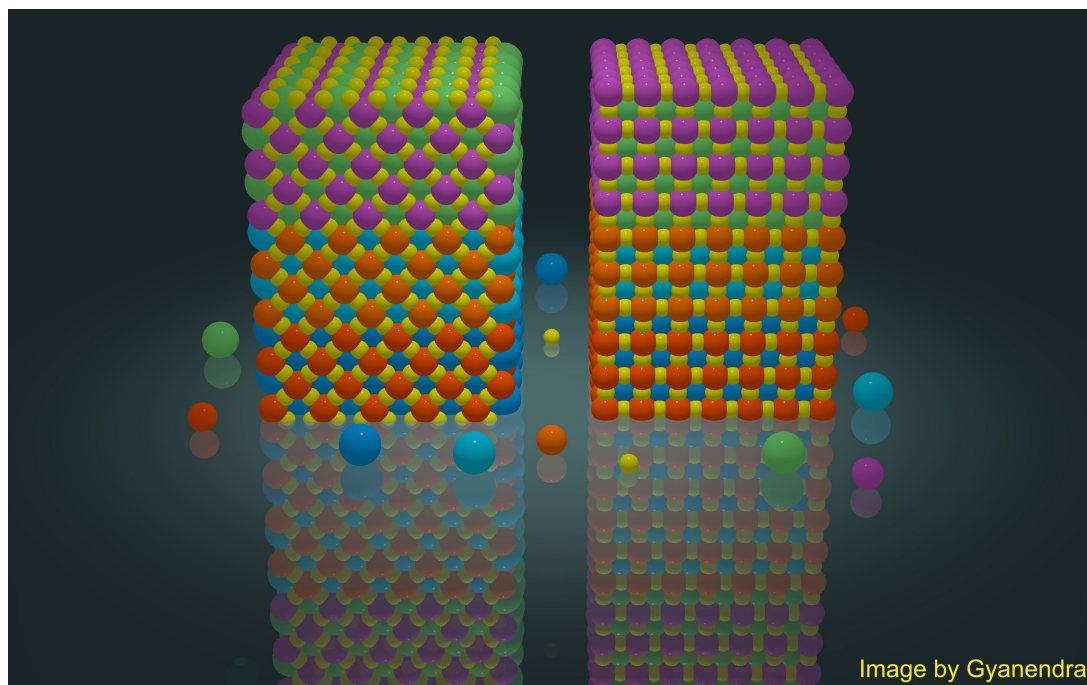


2D oxide interface superconductivity

N. Bergeal

ESPCI Paris – PSL research university – CNRS – Sorbonne University



Outline

Introduction on SrTiO_3 and KTaO_3 based superconducting interfaces

Origin of the Two-Dimensional Electron gas

Band structure and Quantum confinement

Electric field control of superconductivity and phase diagram

Tunneling spectroscopy and microwave conductivity

Mutigap superconductivity

Perspectives on nanodevices

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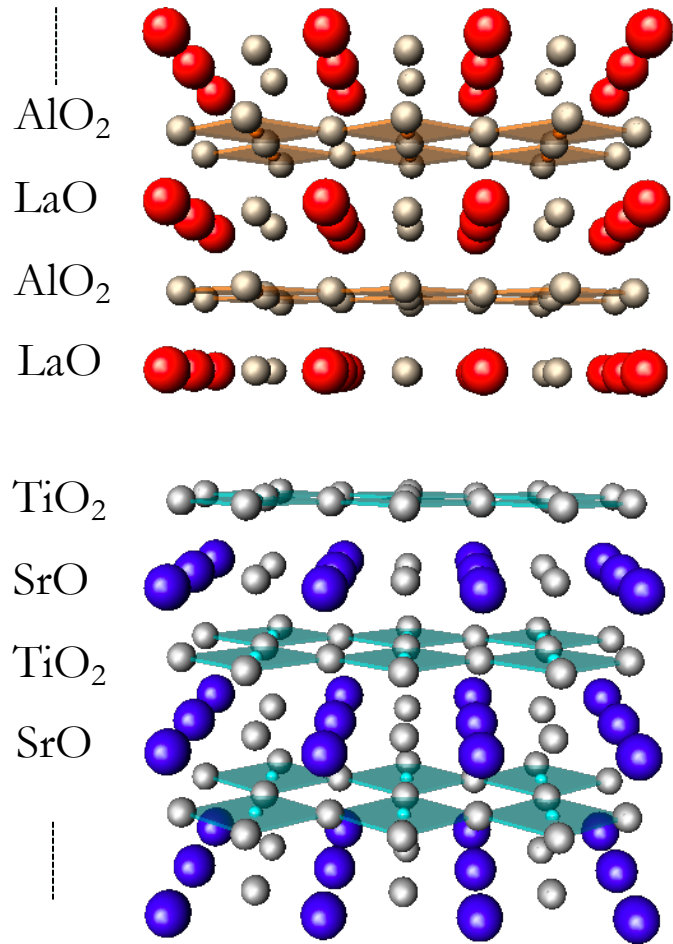
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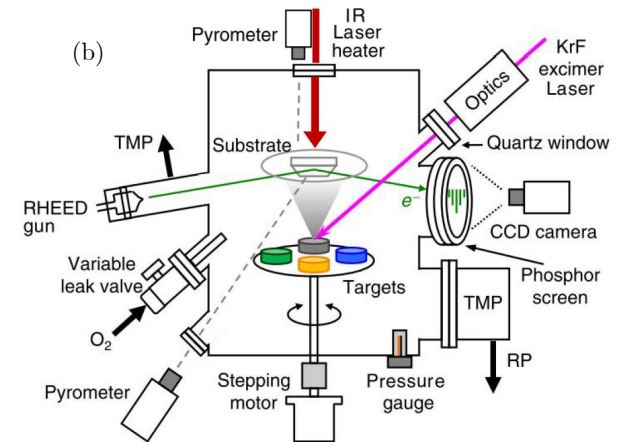
(001)-LaAlO₃/SrTiO₃ heterostructures



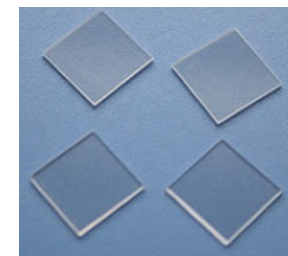
LaAlO₃
band insulator
 $\Delta=5.6$ eV

SrTiO₃
Band insulator
 $\Delta=3.2$ eV

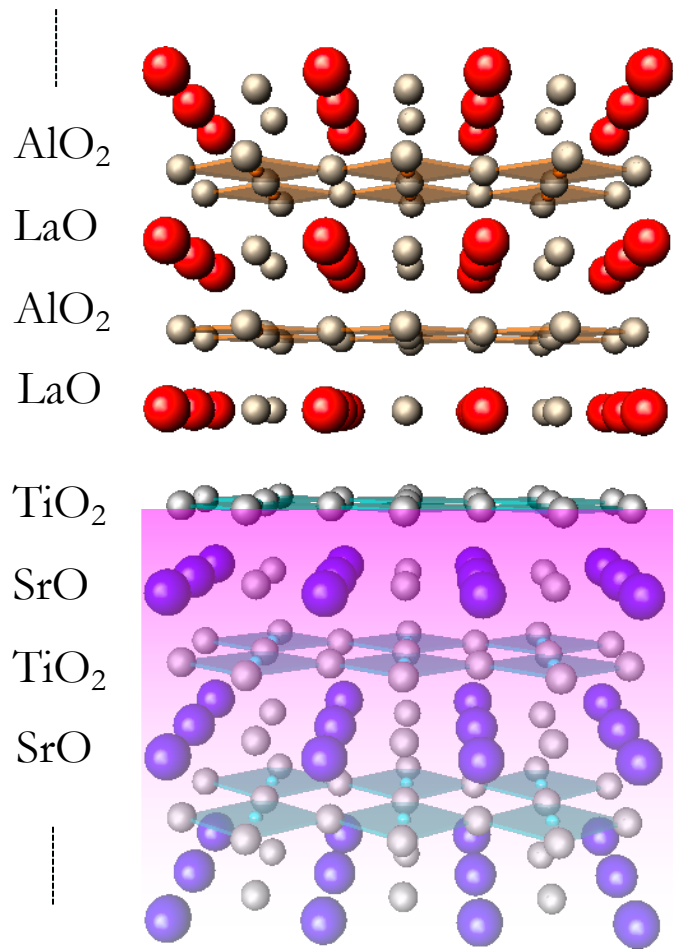
LaAlO₃ epitaxial layer (PLD)



SrTiO₃ commercial substrate



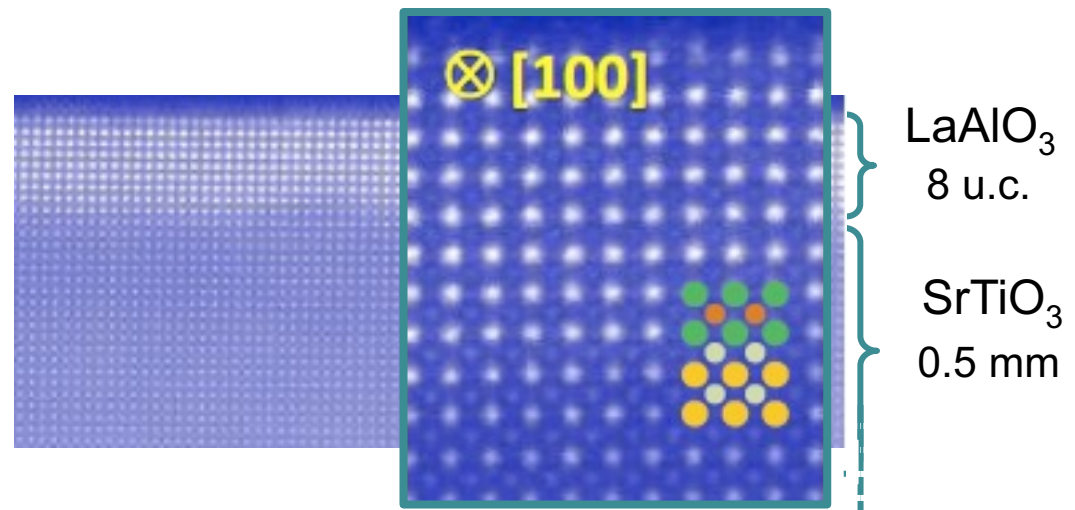
(001)-LaAlO₃/SrTiO₃ heterostructures



J. Mannhart (2DPhysics.com)

✧ Epitaxial growth by Pulsed Laser Deposition

Transmission Electron Microscope (TEM)



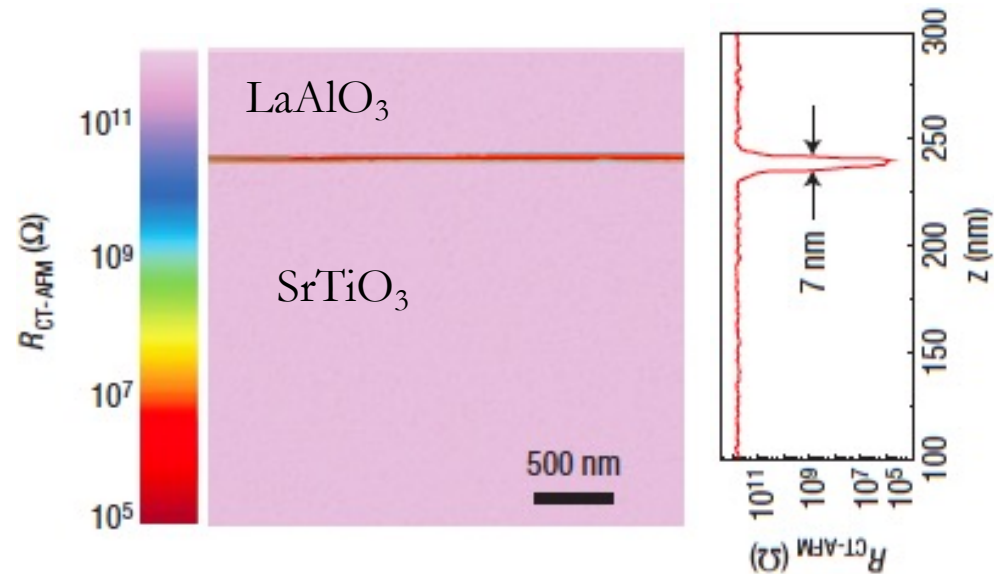
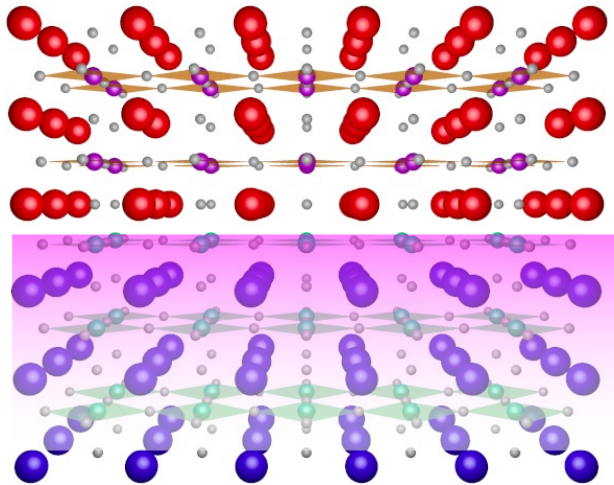
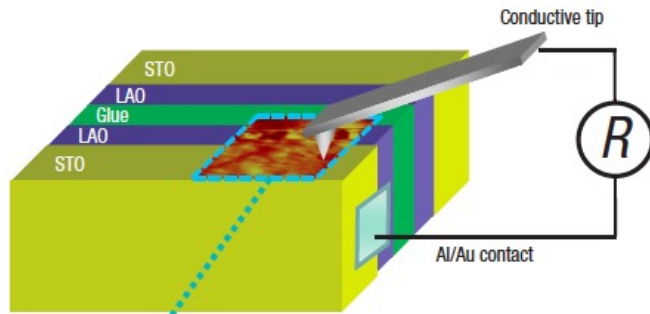
G. Herranz, et al. Nature Comm. (2015)

➡ Formation of a 2-DEG in SrTiO₃

A. Ohtomo & H.Y. Hwang, 427, 423 Nature (2004)

2-Dimensional Electron Gas (2-DEG)

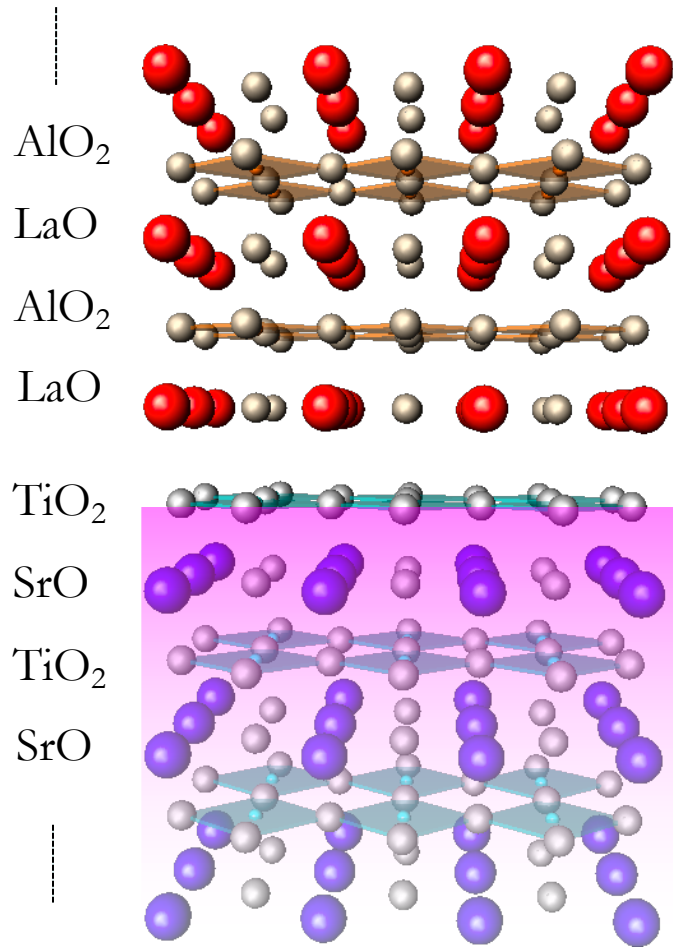
✧ Conductive tip Atomic Force Microscope



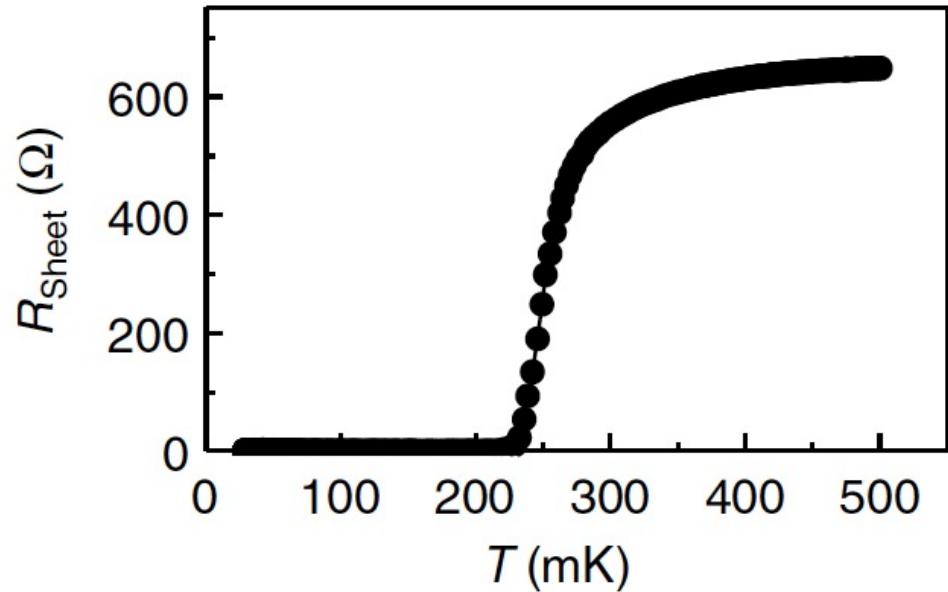
M. Basletic et al. Nature Mat (2008)

➡ 2-DEG extends in the SrTiO₃

(001)- $\text{LaAlO}_3/\text{SrTiO}_3$ heterostructures



✧ A superconducting interface



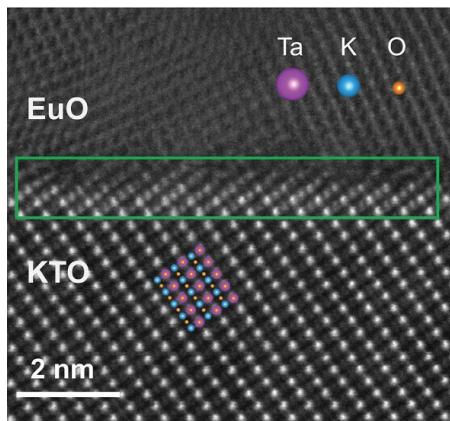
➡ Superconductivity $T_c \approx 300\text{mK}$

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

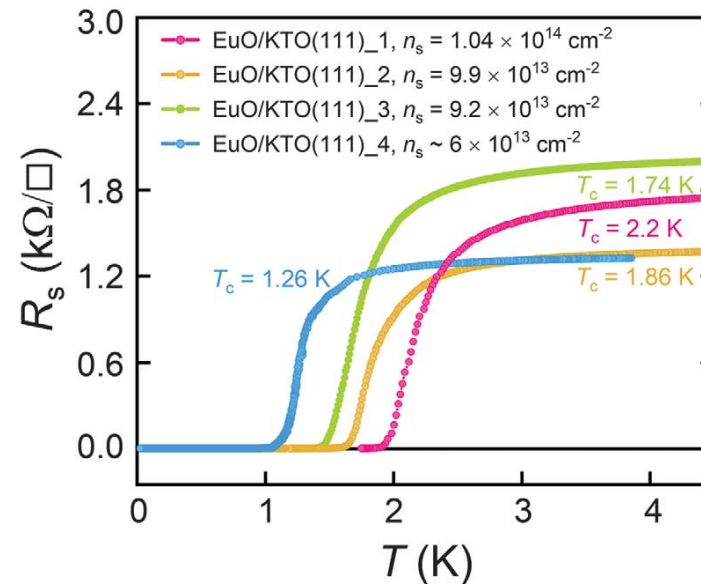
➡ and also in $\text{LaTiO}_3/\text{SrTiO}_3$, $\text{GdTiO}_3/\text{SrTiO}_3$, $\text{AlO}_x/\text{SrTiO}_3$

