Interface superconductivity

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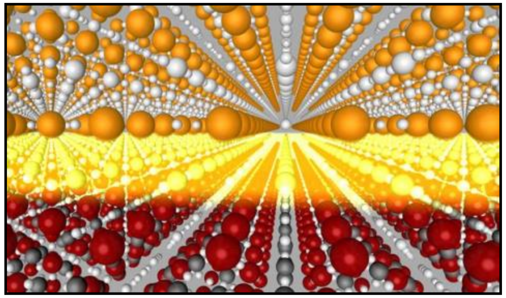


Some inspiration

"I am convinced that often a newcomer to a field has a great advantage because he is ignorant and does not know all the complicated reasons why a particular experiment should not be attempted."

Ivar Giaever, Nobel Lecture

More wise words

“If I have learned anything as a scientist it is that one should not make things complicated when a simple explanation will do.”

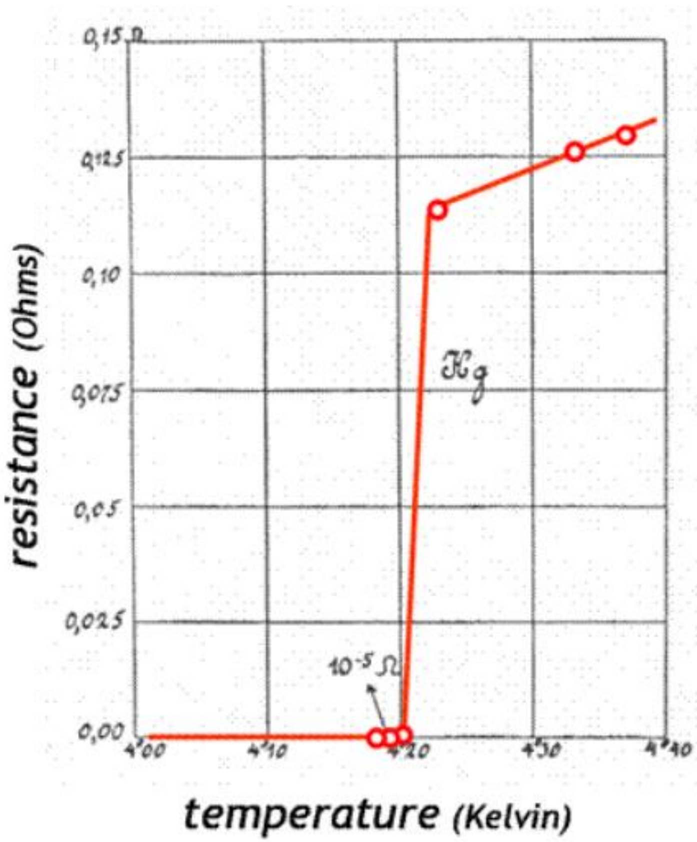
Ivar Giaever, Nobel Lecture

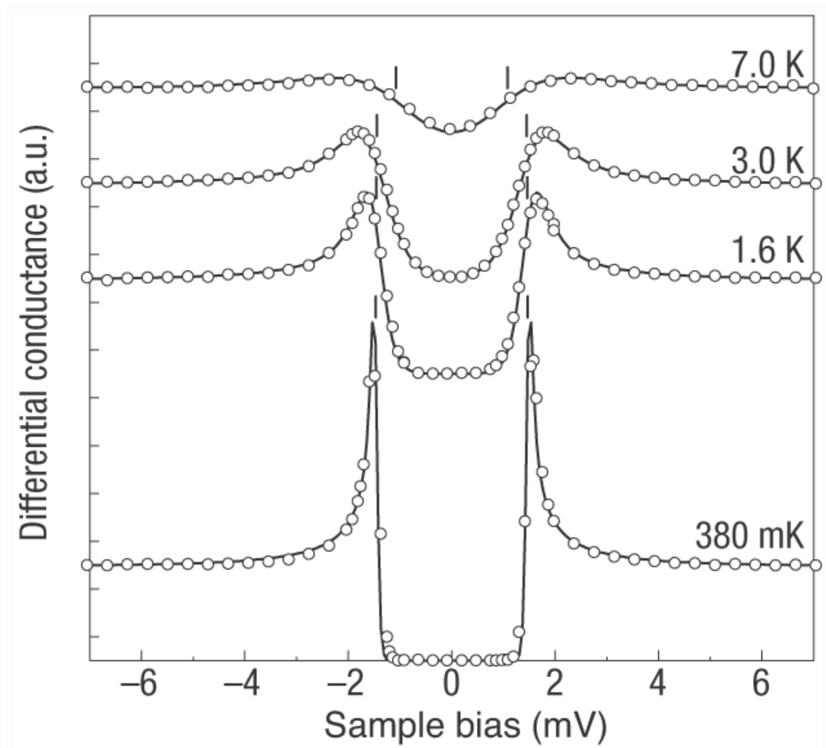
More wise words

"If I have learned anything as a scientist it is that one should not make things complicated when a simple explanation will do.
Thus all the samples we made showing the Josephson effect were discarded as having shorts."

Ivar Giaever, Nobel Lecture

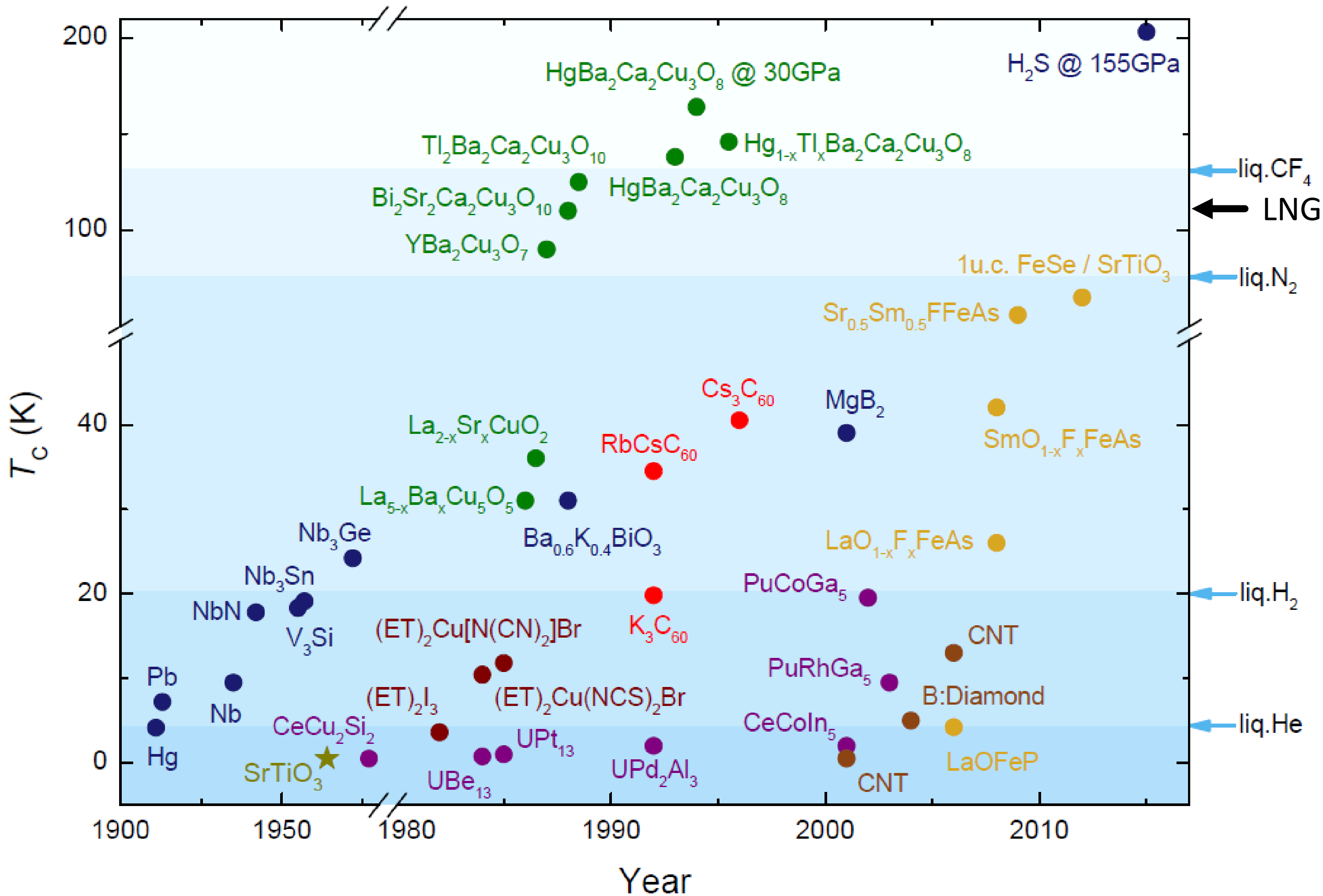
Superconductivity



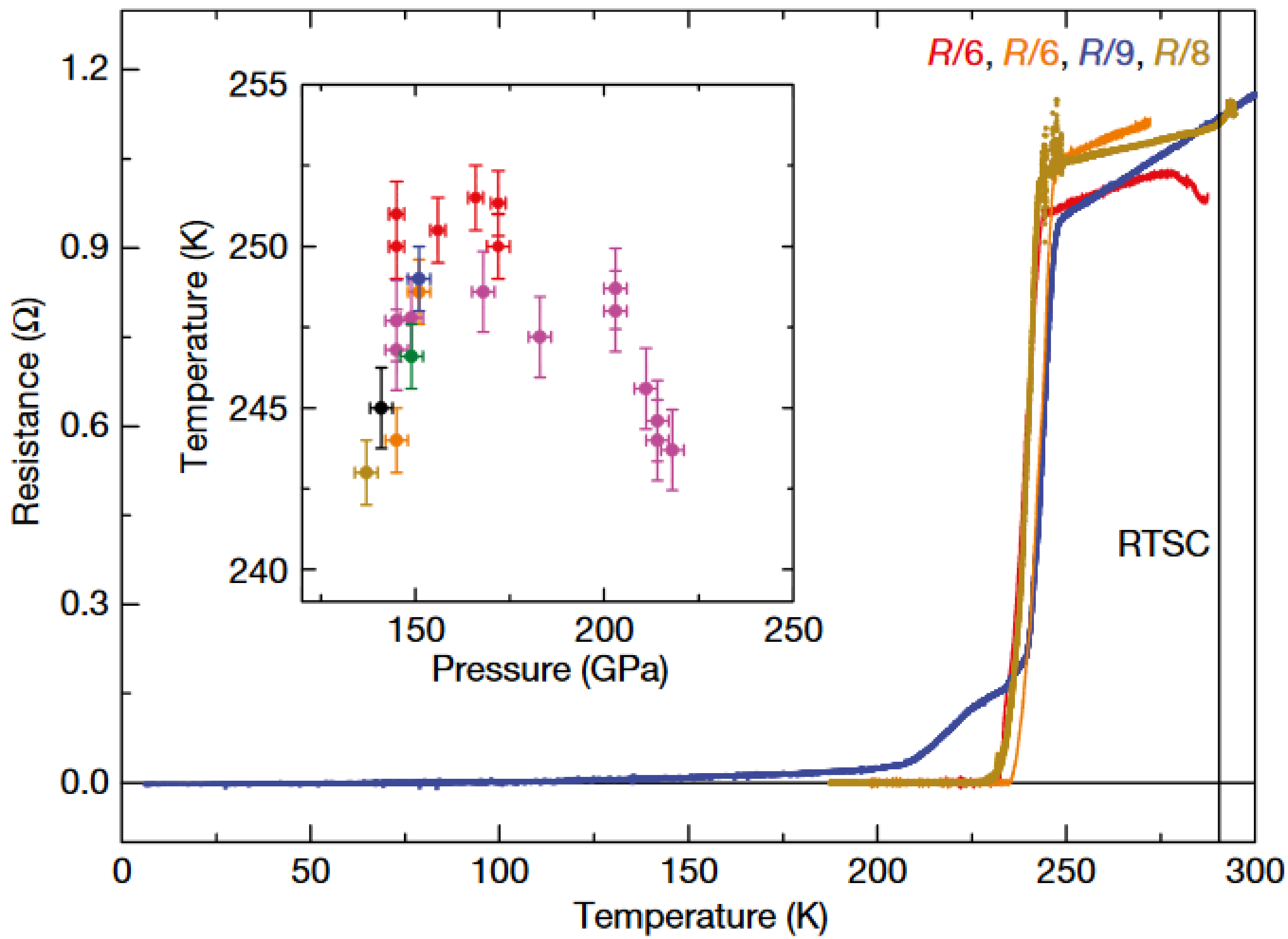


E. W. Hudson, Nature Physics **4**, 271 (2008)

History of T_c



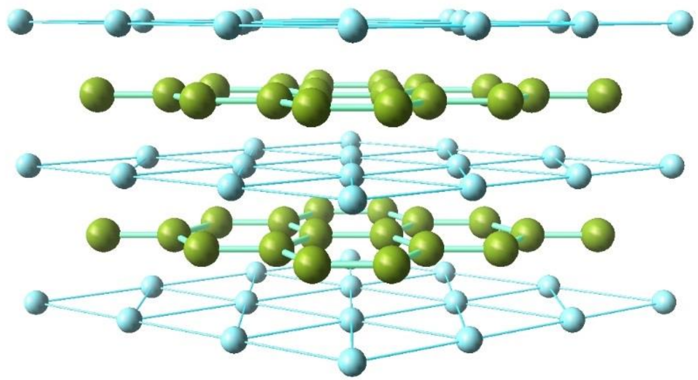
Current record holder: LaH_{10}

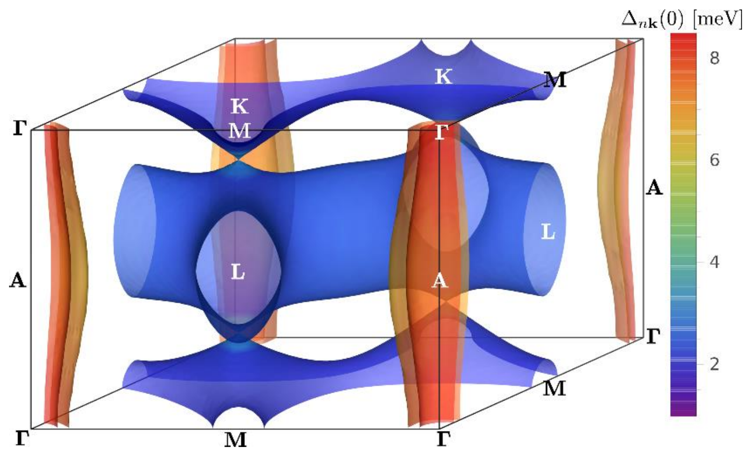


A. P. Drozdov, *et al.*, Nature **569**, 528 (2019)

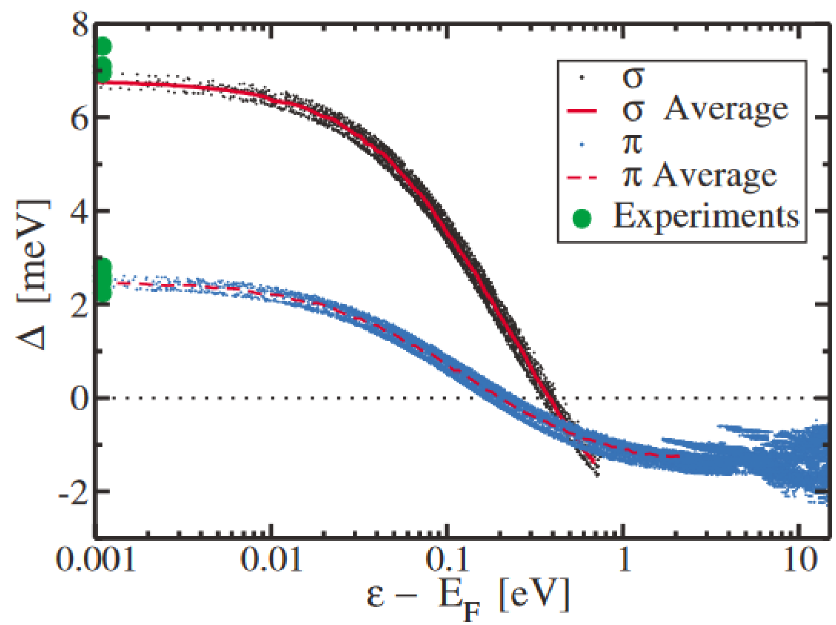
Modern theory: SCDFT

MgB_2





epw.org.uk



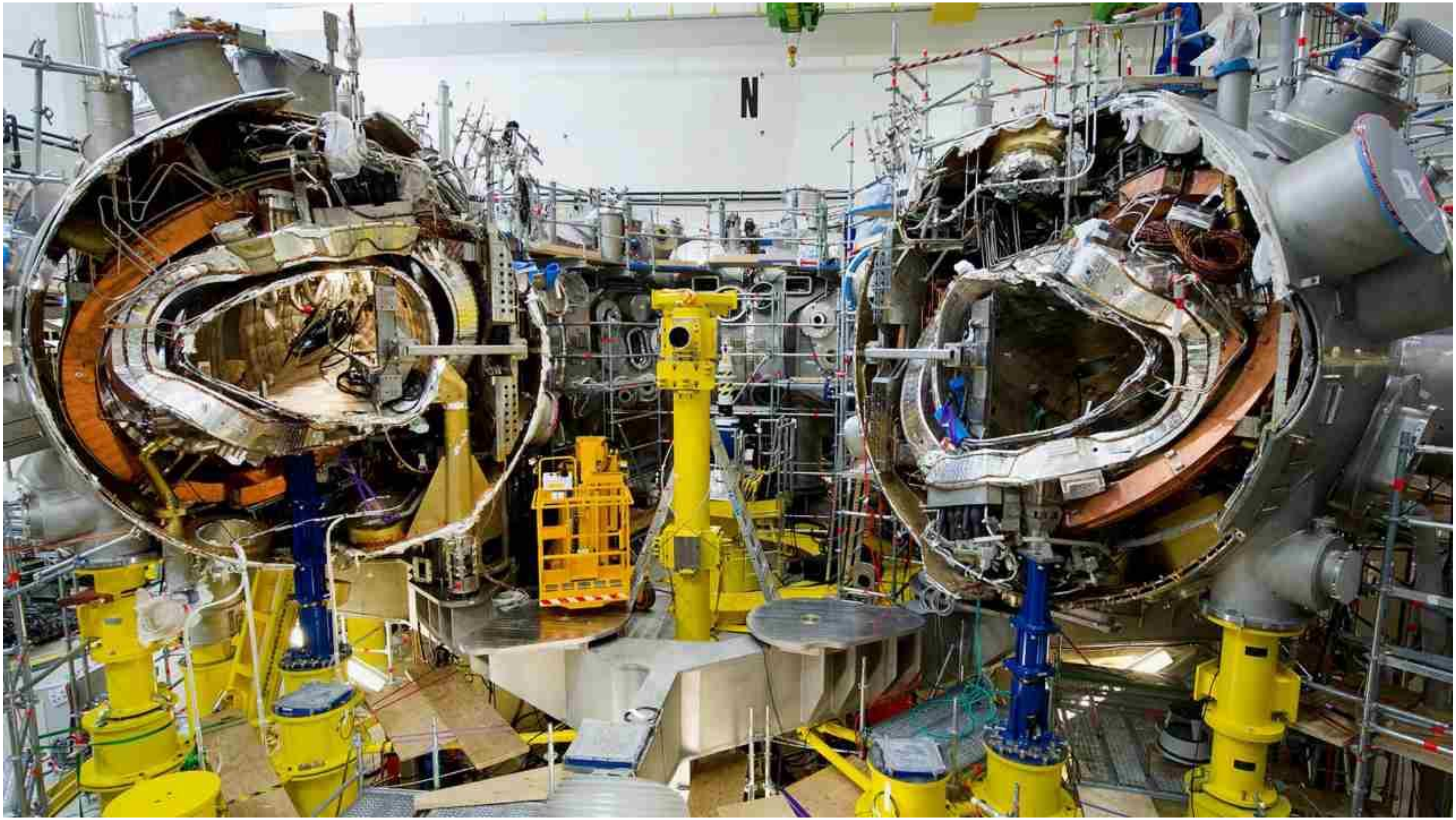
A. Floris, *et al.*, PRL **94**, 037004 (2005)

