Nano-Magnetism at Interfaces in High-Temperature Superconductors?

T. Kopp, C. Laschinger, C.W. Schneider,
A. Weber, J. Mannhart

Institute of Physics, University of Augsburg

Nano-05, May 12, 2005

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G. Hammerl

A. Herrnberger

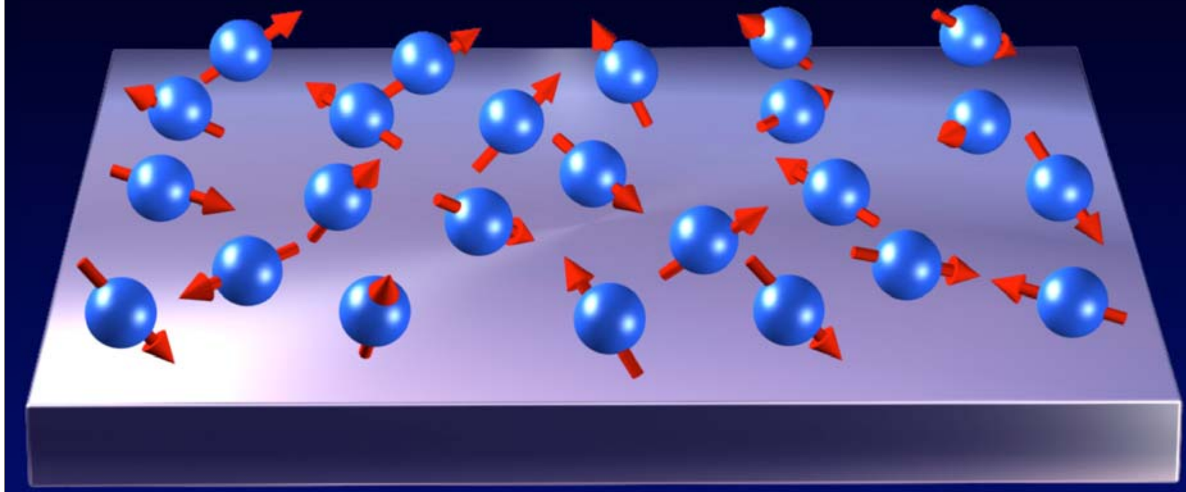
A. Kampf

J.R. Kirtley

K. Wiedenmann

BMBF: 13N6918, ESF: THIOX, DFG: SFB 484

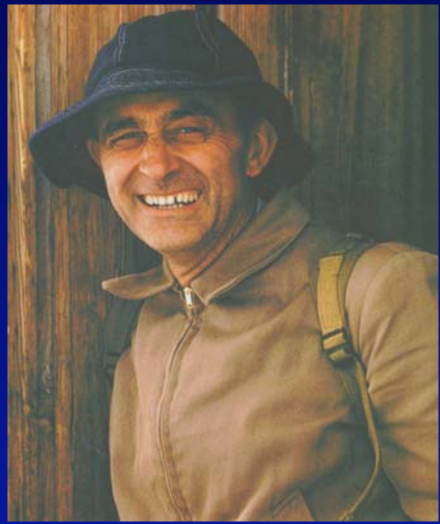
Silicon



Si

electron systems described by

single particle physics / Hartree-Fock model



E. Fermi

Semiconductors and Interfaces → Electronics

pn-junctions, Schottky contacts, Si/SiO_2 interface

- Bipolar devices
- → FETs, QHE, 2DEG
- Lasers, LEDs, optoelectronic

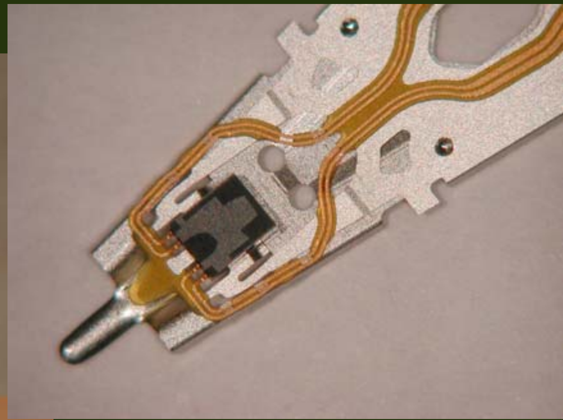
J. Bardeen, W. Brattain and W. Shockley

2004:

>10^{18} transistors fabricated

Magnetic Materials and Interfaces → Spintronics

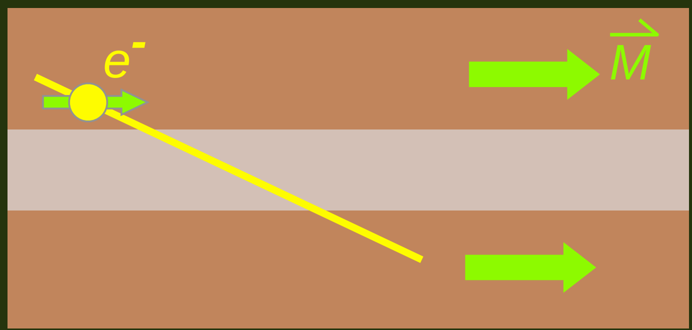
Seagate harddisk



IBM spin valve read head

Magnetic Materials and Interfaces → Spintronics

spin valve small *R*

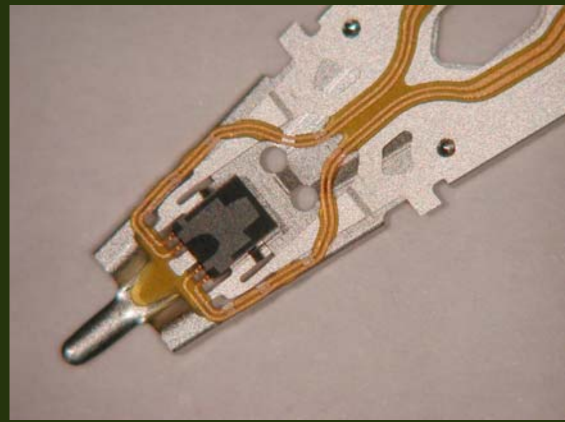


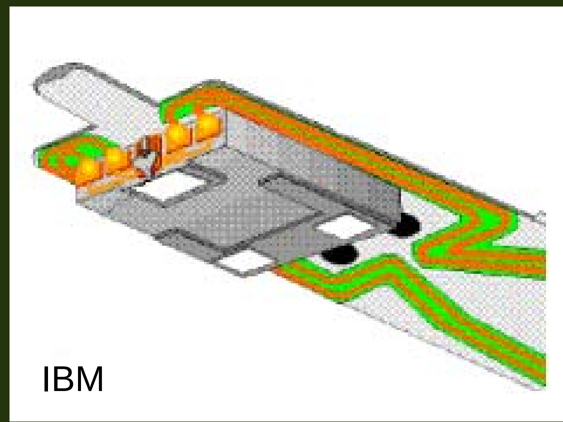
NiFe

Cu

CoFe

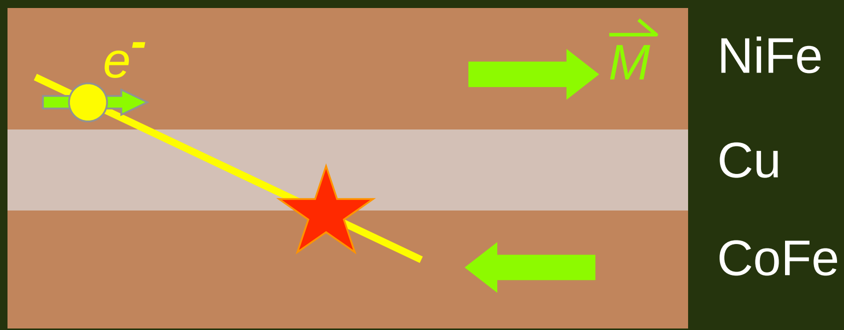
bit on harddisk



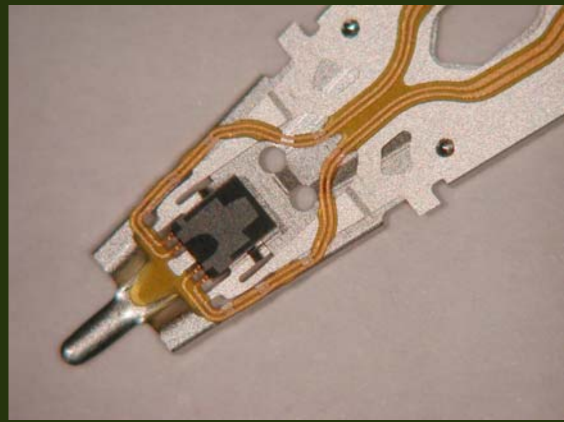


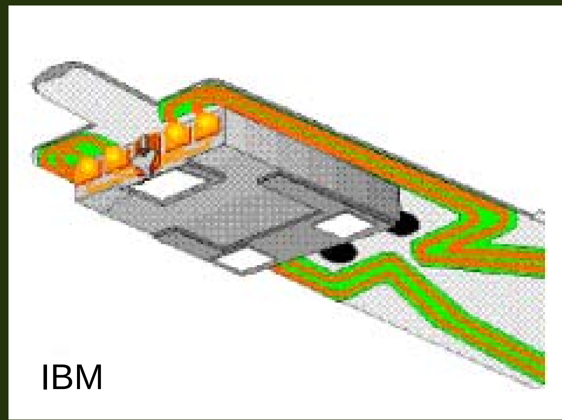
Magnetic Materials and Interfaces ⟶ Spintronics

spin valve small R



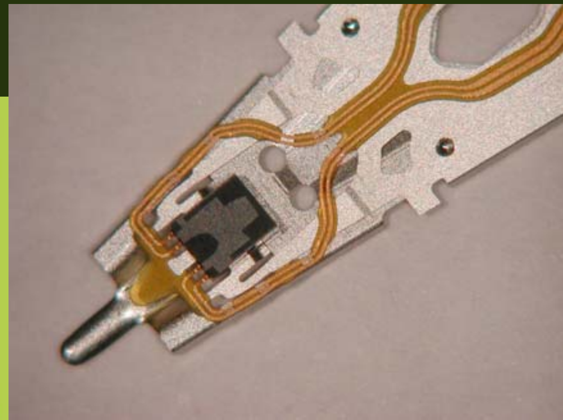
bit on harddisk





GMR driving mechanism:
electron scattering at junctions between ferromagnetic and paramagnetic layers

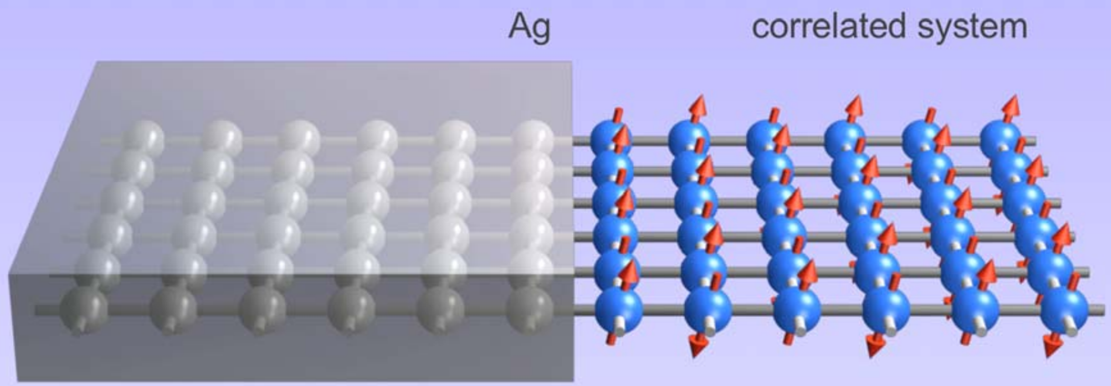
Magnetic Materials and Interfaces → Spintronics



