



The Abdus Salam
International Centre for Theoretical Physics



2035-6

Conference on Superconductor-Insulator Transitions

18 - 23 May 2009

Electric Field Tuning of Superconductivity at the LaAlO₃/SrTiO₃ Interface

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Electric Field Tuning of Superconductivity at the $\text{LaAlO}_3/\text{SrTiO}_3$ Interface

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University of Geneva



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Outline

Conducting and superconducting electron gas

Dimensionality of the SC layer

Berezinskii-Kosterlitz-Thouless transition

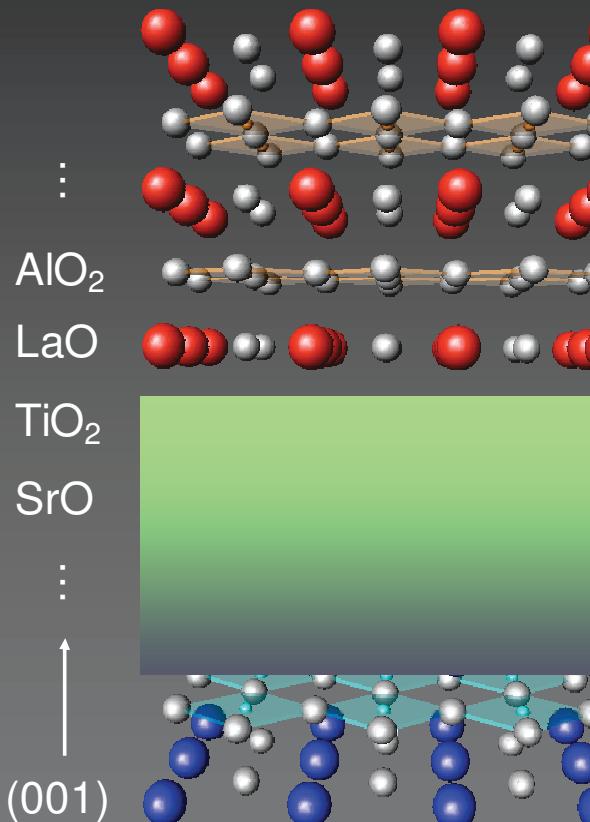
Modulation of the SC

S-I transition and scaling analysis

Nature of the localized state



q2D electron gas



LaAlO₃:

band insulator

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

SrTiO₃:

band insulator

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

quantum paraelectric

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



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A High Mobility Electron Gas at the Interface

A high-mobility electron gas at the LaAlO₃/SrTiO₃ heterointerface

A. Ohtomo^{1,2,3} & H. Y. Hwang^{1,3,4}

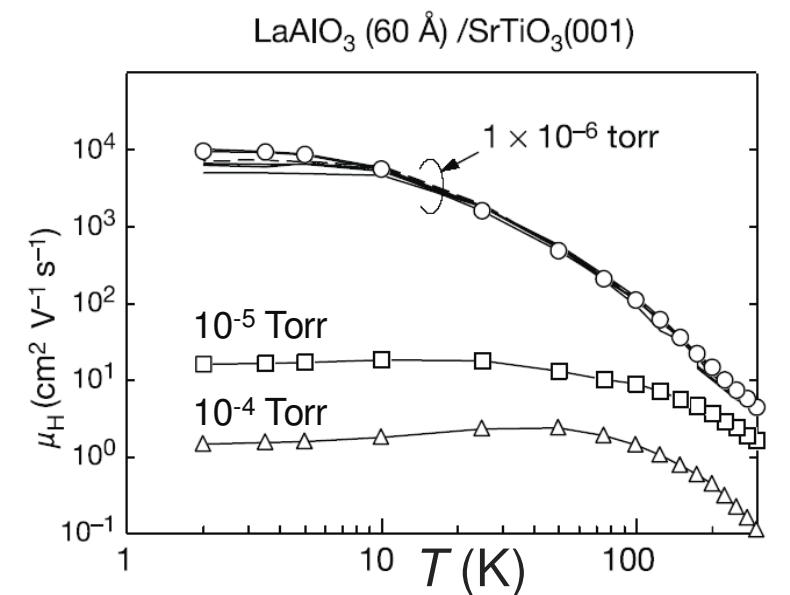
¹Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974, USA

²Institute for Materials Research, Tohoku University, Sendai, 980-8577, Japan

³Japan Science and Technology Agency, Kawaguchi, 332-0012, Japan

⁴Department of Advanced Materials Science, University of Tokyo, Kashiwa, Chiba, 277-8651, Japan

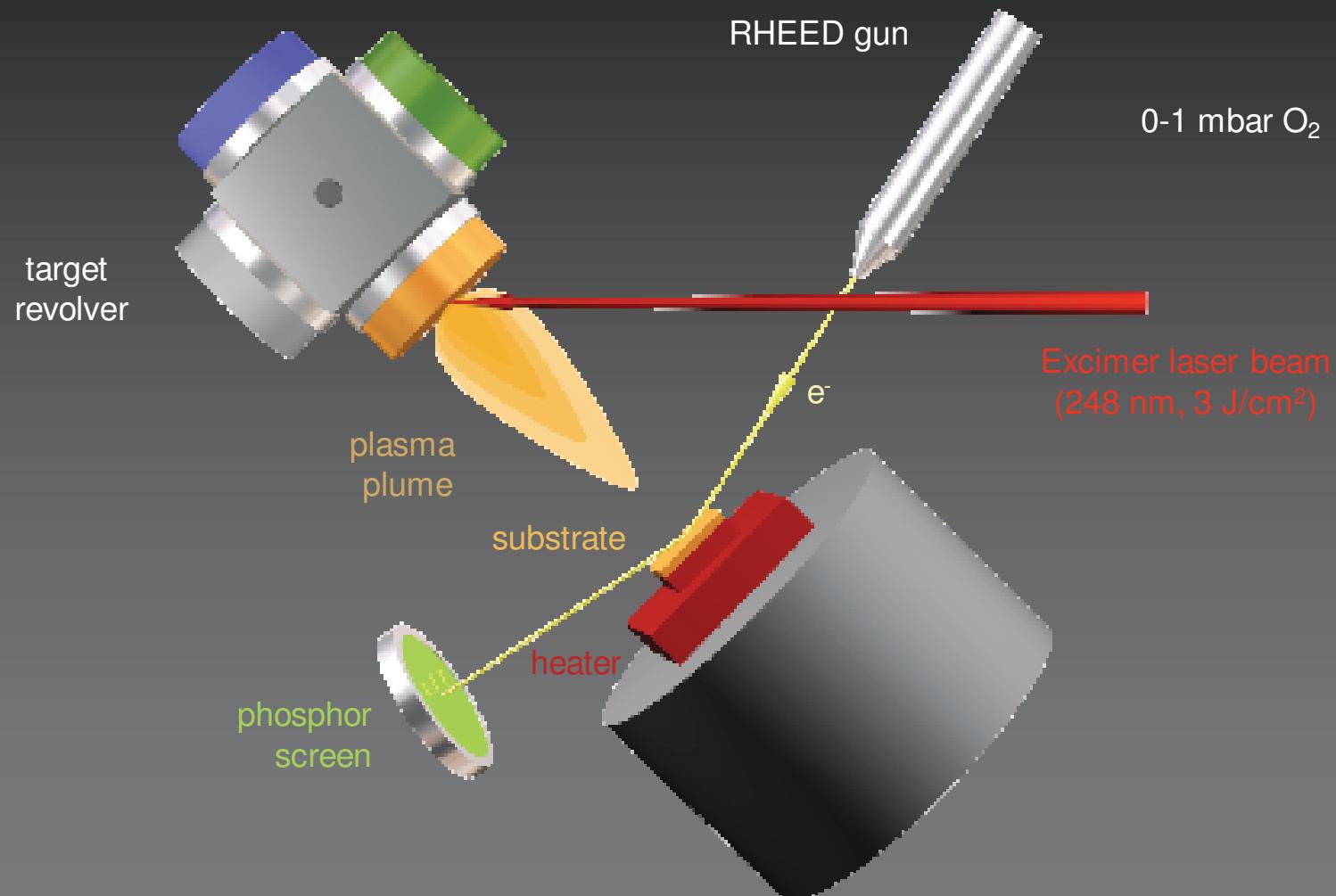
A. Ohtomo, H. Hwang, *Nature* **427**, 423 (2004).
N. Nakagawa *et al.*, *Nature Materials* **5**, 204 (2006).



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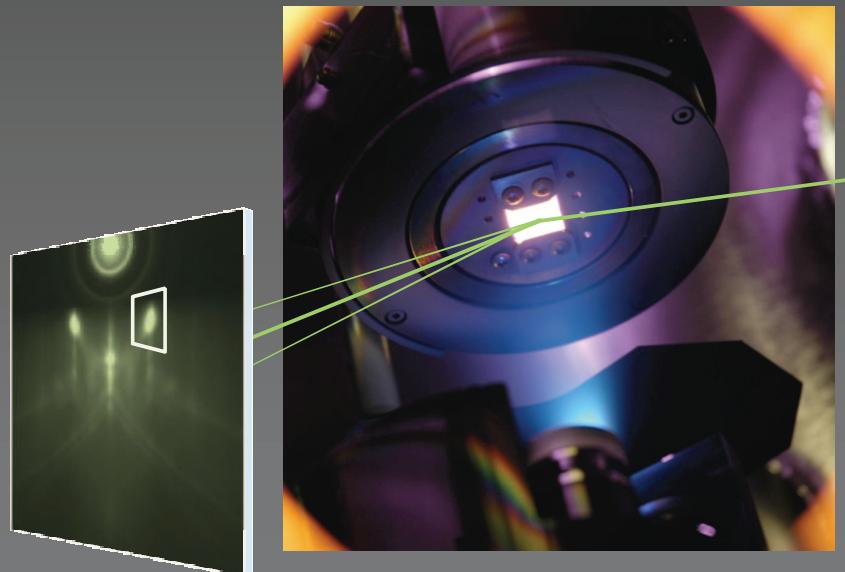
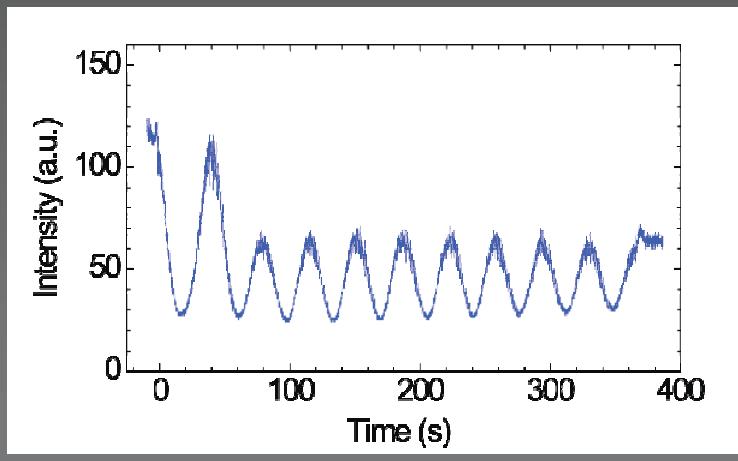


Epitaxial growth by PLD

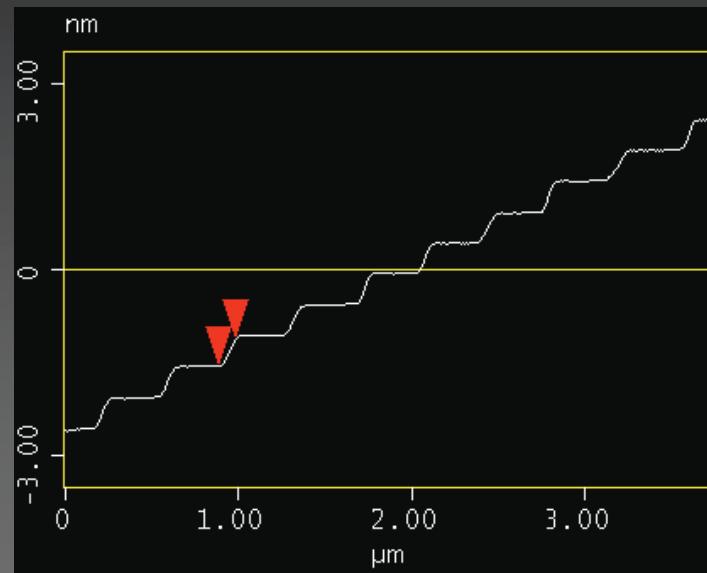
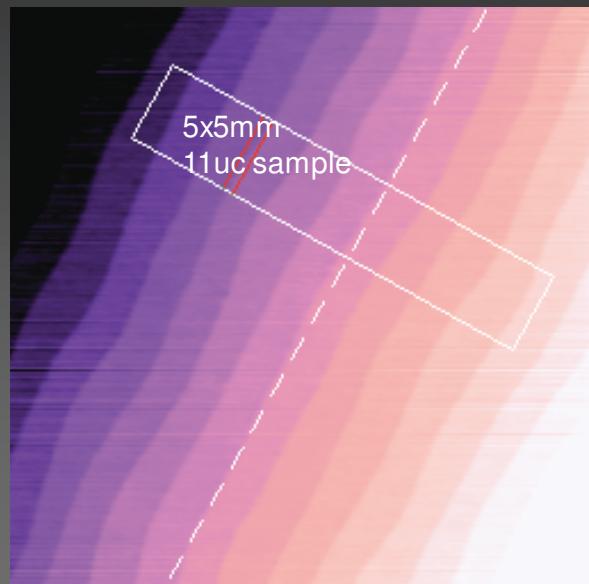


Epitaxial growth by PLD

Layer-by-layer growth
 $T = 800^\circ\text{C}$
 $P \text{ O}_2 = 1 \cdot 10^{-4} \text{ Torr}$
Fluence = 0.6 J/cm^2
Frequency = 1Hz
Post annealing @ 200 mbar O₂



Surface Topography



step height: 0.4
nm

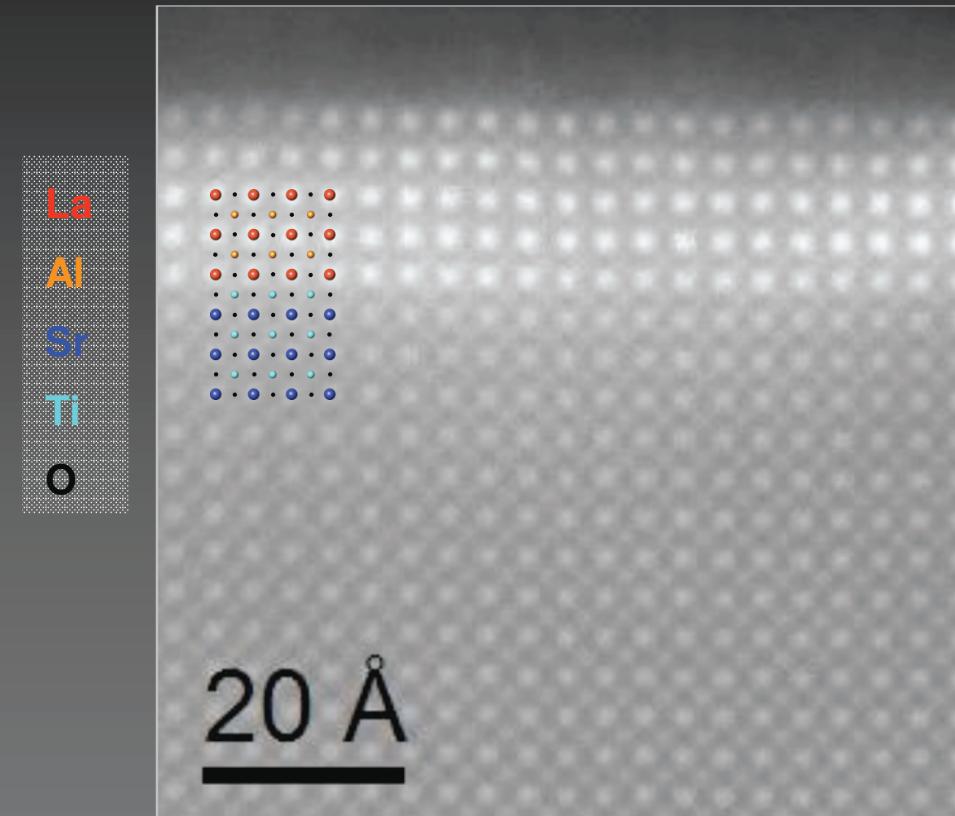


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STEM Cross Section

LAADF



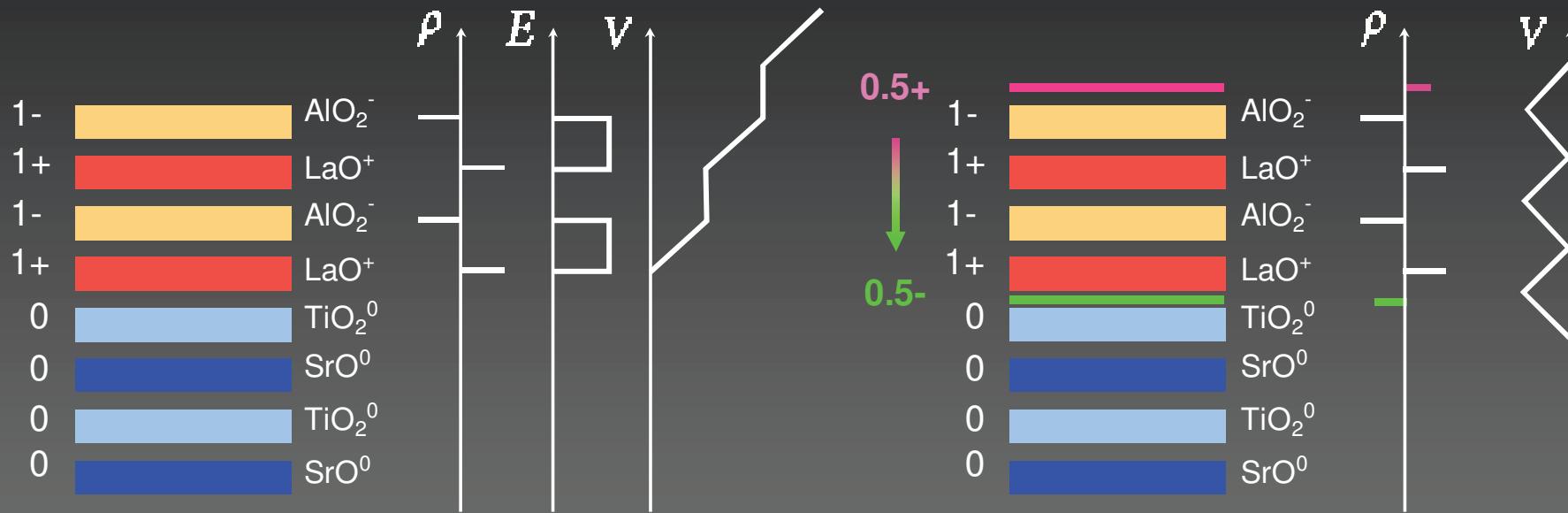
L. Fitting-Kourkoutis, D.A. Muller (Cornell)