Literature

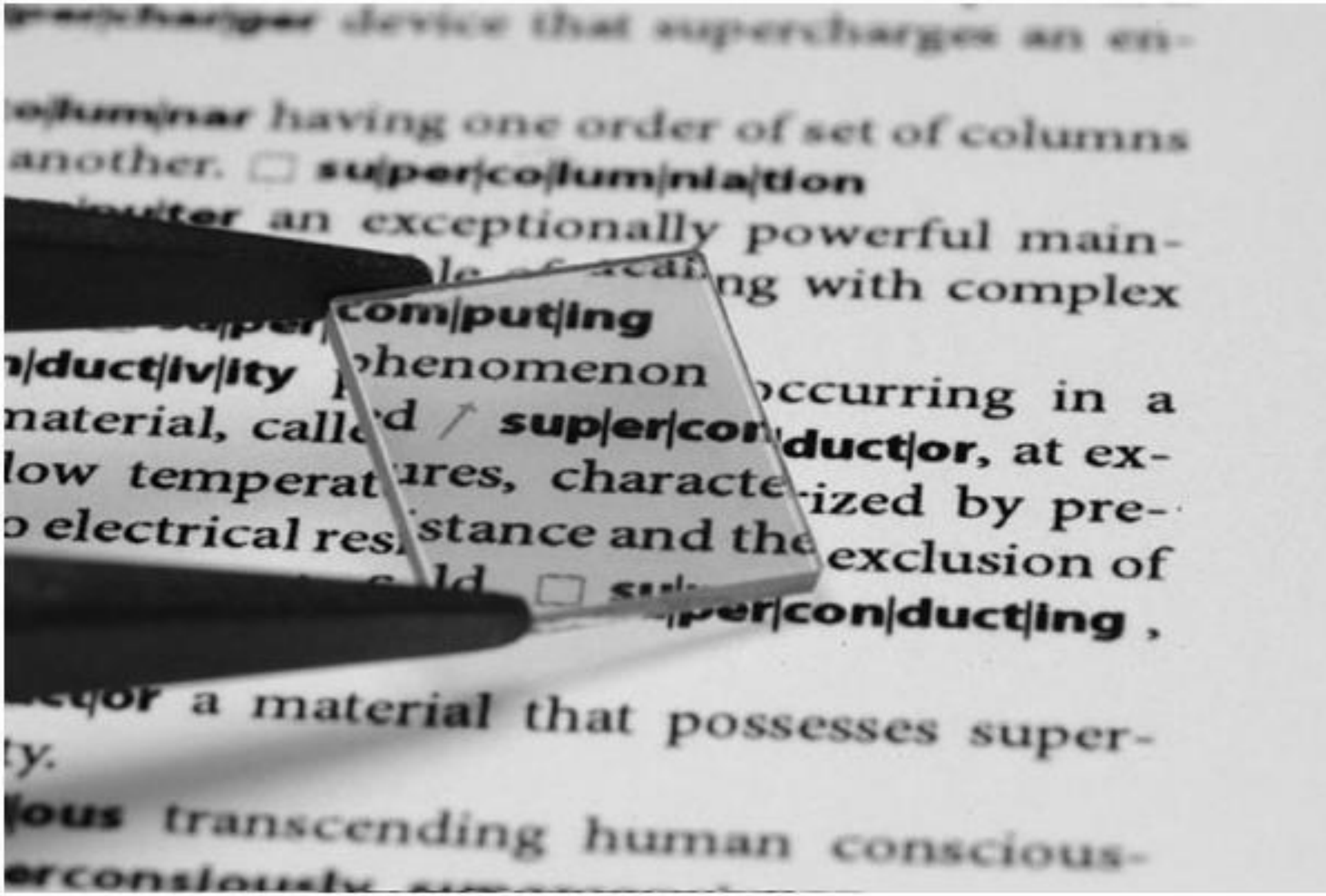
1. J. Pereiro, *et al*., Physics Express **1**, 208-241 (2011)

2. S. Gariglio, *et al*., Phys. C **514**, 189 (2015)

3. H. Boschker, *et al*., Physik Journal **15**, 37 (2016)



Wendelstein 7-X (MPI-IPP, Greifswald, Germany)


device that supercharges an en-
having one order of set of columns
another. □ su|per|co|lum|ni|a|tion
an exceptionally powerful main-
ng with complex
com|put|ing
phenomenon
occurring in a
material, called ↗ sup|er|con|duct|or, at ex-
low temperatures, characterized by pre-
electrical resistance and the exclusion of
per|con|duct|ing ,
a material that possesses super-
transcending human conscious-

Definitions

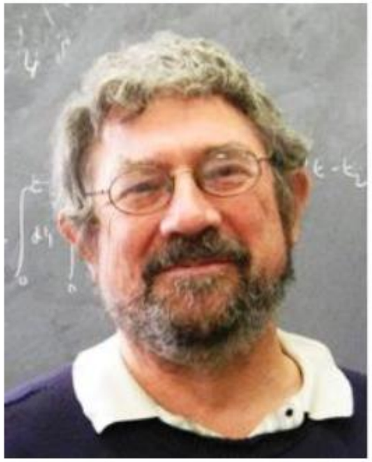
1. Interface superconductivity: superconductivity that occurs at the interface of two materials that are not superconducting in their bulk forms

2. Interface-enhanced superconductivity: superconductivity at the interface of two materials with T_c larger than that of their bulk components

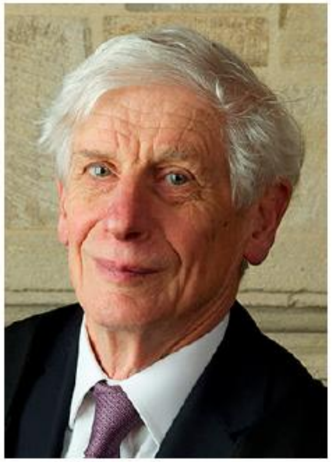
3. Two-dimensional superconductivity: thickness of the superconducting layer is smaller than ξ_0

4. Berezinskii-Kosterlitz-Thouless (BKT): framework for the superconducting phase transition in two dimensions

BKT physics



Kosterlitz



Thouless

Berezinskii

1971: J. Michael Kosterlitz and David J. Thouless investigate vortex Dynamics in 2D films of superfluid Helium

Kosterlitz in the mountains

“Normal” phase transitions

Transition	Order Parameter	Symmetry breaking
Ferromagnetic/Ferroelectric	magnetization	Rotation
Superconducting/Superfluid	$\|\Psi\|^2$	Phase (gauge)
…	…	…

Landau theory

Close to T_c : Order parameter Q is small

Apply continuous perturbation theory

$$F(T,p,\mathrm{Q}) = F_0\,(T,p) + A(T,p)/2\ \ \mathrm{Q}^2 + B(T,p)/4\ \ \mathrm{Q}^4$$

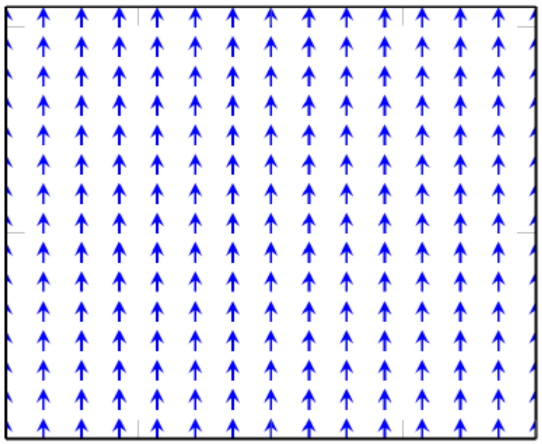
Mermin-Wagner theorem

There is no phase with spontaneous breaking of a continuous symmetry for $T > 0$, in $d \leq 2$ dimensions.

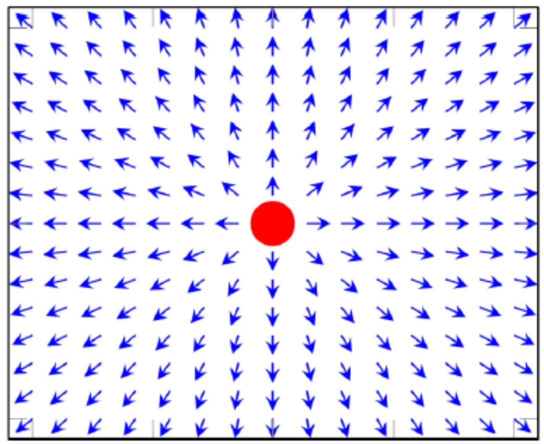
"Undeterred by the general view that the problem was either absurd or impossible, Kosterlitz out of ignorance, and Thouless, out of curiosity, went ahead and essentially solved the problem."

J. M. Kosterlitz and D. J. Thouless, in: *40 Years of BKT Theory*, World Scientific, 2013

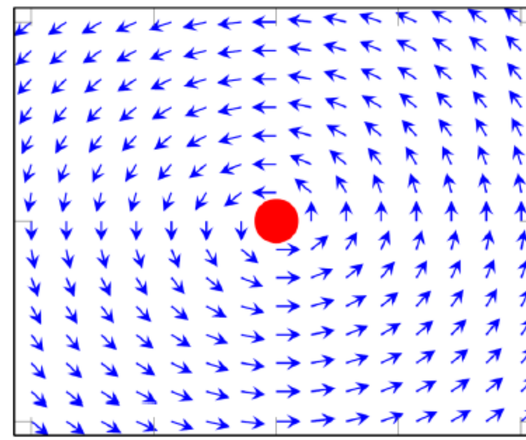
2D XY model



θ without vortex

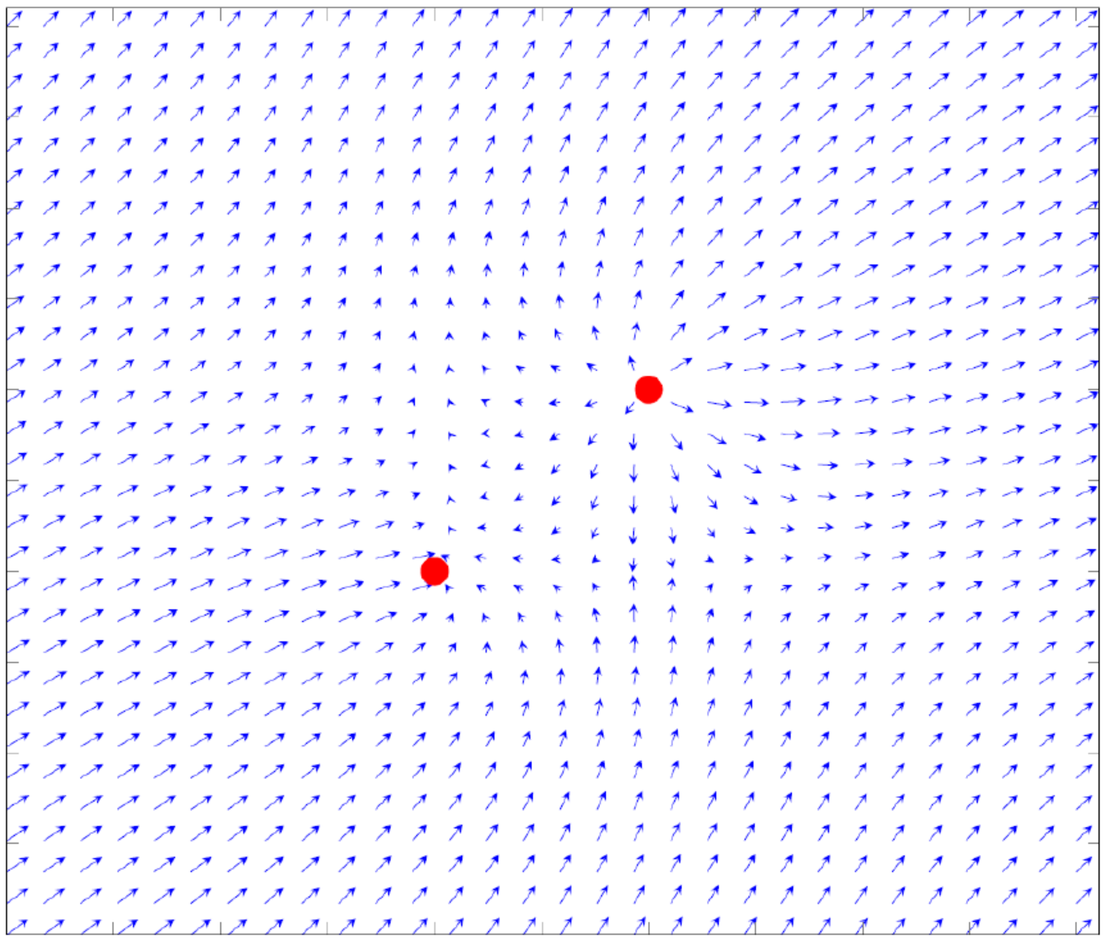


θ with vortex



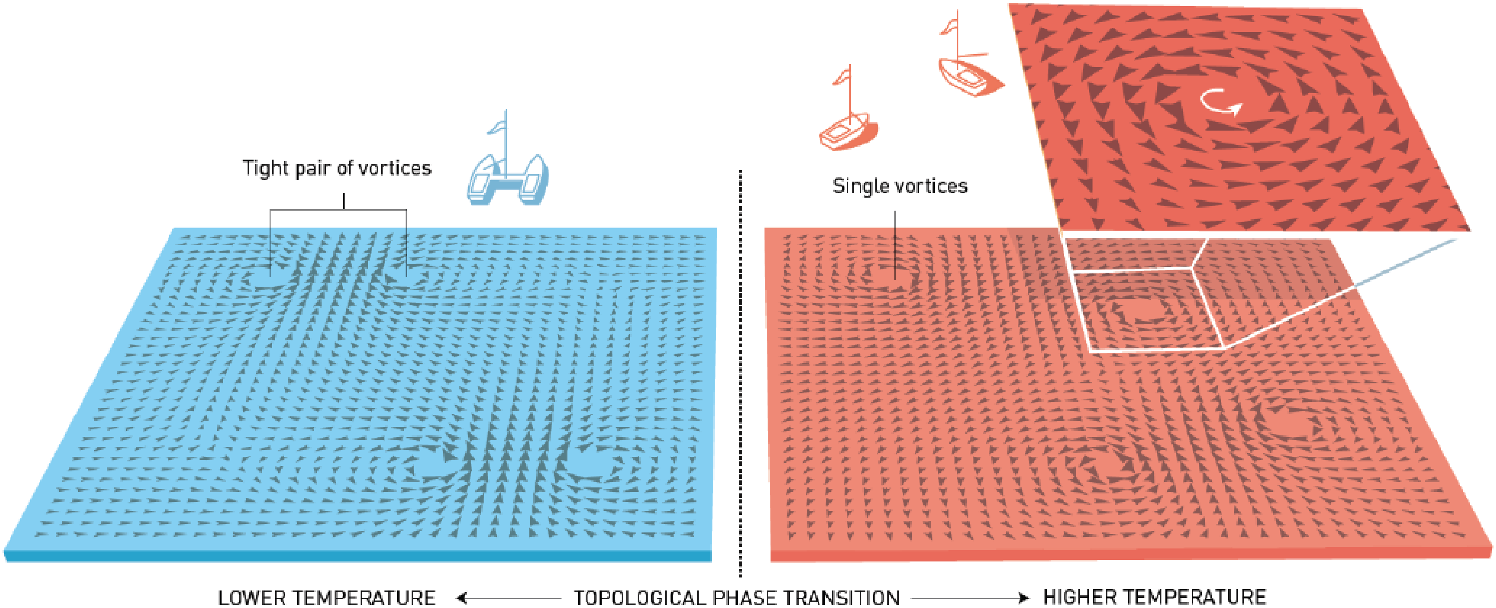
$\nabla\theta$ with vortex

BKT physics



Two vortices with opposite *n* of equal magnitude

The BKT transition



nobelprize.org

Jump in superfluid density

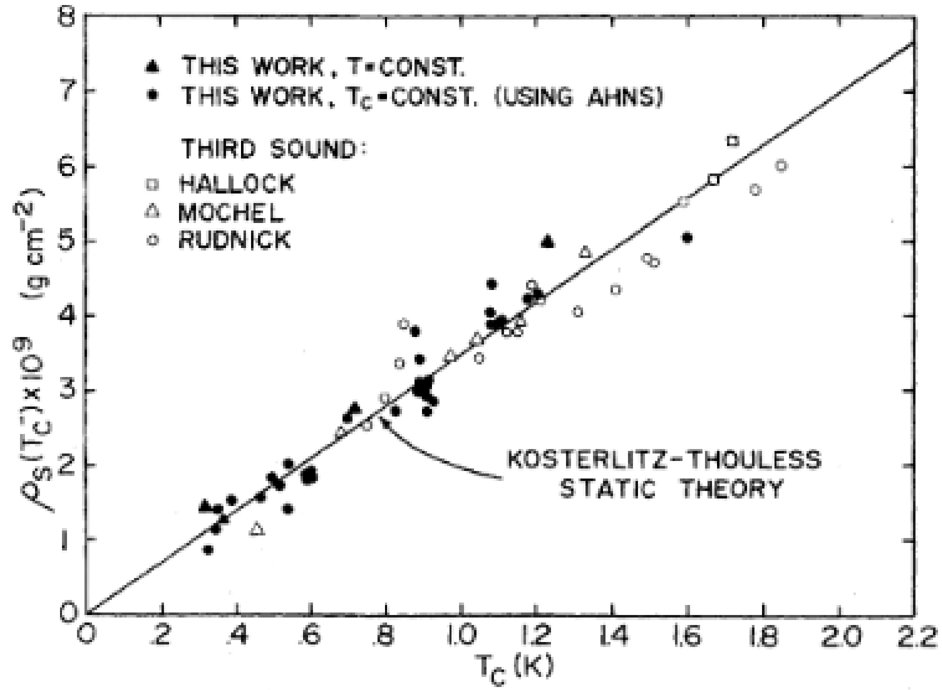


FIG. 3. Results of all of our data, in addition to previous third-sound results for the discontinuous superfluid density jump $\rho_s(T_c^-)$ as a function of temperature. The solid line is the Kosterlitz-Thouless (Refs. 3 and 4) static theory.