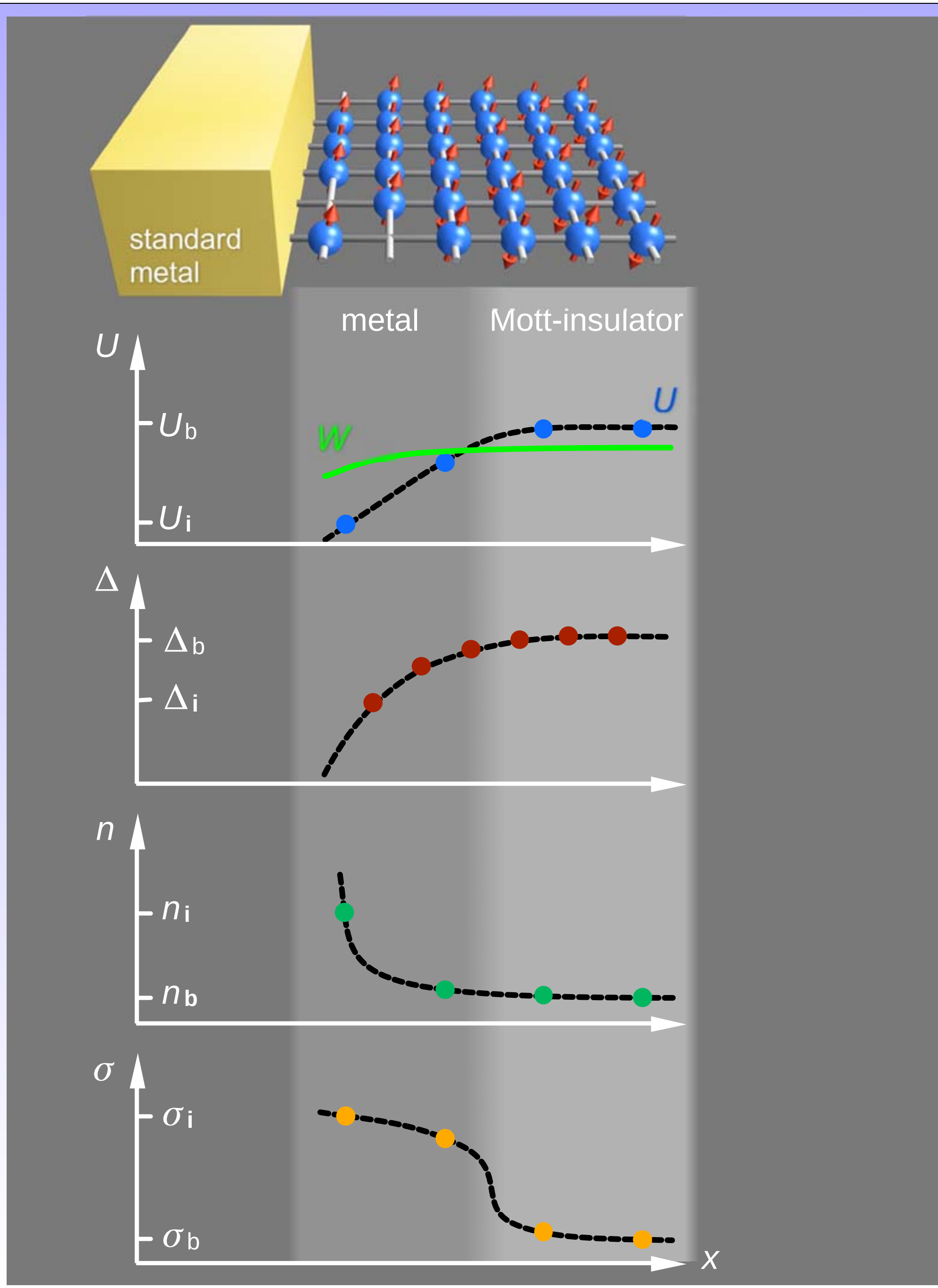
spin valve read head

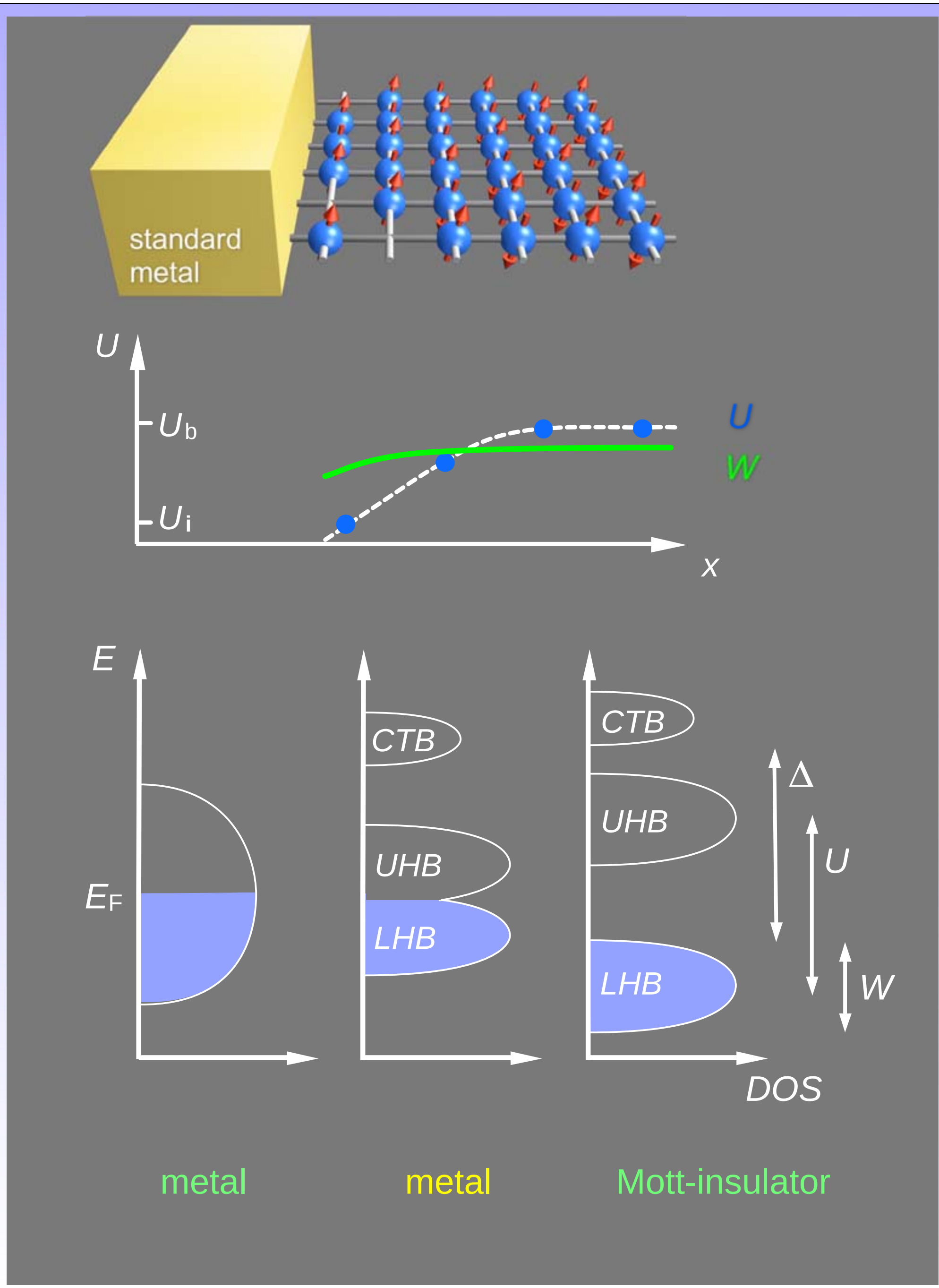
GMR driving mechanism:
electron scattering at junctions between ferromagnetic and paramagnetic layers

Interfaces to Correlated Electron Systems



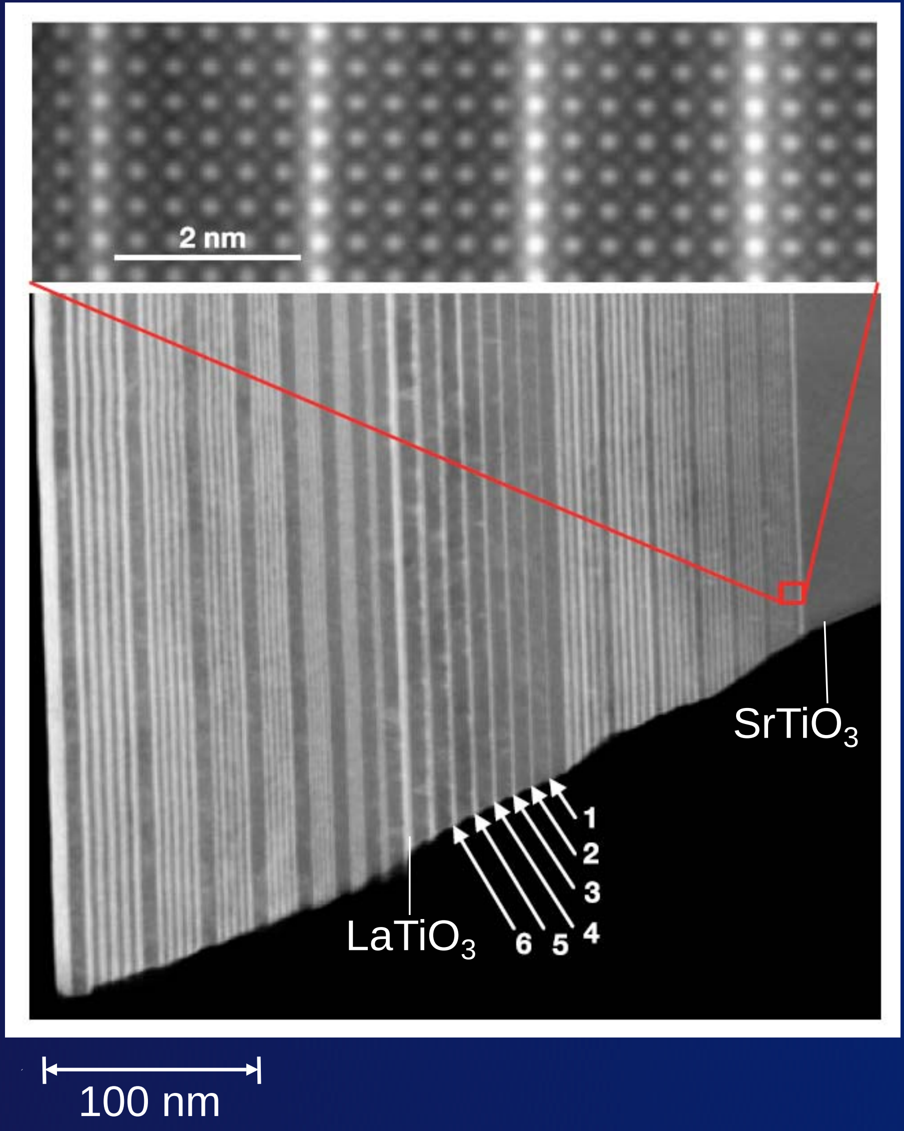
- interfaces in heterostructures: $I(V)$ of tunnel junctions
- contacts: $R_{contact}$, scattering, spin-injection
- grain boundaries: high-T_c cables
- surfaces: photospectroscopy, STM


standard
metal
metal
Mott-insulator
U
U
Ub
Ui
W
Δ
Δb
Δi
n
ni
nb
σ
σi
σb
x



standard
metal
U
U_b
U_i
U
W
x
E
E_F
CTB
UHB
LHB
CTB
UHB
LHB
Δ
U
W
DOS
metal
metal
Mott-insulator

$LaTiO_3$ / $SrTiO_3$ Superlattice

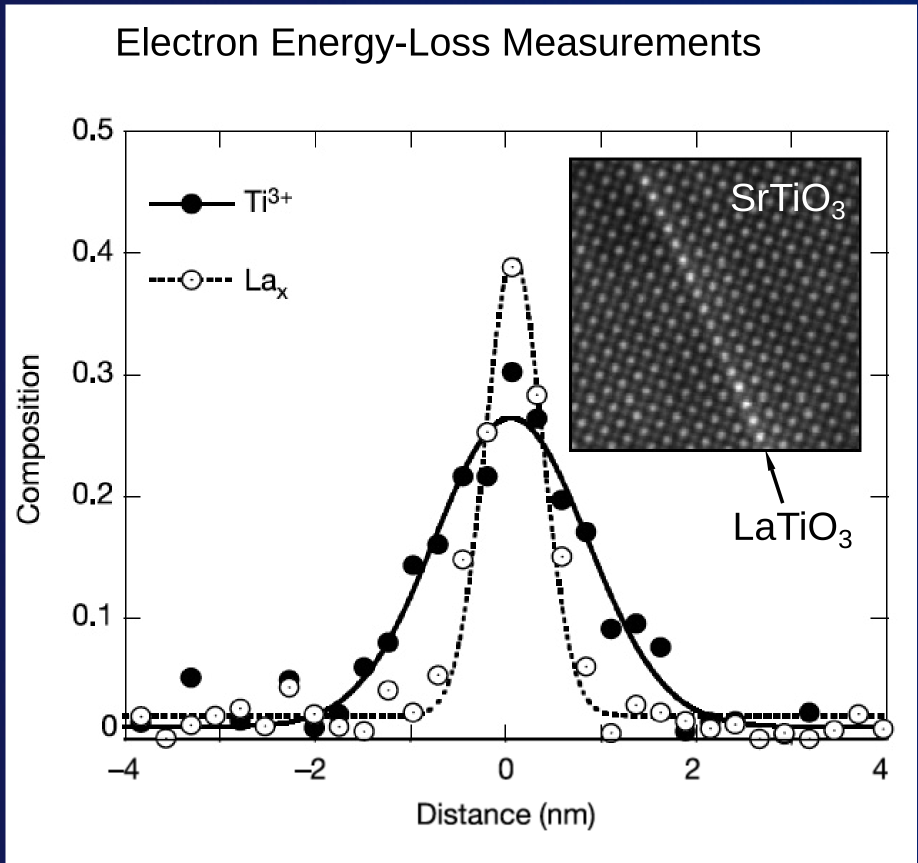


$LaTiO_3$: Mott insulator

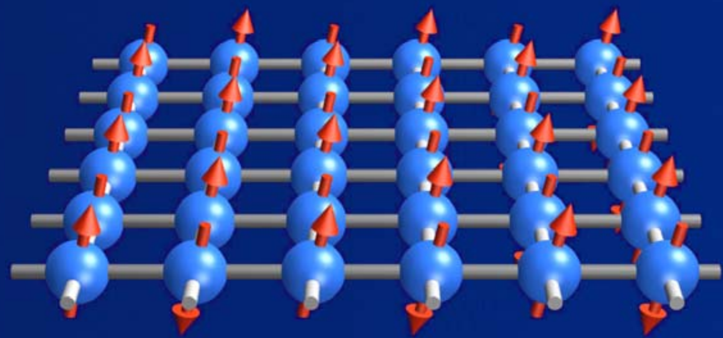
$SrTiO_3$: Band insulator

Ohtomo *et al.*, Nature 419, 378 (2002)

$LaTiO_3$ / $SrTiO_3$ Superlattice



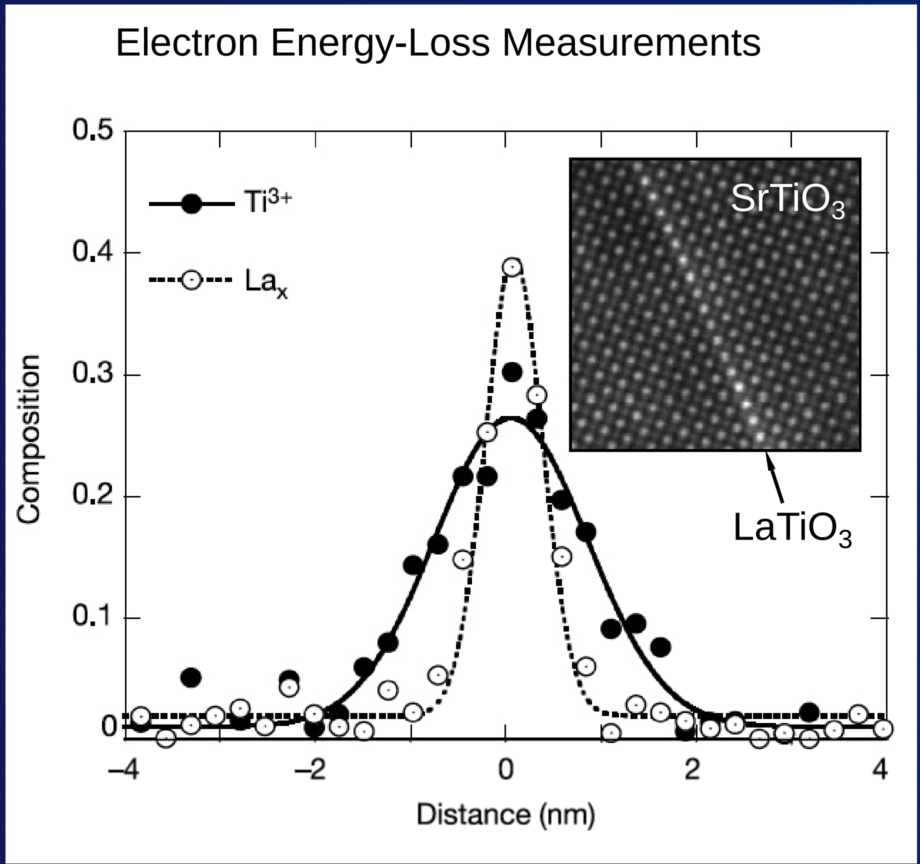
$LaTiO_3$



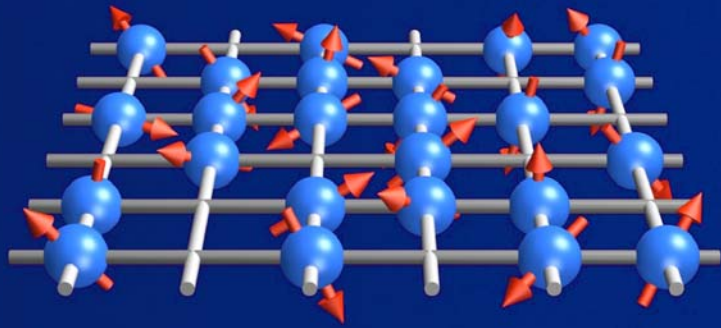
Mott-Insulator

Ohtomo *et al.*, Nature 419, 378 (2002)

$LaTiO_3$ / $SrTiO_3$ Superlattice



LaTiO3 in contact with SrTiO3



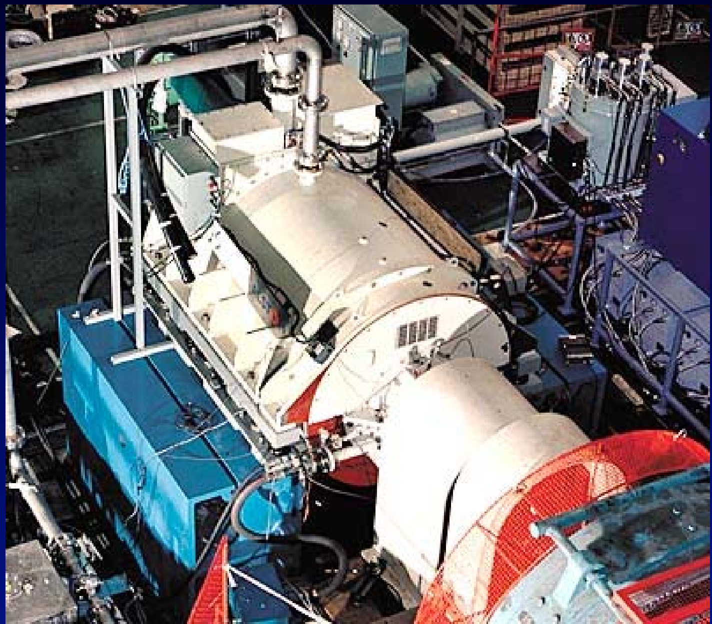
Metal

Ohtomo *et al.*, Nature 419, 378 (2002)

