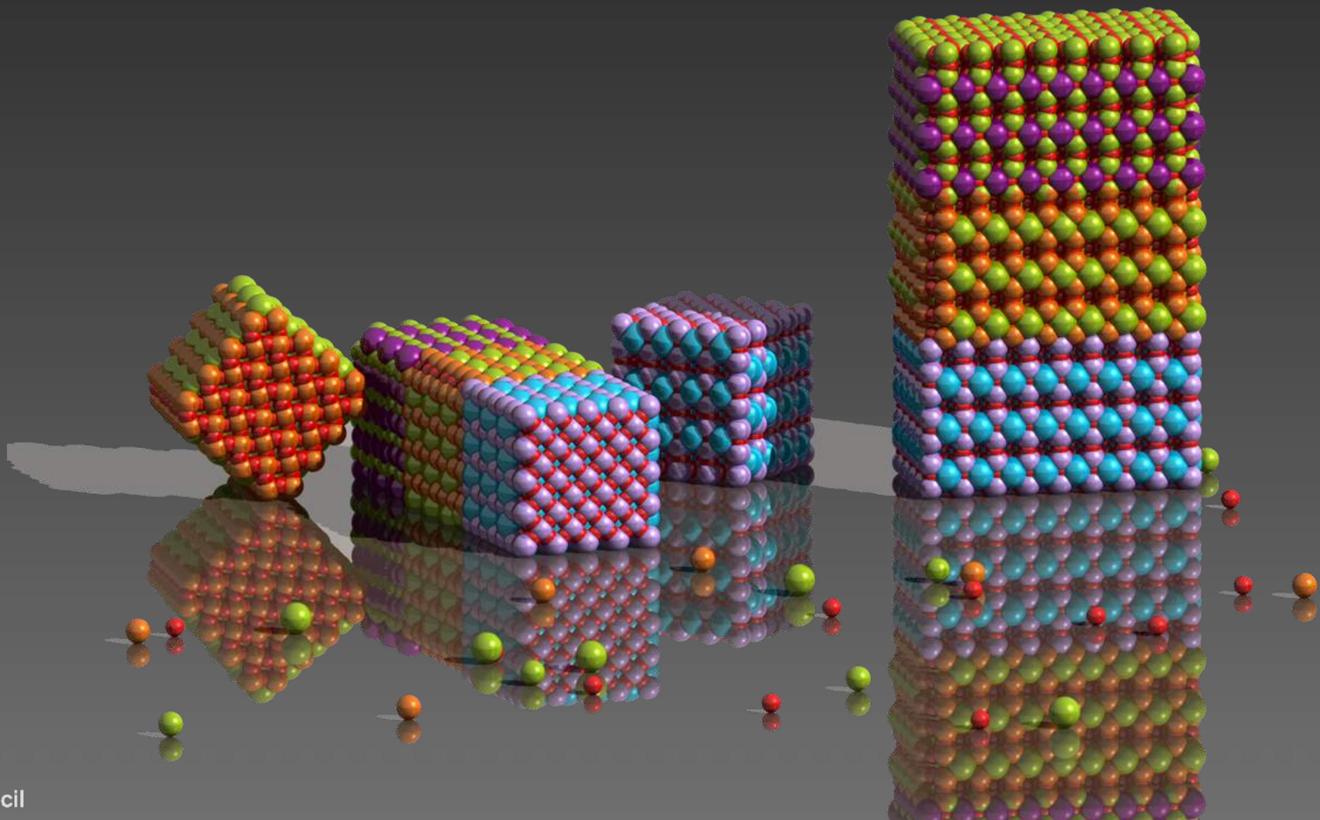
Interfacial Effects and Superconductivity in Oxide Structures

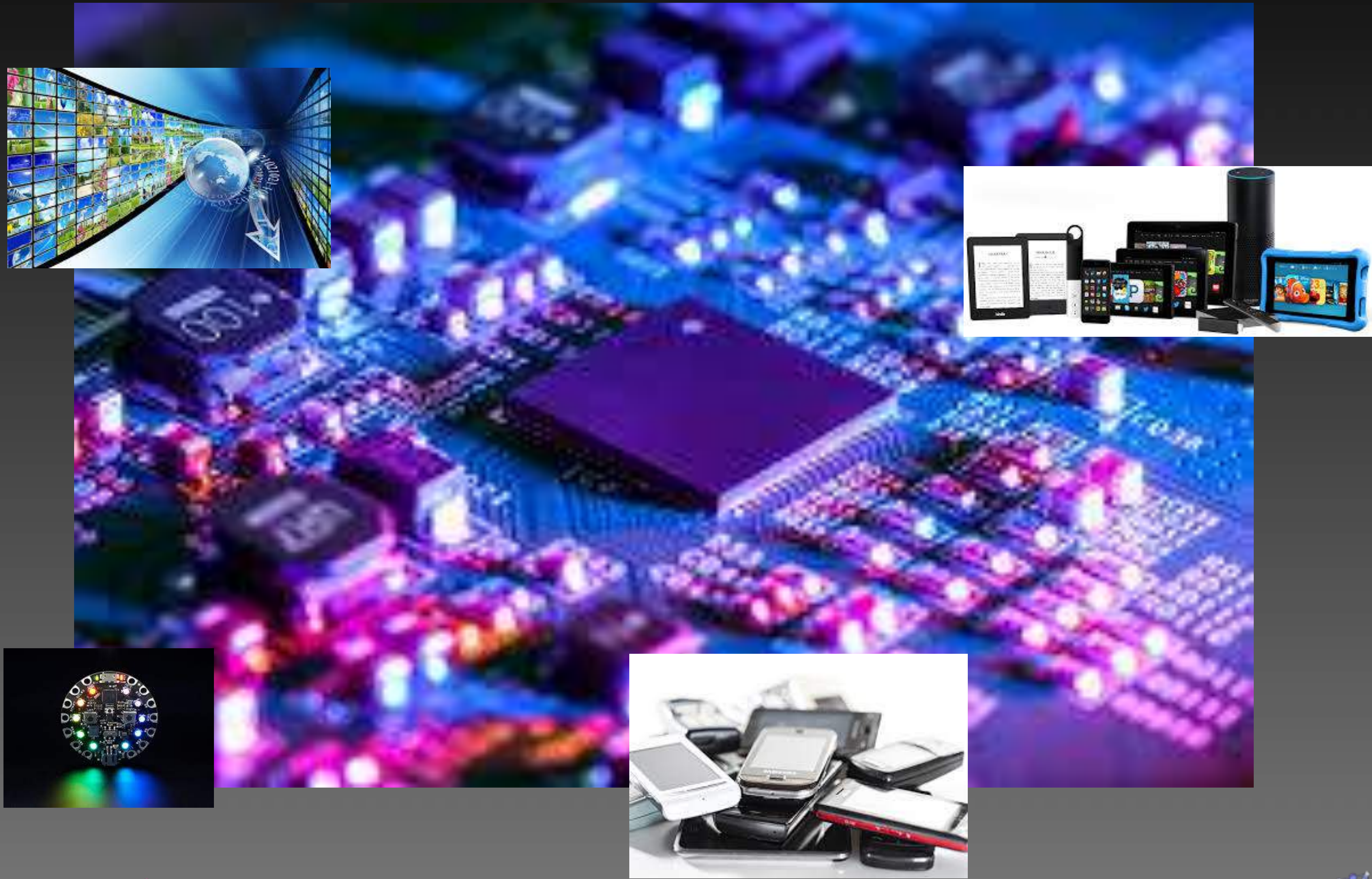
Jean-Marc Triscone
University of Geneva



Joerg Harms, MPI Hamburg

European Research Council
Established by the European Commission
UNIVERSITÉ DE GENÈVE
FNSNF
MaNEP SWITZERLAND

Why looking at oxide structures?



1947 the transistor

J. Bardeen,
W. Brattain,
W. Shockley

Photo: Bell Labs

UNIVERSITÉ DE GENÈVE

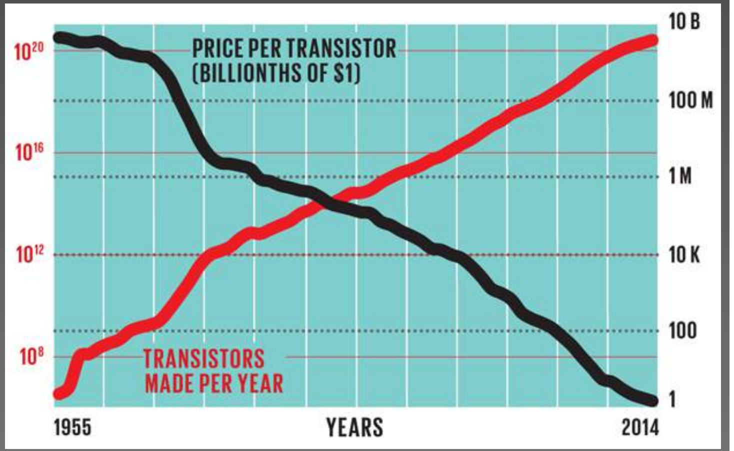
MaNEP SWITZERLAND

Very impressive progress

Transistor history :

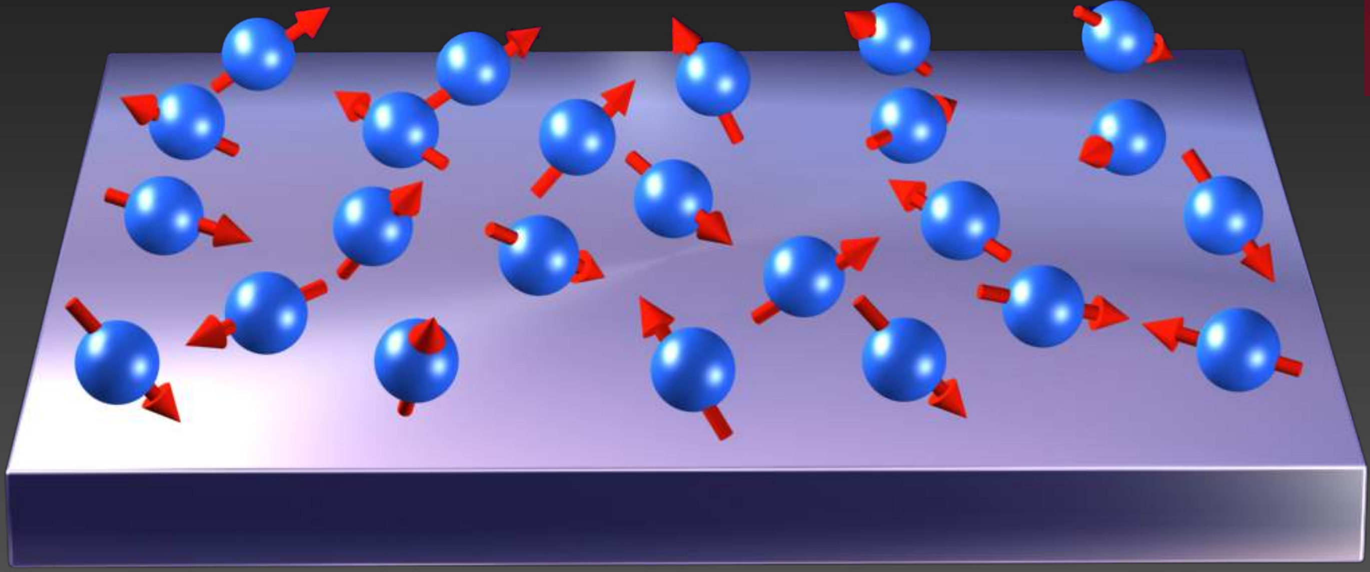
1947 discovery	1 transistor
1971 Intel 4004	2 300 transistors
1993 Intel Pentium	3,1 millions transistors
2001 Intel Pentium 4	42 millions transistors
2007 Intel Dual-Core Titanium 2	1,7 billion transistors

2014: ~ 2.5 10^{20} transistors fabricated



VLSI research

Silicon - a magic material?

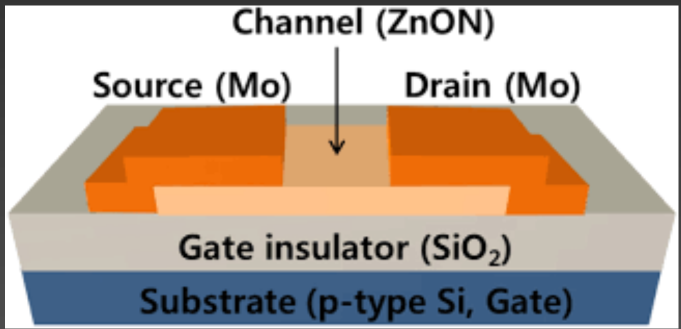


A simple electron system described

by single particle physics

Adapted from J. Mannhart

You need to add an interface: Si/SiO_2



these days, a HfOx gate dielectric

QUASI-ELECTRIC FIELDS AND BAND OFFSETS: TEACHING ELECTRONS NEW TRICKS

Nobel Lecture, December 8, 2000

by

HERBERT KROEMER

ECE Department, University of California, Santa Barbara, CA 93106, USA.

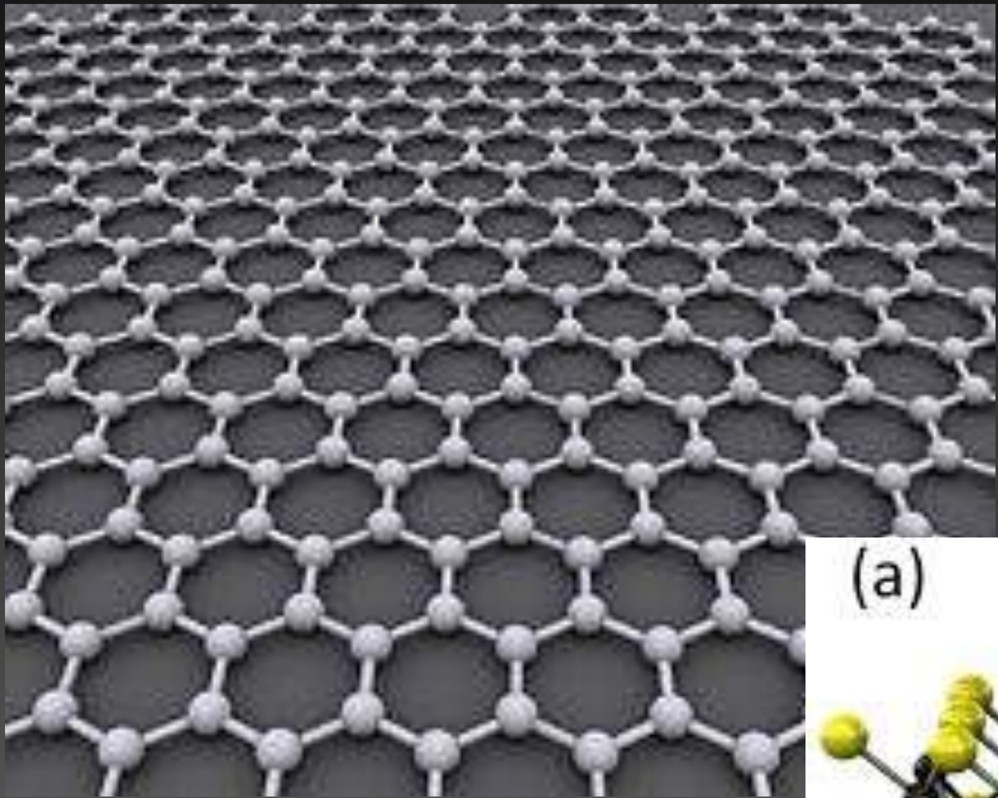
I. INTRODUCTION

Heterostructures, as I use the word here, may be defined as heterogeneous semiconductor structures built from two or more different semiconductors, in such a way that the transition region or interface between the different materials plays an essential role in any device action. Often, it may be said that *the interface is the device.*

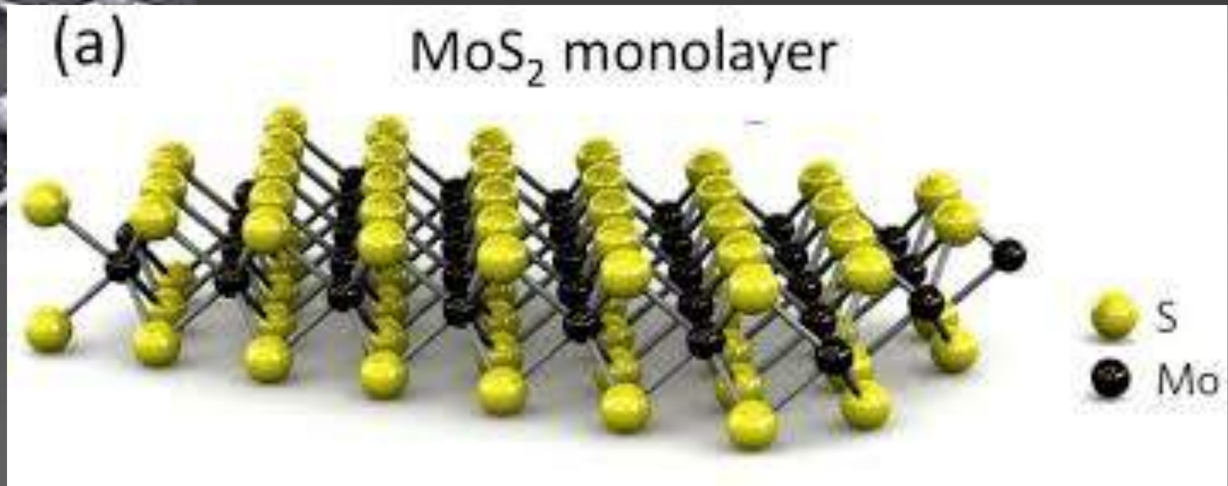
One of the issues : dissipation

A computer farm in Sweden

Searching for other materials



Graphene

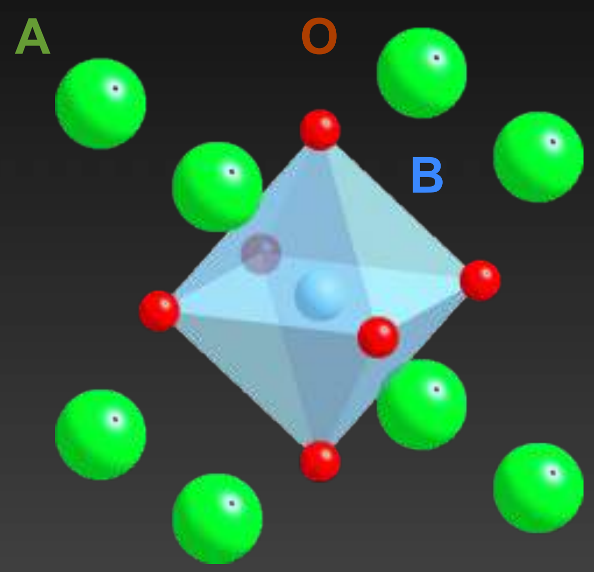


Dichalcogenides

Univ. Twente

UNIVERSITÉ DE GENÈVE

Oxides - perovskites



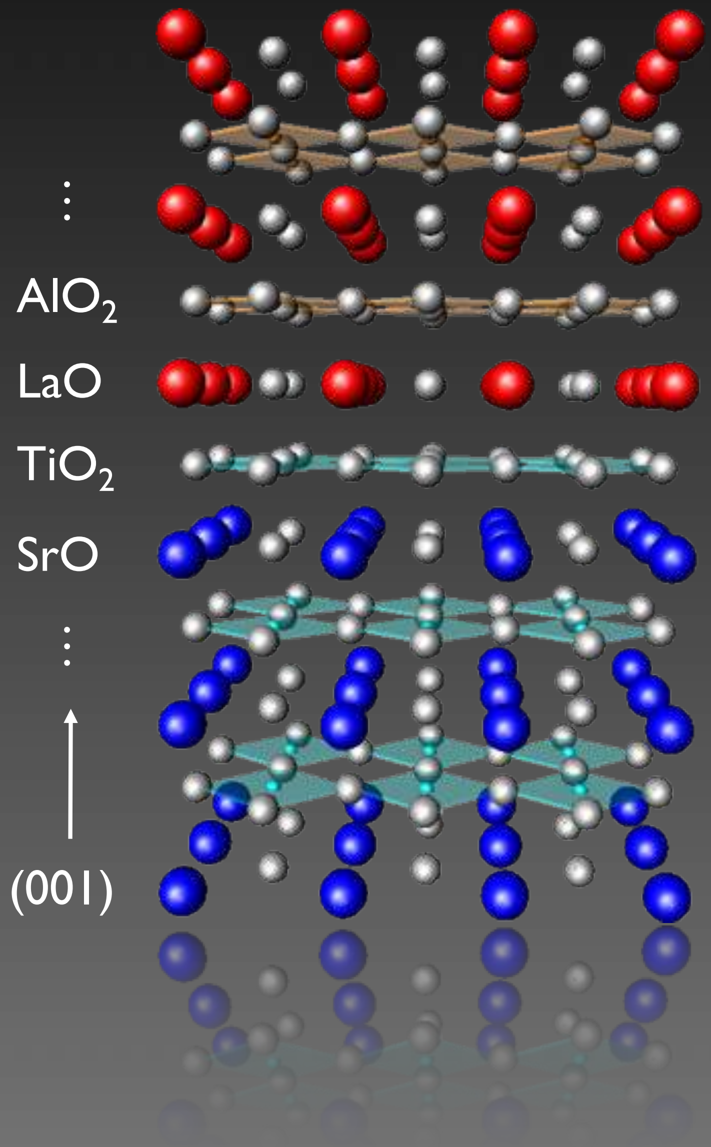
ABO_3

Perovskite - $CaTiO_3$

Perovskite structure - a very common structure on Earth

Oxides → Oxide structures → Oxide interfaces → Oxide interface physics

The $LaAlO_3/SrTiO_3$ interface



$LaAlO_3$:

band insulator

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

$SrTiO_3$:

band insulator

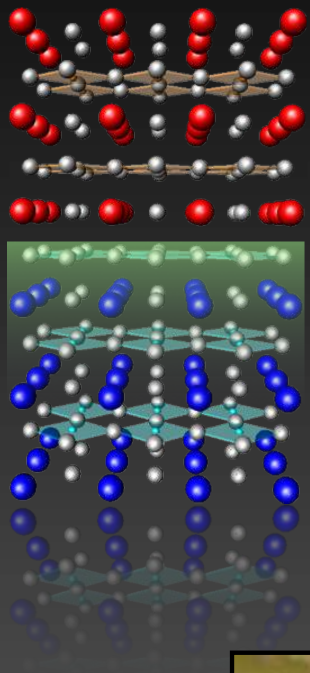
$\Delta = 3.2\,\mathrm{eV},\ \kappa(300\,\mathrm{K}) = 300$

quantum paraelectric

UNIVERSITÉ DE GENÈVE

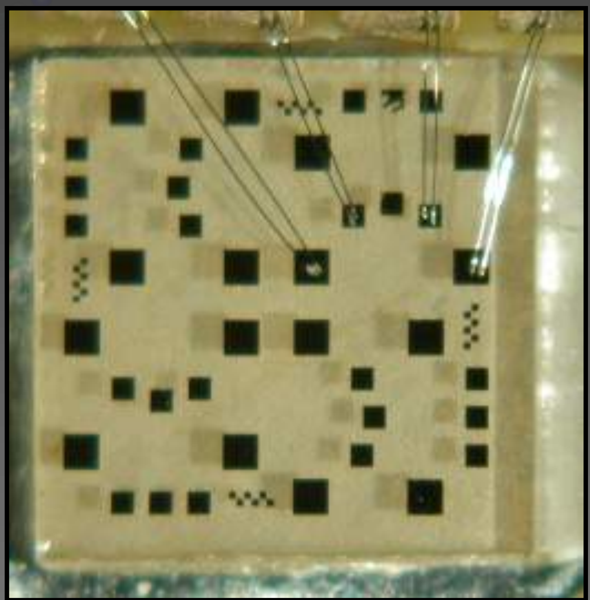
MaNEP SWITZERLAND

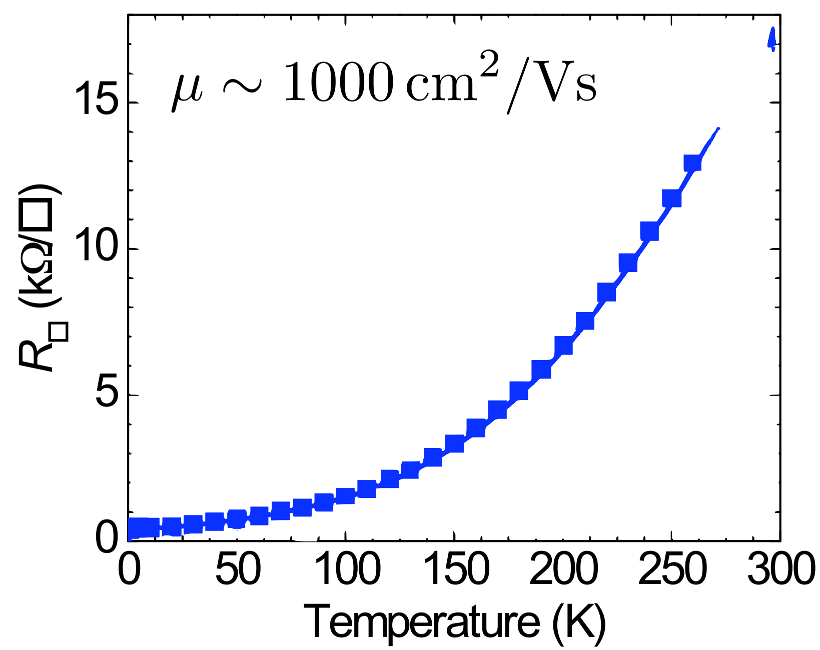
A conducting interface

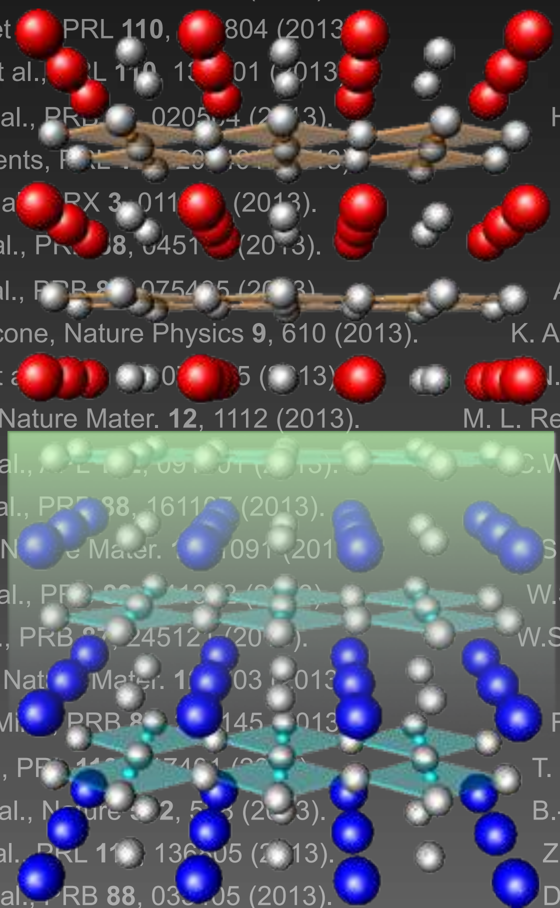


A high-mobility electron gas at the $LaAlO_3/SrTiO_3$ heterointerface

A. Ohtomo[1,2,3] & H. Y. Hwang[1,3,4] *Nature* **427**, 423 (2004)







Y. Xie et al., Adv. Mater. **25**, 4735 (2013).
M. Salluzzo et al., Adv. Mater. **25**, 2333 (2013).
A. Annadi et al., Nature Comm. **4**, 1838 (2013).
A. Annadi et al., PRB **87**, 201102 (2013).
S. Banerjee et al., Nature Physics **9**, 626 (2013).
G. Berner et al., PRL **110**, 247601 (2013).
E. Breckenfeld et [illegible] PRL **110**, [illegible]804 (2013).
C. Cancellieri et al., [illegible] (2013).
S. Caprara et al., [illegible] (2013).
G. Chen, L. Balents, [illegible] (2013).
G. Cheng et al., [illegible] (2013).
F. Cossu et al., [illegible] (2013).
G. [illegible] et al., [illegible] (2013).
M. Gabay, J.-M. Triscone, Nature Physics **9**, 610 (2013).
L.X. [illegible] et al., [illegible] (2013).
M. Honig et al., Nature Mater. **12**, 1112 (2013).
M. [illegible] et al., [illegible] (2013).
Z. Huang et al., PRB **88**, 16110[illegible] (2013).
B. Kalisky et al., Nature Mater. [illegible] (2013).
G. Khalsa et al., [illegible]
Y. Kim et al., PRB [illegible] (2013).
J.-S. Lee et al., Nature Mater. [illegible] (2013).
S.Y. Park, A.J. Millis, PRB [illegible] (2013).
J. Park et al., [illegible]
C. Richter et al., Nature [illegible] (2013).
M. [illegible] et al., PRL [illegible] (2013).
A. Rubano et al., PRB **88**, [illegible] (2013).
M. Salluzzo et al., PRL **111**, 087204 (2013).
Y. Yamada et al., PRL **111**, 047403 (2013).
H.K. Sato et al., APL **102**, 251602 (2013).
F. Trier et al., APL **103**, 031607 (2013).
V.T. Tra et al., Adv. Mater. **25**, 3357 (2013).
D. Li et al., APL Mater. 2, 012102 (2014).

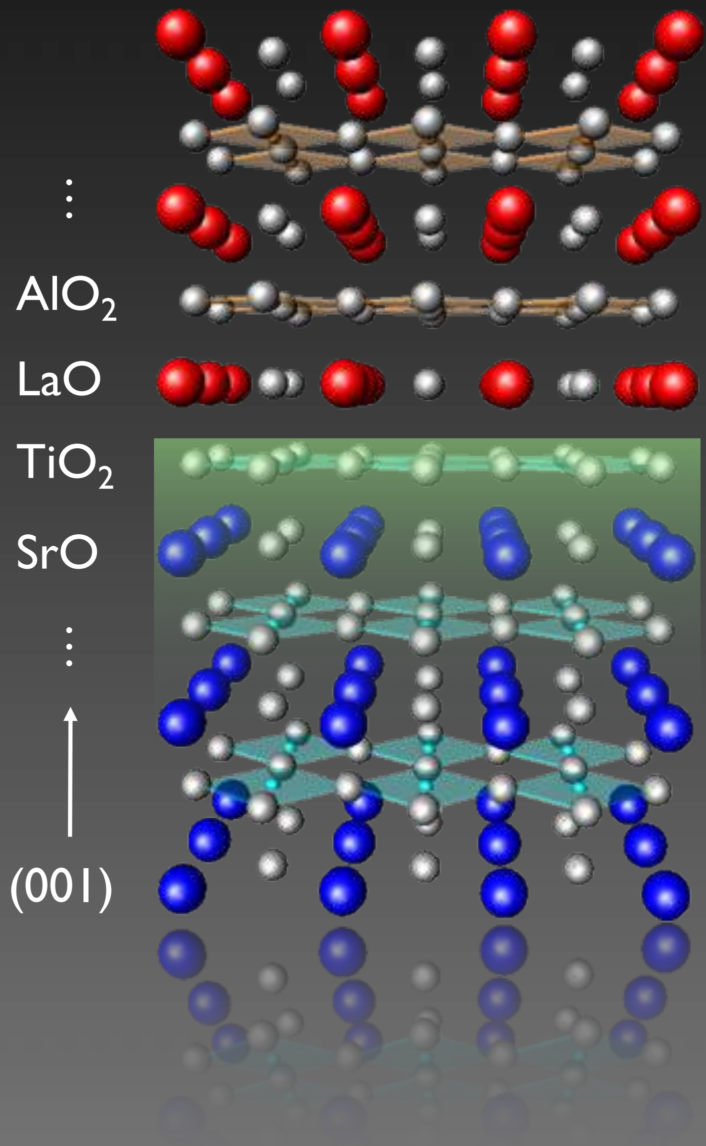
R. Yamamoto *et al.* PRL **107**, 036104 (2011)
P. Delugas *et al.* PRL **106**, 166807 (2011)
S. A. Pauli *et al.* PRL **106**, 036101 (2011)
L. Li *et al.*, *Nature Physics* (2011)
J.A. Bert *et al.*, *Nature Physics* (2011)
D.A. Dikin *et al.*, *PRL* **107**, 56802 (2011)
L. Li *et al.* Science (2011)
Ariando *et al.* Nature Comm. (2011)
H. J Gardner *et al.* Nature Physics (2011)
M. Stengel PRL **106**, 136803 (2011)
H. W. Jang *et al.* Science (2011)
J. W. Park *et al.* Nature Comm (2011)
A. Annadi et al., PRB **86**, 085450 (2012).
K. Aoyama, M. Sigrist, PRL **109**, 237007 (2012).
[illegible]. Banerjee et al., APL **100**, 041601 (2012).
M. L. Reinle-Schmitt et al., Nature Comm. **3**, 932 (2012)
[illegible].W. Bark et al., Nano Letters **12**, 1765 (2012).
J. Bert et al., PRB **86**, 060503 (2012).
S. Caprara et al., PRL **109**, 196401 (2012).
W.S. Choi et al., Adv. Mater. **24**, 6423 (2012).
W.S. Choi et al., Nano Letters **12**, 4590 (2012).
A. Fête et al., PRB **86**, 201105 (2012).
F. Gunkel et al., APL **100**, 052103 (2012).
T. Hernandez et al., PRB **85**, 161407 (2012).
B.-C. Huang et al., PRL **109**, 246807 (2012).
Z. Salman et al., PRL **109**, 257207 (2012).
D.A. Dikin et al., PRB **107**, 056802 (2012).
N. Reyren et al., PRL **108**, 186802 (2012).
K. Au et al., Adv. Mater. **24**, 2598 (2012).
S.-I. Kim et al., Adv. Mater. **25**, 4612 (2013).
H. Liang et al., Sci. Rep. **3**, 1975 (2013).
M. Huijben et al., Adv. Func. Mater. **23**, 5240 (2013).
H.-L. Lu et al., Sci. Rep. **3**, 2870 (2013).