Superconducting KTaO_3 -based interfaces (more recent)

✧ Superconducting 2DEG in (111)-oriented EuO/KTaO_3 and $\text{LaAlO}_3/\text{KTaO}_3$



Liu et al., Science 371, 716 (2021)
Chen et al., Science 372, 721 (2021)



➡ Superconductivity with $T_c^{\text{max}} \approx 2.2\text{K}$

➡ Strong orientationnal dependence of T_c : $T_c(111) \approx 2.2\text{K}$, $T_c(110) \approx 1\text{K}$, $T_c(001) \approx 50\text{mK}$

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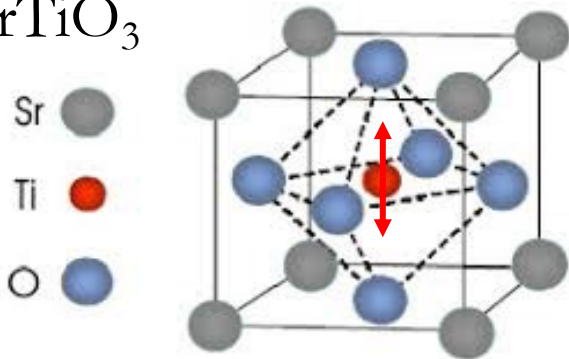
Perspectives on nanodevices

Quantum paraelectric materials SrTiO_3 and KTaO_3

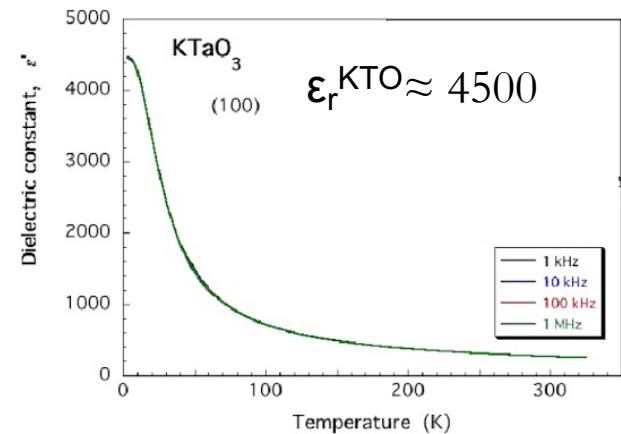
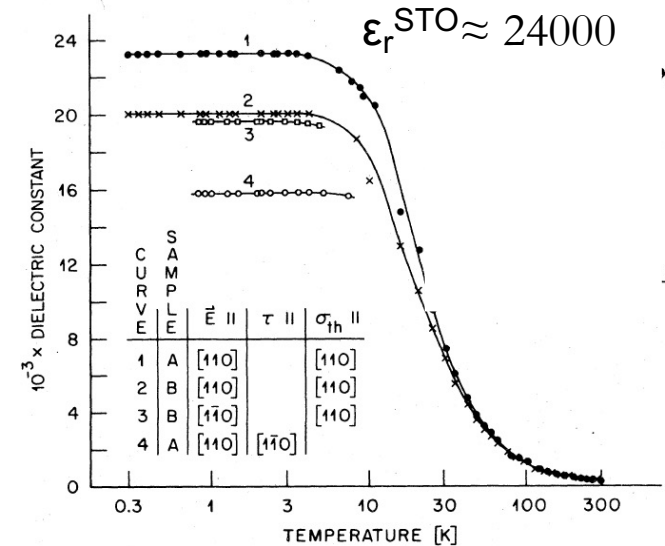
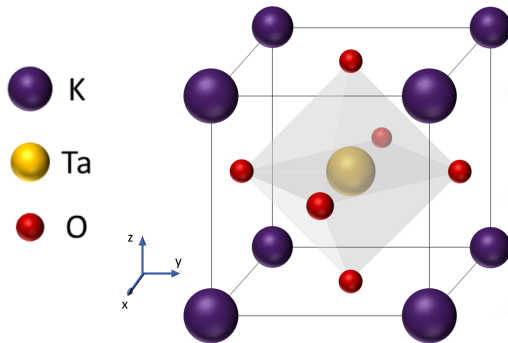
✧ Quantum paraelectricity (incipient ferroelectric)

- ➔ Divergence of the dielectric constant at low T
- ➔ Ferroelectric transition is quenched below 5K

SrTiO_3

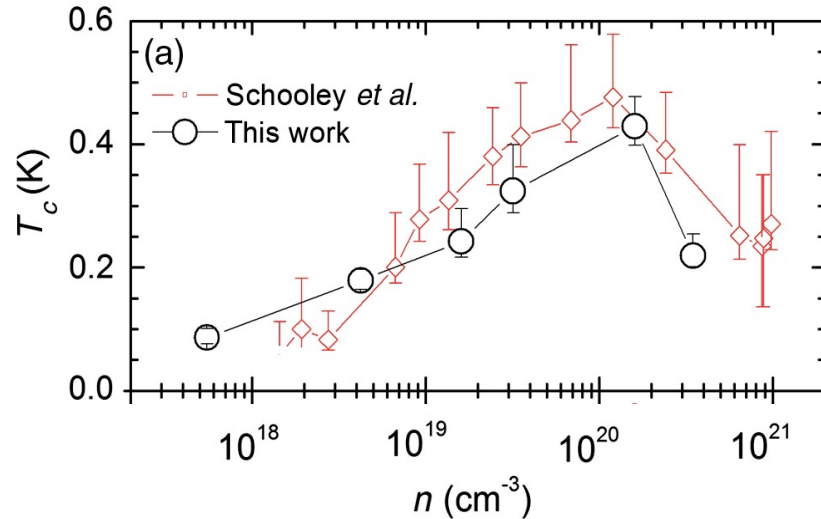


KTaO_3



Bulk Superconductivity in SrTiO_3

✧ Electron doping (Ox vacancies or Nb doping)



➡ Superconductivity survives over more than 3 decades in doping

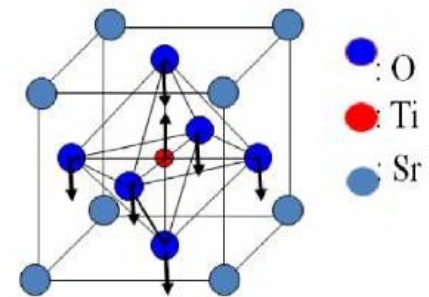
➡ Most dilute superconductor
 $\sim 1e$ for 30 000 uc !
(superc. metal $\sim 5\text{-}20$ e for 1uc)

Lin *et al.* PRX (2013) Koonce PR (1967)

✧ Origin of superconductivity ?

Soft TO phonons, ferroelectric fluctuations...

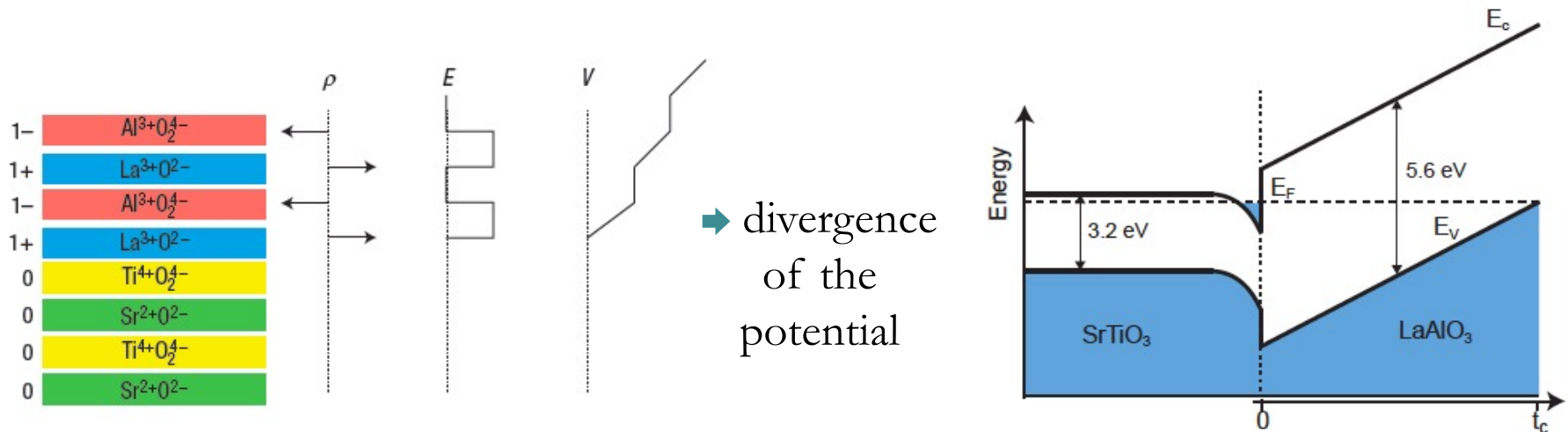
Edge *et al.* PRL 115, 247002 (2015), Gor'kov PNAS 113
4646 (2016), J. Ruhman PRB 84 1103 (2016)...



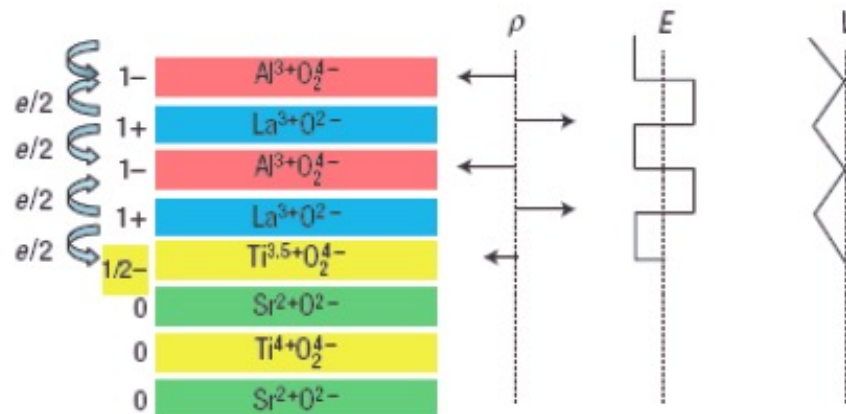
➡ No superconductivity in doped bulk KTaO_3

Formation of the 2-DEG: the “polar catastrophe”

✧ Proposed for $\text{LaAlO}_3 / \text{SrTiO}_3$



→ Electron transfer



Nakagawa, Nature Mat (2006)

Electronic reconstruction : the “polar catastrophe”

✧ Electronic reconstruction

critical thickness : 4 u.c.

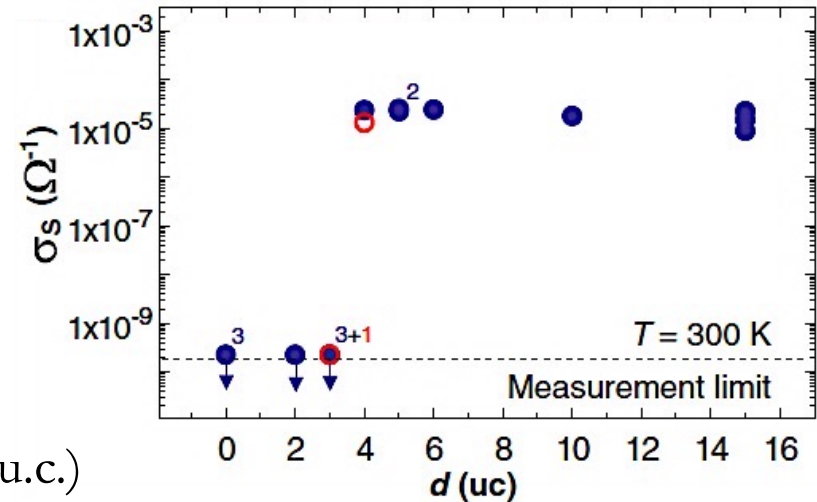
➡ satisfied experimentally but ...

prediction : $n_{\text{sheet}} = 3.3 \cdot 10^{14} \text{ e}^-/\text{cm}^2$ (0.5 e⁻/u.c.)

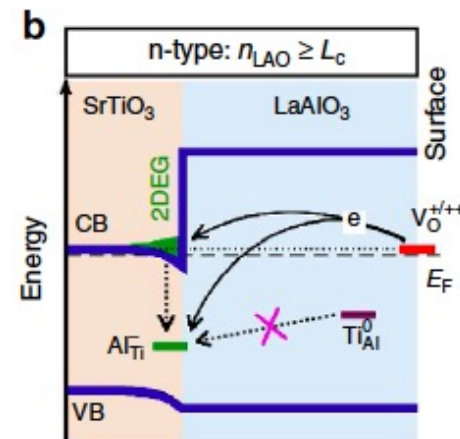
➡ experimentally : $n_{\text{sheet}} = [10^{13}-10^{14} \text{ cm}^{-2}]$

Alternative scenario : polarity induced oxygen vacancies

Yu & Zunger Nat. Commun. (2014)



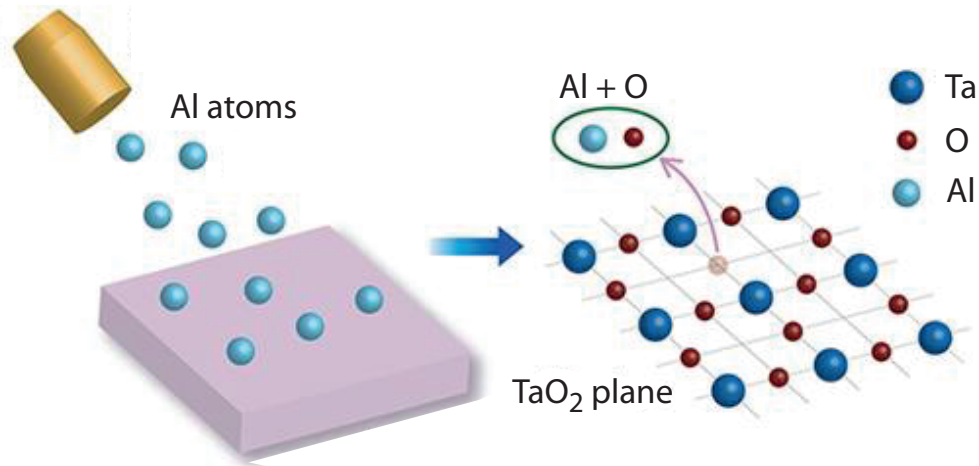
S. Thiel et al. Science (2006)



Synthesis of 2-DEGs by redox process

A reactive metal is deposited on the surface of SrTiO_3 or KTaO_3 substrate

- ➡ Metal is oxidized creating oxygen vacancies near the interface
- ➡ Each oxygen vacancy provides 2 electrons



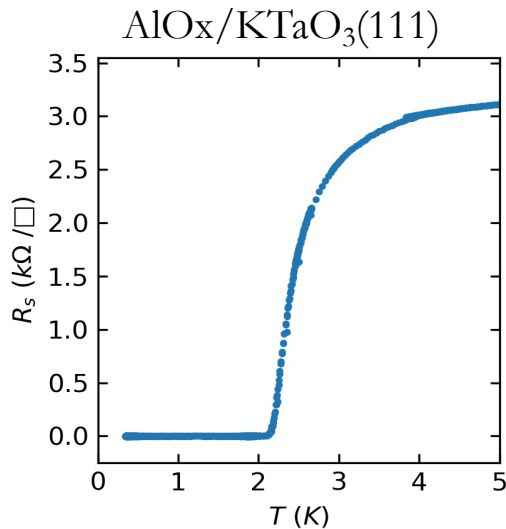
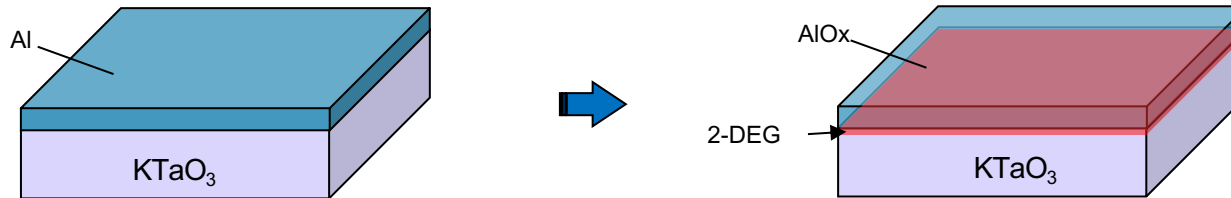
Senkupta et al. J. Appl. Phys. (2018), Vaz et al. Nature Mat. 18, (2019), Rödel et al. Adv. Mater. 28, (2016)

Synthesis of 2-DEGs by redox process

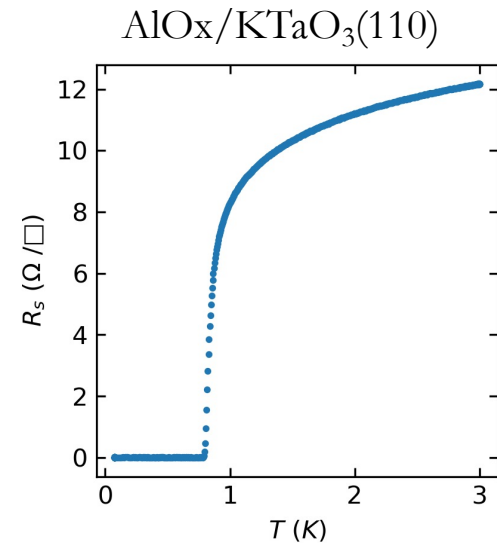
✧ $\text{AlO}_x/(111)\text{-KTaO}_3$ 2-DEGs

Col. ESPCI and LAF Thales-CNRS

- ➔ sputtering of 1-2 nm of Al on KTO substrate ($T \sim 600^\circ \text{C}$)
- ➔ oxidation of Al and reduction of Ta ions



S. Mallik et al. Nature Commun. (2022)



H. Witt et al Adv. Phys. Res. (2023)

SrTiO₃ vs KTaO₃-based interfaces

✧ SrTiO₃ based interfaces

Doped bulk SrTiO₃ is superconducting :
 $T_c \approx 300\text{-}400\text{mK}$

SrTiO₃ based interfaces are all
superconducting

$T_c(001) \approx T_c(110) \approx T_c(111) \approx 300\text{mK}$

Gate tunable superconductivity

✧ KTaO₃ based interfaces

Doped bulk KTaO₃ is not superconducting

Strong orientational dependence of T_c in
KTaO₃ based interfaces

$T_c(111) \approx 2.2\text{K}$, $T_c(110) \approx 1\text{K}$, $T_c(001) \approx 50\text{mK}$

Gate tunable superconductivity

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Band structure and quantum confinement

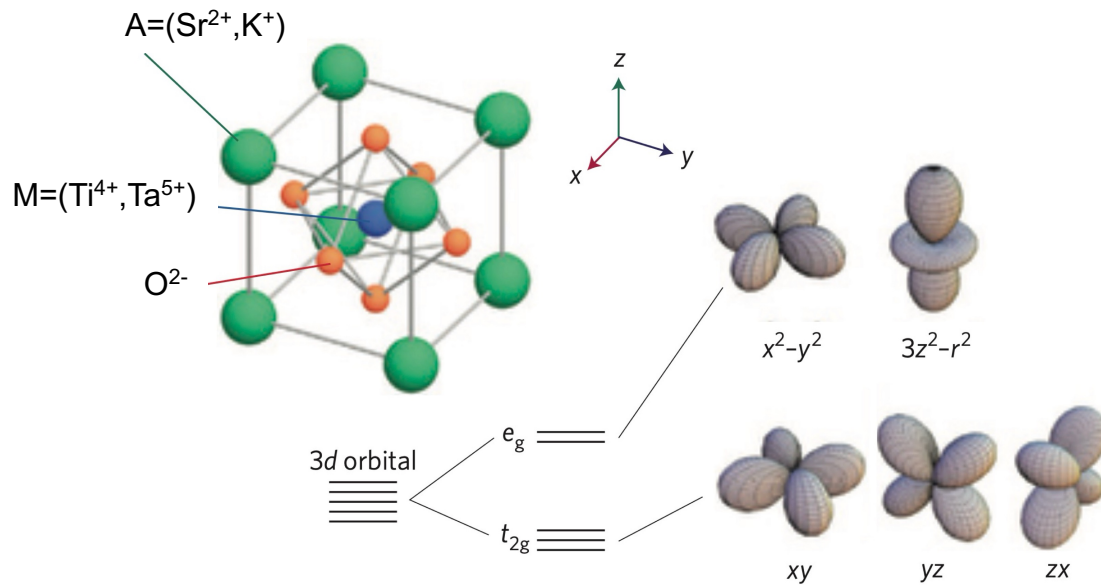
✧ t_{2g} d-orbital

Ti [Ar] $3d^2 4s^2$

In SrTiO_3 , titanium is Ti^{4+} ($3d^0$)

