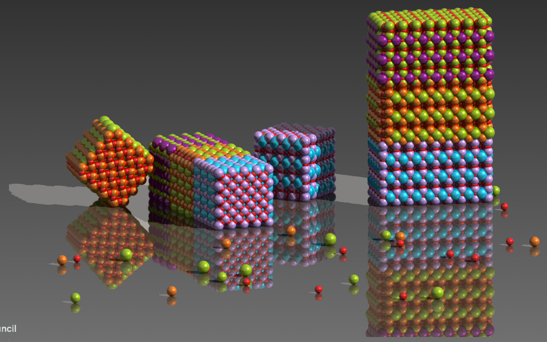
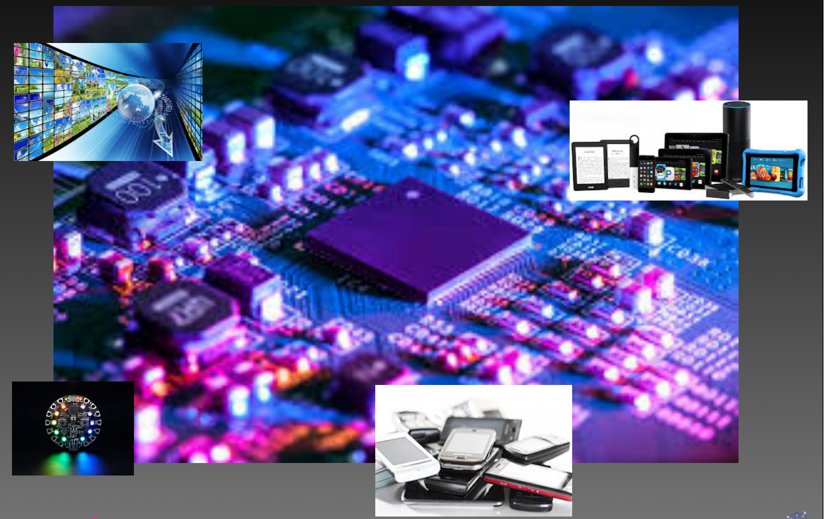
# Oxide interface physics

Jean-Marc Triscone
University of Geneva



Joerg Harms, MPI Hamburg

# Why looking at oxide structures?



# 1947 the transistor

J. Bardeen,
W. Brattain,
W. Shockley

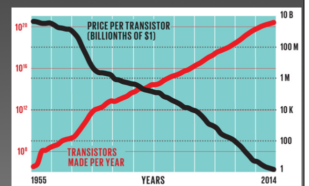
Photo: Bell Labs

# Very impressive progress

Transistor history :

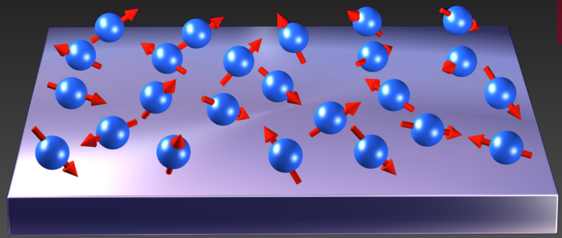
| | |
|---|---|
| 1947 discovery | 1 transistor |
| 1971 Intel 4004 | 2 300 transistors |
| 1993 Intel Pentium | 3,1 millions transistors |
| 2001 Intel Pentium 4 | 42 millions transistors |
| 2007 Intel Dual-Core Titanium 2 | 1,7 billion transistors |

2014: ~ 2.5 $10^{20}$ transistors fabricated




VLSI research

## Silicon - a magic material?



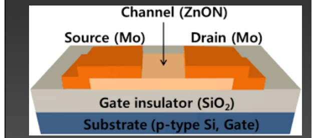
A simple electron system described

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.*

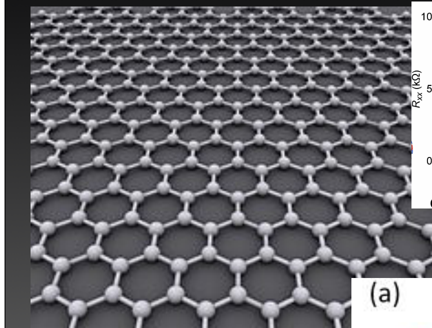


## One of the issues : dissipation

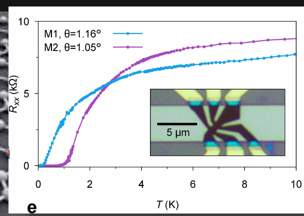
A computer farm in Sweden



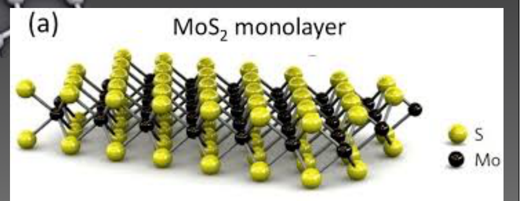
## Searching for / studying other materials



