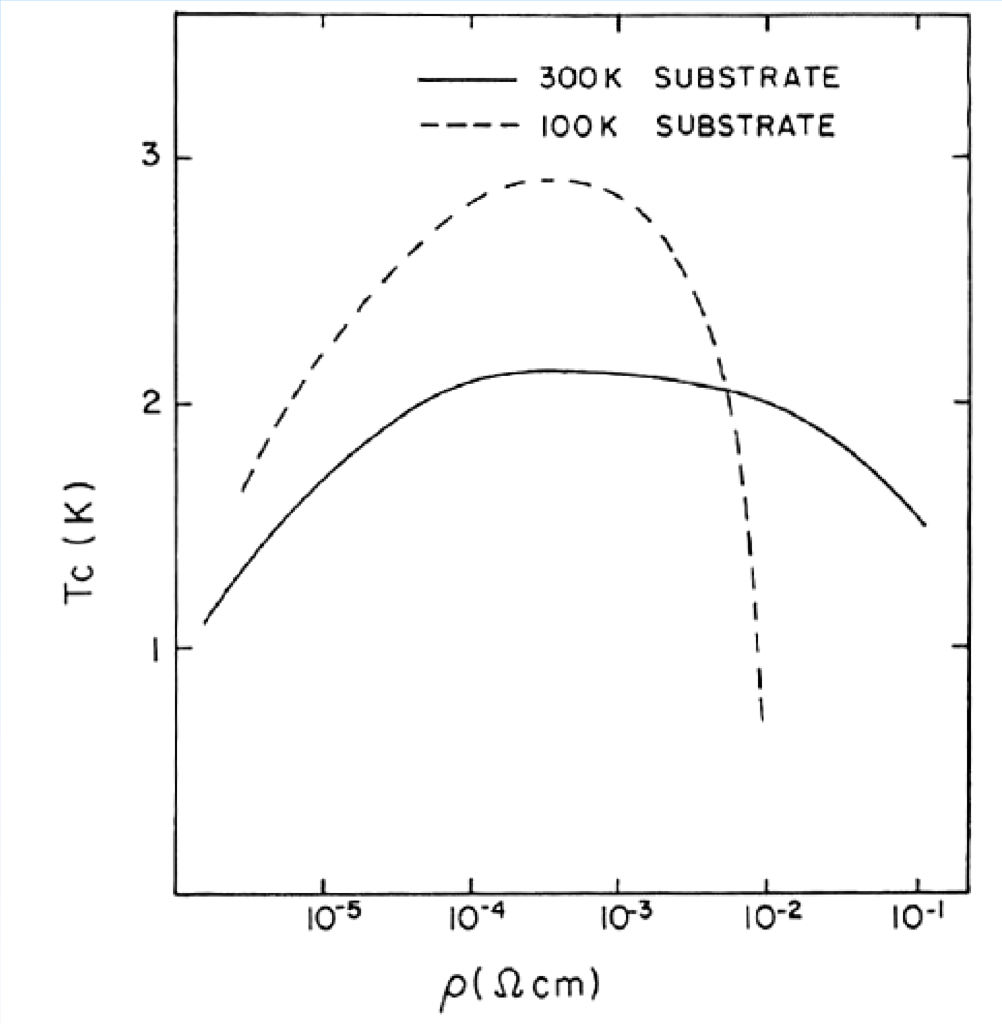
Putting atoms in place by nano-fabrication (*e.g.* by AFM) or epitaxial procedures

link to Grant, Uchida, Bozovic

Design and Fabrication of New Superconducting Materials

II) Boosting T_c by Optimizing the Mesoscopic Structure

Granular Al:



link to Geballe

→ reduction of grain size enhances T_c by factor 3

G. Deutscher:

"New Superconductors: From Granular to High-T_c" (2005)

Design and Fabrication of New Superconducting Materials

II) Boosting T_c by Optimizing the Mesoscopic Structure

1) Kresin Effect: nanoclusters with number of electrons close to magic

Flux Periodicity of Small Superconducting Rings

BdG calculations of superconducting rings with diameter D at T=0:

➢ magnetic flux may Doppler-shift states beyond E_F

➢ state population of the condensate may change with flux

⟶ flux periodicity of superconducting rings:

s-wave: $h/2e$ for $D \gtrsim \xi$, h/e for $D \lesssim \xi$
d-wave: h/e

the 2 of $h/2e$ is a consequence of the *s*-wave symmetry (no nodes)

F. Loder, A. Kampf, T. Kopp, J.M., C.W. Schneider, Y.S. Barash, submitted

Design and Fabrication of New Superconducting Materials

II) Boosting T_c by Optimizing the Mesoscopic Structure

1) Kresin Effect: nanoclusters with number of electrons close to magic

Design and Fabrication of New Superconducting Materials

II) Boosting T_c by Optimizing the Mesoscopic Structure

1) Kresin Effect: nanoclusters with number of electrons close to magic

2) For superconductors with self-organized real space structure:
support this internal structure by starting with an artificial microstructure,
reduction of the energy costs of phase separation

3) High-T_c at interfaces

links to Rice, Scalapino, Geballe, Kresin, Kivelson, Bozovic

Using Interfaces to Enhance T_c

Interfaces to:

1) stabilize superconducting phase / suppress phase transitions

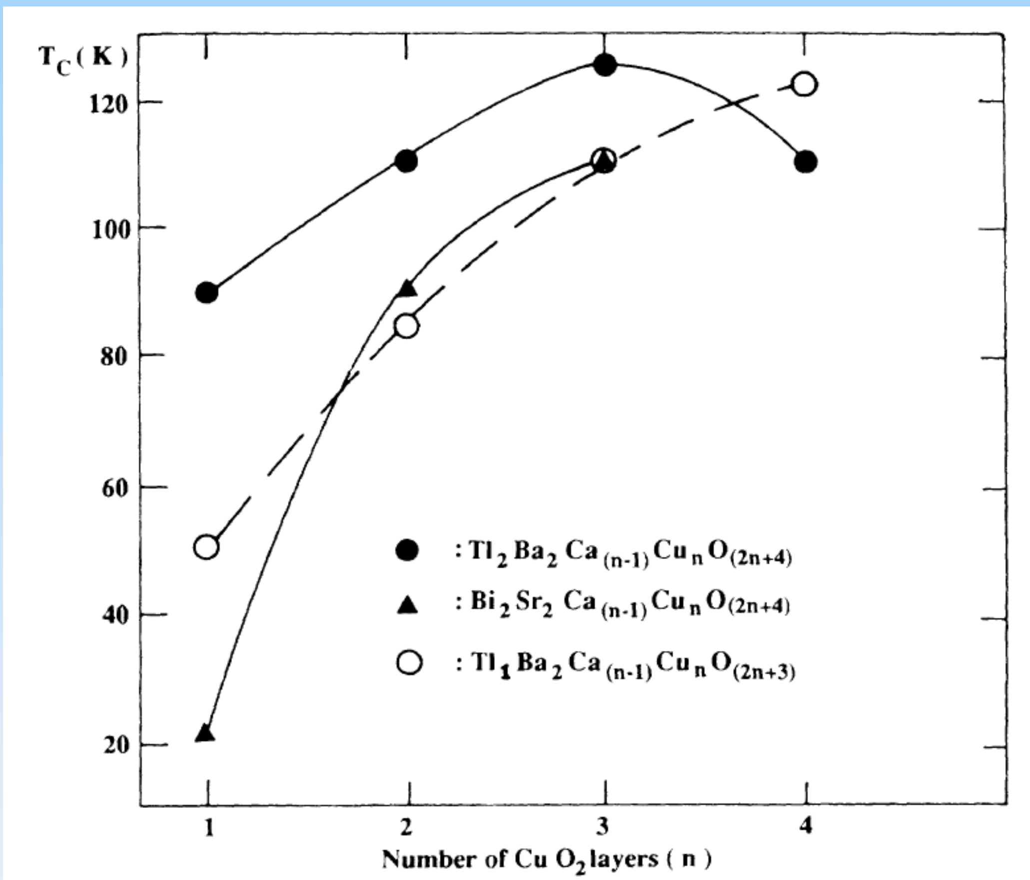
2) optimize doping

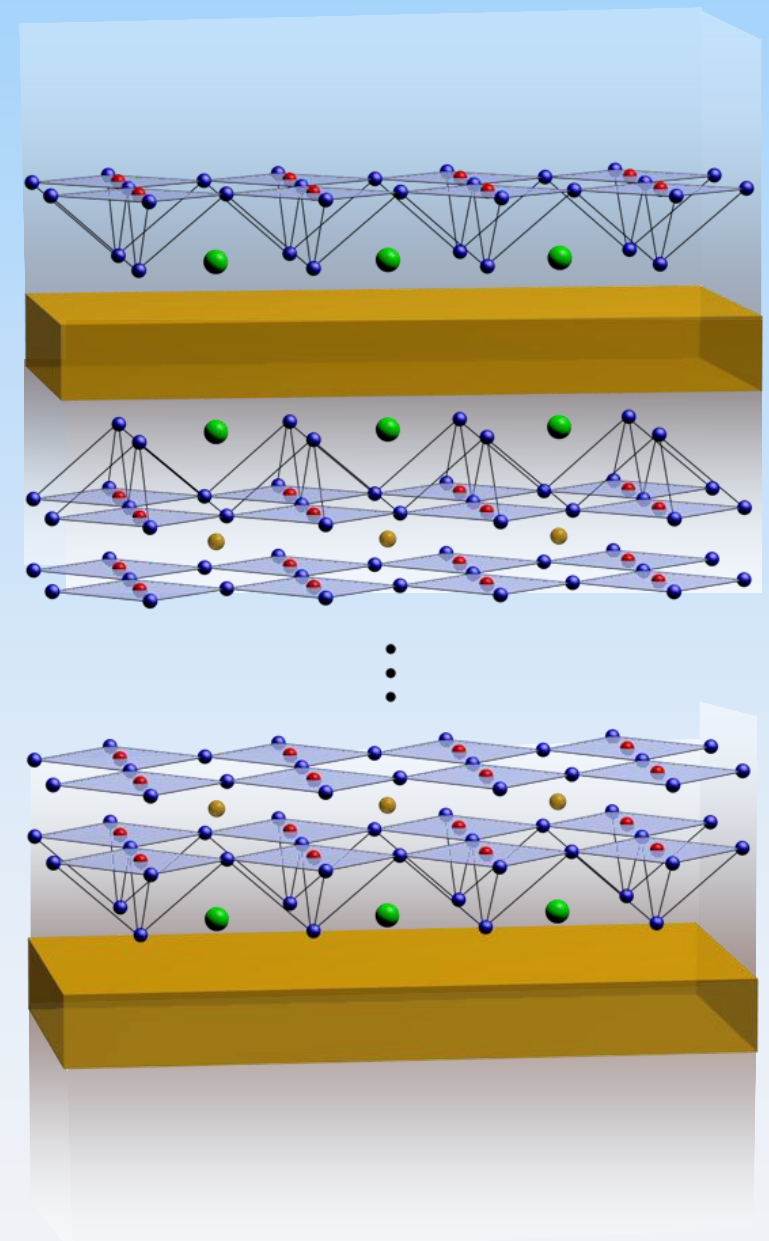
spatially separate doping layer from layer with pair interaction (see HTS)

VOLUME 64, NUMBER 23 PHYSICAL REVIEW LETTERS 4 JUNE 1990

Nonhomogeneous Charge Distribution in Layered High-T_c Superconductors

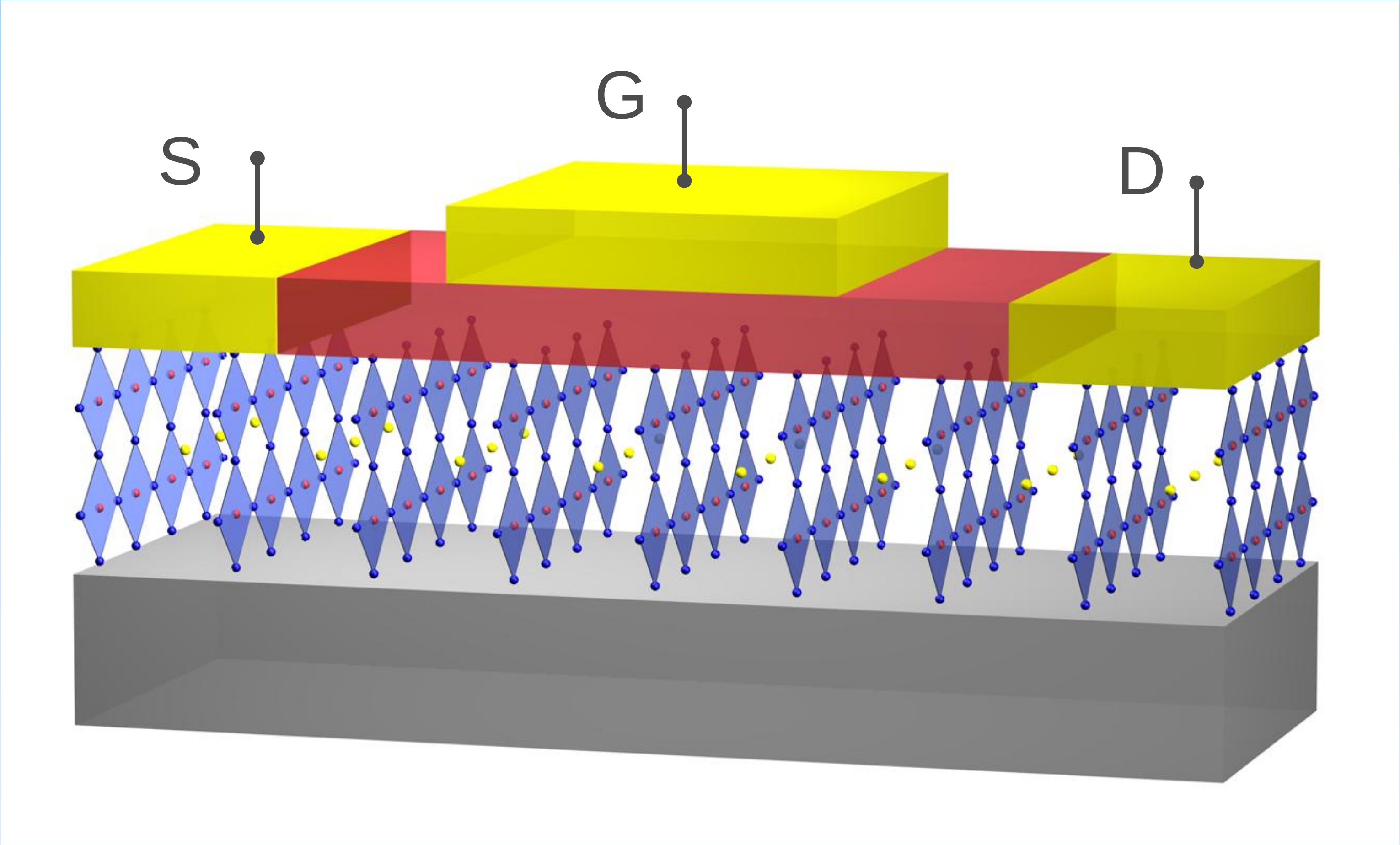
M. Di Stasio,[1] K. A. Müller,[2] and L. Pietronero[1]
[1]Dipartimento di Fisica, Universitá di Roma "La Sapienza," Piazzale Aldo Moro, 2, 00185 Roma, Italy
[2]IBM Research Division, Zurich Research Laboratory, Saumerstrasse 4, 8803 Ruschlikon, Switzerland