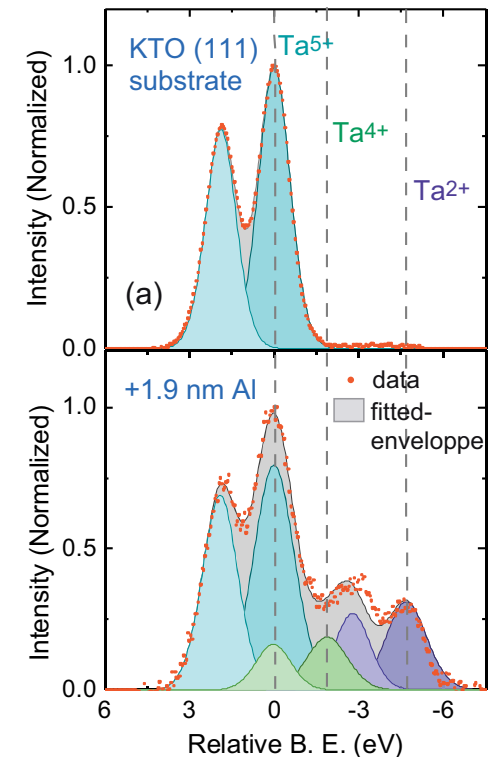
Ta [Xe] $4f^{14} 5d^3 6s^2$

In KTaO_3 , tantalum is Ta^{5+} ($5d^0$)

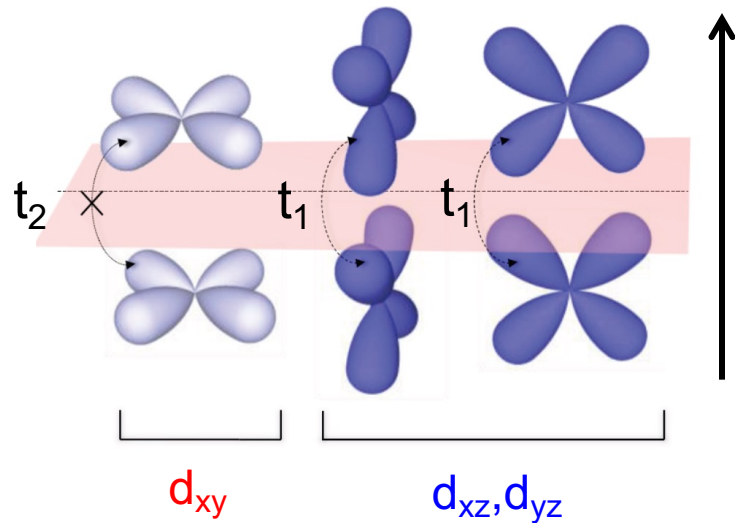


➡ In SrTiO_3 or KTaO_3 - based interfaces electrons of the 2DEG occupy t_{2g} bands

✧ XPS on KTaO_3 interface



Band structure and quantum confinement



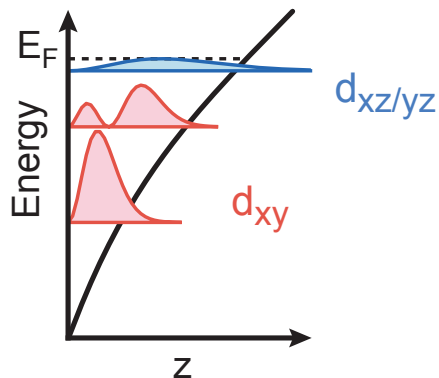
✧ t_{2g} anisotropic bands in SrTiO_3 crystal

$$m_l = -\frac{\hbar^2}{2a^2 t_1} \approx 0.7m_0 \quad m_h = -\frac{\hbar^2}{2a^2 t_2} \approx 14m_0$$

light heavy

t_1 and t_2 obtained by DFT

✧ Interfacial Quantum Well in (001)- LaAlO_3 / SrTiO_3



Self consistent solution of Poisson-Schrödinger equations

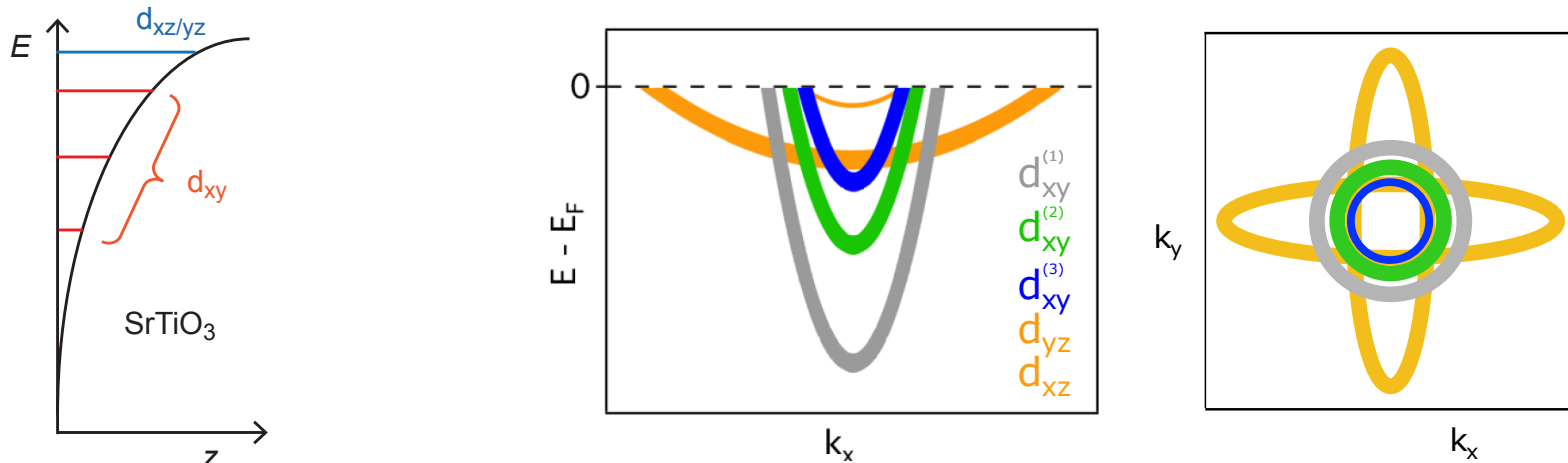
$$\nabla(\epsilon_0 \epsilon_R \nabla \Phi) = -\rho$$

$$V(z) = -e \Phi(z)$$

$$\left[\frac{p^2}{2m} + V(z) \right] \Psi = E \Psi$$

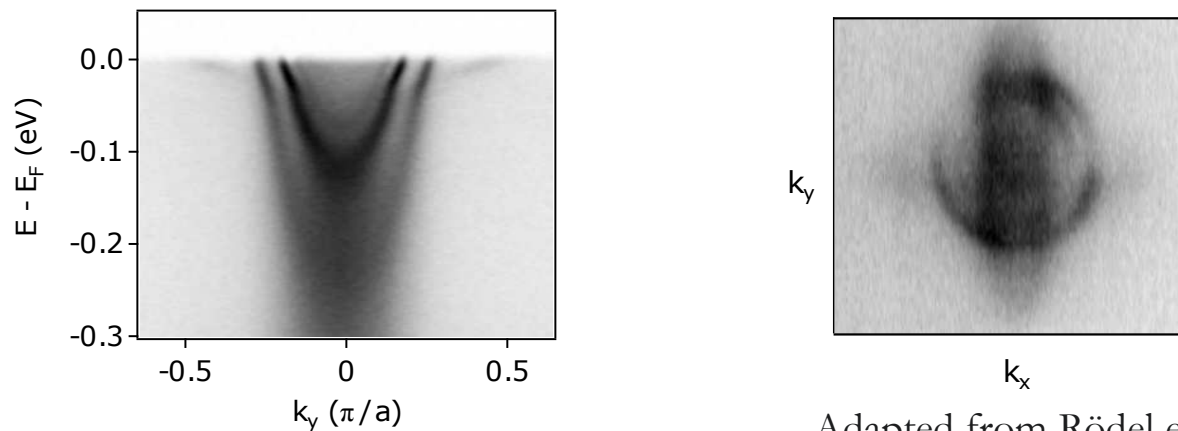
Band dispersions and Fermi contours

✧ Band dispersion in the quantum well



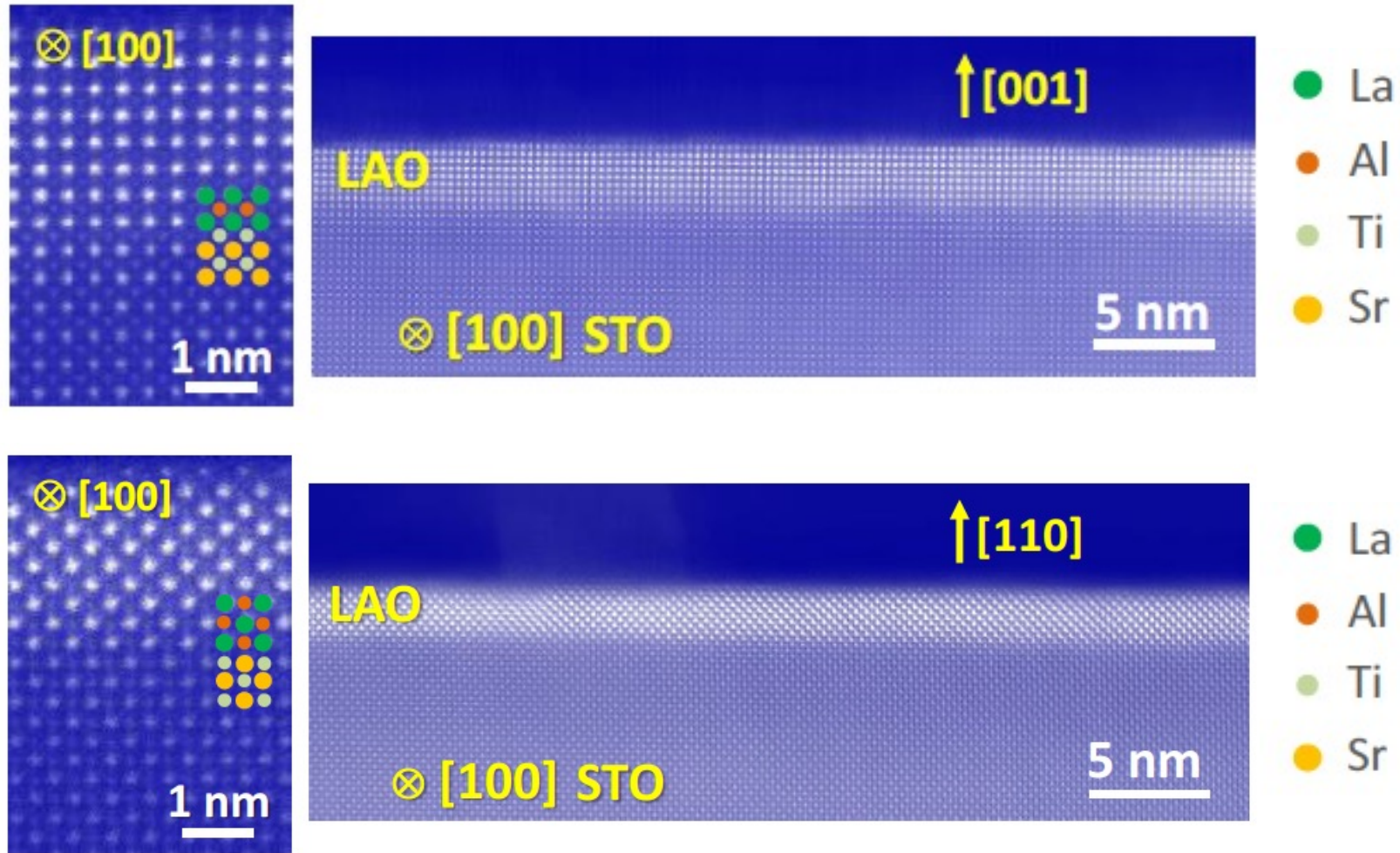
D. Vaz, Phd thesis

✧ ARPES measurements



Adapted from Rödel et al. Adv. Mater., (2016)

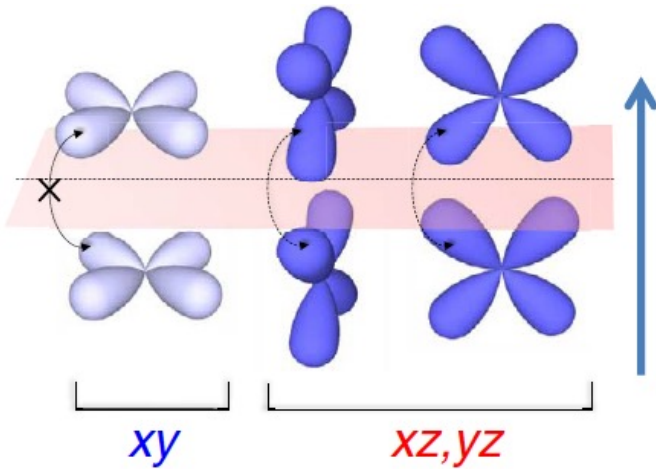
Band engineering : (001) vs (110) oriented $\text{LaAlO}_3/\text{SrTiO}_3$



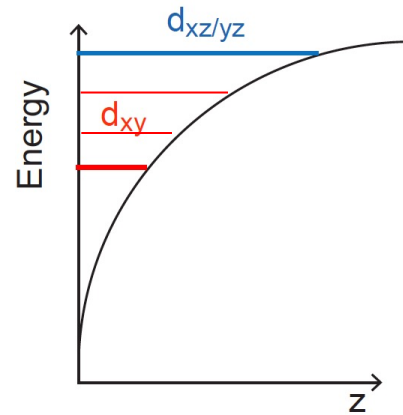
G. Herranz et al. Nature Commun. 6, 6028 (2015).

Orbitals hierarchy

(001)



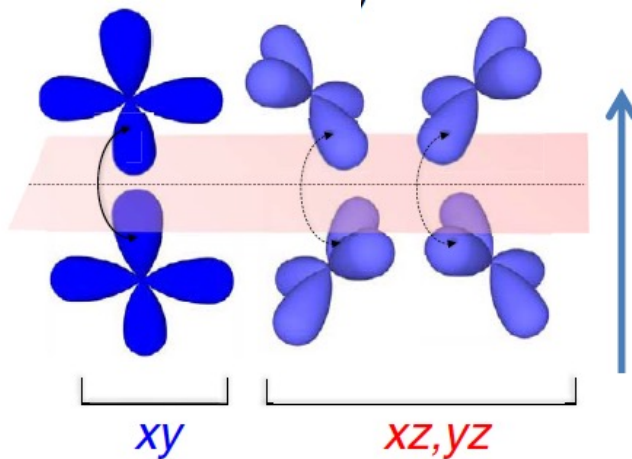
$E^{xy} < E^{xz,yz} \rightarrow d_{xy}$ subbands are mainly filled



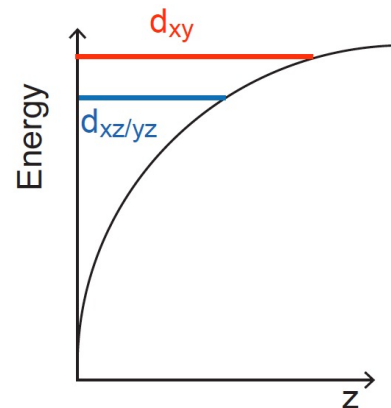
[001] direction

$$\left\{ \begin{array}{l} m_{001}^{xy} \approx 14 \\ m_{001}^{xz,yz} \approx 0.7 \end{array} \right.$$

(110)



$E^{xy} < E^{xz,yz} \rightarrow d_{xz}/d_{yz}$ subbands are mainly filled



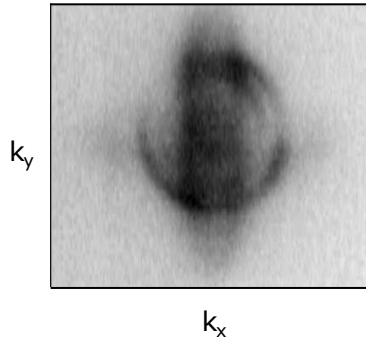
[110] direction

$$\left\{ \begin{array}{l} m_{110}^{xz,yz} \approx 0.65 \\ m_{110}^{xy} \approx 0.35 \end{array} \right.$$

Band engineering by crystal orientation

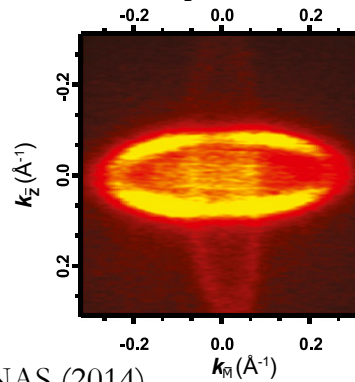
✧ SrTiO₃ interfaces

(001)-orientation



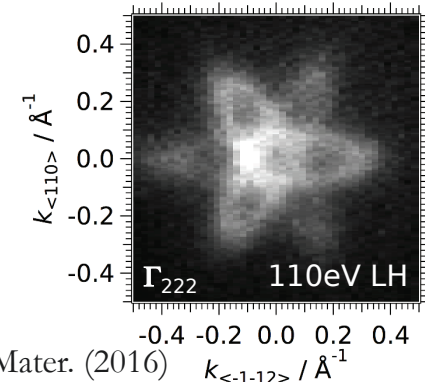
Rödel Adv. Mater. (2016)

(110)-orientation



Wang al. PNAS (2014)

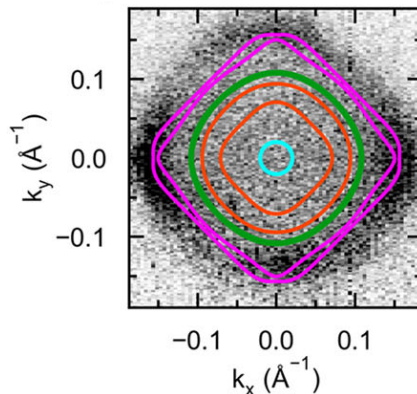
(111)-orientation



Rödel Adv. Mater. (2016)

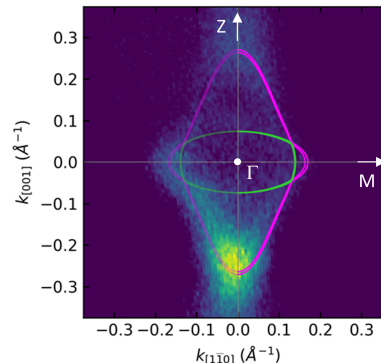
✧ KTaO₃ interfaces

(001)-orientation



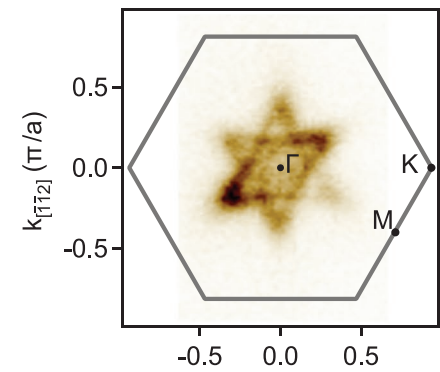
Varotto Nat Com. 2022.

(110)-orientation



Witt (thesis) Adv. Mat.

