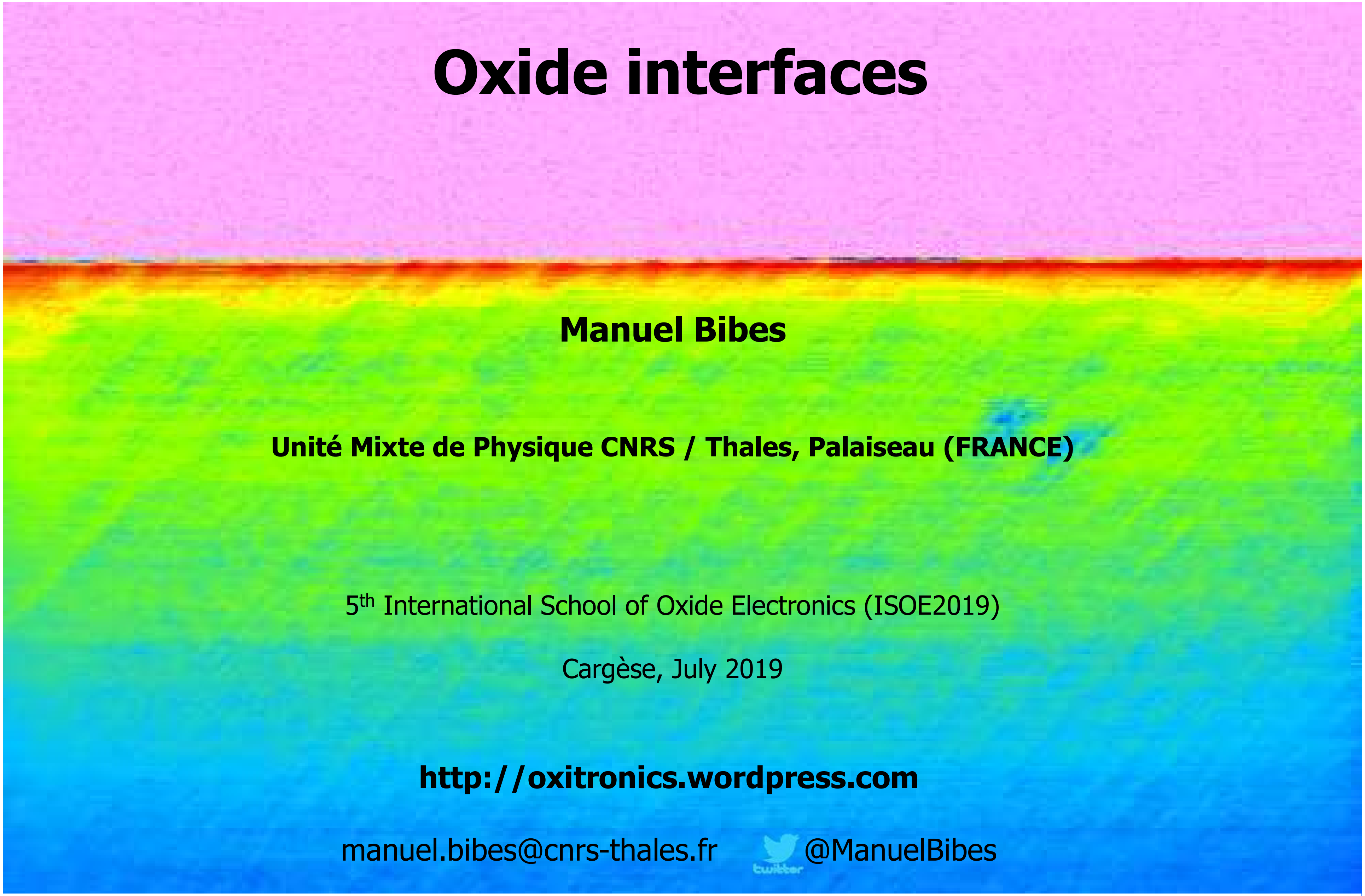

Oxide interfaces

Manuel Bibes

Unité Mixte de Physique CNRS / Thales, Palaiseau (FRANCE)

5th International School of Oxide Electronics (ISOE2019)

Cargèse, July 2019

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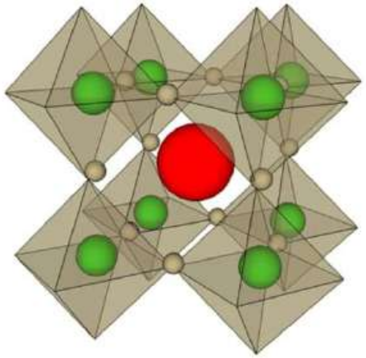
Introduction

Transition metal perovskite oxides

ABO_3



- Very **flexible** structure
  doping, tuning of bond lengths and angles
- Broad range of **electronic states**
  superconductivity, ferroelectricity, magnetic order, orbital order
- Competition : **giant/coupled responses**
  colossal magnetoresistance, magnetoelectric coupling
- Multifunctional heteroepitaxial architectures

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Transition metal perovskite oxides

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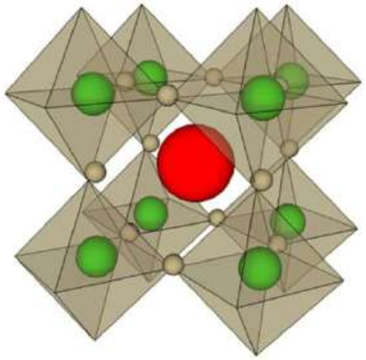

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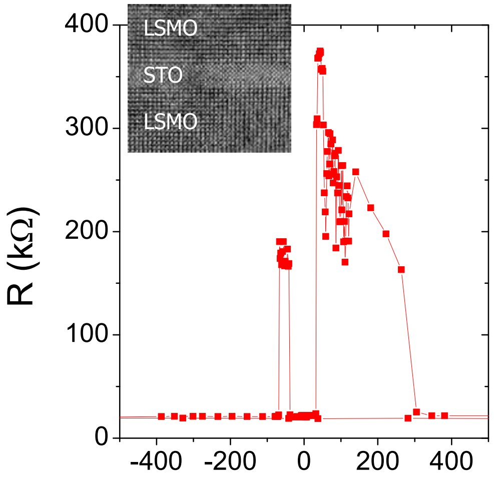
MTJs based on La$_{2/3}$Sr$_{1/3}$MnO$_3$

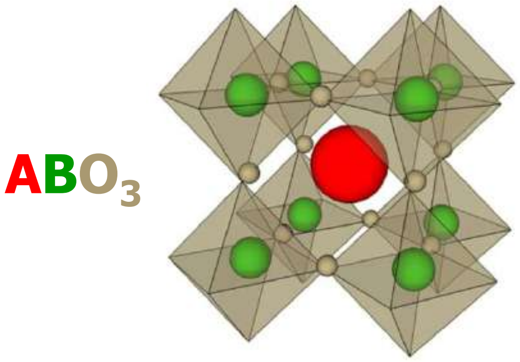


➔ Record TMR >1800%

APL 82, 233 (2003)

Introduction

Transition metal perovskite oxides



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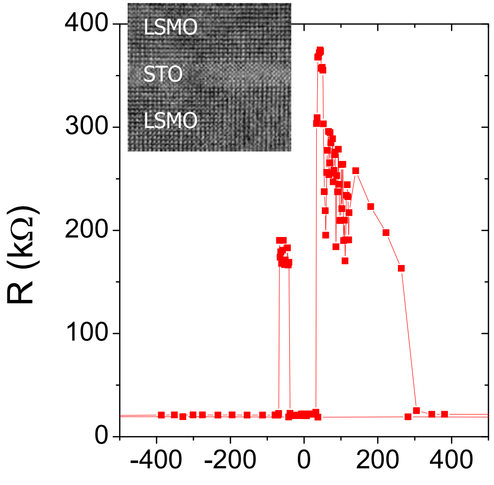

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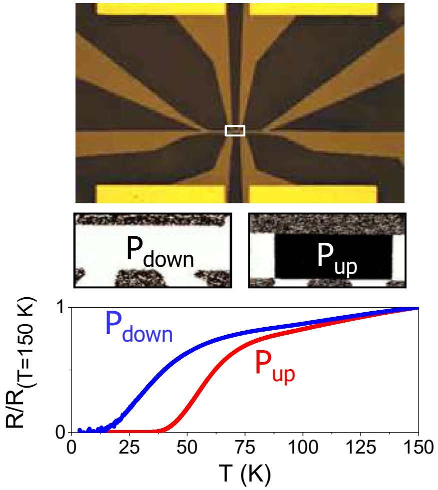
APL 82, 233 (2003)

Ferroelectric FETs based on in $YBa_2CuO_7/BiFeO_3$

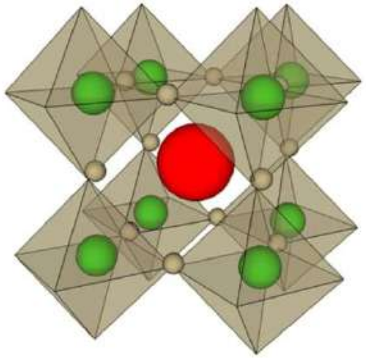


➔ Non-volatile control of SC

PRL 107, 247002 (2011)

Introduction

Transition metal perovskite oxides



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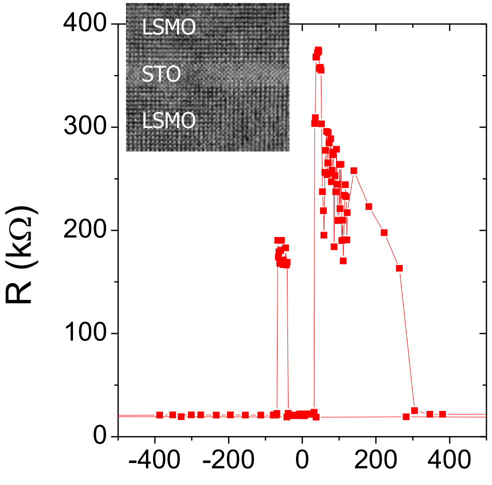

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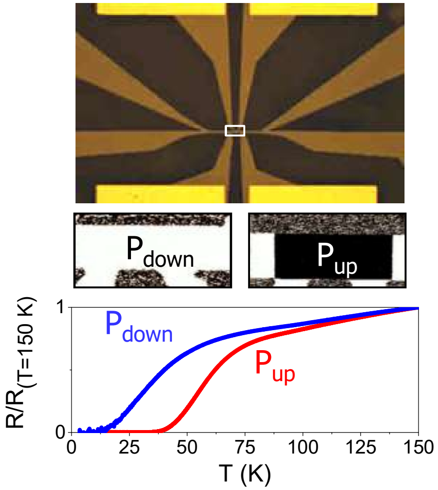
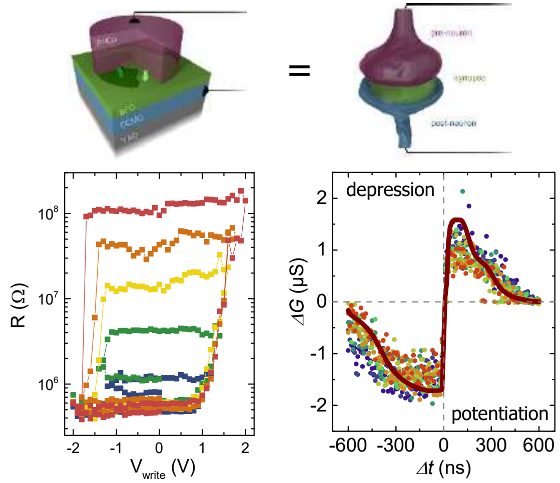


➔ Non-volatile control of SC

PRL 107, 247002 (2011)

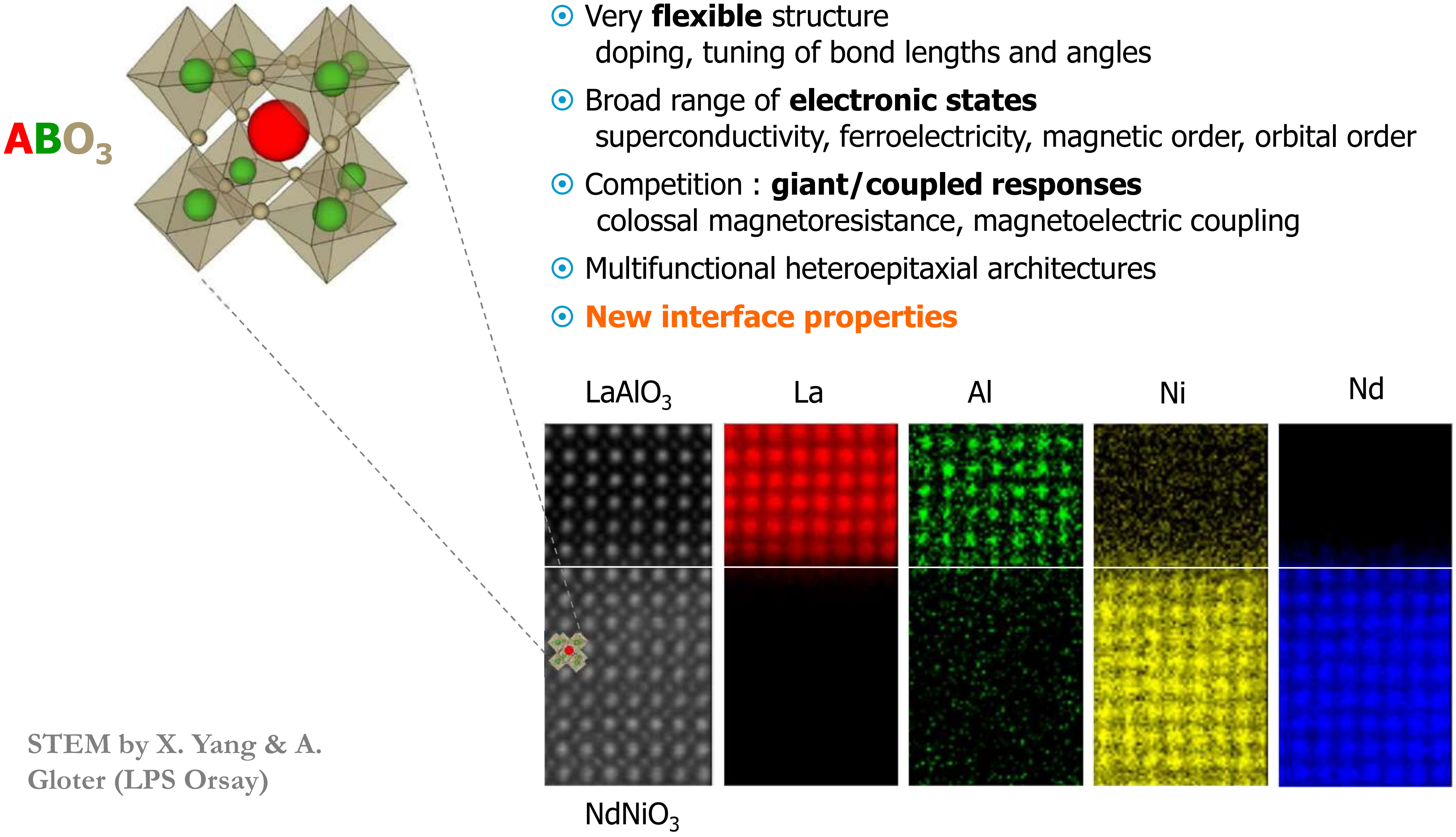
Electronic synapses based on (Ca,Ce)MnO$_3$/BiFeO$_3$ FTJs



➔ Memristive response + learning

Nature 460, 81 (2009) ; Nature Mater. 11, 860 (2012) ; Nature Comm. 8, 14736 (2017)

Transition metal perovskite oxides



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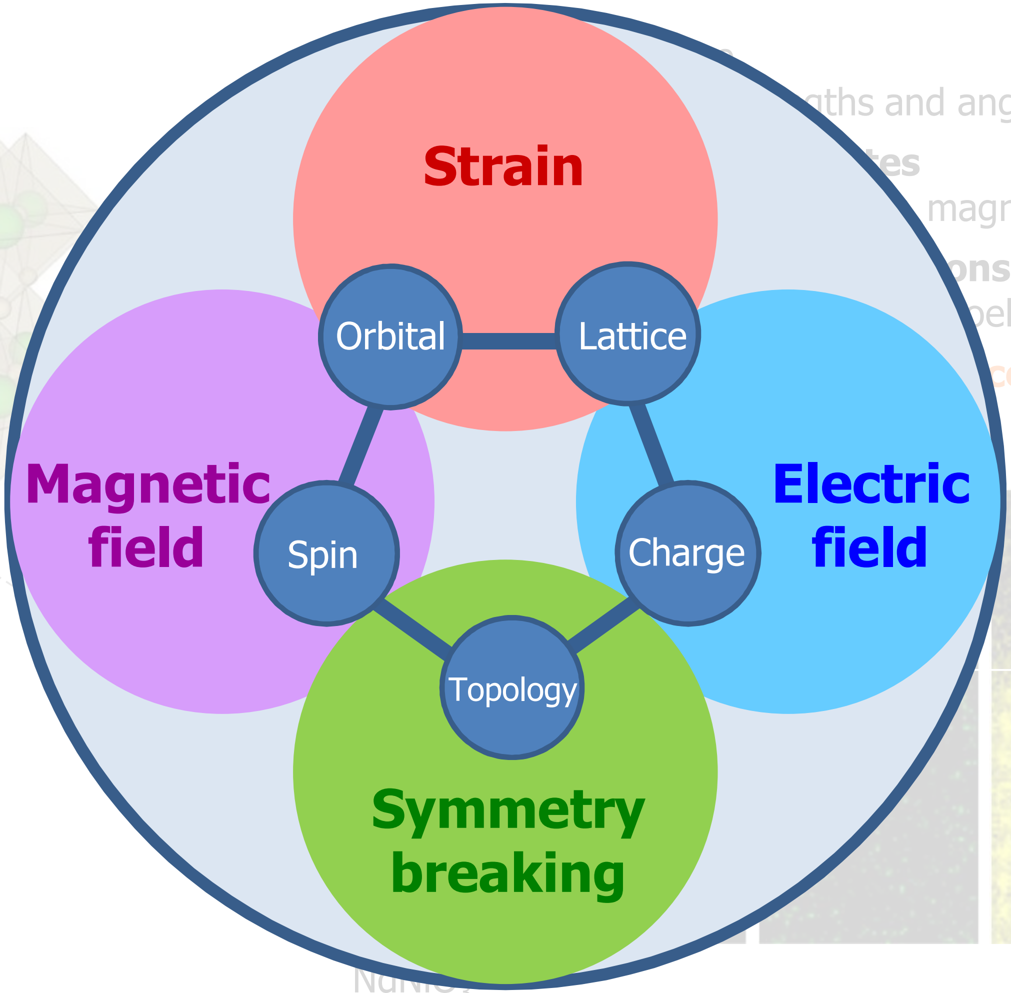
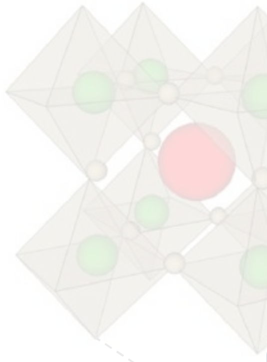
- **New interface properties**

STEM by X. Yang & A. Gloter (LPS Orsay)

➔ **Atomically sharp**

Oxide interfaces : new playground for physicists





gths and angles

tes

magnetic order, orbital order

onses

electric coupling

ces

→ Atomically sharp

STEM by X. Yang & A. Gloter (LPS Orsay)

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1. d_0-oxide-based interfaces

   1.1 Physics of bulk $SrTiO_3$

   1.2 $LaAlO_3/SrTiO_3$ 2DEGs

   1.3 Other $SrTiO_3$ 2DEGs

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   2.1 « Correlated » oxide perovskites

   2.2 Nickelate/Titanate interfaces

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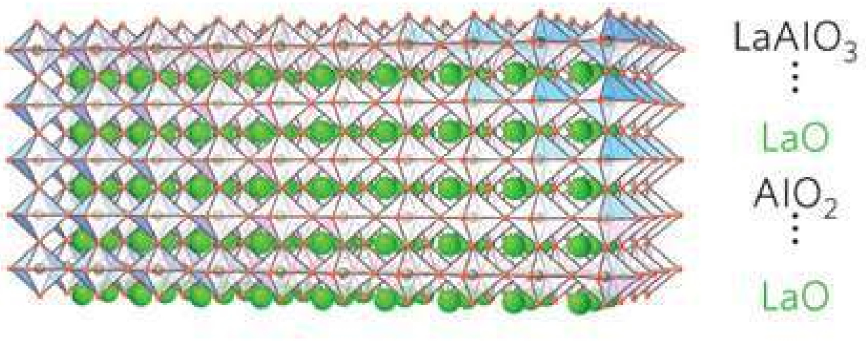
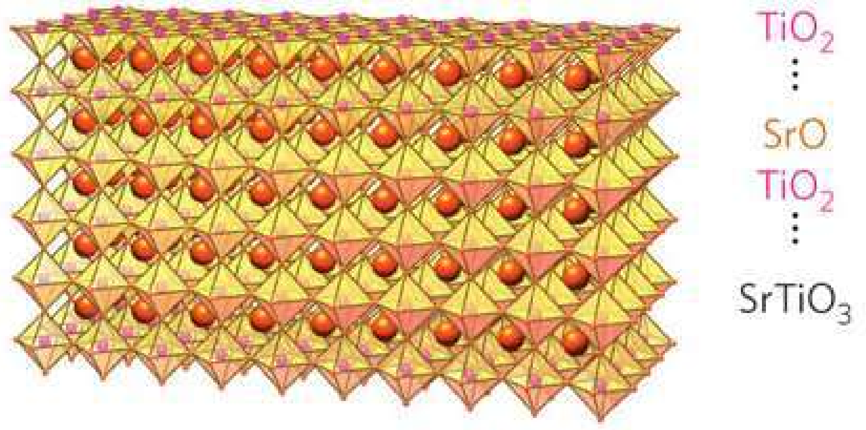
An unexpected discovery





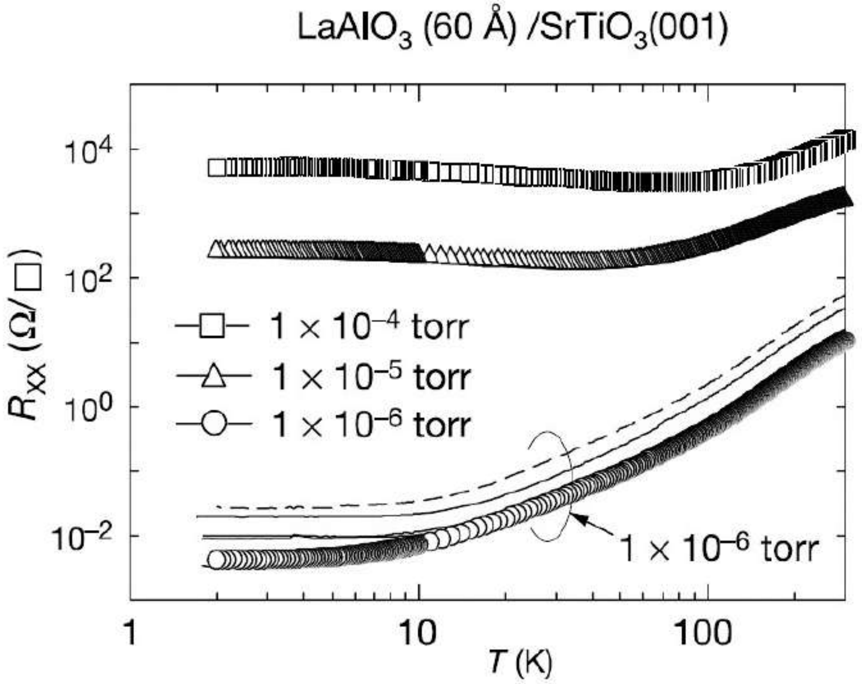
$LaAlO_3$ (LAO)
thin film
(Δ = 5.6 eV)

$SrTiO_3$ (STO)
substrate
(Δ = 3.2 eV)

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

A. Ohtomo[1,2,3] **& H. Y. Hwang**[1,3,4]

[1] *Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974, USA*
[2] *Institute for Materials Research, Tohoku University, Sendai, 980-8577, Japan*
[3] *Japan Science and Technology Agency, Kawaguchi, 332-0012, Japan*
[4] *Department of Advanced Materials Science, University of Tokyo, Kashiwa, Chiba, 277-8651, Japan*



Ohtomo & Hwang, Nature 427, 423 (2004)

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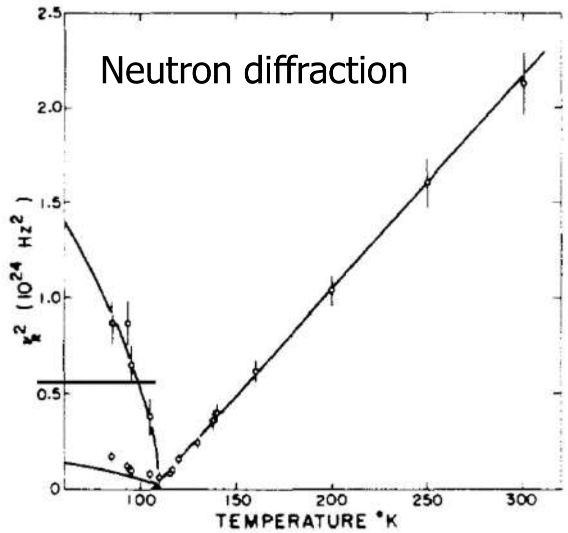
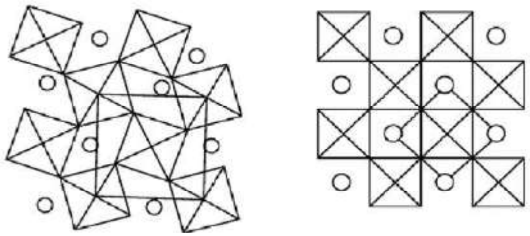
Bulk $SrTiO_3$

Structural properties

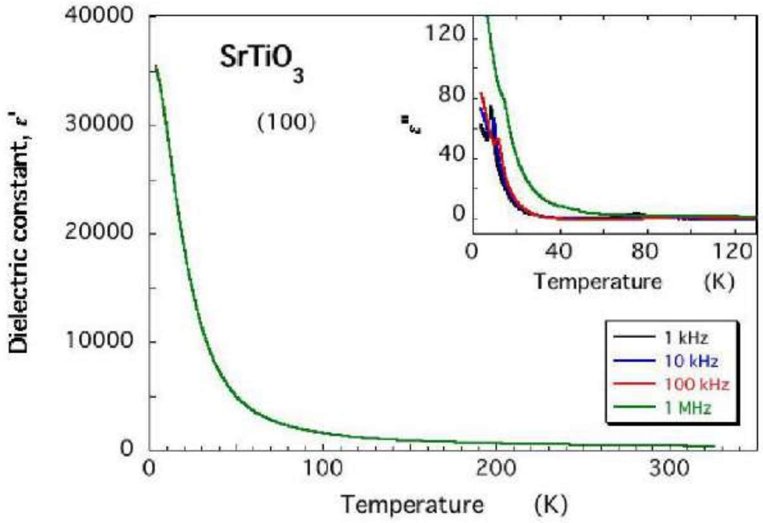


Cowley et al, Solid. State. Commun. 7, 181 (1967)