Graphene



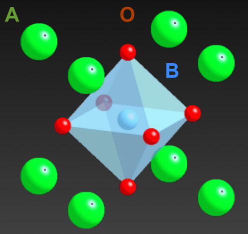

Y. Cao et al. Nature (2018)




Dichalcogenides

Univ. Twente

# Transition metal oxides - perovskites

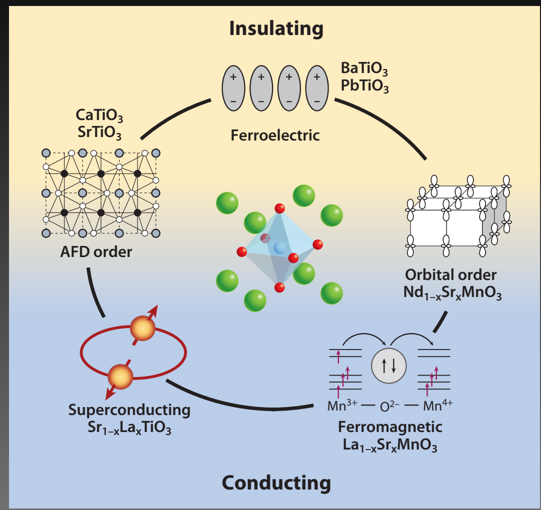


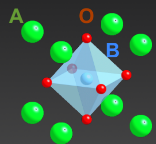

$ABO_3$

Perovskite - $CaTiO_3$
Perovskite structure - a very common structure on Earth

Oxides → Oxide structures → Oxide interfaces

# Oxides display a variety electronic properties



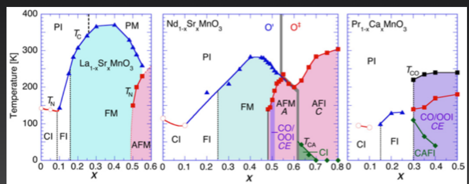

$ABO_3$

Perovskite Structure

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

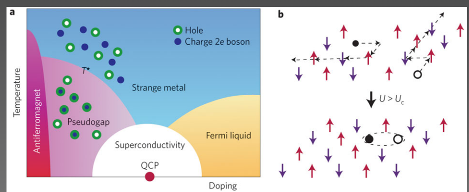
# Complex phase diagrams

Manganites



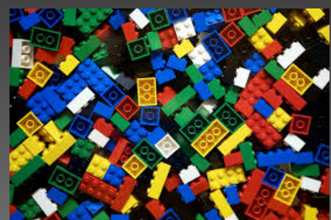

Y. Tokura, *Rep. Prog. Phys.* **69**, 797 (2006)

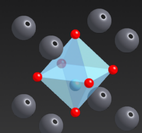
Cuprates



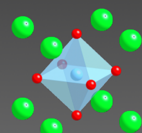

P. Phillips, *Nature Phys.* **6**, 931 (2010)

# Like Lego bricks

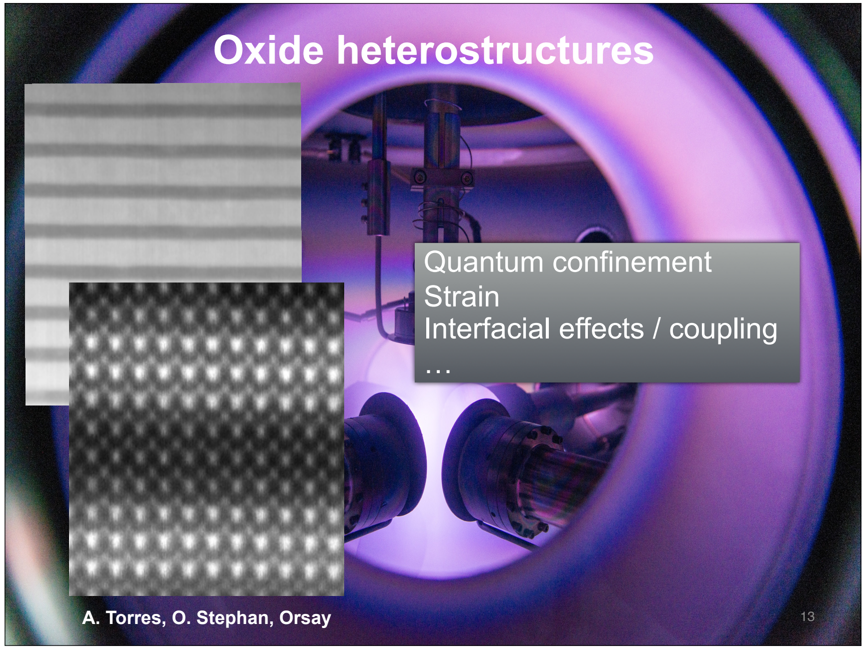



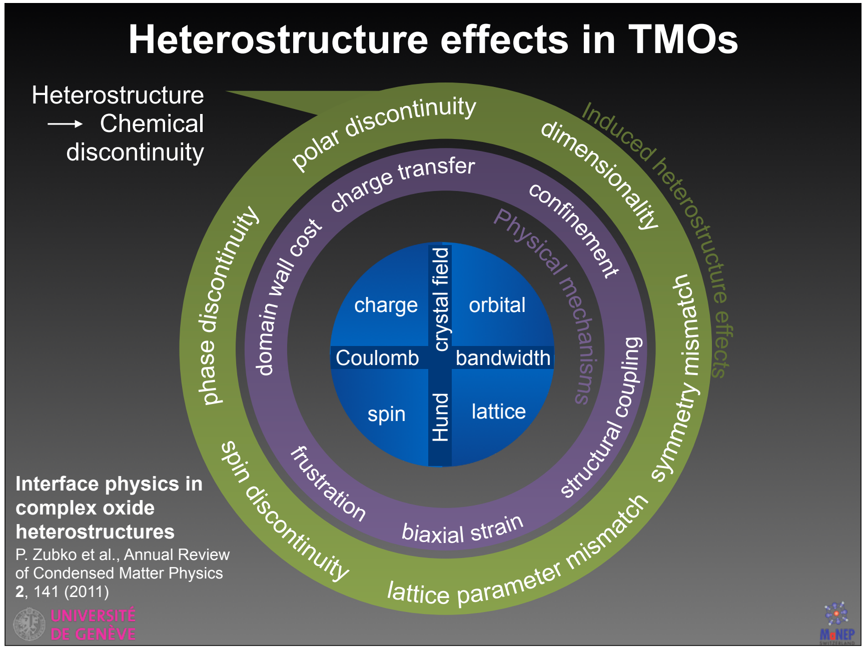


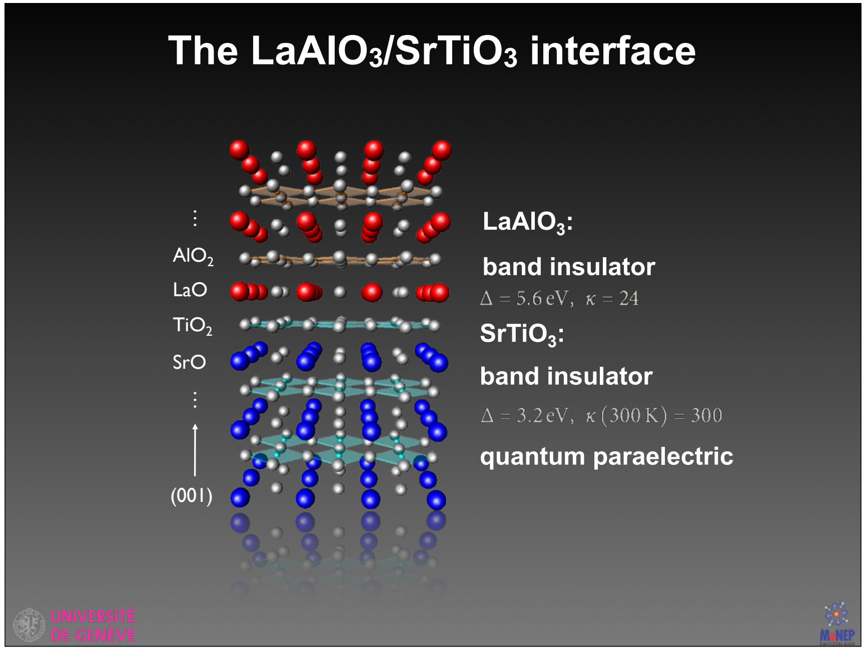
**$PbTiO_3$** ferroelectric $T<T_C$
Tetragonal and ferroelectric
(a=b=3.904Å, c=4.152Å)

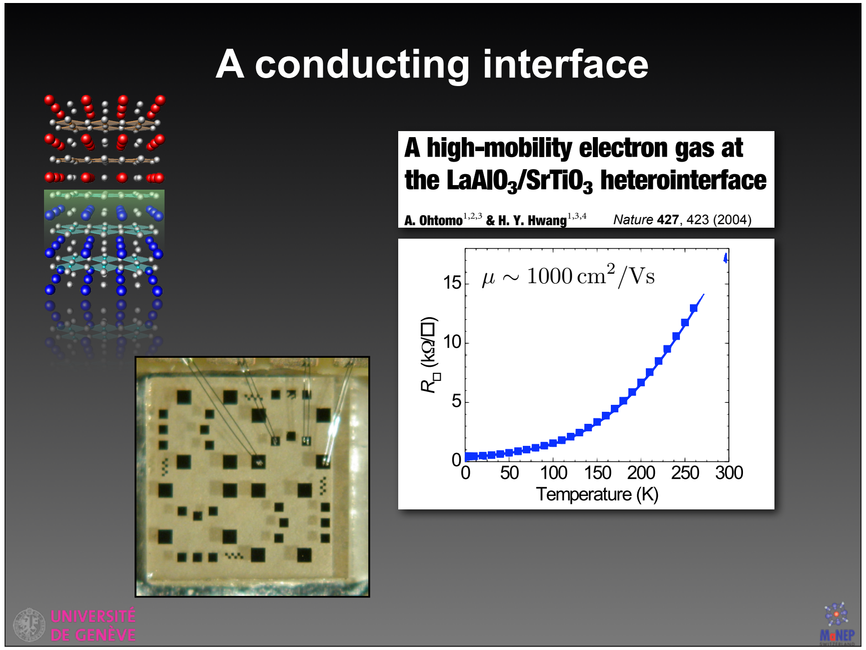


**$SrTiO_3$** paraelectric at all temperatures
(a=b=c=3.905Å)


Oxide heterostructures
Quantum confinement
Strain
Interfacial effects / coupling
…
A. Torres, O. Stephan, Orsay
13