Metallic layer at junction between band insulator and Mott insulator

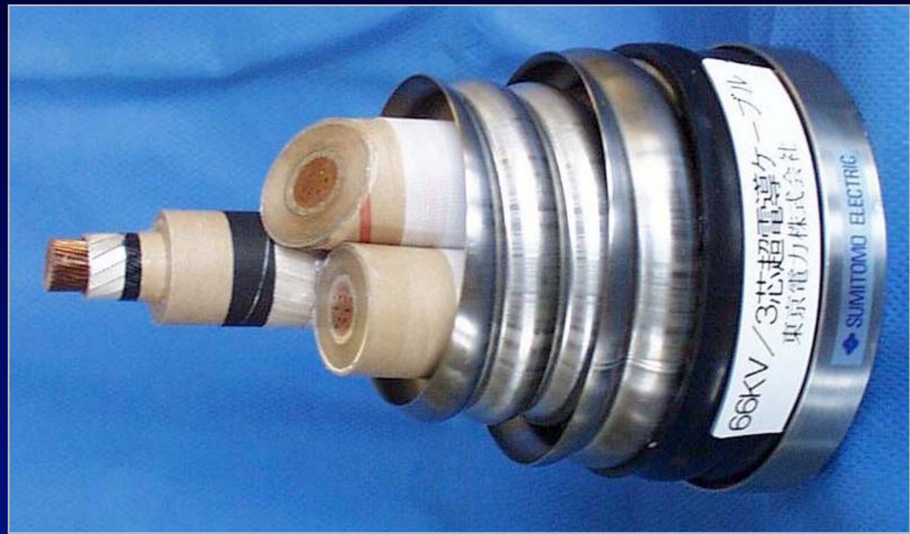
— not for $LaTiO_3$ in $LaAlO_3$ —

HTS-Cables (BSCCO, first generation)



5 MW ship motor

American Superconductor

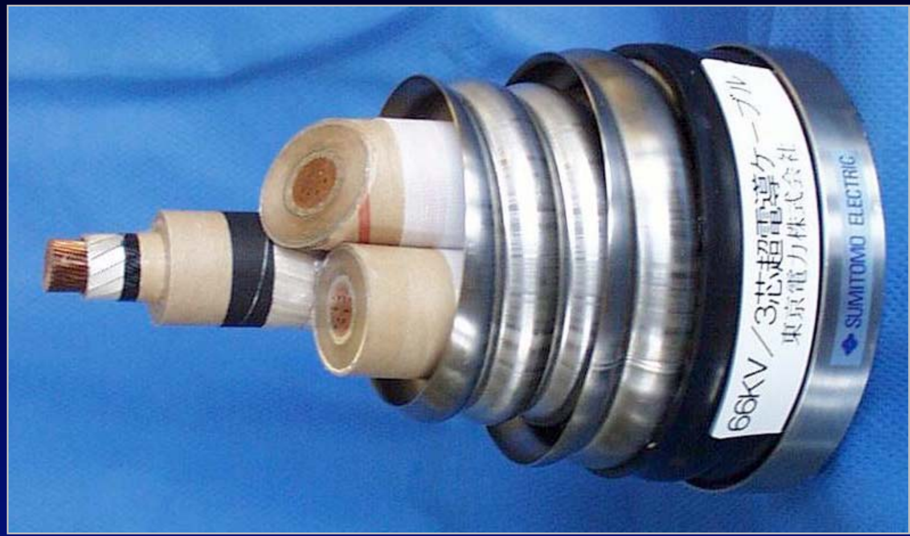


Sumitomo BSCCO-cable,

100 m, 1000 A, 114 MVA, 3-phase

D. Scalapino, J. Mannhart, A. Malozenoff, Physics Today, April 2005, 41

HTS-Cables (BSCCO, first generation)



Too expensive

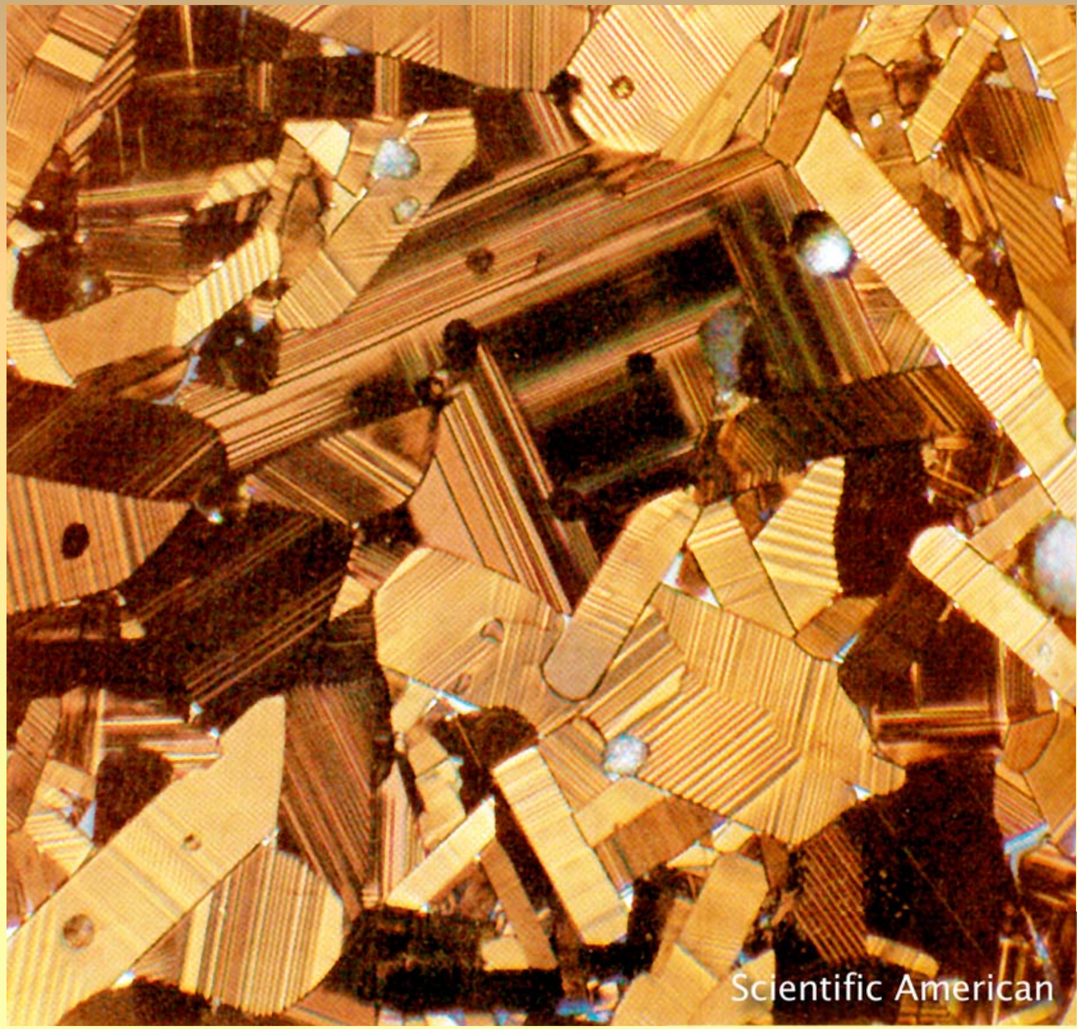
for civilian mass market!