- ⊙ $SrTiO_3$ is cubic at room temperature and above 105 K
- ⊙ Below 105 K, it is tetragonal, with oxygen octahedra tilt pattern $a^0a^0c^-$

Dielectric properties

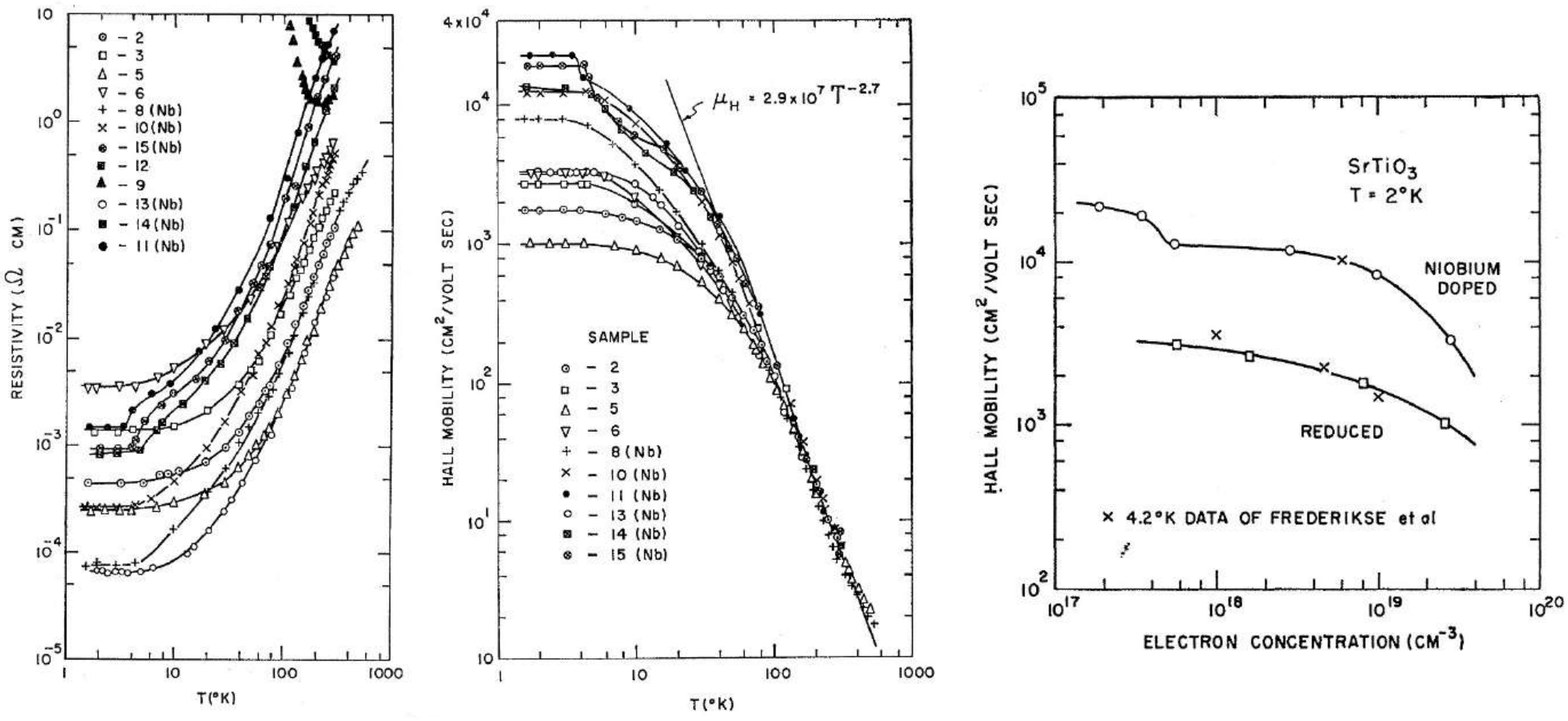


Hideshi et al, JPSJ 85, 045703 (2016)

- ⊙ $SrTiO_3$ has a large dielectric constant that diverges at low temperature
- ⊙ « Quantum paraelectric » : ferroelectric instability suppressed by quantum fluctuations

Bulk $SrTiO_3$

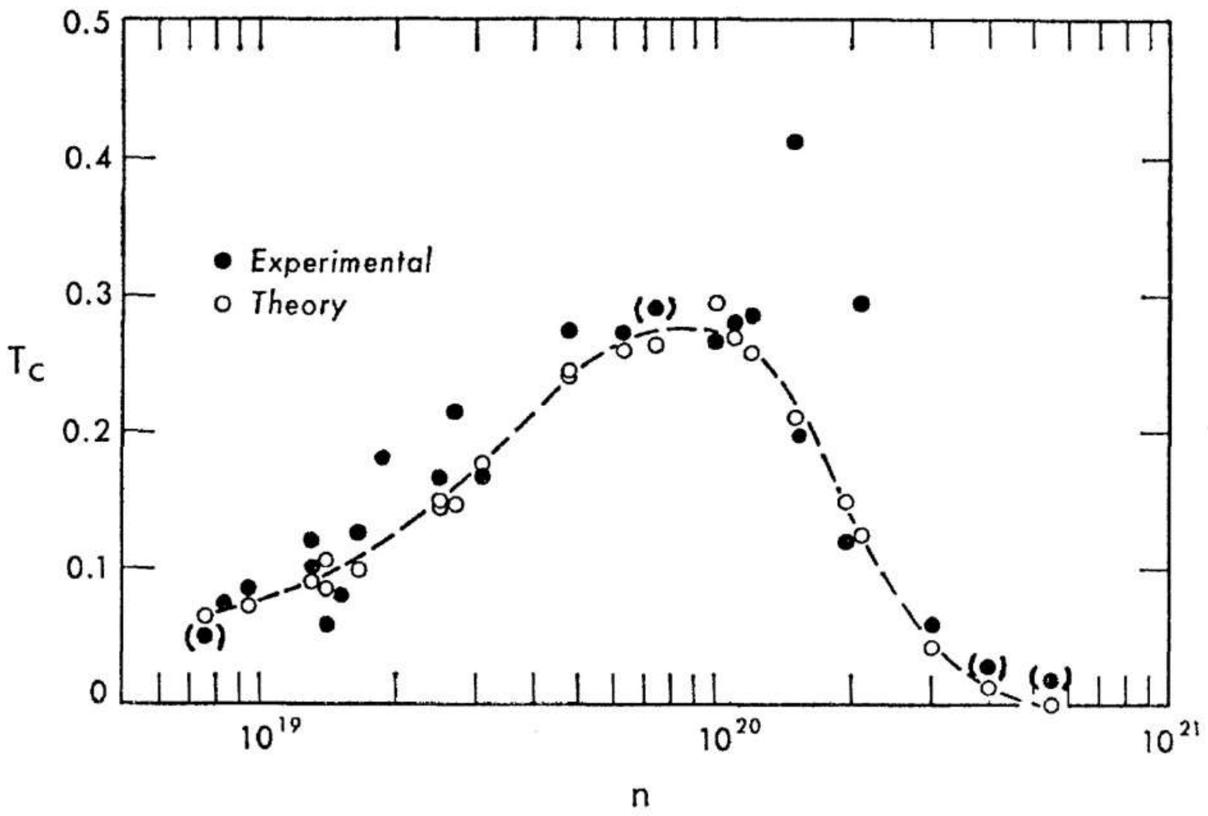
Transport properties of electron doped $SrTiO_3$



- ⊙ $SrTiO_3$ can be (n-type) doped into a metal by La substitution at the Sr site, Nb substitution at the Ti site, or by the creation of oxygen vacancies
- ⊙ Minute doping amounts (e.g. 10 ppm) are enough to induce metallicity
- ⊙ Electron mobility is very high (>10000 cm²/Vs) at low T and decreases with doping

Tufte and Chapman PR 155, 796 (1967)

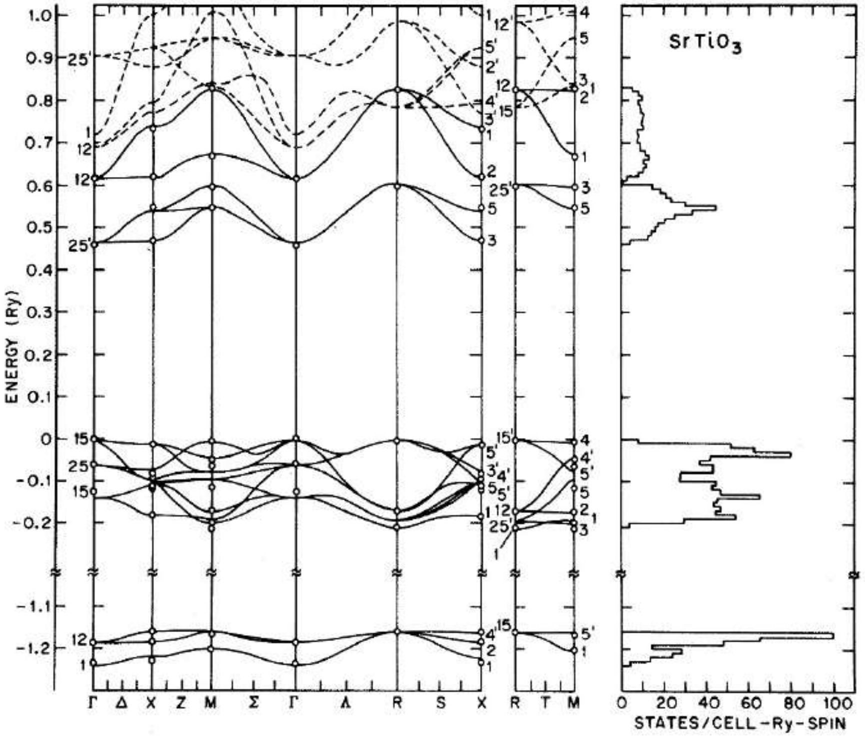
Superconductivity in electron doped $SrTiO_3$



- $SrTiO_3$ becomes superconducting below about 300 mK for doping levels > a few 10^{18} cm-3
- Dome-like phase diagram as in high T_C superconductors

Koonce PR, 163, 780 (1967)

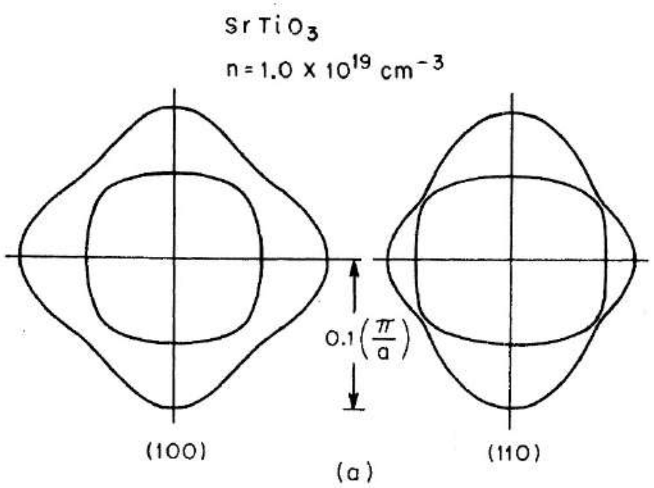
Electronic structure of $SrTiO_3$



Ti t_{2g}

O 2p

Mattheiss PRB 6, 4718 (1972)



- ⊙ $SrTiO_3$ is a band insulator, with the valence band made of O 2p states and the conduction band of Ti 3d t_{2g} states
- ⊙ The gap is at the Gamma point with two degenerate bands with small and large effective masses
- ⊙ The light electron band has a « circular » Fermi surface around Gamma while the heavy electron band consists of a double ellipse.

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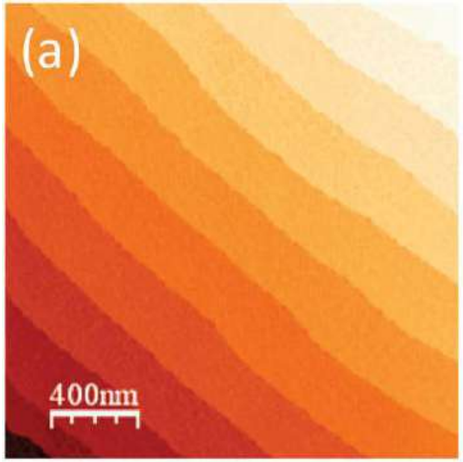
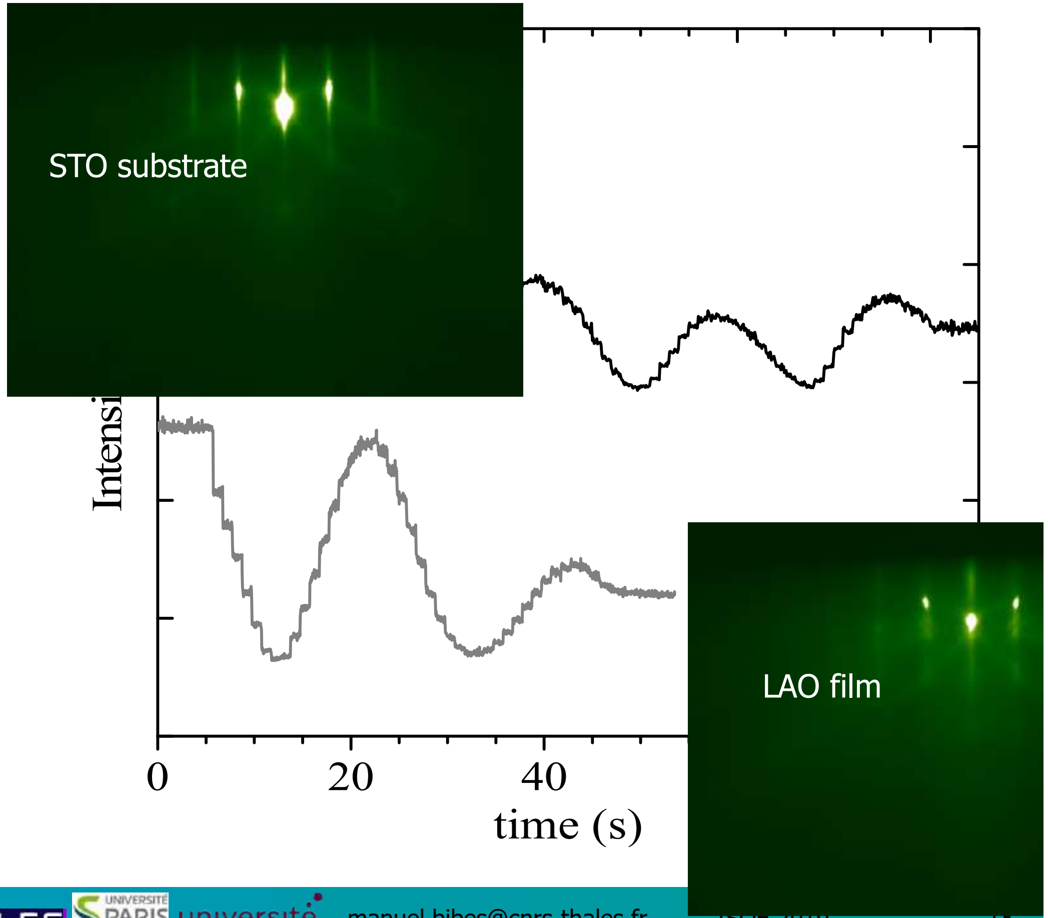
How to grow LAO/STO 2DEGs ?

TiO_2-terminated substrate



PLD growth conditions for $LaAlO_3$

- 700-800°C
- 2 x 10^{-4} mbar of O_2
- KrF excimer (248nm) – 0.6-1.2 J/cm^2 at 1 Hz
- in-situ annealing in high O_2 pressure (0.2-1 bar) at T ≥ 500°C for 30-60’

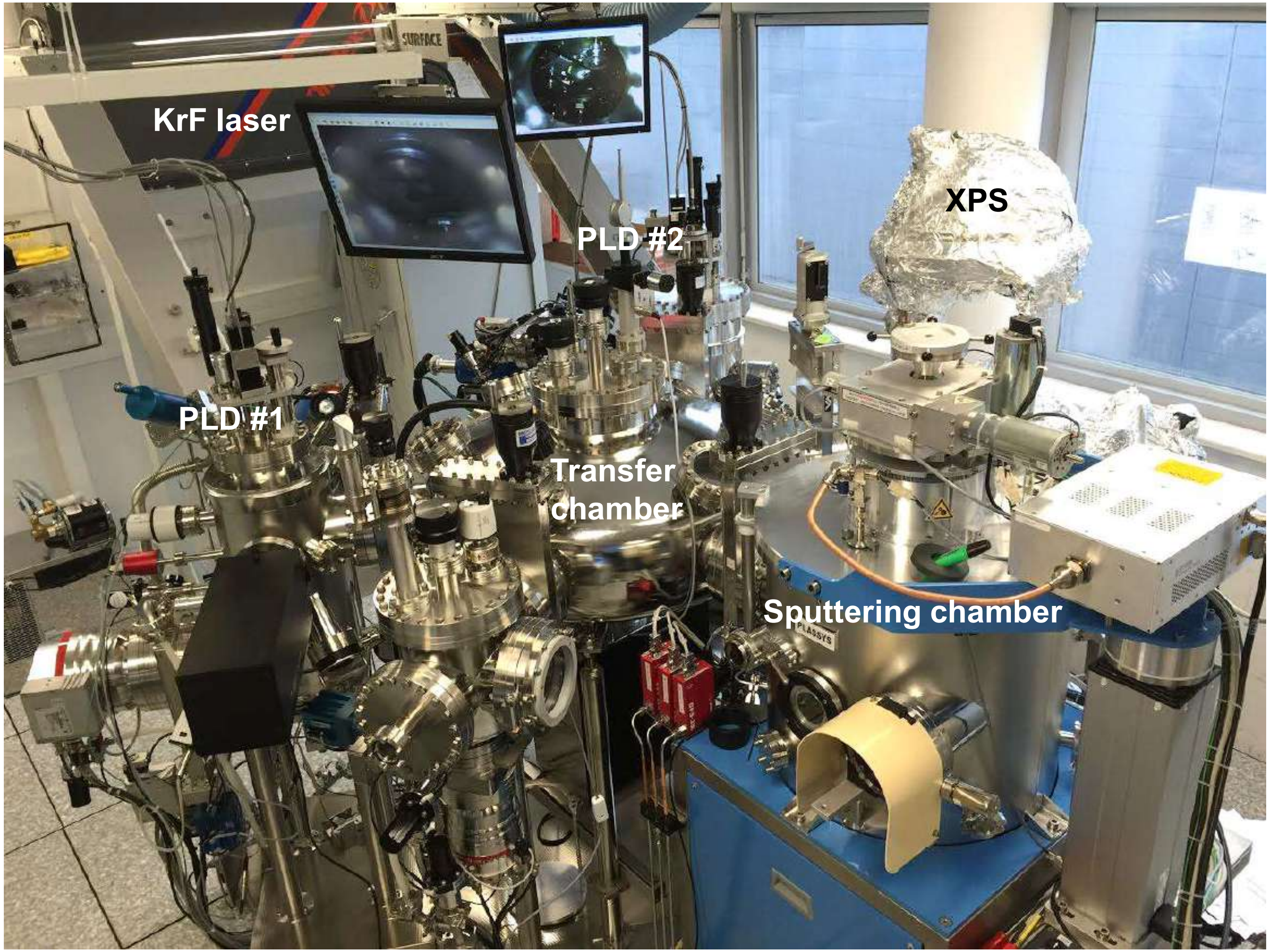


Essential steps:

- Use a TiO_2 terminated STO single crystal
- Grow an integer number of LAO unit cells ≥ 4
- Post-anneal in O_2

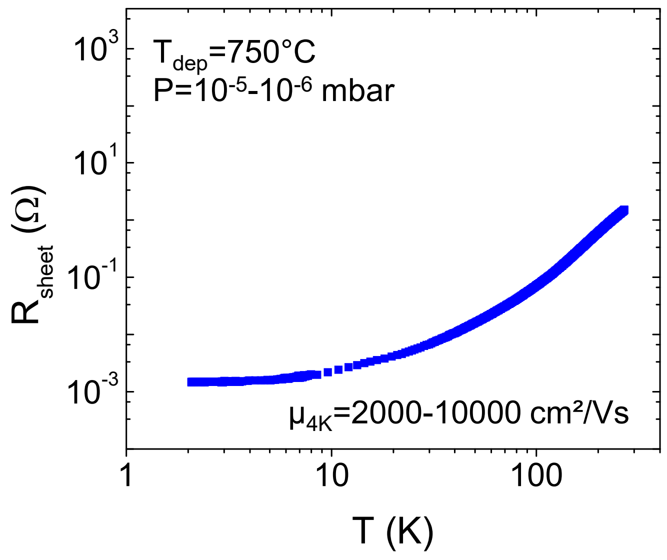
Lesne, MB et al, Nature Comm. 5, 4291 (2014)
Vaz, MB et al, Adv. Mater. 29, 1700486 (2017)

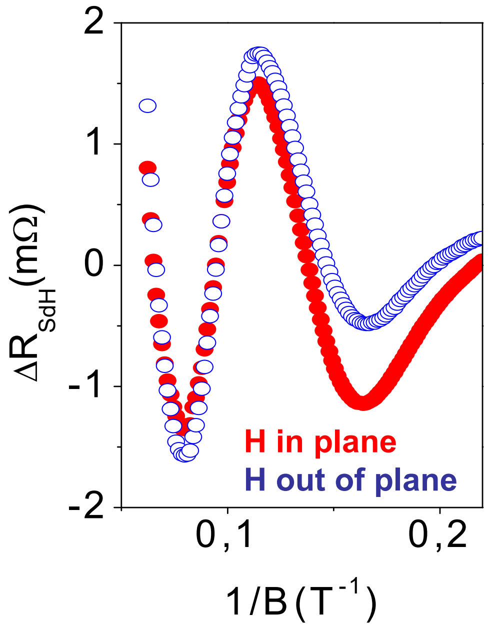
Coupled PLD+sputtering deposition system



Do we really have a 2DEG ? How to measure its thickness ?

Magnetotransport measurements

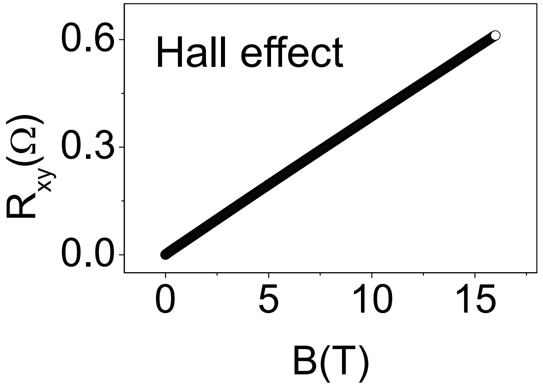




High-field magnetoresistance: Observation of Shubnikov-de Haas oscillations

$$F_{SdH} = \frac{\hbar k_F^2}{2e} \qquad n = \frac{k_F^3}{3\pi^2}$$

SdH oscillations provide the carrier density (cm^{-3})



Hall measurement provide the sheet carrier density (cm^{-2})

$$\text{SdH} \rightarrow \boxed{n} \times \underset{\uparrow}{t_{gas}} = (1/e)\,\boxed{B/R_{xy}} \leftarrow \text{Hall}$$

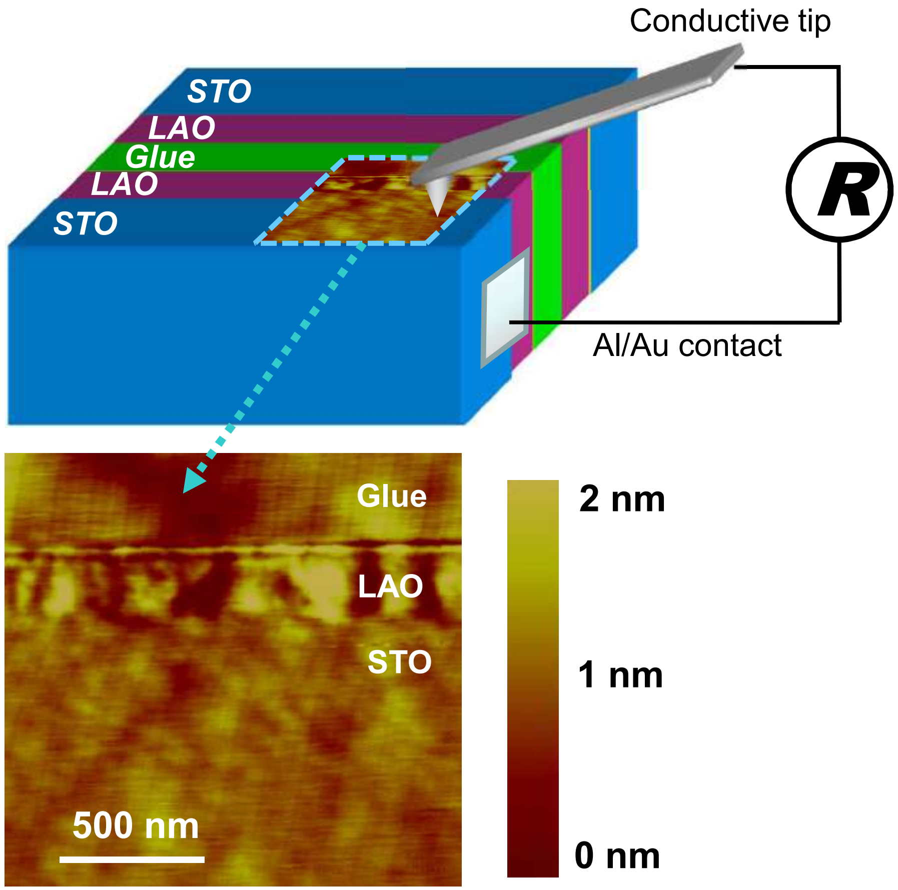
Determination of the electron gas thickness : ~500 µm

Herranz, MB et al, PRL 98, 216803 (2007)

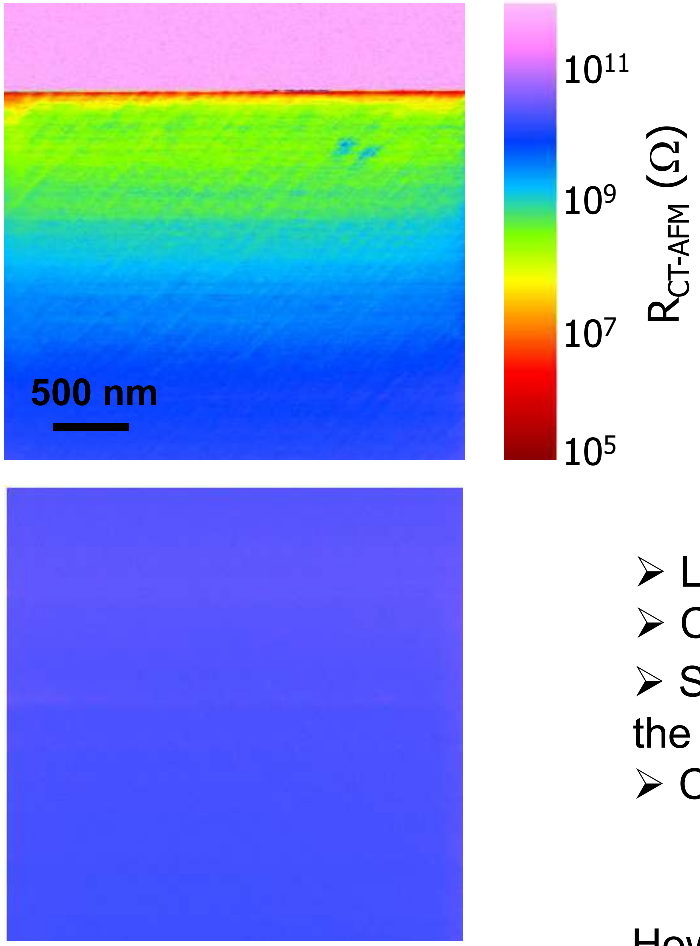
- Metallic behaviour, high mobility, quantum oscillations : nice sample !
- But : electron gas thickness is **500 µm** ! Hint : this sample was **not post-annealed in oxygen**

