Physics in a STO-capped LAO/STO hetero-interface

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목 차

Oxide electronics: an opportunity

Future of Electronics

All-in-one mobile phone

From Nokia

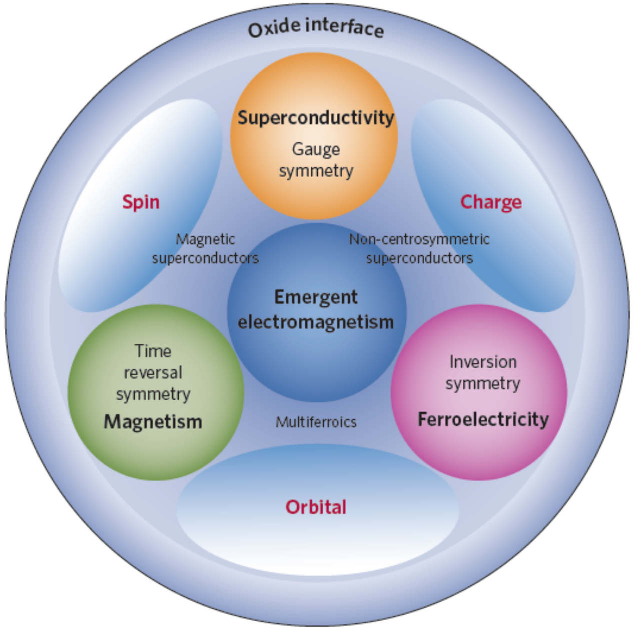
Transparent display

From "Avatar"

AI robot

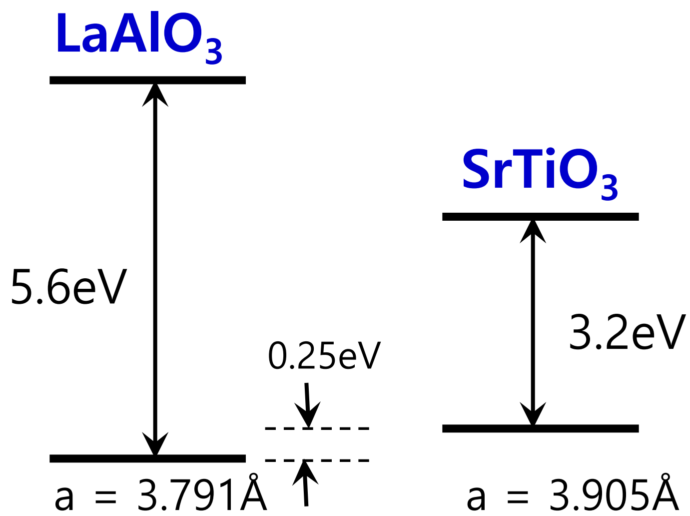
From "Transformers"

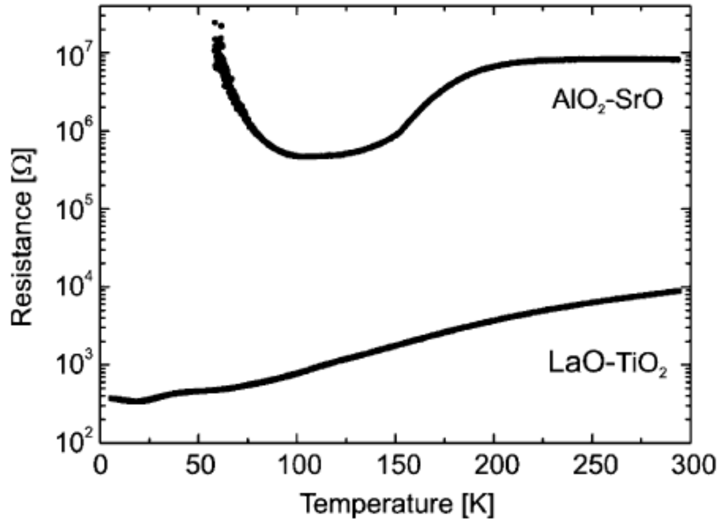
Higher speed, higher density, smaller (thinner) size, and multifunctionality

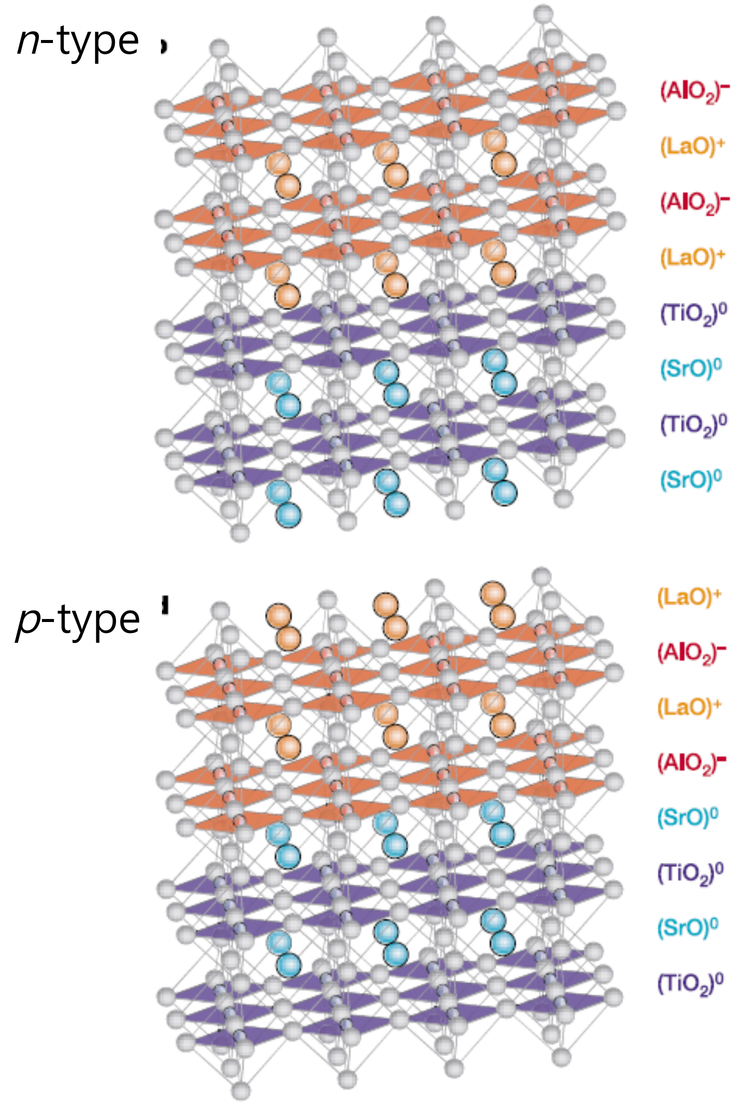


New semiconductors: Control of electronic and spin transports at nanoscale

$LaAlO_3/SrTiO_3$ hetero-interface

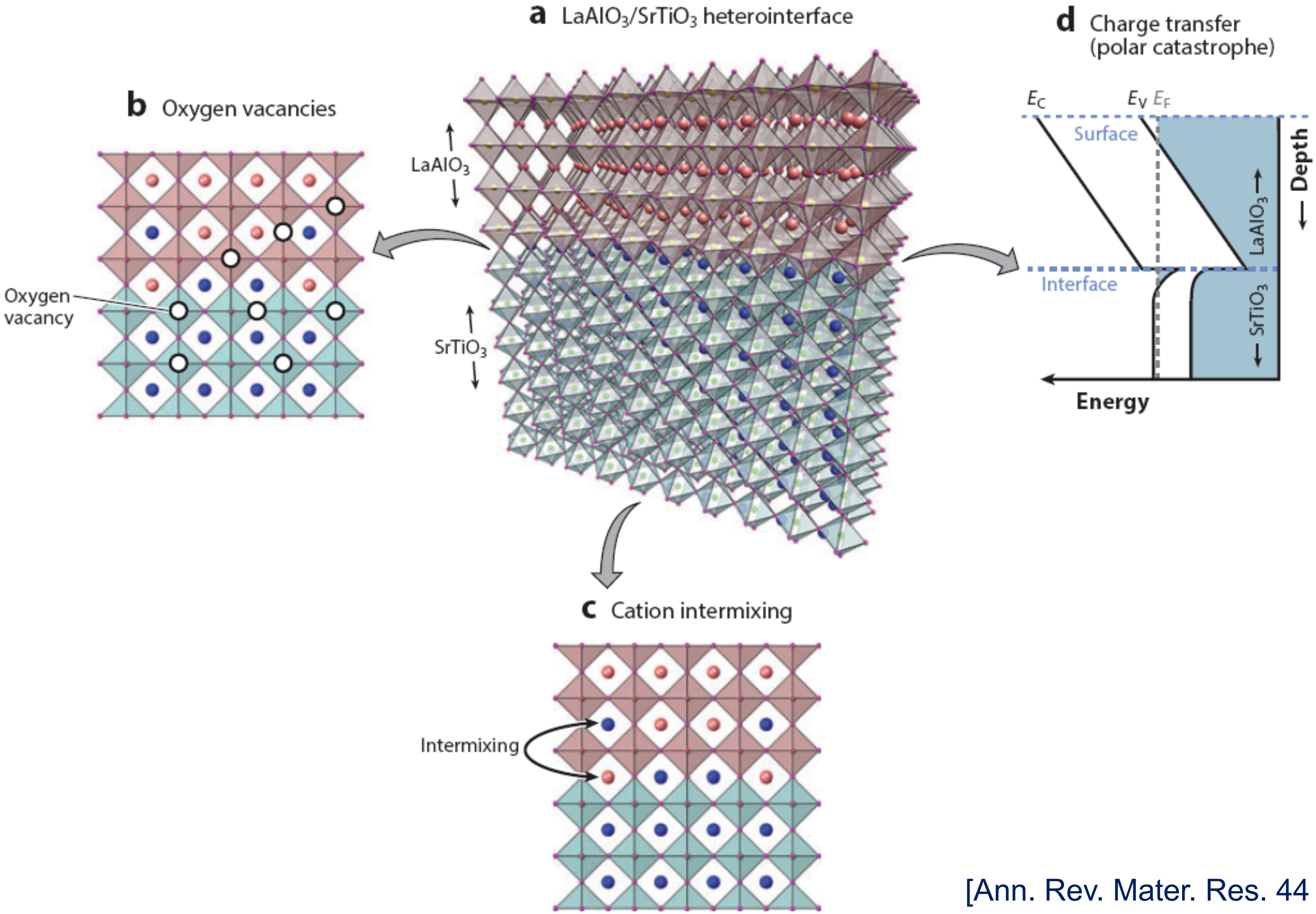






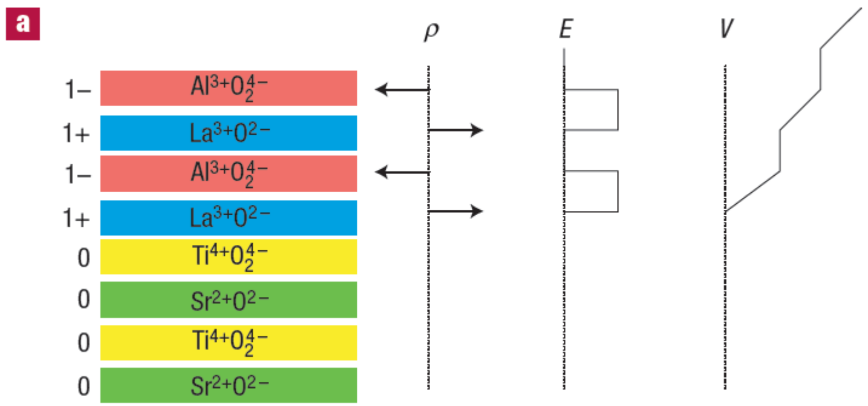
[Otomo & Hwang, Nature 427 (2004)]

Conduction mechanism: models



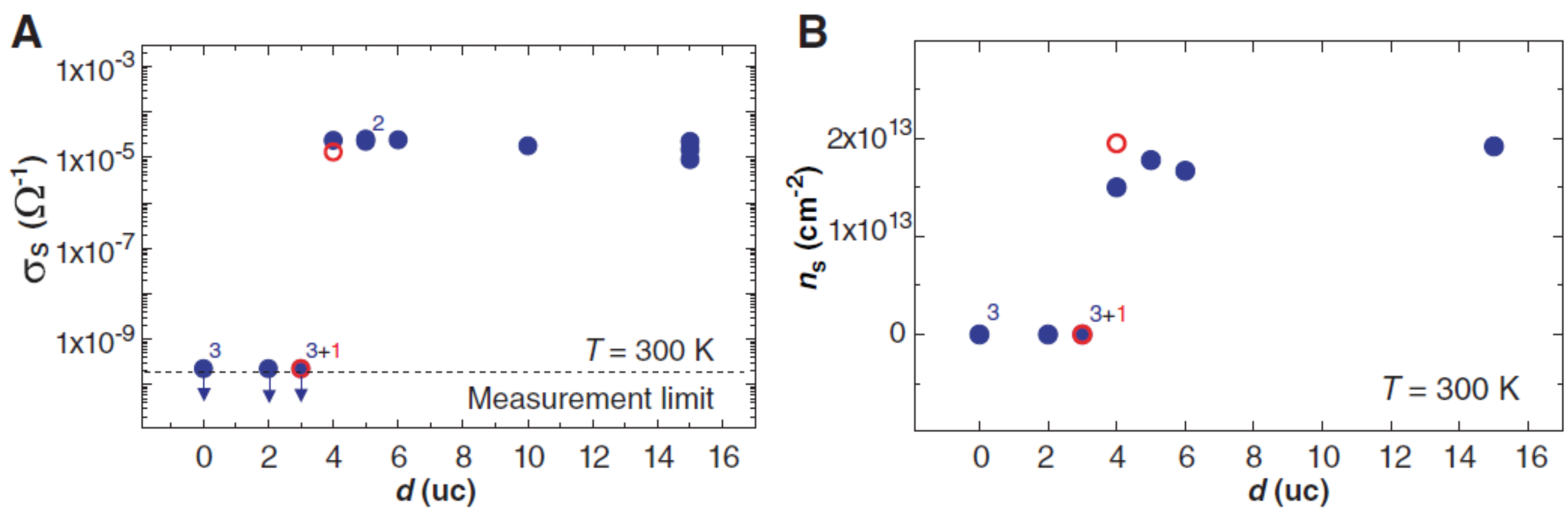
[Ann. Rev. Mater. Res. 44 (2014)]