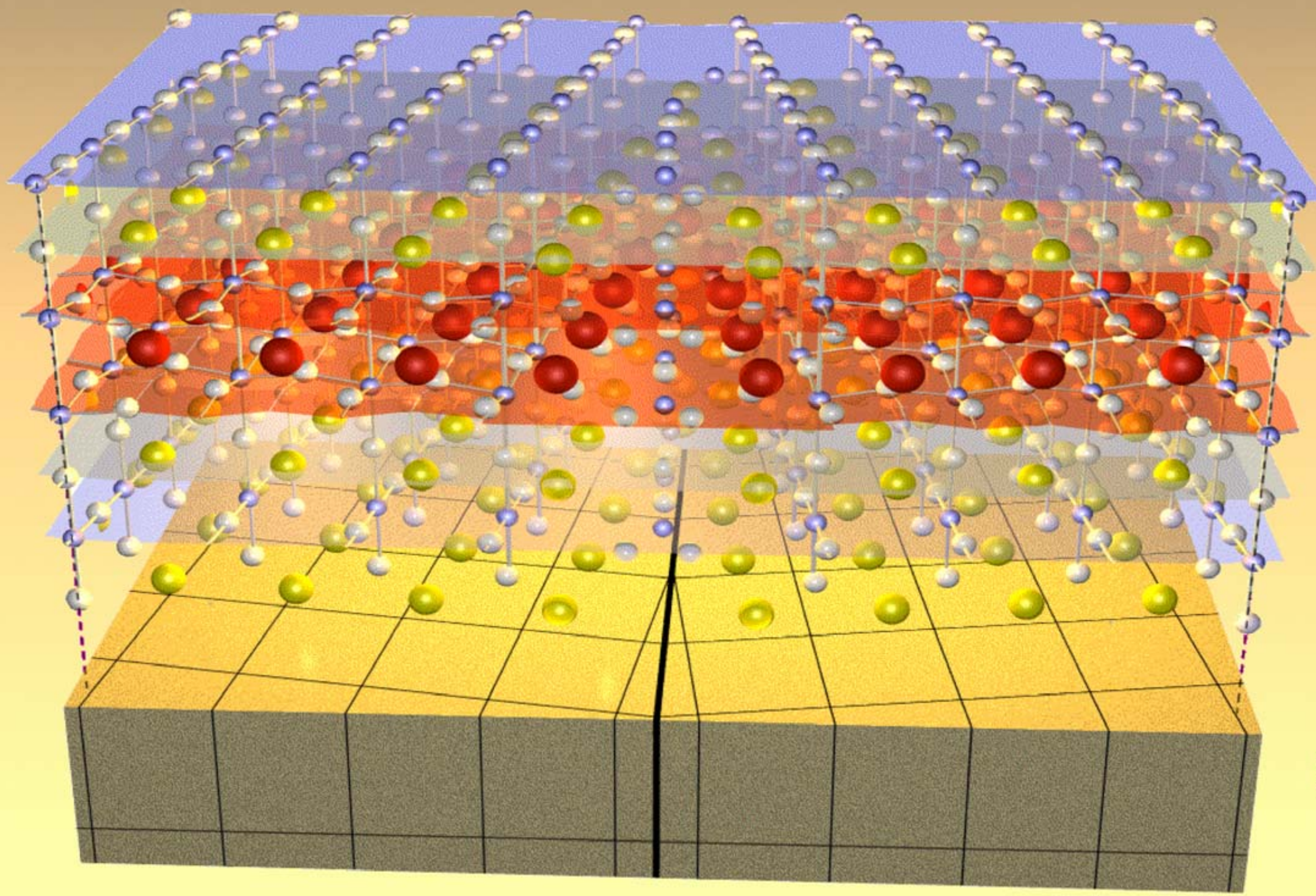
Sumitomo BSCCO-cable,

100 m, 1000 A, 114 MVA, 3-phase

D. Scalapino, J. Mannhart, A. Malozenoff, Physics Today, April 2005, 41

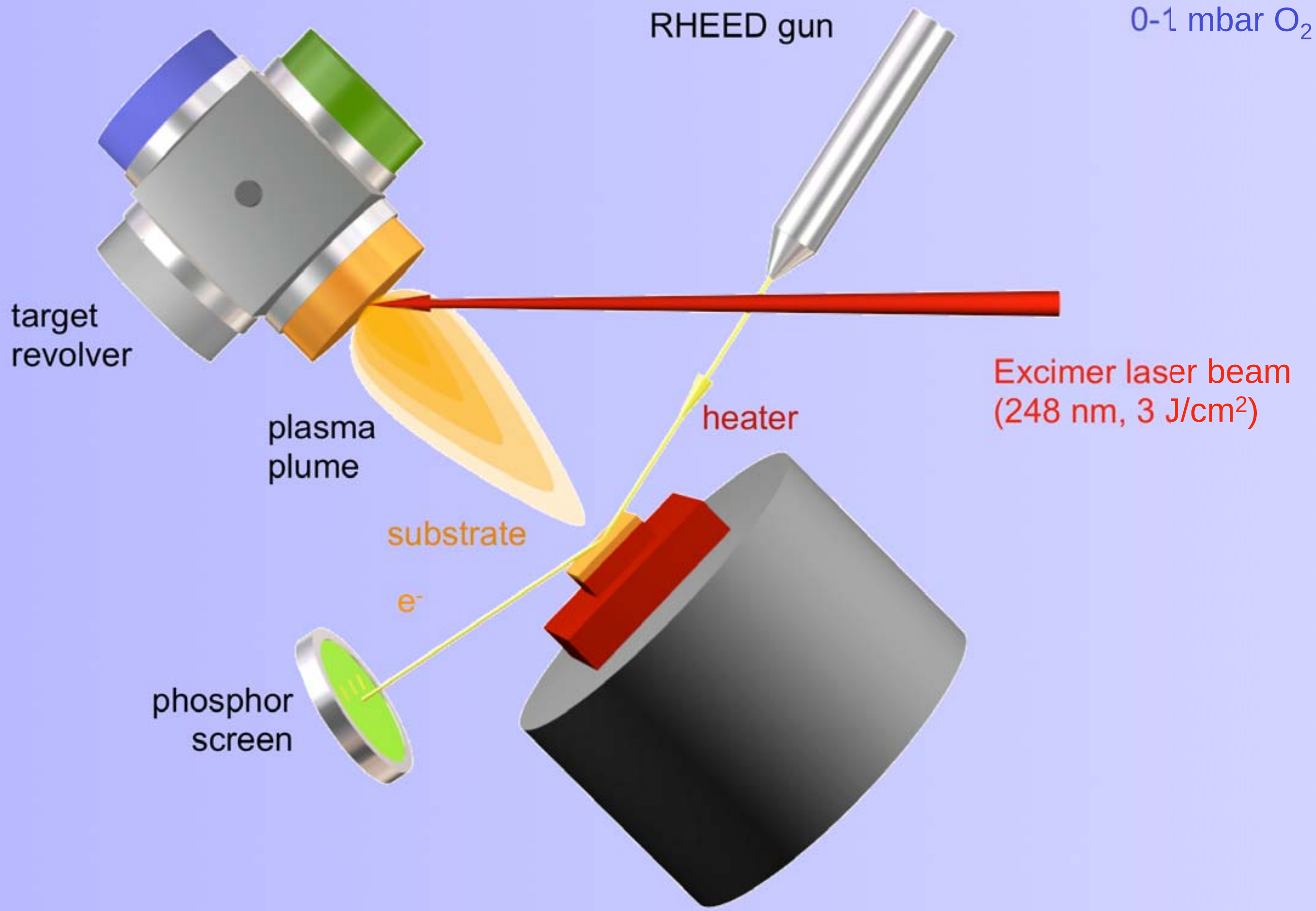
Polycrystalline $YBa_2Cu_3O_{7-\delta}$



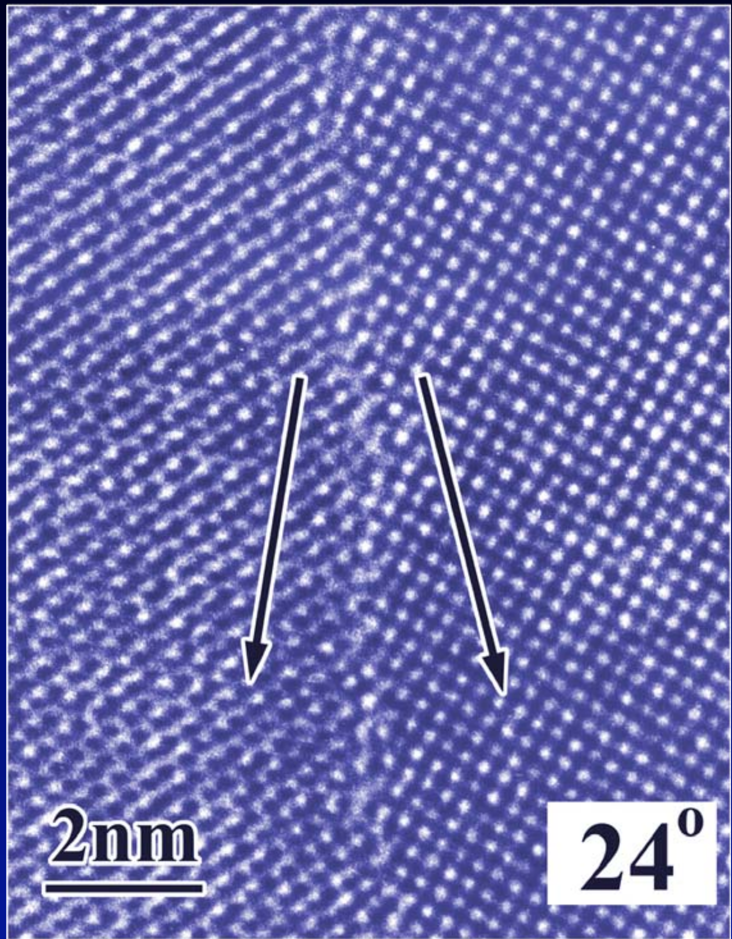


J. Mannhart and P. Chaudhari, Physics Today 11, 48 (2001)

Epitaxial Growth by Pulsed Laser Deposition



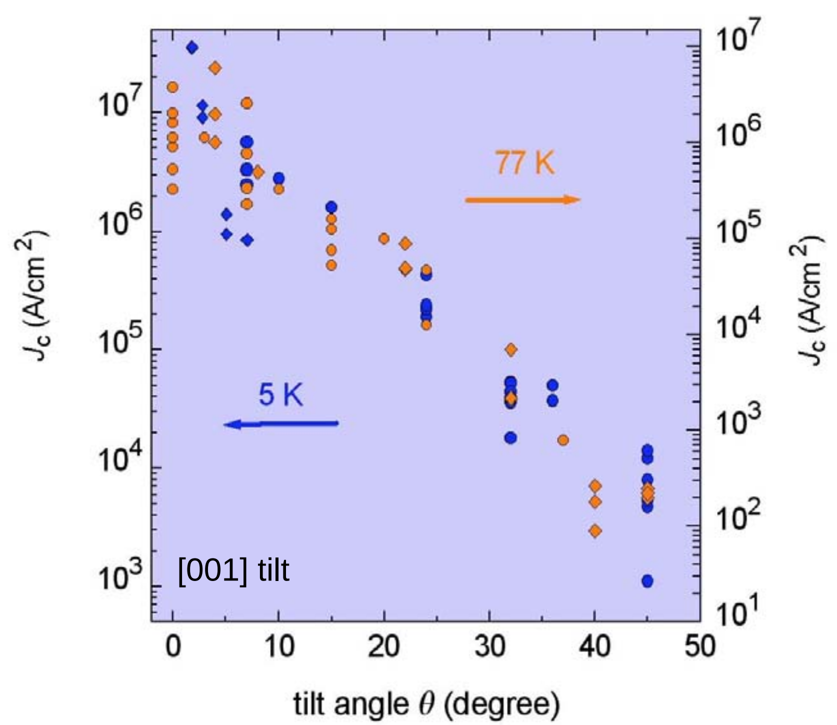
Grain Boundary in a Bicrystalline $YBa_2Cu_3O_{7-\delta}$ Film



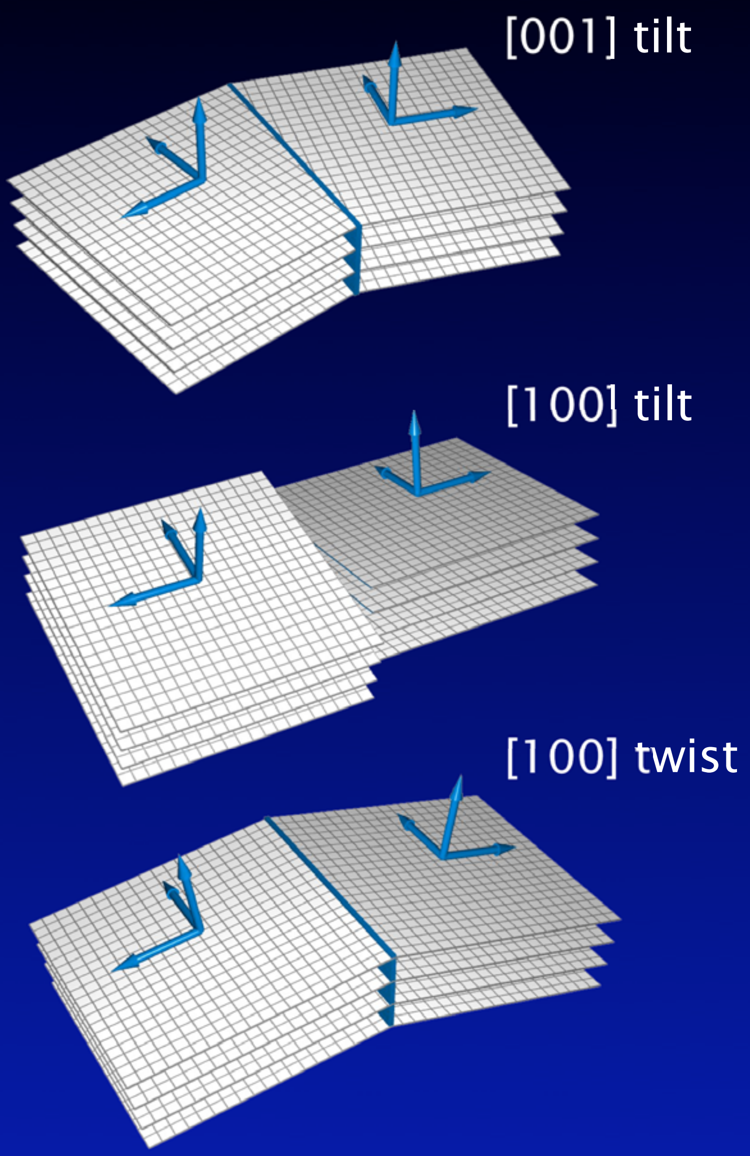
24˚, [001]-tilt

J.G. Wen et al. (2000)

Grain Boundaries in Bicrystalline $YBa_2Cu_3O_{7-\delta}$ Films

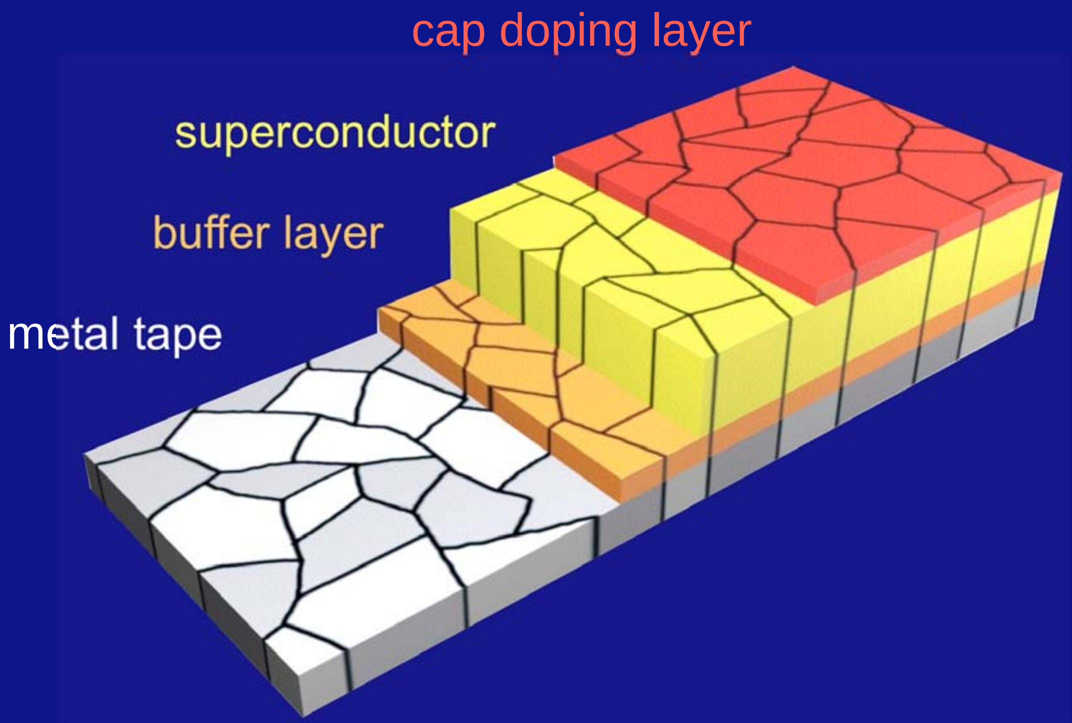


Data from Ivanov *et al.* (1991), Hilgenkamp *et al.* (1998), Heinig *et al*. (1999), Verbelyi *et al.* (2001)



Phys. Rev. B 41, 4038 (1990)
Rev. Mod. Phys. 74, 485 (2002)

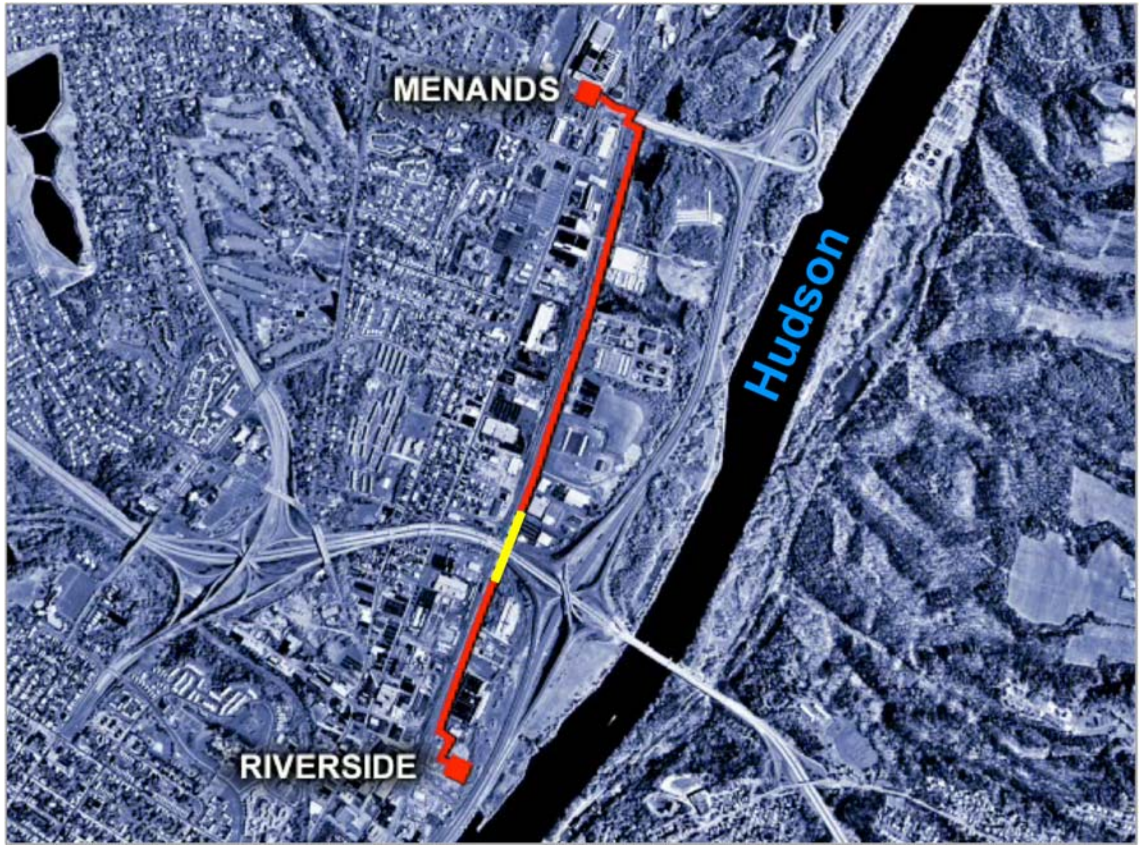
Coated Conductors: Second Generation of HTS-wires



Coated Conductors: Second Generation of HTS-wires

Los Alamos: 1 400 A/cm width (76 K)

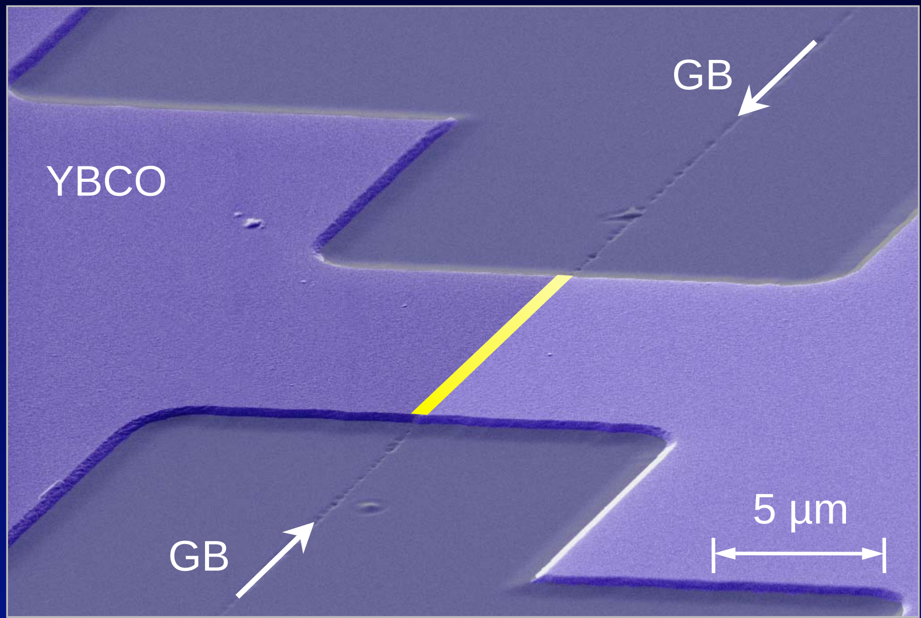
Purpose: Demonstration of long length HTS cable in the US grid
Members: Super Power / SEI / Niagara-Mohawk /BOC
Project costs: 26 M$ including NY (6 M$) and DOE (13 M$)