A. Ohtomo, H. Hwang, *Nature* **427**, 423 (2004)
S. Okamoto, A.J. Millis, *Nature* **428**, 630 (2004)
S. Thiel *et al., Science* **313**, 1942 (2006)
N. Nakagawa *et al., Nature Materials* **5**, 204 (2006)
M. Huijben *et al., Nature Materials* **5**, 556 (2006)
C.W. Schneider, *APL* **89**, 122101 (2006)
A. Brinkman *et al., Nature Materials* **6**, 493 (2007)
G. Herranz *et al., PRL* **98**, 216803 (2007)
W. Siemons *et al., PRL* **98**, 196802 (2007)
P.R. Willmott *et al., PRL* **99**, 155502 (2007)
A. Kalabukov *et al., PRB* **75**, 121404(R) (2007)
Z. Popovic *et al., PRL* **101**, 256801 (2008)
M. Basletic *et al., Nature Materials* **7**, 621 (2008)
C. Cen *et al., Nature Materials* **7**, 298 (2008)
S. Thiel *et al., PRL* **102**, 046809 (2009)
R. Pentchevа*et al., PRL* **102**, 107602 (2009)
M. Salluzzo *et al., PRL* **102**, 166804 (2009)
O. Copie *et al., PRL* **102**, 216804 (2009)
M. Sing *et al., PRL* **102**, 176805 (2009)
C. Bell *et al., APL* **94**, 222111 (2009)
C. Bell *et al., PRL* **103**, 226802 (2009)
C. Cen *et al., Science* **323**, 1026 (2009)
C.L. Jia *et al., PRB* **79**, 081405(R) (2009)
W. Son *et al.*, PRB **79**, 245411 (2009)
G. Singh-Bhalla *et al., Nature Physics* (2010)
A. D. Caviglia *et al. PRL* **105**, 236802 (2010)
M. Ben Shalom *et al.* PRL **105**, 206401 (2010)
A. D. Caviglia *et al.* PRL **104**, 126803 (2010)
A. Dubroka *et al.* PRL **104**, 156807 (2010)
M. Ben Shalom *et al.* PRL **104**, 126802 (2010)
M. Breitschaft *et al.*, PRB **81**, 153414 (2010)
M. R. Fitzsimmons *et al.* PRL **107**, 217201 (2011)
C. Cancellieri *et al.* PRL **107**, 056102 (2011)

UNIVERSITÉ DE GENÈVE

MaNEP SWITZERLAND

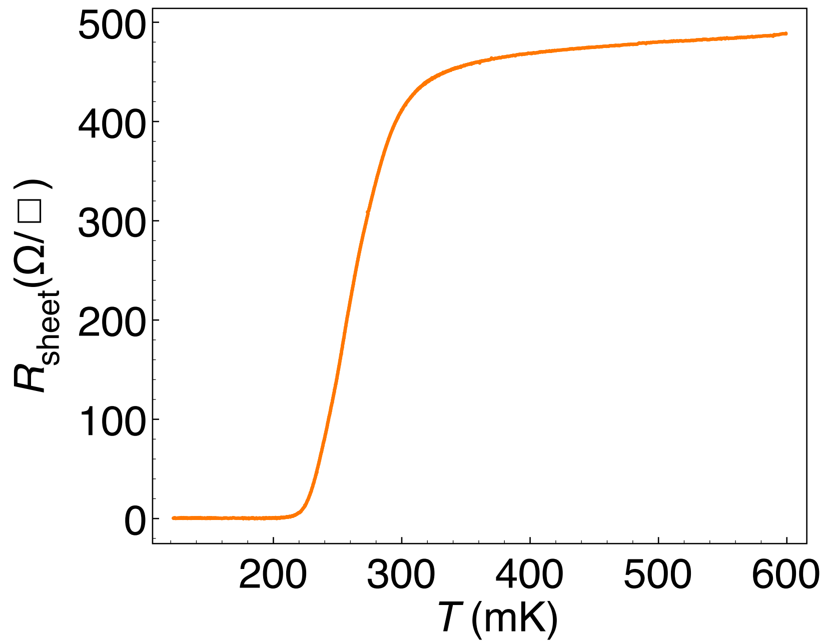
Superconductivity at low T



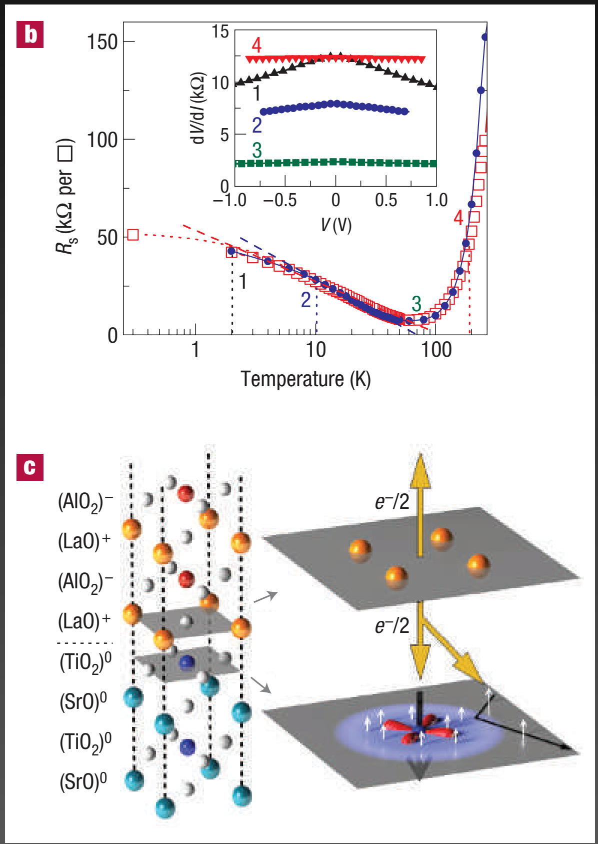
Superconducting Interfaces Between Insulating Oxides

N. Reyren,[1] S. Thiel,[2] A. D. Caviglia,[1] L. Fitting Kourkoutis,[3] G. Hammerl,[2] C. Richter,[2] C. W. Schneider,[2] T. Kopp,[2] A.-S. Rüetschi,[1] D. Jaccard,[1] M. Gabay,[4] D. A. Muller,[3] J.-M. Triscone,[1] J. Mannhart[2]*

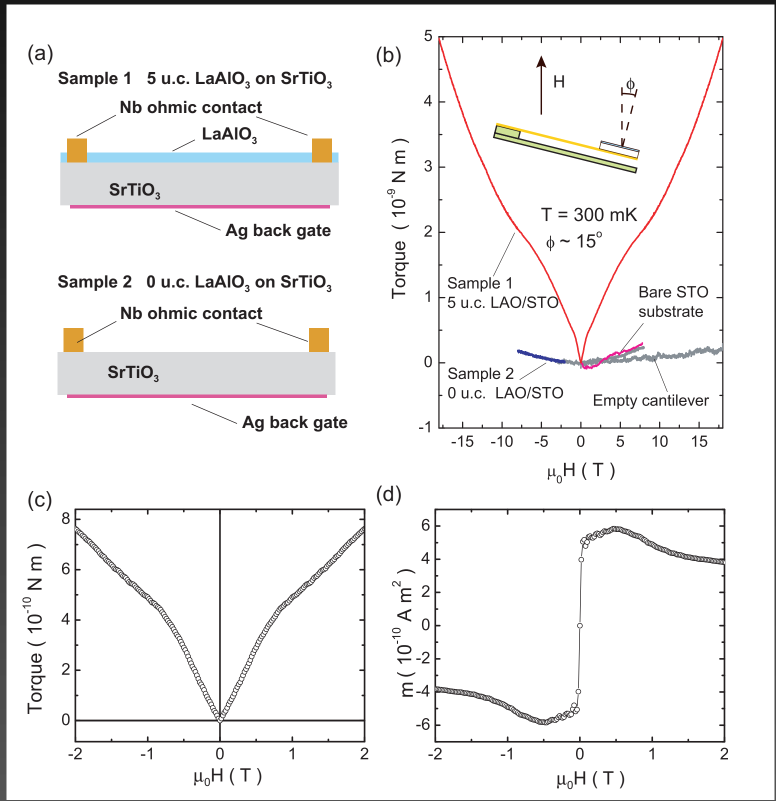
Science **317**, 1196 (2007)



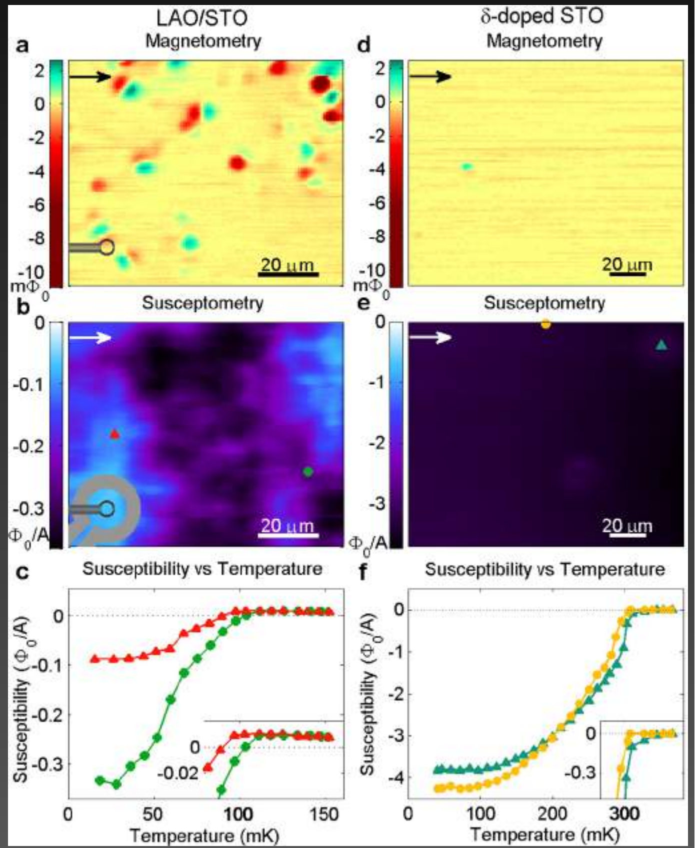
Magnetism



Brinkman et al.



Li et al.



Bert et al.

A. Brinkman *et al.,* Nat. Mater. **6**, 493-496 (2007)
D. A. Dikin *et al.,* Phys. Rev. Lett. 107, 056802 (2011)
Ariando *et al.,* Nat. Commun. **2**, 188 (2011)
L. Li et al. Nature Physics **7**, 762 (2011)
J.A. Bert et al.Nature Physics **7**, 767 (2011)
N. Pavlenko et al. Phys. Rev. B 85, 020407 (2012)

UNIVERSITÉ DE GENÈVE

A new field of research

Breakthrough of the Year

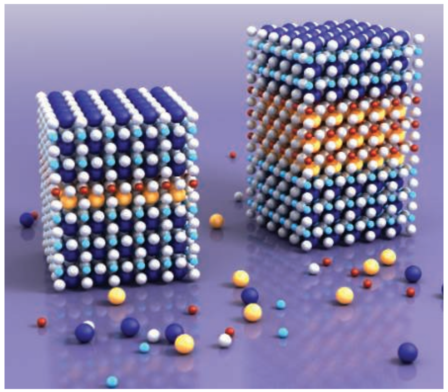
21 DECEMBER 2007 VOL 318 SCIENCE www.sciencemag.org

Published by AAAS

5 **BEYOND SILICON?** Sixty years ago, semiconductors were a scientific curiosity. Then researchers tried putting one type of semiconductor up against another, and suddenly we had diodes, transistors, microprocessors, and the whole electronic age. Startling results this year may herald a similar burst of discoveries at the interfaces of a different class of materials: transition metal oxides.

Transition metal oxides first made headlines in 1986 with the Nobel Prize–winning discovery of high-temperature superconductors. Since then, solid-state physicists keep finding unexpected properties in these materials—including colossal magnetoresistance, in which small changes in applied magnetic fields cause huge changes in electrical resistance. But the fun should really start when one oxide rubs shoulders with another.

If different oxide crystals are grown in layers with sharp interfaces, the effect of one crystal structure on another can shift the positions of atoms at the interface, alter the population of electrons, and even change how

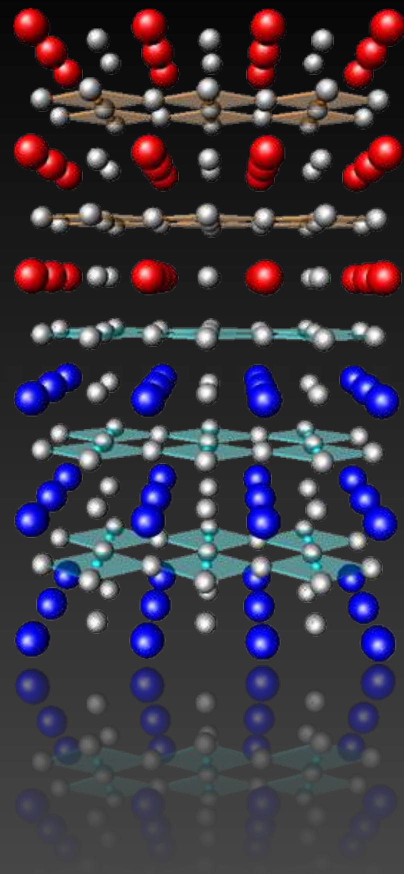


Tunable sandwich. In lanthanum aluminate sandwiched between layers of strontium titanate, a thick middle layer (*right*) produces conduction at the lower interface; a thin one does not.

UNIVERSITÉ DE GENÈVE

MaNEP SWITZERLAND

Outline



Why oxide heterostructures / interfaces?

The $LaAlO_3/SrTiO_3$ system

Origin of the conductivity

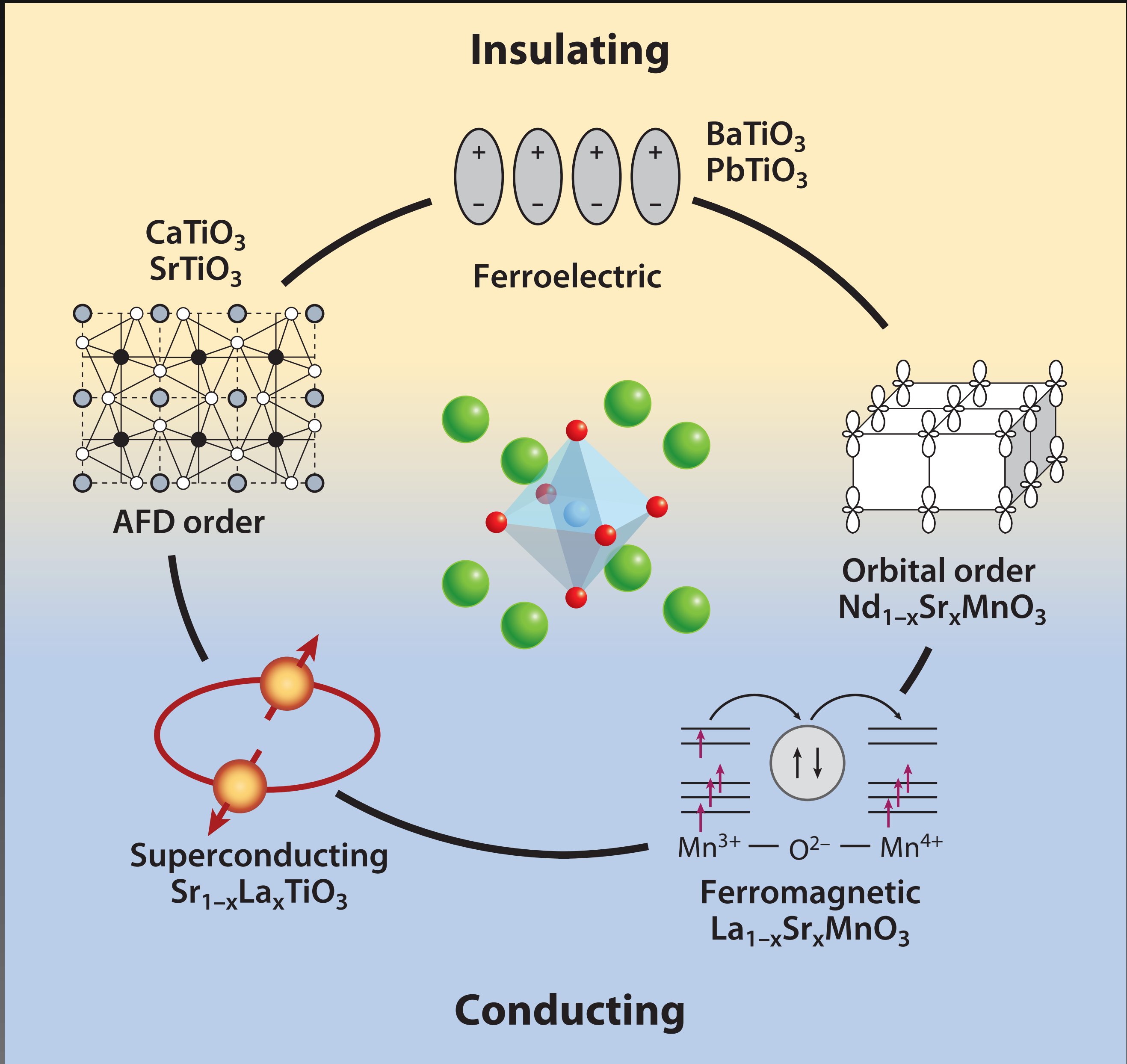
FE control of the electronic properties

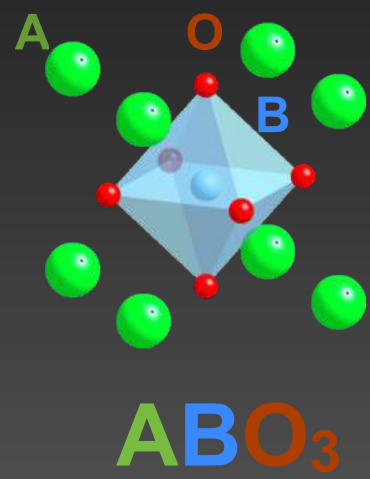
Electronic structure

Superconductivity

Exciting developments

Oxides display a variety electronic properties



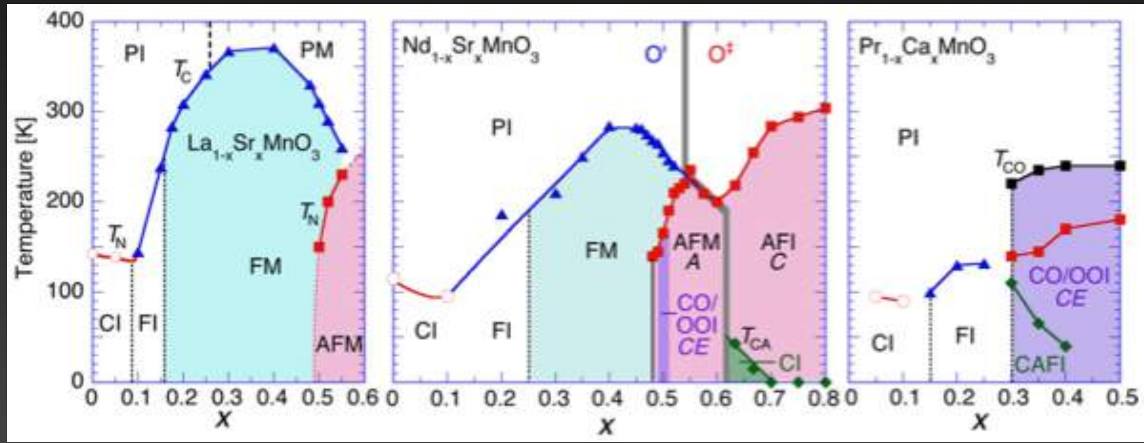


Perovskite Structure

P. Zubko et al., *Ann. Rev. Cond. Matter Phys.* **2**, 141 (2011)

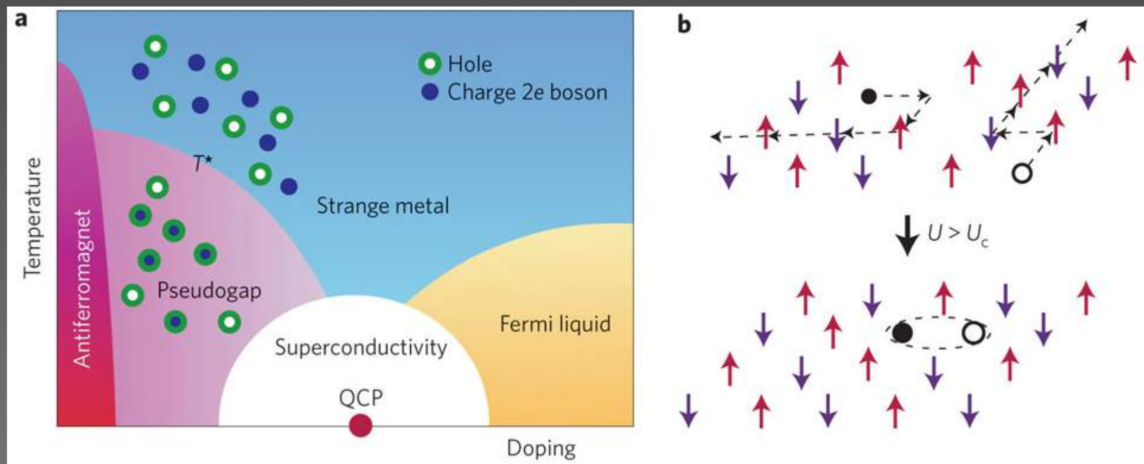
Complex phase diagrams

Manganites



Y. Tokura, *Rep. Prog. Phys.* **69,** 797 (2006)

Cuprates

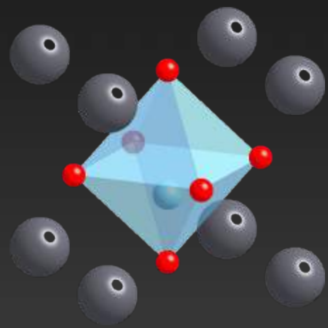


P. Phillips, *Nature Phys.* **6,** 931 (2010)

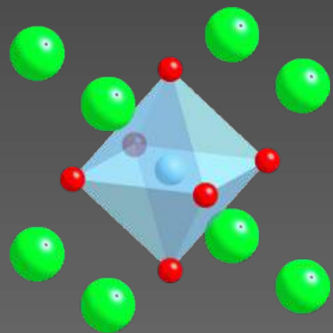
UNIVERSITÉ DE GENÈVE

MaNEP SWITZERLAND

Like Lego bricks

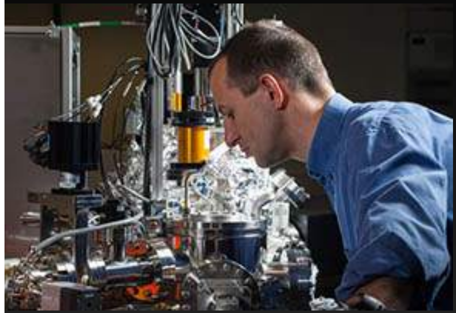


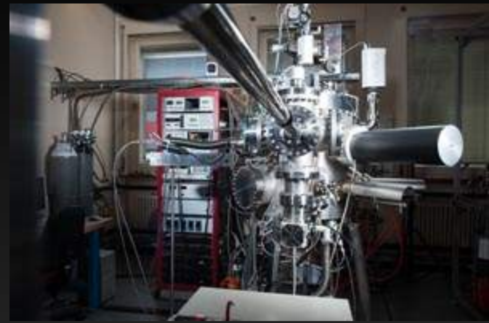
$PbTiO_3$ ferroelectric $T<T_C$
Tetragonal and ferroelectric
(a=b=3.904Å, c=4.152Å)

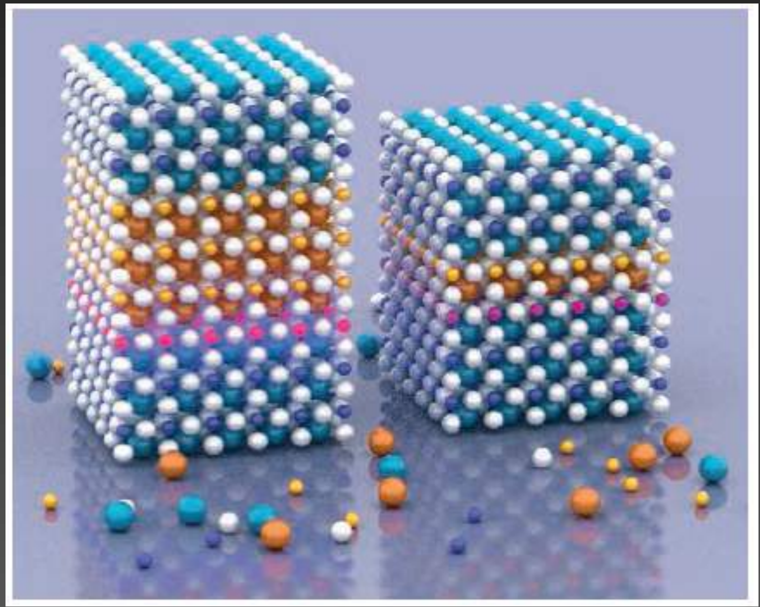


$SrTiO_3$ paraelectric at all temperatures
(a=b=c=3.905Å)

Atomic construction







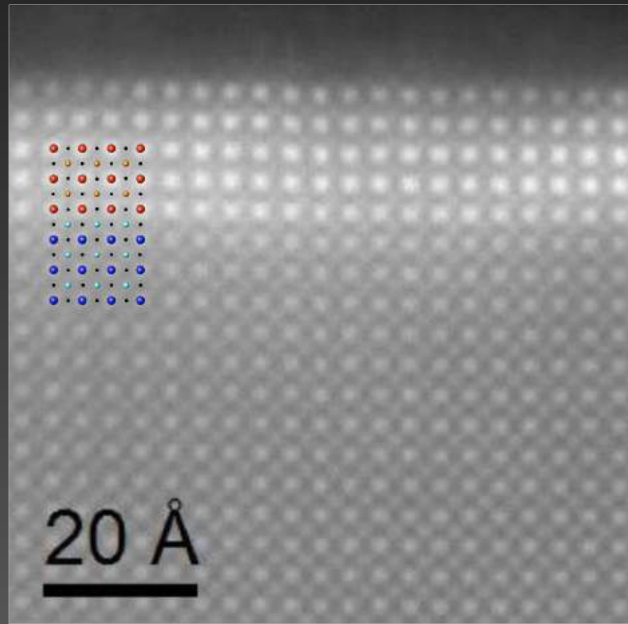
La

Al

Sr

Ti

O

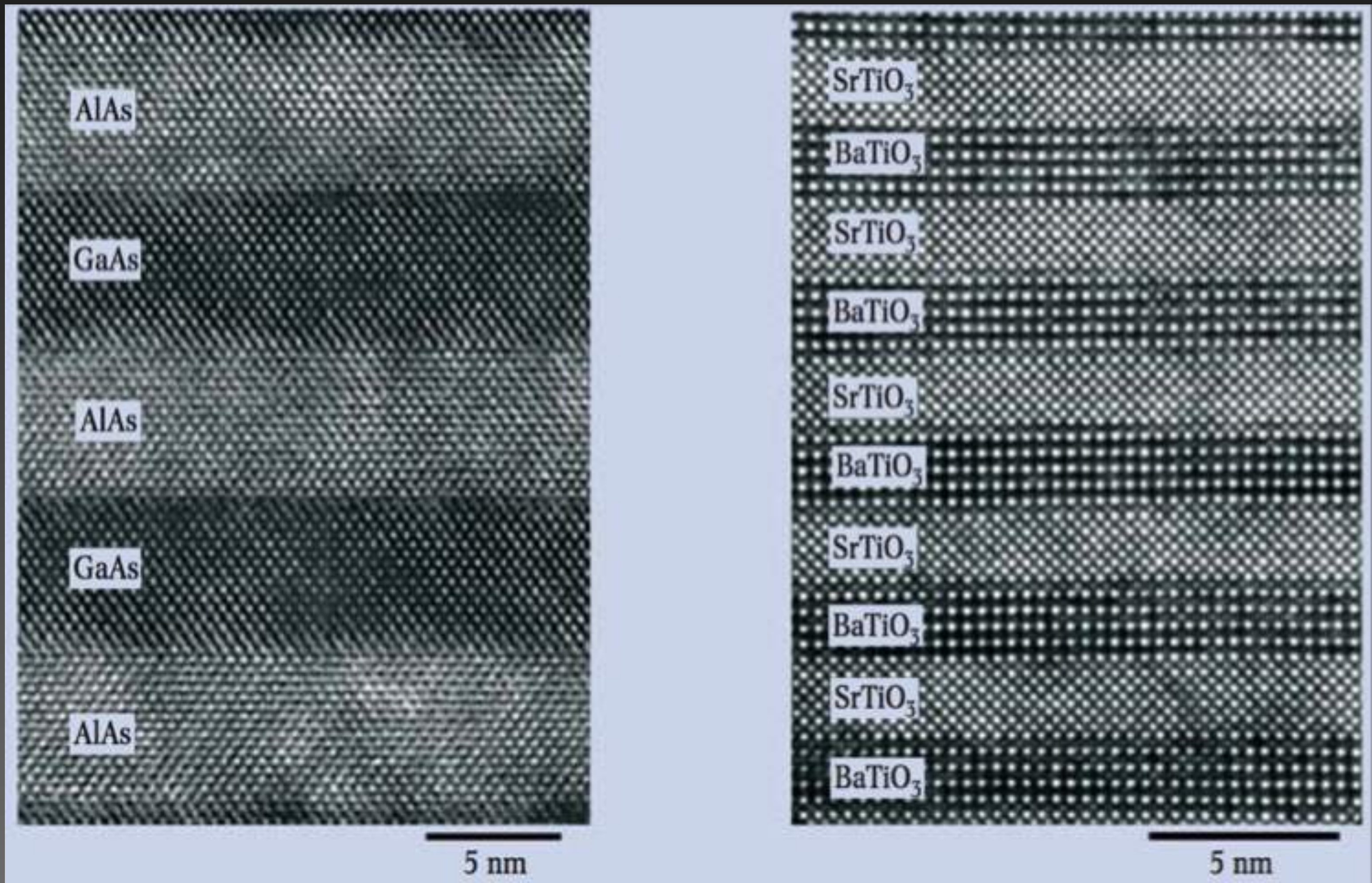


Dave Muller, Cornell

It is possible today to assemble these perovskite materials with atomic layer control in heterotructures

Oxide heterostructures

Epitaxial Growth of Functional Compounds



A.K. Gutakovskii *et al.* (1995) D.G. Schlom *et al.* (2001)

Oxide interface physics

ZnO/(Mg,Zn)O

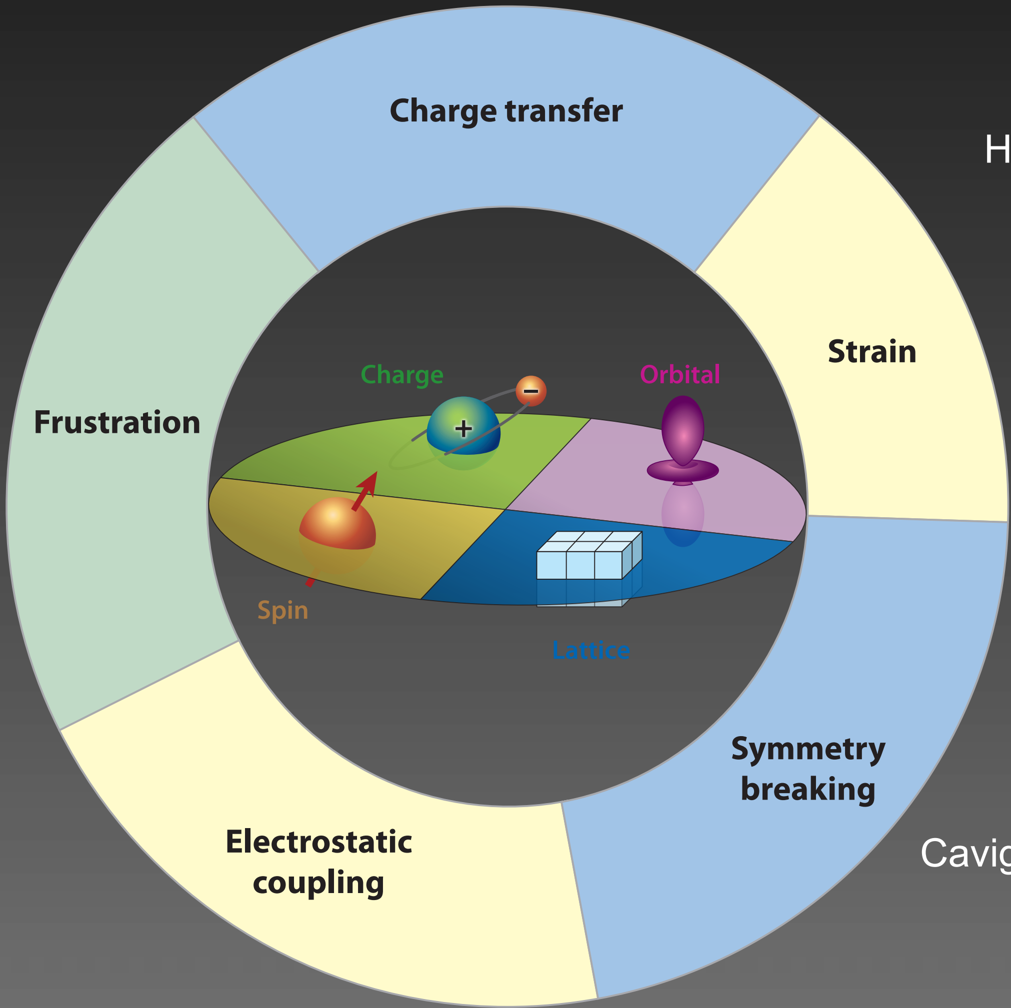
Tokura and Nagaosa
Science **288**, 462 (2000)

Tsukazaki et al. Science **315**, 1388 (2007)
Ohtomo and Hwang Nature **427**, 423 (2004)

$LaAlO_3/SrTiO_3$

$DyScO_3/SrTiO_3$

Haeni et al. Nature **430**, 758 (2004)



$PbTiO_3/SrTiO_3$

Bousquet et al. Nature
452, 732 (2008)

$LaAlO_3/SrTiO_3$

Caviglia et al. PRL **104**, 126803 (2010)

Interface physics in complex oxide heterostructures

P. Zubko et al., Annual Review of Condensed Matter Physics **2**, 141 (2011)

The «Geneva» $LaAlO_3/SrTiO_3$ Team

Stefano Gariglio

Margherita Boselli

Adrien Waelchli

Ritsuko Eguchi

Andrea Caviglia
(now in Delft)

Nicolas Reyren
(CNRS Paris)

Claudia Cancellieri
(now at EMPA)

Daniela Stornaiuolo
(now in Naples)

Zhenping Wu
(now in Beijing)

Denver Li
Stanford

UNIVERSITÉ DE GENÈVE

and collaboration with

Marc Gabay (Orsay)

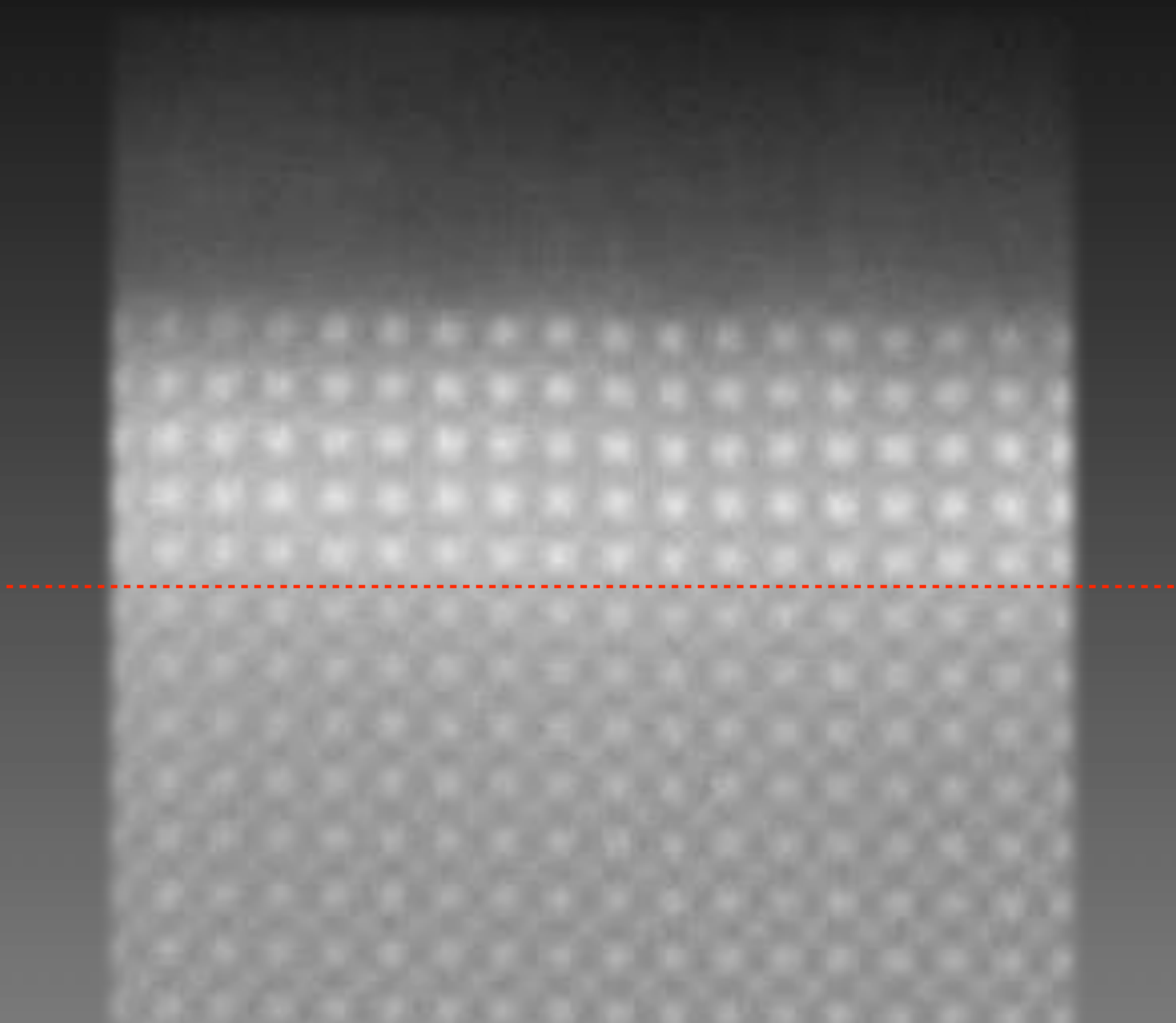
Philippe Ghosez (Liège)

Jochen Mannhart
(MPI Stuttgart)

Odile Stéphan
(Orsay)