Heterostructure effects in TMOs
Heterostructure → Chemical discontinuity
polar discontinuity
dimensionality
Induced heterostructure effects
phase discontinuity
charge transfer
confinement
domain wall cost
Physical mechanisms
charge
orbital
crystal field
Coulomb
bandwidth
spin
Hund
lattice
symmetry mismatch
structural coupling
frustration
biaxial strain
spin discontinuity
lattice parameter mismatch
Interface physics in complex oxide heterostructures
P. Zubko et al., Annual Review of Condensed Matter Physics 2, 141 (2011)
UNIVERSITÉ DE GENÈVE
MaNEP


The LaAlO3/SrTiO3 interface
AlO2
LaO
TiO2
SrO
(001)
LaAlO3:
band insulator
Δ = 5.6 eV, κ = 24
SrTiO3:
band insulator
Δ = 3.2 eV, κ (300 K) = 300
quantum paraelectric
UNIVERSITÉ DE GENÈVE
MaNEP


A conducting interface
A high-mobility electron gas at the LaAlO3/SrTiO3 heterointerface
A. Ohtomo & H. Y. Hwang
Nature 427, 423 (2004)
μ ~ 1000 cm²/Vs
R□ (kΩ/□)
15
10
5
0
0 50 100 150 200 250 300
Temperature (K)
UNIVERSITÉ DE GENÈVE
MaNEP

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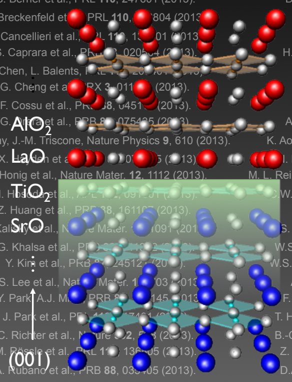
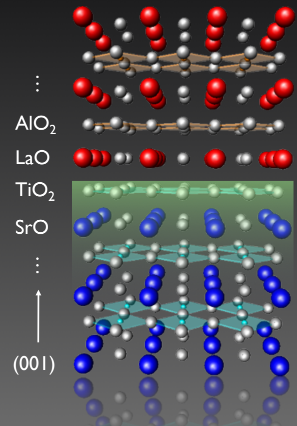




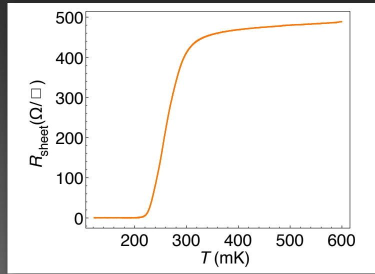

# Superconductivity at low T




**Superconducting Interfaces Between Insulating Oxides**

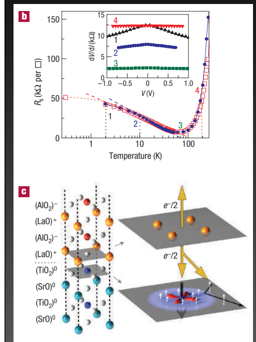
N. Reyren,[1] S. Thiel,[2] A. D. Caviglia,[1] L. Fitting Kourkoutis,[3] G. Hammerl,[2] C. Richter,[2] C. W. Schneider,[2] T. Kopp,[2] A.-S. Rüetschi,[1] D. Jaccard,[1] M. Gabay,[4] D. A. Muller,[3] J.-M. Triscone,[1] J. Mannhart[2]*

*Science* **317**, 1196 (2007)

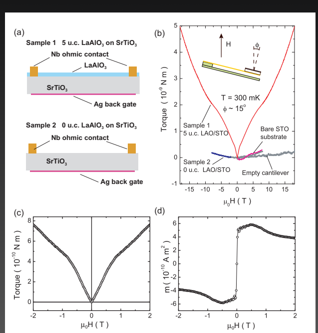




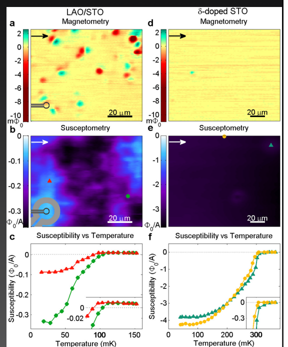

# Magnetism



Brinkman et al.



Li et al.




Bert et al.

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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)



# A new field of research

## Breakthrough of the Year

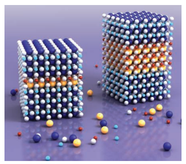
21 DECEMBER 2007 VOL 318 **SCIENCE** www.sciencemag.org

*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.

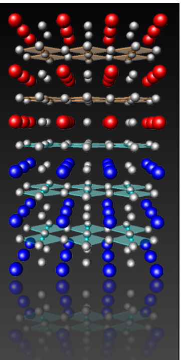
Transition metal oxides first made headlines in 1986 with the Nobel Prize–winning discovery of high-temperature superconductors. Since then, solid-state physicists keep finding unexpected properties in these materials—including colossal magnetoresistance, in which small changes in applied magnetic fields 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.

# Outline



Origin of the conductivity

FE control of the electronic properties

Electronic structure

Superconductivity

Exciting developments

# The «Geneva» $LaAlO_3/SrTiO_3$ Team

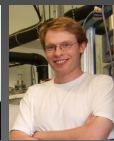
Stefano Gariglio

Margherita Boselli

Adrien Waelchli

Gernot Scheerer

Andrea Caviglia
(now in Delft)



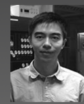
Nicolas Reyren
(CNRS Paris)

Claudia Cancellieri
(EMPA)

Daniela Stornaiuolo
(Naples)

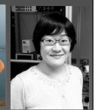
Wei Liu
(KLA-Tencor US)

Alexandre Fête
(Rolex)



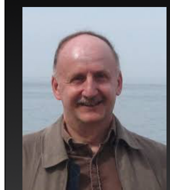
Zhenping Wu
( Beijing)

Denver Li
(Stanford)



Ritsuko Eguchi
(Okayama)

# and collaboration with



Marc Gabay (Orsay)

Philippe Ghosez (Liège)

Jochen Mannhart
(MPI Stuttgart)