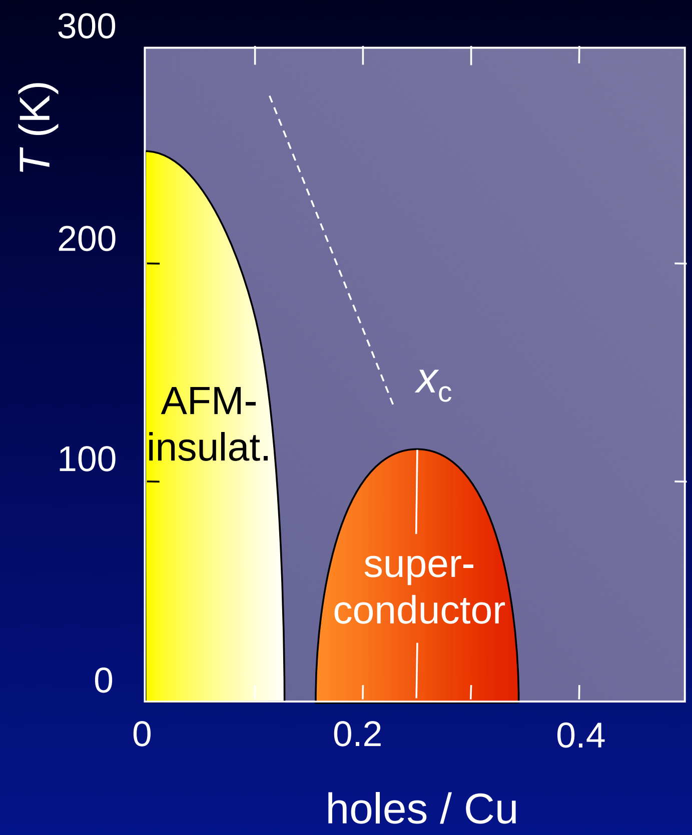


- 34.5 kV
- 48 MVA
- three phase

planned completion 12/2006

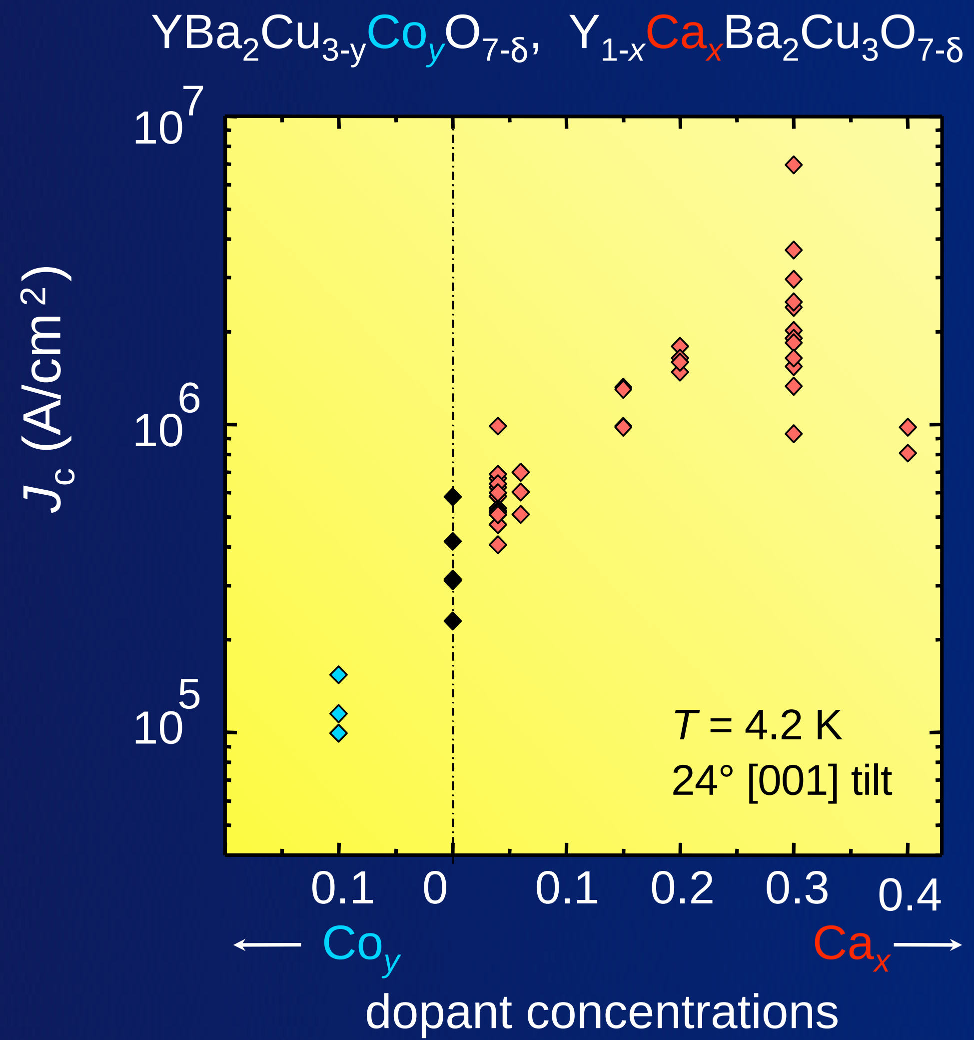
Grain Boundary Interfaces - Mechanism I



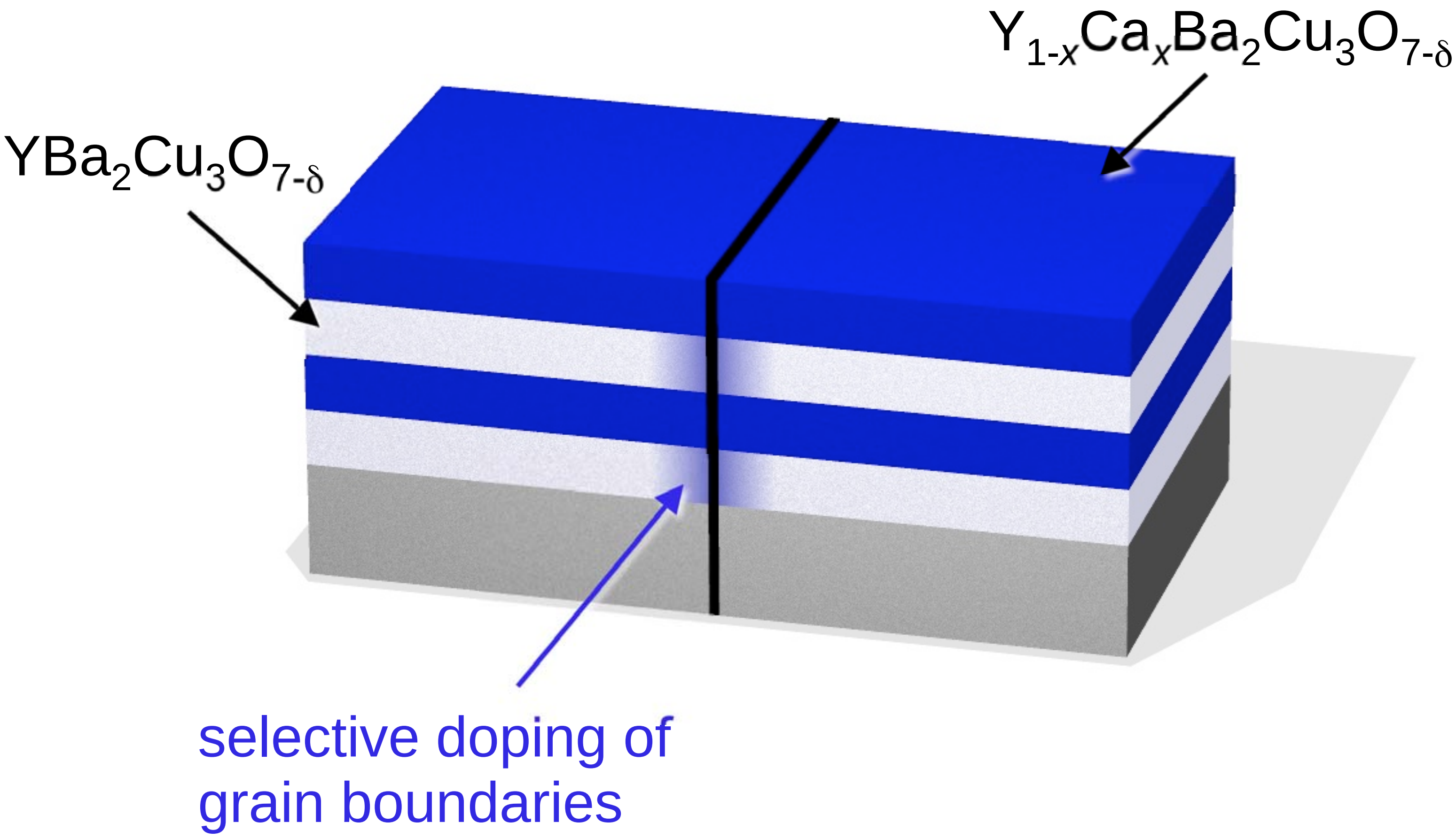


in 1-2 nm wide layer: phase transition into insulating phase

J_c of Grain Boundaries in Doped Superconductors

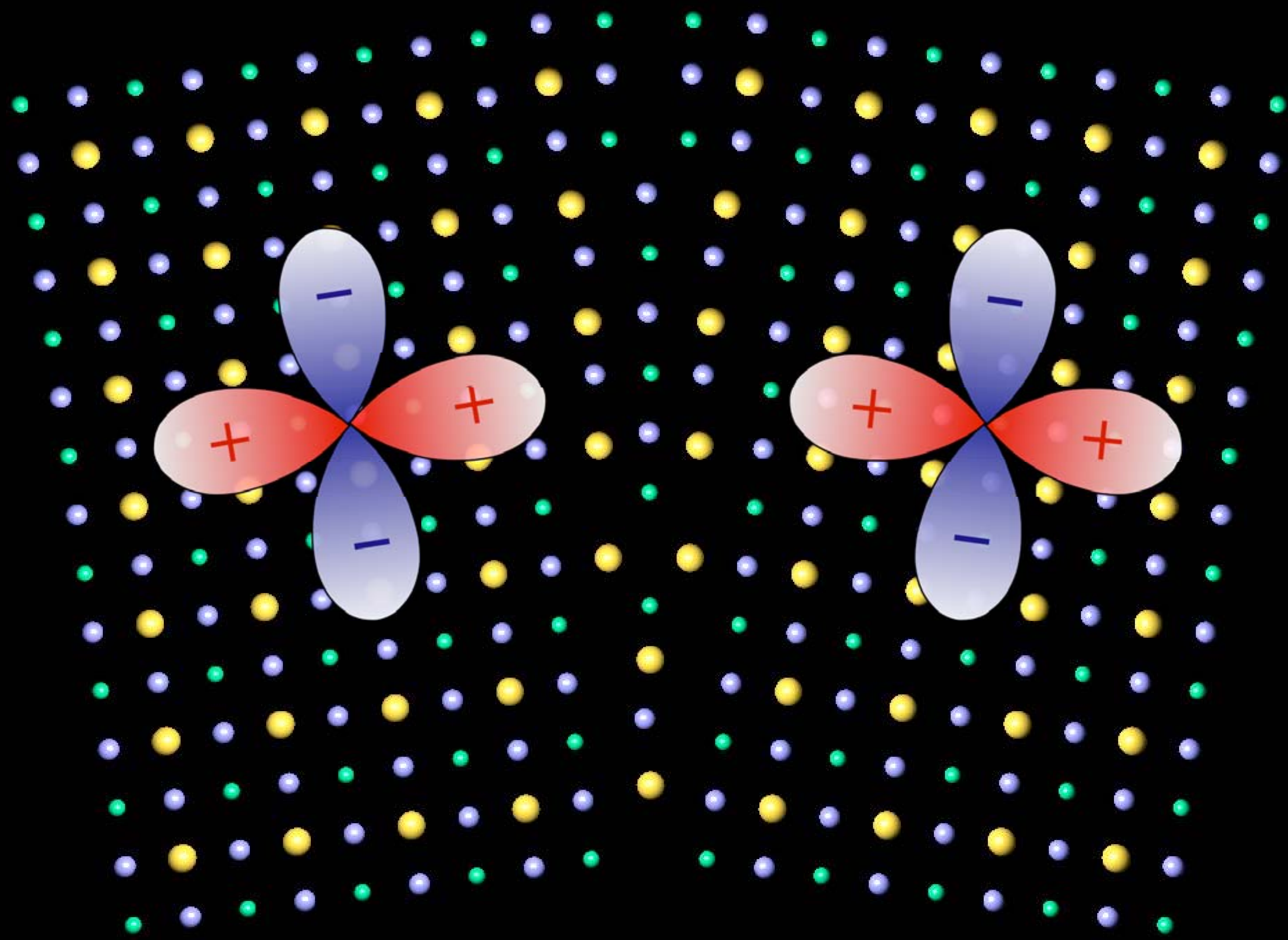


Doping Heterostructures

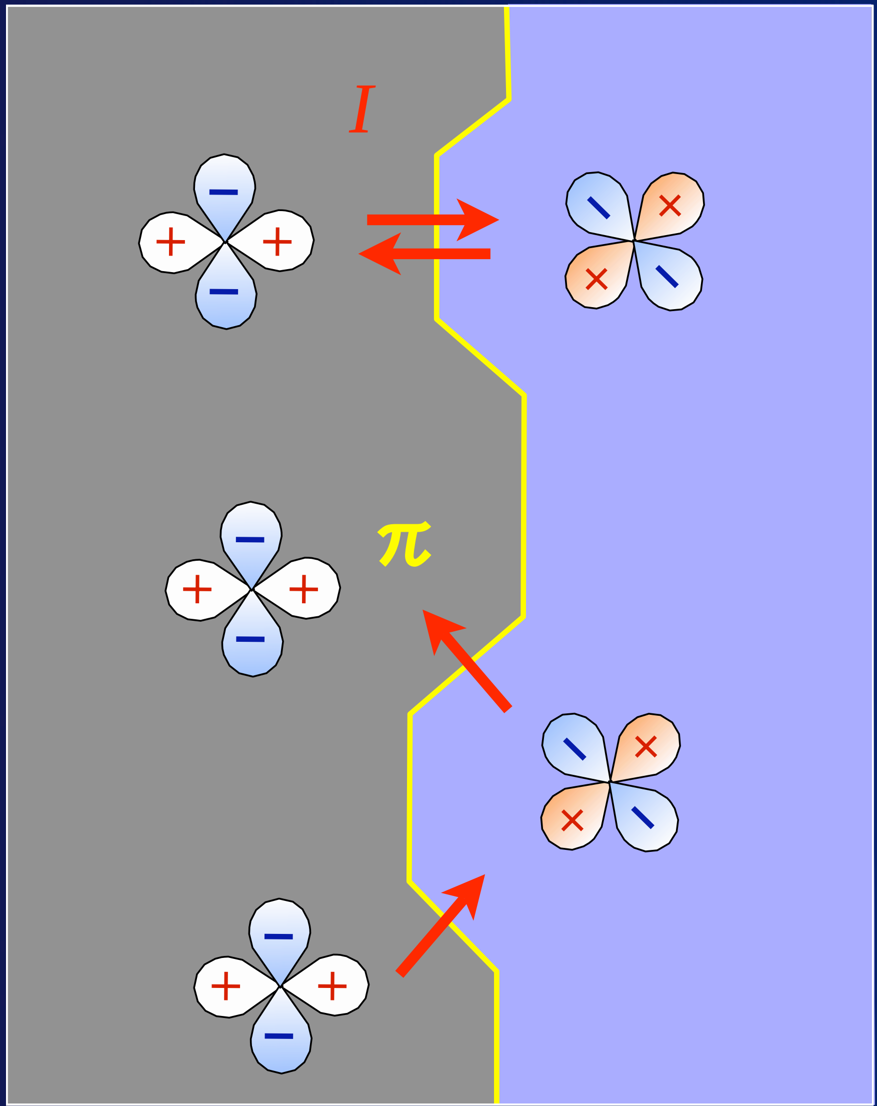


Hammerl *et al.*, *Nature* **407**, 167 (2000)