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Polar discontinuity



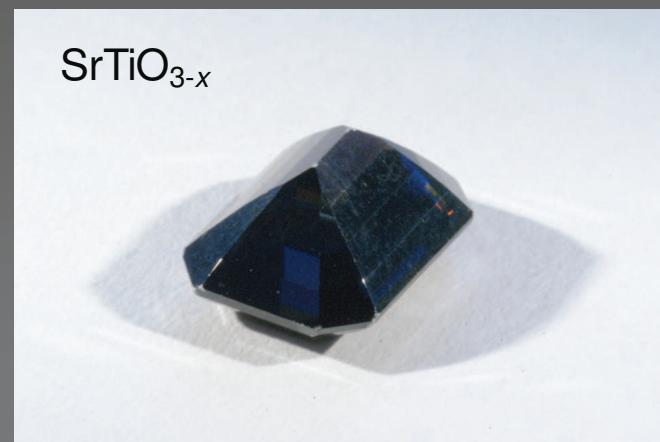
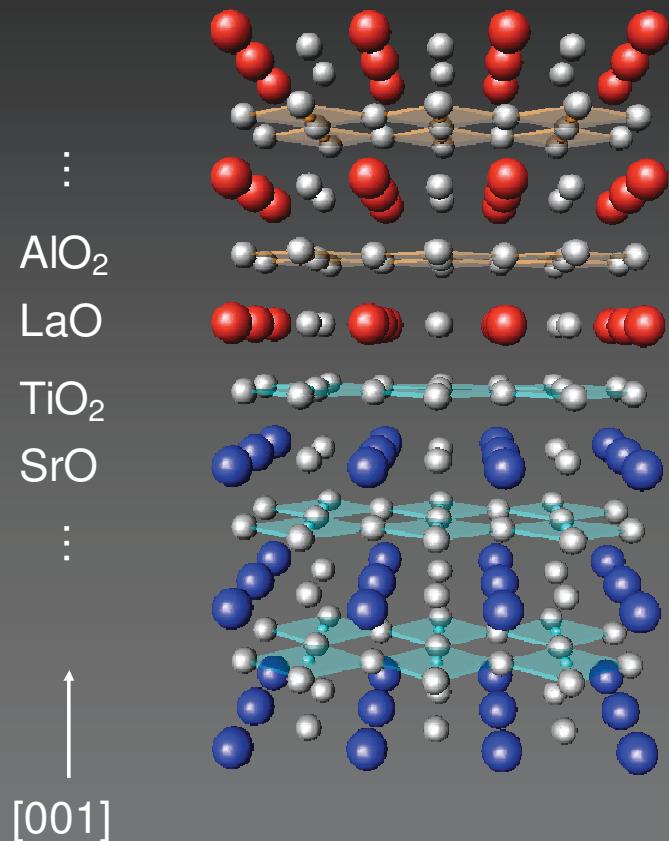
N. Nakagawa *et al.*, Nature Materials (2006)



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Oxygen vacancies - La/Sr intermix

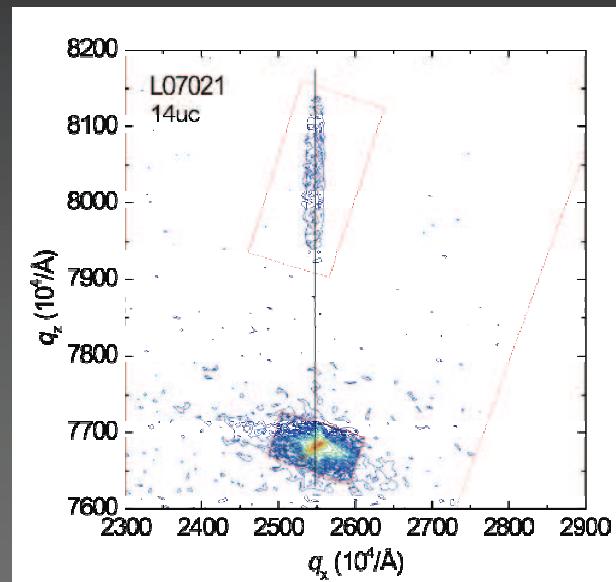
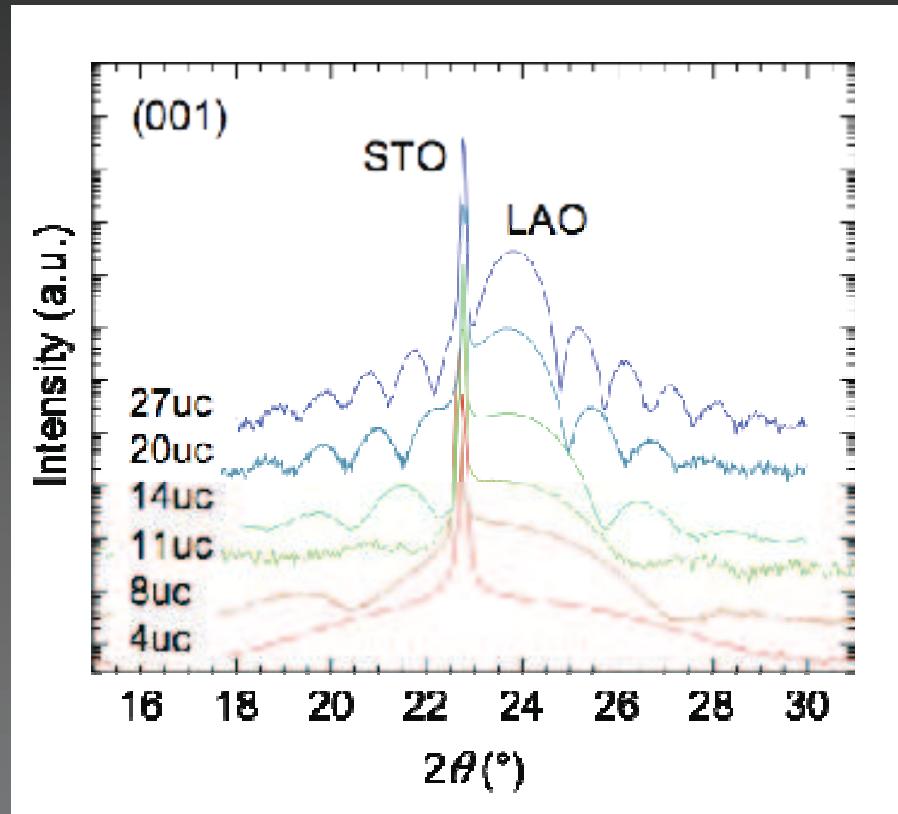


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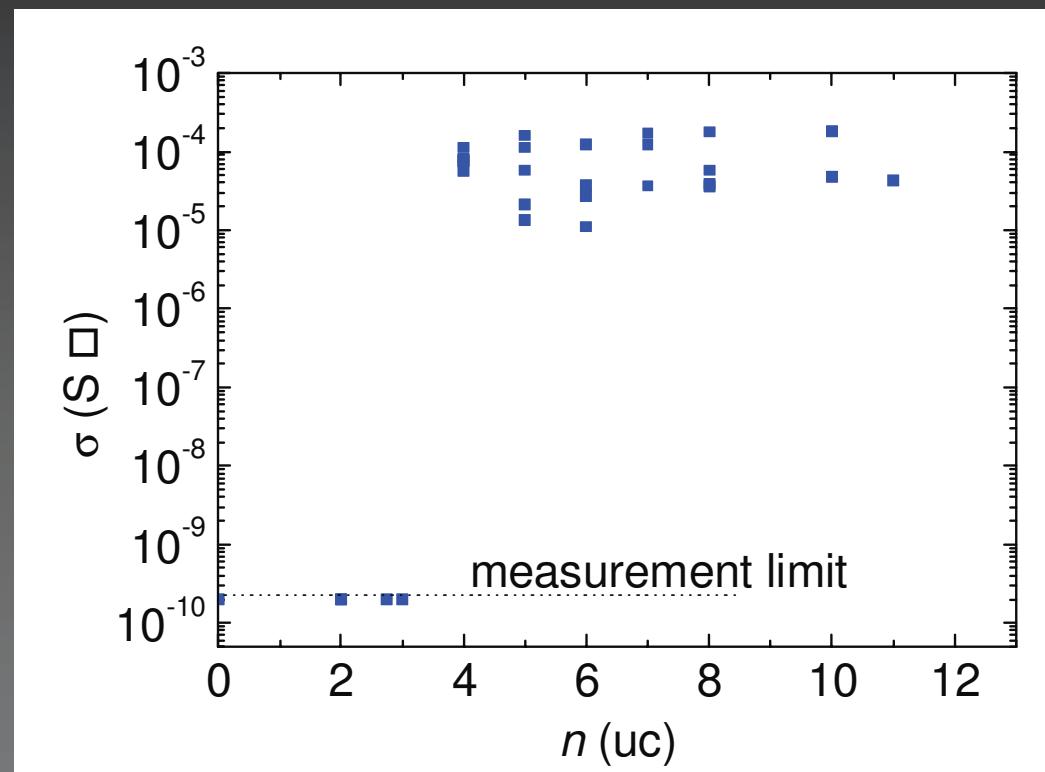
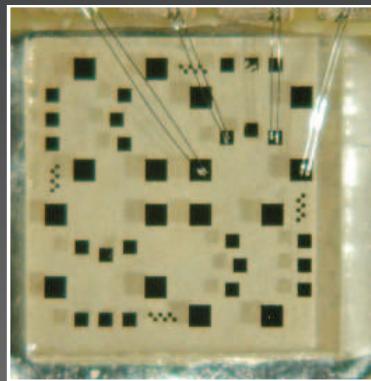
J. Mannhart, D.G. Schlom, Nature N&V 430, 620 (2004)



Role of the LaAlO₃ thickness

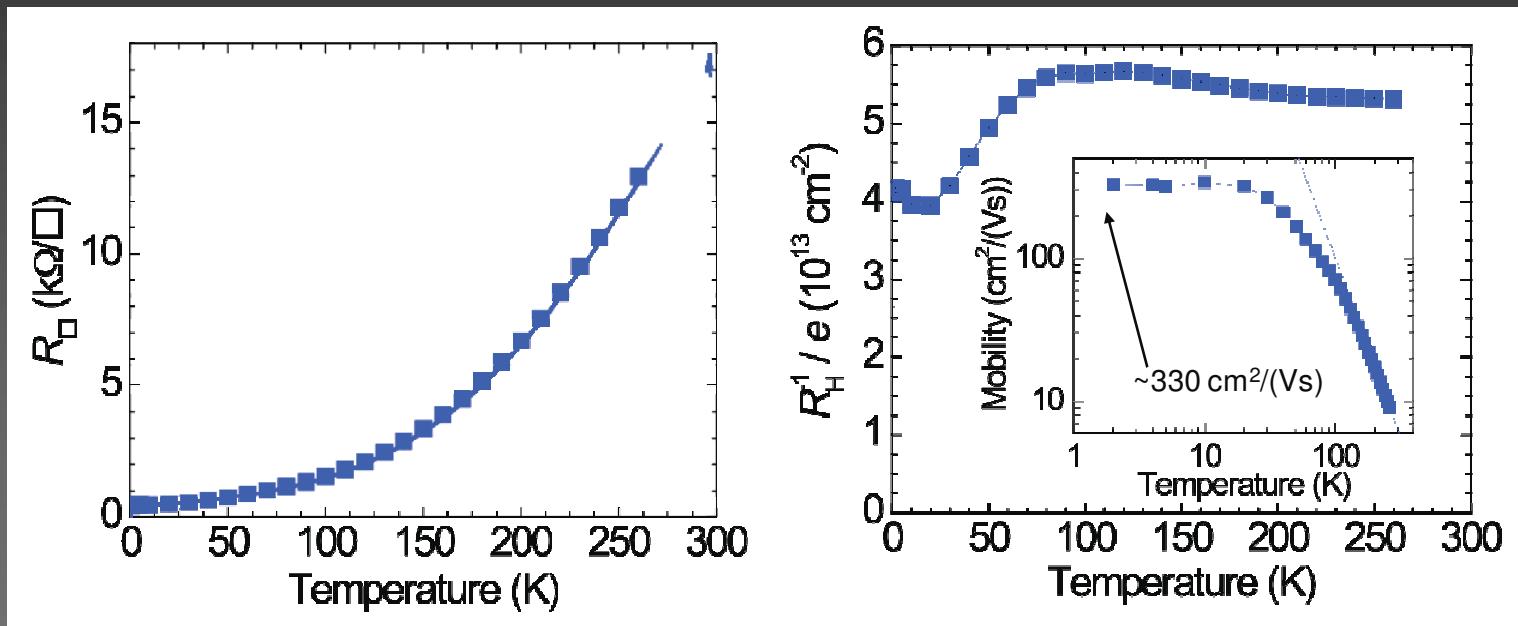


Role of the LaAlO₃ thickness



Transport properties

8 u.c. LaAlO₃ film

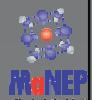


Hall measurements: sheet carrier density $n_{2D} \sim 2\text{-}10 10^{13} \text{ cm}^{-2}$

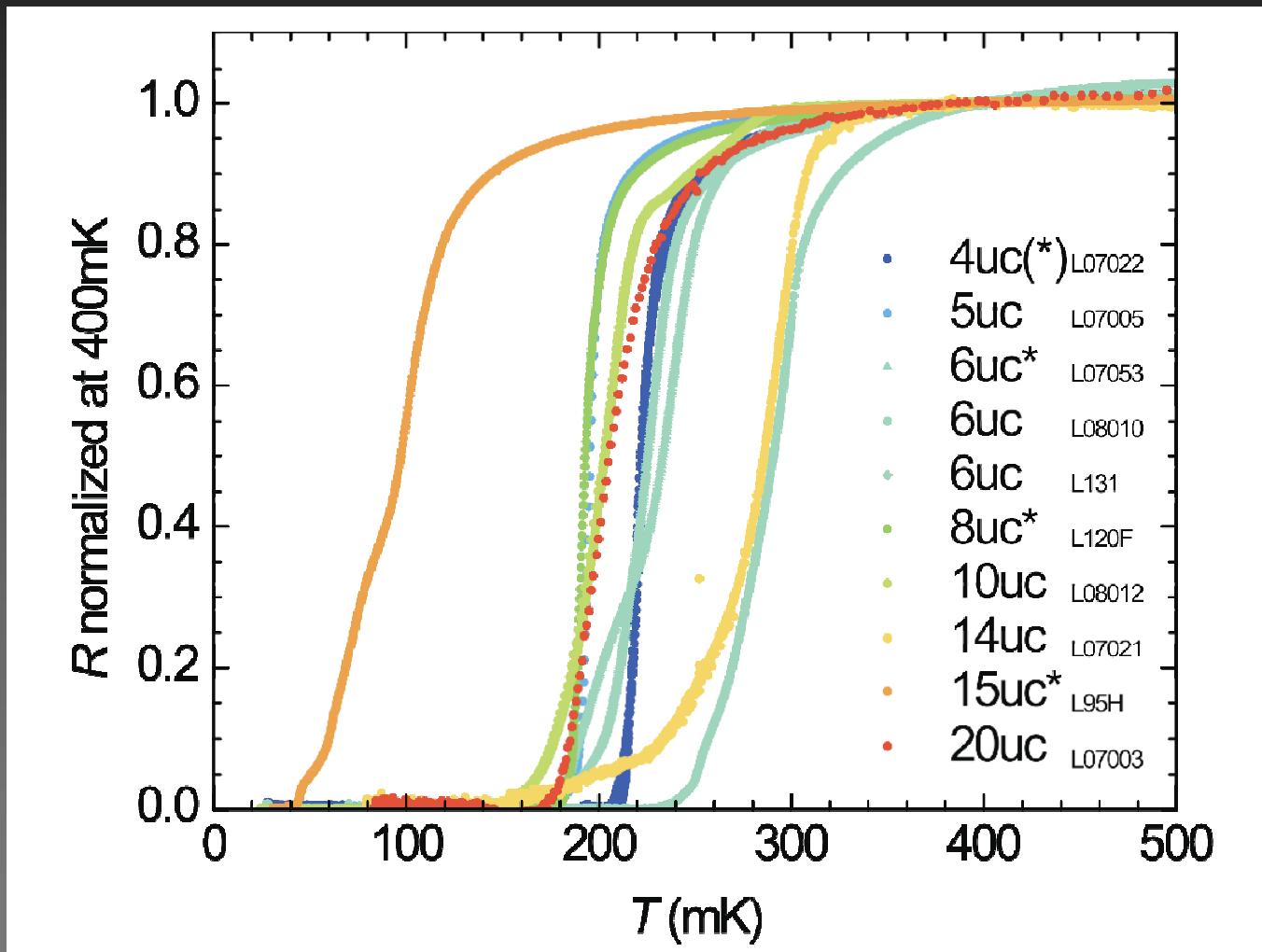


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S. Gariglio *et al.*, J. Phys.: Condens. Matter **21**, 164213 (2009)