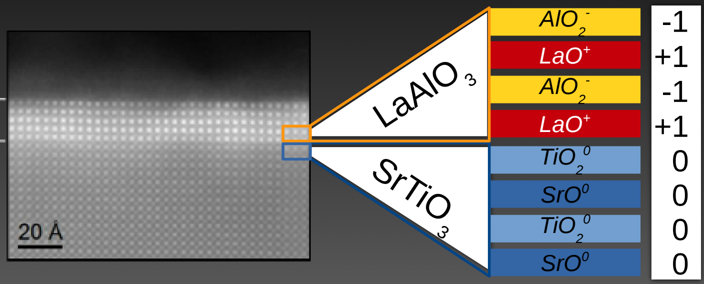
Alexey
Kuzmenko

Dirk
van der Marel

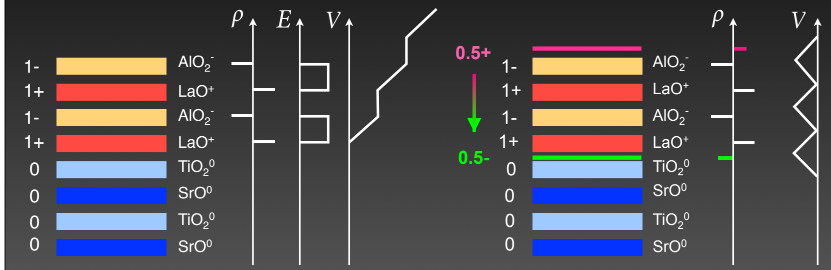
and their groups

# Why is the Interface Conducting?

# The polar catastrophe scenario




# The polar catastrophe scenario

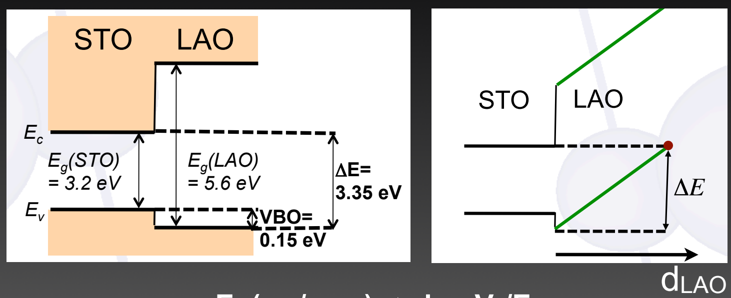



$3\ 10^{14}$ e/cm$^2$

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

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

# Testing the polar catastrophe scenario

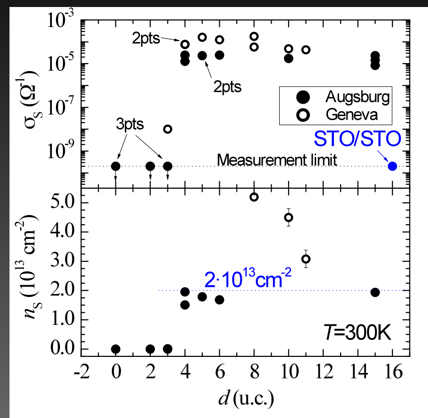



$E=(\sigma_0 / \varepsilon_r\, \varepsilon_0) \Rightarrow d_c = V_c/E$

with $V_c$=3.35 V, $\sigma_0 = 3\ 10^{14}$ e/cm$^2$ and $\varepsilon_r$=25, $d_c$ = 3.5 u.c.

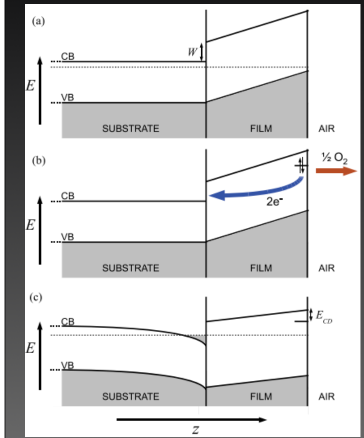
See also R. Pentcheva and W. Pickett PRL 102, 107602 (2007)

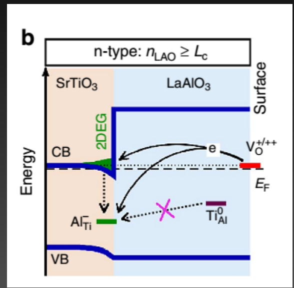
# $LaAlO_3$ critical thickness




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)

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# A lot of work here in France

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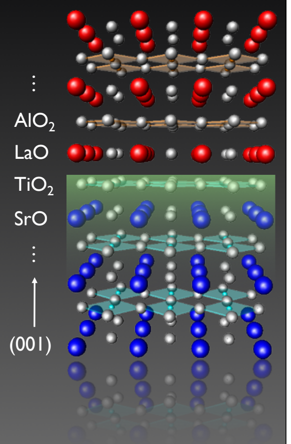
# Doping Control - Electric Field Effect

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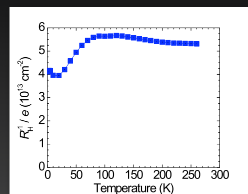
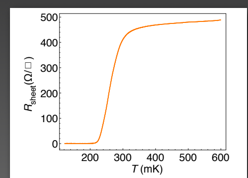
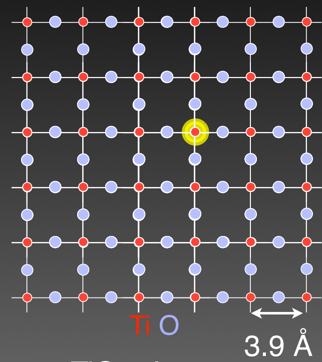
# Doping control using the field effect




$TiO_2$-plane

~2-8×$10^{13}$/cm$^2$

mobilities 100-1000 cm$^2$/Vs

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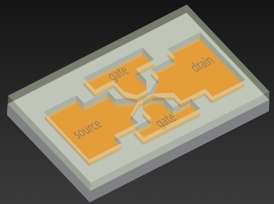
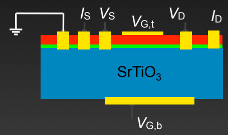
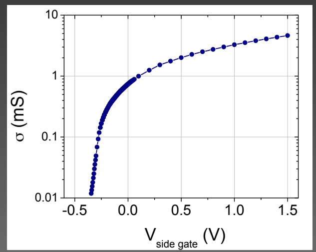
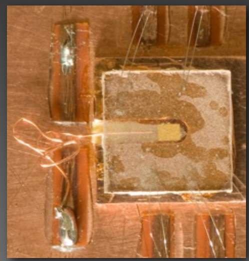
# Transport and field effect control



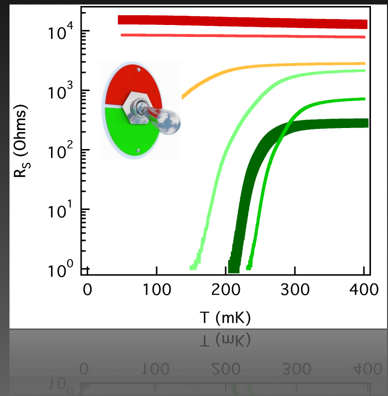



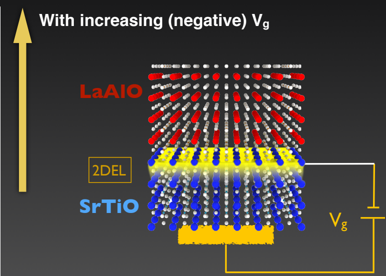



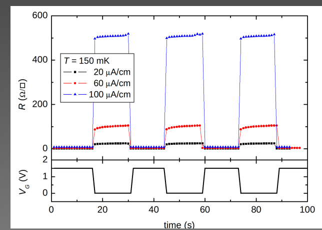
Side gating



# A superconducting switch



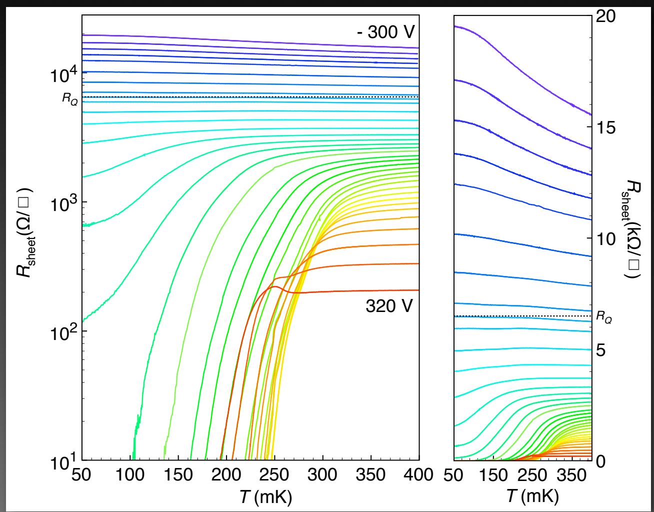




A.D. Caviglia et al. Nature **456**, 624 (2008)