(111)-orientation



F. Bruno Adv. Elec. Mat. (2019)

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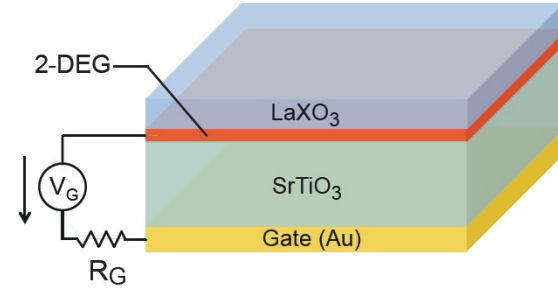
Perspectives on nanodevices

Electric field effect

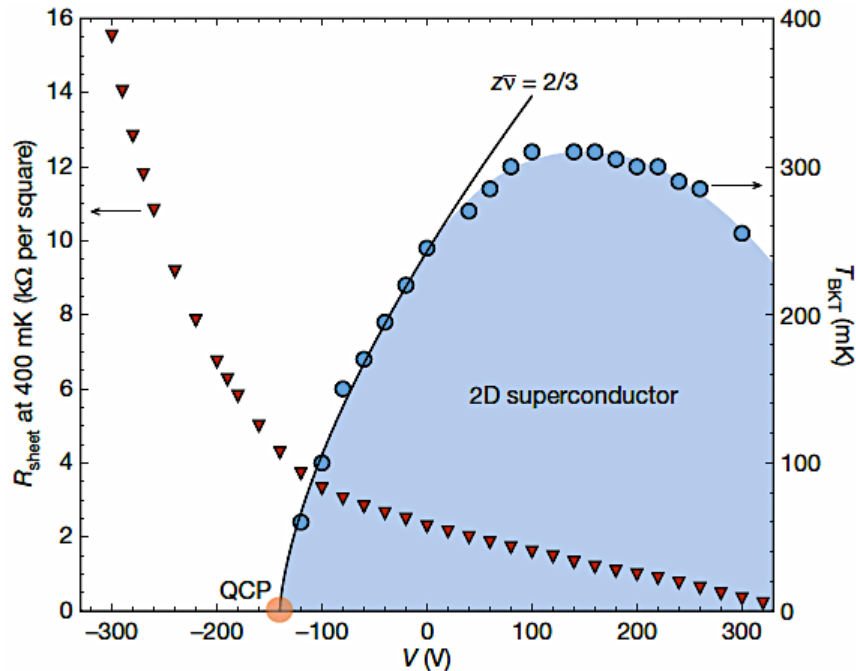
✧ Back-gating control

$$n \approx 2 \cdot 10^{13} - 2 \cdot 10^{14} \text{ e.cm}^{-2} \rightarrow \Delta n \approx \pm 50\%$$

✧ Superconducting phase diagram

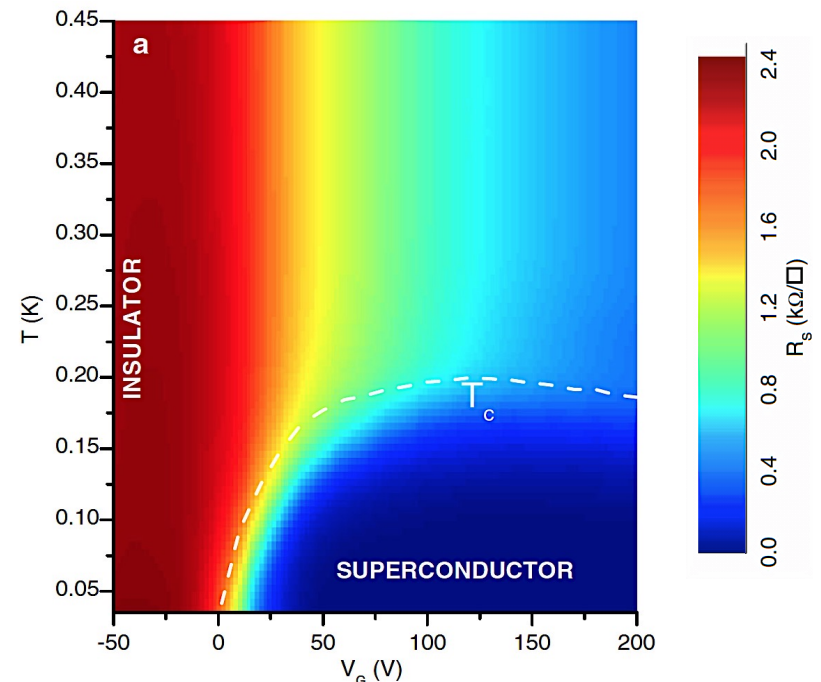


(001)-LaAlO₃/SrTiO₃



A. Caviglia et al. Nature (2008)

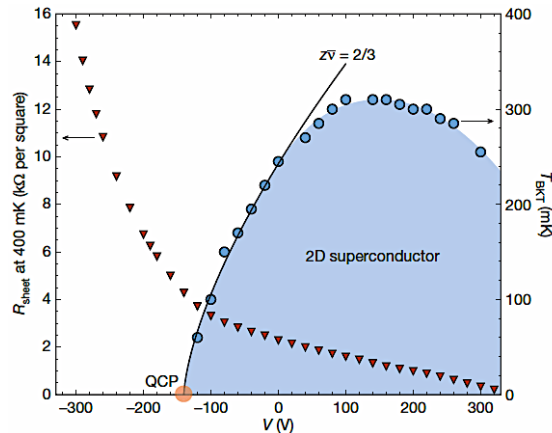
(001)-LaTiO₃/SrTiO₃



J. Biscaras et al. Phys. Rev. Lett. (2012)

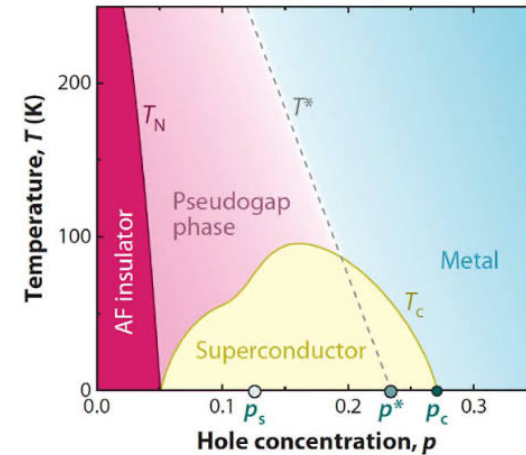
Dome-shaped superconducting phase diagrams

✧ (001)- $\text{LaAlO}_3/\text{SrTiO}_3$



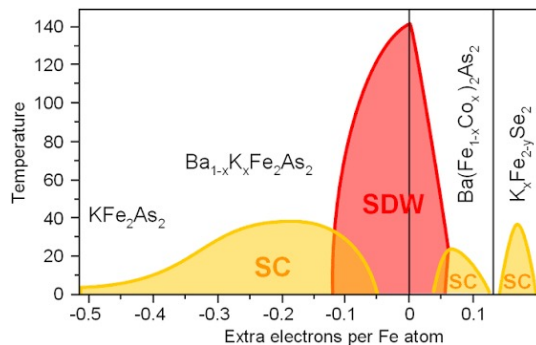
A. Caviglia et al. Nature (2008)

✧ High- T_c superc. cuprates



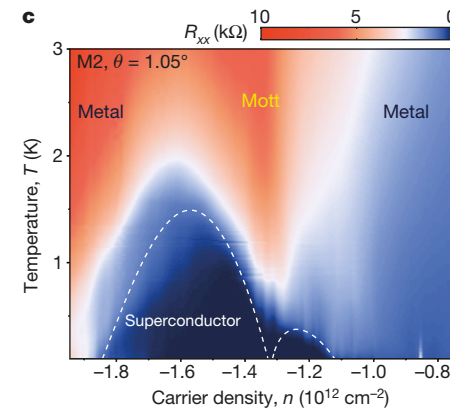
L. Taillefer, Annu. Rev. Condens. Matter Phys. (2010)

✧ Iron pnictide superconductors



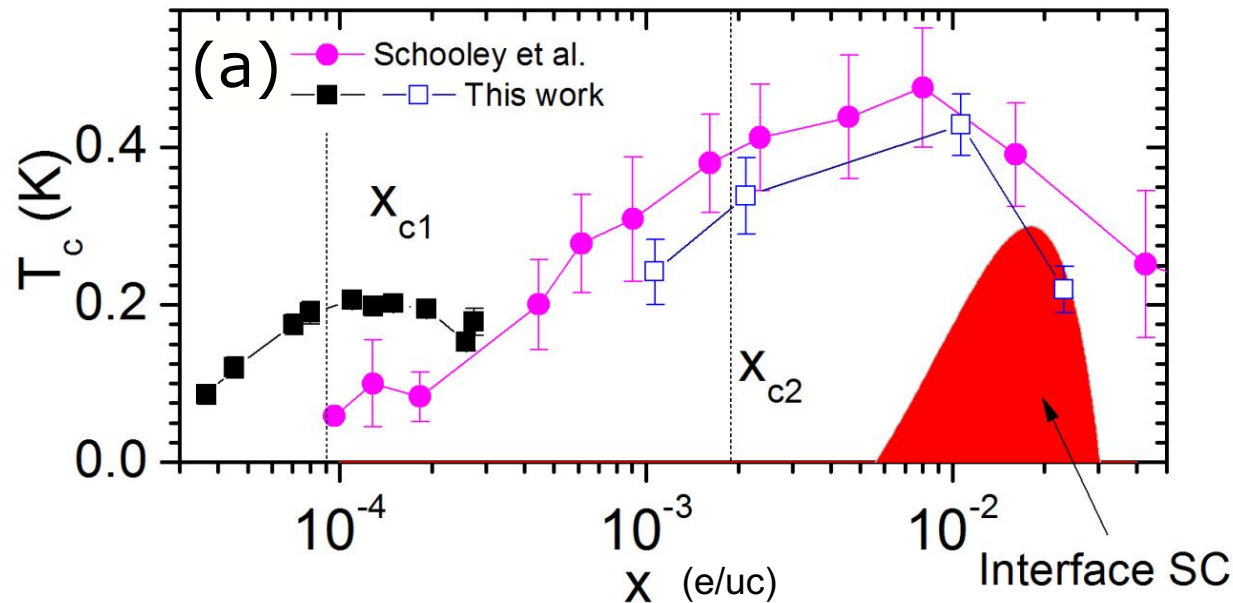
A Kordyuk, J. Supercond Nov Magn 26, 2837 (2013)

✧ Twisted bilayer graphene



Cao, Nature 556 (2018)

(001)- $\text{LaAlO}_3/\text{SrTiO}_3$ interface vs doped bulk SrTiO_3



Maria N. Gastiasoro et al, Annals of Phys. (2020)

- ➡ The interface phase diagram is much less extended in doping range
- ➡ Quantum Confinement at the interface must play a role

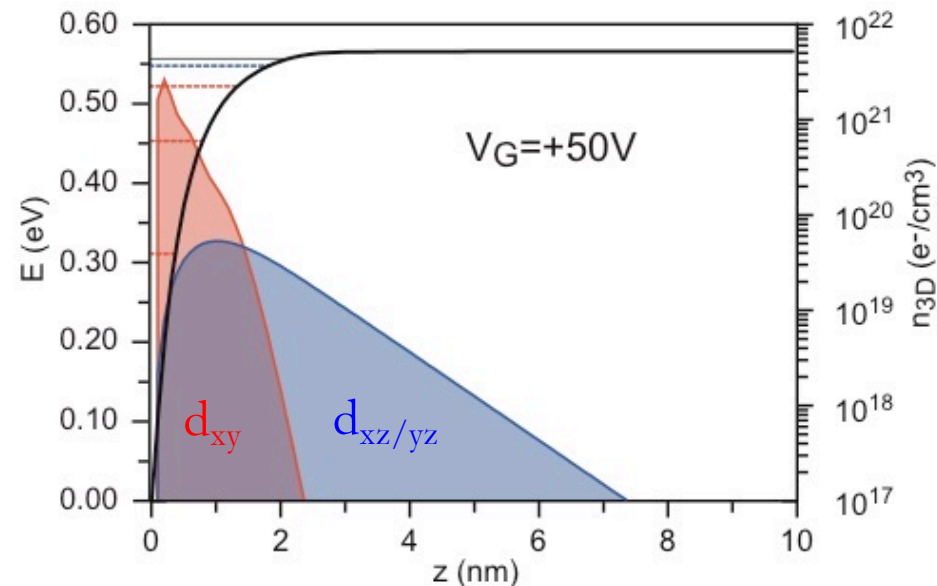
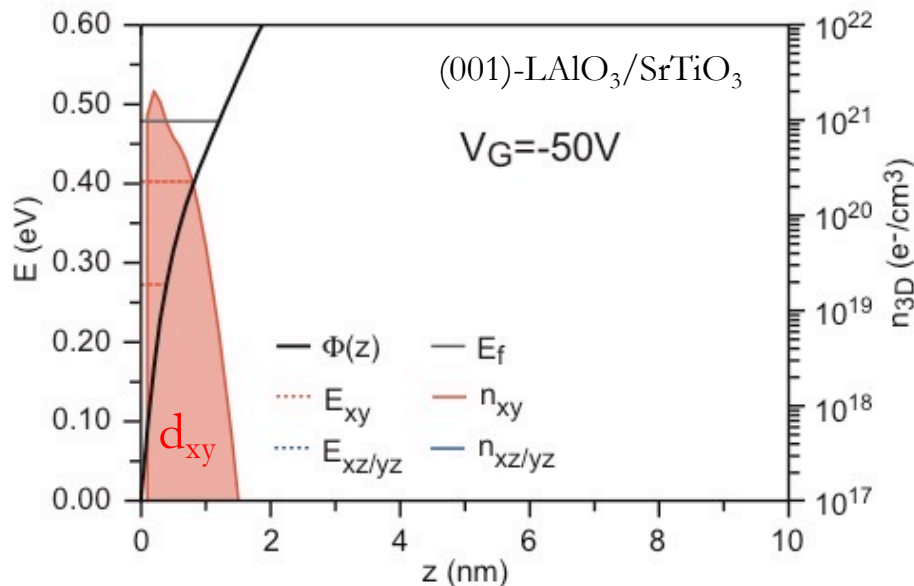
Band structure and electrostatic doping

✧ Self consistent solution of Poisson-Schrödinger equations

Poisson $\nabla(\epsilon_0 \epsilon_R \nabla \Phi) = -\rho$
 $V(z) = -e \Phi(z)$

Schrödinger $\left[\frac{p^2}{2m} + V(z) \right] \Psi = E \Psi$

➡ Must include the role of gate voltage and gate-dependent dielectric constant

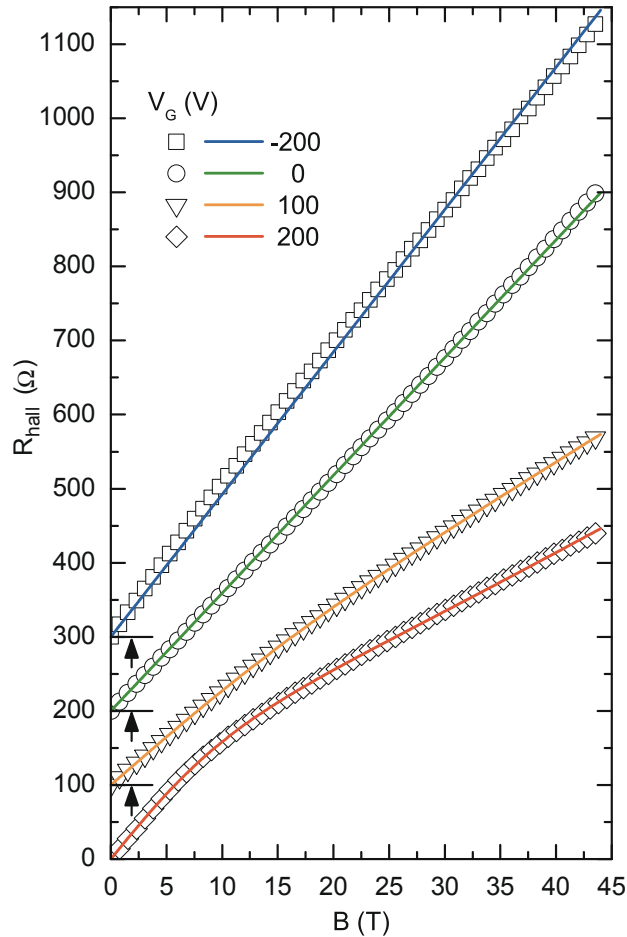


d_{xy} : confined, weak density of states

$d_{xy/yz}$: delocalized (bulk-like), high density of states

Multiband transport in (001)- $\text{LaAlO}_3/\text{SrTiO}_3$

✧ Non-linear Hall effect

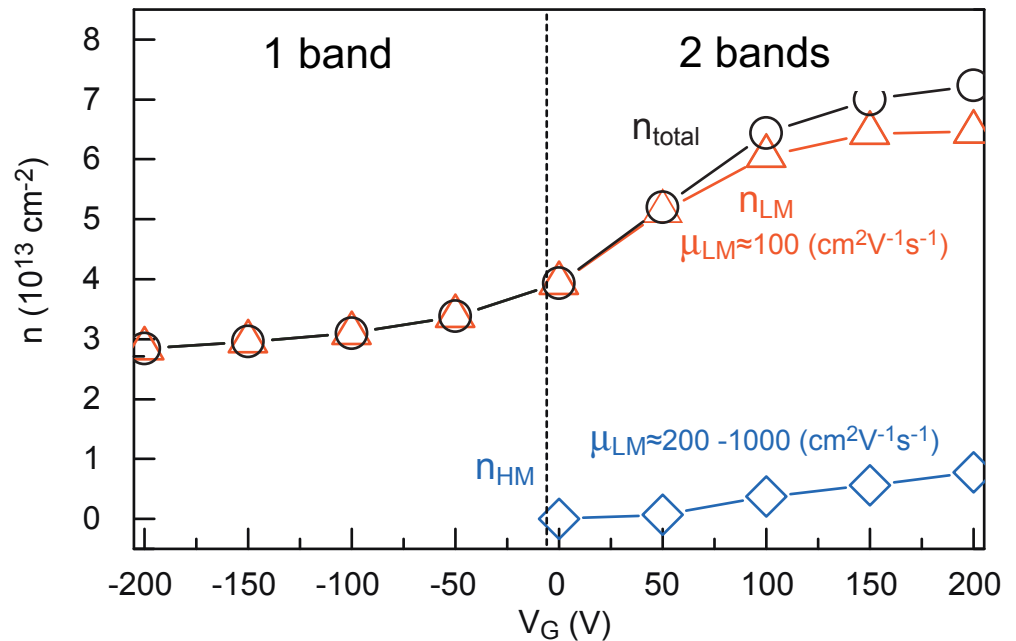


J. Biscaras et al Phys. Rev. Lett. (2012)

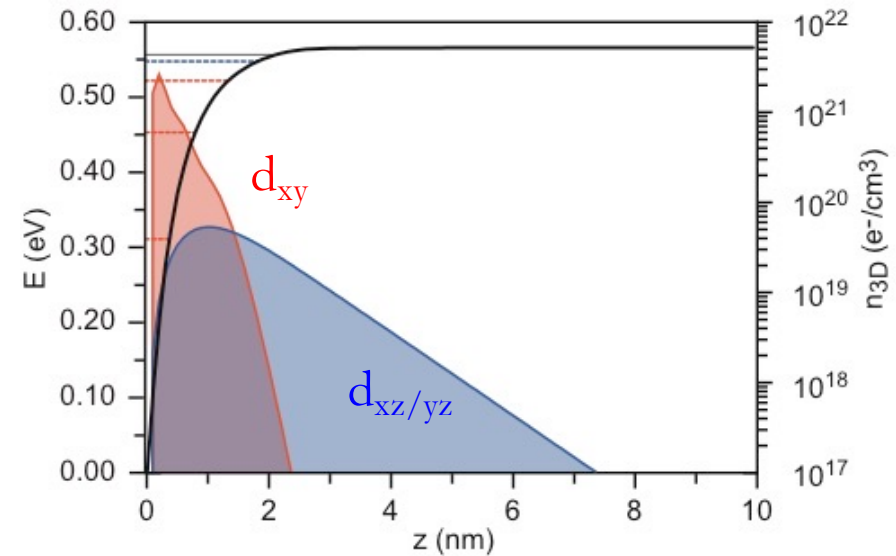
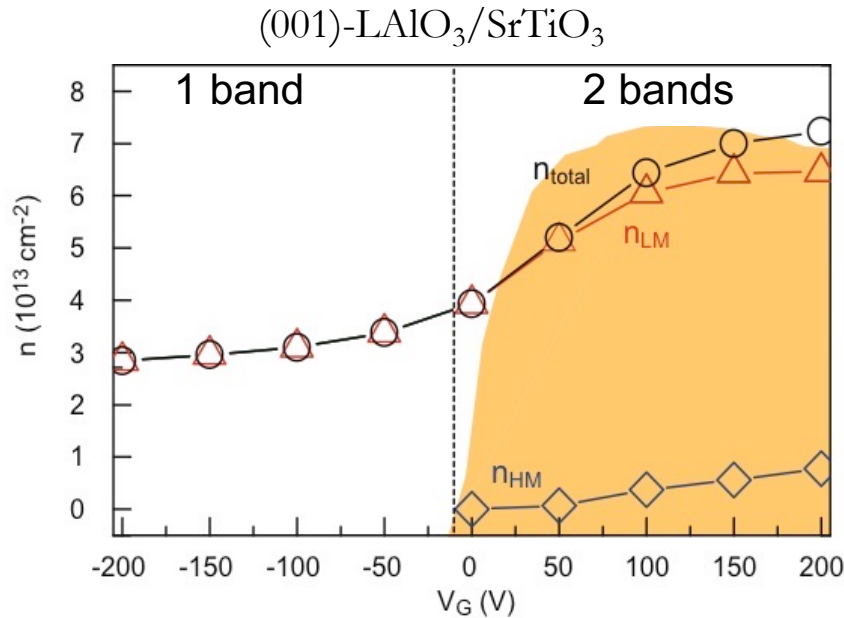
linear regime (depleted) $\longleftrightarrow$ non-linear (doped)