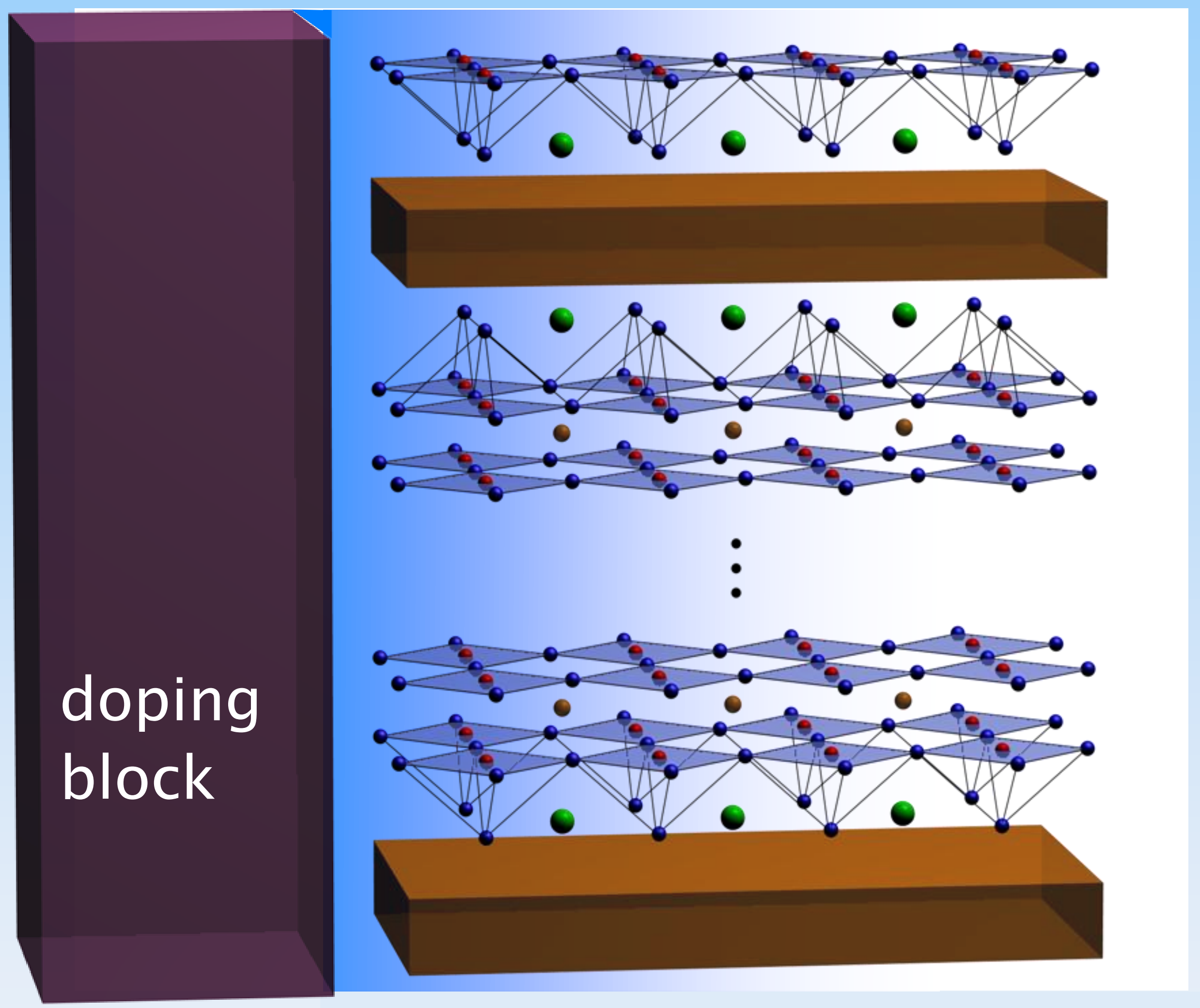
link to Uchida

Field Effect Doping of *a*-axis Oriented Infinite Layer Compounds



collaboration with S.I. Lee, Pohang University

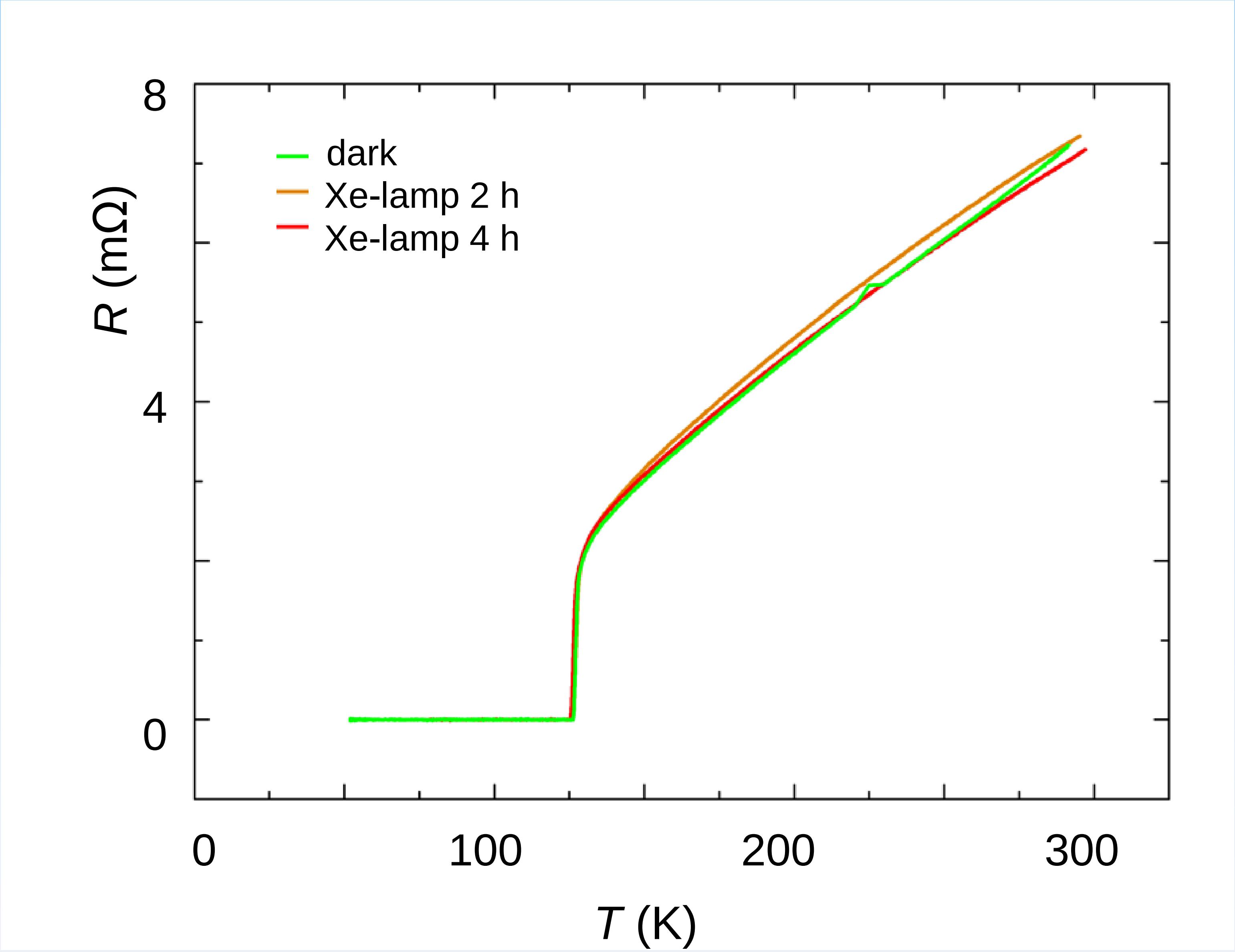
Doping of Compounds with Large number of CuO_2 planes



collaboration with S.I. Lee, Pohang University

Doping of Compounds with Large number of CuO_2 planes

Photodoping of $HgBa_2Ca_3Cu_4O_x$



collaboration with S.I. Lee, Pohang University

Using Interfaces to Enhance T_c

Interfaces to:

1) stabilize superconducting phase / suppress phase transitions

2) optimize doping

spatially separate doping layer from layer with pair interaction (see HTS)

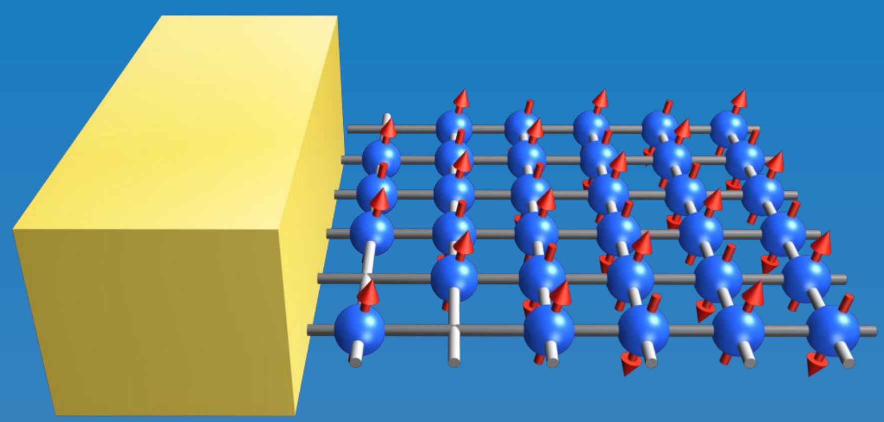
3) create novel electronic phases:

— correlation parameters at interfaces different from those of bulk —

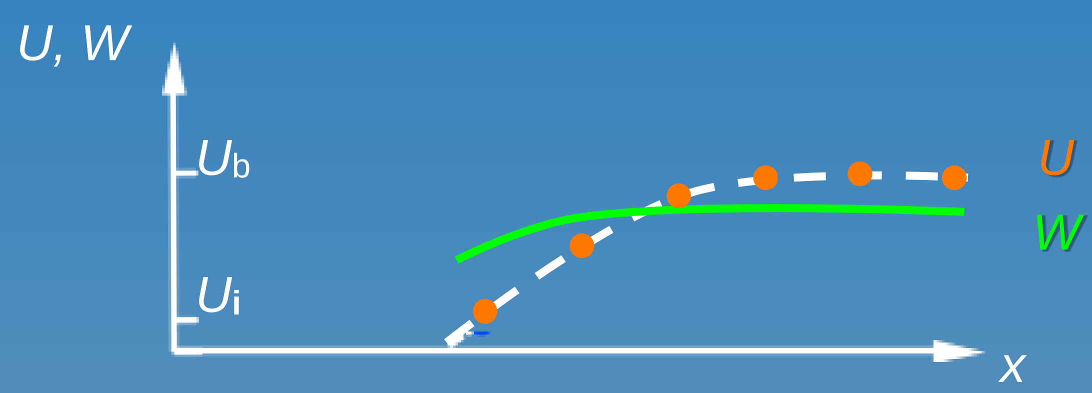
Interfaces to Correlated Electron Systems

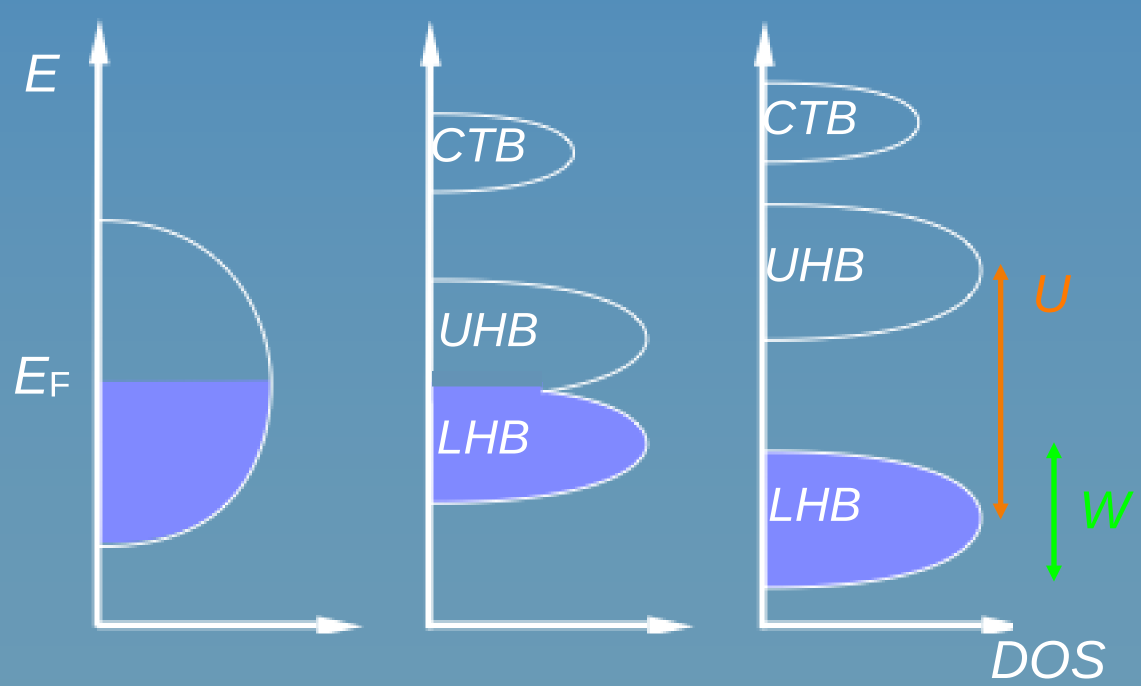
G. Sawatzky,
A. Millis,
J.M.

standard metal



Mott-insulator





metal metal Mott-insulator

J. M. in “Thin Films and Heterostructures for Oxide Electronics” Springer (2005)

Using Interfaces to Enhance T_c

Interfaces to:

1) stabilize superconducting phase / suppress phase transitions

2) optimize doping
spatially separate doping layer from layer with pair interaction (see HTS)

3) create novel electronic phases:
— correlation parameters at interfaces different from those of bulk —

4) use interface chemistry / induce defects

5) create *E* and *B* - fields, break inversion symmetry

6) spatially separate pairing interaction from flow of carriers

PHYSICAL REVIEW VOLUME 134, NUMBER 6A 15 JUNE 1964

Possibility of Synthesizing an Organic Superconductor*

W. A. LITTLE
Department of Physics, Stanford University, Stanford, California
(Received 13 November 1963; revised manuscript received 27 January 1964)

London's idea that superconductivity might occur in organic macromolecules is examined in the light of the BCS theory of superconductivity. It is shown that the criterion for the occurrance of such a state can be met in certain organic polymers. A particular example is considered in detail. From a realistic estimation of the matrix elements and density of states in this polymer it is concluded that superconductivity should occur even at temperatures well above room temperature. The physical reason for this remarkable high transition temperature is discussed. It is shown further that the superconducting state of these polymers should be distinguished by certain unique chemical properties which could have considerable biological significance.

PHYSICAL REVIEW B VOLUME 7, NUMBER 3 1 FEBRUARY 1973

Model for an Exciton Mechanism of Superconductivity*

David Allender,† James Bray, and John Bardeen
Department of Physics and Materials Research Laboratory, University of Illinois, Urbana, Illinois 61801
(Received 7 August 1972)

The exciton mechanism of superconductivity is discussed with respect to a particular model, a thin metal layer on a semiconductor surface. In this model, the metal electrons at the Fermi surface tunnel into the semiconductor gap where they interact with virtual excitons, producing a net attractive interaction among the electrons in direct analogy with the phonon mechanism of superconductivity. The physical requirements for successful realization of the exciton mechanism in a metal-semiconductor system are explored in detail, and the relevant parameters are described. Estimates are made for electron tunneling and band-bending effects, and an electron-exciton coupling constant is defined and estimated. Finally, an appropriately modified integral equation for the superconducting energy gap is solved numerically to yield transition temperatures both for a pure-exciton mechanism and for the exciton and phonon mechanisms acting simultaneously.

ON SURFACE SUPERCONDUCTIVITY

V. L. GINZBURG
P.N. Lebedev Institute of Physics, USSR Academy of Sciences, Moscow

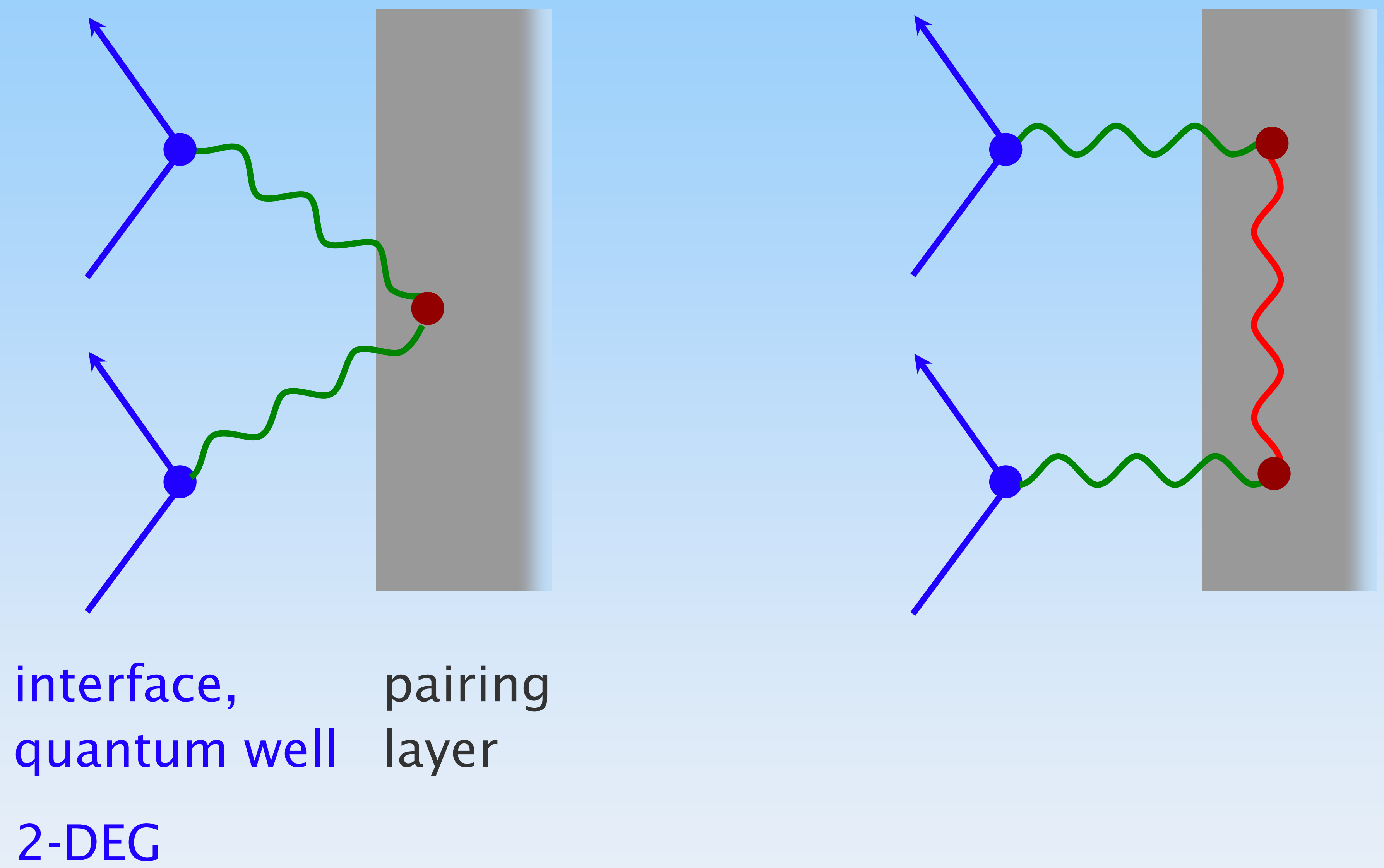
Received 21 October 1964

The superconductivity usually considered is a three-dimensional effect of ordering. However, a two-dimensional (surface) superconductivity is also conceivable [1] just as, for instance, a surface ferromagnetism [2].

We can consider two types of surface superconductivity. We assume in the first case that a resulting attraction takes place between electrons in the layer of metal near to the surface, while repulsion prevails in the volume. Such a difference may be connected with the fact that the interaction varies near the surface, for instance, due to the

exchange by surface photons, variation of screening, etc. The second case of surface superconductivity is connected with the transition into the superconducting state of electrons in surface states of the crystal. In that case, of course, the crystal may be non-metallic in the volume ; if, however, the surface band is filled only partially, we shall deal, so to say, with a surface metal.

