university of groningen

Quantum Phase Control on Ion-Gated Interfaces

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Device Physics of Complex Materials

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SPICE
Mainz 2015

Outline

- **Background**
  - *Field effect transistor*
  - *Field effect control of quantum phases*
  - *Experimental attempts*
- **Introduction to ion-gated transistors**
  - *Basic Concept of Device*
  - *Variations in making devices and early success*
- **New ingredient in 2D superconductors**
  - *Zeeman-protected superconductor*
  - *Ising superconductivity*
  - *Towards total control of superconductivity*
  - *Superconducting transistors*
  - *New chances in monolayers*
  - *CVD growth, monolayer superconducting transistor*

Carrier Density Controls Electronic Properties

Sheet Carrier Density *n* (cm^{-2})

10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16}

Insulator

Dielectrics
Ferroelectrics
Multi-ferroics
......

Semiconductor

p-n junction, Transistor, Solar cell
Light emitting diode, Quantum dot *etc*.

Quantum Hall Effect, Dirac Fermions
Topological Insulators

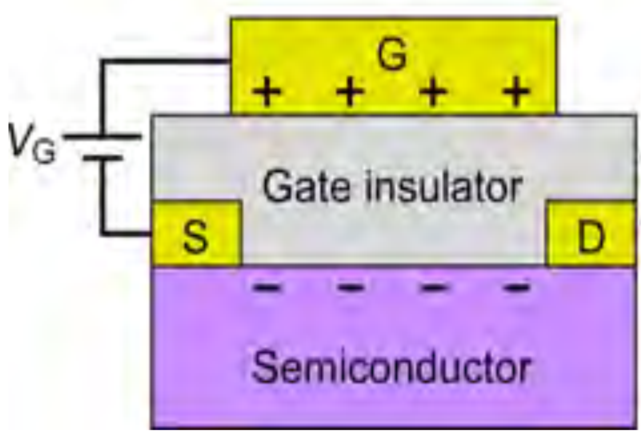
Metal

Superconductivity
Mott transition
Heavy Fermion
....
Strongly correlated Systems

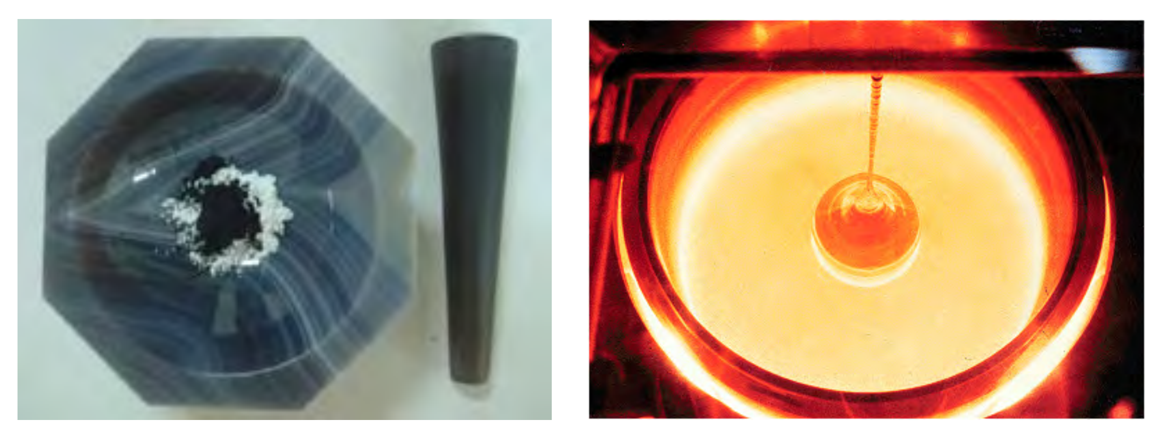
Chemical Doping

Field-Effect Doping

Transistors

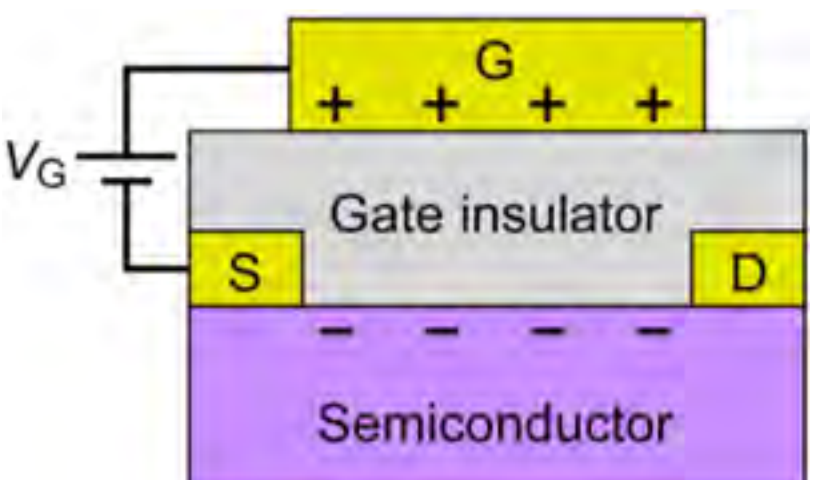


Chemical Reactions



Field Effect Transistor and Superconductivity

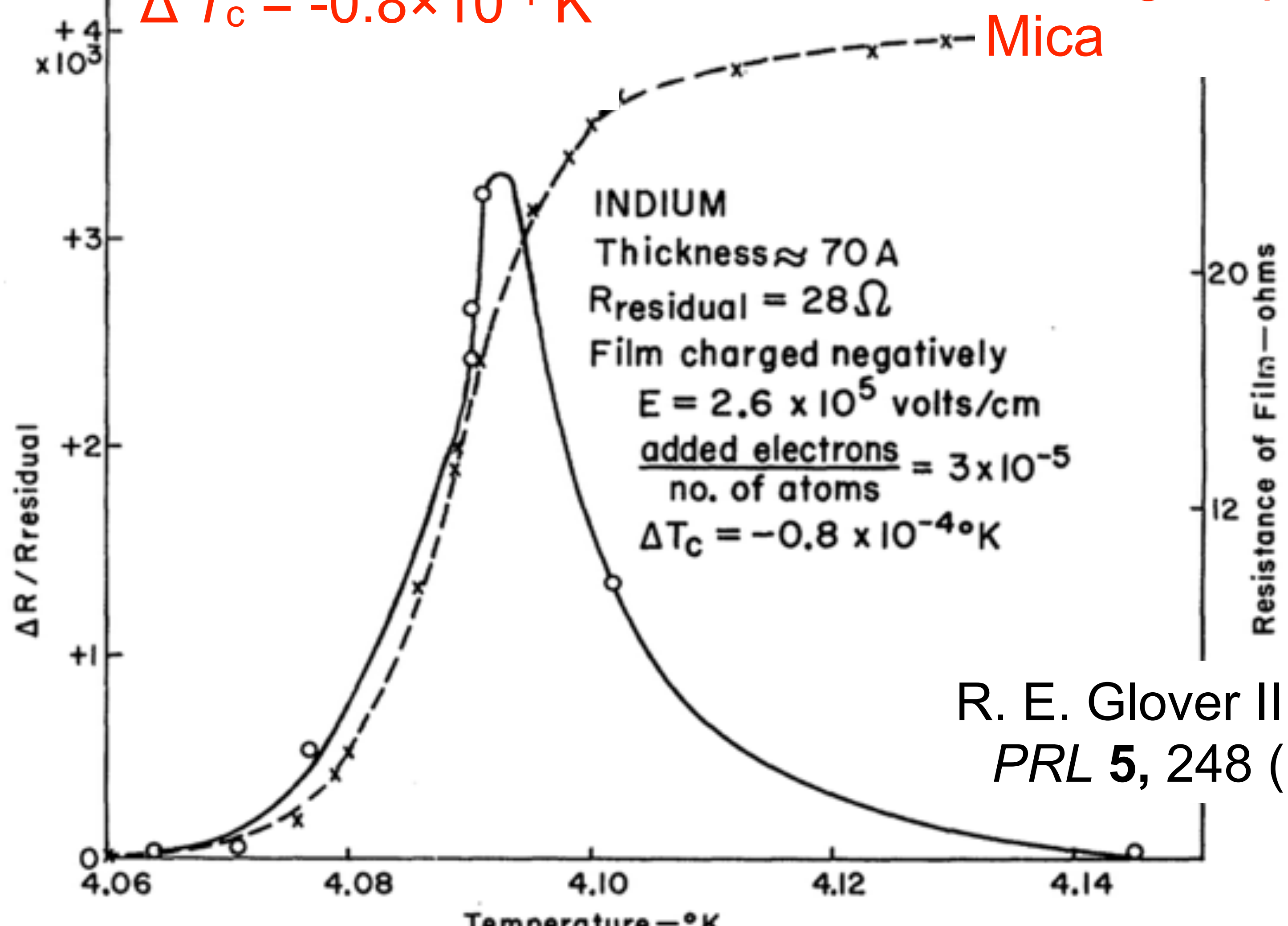
John Bardeen
Noble Prize in Physics
Transistor (1956)
BCS theory of Superconductivity (1972)



Field effect control of T_c in superconductor ?

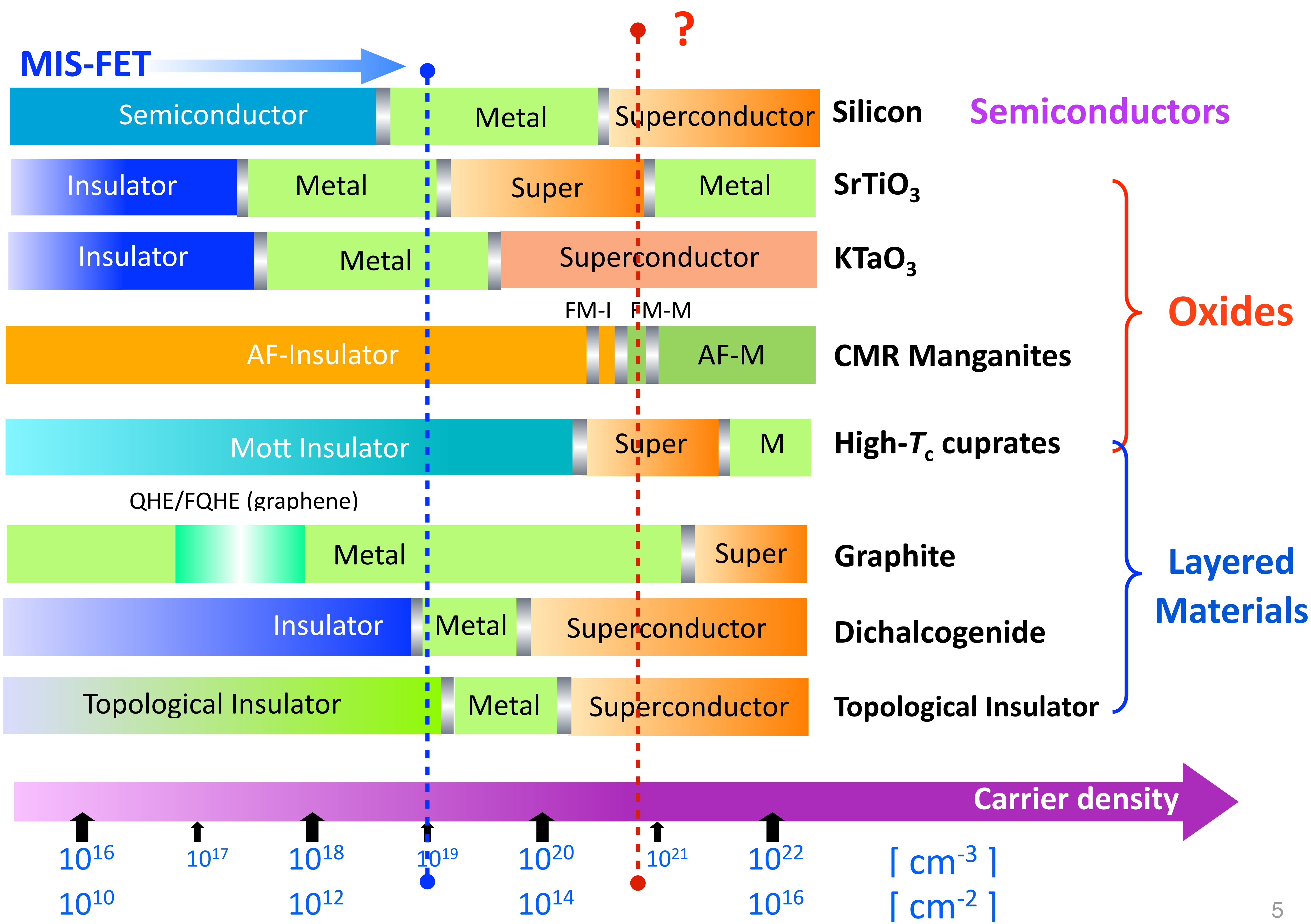
Indium
T_c = 4.1 K
ΔT_c = -0.8×10^{-4} K

@ 0.26 MV/cm
Through 5 μm
Mica



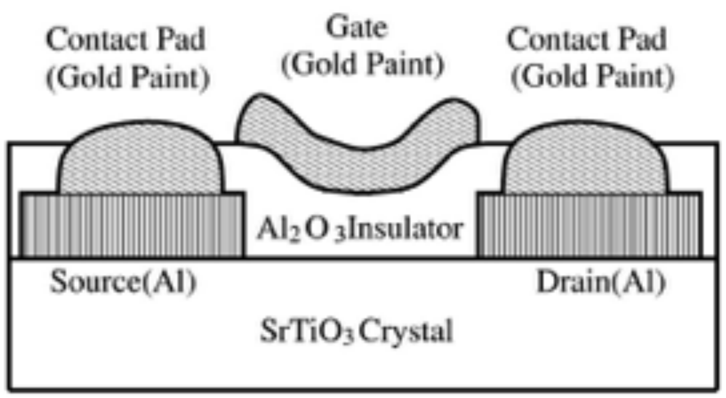
R. E. Glover III, *et al*., *PRL* **5,** 248 (1960)

Carrier density dependence of materials properties

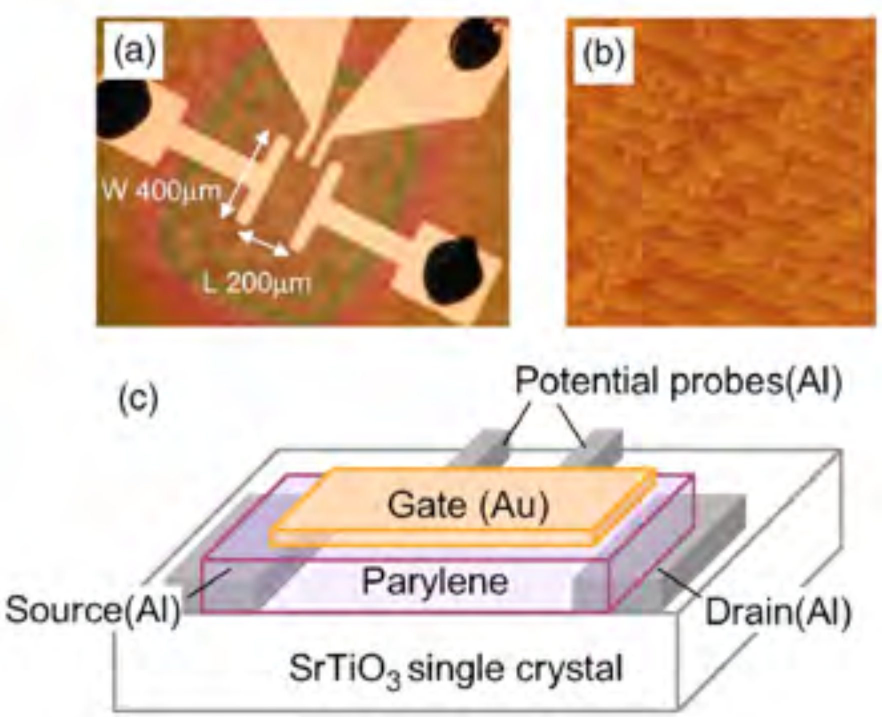


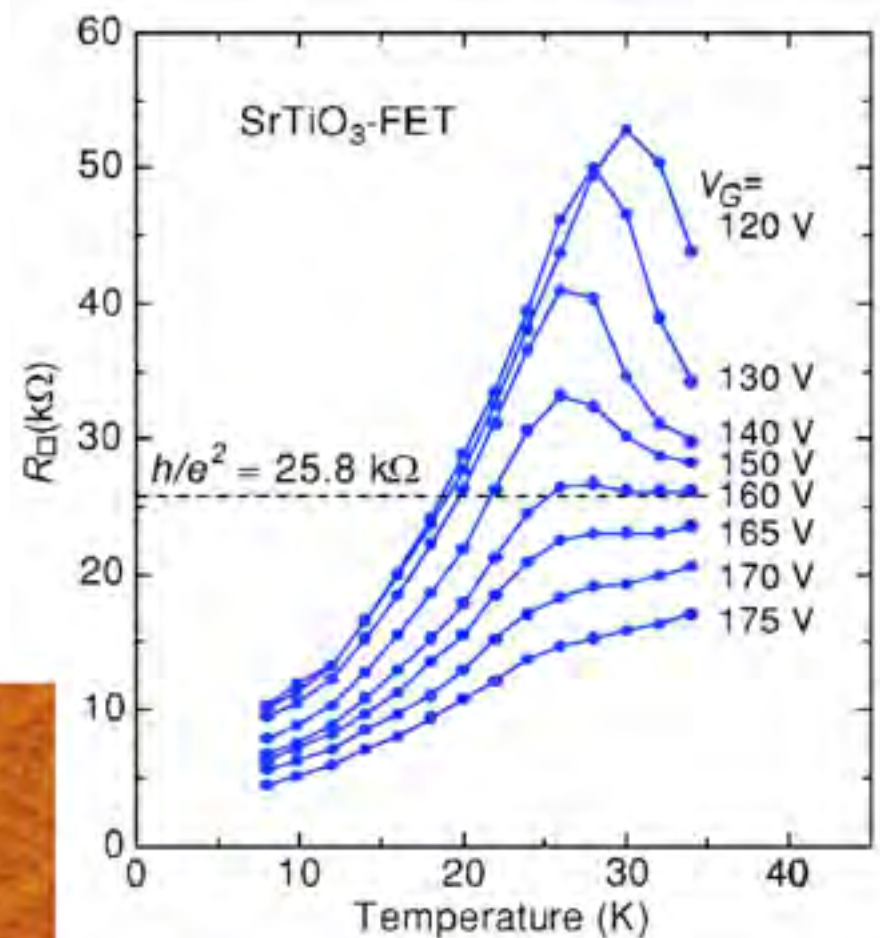
Solid State Gating on $SrTiO_3$

Proper material: $SrTiO_3$ with optimized gate by Inoue, Nakamura *et al.*

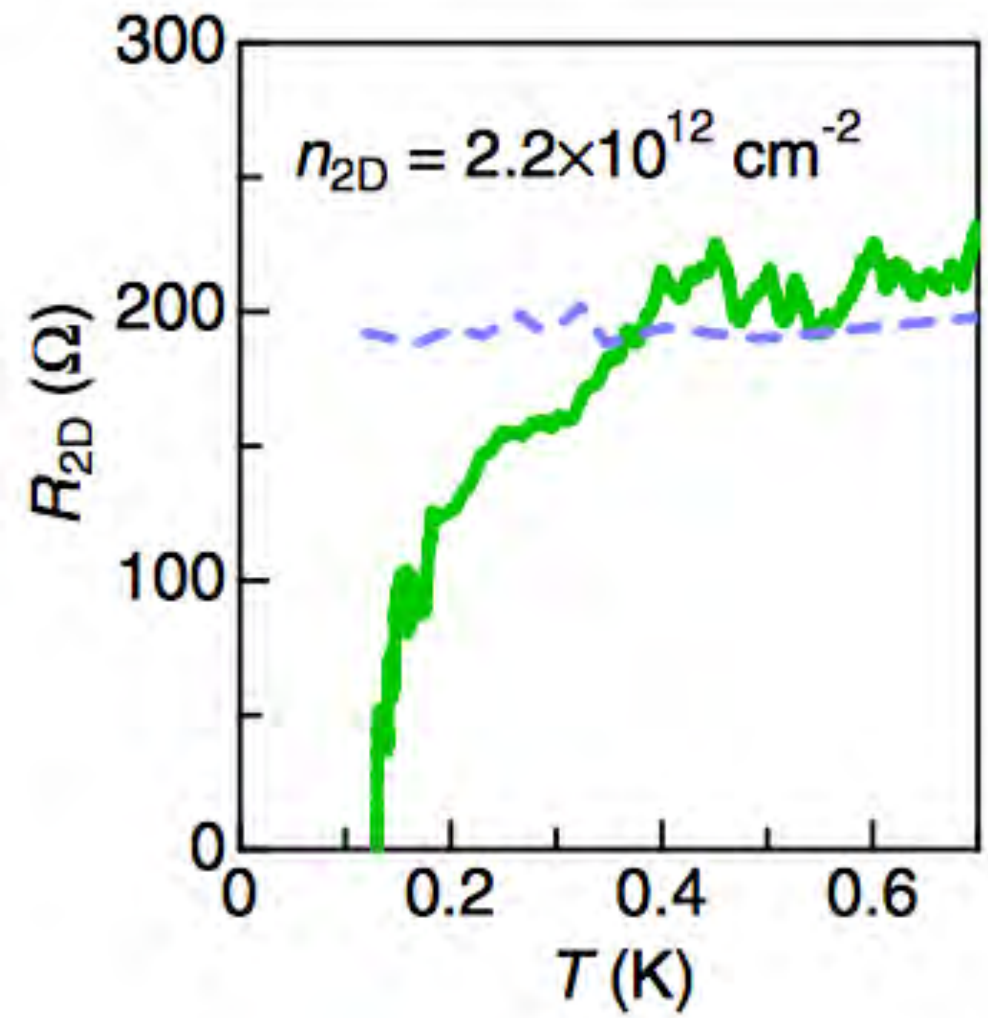


K. Ueno, *et al.*
APL **83**, 1755 (2003)





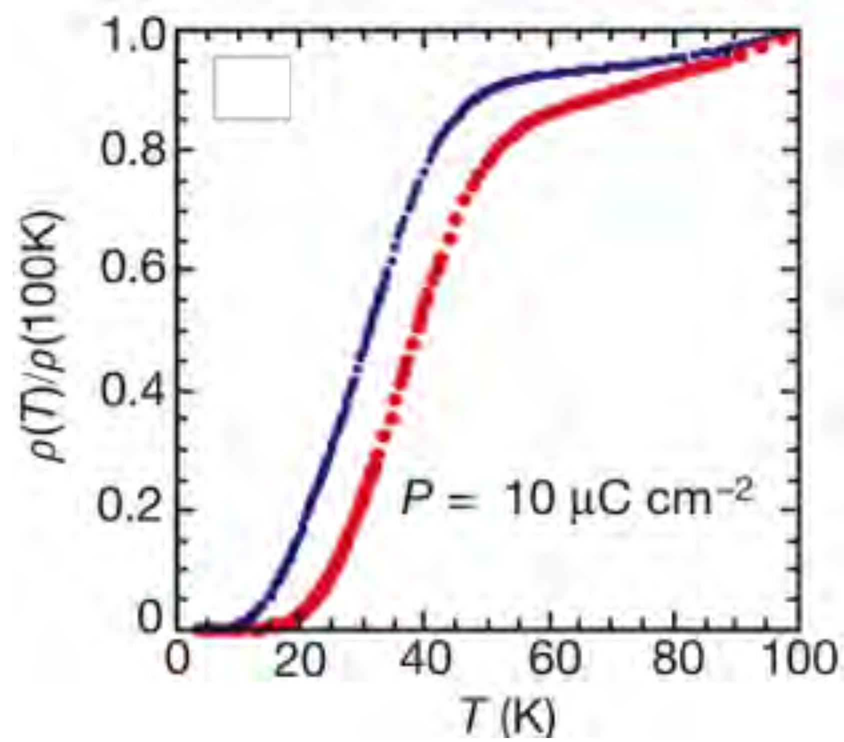
H. Nakamura, *et al.*
APL **89**, 133504 (2006)