Grain Boundary Interfaces - Mechanism II

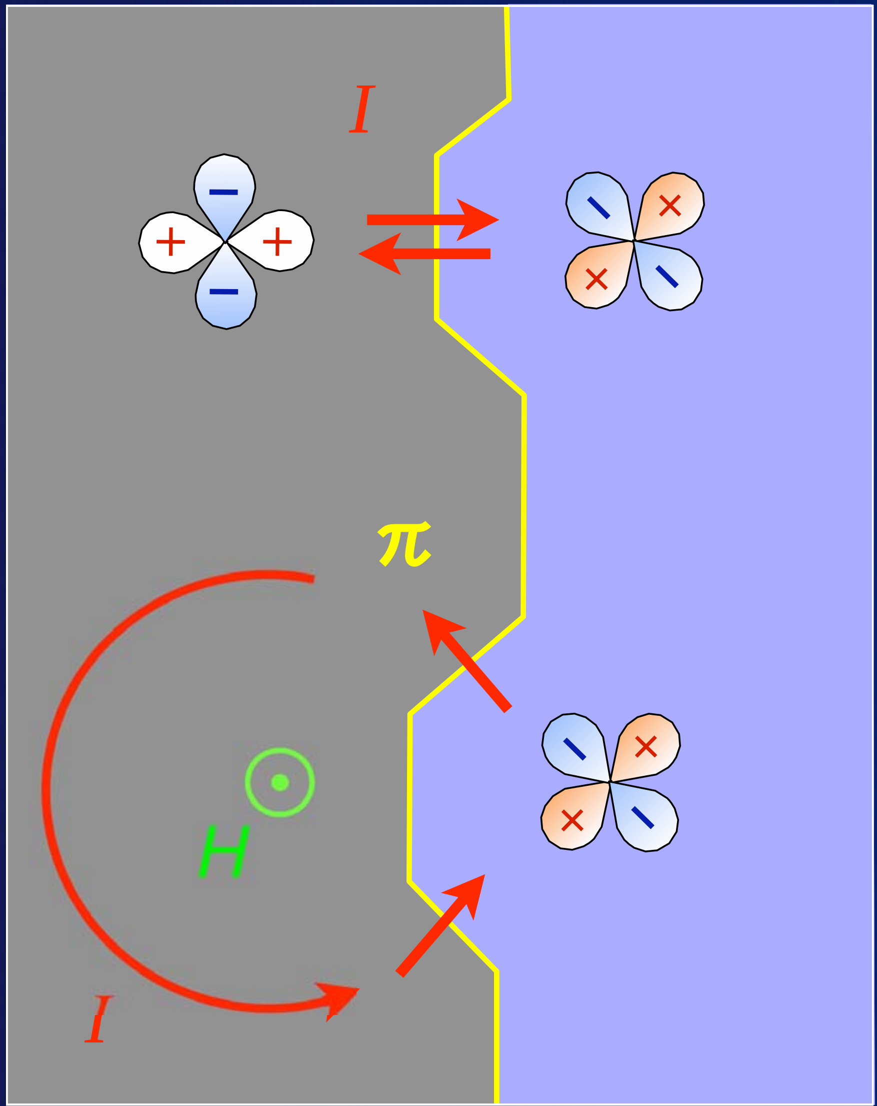


π - Josephson Junctions at Grain Boundaries



45° boundary

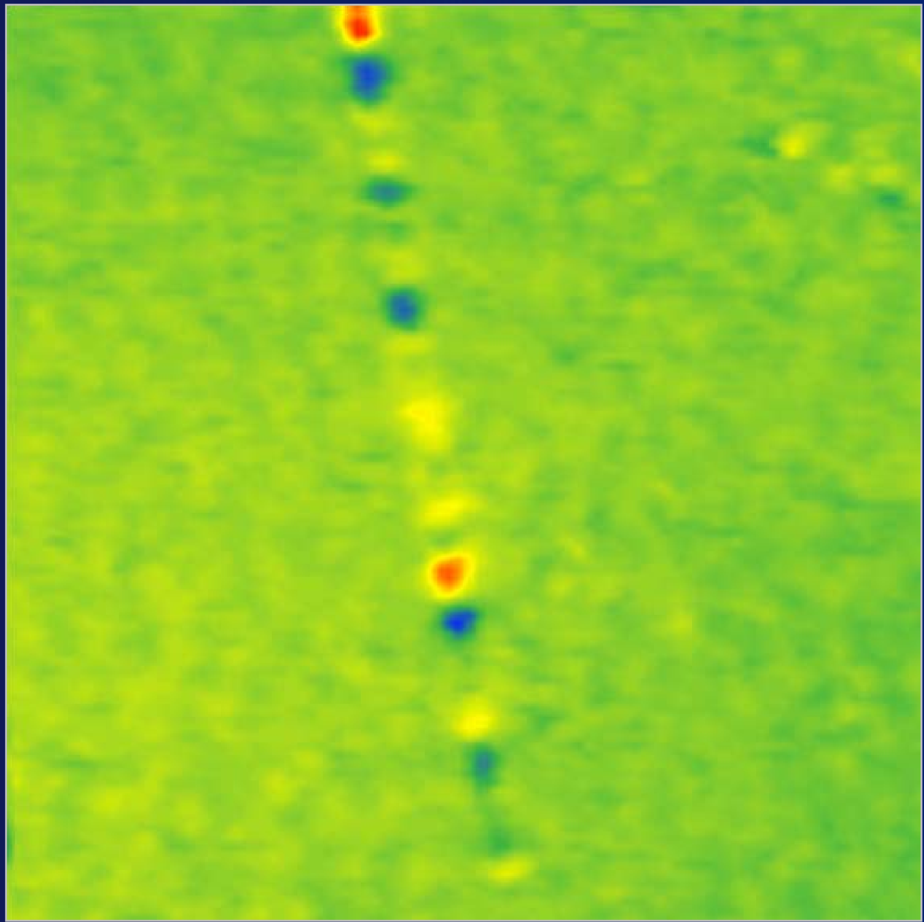
π - Josephson Junctions at Grain Boundaries



junction generates magnetic flux on length scale of 100 nm

45° boundary

Scanning SQUID Image of a 45˚ $YBa_2Cu_3O_{7-\delta}$ Boundary



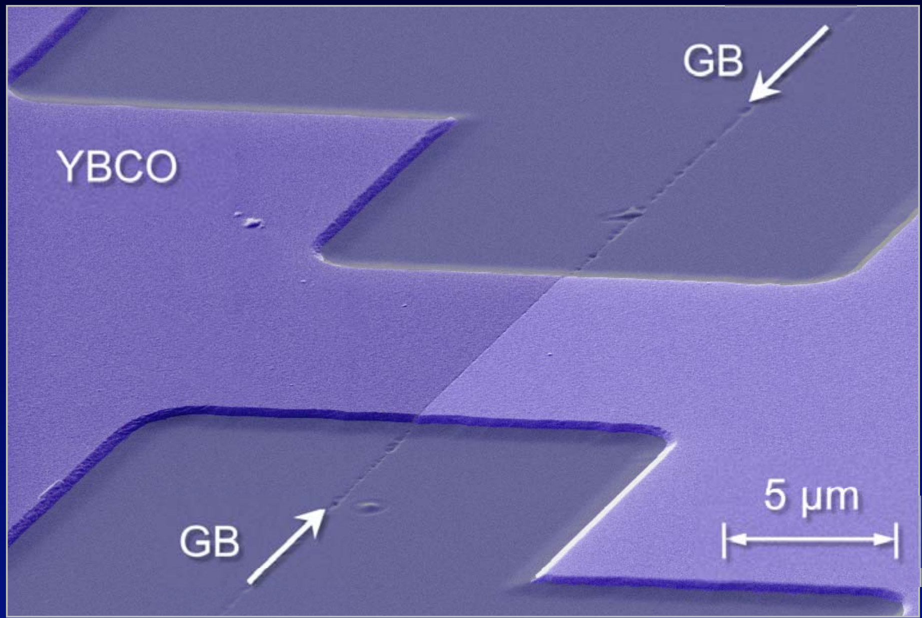
J.R. Kirtley

Phys. Rev. Lett. 77, 2782 (1996)

T = 4.2 K

200 µm

Does the Temperature Range $T > T_c$ Provide Further Information on the Mechanisms?

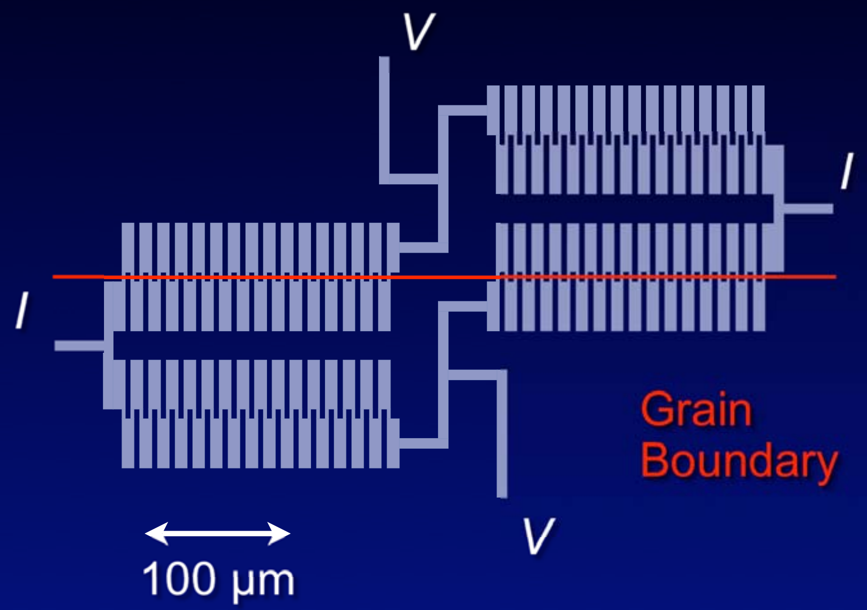


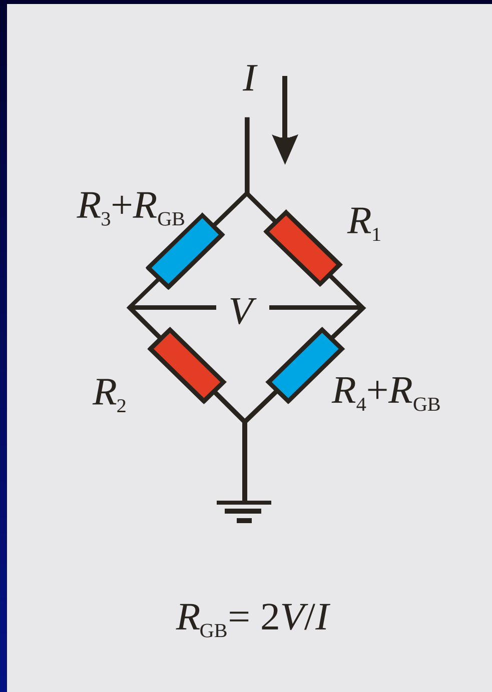
$R_{g1,2} > 10 \times R_{gb}$

Measurement problem:

Resistance of the grains R_g in series to the interface resistance R_{gb}

Sample Layout: Meander Structure

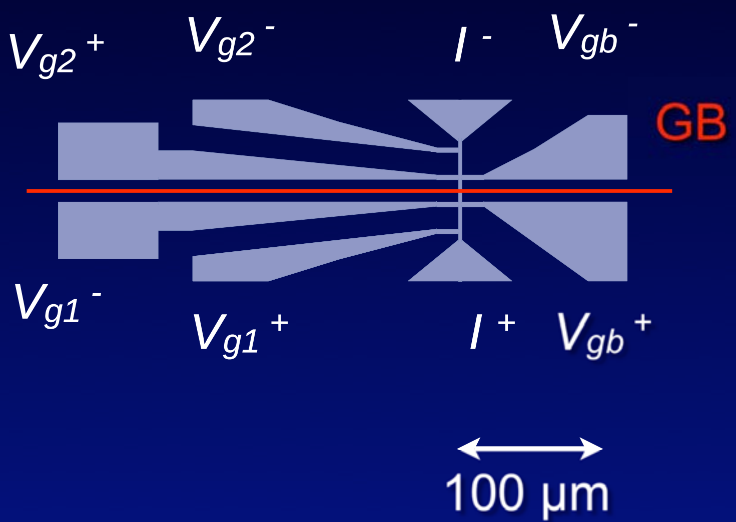




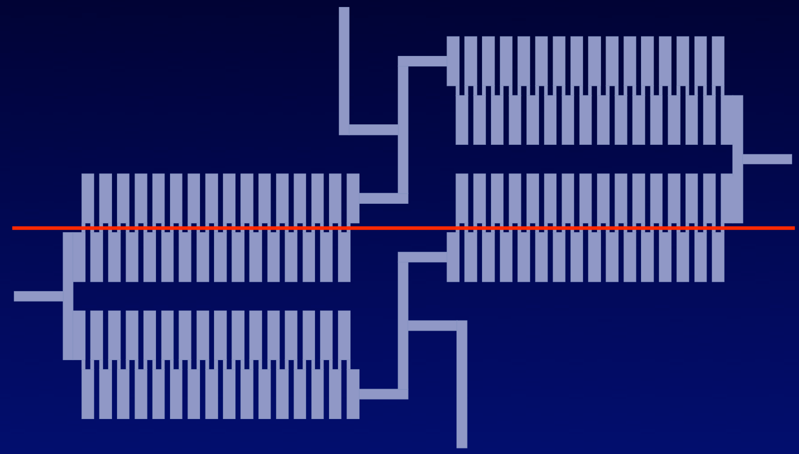
developed by N.D. Mathur *et al.* for LCMO