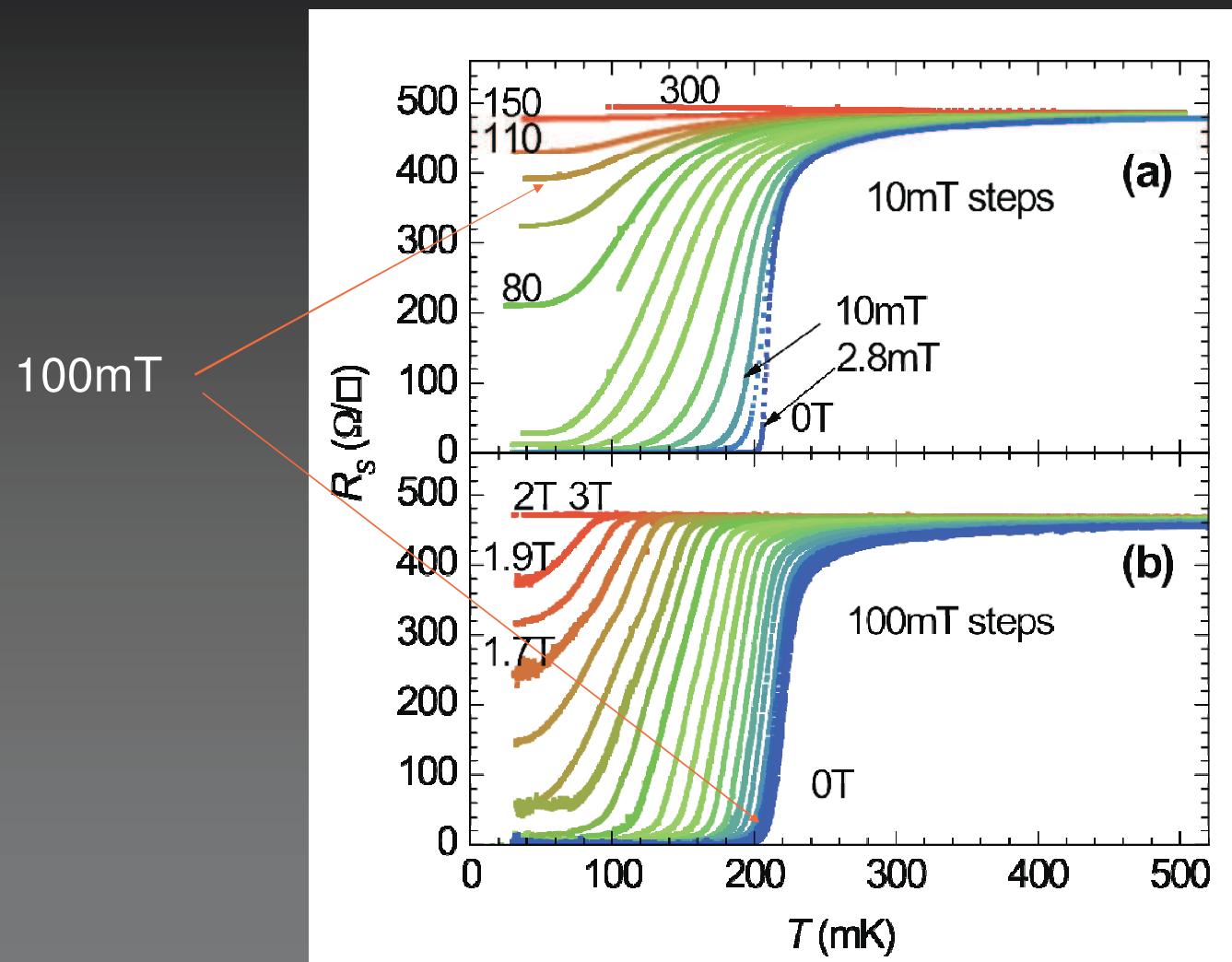
Superconductivity



Anisotropy of transport properties in magnetic fields



Transport anisotropy

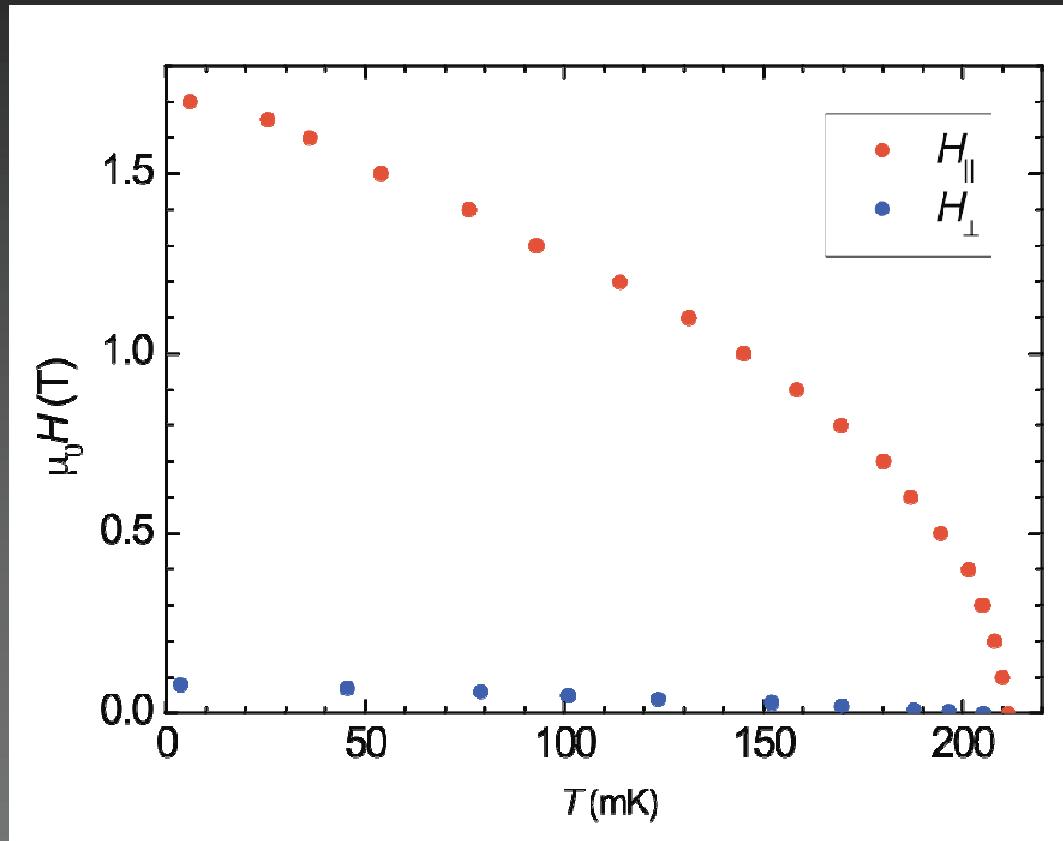


$H \perp$

$H \parallel$



SC Thickness



$$\mu_0 H_{\perp}(T) = \frac{\Phi_0}{2\pi\xi_{\parallel}^2(T)}$$

$$\xi_{\parallel}(T=0) \sim 60 \text{ nm}$$

$$\mu_0 H_{\parallel}(T) = \frac{\sqrt{3}\Phi_0}{\pi d \xi_{\parallel}(T)}$$

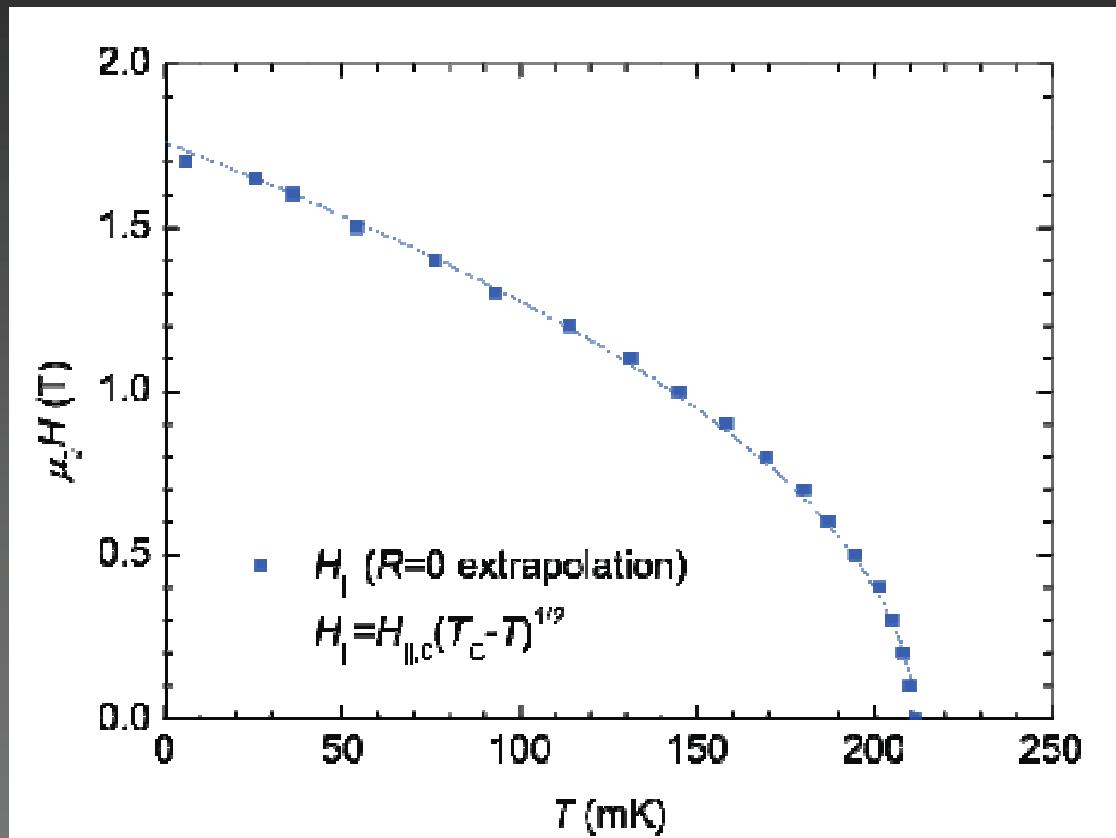
$d \approx 10 \text{ nm}$



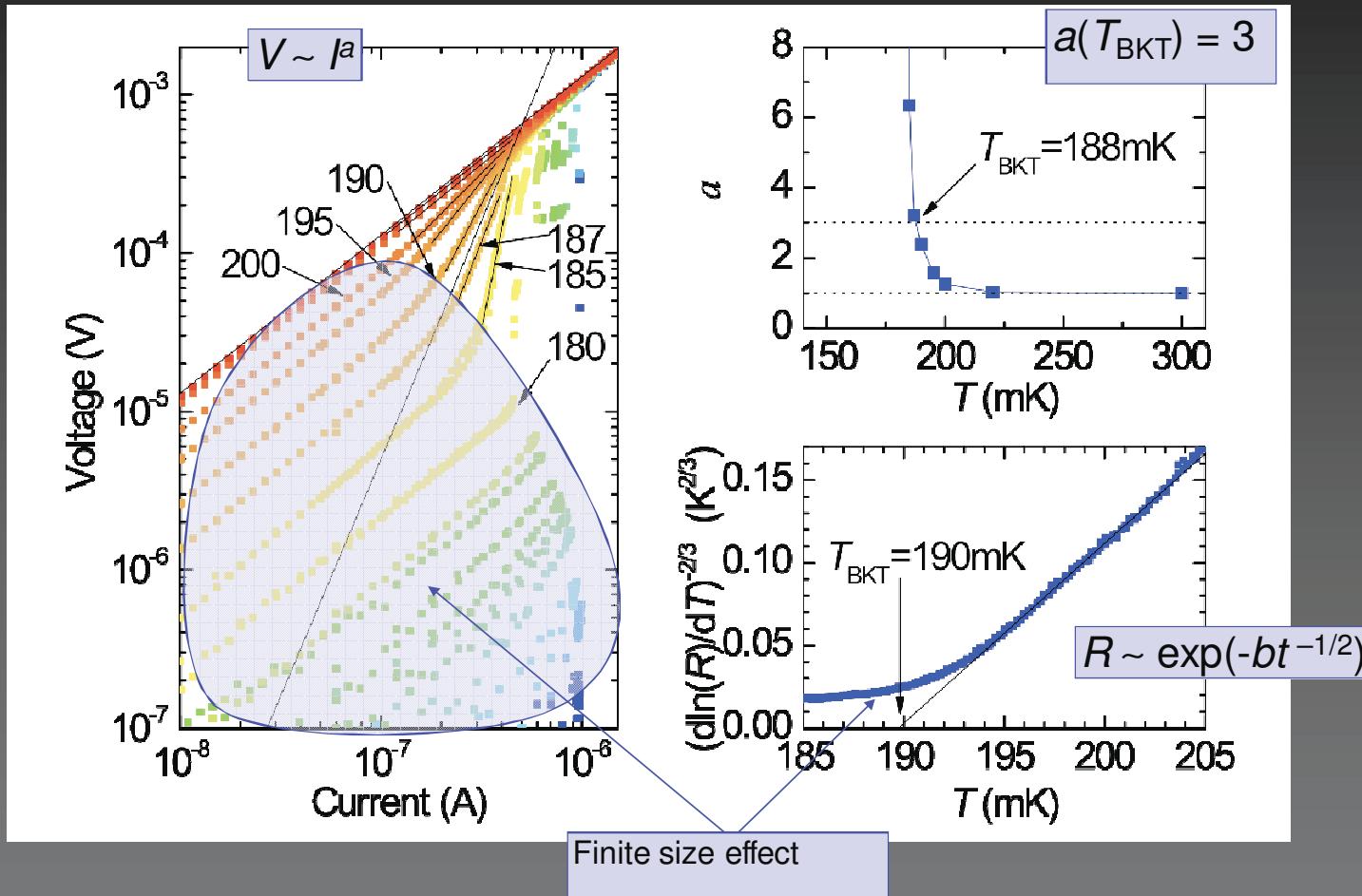
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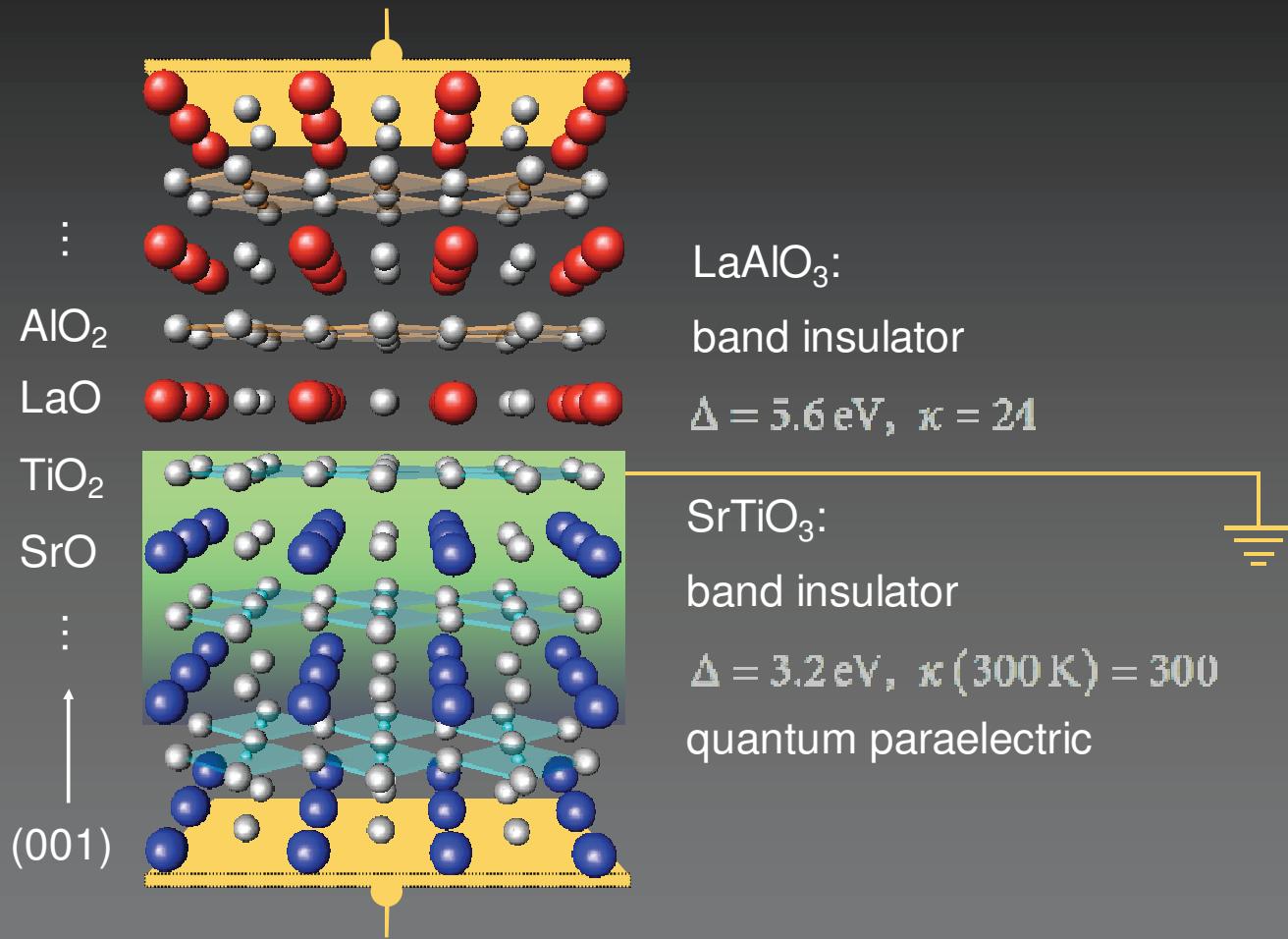
SC Thickness