Polar catastrophe model



[Nakagawa et al., Nat. Mater. 5, 204 (2006)]

Critical thickness of conduction

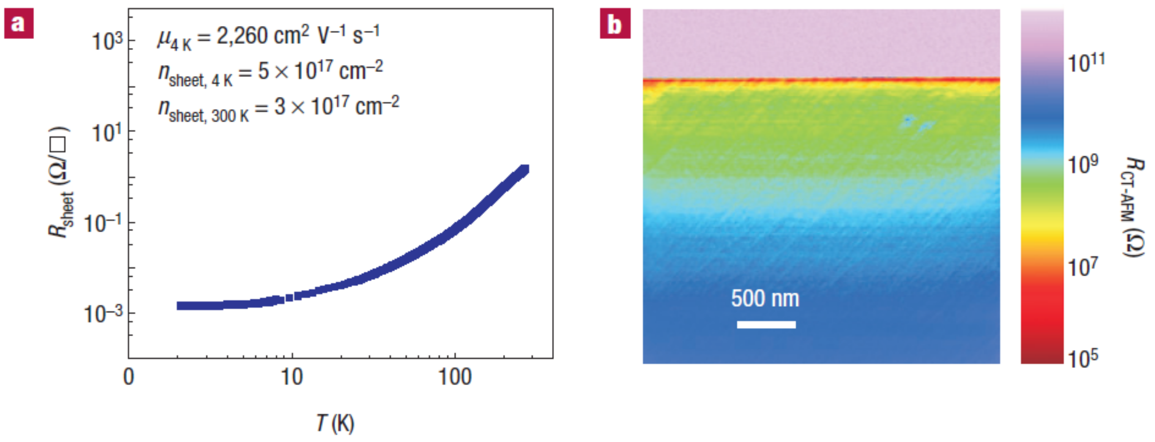


[Thiel *et al.*, Science 313, 1942 (2006)]

Oxygen vacancy vs. Polar catastrophe

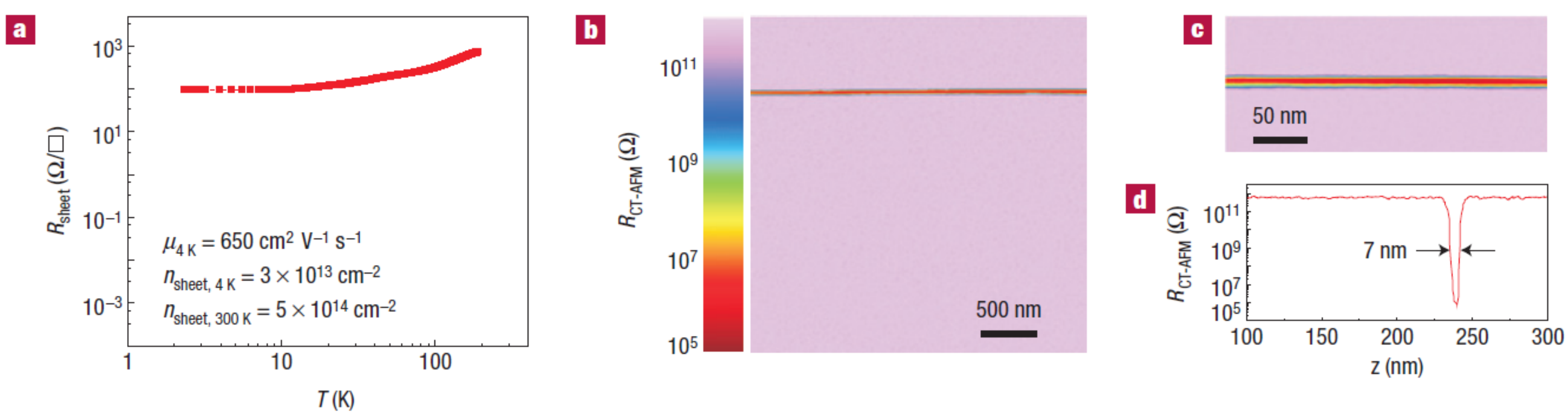
Introduction

'Non-annealed' LAO/STO interface



[Nat. Mater. 7, 621 (2008)]

'*In-situ* annealed' LAO/STO interface

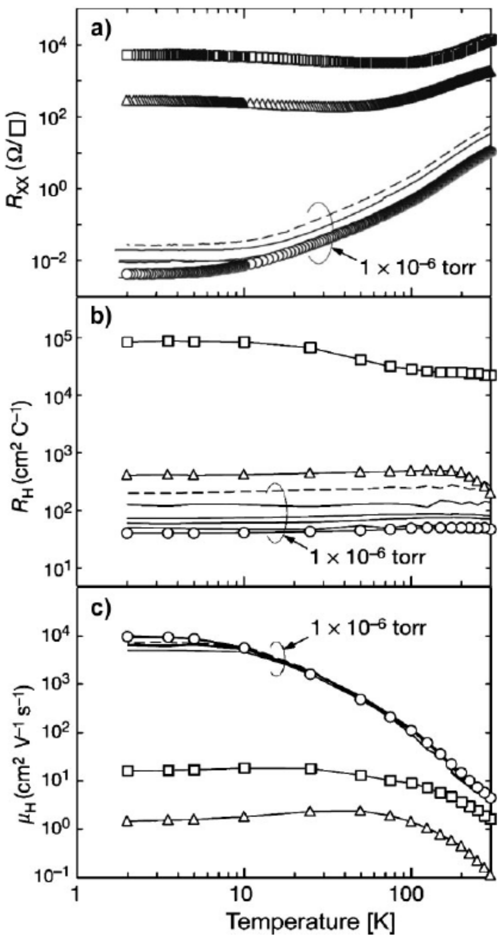


❖ Oxygen vacancies increase the carrier density.

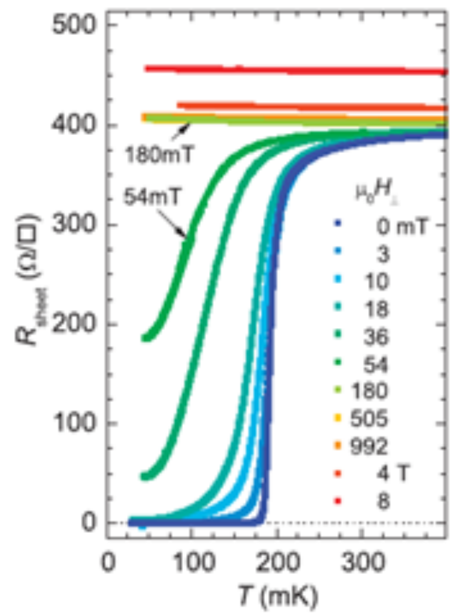
❖ Finite carrier density even after annealing : polar discontinuity and 2DEG at interface

Electrical transport properties

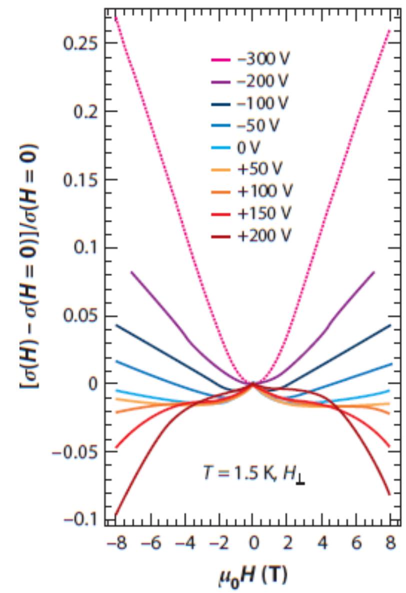
Growth condition dependence

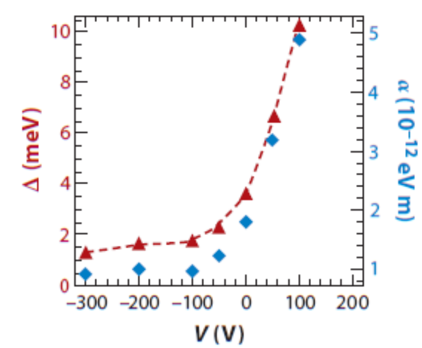


Superconductivity



Strong SO coupling

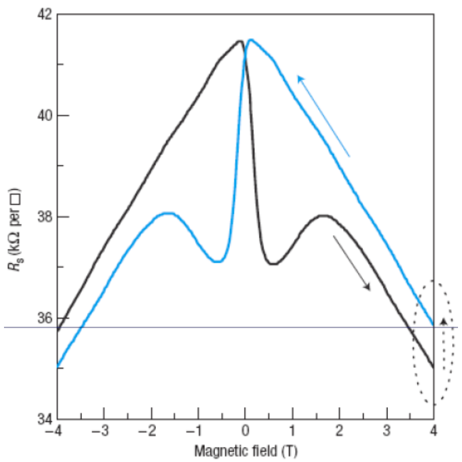




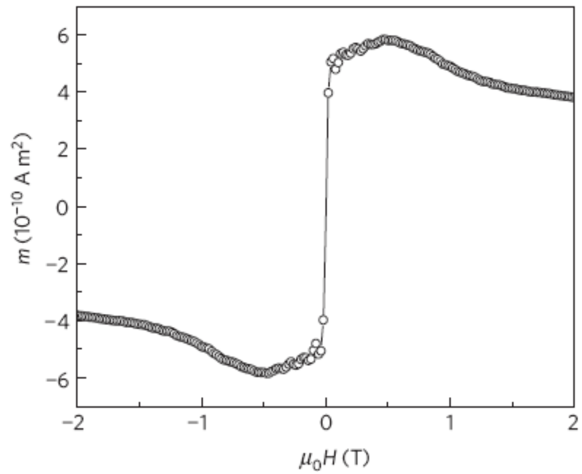
Otomo & Hwang, Nature 427 (2004)
Thiel *et al.*, Science 313 (2007)
Reyren *et al.*, Science 317 (2007)
Caviglia *et al.*, PRL 104 (2010)