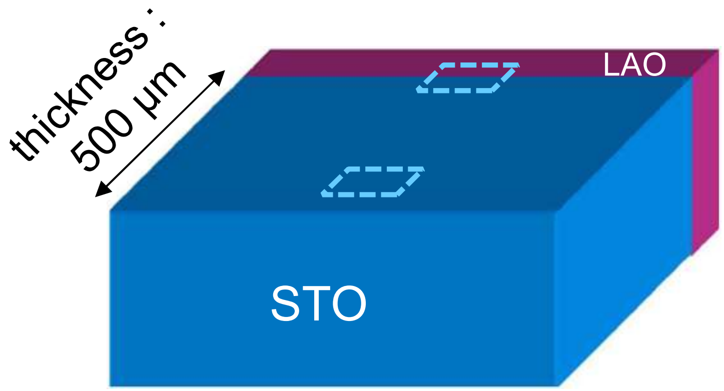
Conductive-tip AFM in cross-section samples

Local measurement of transport properties



Resistance mapping of non-annealed samples





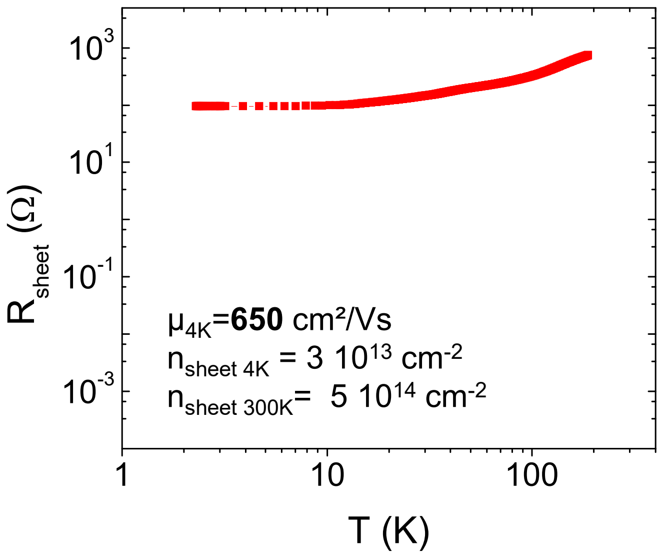
- ➢ Low resistance (~10^6 Ω) at LAO/STO interface
- ➢ Conductance increases over 1-2 µm up to ~5.10^{10} Ω
- ➢ STO substrate is conductive far away (500 µm) from the interface
- ➢ Confirmation of SdH results

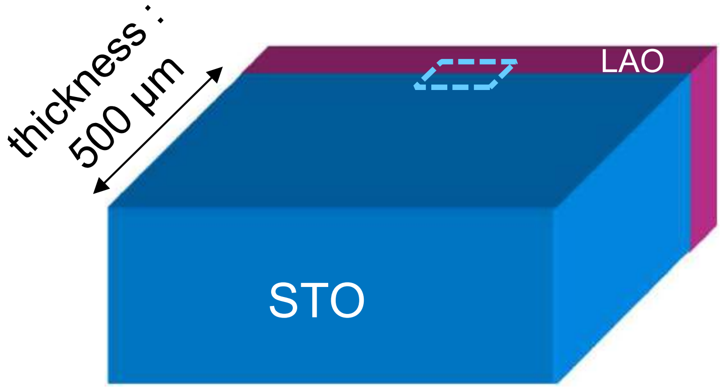
How to isolate the large conductivity at the interface ?
Get rid of oxygen vacancies : in-situ annealing

(as in Thiel et al, Science 313, 1942 (2006); Reyren et al, Science 317, 1196 (2007))

Basletic, MB, et al Nature Mater. 7, 621 (2008)

Resistance mapping of in-situ annealed sample





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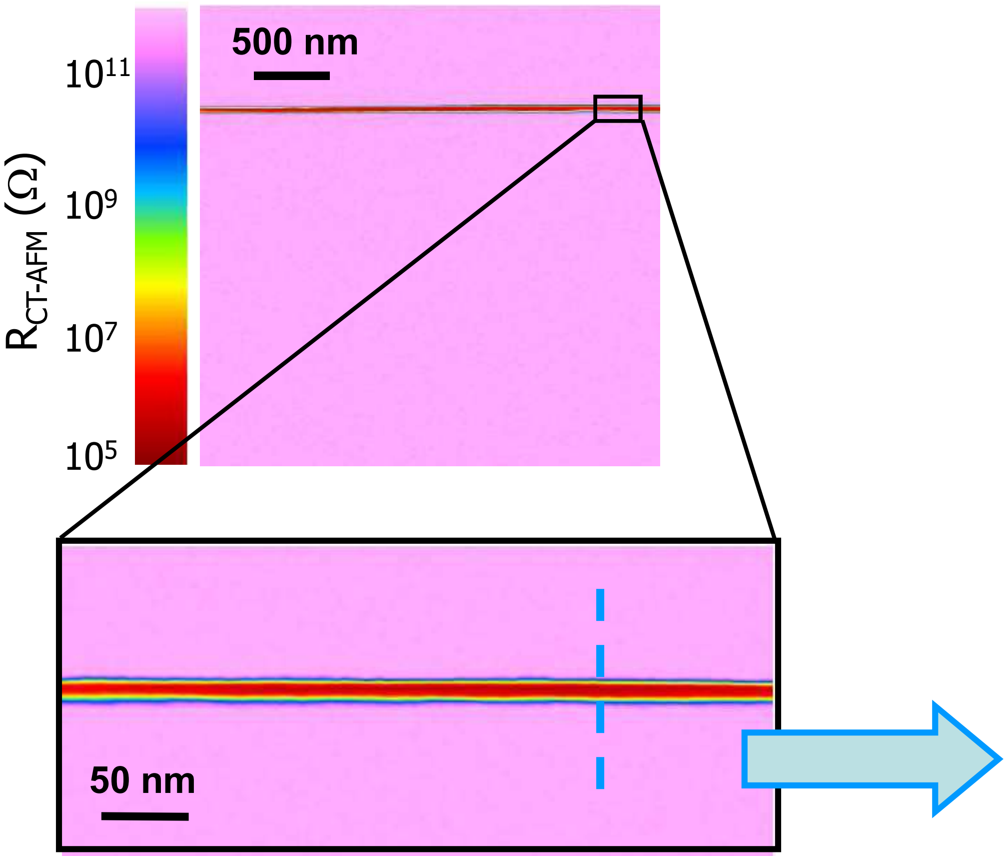
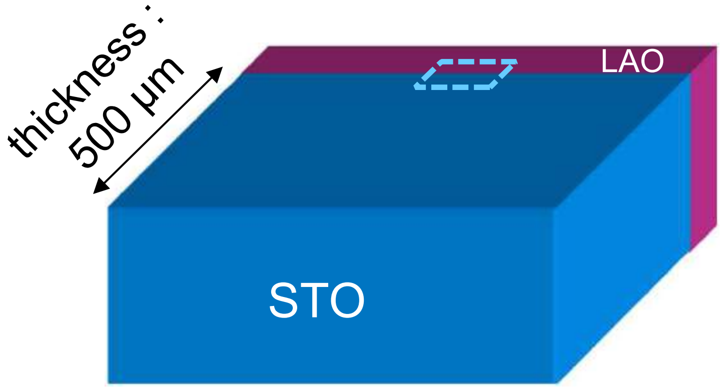
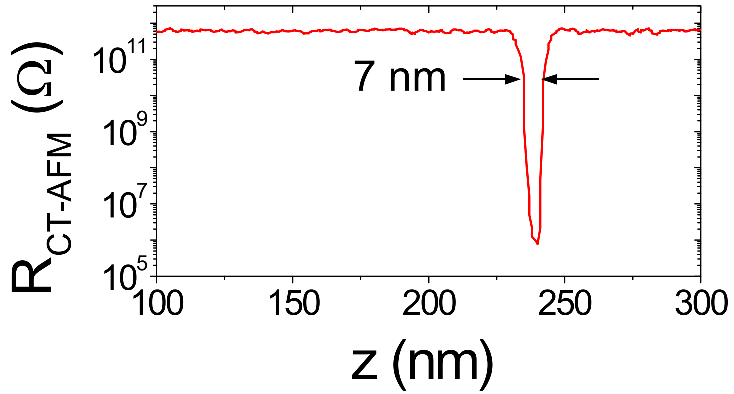




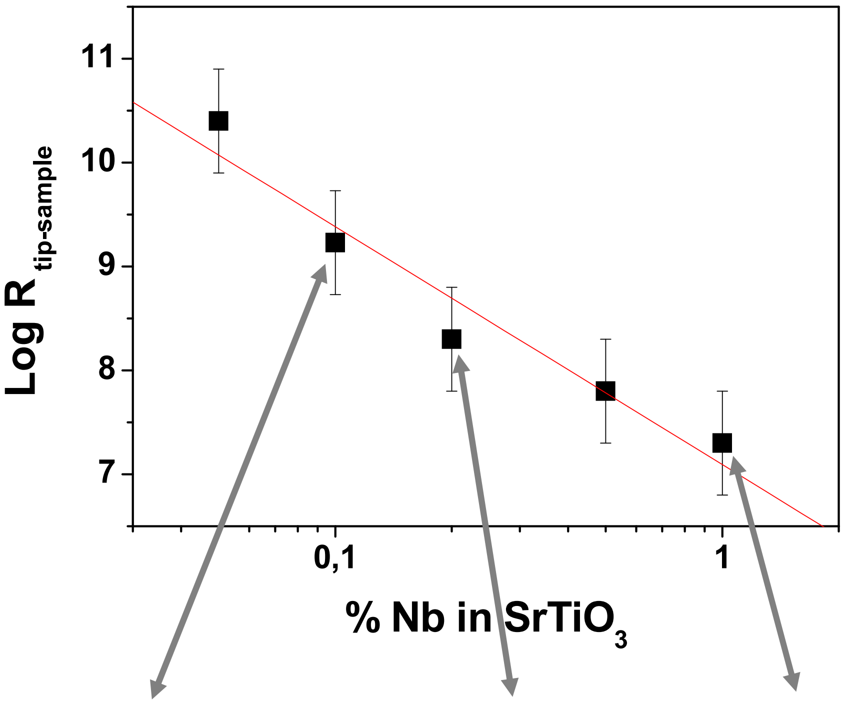


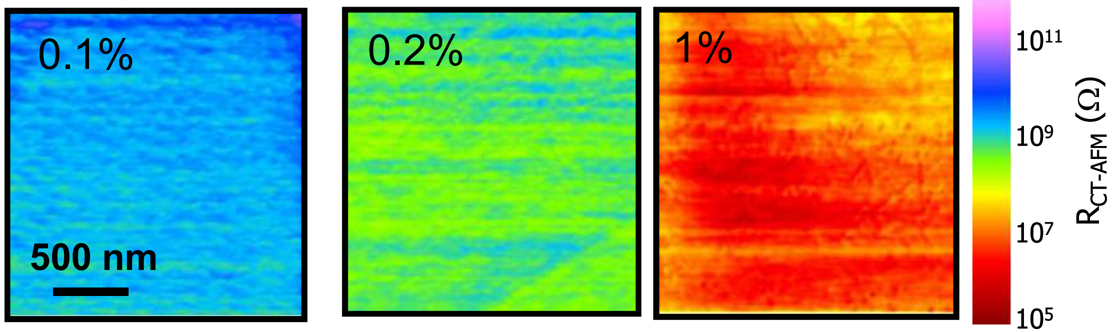
- Low resistance (~10^5 Ω) at LAO/STO interface
- STO substrate is highly insulating far away (500 µm) from the interface
- Conduction is **confined** at the interface
- Thickness of the metallic gas : **7 nm** (upper estimate)

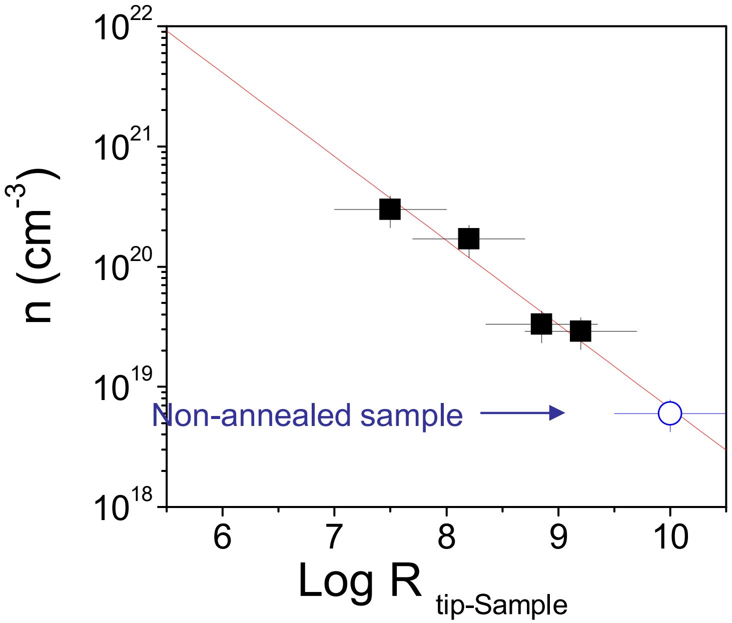
Basletic, MB, et al Nature Mater. 7, 621 (2008)

From resistance to carrier density

Calibration of $R_{tip-sample}$ vs n using Nb-doped $SrTiO_3$ crystals

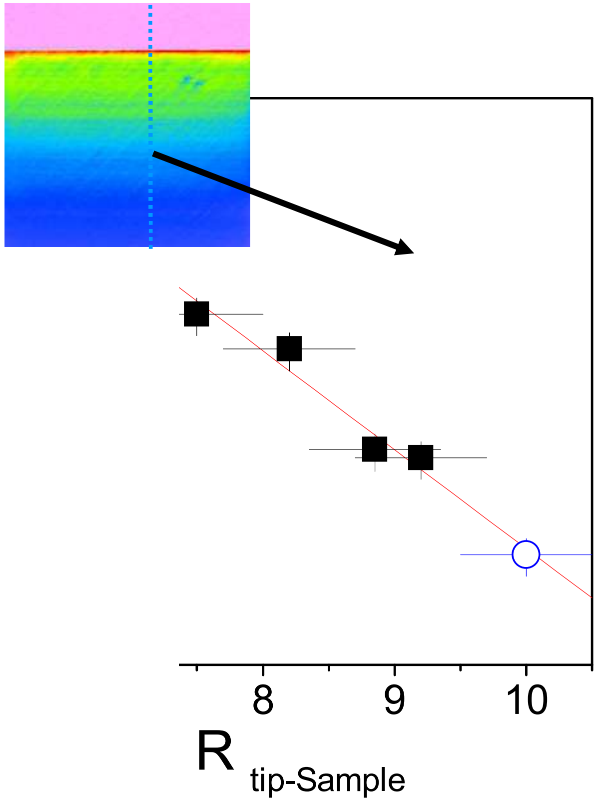


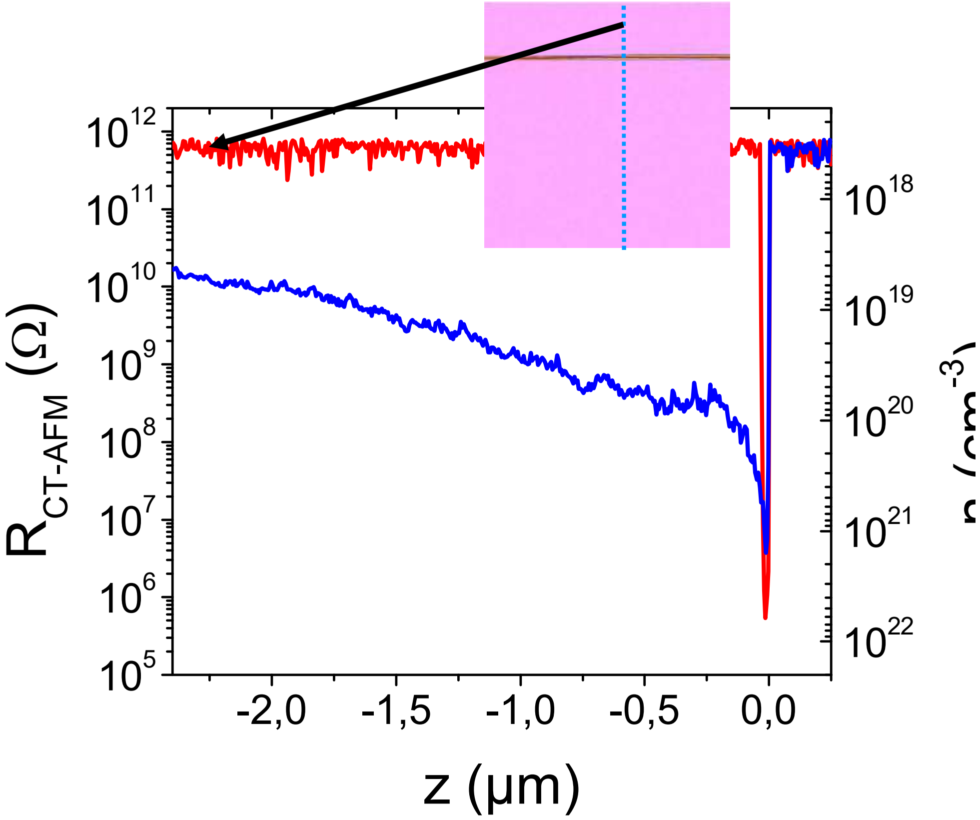




- ➢ Direct correspondence between $R_{tip-sample}$ and n
- ➢ Valid for different types of dopant (Nb, O vac.)

Local mapping of the charge carrier distribution





Non annealed sample

Carrier density away from interface : 5.10^{18} cm^{-3} : t_{gas}≈600 µm

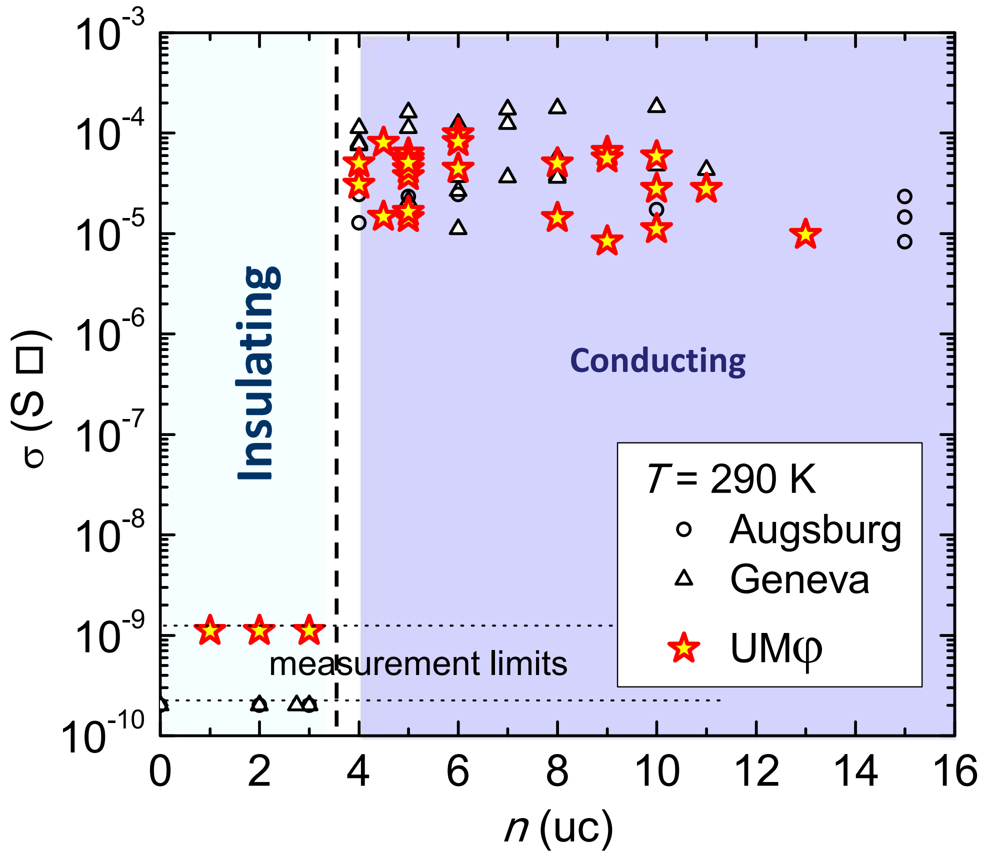
In-situ annealed sample

Carrier density at the interface : 7.10^{21} cm^{-3} : **t_{gas}≈1 nm**

Basletic, MB, et al Nature Mater. 7, 621 (2008)

Critical thickness for conductivity

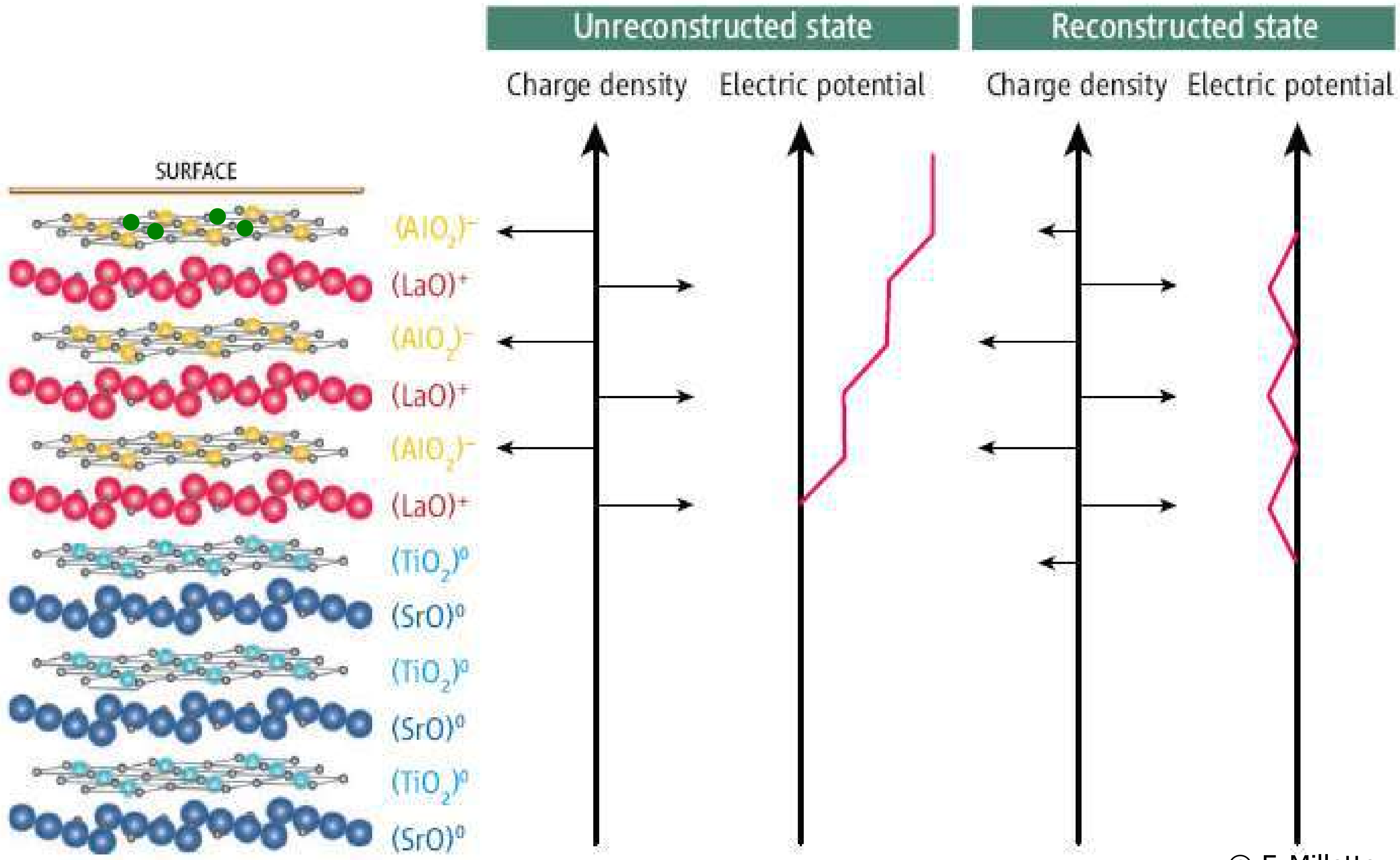
Interfacial conductivity *vs.* LAO thickness