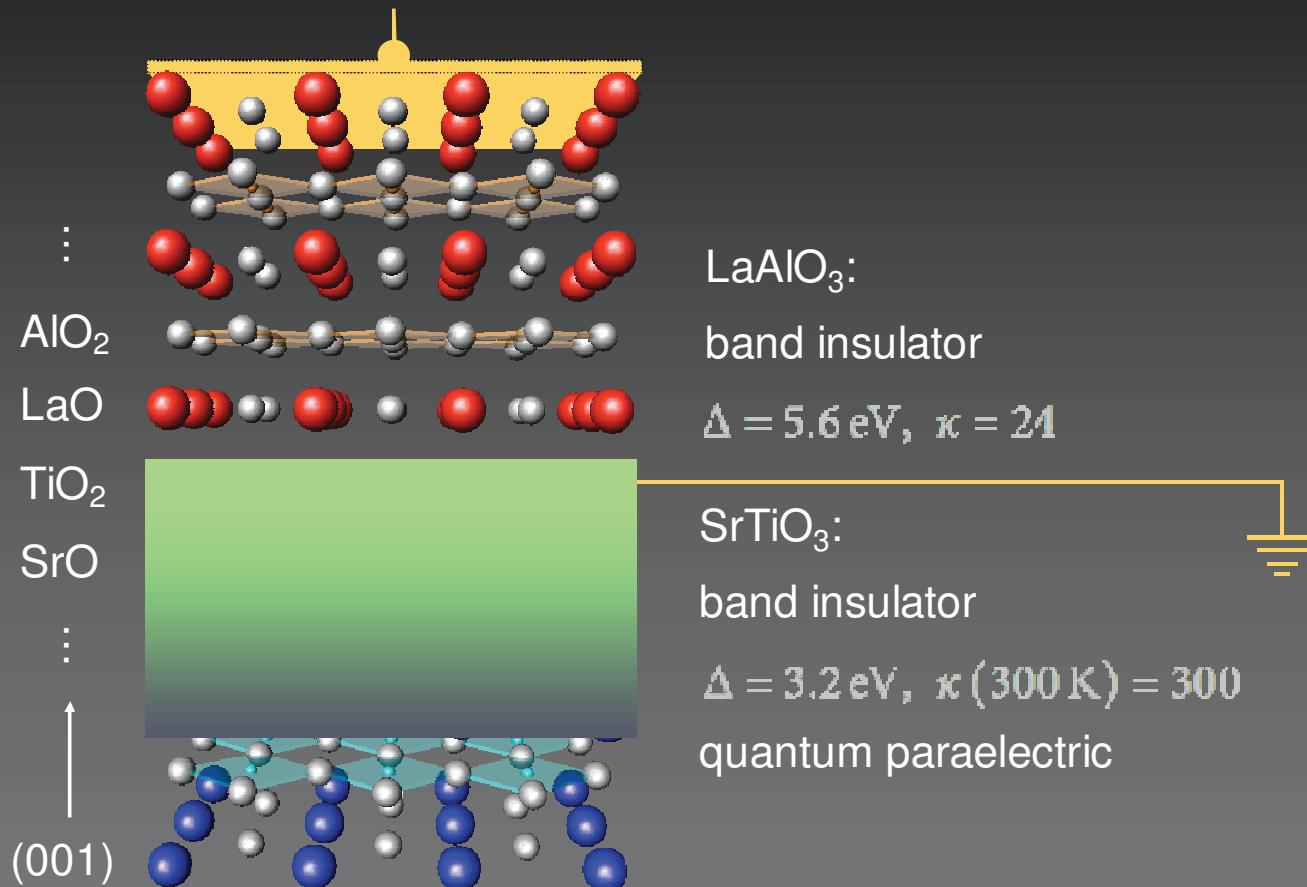
2D Superconductivity



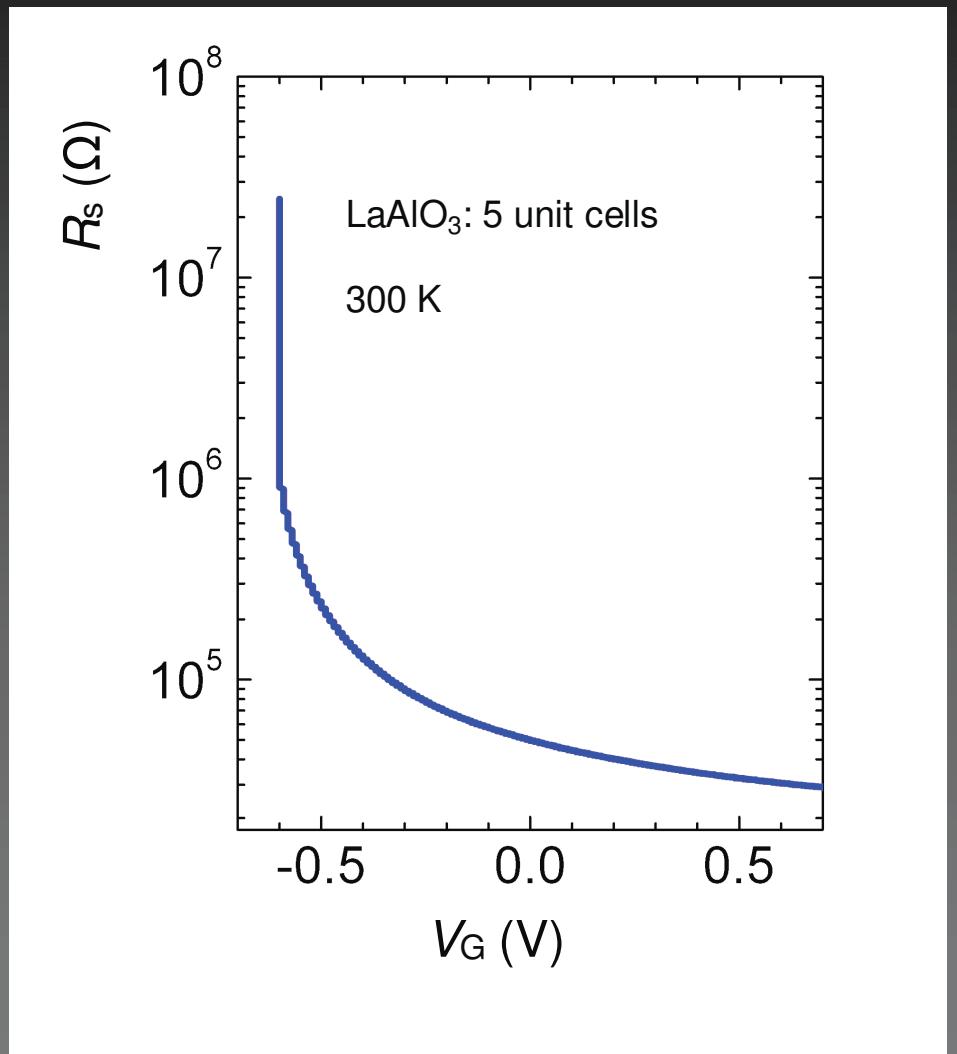
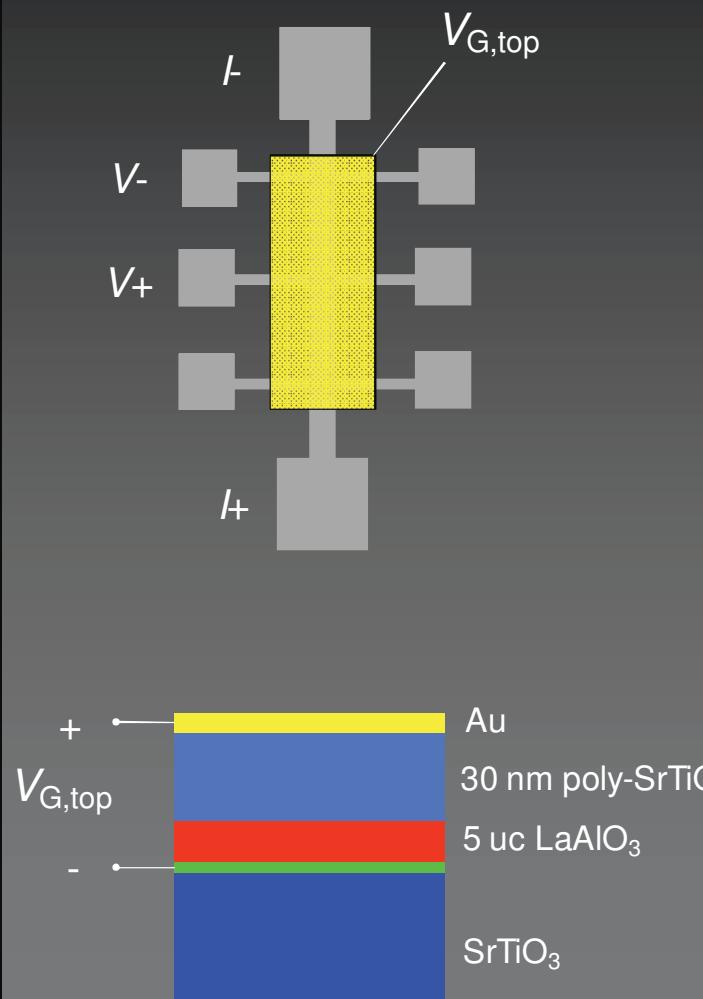
Field effect experiments



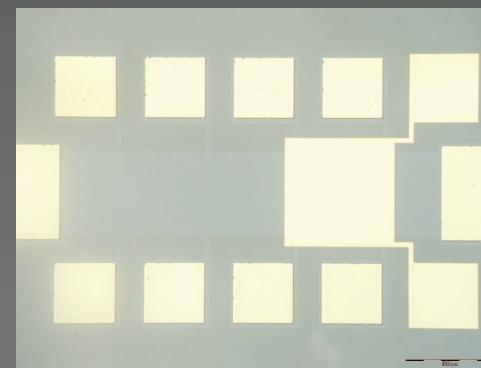
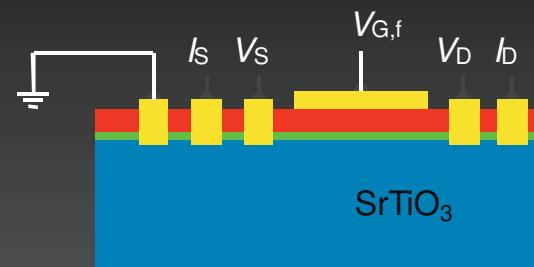
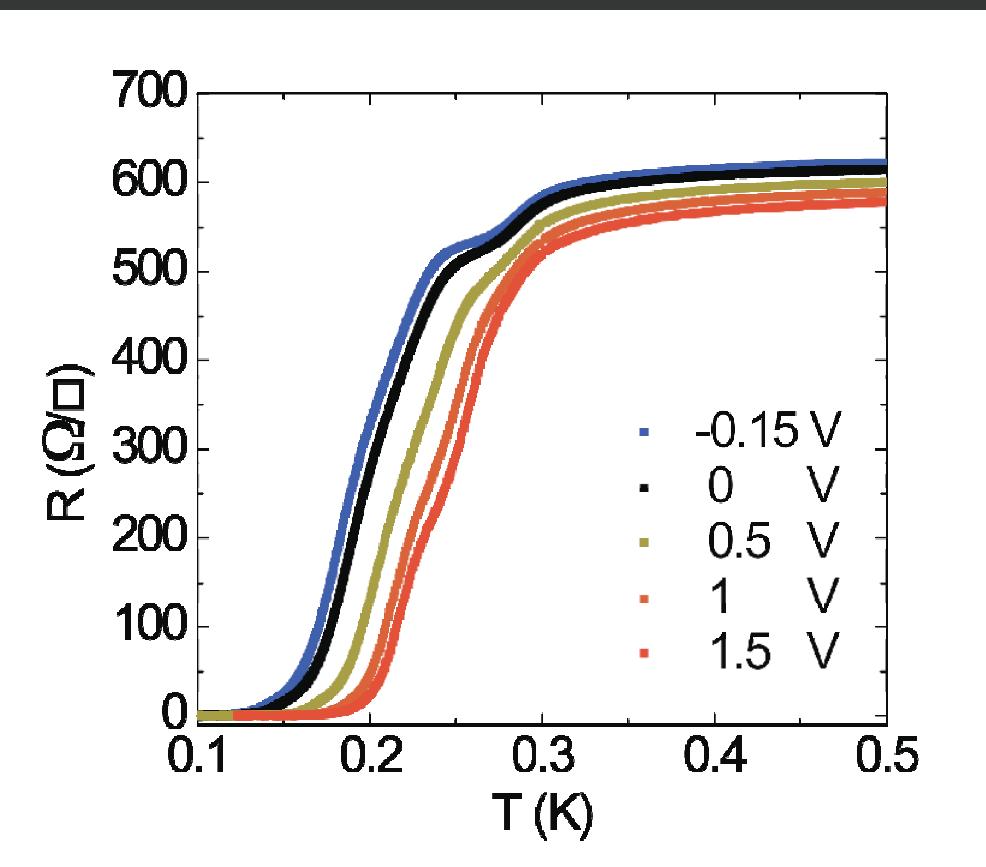
Top gate device