D. J. Bishop, *et al.*, PRL **40**, 1727 (1978)

Theory of interface superconductivity

Central idea

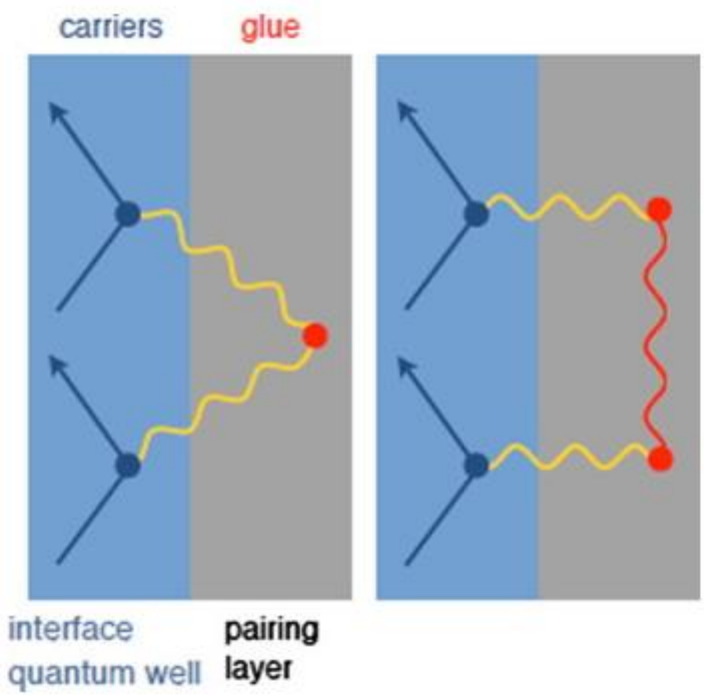


Fig. 1.

(Left) Two electrons (blue) interact (yellow) with a site (red) in the pairing layer, creating a virtual excitation. This excitation, for example polarization of an oxygen ion, causes the pairing. (Right) Each electron excites a different site in the pairing layer, but both sites are coupled (red), and by this close the pairing channel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

S. Gariglio, *et al.*, Phys. C **514**, 189 (2015)

Early days

PHYSICAL REVIEW B VOLUME 4, NUMBER 3 1 AUGUST 1971

Dynamic Effective Electron-Electron Interaction in the Vicinity of a Polarizable Molecule*

W. A. Little
Stanford University, Stanford, California 94305

and

H. Gutfreund
Department of Theoretical Physics, Hebrew University, Jerusalem, Israel
(Received 24 February 1971)

ON SURFACE SUPERCONDUCTIVITY

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

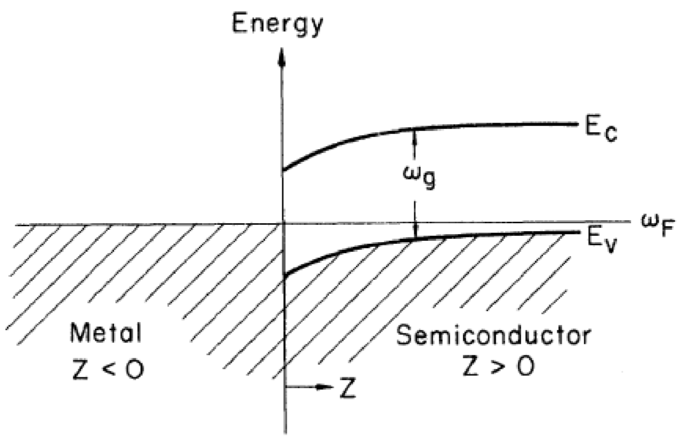
Received 21 October 1964

High T_c possible?

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)



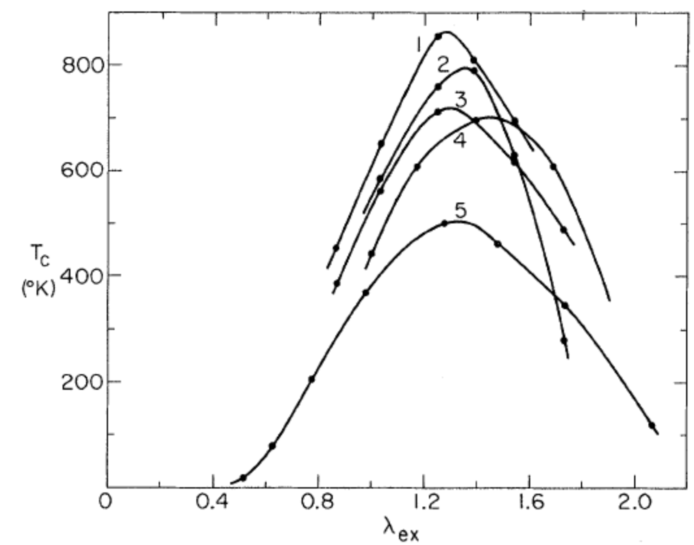
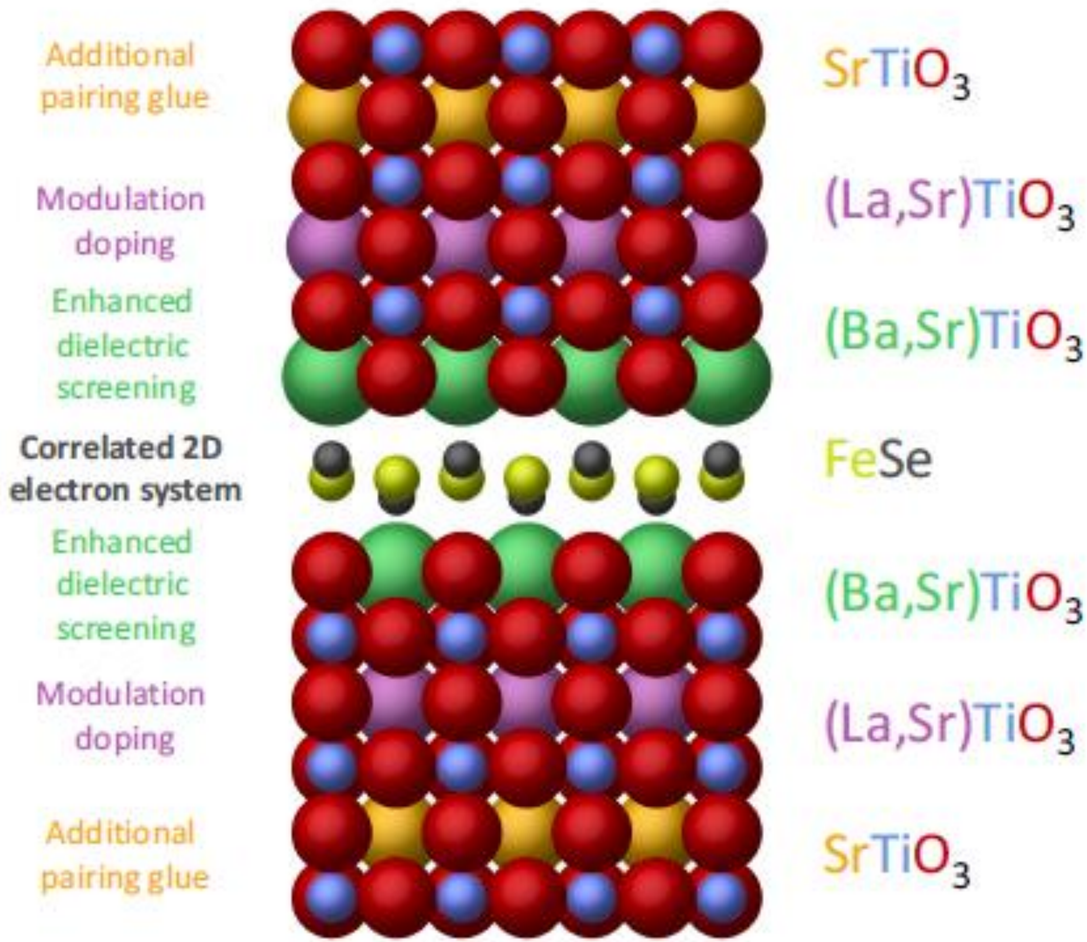


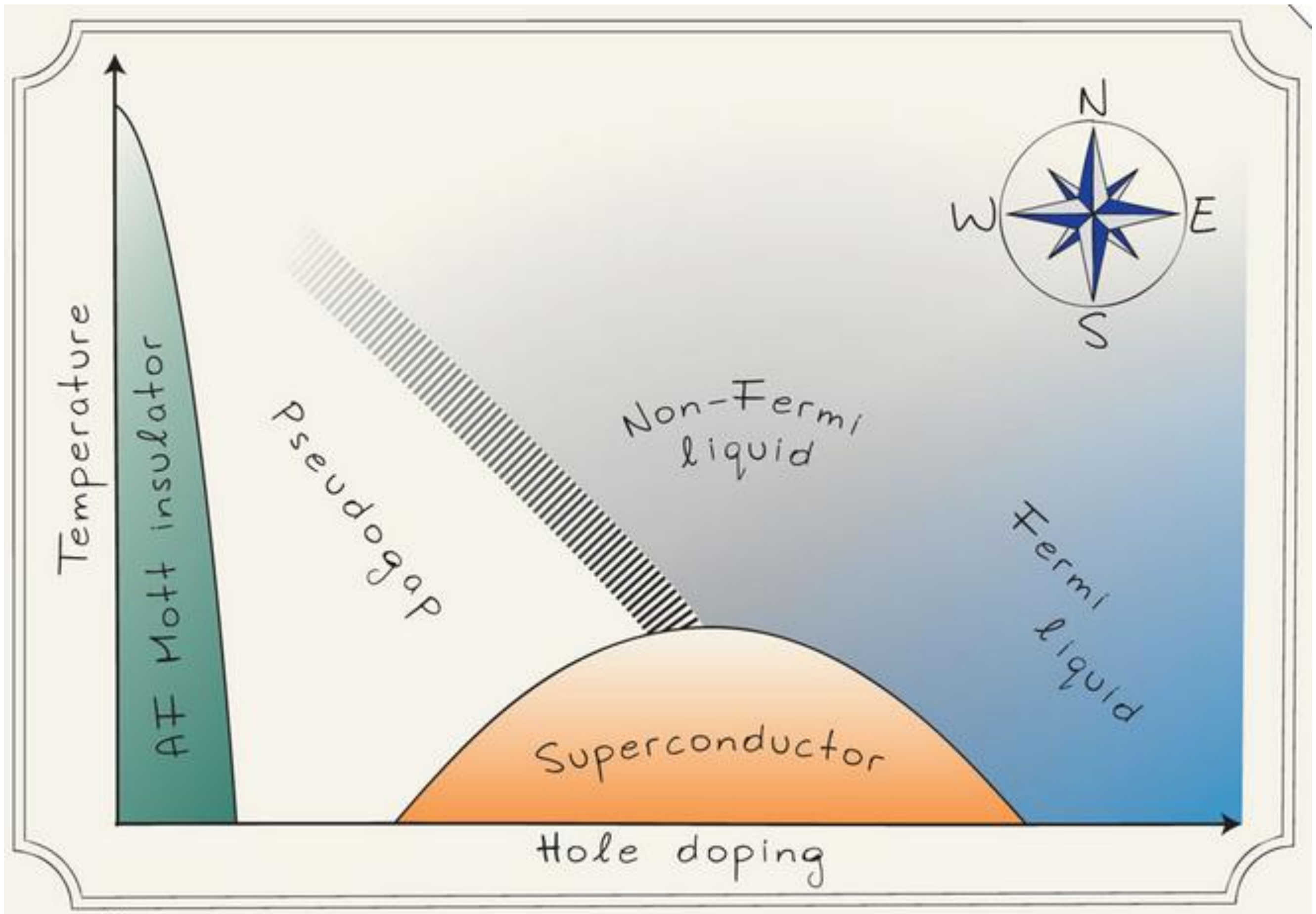
FIG. 8. Family of curves illustrating maximum values of T_c for the exciton mechanism alone if λ_{ex} is unrestricted in magnitude. Note that for the model discussed in this present paper $\lambda_{ex} < 0.5$. The very high values of T_c are unrealistic for any model. The following data were found:

Building superconductors from scratch



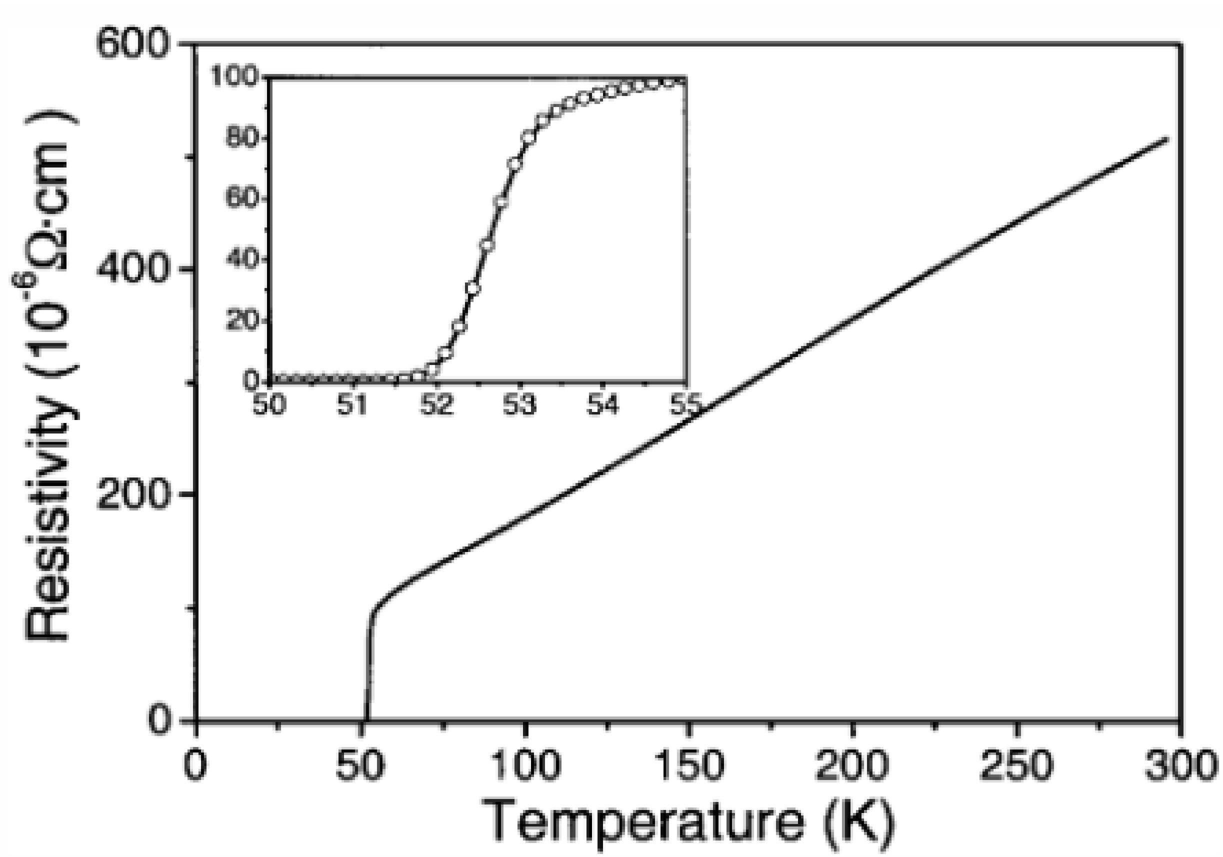
Examples

Cuprates



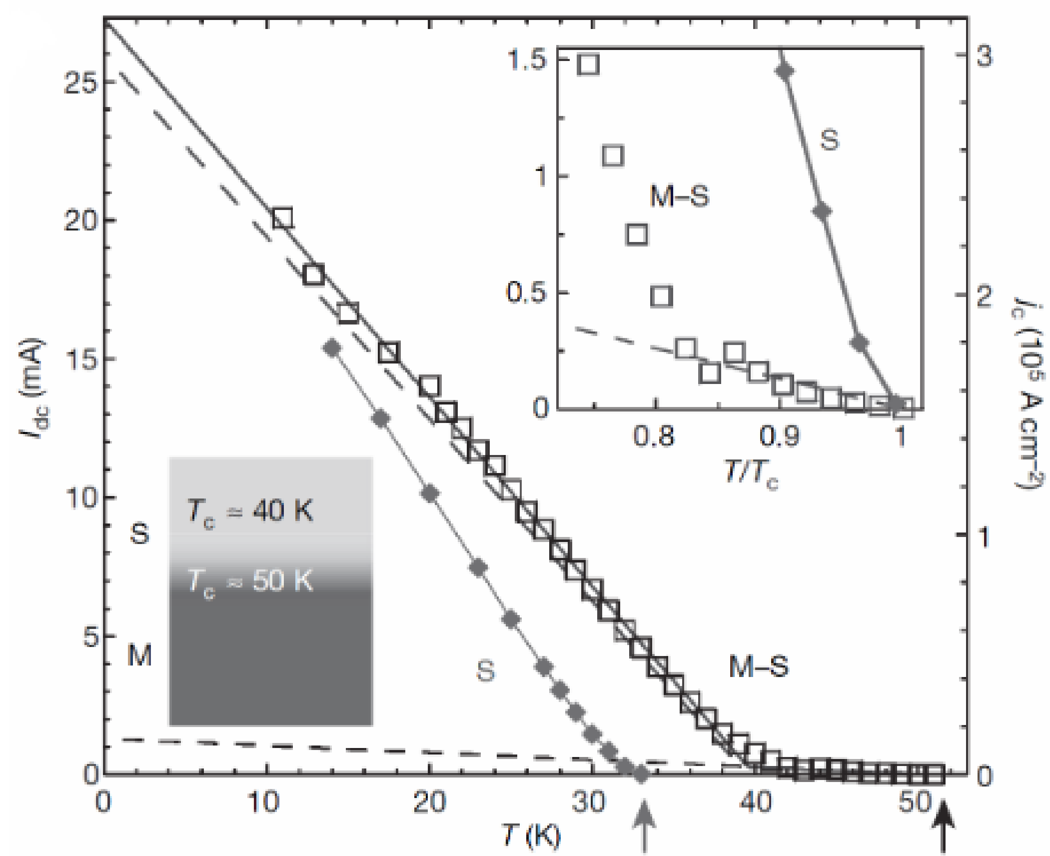
Temperature
AF Mott insulator
Pseudogap
Non-Fermi liquid
Fermi liquid
Superconductor
Hole doping
N
E
S
W