works well, excellent sample homogeneity required

Sample Layout: Three-Bridge Structure

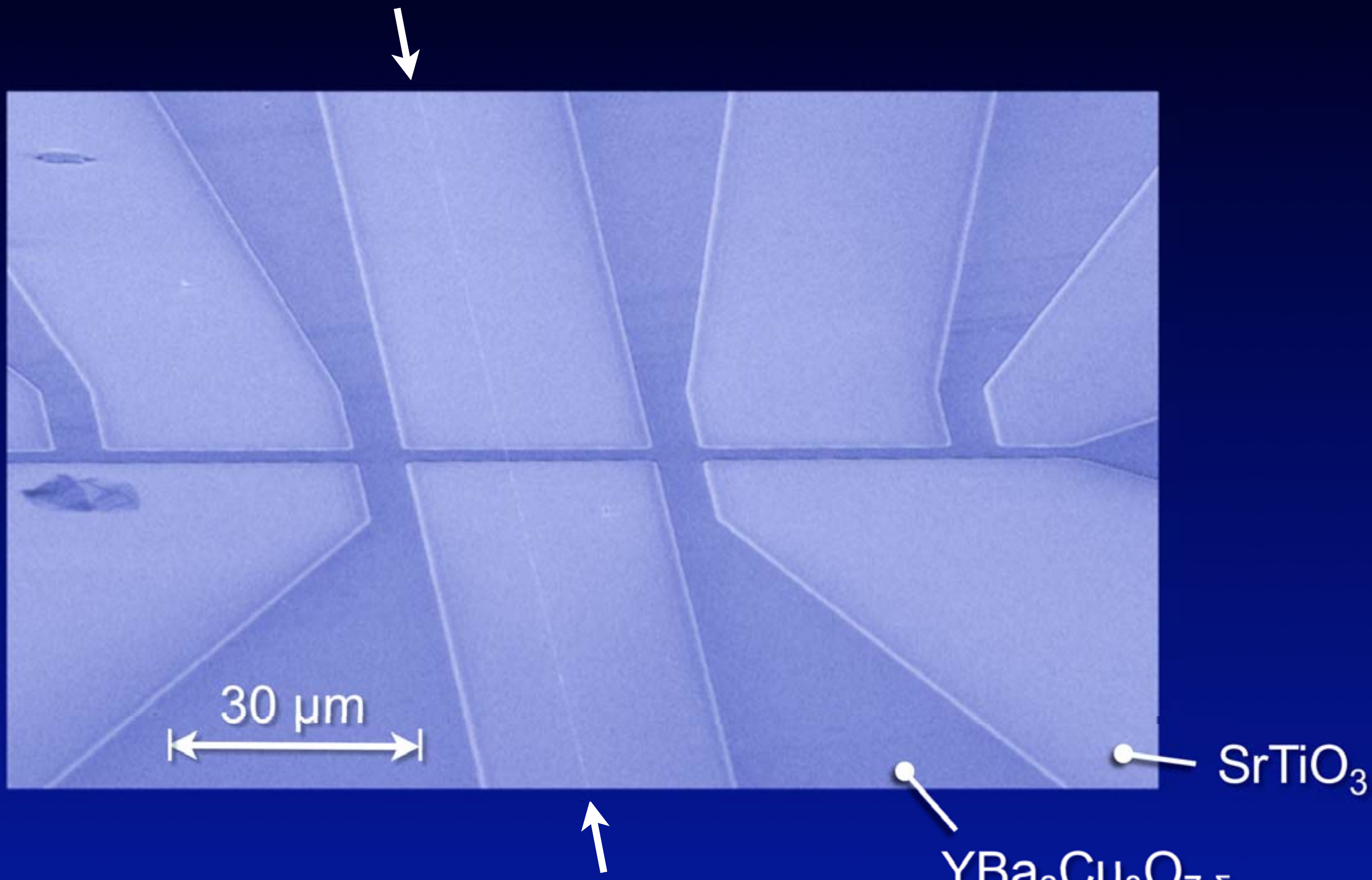


new design

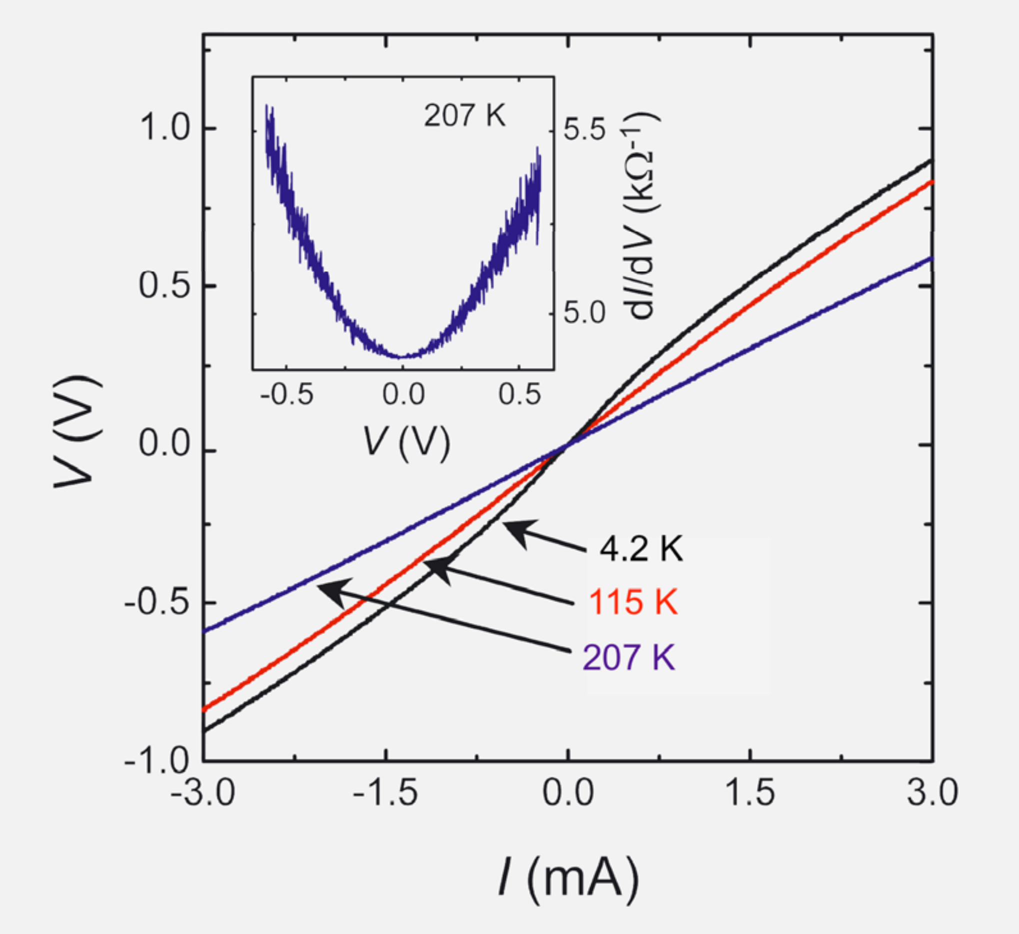


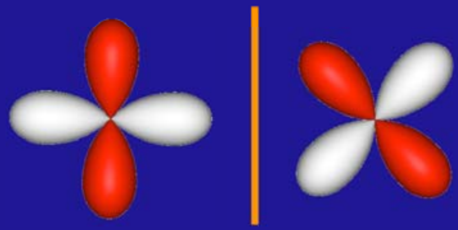
old design

Three-Bridge Structure



Measured $I(V)$-Characteristic (23 Junctions in Series)



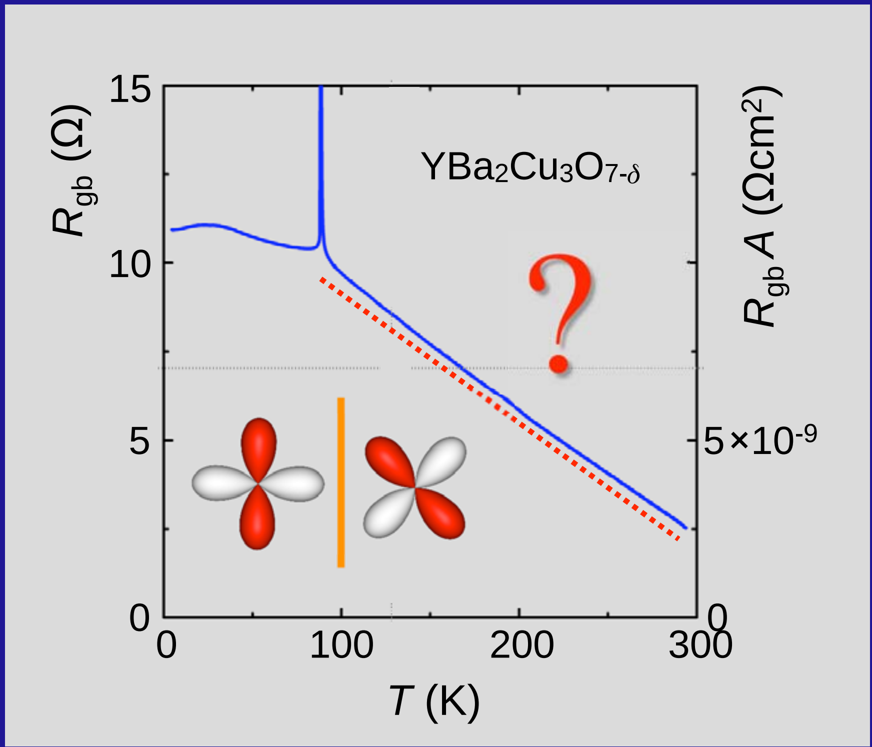


(001)/(110) tilt boundary

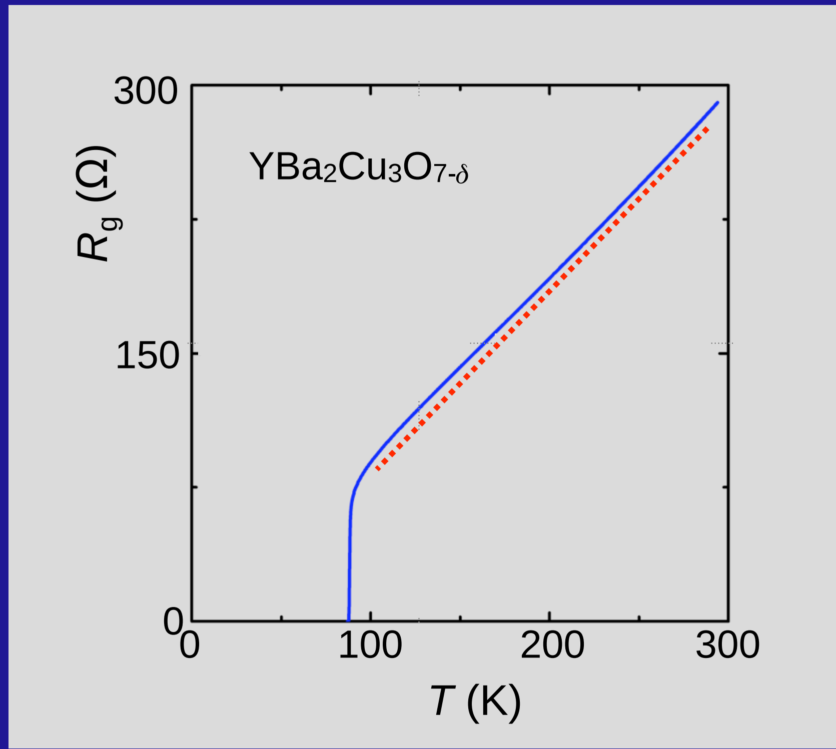
C.W. Schneider *et al.*, Phys. Rev. Lett. **92**, 257003 (2004)

Measured *R*(*T*)-Characteristics

(001)/(110)-tilt Grain Boundary



Epitaxial Film

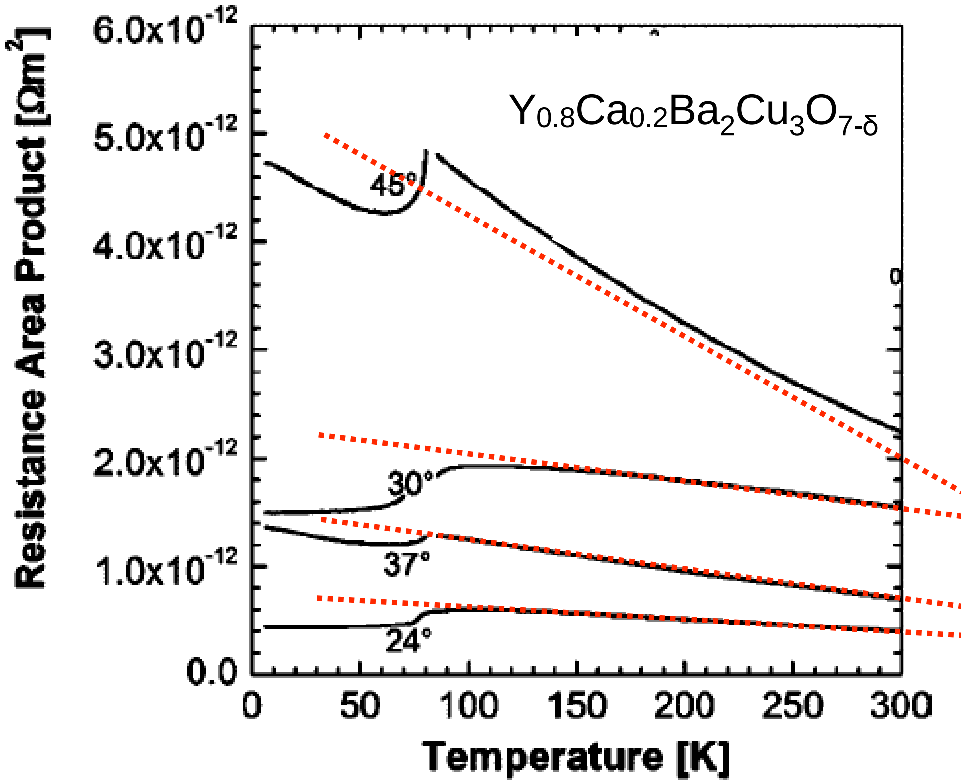


C.W. Schneider *et al.*, Phys. Rev. Lett. **92**, 257003 (2004)

PHYSICAL REVIEW B **71**, 094509 (2005)

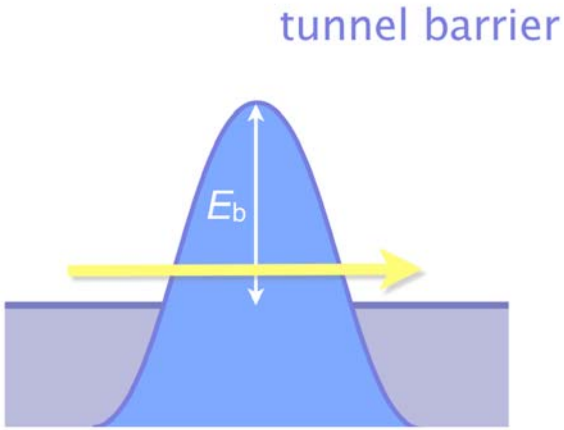
Normal-state properties of high-angle grain boundaries in $(Y,Ca)Ba_2Cu_3O_{7-\delta}$

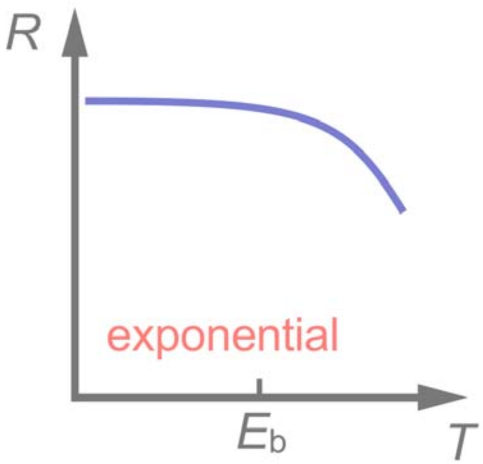
S. H. Mennema, J. H. T. Ransley, G. Burnell, J. L. MacManus-Driscoll, E. J. Tarte, and M. G. Blamire
Department for Materials Science and Metallurgy, University of Cambridge, Pembroke Street, CB2 3QZ, Cambridge, United Kingdom
(Received 27 August 2004; published 18 March 2005)