➔ **Critical thickness** threshold for conductivity =
4 unit cells (uc) of LAO

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

Mechanism for 2DEG formation : electronic reconstruction



Ohtomo and Hwang, Nature Mater

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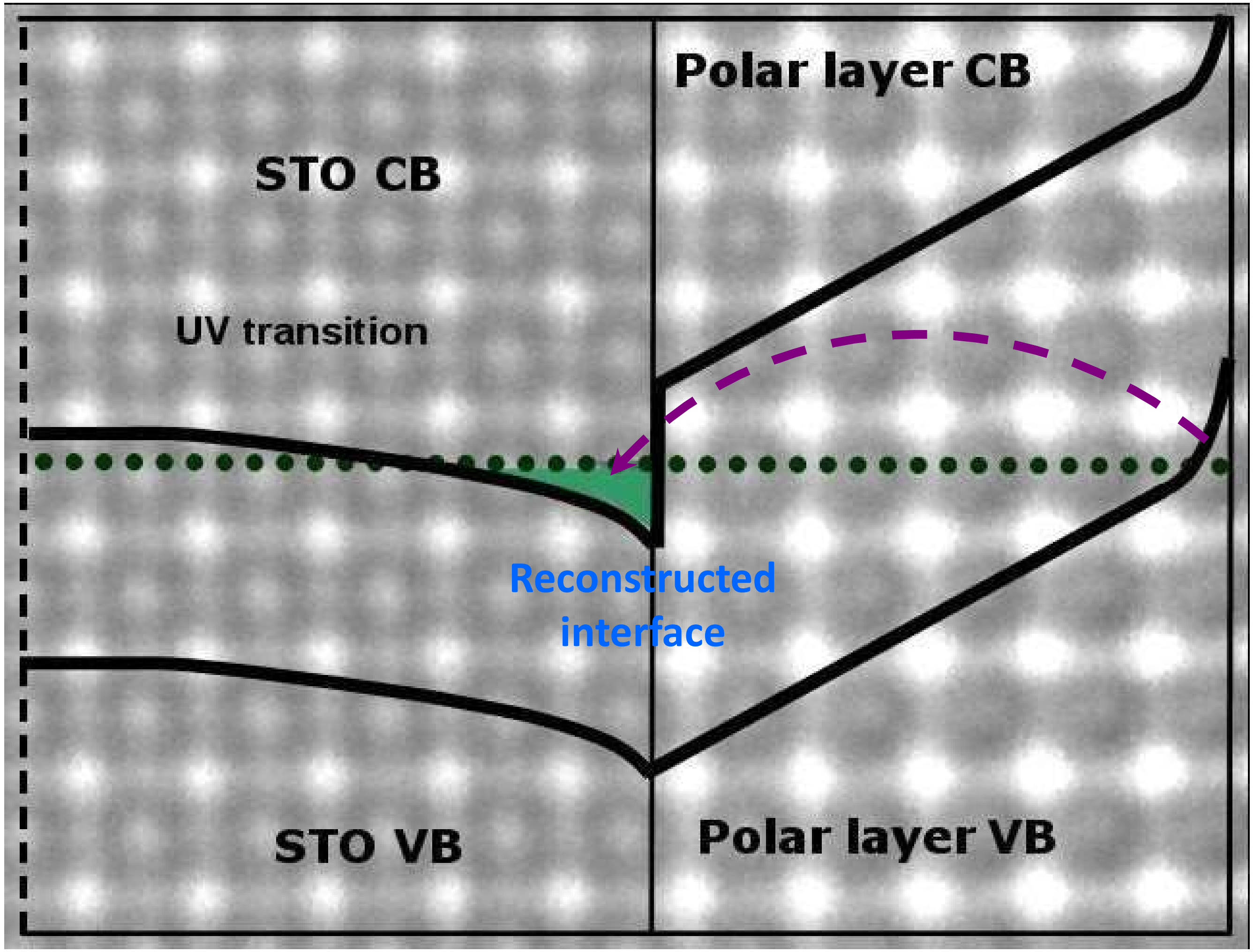
Mechanism for 2DEG formation : electronic reconstruction



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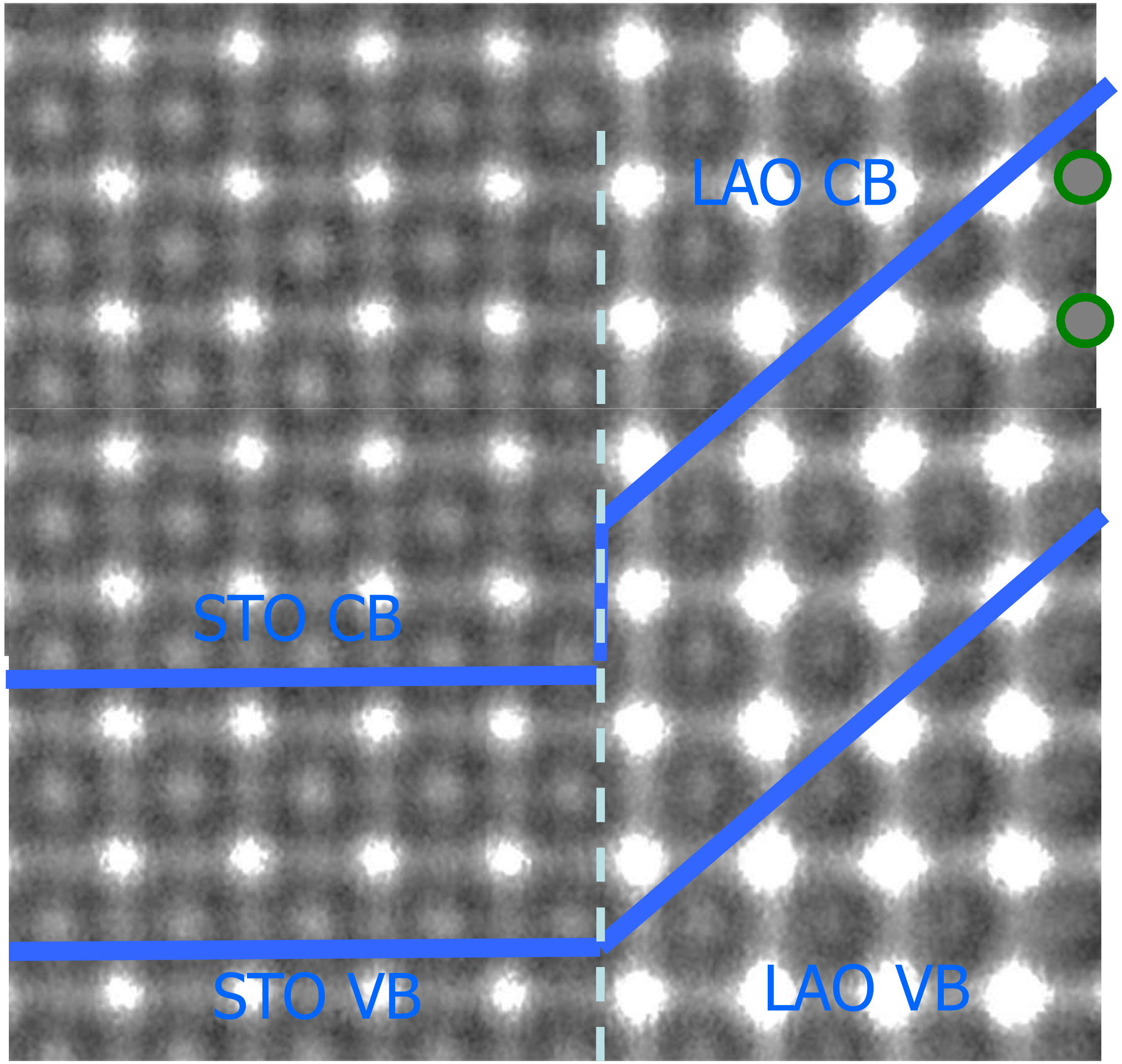
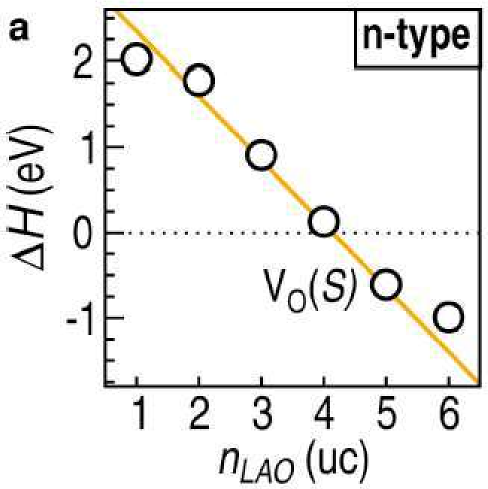
Mechanism for 2DEG formation : oxygen vacancies at LAO surface

Yu and Zunger, Nature Comm. 5, 5118 (2014)



← $V_O^{++}+2e^-$



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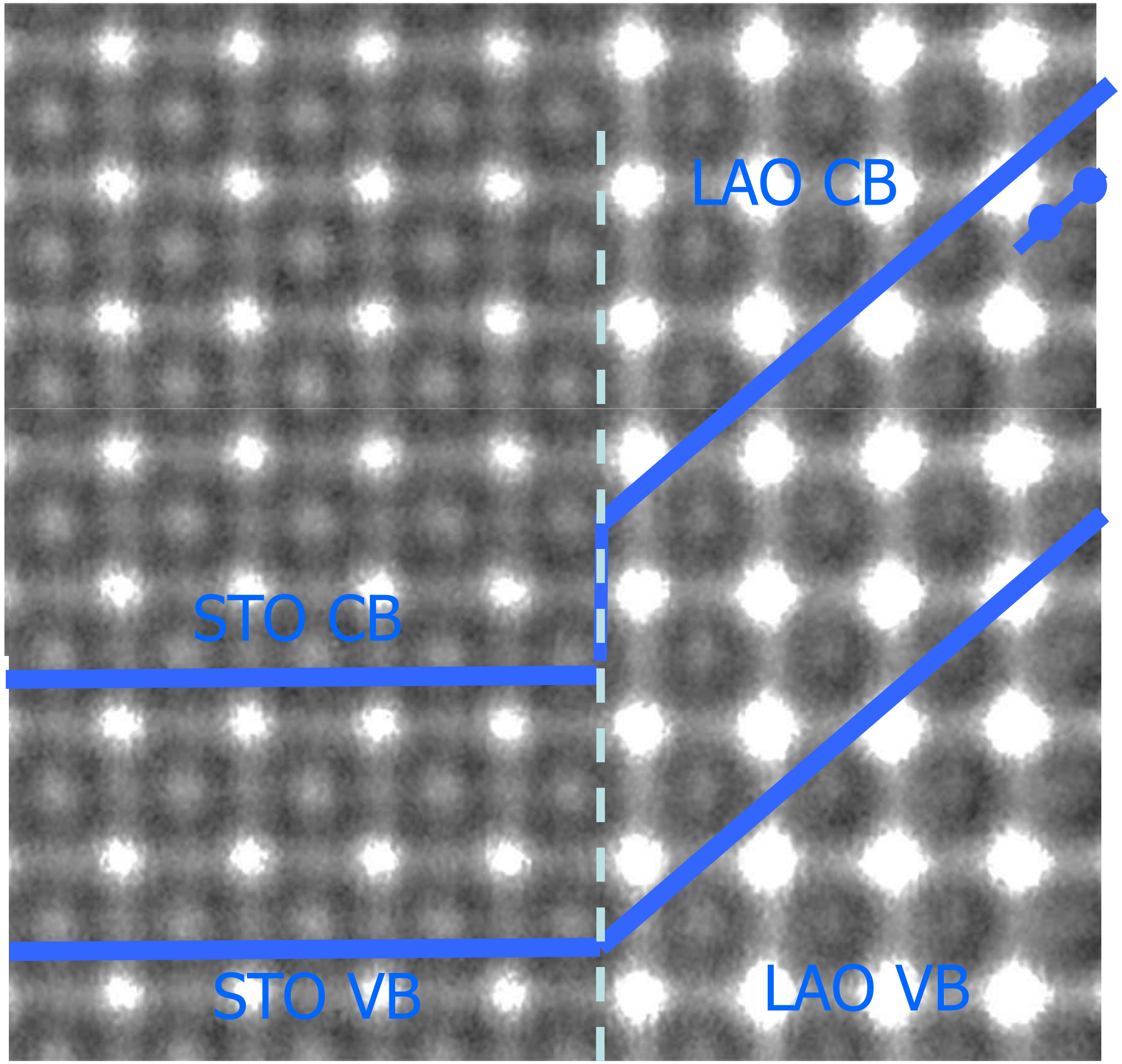
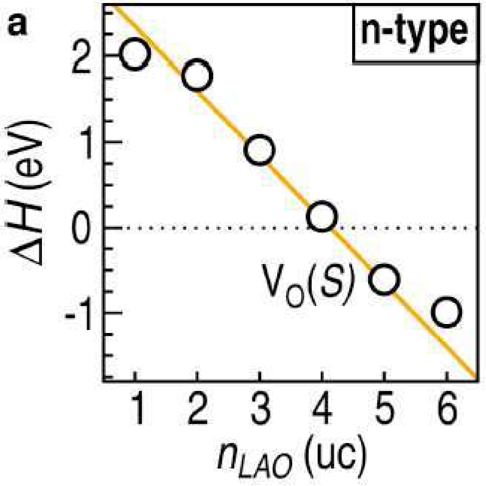
Mechanism for 2DEG formation : oxygen vacancies at LAO surface

Yu and Zunger, Nature Comm. 5, 5118 (2014)



V_O^{++}+2e-



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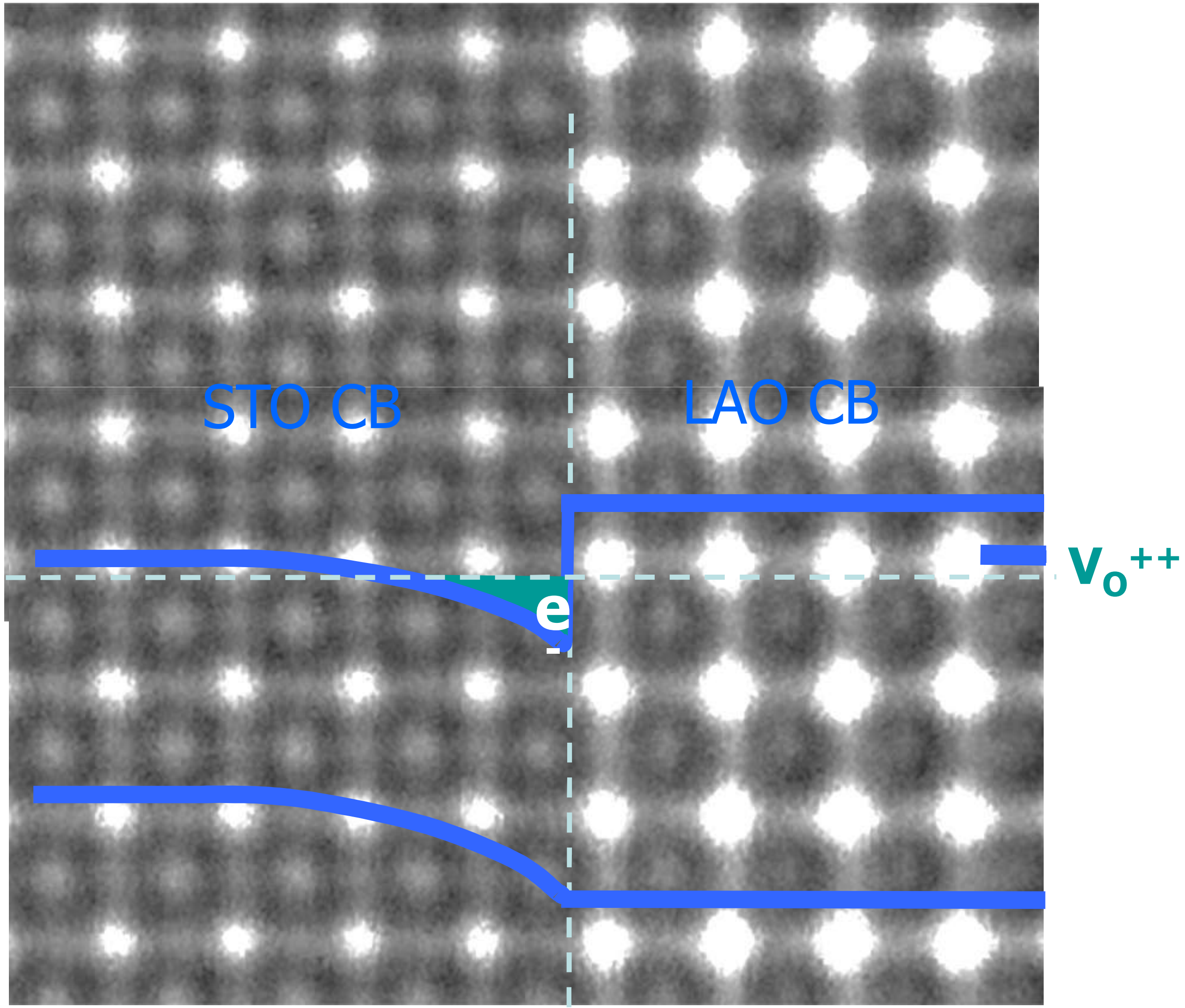
Mechanism for 2DEG formation : oxygen vacancies at LAO surface

Yu and Zunger, Nature Comm. 5, 5118 (2014)



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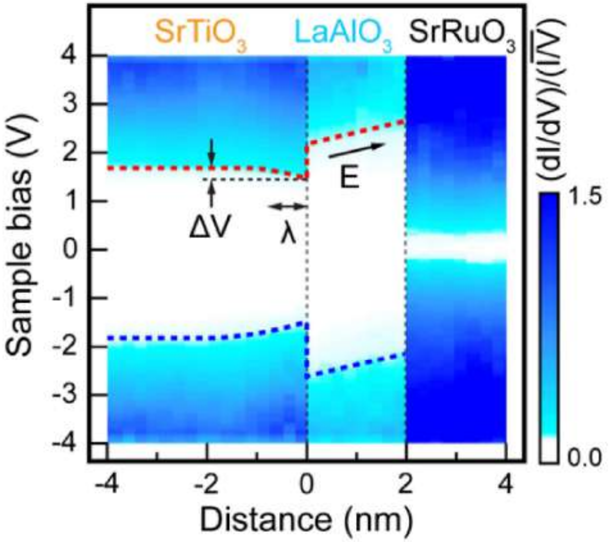
Mechanism for 2DEG formation : conclusion

So which mechanism is it ?

Hard to tell because

- Both mechanisms require a polar interface, i.e. no 2DEG for SrO-terminated STO
- Both mechanisms lead to a critical thickness of 4 unit cells
- But after 2DEG formation, there should be an E field in the 2DEG in the polar catastrophe scenario, but not in Yu and Zunger's model

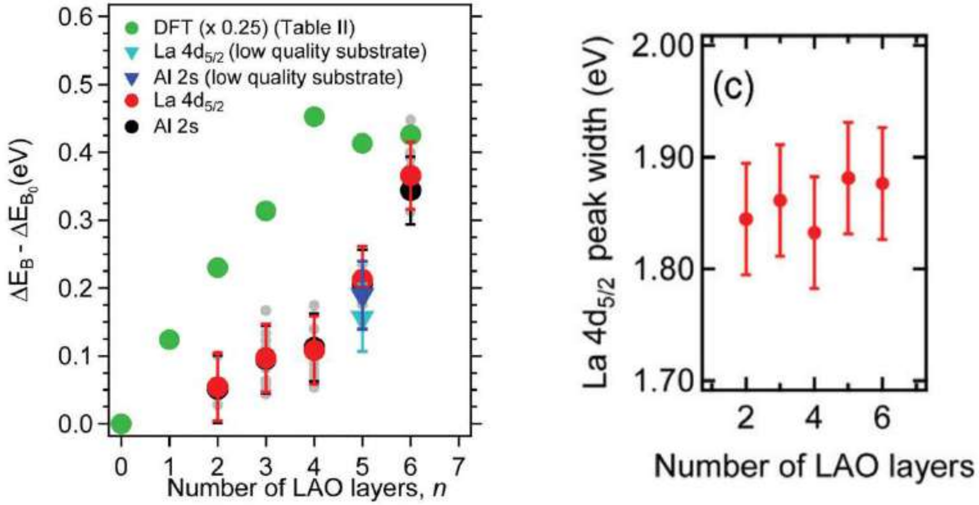
Cross section scanning tunnel spectroscopy



- Electric field visible in LAO

Huang et al, PRL 109, 246807 (2012)

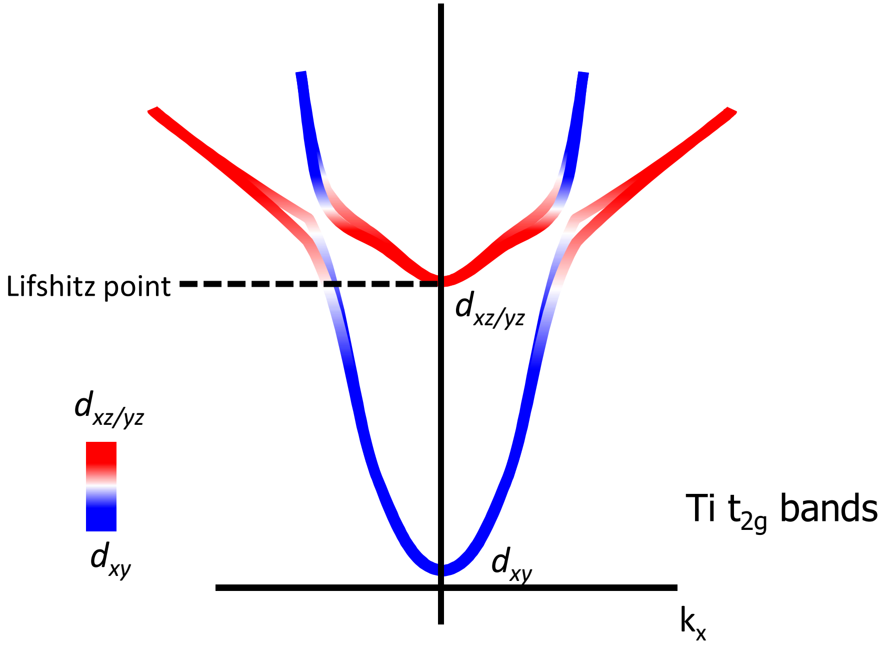
Hard X-ray photoemission spectroscopy

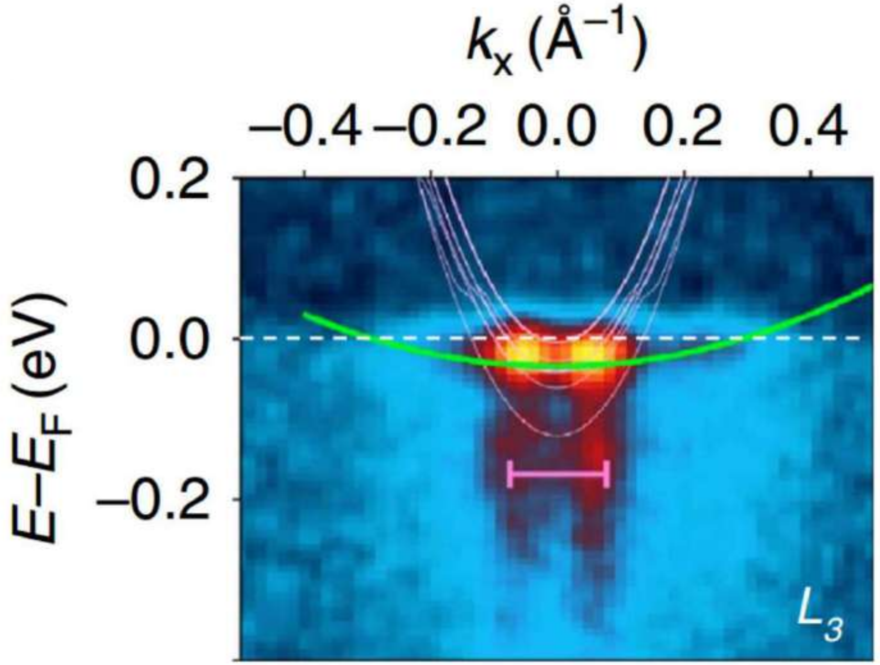


- Core level shifts disagree with theory and no broadening

Slooten et al, PRB 87, 085128 (2013)

Electronic structure of the 2DEG





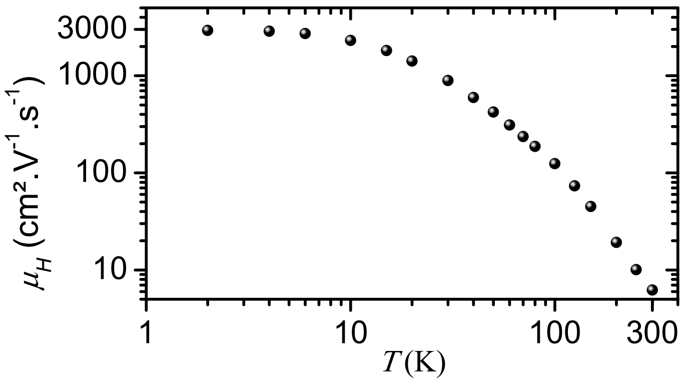
- Compared to bulk STO, the degenerescence of the t_{2g} states is lifted (splitting is 50-100 meV)
- Low lying d_{xy} band with light mass
- Above Lifshitz point, onset of second band with $d_{xz/yz}$ character and heavier mass
- Avoided crossing due to orbital mixing and spin orbit coupling

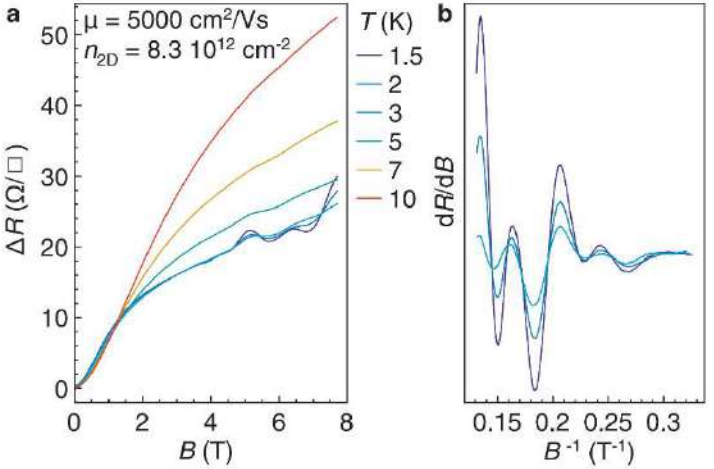
- Experimental ARPES mapping of the band structure in LAO/STO
- Poor signal quality due to LAO overlayer
- Yet, the main features of the band structure are observed.