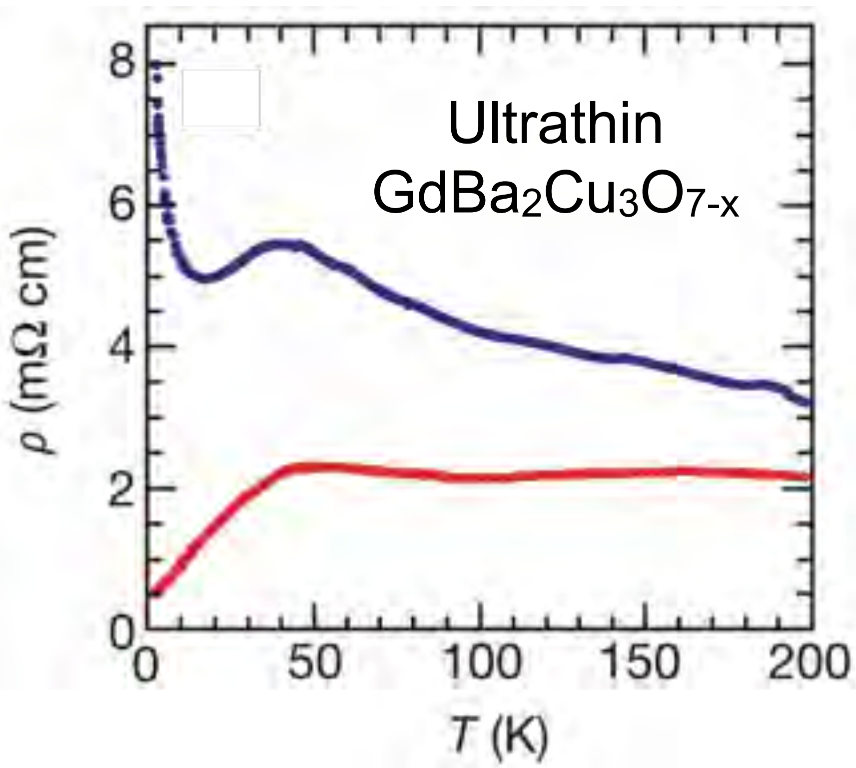


H. Nakamura, *et al.*
JPSJ **78**, 083713 (2009)

Thin Film with Ferroelectric Gate: $PbTiO_3$

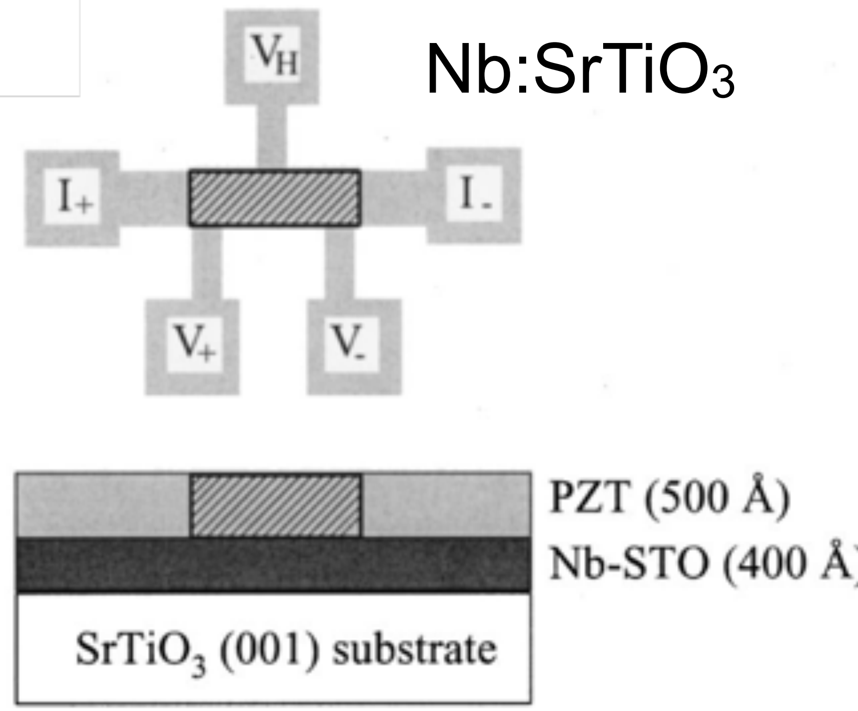
Films gated with PZT by Takahashi, Ahn, Triscone *et al.*

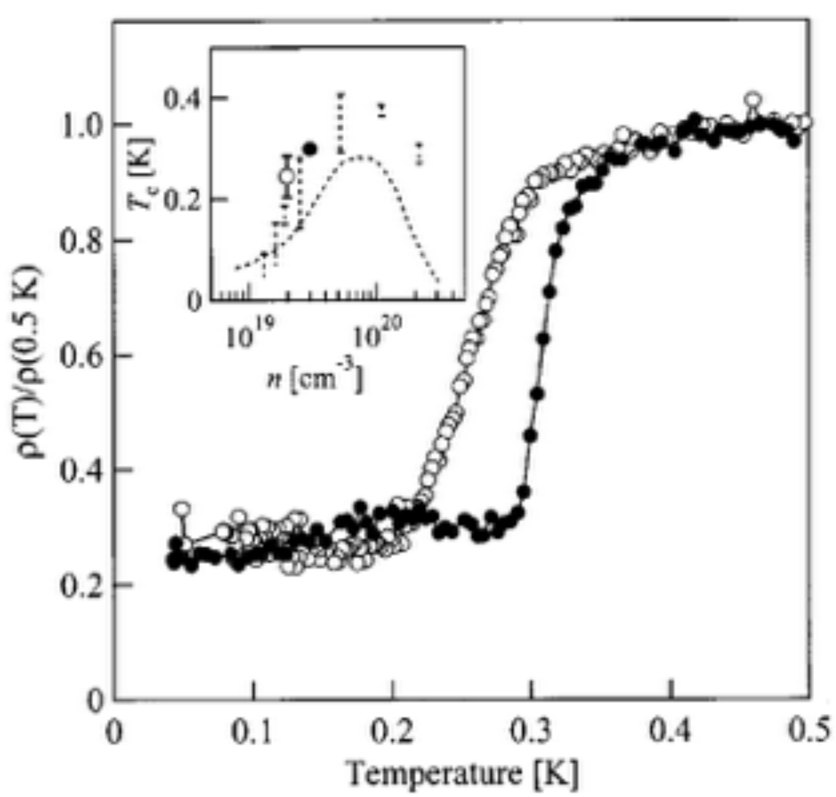




C. H. Ahn *et al.*
Science **284**, 1152 (1999)

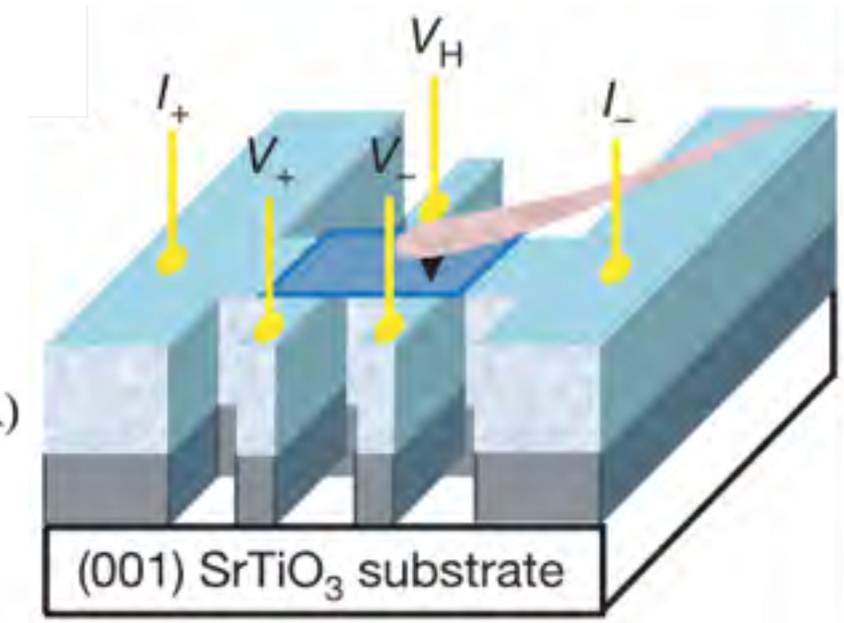
Nb:$SrTiO_3$

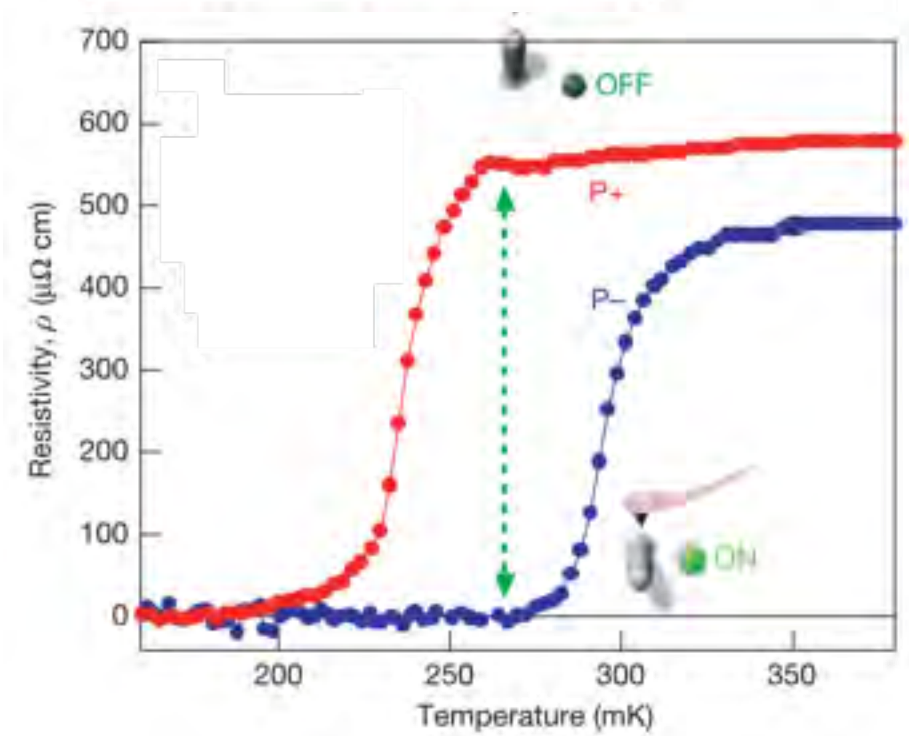




K. Takahasi *et al.*
APL **84**, 1722 (2004)

AFM gating on Nb:$SrTiO_3$

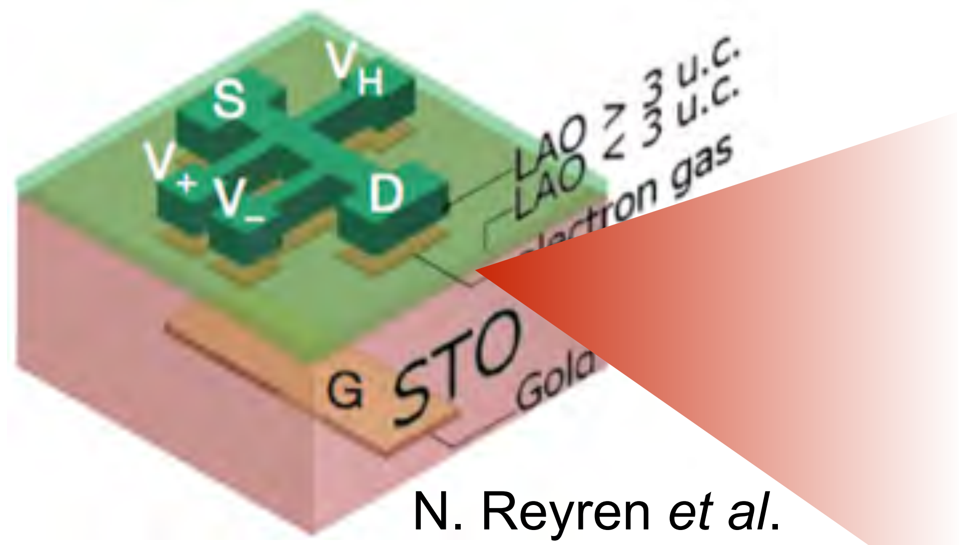


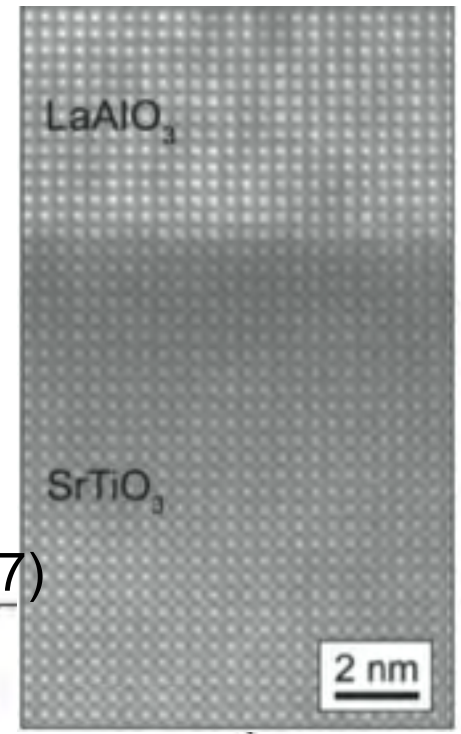


K. Takahasi *et al.*
Nature **441**, 195 (2006)

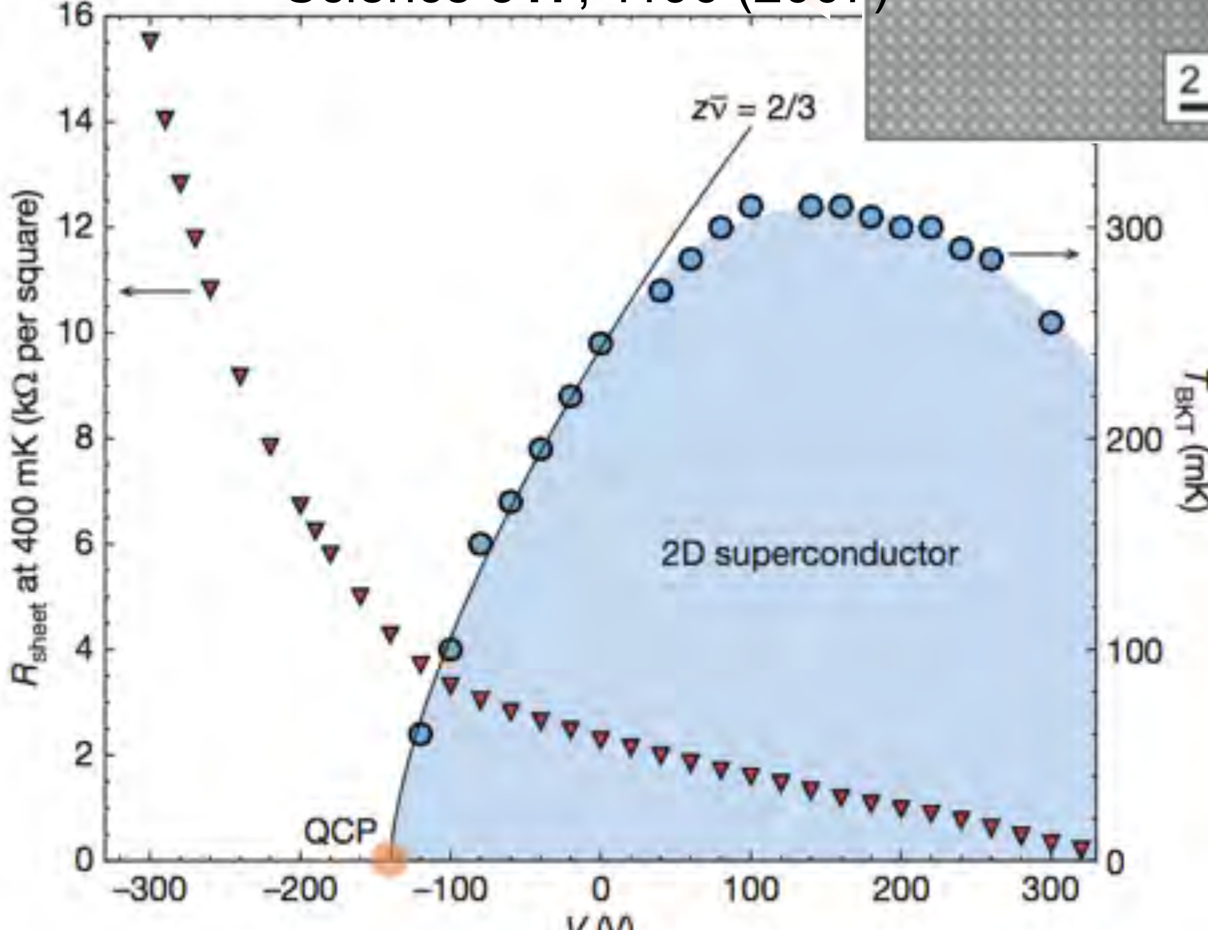
$SrTiO_3$ Gate on Interface Superconductivity: $LaAlO_3/SrTiO_3$

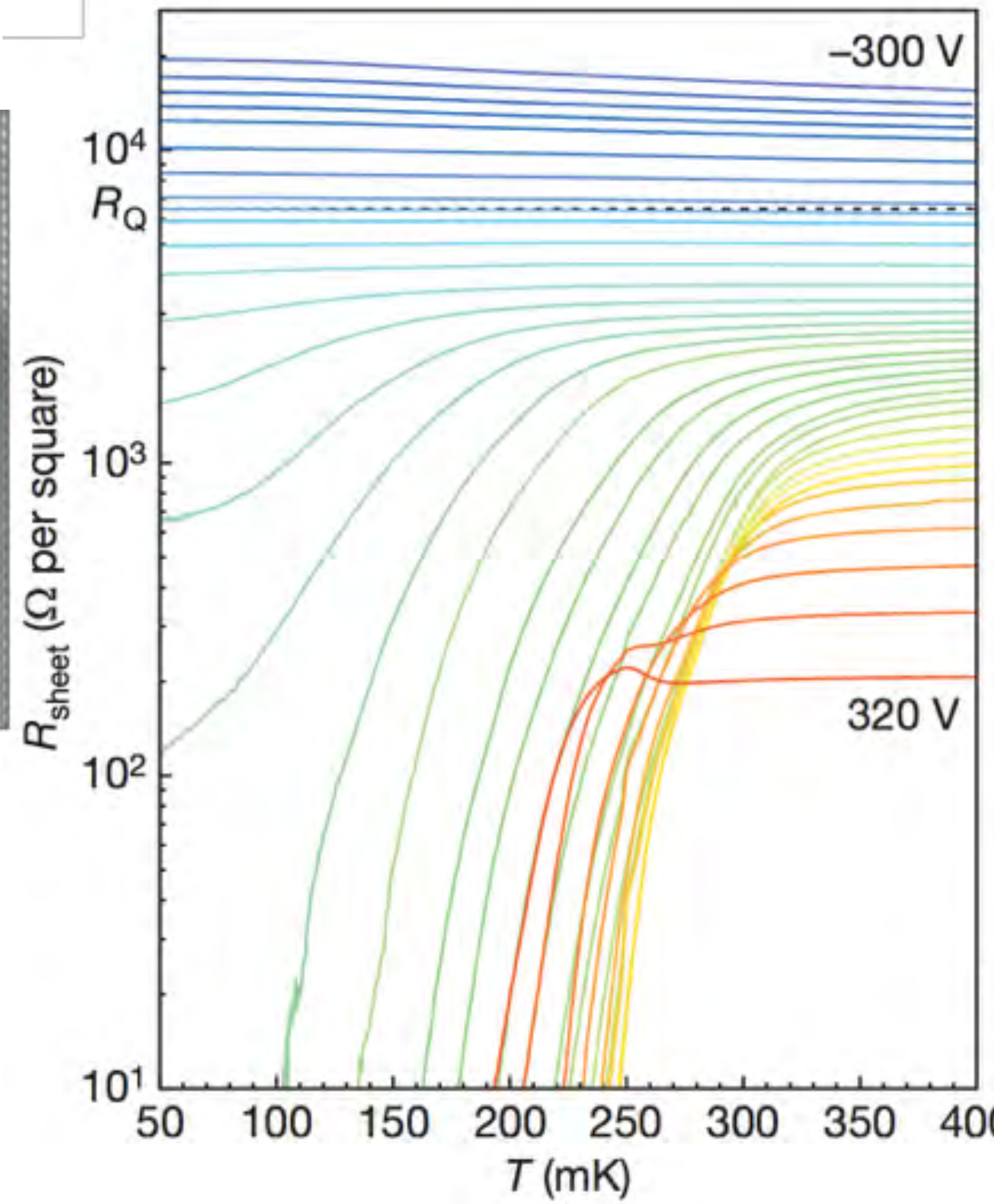
LAO/STO interface gated with STO substrate
by Reyren, Caviglia, Triscone *et al.*