→ two-carrier analysis (n_1, μ_1, n_2, μ_2)

$$R_{\text{Hall}} = \frac{B}{e} \frac{\frac{n_1 \mu_1^2}{1 + \mu_1^2 B^2} + \frac{n_2 \mu_2^2}{1 + \mu_2^2 B^2}}{\left[\frac{n_1 \mu_1}{1 + \mu_1^2 B^2} + \frac{n_2 \mu_2}{1 + \mu_2^2 B^2} \right]^2 + \left[\frac{n_1 \mu_1^2 B}{1 + \mu_1^2 B^2} + \frac{n_2 \mu_2^2 B}{1 + \mu_2^2 B^2} \right]^2},$$



Multi-band transport and superconductivity



✧ Superconductivity emerges when high-mobility carriers appear in the 2D gas

transition $d_{xy} \longleftrightarrow d_{xy} + d_{xz/yz}$
LM HM

density of states: $N_0^{xz/yz} = \frac{m_{xz/yz}}{\pi \hbar^2} > N_0^{xy}$

➔ favorable for superconductivity $T_c \propto e^{-\frac{1}{N_0 V}}$

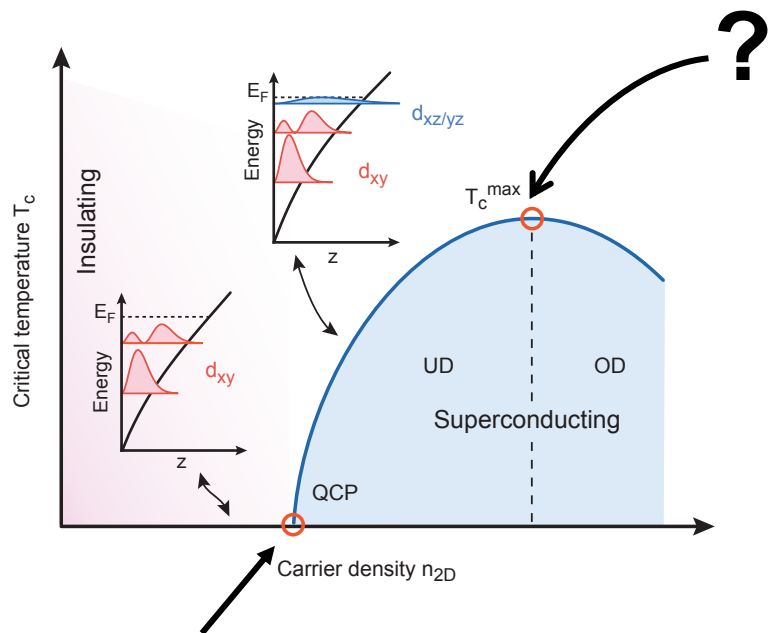
✧ $d_{xz/yz}$ band is responsible for superconductivity

J. Biscaras et al. Phys. Rev. Lett. (2012)

See also Gariglio et al. APL Mater. (2016),

Valentinis et al. Phys. Rev. B (2017)

Superconducting Phase diagram (001)- $\text{LaAlO}_3/\text{SrTiO}_3$



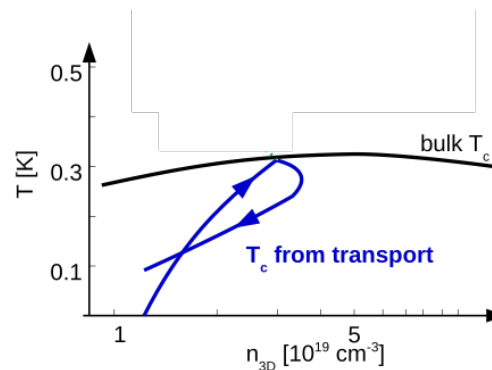
Superconductivity emerges when $d_{xz/yz}$ bands are filled

Gariglio et al. APL Mater. 4, 060701(2016)

Maniv et al. Nature Comm. 6, 8239 (2015)

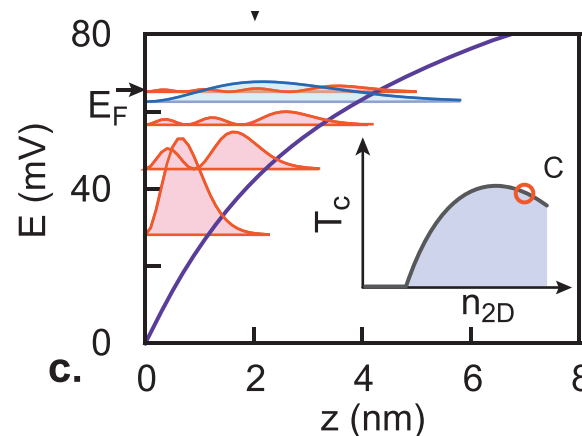
Valentinis et al. Phys. Rev. B 96, 094518 (2017)

1) $T_c^{\max}$ could correspond to a maximum of n_{3D}



S. Gariglio APL Mater (2016)

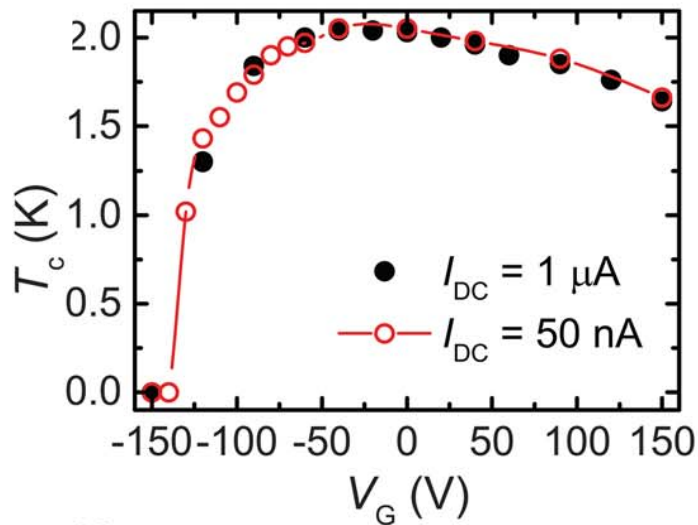
2) $T_c^{\max}$ could correspond to the formation of two-gap superconductivity with repulsive coupling ($s \pm$ wave superconductivity)



Jouan et al. dv. Mat. Int. (2022), Trevisan et al. PRL (2018)

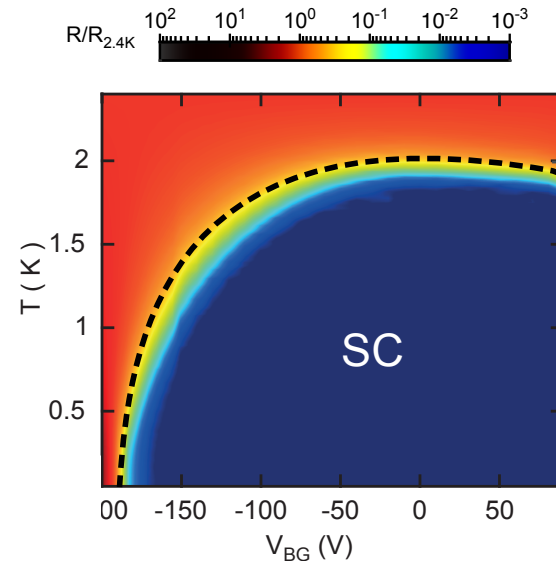
Phase diagram of (111)-KTaO₃ interfaces

✧ LaAlO₃/(111)-KTaO₃



Chen et al., Science 372, 721 (2021)

✧ AlO_x/(111)-KTaO₃



H. Witt, PhD thesis

- ➡ Similar dome shaped superconducting phase diagram with $T_c^{\max} \approx 2.2K$
- ➡ Little is known about the link between band structure and superconductivity

Outline

Introduction on SrTiO_3 and KTaO_3 based superconducting interfaces

Origin of the Two-Dimensional Electron gas

Band structure and Quantum confinement

Electric field control of superconductivity and phase diagram

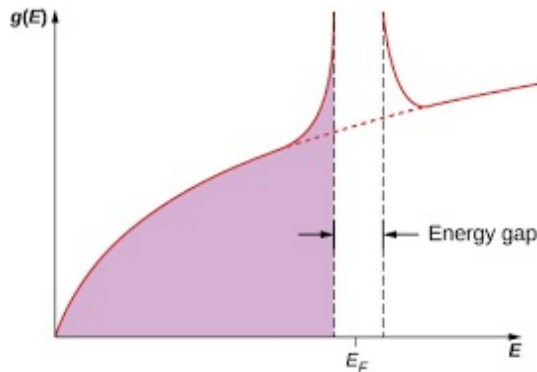
Tunneling spectroscopy and microwave conductivity

Mutigap superconductivity

Perspectives on nanodevices

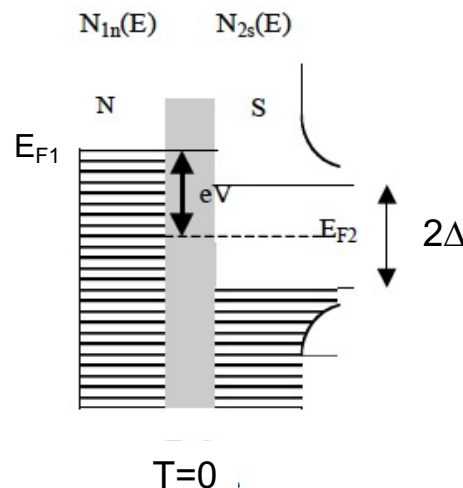
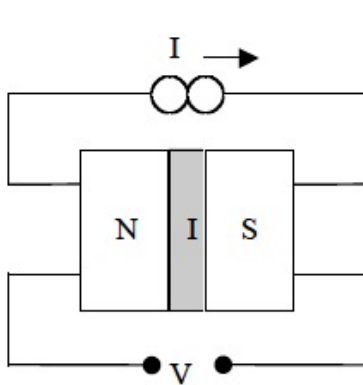
Tunneling spectroscopy of (001)- $\text{LaAlO}_3/\text{SrTiO}_3$

✧ Superconducting Density of States



$$N_s(E) = \begin{cases} 0, & E \leq |\Delta|, \\ N(0) \frac{E}{\sqrt{E^2 - |\Delta|^2}}, & E > |\Delta|. \end{cases}$$

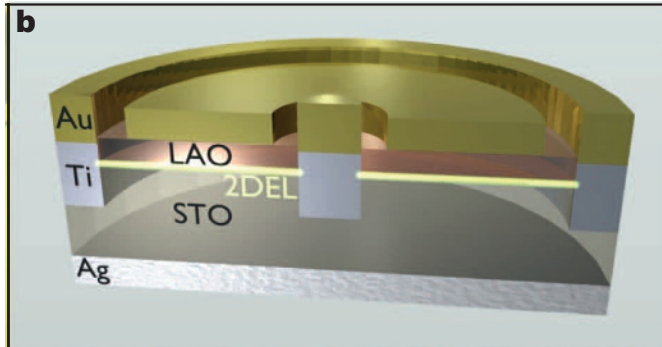
✧ Normal-Insulator-Superconductor Tunnel junction



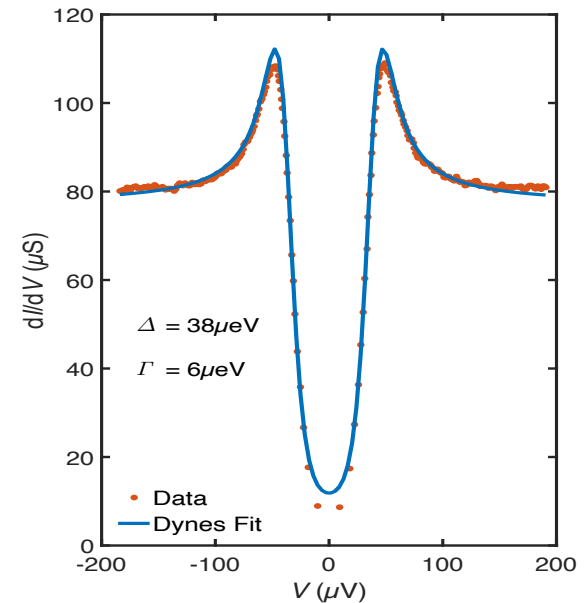
$$G_{ns}(V) = \frac{dI_{ns}}{dV} \propto N_{2s}(eV)$$

Tunneling spectroscopy of (001)- $\text{LaAlO}_3/\text{SrTiO}_3$

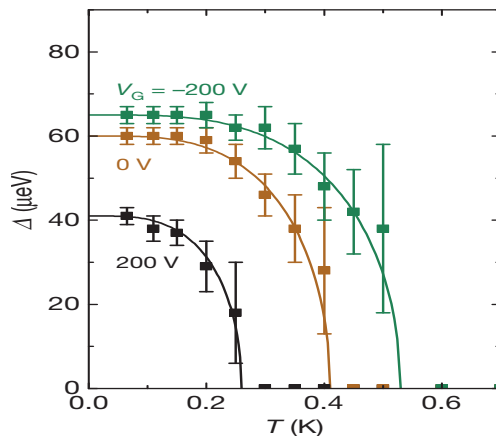
✧ Au- $\text{LaAlO}_3/\text{SrTiO}_3$ tunnel junction



Tunnel spectrum



Temperature dependence of the gap

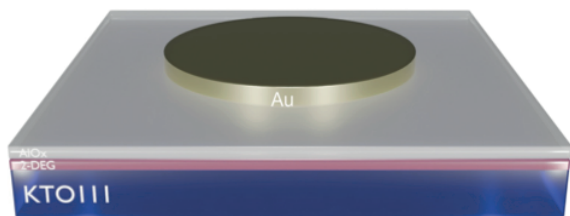


➔ BCS like gap ...but low resolution spectroscopy

Richter et al Nature (2013), Kuerten, PRB (2017)

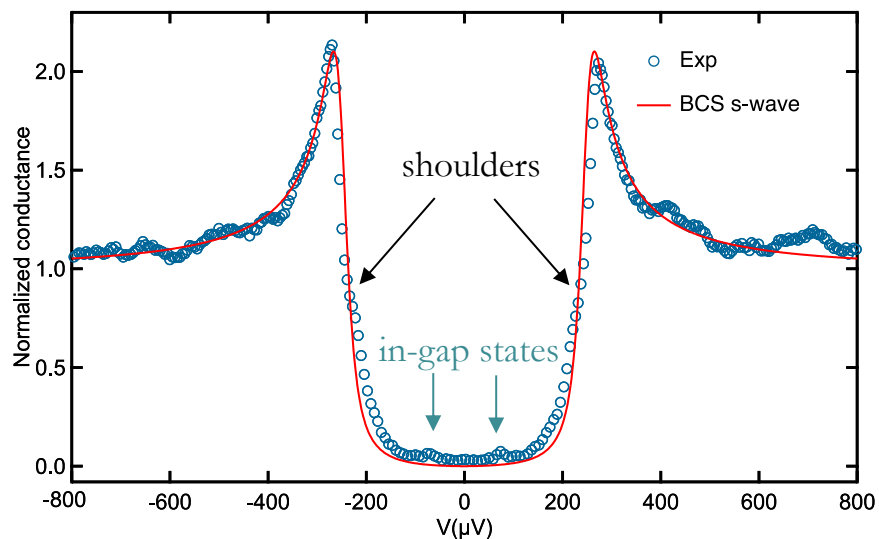
Tunneling spectroscopy in (111)-KTaO₃ 2DEGs

✧ Planar tunnel junctions Au/AlO_x(4nm)/KTaO₃(111)



Col. M. Bibes (LAF CNRS-Thales)

✧ Low temperature tunneling spectrum (T=50 mK)



➡ Direct measurement of the superconducting gap structure $\Delta(0) \approx 250 \mu\text{eV}$

➡ Fully gapped but not a pure s-wave BCS gap

➡ Shoulders structure suggests a second gap

➡ In-gap structures

H. Witt (PhD thesis)

Microwave measurement of superfluid stiffness

✧ Electrodynamics of superconductors (Mattis and Bardeen theory)

$$\sigma(\omega) = \sigma_1(\omega) - i\sigma_2(\omega)$$

unpaired
electrons

Cooper
pairs

$$\sigma_2(\omega) = \frac{1}{L_k \omega} \quad L_k: \text{kinetic inductance}$$

$(\hbar\omega \ll \Delta)$

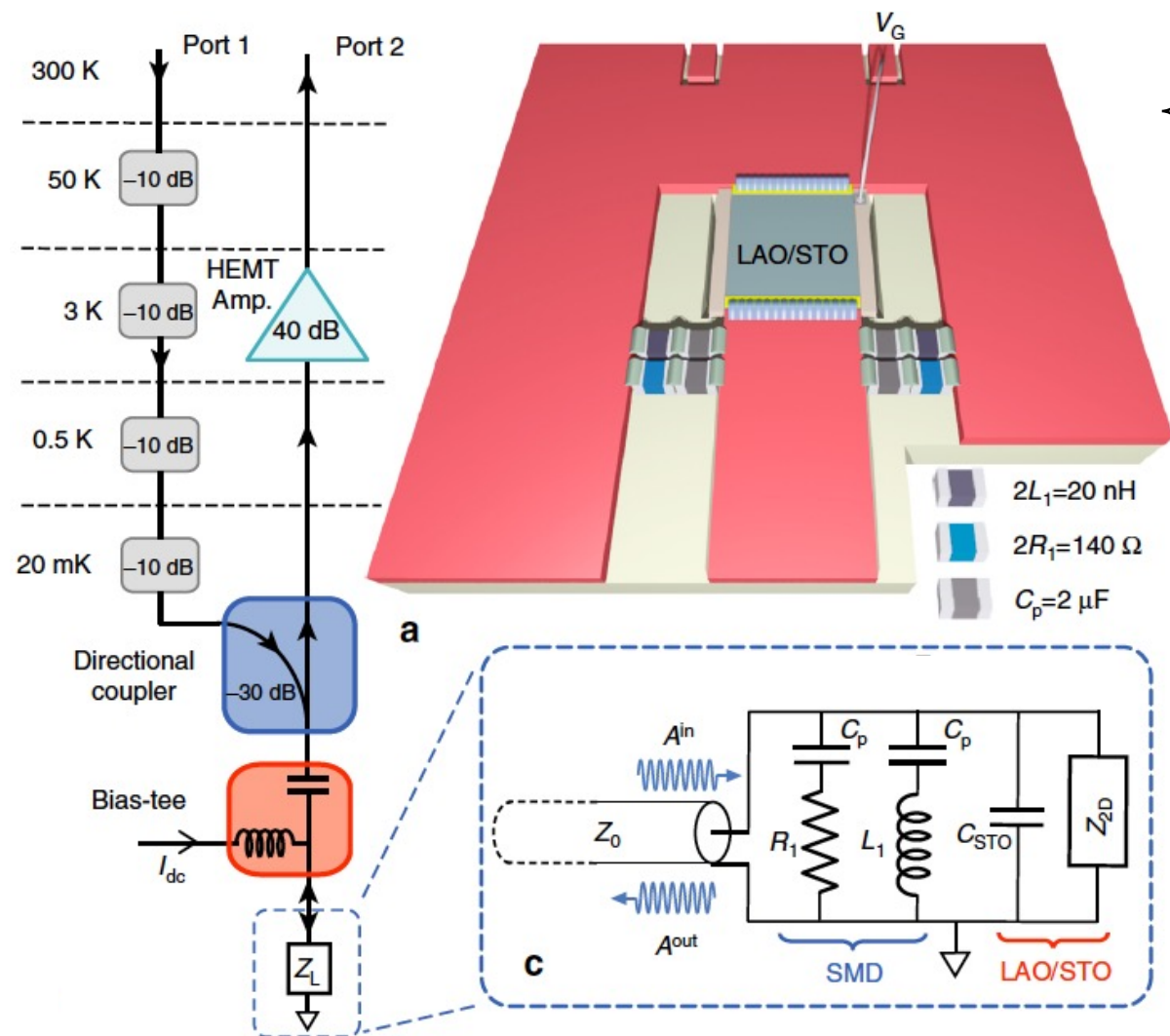
➡ Superfluid stiffness $J_s = \frac{\hbar^2}{4e^2 L_k}$