Cancellieri et al, PRB 89, 121412 (2014)

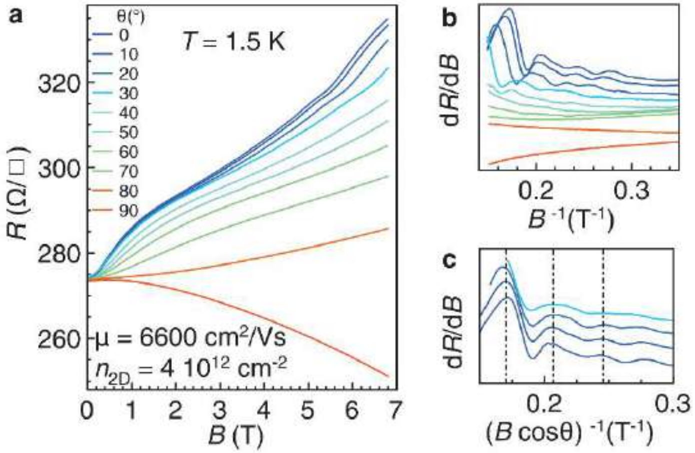
Electronic properties of the 2DEG

High electron mobility





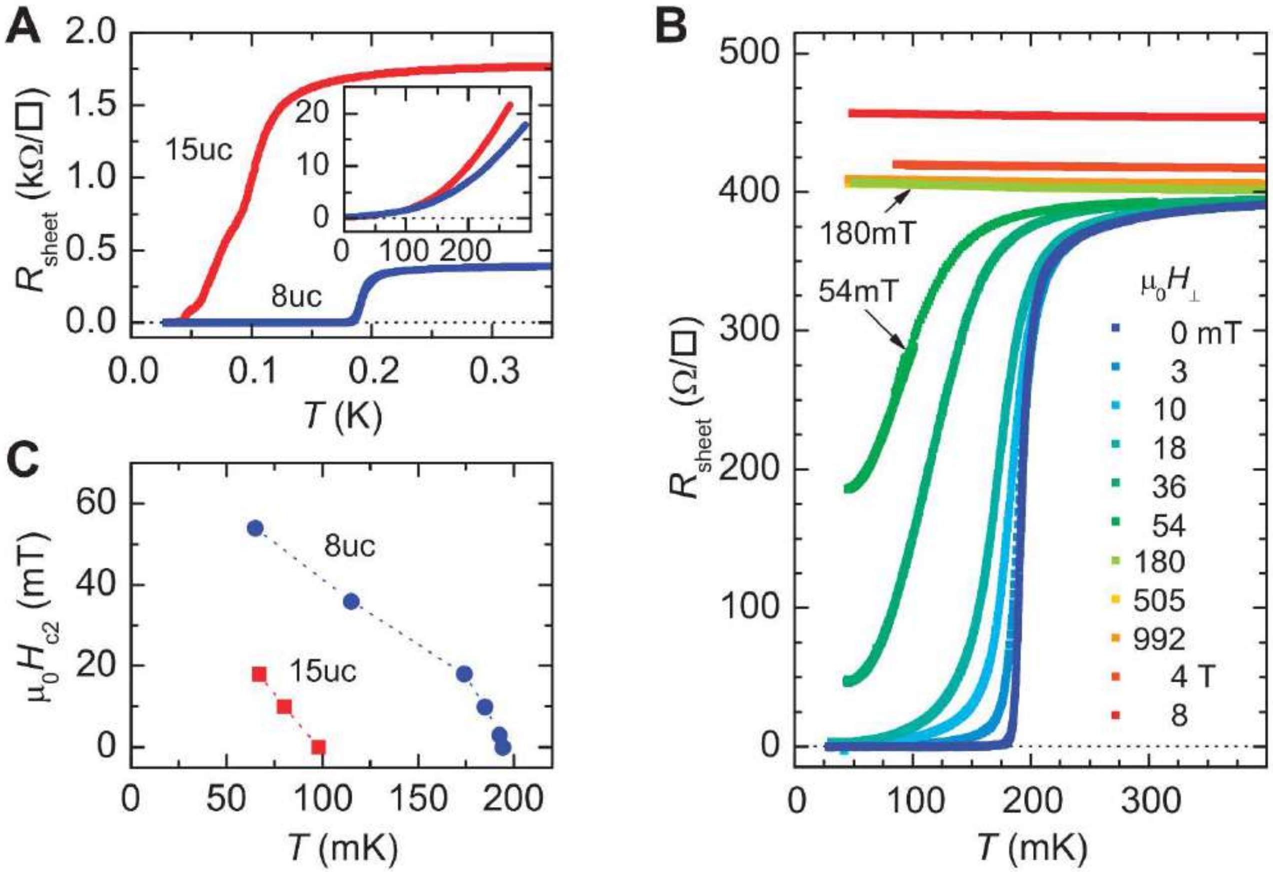
- ⊙ At low T electron mobility can reach a few 1000 cm²/Vs
- ⊙ Accordingly, Shubnikov de Hass oscillations can be observed (criterion is Bμ >> 1)
- ⊙ Angle dependence of the oscillations reveal the 2D nature of the 2DEG



Caviglia et al, PRL 105, 236802 (2010)

Electronic properties of the 2DEG

Superconductivity

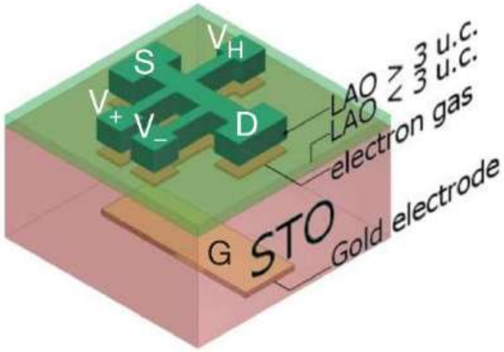


- ⊙ 2DEG is superconducting at T<200 mK (like n-type doped bulk STO)
- ⊙ Superconductivity is 2 dimensional

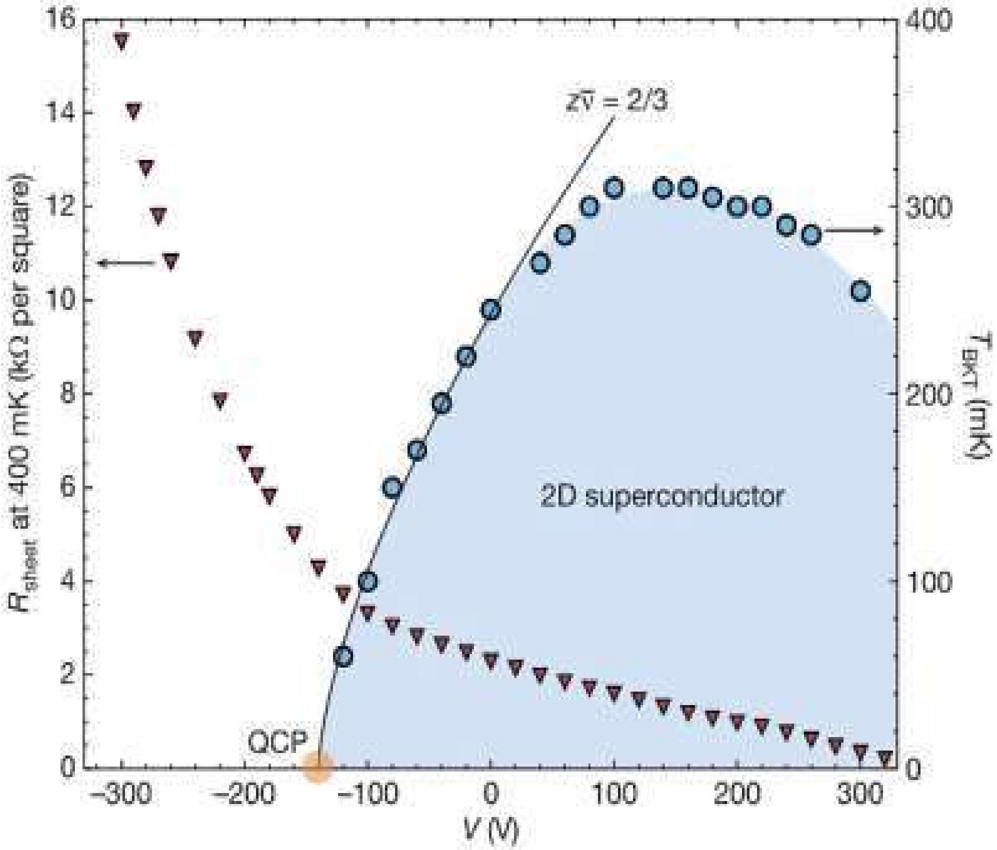
N. Reyren et al., Science 317, 1196 (2007)

Electronic properties of the 2DEG

Electrostatic gating

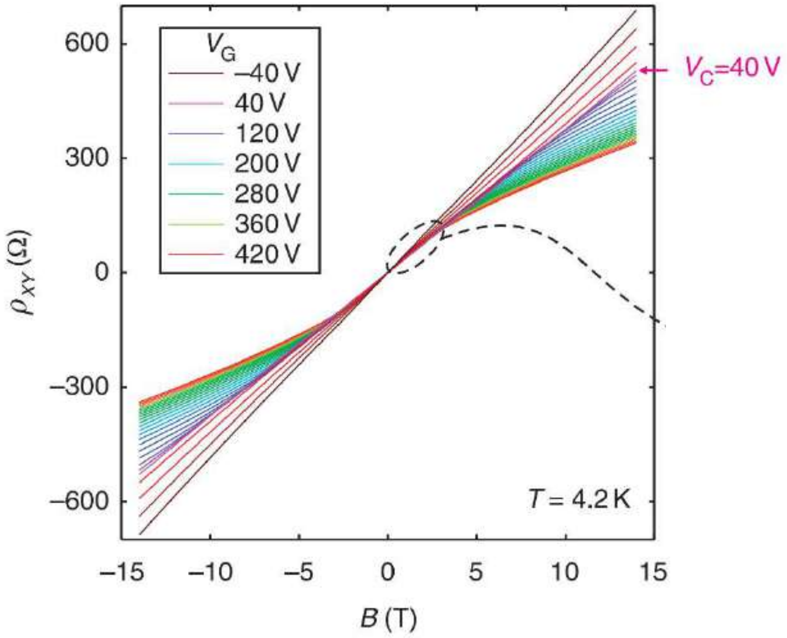


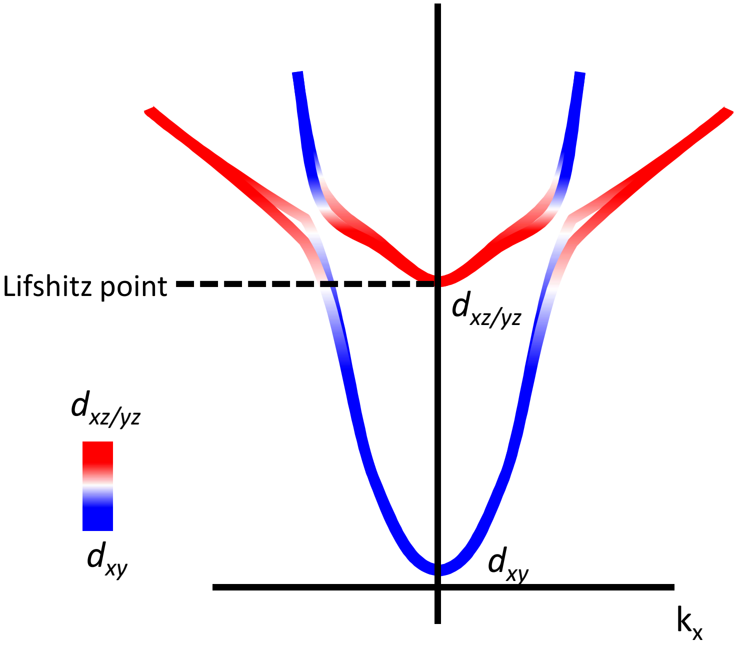
A. D. Caviglia et al.,
Nature 456, 624 (2008)



- ⊙ Positive gate voltage accumulates electrons in the 2DEG and negative gate voltage depletes electrons
- ⊙ Accordingly, the 2DEG normal state resistance varies over more than one order of magnitude
- ⊙ Superconductivity T_C is modulated in a dome-like dependence

Electrostatic gating



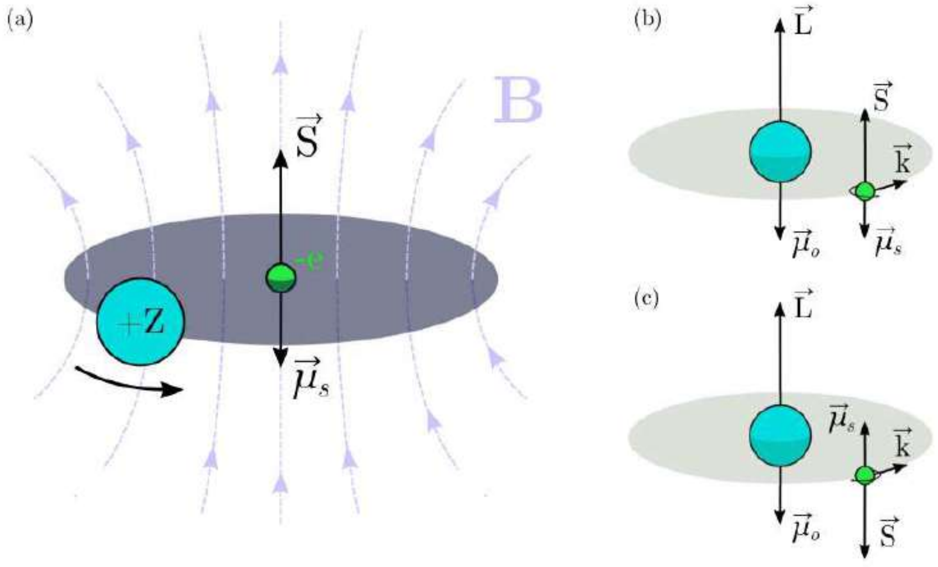


- At low carrier density (negative gate voltages), the Hall effect is linear : one type of carriers
- Upon adding carriers, the Hall effect becomes non-linear : two types of carriers
- Gate induced Lifshitz transition (at 1.5-2.5 10^{13} cm^{-2})

Joshua et al, Nature Comm. 3, 1129 (2012)

Electronic properties of the 2DEG

Signatures of spin-orbit coupling



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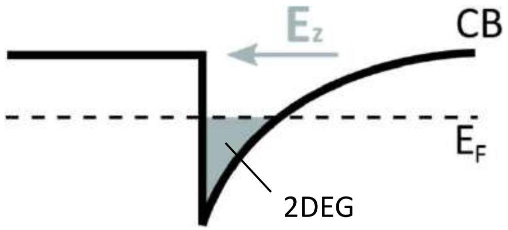
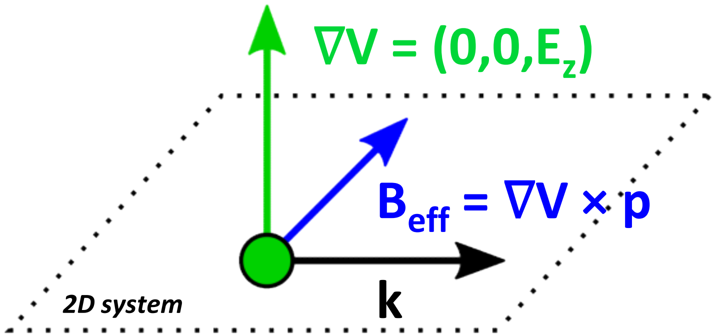


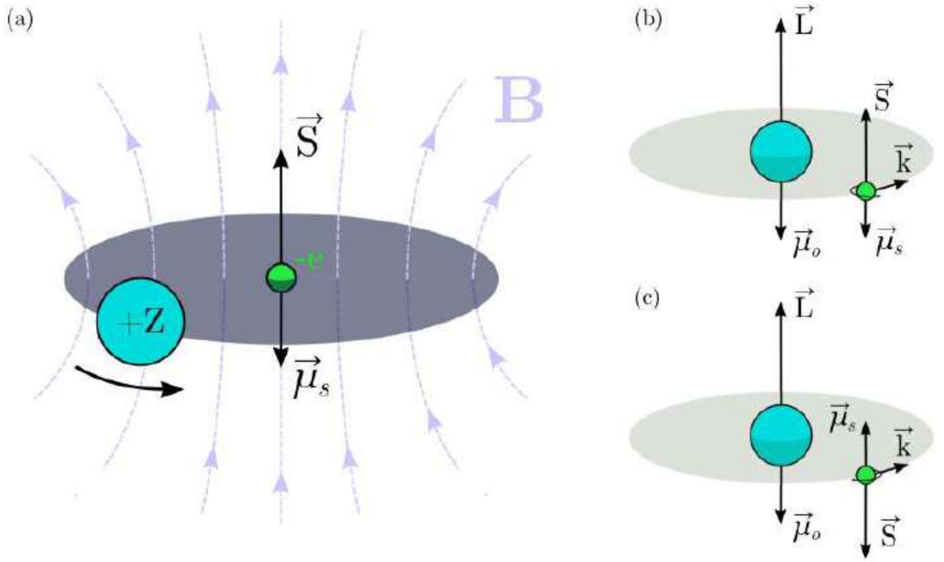


$\nabla V = (0,0,E_z)$

$B_{eff} = \nabla V \times p$

Electronic properties of the 2DEG

Signatures of spin-orbit coupling



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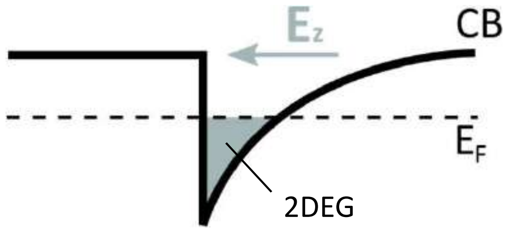
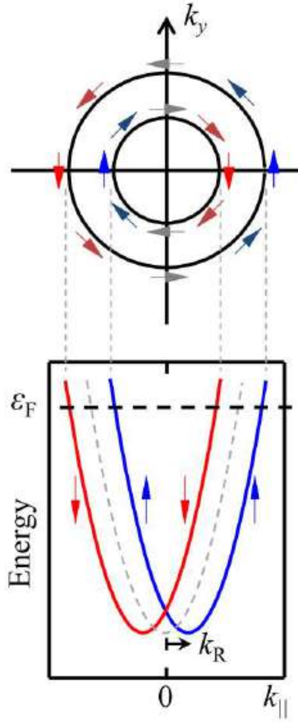
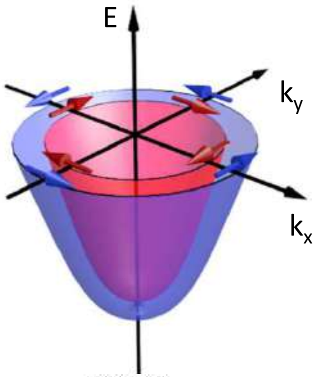






- ⊙ Spin orbit interaction + inversion symmetry breaking (**E** // **z**)

➔ **Rashba effect**

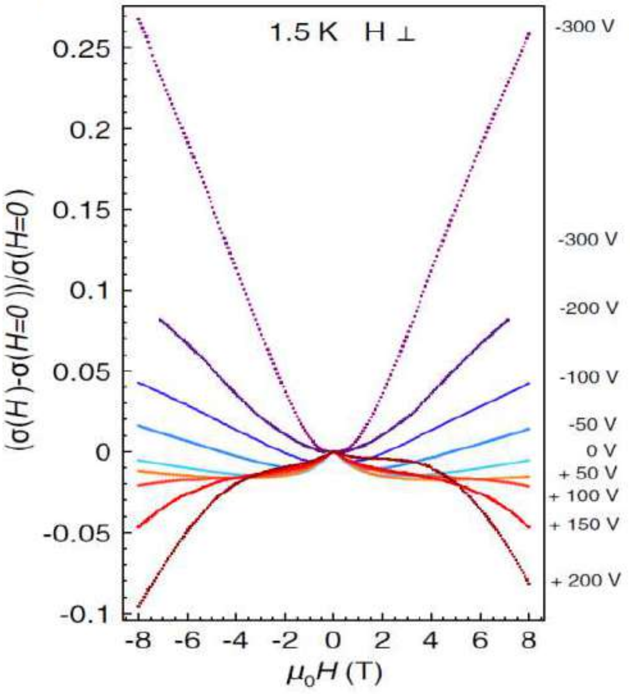
$$H_R = \alpha_R\,(\boldsymbol{z} \times \boldsymbol{k}) \cdot \boldsymbol{\sigma}$$

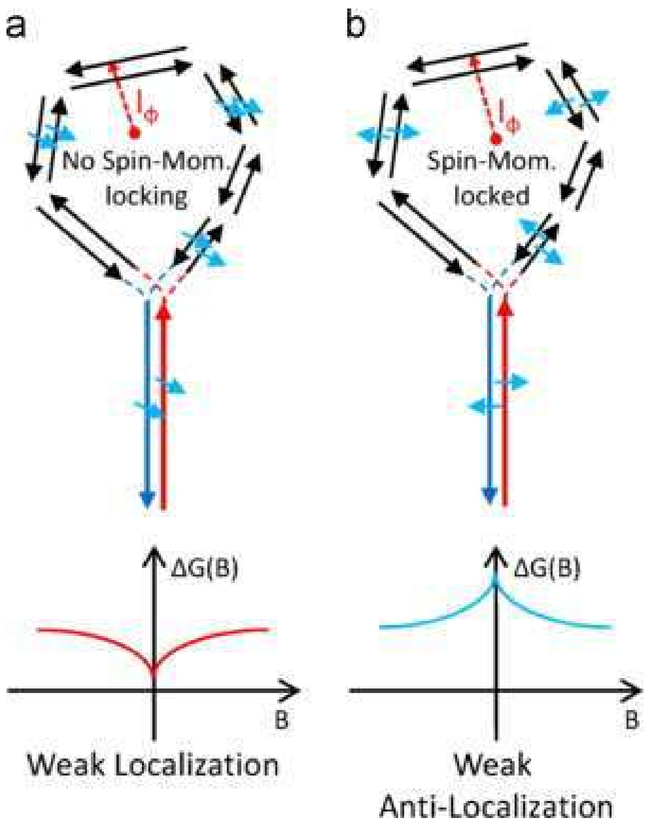
$$\varepsilon_k = \frac{\hbar^2 k^2}{2m^*} \pm \alpha_R k$$

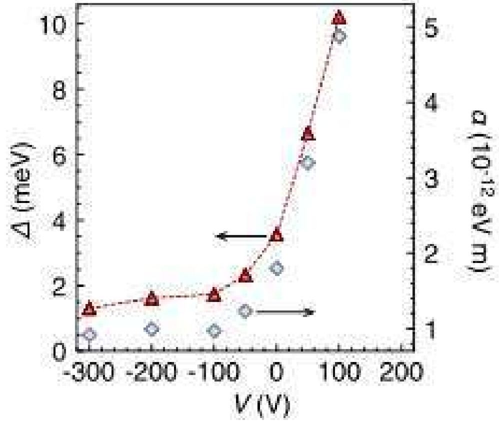
Yu. A. Bychkov & E. I. Rashba,
JETP Lett. 39, 78 (1984)

Electronic properties of the 2DEG

Signatures of spin-orbit coupling







- Magnetoresistance shows signs of weak localization and weak antilocalization
- WAL is a signature of Rashba SOC
- Rashba coefficient α_R is 10-50 meV.Å, i.e. 10-100 times lower than record systems like Bi/Ag interfaces
- Rashba coefficient is strongly tunable by gate voltage

A.D. Caviglia et al., PRL. 104, 126803 (2010)

Outline

1. **d_0-oxide-based interfaces**

   1.1 Physics of bulk $SrTiO_3$

   1.2 $LaAlO_3/SrTiO_3$ 2DEGs

   1.3 Other $SrTiO_3$ 2DEGs

   1.4 2DEGs not based on $SrTiO_3$

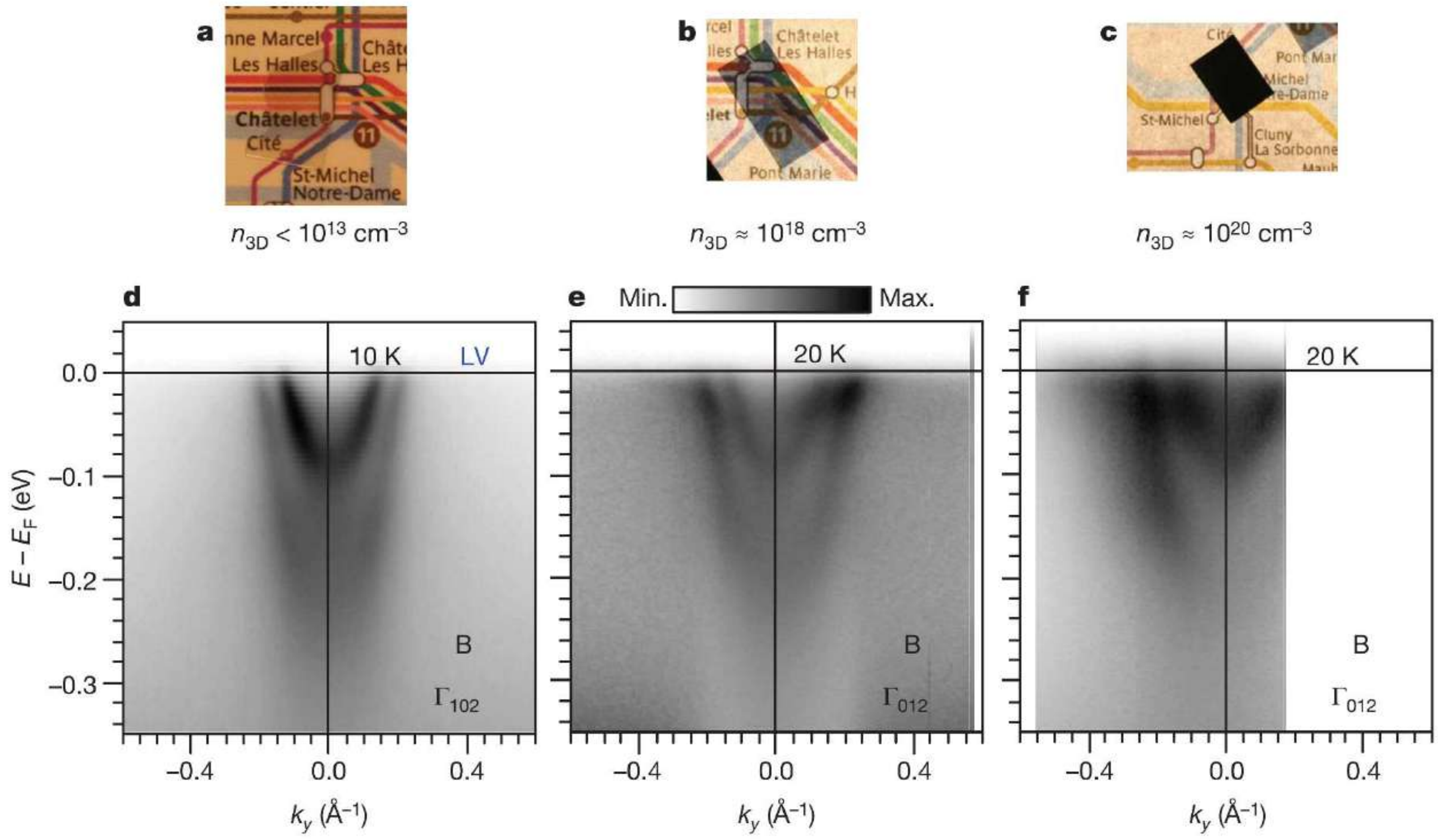
2. Interfaces between oxides with partially filled d shells

   2.1 « Correlated » oxide perovskites

   2.2 Nickelate/Titanate interfaces

Other types of $SrTiO_3$-based $2DEG_S$

A 2DEG at the surface of STO

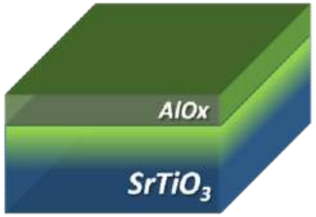


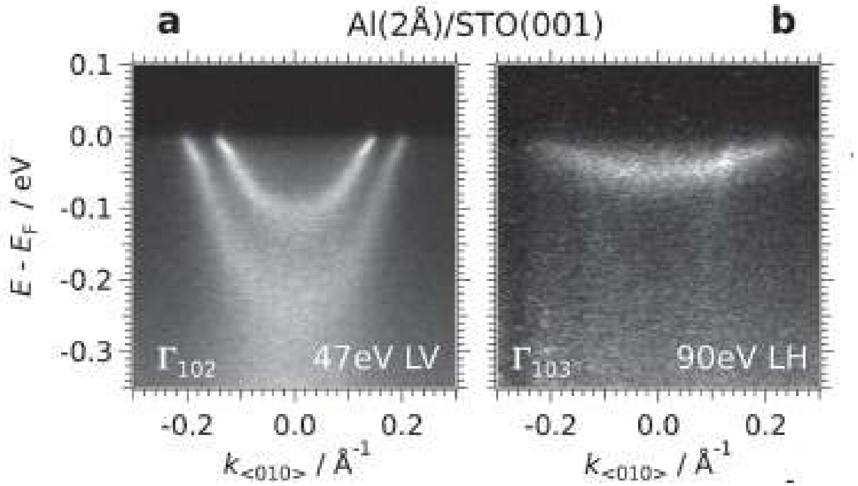
- Fracturing a STO crystal in vacuum creates a 2DEG at its surface
- 2DEG electronic structure very similar to that of the LAO/STO 2DEG

Santander, MB et al, Nature 469, 189 (2011)

Other types of $SrTiO_3$-based $2DEG_S$

A 2DEG at Al/STO interfaces

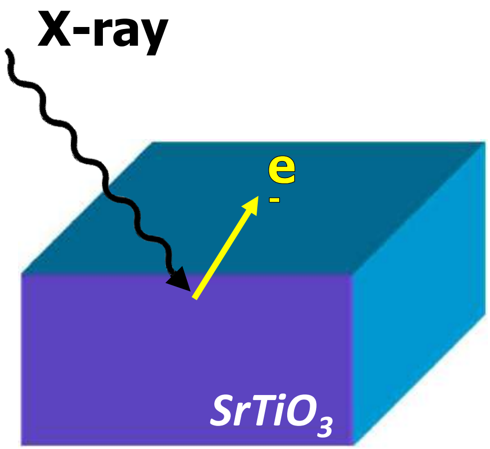


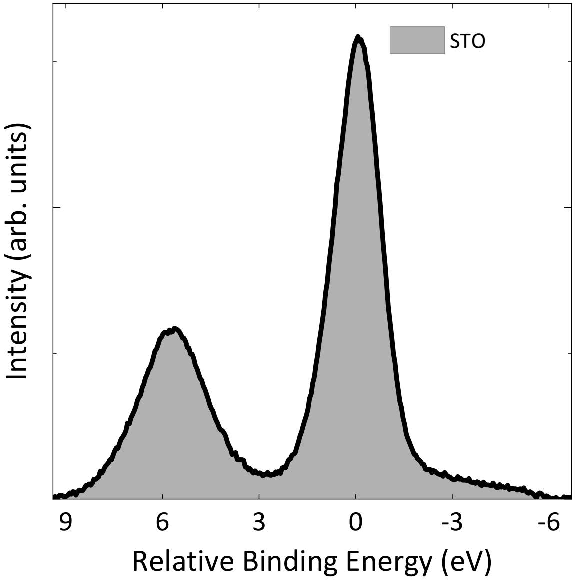


T.C. Rödel et al., Adv. Mater. 28, 1976 (2016)

- Reactive metals ➔ Oxygen vacancies release electrons to form a 2DEG
- Room temperature growth
- What about the polar catastrophe mechanism ? Is the 2DEG formation only driven by oxygen vacancies ?