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

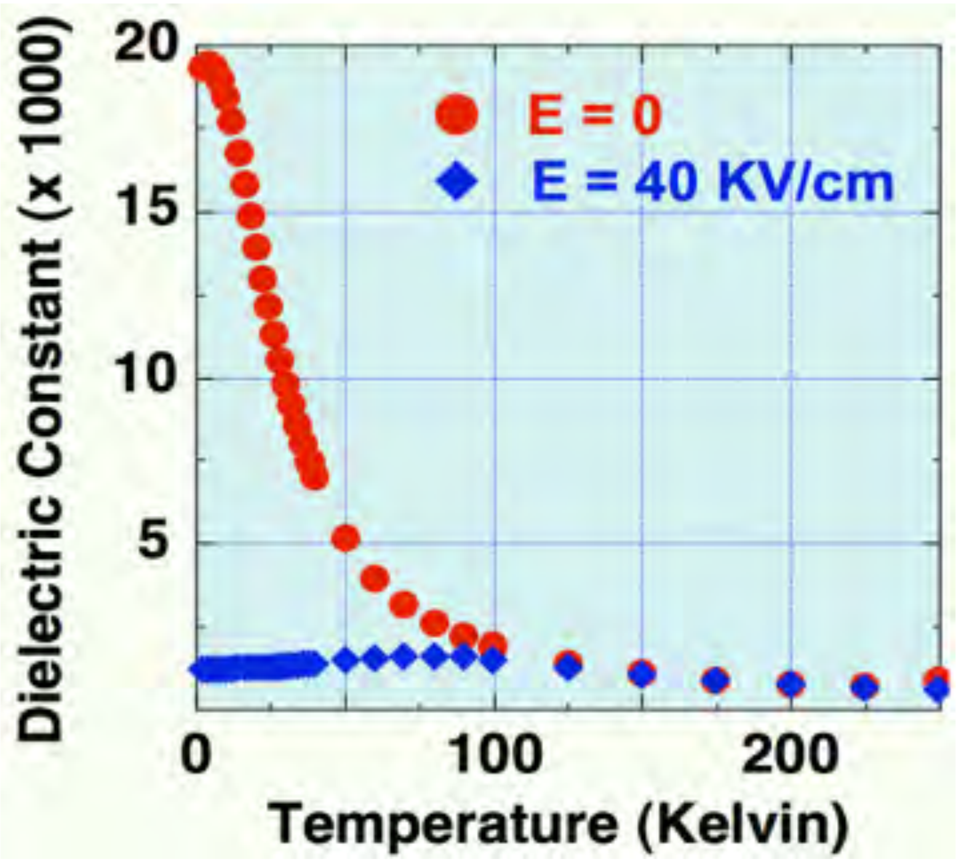


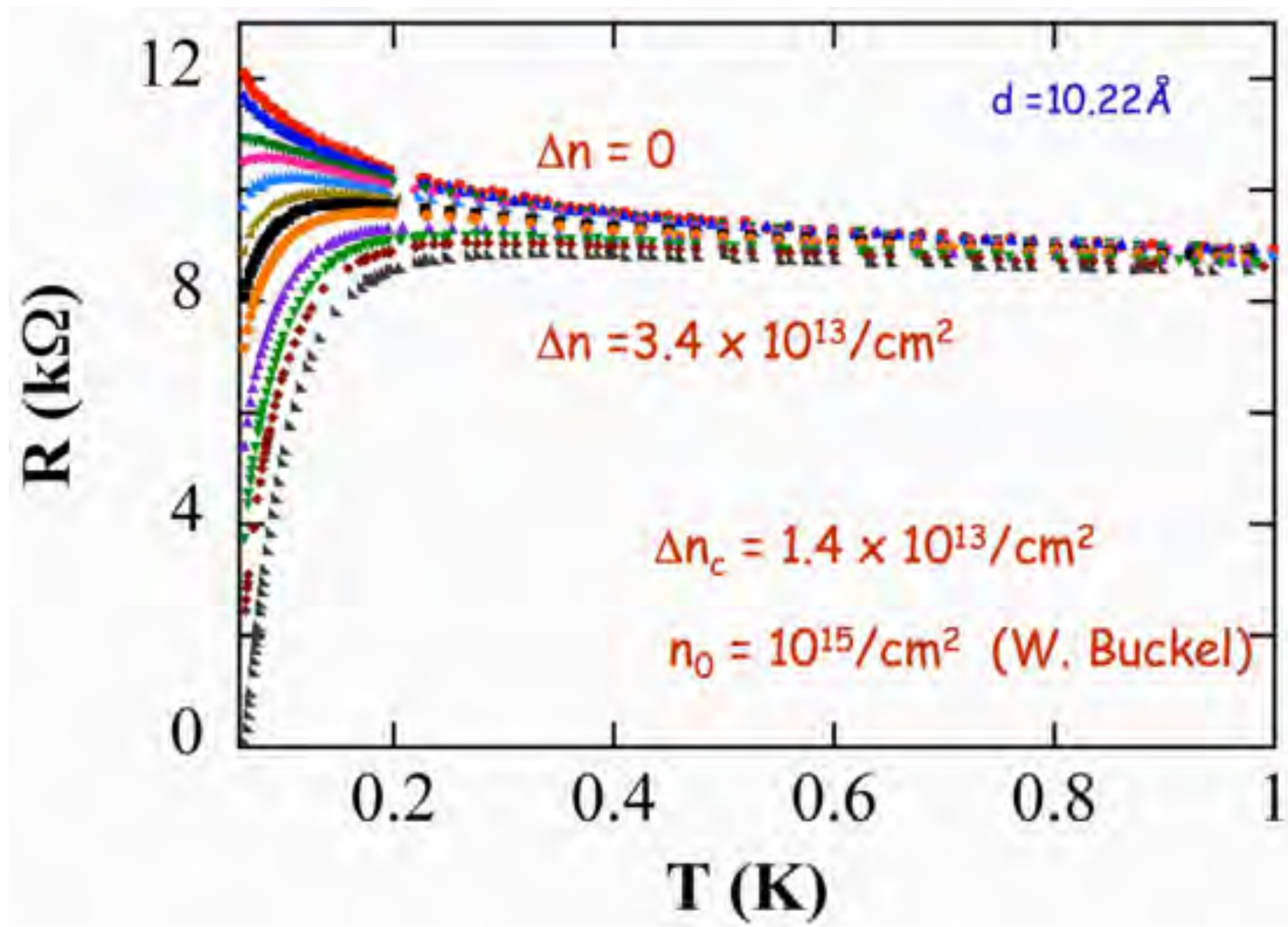


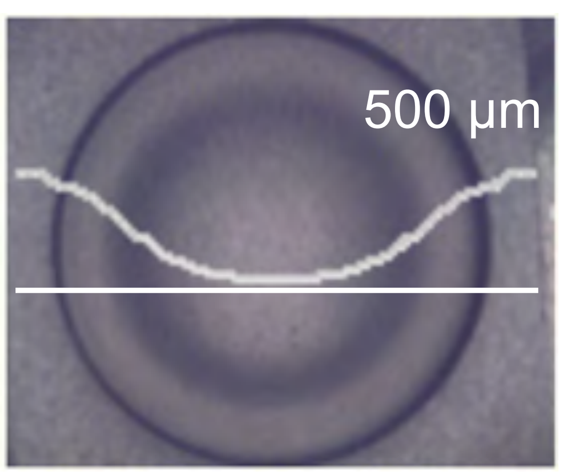
D. Caviglia, *et al.*,
Nature **456**, 624 (2008)

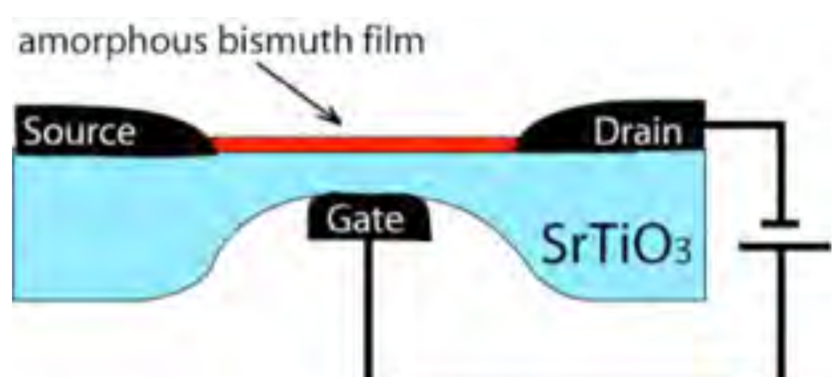
Metallic Thin Film

Optimized SrTiO3 Gate for Metal thin films Bhattacharya, Goldman *et al.*





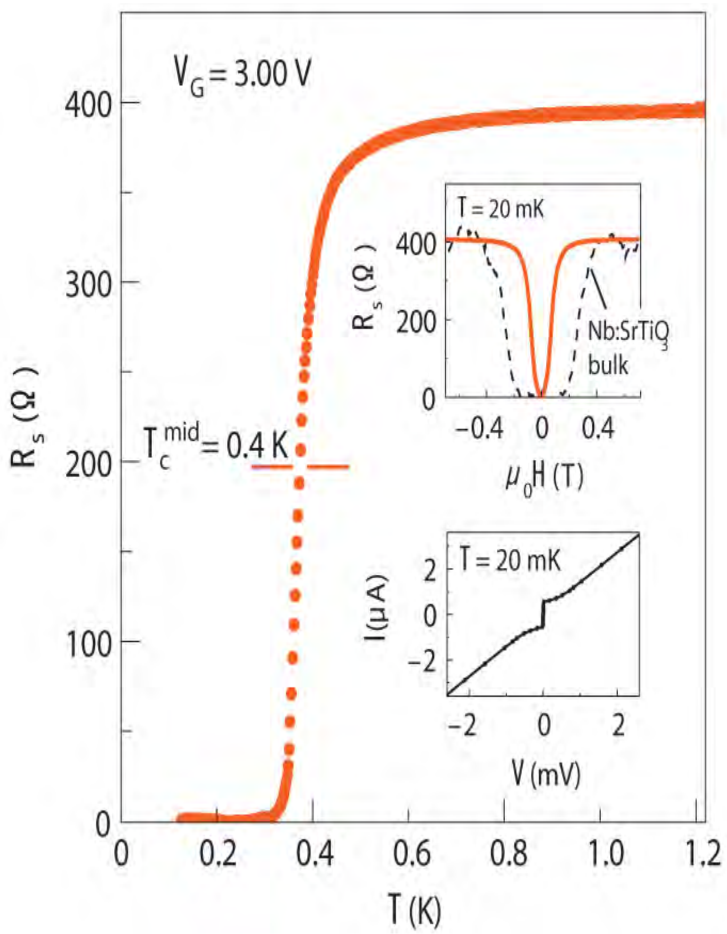




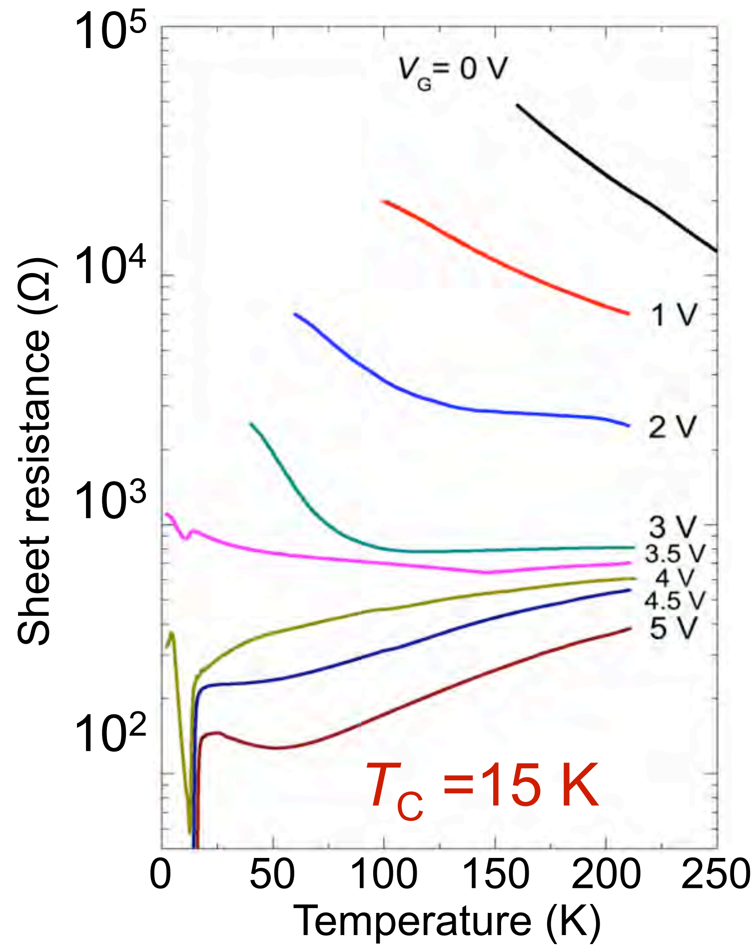
A. Bhattacharya

Gate-Induced Superconductivity (GIS)

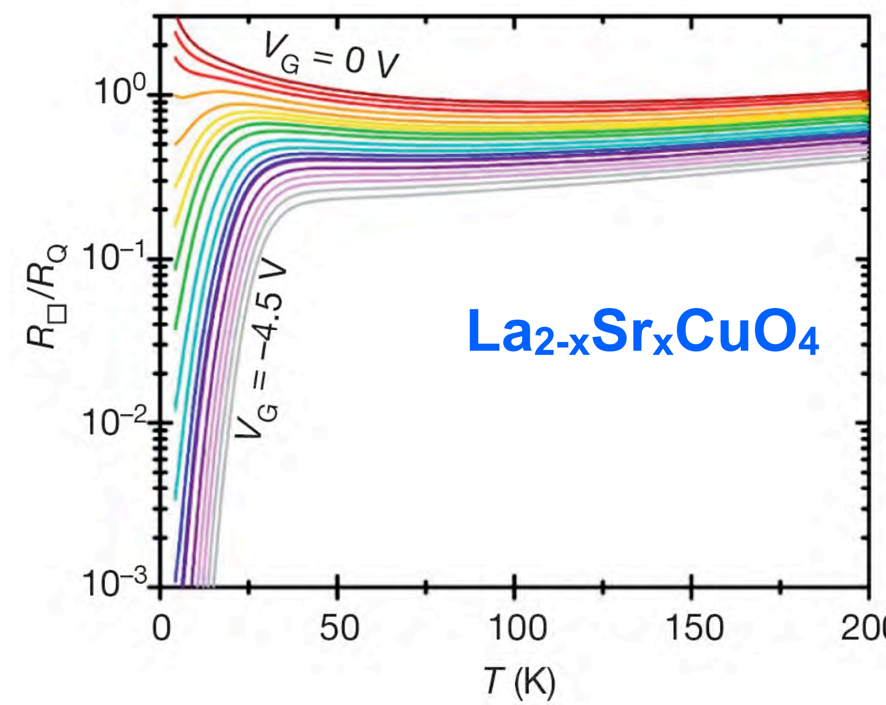
$SrTiO_3$ Ueno *et al.* (2008)



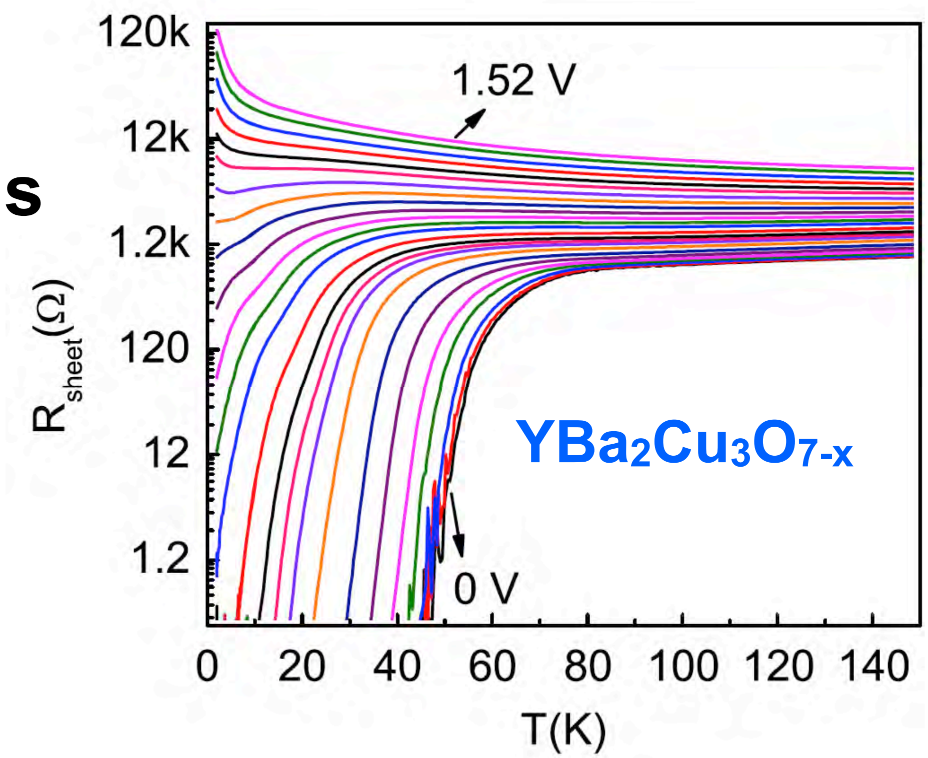
ZrNCl Ye *et al.* (2010)



I. Bozovic Group *Nature* (2011)



A. Goldman Group *PRL* (2011)



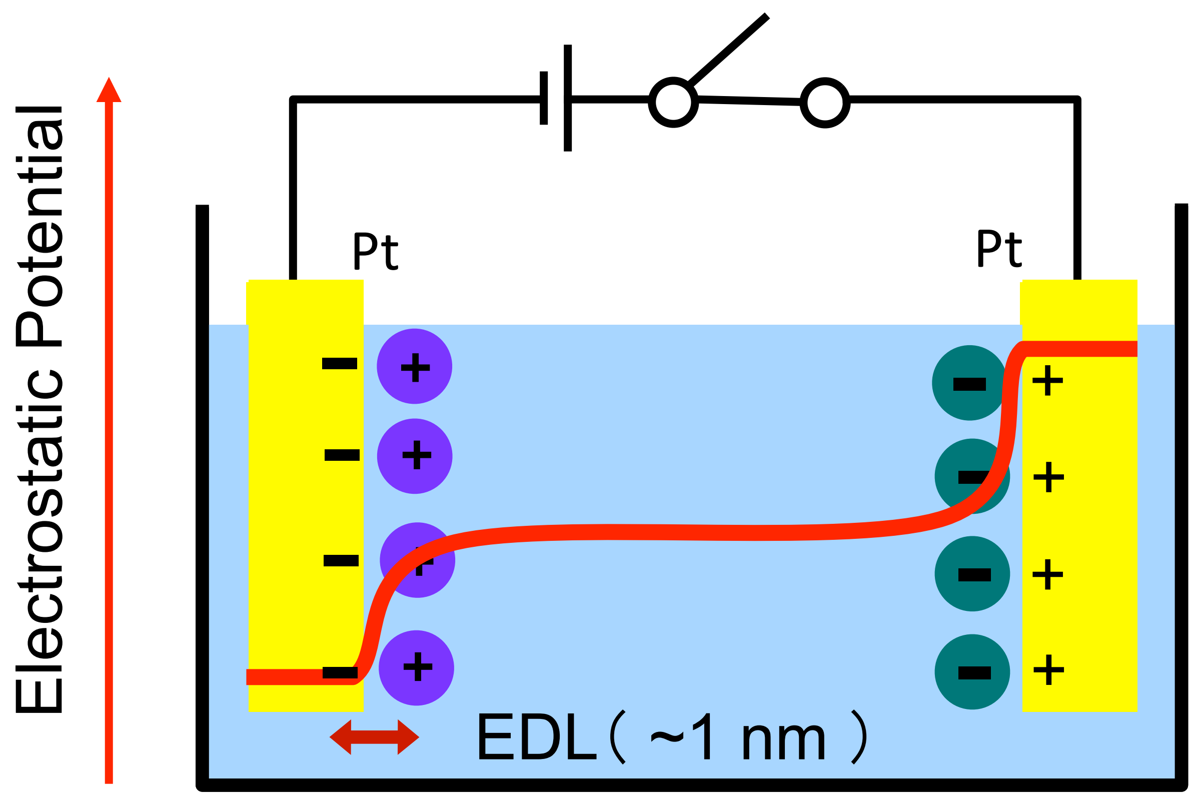
All ionic gating method on
Substrate, MBE or PLD thin films, 2D Materials

Remaining Challenges:
Switching Insulator
Controllability
Device Flavor

Alternative Idea: Electric Double Layer (EDL)

Electric Double Layer (EDL)
at interfaces between electronic and ionic conductors

Electrochemical cell

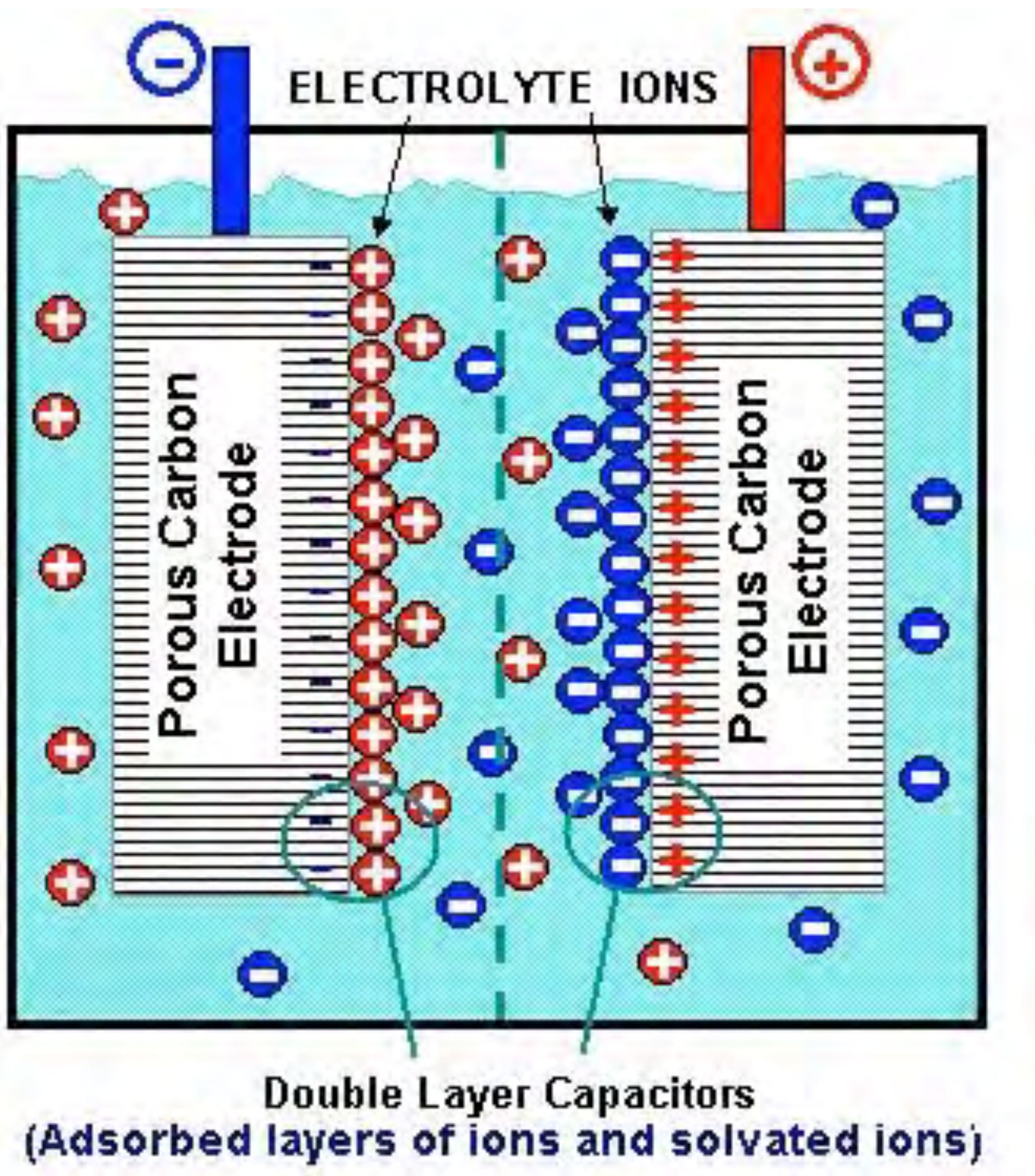


Helmholtz's electric double layer (1853)

Hermann von Helmholtz
(1821-1894)