➡ Superfluid density $n_s = \frac{4m}{h^2} J_s$

➡ Measurements of $\sigma(\omega)$ can be done in transmission or reflection

typically $\omega \sim 1\text{-}10$ GHz

Superfluid stiffness of (001)- $\text{LaAlO}_3/\text{SrTiO}_3$ interfaces



(001) orientation

✧ Superfluid stiffness ($\hbar\omega \ll \Delta$) :

$$J_s = \frac{\hbar^2}{4e^2 L_k}$$

 L_k : kinetic inductance

✧ RLC resonant circuit

➡ resonance freq :

$$\omega_0 = \frac{1}{\sqrt{L_{tot} C_{STO}}}$$

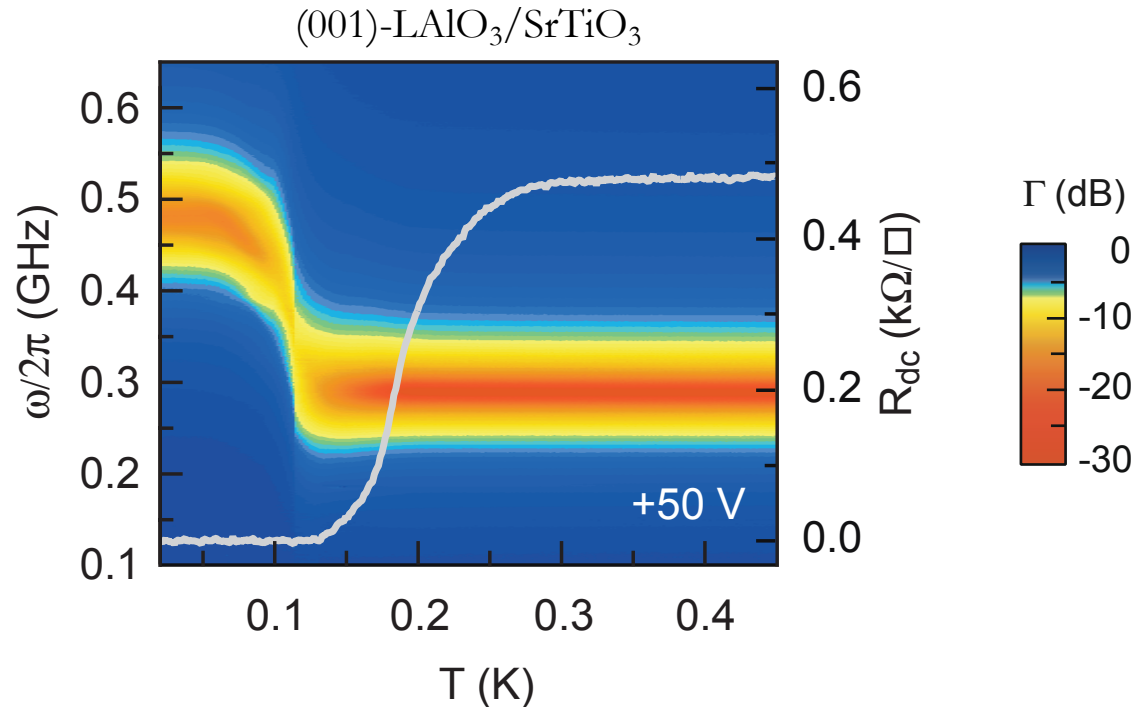
reflection coefficient :

$$\Gamma(\omega) = \frac{A^{out}}{A^{in}} = \frac{Z_L(\omega) - Z_0}{Z_L(\omega) + Z_0}$$

G. Singh et al Nature Commun. 9, 407 (2018)

Microwave response in the superconducting state

- ✧ Temperature dependence of the reflection coefficient

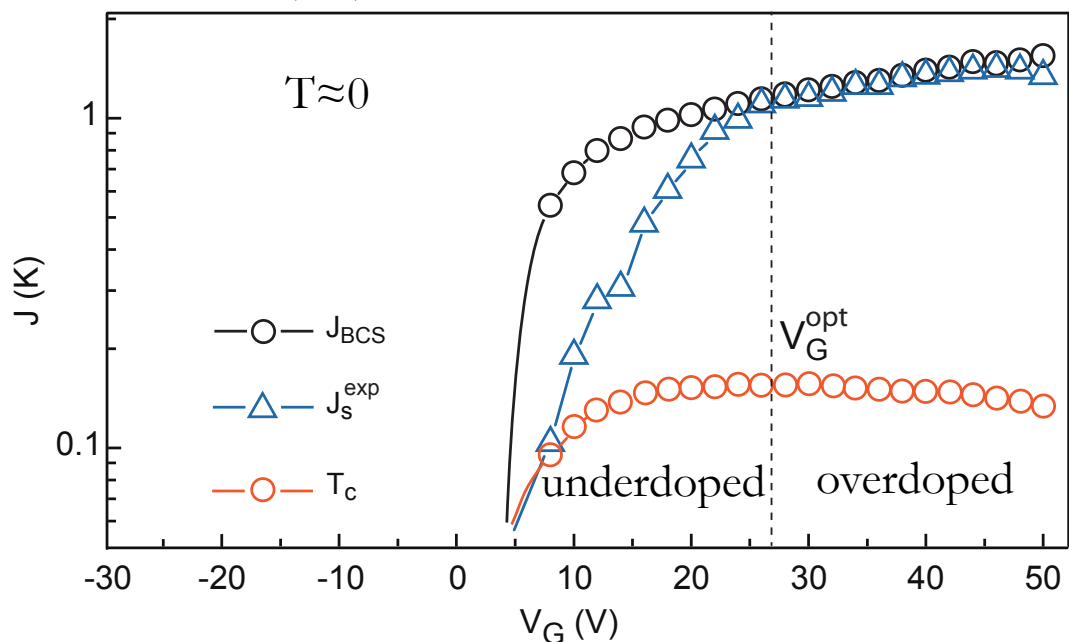


Superconducting transition ➡ shift of ω_0 toward high frequencies

Total inductance :
$$L_{tot} = \frac{L_1 L_k(T)}{L_1 + L_k(T)} \quad \rightarrow \quad L_k(T) \quad \rightarrow \quad \text{Superfluid stiffness } J_s(T, V_G)$$

Superfluid stiffness of at $T \approx 0\text{K}$

(001)- $\text{LaAlO}_3/\text{SrTiO}_3$



G. Singh et al Nature Commun. 9, 407 (2018)

BCS dirty limit ($\hbar / \tau \gg \Delta(0)$) :

$$J_s(T = 0) = \frac{\pi \hbar}{4e^2 R_n} \Delta(0)$$

with $\Delta(0) = 1.76 k_B T_c$

Overdoped : Transition is controlled by electron pairing : BCS like

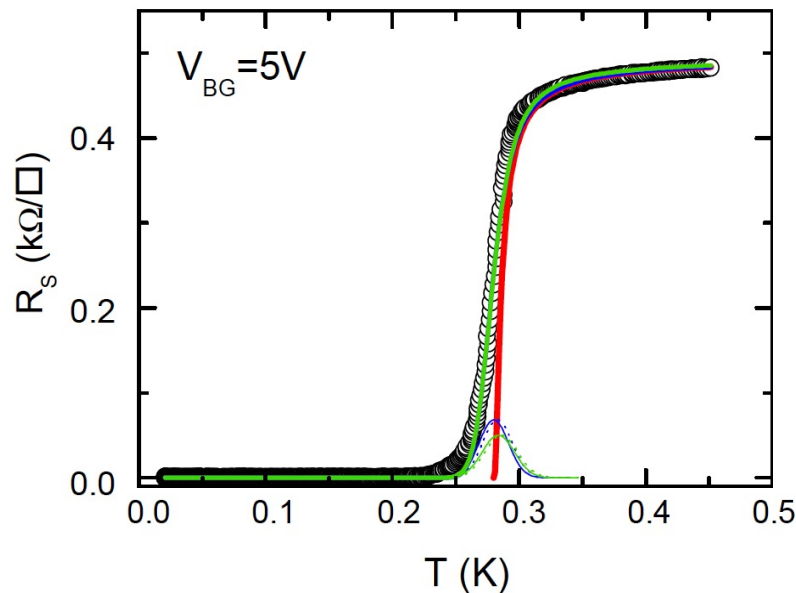
➡ consistent with tunneling data Richter et al. Nature 502, 528-531 (2013)

Underdoped : transition is controlled by the loss of phase coherence

➡ phase fluctuations reinforced by spatial inhomogeneities

Berezinski-Kosterlitz-Thouless : role of disorder

✧ Superconducting transition en $R(T)$ curves



S. Hurand PhD thesis

Halperin & Nelson analysis

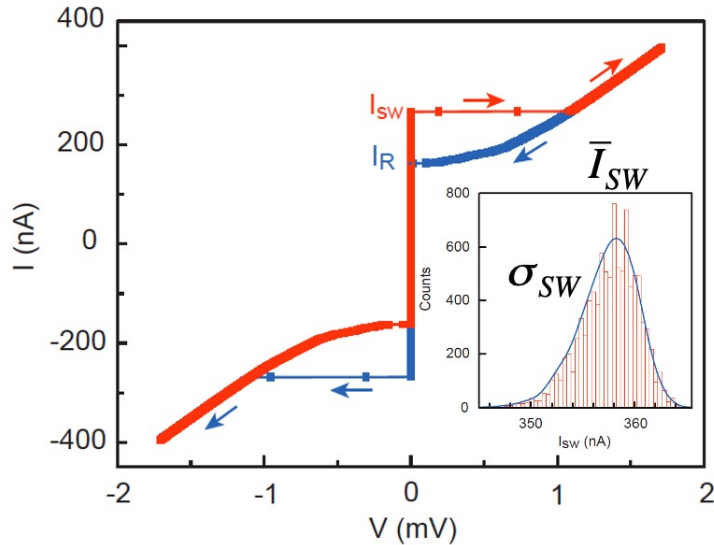
➡ Include amplitude and phase fluctuations

$$R_S(T) = R_N \frac{1}{1 + \frac{4}{A^2} \sinh^2 \left(b \sqrt{\frac{T_C - T_{KT}}{T_{KT}}} \sqrt{\frac{T_{KT}}{T - T_{KT}}} \right)}$$

➡ Only works if we introduce a inhomegenous distribution of T_c

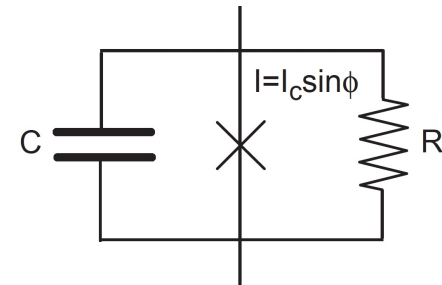
Role of disorder

✧ Current-voltage characteristics



➡ Switching current and hysteresis

➡ Similar to the dynamic of a Josephson junction

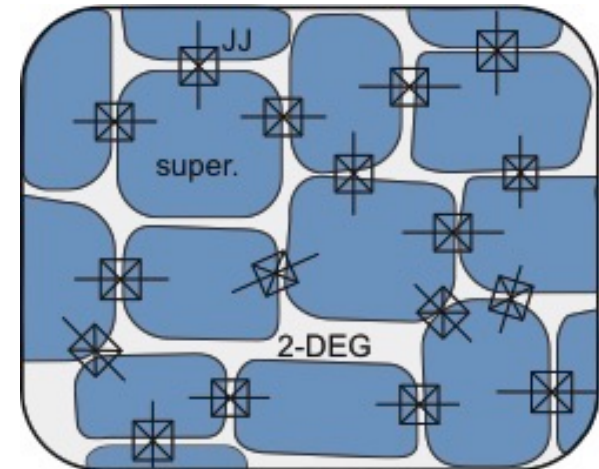


➡ The 2D gas behaves as a Josephson junction array

$V_G \gg 0$: dense array, quasi homogeneous

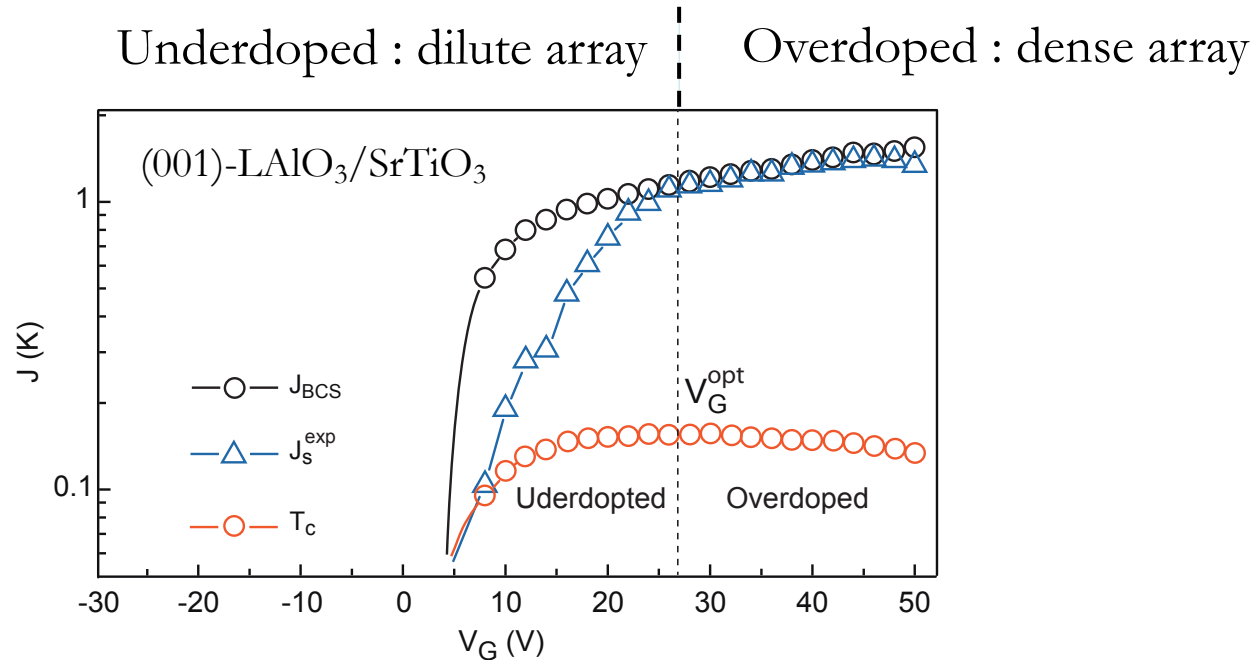
$V_G \ll 0$ dilute array, inhomogeneous

S. Hurand Phys. Rev. B. 99, 104515 (2019)



Superfluid stiffness and disorder

✧ Disorder Josephson junctions array



✧ Origin of disorder

- material related : domains

- intrinsic : electronic phase separation

B. Kalisky Nat. Mater. 12, 1091 (2013)

N. Scopigno Phys. Rev. Lett. 116, 026804 (2016)

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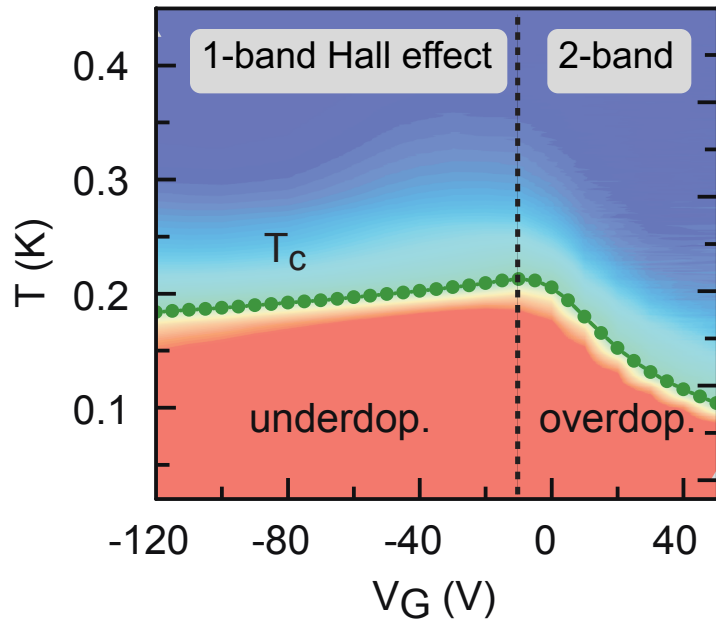
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Multiband transport in (110)- oriented interfaces

✧ Transition single-band transport / multiband transport



Linear regime(depleted) $\longleftrightarrow$ non-linear (doped)

$$d_{xz/yz} \longleftrightarrow d_{xz/yz} + d_{xy}$$

➔ Transition occurs at optimal doping

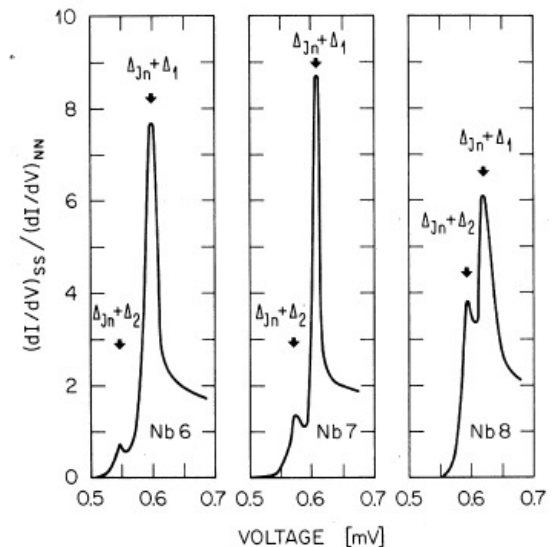
✧ Two-band superconductivity in the overdoped regime ?

➔ observed in bulk SrTiO_3 by tunnelling

Binning et al PRL (1980)

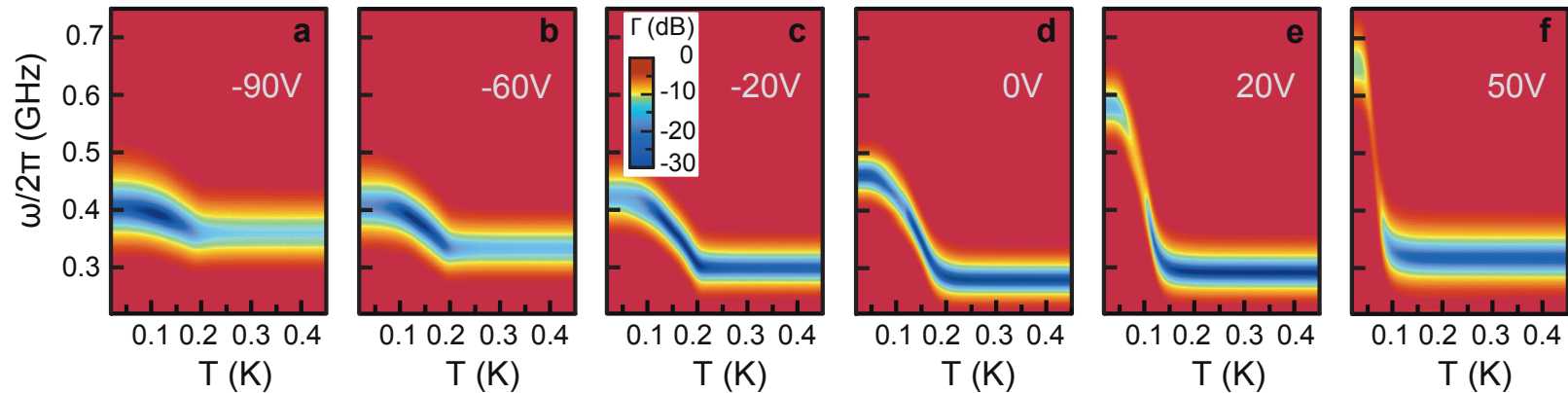
➔ predicted in $\text{LaAlO}_3/\text{SrTiO}_3$