Magnetic transport properties

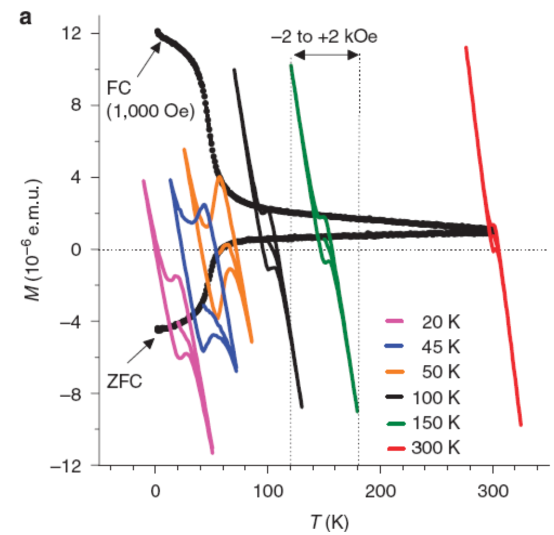
Hysteresis in MR



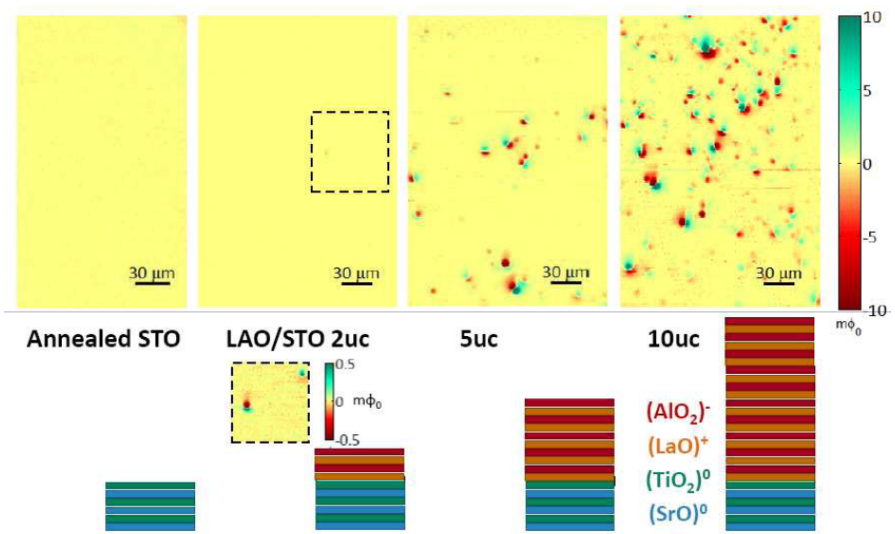
Magnetic moment



Phase separation

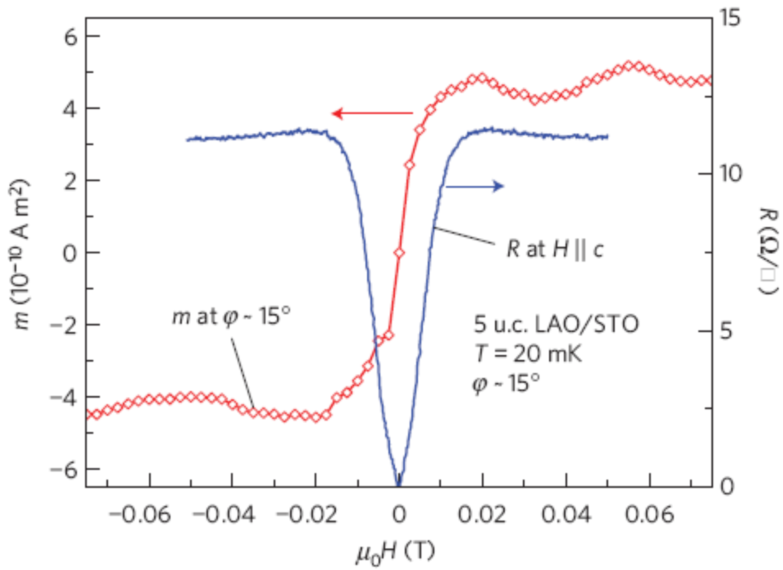


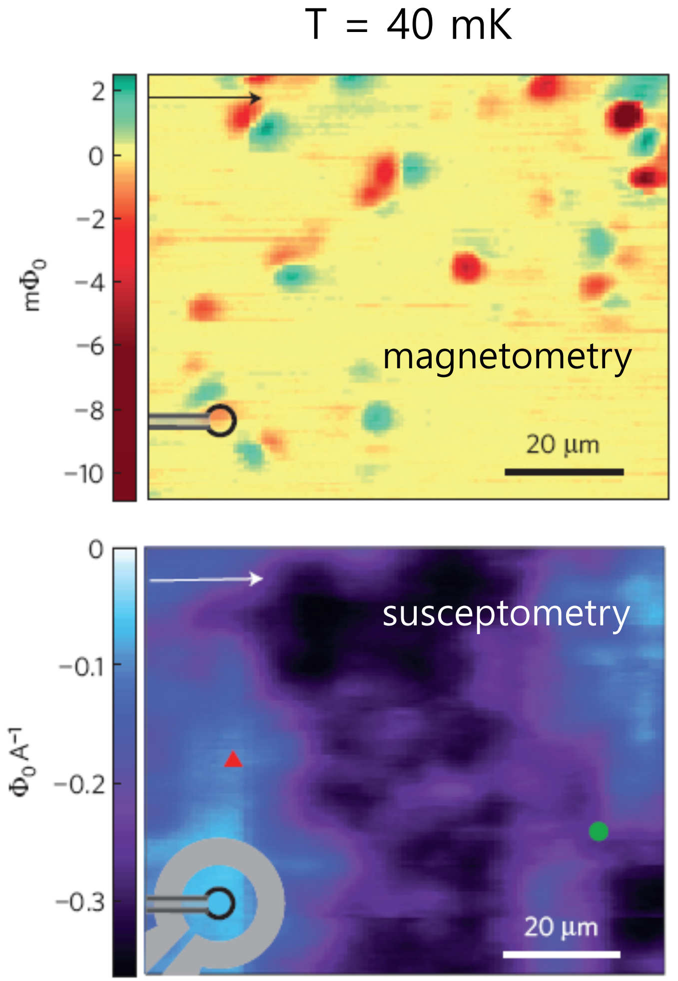
Scanning SQUID microscopy study



Brinkman *et al.*, Nat. Mat. 5 (2007)
Li *et al.*, Nat. Phys. 7 (2011)
Ariando *et al.*, Nat. Com. 2 (2011)
Kalisky *et al.*, Nat. Com. 3 (2012)

Magnetism and Superconductivity



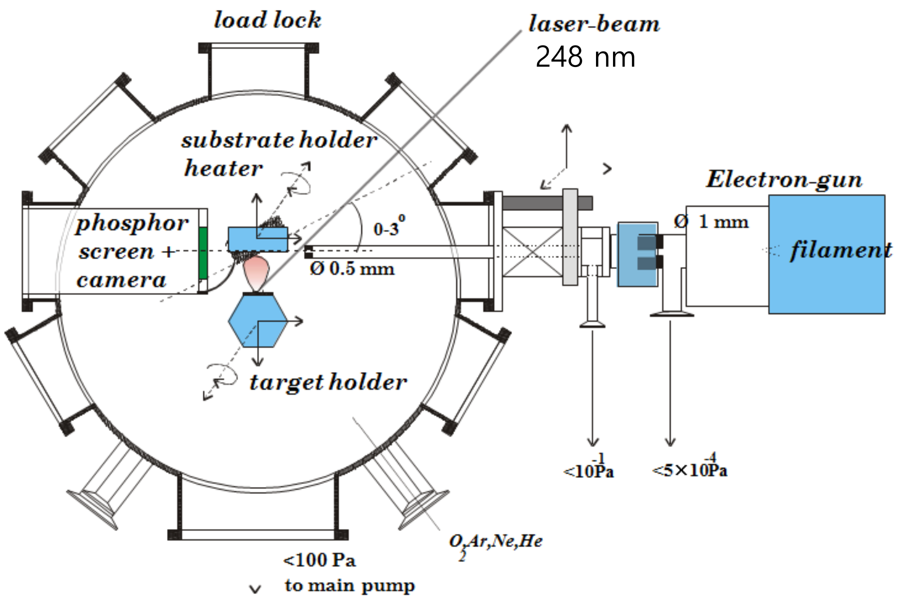


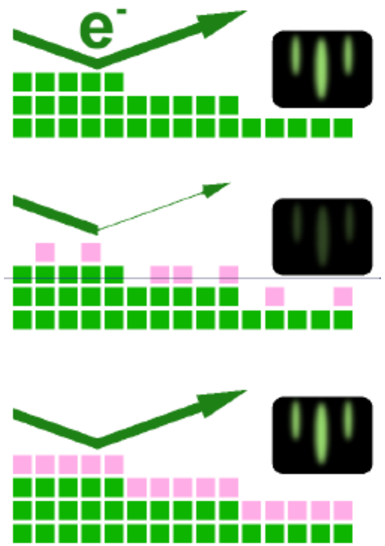
Superconductivity and Magnetism coexist at $LaAlO_3/SrTiO_3$ hetero-interface!!

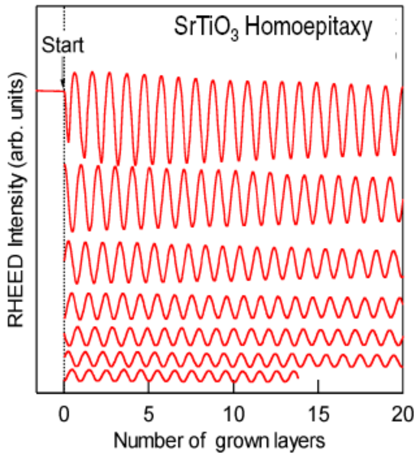
Bert *et al.*, Nat. Phys. 7 (2011)
Li *et al.*, Nat. Phys. 7 (2011)

Pulsed Laser Deposition

Introduction







RHEED
(Reflection High-Energy Electron Diffraction)

Sample preparation

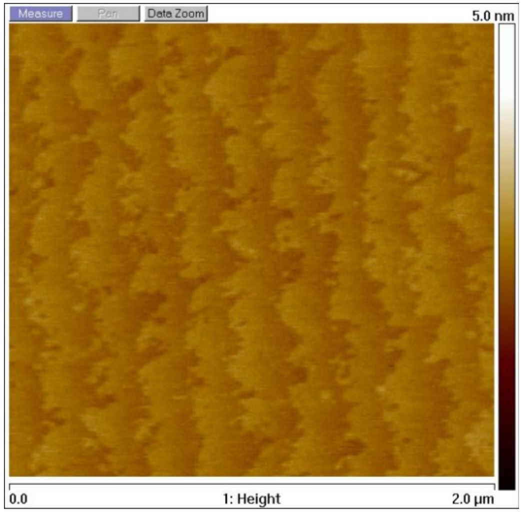
I. Chemical treatment → TiO_2-terminated STO substrate

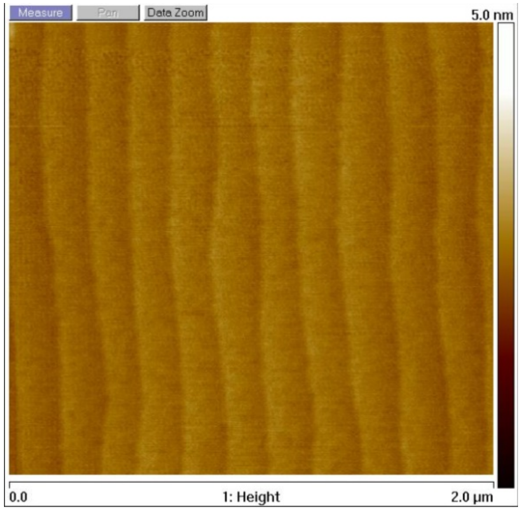
II. Physical treatment 950 ºC, 2 x 10^{-5} Torr, 2 hours

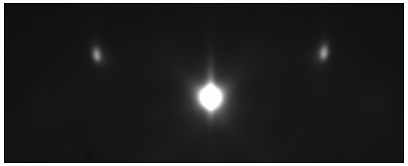
III. Deposition 750 ºC, 1 x 10^{-5} Torr, 4 Hz

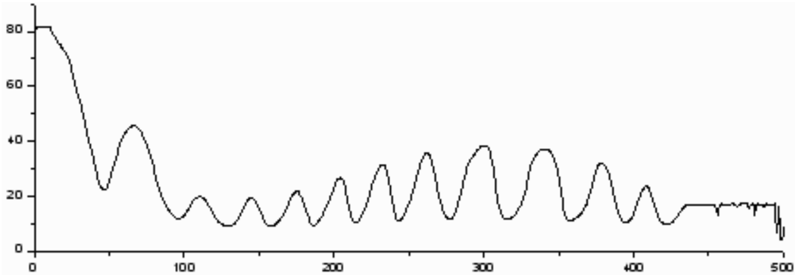
IV. Post-annealing 750 ºC, 500 mTorr, 30 min