Charge Accumulation Device

Electric Double Layer Capacitor



Module of EDL capacitor

Maxwell Technologies

Nippon Chemi-Con Corp

Electric Double Layer Transistors

Solid Gate Dielectric

SiO_2, HfO_2, *etc.*

Channel semiconductor

Oxide

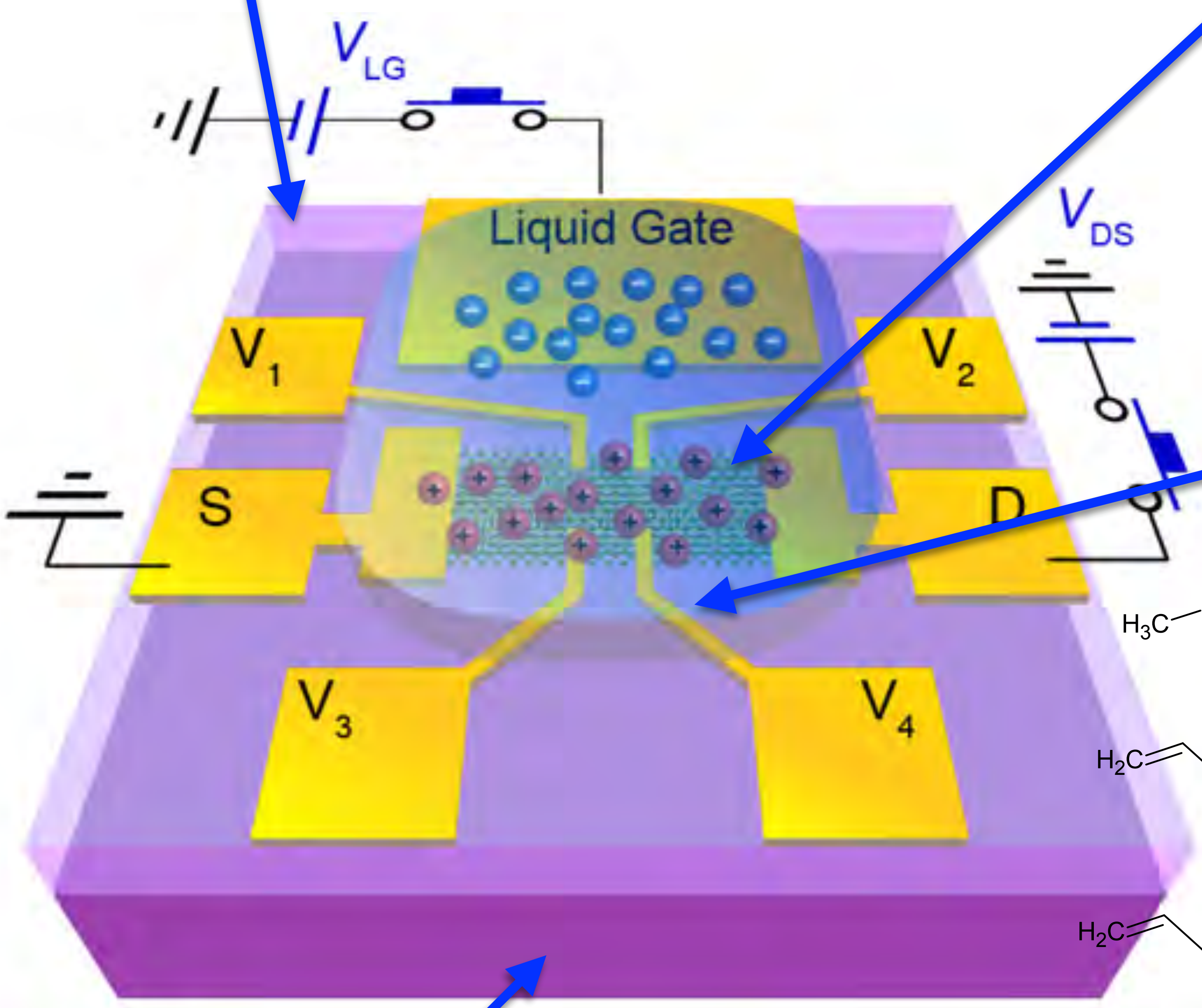
Si, GaAs

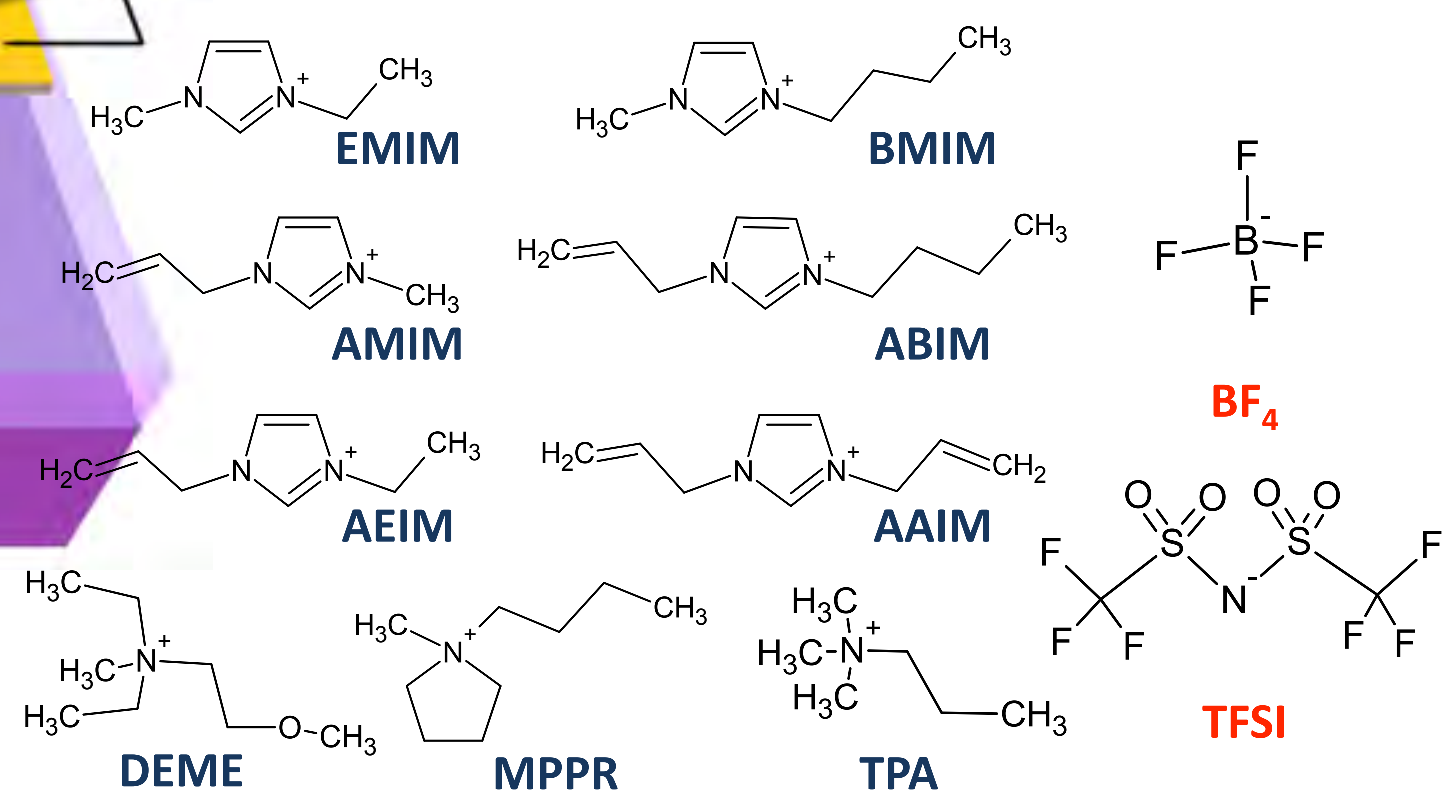
Chalcogendes

Au, Pt, Au, Co, *etc.*

Ionic media

Inorganic, Organic





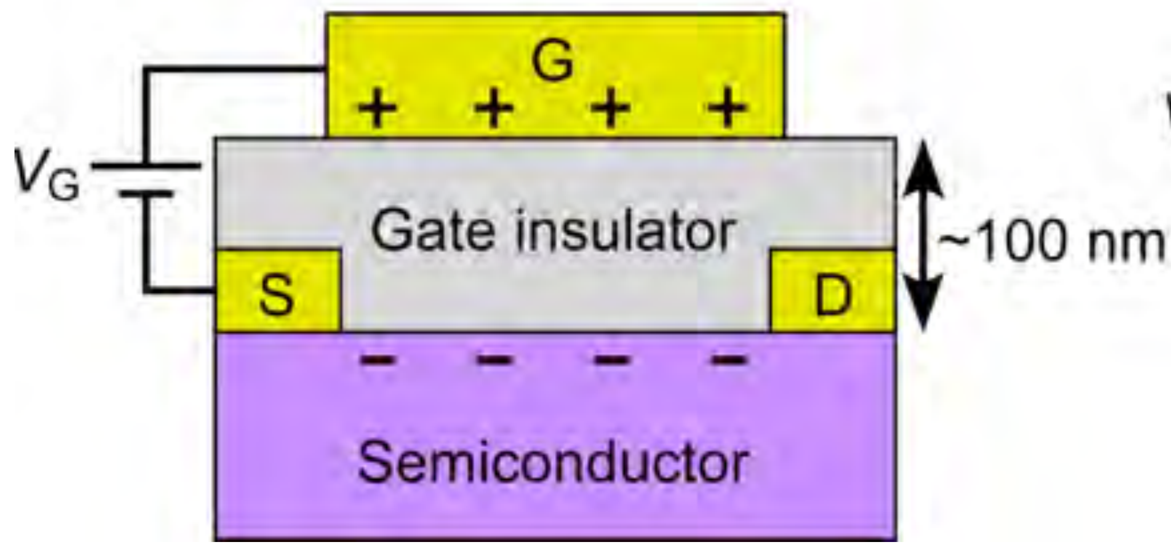
Substrate

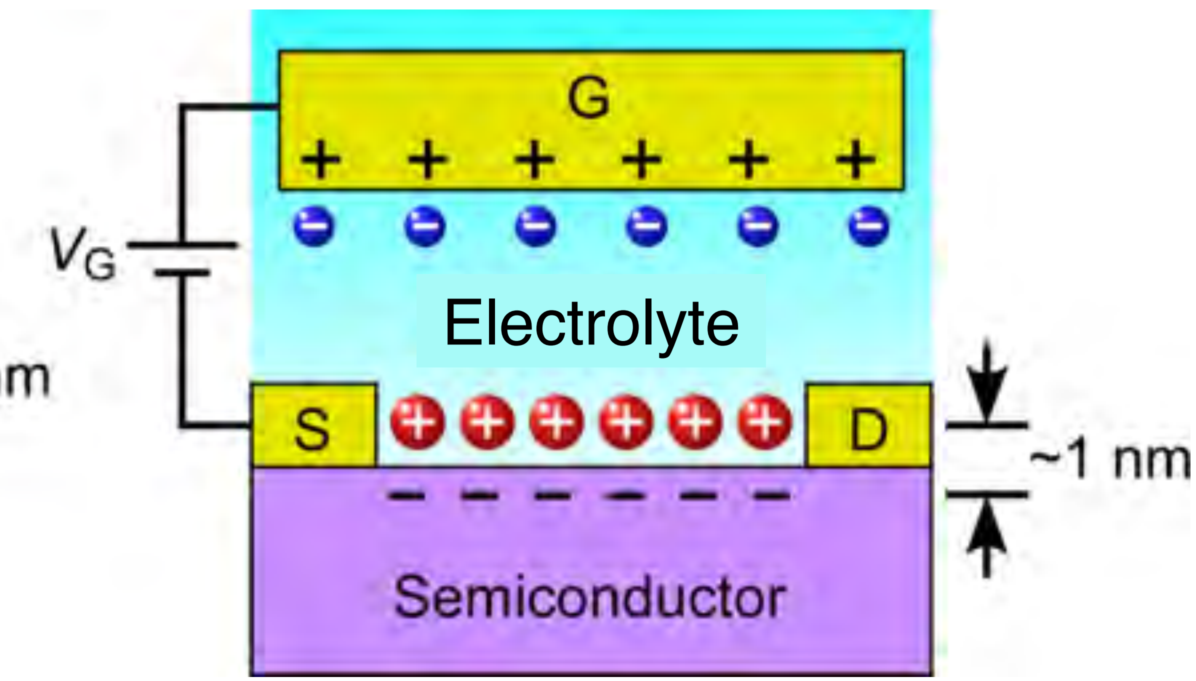
Doped Si, Nb doped $SrTiO_3$

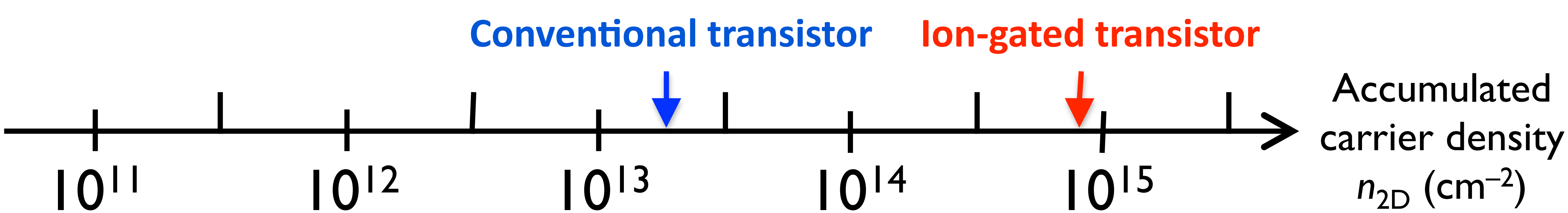
Electrical Double Layer Transistors

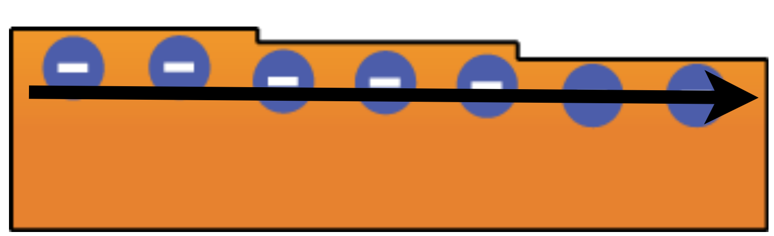
Ion-gated Transistor
Electric double layer transistor (EDLT)

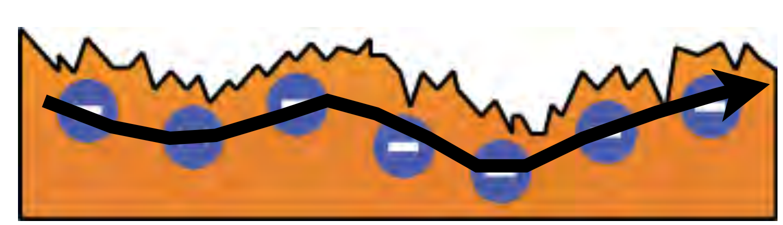
Conventional FET



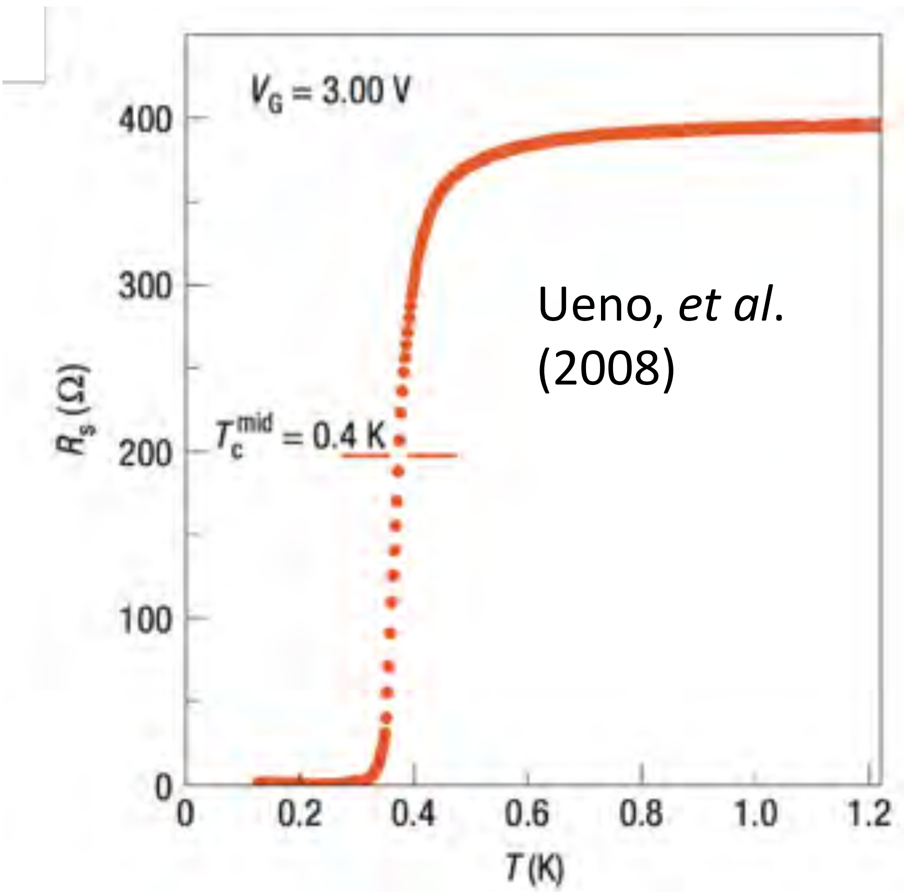


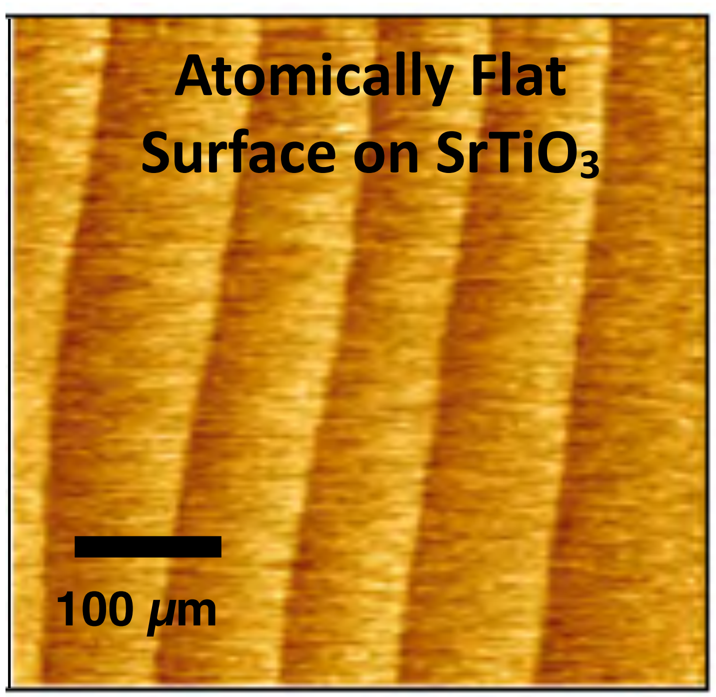






Inducing Superconductivity in $SrTiO_3$





- **Material showing superconductivity with lowest density of carriers**

  $n_{3D} = 10^{18} \sim 10^{19}\ cm^{-2}$

- **Readily atomically flat surface**

  Commercial wafer

  HF etching for atomically flat surface

- **Quantum paraelectric material**

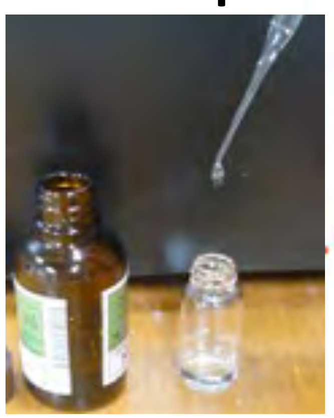
  Larger dielectric constant ~ 1000

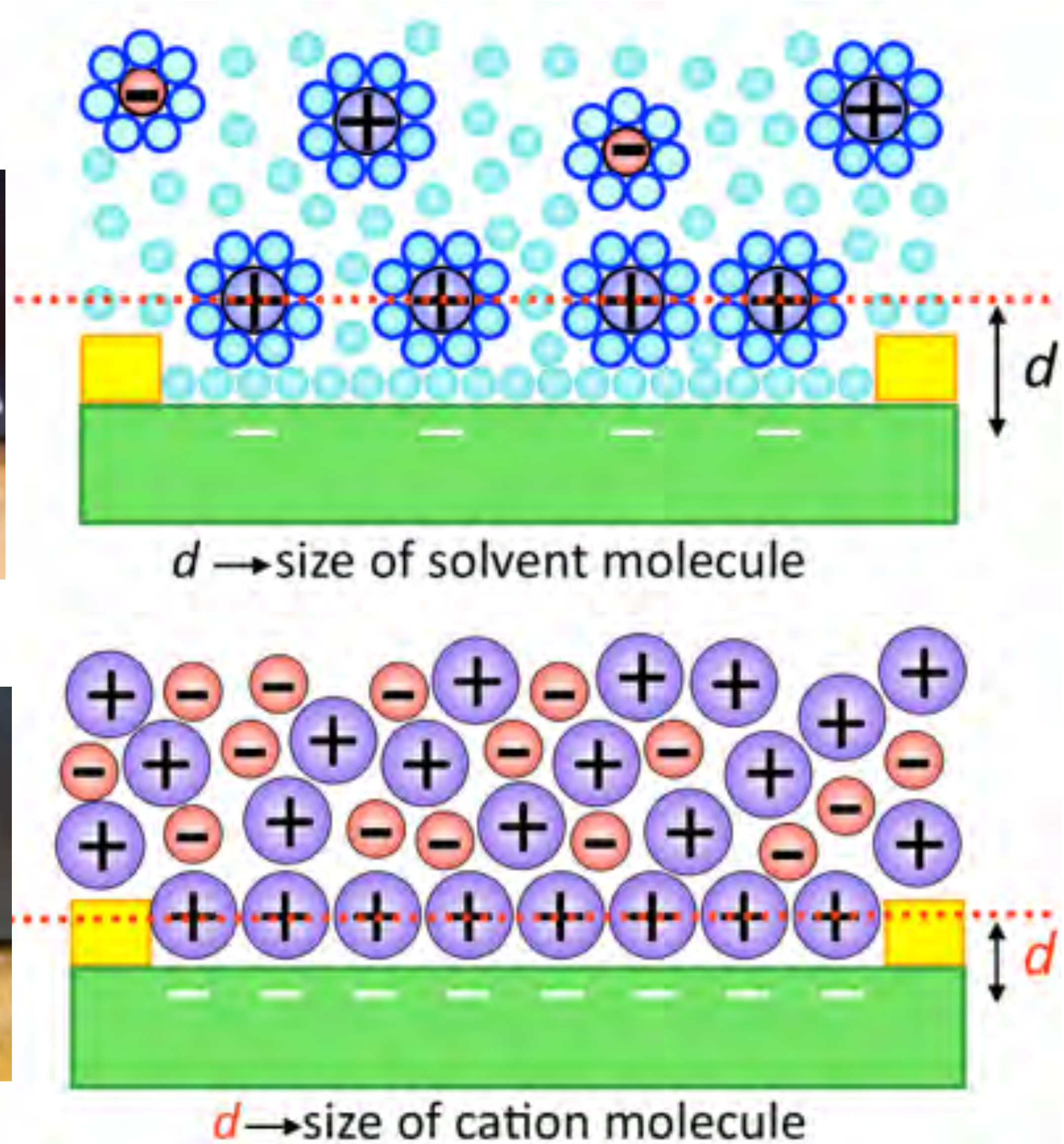
field-induced SC	T_c (K)	Carrier Density (3D, $x10^{19} cm^{-3}$)	Atomically Flat Surface ?
$SrTiO_3$	0,3	1	Commercial
Other materials	**much higher**	**10 ~ 100**	**Difficult**

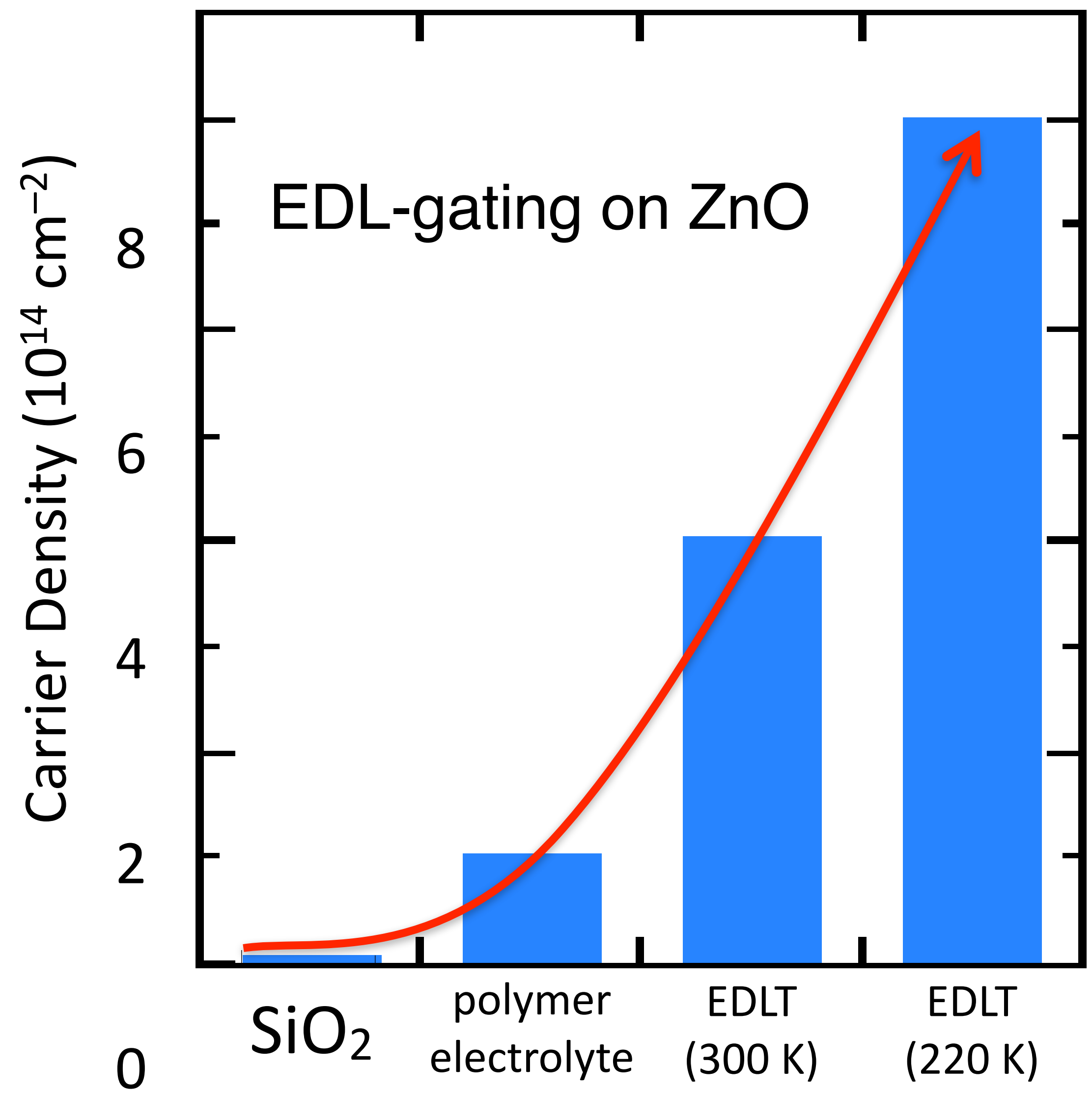
Gating with ionic liquids for higher doping