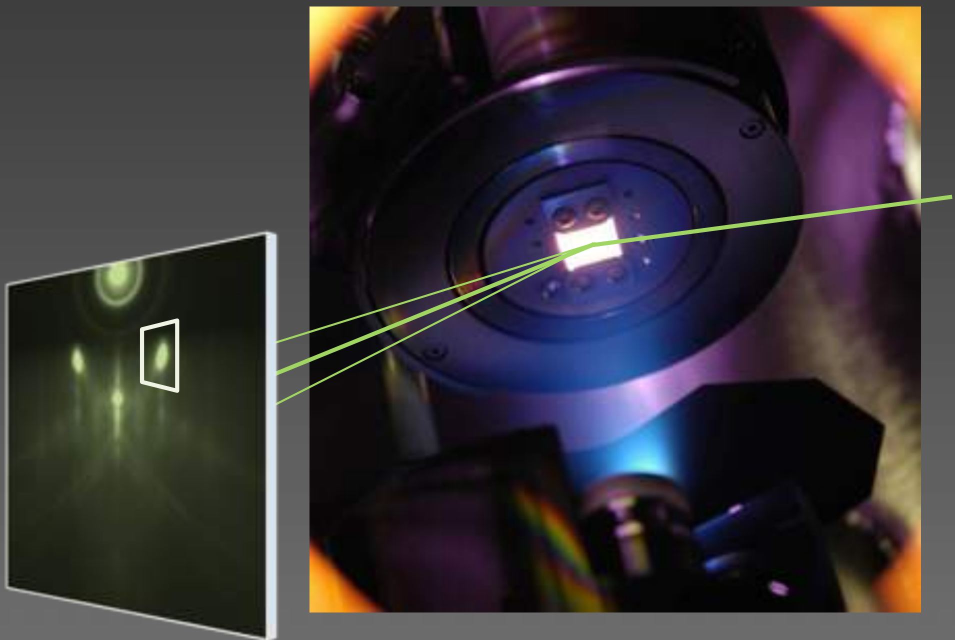
and their groups

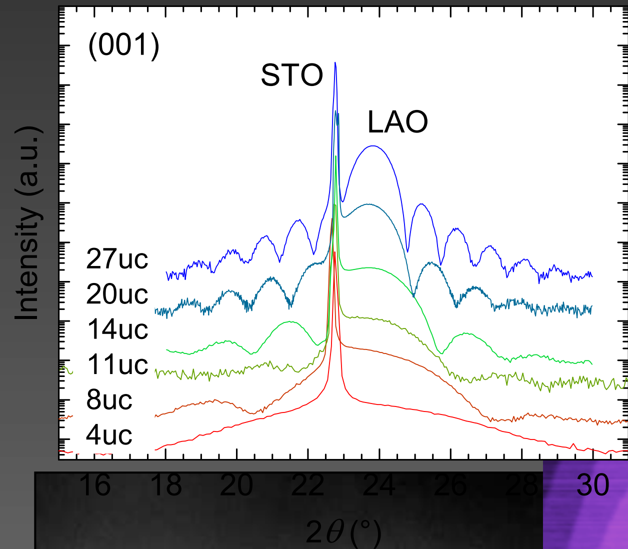
The $LaAlO_3/SrTiO_3$ system

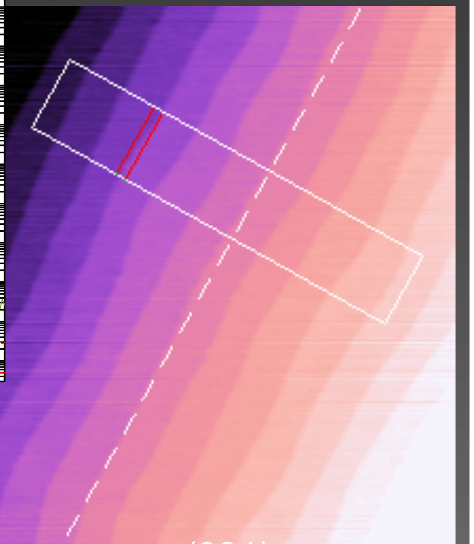


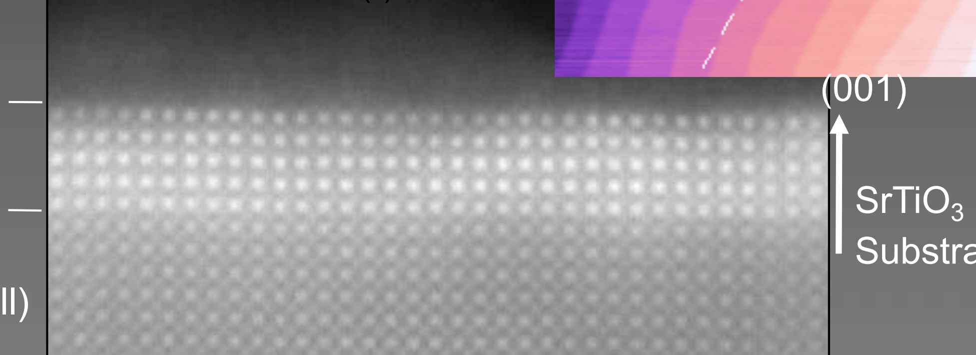
$LaAlO_3$ epitaxial growth by PLD

Layer-by-layer growth
T = 720, 800, 890°C
P O_2 = $1\cdot10^{-4}$ Torr
Fluence = 0.6 J/cm^2
Frequency = 1Hz
Post annealing @ 200 mbar O_2









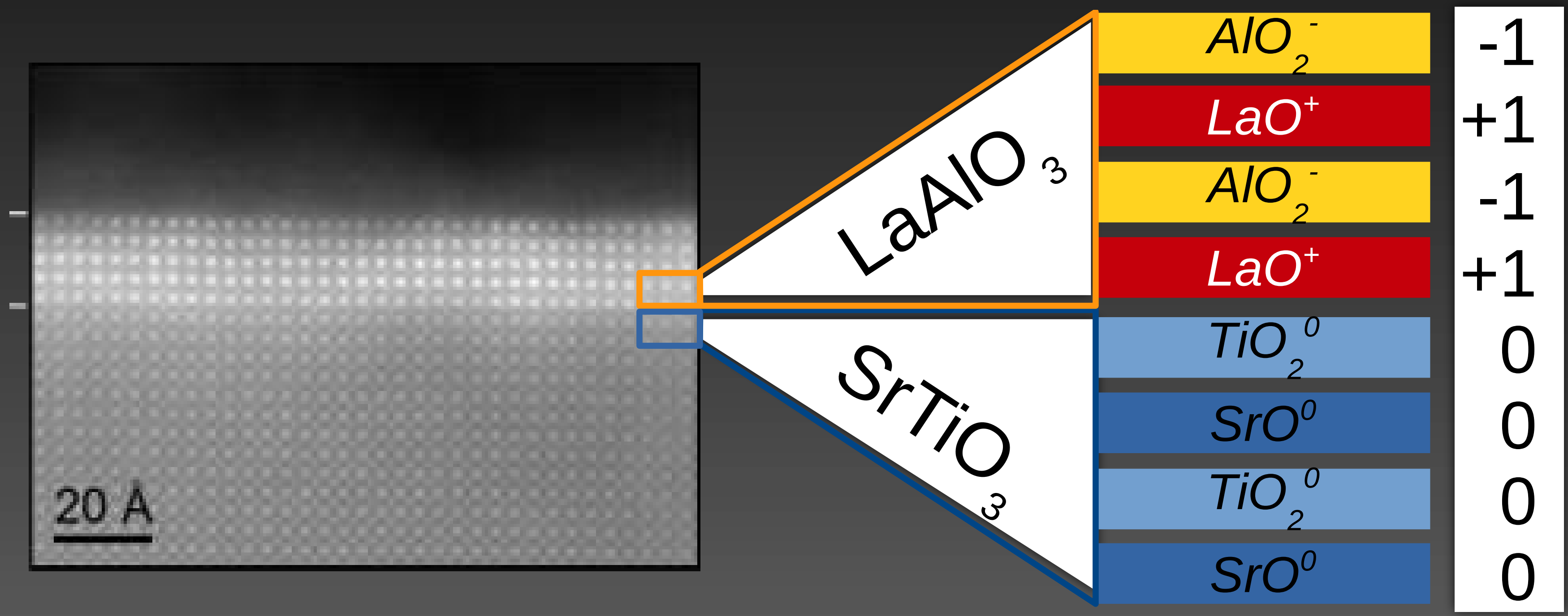
UNIVERSITÉ DE GENÈVE

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

MaNEP SWITZERLAND

Why is the Interface Conducting?

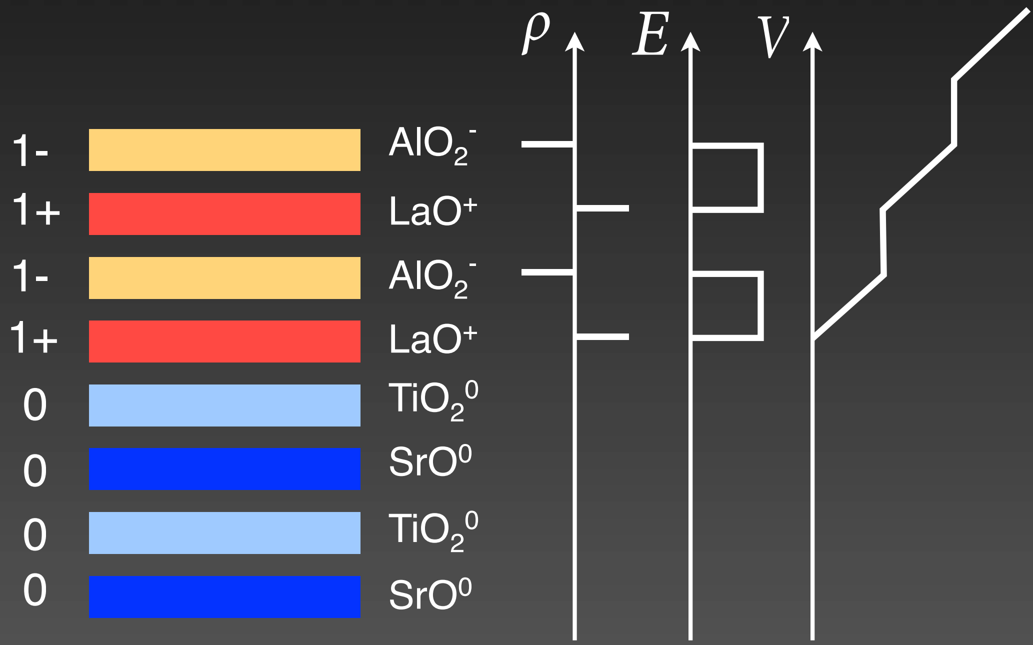
The polar catastrophe scenario

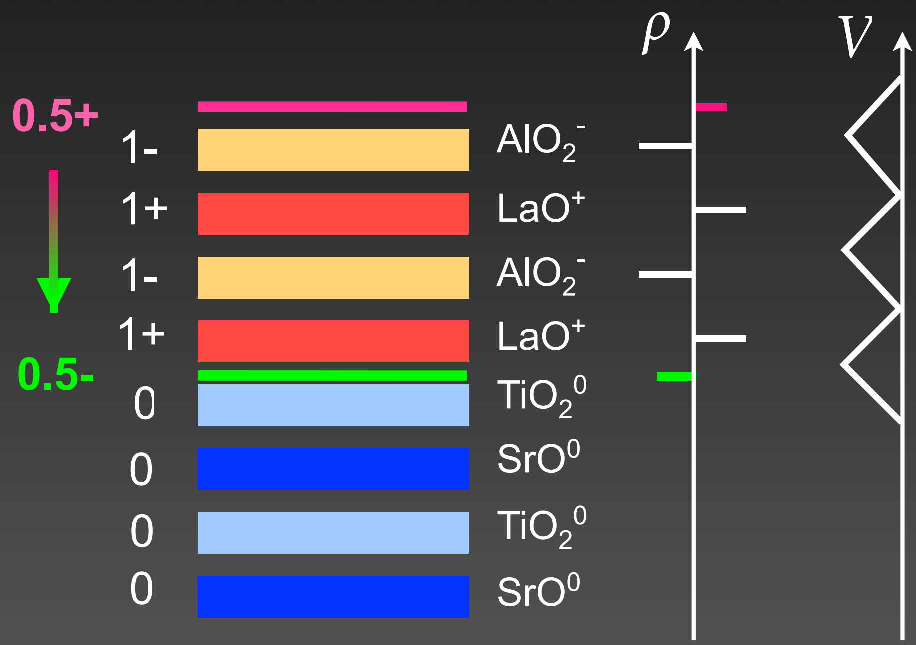


UNIVERSITÉ DE GENÈVE

MaNEP SWITZERLAND

The polar catastrophe scenario





$3\ 10^{14}$ e/cm^2

N. Nakagawa *et al.*, Nature Materials (2006).

GaAs/Ge W.A. Harisson et al. PRB **18**, 4402 (1978).

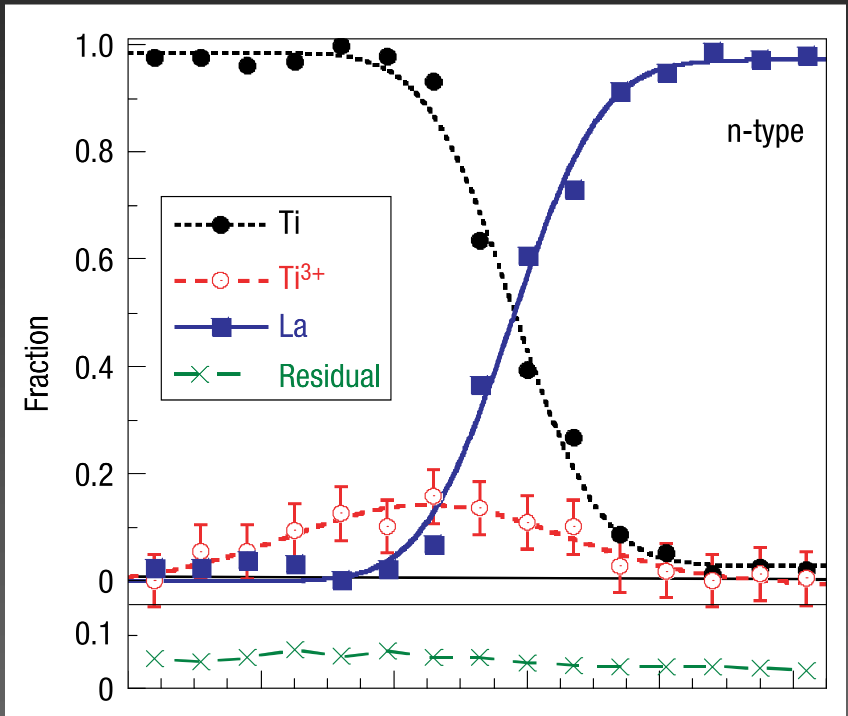
Chemical Doping

Why some interfaces cannot be sharp

NAOYUKI NAKAGAWA[1,2], HAROLD Y. HWANG[1,2] AND DAVID A. MULLER[3]*

[1]Department of Advanced Materials Science, University of Tokyo, Kashiwa, Chiba 277-8561, Japan
[2]Japan Science and Technology Agency, Kawaguchi 332-0012, Japan
[3]School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14583, USA
*e-mail: davidm@ccmr.cornell.edu

Nat. mater. **5**, 204 (2006)



La/Sr intermixing

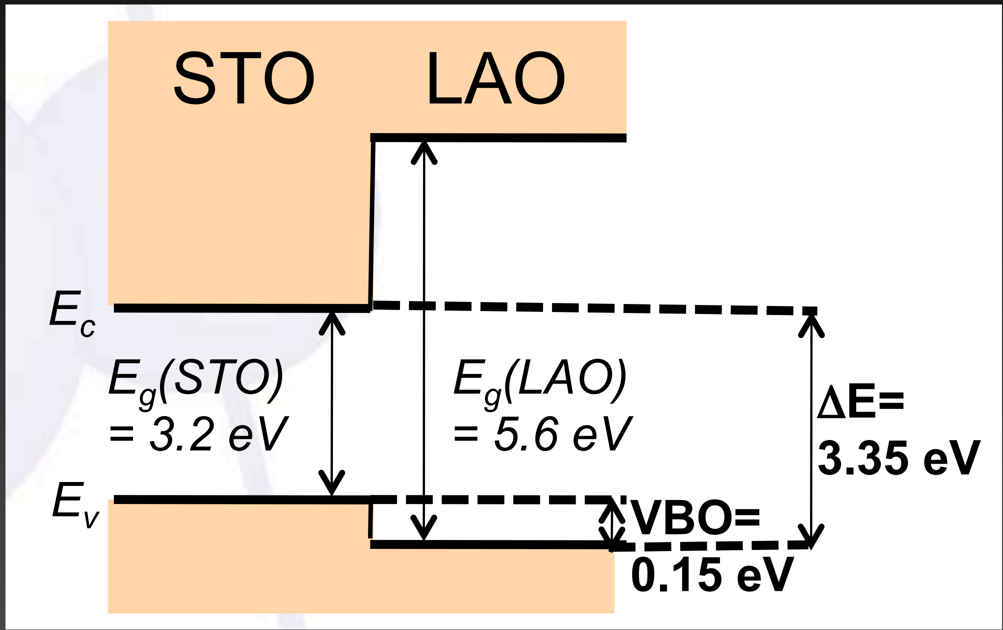
P.R. Willmott et al. PRL **99**, 155502 (2007)
A.S. Kalabukhov et al. PRL **103**, 146101 (2009)

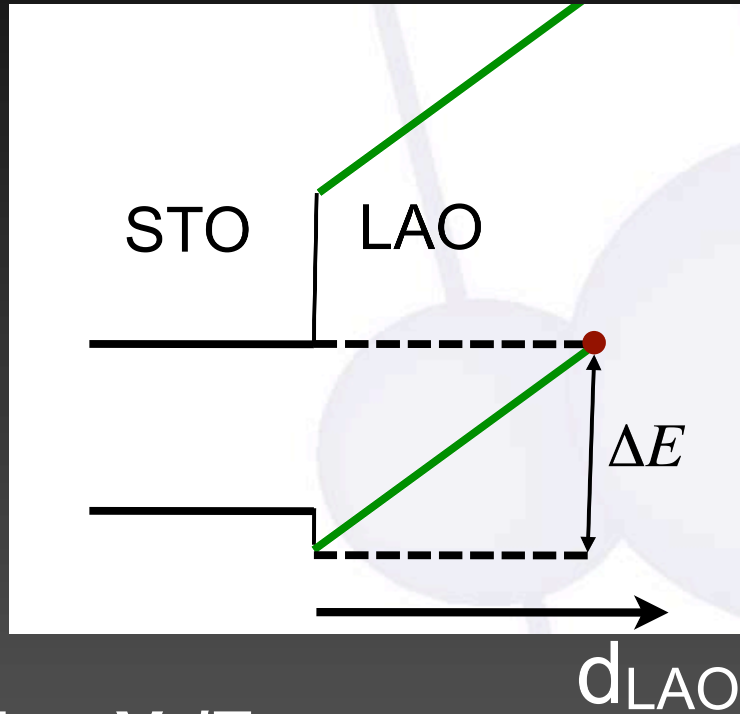
J. Mannhart, D.G. Schlom, Nature N&V **430**, 620 (2004)

UNIVERSITÉ DE GENÈVE

MaNEP SWITZERLAND

Testing the polar catastrophe scenario





$$E=(\sigma_0 / \varepsilon_r \varepsilon_0) \Rightarrow d_c = V_c/E$$

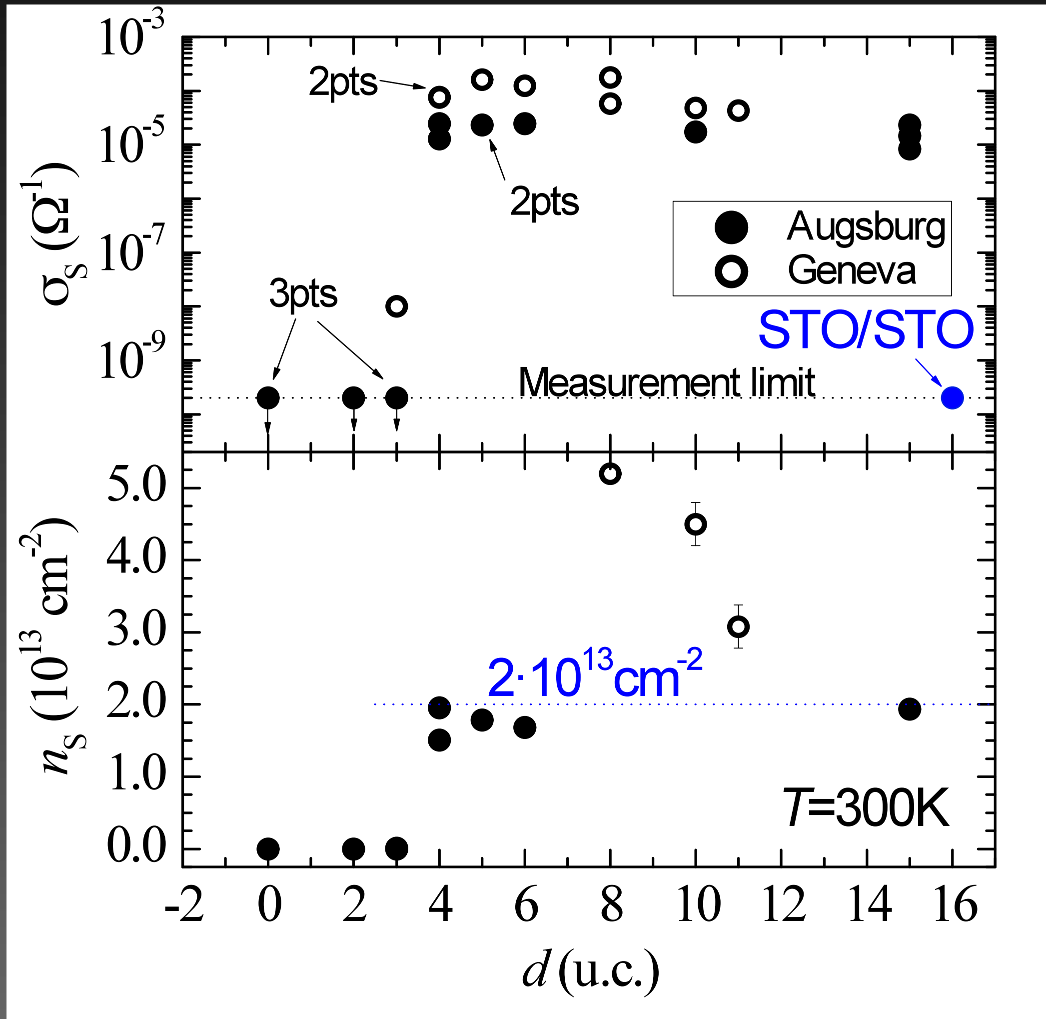
with V_c=3.35 V, σ_0 = 3 10^{14} e/cm^2 and ε_r =25, d_c = 3.5 u.c.

See also R. Pentcheva and W. Pickett PRL 102, 107602 (2007)

UNIVERSITÉ DE GENÈVE

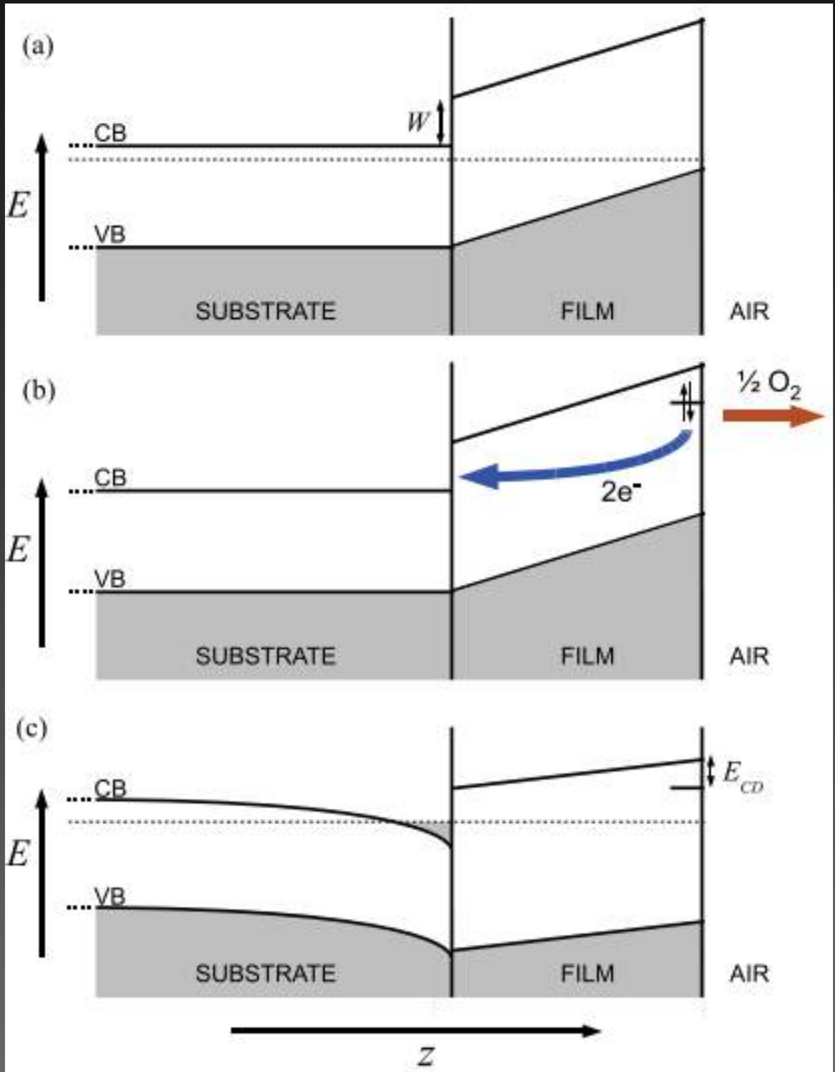
MaNEP SWITZERLAND

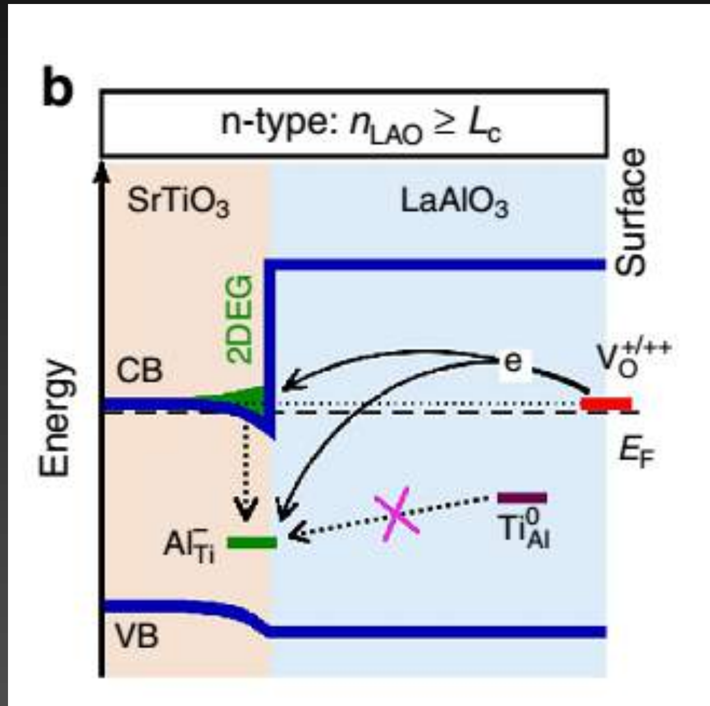
$LaAlO_3$ critical thickness



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

Oxygen vacancy formation at the LAO surface





See also,

Liping Yu and Alex Zunger Nat. Com. 2015

J. Zhou et al. Singapore, UBC

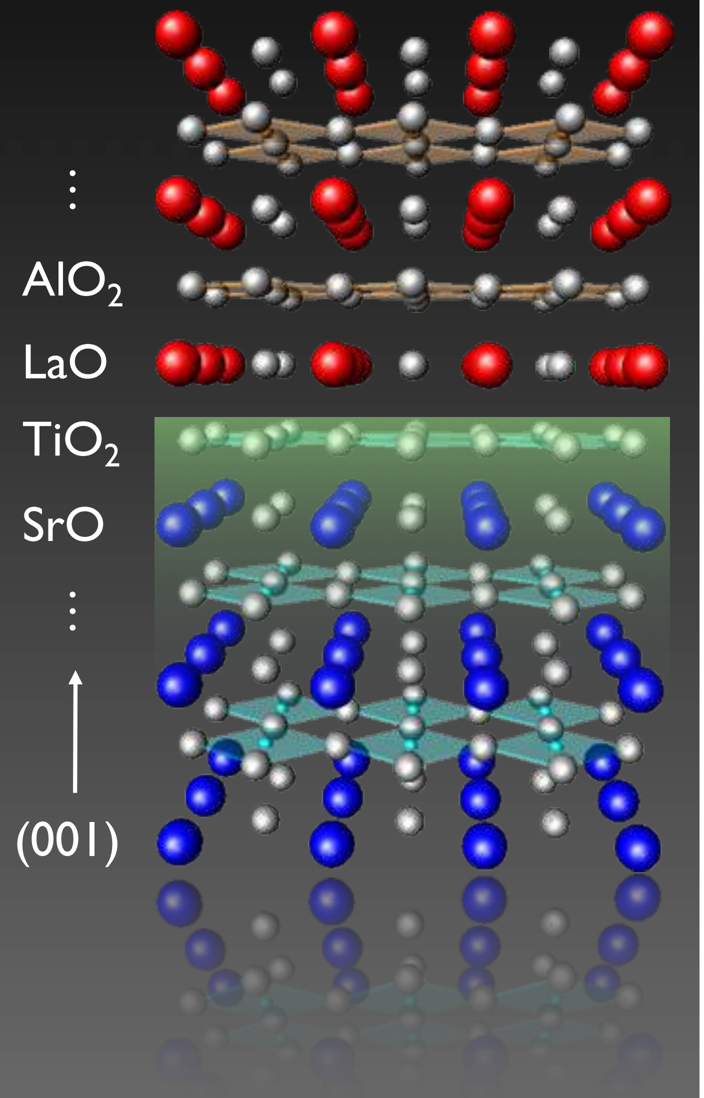
N. C. Bristowe et al., *Phys. Rev. B* **83,** 205405 (2011)