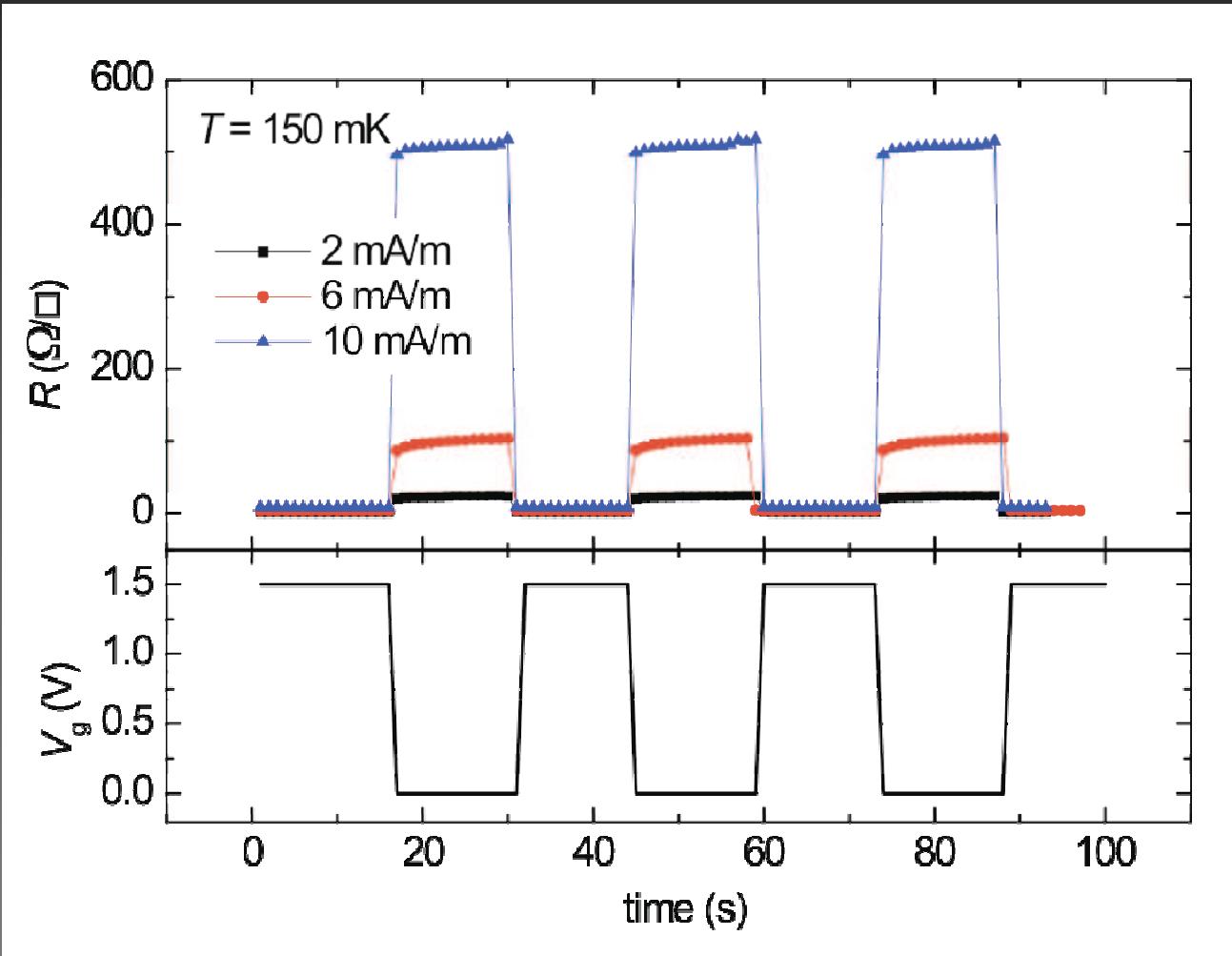
Top gate



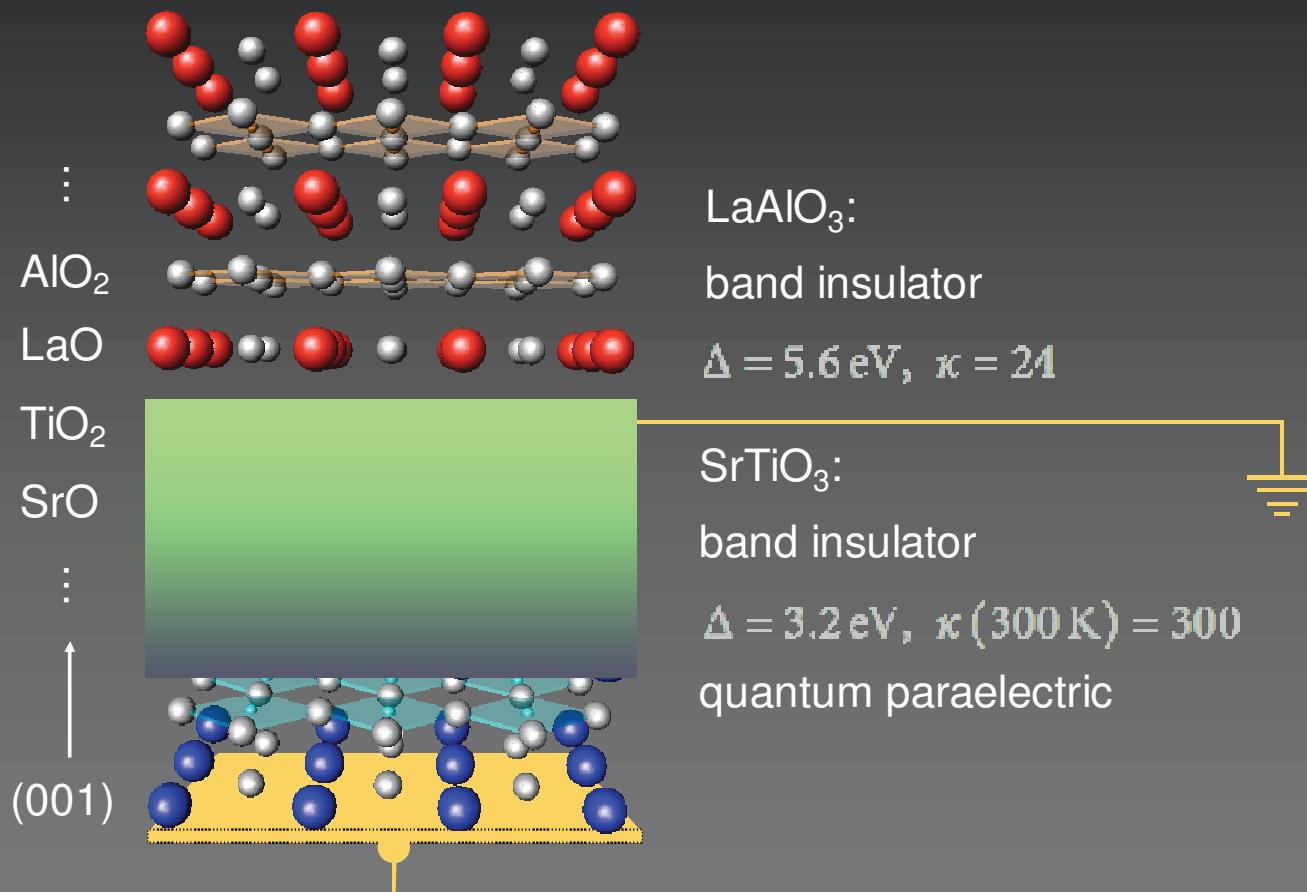
SC modulation with 1 V



Superconducting switch

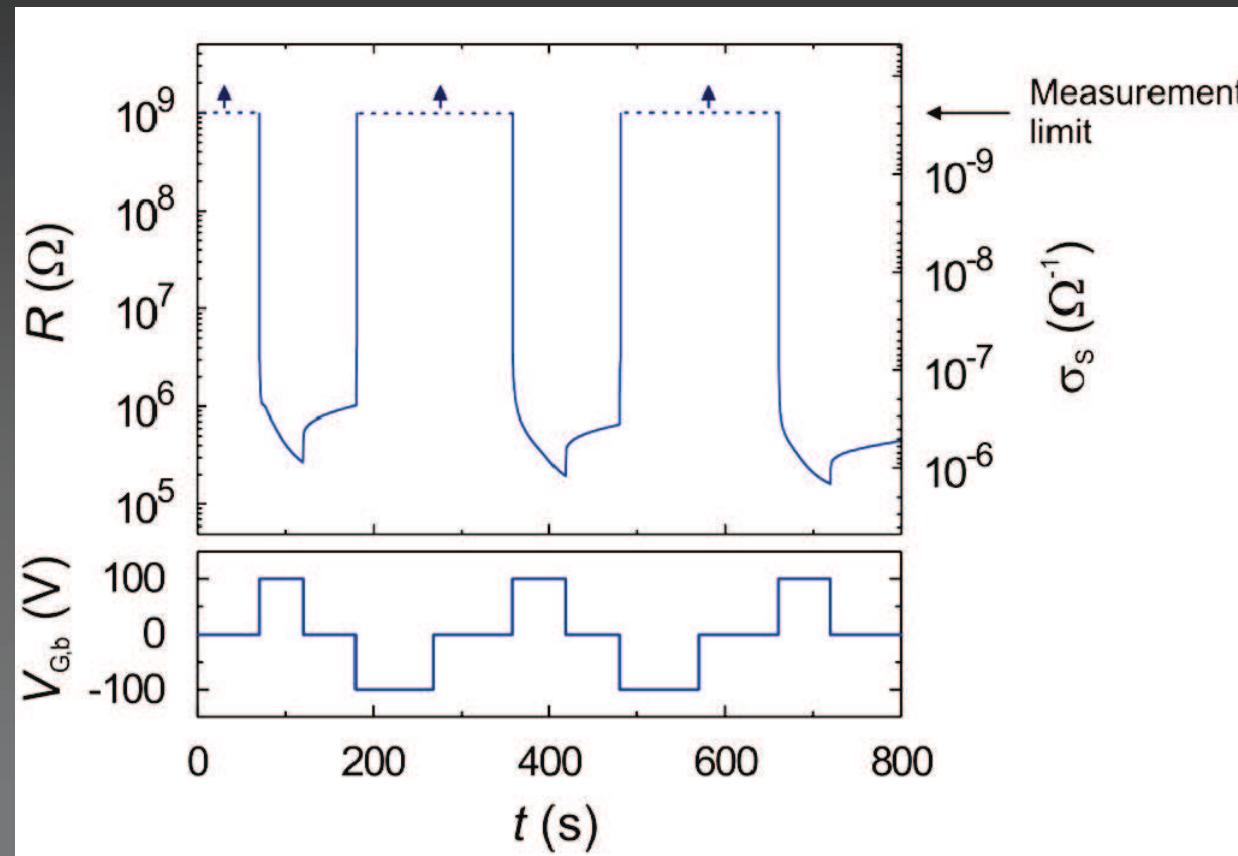


Back gate device

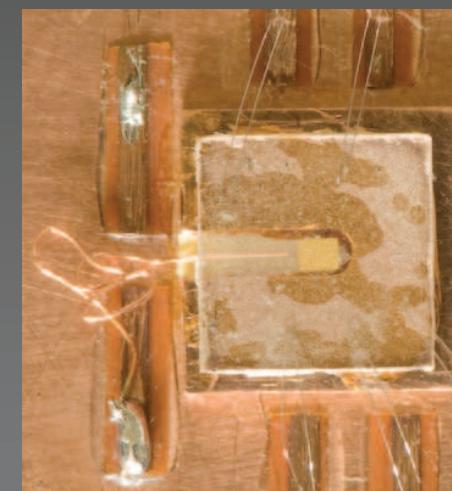
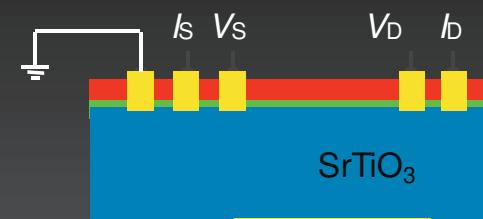
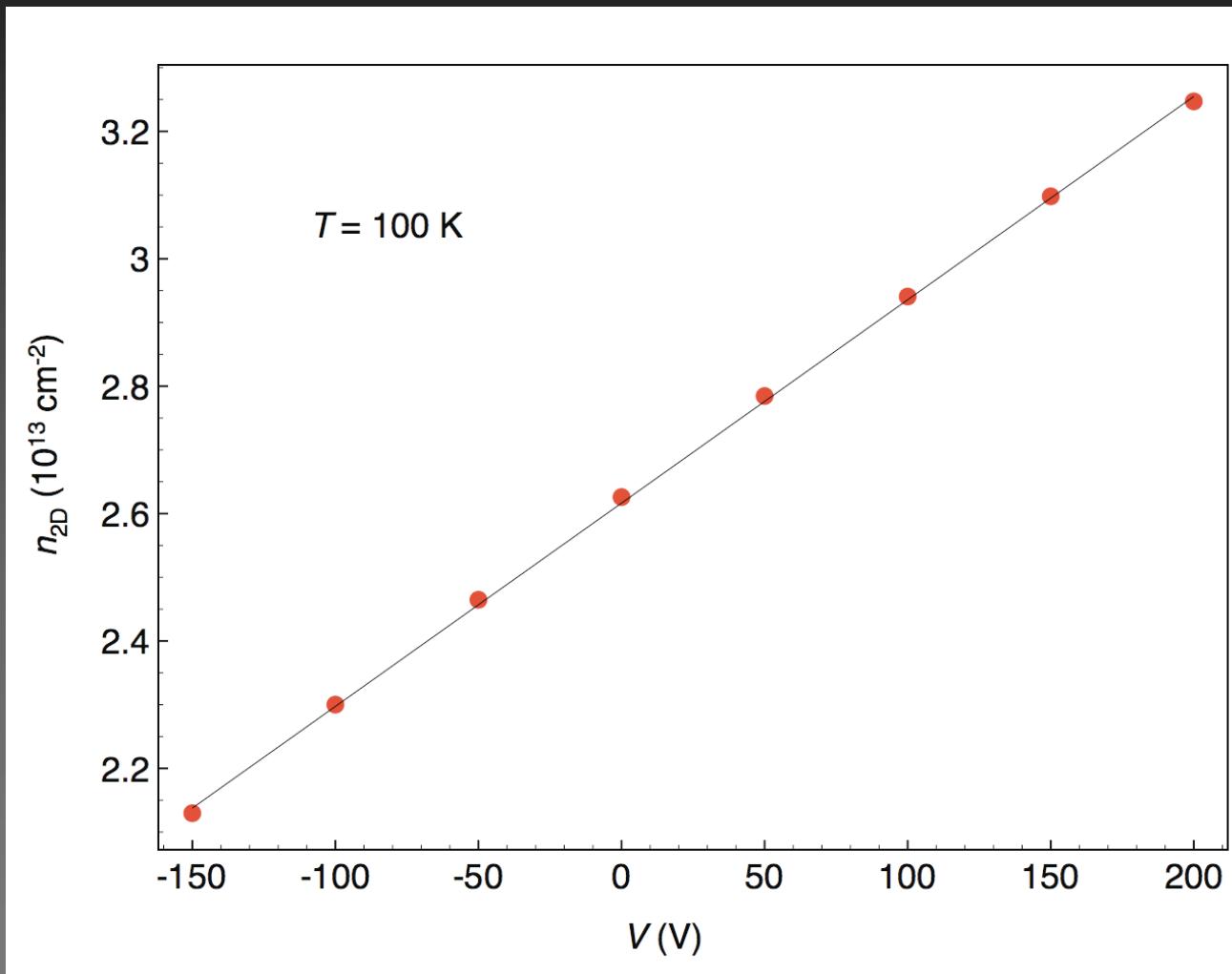