Polymer Electrolyte

Ionic Liquid







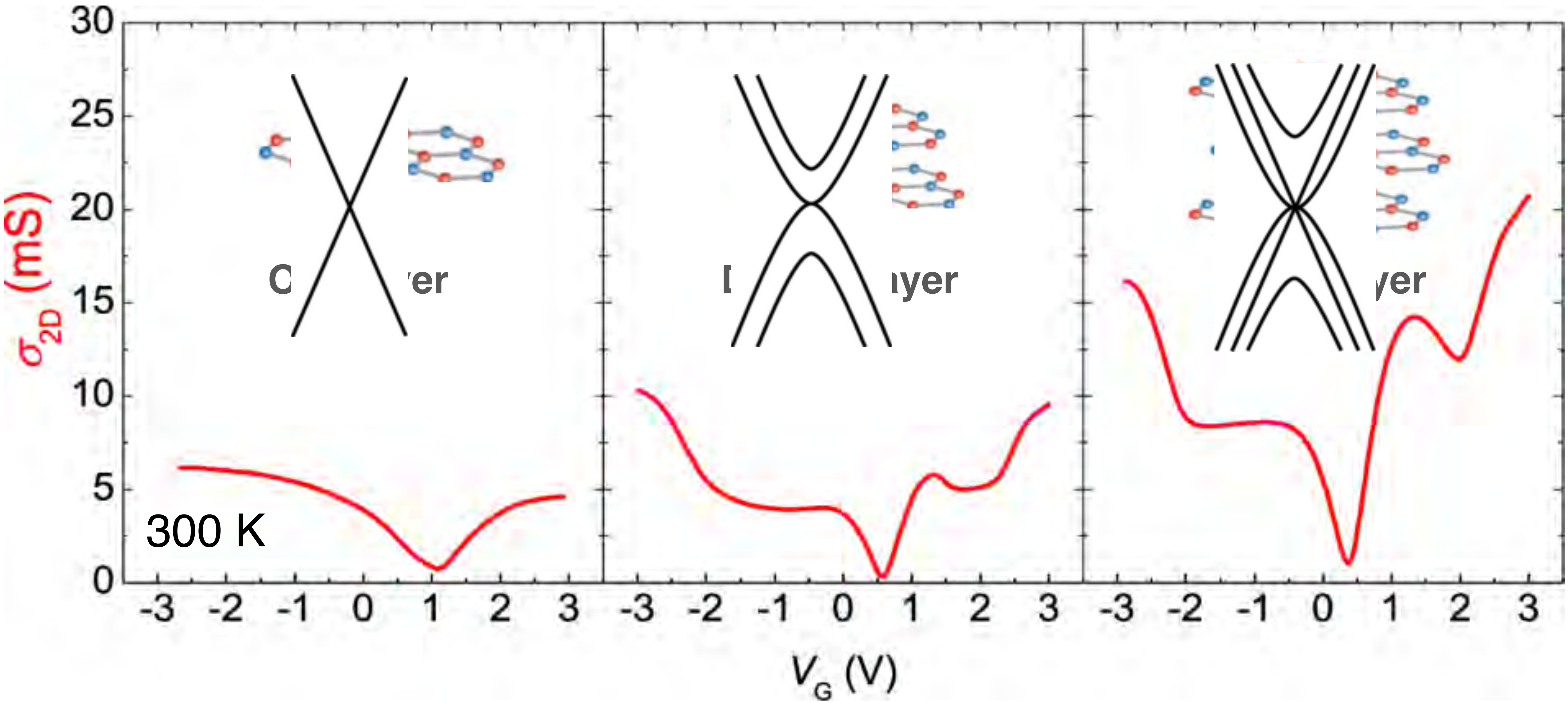
4×10^{14} cm^{-2} very large carrier density !

Monolayer fullerene ~ 1 x 10^{14} molecules/cm^2

Monolayer perovskite ~ 1 x 10^{15} unit cells/cm^2

Application to Graphene and Its Multilayers

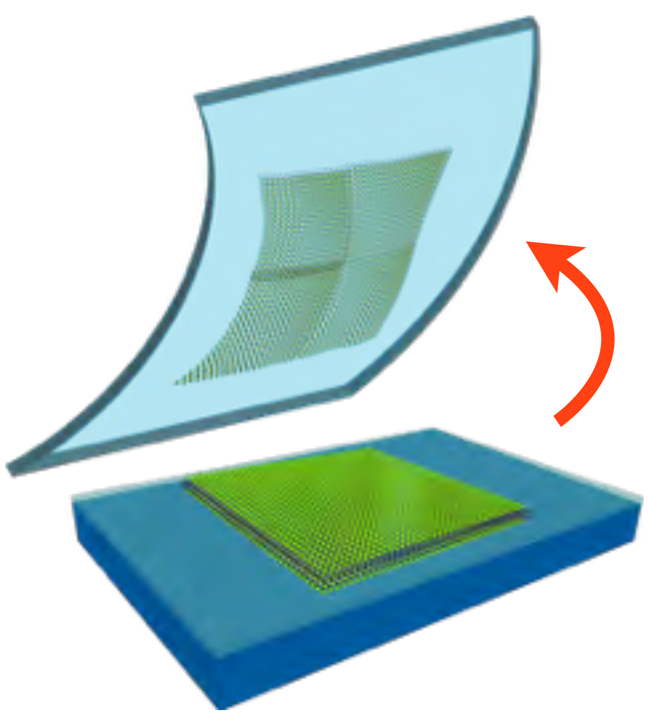
JTY *et al*. PNAS (2011)



Bi- and trilayer graphenes:
New conduction channel at the high carrier density regime

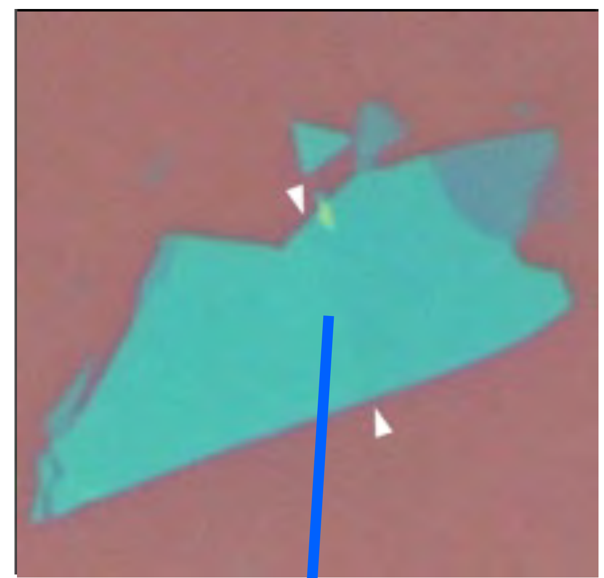
Easy fabrication of atomically flat surface

Ye, *et al.*, *Nat. Mater.* 9, 125 (2010)

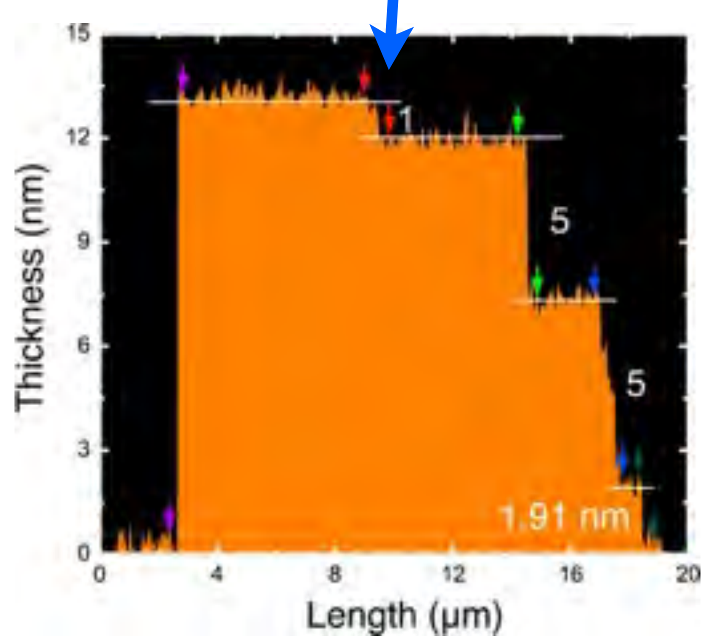


Scotch tape method (micro-cleavage)

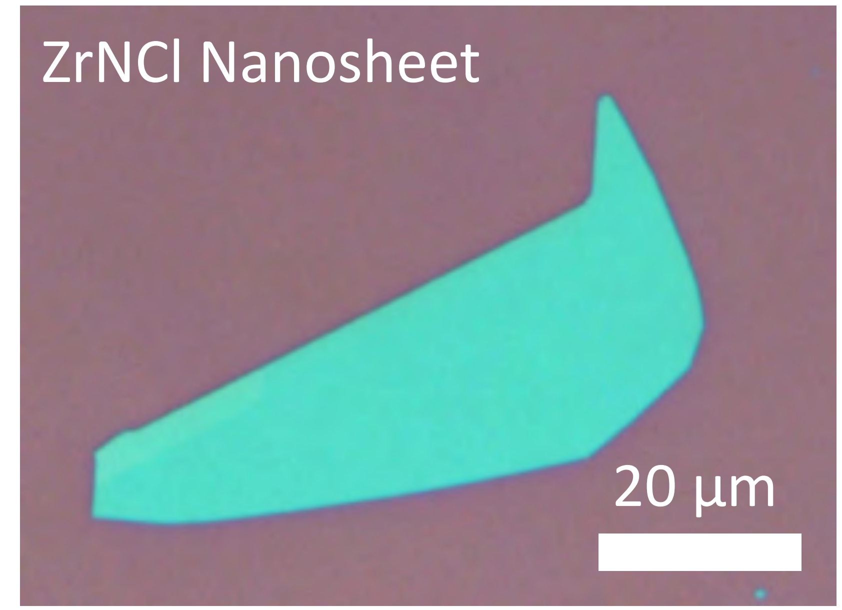
Optical Micrograph

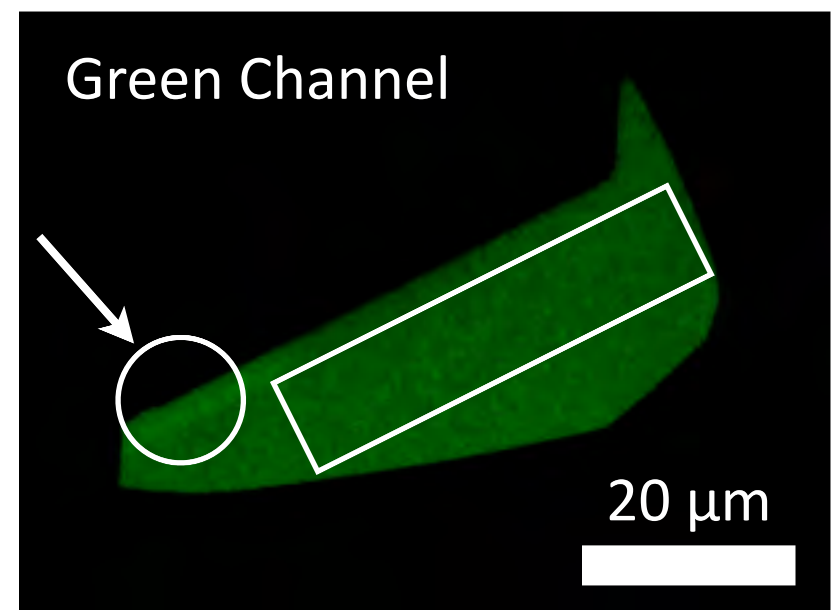


AFM Hight Profile



Easy-identification of Surface Profile

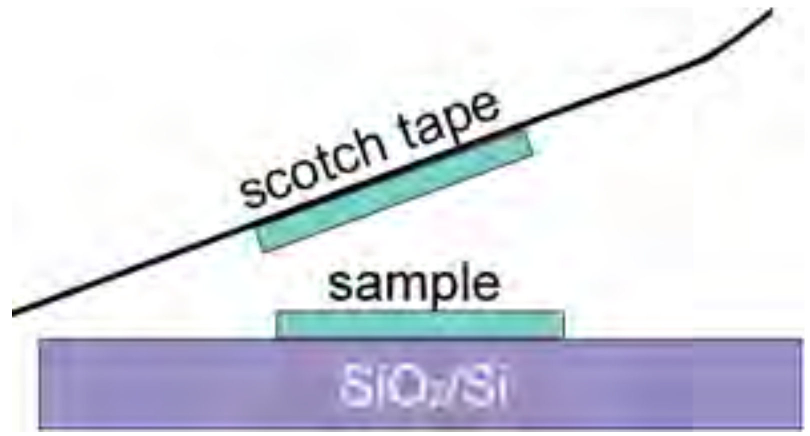




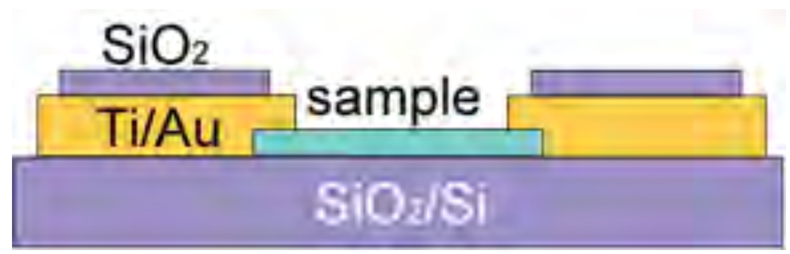
Making FET on a atomically flat surface

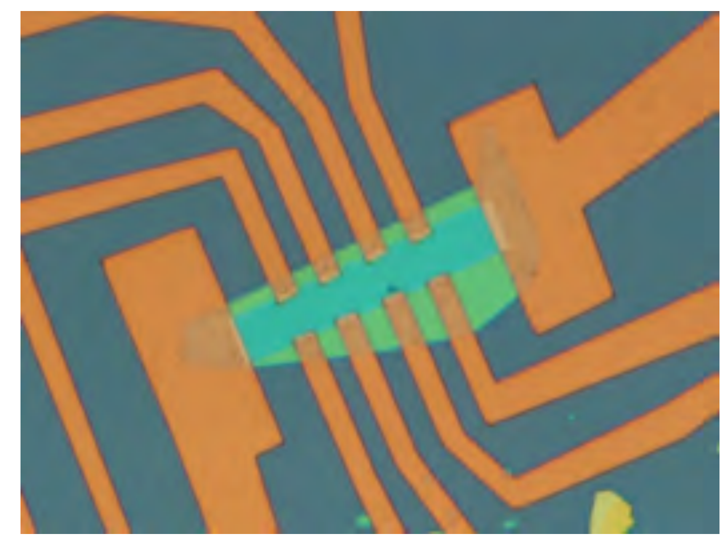
A Typical Device Fabrication

1.Micro-clevage

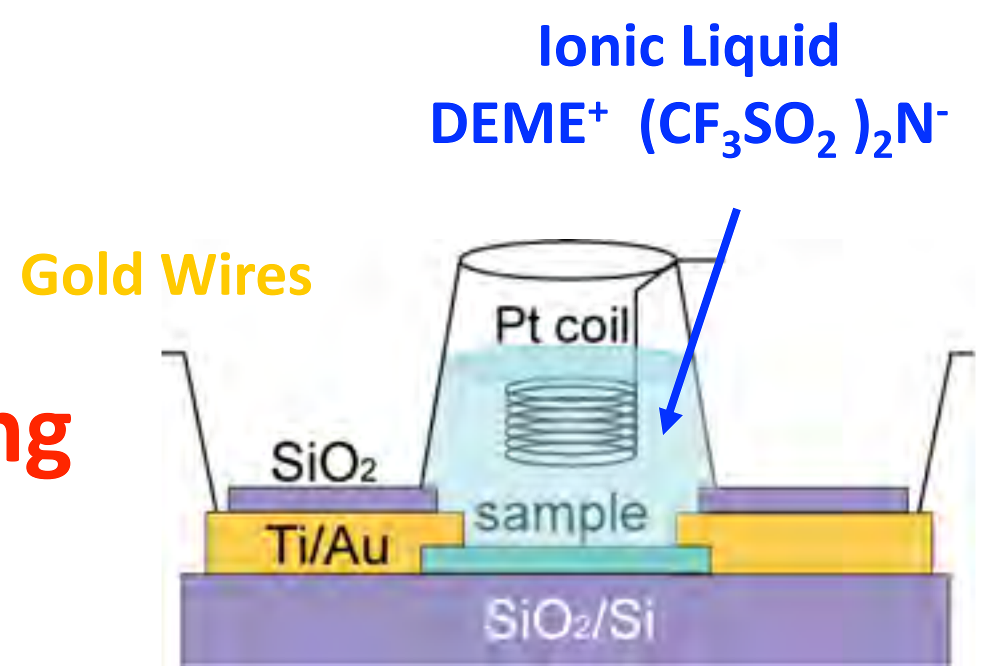


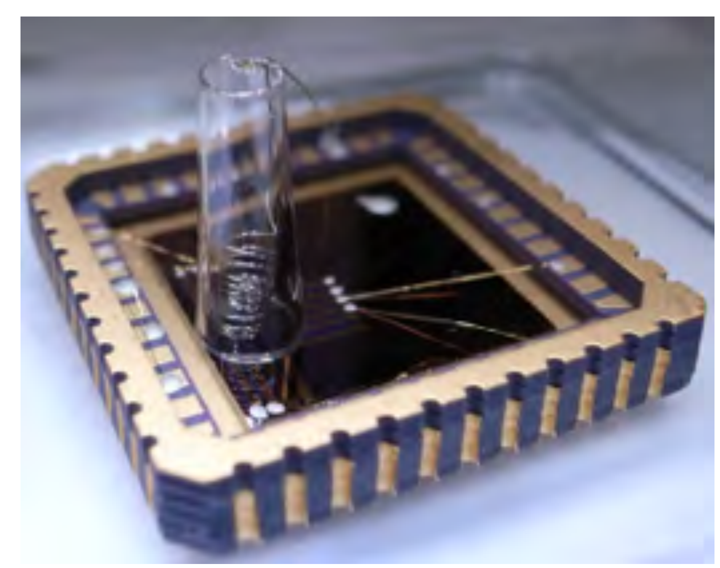
2.Electrodes





3.Device Packing

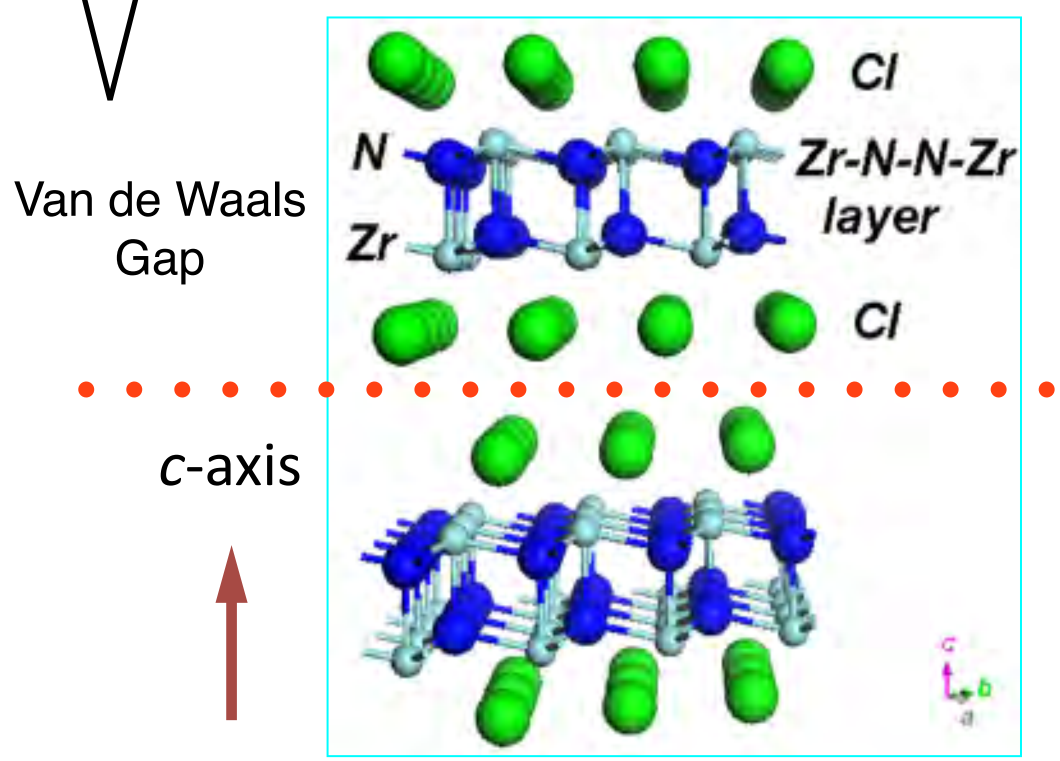




First Target: ZrNCl

Ye *et al.*, *Nat. Mater.* (2010)