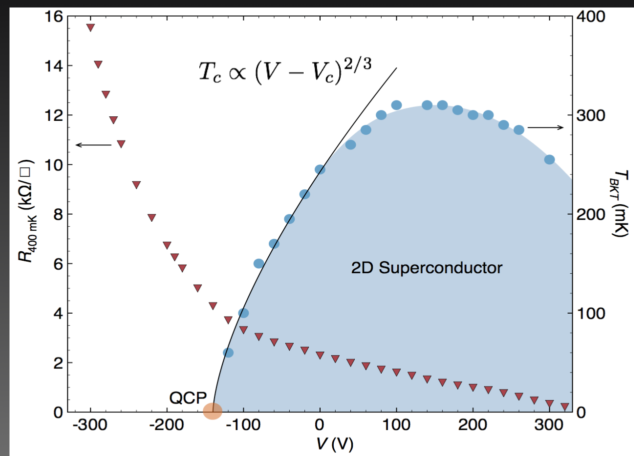
# Modulation of SC




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



# System phase diagram




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

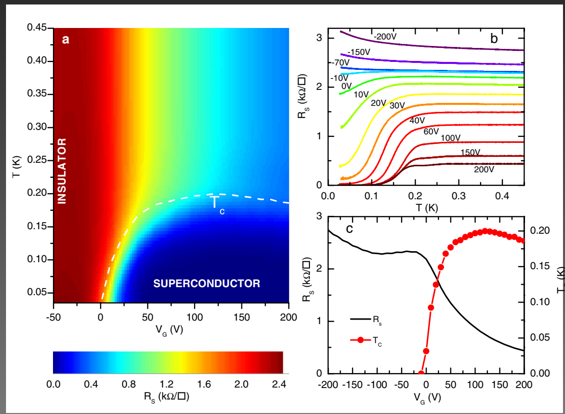
# Other conducting oxide interfaces

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




N. Bergeal
J. Lesueur
ESPCI

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# Quantum Confinement

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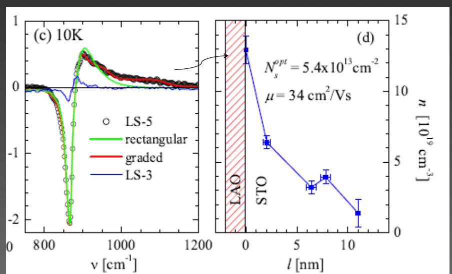
# Confinement and electronic structure

**RT d<7nm**

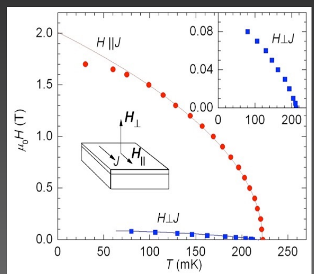
**12 nm at low T**


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**

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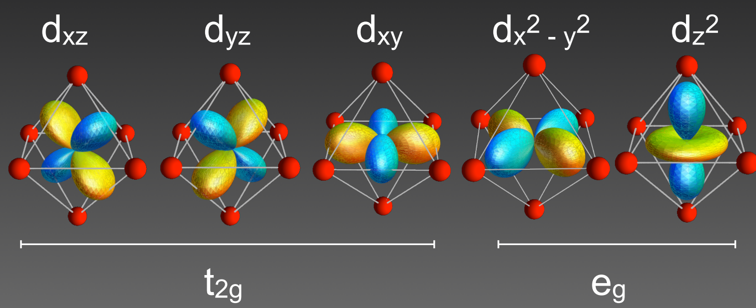
# At the interface, the electrons are on the $SrTiO_3$ side, in the Ti 3d band

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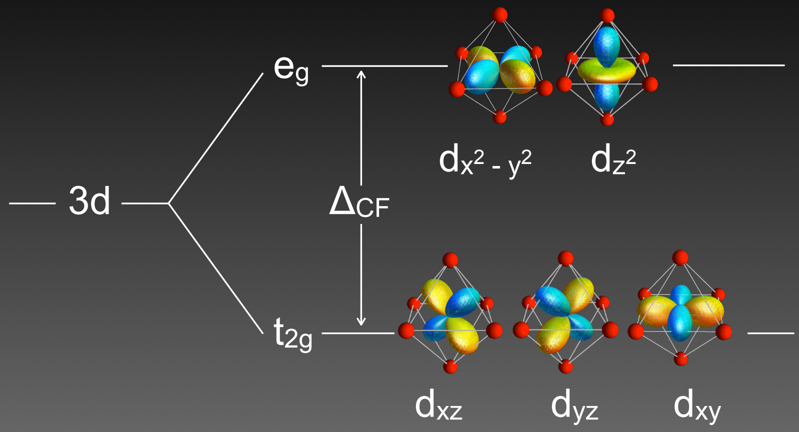
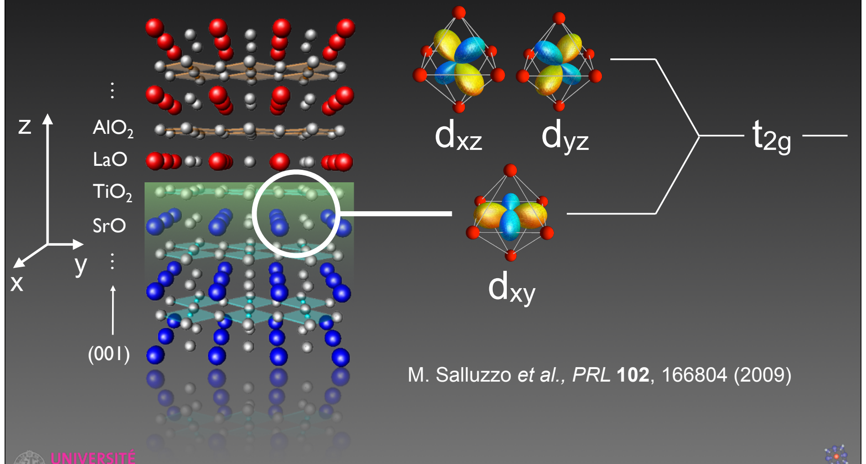
# $t_{2g}$-$e_g$ splitting and crystal field