Field-effect on the q2-DEG

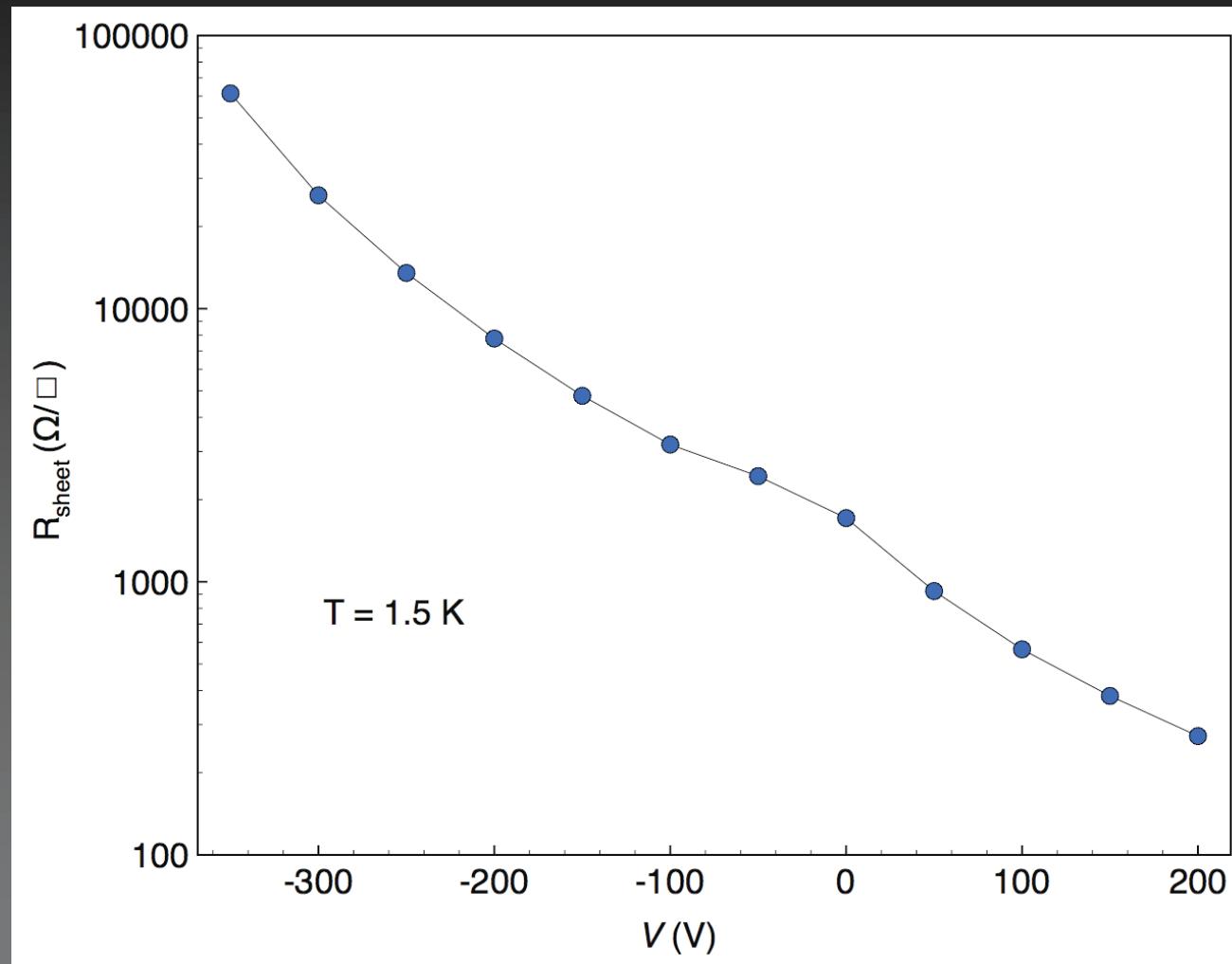
3 uc LaAlO₃ @ room temperature



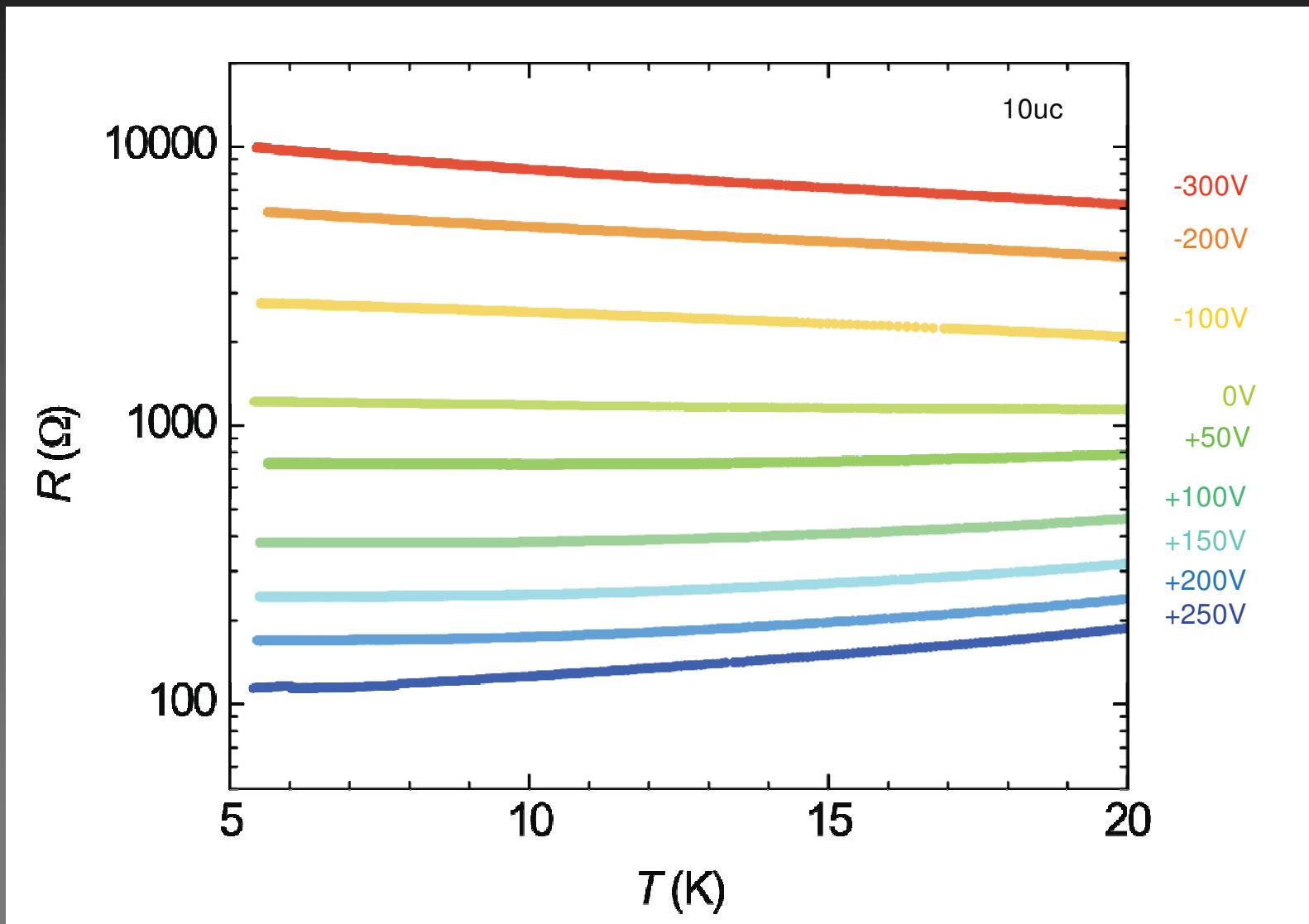
n_{2D} modulation



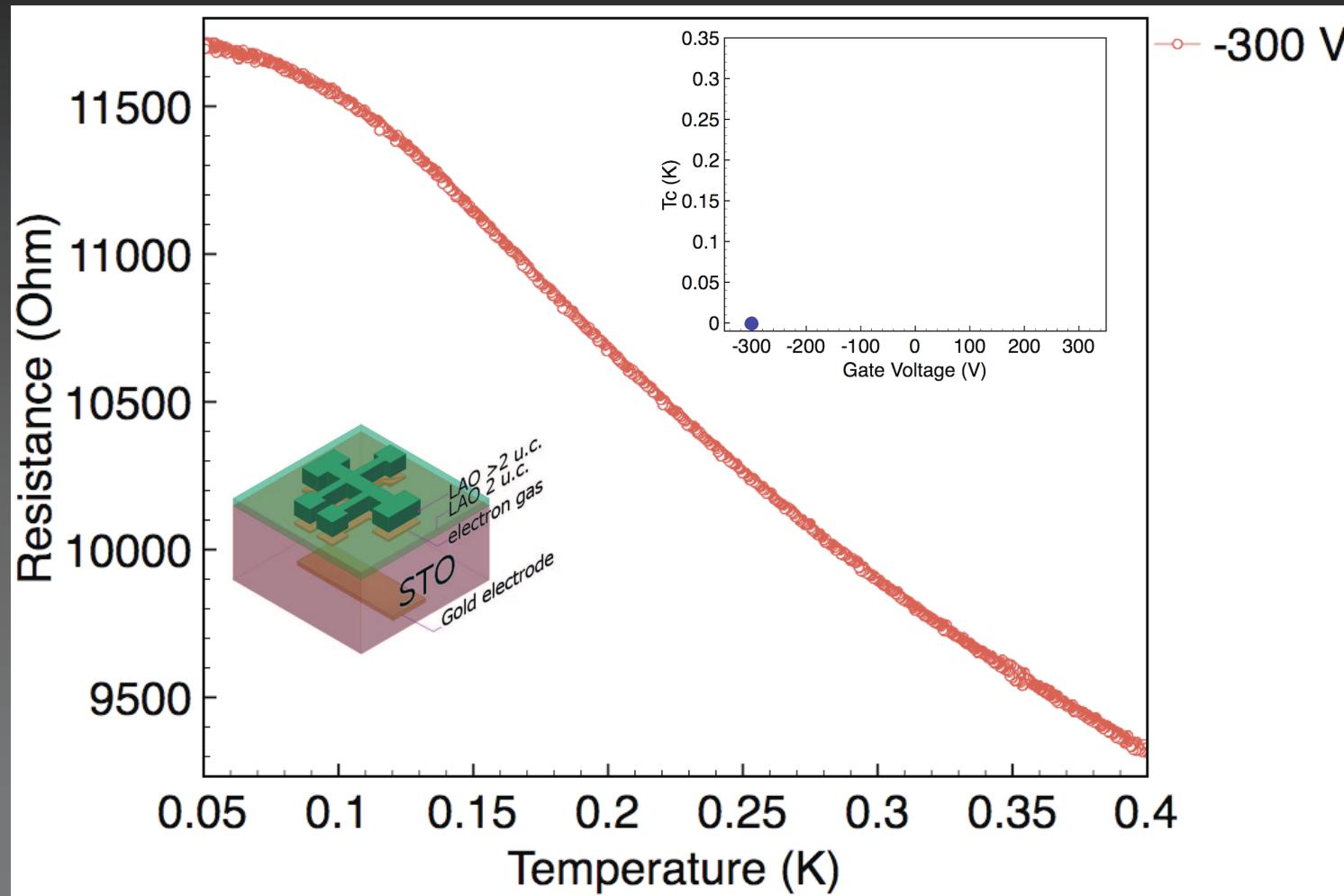
R_{sheet} modulation



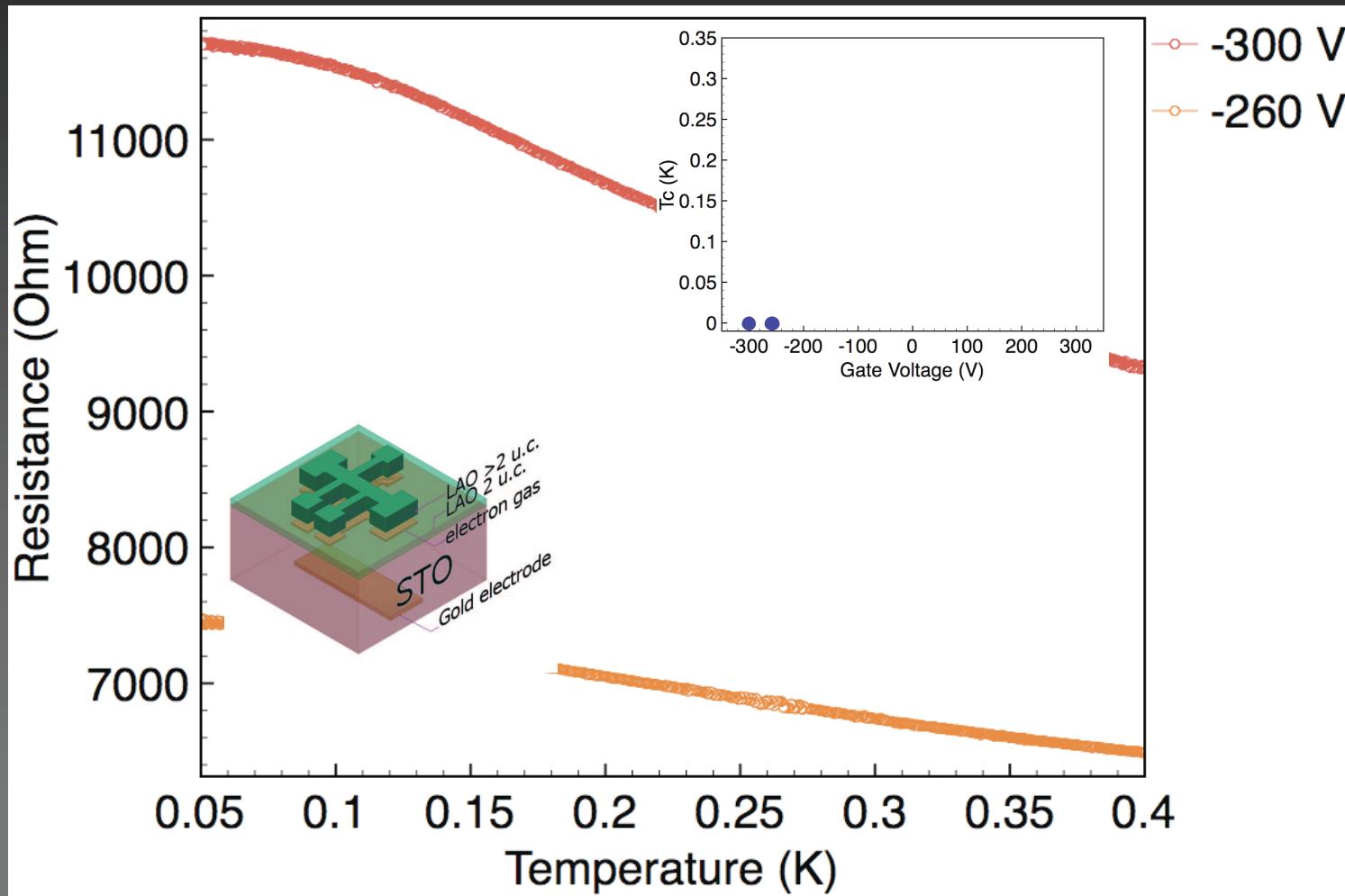
MI transition



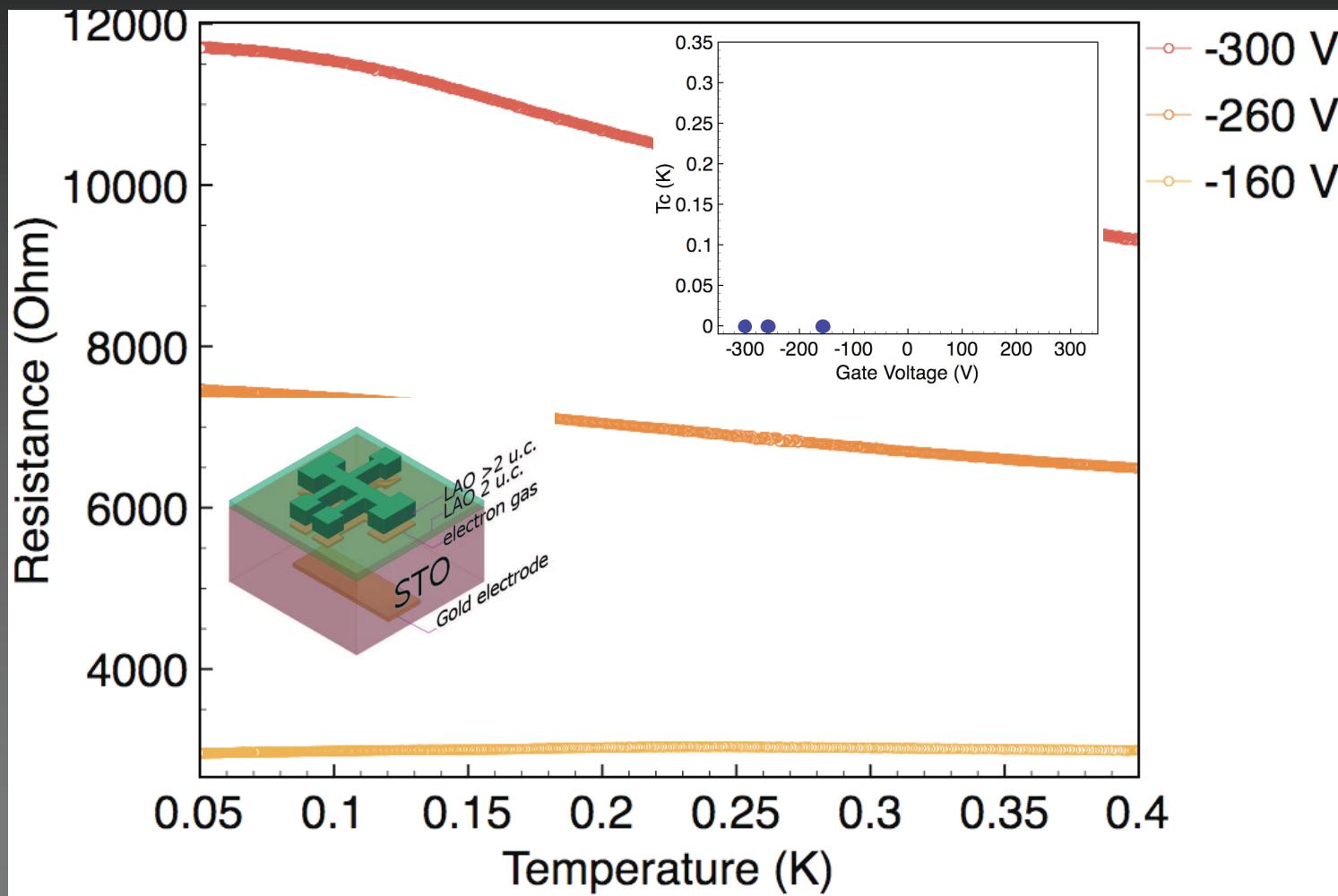
Modulation of SC



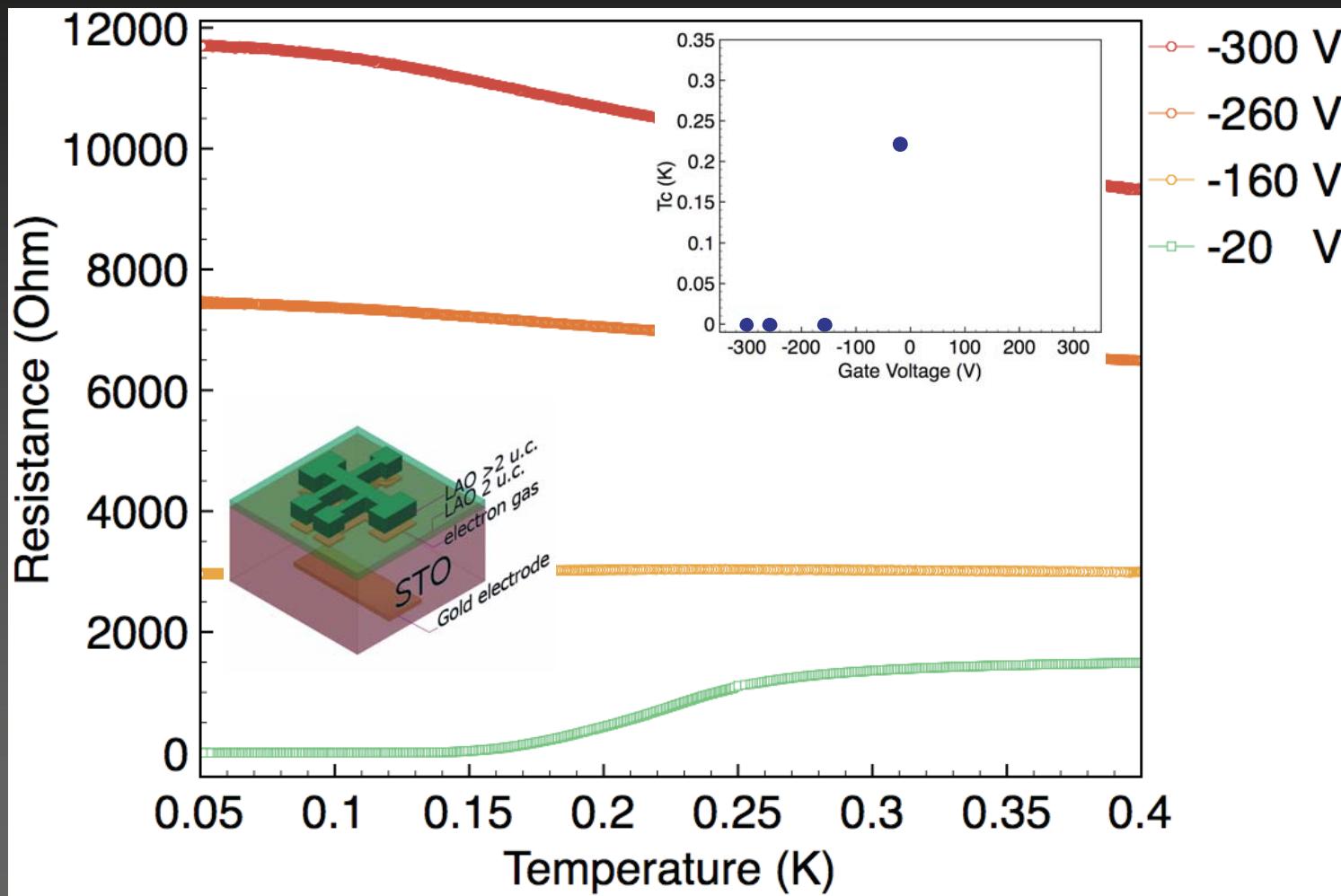
Modulation of SC



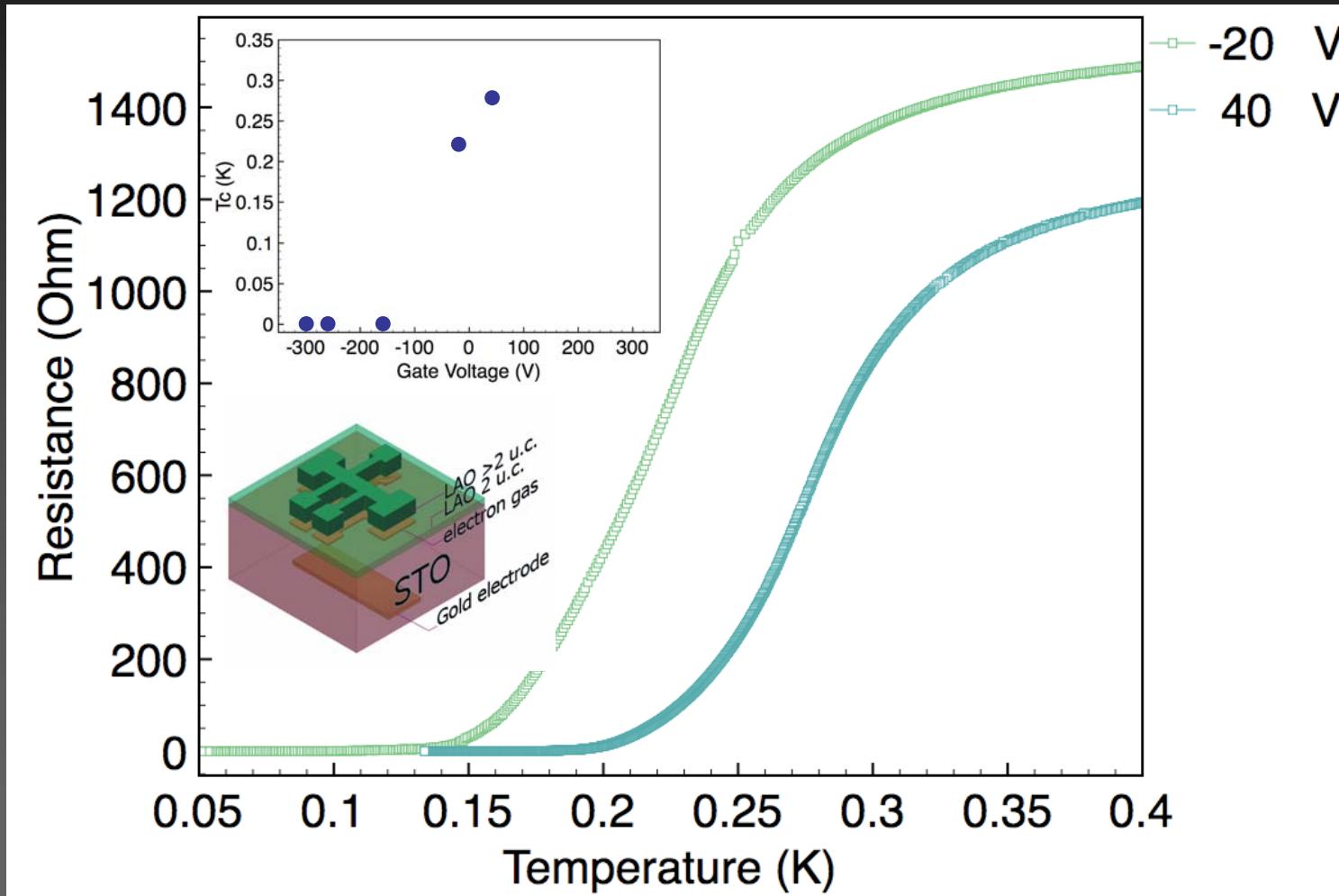
Modulation of SC



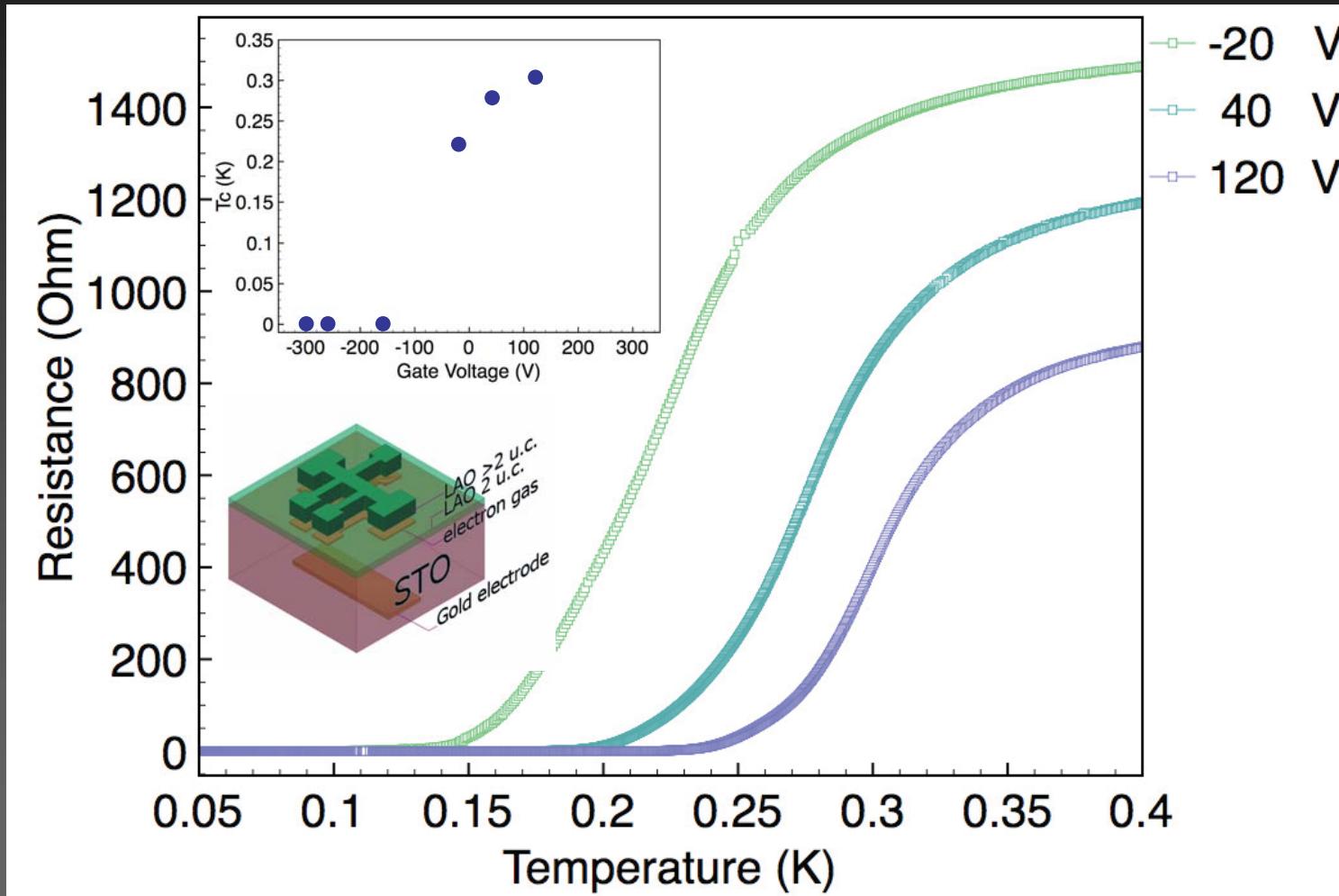
Modulation of SC



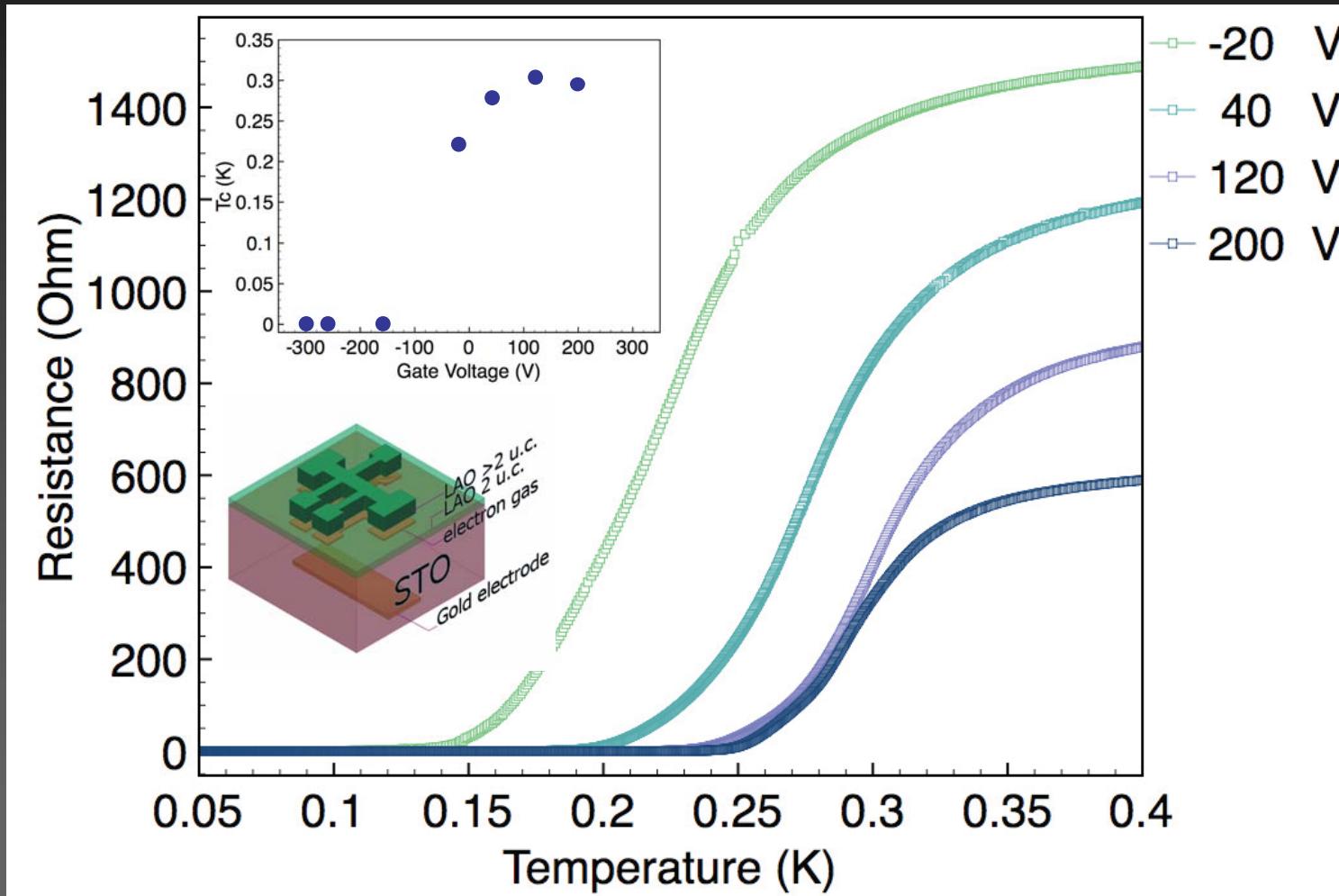
Modulation of SC



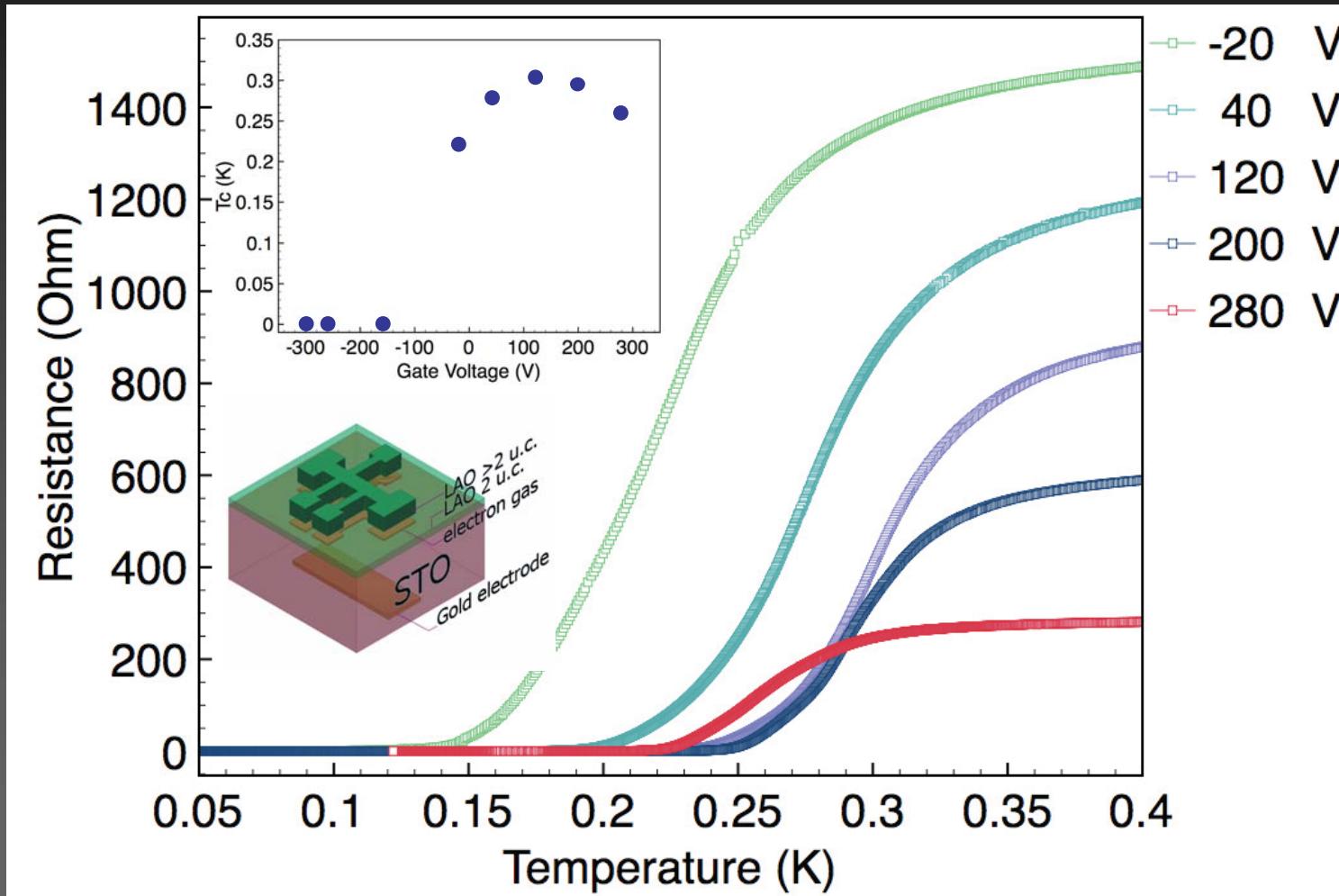
Modulation of SC



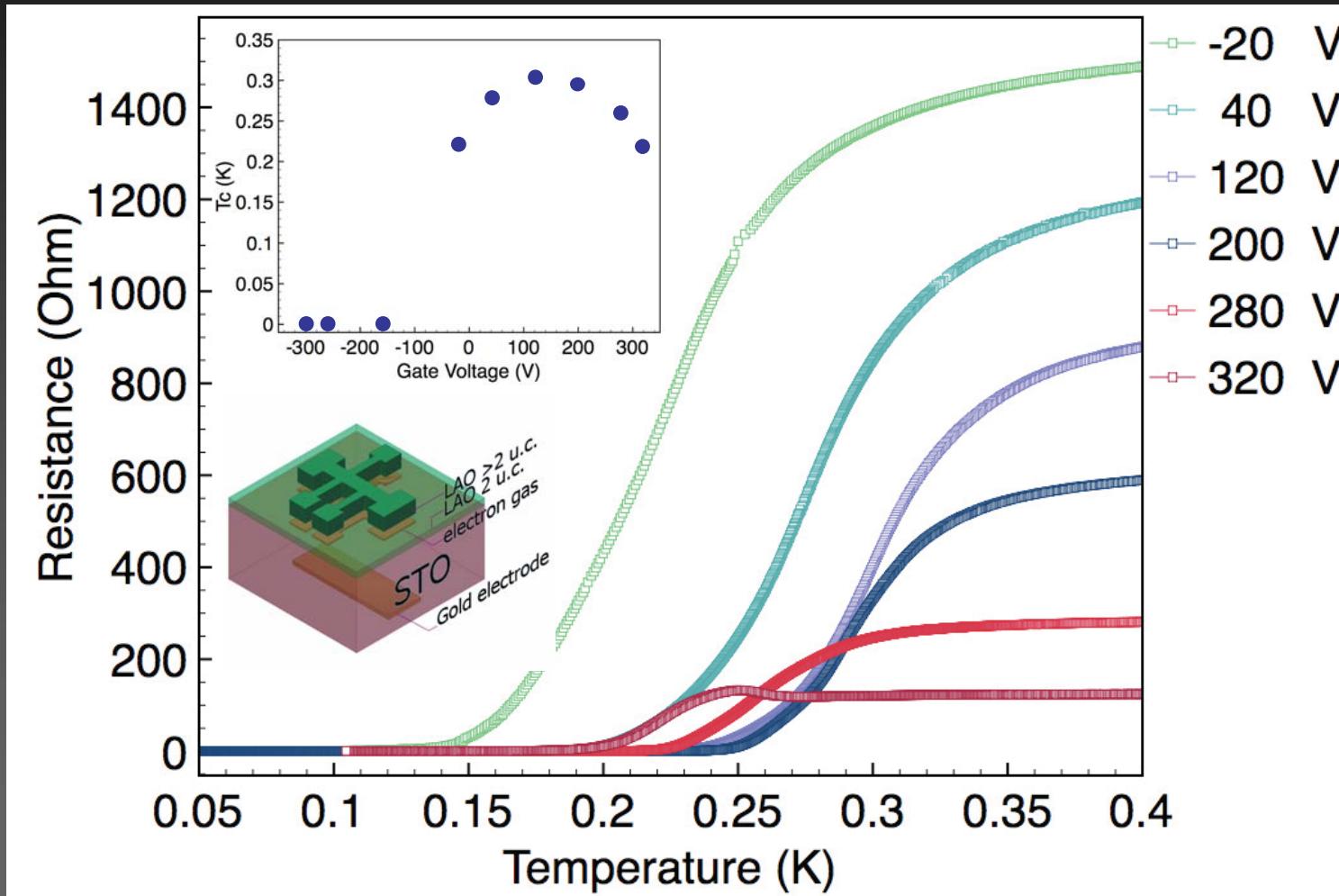