N. C. Bristowe et al., J. Phys.: Condens. Matter 26 143201 (2014)

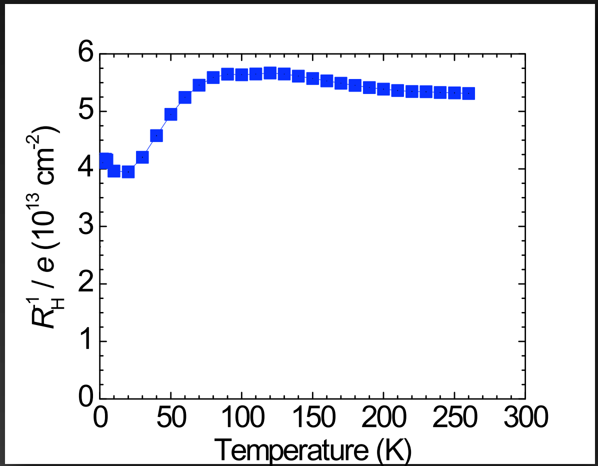
UNIVERSITÉ DE GENÈVE

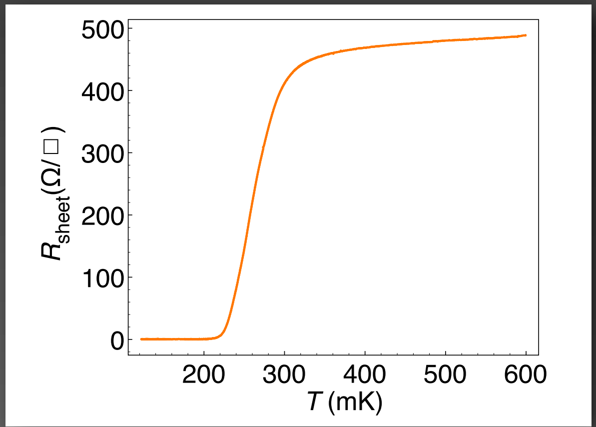
MaNEP SWITZERLAND

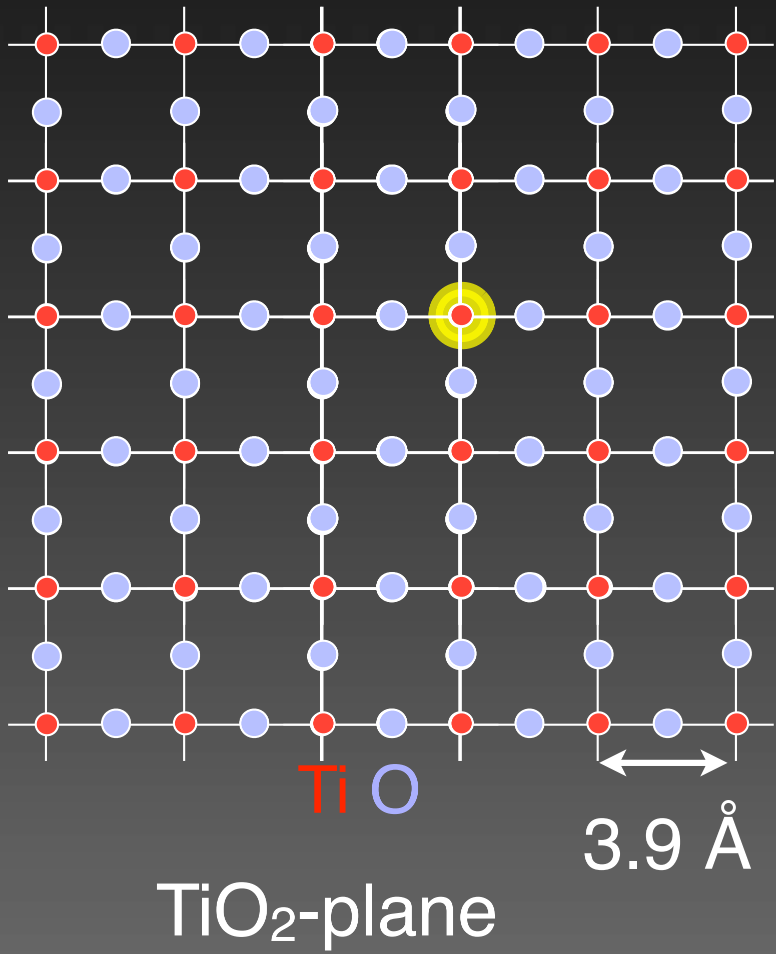
Doping Control - Electric Field Effect



Transport and FE control



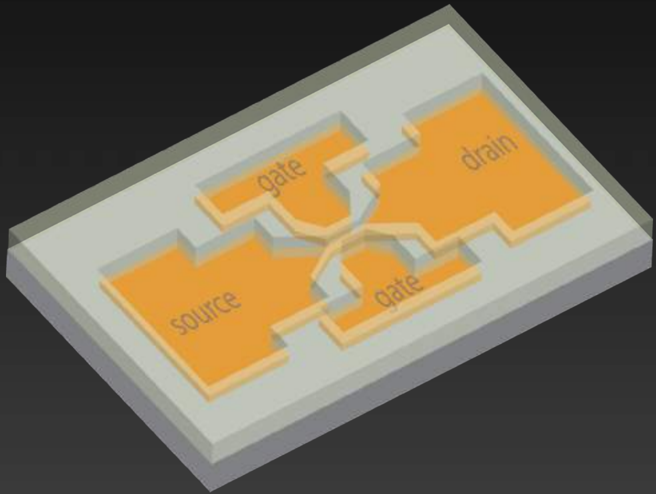


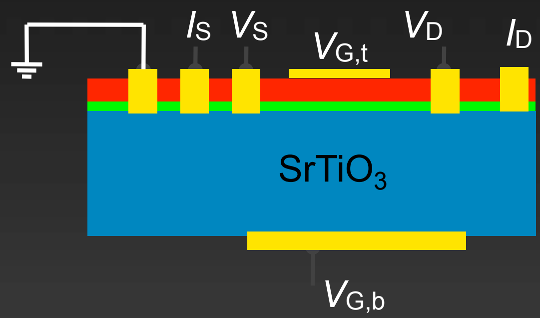


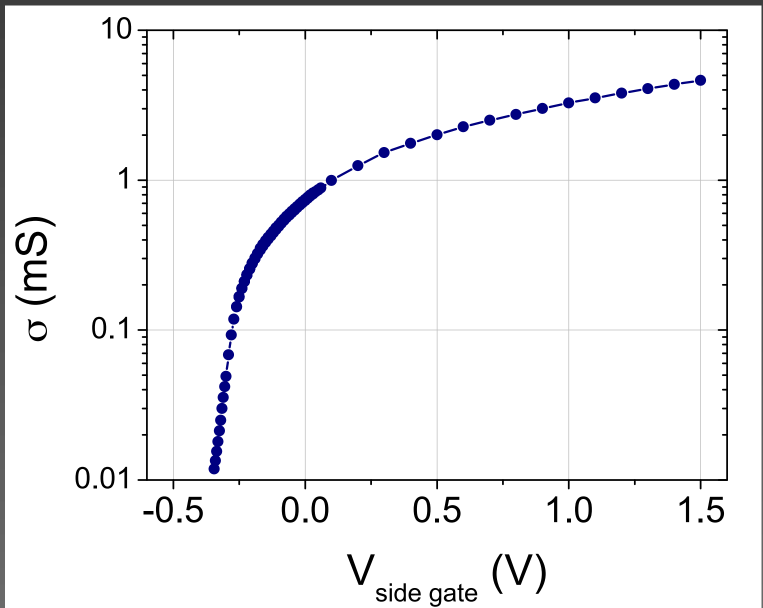
~2-8×10^{13}/cm^2

mobilities 100-1000 cm^2/Vs

Transport and field effect control

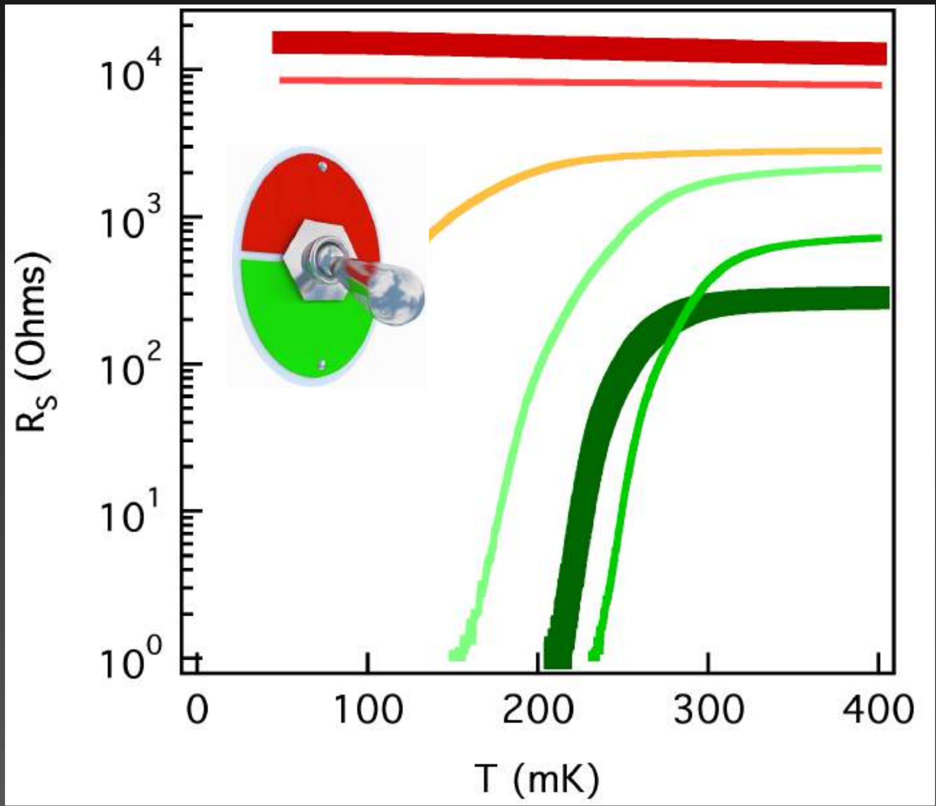


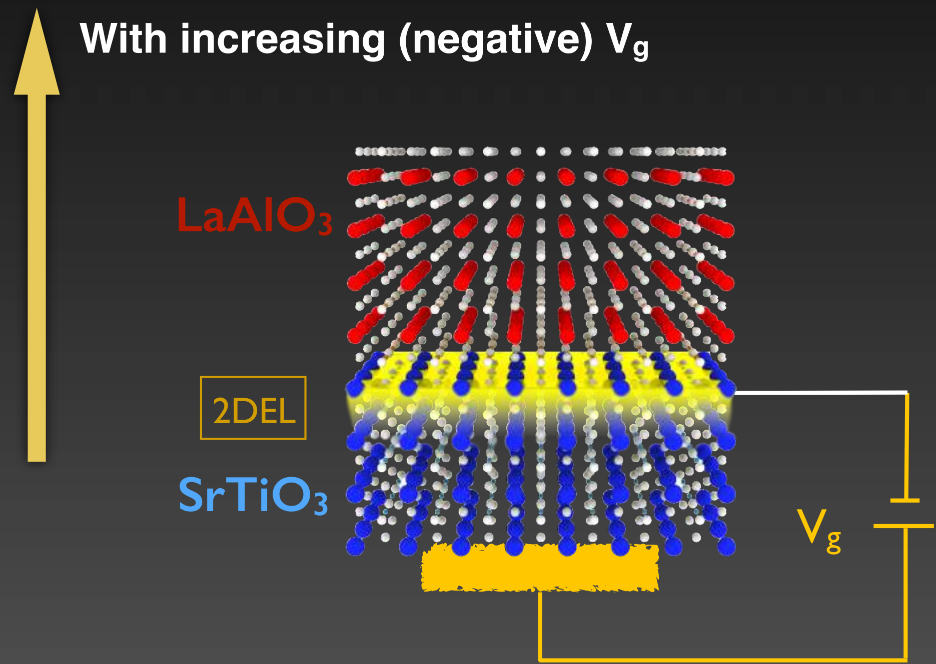


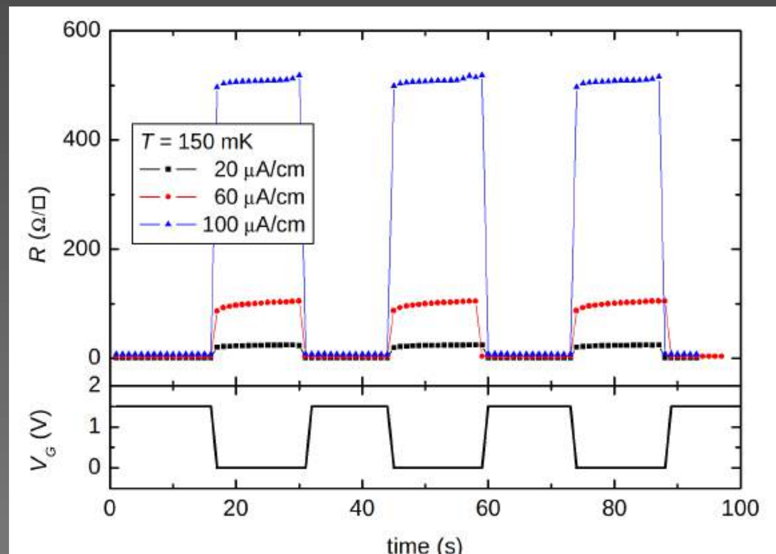


Side gating

A superconducting switch

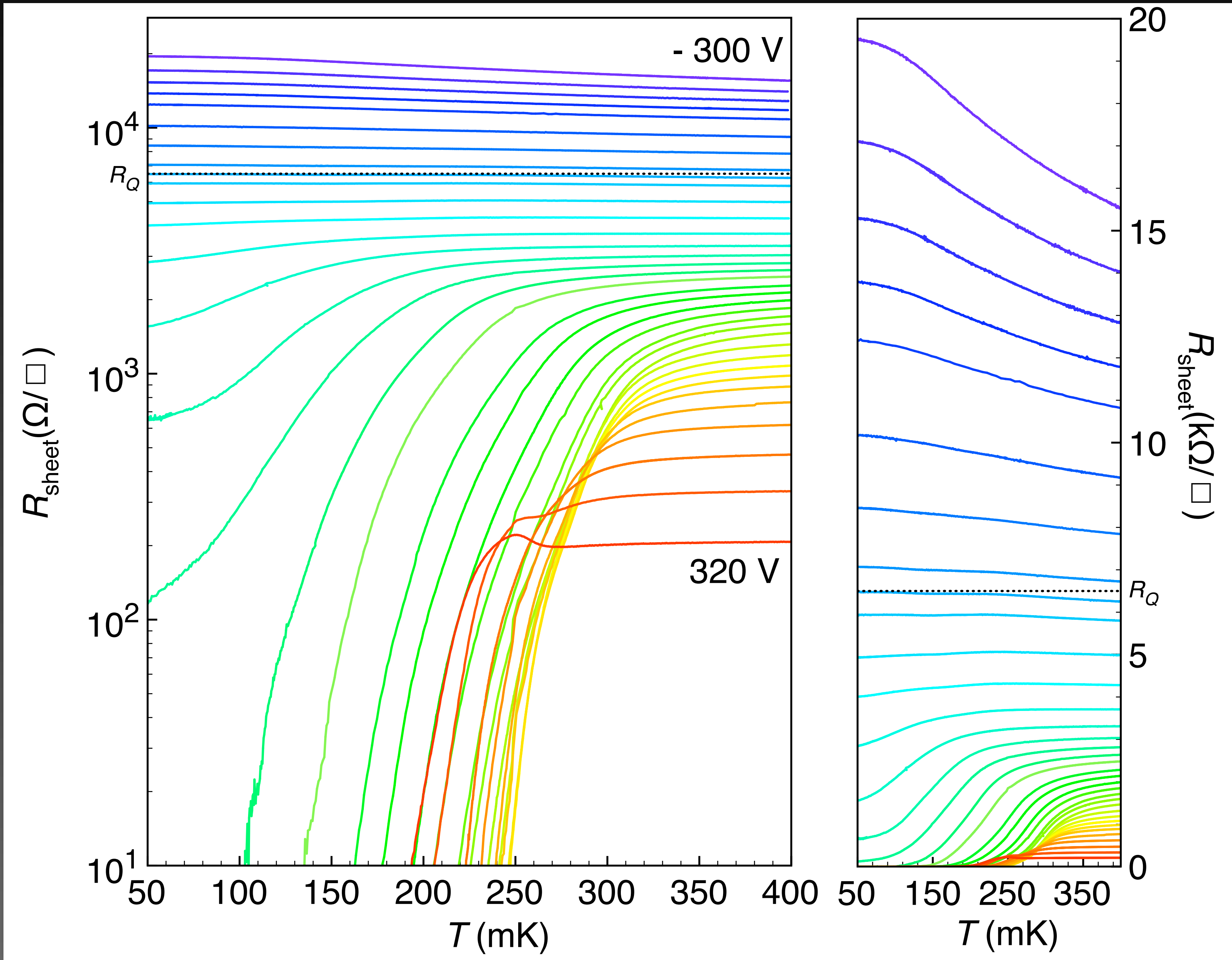






A.D. Caviglia et al. Nature **456**, 624 (2008)

Modulation of SC

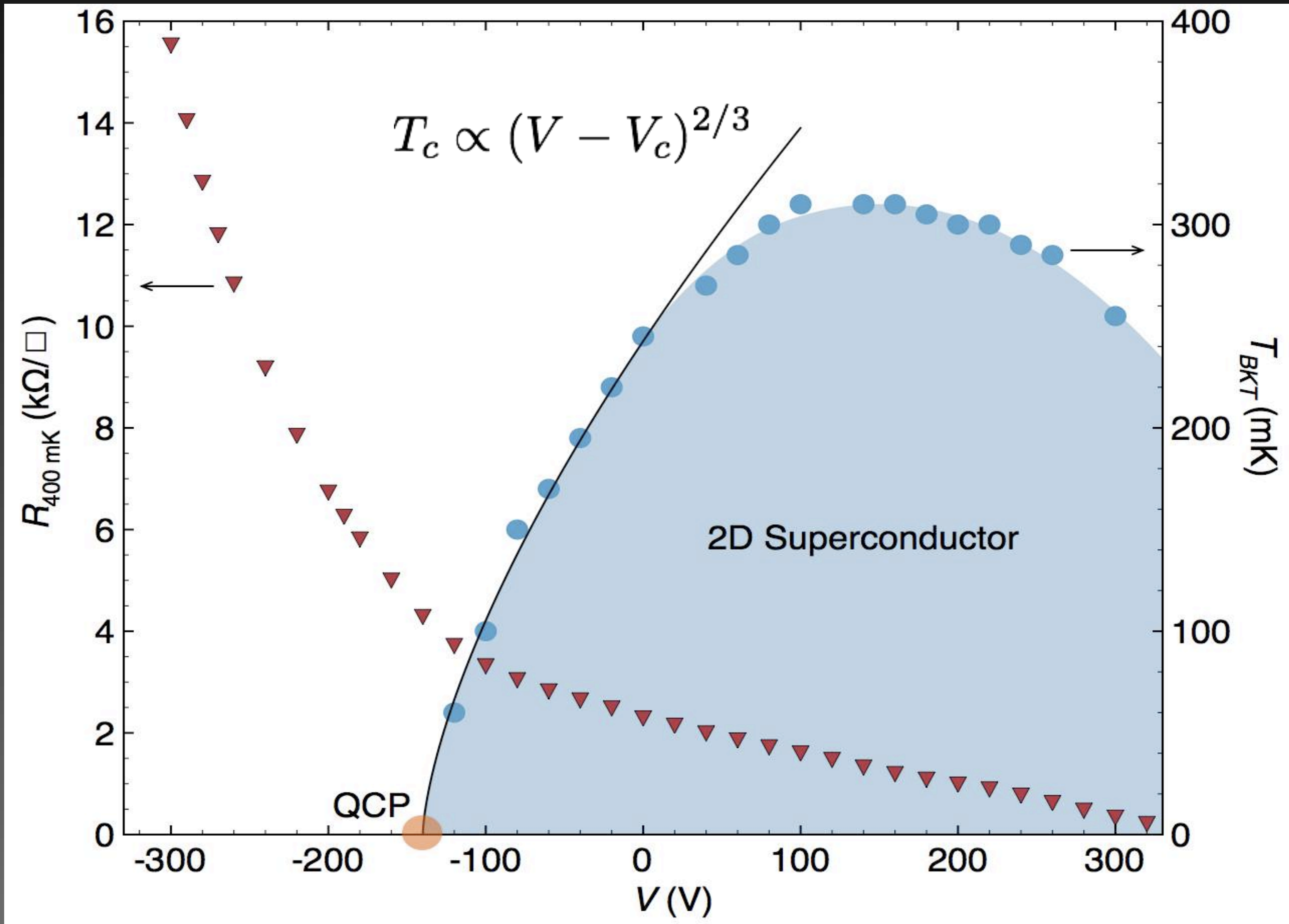


A.D. Caviglia *et al*, Nature **456**, 625 (2008)

UNIVERSITÉ DE GENÈVE

MaNEP SWITZERLAND

System phase diagram



See also C. Bell et al. PRL **103**, 226802 (2009).

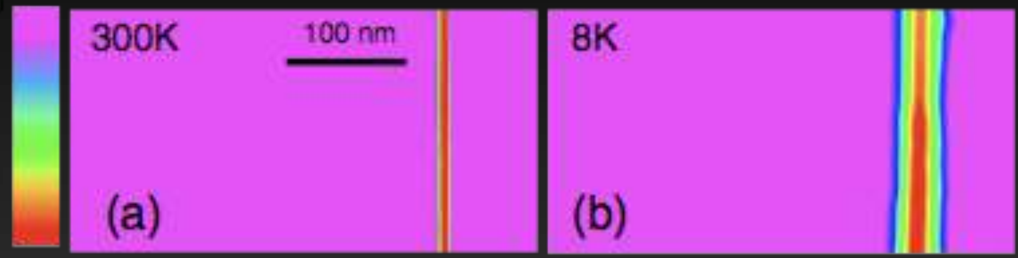
UNIVERSITÉ DE GENÈVE

Quantum Confinement

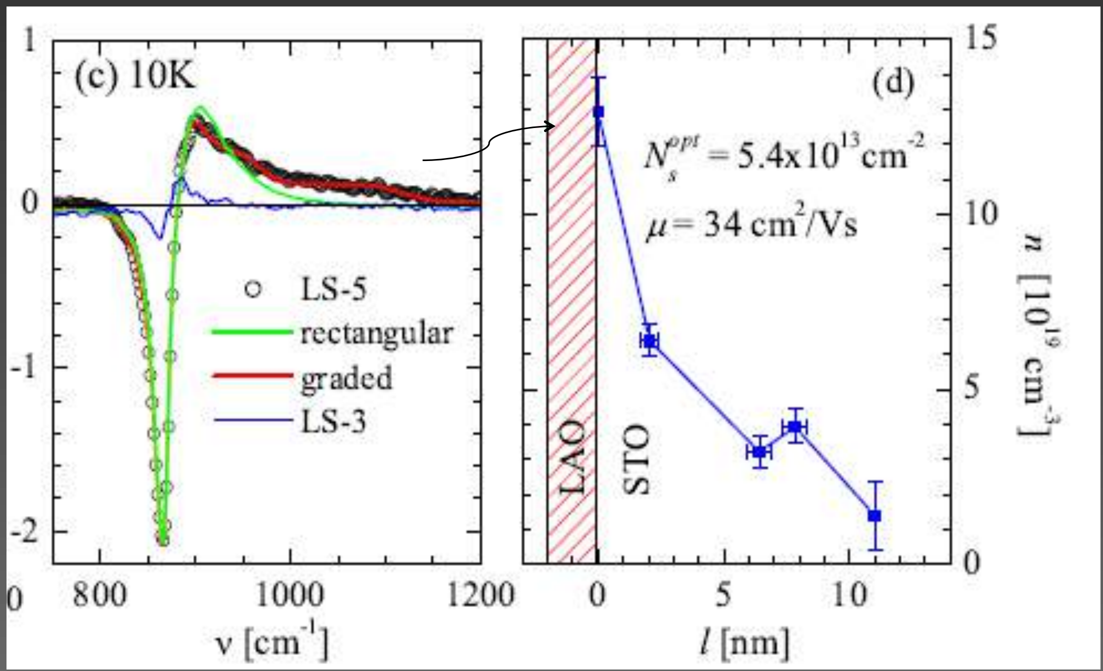
Confinement and electronic structure

RT d<7nm

12 nm at low T

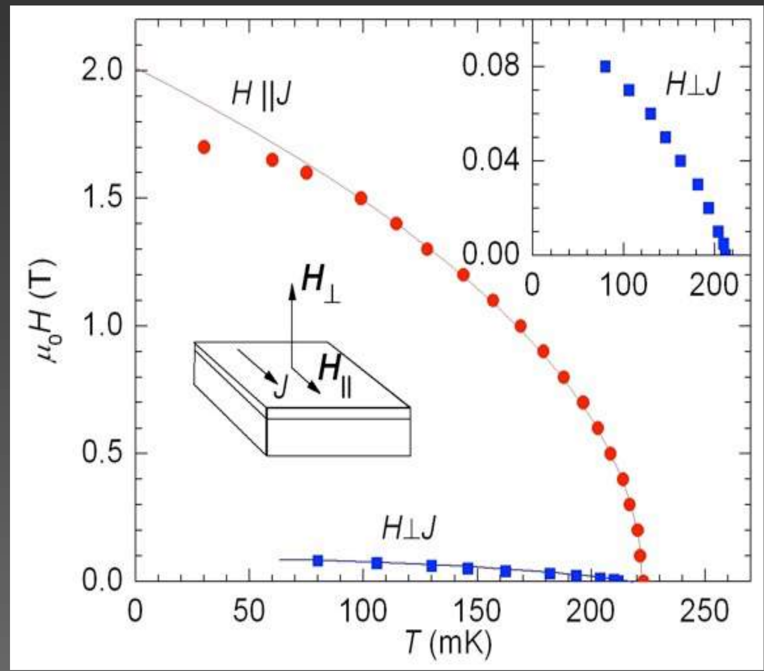


M. Basletic et al, Nat. Mater. 7, 621 (2008)
O. Copie et al, Physical Review Letters. **102**, 216804 (2009)



A. Dubroka et al, PRL **104**, 156807 (2010)

11 nm at 10K



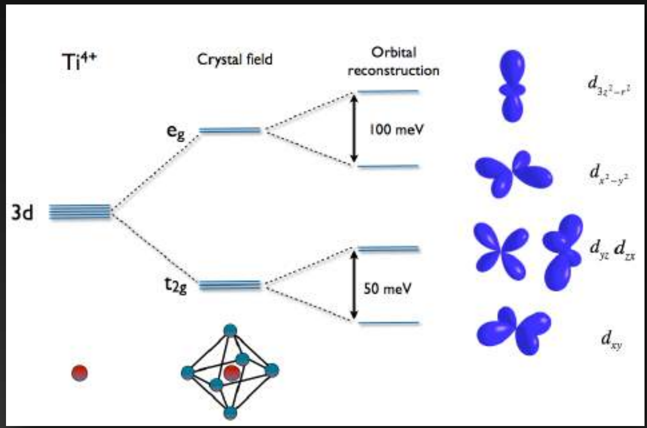
N. Reyren et al. APL **94**, 112506 (2009)

10 nm

UNIVERSITÉ DE GENÈVE

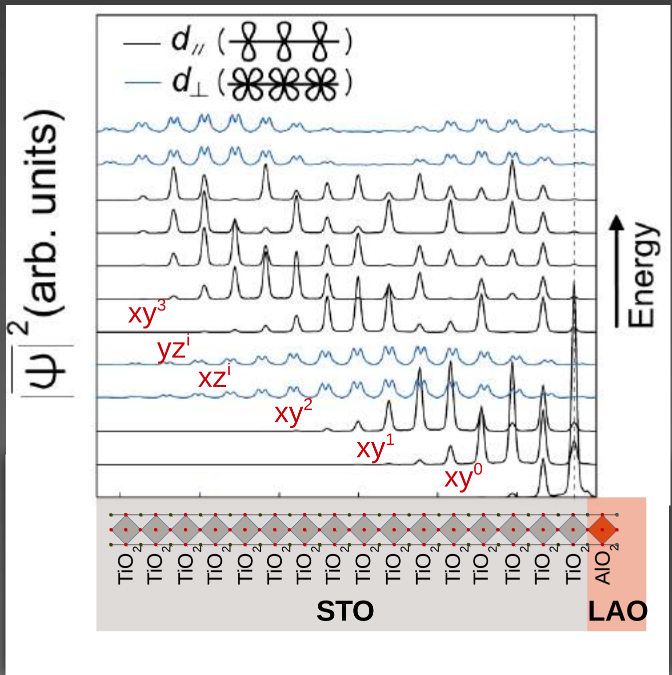
MaNEP SWITZERLAND

Confinement and electronic structure

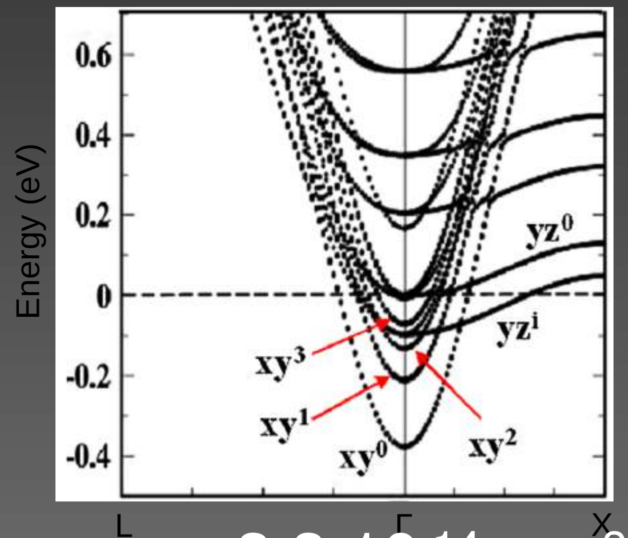


The electrons are
in the Ti 3d band -
in t_{2g} «orbitals»

M. Salluzzo *et al.*, *PRL* **102**, 166804 (2009)



Son *et al.*, PRB **79**, 245411



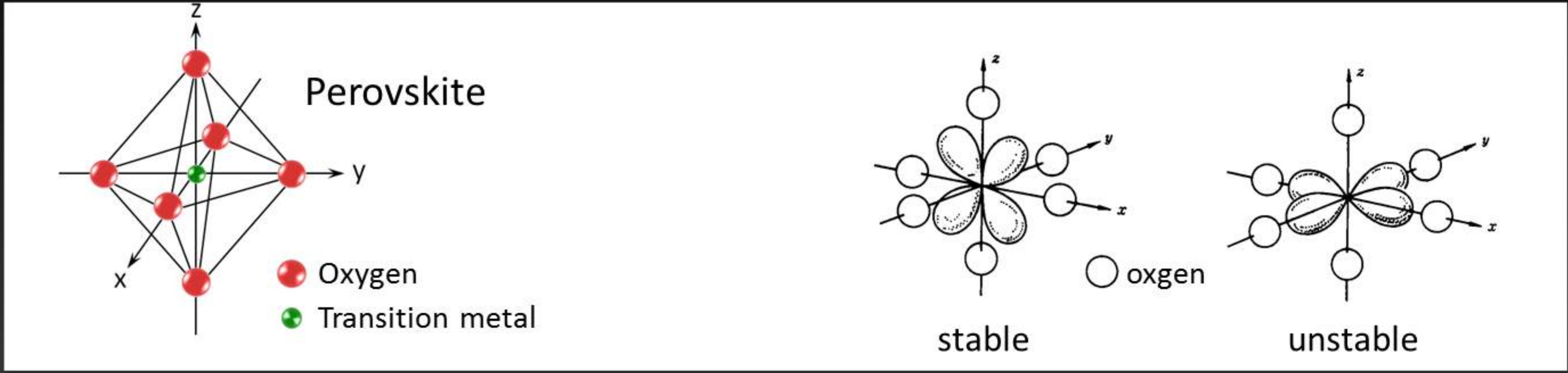
n_S=3.3 10 ^{14} cm^{-2}

Delugas *et al.*, PRL **106**, 166807 (2011)

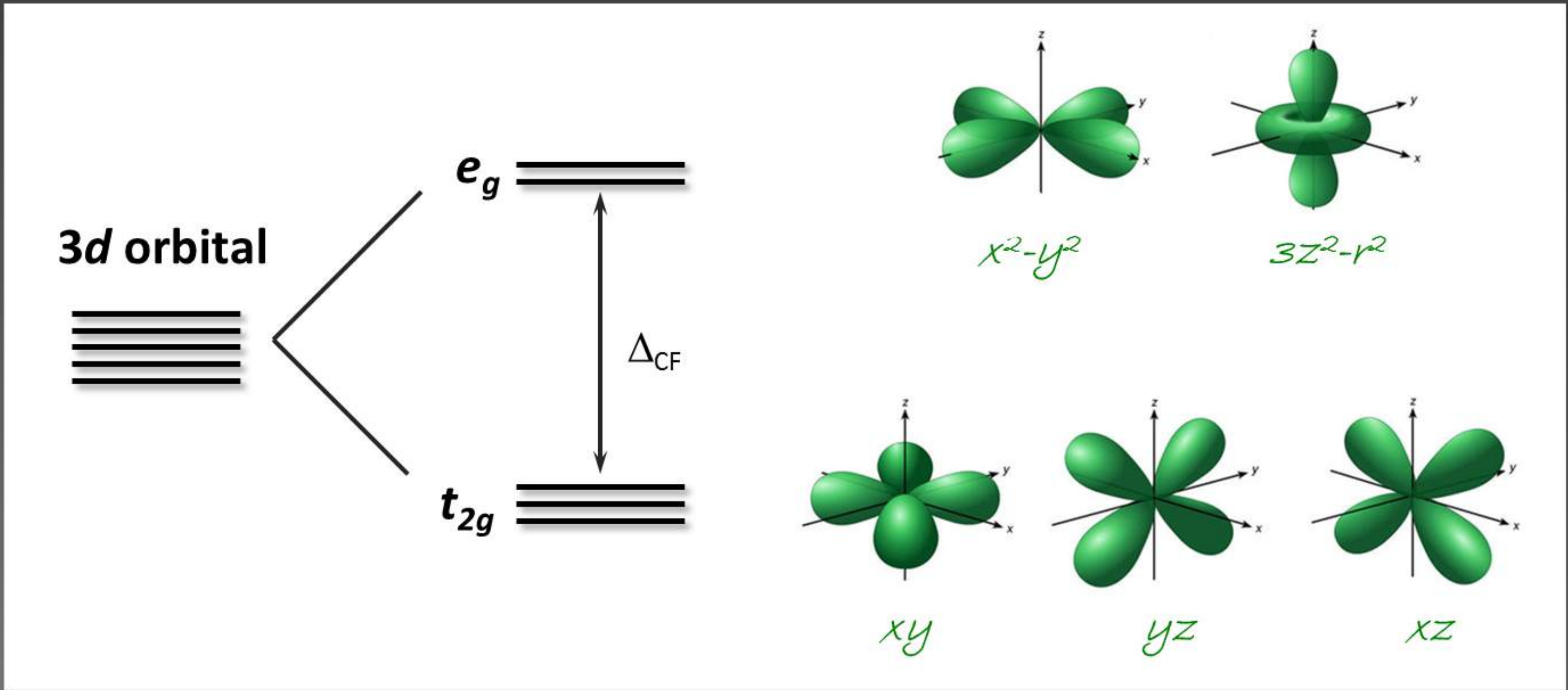
UNIVERSITÉ DE GENÈVE

MaNEP SWITZERLAND

t_{2g}-e_g splitting and crystal field



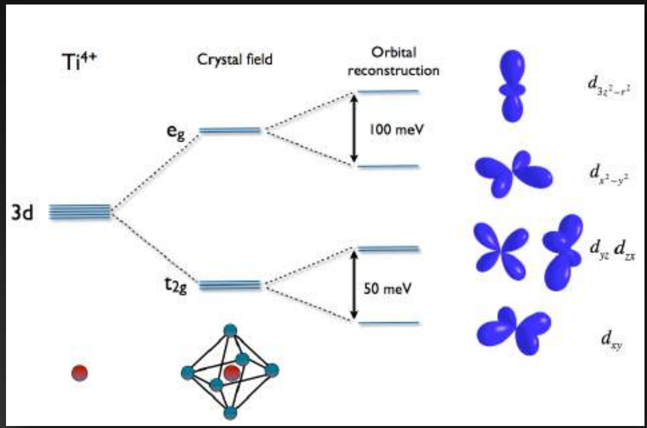
d-orbitals: t_{2g} e_g



UNIVERSITÉ DE GENÈVE

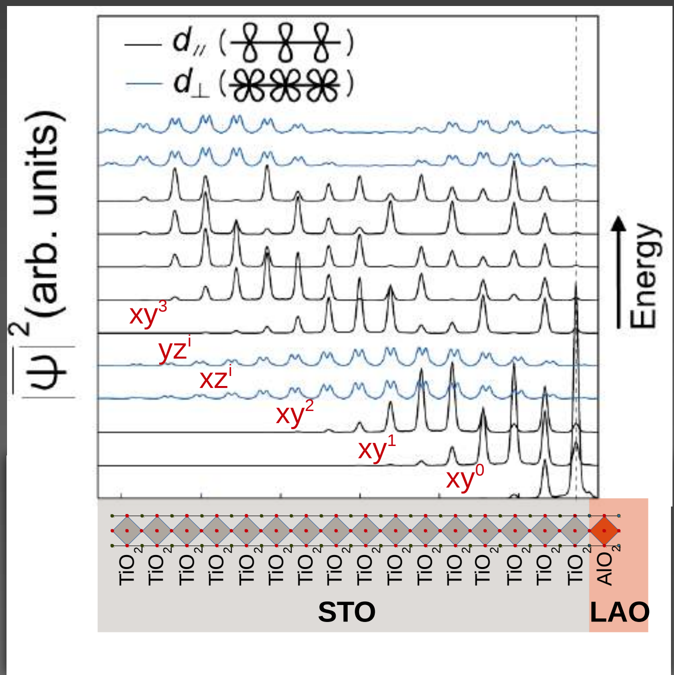
MaNEP SWITZERLAND

Confinement and electronic structure

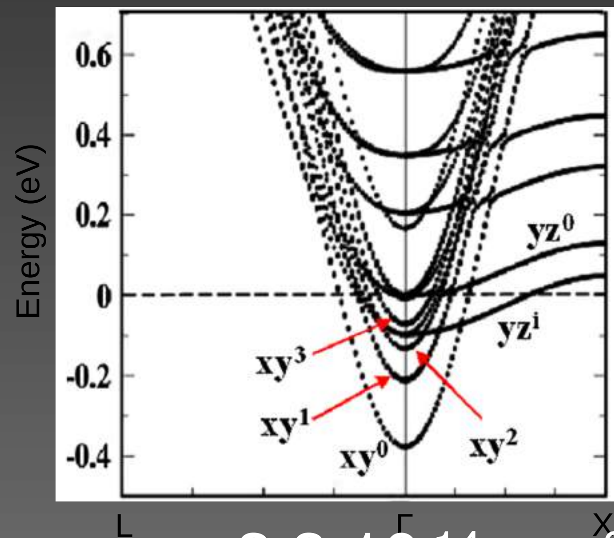


The electrons are
in the Ti 3d band -
in t_{2g} «orbitals»

M. Salluzzo *et al., PRL* **102**, 166804 (2009)



Son *et al.*, PRB **79**, 245411

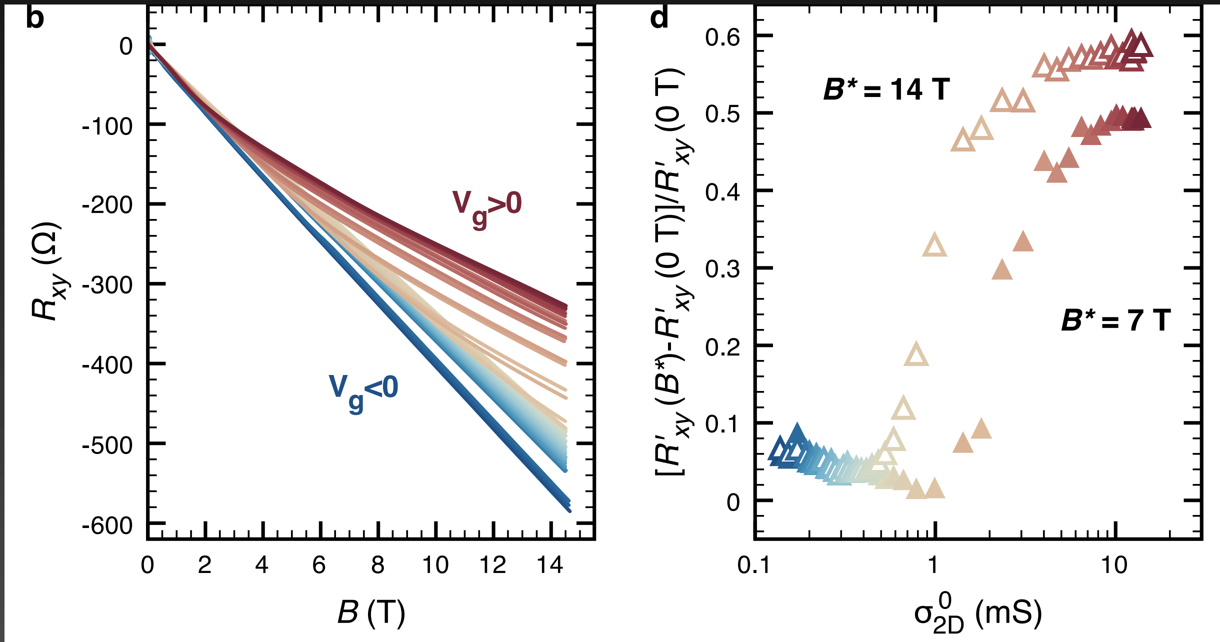


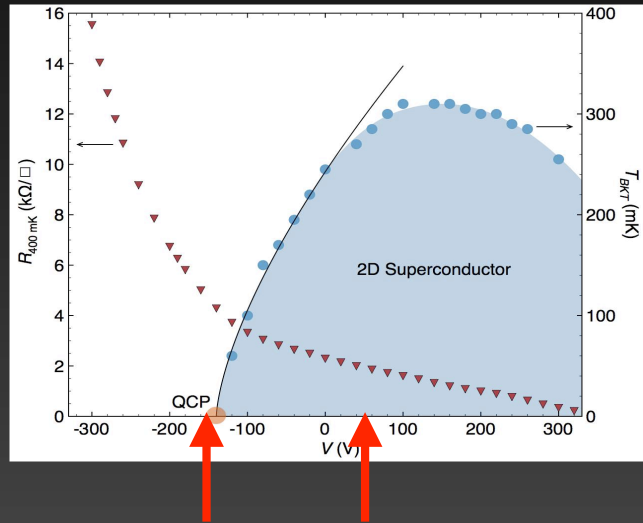
n_S=3.3 10 ^{14} cm^{-2}

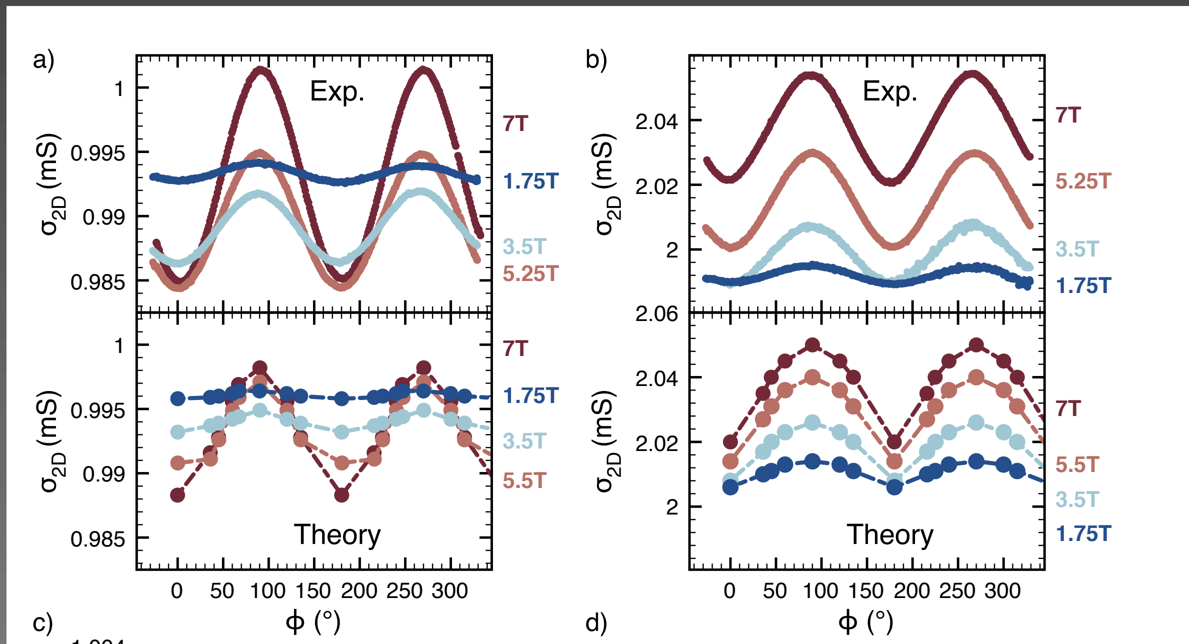
Delugas *et al.*, PRL **106**, 166807 (2011)