Spatial Separation of Carriers and Pairing Interaction

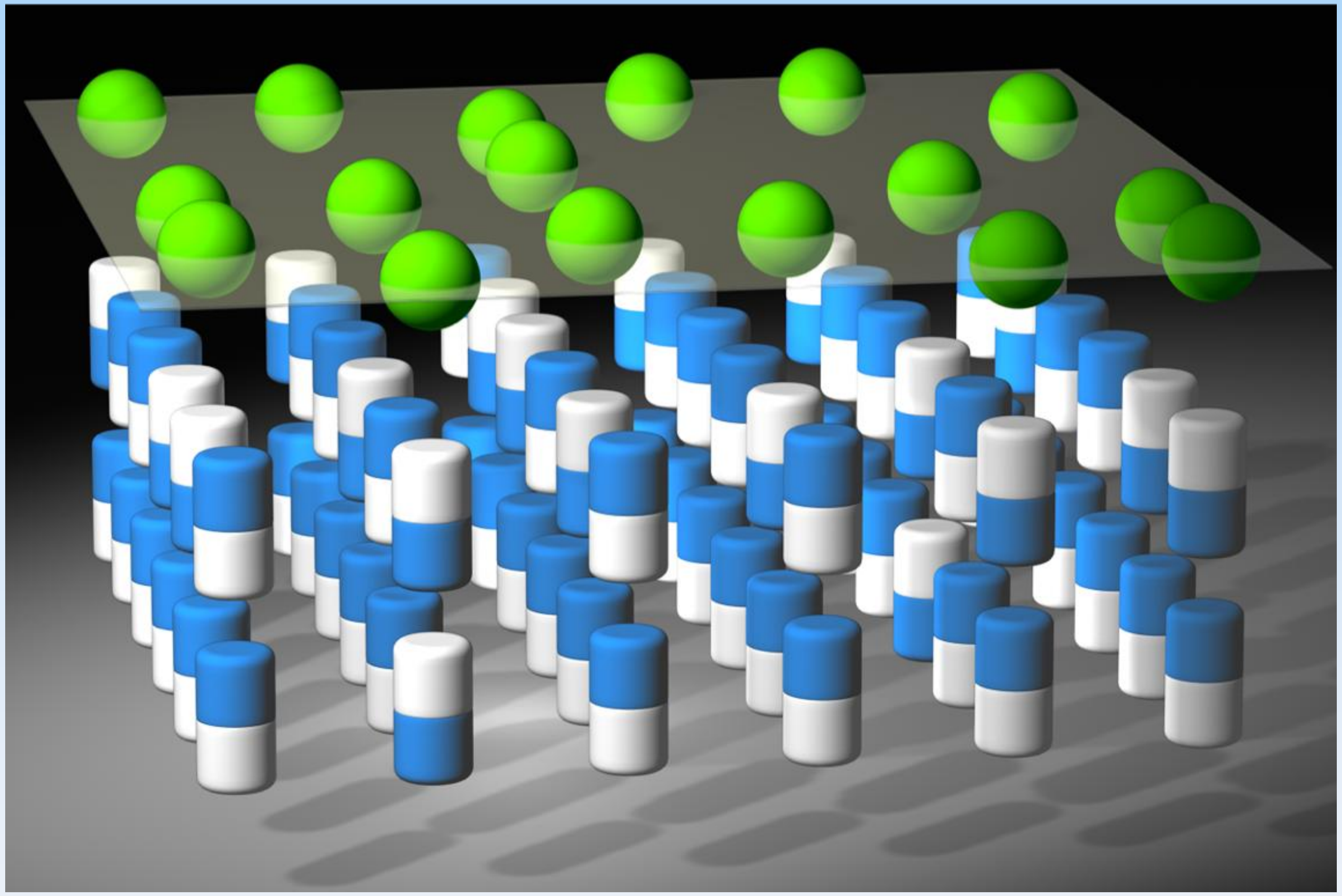


Spatial Separation of Carriers and Pairing Interaction

Model System:

mobile charge carriers at the interface,

pairing by virtual polarizations of the adjacent layer



mobile electrons

(TiO_2)

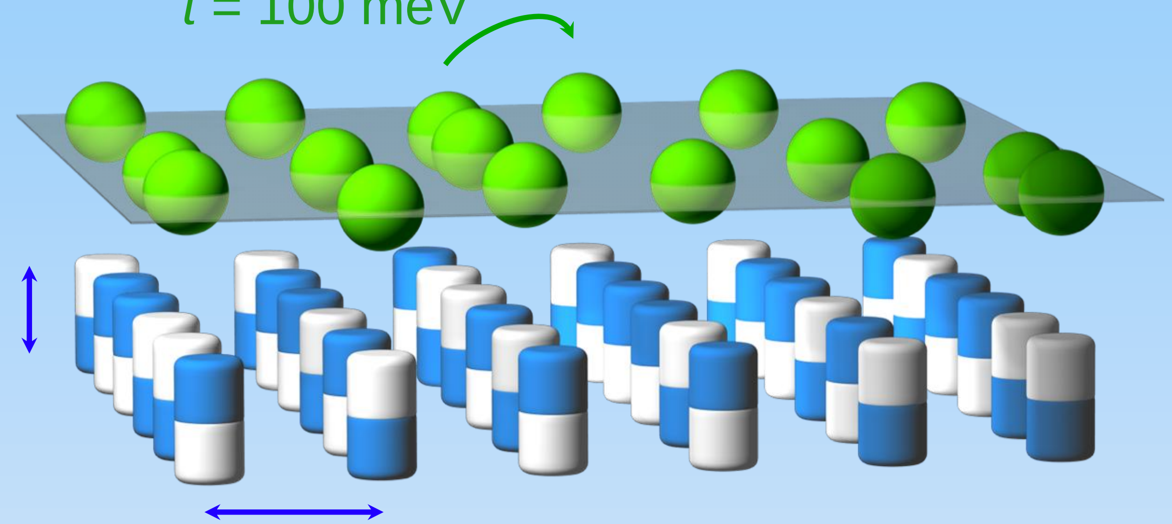
polarizable dipoles

($SrTiO_3$)

V. Koerting *et al.*, PRB **71**, 104510 (2005)

Spatial Separation of Carriers and Pairing Interaction

Model System:



$$H_{\text{tot}} = H_t + H_{e-e} + H_\mu + H_{2l} + H_{\text{ext}} + H_{\text{int}}$$

$$H_t = -t \sum_{<i,j>,\sigma} c^\dagger_{i,\sigma} c_{j,\sigma}$$

$$H_{e-e} = U \sum_i n_{i,\uparrow} n_{i,\downarrow} + V \sum_{<i,j>} (1 - n_i)(1 - n_j)$$

$$H_\mu = -\mu \sum_{i,\sigma} c^\dagger_{i,\sigma} c_{i,\sigma}$$

$$H_{2l} = \frac{1}{2} \Delta_{pd} \sum_i (p^\dagger_i p_i - d^\dagger_i d_i)$$

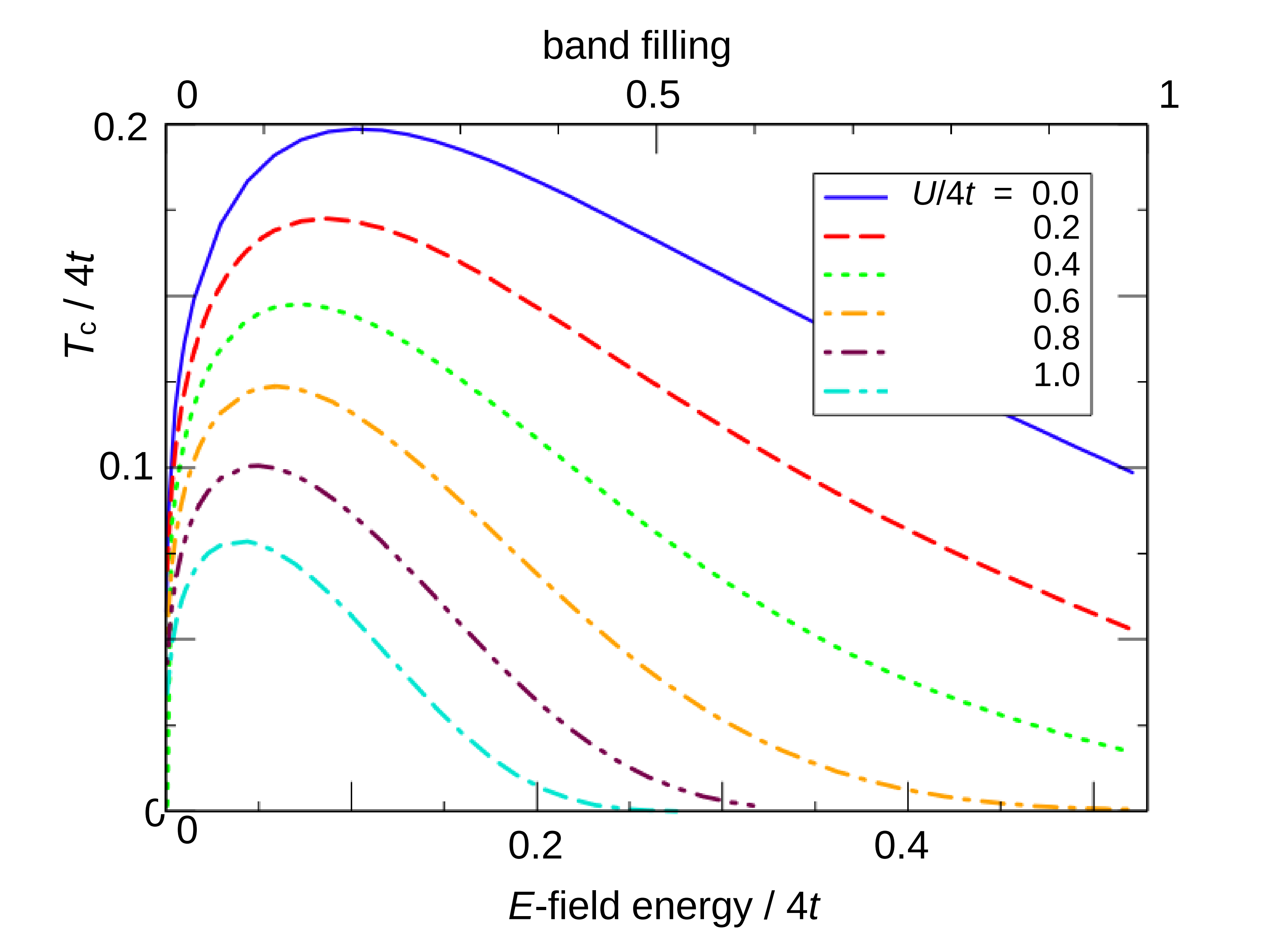
$$H_{\text{ext}} = \varepsilon_g \sum_i (p^\dagger_i d_i - d^\dagger_i p_i)$$

$$H_{\text{int}} = V_{pd} \sum_{i,\sigma} c^\dagger_{i,\sigma} c_{i,\sigma} (p^\dagger_i d_i + d^\dagger_i p_i)$$

V. Koerting *et al.*, PRB **71**, 104510 (2005)

Spatial Separation of Carriers and Pairing Interaction

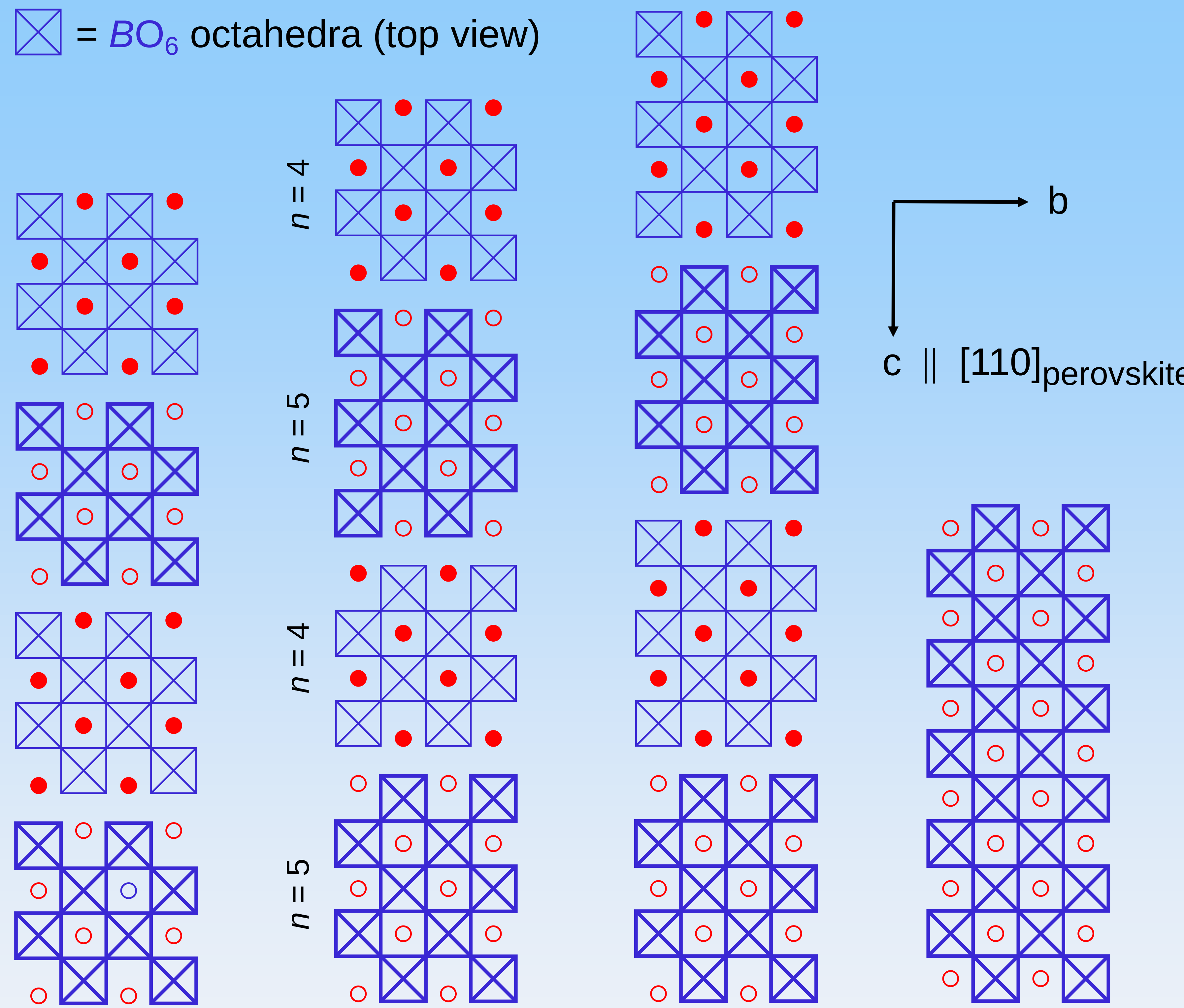
Model System:



t = 100 meV

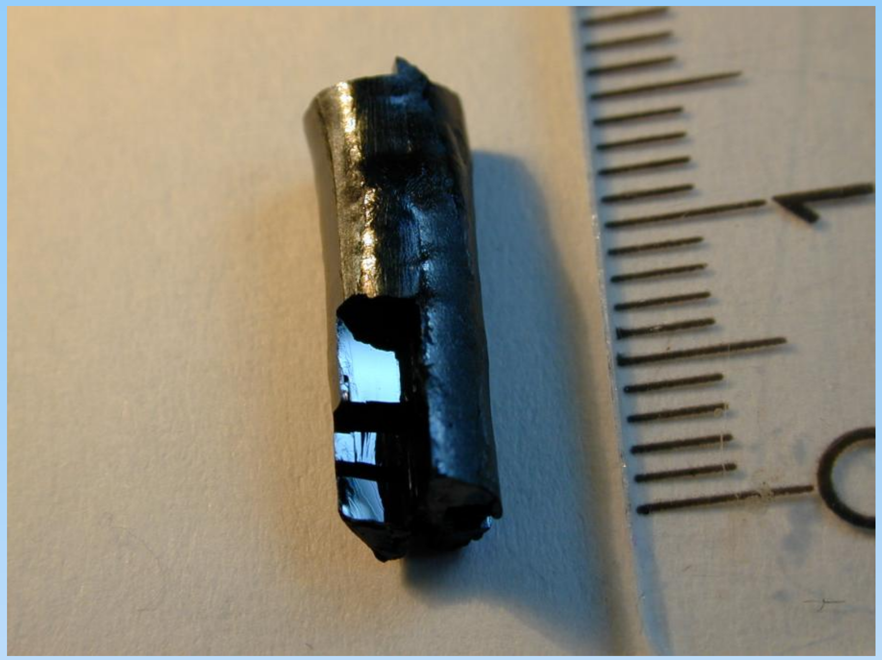
V. Koerting *et al.*, PRB **71**, 104510 (2005)

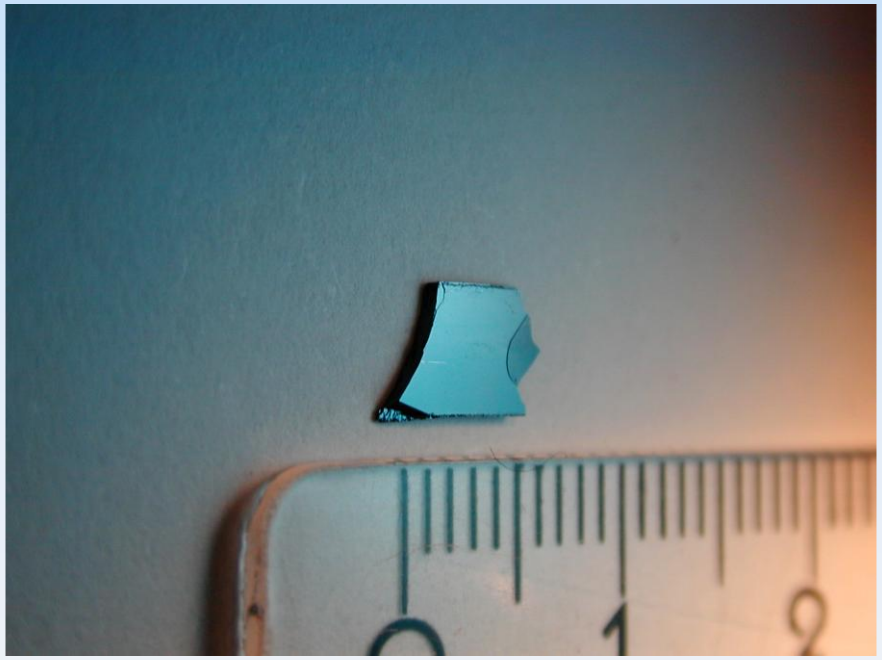
Idealized
(i.e. non-distorted)
crystal structure of
$A_nB_nO_{3n+2}$ = ABO_x



n = 4	*n* = 4.5	*n* = 5	*n* = □
$A_4B_4O_{14}$	$A_{4.5}B_{4.5}O_{15.5}$	$A_5B_5O_{17}$	ABO_3 perovskite
$ABO_{3.50}$	$ABO_{3.444}$	$ABO_{3.40}$	ABO_3