R. M. Fernandes (2013), Trevisan et al. PRL (2018)



Superfluid stiffness in (110)-oriented interfaces

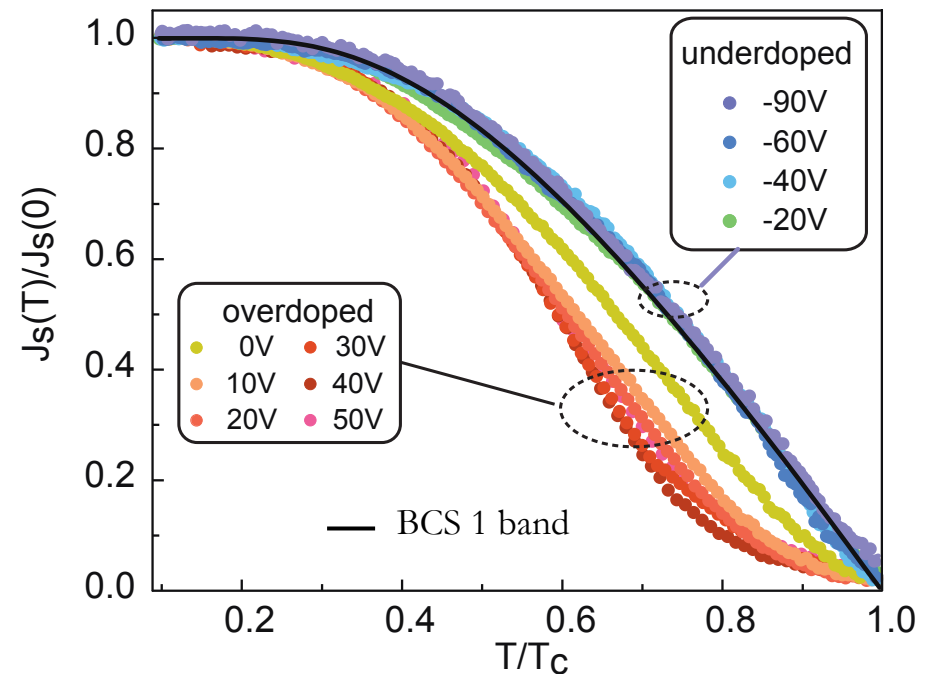
✧ Resonant microwave transport



✧ Temperature dependence of $J_s(T)$

transition :

1-band superc. $\longleftrightarrow$ 2-band superc.
(underdoped) (overdoped)

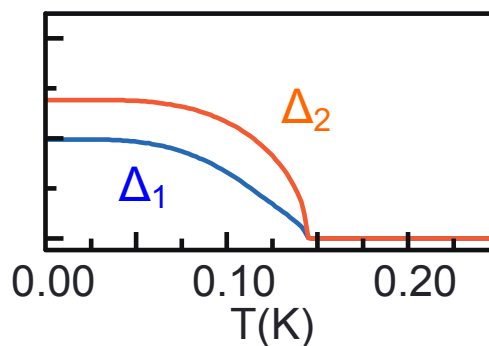
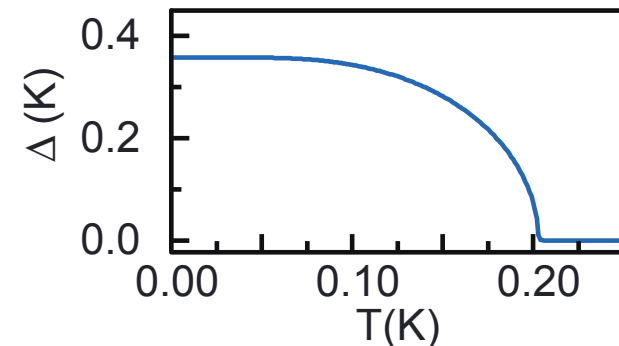
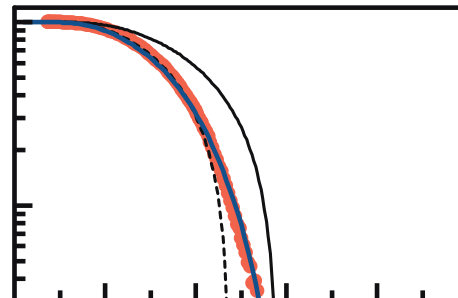
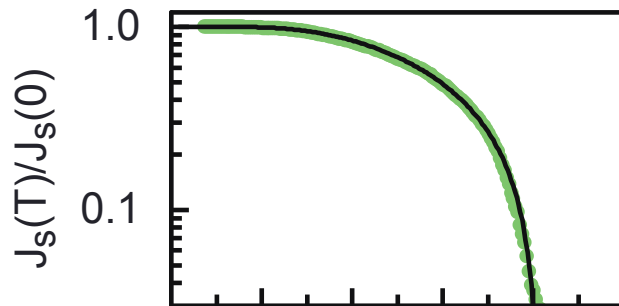
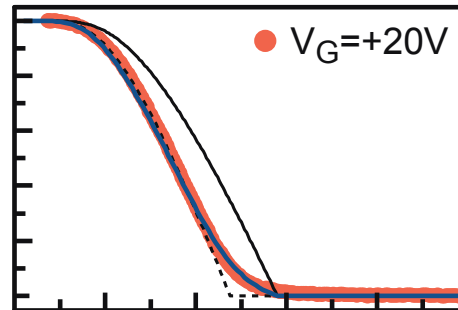
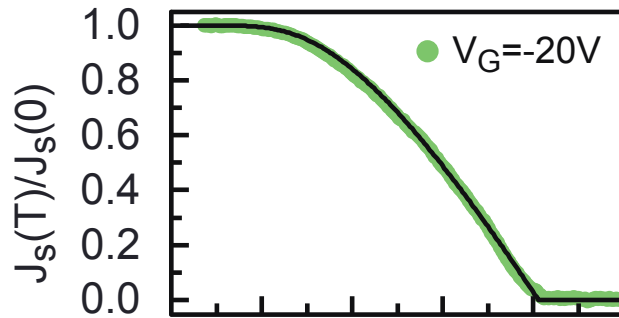


G. Singh et al. Nat. Mat. (2019)

Quantitative analysis of $J_s(T)$

1-band

2 bands



Kogan et al PRB 80, 014507 (2009)

Intraband couplings

$$\lambda_{11}, \lambda_{22}$$

Interband couplings

$$\lambda_{12}, \lambda_{21}$$

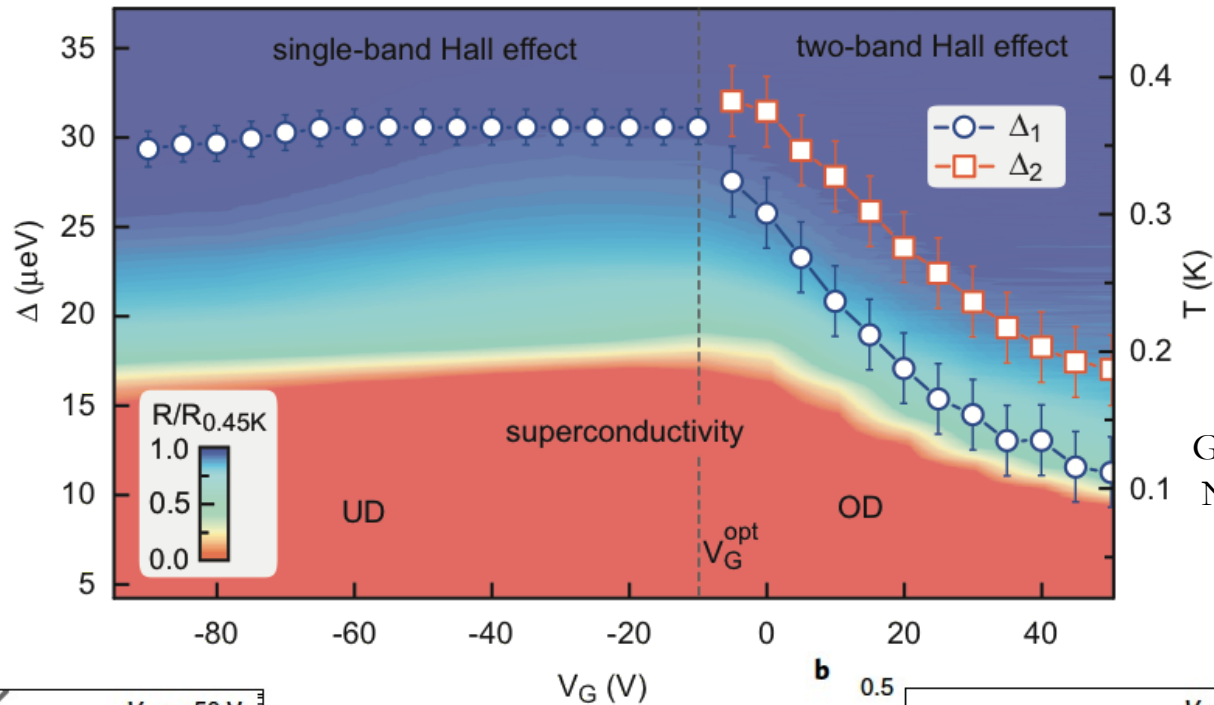
→ gap energies $\Delta_1(T), \Delta_2(T)$

→ Normalised stiffness

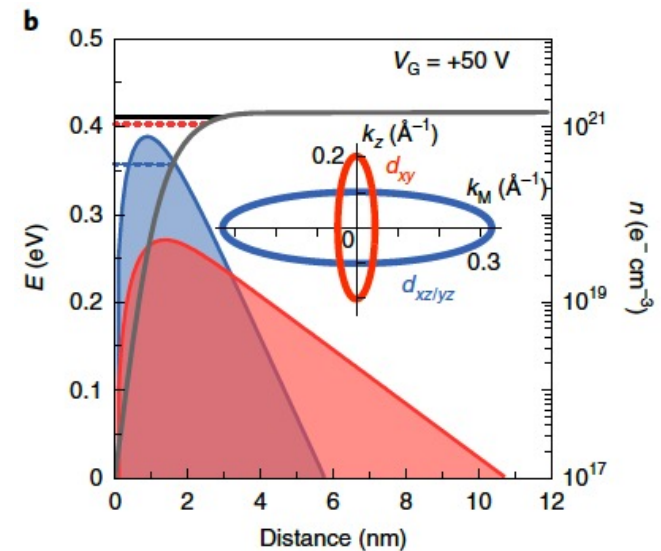
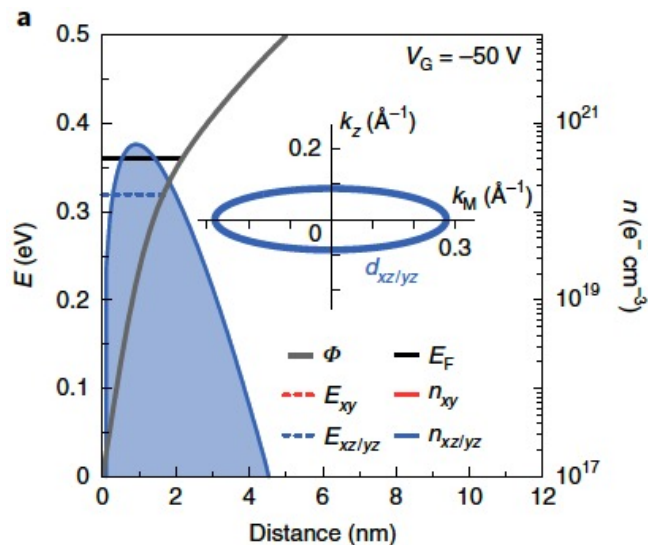
$$J_{s1}(T)/J_{s1}(0), J_{s2}(T)/J_{s2}(0)$$

$$j_s(T) = \gamma j_{s1}(T) + (1 - \gamma) j_{s2}(T)$$

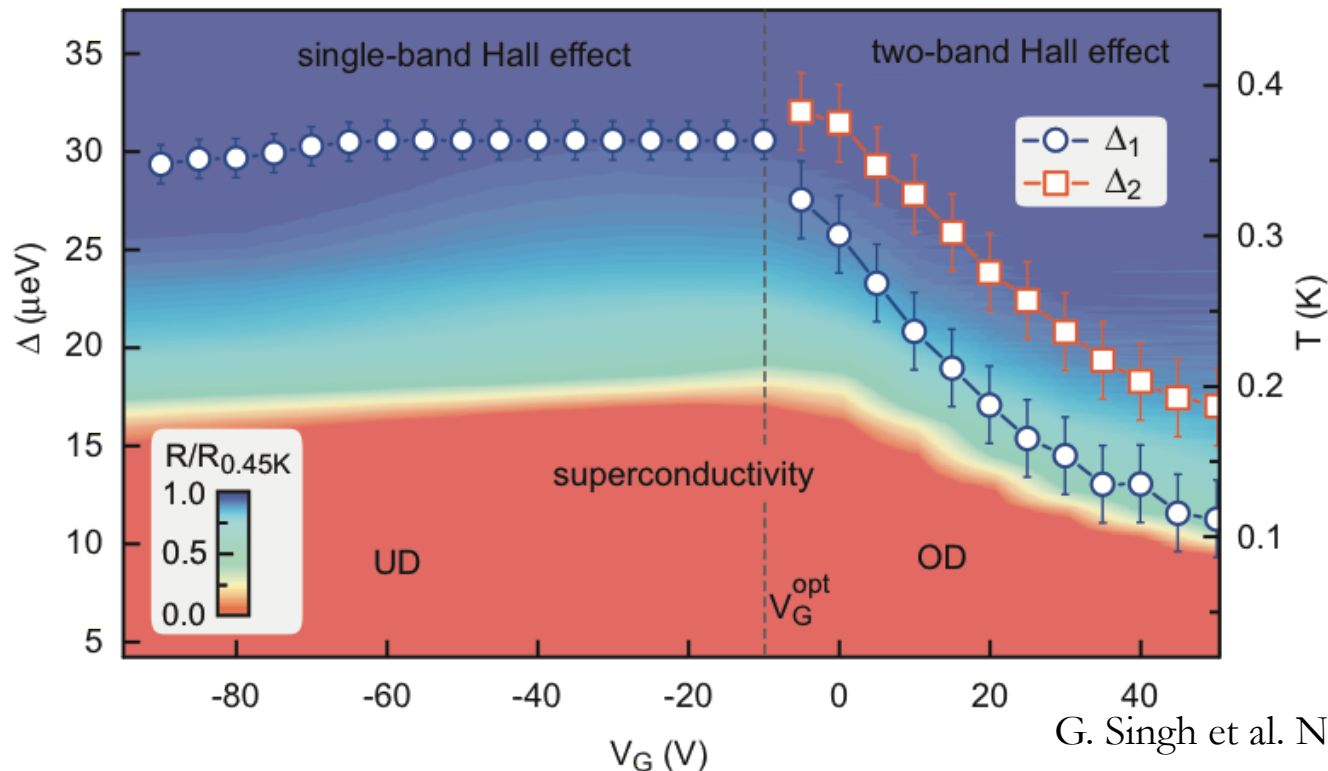
Phase diagram of 110-oriented interfaces



G. Singh et al.
Nat. Mat. (2019)



Phase diagram of 110-oriented interfaces



G. Singh et al. Nat. Mat. (2019)

✧ Relative sign of the two superconducting order parameters (gaps)

➡ $s_{\mp}$ -wave (attractive $\lambda_{12} > 0$) or $s_{\pm}$ - wave (repulsive $\lambda_{12} < 0$) ?

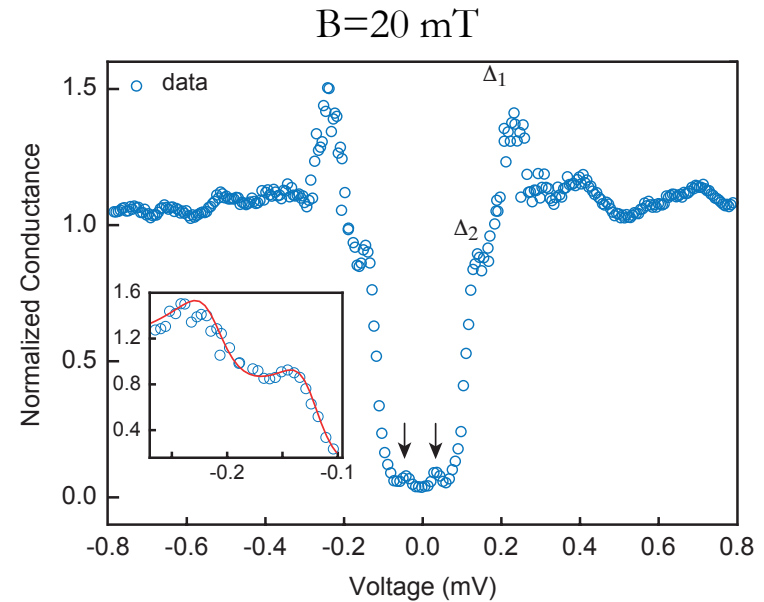
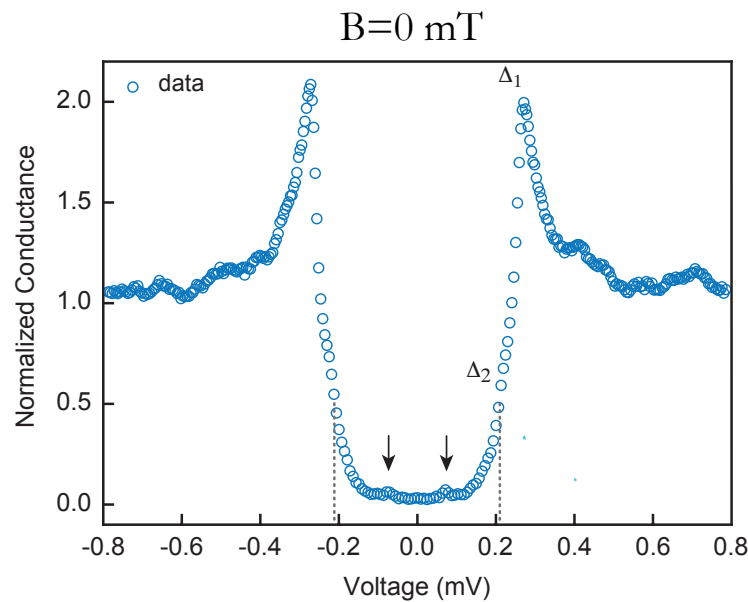
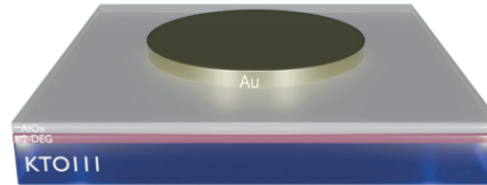
FeSe ➡ Hanaguri et al Science (2010), Sprau et al Science (2017)

➡ $s_{\pm}$ -wave could explain the decrease of T_c in the overdoped regime

Trevisan et al. PRL (2018)

Two-gap Superconductivity in (111)-KTaO₃ 2DEGs

✧ Effect of a Magnetic field



➡ Shoulders evolve into clear quasiparticle peaks

➡ Two-gap superconductivity : Δ_1 , Δ_2

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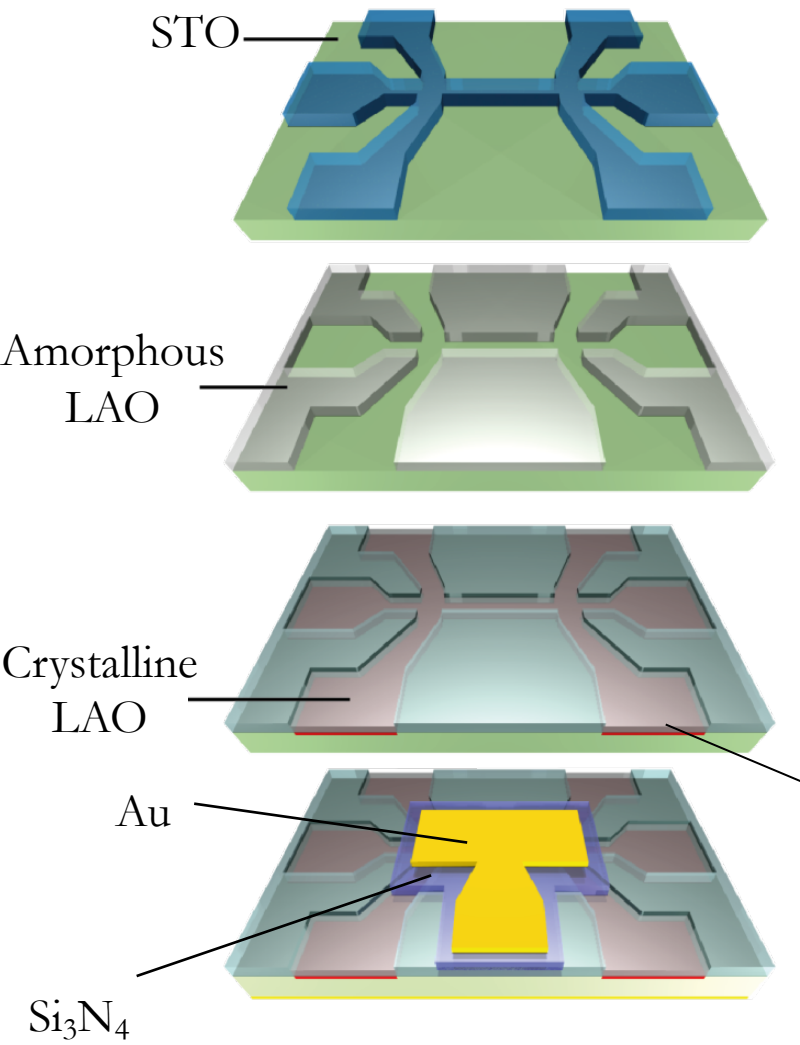
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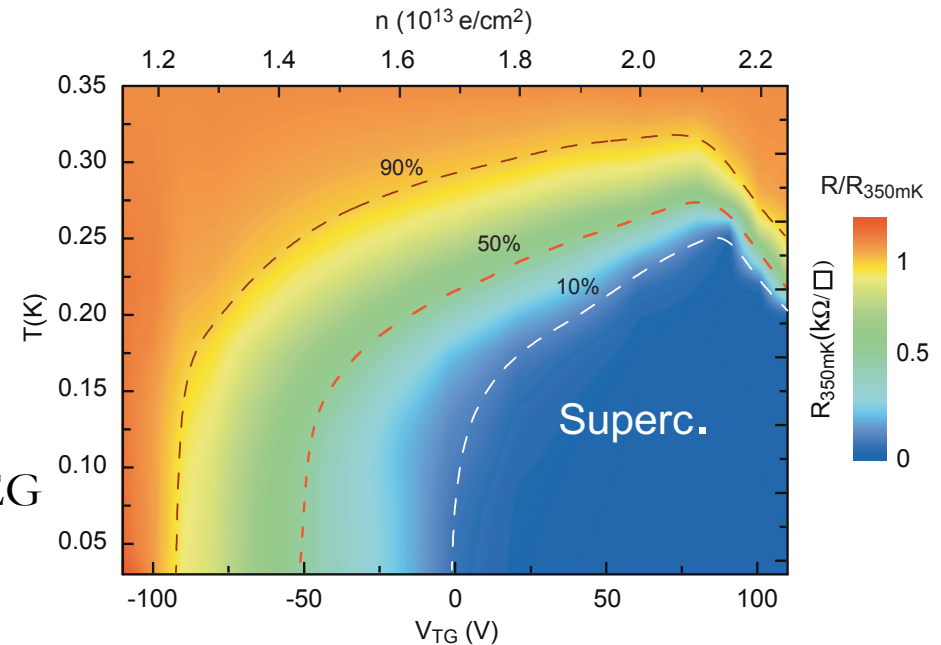
Perspectives on nanodevices