A 2DEG in Al/STO





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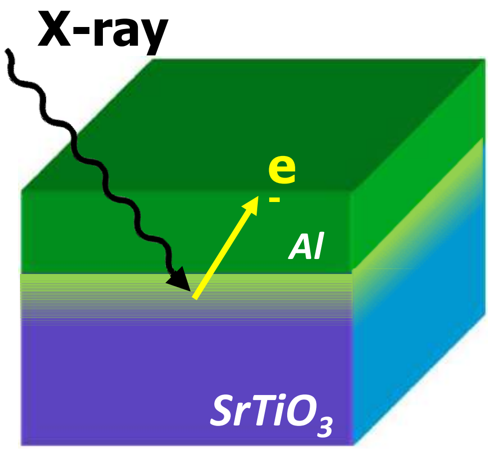
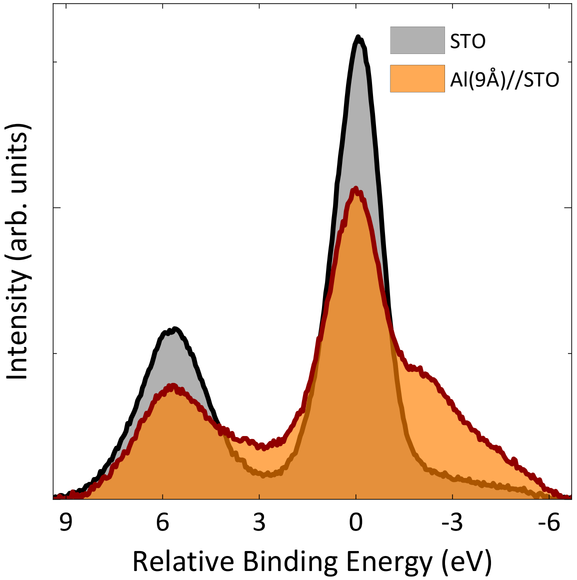
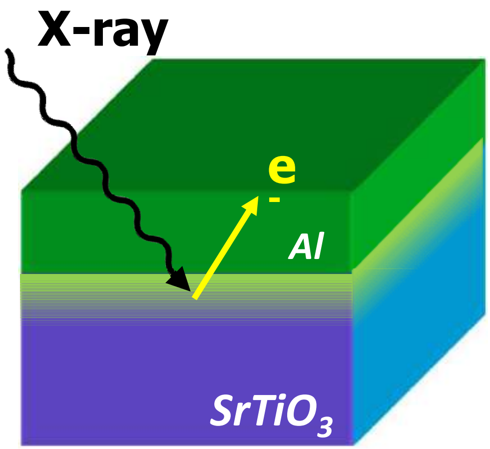
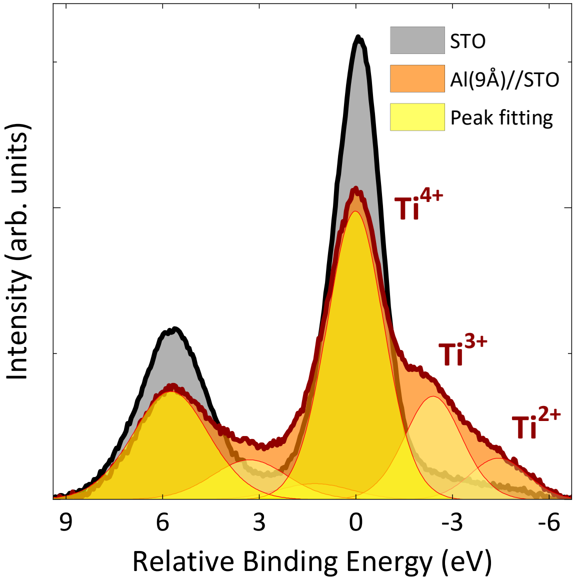




- Deposition of 9 Å of aluminum
- Aluminum pulls oxygen from the STO
- Oxygen vacancies are formed

A 2DEG in Al/STO





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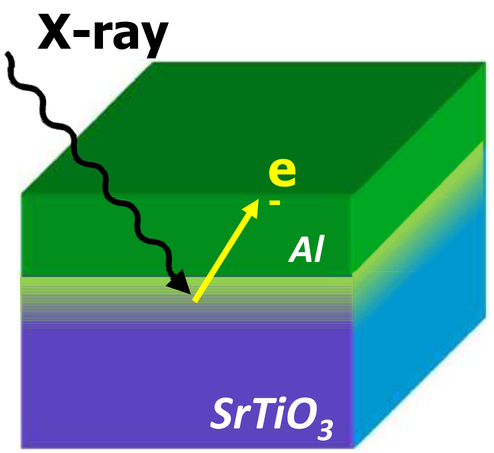
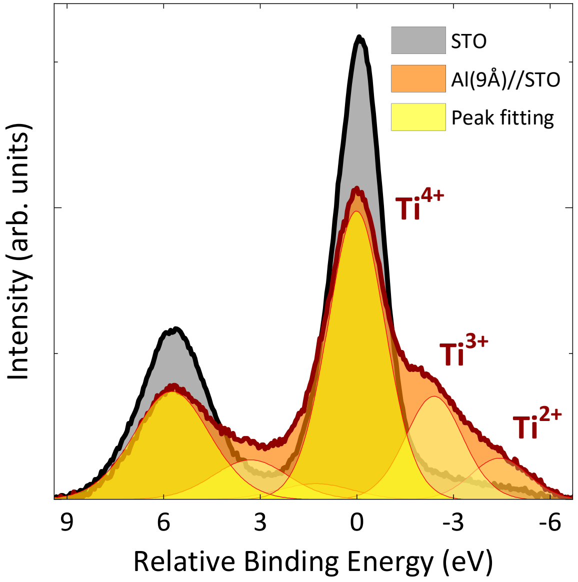
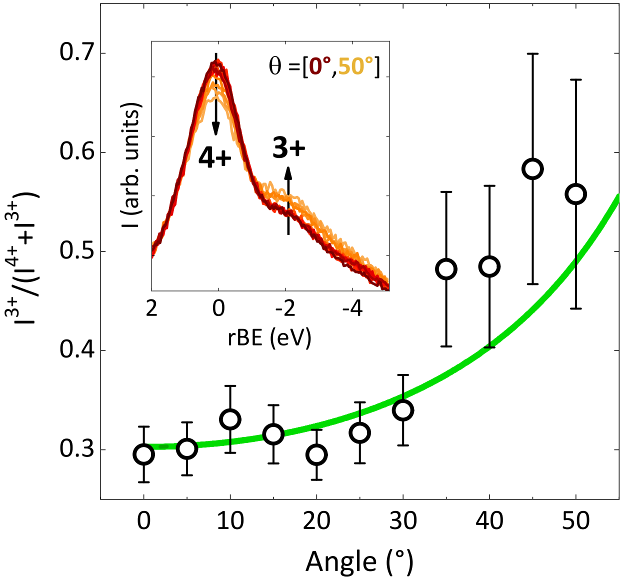
A 2DEG in Al/STO

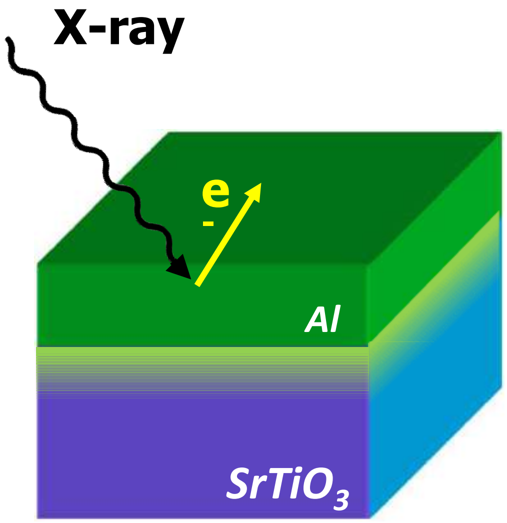


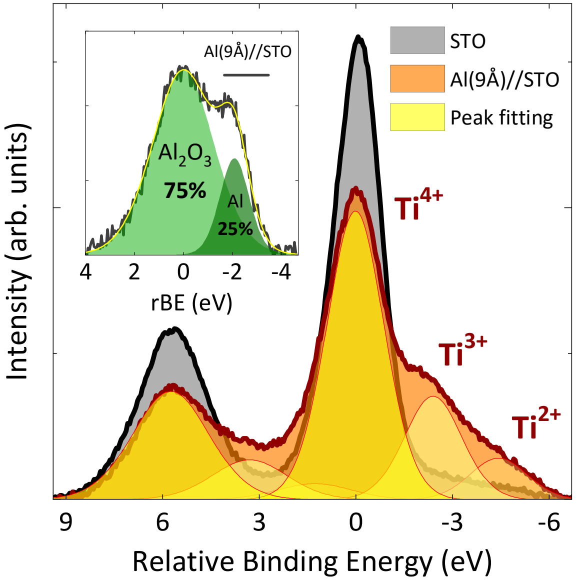


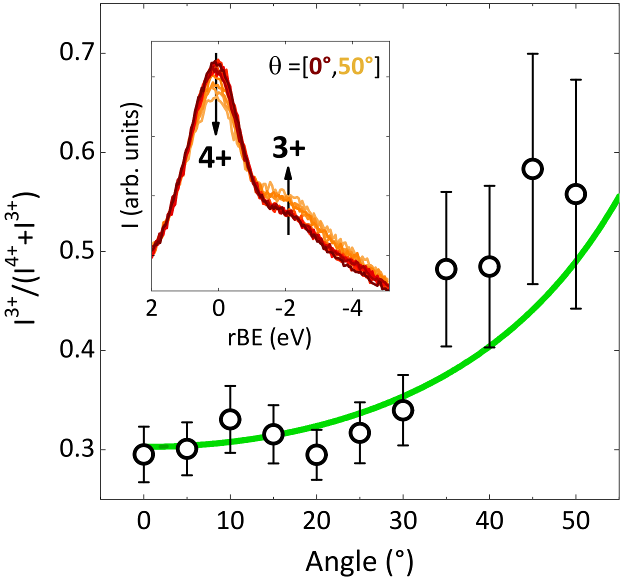


- Deposition of 9 Å of aluminum
- Aluminum pulls oxygen from the STO
- Oxygen vacancies are formed
- A 2DEG emerges at the interface

A 2DEG in Al/STO







- Deposition of 9 Å of aluminum
- Aluminum pulls oxygen from the STO
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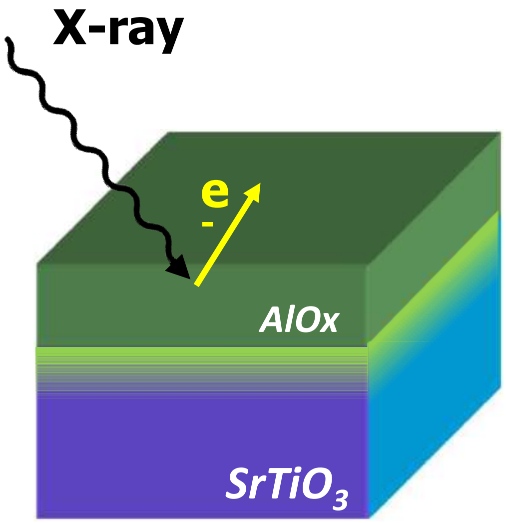
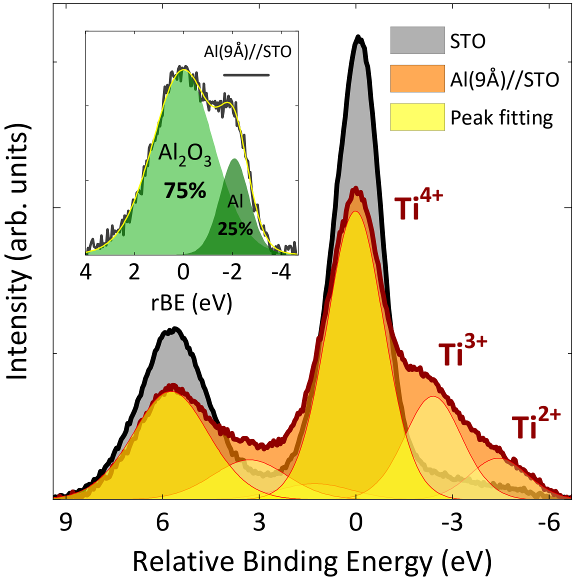
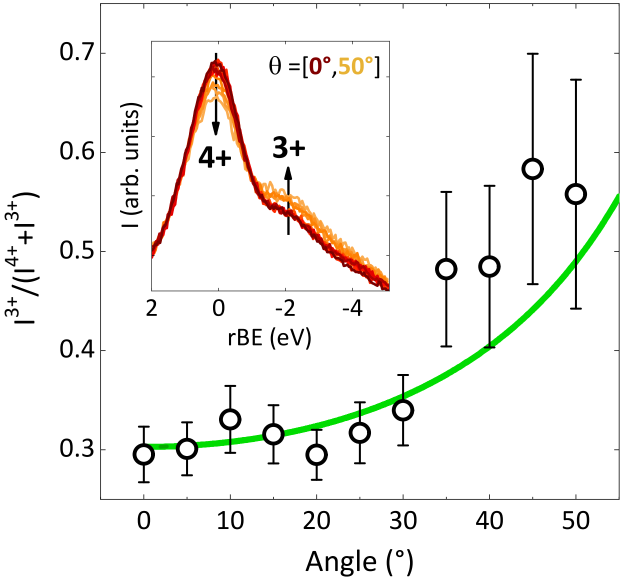
- A 2DEG emerges at the interface

A 2DEG in Al/STO

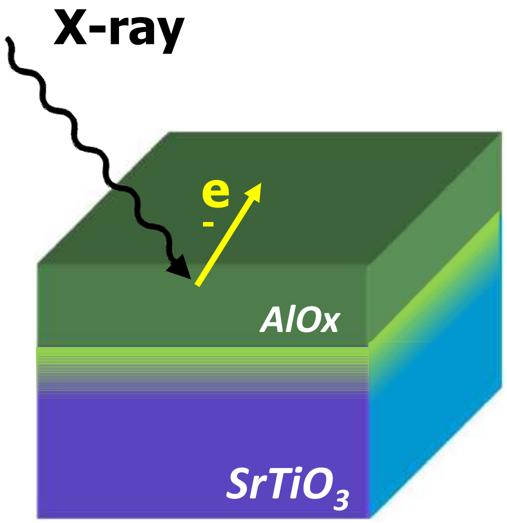


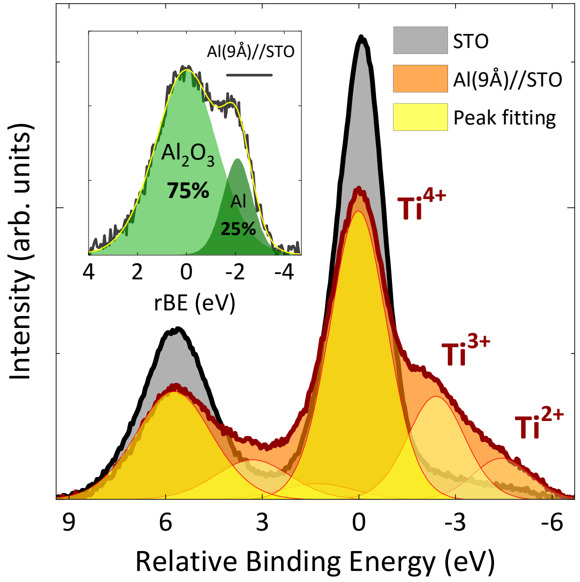


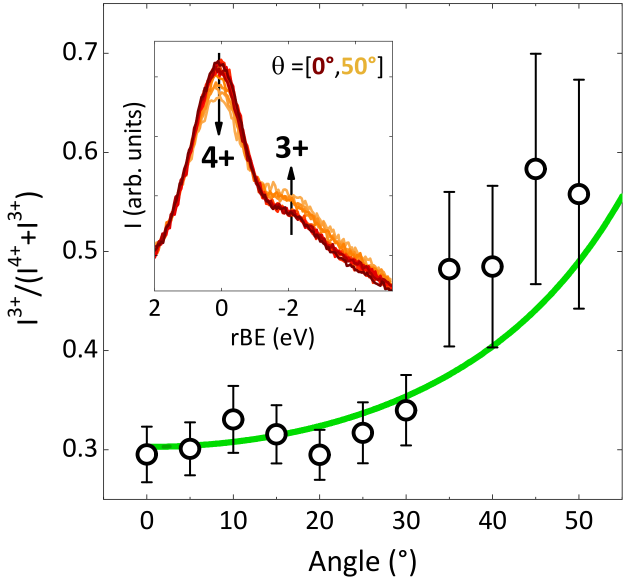


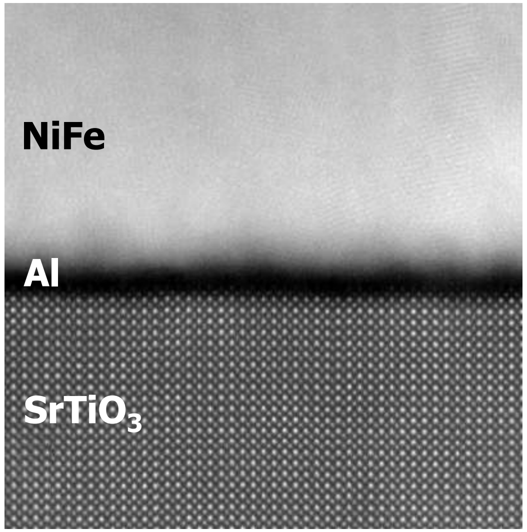
- Deposition of 9 Å of aluminum
- Aluminum pulls oxygen from the STO
- Oxygen vacancies are formed
- A 2DEG emerges at the interface
- The deposited aluminum layer is completely oxidized

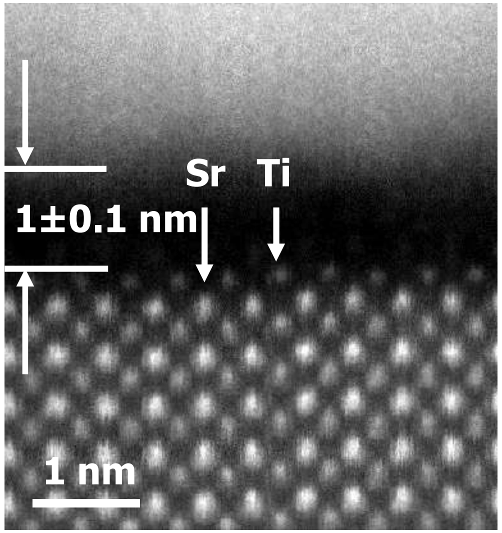
A 2DEG in Al/STO

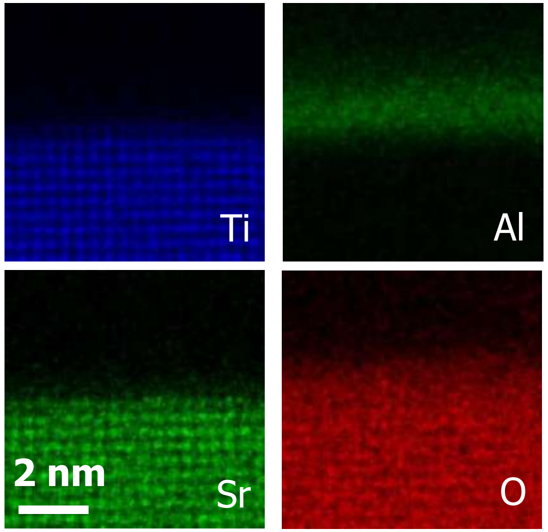








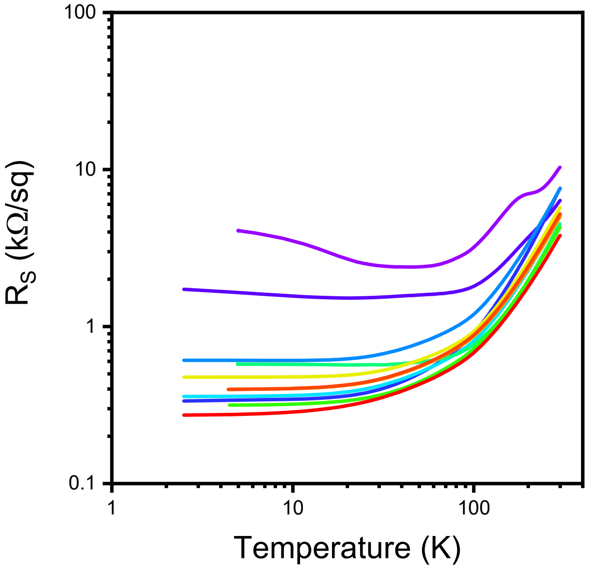


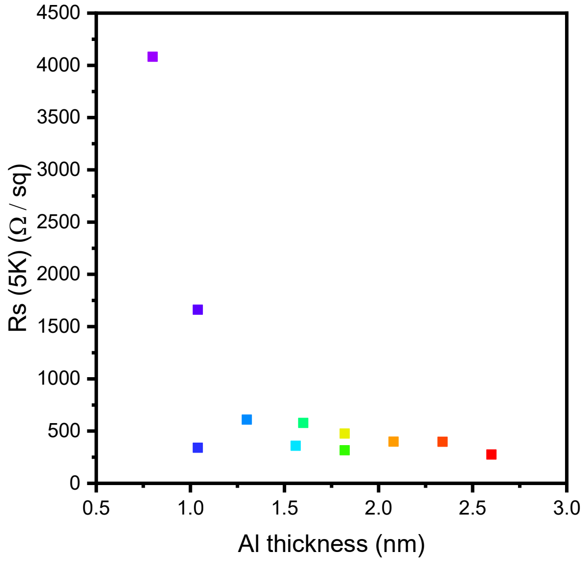


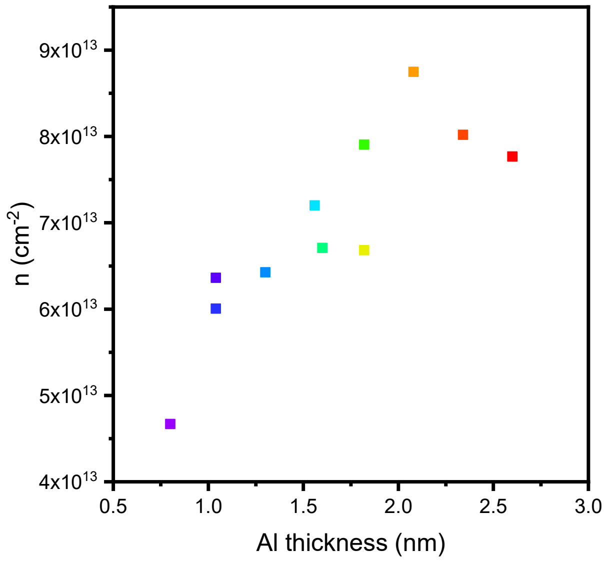
- Presence of 1 nm AlOx layer at interface with STO
- Very little interdiffusion if any

A 2DEG in Al/STO

Dependence of transport properties with Al thickness



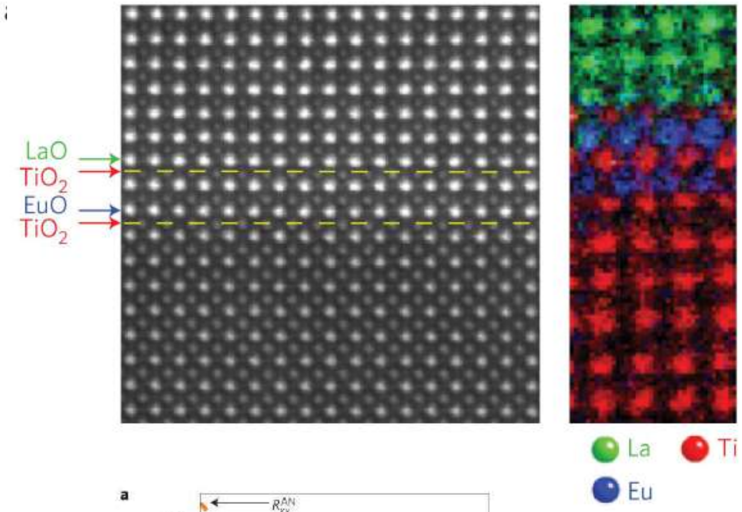


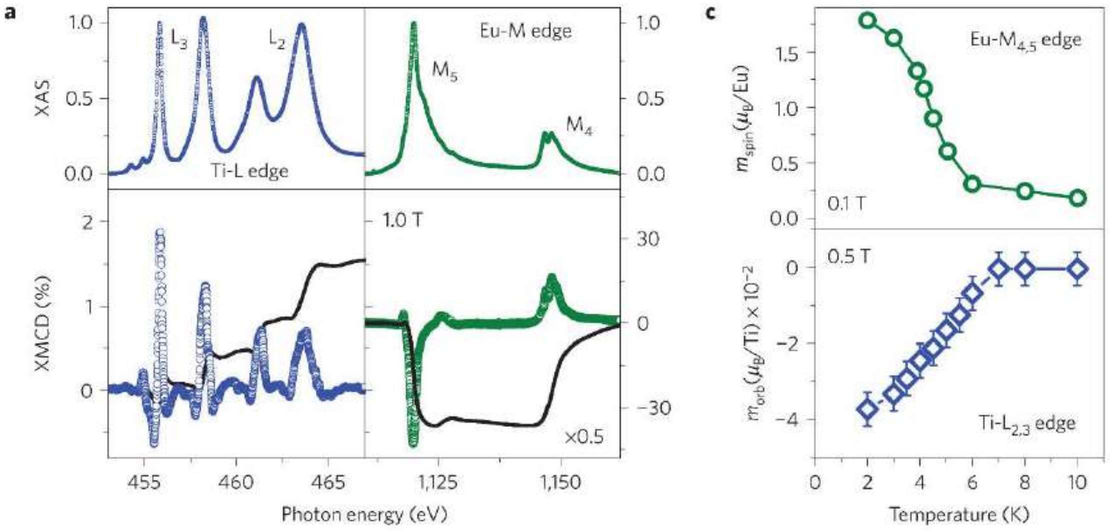


- Conductivity and carrier density increase with Al thickness
- More oxygen vacancies, more carriers
- **Check Luis Moreno’s poster tomorrow !**