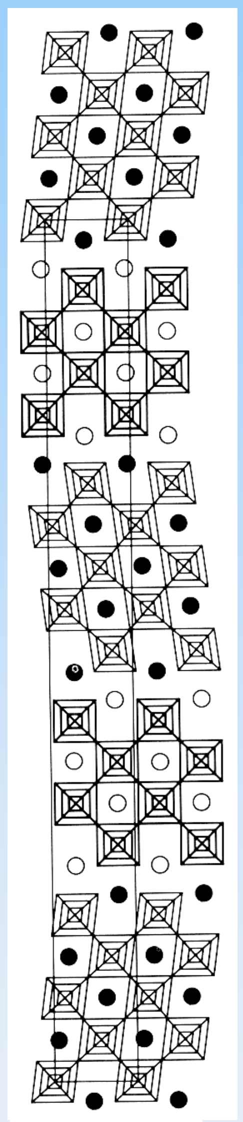
$SrNbO_{3.4}$

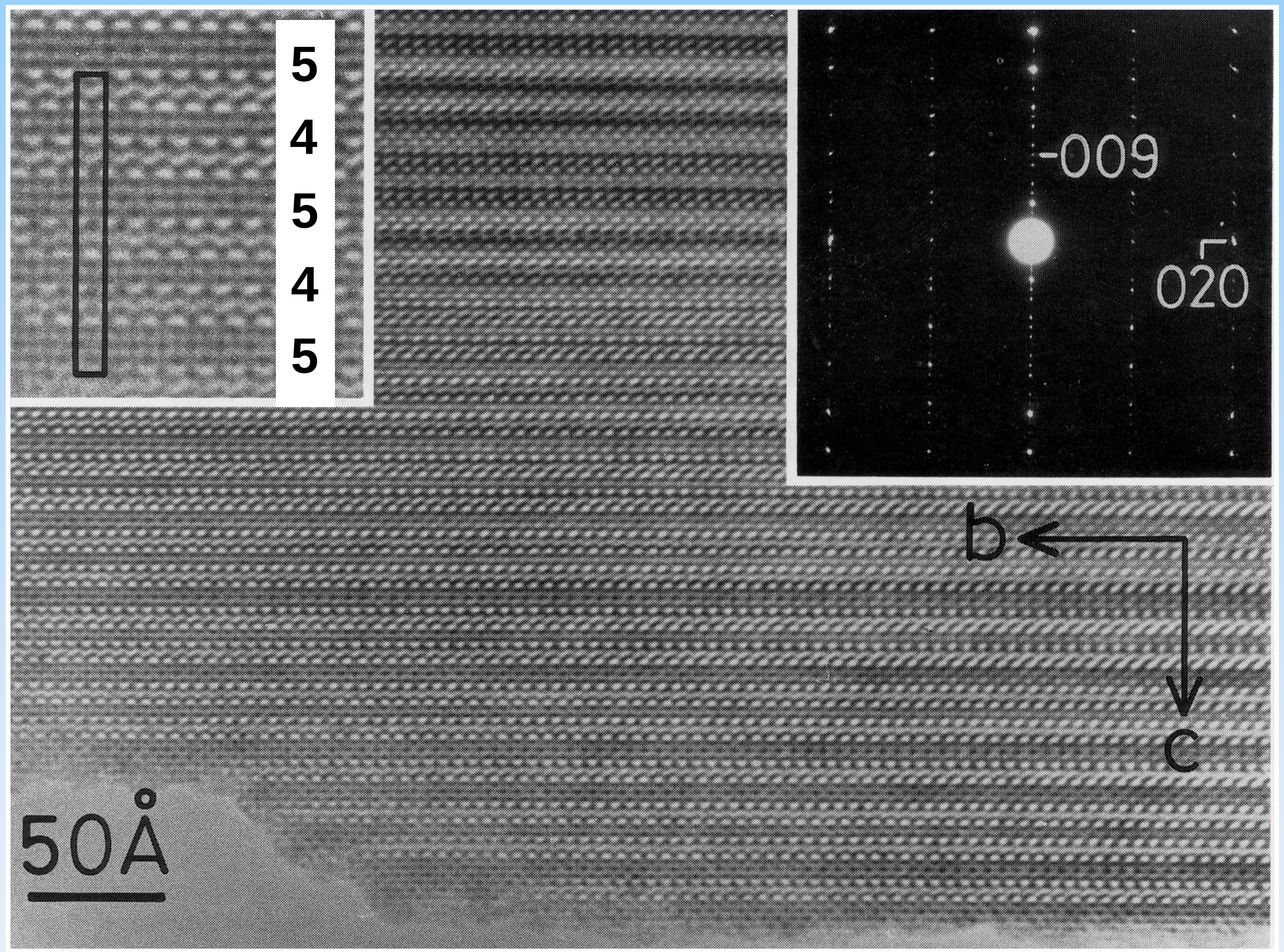




F. Lichtenberg

$A_nB_nO_{3n+2} = ABO_x$ Niobates and Titanates

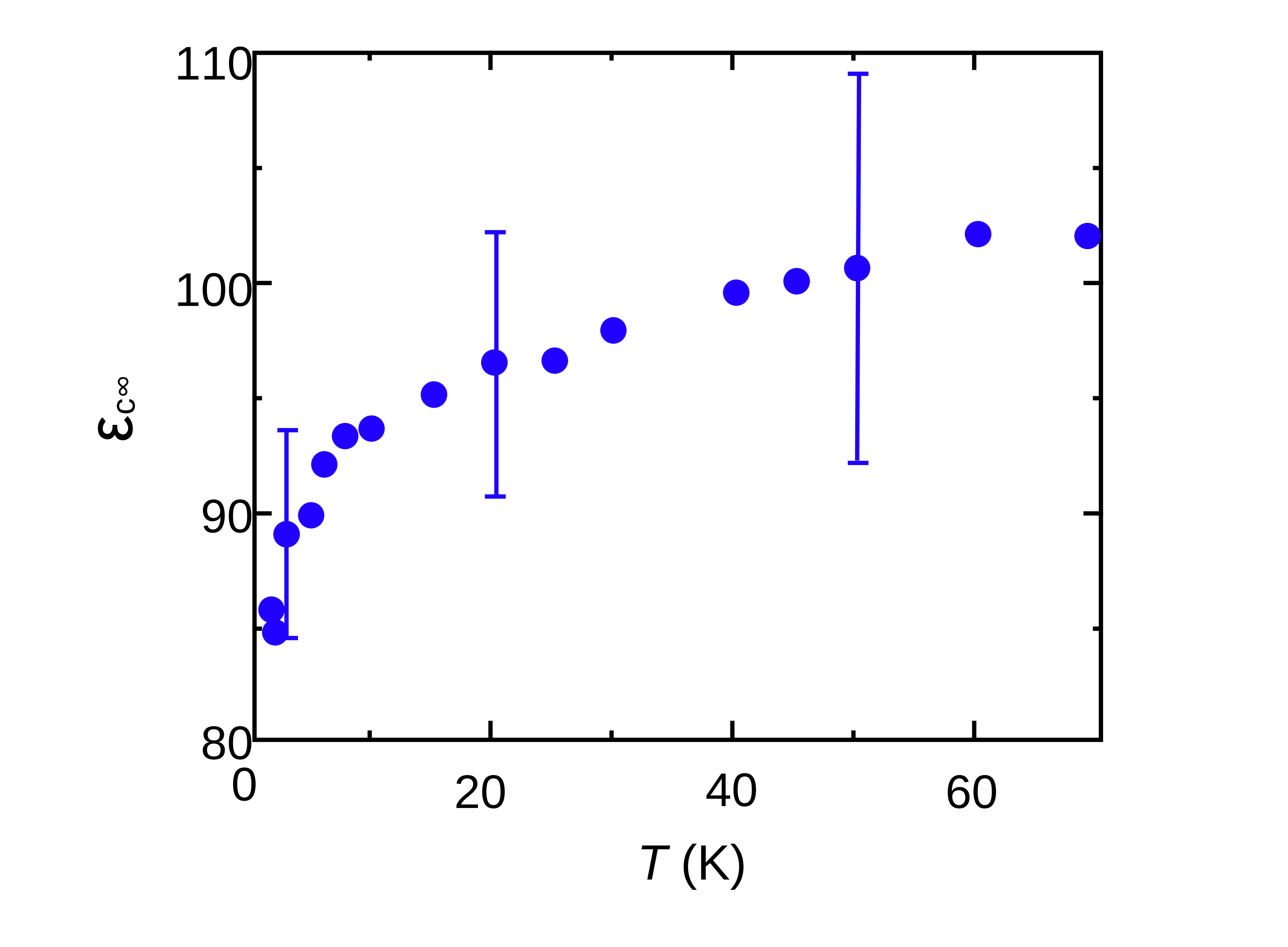




$SrNbO_{3.45}$

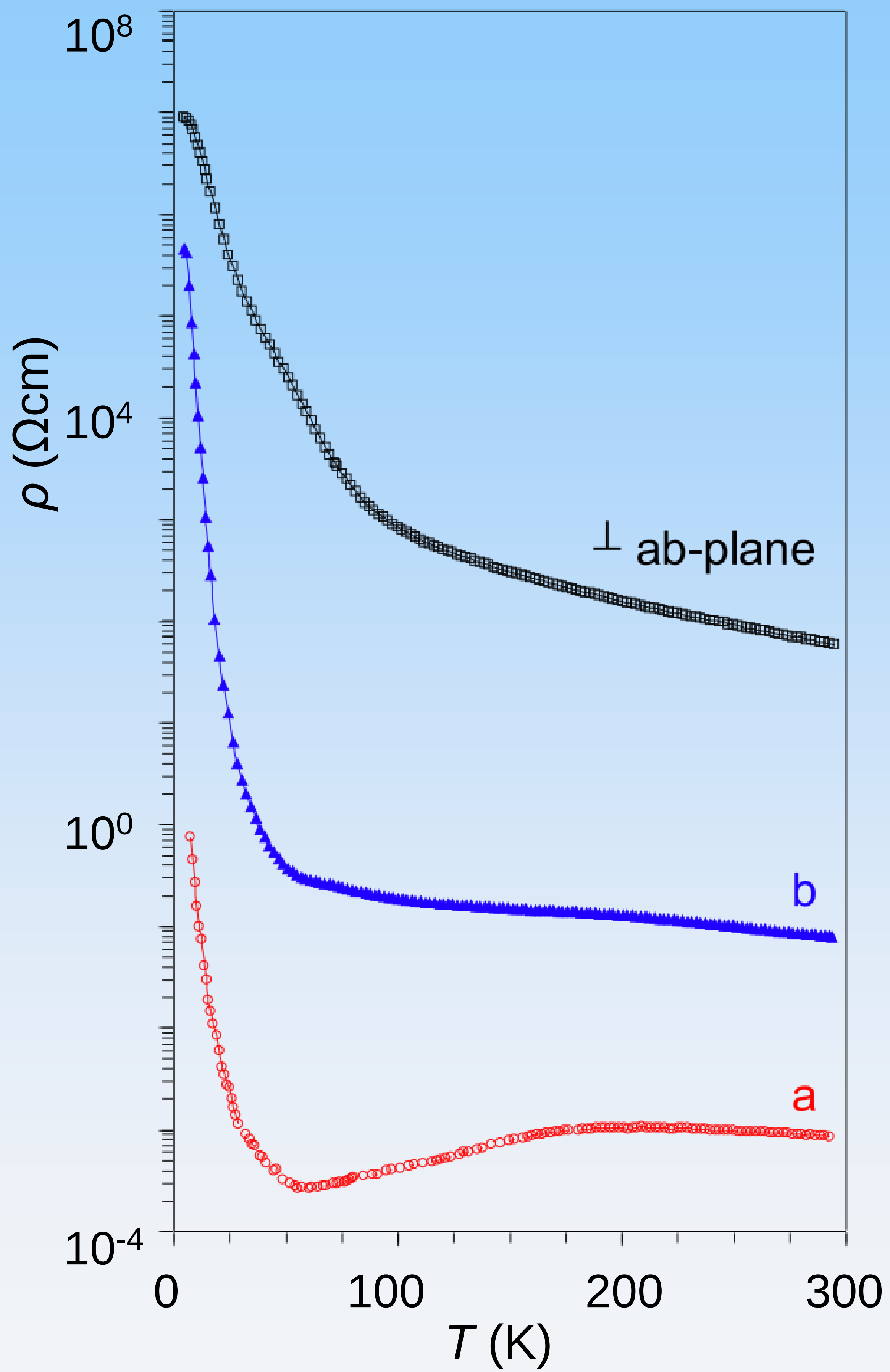
F. Lichtenberg, D. Widmer, J.G. Bednorz, T. Williams, A. Reller, Z. Phys. B **84**, 369 (1991)

Electric Susceptibility of $SrNbO_{3.41}$ along *c*-axis



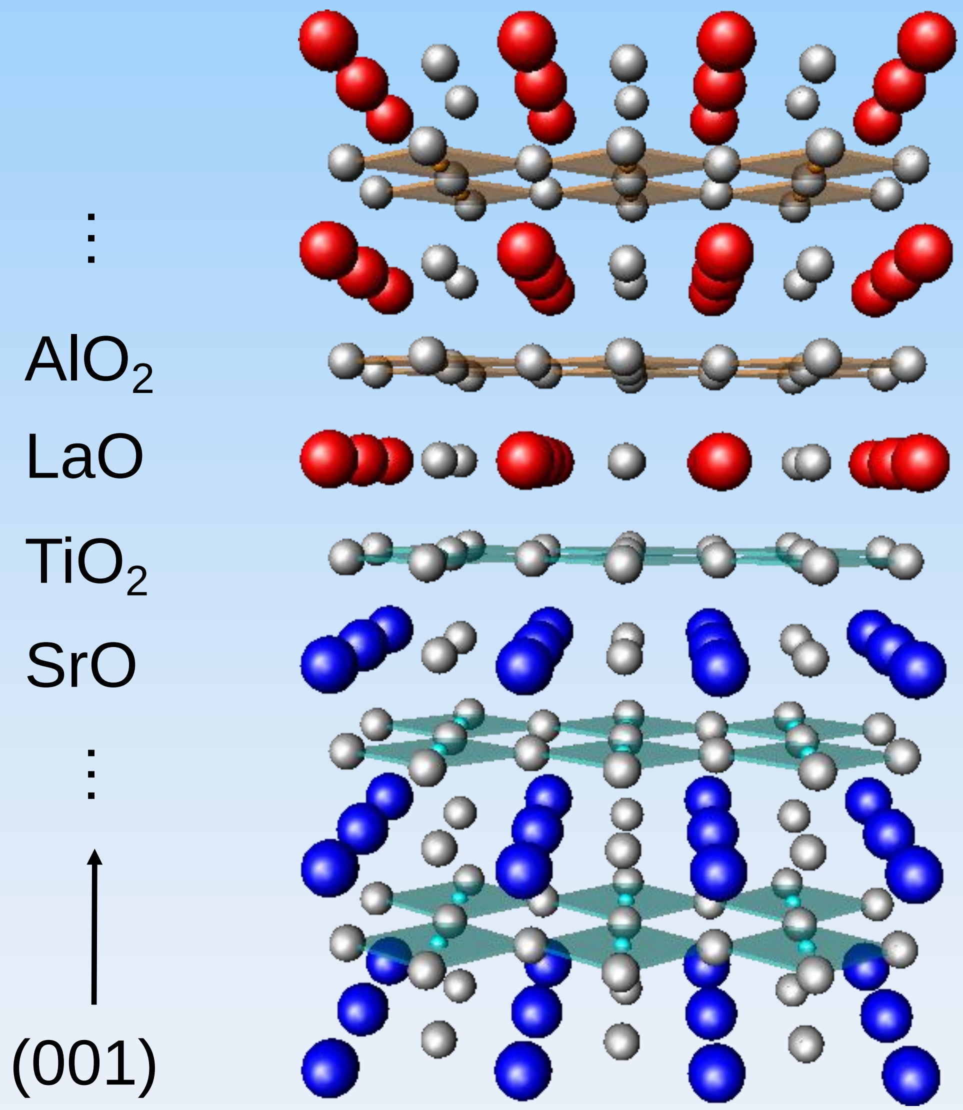
V. Bobnar *et al.*, Phys. Rev. B (2002)

$LaTiO_{3.41}$ $3d^{0.18}$



F. Lichtenberg *et al.*, Prog. Solid State Chem. 29, 1 (2001)

The $LaAlO_3$ / $SrTiO_3$ Interface



$LaAlO_3$:

band insulator

$\Delta = 5.6\,\mathrm{eV}, \;\; \kappa = 24$

$SrTiO_3$:

band insulator

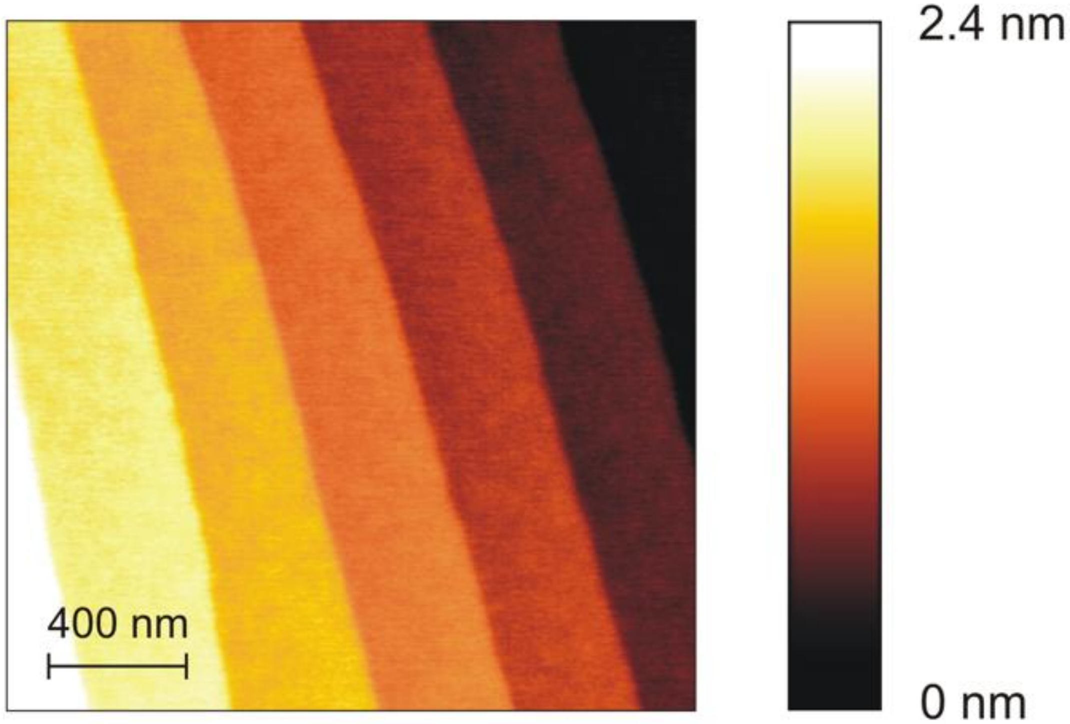
$\Delta = 3.2\,\mathrm{eV}, \;\; \kappa\,(E = 0,\, 4.2\,\mathrm{K}) = 2 \times 10^4$