V. Metal deposition Ti / Co / Au (Sputtering)

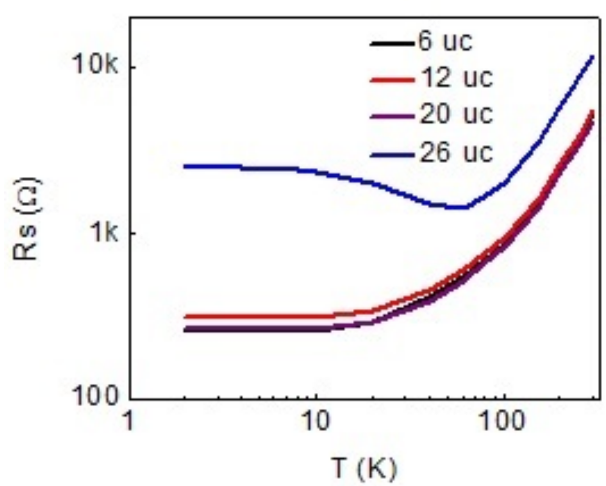


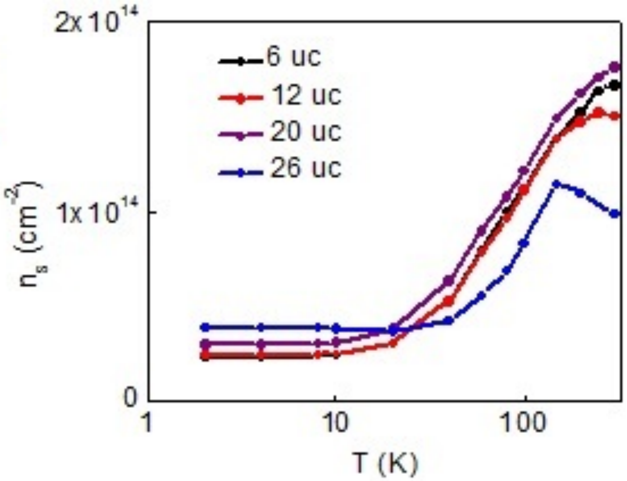


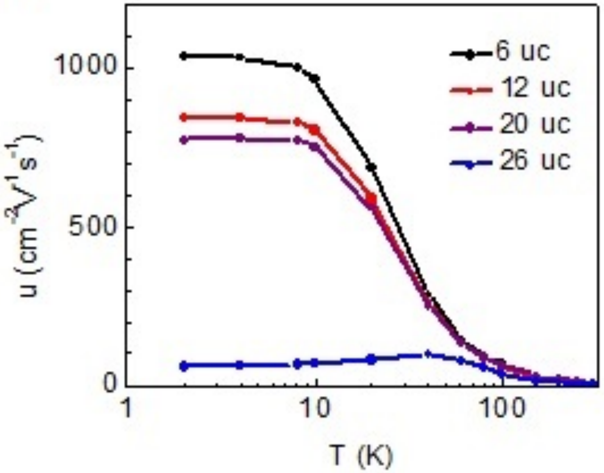


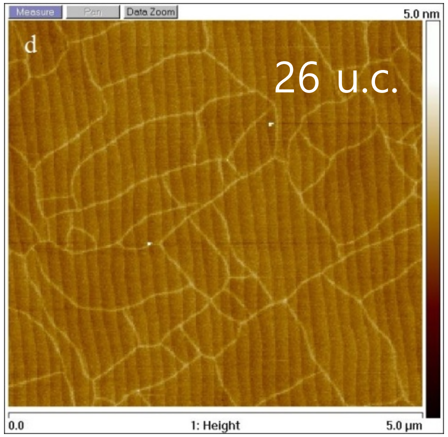


Thickness dependence of resistance





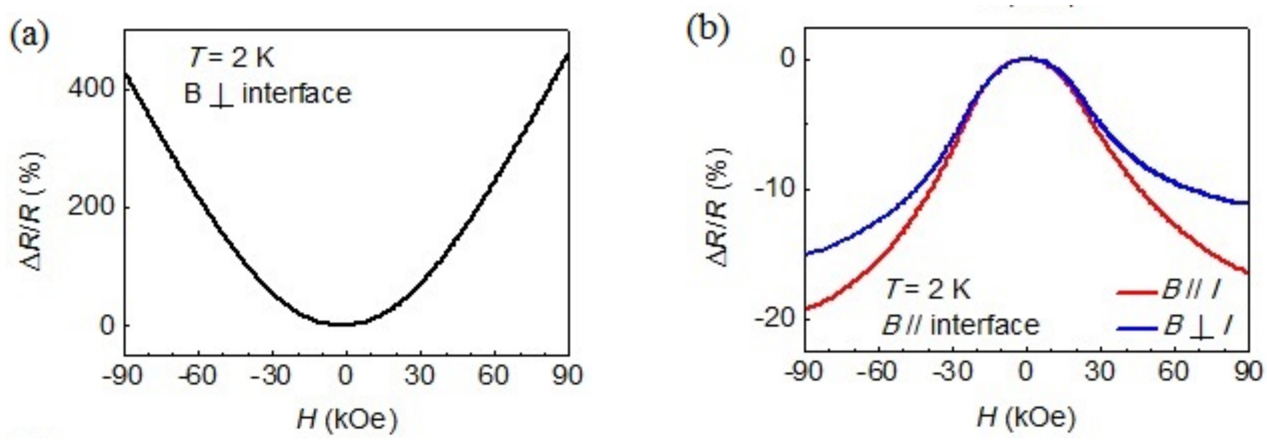




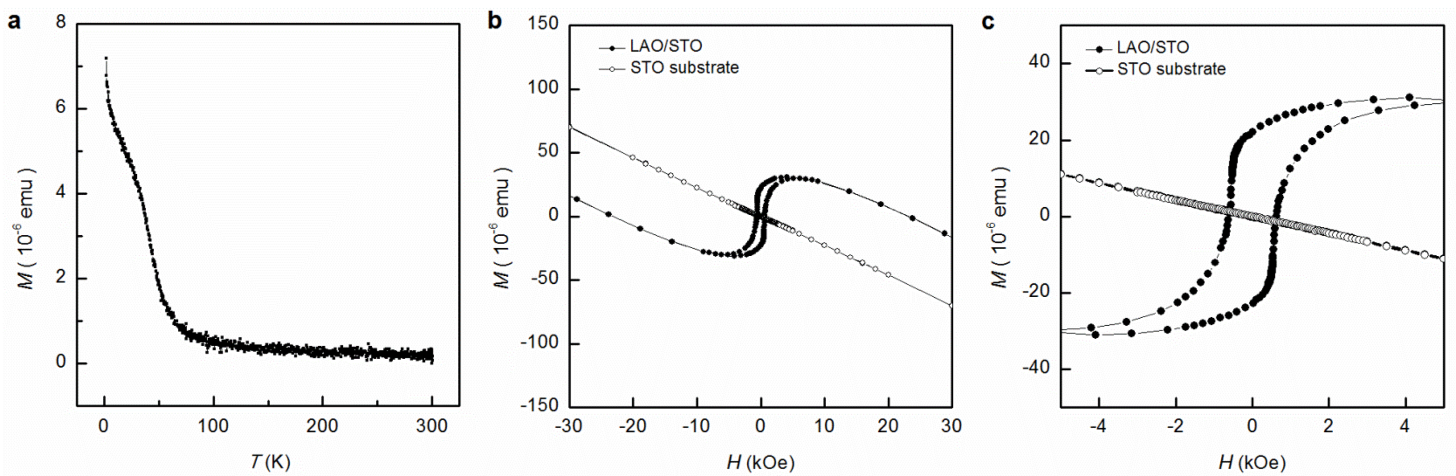
van der Pauw method

Magnetic transport properties

Magneto-Resistance

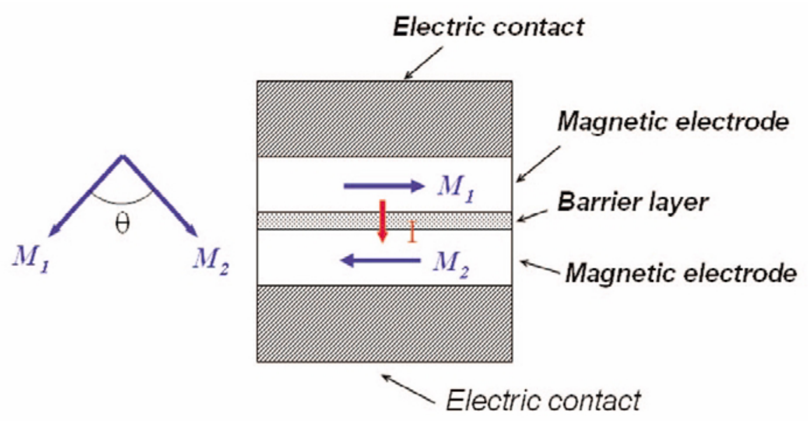


Magnetization



Tunneling Magneto-Resistance (TMR)

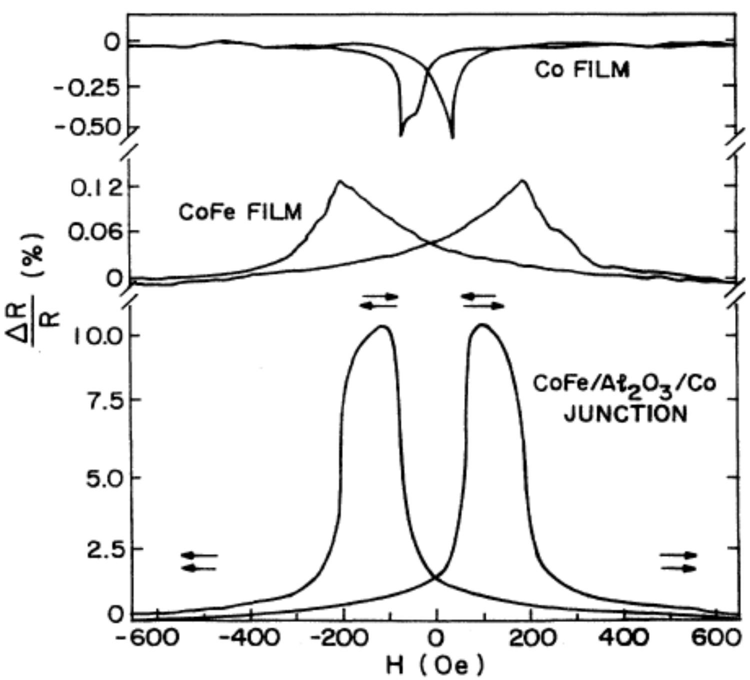
Spin transport



$$TMR\ Ratio = \frac{G_P - G_{AP}}{G_{AP}} = \frac{R_{AP} - R_P}{R_P}$$

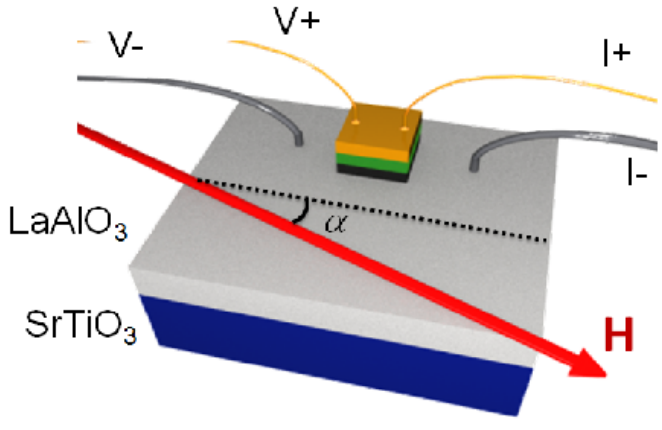
TMR dependent on :

- insulator material
- barrier height and width
- barrier impurities
- ferromagnet/barrier interface

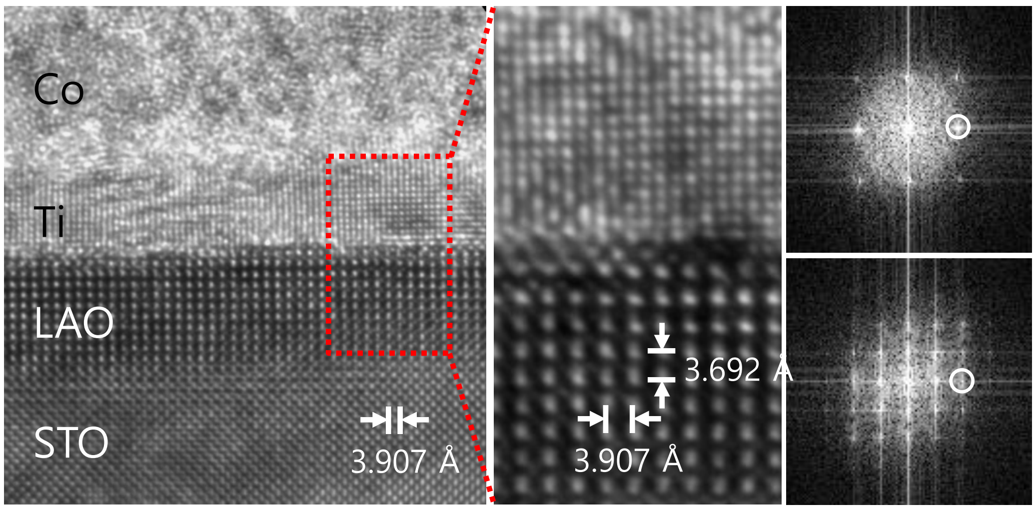


[Moodera et al., PRL 74 (1995)]