Field-effect devices in $\text{LaAlO}_3/\text{SrTiO}_3$



➔ Amorphous LaAlO_3 template method

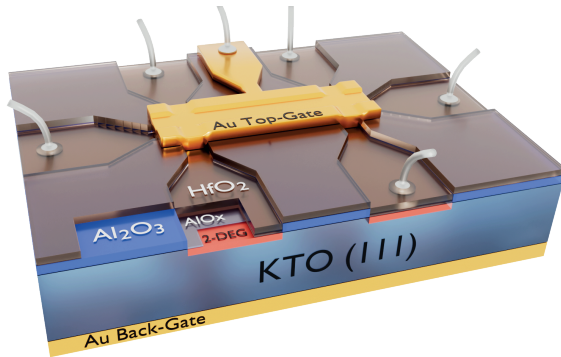
Stornaiuolo et al Appl. Phys. Lett. 101, 222601 (2012)



S. Hurand et al Sci. Rep. 5, 1275 (2015) & APL 108, 052602 (2016)

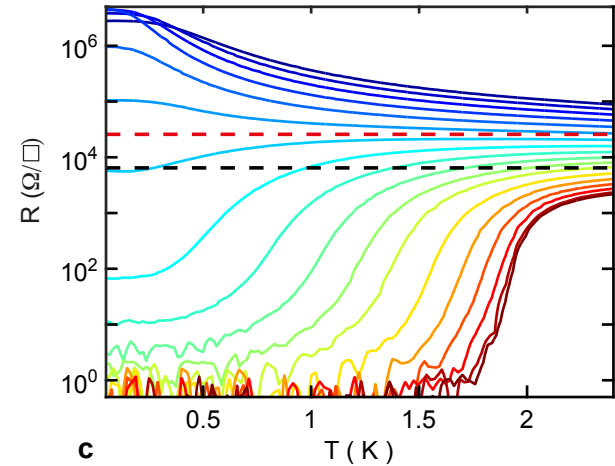
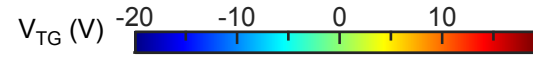
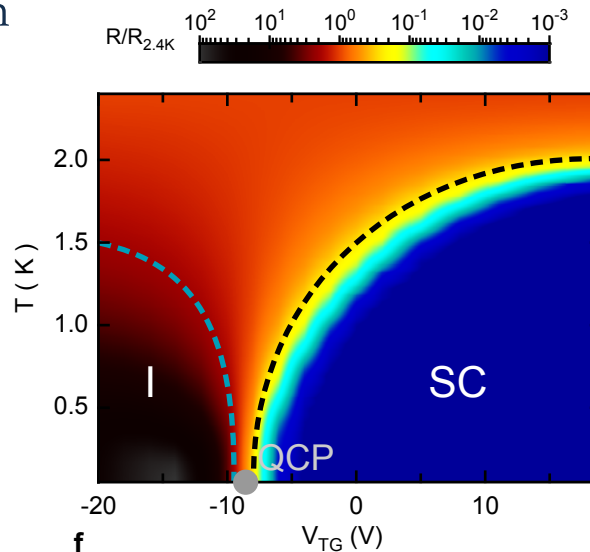
Field-effect devices in $\text{AlO}_x/\text{KTaO}_3$

✧ Top-gate devices



ESPCI and LAF, CNRS-Thales

✧ Phase diagram

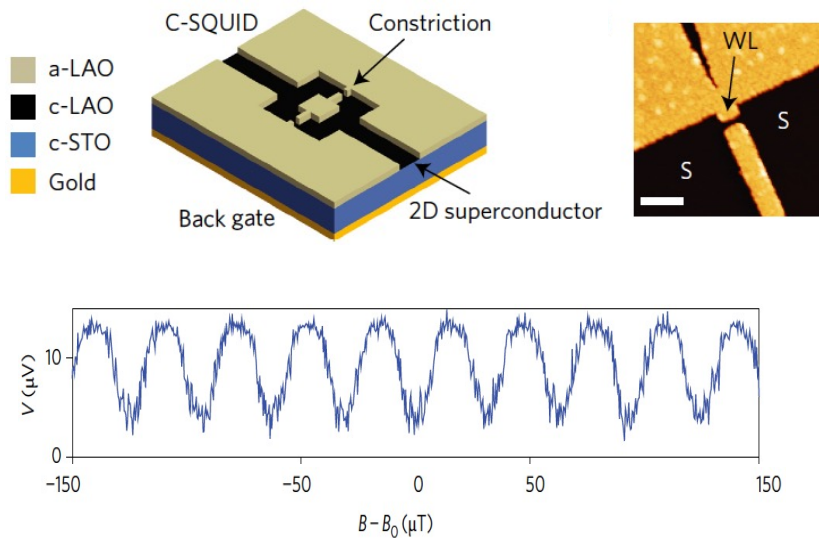


➡ Superconductor-Insulator Transition

➡ Quantum Critical Point at $T=0$

LaAlO₃/SrTiO₃ 2DEGs : a new platform for nanoelectronics ?

Josephson junctions and SQUIDs

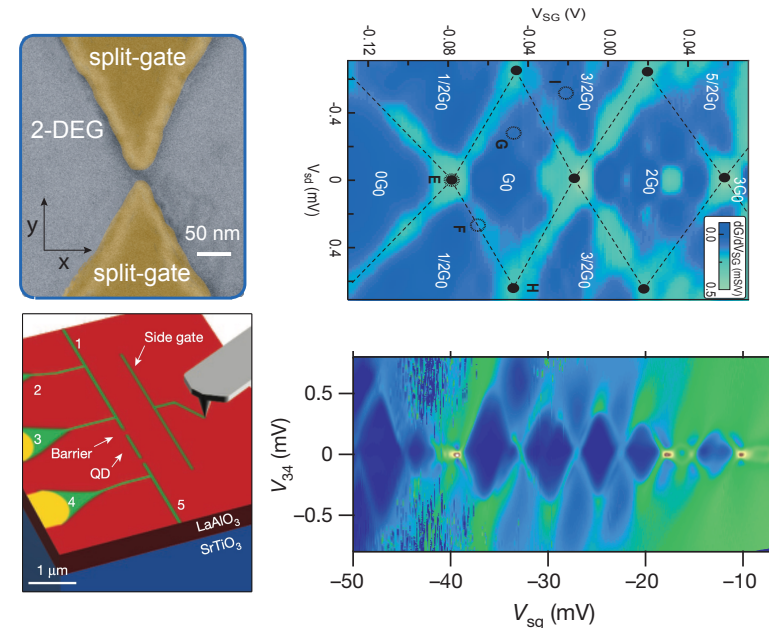


S. Goswami et al. Nat Nanotech. (2016)

D. Stornaiuolo PRB 95, 140502(R) (2017)

G. Singh et al. Npj Quantum Mater. 7, 2 (2022)

Quantum Point Contact and Q-DOT



A. Jouan et al. Nature Elec. 3, 201 (2020)

G. Cheng et al. Nature, 521, 196 (2015)

A. V. Bjørliig Phys. Rev. Mat. 4, 122001(R) (2020)

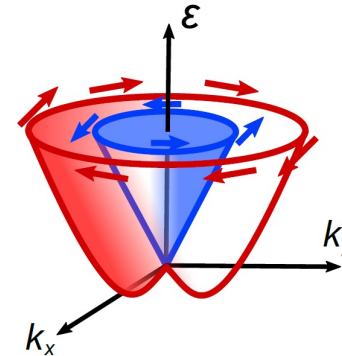
➡ Nanodevices can be made but superconductivity is very fragile (low T_c), which hampers future developments towards nanodevices

Rashba spin-orbit coupling in $\text{LaAlO}_3/\text{SrTiO}_3$

✧ Rashba spin-orbit coupling

➡ Breaking of translational symmetry

$$\hat{H}_R = \alpha(\vec{\sigma} \wedge \vec{k}) \cdot \vec{z}$$



✧ Experimental evidence of Rashba spin-orbit coupling

➡ Magnetoconductance and weak-localization

A. Caviglia et al Phys. Rev. Lett. (2010)

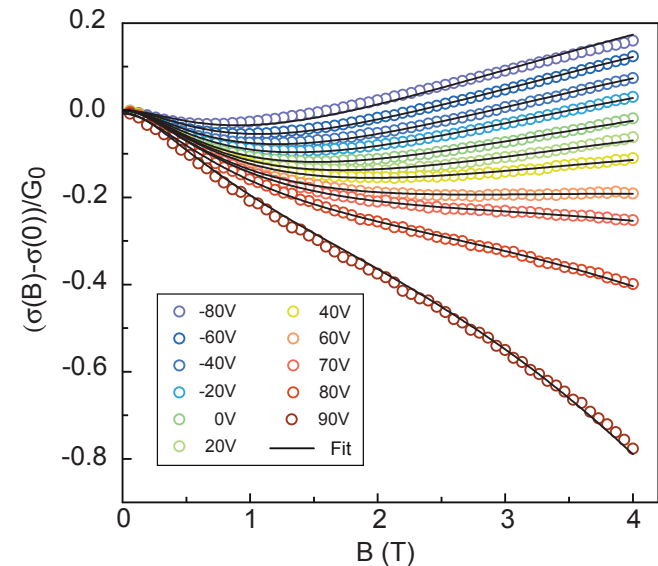
G. Singh et al. Phys. Rev. B (2017)

➡ Spin-orbit relaxation time $\tau_{so} = \frac{\hbar^4}{4\alpha^2 D m^2} \propto \frac{1}{\tau}$

➡ Spin-to-charge interconversion through direct or inverse Edelstein effect

D. C. Vaz et al. Nature Mat. 18, 1187–1193 (2019)

D. C. Vaz et al. Phys. Rev. Mat. 4, 071001(R) (2020)

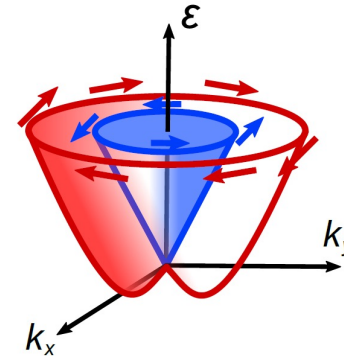


Rashba spin-orbit coupling in $\text{LaAlO}_3/\text{SrTiO}_3$

✧ Rashba spin-orbit coupling

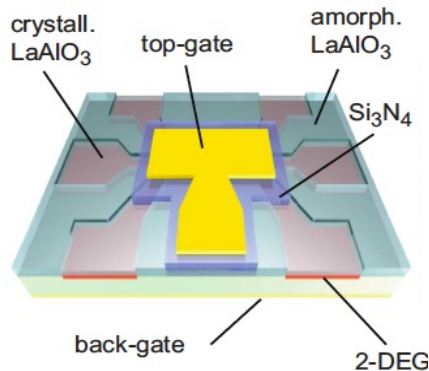
➡ Breaking of translational symmetry

$$\hat{H}_R = \alpha(\vec{\sigma} \wedge \vec{k}) \cdot \vec{z}$$

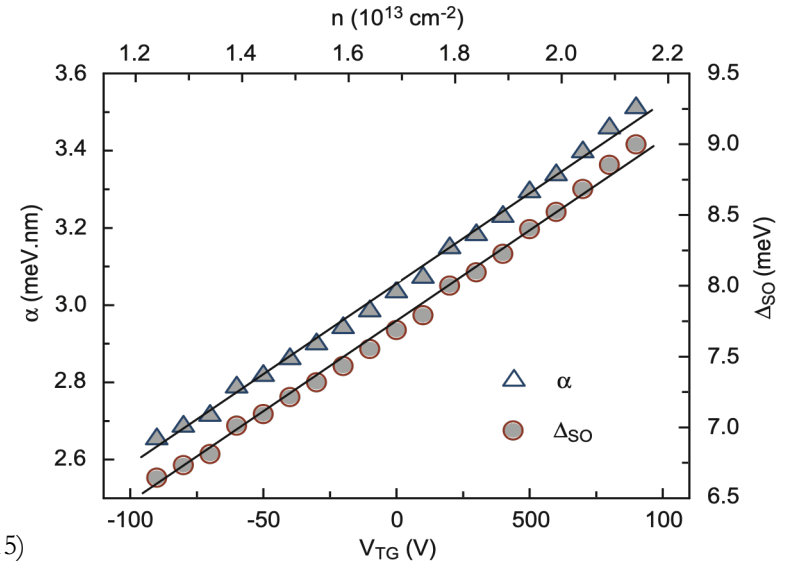


✧ Experimental evidence of Rashba spin-orbit coupling

➡ gate-tunable Rashba SOC



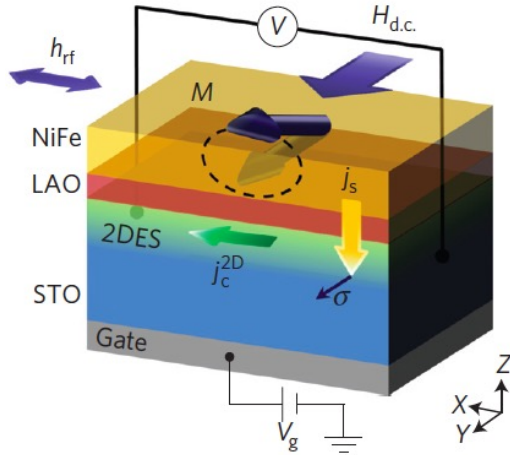
S. Hurand et al. Sci. Rep. 5, 12751 (2015)



Towards spintronics devices

✧ Spin to charge conversion with Inverse Edelstein effect

UMR Thales-CNRS (M. Bibes, A. Barthélémy), CEA (L. Villa)



E. Lesne et al. Nat. Mat. 15, 1261 (2016)

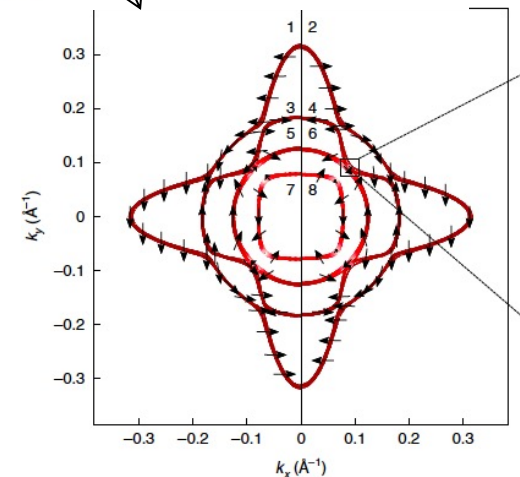
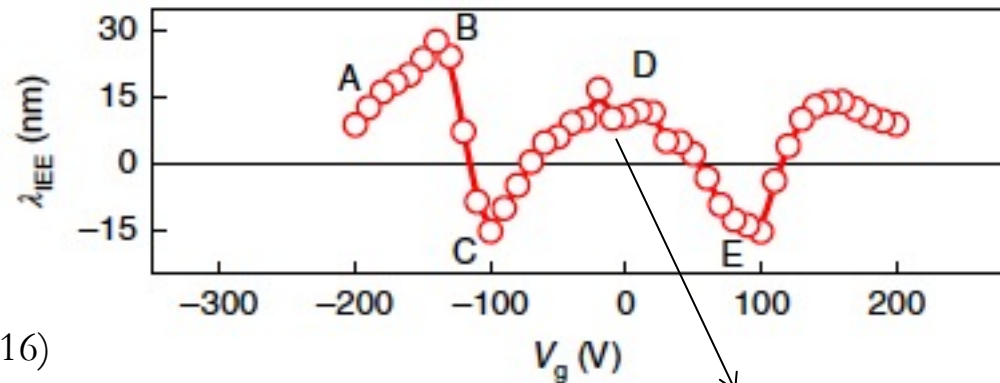
Conversion efficiency :

$$\lambda_{IEE} = \frac{j_c^{2D}}{j_s} = \frac{\alpha_R \tau}{\hbar} > 25 \text{ nm}$$

➡ larger than in other system (TI, Ag111...)

D. Vaz et al. Nat. Mat. (2019)

➡ Spin current is converted into a charge current



Towards topological superconductivity

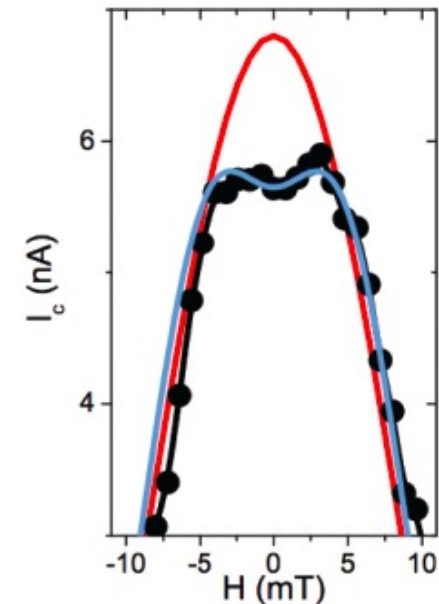
Rashba spin-orbit coupling and superconductivity are the two main ingredients to realize topological superconductivity that accommodates Majorana Zero Energy modes

➡ Possible signatures of unconventional (topological ?) superconductivity

D. Stornaiuolo PRB 95, 140502(R) (2017) G. Singh et al. Npj Quantum Mater. 7, 2 (2022).

➡ Superconductivity in $\text{LaAlO}_3/\text{SrTiO}_3$ is very fragile which hampers future developments towards topological superconductivity

➡ KTaO_3 –based interfaces with higher T_c and strong SOC open new perspectives



Conclusions

Both SrTiO_3 and KTaO_3 are quantum paraelectric materials

A superconducting 2-DEG can be synthesized at the interface with an overlayer, e.g. $\text{LaAlO}_3/\text{SrTiO}_3$, $\text{LaTiO}_3/\text{SrTiO}_3$, $\text{AlO}_x/\text{SrTiO}_3$, $\text{LaAlO}_3/\text{KTaO}_3$, EuO/KTaO_3 , $\text{AlO}_x/\text{KTaO}_3$...

A strong orientational dependence of superconductivity is seen in KTaO_3 -based interfaces, but not in SrTiO_3 based interfaces.

The interfacial quantum well accommodates a very rich band structure built on t_{2g} d-orbitals.

Carrier density can be controlled by electric field effect, leading to a dome shaped superconducting phase diagram.

Superconductivity in oxides interfaces, involves (most likely) several superconducting condensates.

Oxide interfaces display a strong Rashba spin-orbit coupling, controllable by electric field.

Superconducting oxide interfaces form a rich platform for nanoelectronics, including spintronics and topological electronics.