Electrons are in $t_{2g}$ orbitals



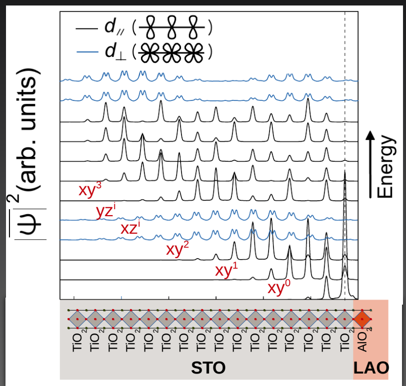
# Confinement and electronic structure



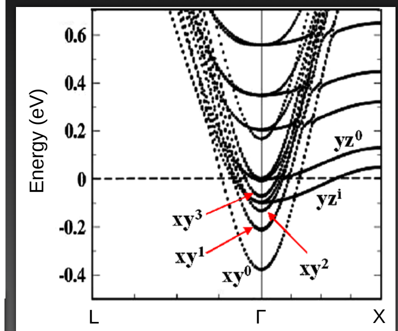

M. Salluzzo *et al.*, *PRL* **102**, 166804 (2009)



# Confinement and electronic structure




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

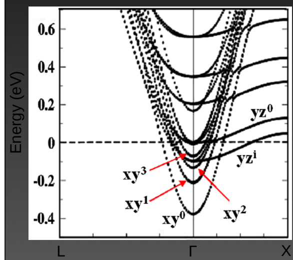


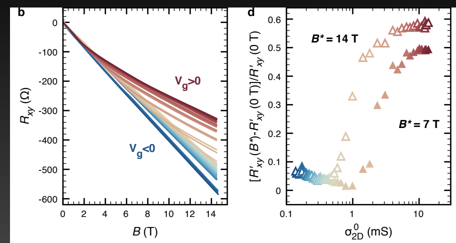

$n_s$=3.3 $10^{14}$ $cm^{-2}$

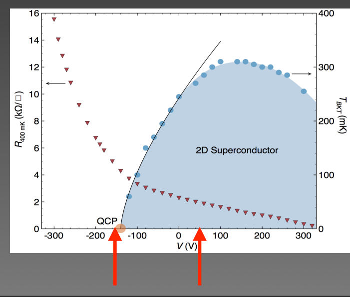
Delugas *et al.*, PRL **106**, 166807 (2011)



# Multi-bands behavior



# Bulk and Interface Superconductivity



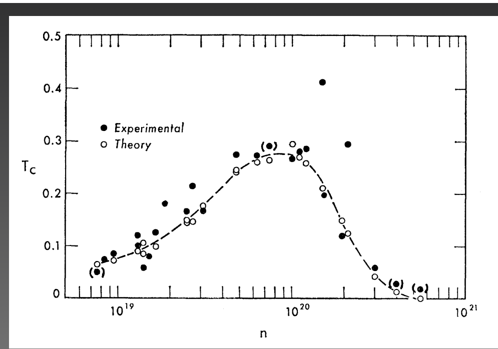
# Superconductivity in bulk $SrTiO_3$

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.

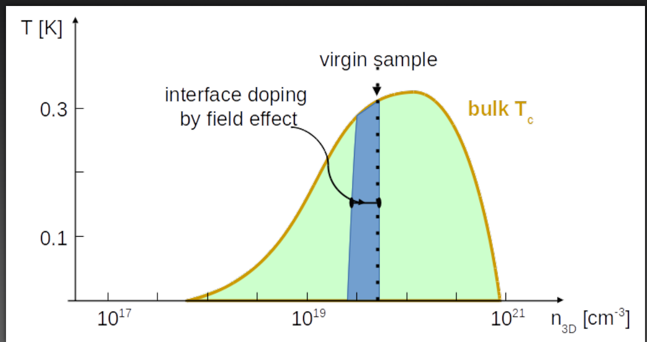
(Received 5 July 1967)




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

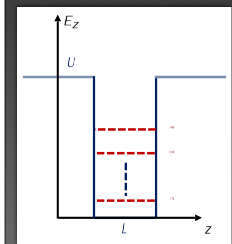


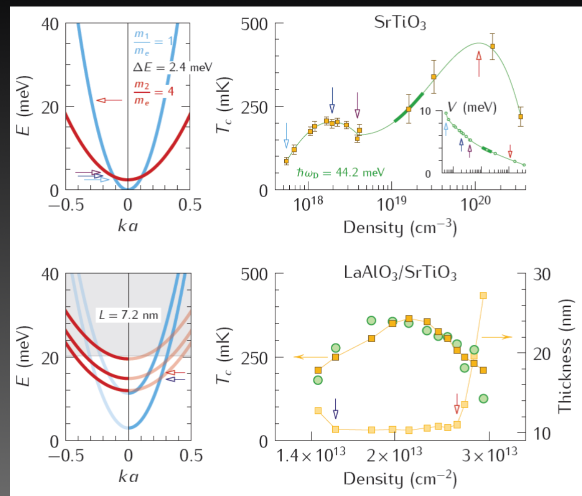
# Bulk and interface SC






# Bulk and interface SC




D. Valentinis et al. PRB **96**, 094518 (2017)
Bulk data from X. Lin et al. PRL **112**, 207002 (2014)

# Some open questions:

# Superconductivity in $SrTiO_3$

# The Possible Role of Spin-orbit

# The Underdoped Regime

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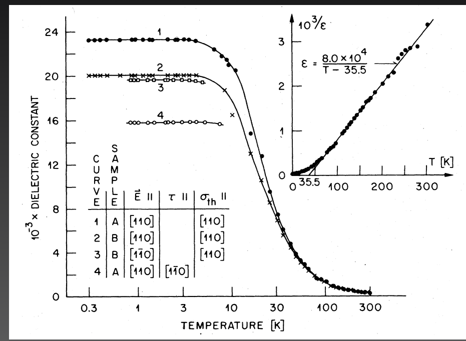
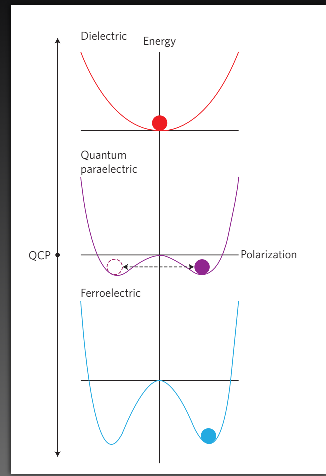
MaNEP

# $SrTiO_3$ - a quantum paraelectric




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




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

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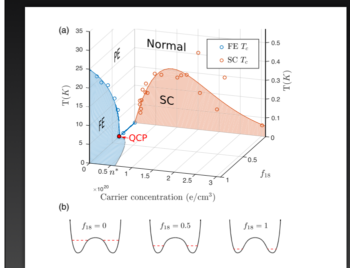
# Origin of the SC state



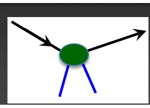

Proximity to a QCP- ferroelectric fluctuations
J.M. Edge et al. PRL **115**, 247002 (2015)

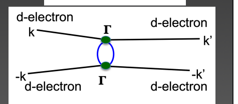
**A possible mechanism for superconductivity in doped $SrTiO_3$**

D. van der Marel, F. Barantani, C. W. Rischau[1]

[1]Department of Quantum Matter Physics, University of Geneva, 24 Quai Ernest-Ansermet, 1211 Geneva 4, Switzerland

Preprint
Pairing through the exchange of two TO phonons






Superconductivity in the vicinity of a ferroelectric quantum phase transition

S. E. Rowley[1,2,*], C. Enderlein[2,3,*], J. Ferreira de Oliveira[2], D. A. Tompsett[1], E. Baggio Saitovitch[2], S. S. Saxena[1,4,*] and G. G. Lonzarich[1,*]