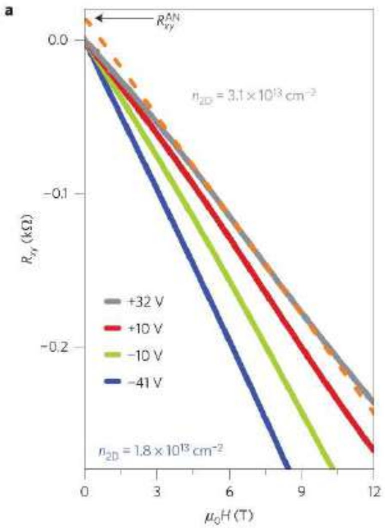
Engineering a magnetic 2DEG

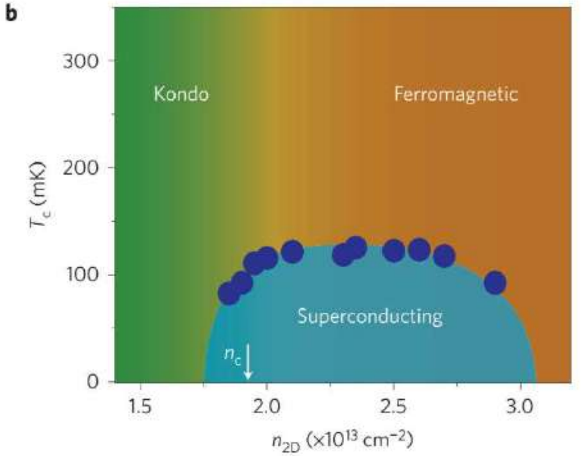
Insert a monolayer of $EuTiO_3$ between LAO and STO





- ⊙ XMCD at Ti and Eu edges





- ⊙ Coexistence of ferromagnetism and superconductivity, tunable by gate voltage

- ⊙ Anomalous Hall effect

Stornaiuolo et al, Nature Mater 15, 278 (2016)

Outline

1. **d_0-oxide-based interfaces**
   - 1.1 Physics of bulk $SrTiO_3$
   - 1.2 $LaAlO_3/SrTiO_3$ 2DEGs
   - 1.3 Other $SrTiO_3$ 2DEGs
   - **1.4 2DEGs not based on $SrTiO_3$**
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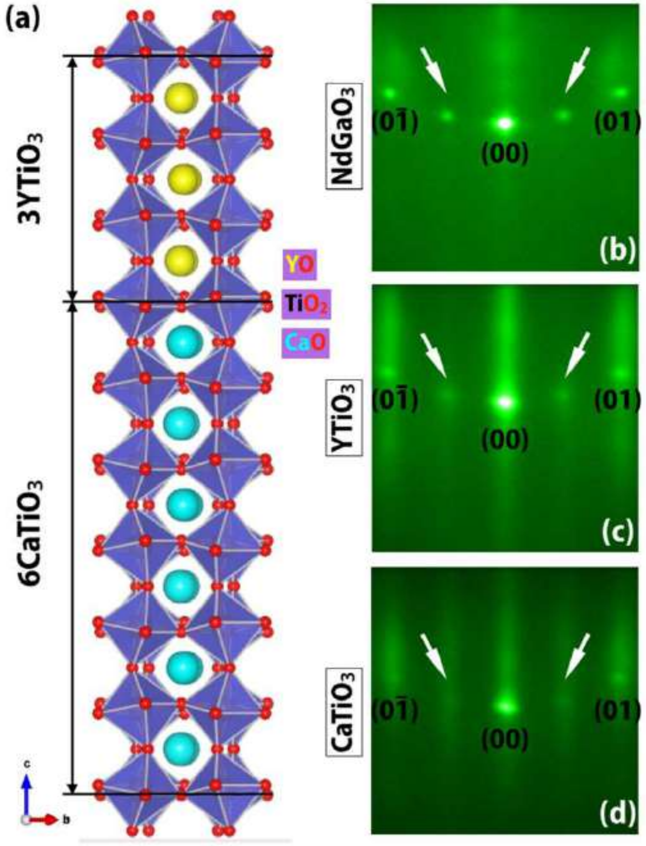
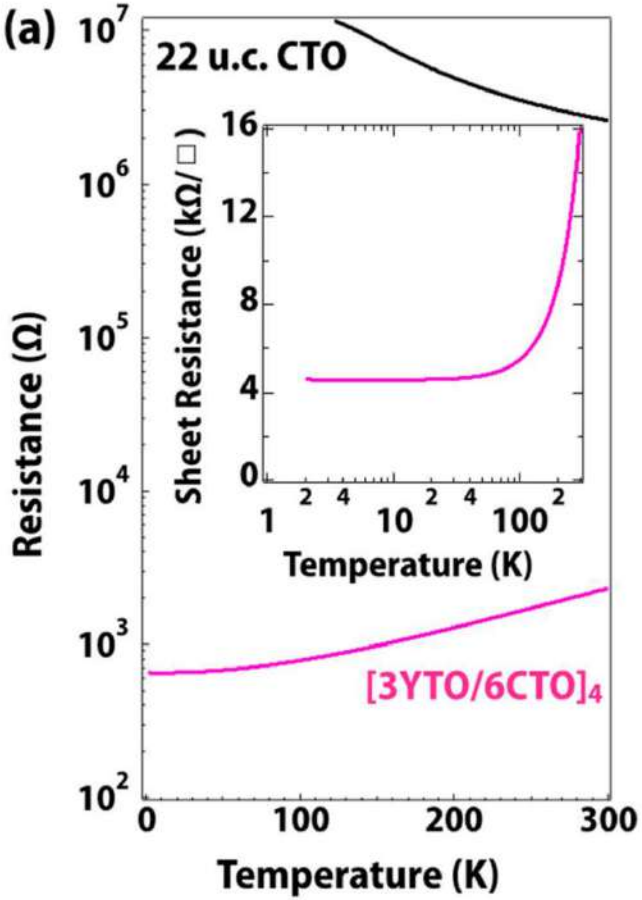
   - 2.1 « Correlated » oxide perovskites
   - 2.2 Nickelate/Titanate interfaces

2DEGs in non STO systems

Metallic interface between $CaTiO_3$ and $YTiO_3$



Liu et al, APL 107 191602 (2015)

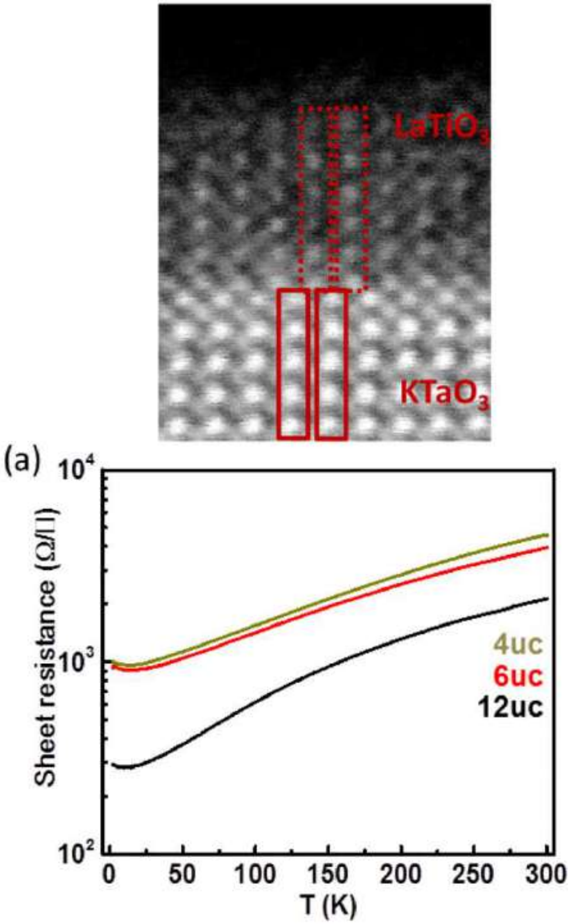


- $CaTiO_3/YTiO_3$ bilayer is grown on NdGaO3 substrate
- Conductive interface appears (2DEG ?) : charge transfer from YTO to CTO ?

2DEGs in non STO systems

2DEGs based on $KTaO_3$

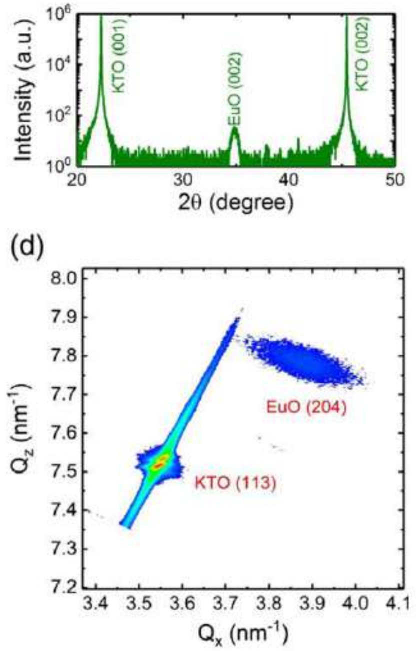
$LaTiO_3/KTaO_3$

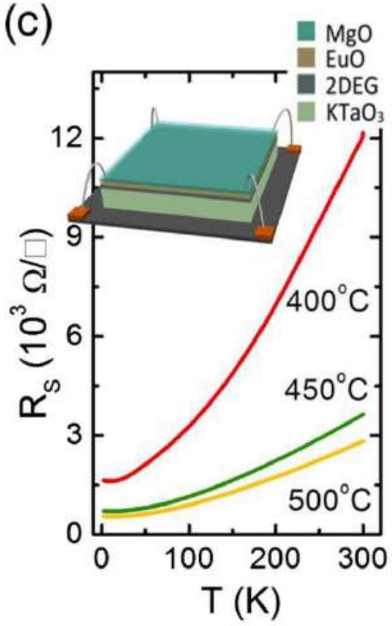


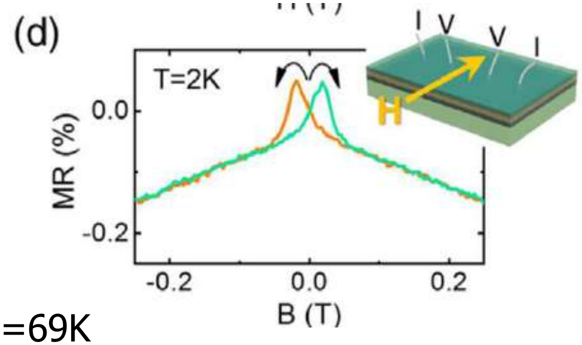
Zou et al, APL Mater. 3, 036104 (2015)

- $LaTiO_3$ film grown on $KTaO_3$ single crystal
- Conductive interface looking like 2DEG

$EuO/KTaO_3$







Zhang et al PRL 121, 116803 (2018)

- EuO is FM insulator with T_C=69K
- EuO film grown on $KTaO_3$ single crystal
- Conductive interface with magnetoresistance : magnetic 2DEG

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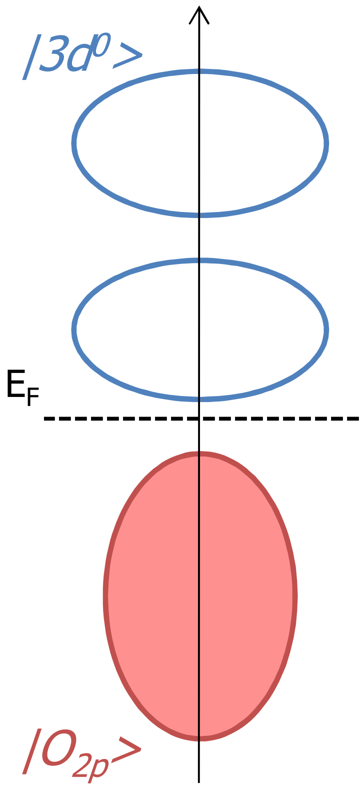
Interfaces between oxides with partially filled d shells

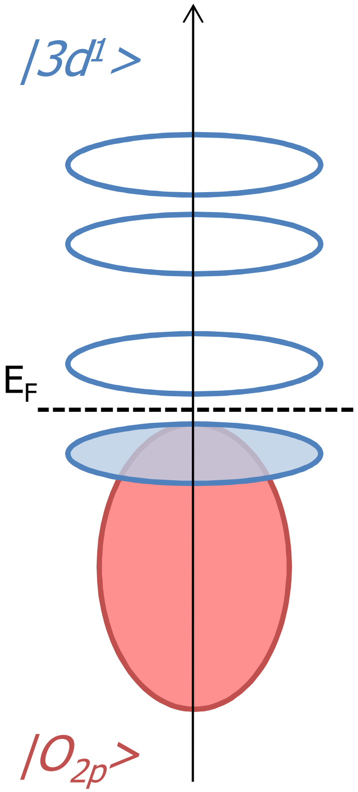
$R^{2+}Ti^{4+}O_3$



- No ***d*** electrons
- No magnetism

Interfaces between oxides with partially filled d shells

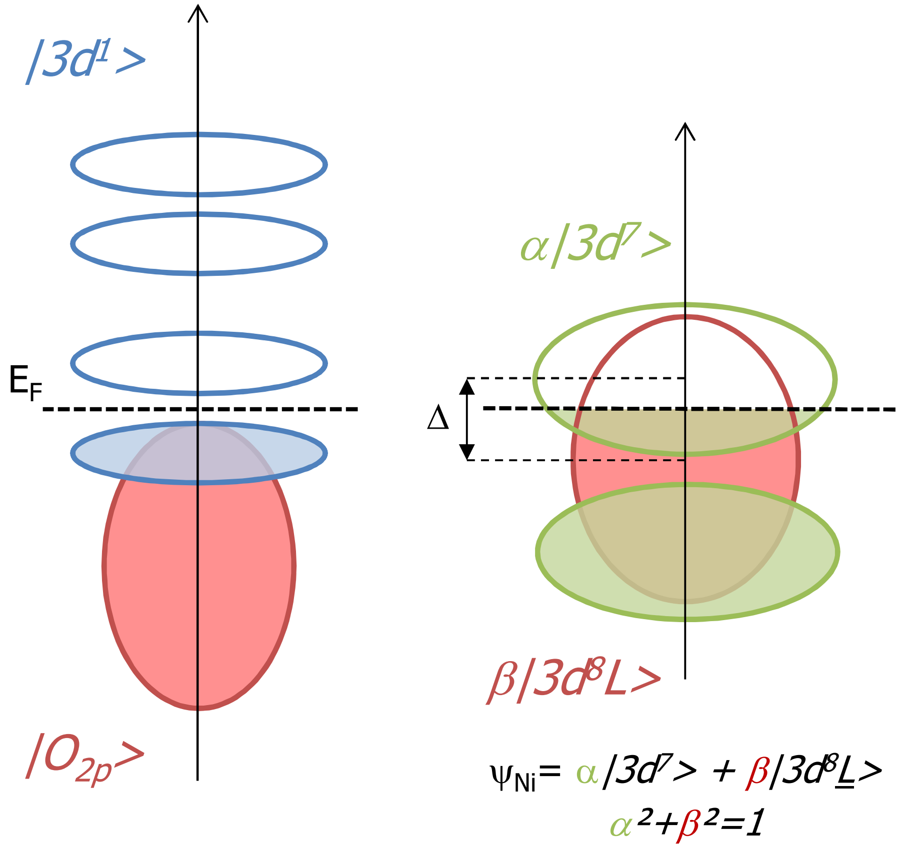
$R^{3+}Ti^{3+}O_3$



- ***d*** electrons
- Magn/orb order
- **Mott insulator**

Interfaces between oxides with partially filled d shells

$R^{3+}Ti^{3+}O_3$ $R^{3+}Ni^{3+}O_3$



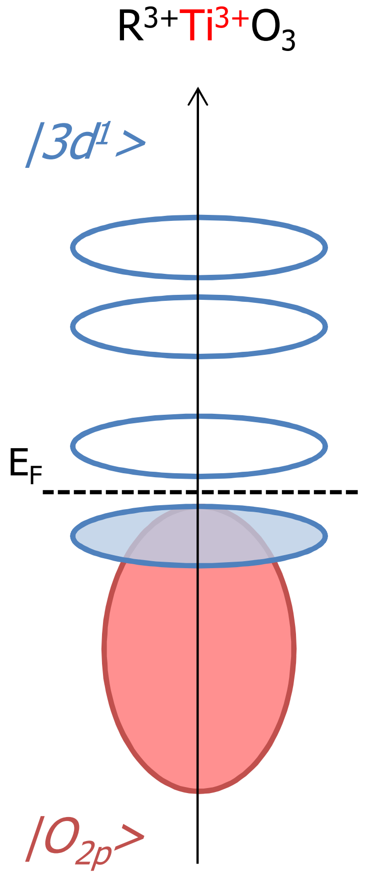
$\psi_{Ni} = \alpha|3d^7> + \beta|3d^8\underline{L}>$

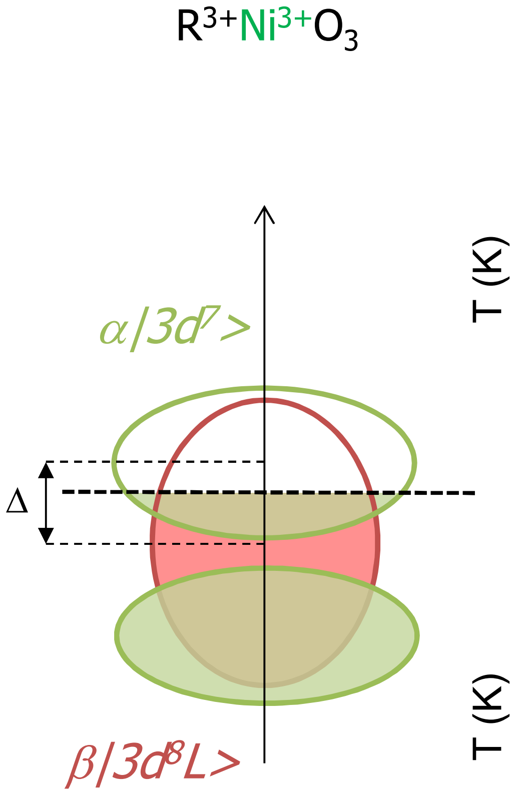
$\alpha^2+\beta^2=1$

- ***d*** electrons
- Magn/orb order
- **Mott insulator**

- ***d*** electrons
- Magn/orb order
- Strong covalence

Interfaces between oxides with partially filled d shells





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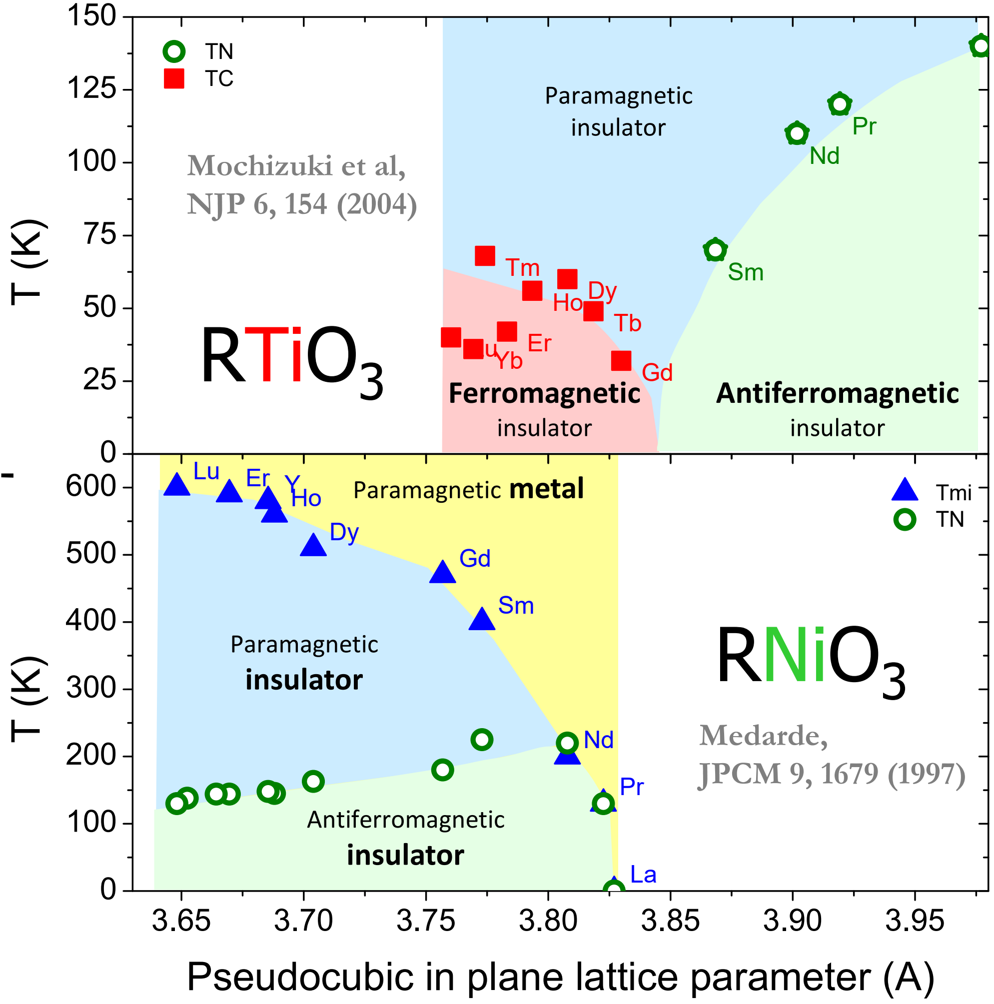


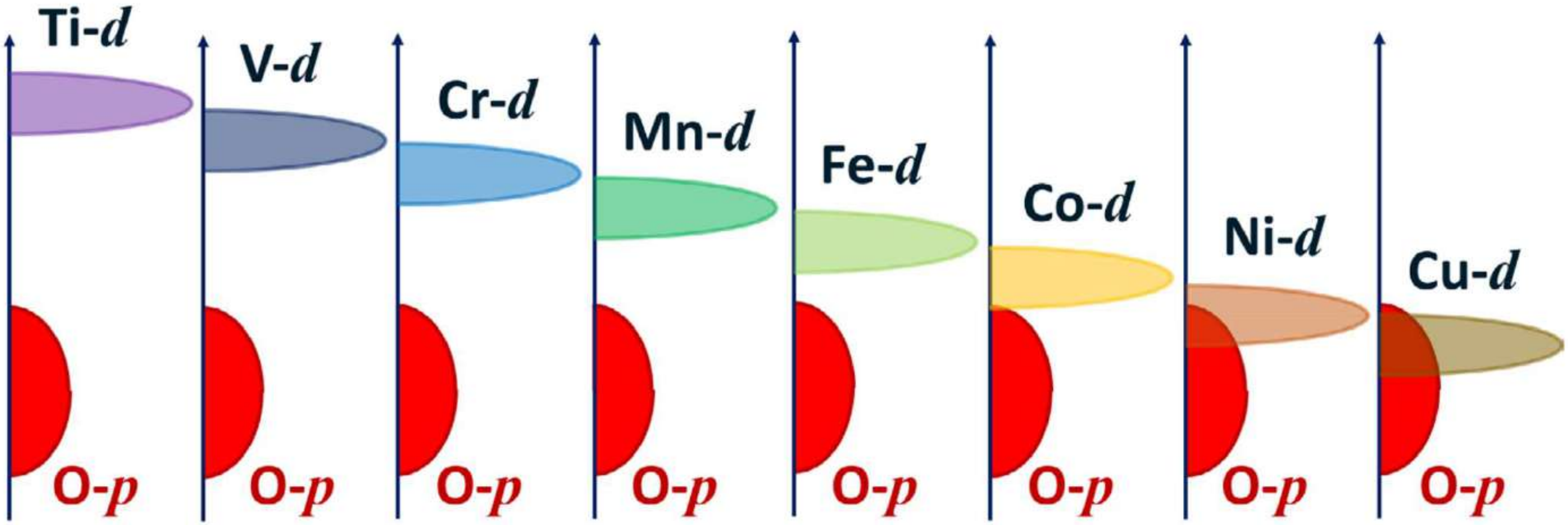
- ***d*** electrons
- Magn/orb order
- **Mott insulator**

- ***d*** electrons
- Magn/orb order
- Strong covalence

- Very rich phase diagrams
- **Magnetic instabilities** (Ferro/Antiferro)
- **Electronic instabilities** (Metal/Insulator)

Interfaces between oxides with partially filled d shells

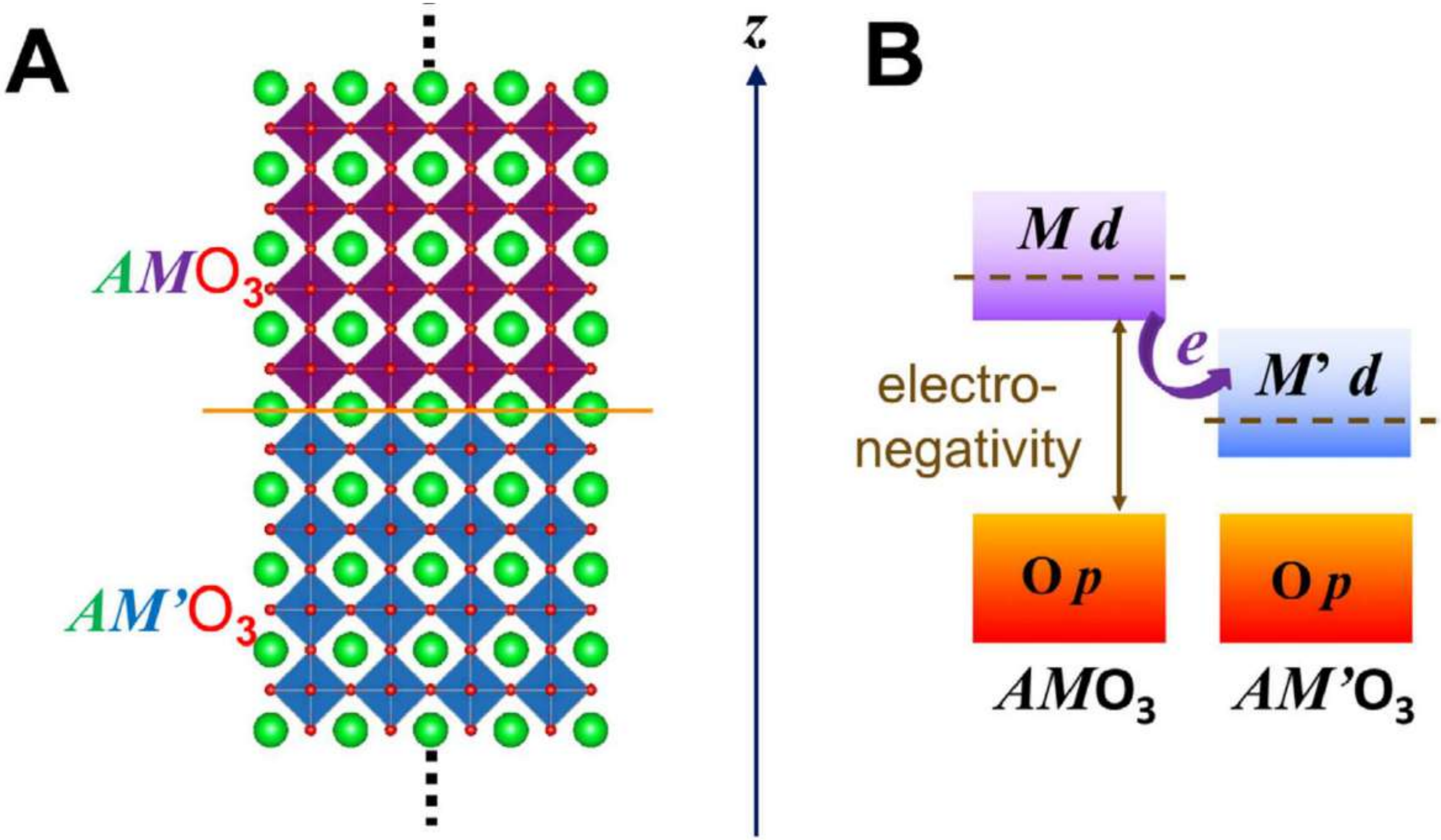
Electronic structure of transition metal perovskites



- As the mass of transition metal elements increases, the metal d level decreases.
- For titanates, Ti-d states lie above O-p by about 3 eV.
- For nickelates and cuprates, Ni-d and Cu-d states even lie below O-p states, leading to a ‘negative charge transfer’ energy and strong hybridization.