LSCO interface



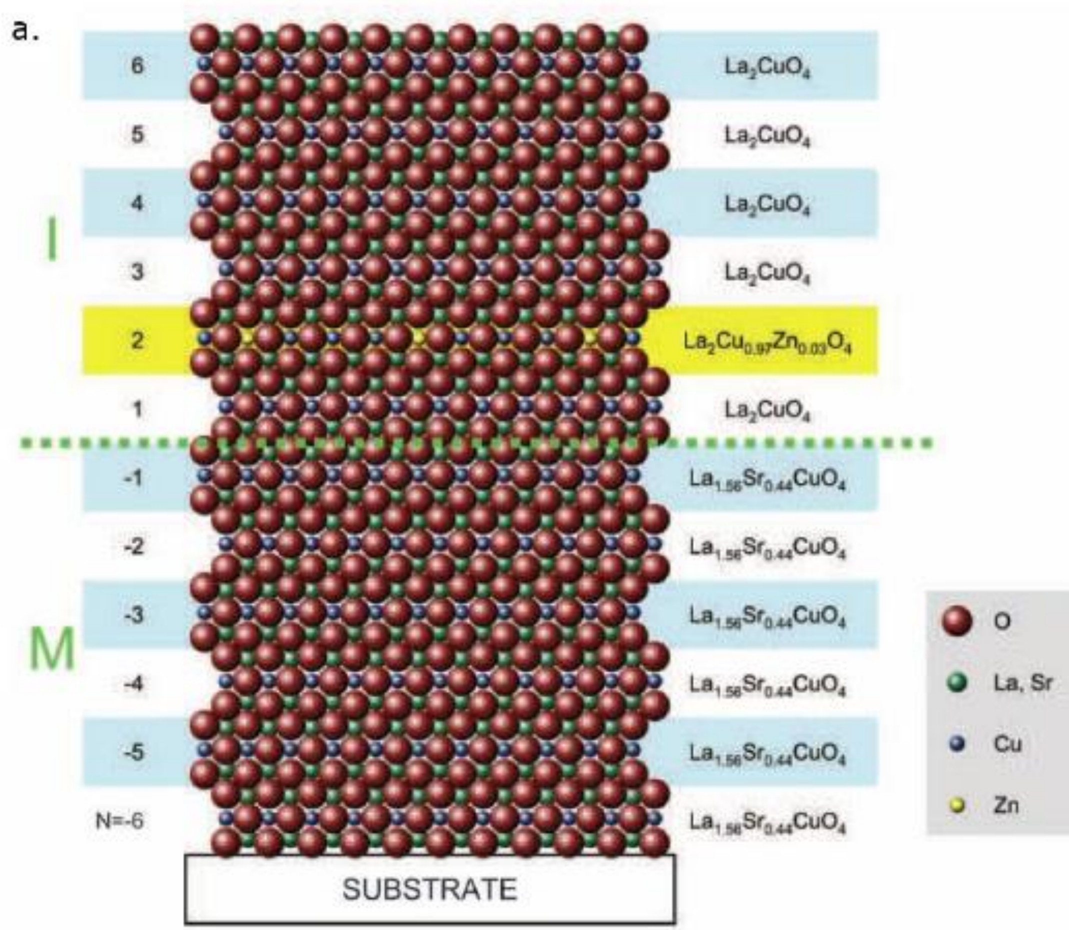
Ivan Bozovic group

Interface superconductivity



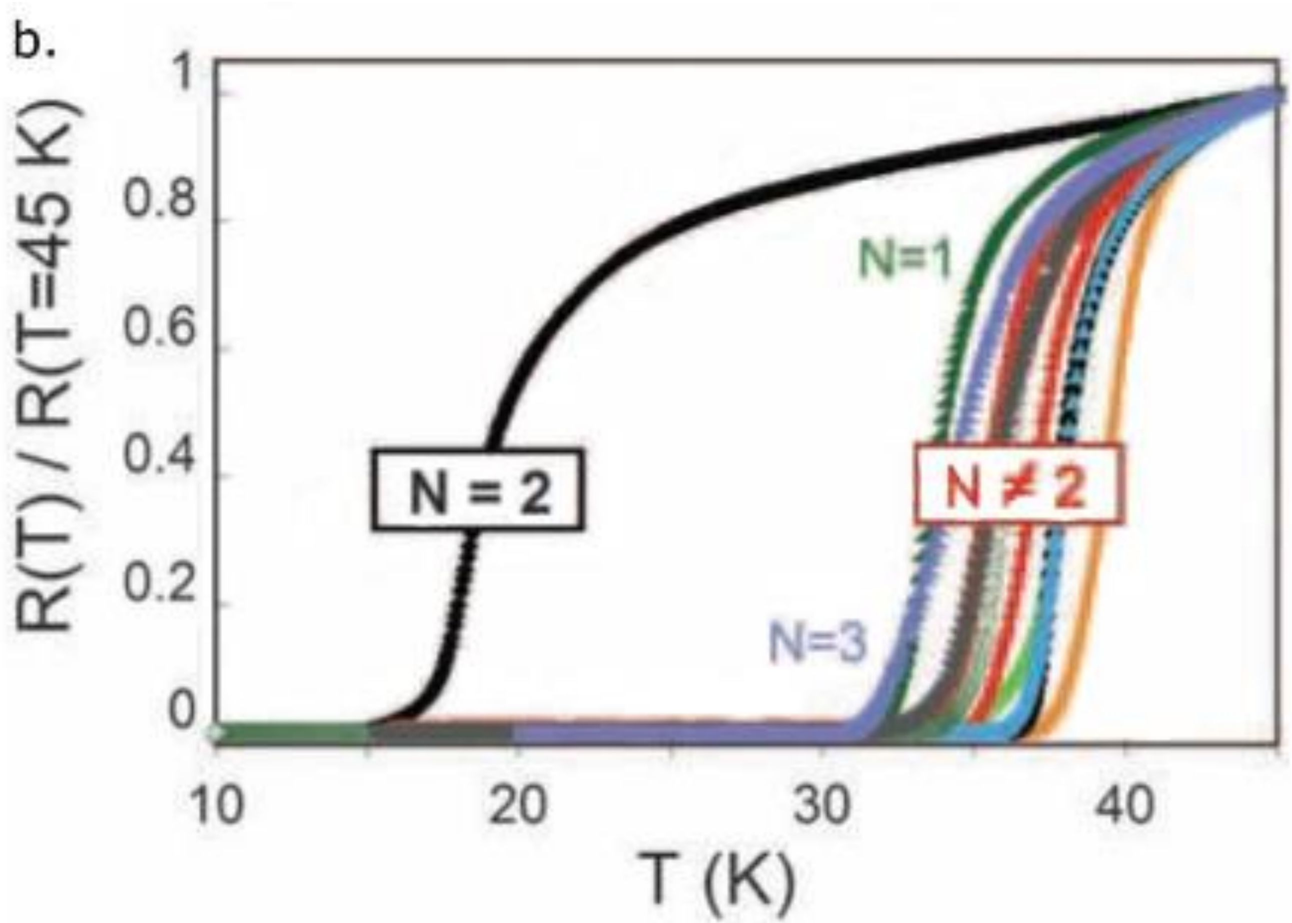
A. Gozar, *et al.*, Nature **455**, 782 (2008)

Profiling the wavefunction



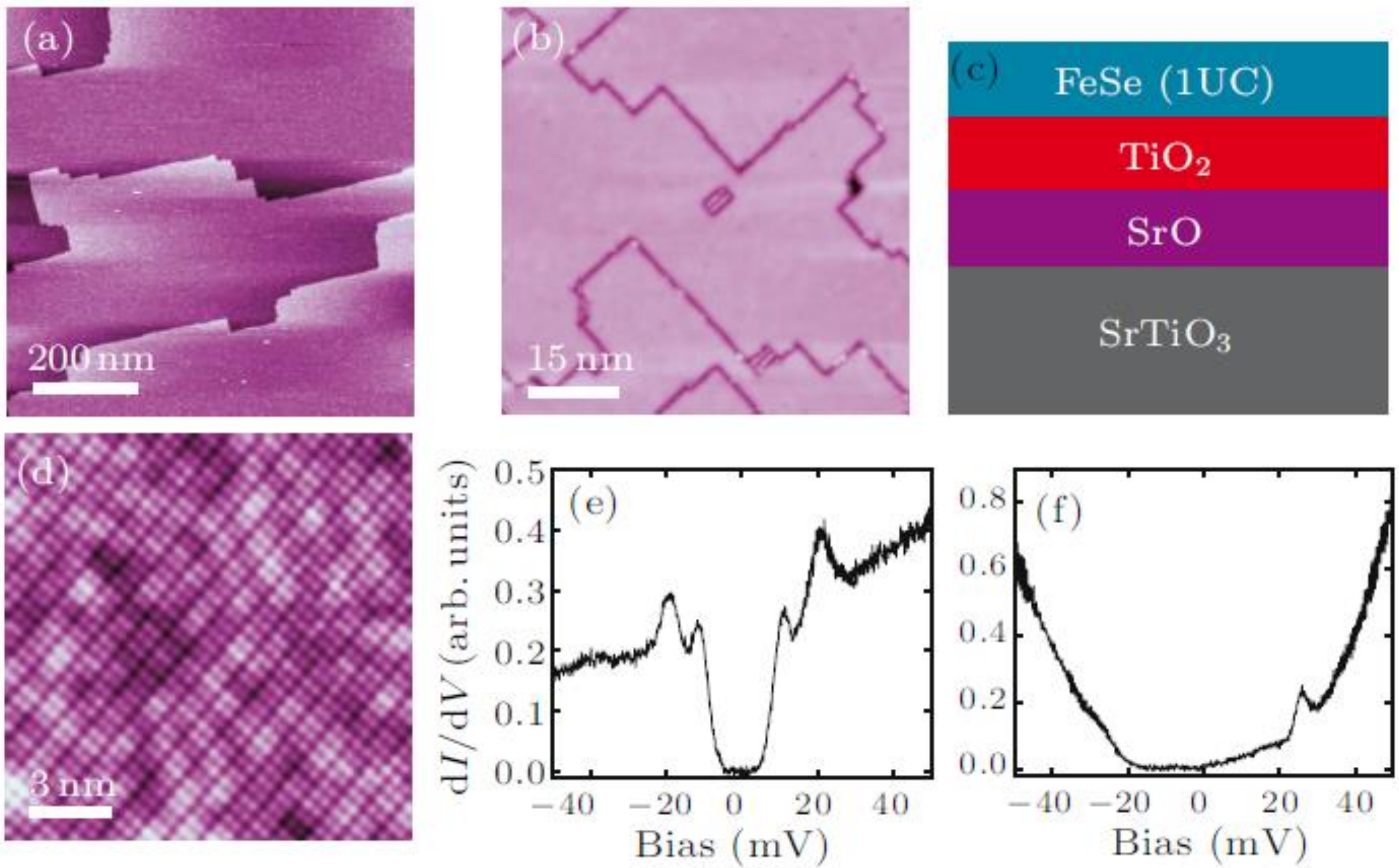
Ivan Bozovic group

Only one layer is dominant



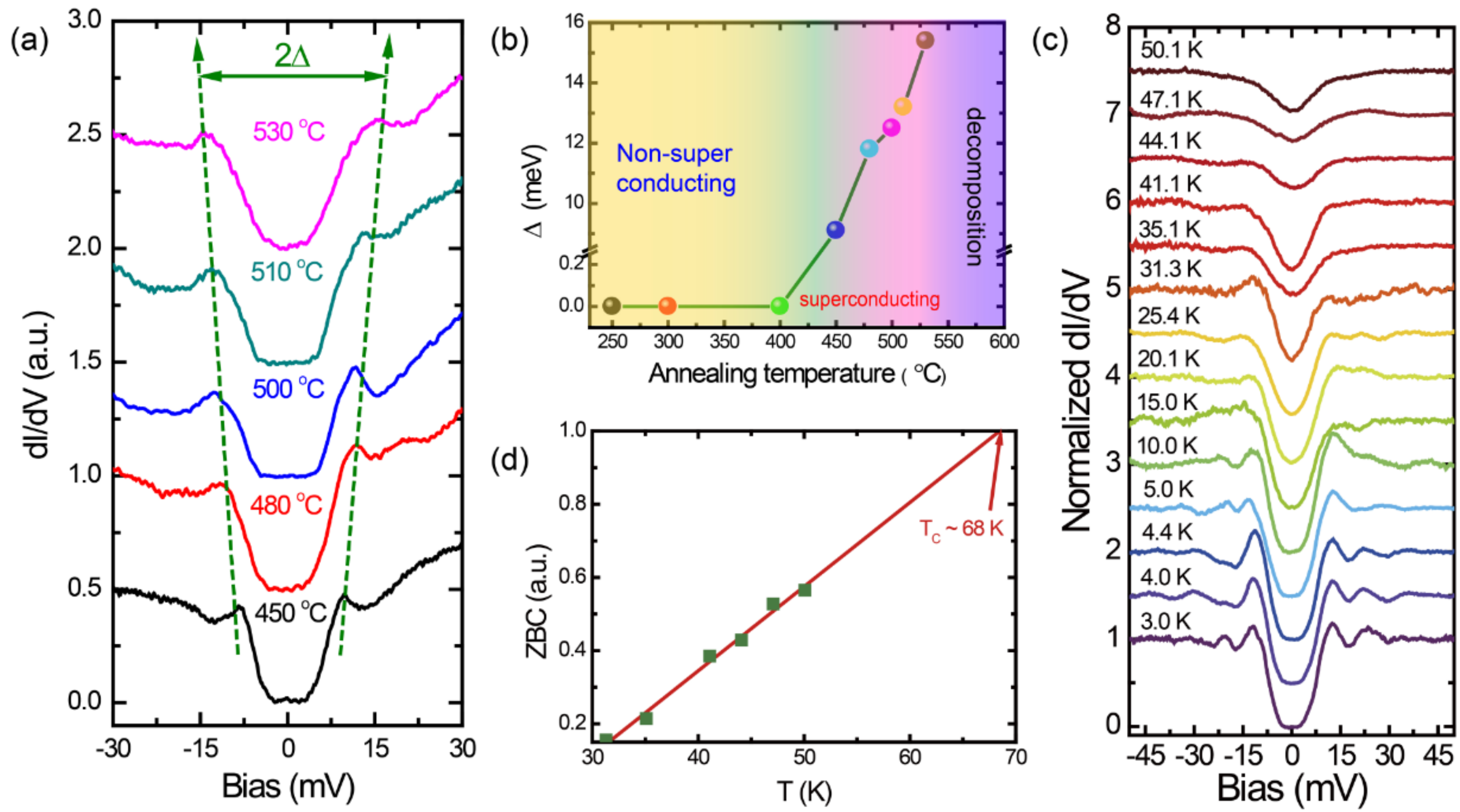
G. Logvenov, *et al.*, Science **326**, 699 (2009)

FeSe-$SrTiO_3$



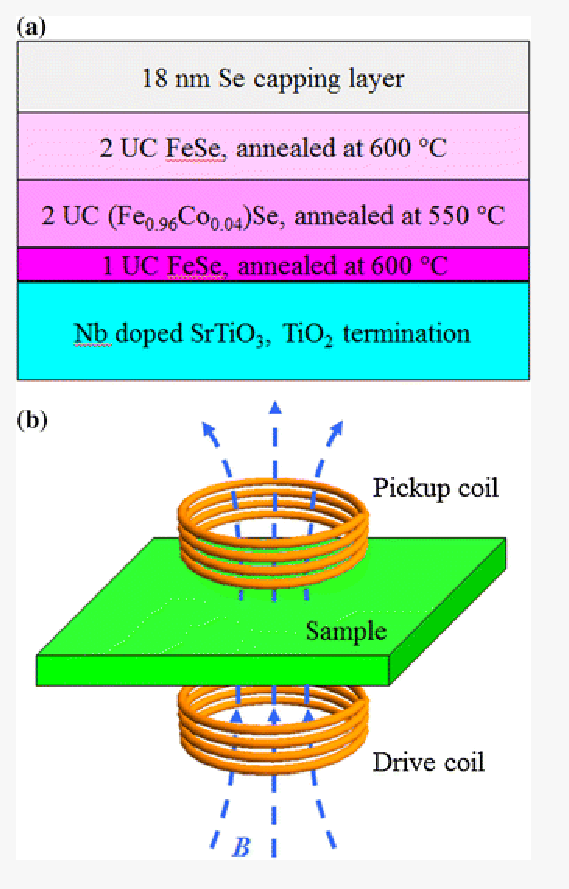
Q. Y. Wang, *et al.*, Chin. Phys. Lett. **29**, 037402 (2012)

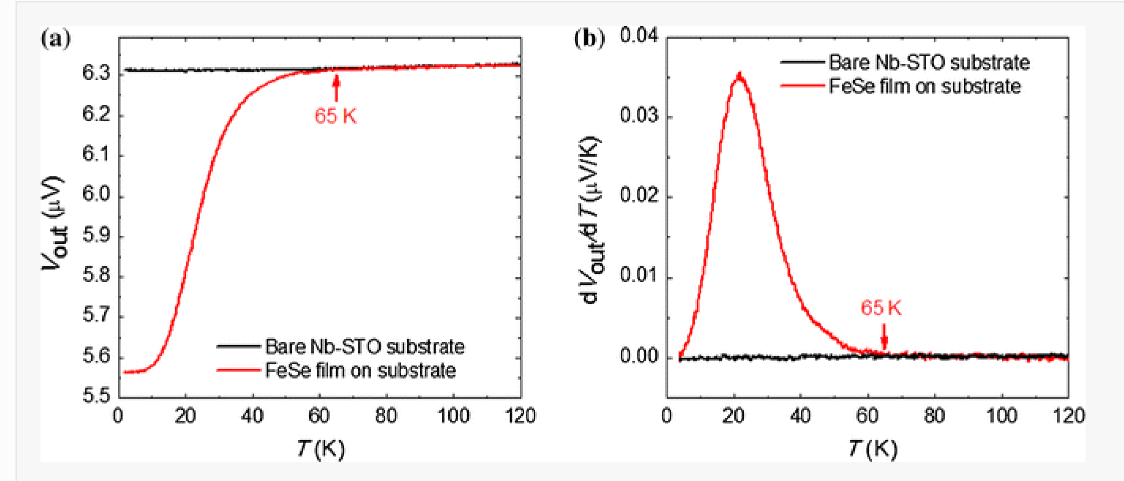
Doping from oxygen vacancies in $SrTiO_3$