Preprint
$T_c$ decreases with P and the increase of the frequency of the soft TO polar phonon mode - pairing through hybrid longitudinal modes

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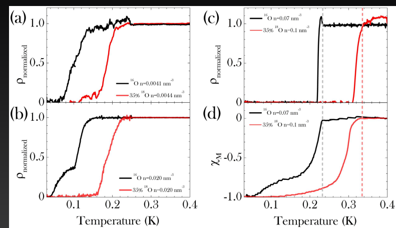
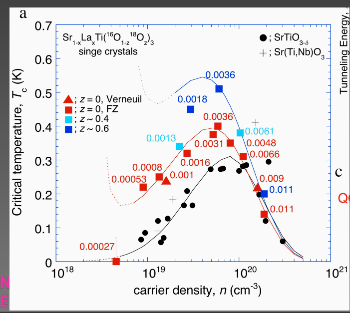
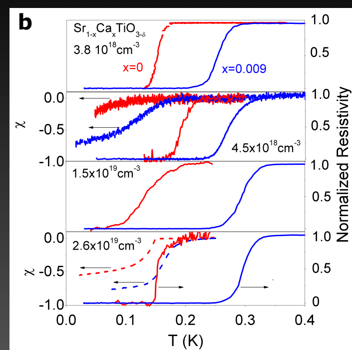
# $O^{18}$-$O^{16}$




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




# Ca-doped




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

H. Tomioka et al. Nat. Comm. **10**, 738 (2019)
La-doped $SrTiO_3$ -$O^{16}$-$O^{18}$
$T_c$ around 0.5K

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## Spin-orbit Coupling

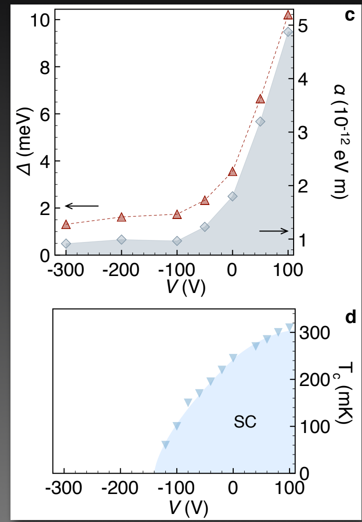


## Very large tunable spin-orbit coupling

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

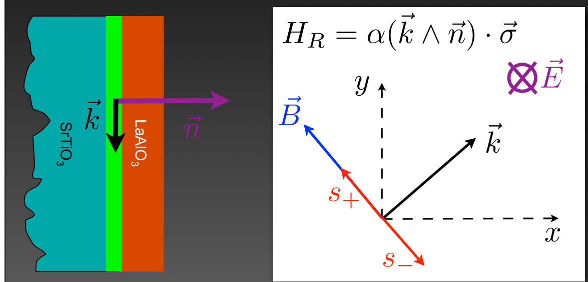
$$\Delta = 2\alpha k_F$$

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






## Rashba spin-orbit coupling



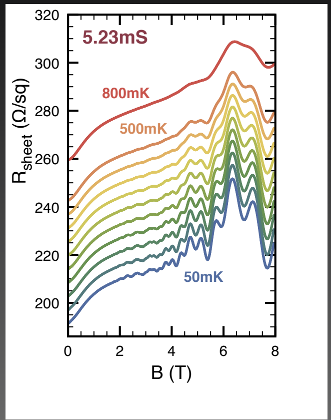

The electrons experience an internal magnetic field oriented in the 2DEL plane

Role of spin-orbit coupling on superconductivity?