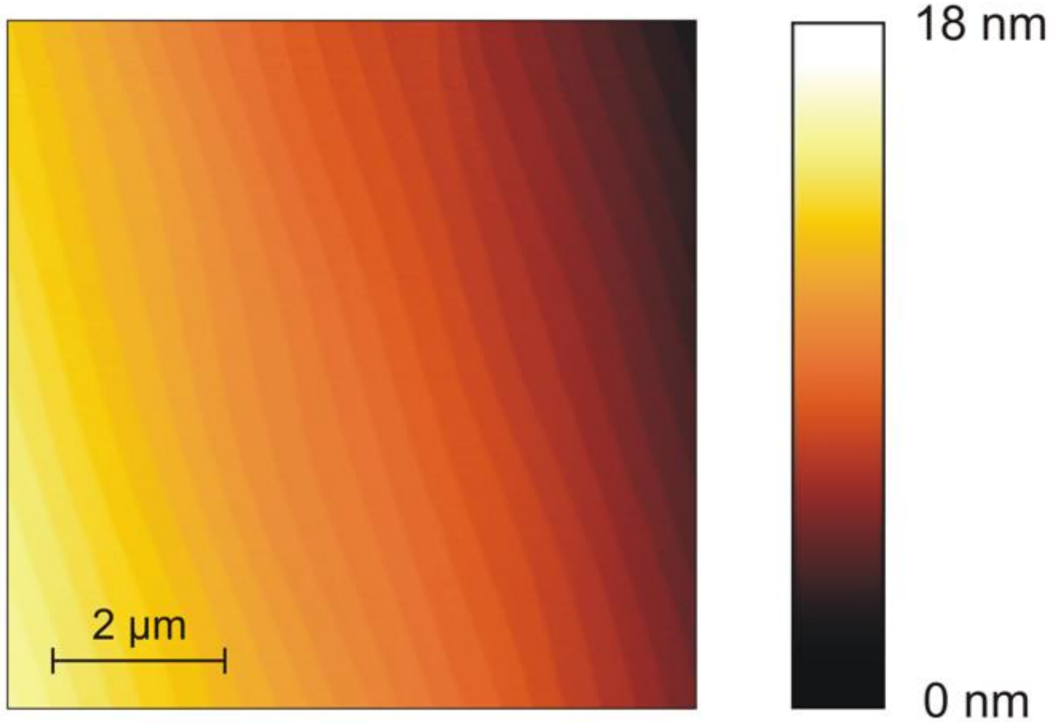
quantum paraelectric

link to Bozovic

A. Ohtomo, H. Hwang, Nature **427**, 423 (2004)

AFM Images of $LaAlO_3$ (5 uc) / $SrTiO_3$ Heterostructure

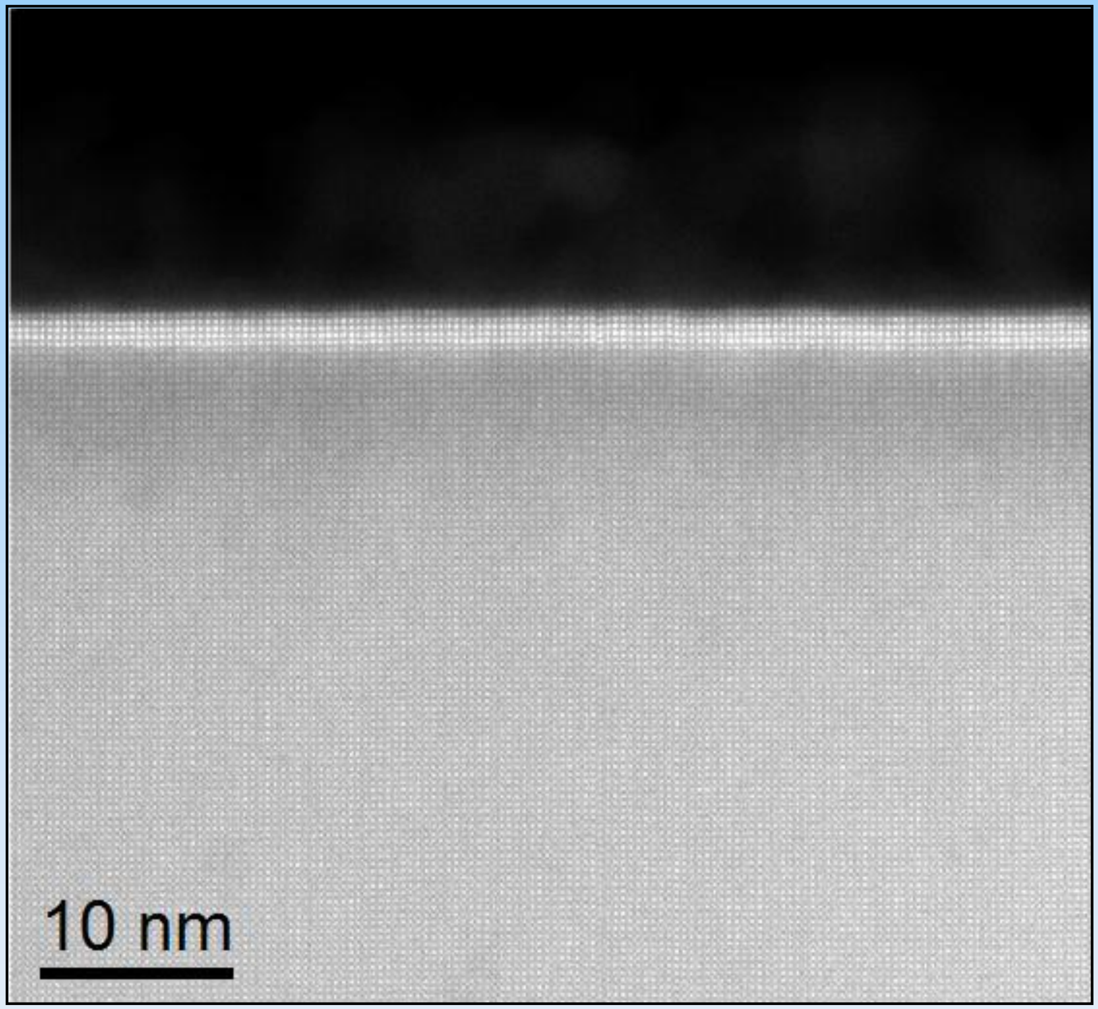




step height: 0.4 nm

STEM: Cross Section

HAADF

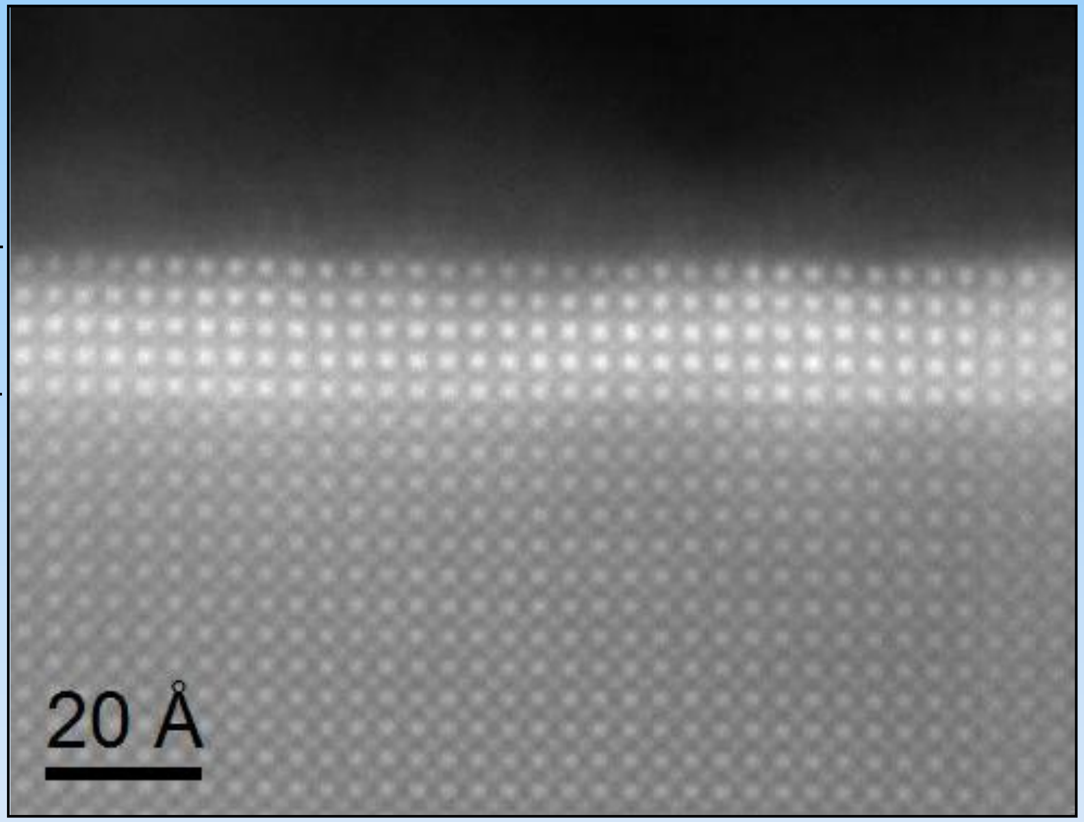


5 uc
$LaAlO_3$

(001)

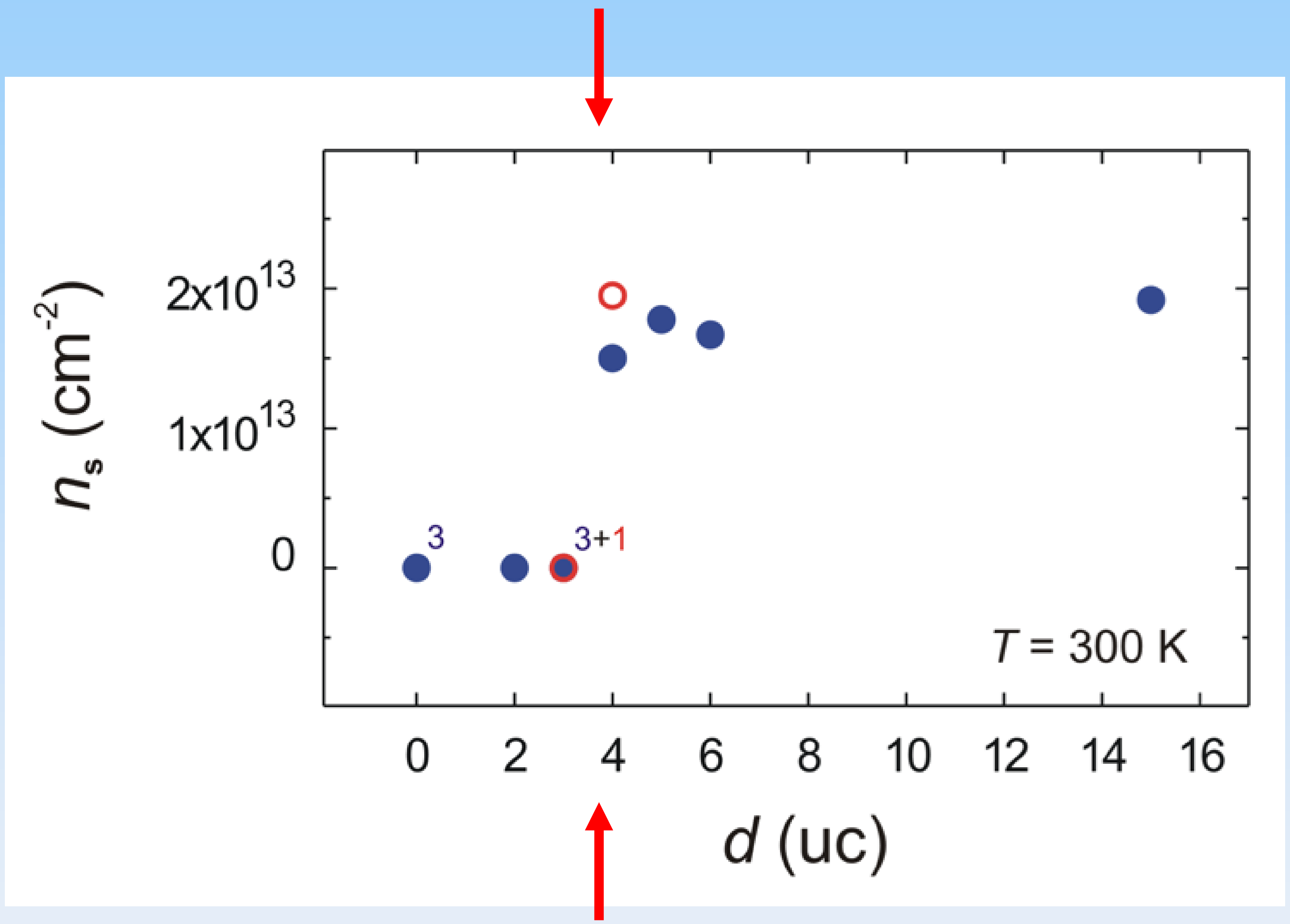
$SrTiO_3$
Substrate

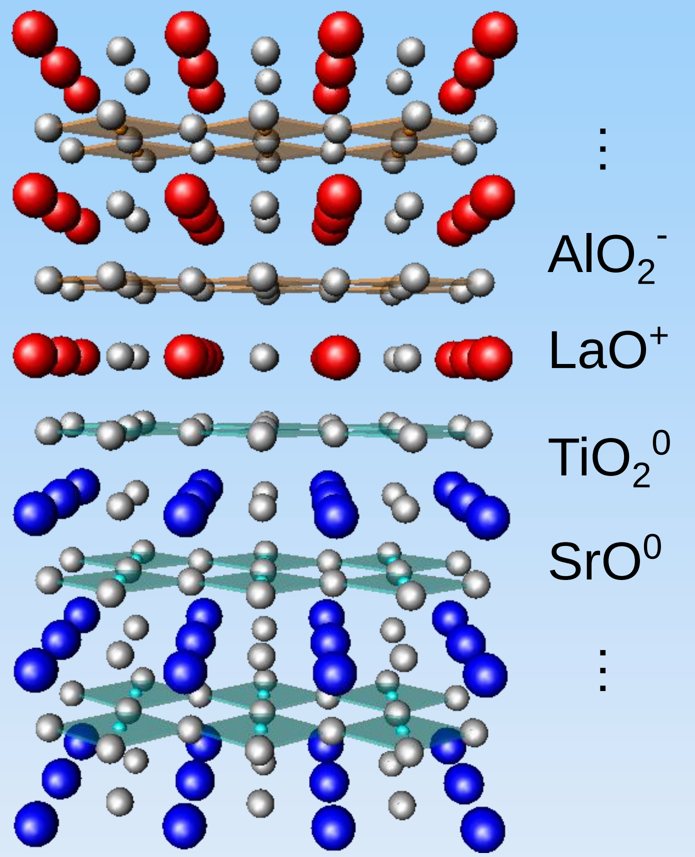
LAADF



L. Fitting-Kourkoutis, D.A. Muller (Cornell)

Interface Conductance *vs* Number of $LaAlO_3$ Unit Cells





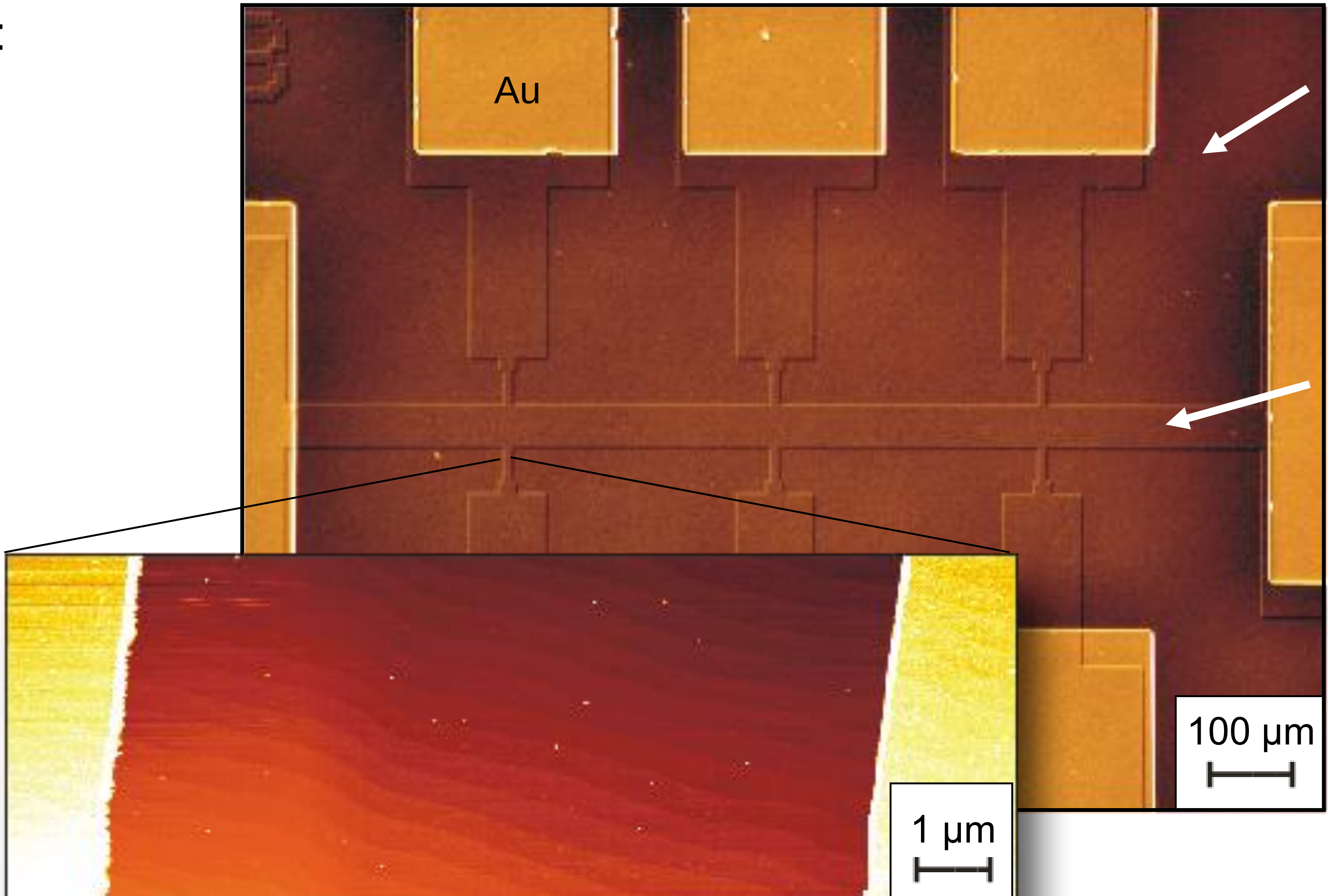
critical thickness

d_c = 4 uc

S. Thiel *et al.*, Science **313**, 1942 (2006)

Pattern Containing q2-DEG

Optical:



2 uc $LaAlO_3$
+
10 nm poly $LaAlO_3$

5 uc epi $LaAlO_3$

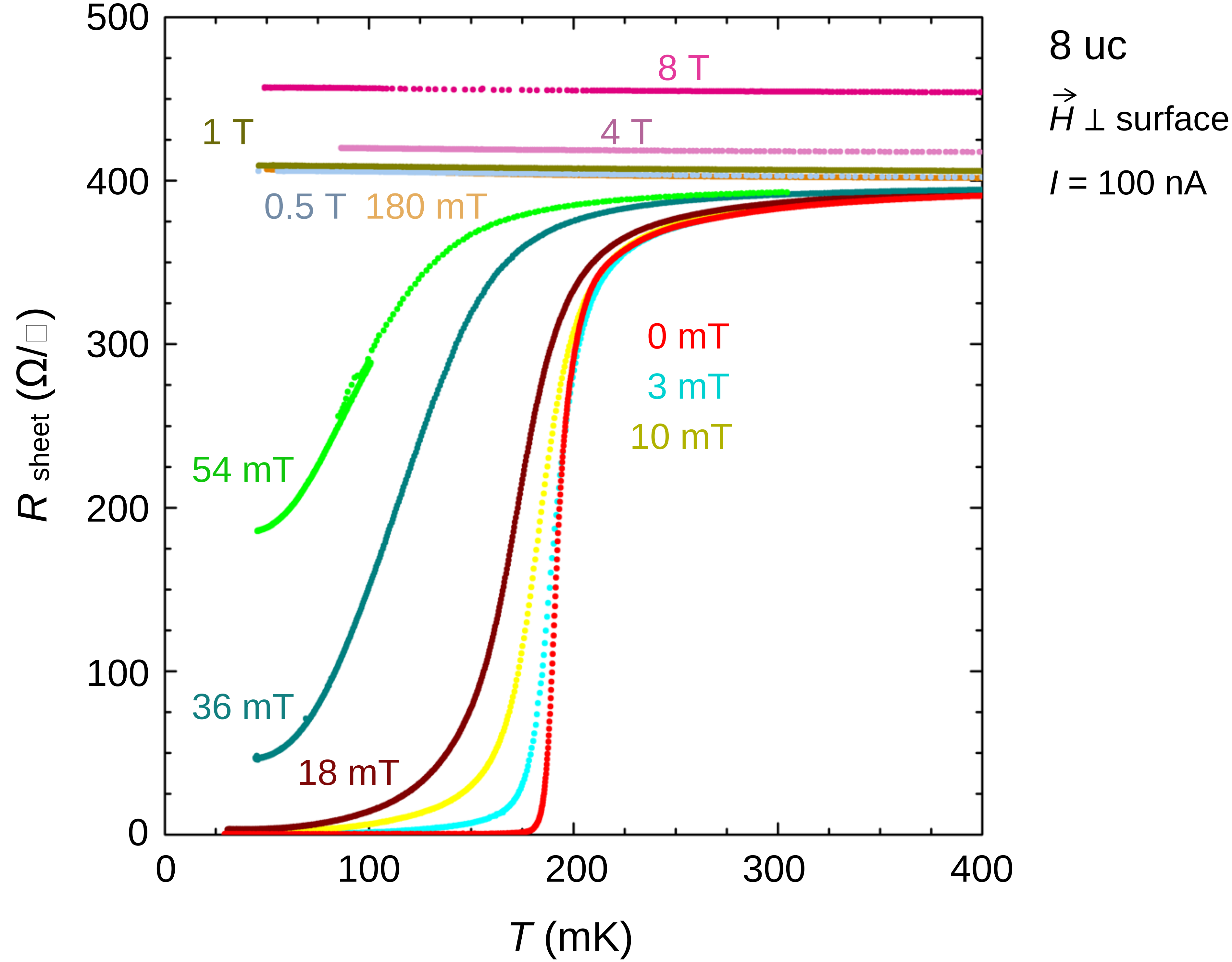
AFM:

2 uc $LaAlO_3$
+
10 nm poly $LaAlO_3$

5 uc epi-$LaAlO_3$

C.W. Schneider et al., Appl. Phys. Lett. 89, 122101 (2006)

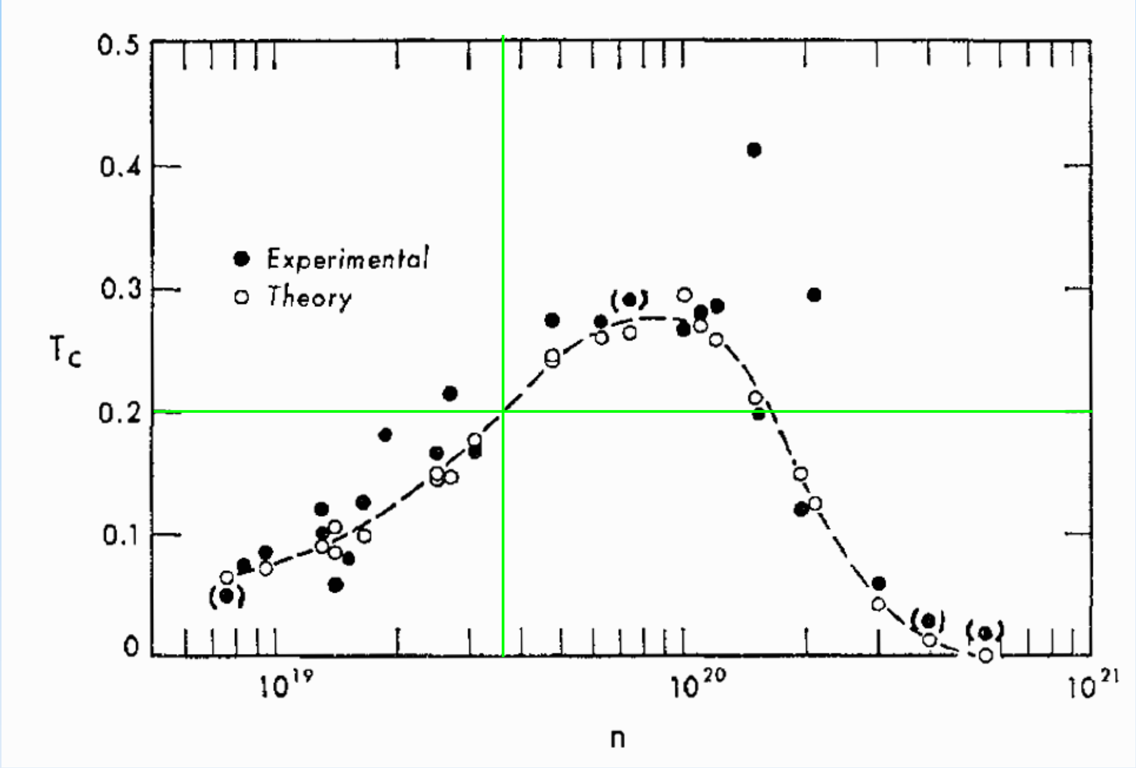
Low Temperature Transport of the Electron Gas



N. Reyren, J.-M. Triscone *et al.*, submitted

Upper Limit to the Thickness of the Superconducting Sheet

➢ T_c = 200 mK ➞ $n \gtrsim 3\times10^{19}$ /cm^3



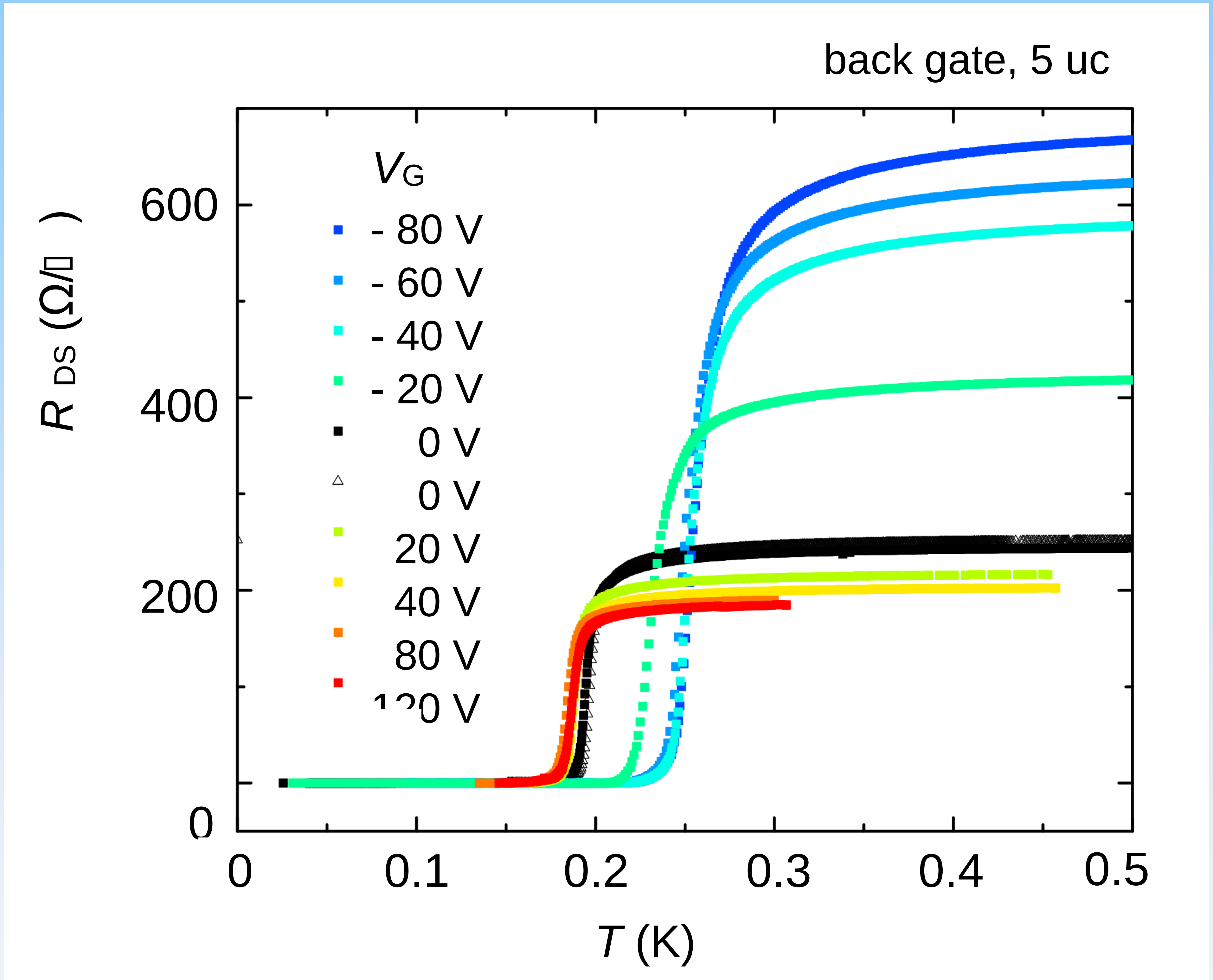
C.S. Koonce, M.L. Cohen *et al.*,
PRL **163**, 380 (1967)

➢ Hall measurements: $n_S \simeq 3\times10^{13}$ /cm^2

➞ $t \lesssim 10$ nm

link to Cohen, Geballe

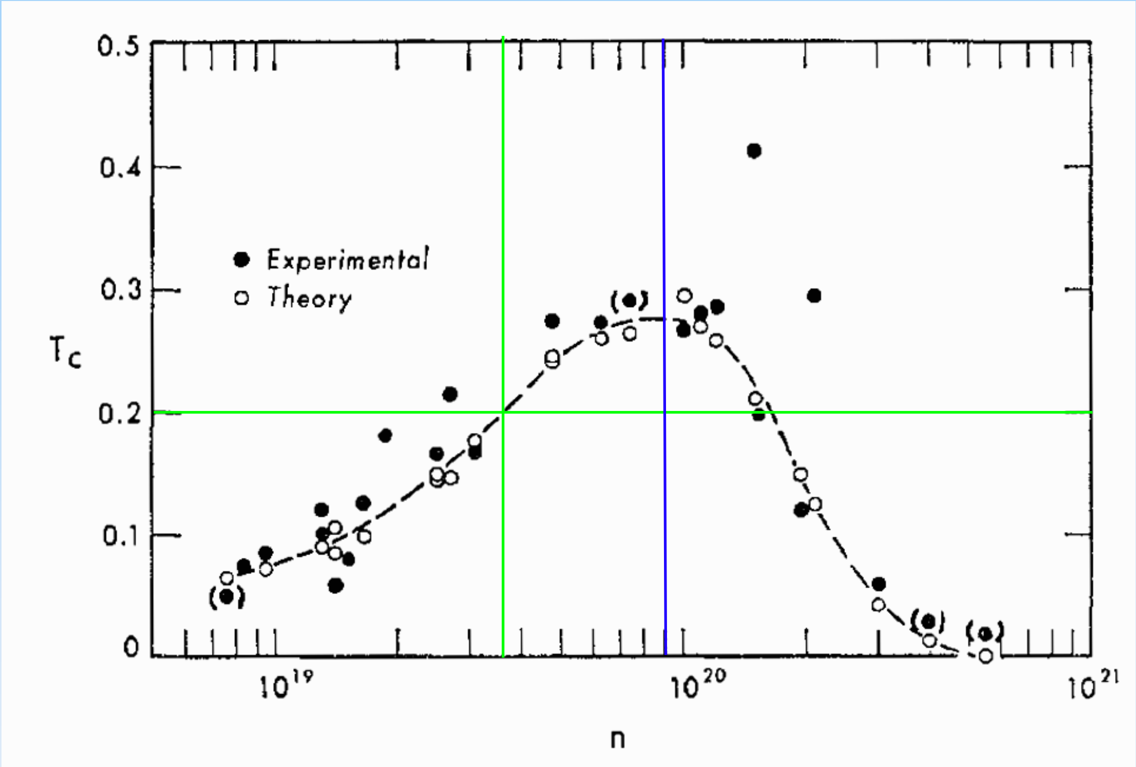
Tuning T_c with Gate Voltages



N. Reyren *et al.*, to be published

Upper Limit to the Thickness of the Superconducting Sheet

overdoped → $n \gtrsim 9\times10^{19}$ /cm^3

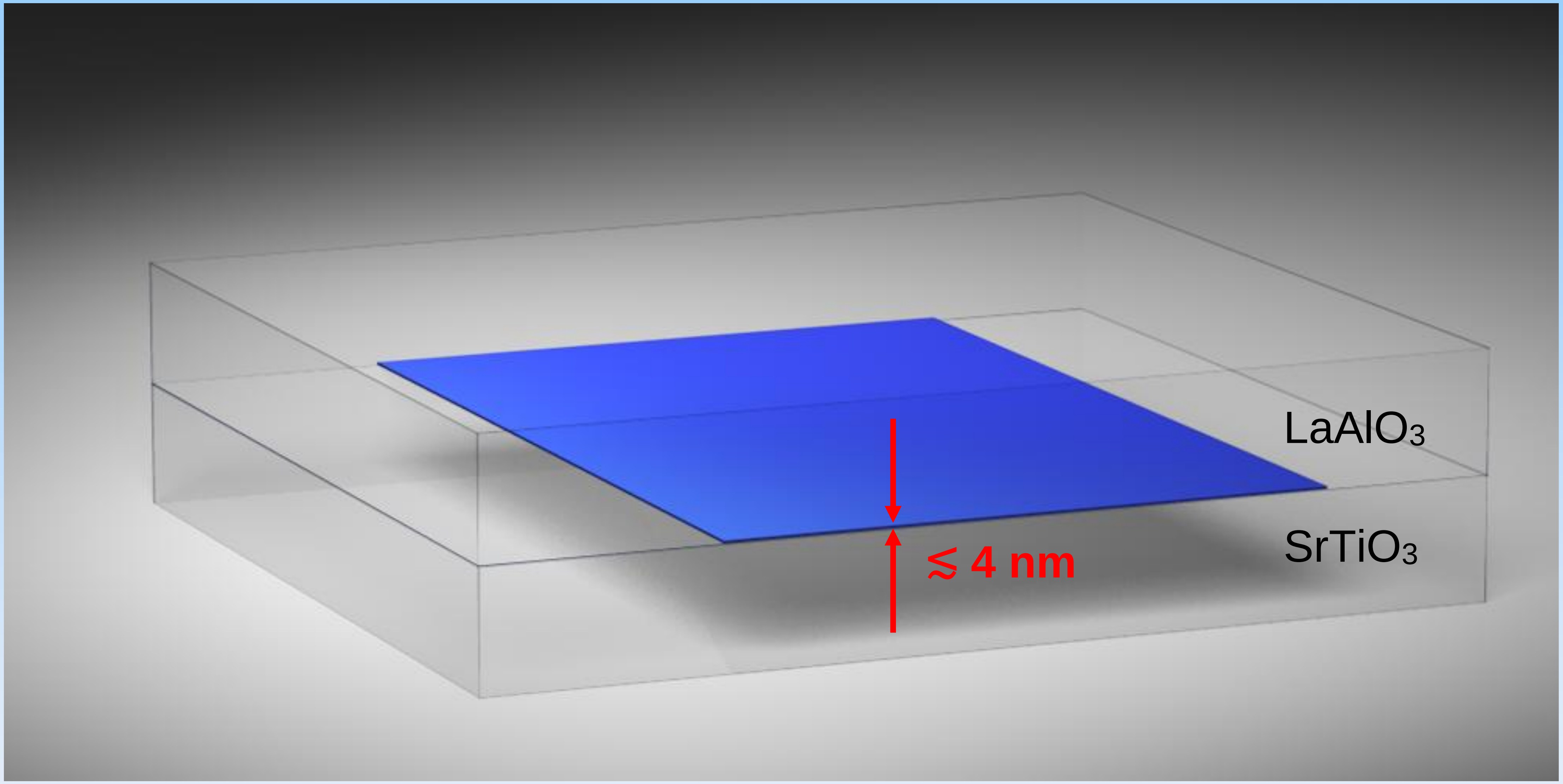


C.S. Koonce, M.L. Cohen *et al.*,
PRL **163**, 380 (1967)

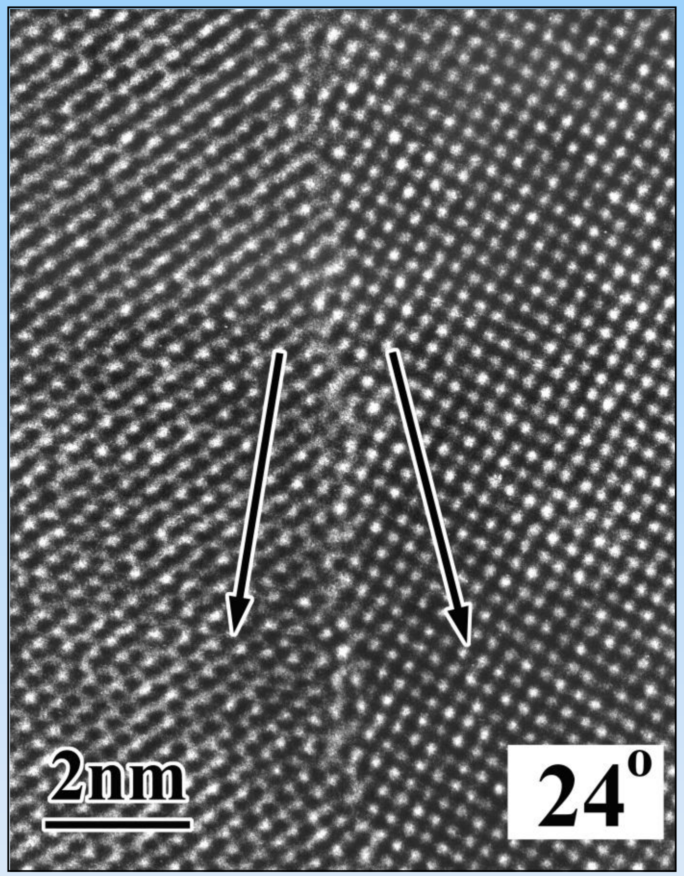
➢ Hall measurements: $n_S \simeq 3\times10^{13}$ /cm^2