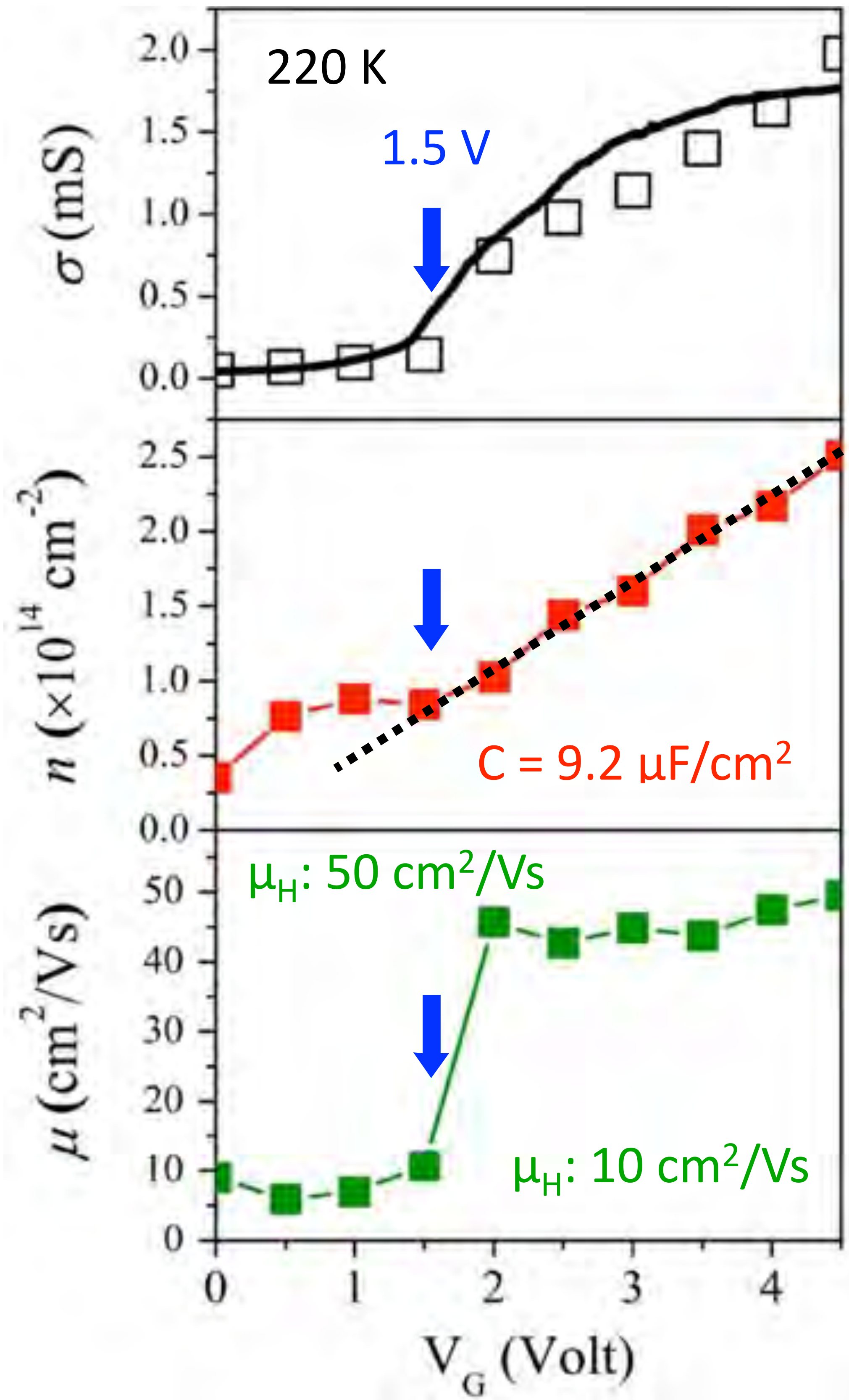
Scotch Tape Method



Alkali-doping

$Li_{0.06}ZrNCl$ $T_c = 15$ K

Y. Taguchi *et al*. *PRL* (1998)



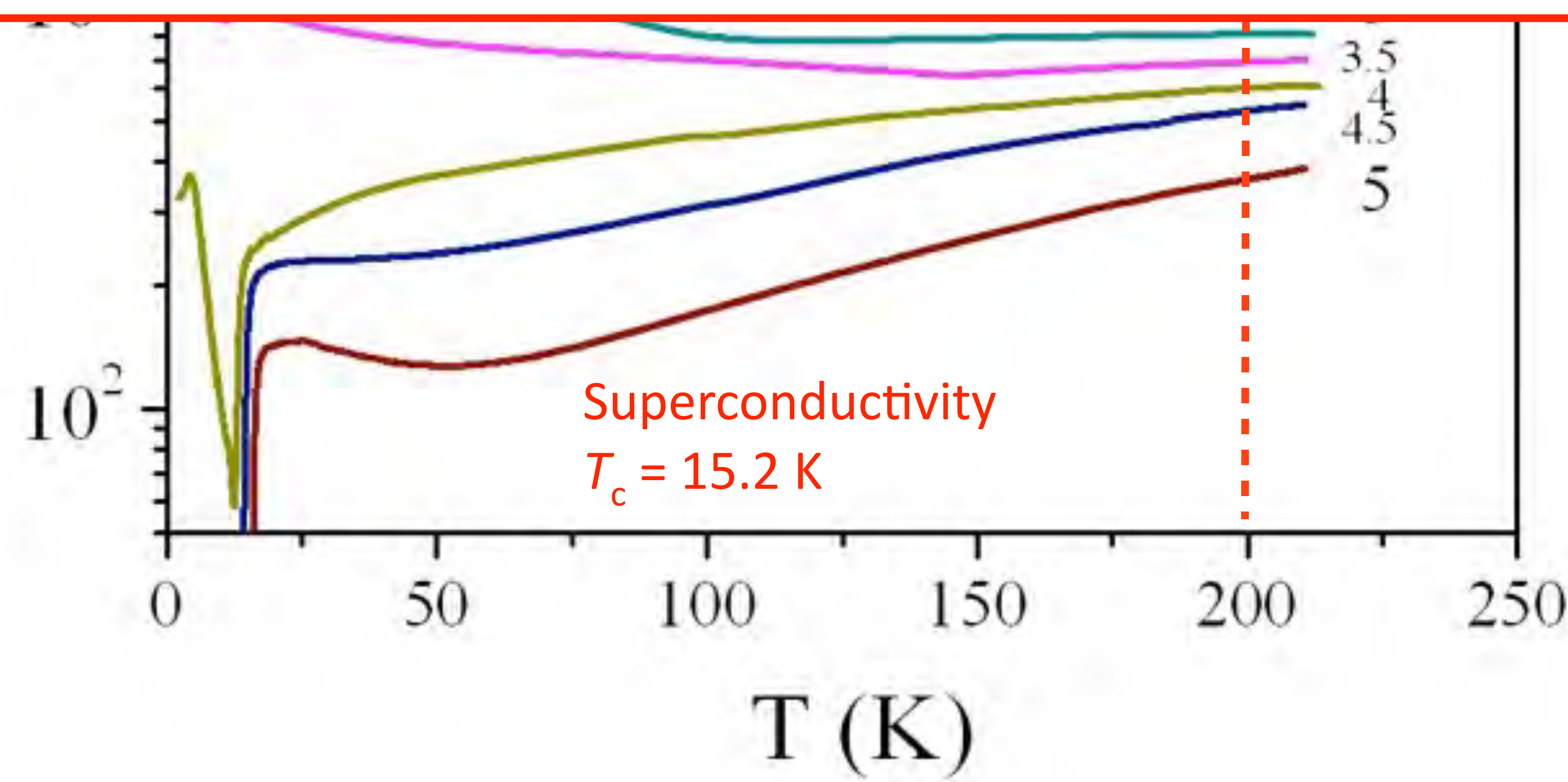
Field-induced Interface Superconductivity in ZrNCl Nanosheets

Ye *et al.*, *Nat. Mater.* 9, 125 (2010)

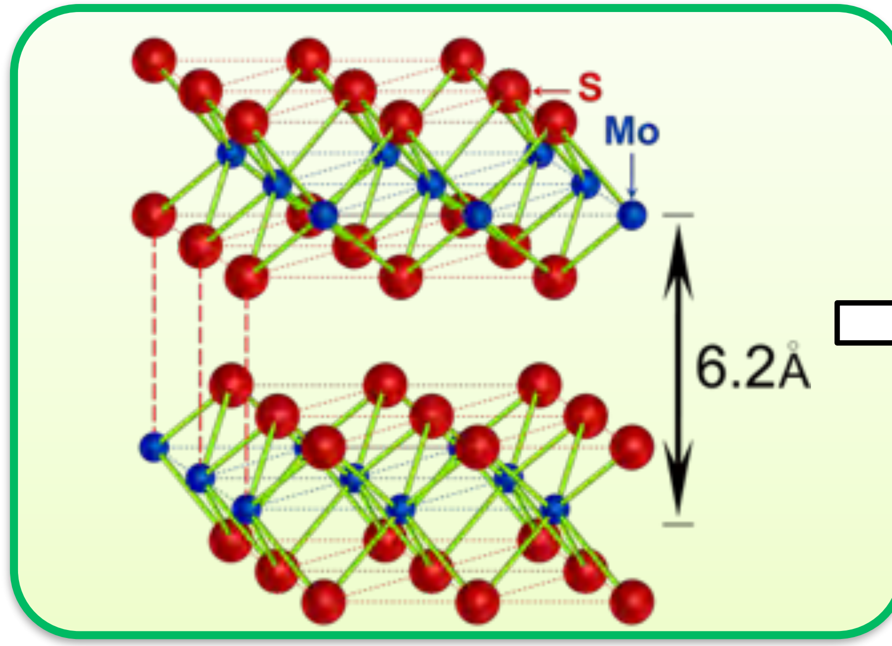
1. **Possible for high T_c**
2. **Accessing carrier density of normal superconductors**
3. **A protocol for other nanosheets**

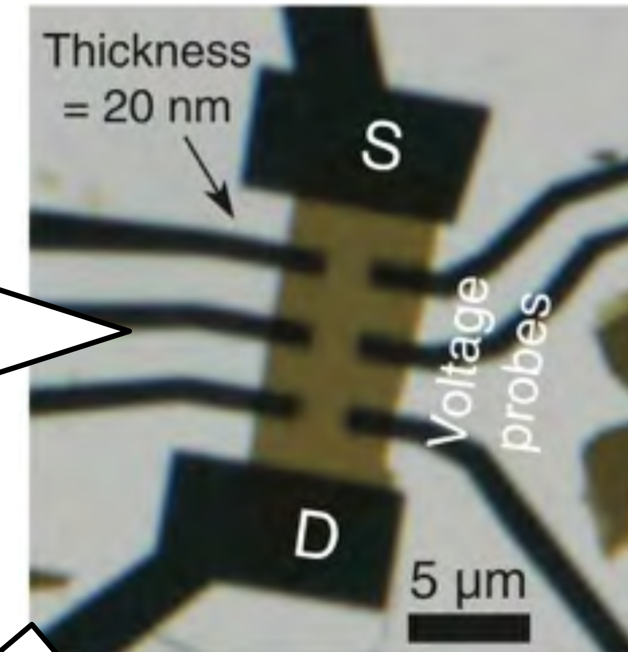
   Importance of flat surface

   Ionic liquid



Changing the Role of MoS_2

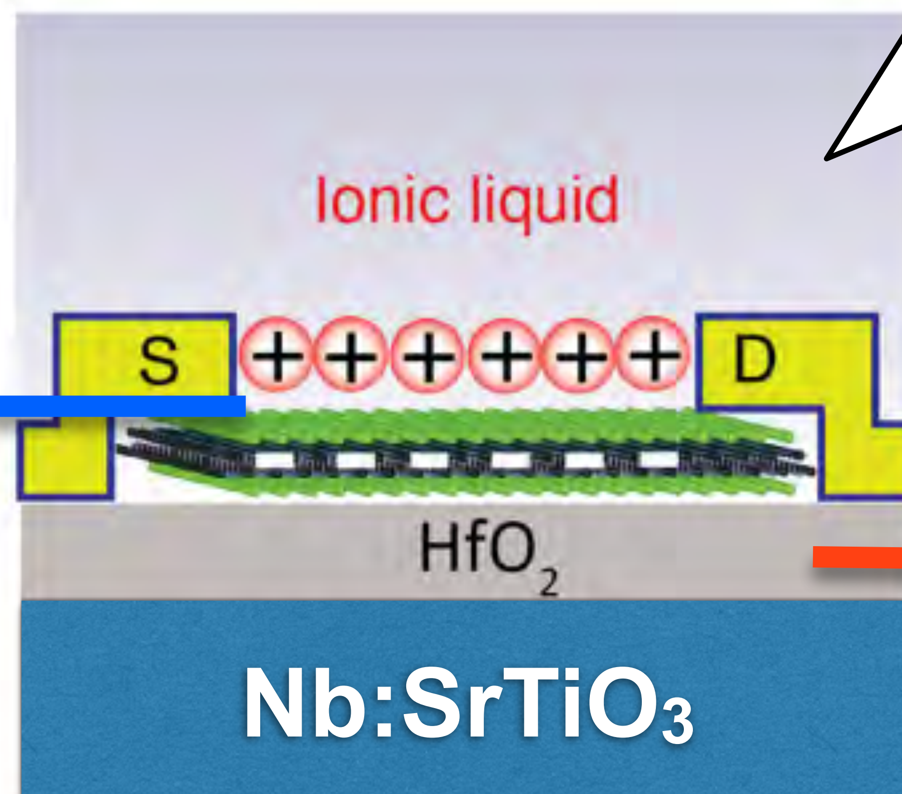




Coarse tuning in ~10^{14} cm^{-2}

at > 200 K

Field-induced superconductivity



Double-gate thin flake device

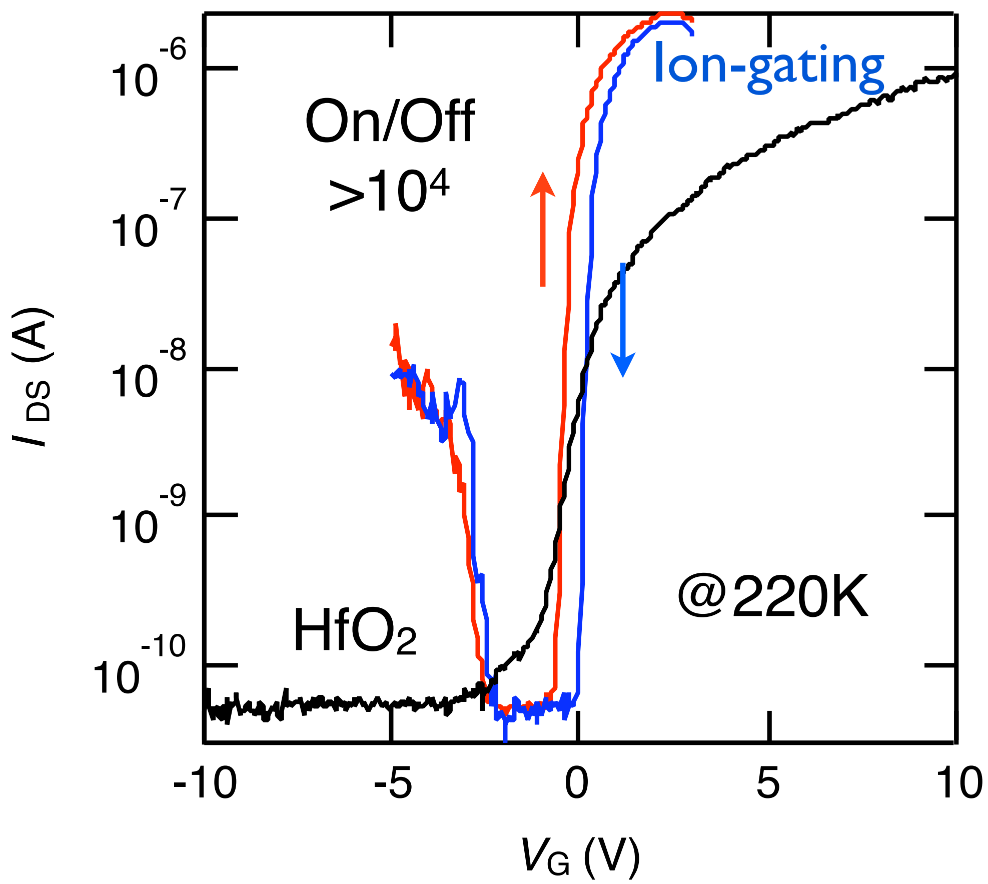
Fine tuning in ~10^{13} cm^{-2}

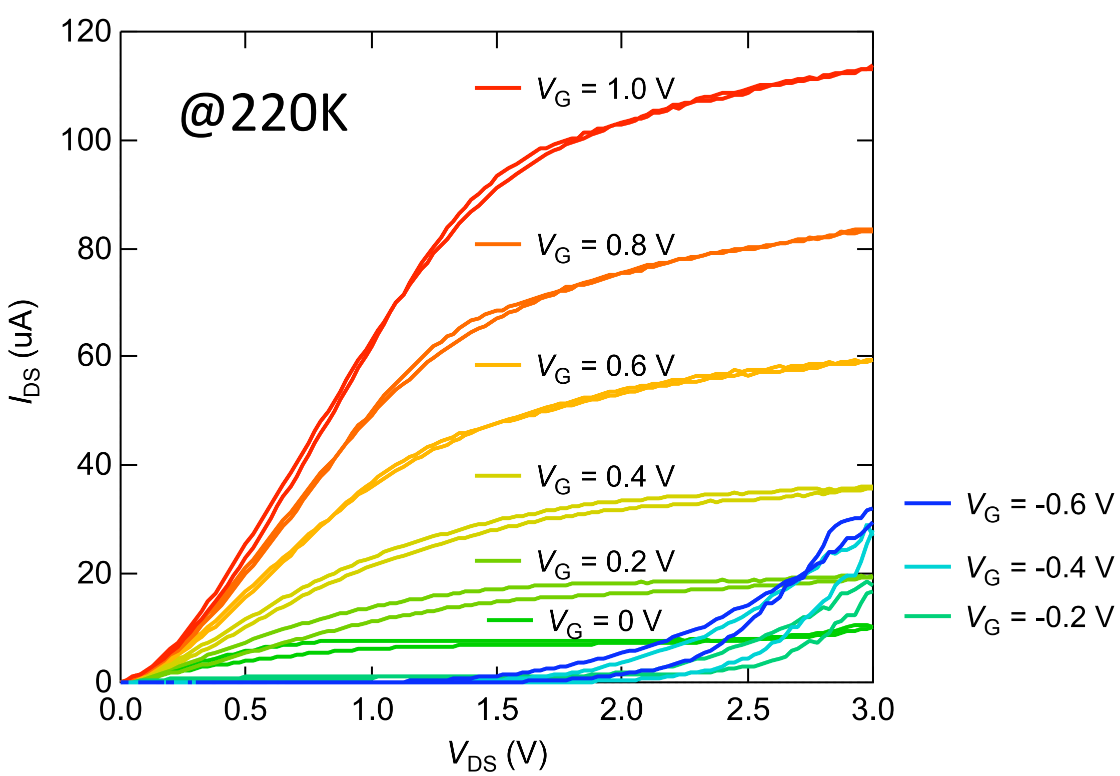
at any temperature

Detailed mapping of the electronic properties

Transistor Operations

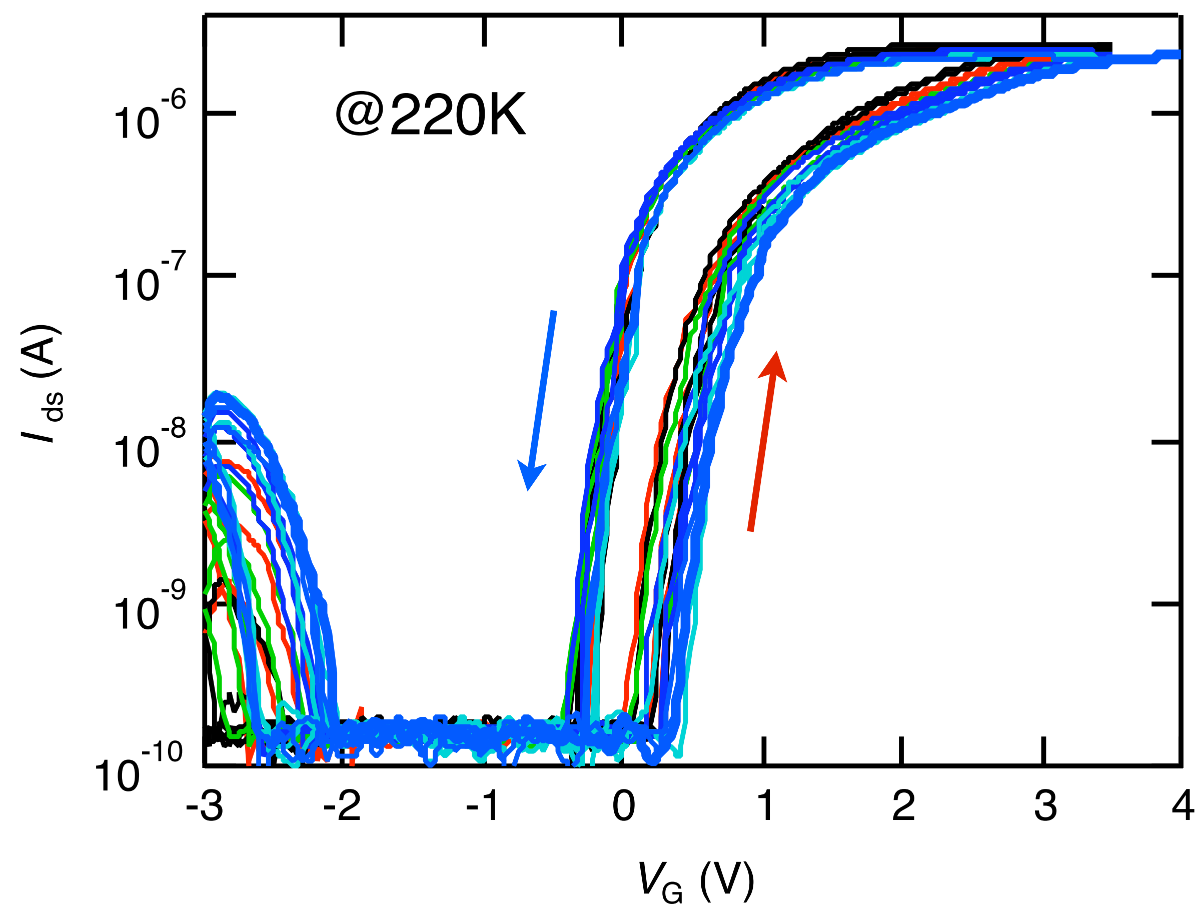
Zhang, Ye *et al*. *Nano Lett.* (2012)





Electrostatic? Transistor Operation?