UNIVERSITÉ DE GENÈVE

Hall response and parallel field measurements







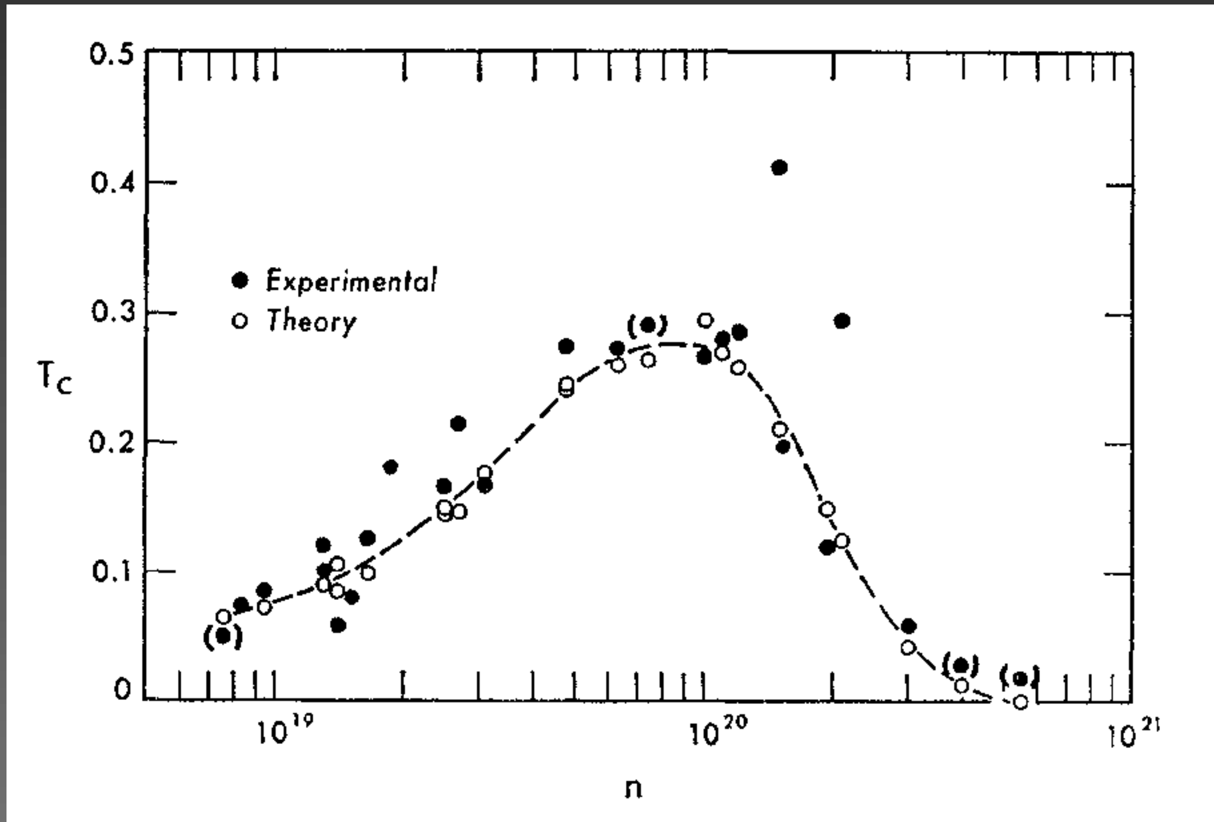
Bulk and Interface Superconductivity

Superconductivity in bulk $SrTiO_3$

PHYSICAL REVIEW VOLUME 163, NUMBER 2 10 NOVEMBER 1967

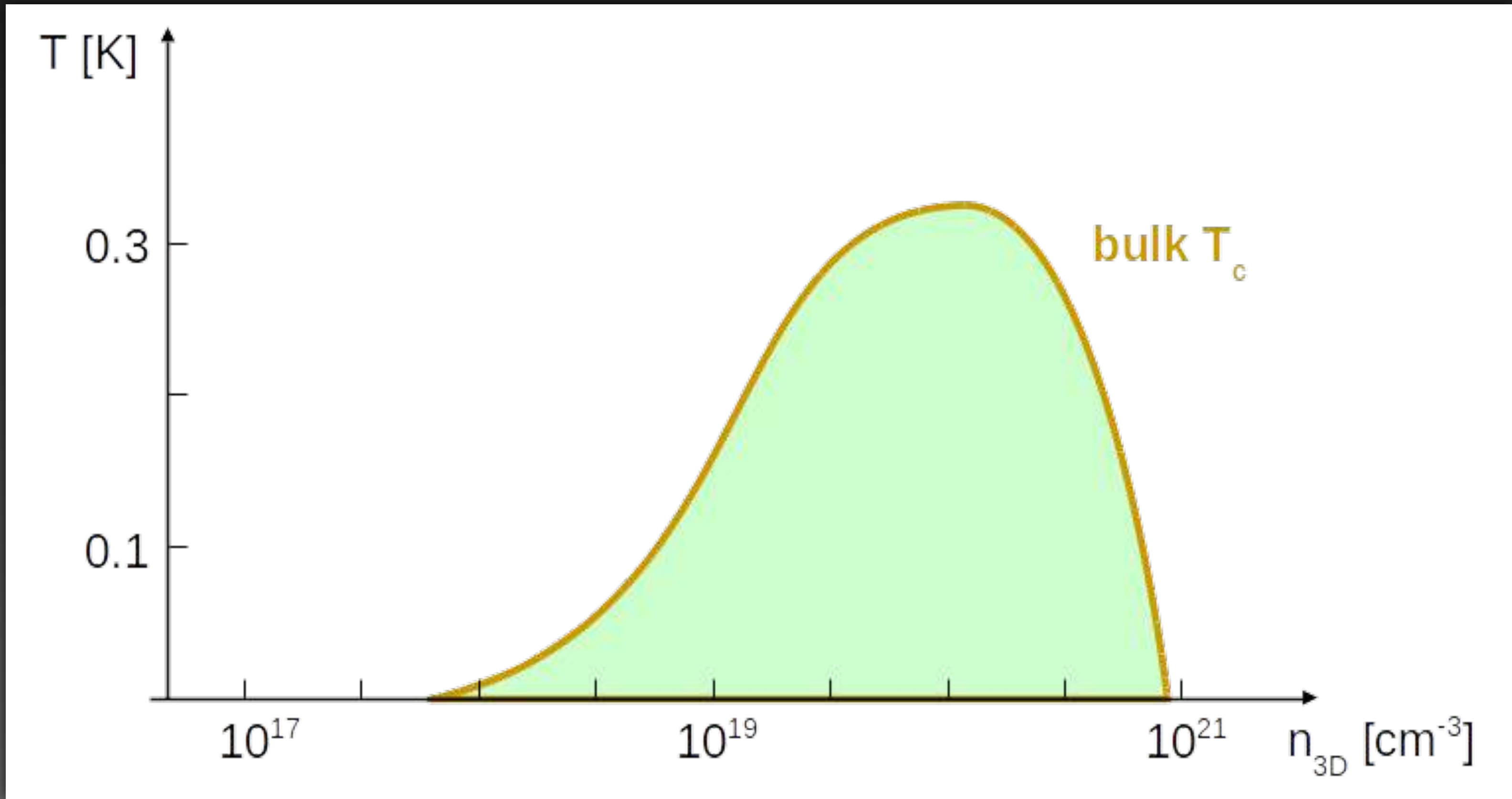
Superconducting Transition Temperatures of Semiconducting $SrTiO_3$

C. S. KOONCE* AND MARVIN L. COHEN†
Department of Physics, University of California, Berkeley, California
AND
J. F. SCHOOLEY,‡ W. R. HOSLER,§ AND E. R. PFEIFFER
National Bureau of Standards, Washington, D. C.
(Received 5 July 1967)

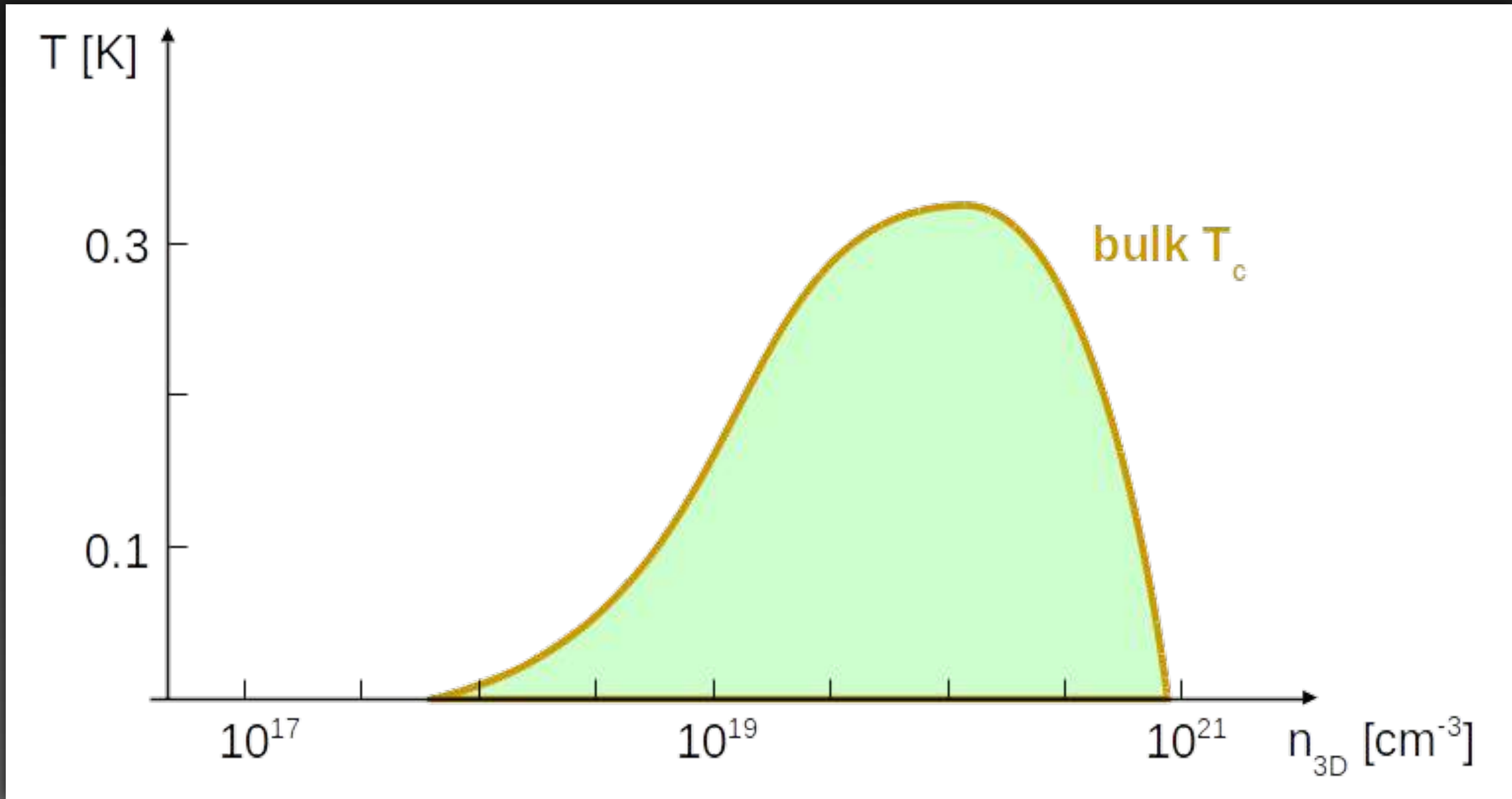


See also X. Lin et al. PRL **112**, 207002 (2014)

Bulk and interface SC



Bulk and interface SC

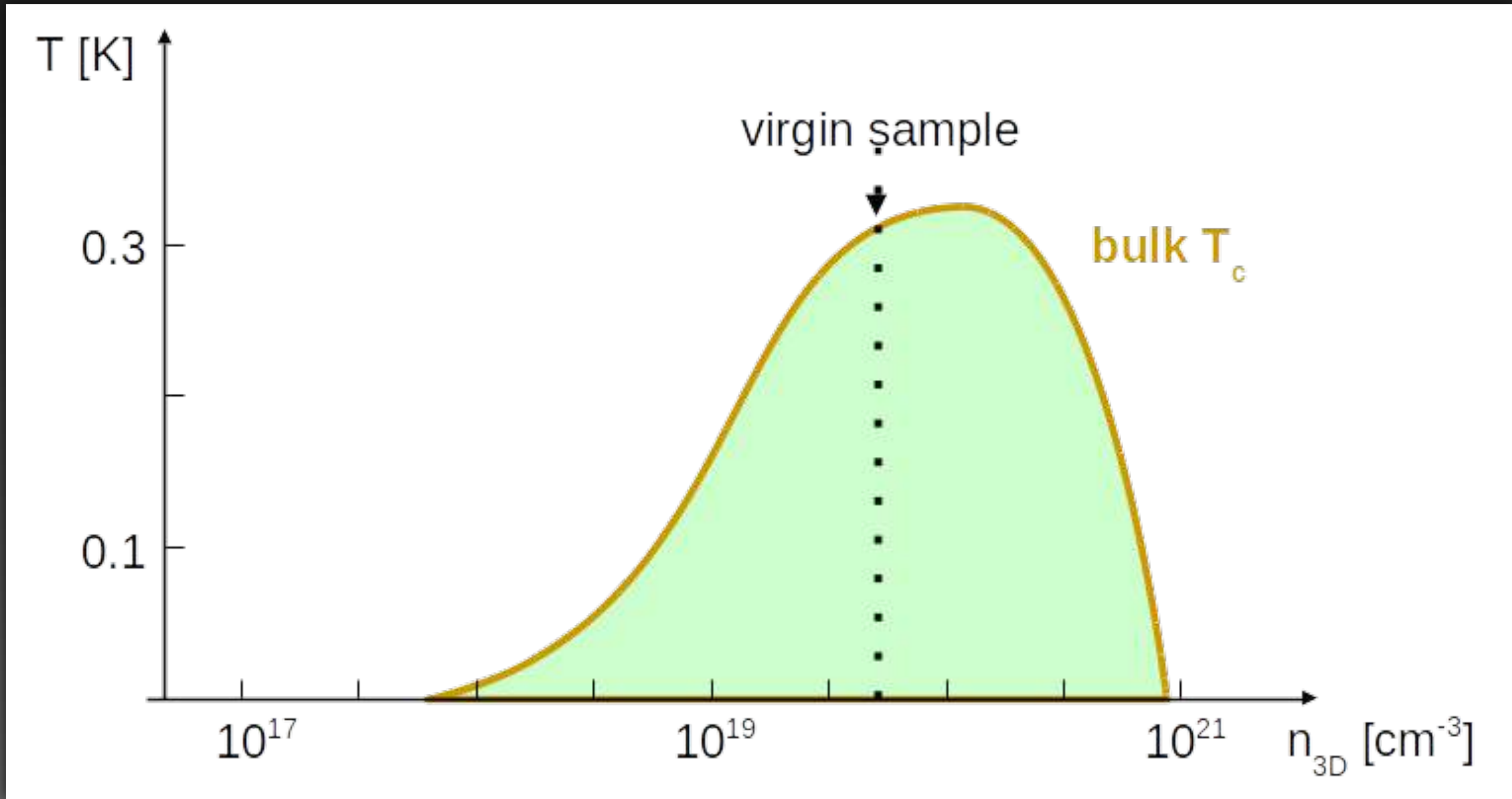


$n_{3D}=n_{2D}/d$

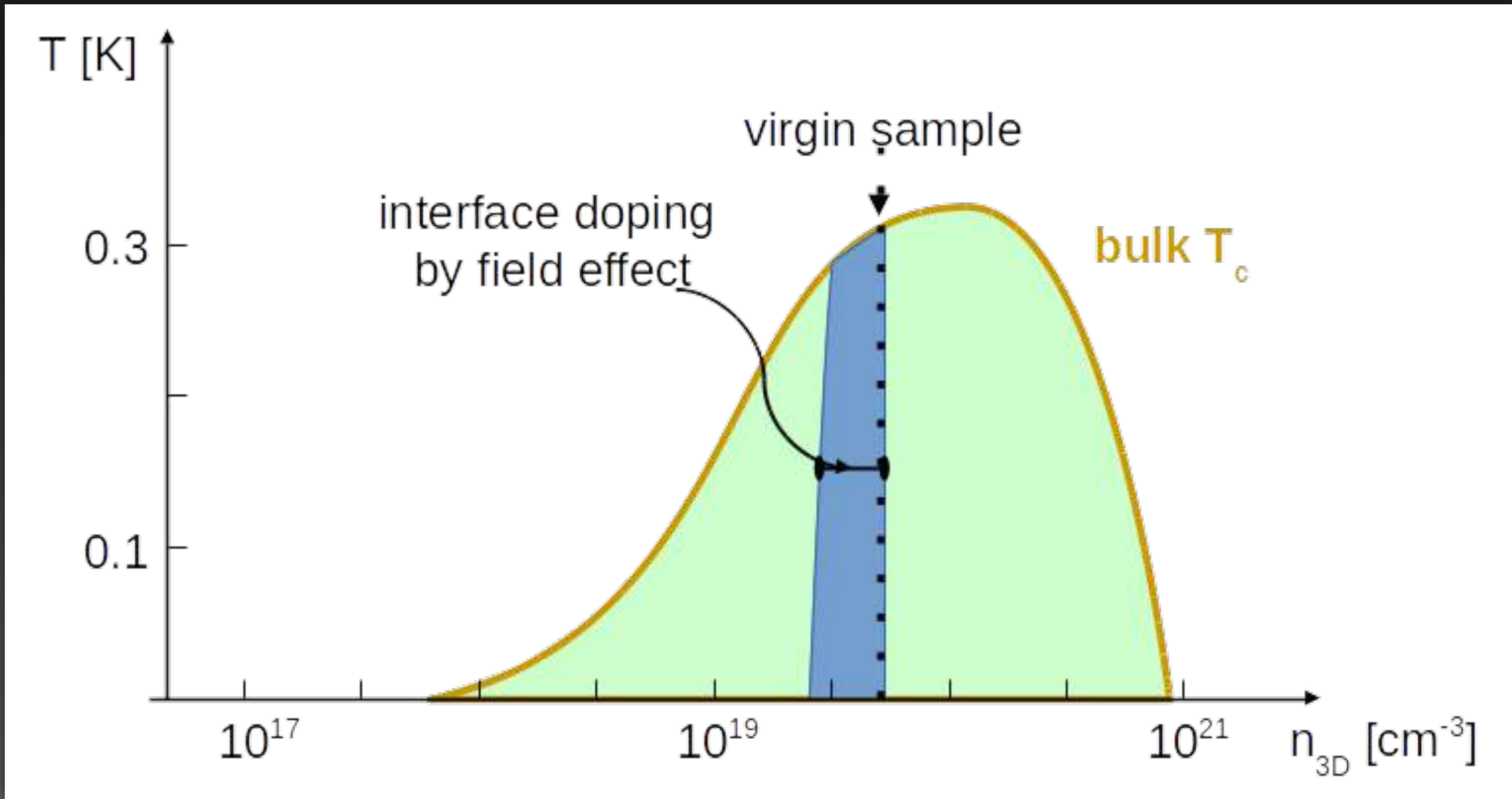
Virgin: $n_{2D}=3\ 10^{13}\ cm^{-2}$

$d=10nm$

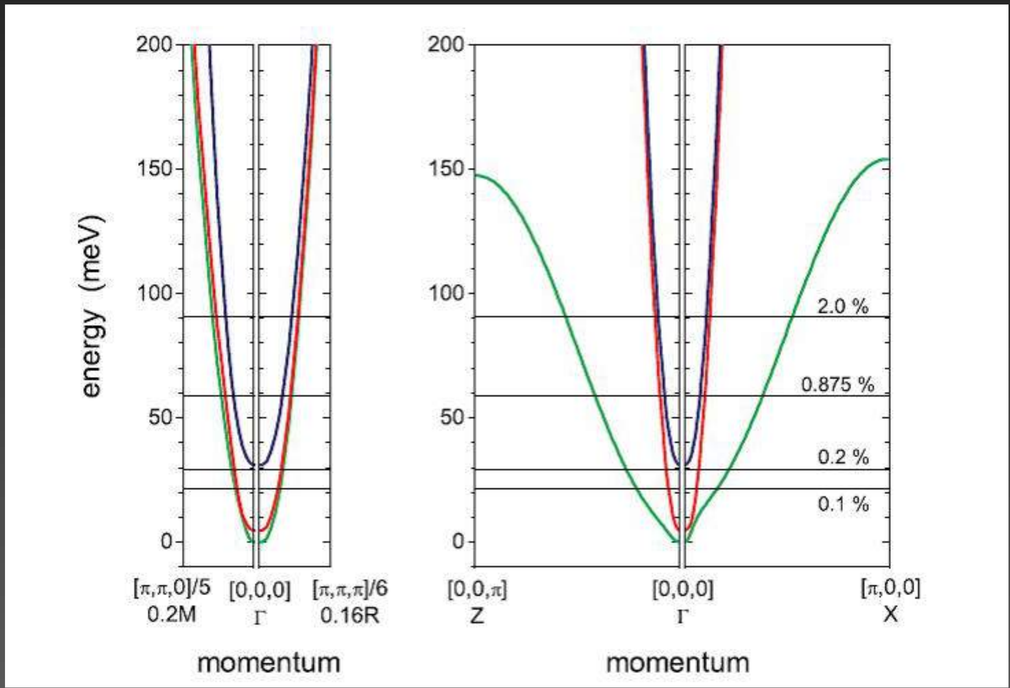
Bulk and interface SC



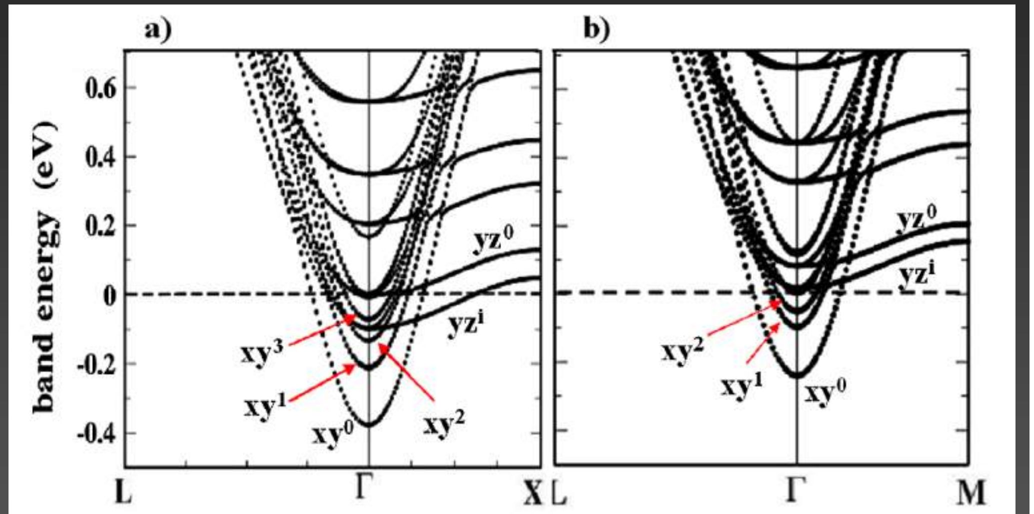
Bulk and interface SC



Quantum confinement
Role of the d_{xz}, d_{yz} subbands



Bulk: D. van der Marel et al.
PRB 84, 205111 (2011)



n_s=3.3 10 ^{14} cm^{-2} ← n_{2D}

Delugas *et al.*, PRL **106**, 166807 (2011)

T_c goes as exp(-1/(N(0)V))

UNIVERSITÉ DE GENÈVE

MaNEP SWITZERLAND

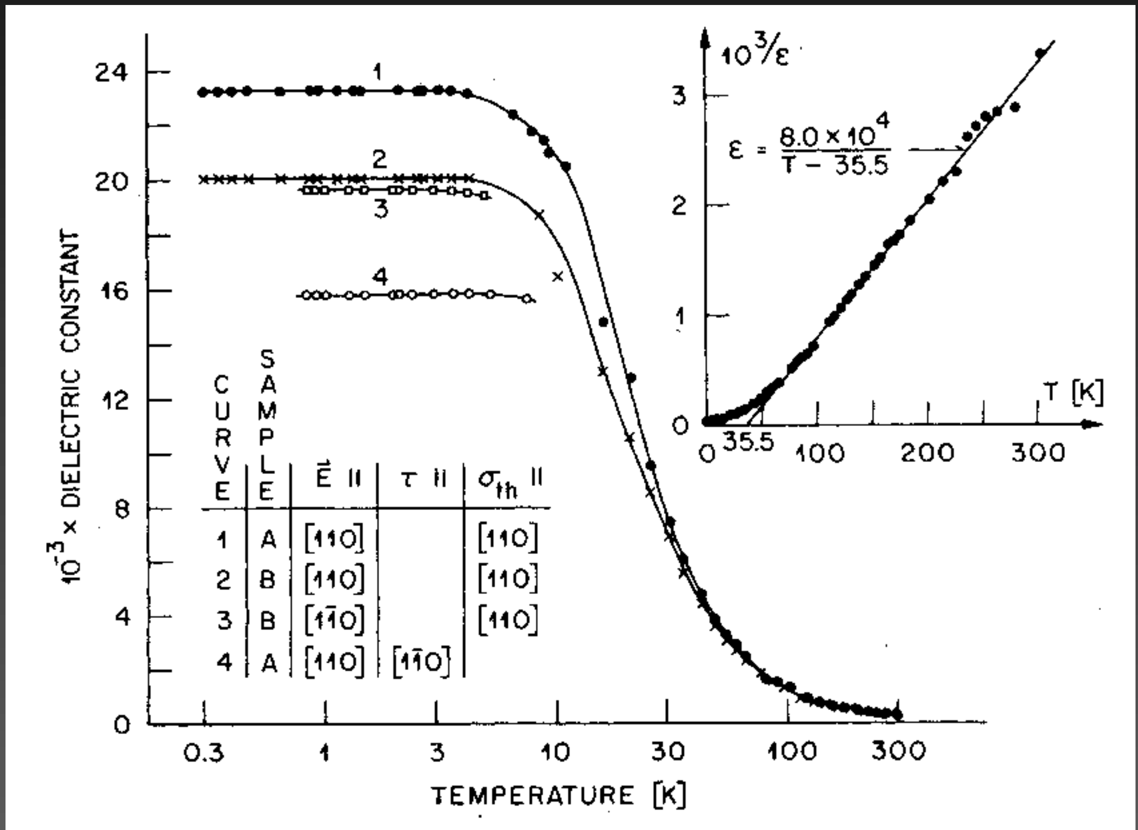
Open questions:

Superconductivity in $SrTiO_3$

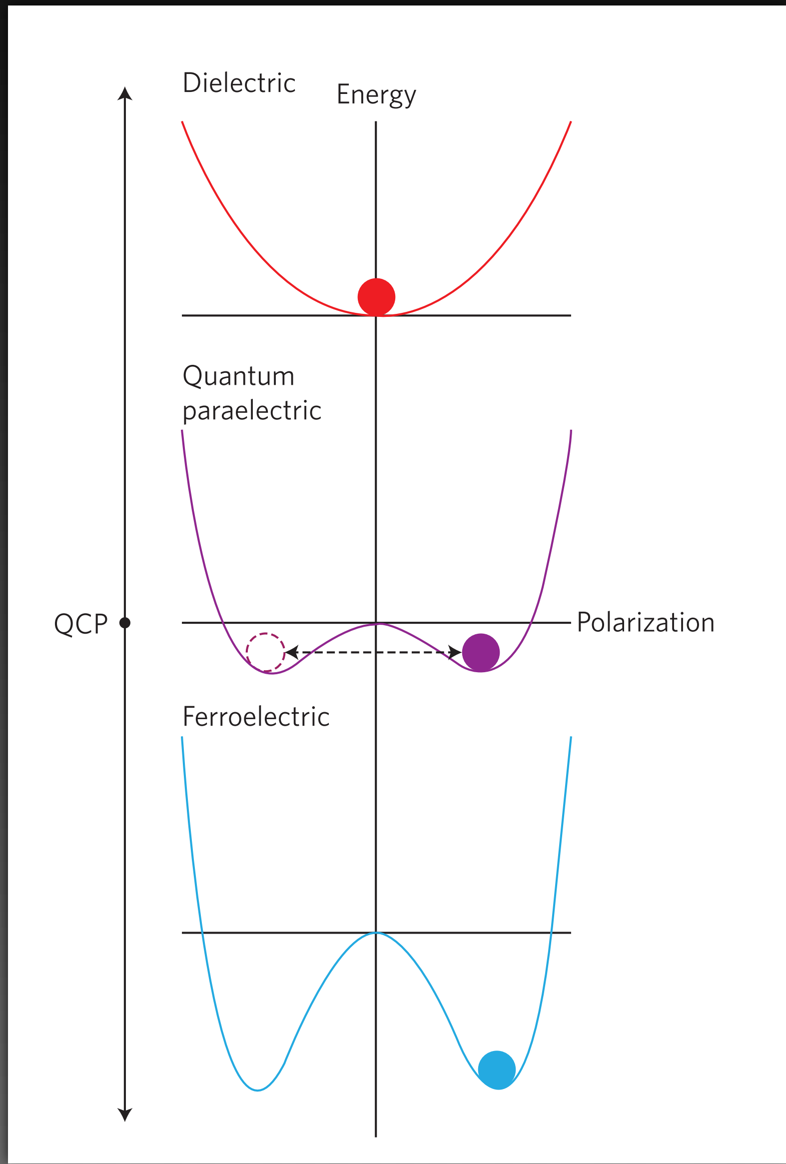
The Possible Role of Spin-orbit

The Underdoped Regime

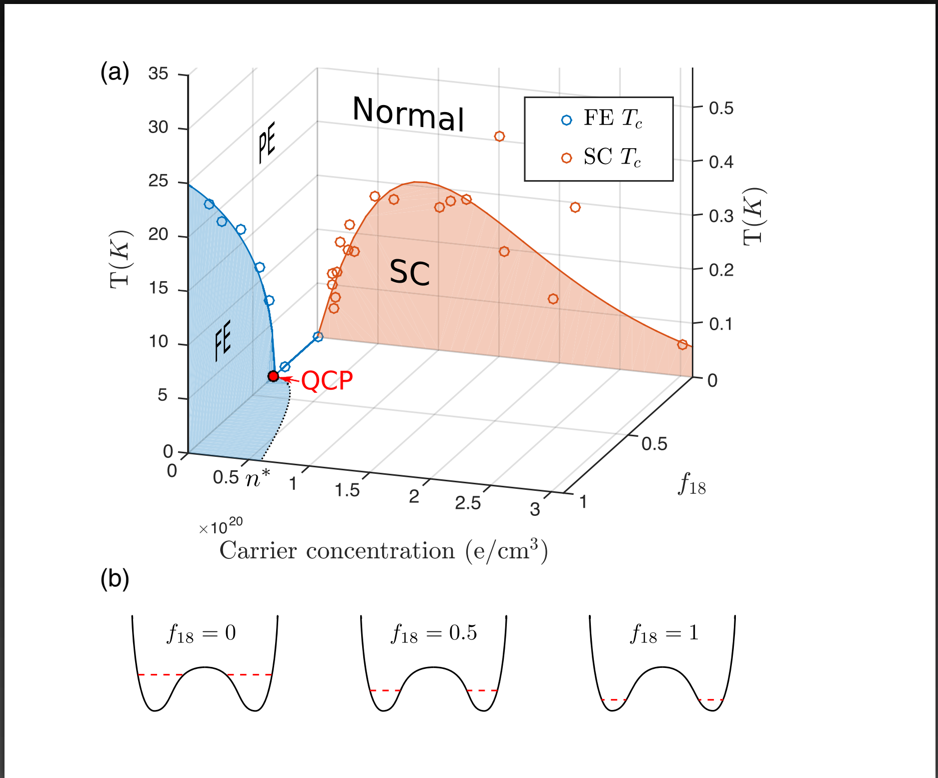
$SrTiO_3$ - a quantum paraelectric

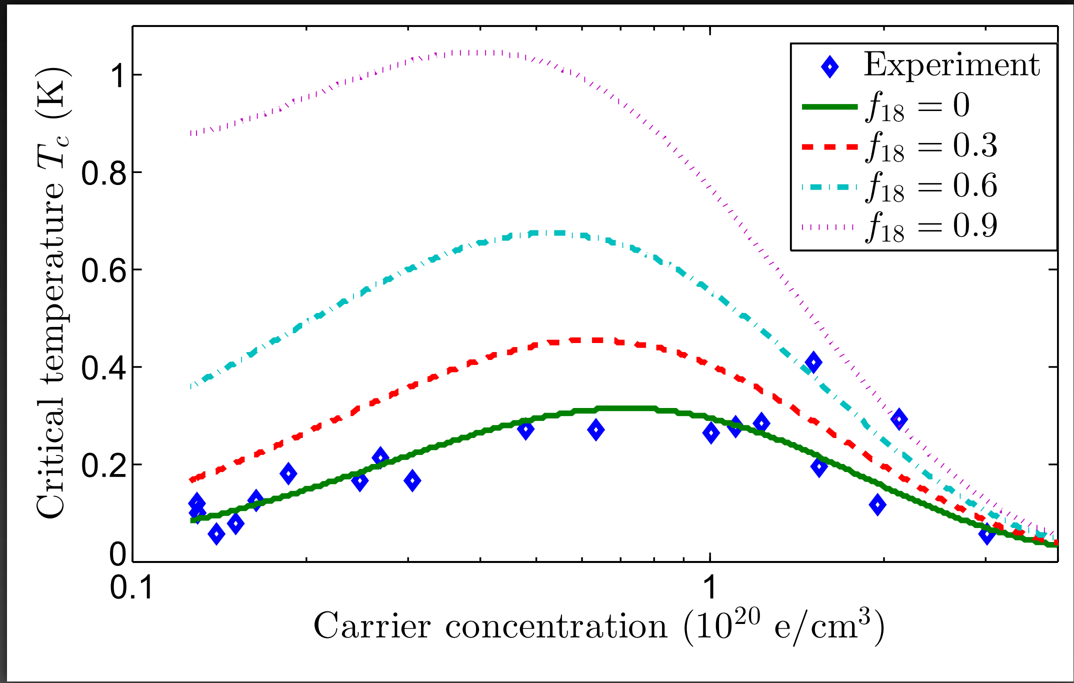


K.A. Müller and H. Burkard PRB **19**, 3593 (1979)



Role of the ferroelectric soft mode





O^{18} for O^{16}

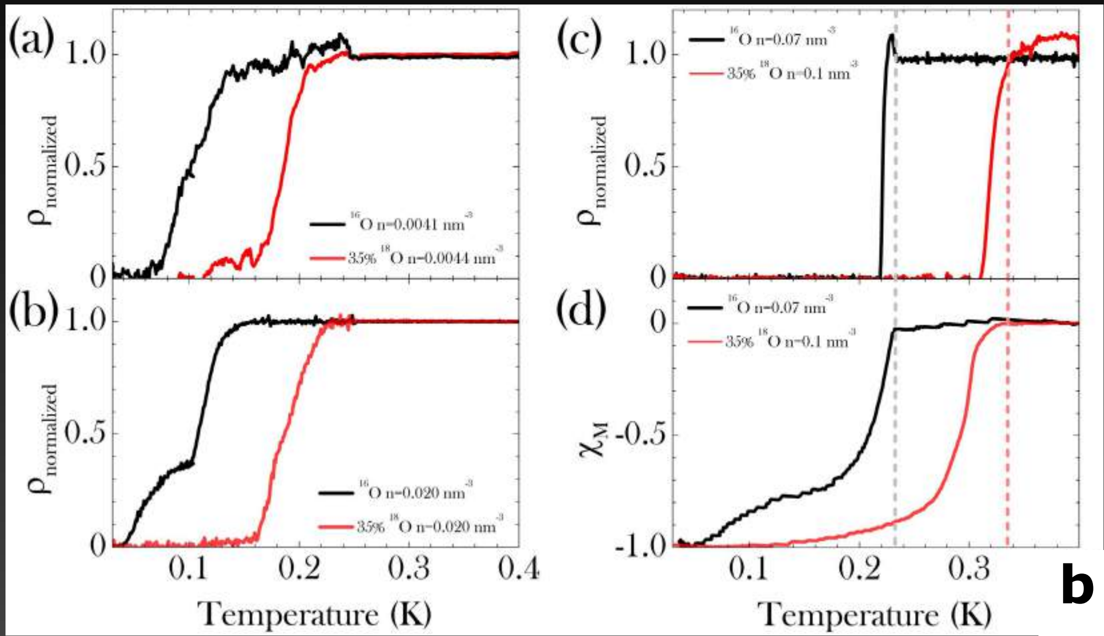
$$\lambda = \int_0^\infty \alpha^2(\omega)F(\omega)\frac{d\omega}{\omega}, \quad \lambda = \alpha^2 \frac{1}{\omega_{\mathbf{q}=0}(f_{18}, E_F)},$$

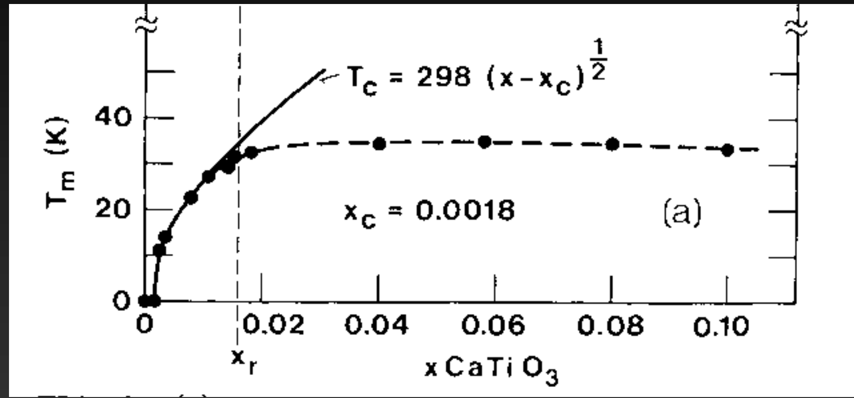
J.M. Edge et al. PRL **115**, 247002 (2015)