W. Zhang, *et al.*, PRB **89**, 060506(R) (2014)

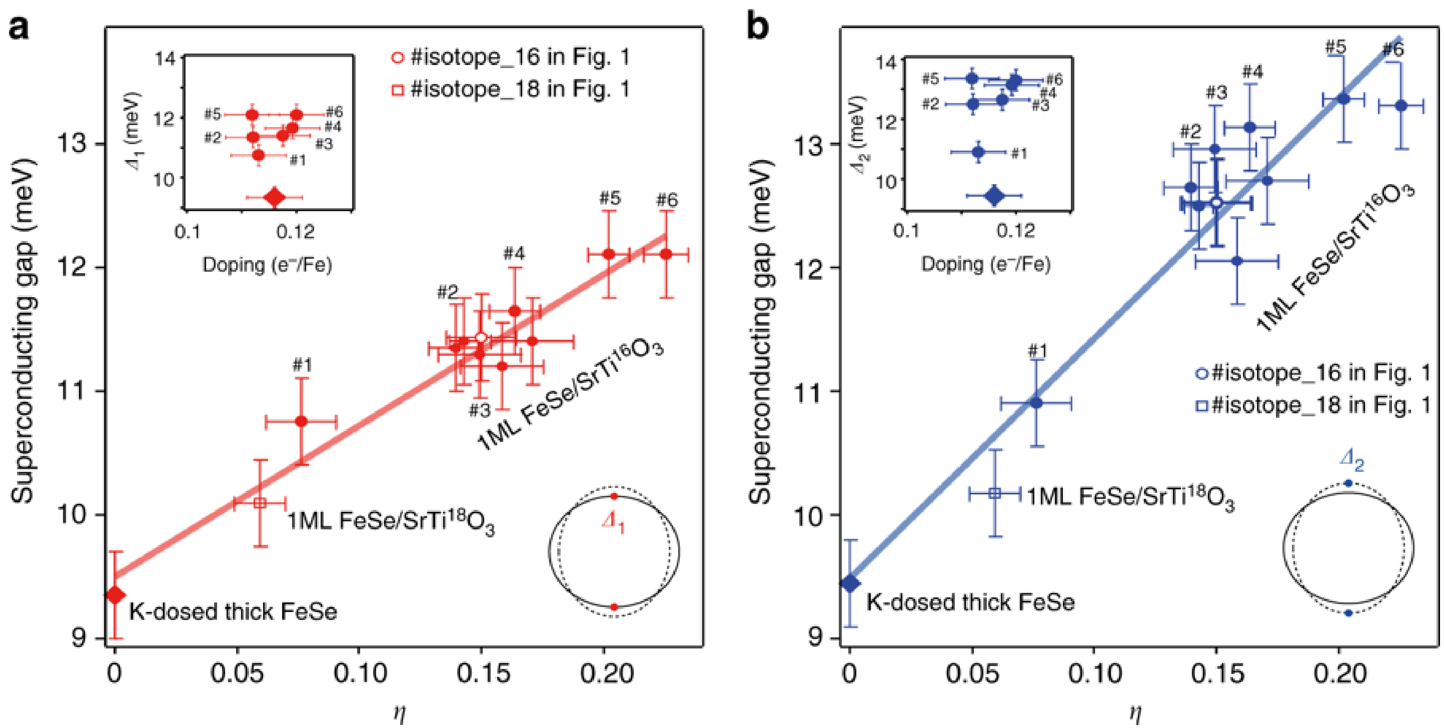
Meissner effect





Z. Zhang, *et al.*, Sci. Bull. **60**, 1301 (2015)

Phonons from $SrTiO_3$



Q. Song, *et al.*, Nature Commun. **10**, 758 (2019)

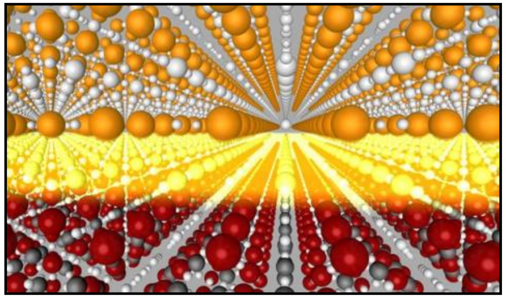
Other

1. PbTe-PbSe
2. MgO-Mg
3. $LaAlO_3$-$SrTiO_3$
4. Graphite
5. Na:WO_3

Gate-tunable superconductivity

Hans Boschker

Department Solid-State Quantum Electronics
Max Planck Institute for Solid State Research
Stuttgart, Germany



Field effect – parallel plate capacitor

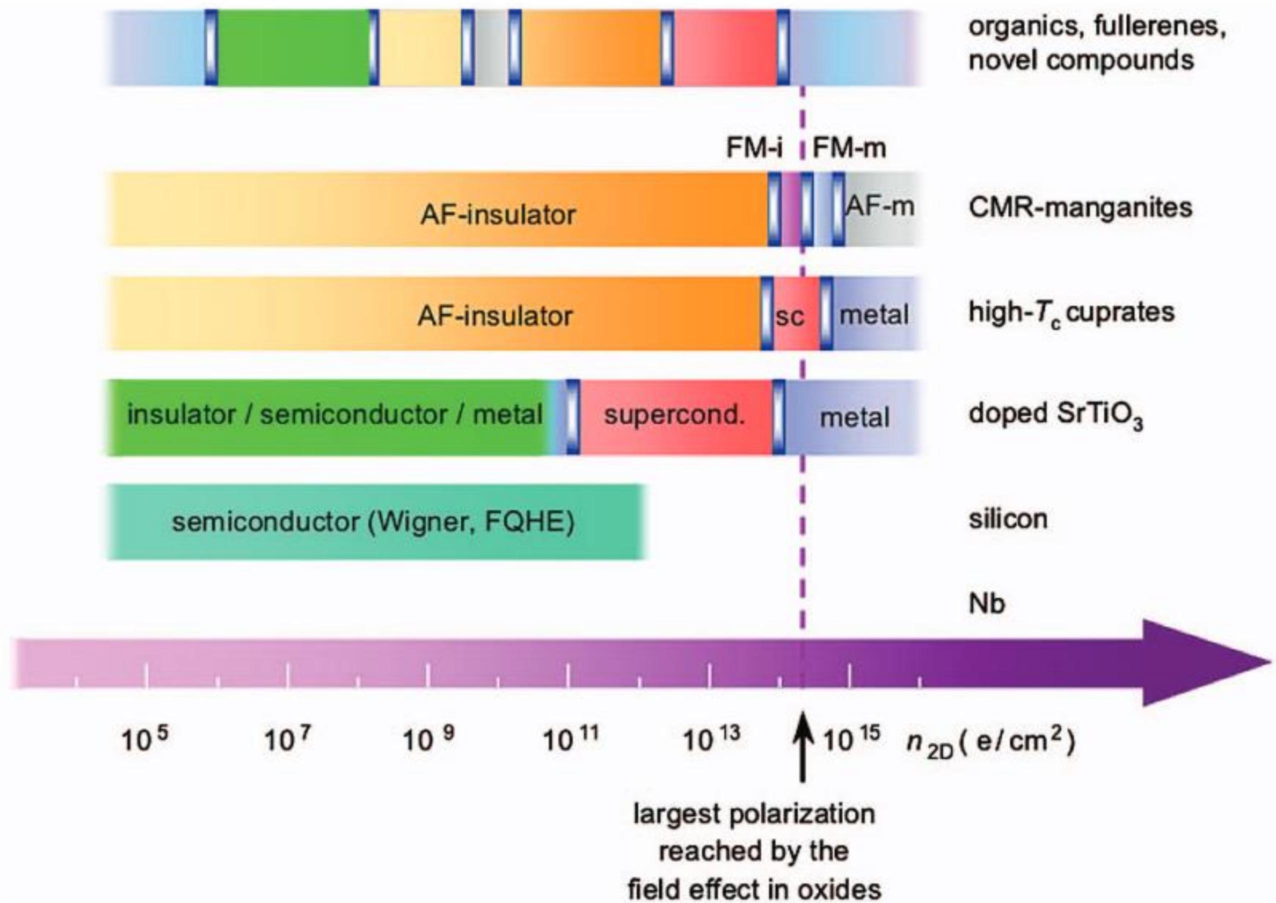
$$Q = C\,V$$

$$C = \epsilon\epsilon_0 \frac{A}{d}$$

Si MOSFET
Topgate: 1 V => ΔQ = 5 10^{12} cm^{-2}

LAO-STO:
Topgate: 1 V => ΔQ = 3 10^{13} cm^{-2}
Backgate: 100 V => ΔQ = 1 10^{13} cm^{-2}

How much polarization do we need?



C. H. Ahn, *et al.*, RMP **78**, 1185 (2003)

History

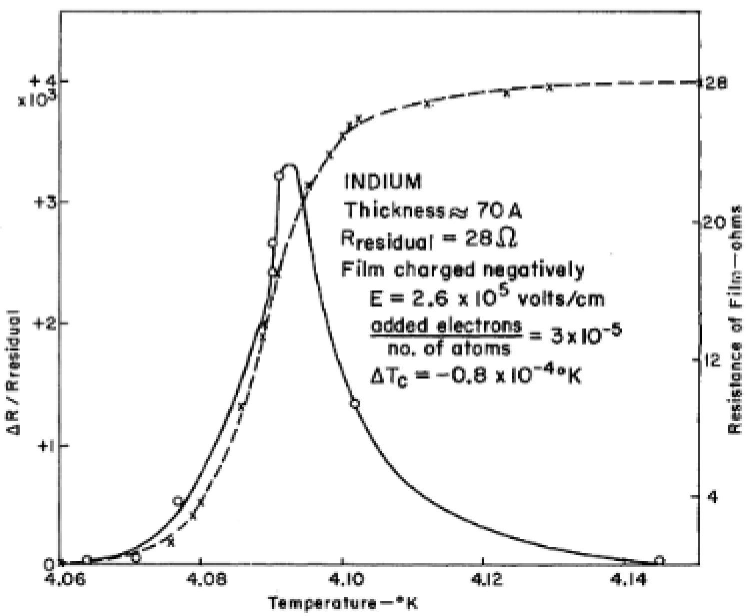


FIG. 1. Transition curve and change of resistance caused by negative charging of an indium film. Positive charging causes a change in resistance of the same size but in the opposite direction.

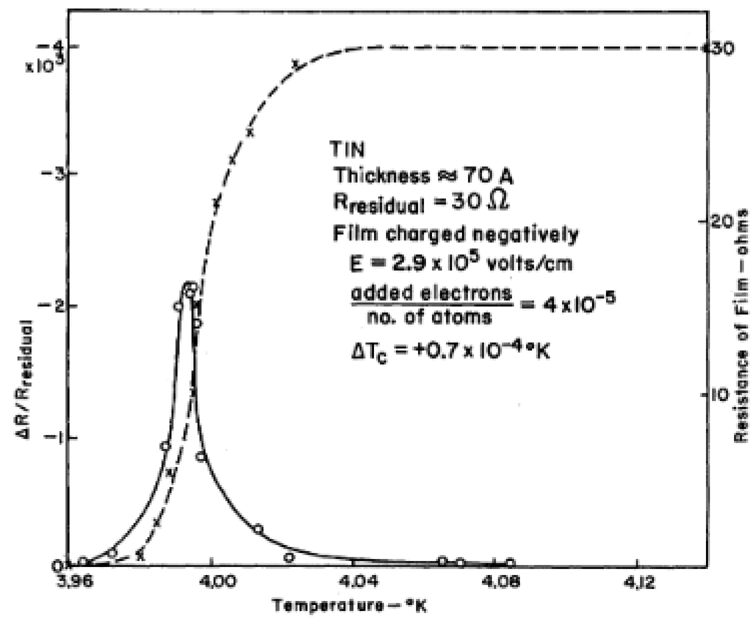


FIG. 2. Transition curve and change of resistance caused by negative charging of a tin film. Positive charging produces a change in resistance of the same size but in the opposite direction.

R.E. Glover and M.D. Sherrill, PRL **5**, 248 (1960)

History

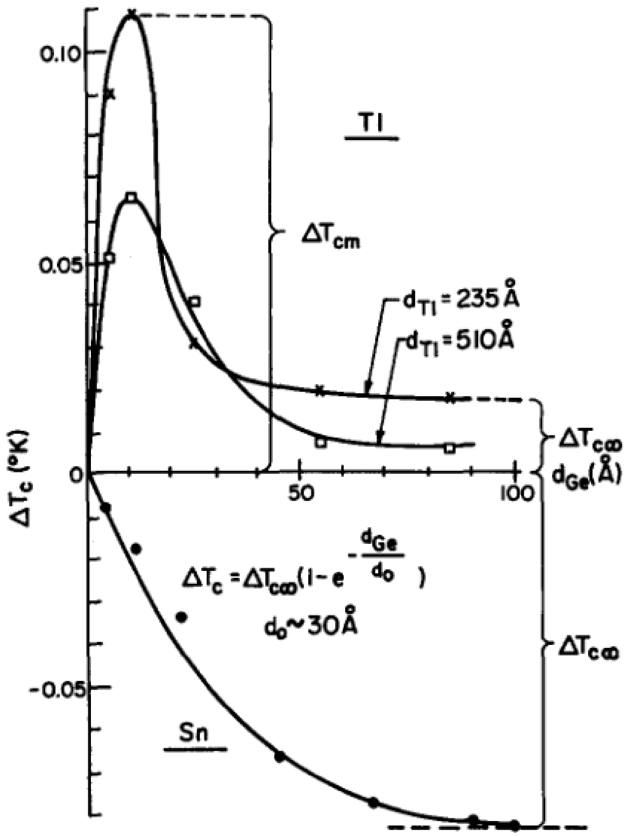


Fig.1. The change of transition temperature of a 315 Å Sn film as a function of the thickness of a Ge coating and the change of transition temperature of two simultaneously deposited Tl films as a function of the thickness of a Ge coating.
● 315 Å Sn film, □ 510 Å Tl film, × 235 Å Tl film.

The effect of the deposition of thin Ge coatings on thin Sn and Tl films is reported. T_c for Sn is reduced while T_c for Tl is increased. An anomalous increase in T_c for Tl appears for approximately a monolayer coating of Ge which is interpreted as evidence for "surface superconductivity". The decrease in T_c for Sn is attributed to the removal of electrons from the Sn to form the contact potential.

D.G. Naugle, Physics Lett. **25A**, 688 (1967)

YBCO FET

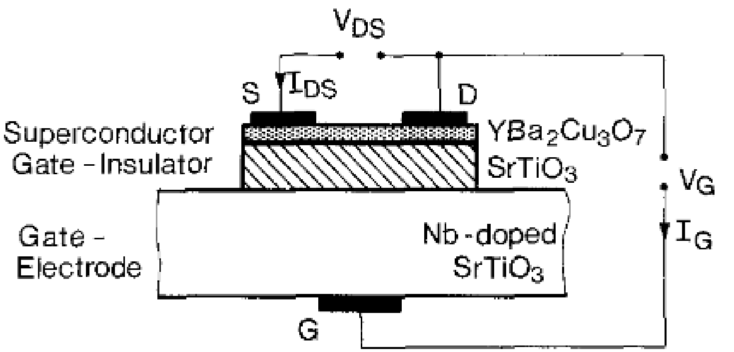
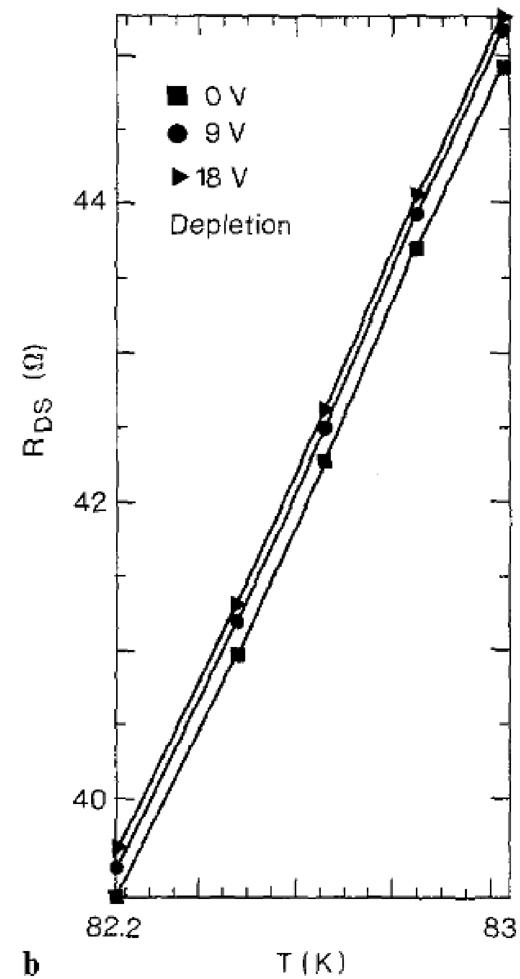