→ $t \lesssim 4$ nm

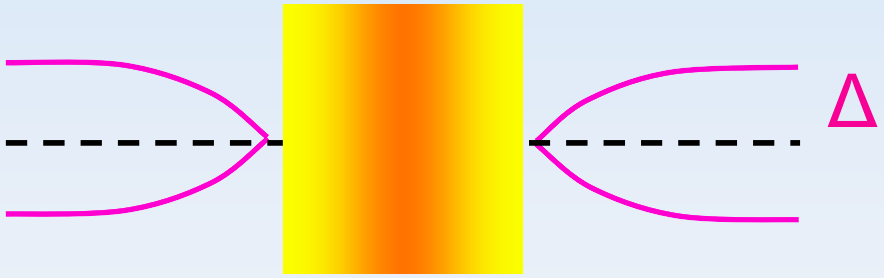
link to Cohen, Geballe

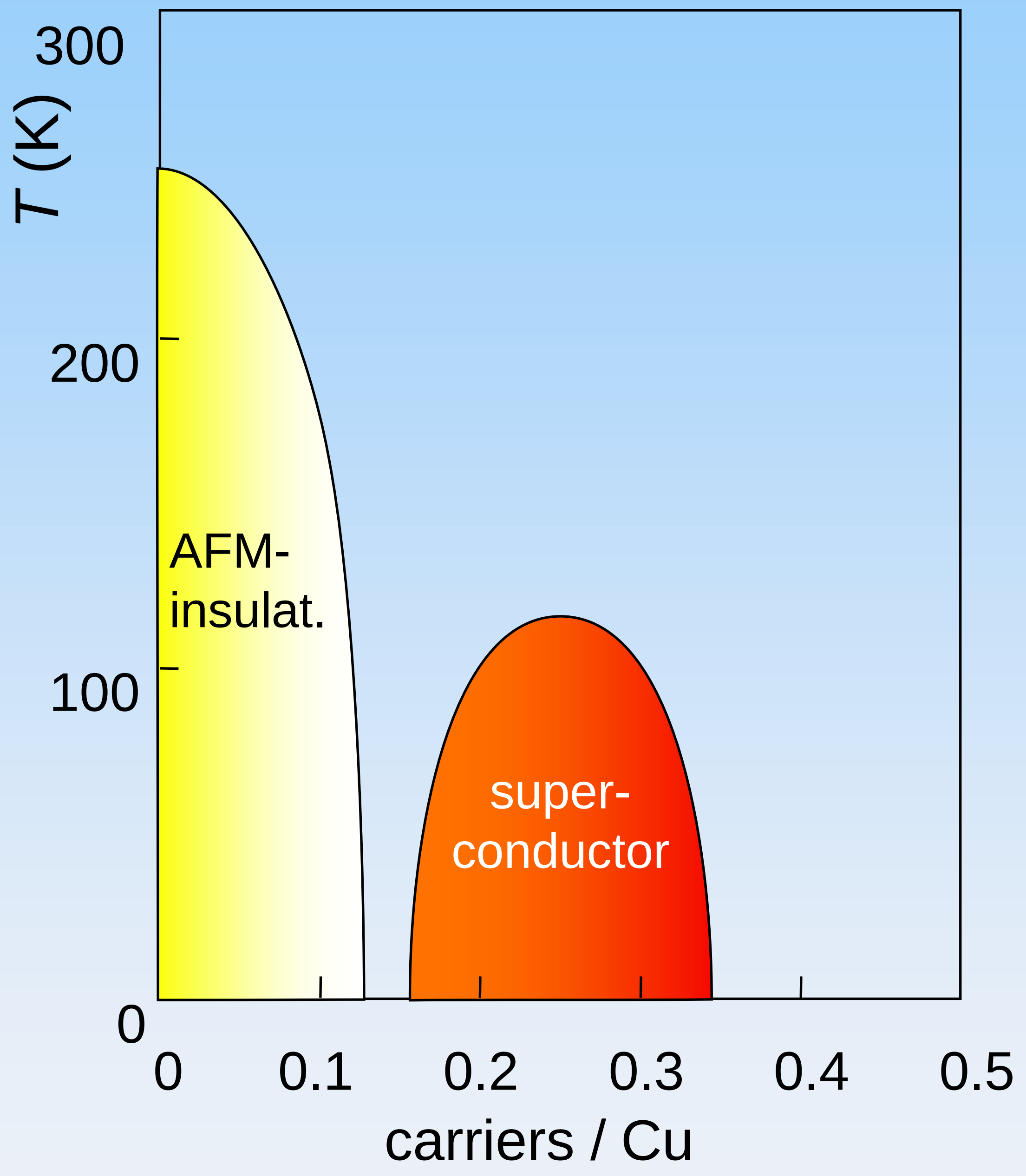

LaAlO3
SrTiO3
≲ 4 nm

Insulating Layers at High-T_c Grain Boundaries



J.G. Wen

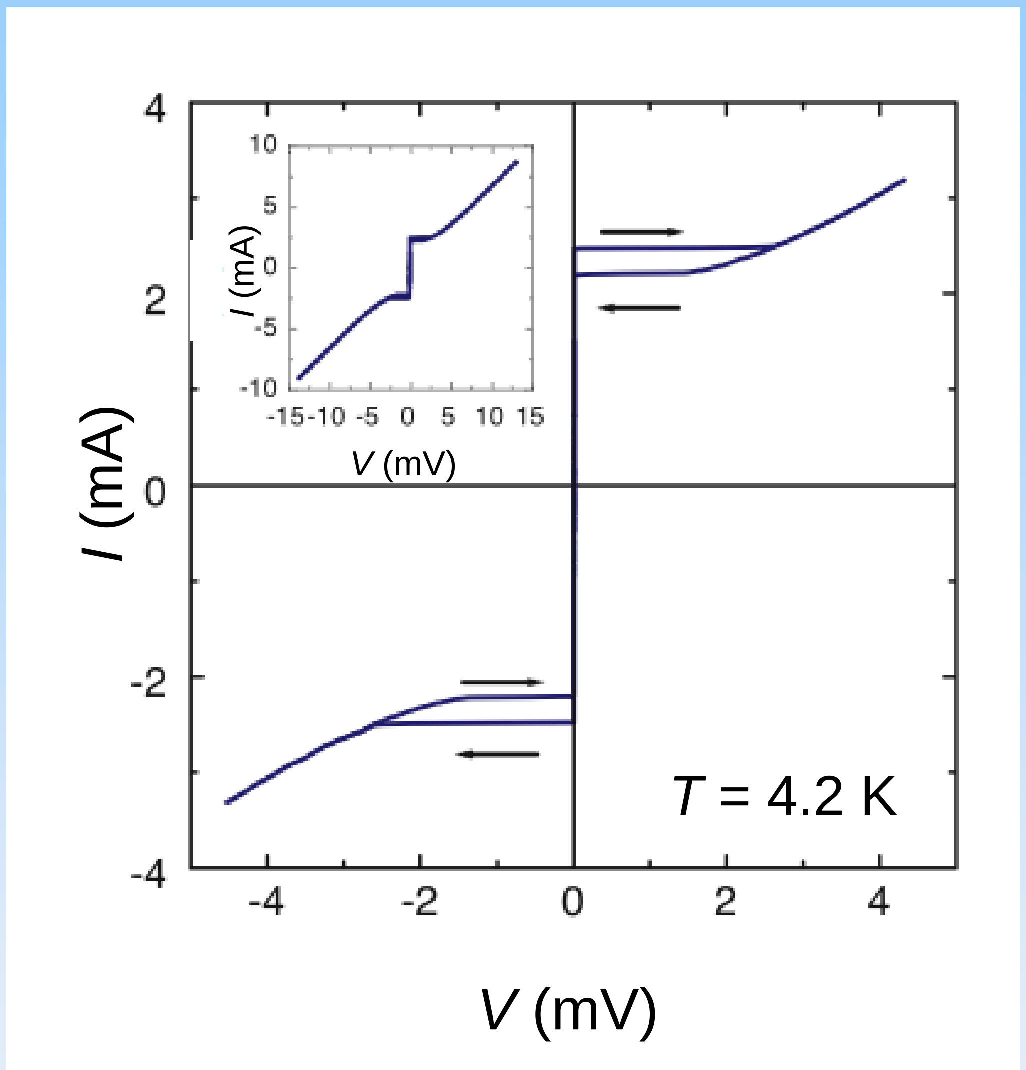




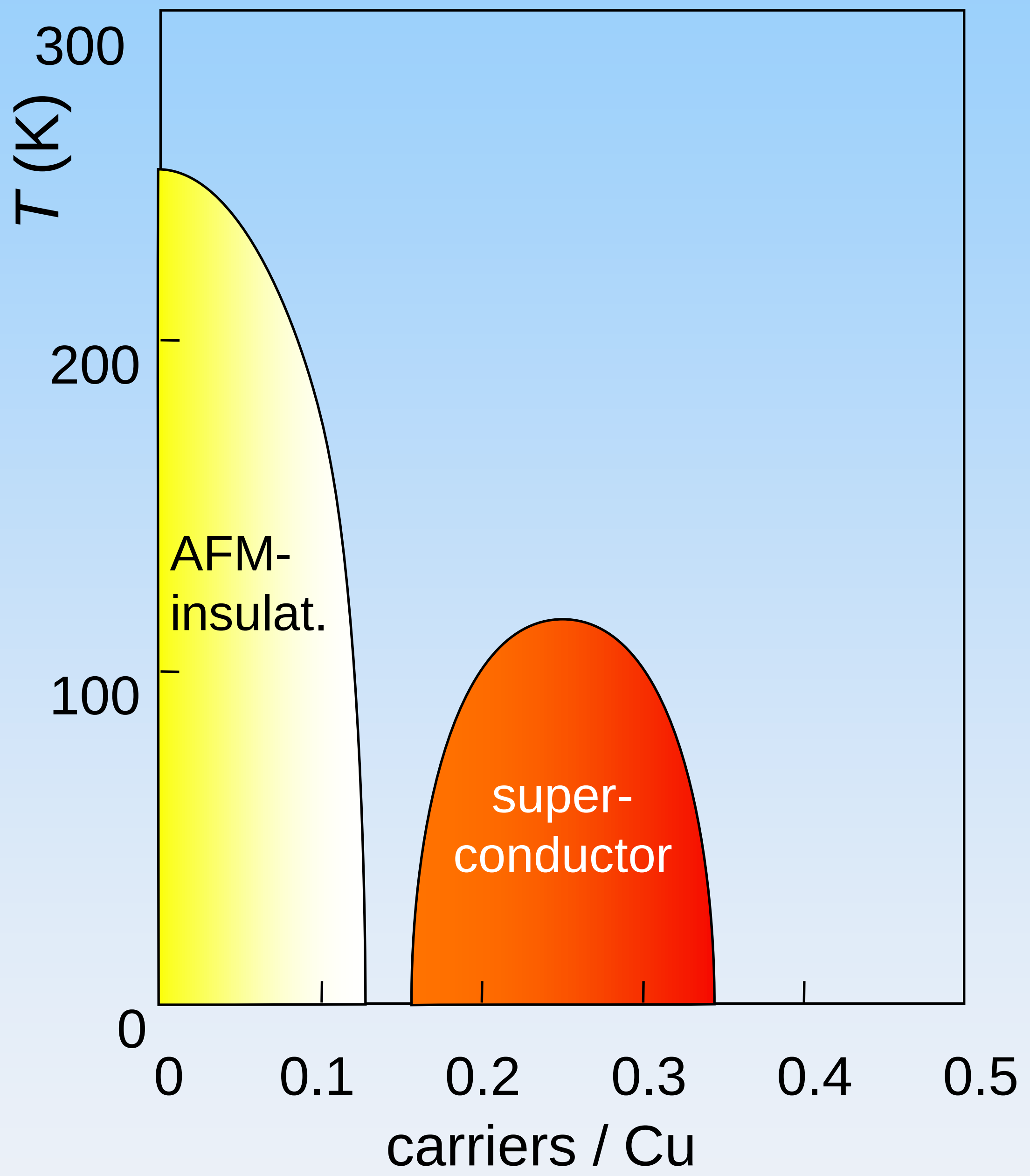
link to Gurevich

J. Mannhart and H. Hilgenkamp, Supercond. Sci. Technol. **10**, 880 (1997)

Insulating Layers at High-T_c Grain Boundaries

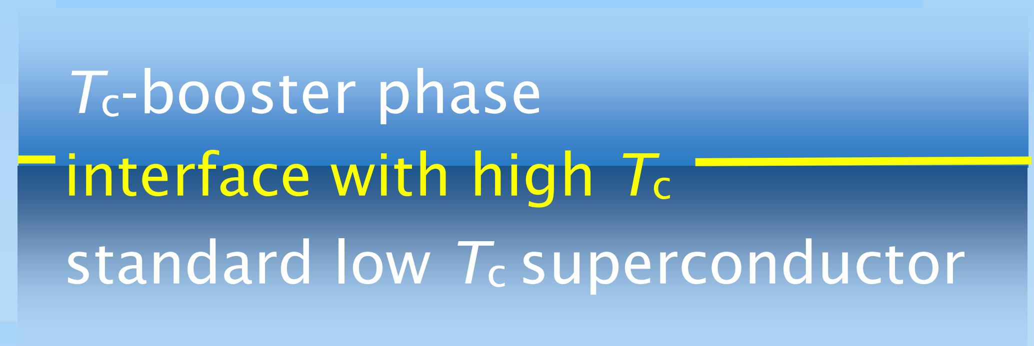


24° $YBa_2Cu_3O_{7-x}$ grain boundary



J. Mannhart and H. Hilgenkamp, Supercond. Sci. Technol. **10**, 880 (1997)

Proposal: Boosting T_c with second phases:



- inducing correlations at interfaces
- providing pairing interactions
- doping the interfaces
- generating electric and magnetic fields
- generating stress/strain at interface
- extending stability range of superconducting phase

link to Chu, Bozovich

Searching for the Preferable Mesoscopic Structure

Phase coherence problem :

$$E_{\mathrm{J}} = \frac{\hbar I_{\mathrm{c}}}{2e}$$

$d = 10\,\mathrm{nm},\ w = 10\,\mu\mathrm{m}$

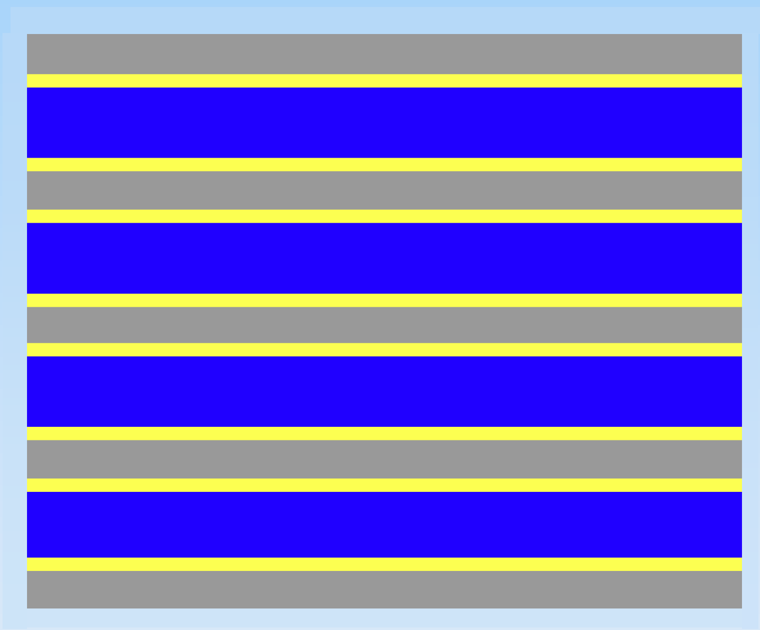
$\longrightarrow$ $J_{\mathrm{c}}(300\,\mathrm{K}) \geq 10^6\,\mathrm{A/cm^2}$ required for $R\,(300\,\mathrm{K}) \approx 0$

$\longrightarrow$ mesoscopic structure requires interfaces connected in parallel

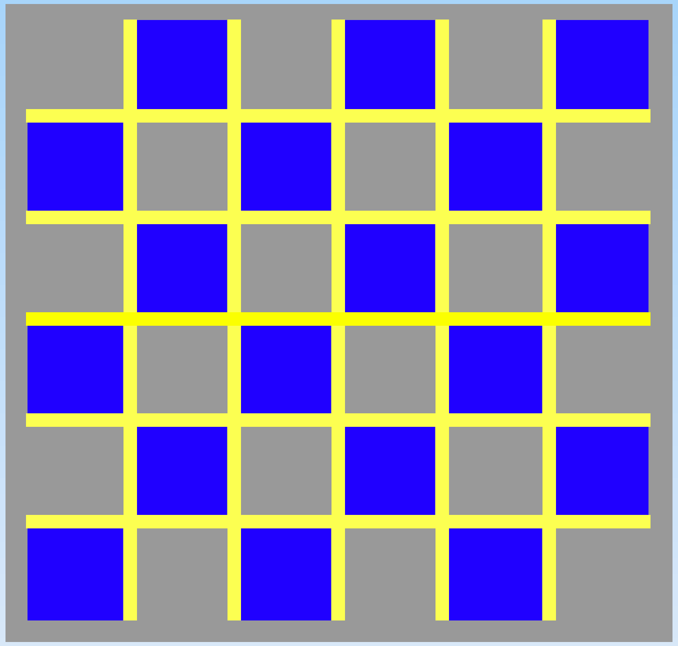
links to Beasley, Gurevich

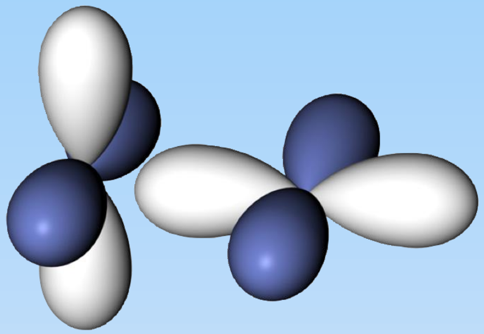
Searching for the Preferable Mesoscopic Structure

cross-sections:



small c-axis coupling



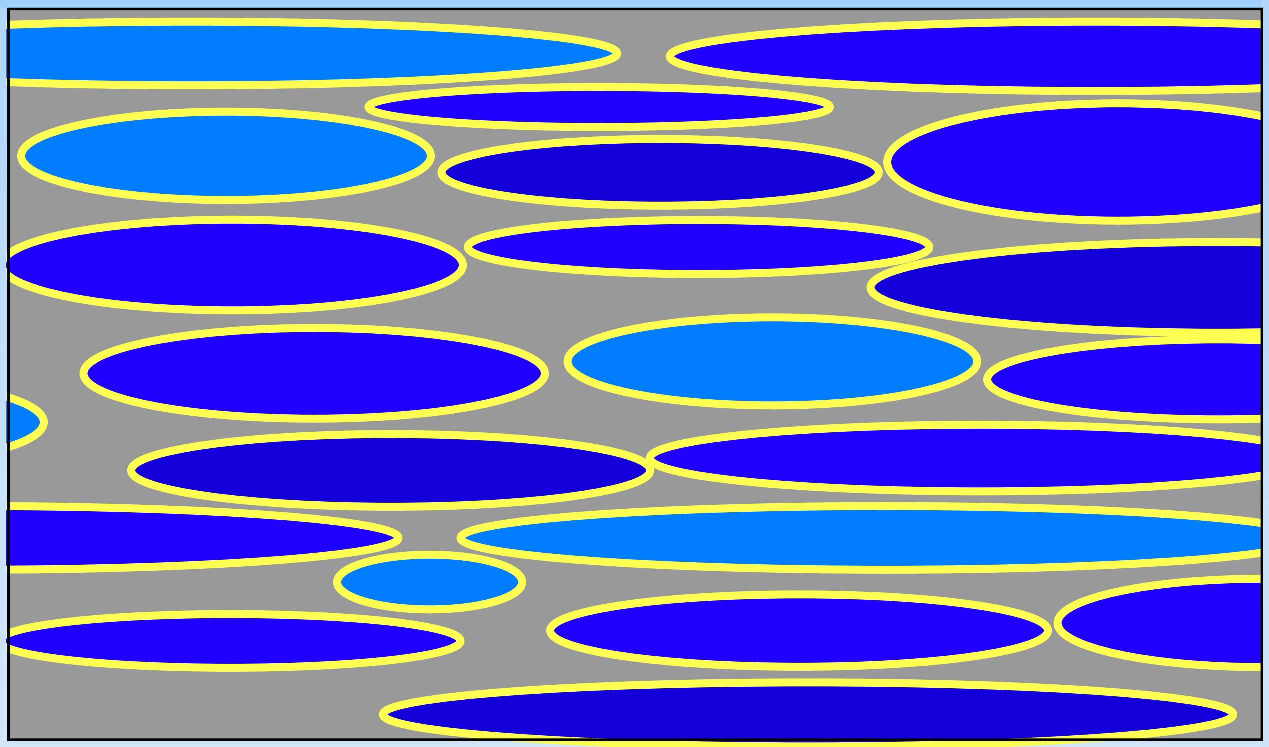


problematic for anisotropic superconductors

length scales: correlation lengths, λ_{el}, ξ, ...