UNIVERSITÉ DE GENÈVE

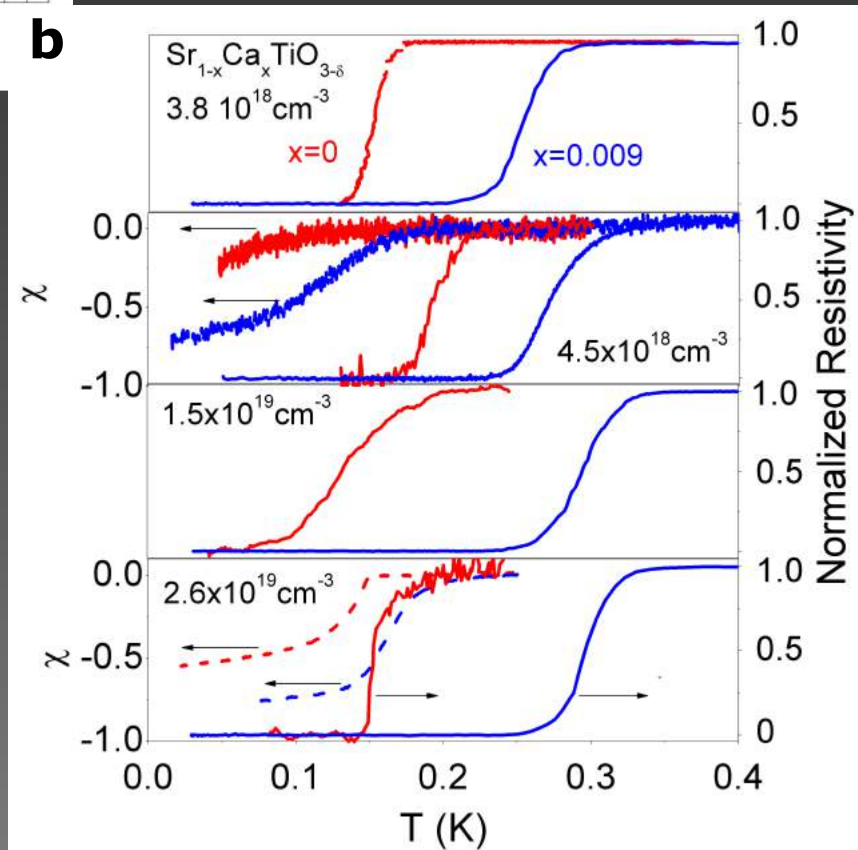
O^{18}-O^{16}

Ca-doped





J.G. Bednorz and K.A. Müller
PRL 52, 2289 (1984)



A. Stucky et al. Scientific reports **6**, 37582 (2016) - O^{18} doped $SrTiO_3$

C.W. Rischau et al. Nature Physics 2017 - Ca-doped $SrTiO_3$

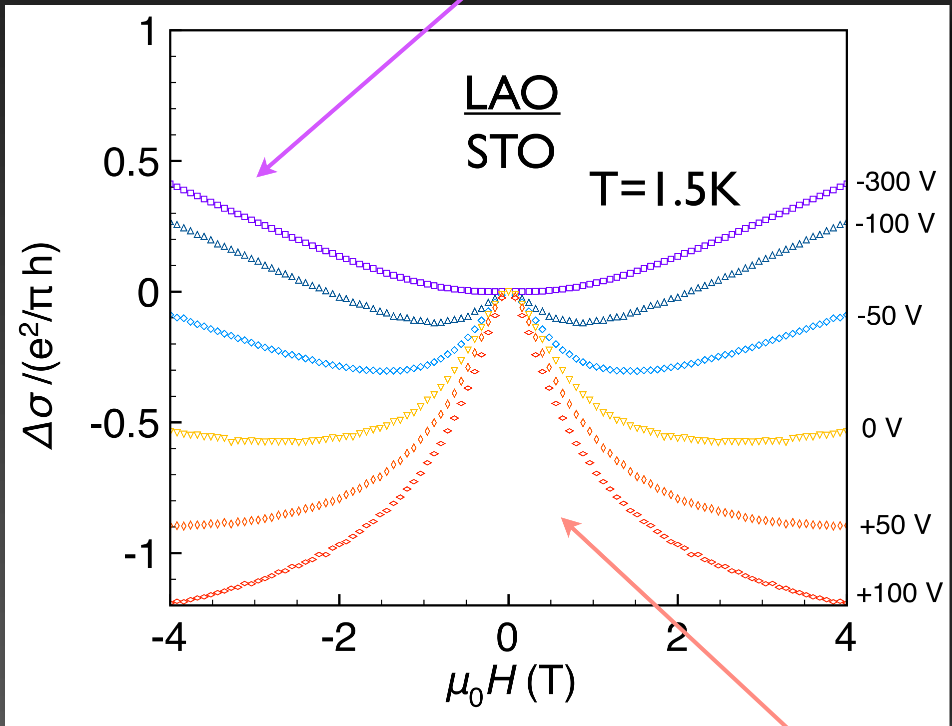
M. Gabay and J.-M. Triscone
N&V Nature Physics 2017

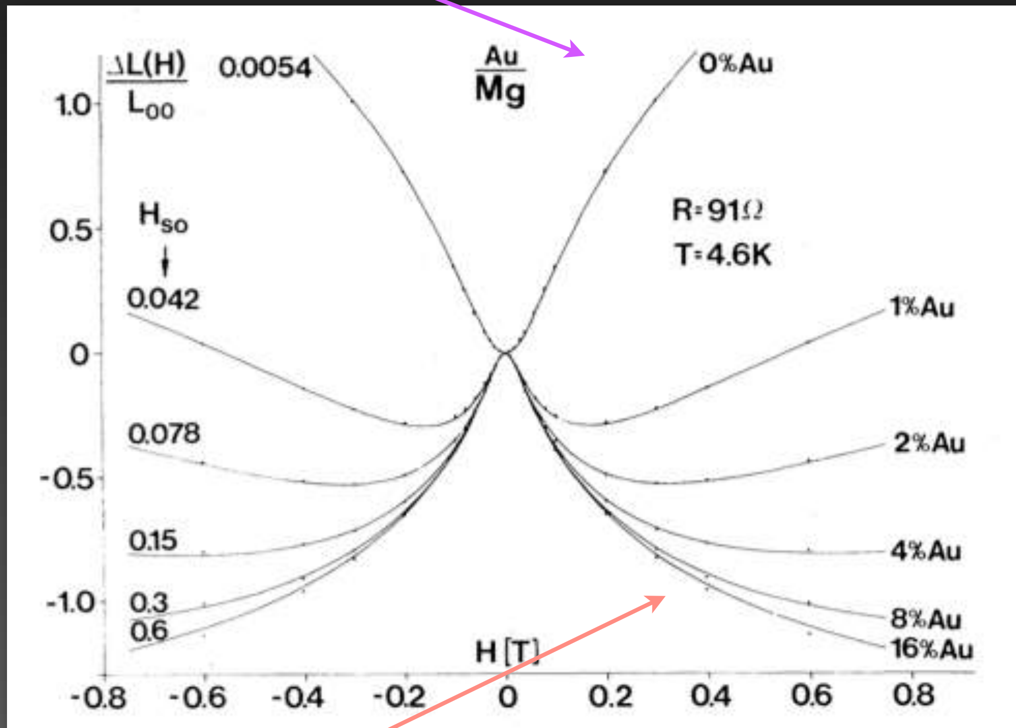
UNIVERSITÉ DE GENÈVE

Breaking of Inversion Symmetry and Spin-orbit Coupling

Weak localization - weak antilocalization

Weak localization





A.D. Caviglia et al., Phys. Rev. Lett. **104**, 126803 (2010)

G. Bergman, Phys Rev Lett **48**, 1046 (1982)

Weak anti-localization

Strong spin-orbit interaction

UNIVERSITÉ DE GENÈVE

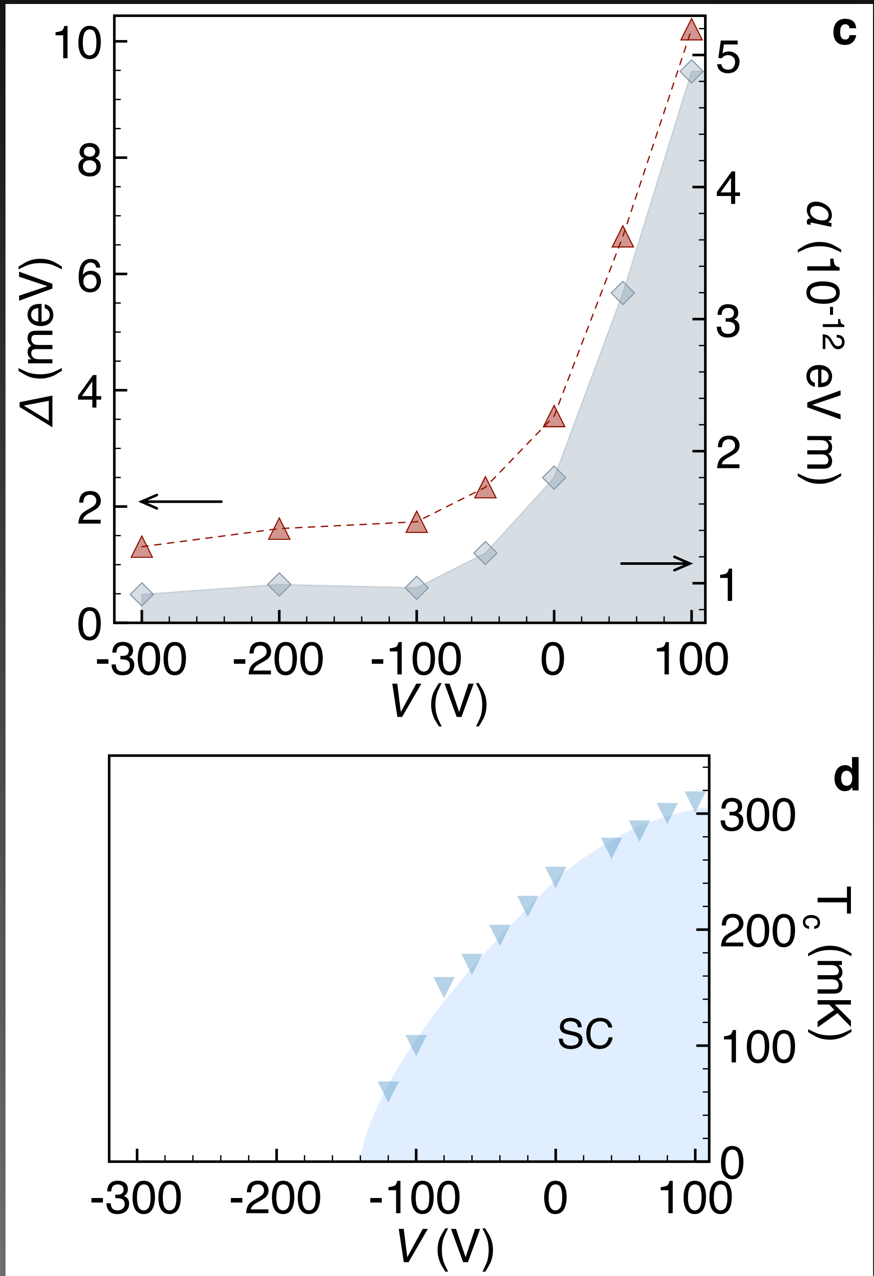
MaNEP SWITZERLAND

Very large tunable spin-orbit coupling

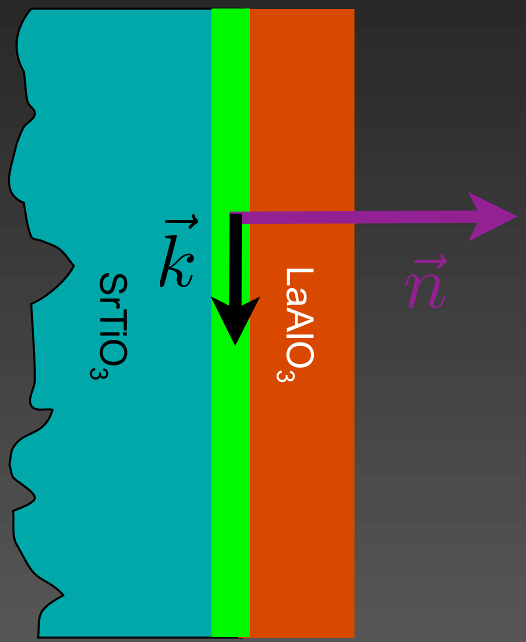
$$\alpha = \frac{\hbar}{m}\sqrt{\frac{\hbar e H_{\rm so}}{2}}$$

$$\Delta = 2\alpha k_F$$

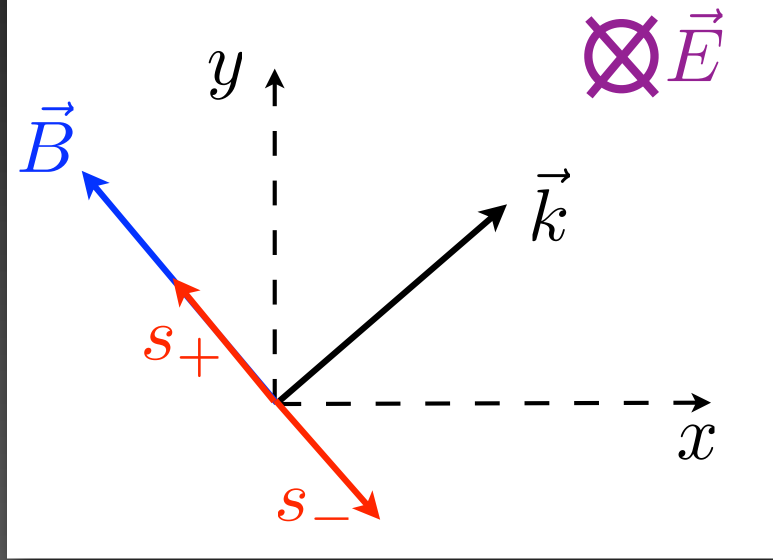
Δ=10meV is much larger than the SC gap (~40μeV)



Rashba Spin-Orbit Coupling

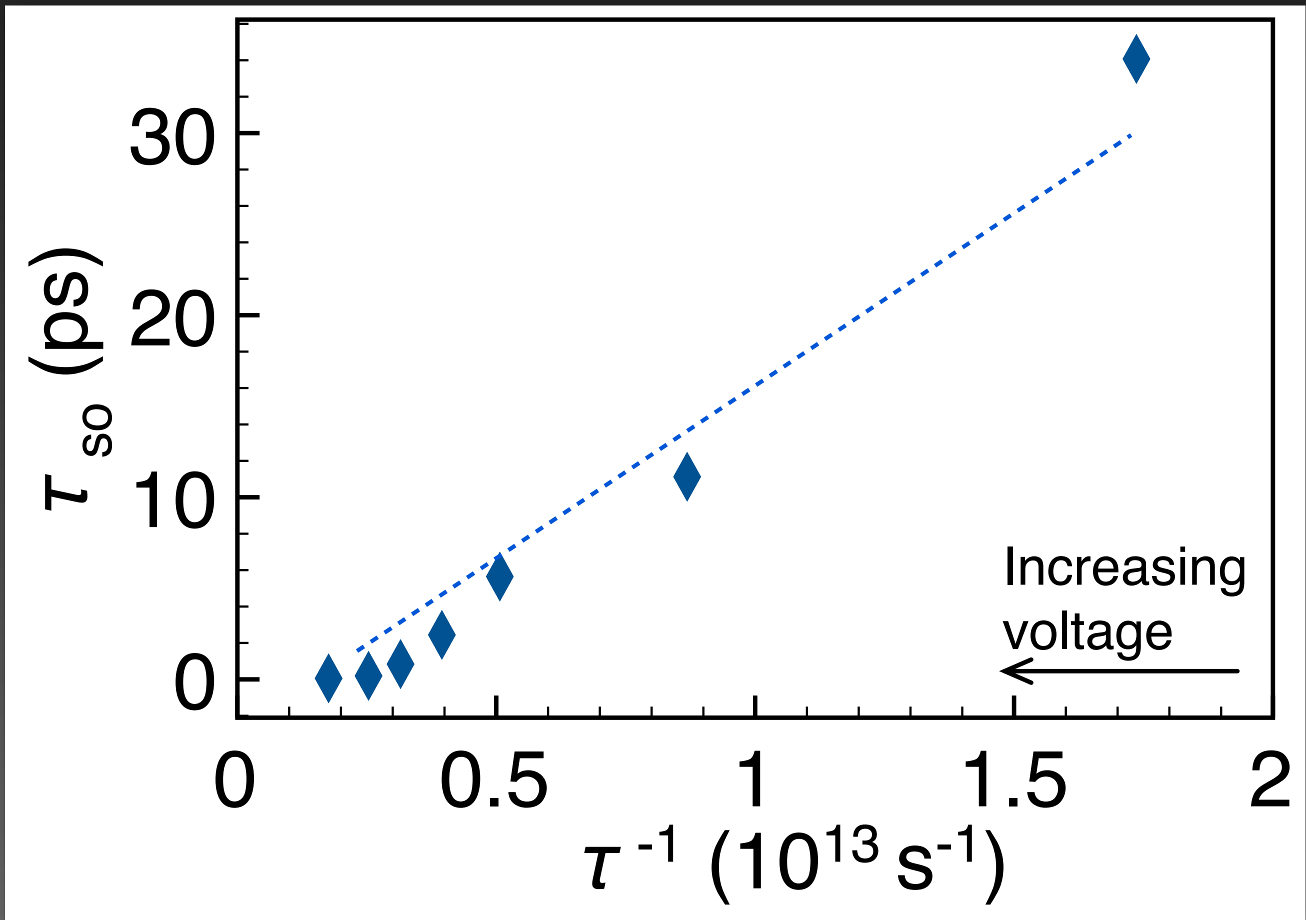


$$H_R = \alpha(\vec{k} \wedge \vec{n}) \cdot \vec{\sigma}$$



The electrons experience an internal magnetic field oriented in the 2DEL plane

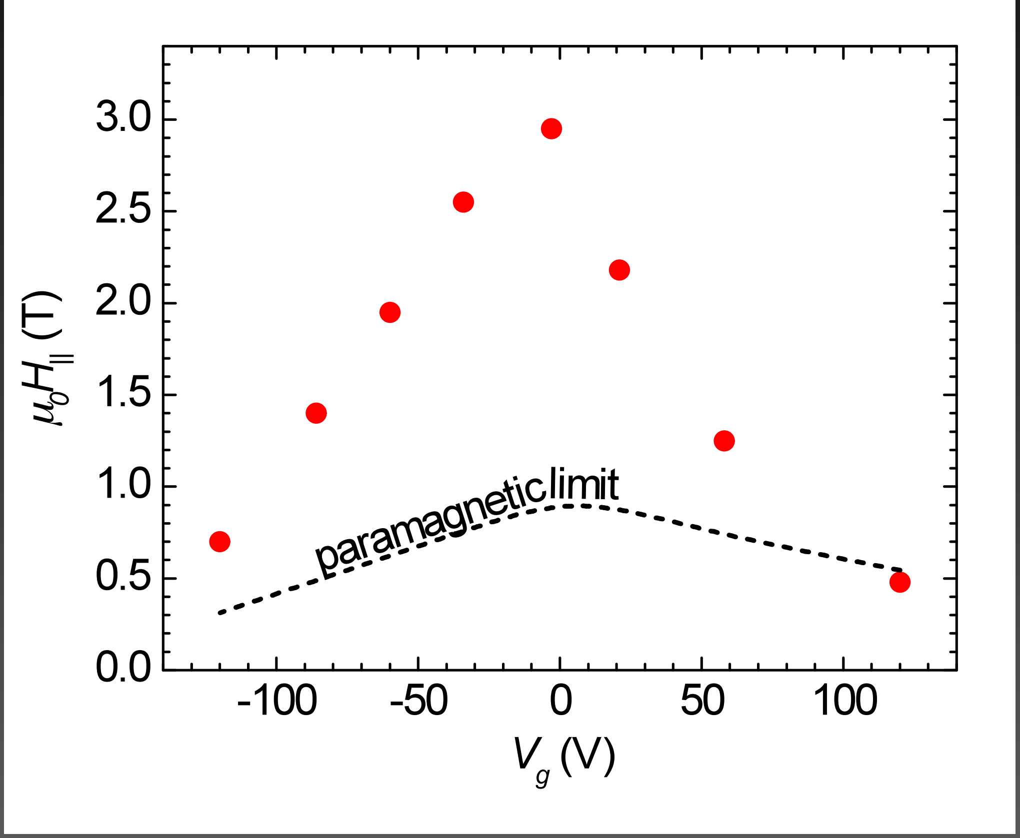
Rashba spin-orbit coupling



D'yakonov - Perel'

$$\tau_{\mathrm{so}} \propto \tau^{-1}$$

Signatures of spin-orbit coupling

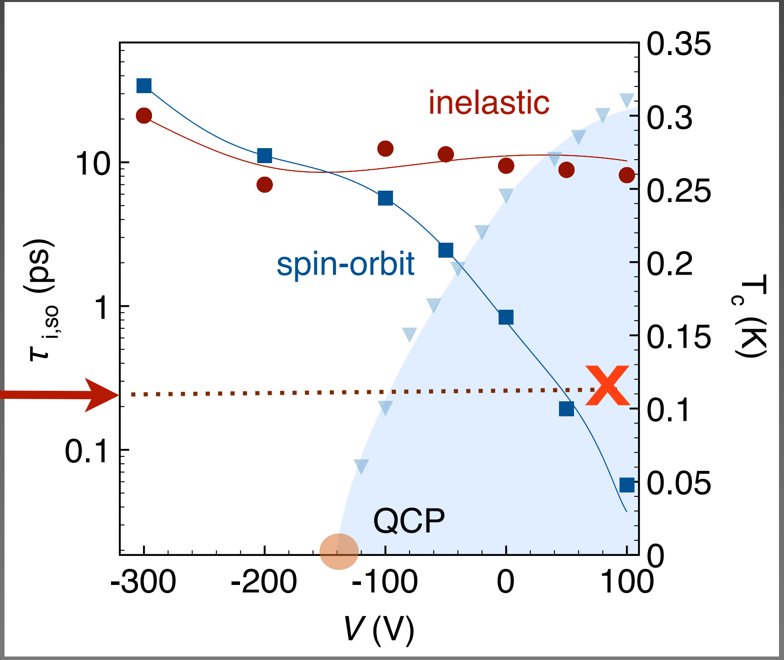


$$\mu_0 H_p = \frac{\Delta(0)}{\sqrt{2}\mu_B} = 1.84 T_c$$

$$\tau_{so} = 0.602^2 \hbar^2 / (T_{co} k_B)(H_p / H_{co})^2$$

R.A. Klemm et al. PRB 12, 877 (1975)

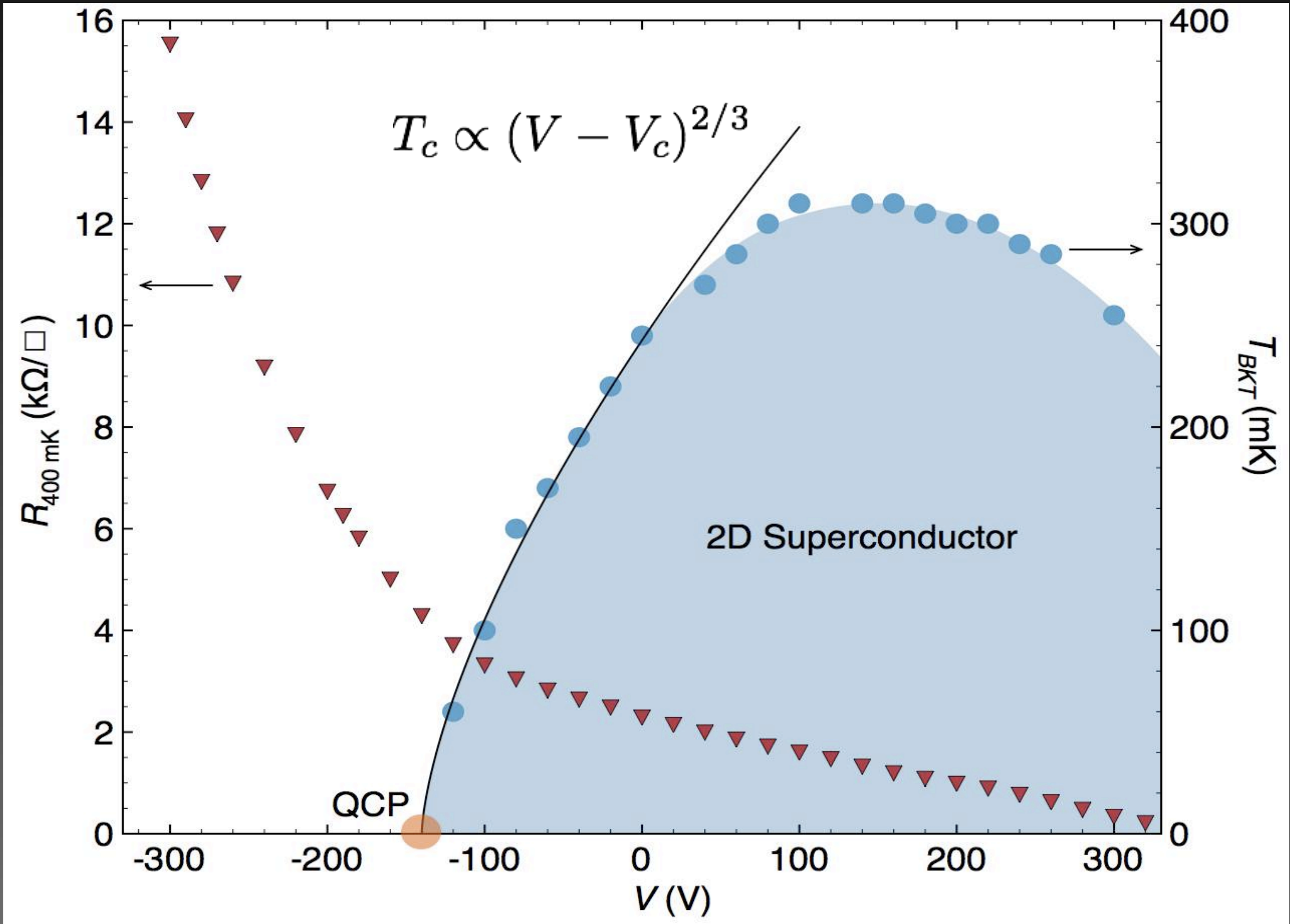
$\tau_{s0} = 2.4\ 10^{-13}$ s



See also M. Ben Shalom et al. PRL **104**, 126802 (2010)

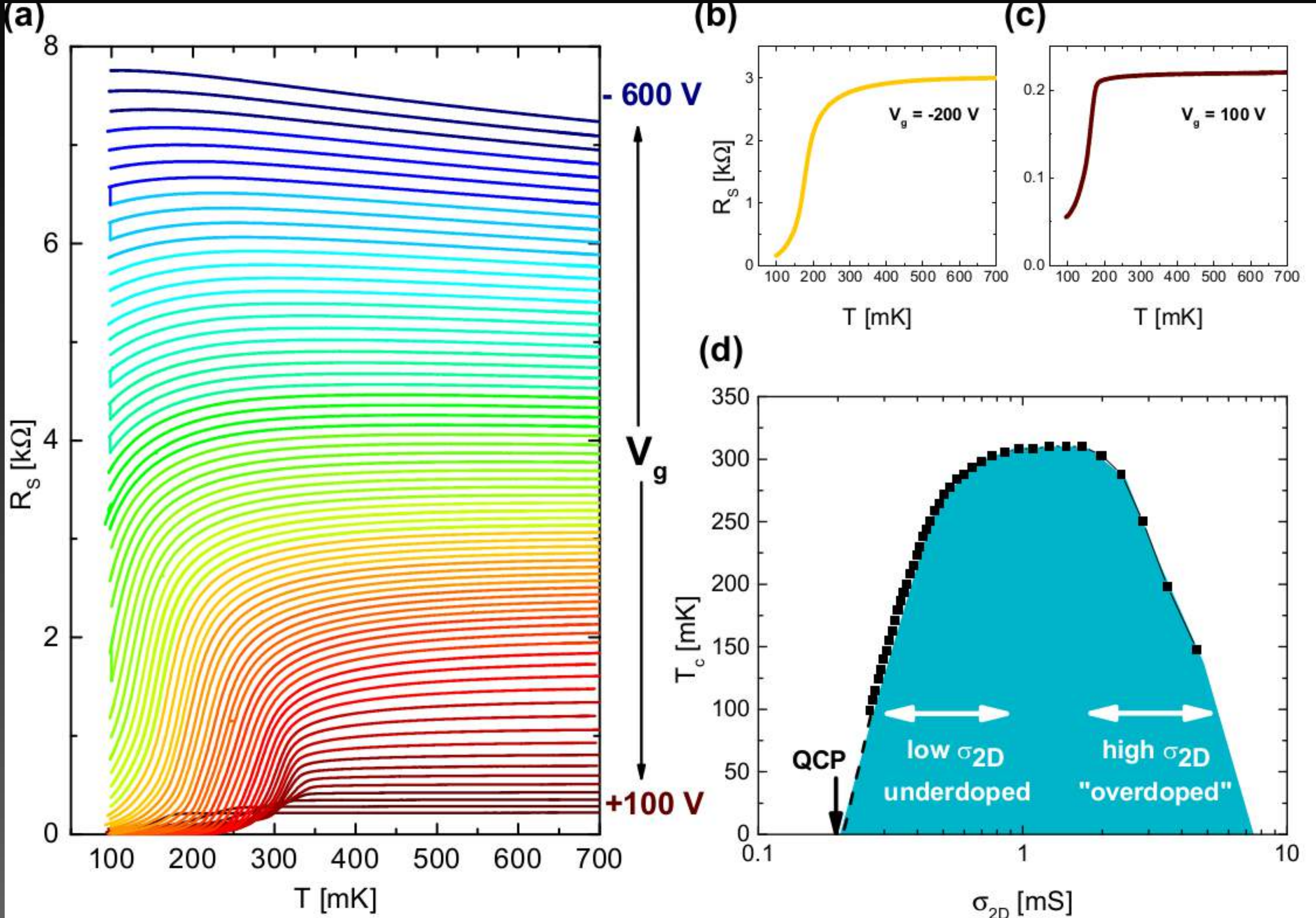
Tunneling Results and the Underdoped Regime

System phase diagram



See also C. Bell et al. PRL **103**, 226802 (2009).

UNIVERSITÉ DE GENÈVE

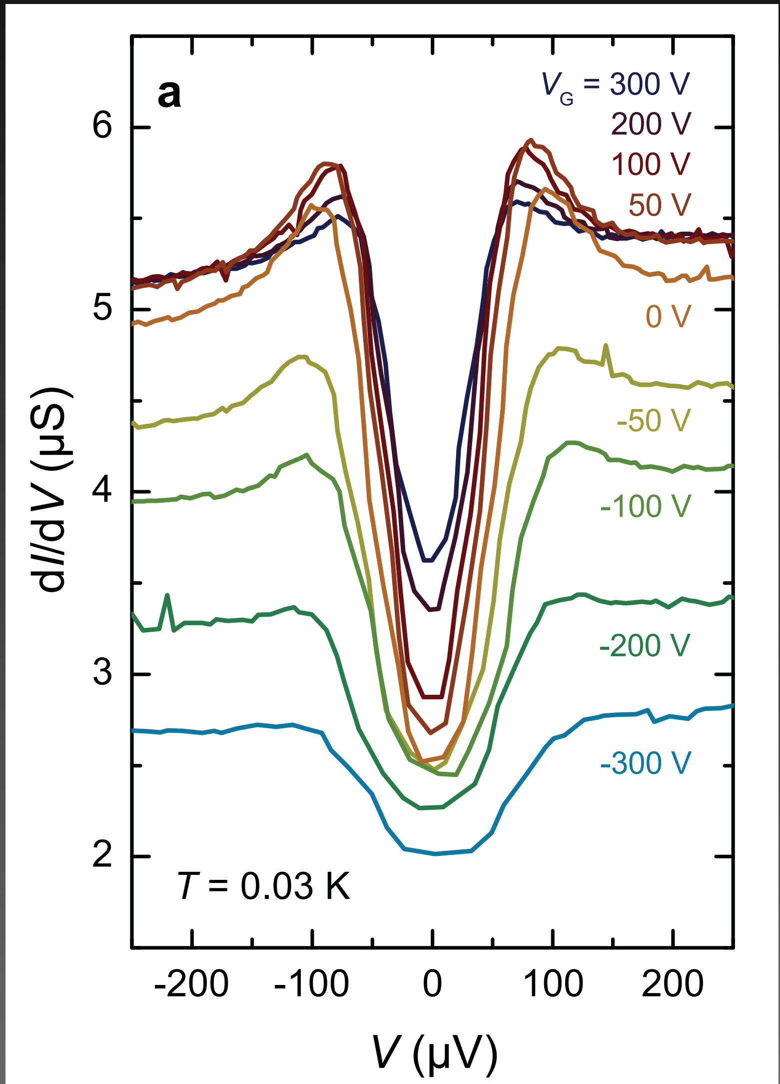


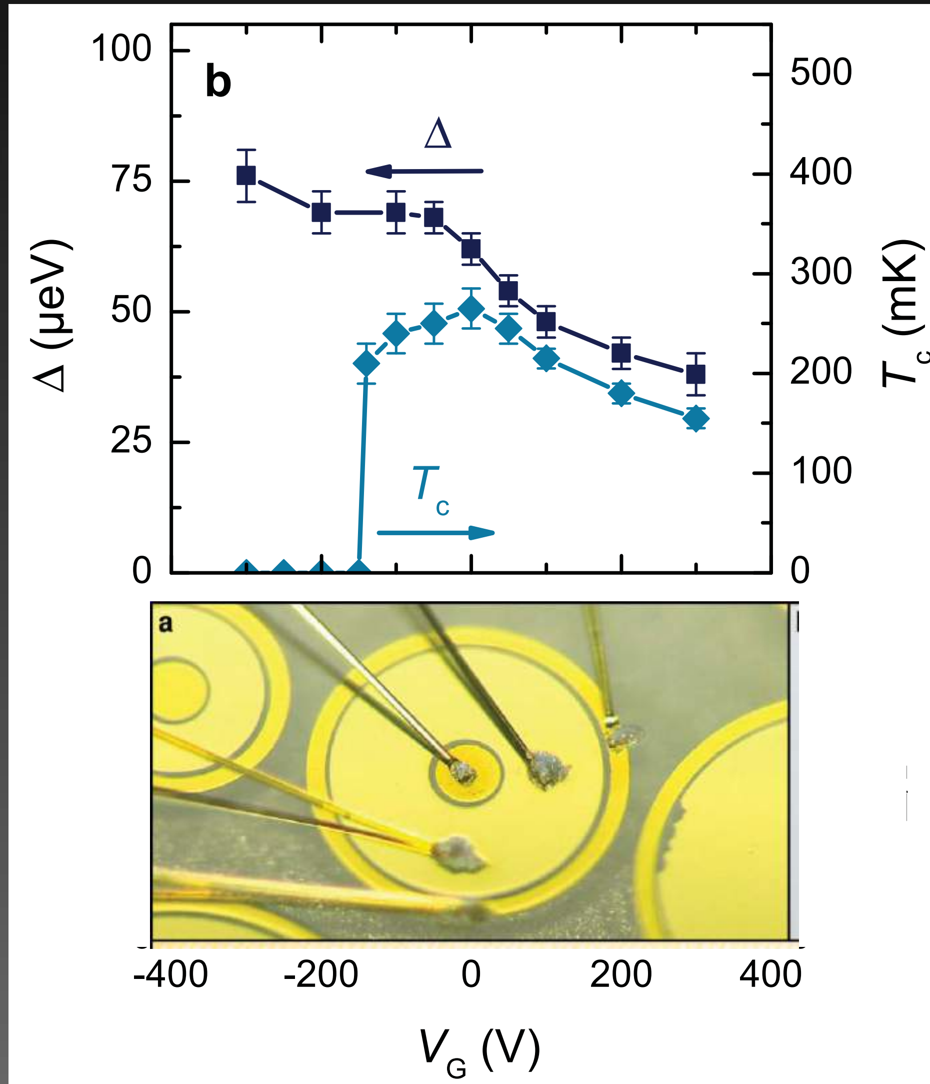
S. Gariglio et al. APL Mat. 4, 060701 (2016)

See also C. Bell et al. PRL 103, 226802 (2009)

In $LaTiO_3/SrTiO_3$ J. Biscaras et al. PRL 108, 247004 (2012)

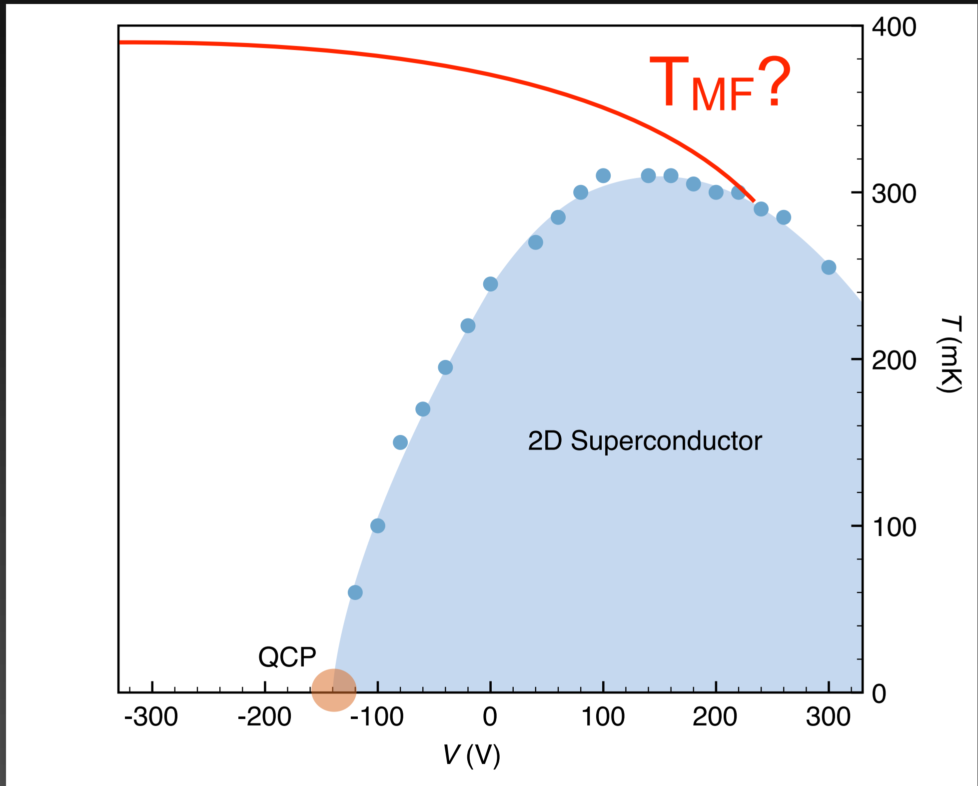
S-I-N tunneling measurements





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

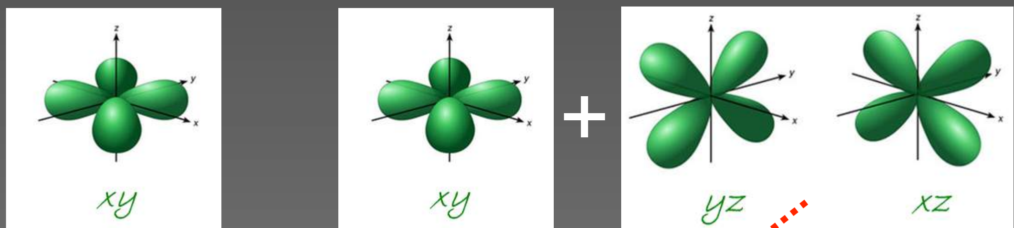
How to understand the data - BKT ?