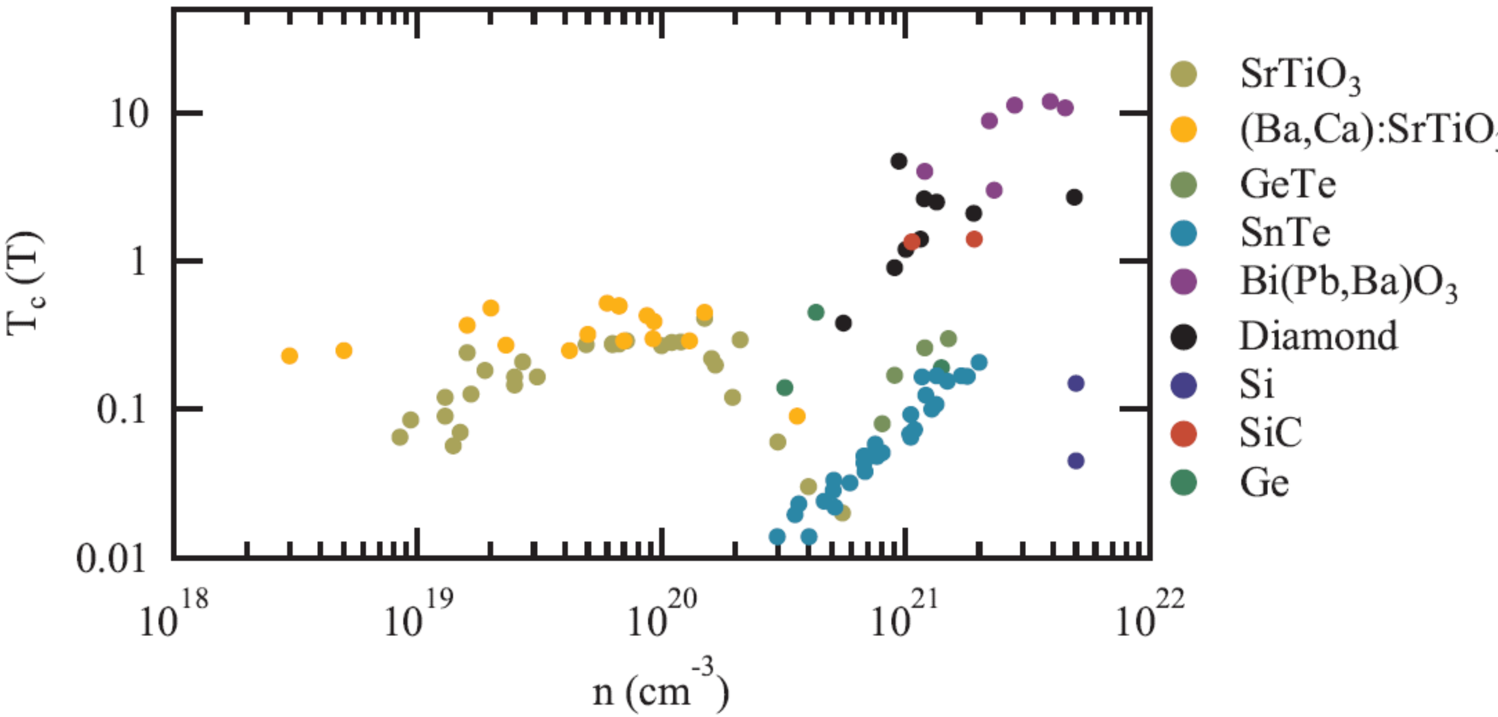
Fig. 1. Sketch of the inverted MISFET structure (cross section)



1% resistance change
10 nm film

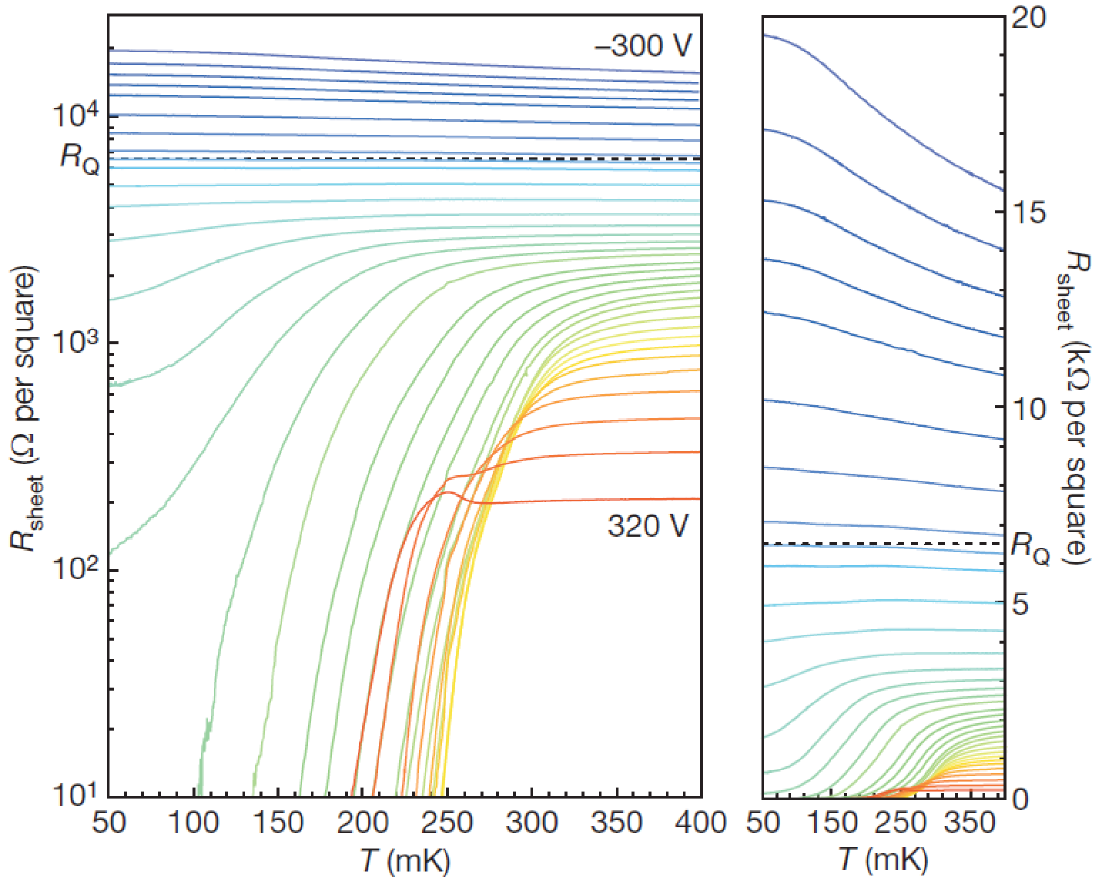
J. Mannhart, *et al.*, Z. Phys. B **83**, 307 (1991)

Superconductivity in $SrTiO_3$



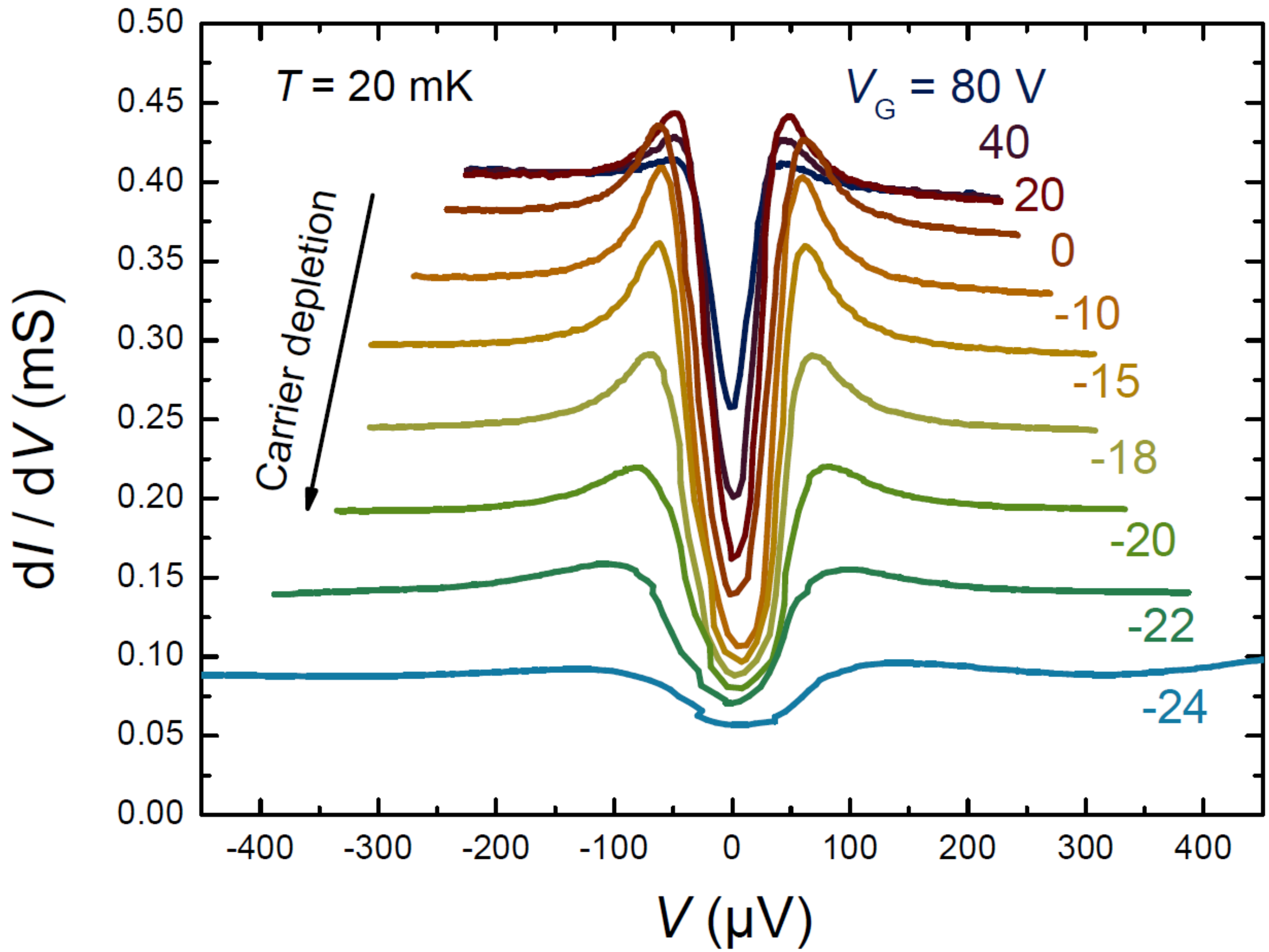
Y. Kozuka, PhD thesis, University of Tokyo

Electrostatic control of a superconductor

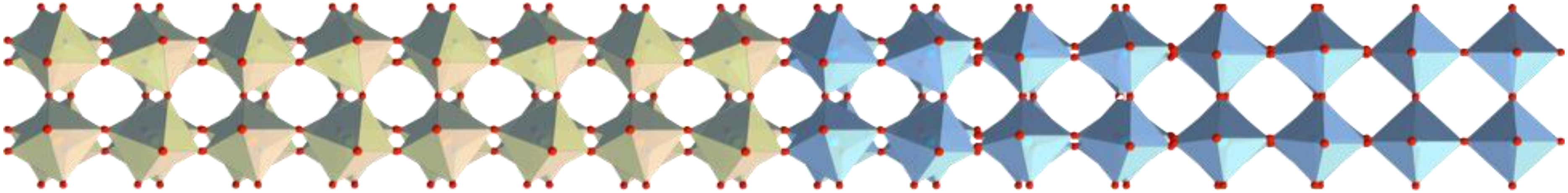


A.D. Caviglia, *et al.*, Nature **456**, 624 (2008)

Superconducting gap



C. Richter, *et al.*, Nature **502**, 528 (2013)



Quantum Interference in an Interfacial Superconductor*

** Nature Nanotechnology, vol. 11, pp. 861, 2016*

Emre Mulazimoglu

Experimental
Srijit Goswami (TU Delft)
Mafalda Monteiro (TU Delft)
Lieven Vandersypen (TU Delft)
Andrea Caviglia (TU Delft)

Theory/Simulations
Yaroslav Blanter (TU Delft)
Roman Wölbing (U. Tuebingen)
Dieter Koelle (U. Tuebingen)
Reinhold Kleiner (U. Tuebingen)