Chen and Millis, JPCM, 29, 243001 (2017)

Interfaces between oxides with partially filled d shells



- Due to continuity of oxygen lattice, oxygen p states will align
- Charge transfer will occur from material to larger electronegativity to material with smaller electronegativity

Chen and Millis, JPCM, 29, 243001 (2017)

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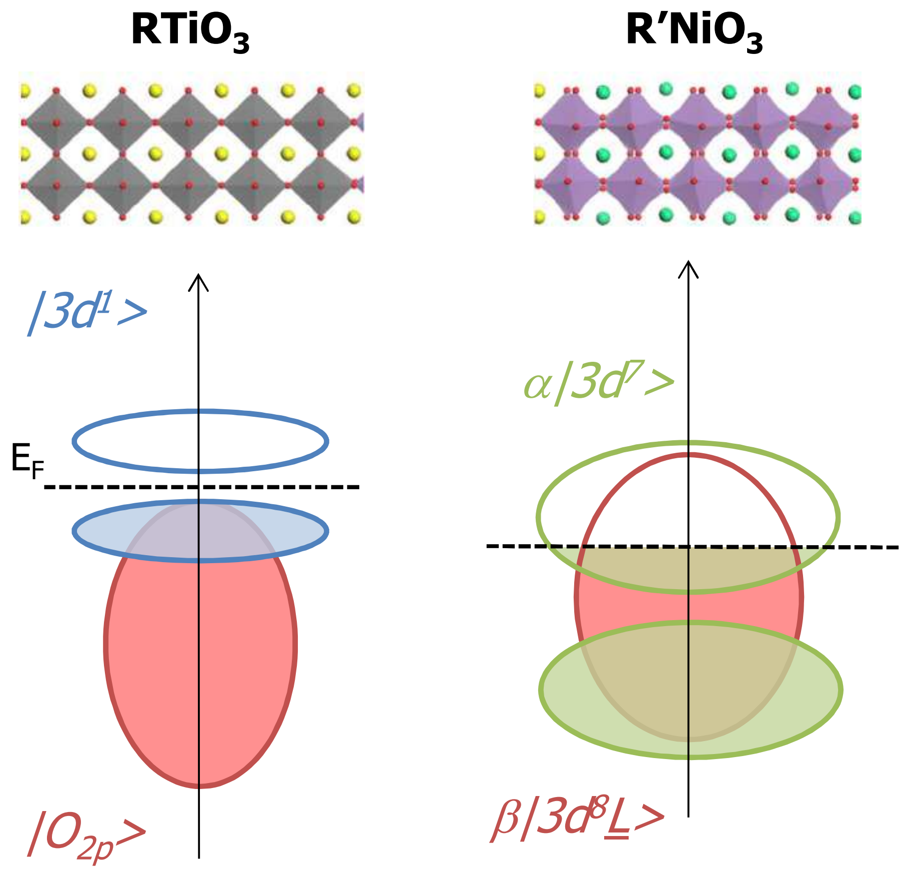

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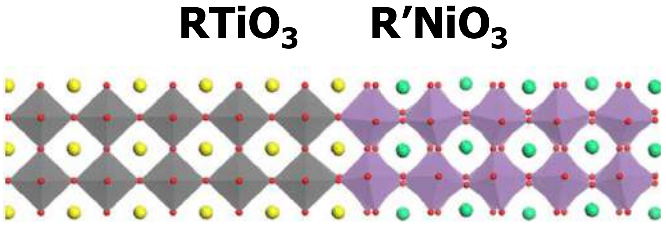
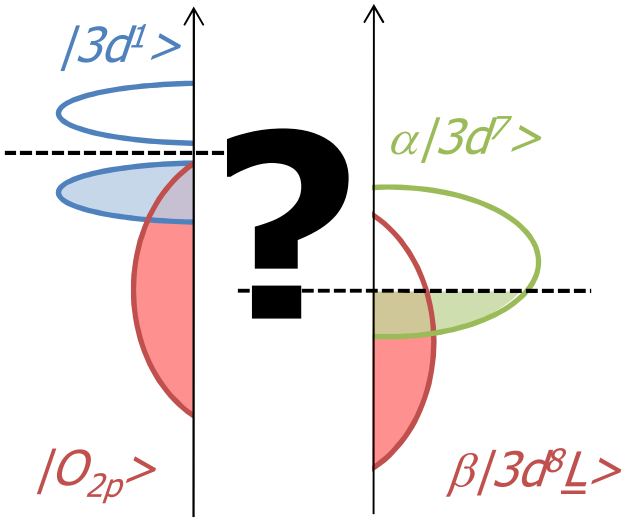
Interfaces between oxides with partially filled d shells

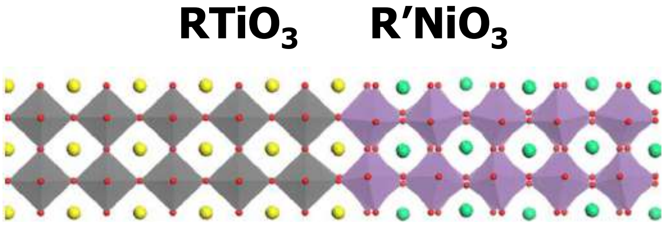


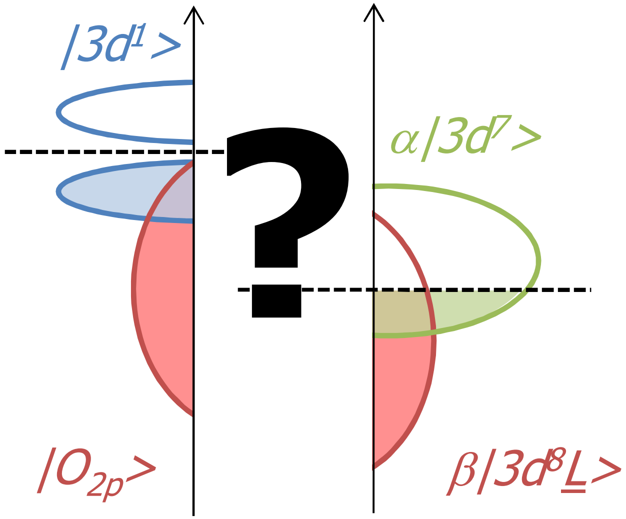


Unusual band structure ➔ complex electronic reconstruction at interface

Degrees of freedom : charge, structure, orbital, spin

Interfaces between oxides with partially filled d shells





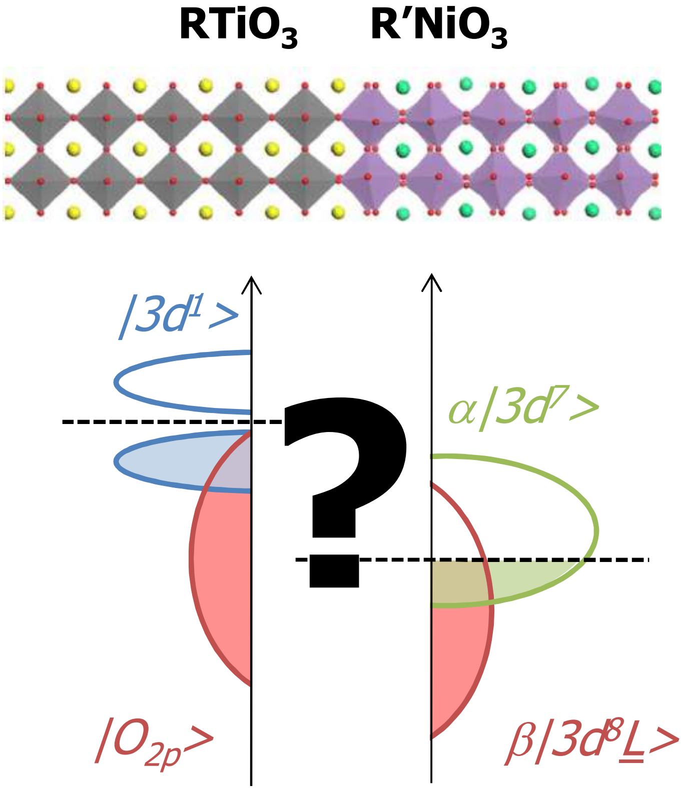
Unusual band structure ➔ complex electronic reconstruction at interface

Degrees of freedom : charge, structure, orbital, spin

Various predicted **new properties** in related systems

- **Ferromagnetic 2-dimensional electron gases** in $LaTiO_3/SrTiO_3$ Okamoto & Millis, Nature (2004)
- **Superconductivity** in $LaNiO_3/LaMnO_3$ Chaloupka et al, PRL (2008)
- **New spin/orbital states** in $GdTiO_3/SrTiO_3$ Li et al, ArXiv (2013) ; in $LaTiO_3/LaNiO_3$ Millis et al, PRL (2013)
- **New ferroelectrics** in $LaGaO_3/YGaO_3$ Rondinelli & Fennie, Adv. Mater. (2012)

Interfaces between oxides with partially filled d shells



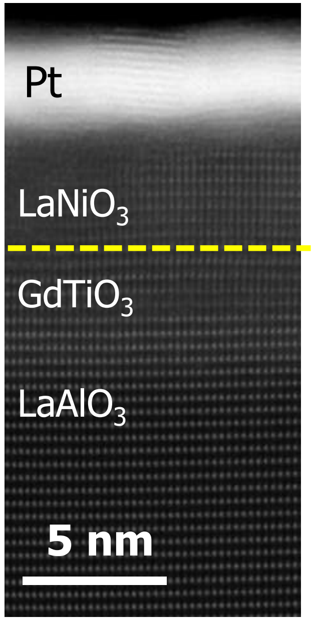
Unusual band structure ➔ complex electronic reconstruction at interface

Degrees of freedom : charge, structure, orbital, spin

- Here systematic study of interface properties between $GdTiO_3$ and $RNiO_3$
- Change rare-earth (La, Nd, Sm) : **tune bandwidth**, **bond angles**, **p-d energy**, etc

Interfaces between titanates and nickelates

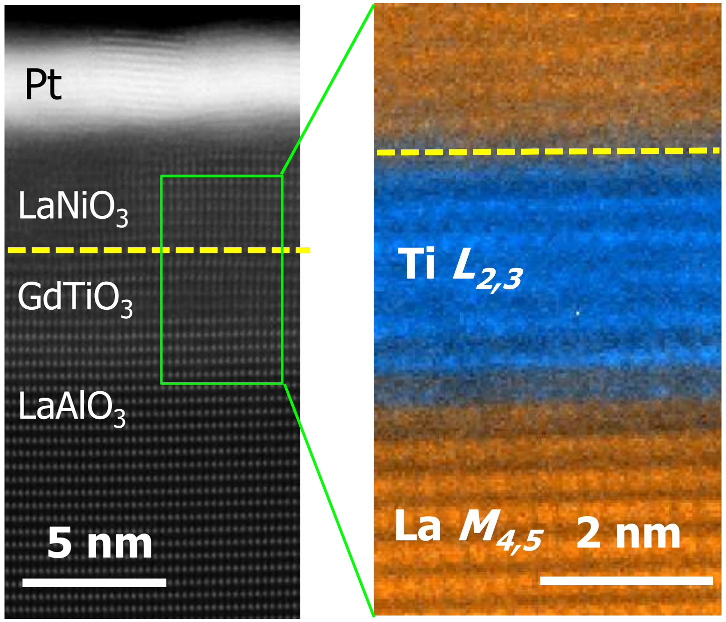
Electronic reconstruction at $RNiO_3/GdTiO_3$ interfaces



- Epitaxial growth of bilayer system

Interfaces between titanates and nickelates

Electronic reconstruction at
$RNiO_3/GdTiO_3$ interfaces

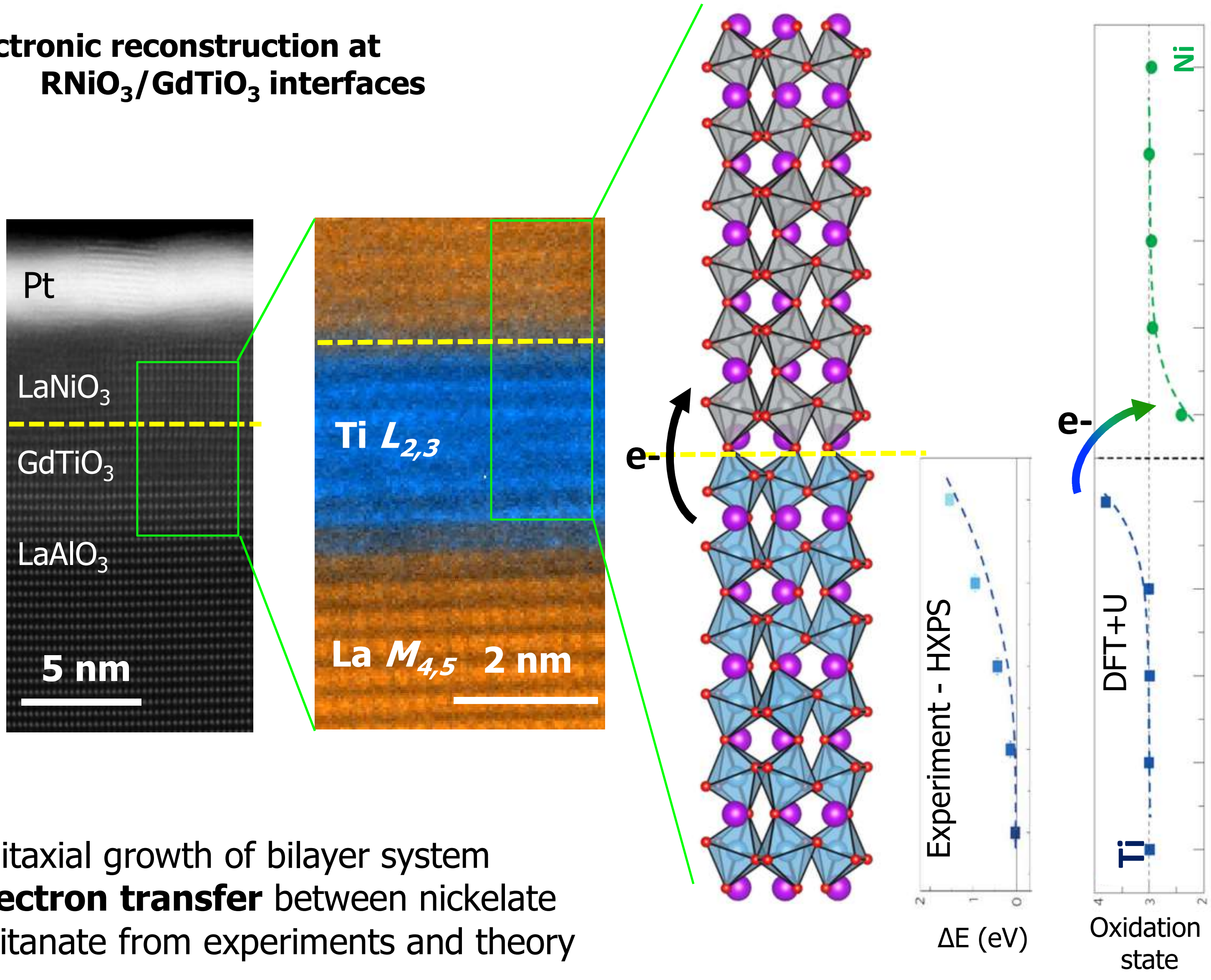


- Epitaxial growth of bilayer system

Grisolia, MB et al, Nature Phys. 12? 484 (2016)

Interfaces between titanates and nickelates

Electronic reconstruction at $RNiO_3/GdTiO_3$ interfaces



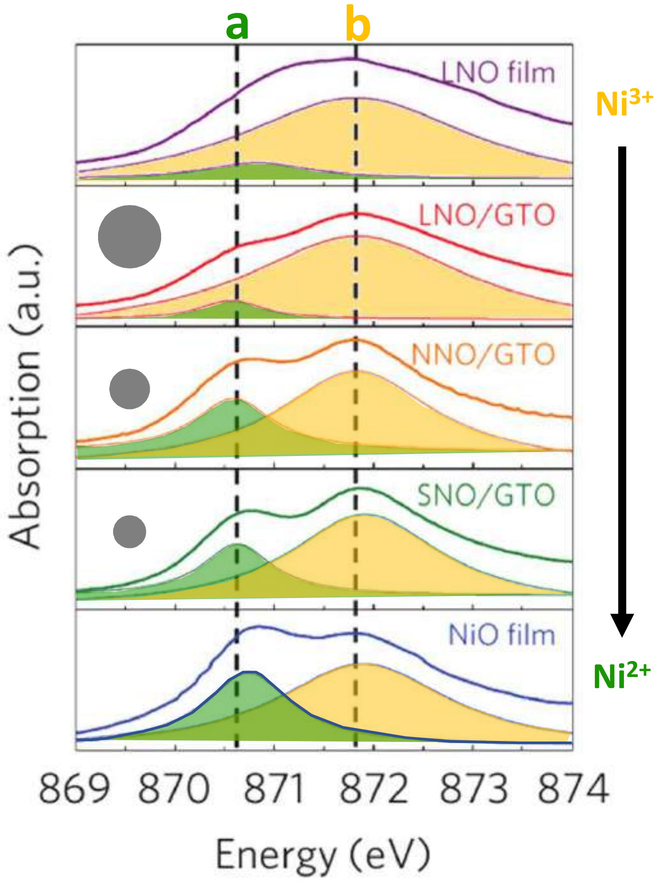
- Epitaxial growth of bilayer system
- **Electron transfer** between nickelate and titanate from experiments and theory

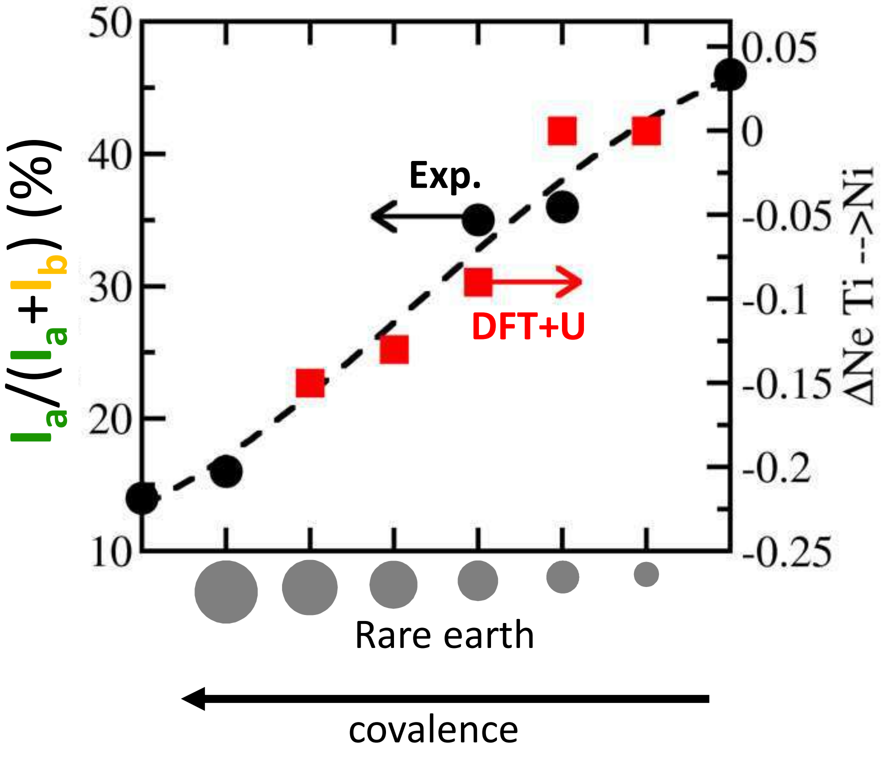
Grisolia, MB et al, Nature Phys. 12? 484 (2016)

Interfaces between titanates and nickelates

Electronic reconstruction at $RNiO_3/GdTiO_3$ interfaces : role of covalence

Exp. : XAS - Ni L_3 edge



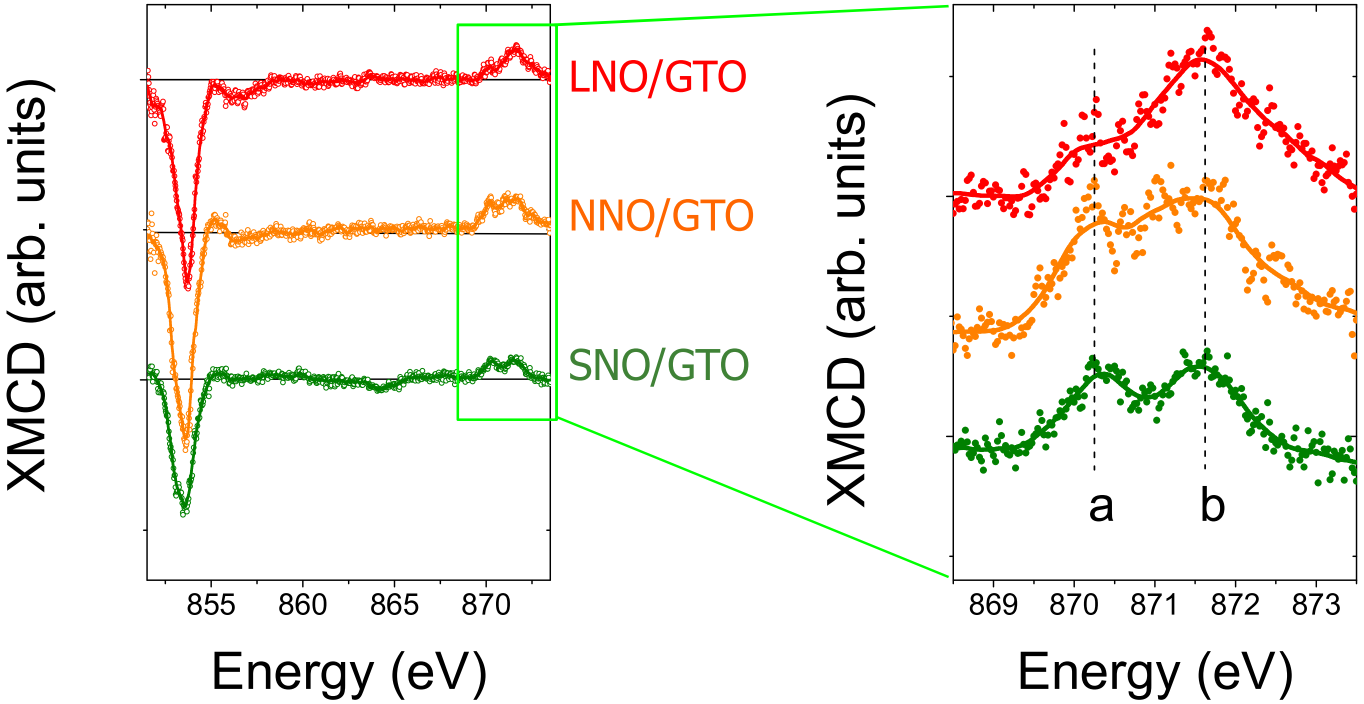


- ⊙ Amount of charge transferred from titanate to nickelate **modulated by covalence** in nickelate material

Grisolia, MB et al, Nature Phys. 12? 484 (2016)

Interfaces between titanates and nickelates

Magnetic properties of $RNiO_3$/$GdTiO_3$ interfaces



- XMCD is observed at Ni $L_{2,3}$ edge for all bilayers while individual nickelates are AF
- Strong signature of **Ni^{2+} magnetism**
- « Covalent exchange » can induce ferromagnetic coupling between Ni^{2+} and Ni^{3+}

➔ **Novel magnetic state in nickelates**

Goodenough, PR 100, 554 (1955)
Goodenough, J. Solid State Chem. 127, 126 (1996)

Grisolia, MB et al, Nature Phys. 12? 484 (2016)

Conclusions and perspectives

- Oxide interfaces have **unexpected electronic and magnetic properties**
- Some properties derive from the bulk of the compounds involved, **some are readily new**
- **Inversion symmetry breaking** is key to most new properties
- Most literature focuses on $SrTiO_3$ and related d^0 compounds like $KTaO_3$
- Much work remains to be done for **interfaces between non d^0 perovskites**
- Harder to grow as interesting couples often need to be grown in different conditions
- Parameter space is huge and more **exotic phenomena** should arise from orbital and spin reconstruction (**topological effects**)

MB et al, Adv. Phys. 60, 5 (2011)
J. Varignon, MB et al., Nature Phys. 14, 322 (2018)