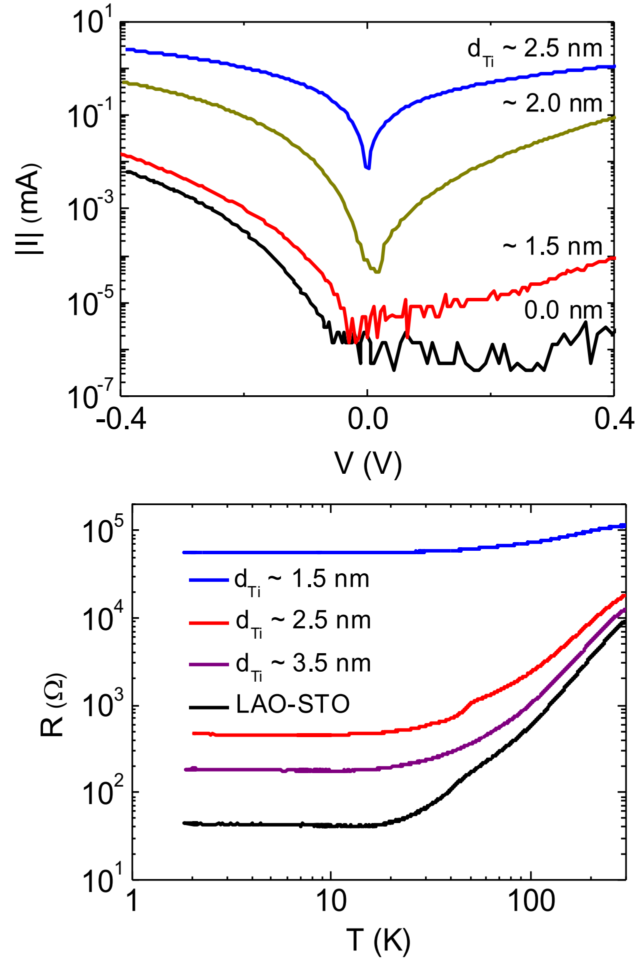
Device fabrication & optimization



HR-TEM

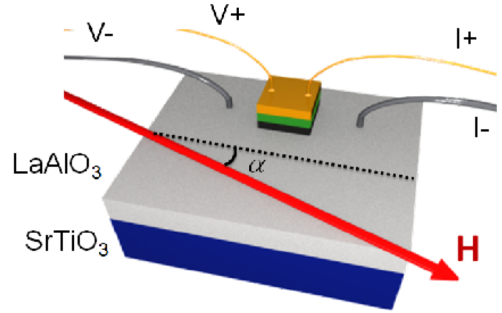


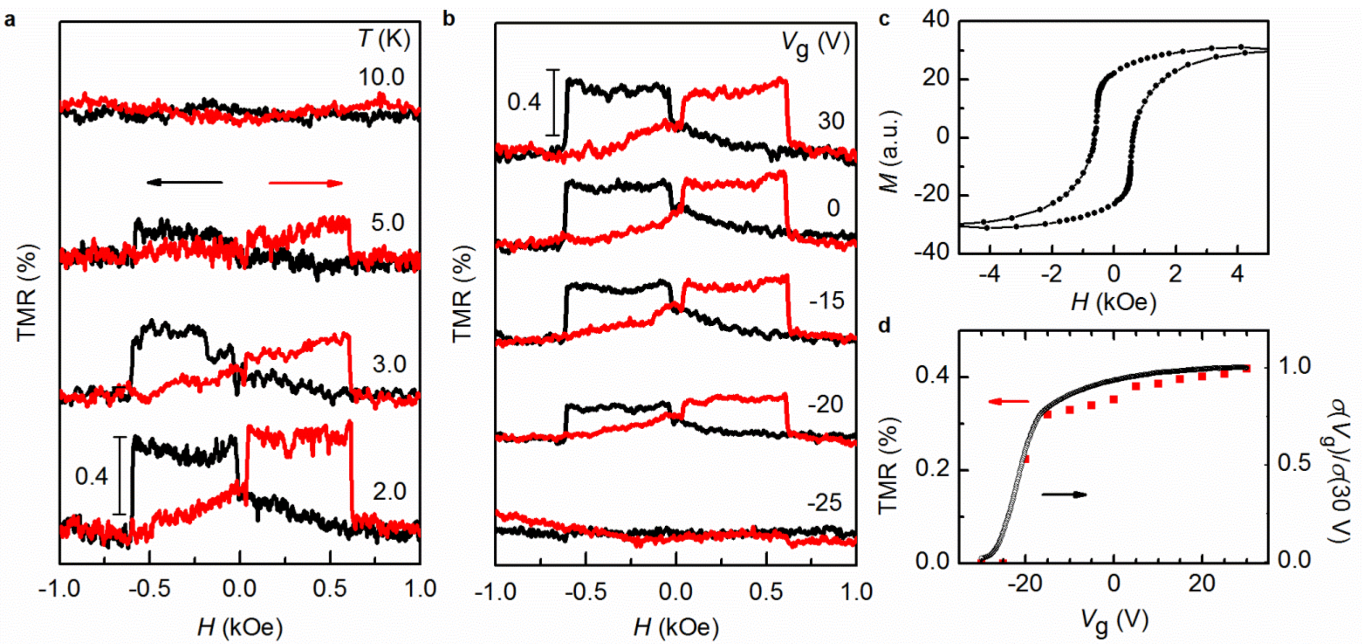
Insertion of Ti interlayer



Observation of TMR

$\alpha = 0^o$



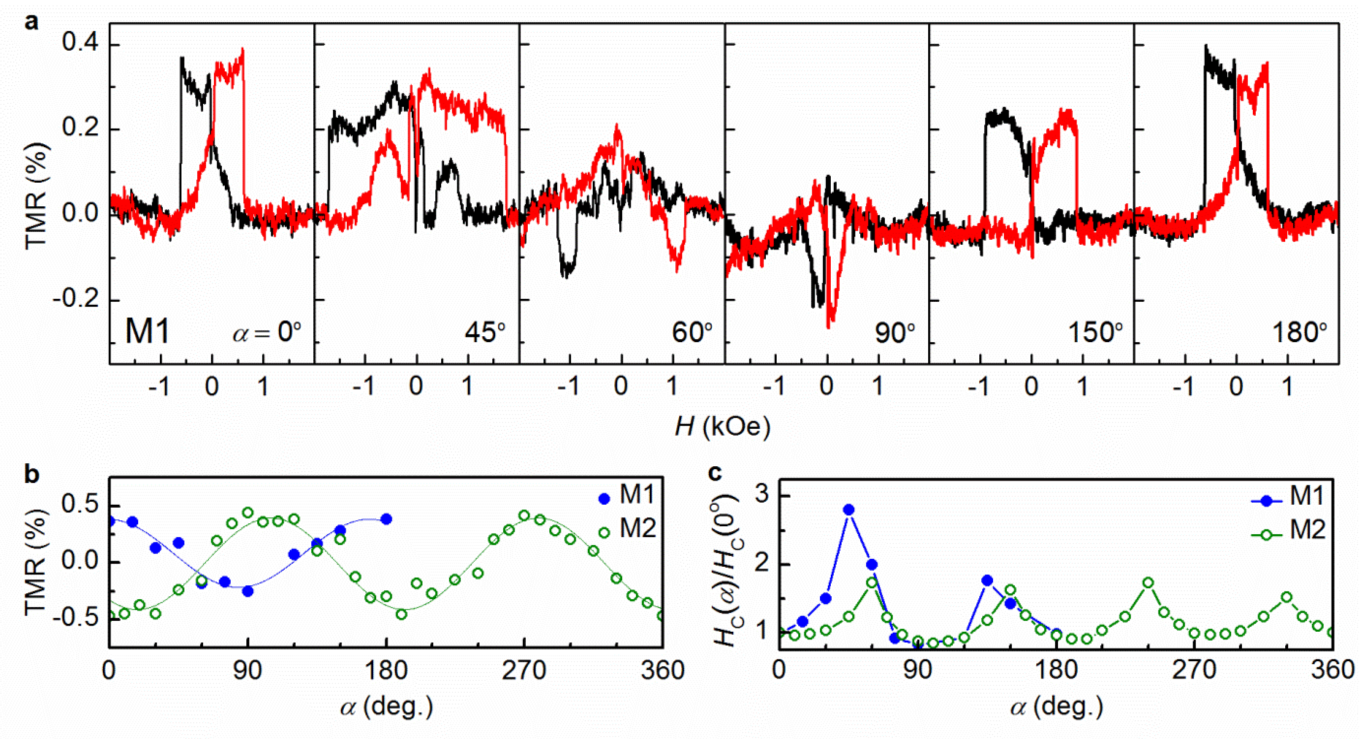


Observation of TMR → macroscopic ferromagnetism

→ itinerant scenario

Angular anisotropy of TMR

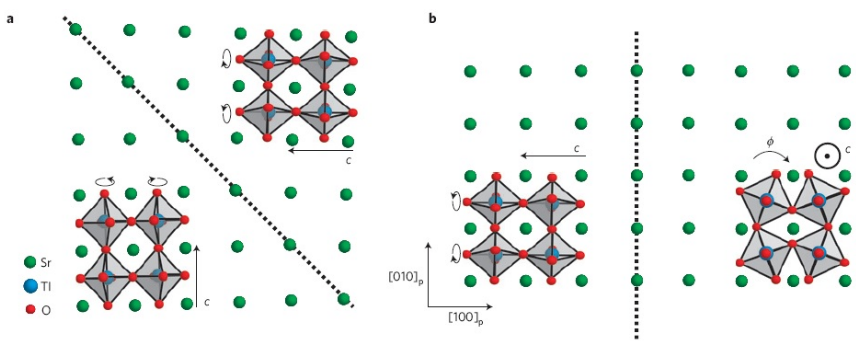
Spin transport

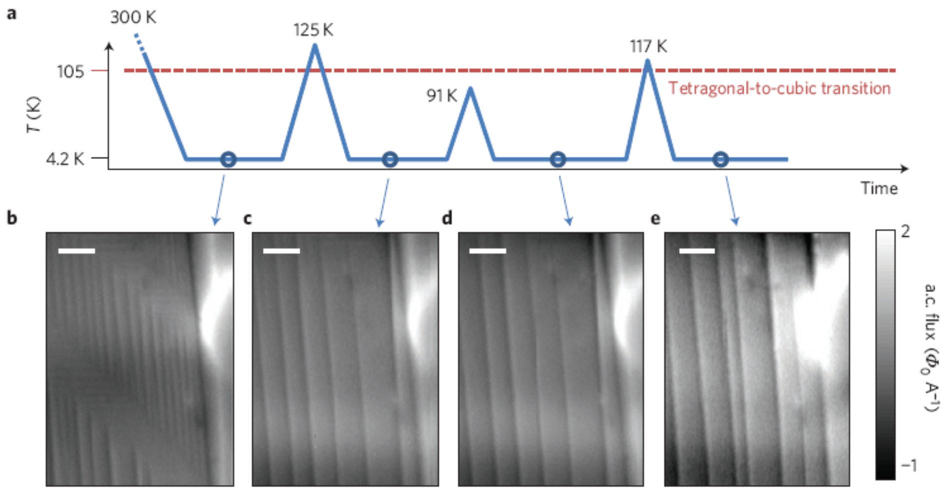


- ❖ **2-fold symmetry of TMR due to the uni-axial nature of conduction**
- ❖ **4-fold symmetry of H_C due to the crystalline structure of STO**

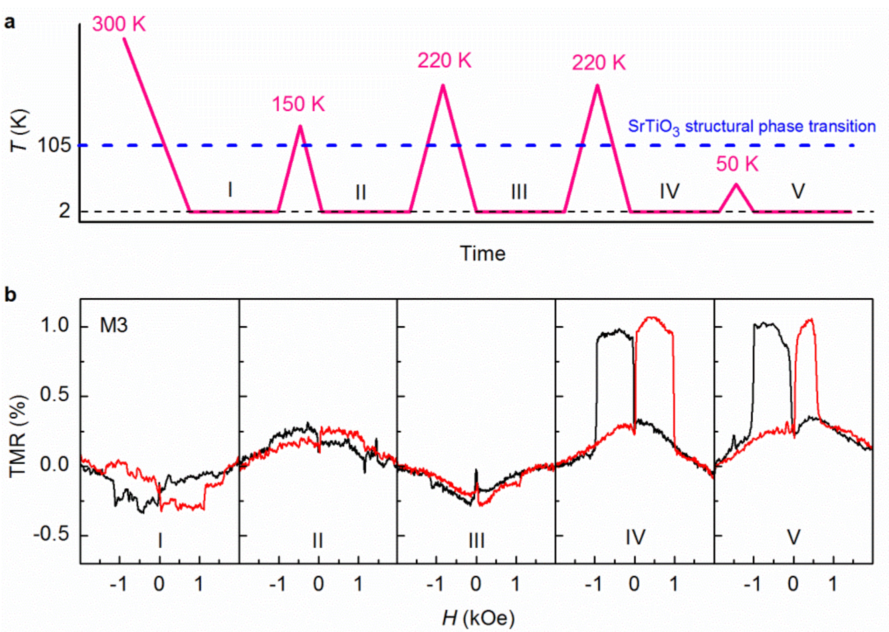
TMR and STO structure

Structural phase transition of STO





[Kalisky *et al.*, Nat. Phys. 12 (2013)]

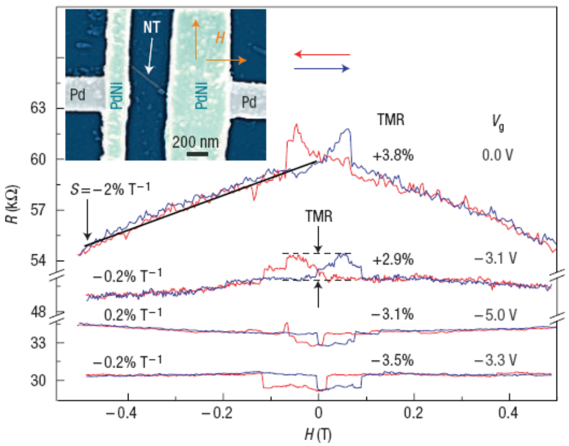


TMR sign is associated with

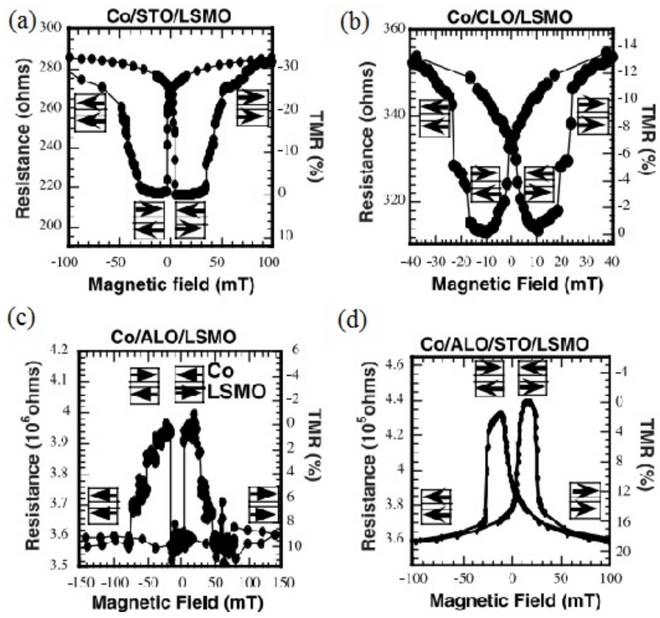
the structure the STO substrates!!

TMR sign reversal

Electric field



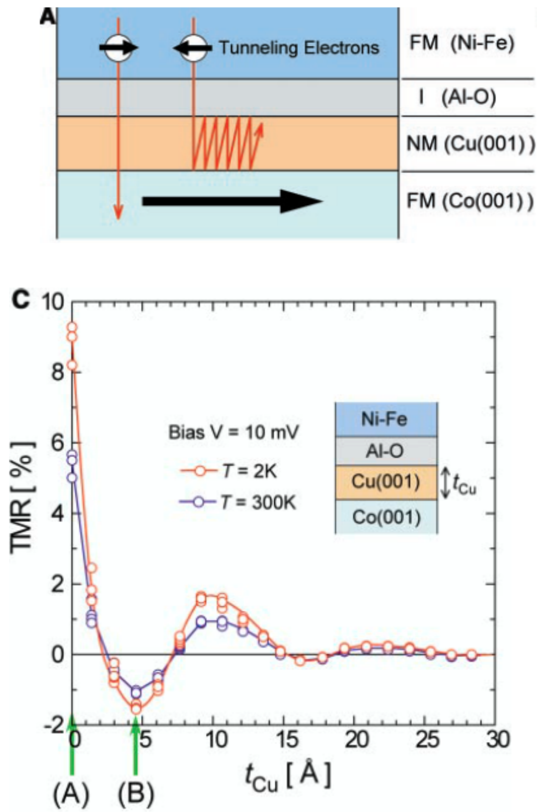
FM/I interface



d-d bonding → negative TMR

sp-d bonding → positive TMR

Resonant tunneling effect



Theoretical model for our system must includes

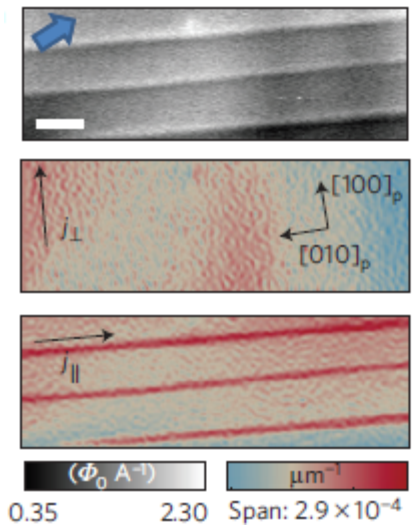
1) directionality of electric conduction
2) strong Rashba spin-orbit coupling

Sahoo *et al.*, Nature Phys. 1 (2005)
De Teressa *et al.*. Science 286 (1999)
Yuasa *et al.*, Science 297 (2002)

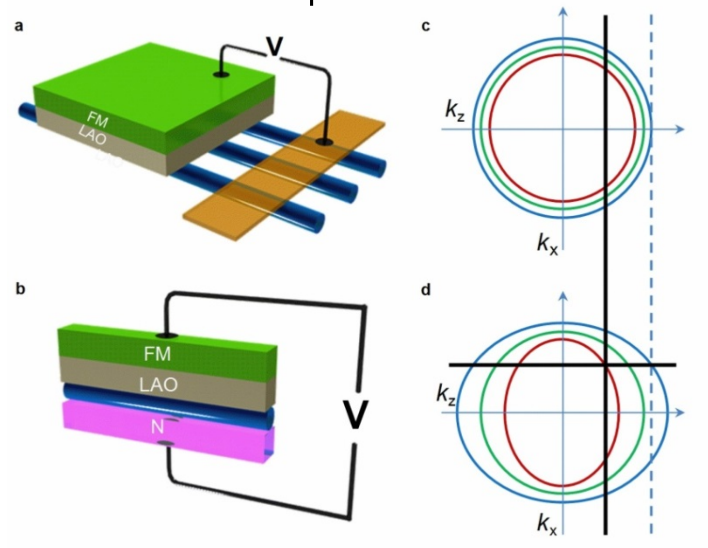
Model for TMR sign reversal

Spin transport

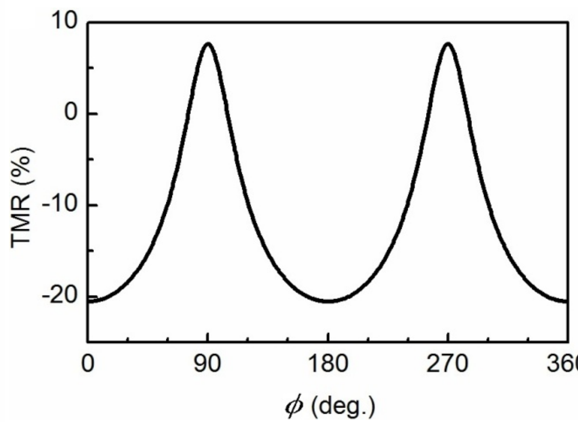
Narrow conducting paths



Model assumption



Model calculations



Hamiltonian: $$H = \frac{1}{2m}(p_x^2 + p_z^2) + U(z) - \frac{\alpha(z)}{\hbar} p_x \sigma_y - \boldsymbol{\Delta}(z) \cdot \boldsymbol{\sigma}$$