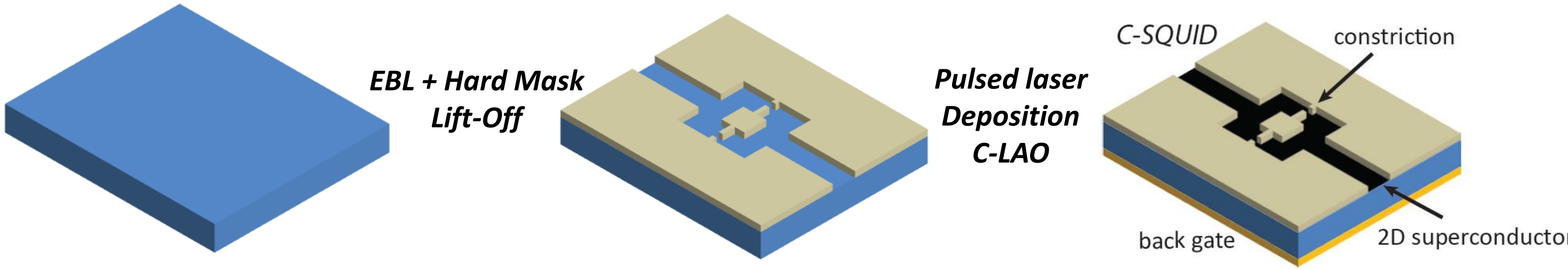
TU Delft
Delft University of Technology

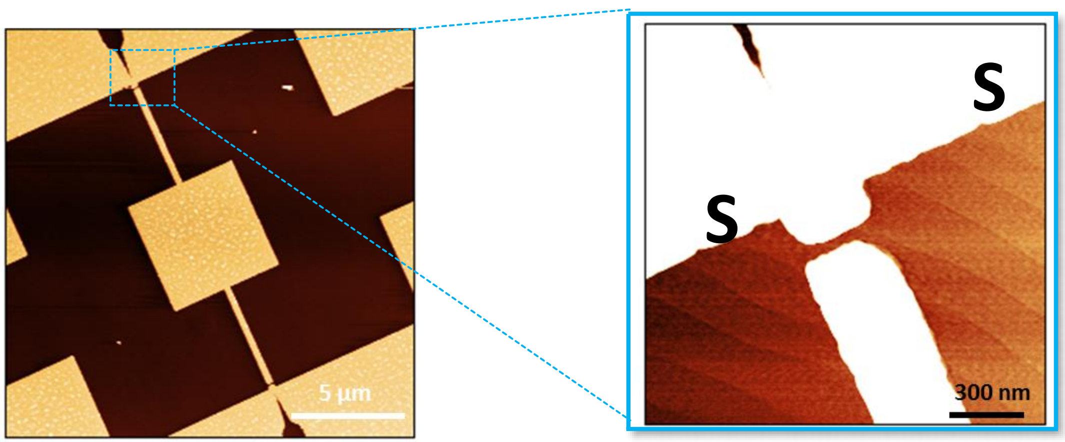
KAVLI INSTITUTE
of Nanoscience Delft

NanoFront

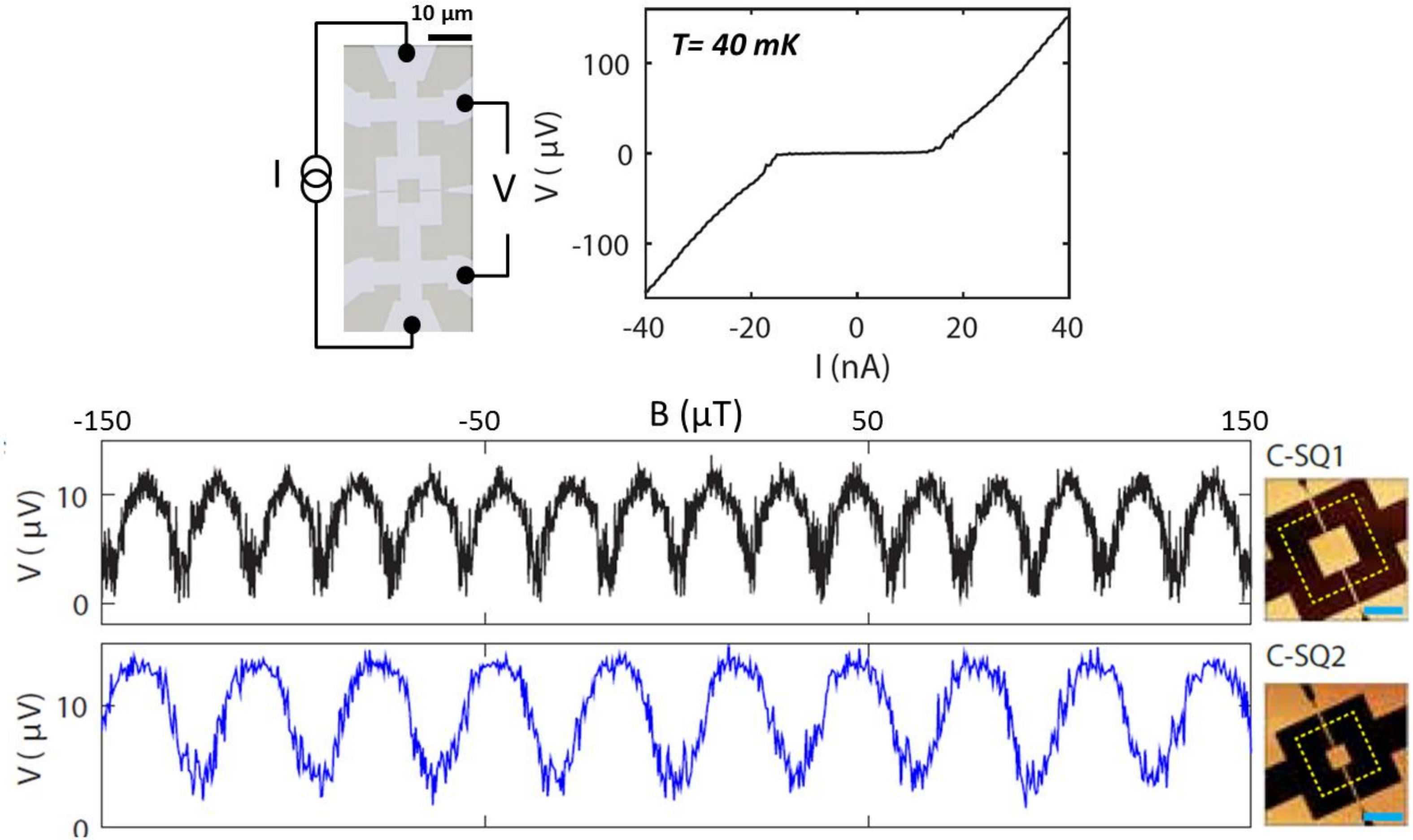
FOM

Constriction SQUID at LAO/STO Interfaces

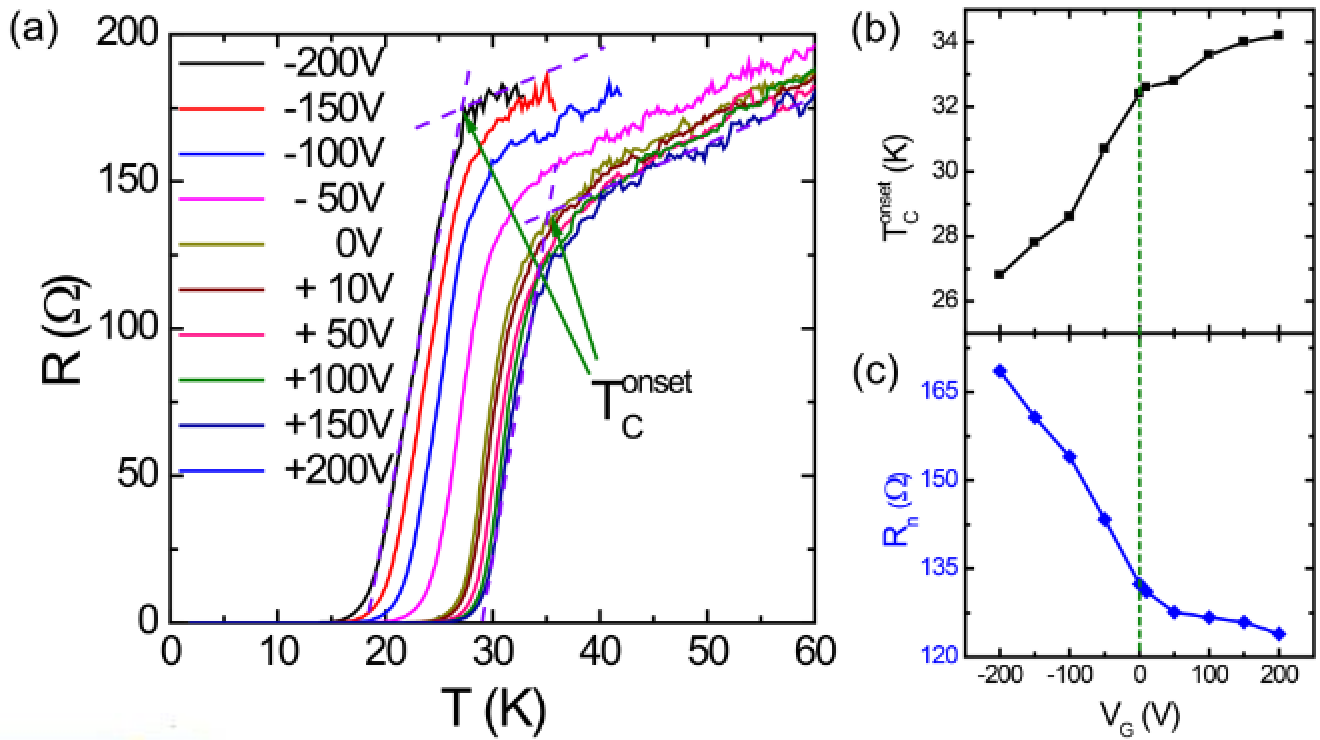


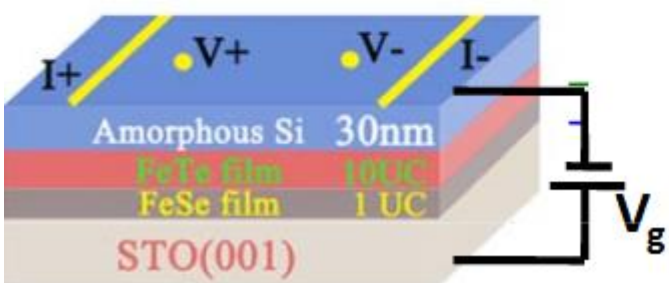


Constriction SQUID at LAO/STO Interfaces



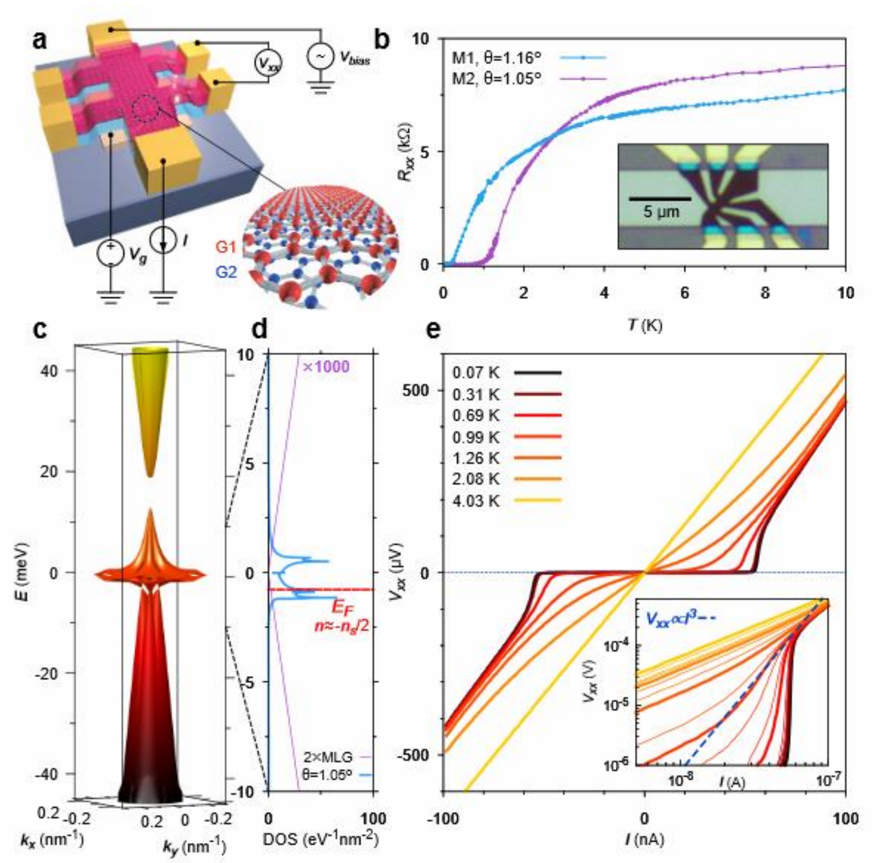
Gating FeSe-$SrTiO_3$

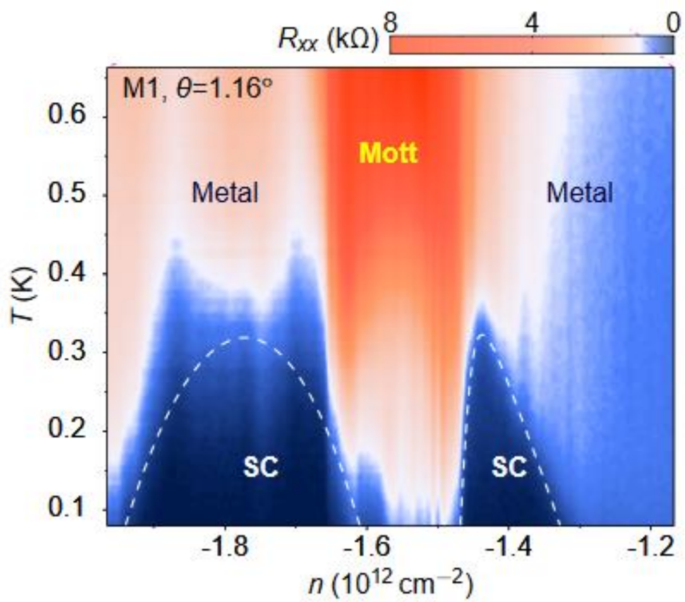




W. Zhang, *et al.*, PRB **89**, 060506(R) (2014)

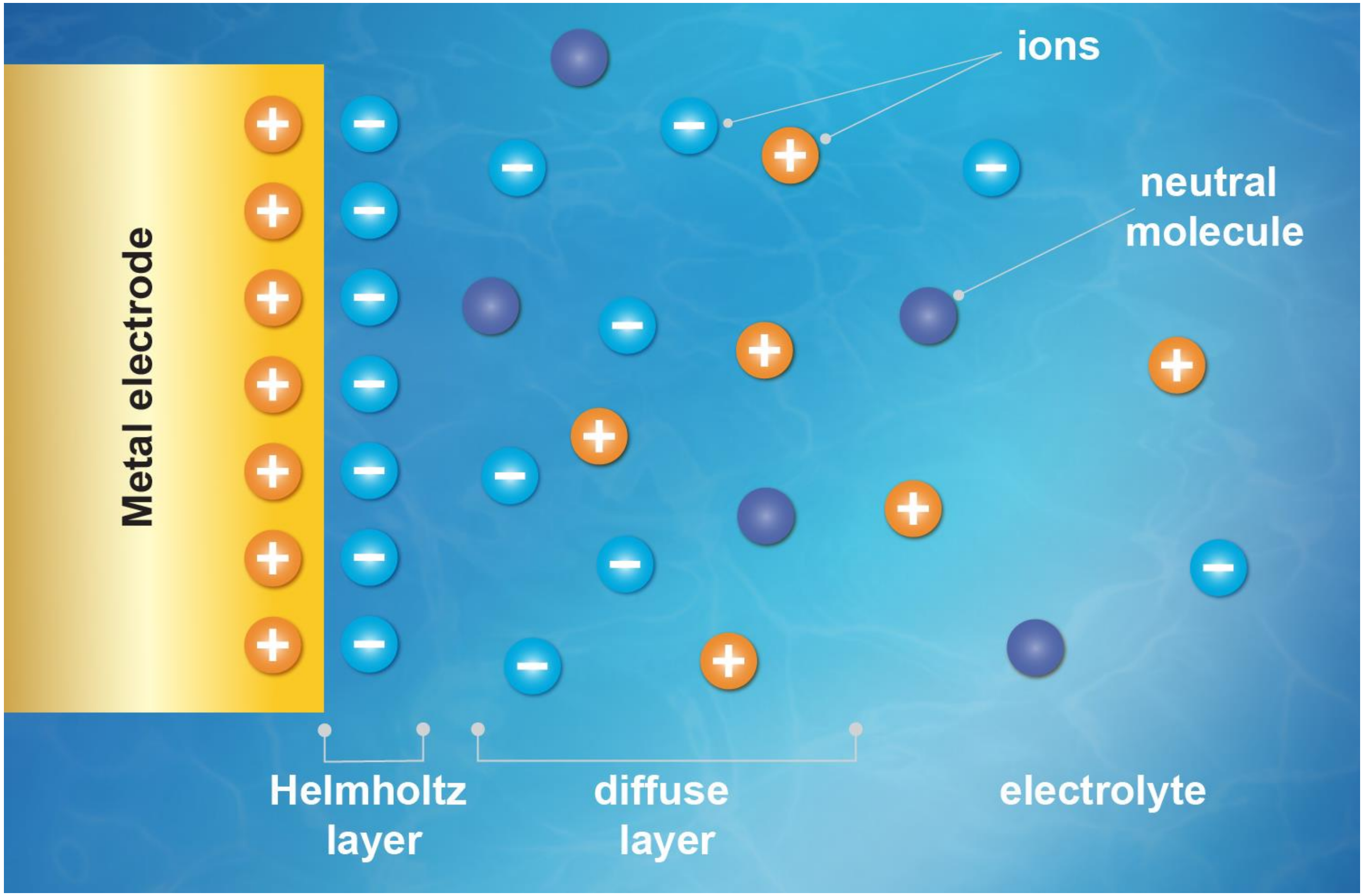
Graphene Heterostructures



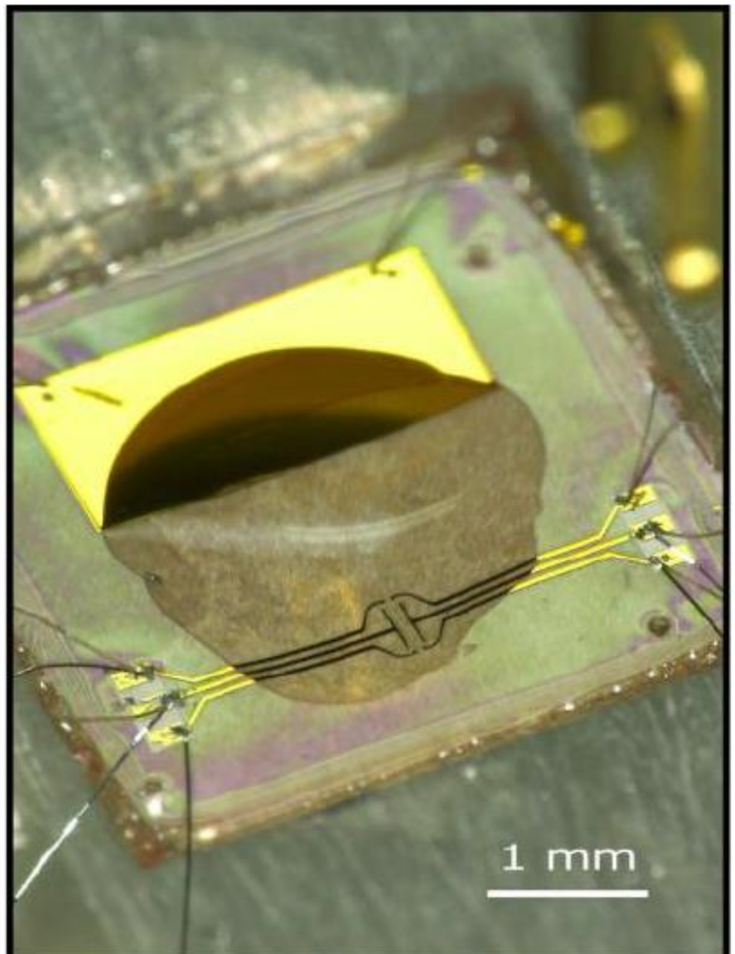


Y. Cao, *et al.*, Nature, 10.1038/nature26160 (2018)

Electrolyte gating



Typical layout

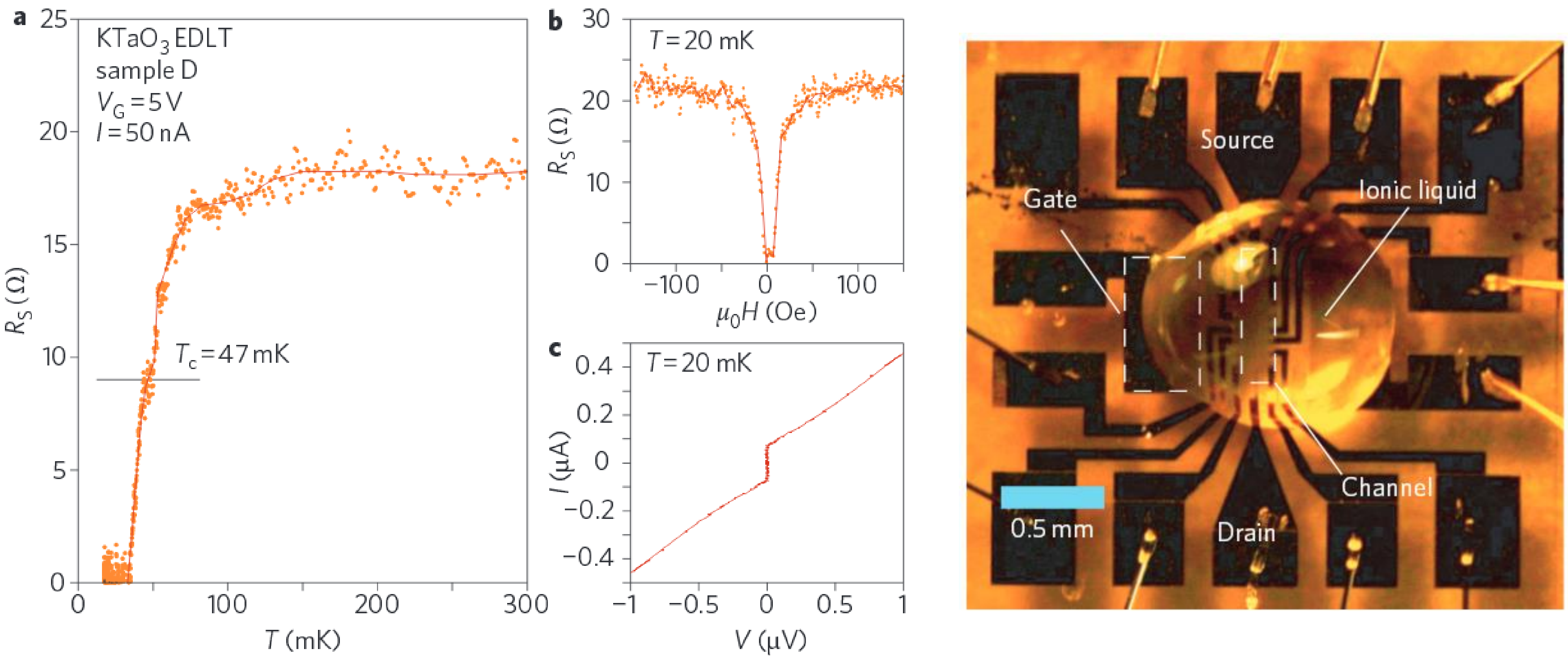


Electrolyte gating

Advantage:
huge polarization of order 10^{15} cm^{-2}
Easy fabrication
Not many shorts

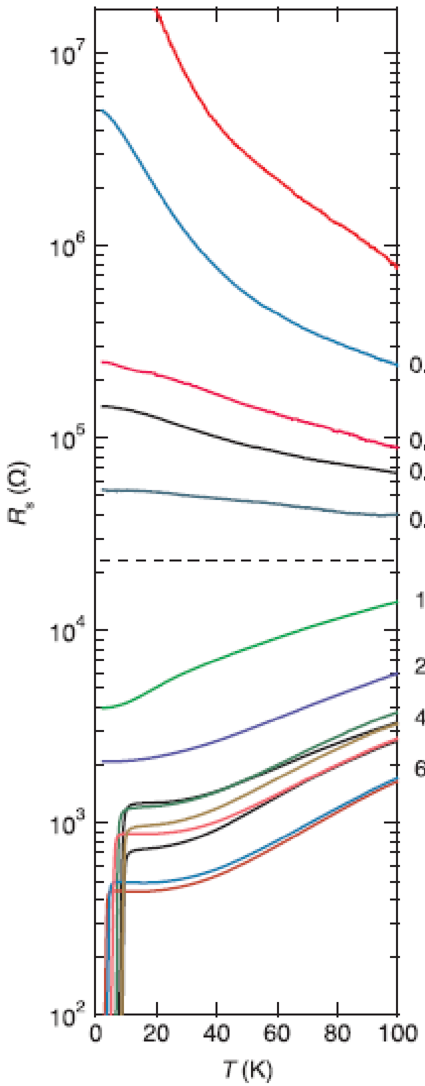
Disadvantage:
Electrolytes freeze, gate voltage change only possible above melting temperature
Electrochemical modification of material
Low frequency operation
Droplets are large