Modulation of SC



Modulation of SC



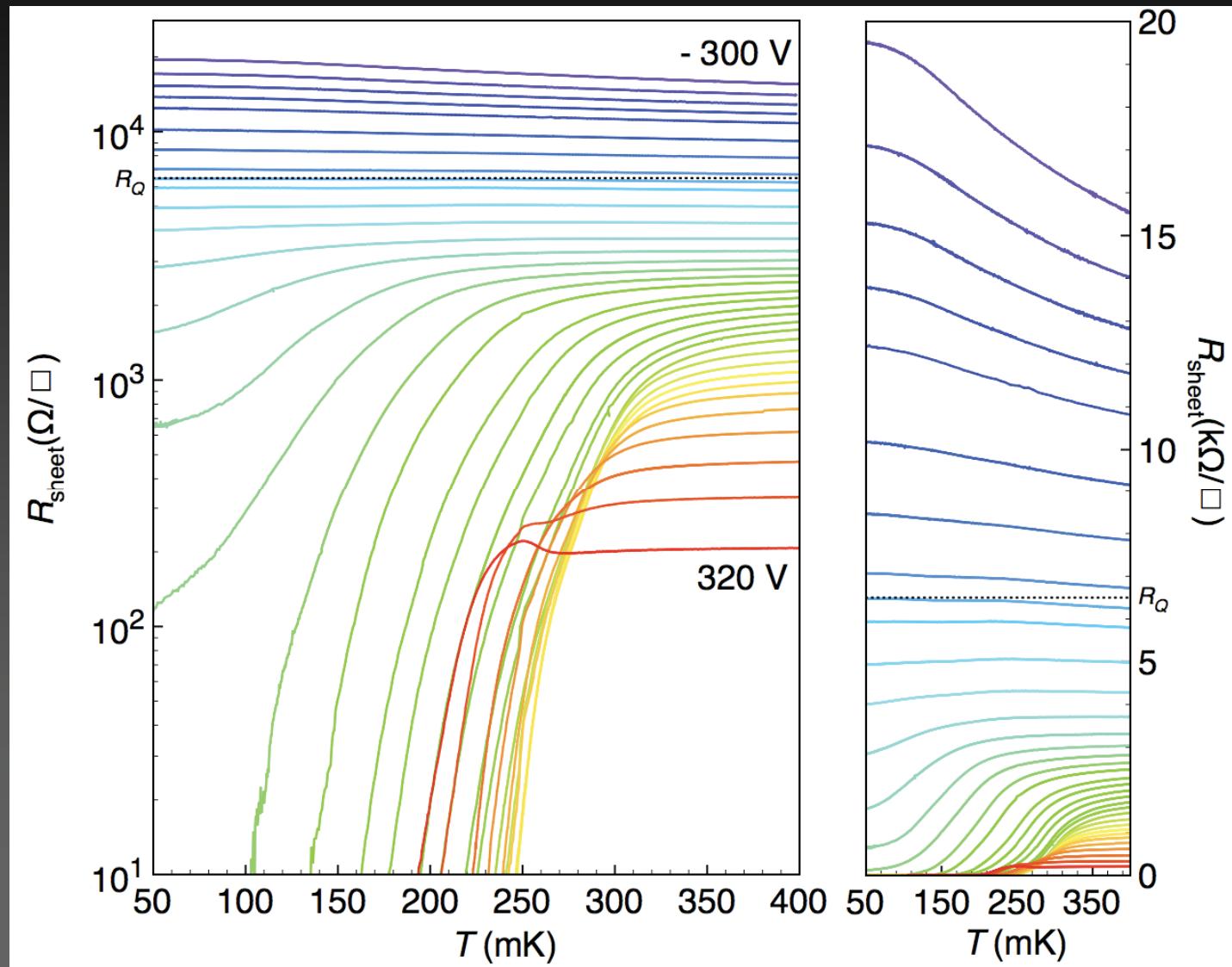
Modulation of SC



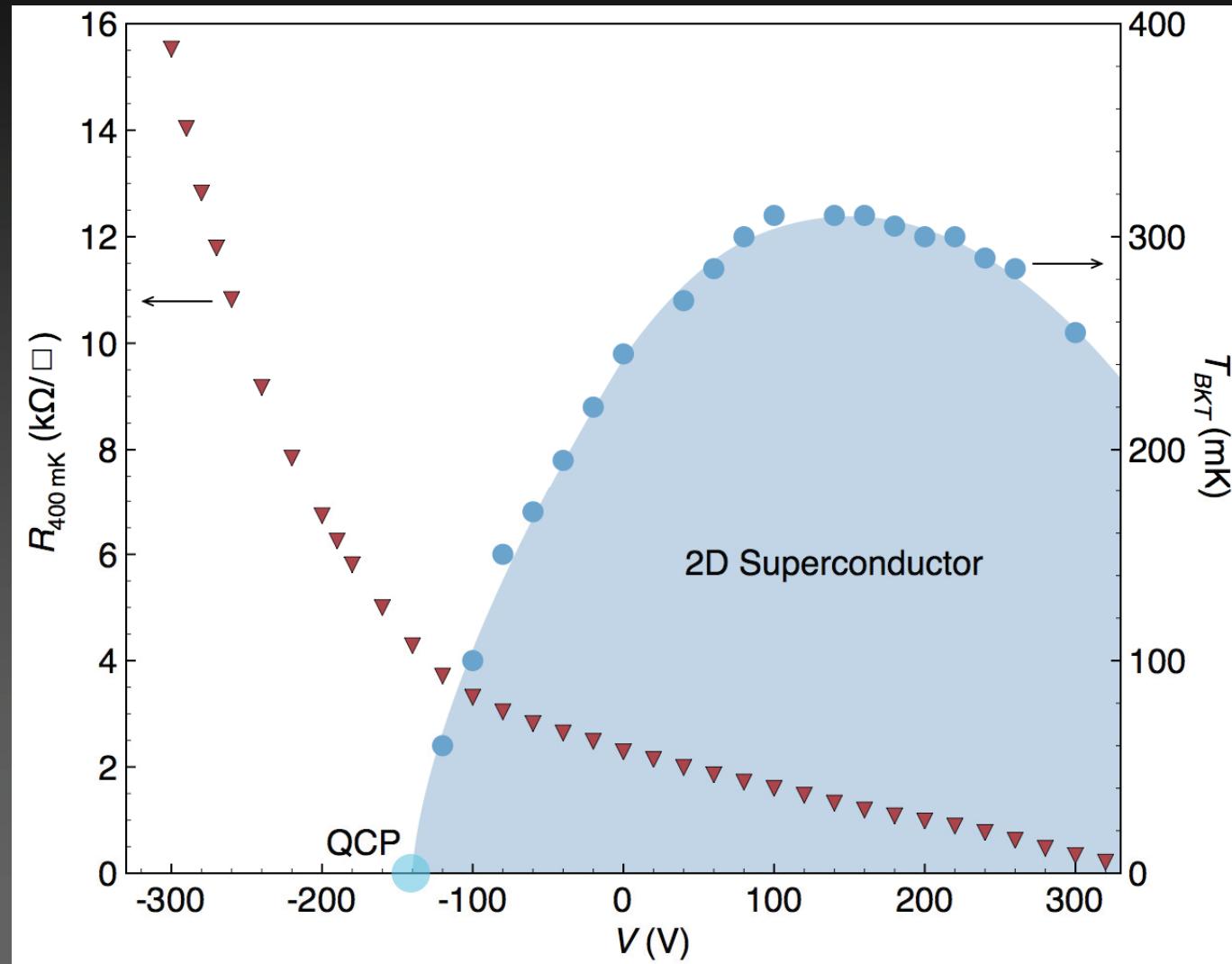
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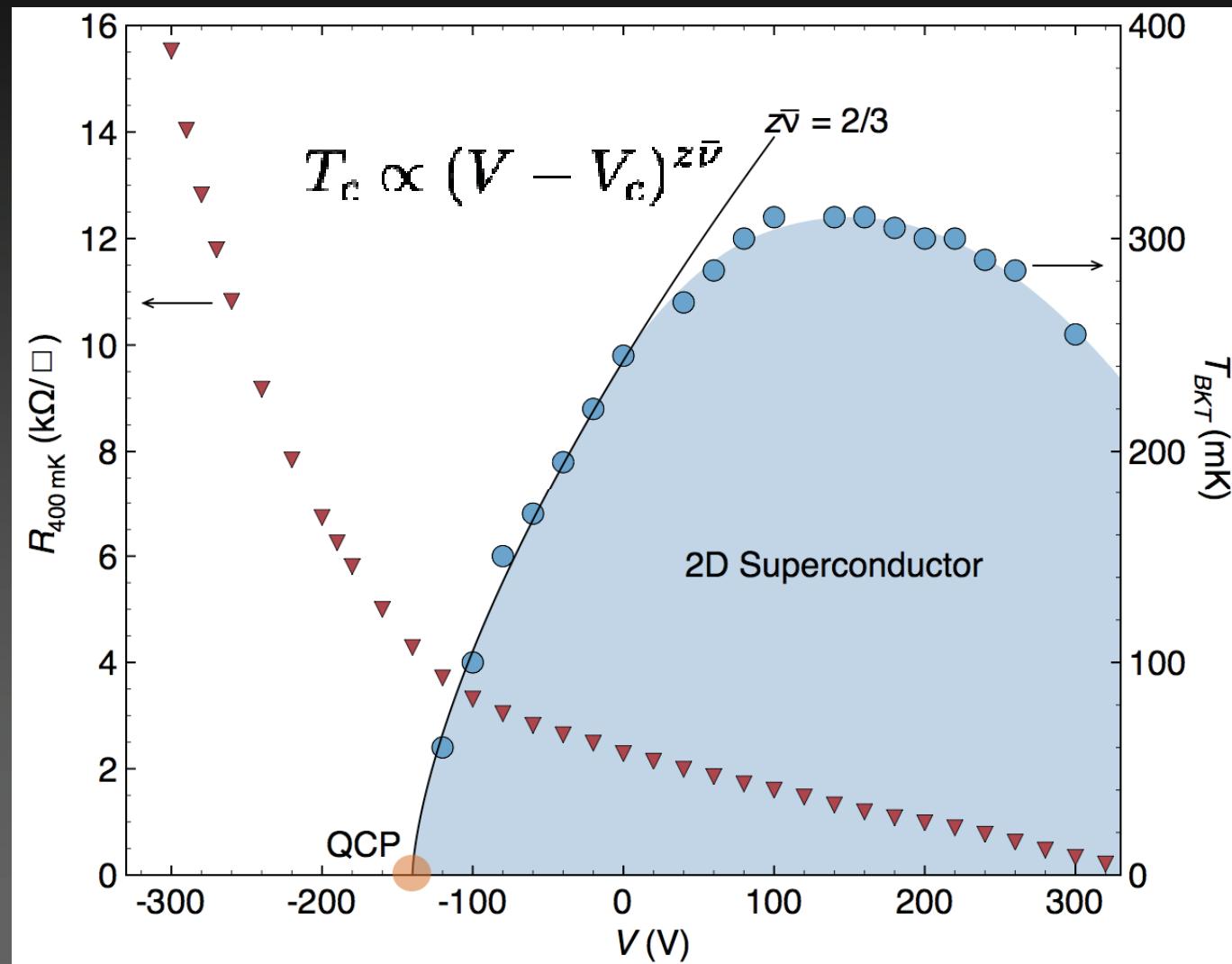
Modulation of SC



Phase diagram



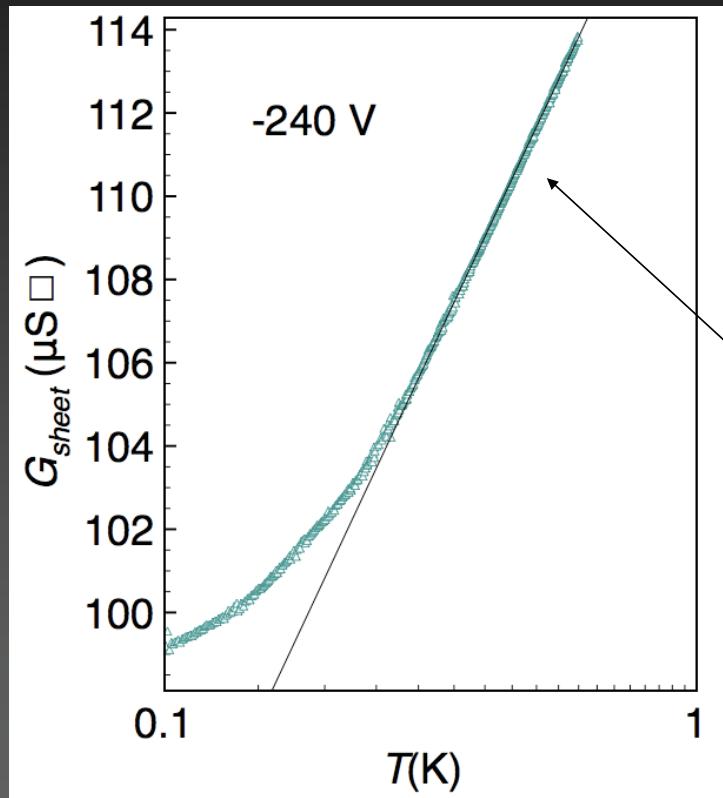
Phase diagram



What is the nature of the localized state?



Weak localisation



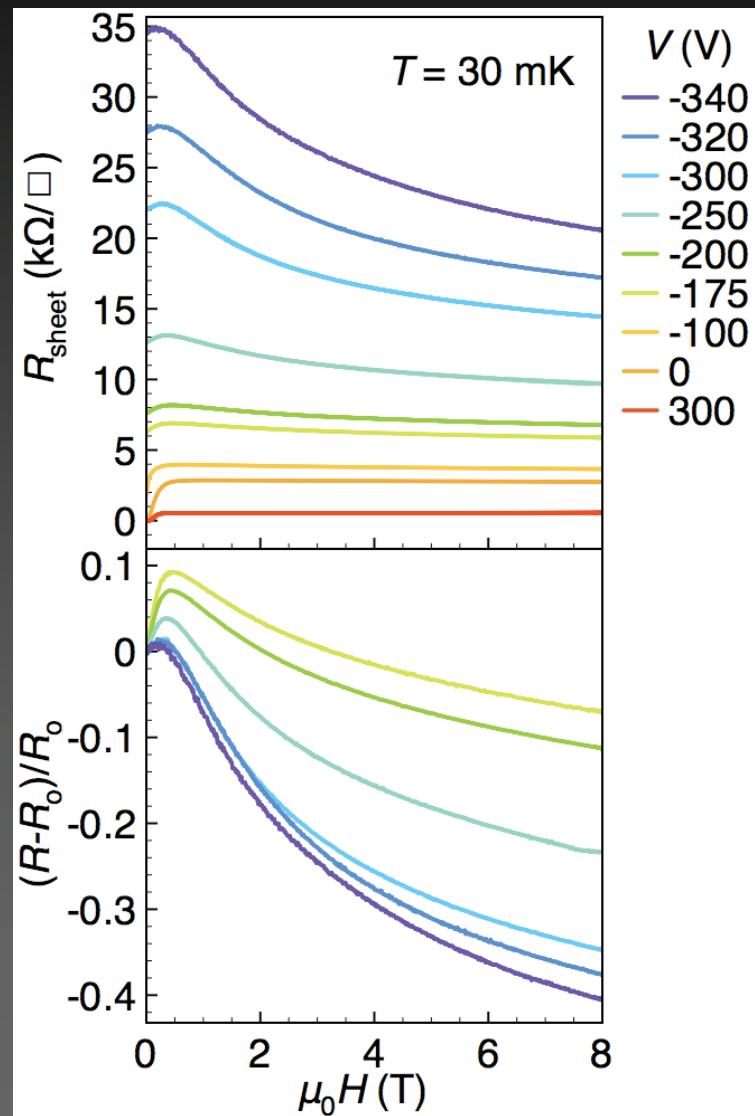
Theoretical prediction

$$\frac{d\sigma}{d \ln T} = \frac{e^2}{\pi h} = 1.23 \times 10^{-5} \text{ S}$$

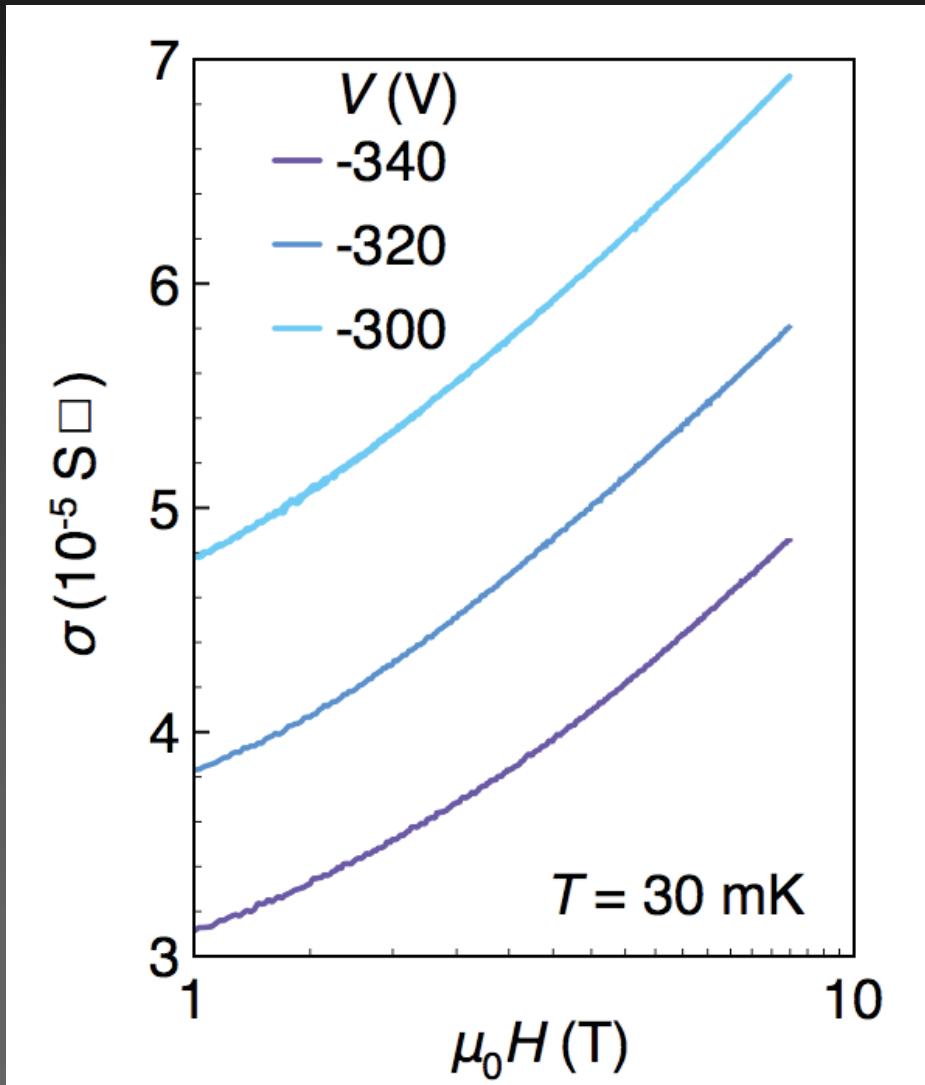
$$\frac{d\sigma}{d \ln T} \simeq 1.2 \cdot 10^{-5} \text{ S}$$



Negative MR



Weak localisation



Theoretical prediction

$$\frac{d\sigma}{d \ln H} = \frac{e^2}{\pi h} = 1.23 \times 10^{-5} \text{ S}$$



Conclusions

A quantum phase transition has been observed separating a localized state from a superconducting state.

The superconducting state has a 2D nature and signatures of a BKT transition.

The localized state displays characteristics of a weak localization mechanism.



Acknowledgements

Nicolas Reyren, Andrea Caviglia, Claudia Cancellieri, Didier Jaccard, Jean-Marc Triscone

University of Geneva



Stefan Thiel, German Hammerl, Jochen Mannhart

University of Augsburg

Marc Gabay *University of Paris*

Toni Schneider *University of Zurich*