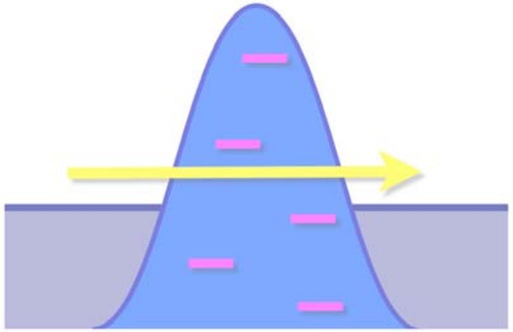
Grain Boundary Mechanism

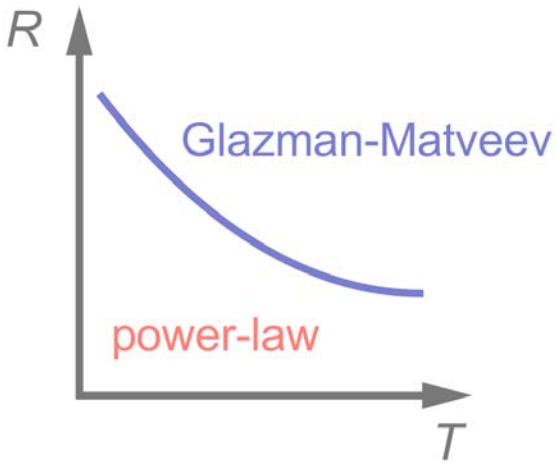
Tunneling



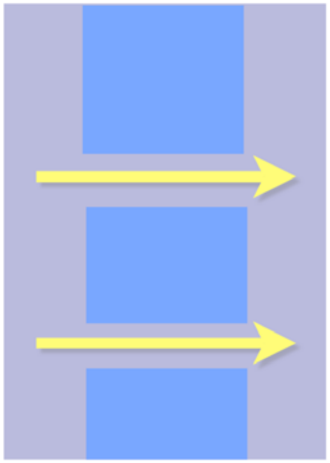


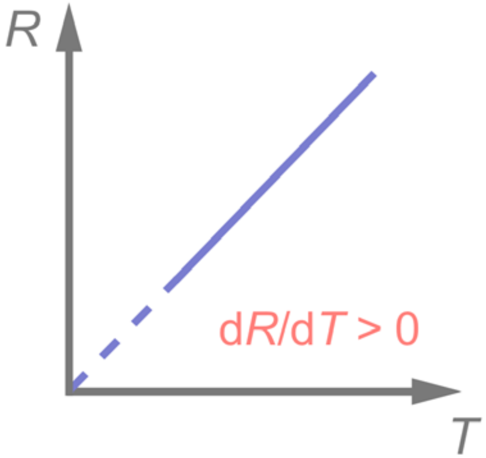
Resonant Tunneling



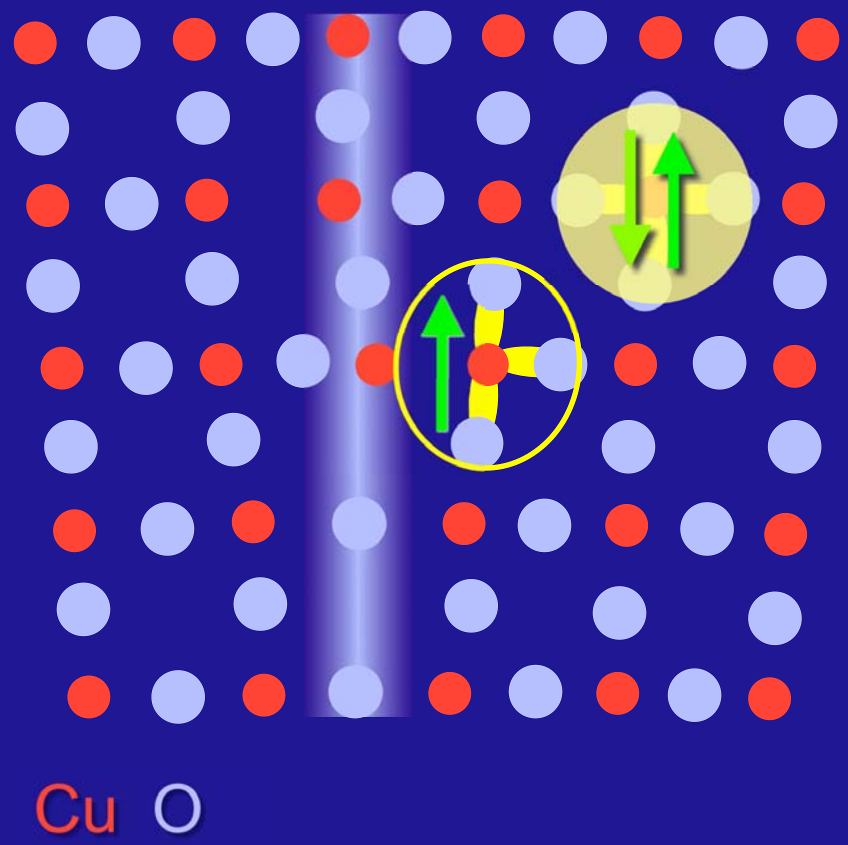


Nanobridges



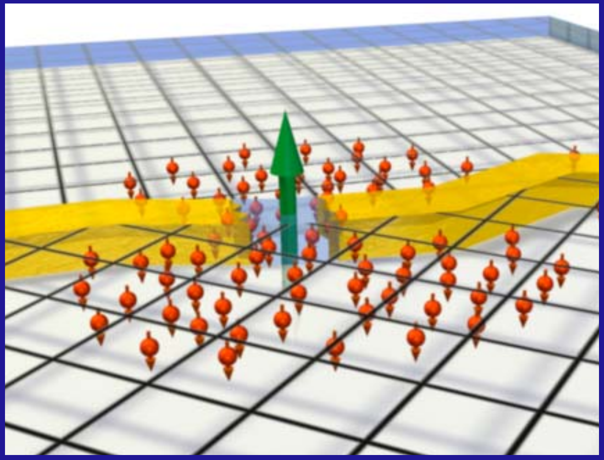


Magnetic Scattering Centers at Grain Boundaries?



Cu spins, that are

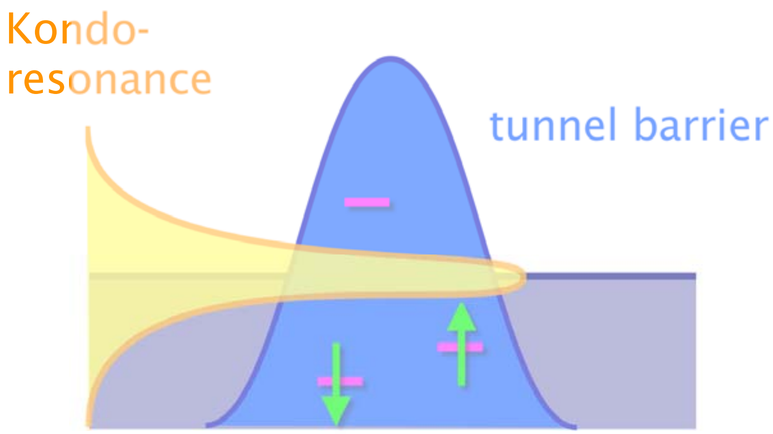
- unshielded
- immobile
- disordered



Kondo-resonance?

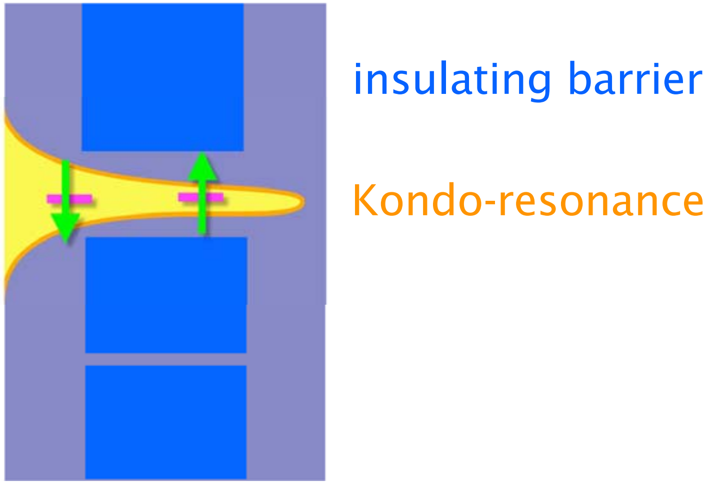
Magnetic States at Grain Boundaries

Tunneling



- magnetic states assist tunneling
- $T < T_K$: pronounced Kondo-resonance
  Kondo-assisted tunneling

Nanobridges



- magnetic states scatter charges
- $T < T_K$: pronounced Kondo-resonance
  strong Kondo-scattering

→ Kondo-wall

R decreases with *T*, how?

Kondo Disorder at Grain Boundaries

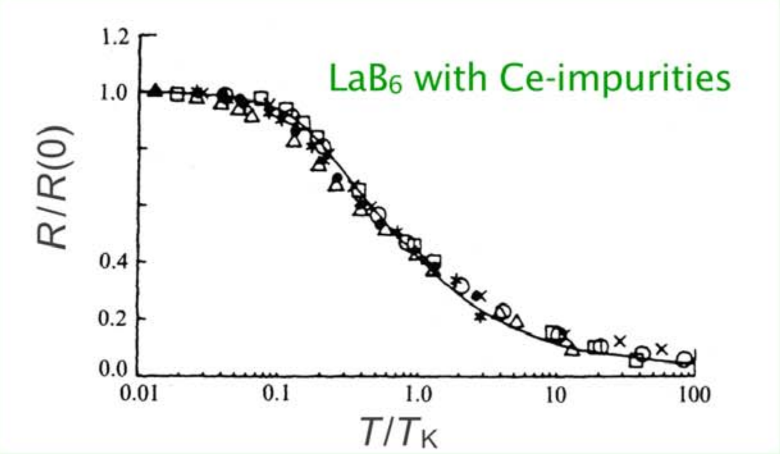
C. Laschinger, T. Kopp (2005)

1) Single Kondo impurity:

$$T << T_K \quad \Rightarrow \quad R(T/T_K) \propto 1 - c\,(T/T_K)^2$$

$$T >> T_K \quad \Rightarrow \quad R(T/T_K) \propto 1/\ln^2 (T/T_K)$$

R scales with $a' = (T_K/T)$



Data: Bickers *et al.*, PRL **54**, 230 (1985)
NCS-Calculation: Winzer *et al.*, Sol. St. Com. **16**, 521 (1975)

2) Kondo impurities with distribution of T_K (disordered interface):

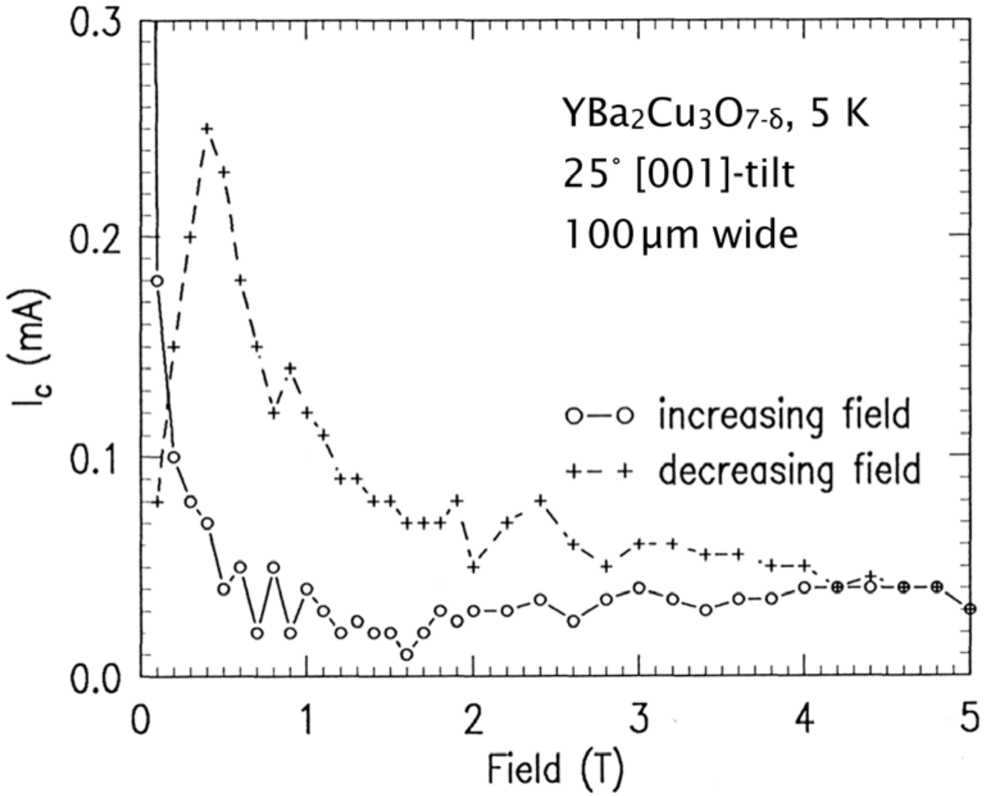
$$\hat{R}(T) \approx const - P(0)\,T \int R(1/a')\,da'$$

→ $\hat{R}(T)$ decreases linearly with T

range of linearity is given by width of T_K distribution

compare with $R(T)$ of HFS:
Miranda *et al.*, PRL 78, 290 (1997)

Nanobridges across Grain Boundaries?



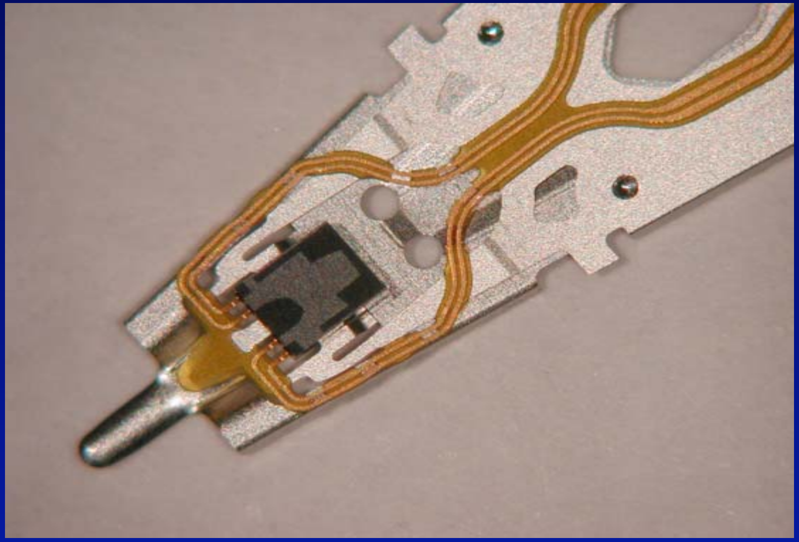
M. Däumling *et al.*, Appl. Phys. Lett. 61, 1355 (1992)

B.H. Moeckly *et al.*, Phys. Rev. B 47, 400 (1993)

Summary

Great Challenge: Interfaces in Correlated Electron Systems

- Immense technological relevance
- Exciting and complex physics



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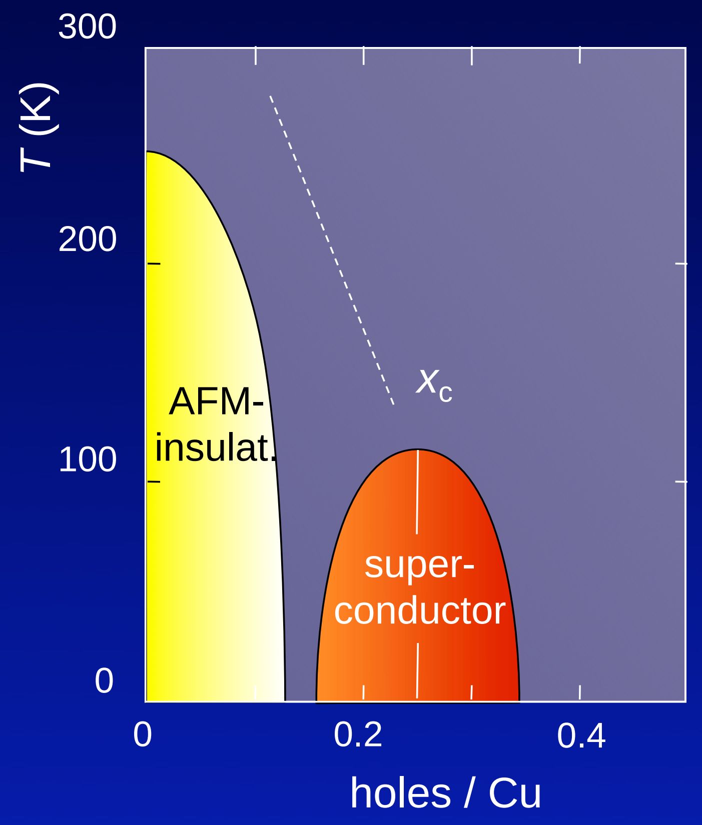
Example: grain boundaries in HTS



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