❖ Reversibility ❖ Response time



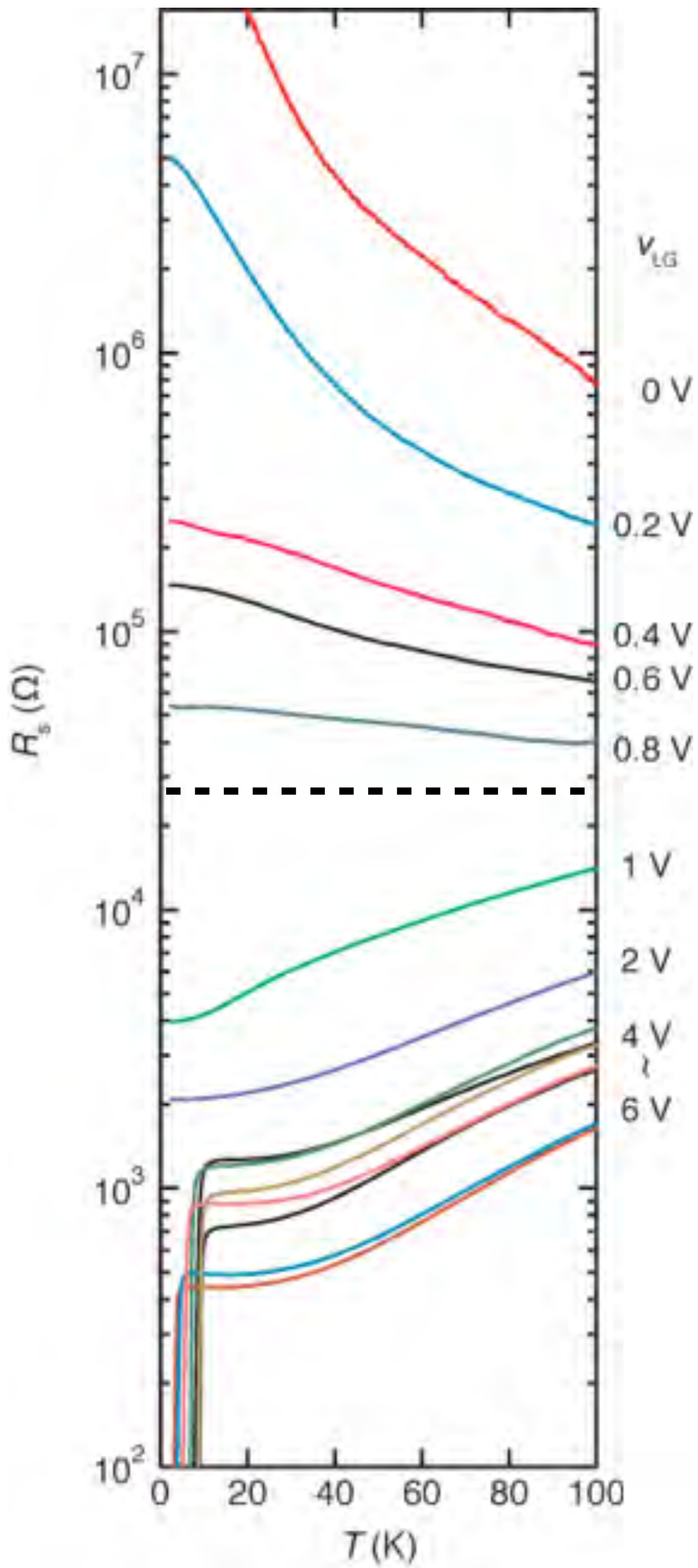
Fully Reversible ***On/Off states***

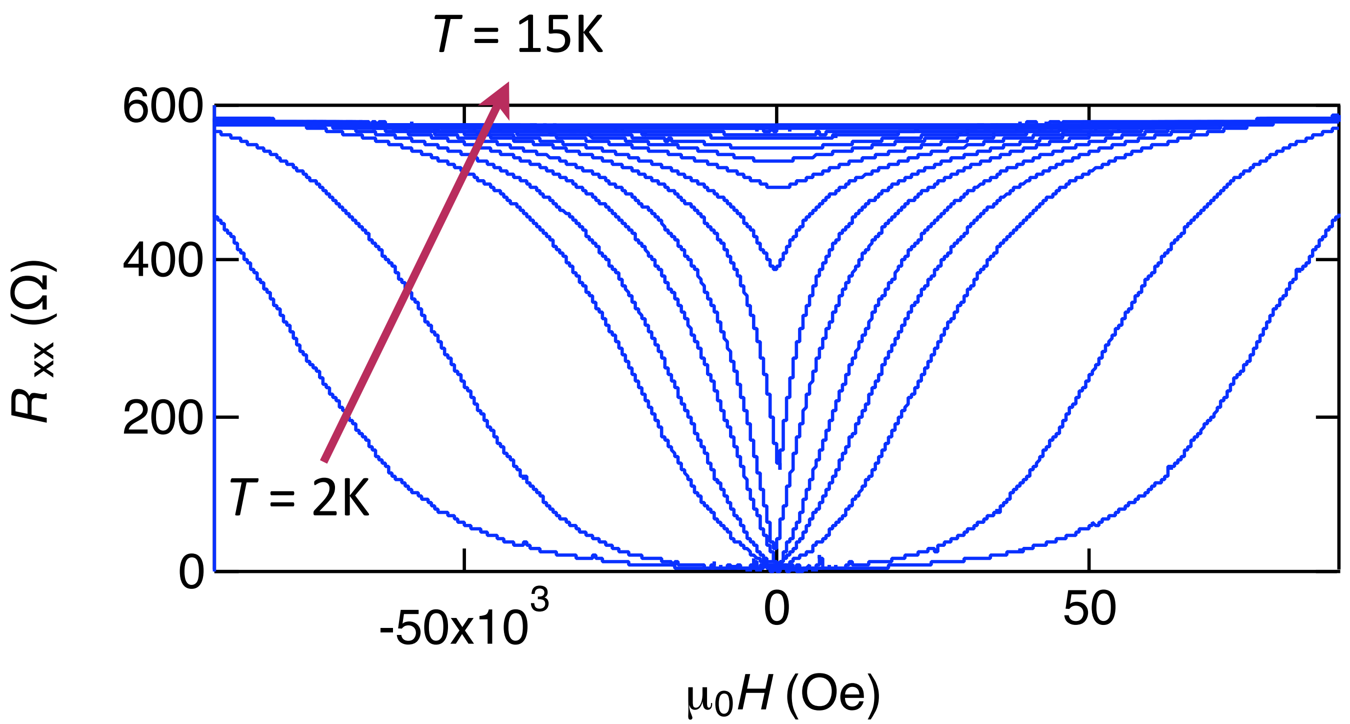
Quick Response ***3 min/cycle***
@220 K

Electrostatic

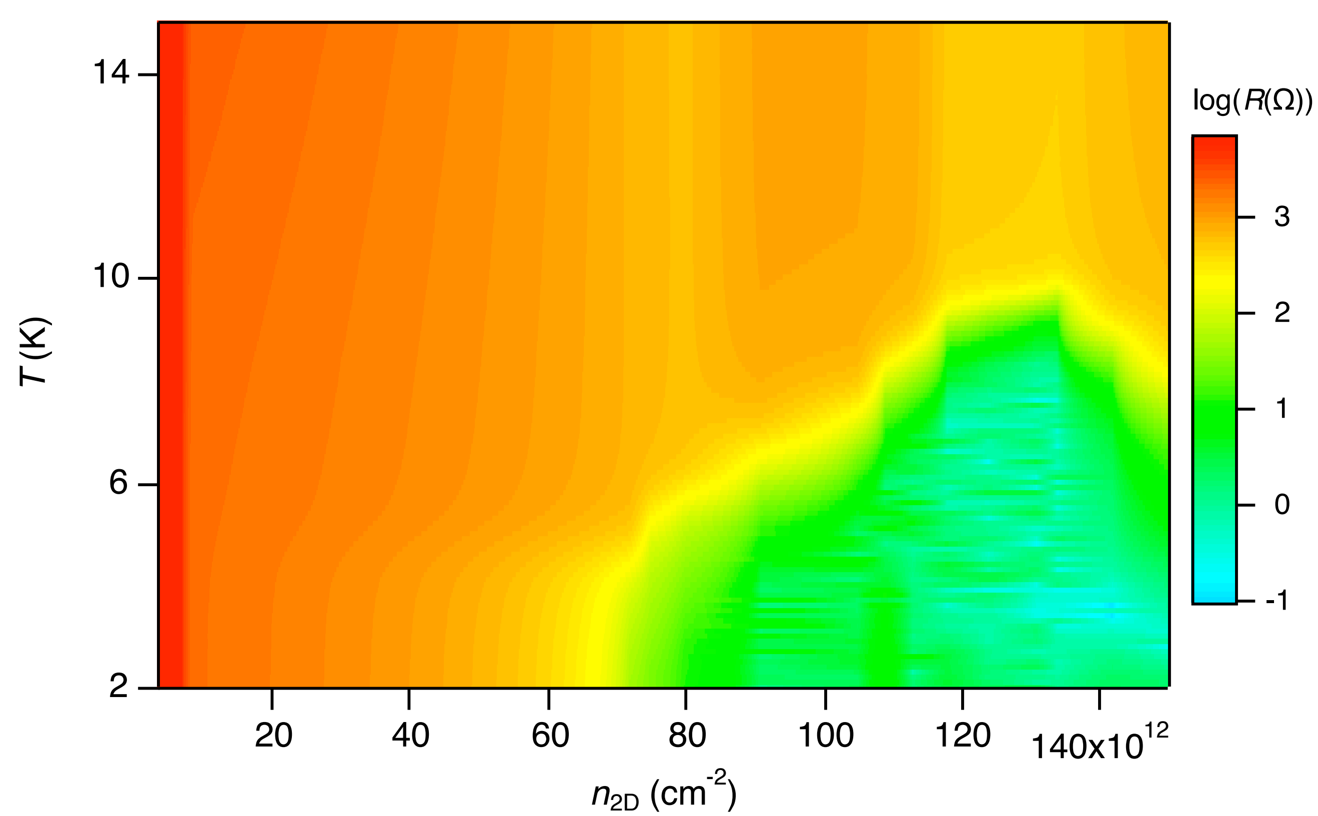
carrier accumulation (@220K)