Kosterlitz-Thouless

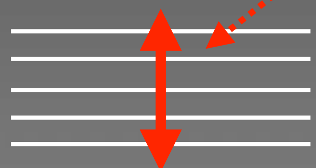
$$k_B T_{KT} = \frac{\Phi_0^2}{32\pi^2} \frac{d}{\lambda^2}$$

M. R. Beasley, J.E. Mooij, T.P. Orlando, PRL **42**, 1165 (1979)



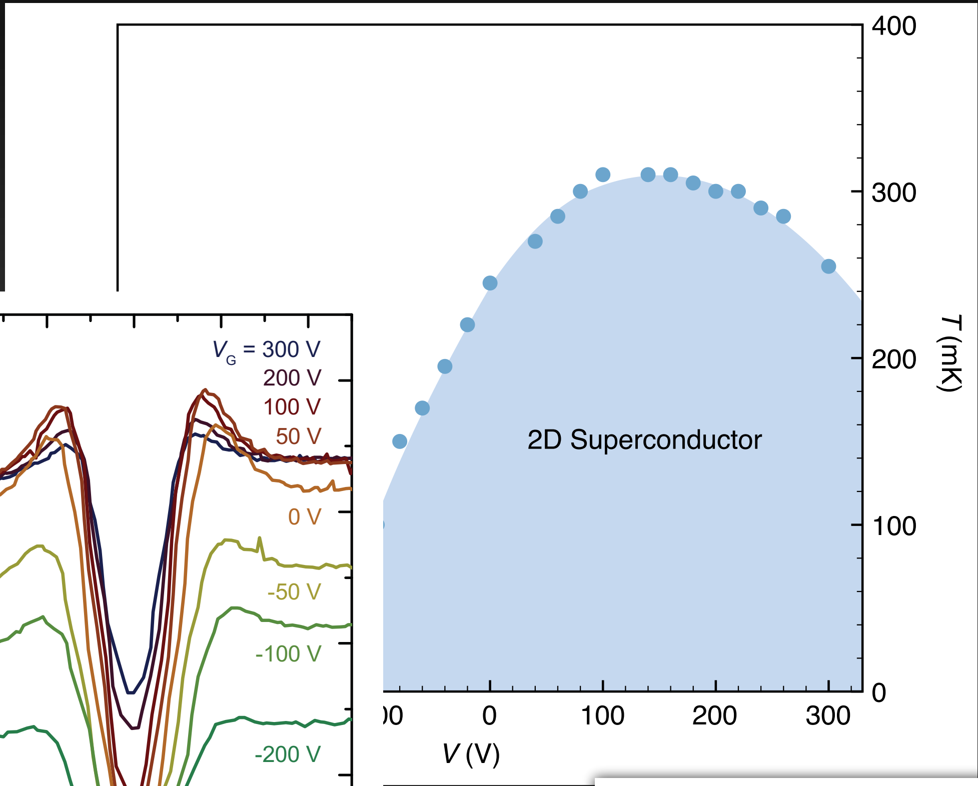
d_{xz}, d_{yz} couple the « xy planes » ?

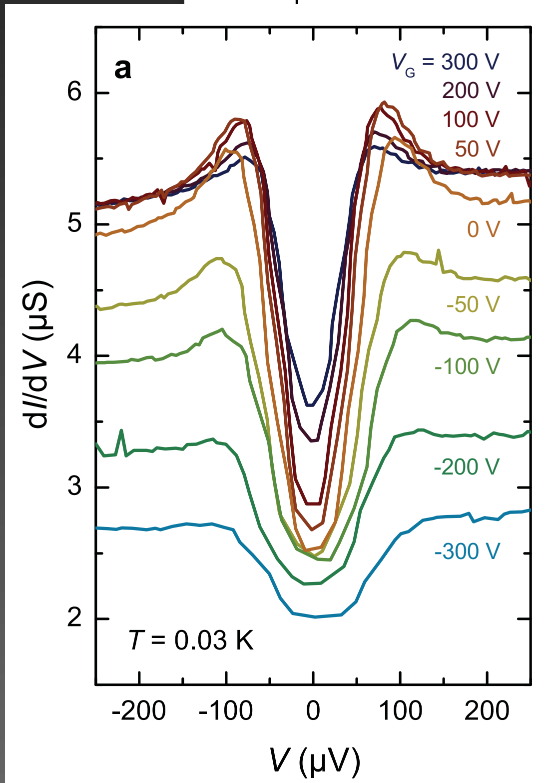
d=1

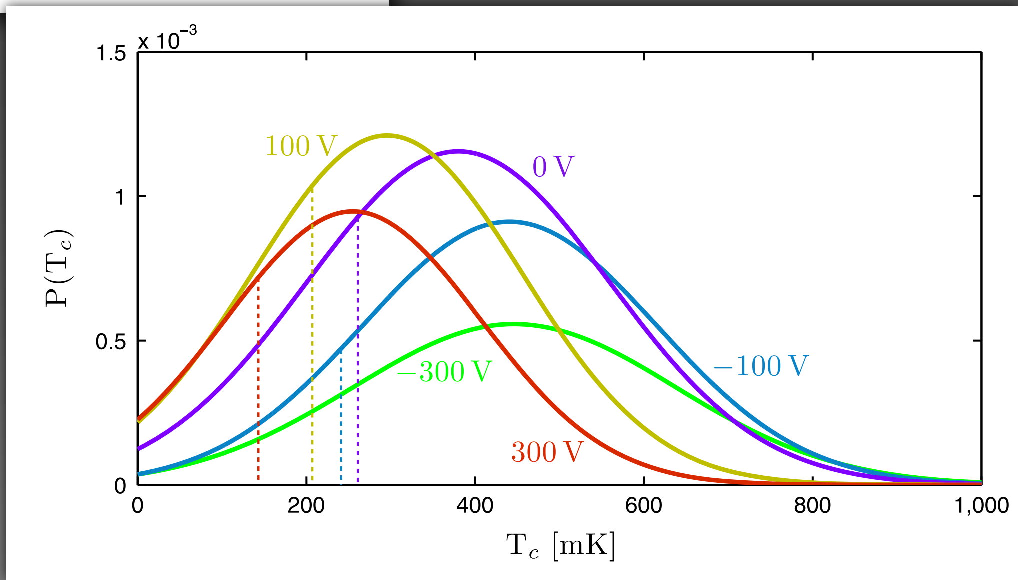


d=25

How to understand the data - disorder?







D. Bucheli, S. Caparra and M. Grilli, SUST **28**, 45004 (2015)

Recent Results
Exciting Developments

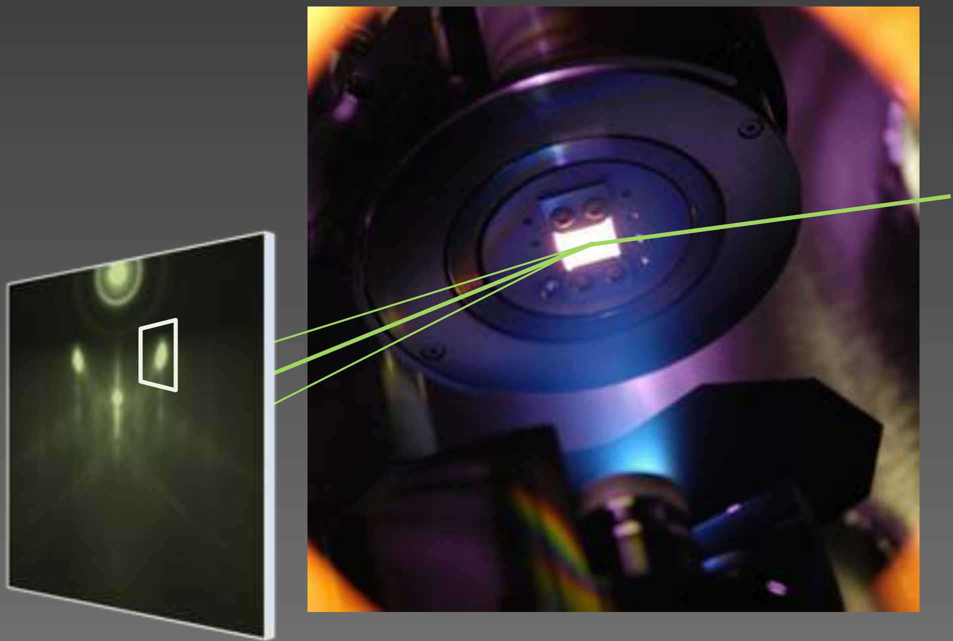
High mobility samples

Layer-by-layer growth
T = 650°C
P $O_2 = 1 \cdot 10^{-4}$ Torr
Fluence = 0.6 J/cm^2
Frequency = 1Hz
Post annealing @ 200 mbar O_2

Low sheet carrier density
Mobilities up to 8000 cm^2/Vs

$$\omega_c \tau = \mu B >> 1$$

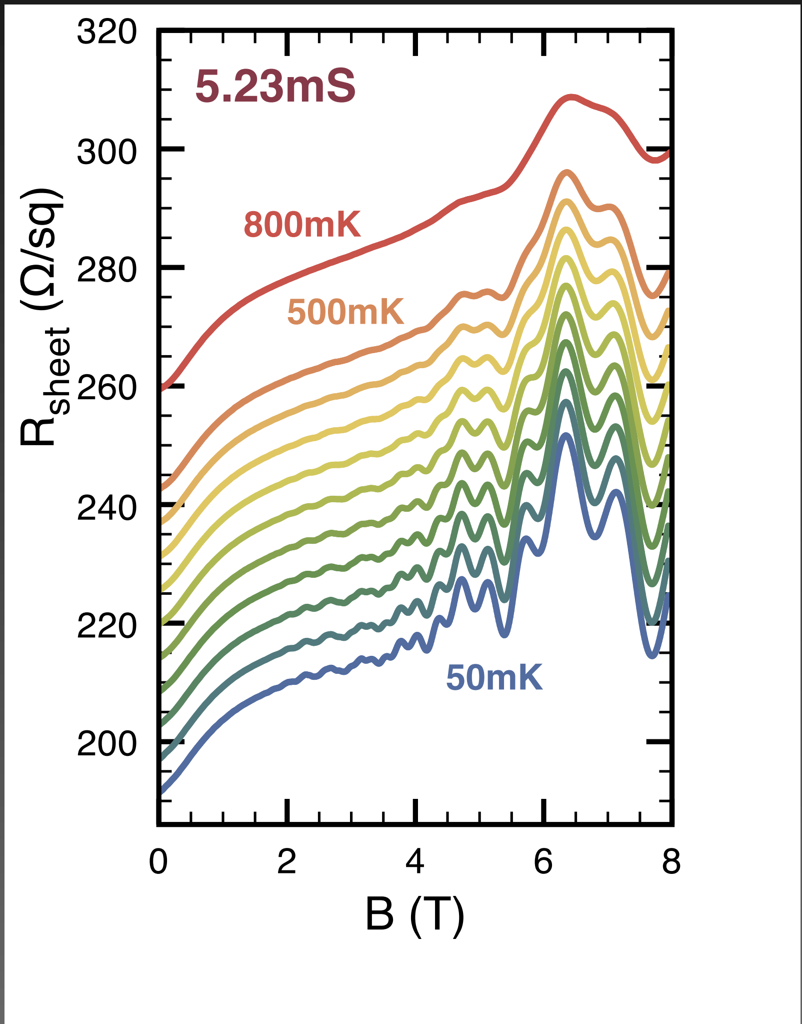
$$\hbar \omega_c = \hbar e B / m > k_B T$$



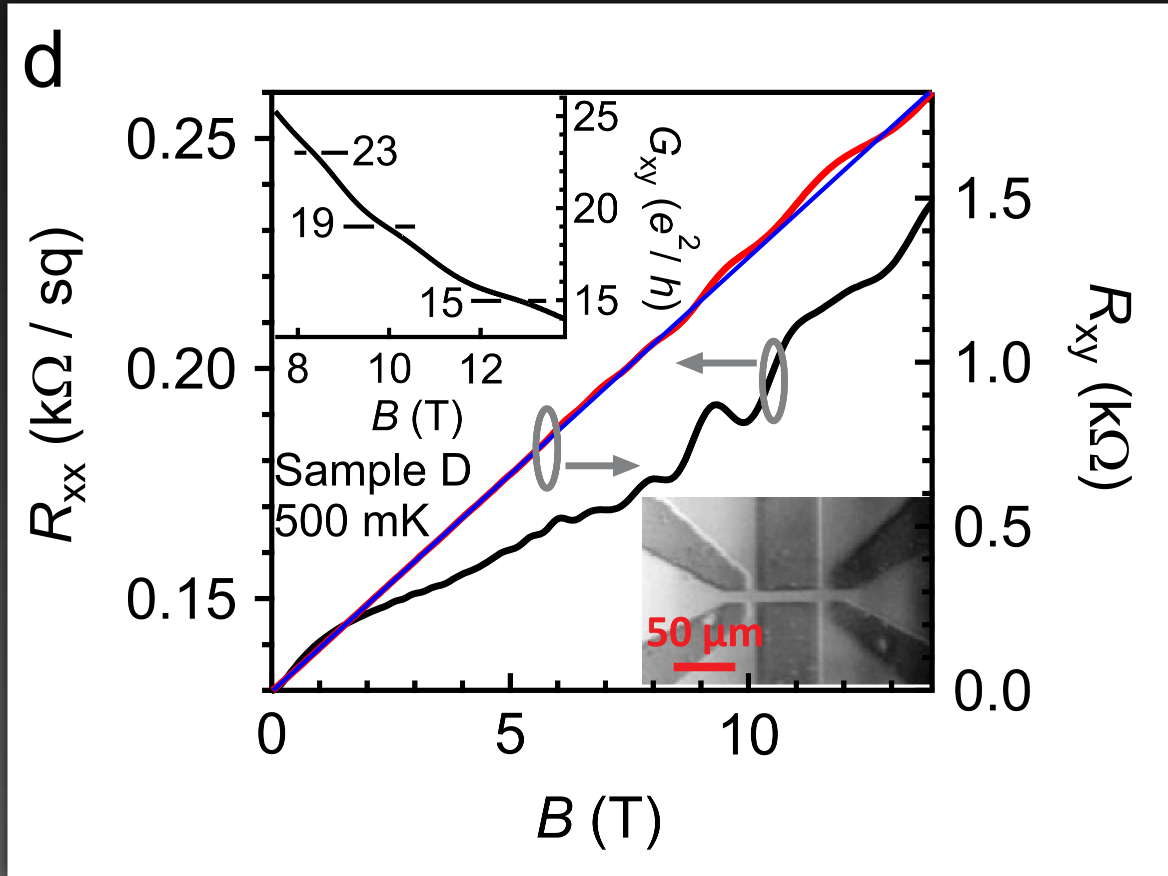
UNIVERSITÉ DE GENÈVE

MaNEP SWITZERLAND

High mobility samples



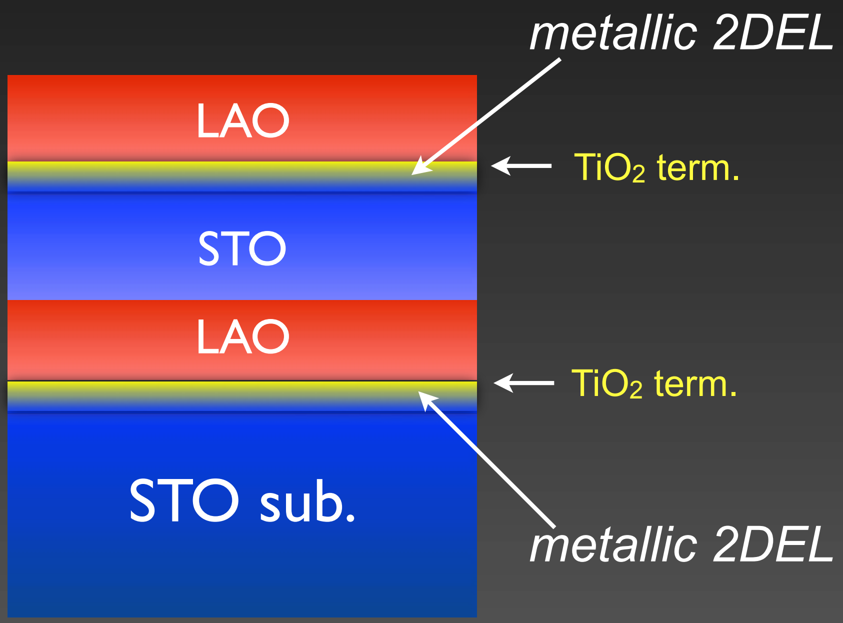
A. Fête et al. New Journal of Physics **16**, 112002 (2014)

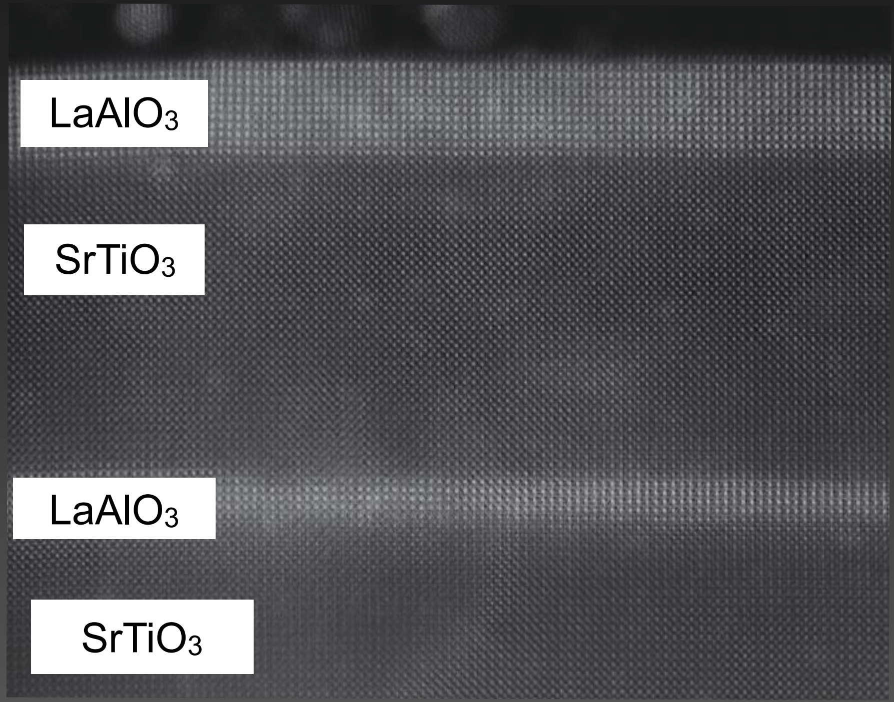


Y. Xie et al. Solid State Com. **197**, 25 (2014)

UNIVERSITÉ DE GENÈVE

Bi-interfaces

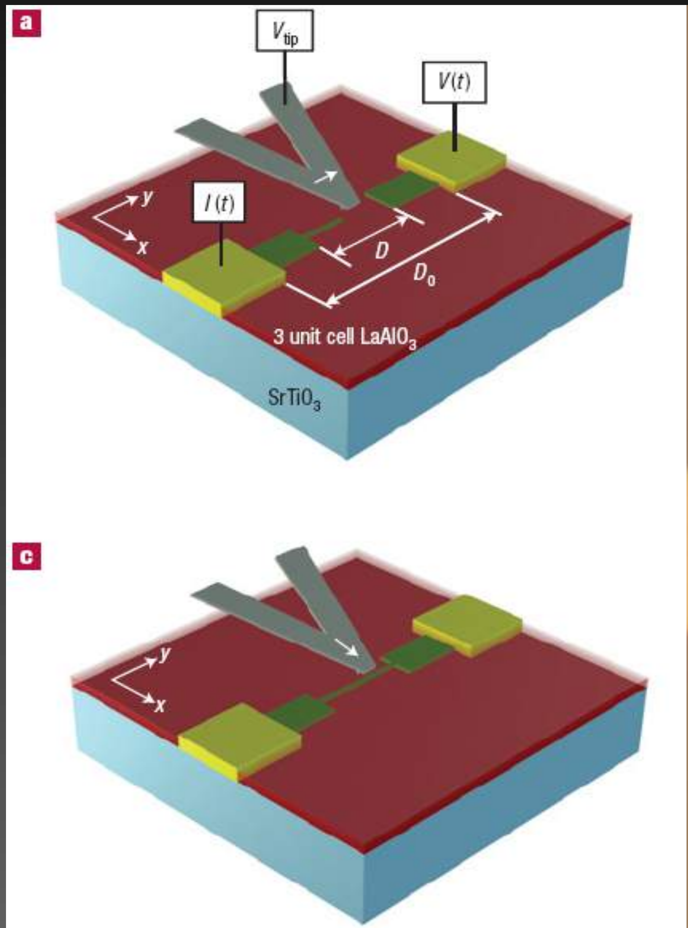


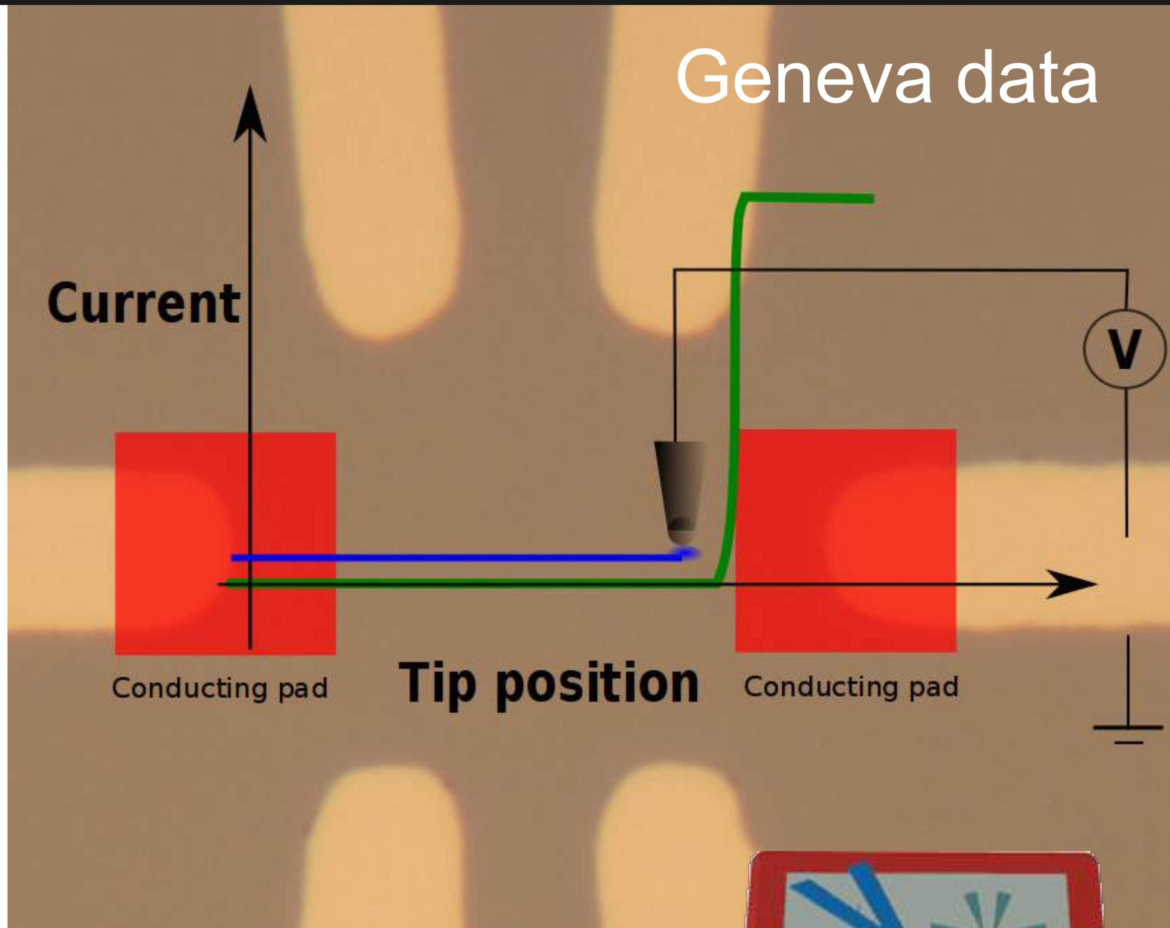


G. Tieri, A. Gloter, O. Stephan (Orsay)

D. Li et al. APL Materials **2**, 012102 (2014)
and D. Li et al. in preparation

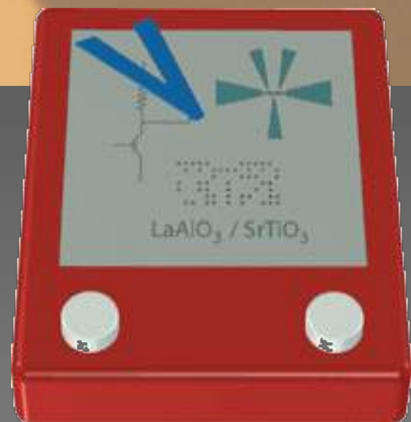
Writing nanoscale electronic circuits





Jeremy Levy in Pittsburgh

C. Cen *et al*, Nat. Mater. **7**, 298 (2008)
C. Cen et al. Science **323**, 1026 (2009)

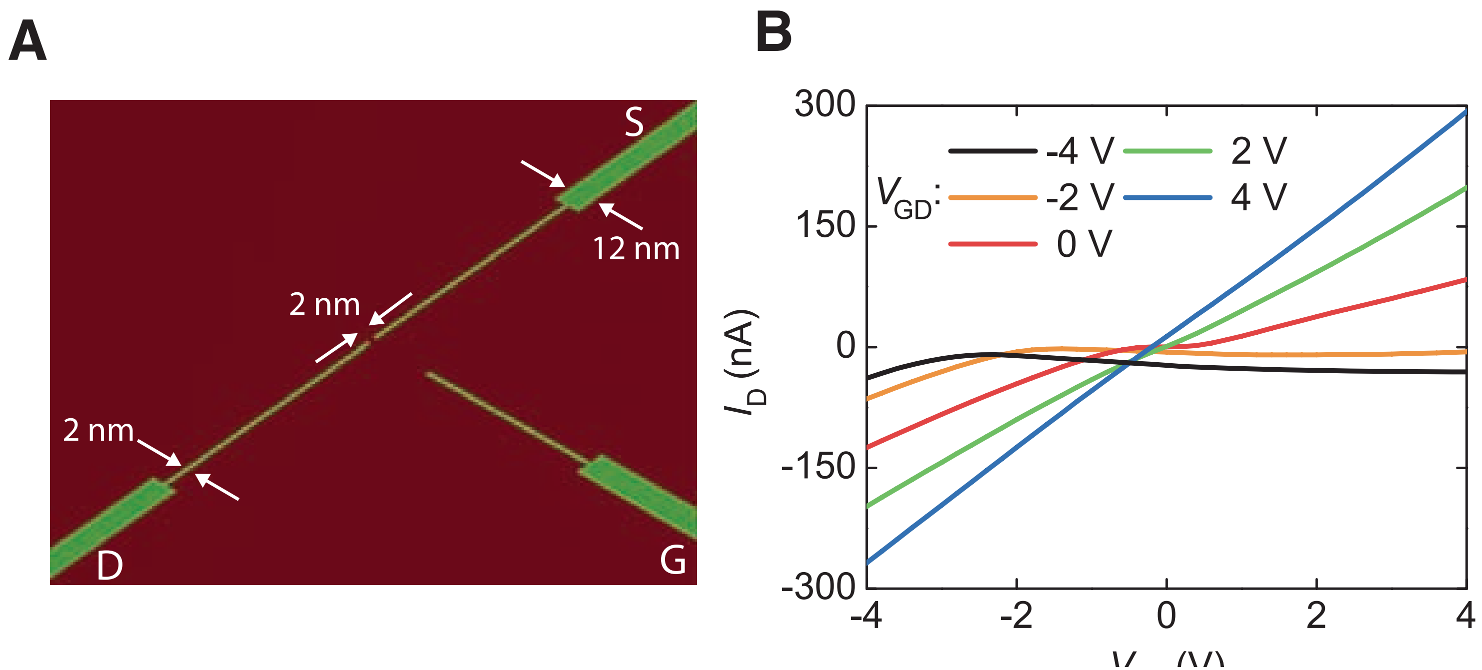


UNIVERSITÉ DE GENÈVE

Science
AAAS

Oxide Nanoelectronics on Demand
Cheng Cen, *et al.*
Science **323**, 1026 (2009);
DOI: 10.1126/science.1168294

Fig. 2. SketchFET device. (**A**) Schematic diagram of SketchFET structure. S, source electrode; D, drain electrode; G, gate electrode. (**B**) *I-V* characteristic between source and drain for different gate biases $V_{GD} = -4$ V, -2 V, 0 V, 2 V, and 4 V. (**C**) Intensity plot of I_D (V_{SD}, V_{GD}).



UNIVERSITÉ DE GENÈVE
MaNEP SWITZERLAND

Pairing without superconductivity

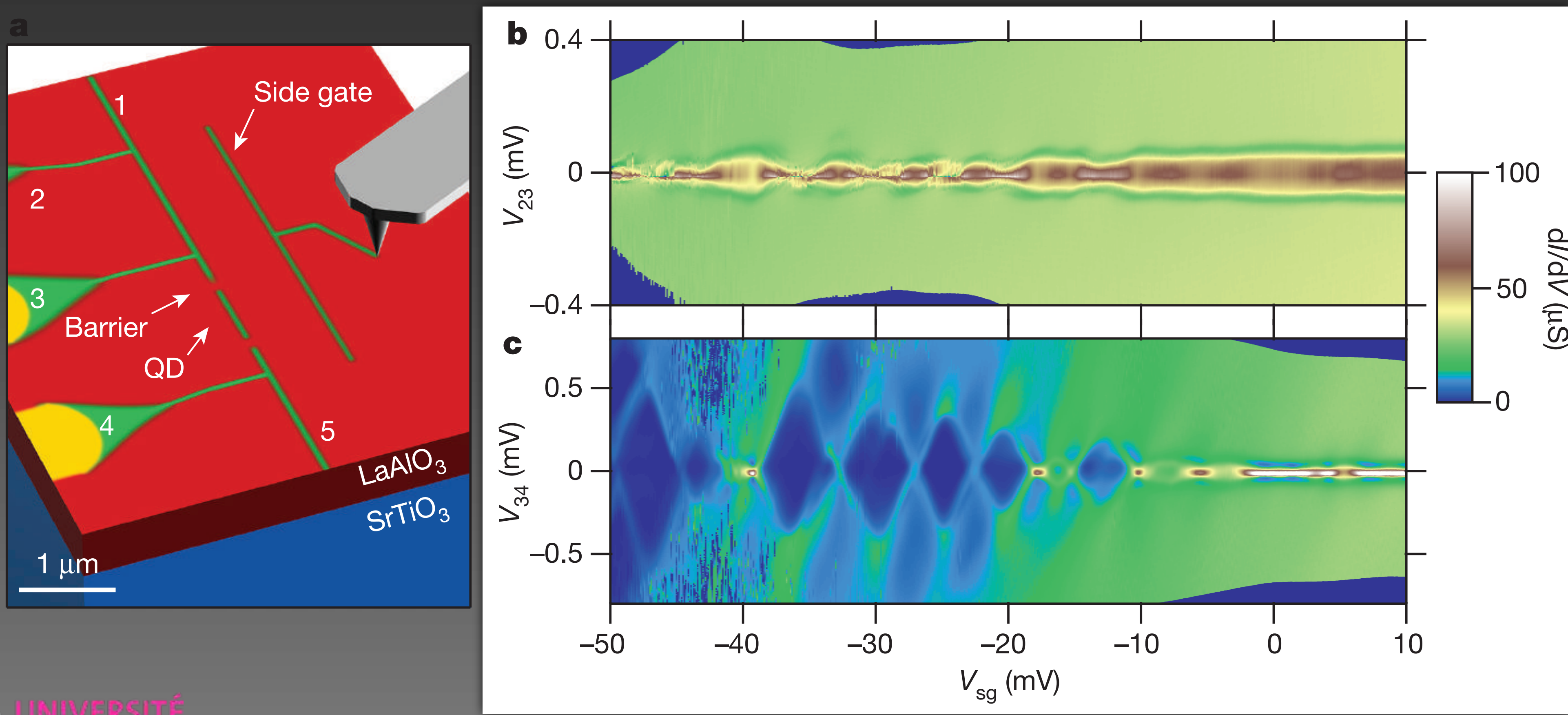
LETTER

doi:10.1038/nature14398

Electron pairing without superconductivity

Guanglei Cheng[1,2], Michelle Tomczyk[1,2], Shicheng Lu[1,2], Joshua P. Veazey[1]†, Mengchen Huang[1,2], Patrick Irvin[1,2], Sangwoo Ryu[3], Hyungwoo Lee[3], Chang-Beom Eom[3], C. Stephen Hellberg[4] & Jeremy Levy[1,2]