$\longrightarrow$ mesoscopic structure required

Searching for the Preferable Mesoscopic Structure



structure of some
early HTS USOs?

(superconducting) matrix: HTS, organics, whatever ...

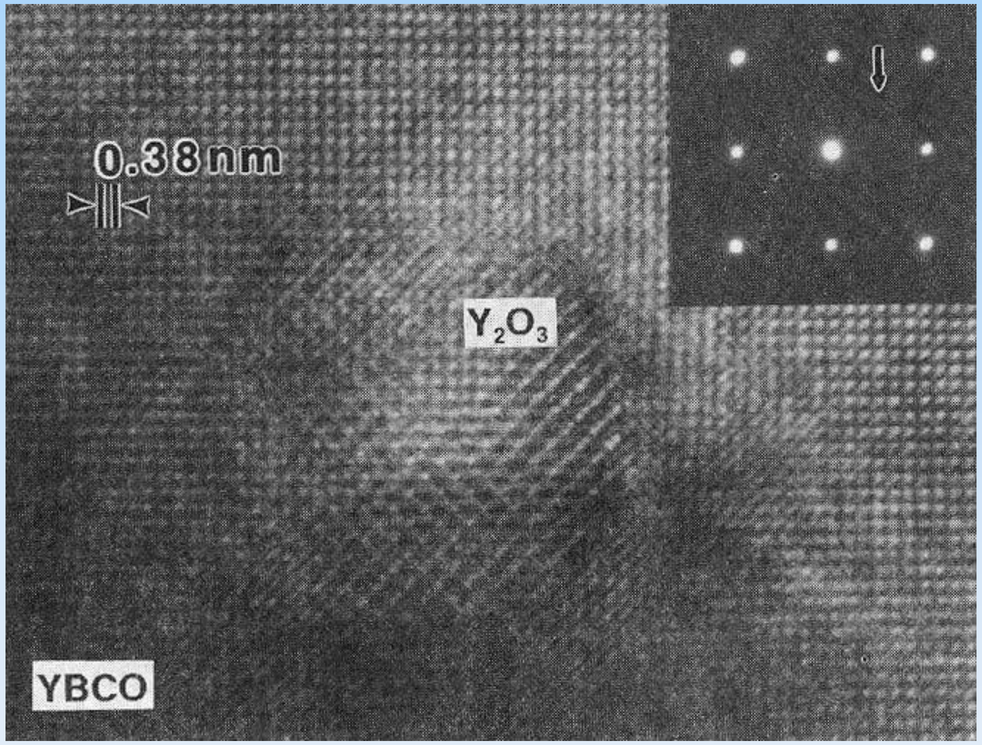
T_c booster phase

interfaces with boosted T_c
effectively percolating

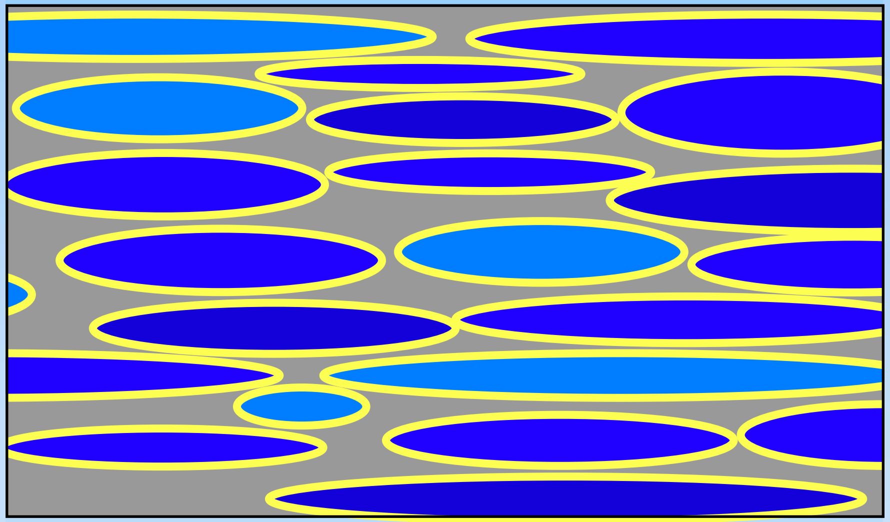
How to Grow the Hybrid-Structures?

Bulk and film methods

Y_2O_3 in epitaxial $YBa_2Cu_3O_{7-x}$ film



A. Catana *et al.*, Appl. Phys. Lett. **60**, 1016 (1992)

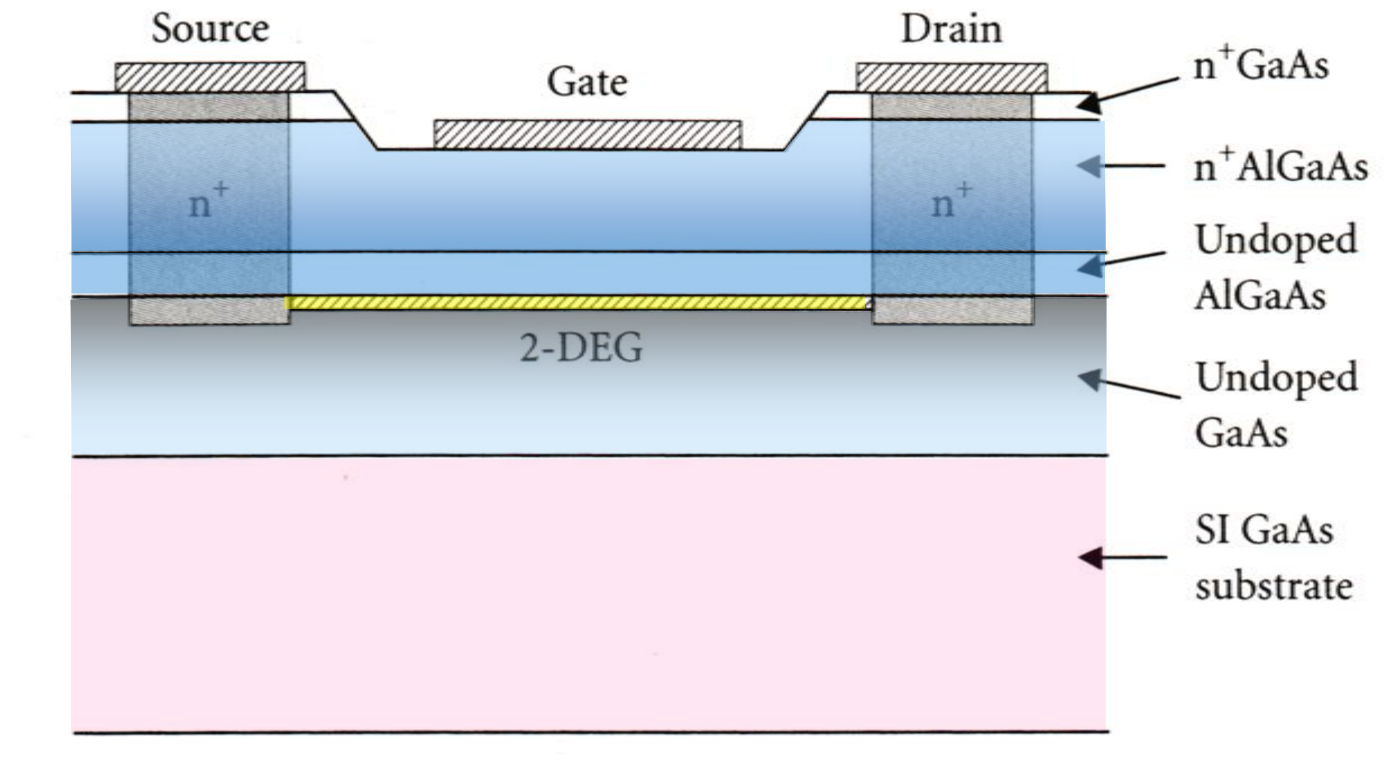


The growth problem of interest for a spectrum of applications

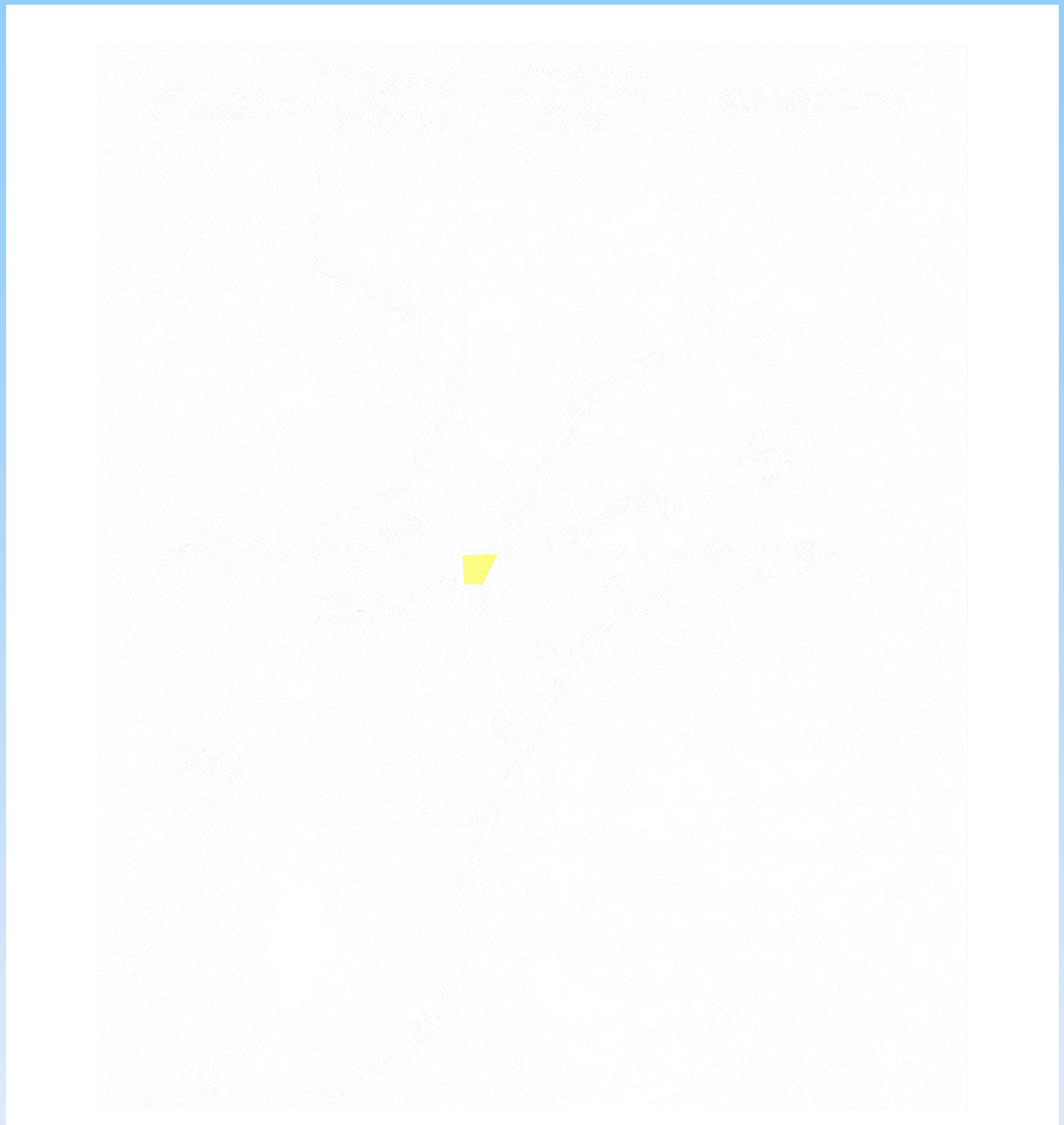
first industrial solutions for the growth of nano-scale inclusions in coated conductors

link to Gurevich

Analogon: III-V Heterostructures

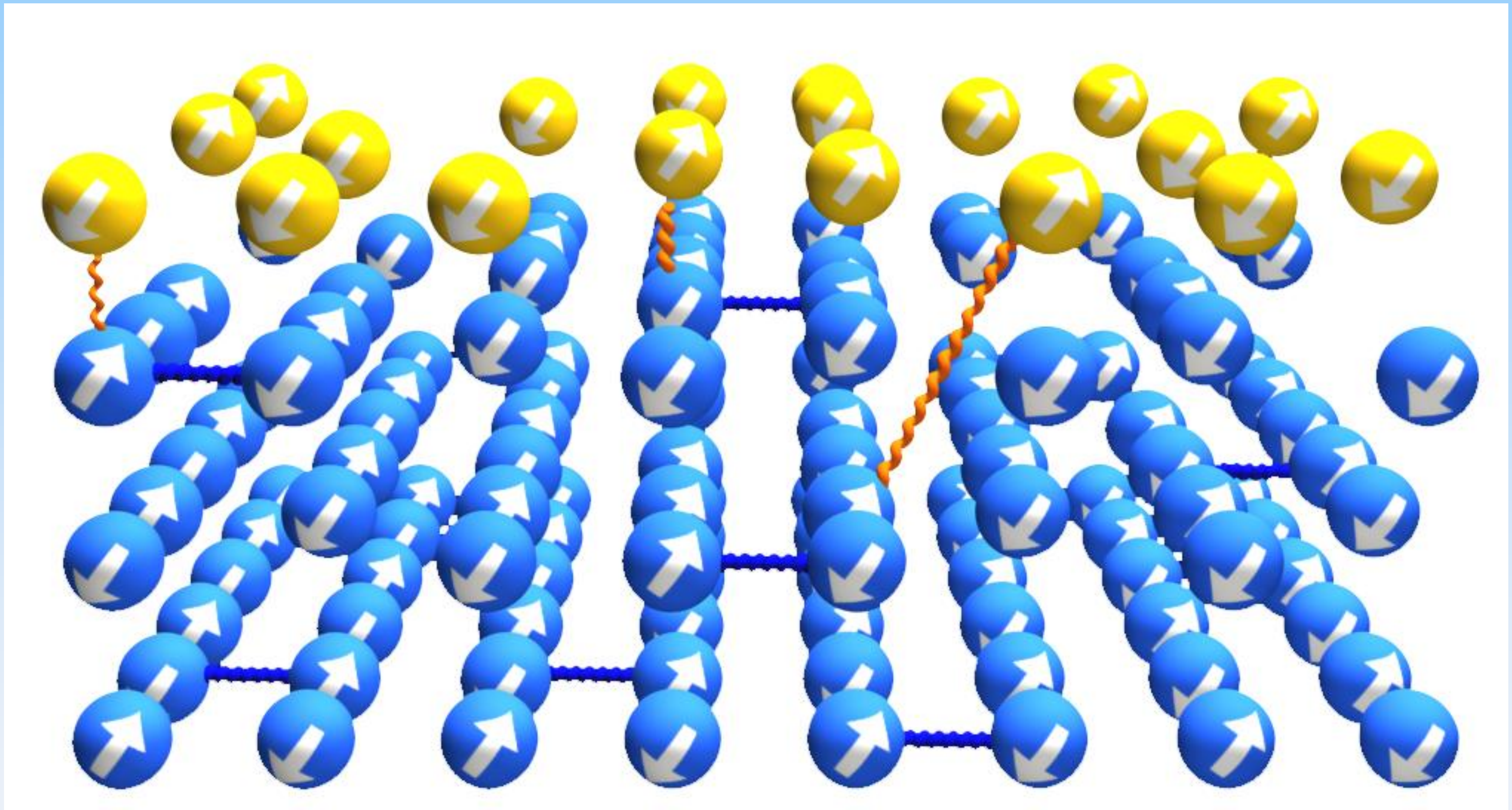


AlGaAs/GaAs-HEMT



S.M. Sze: „High Speed Semiconductor Devices“

Mobile Electrons at Interfaces of Complex Materials



Conclusion:

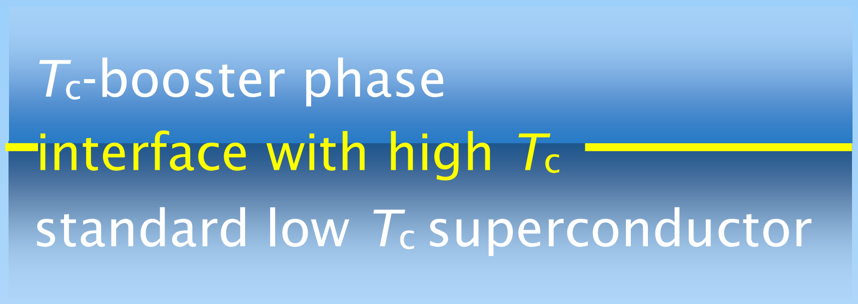
Use Mesoscopic Structure to Enhance T_c

- ➢ Kresin Effect: nanoclusters with number of electrons close to magic
- ➢ For superconductors that like a self-organized internal structure:

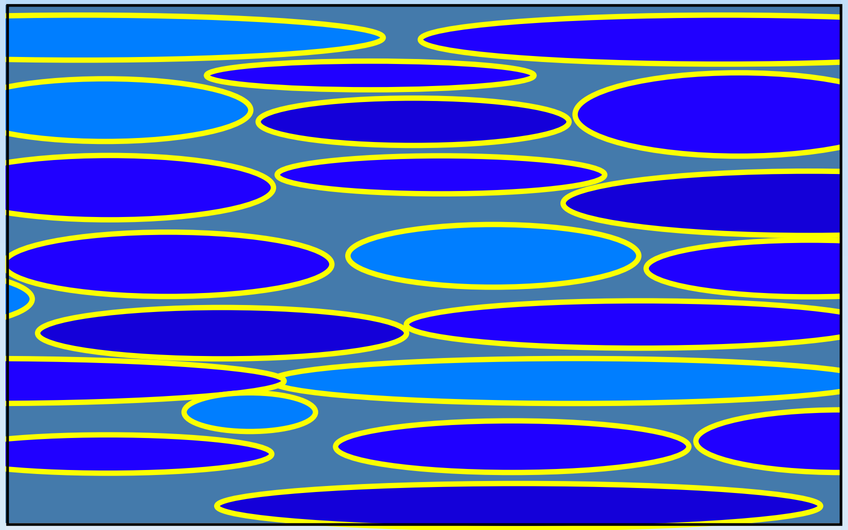
  add matching microstructure
- ➢ "Hybrid" superconductors to gain a high-T_c at interfaces

Conclusion:

“Hybrid” Superconductors:



- superconducting matrix
- second phase to enhance T_c of interface layers
- optimization of the mesoscopic structure



Road to higher T_c’s?