Rashba SOC at the oxide interface

$$\alpha(z) = \begin{cases} \alpha_0 & (0 < z < d) \\ 0 & (\text{otherwise}) \end{cases}$$

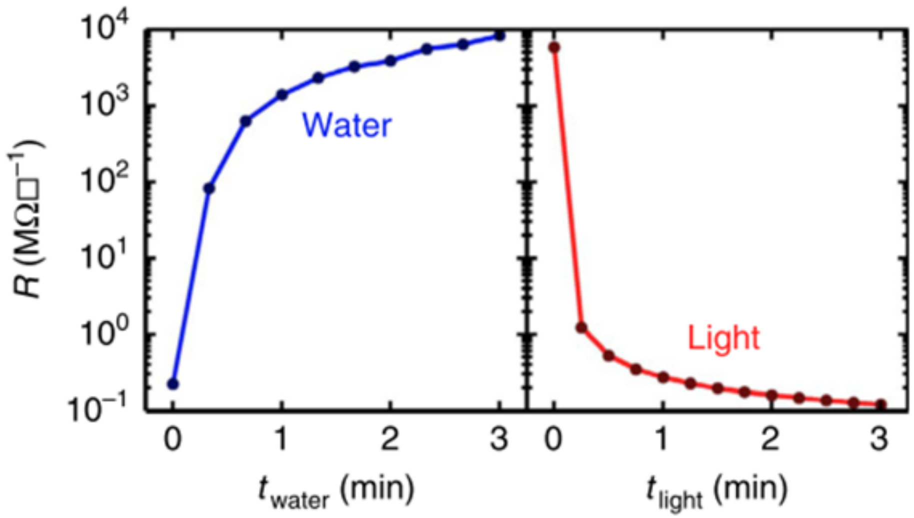
Zeeman spin-splitting of Co electrode

$$\boldsymbol{\Delta}(z) = \begin{cases} \Delta_1(-\sin\phi, \cos\phi, 0) & (z > d) \\ \Delta_2(-\sin\phi, \cos\phi, 0) & (0 < z < d) \\ 0, & (z < 0) \end{cases}$$

STO-capped LAO/STO: motivations

STO/LAO/STO

Degradation of the conduction channel by moisture



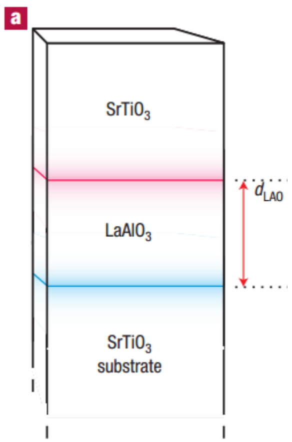
Brown *et al.,* Nat. Comm. 10681 (2015)

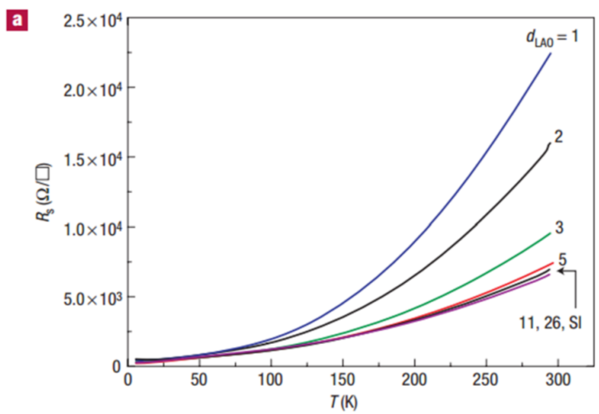
LAO is chemically reactive with moisture in air!!

STO-capped LAO: previous results

STO/LAO/STO

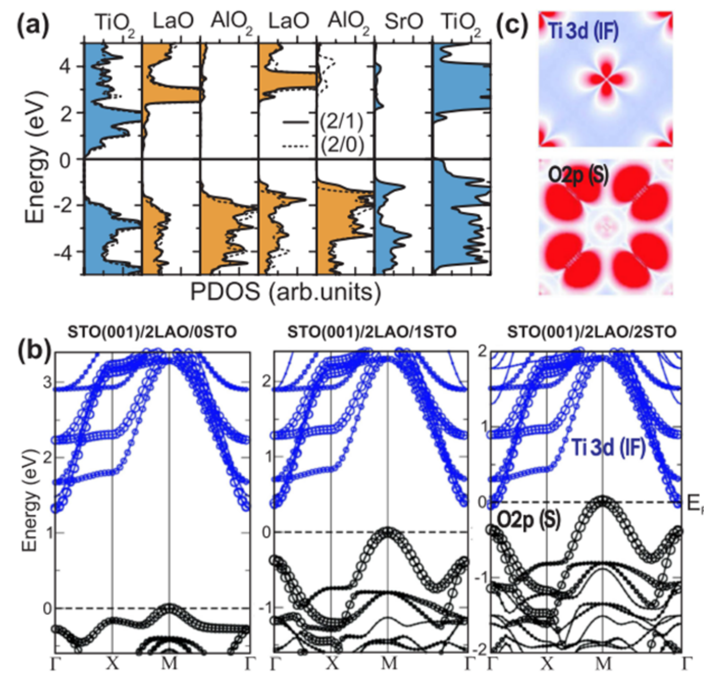
Conduction in a STO-capped LAO/STO





Change of the RT characteristics with LAO thickness

(STO thickness = 10 uc)

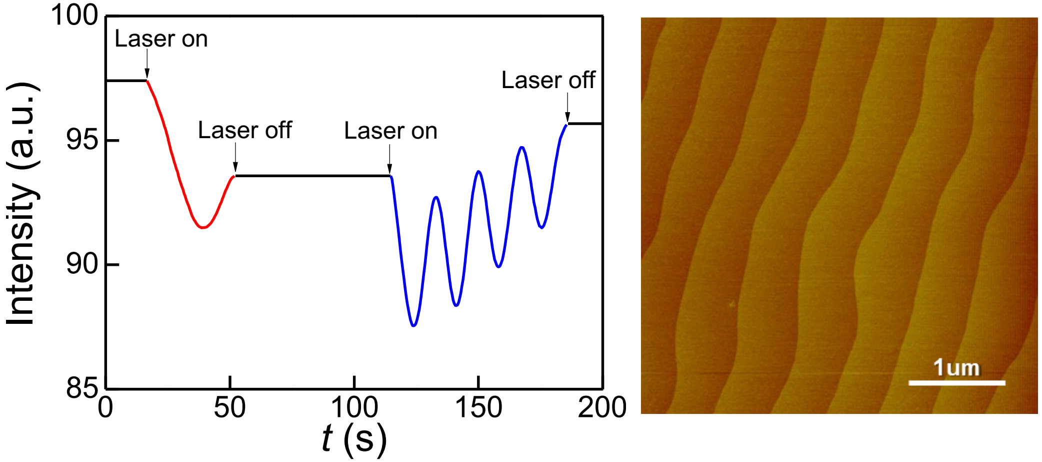


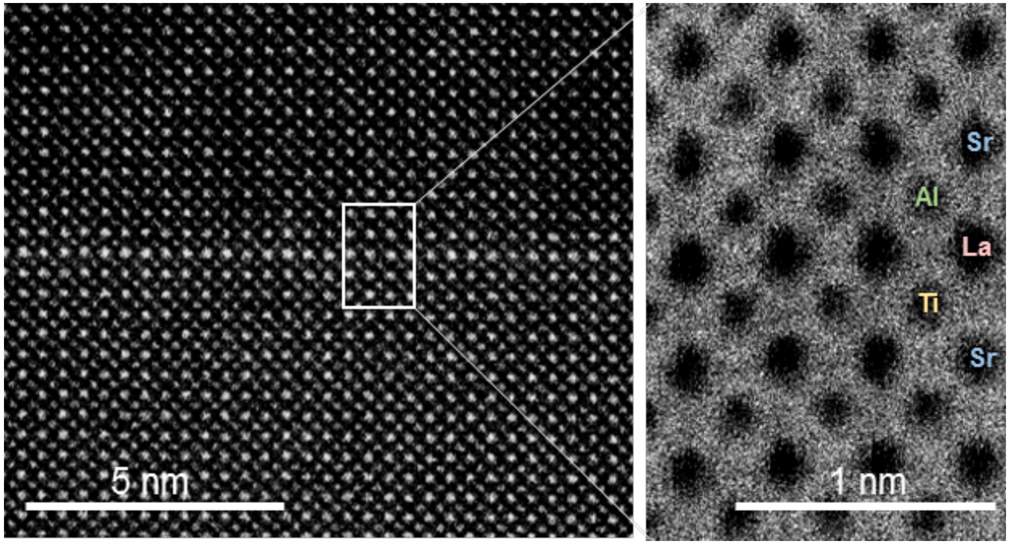
Huijben *et al.*, Nat. Mat. 5 (2006)
Pentcheva *et al.*, PRL 104 (2010)