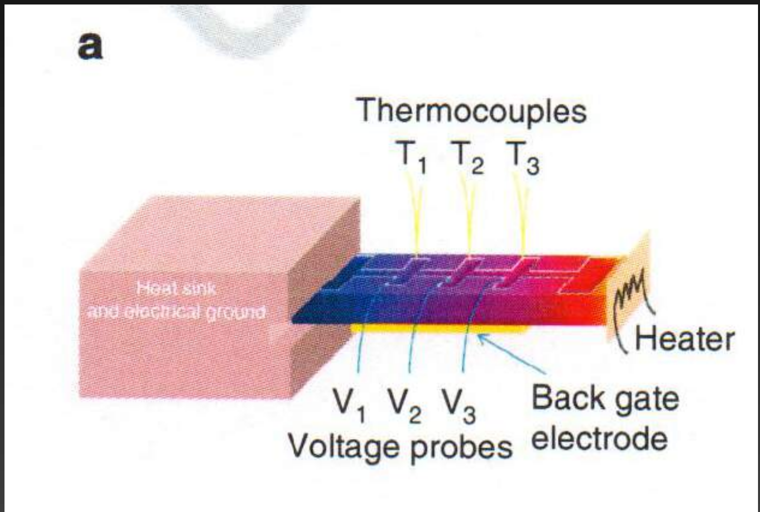
Nature 2015

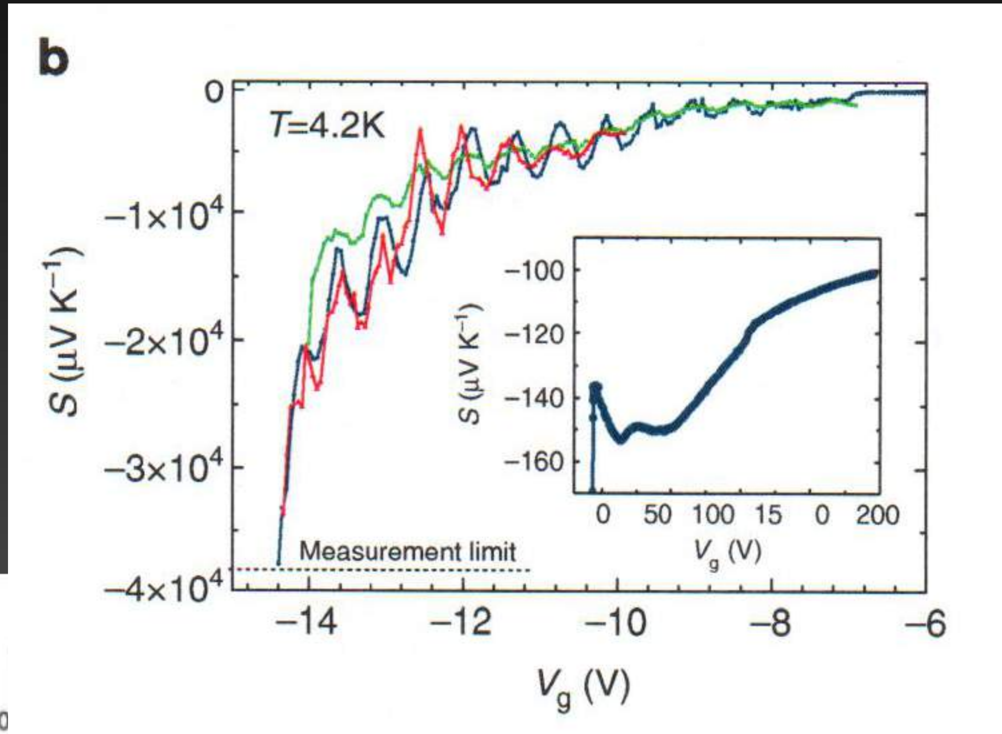


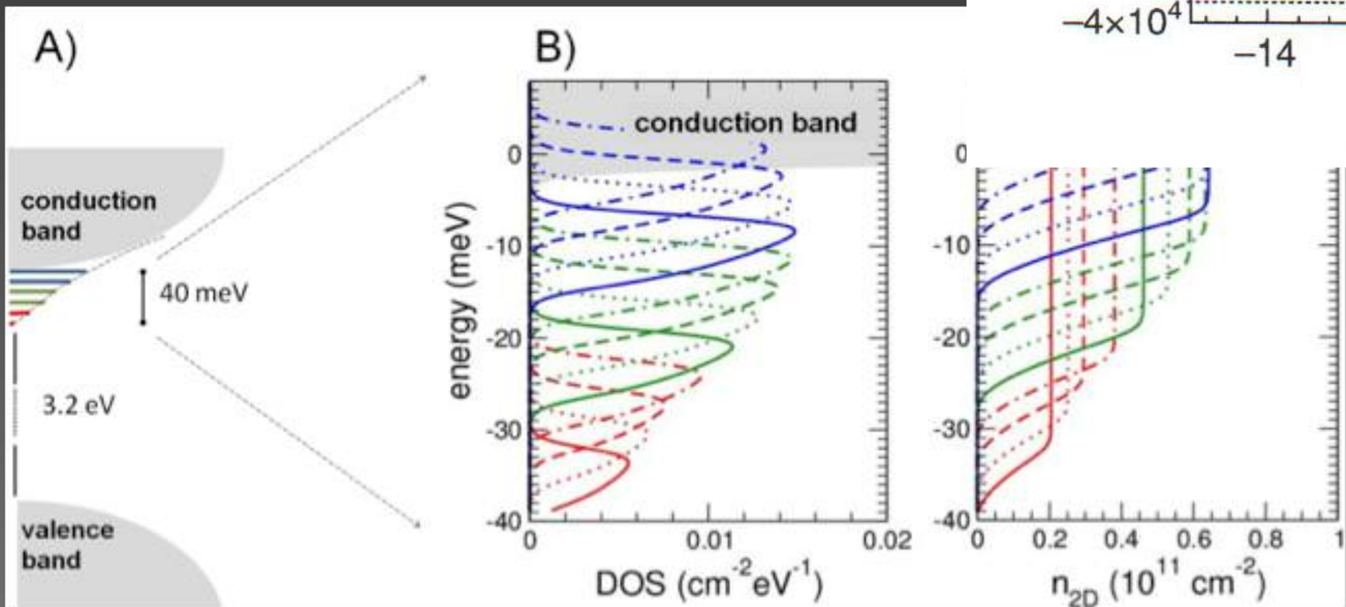
UNIVERSITÉ DE GENÈVE

MaNEP SWITZERLAND

Localized states probed using thermopower

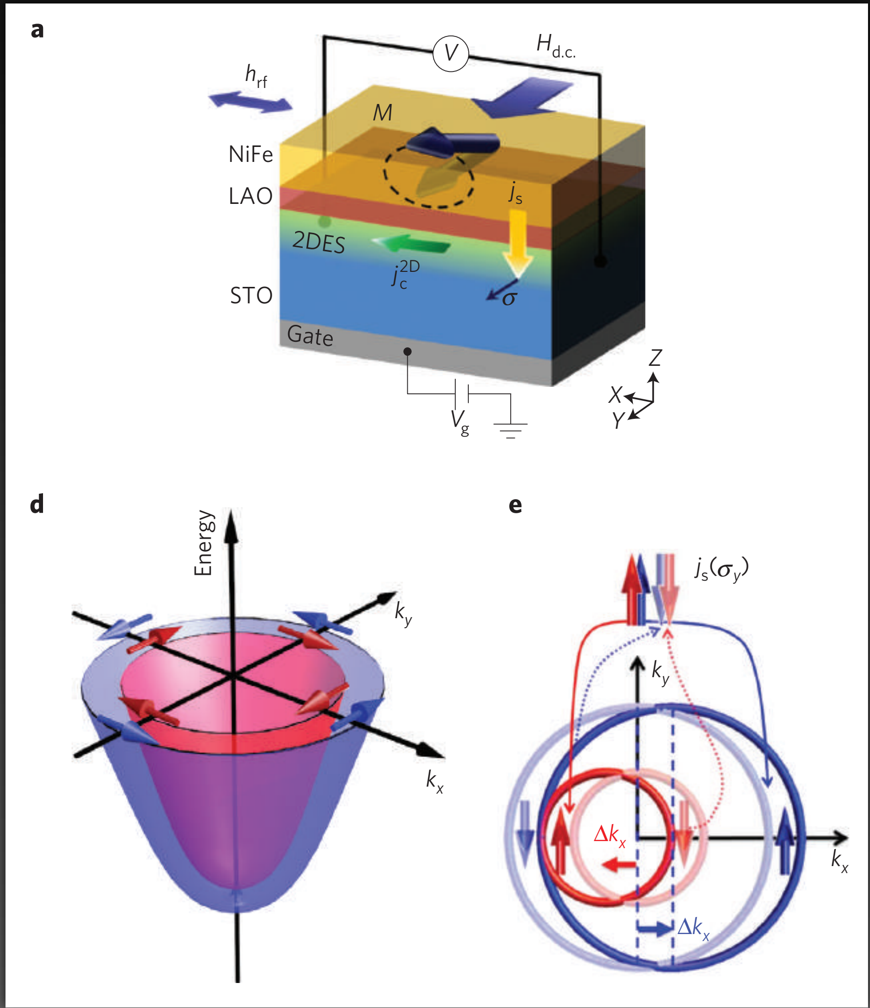


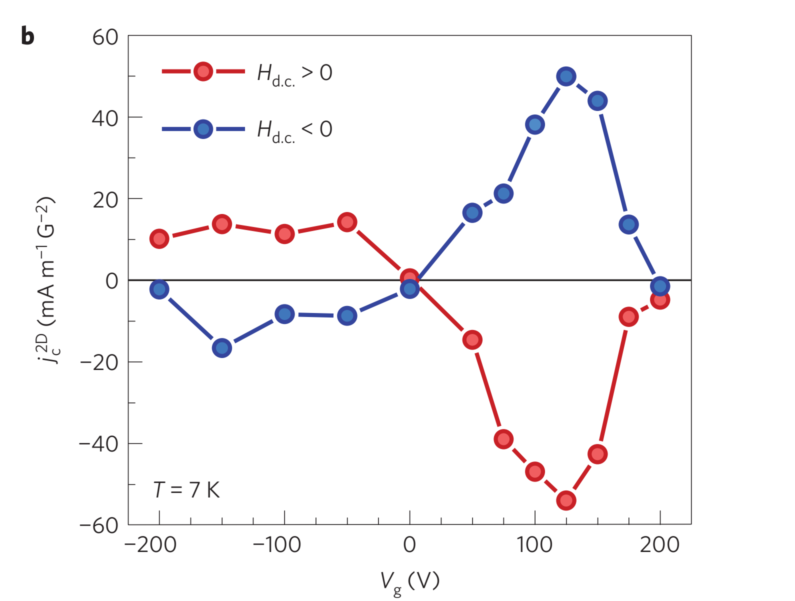




Ilaria Pallecchi et al.
Nature Com. **6**, 7668 (2015)

Inverse Rashba-Edelstein effect





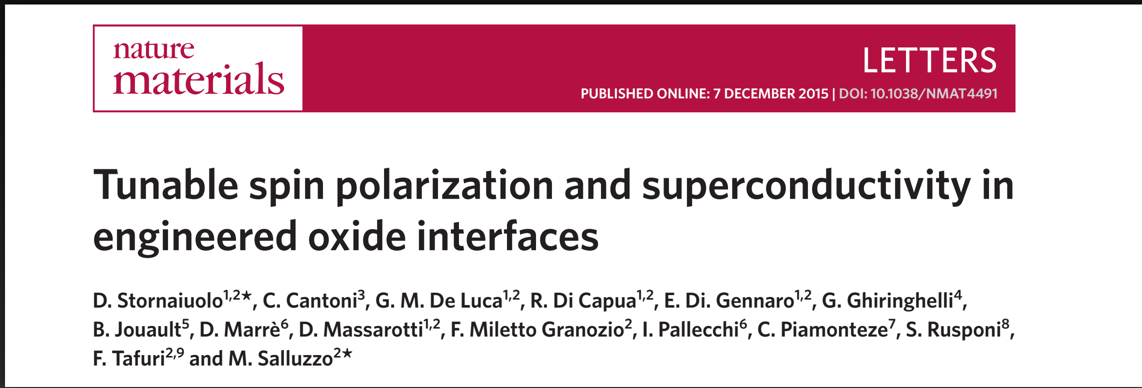
$$j_{dc}=2\pi j_s \alpha \tau / h$$

E. Lesne et al. Nature Materials **15**, 1261 (2016)

J.-Y. Chauleau et al., EPL 116, 17006 (2016)

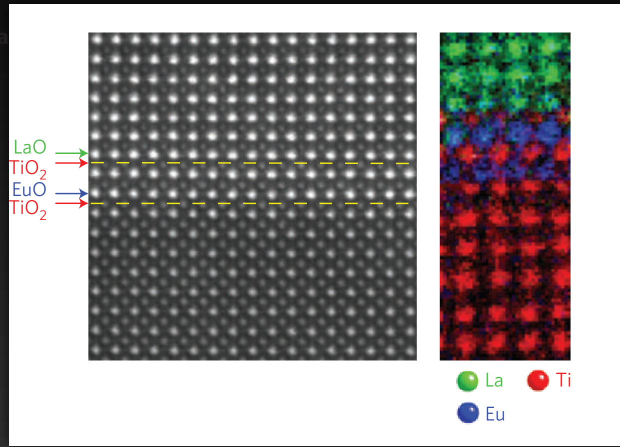
A spin-polarized 2DEL

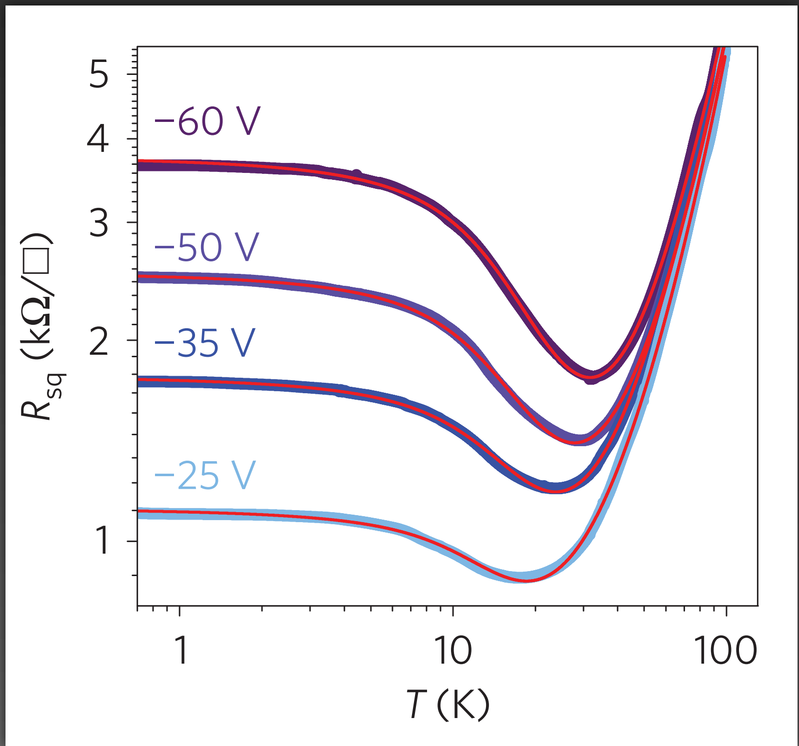
Naples group

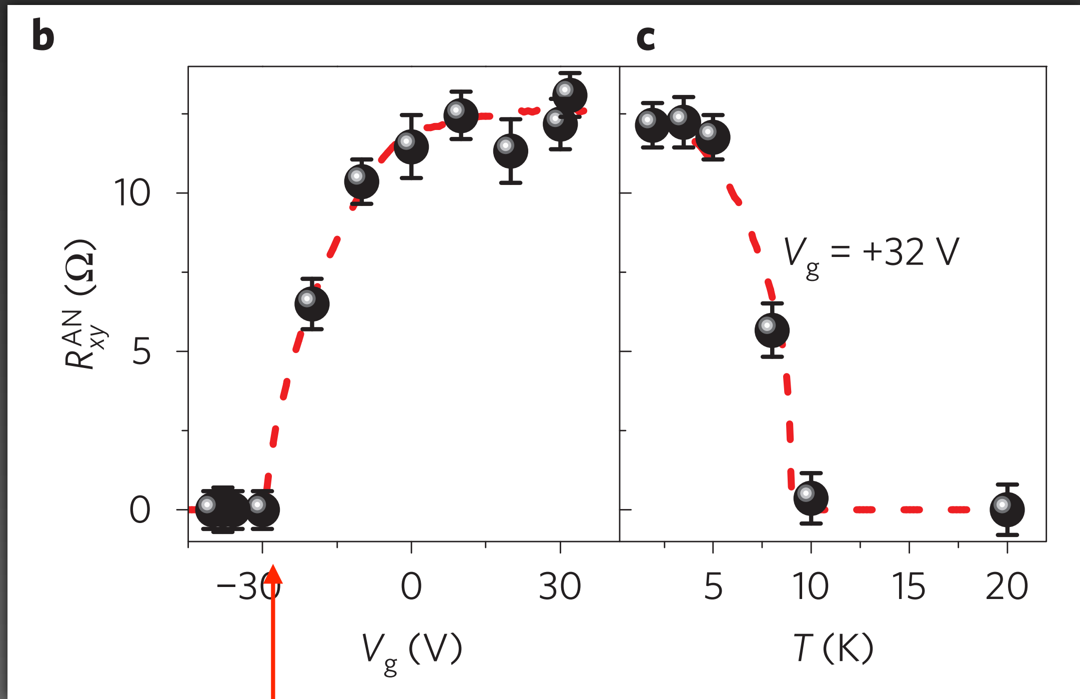

nature materials LETTERS
PUBLISHED ONLINE: 7 DECEMBER 2015 | DOI: 10.1038/NMAT4491

Tunable spin polarization and superconductivity in engineered oxide interfaces

D. Stornaiuolo[1,2]*, C. Cantoni[3], G. M. De Luca[1,2], R. Di Capua[1,2], E. Di. Gennaro[1,2], G. Ghiringhelli[4], B. Jouault[5], D. Marrè[6], D. Massarotti[1,2], F. Miletto Granozio[2], I. Pallecchi[6], C. Piamonteze[7], S. Rusponi[8], F. Tafuri[2,9] and M. Salluzzo[2]*





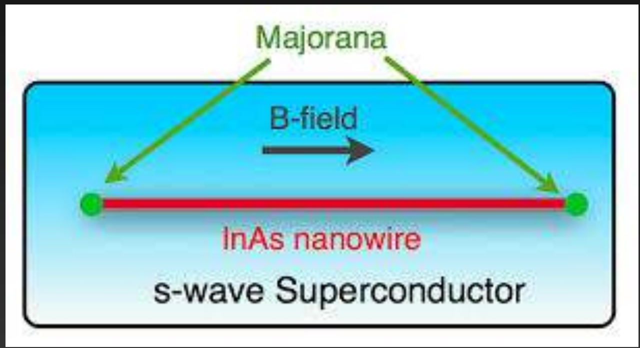


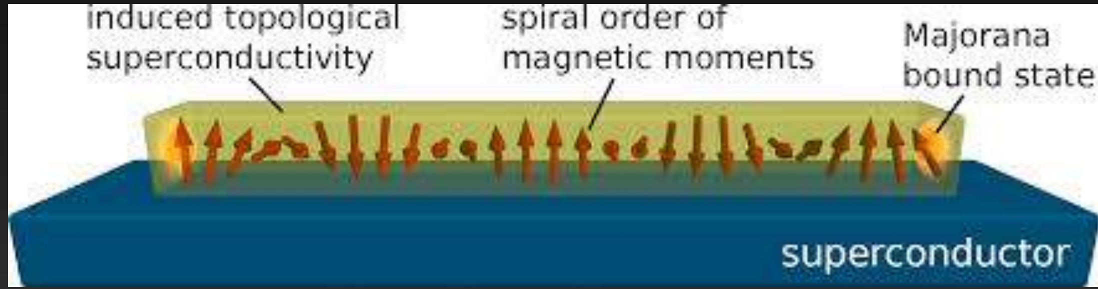
Kondo n_c FM (below n_c, no xz,yz)

Nature Materials **15**, 278 (2016)

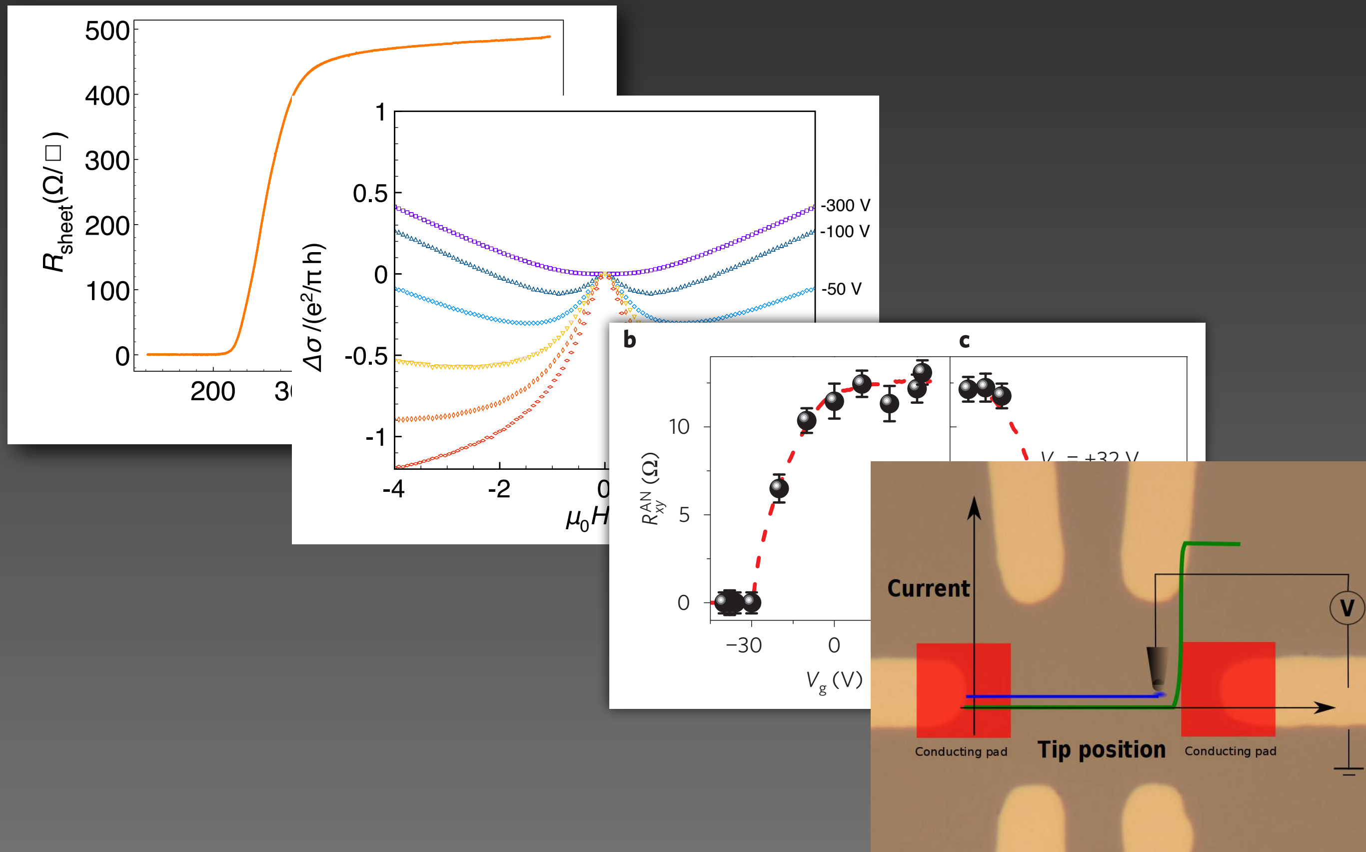
$EuTiO_3$ - ferro below 7-8K

A platform for Majorana fermions?

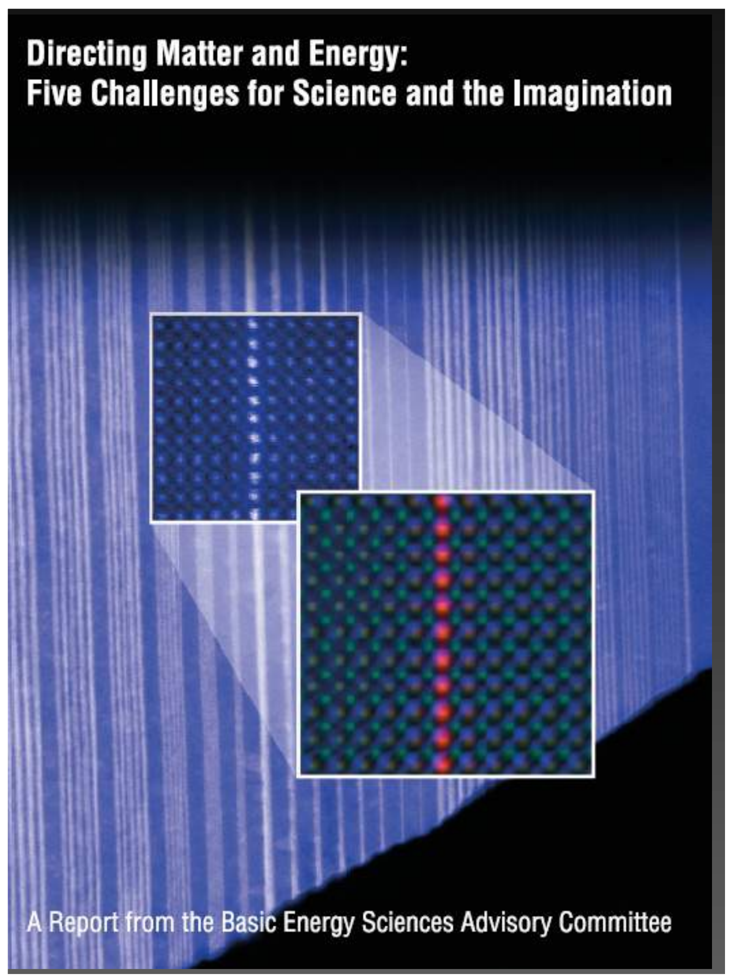




Ingredients:
Superconductivity
Spin-orbit
Zeeman field
1D-wire



Other conducting oxide interfaces



http://www.sc.doe.gov/bes/reports/abstracts.html#GC

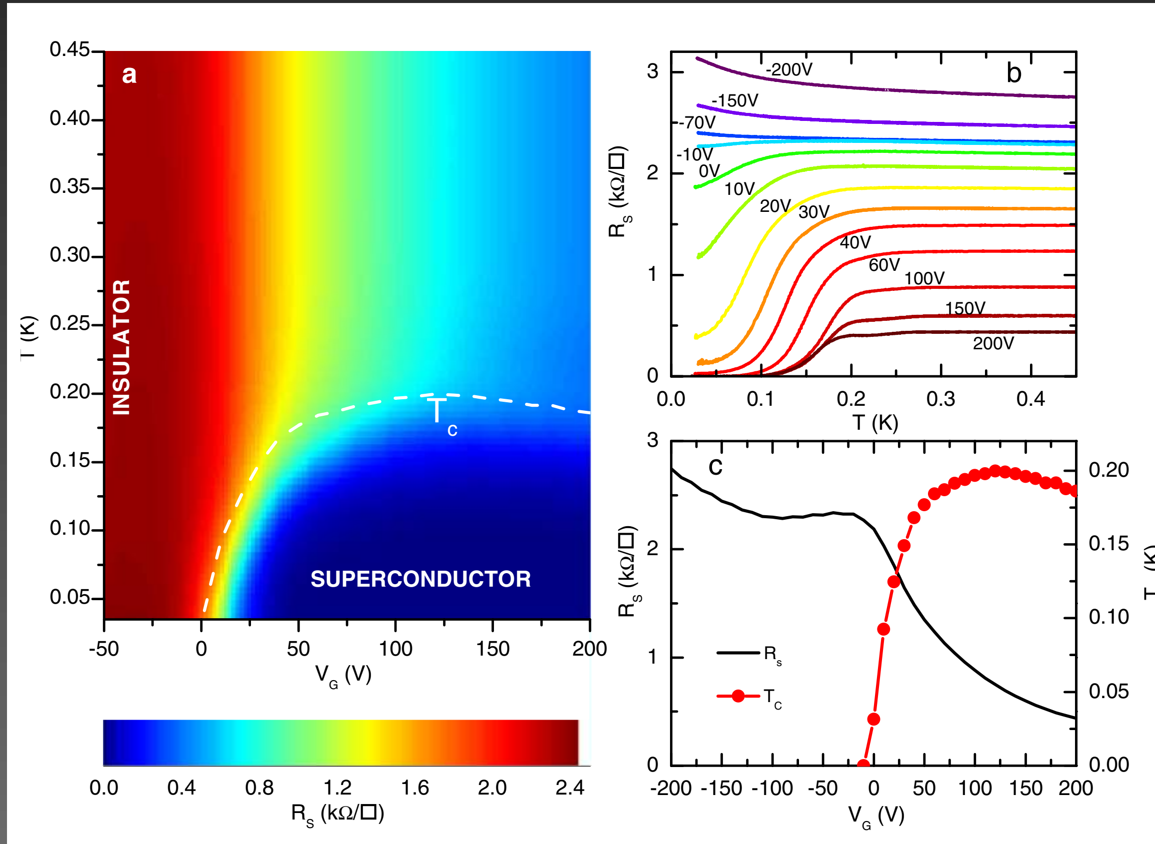
A. Ohtomo et al.
Nature **419**, 378 (2002)

NATURE COMMUNICATIONS | ARTICLE

Two-dimensional superconductivity at a Mott insulator/band insulator interface $LaTiO_3/SrTiO_3$

J. Biscaras, N. Bergeal, A. Kushwaha, T. Wolf, A. Rastogi, R.C. Budhani & J. Lesueur

Nature Communications **1**, Article number: 89 doi:10.1038/ncomms1084
Received 29 July 2010 Accepted 06 September 2010 Published 05 October 2010



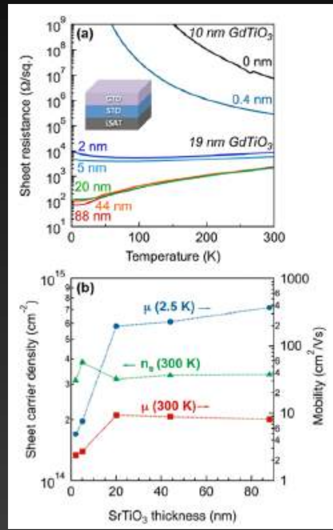
Jérôme Lesueur, ESPCI

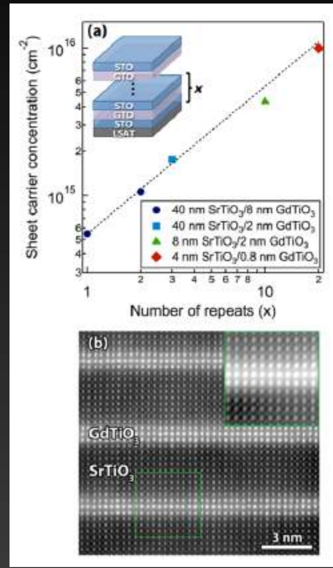
UNIVERSITÉ DE GENÈVE

MaNEP SWITZERLAND

Other conducting oxide interfaces

Charge transfer with expected number of carriers
+ heterostructure with scalable carrier density

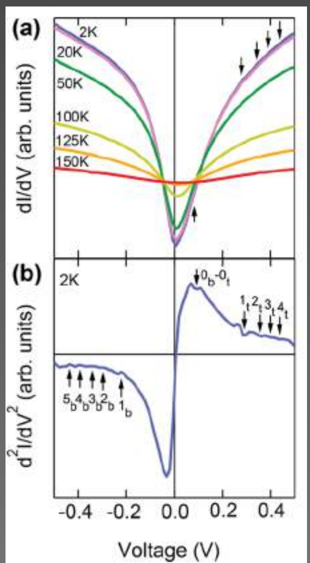




P. Moetakef *et al.*, APL **99**, 232116 (2011)

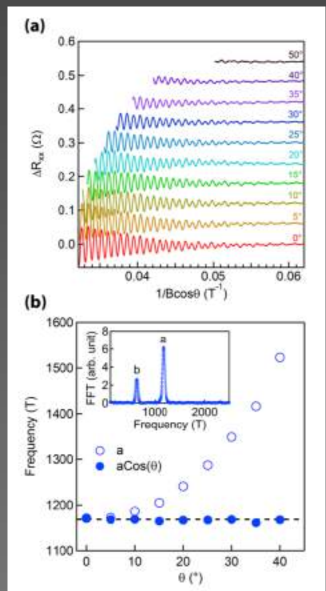
GdTiO$_3$/SrTiO$_3$
S. Stemmer Santa Barbara

Tunneling between 2 STO/GTO quantum wells reveals their subband structure



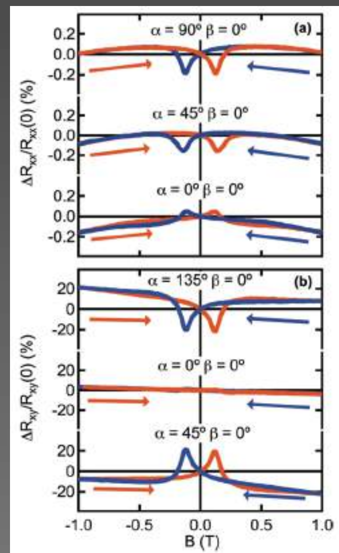
S. Raghavan *et al.*, APL **103**, 212103 (2013)

2D SdH oscillations



P. Moetakef *et al.*, APL **101**, 151604 (2012)

Interface induced magnetism is revealed by magnetotransport in ultra-thin STO layers embedded in GTO



C. A. Jackson, PRB **88**, 180403 (2013)

A new oxide electronics?

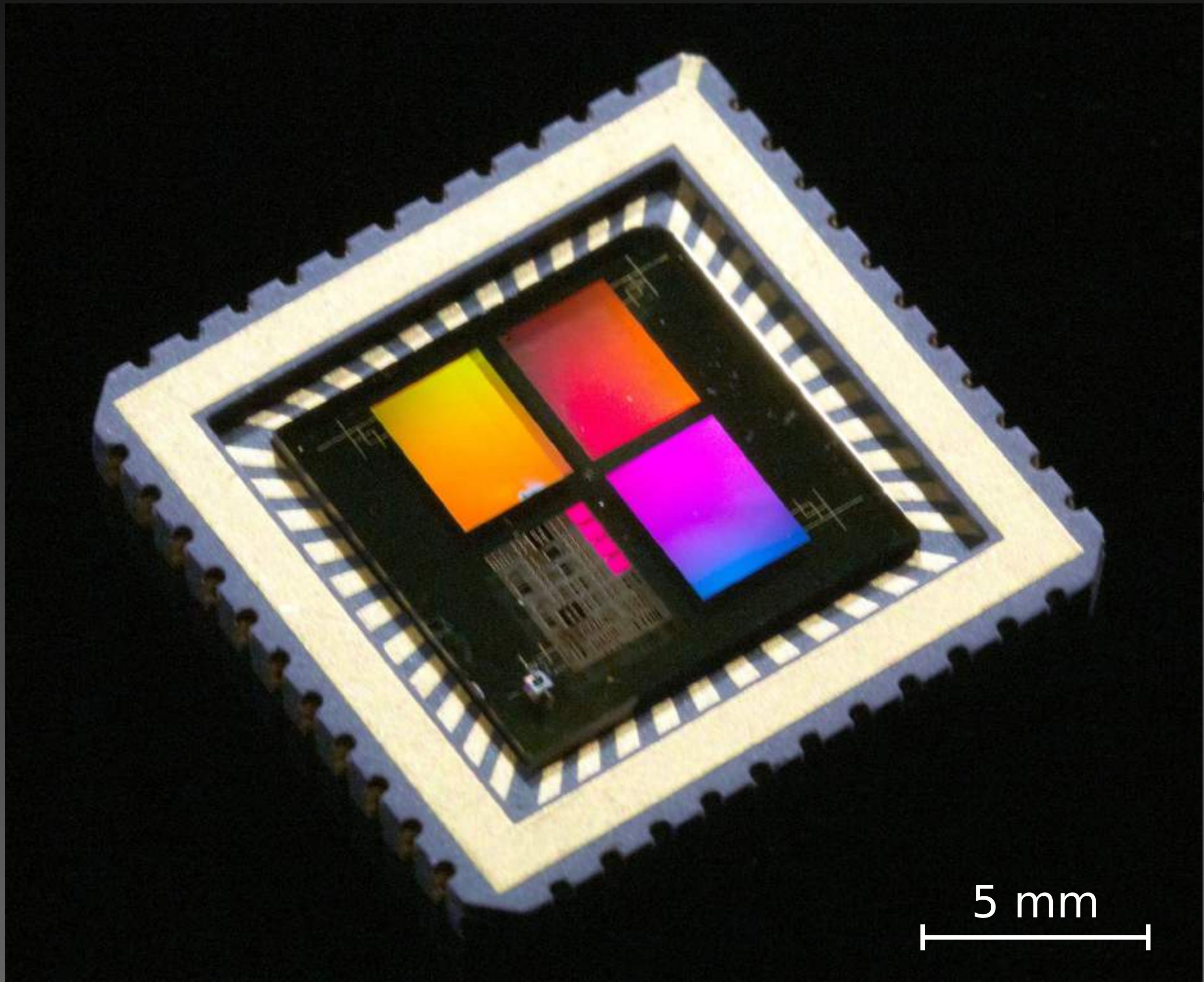
1947 Bell Labs

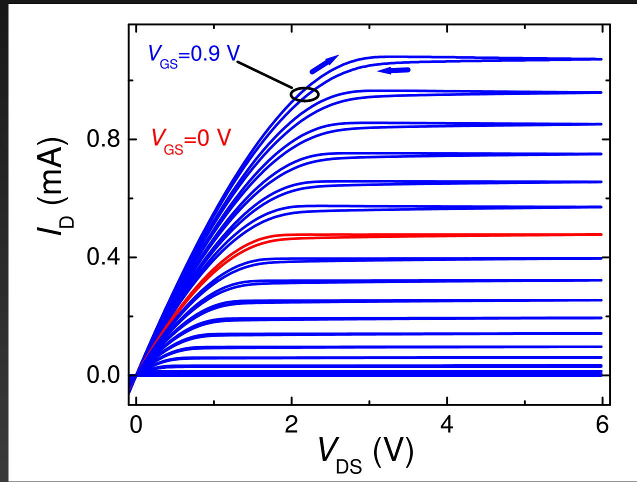
2009 UNIGE

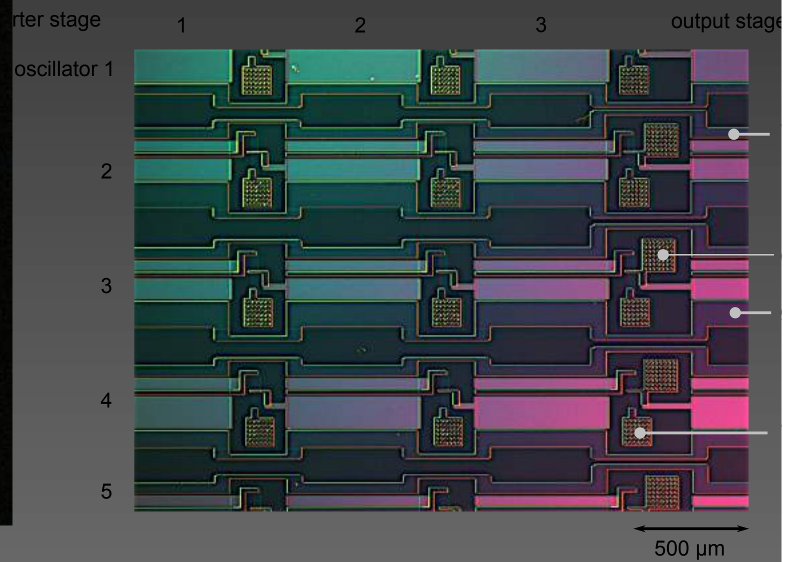
UNIVERSITÉ DE GENÈVE

MaNEP SWITZERLAND

2009-2014 - a million transistors







R. Jany et al.

UNIVERSITÉ DE GENÈVE

J. Mannhart - MPI Stuttgart

MaNEP SWITZERLAND

Reviews

J. Mannhart, and D. G. Schlom, *Science* **327**, 1607 (2010)

P. Zubko, S. Gariglio, M. Gabay, P. Ghosez, and J.-M. Triscone, *Annu. Rev. Condens. Matter Phys.* **2**, 141 (2011)

H. Y. Hwang, Y. Iwasa, M. Kawasaki, B. Keimer, N. Nagaosa, and Y. Tokura, *Nature Materials* **11**, 103 (2012)

Stefano Gariglio, Marc Gabay and Jean-Marc Triscone APL Materials **4,** 060701 (2016)