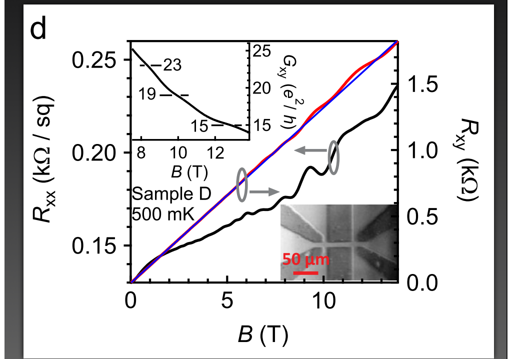


## Exciting Developments

## High mobility samples

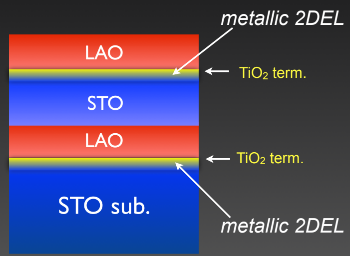


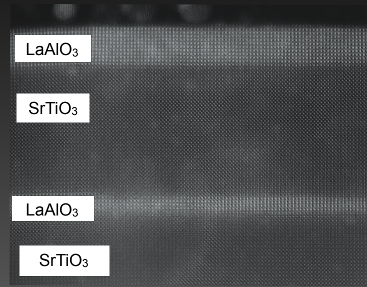

A. Fête et al. New Journal of Physics **16**, 112002 (2014)




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

## Bi-interfaces

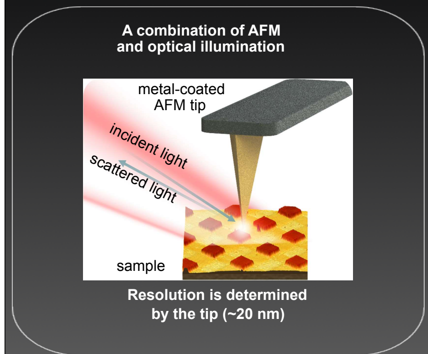


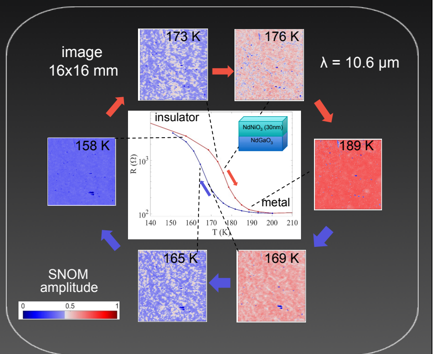




G. Tieri, A. Gloter, O. Stephan (Orsay)

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

## Imaging the 2DES using Cryo-SNOM



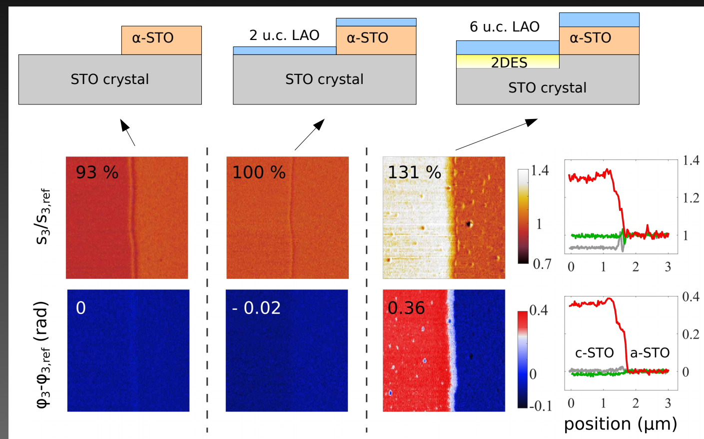




**Cryogenic Scanning Near-Field Optical Microscope (Cryo-SNOM)**

D. van der Marel's group, A. Kuzmenko and W. Luo (University of Geneva)

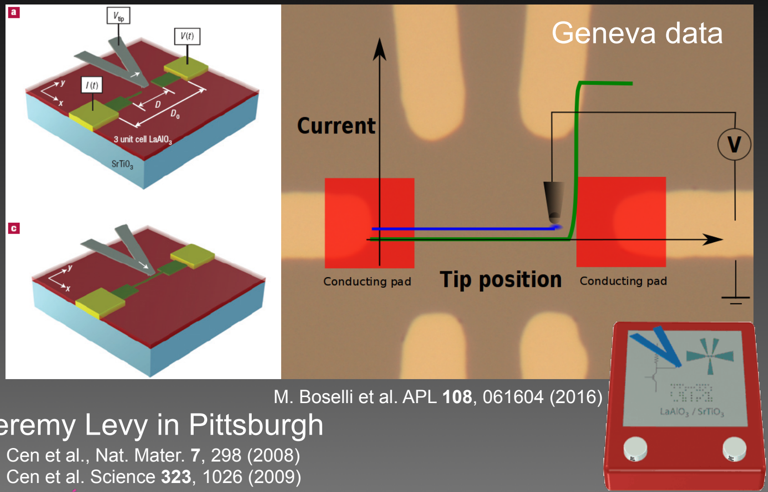
- See also K.W. Post et al. Nat. Phys. (2018)
- PEEM, see G. Mattoni et al., Nat. Comm. 7, 13141 (2016)

## Imaging the 2D conducting interface




- W. Luo, M. Boselli et al. 2019, Nature Com. (2019)

# Writing nanoscale electronic circuits




M. Boselli et al. APL **108**, 061604 (2016)

Jeremy Levy in Pittsburgh

C. Cen et al., Nat. Mater. **7**, 298 (2008)

C. Cen et al. Science **323**, 1026 (2009)



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**Science** AAAS

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

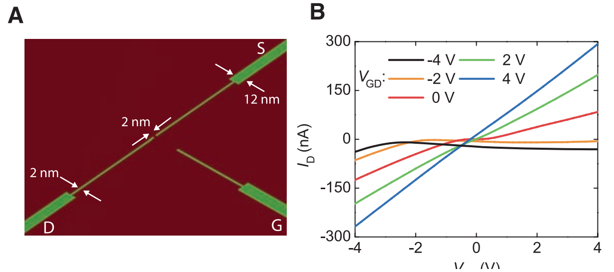


**Fig. 2.** SketchFET device. **(A)** Schematic diagram of SketchFET structure. S, source electrode; D, drain electrode; G, gate electrode. **(B)** *I-V* characteristic between source and drain for different gate biases $V_{GD} = -4$ V, $-2$ V, 0 V, 2 V, and 4 V. **(C)** Intensity plot of $I_D$ ($V_{SD}$,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



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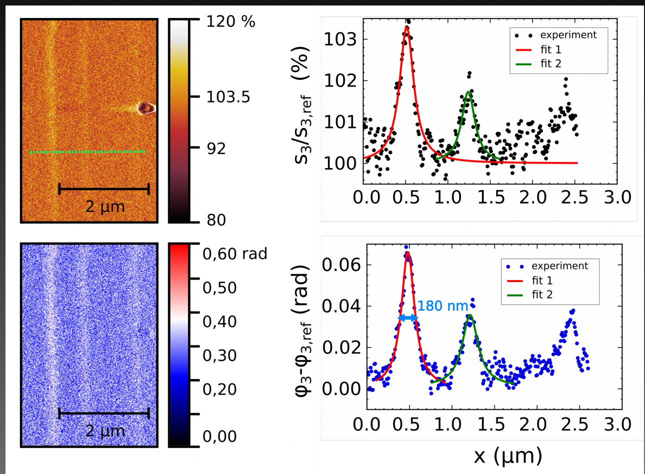
# Imaging AFM written nanowire




- W. Luo, M. Boselli et al. 2019, Nature Com. (2019)



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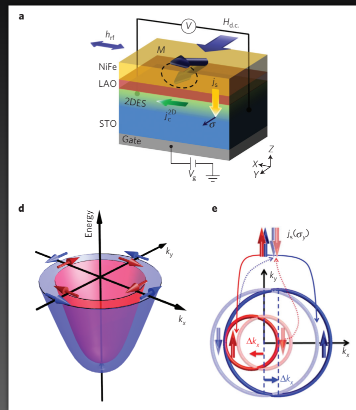
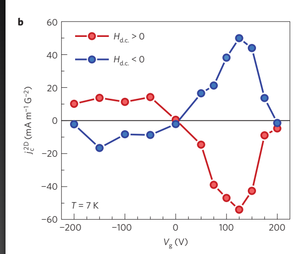
# Inverse Rashba-Edelstein effect




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

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

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

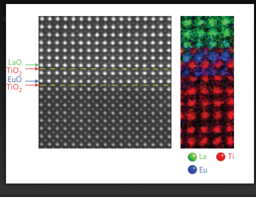
# A spin-polarized 2DEL

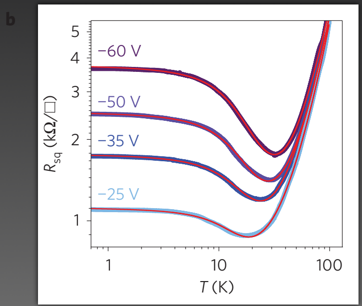
## Naples group

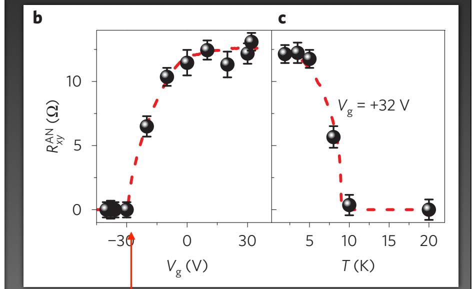
nature materials — LETTERS
PUBLISHED ONLINE: 7 DECEMBER 2015 | DOI: 10.1038/NMAT4491

**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

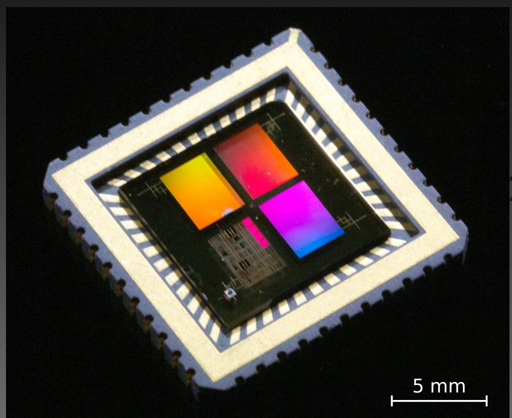
# Beyond silicon?

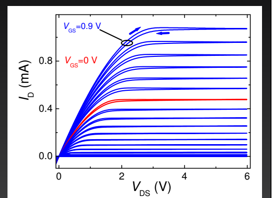
1947 Bell Labs

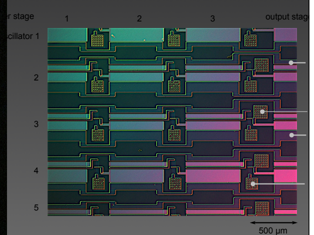
2009 UNIGE

# A new oxide electronics?

## 2009-2014 - a million transistors

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J. Mannhart - MPI Stuttgart

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