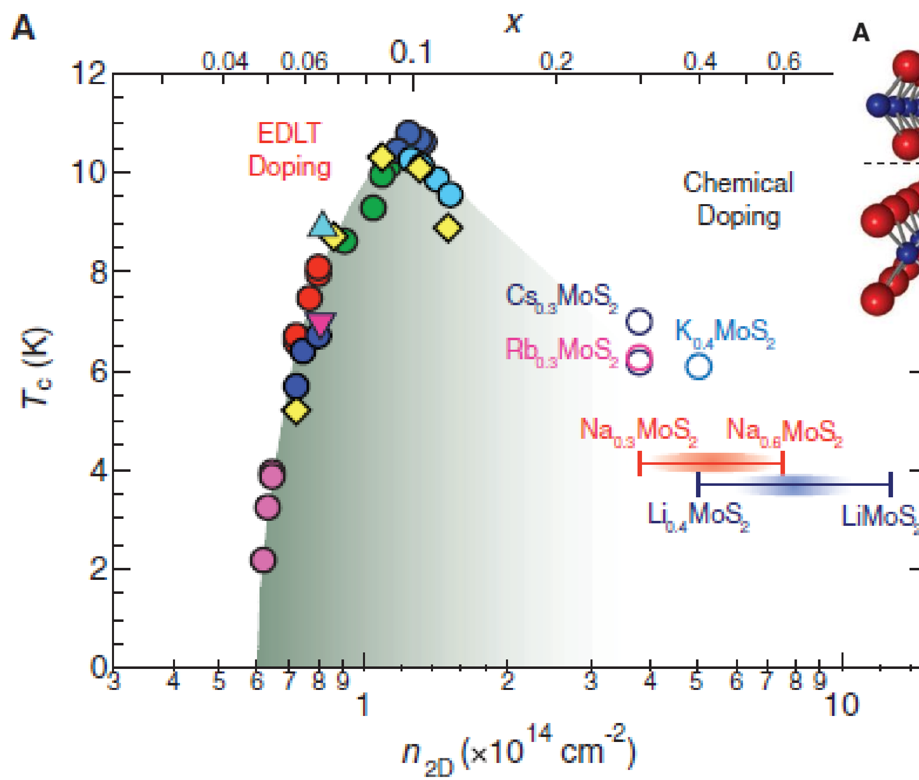
$KTaO_3$ becomes superconducting

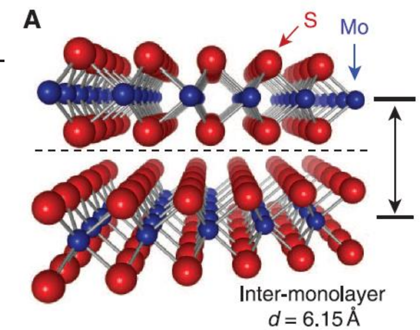


K. Ueno, *et al.*, Nature Nano **6**, 408 (2011)

Superconducting dome in MoS_2

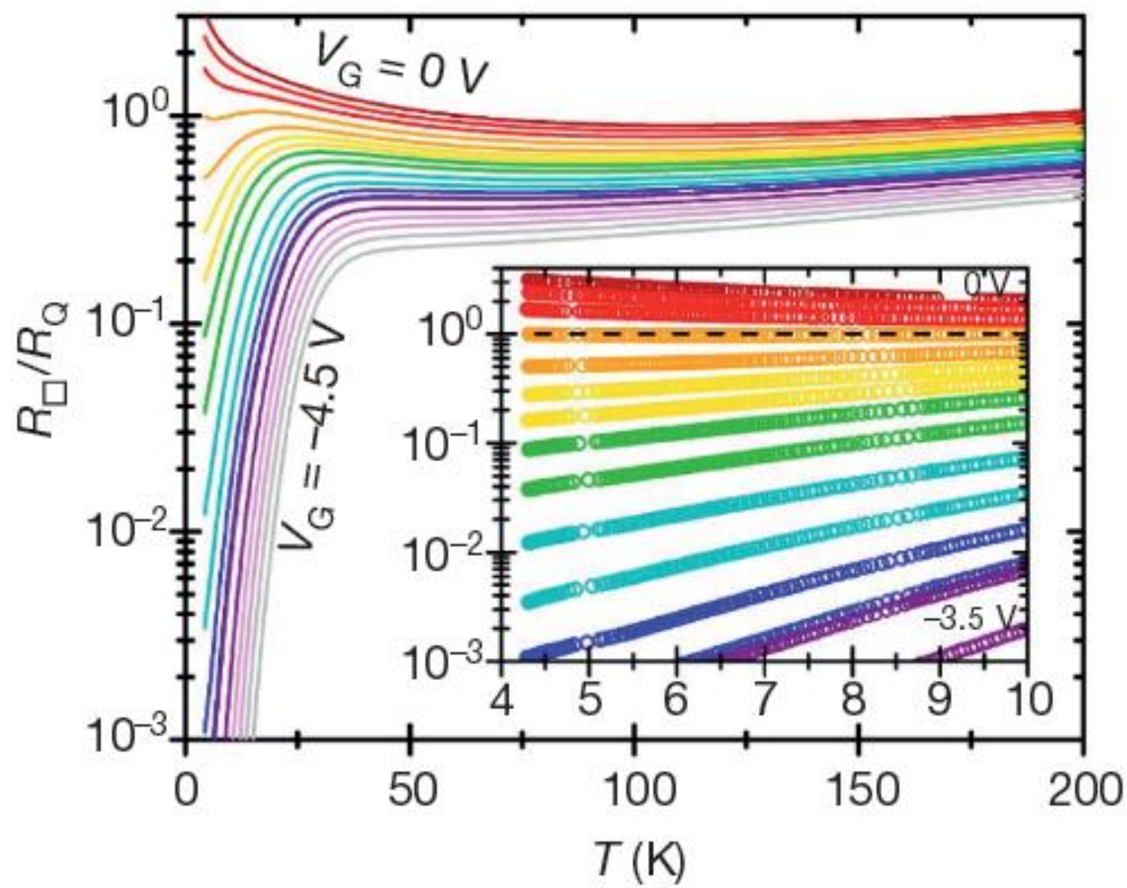






Y. T. Ye, *et al.*, Science **79**, 084508 (2016)

Gate voltage control of the cuprates



A. T. Bollinger, *et al.*, Nature **472**, 458 (2011)

EDL superconductivity

TOPICAL REVIEW

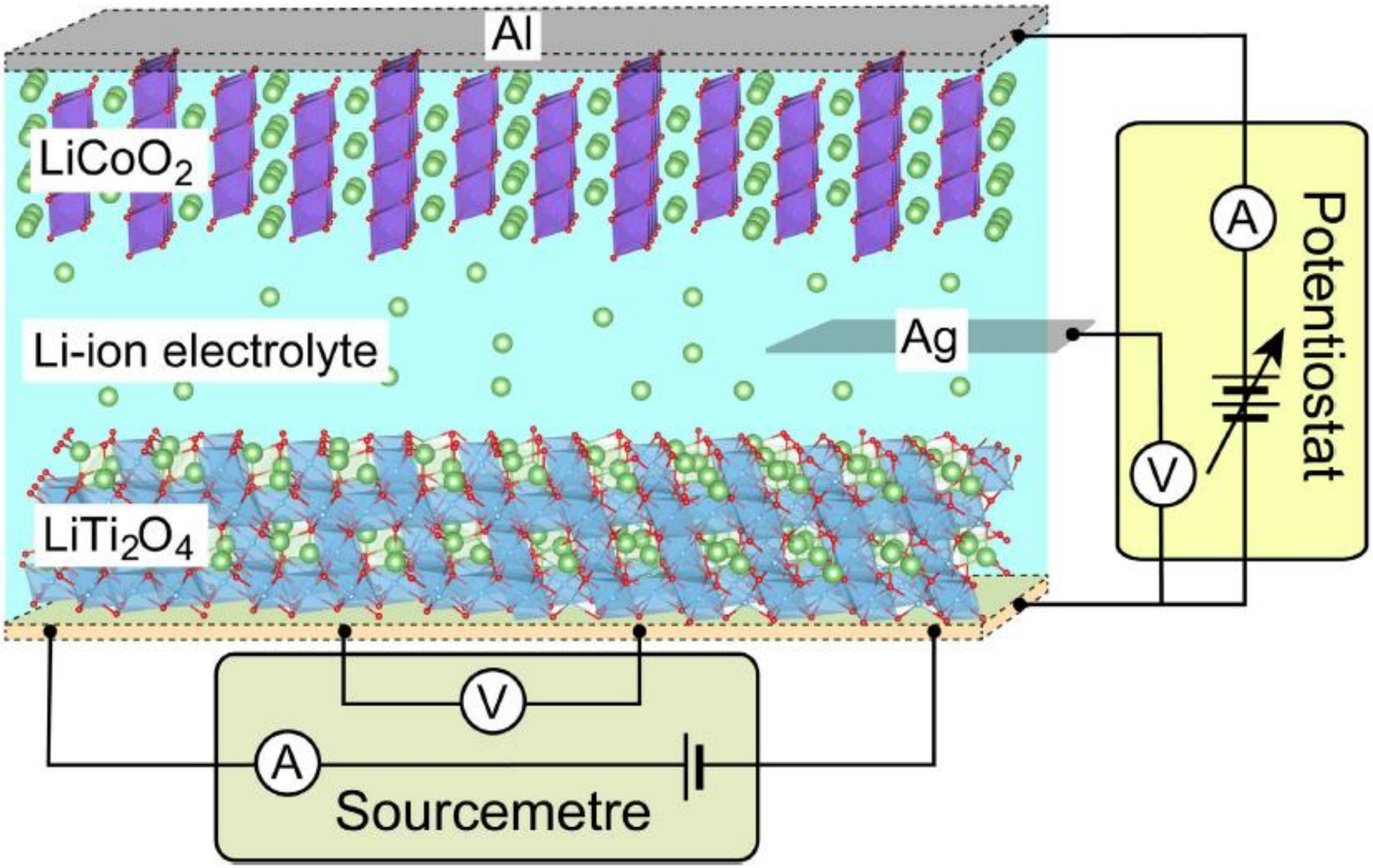
Gate-induced superconductivity in two-dimensional atomic crystals

Yu Saito[1], Tsutomu Nojima[2] and Yoshihiro Iwasa[1,3]

Published 14 July 2016 •

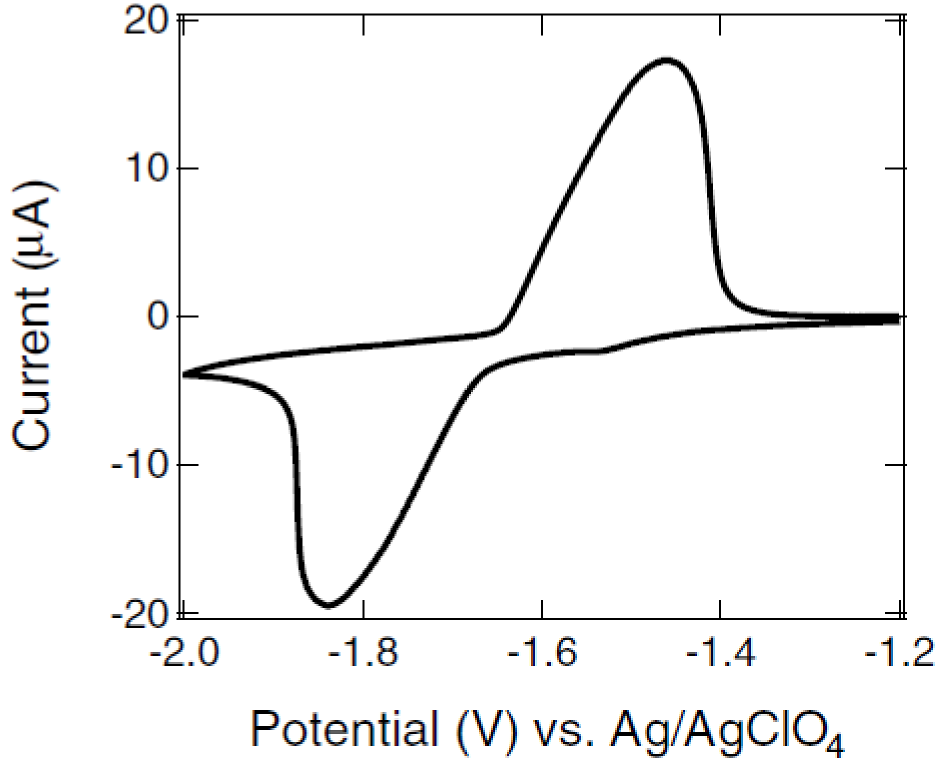
Also:
$SrTiO_3$
ZrNCl
$NbSe_2$
Atomically thin MoS_2
WS_2
$MoSe_2$
$MoTe_2$
$La_{2-x}Sr_xCuO_4$
$La_2CuO_{4+\delta}$
$YBa_2Cu_3O_{7-\delta}$
$Pr_{2-x}Ce_xCuO_4$

Superconductivity in a battery



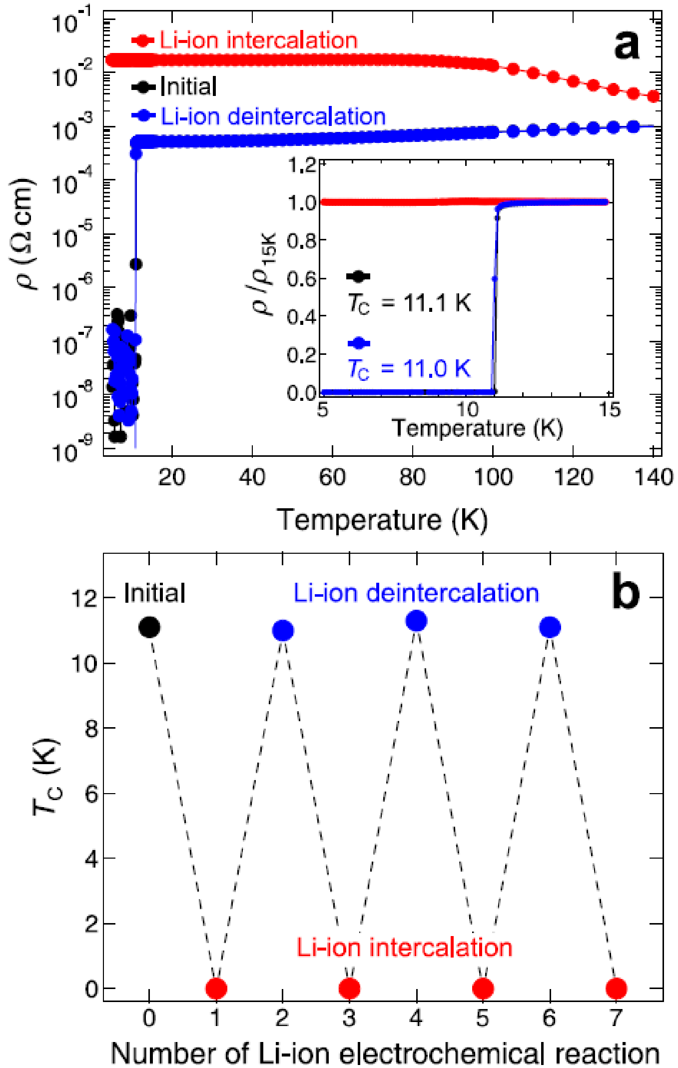
K. Yoshimatsu, *et al.*, Sci. Rep. **5**, 16325 (2015)

Superconductivity in a battery



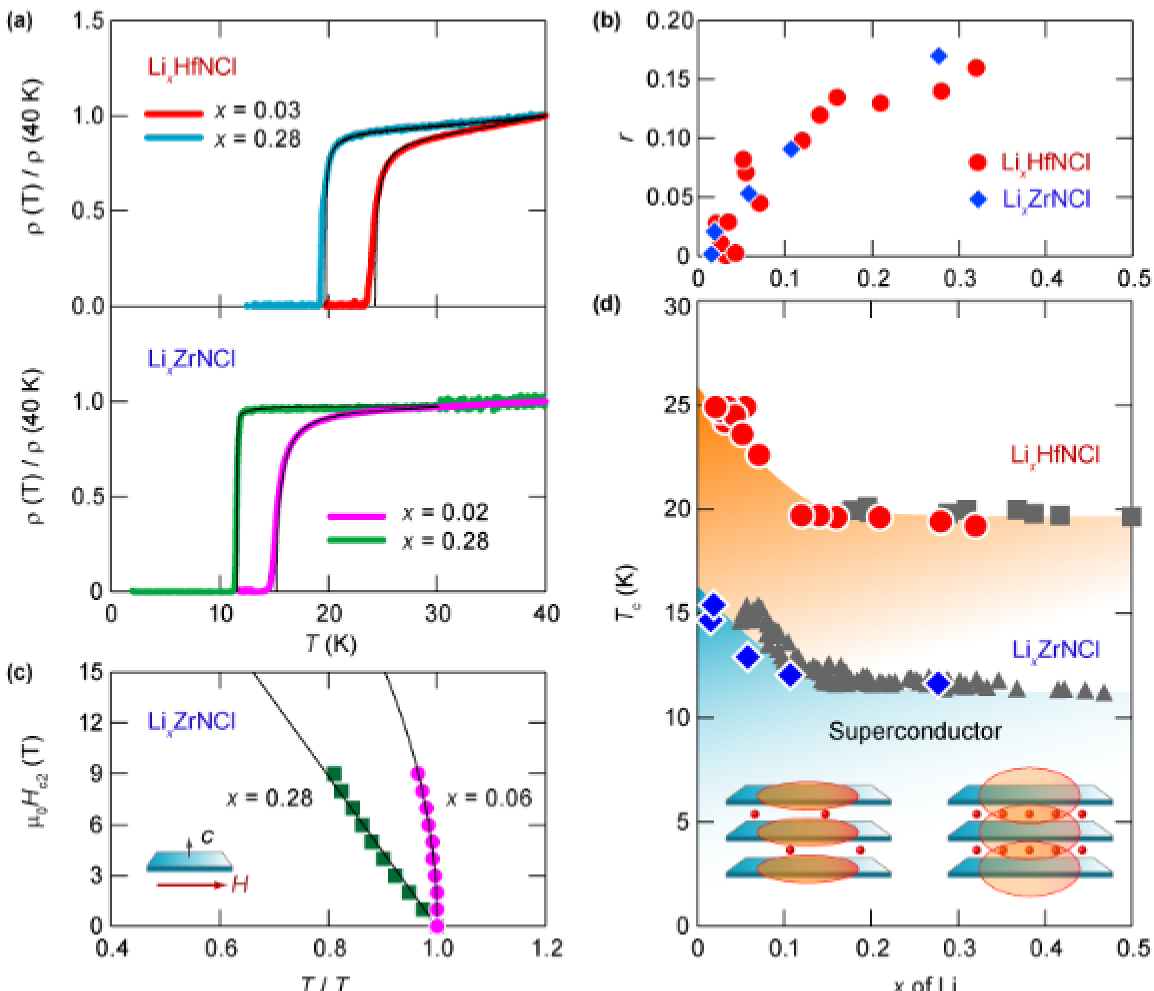
K. Yoshimatsu, *et al.*, Sci. Rep. **5**, 16325 (2015)

Superconductivity in a battery



K. Yoshimatsu, *et al.*, Sci. Rep. **5**, 16325 (2015)

Electrochemical Intercalation



Y. Nakagawa, *et al.*, Phys. Rev. B **98**, 064512 (2018)

Conclusions

- ✓ New superconductors to be found at interfaces
- ✓ Possibility to systematically investigate and optimize superconductivity
- ✓ New types of devices