Sample growth

STO/LAO/STO

Growth of monolayer LAO capped by STO

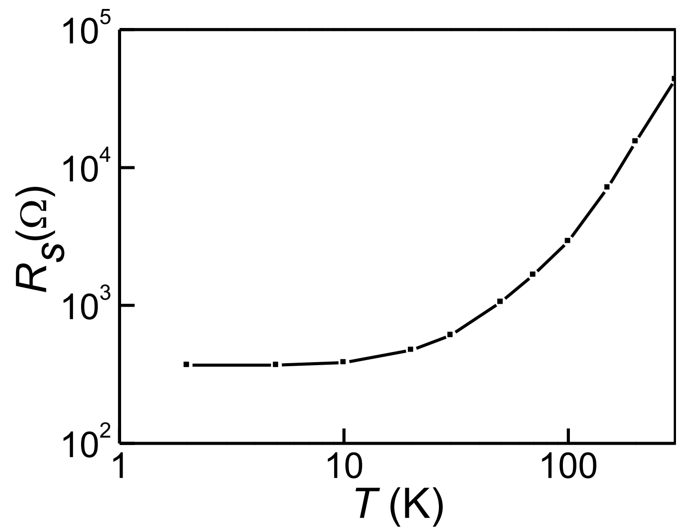


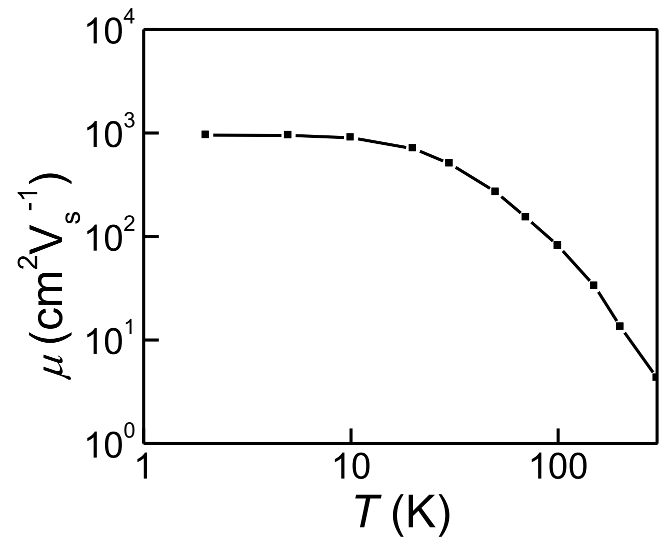


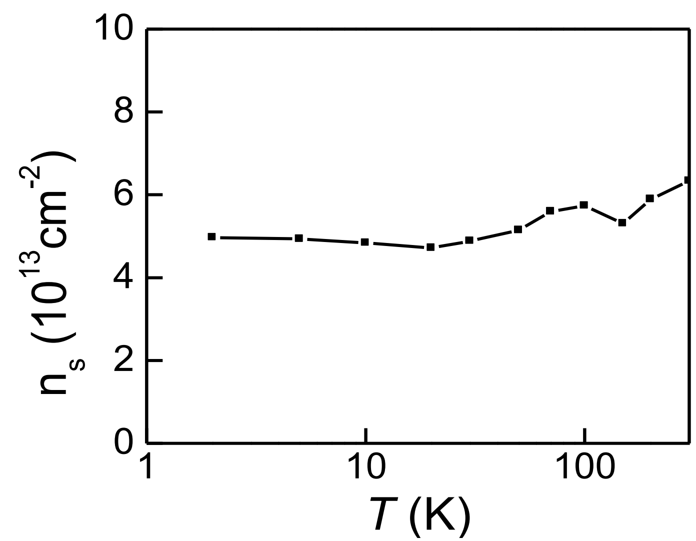
Transport properties

STO/LAO/STO

Transport properties of monolayer LAO capped by STO





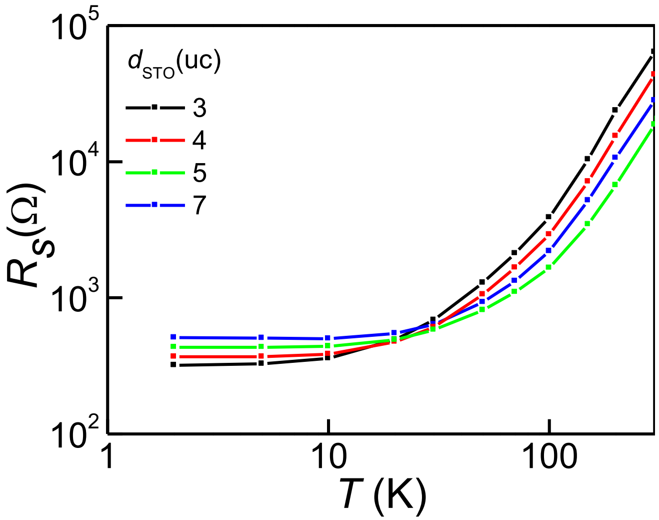


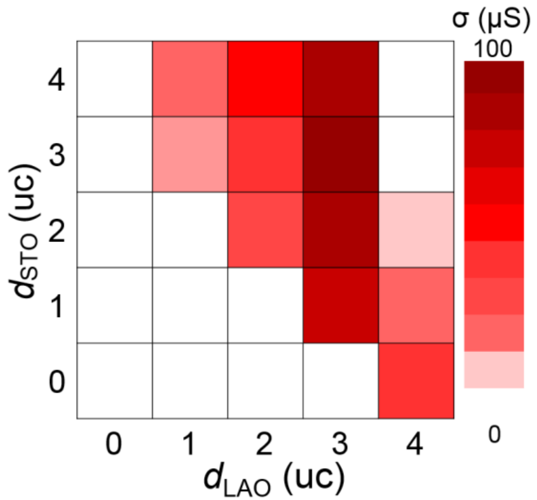
STO(4 uc)/LAO (1uc)/STO

Similar behavior with uncapped LAO/STO

Thickness dependence

STO/LAO/STO



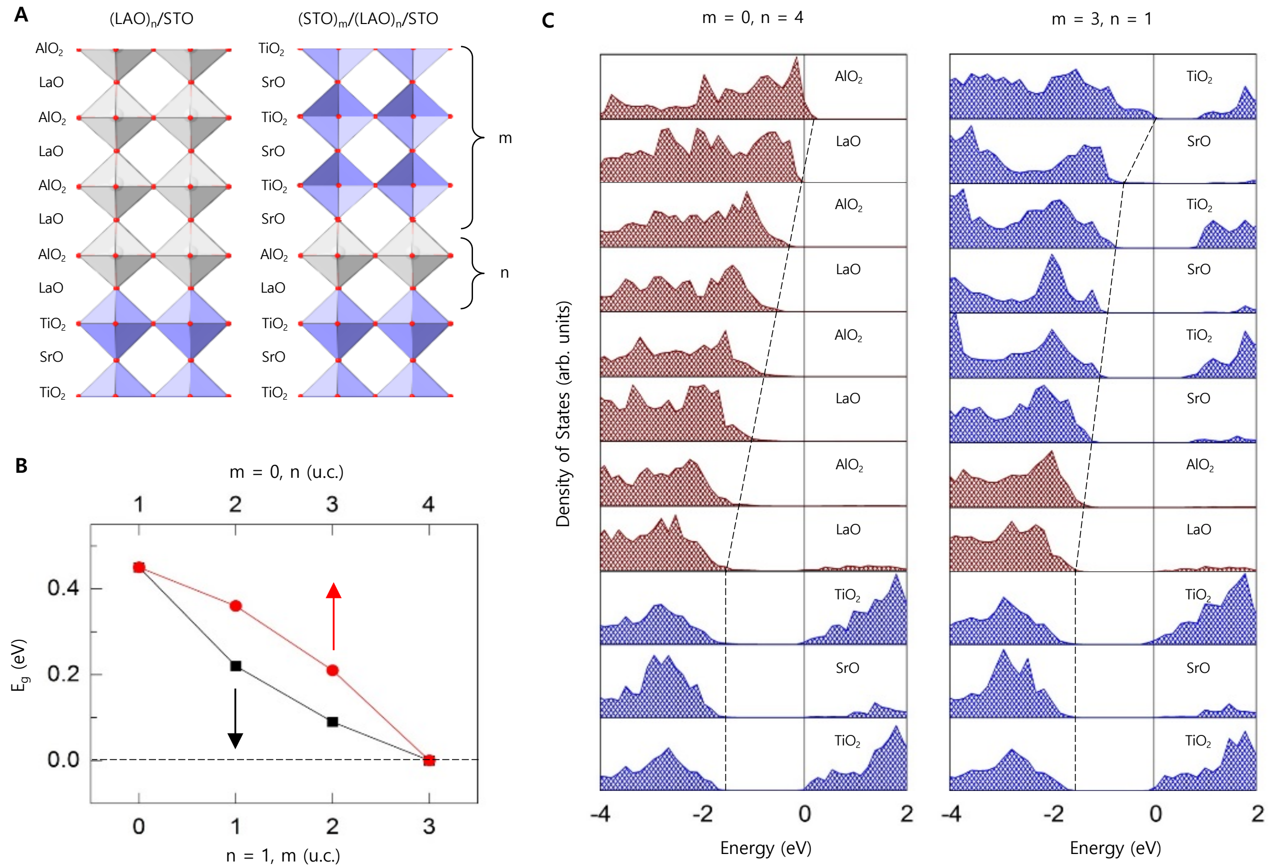


Critical thickness for conduction: $d_{STO} + d_{LAO} = 4$

Band calculation

STO/LAO/STO

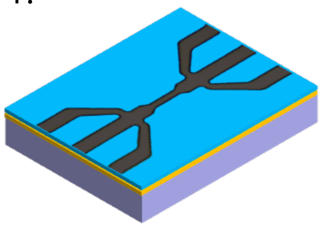
n-channel near interface & *p*-channel at the surface!!



Device fabrication

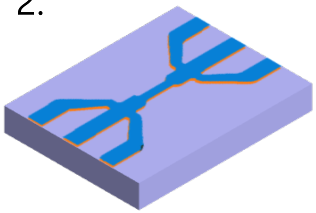
STO/LAO/STO

1.



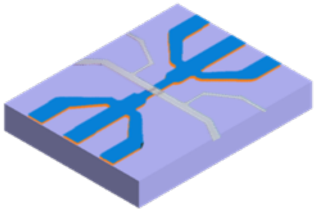
Growth of STO(7 uc)/LAO (1 uc) and photolithography

2.



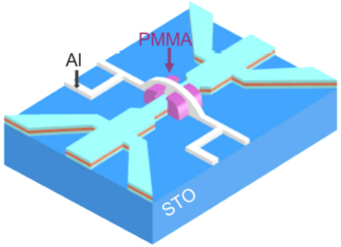
Ar-ion milling and post annealing

3.



PMMA hardening and e-beam lithography

4.



Sputtering of Ti(8 nm)/Al(140 nm)

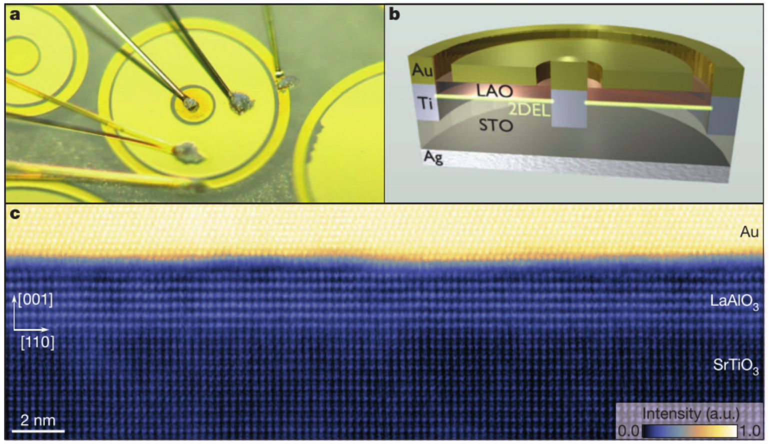
What to be overcome

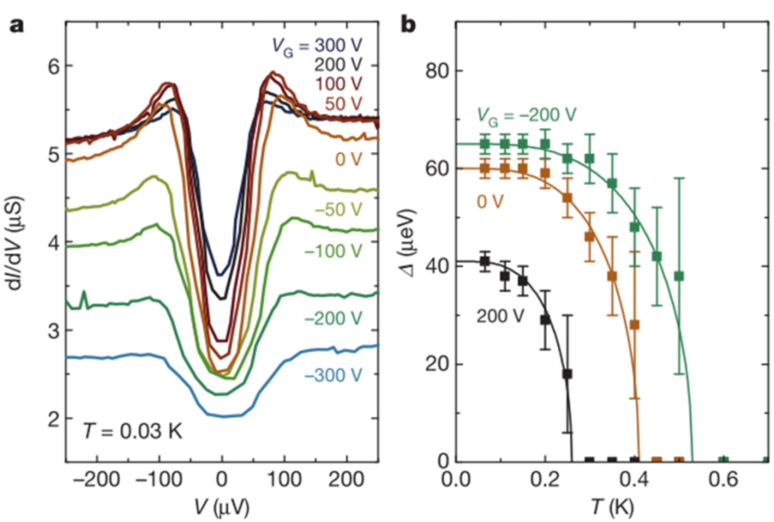
- ✓ Charging effect
- ✓ Leakage through side channel
- ✓ Degradation during fabrication
- ✓ Ohmic contact to the surface

No Josephson tunnel junction yet!

Device fabrication

STO/LAO/STO





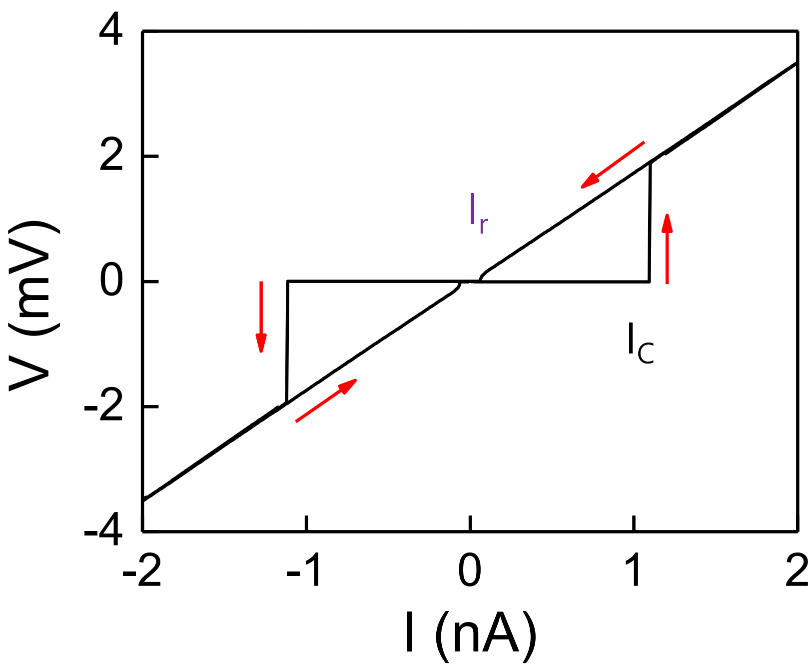
Richter *et al*. Nature **502**, 528 (2013)

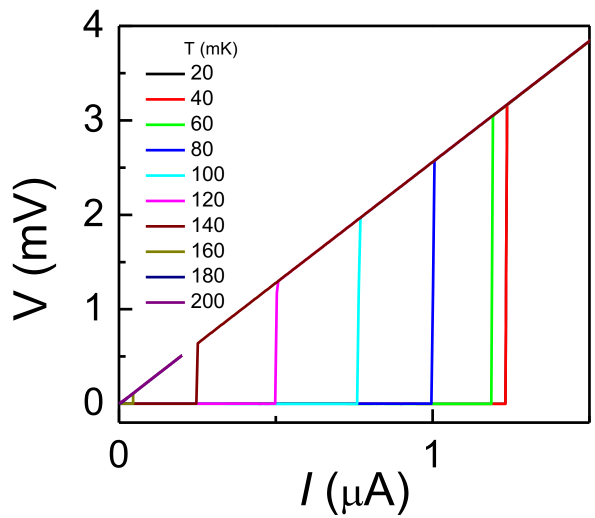
Superconductor-Normal metal junction

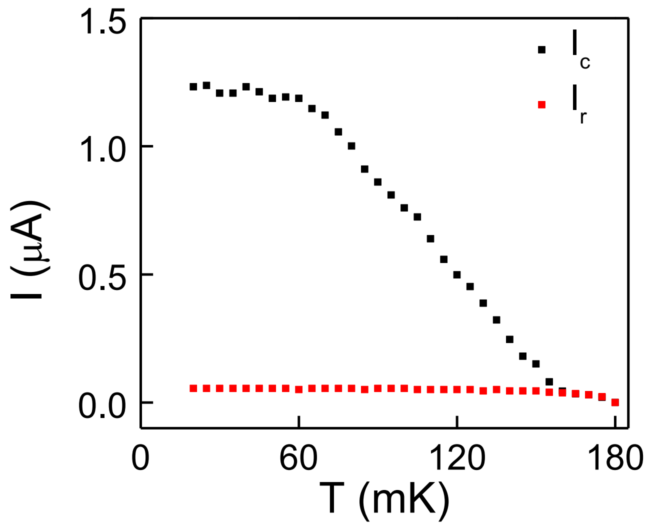
: gap estimation with large uncertainty

Results: superconductivity

STO/LAO/STO



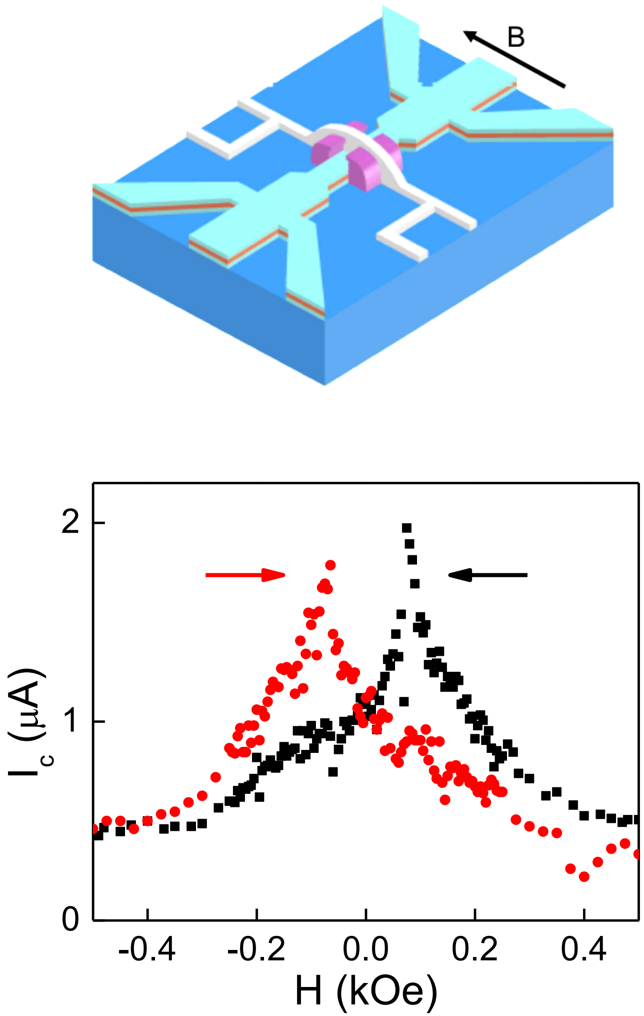


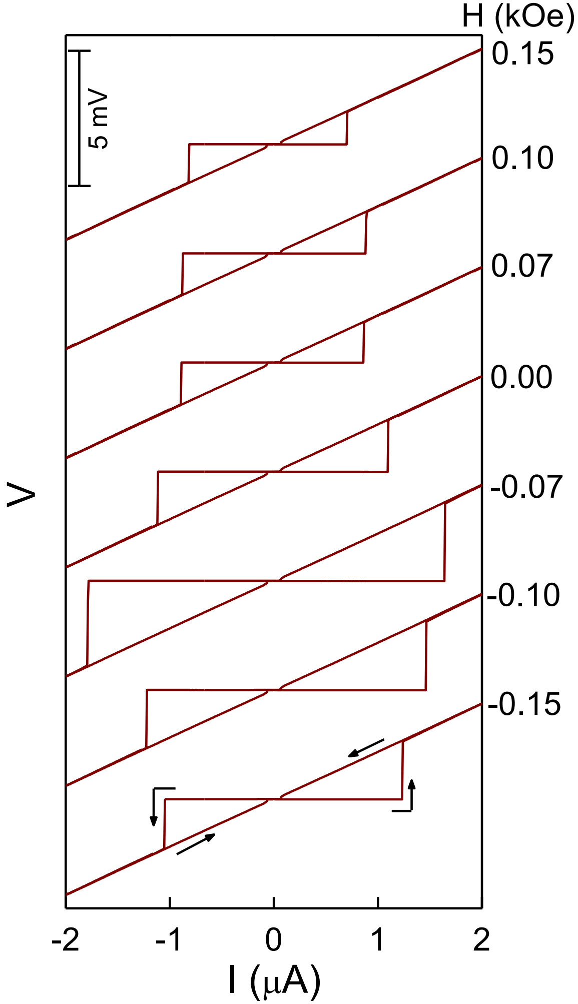


Single layer of LAO capped by STO is superconducting!!

Unusual magnetic-field dependence

STO/LAO/STO





Hysteresis in $I_c(H)$

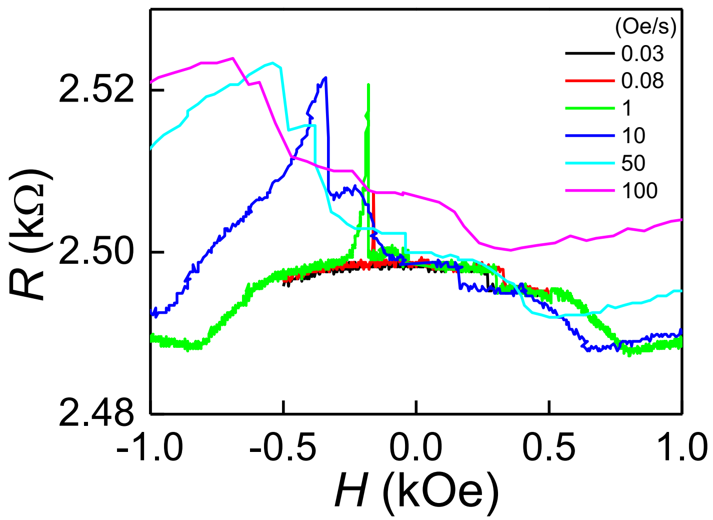
Ferromagnetism?

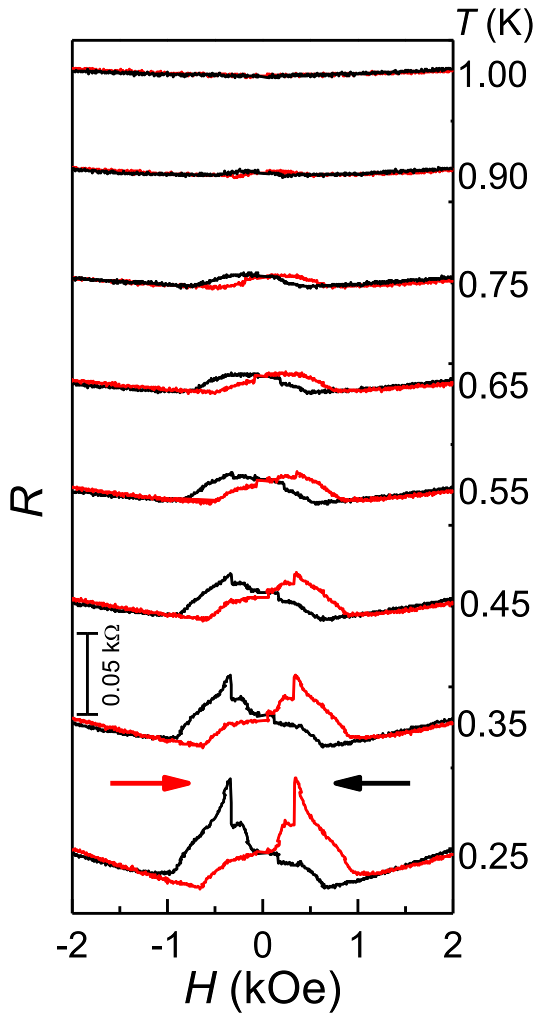
Inverted direction

Diamagnetic effect?

Magnetoresistance

STO/LAO/STO





Hysteresis in MR

Dynamic effect

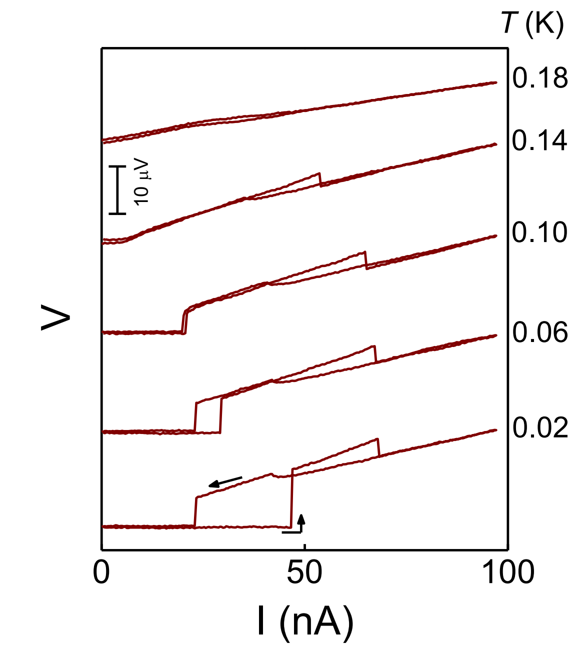
Ferromagnetism?

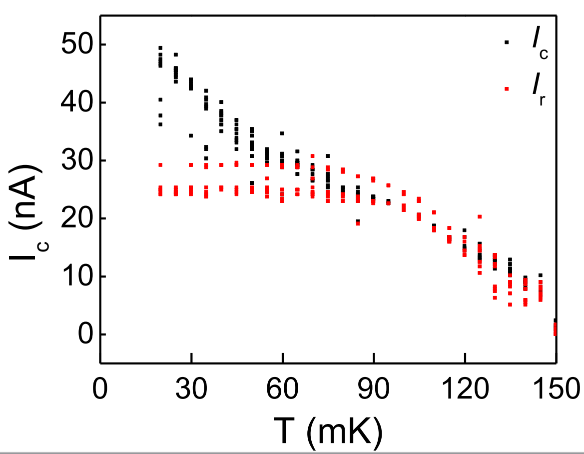
Effect of Al?

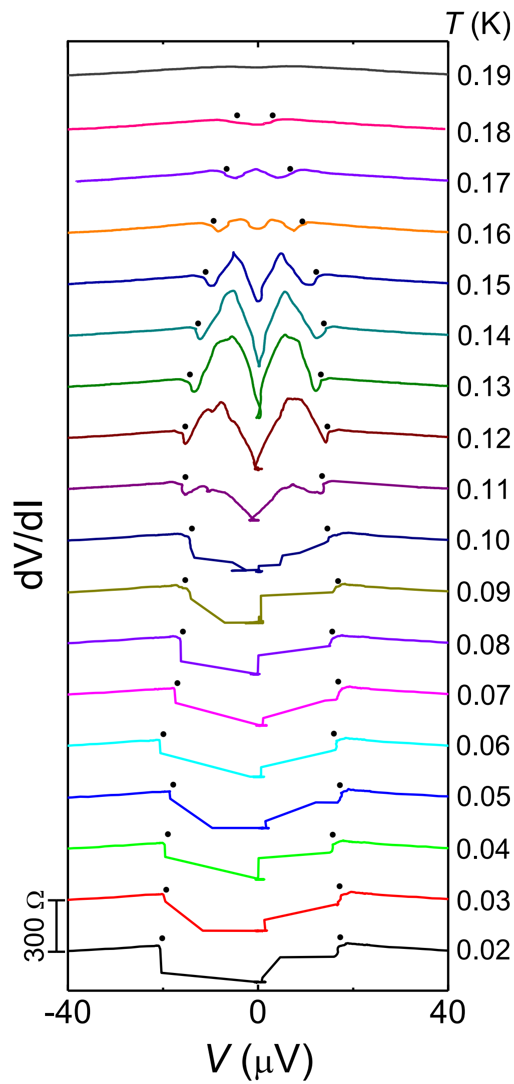
STO-capped STO/LAO: superconductivity

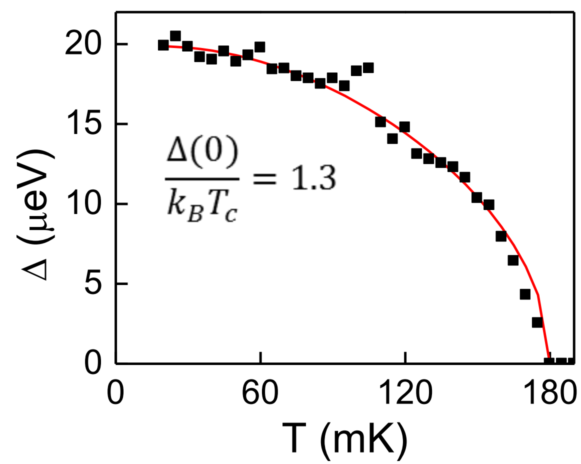
STO/LAO/STO

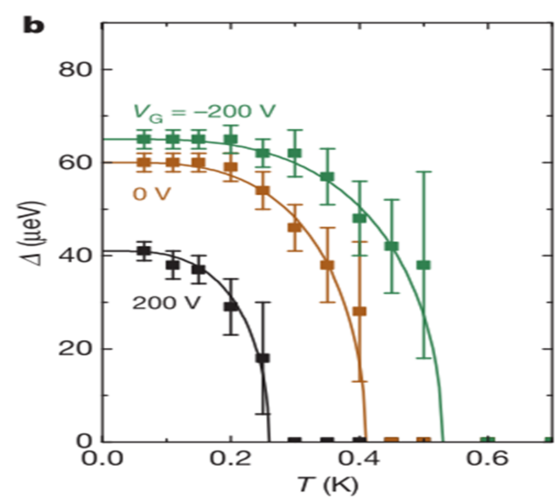
Gap estimation from differential resistance curves





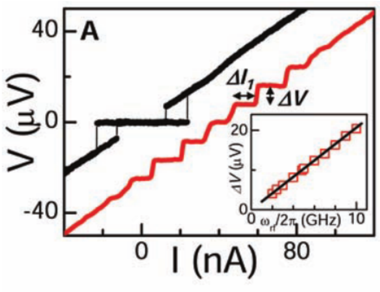




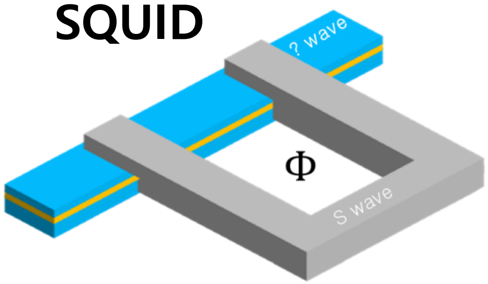


Future works

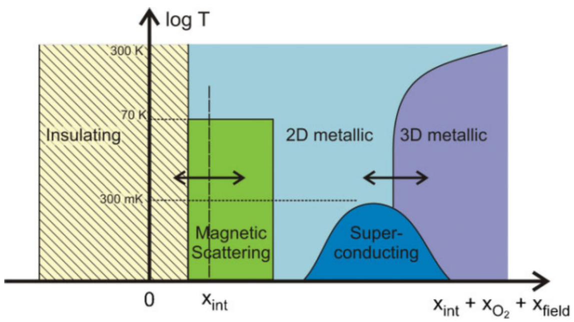
Shapiro step



SQUID

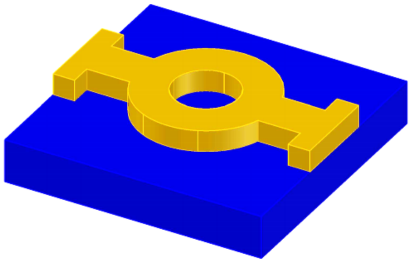


Gate dependence

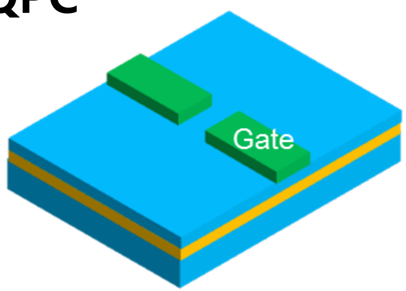


LAO/STO phase diagram

Aharonov-Bohm ring



QPC



Many things to do!!

Better Standards, Better Life!

감사합니다

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