Gate-Induced Superconductivity in MoS_2

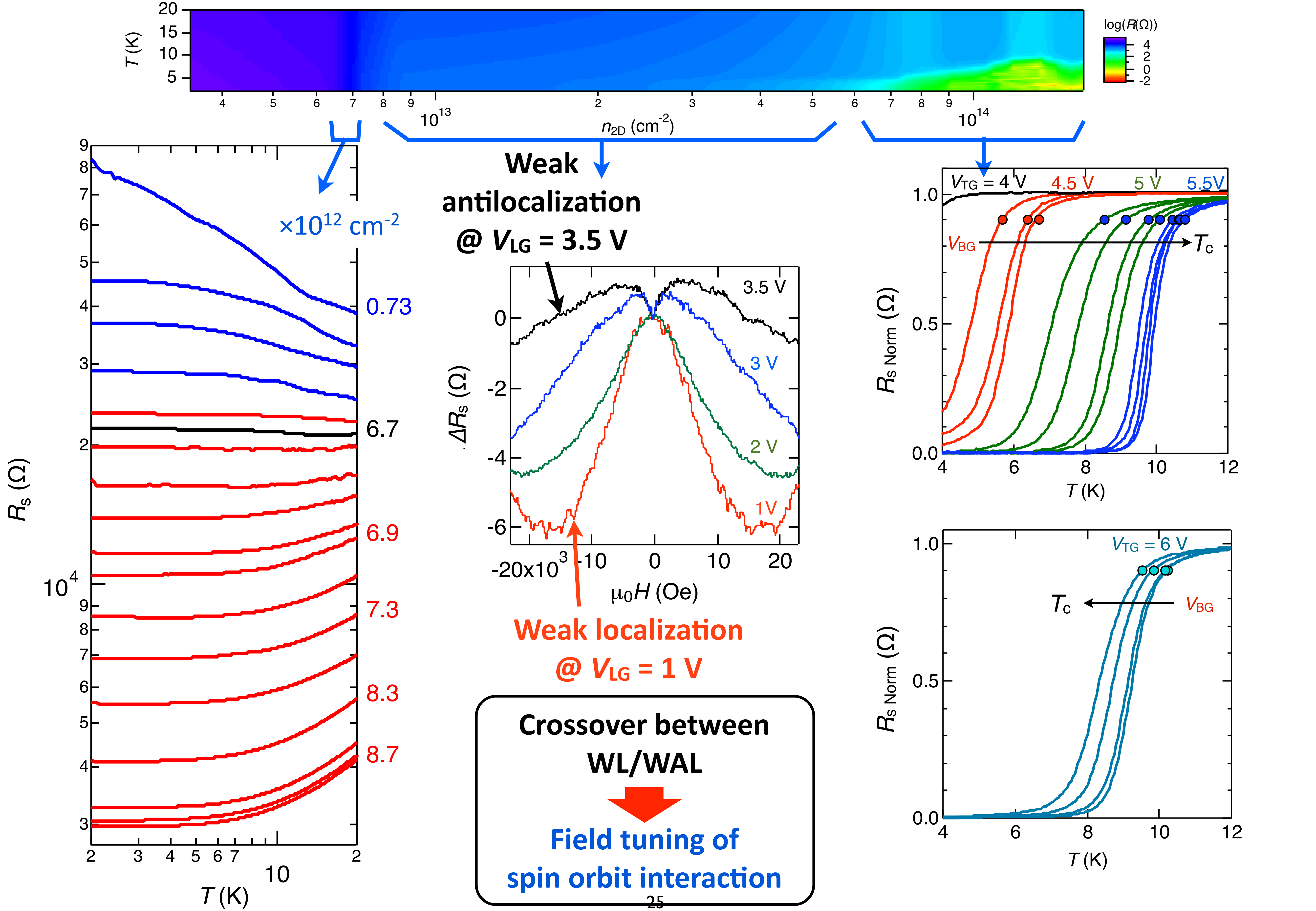




Zero Resistance, magnetic field dependence: **Confirmed**

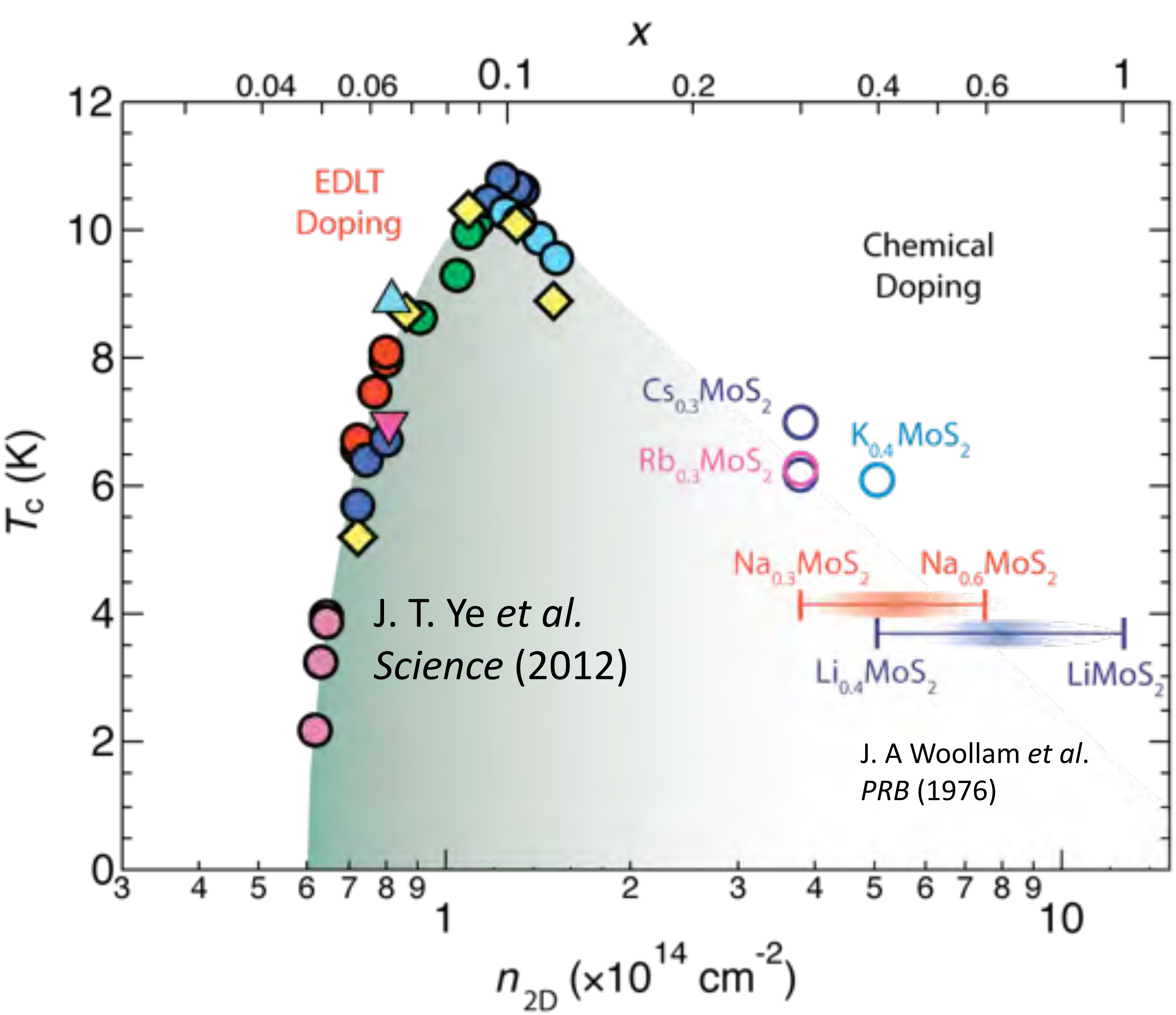


Gate Control of Electronic Phases in MoS_2

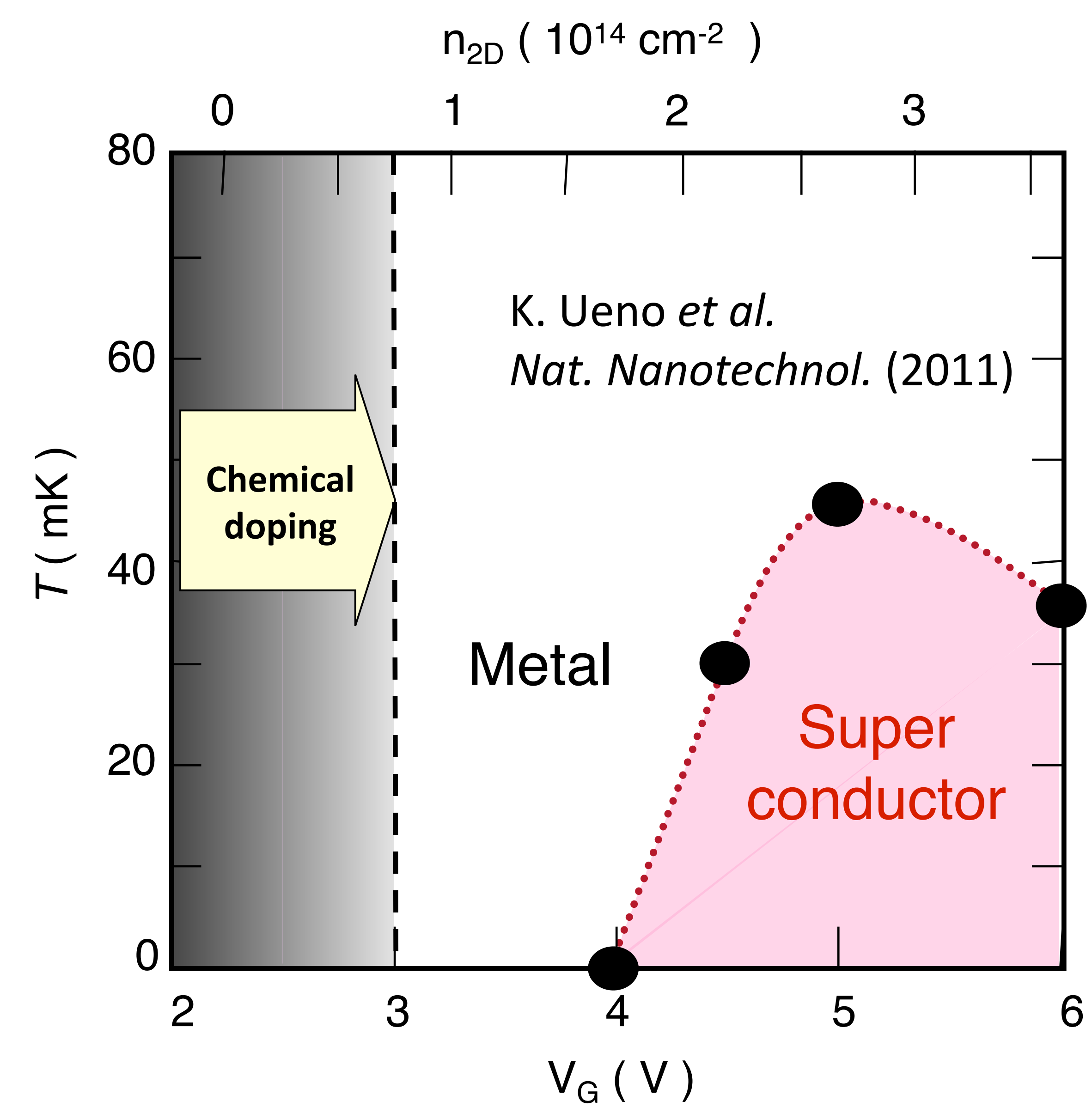


Accessing new regions of carrier density

Layered Material: MoS_2

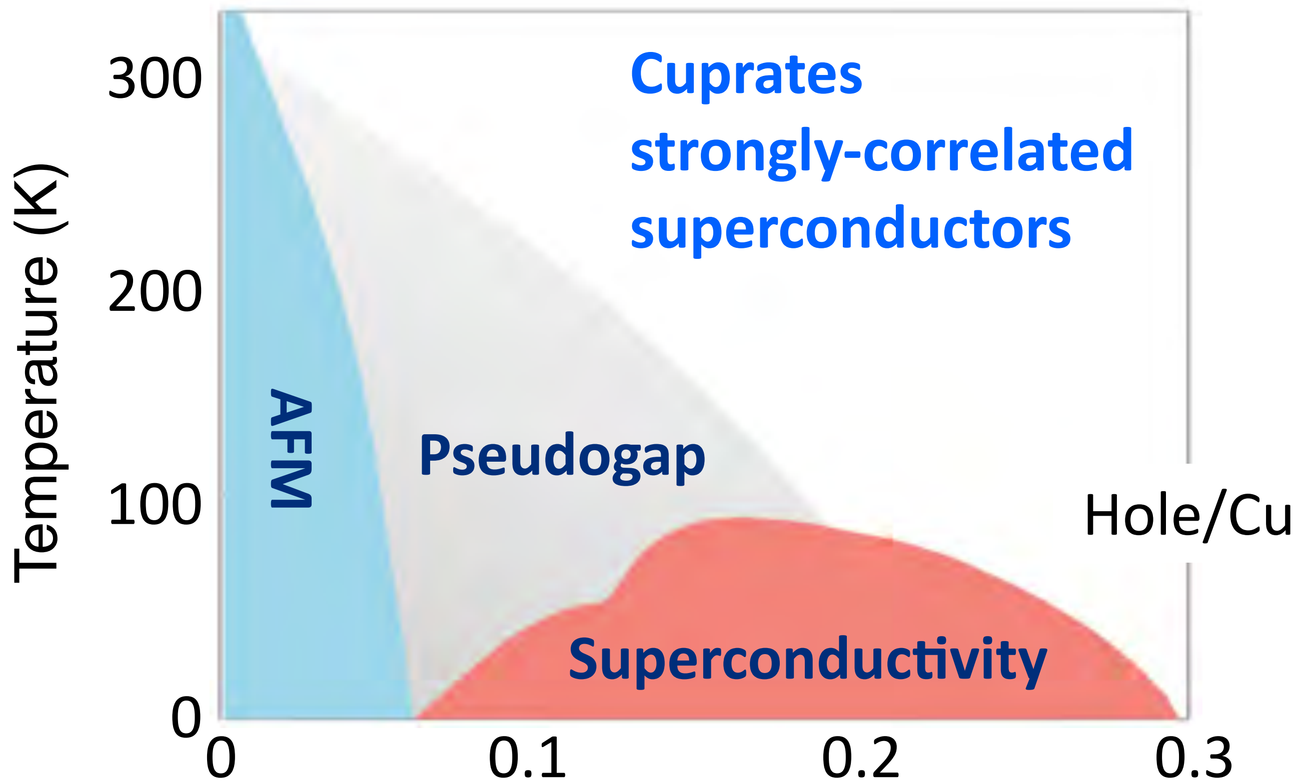


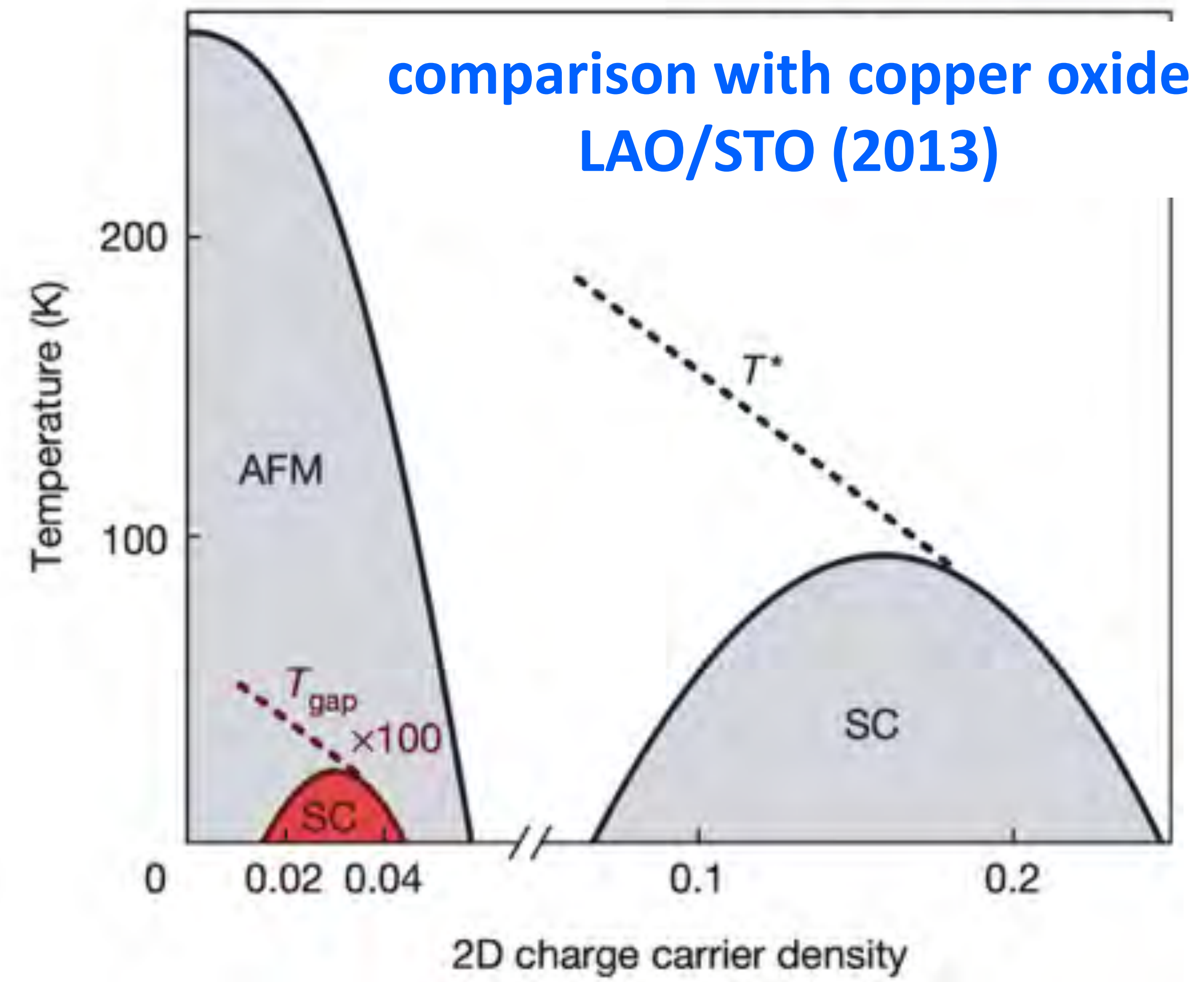
Oxide: $KTaO_3$

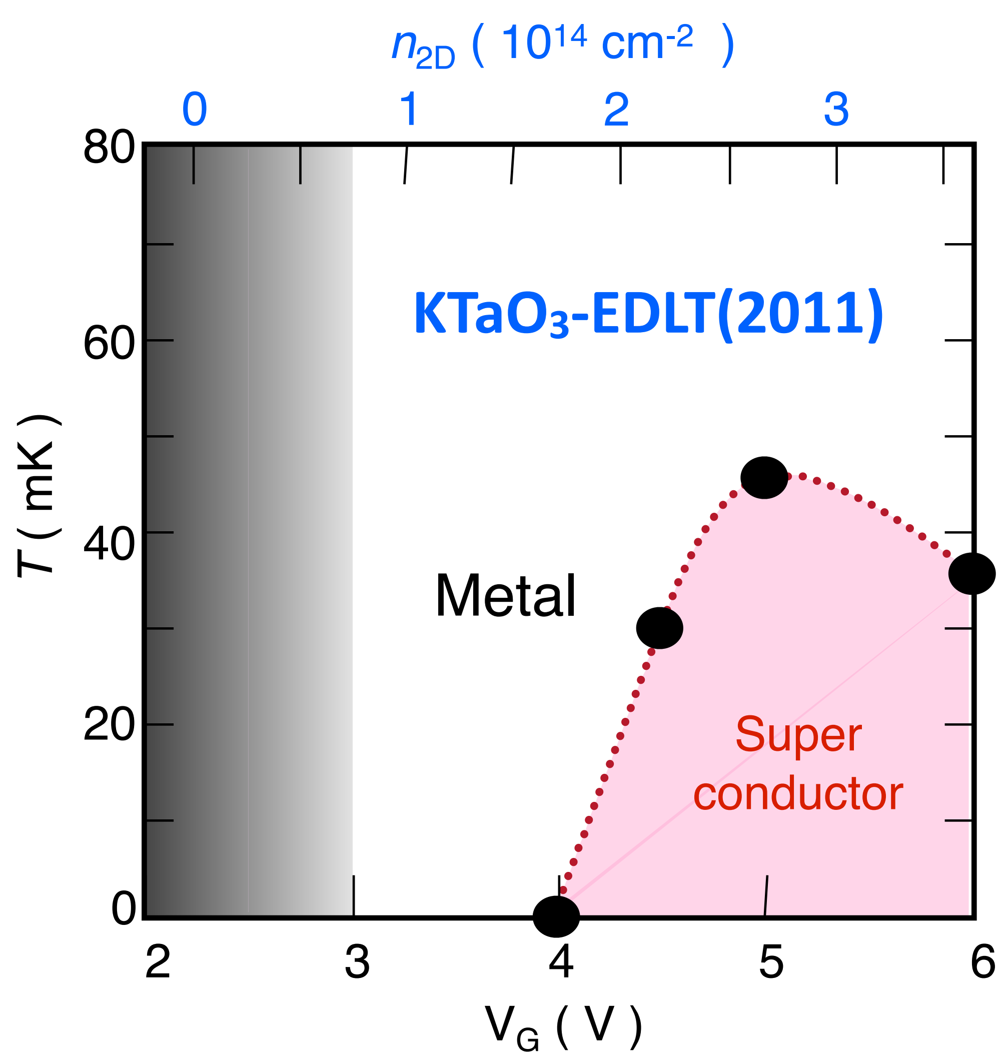


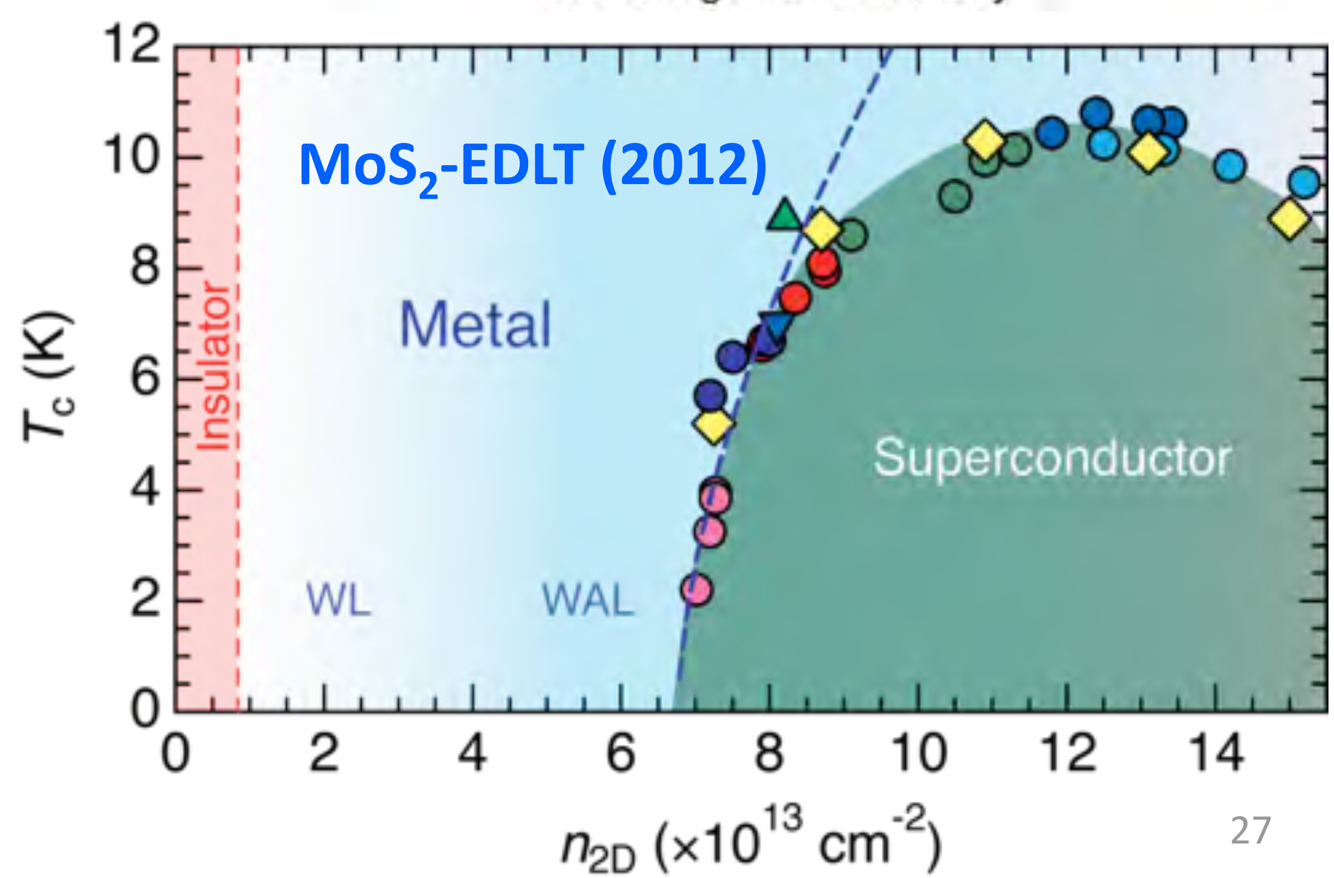
- Optimum doping is at a much lower *x*
- Highest T_c among MX_2 ($NbSe_2$ 7K)

Superconducting domes in doped band insulators

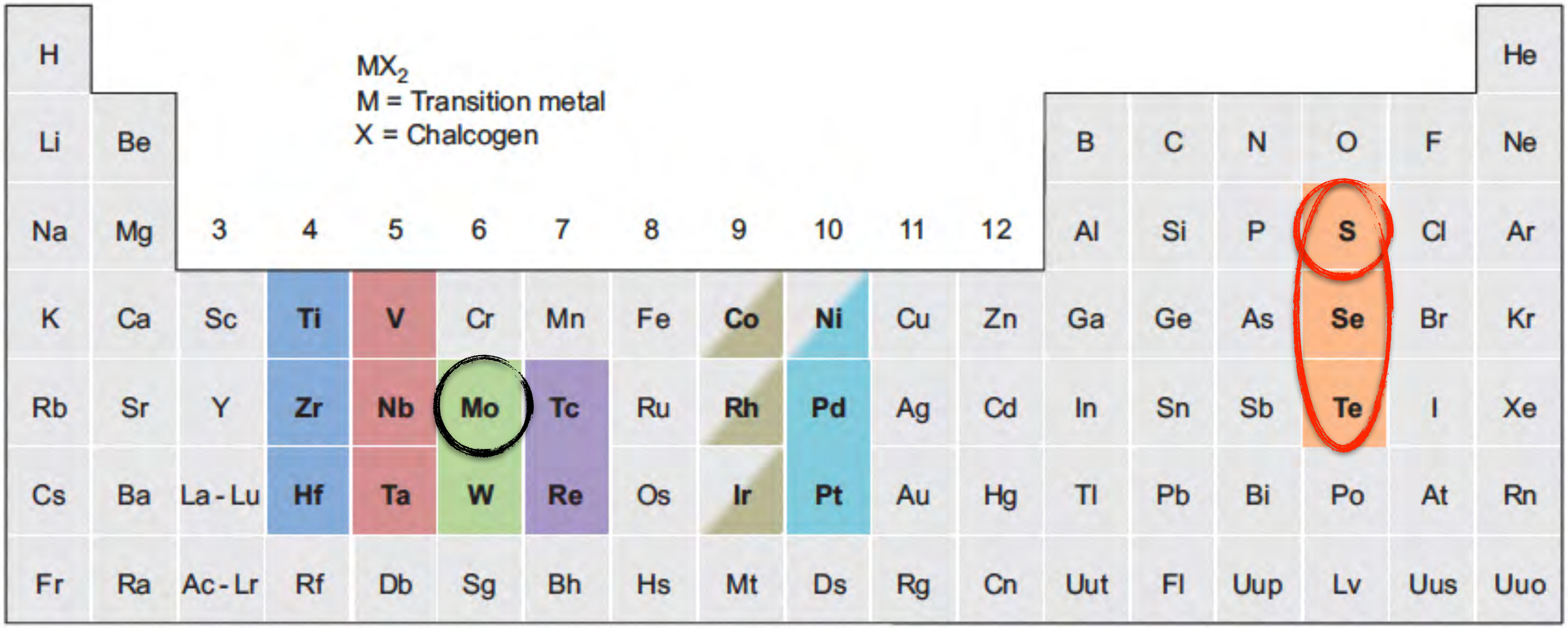








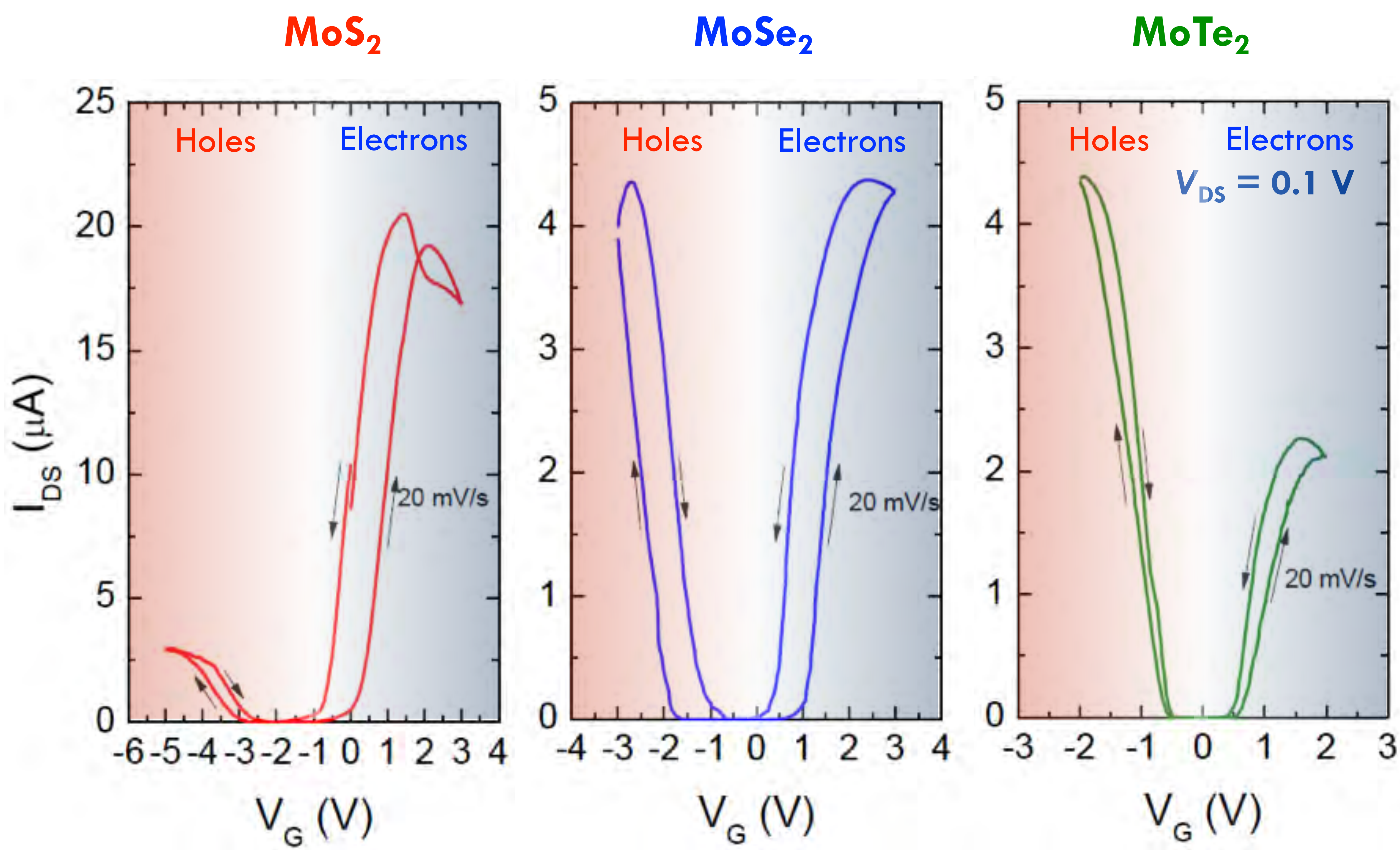
Various kinds of semiconducting MX_2



Anything interesting?

Superconducting Series Using Ionic Gating?

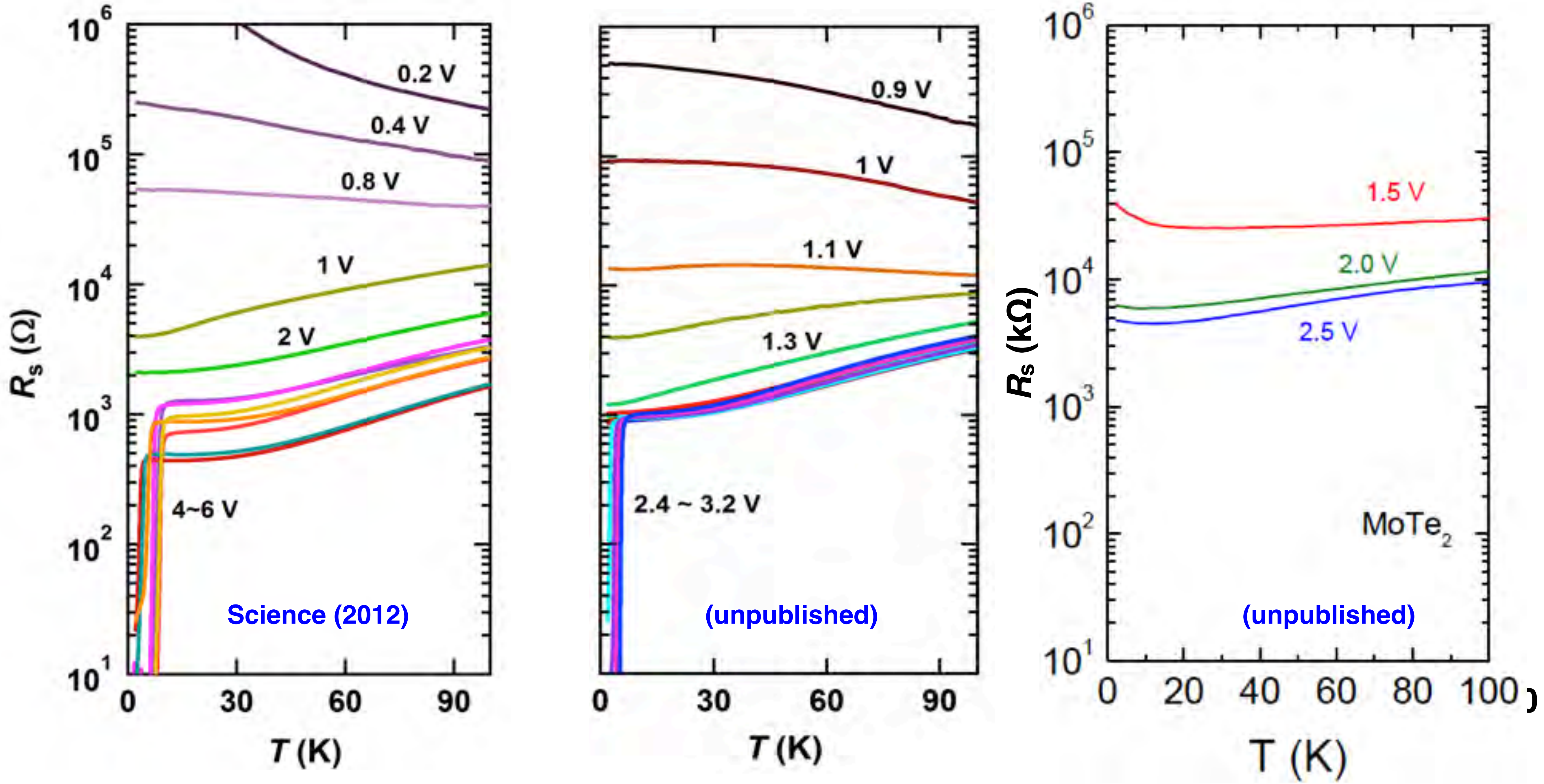
Various kinds of semiconducting MoX_2



All MoX_2 – Ambipolar Transistor Operation

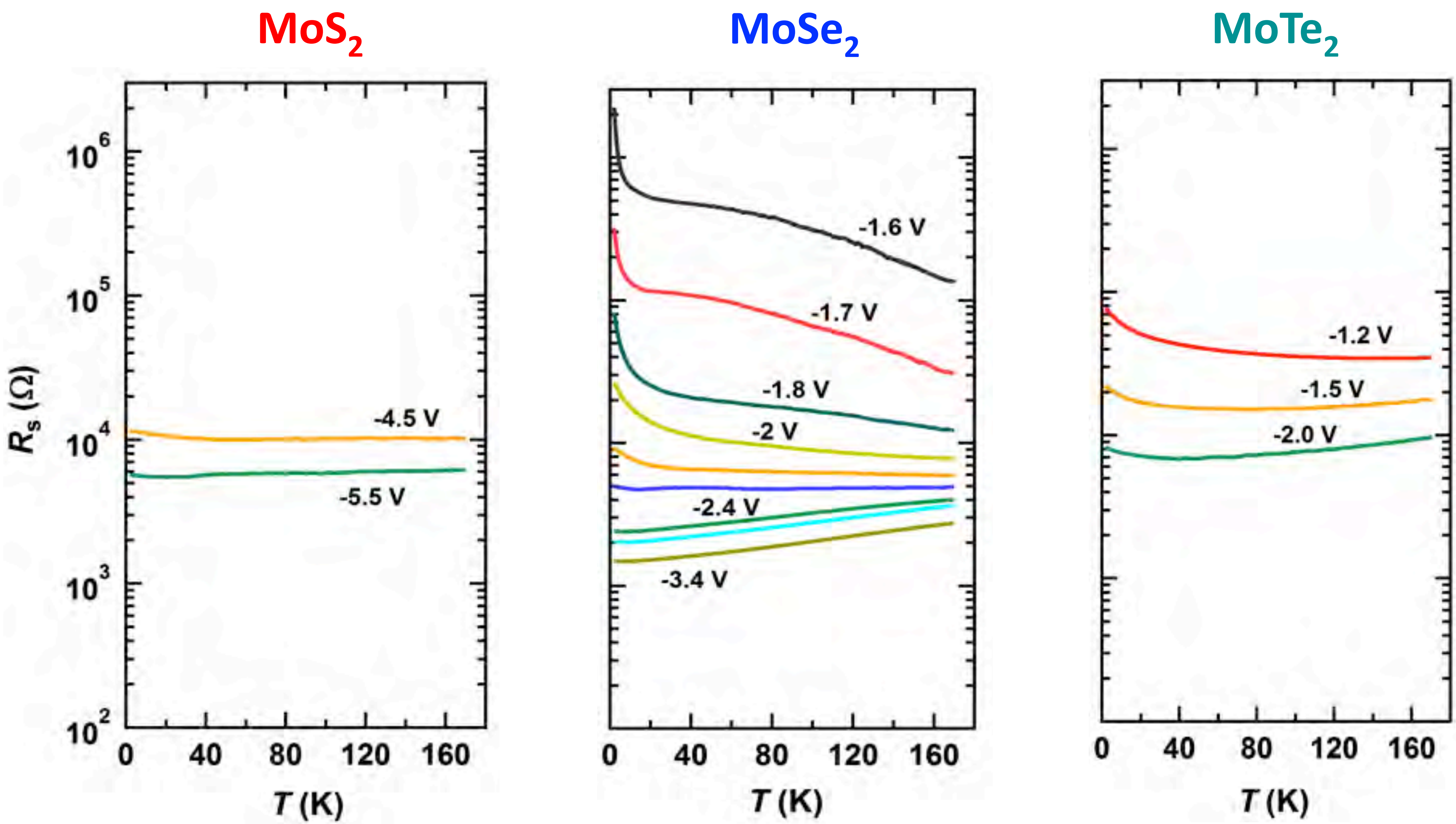
MoX_2 – by Electron Transport

MoS_2 (T_c = 10 K)	$MoSe_2$ (T_c = 7 K)	$MoTe_2$ (T_c = 2.8 K)



Inducing Superconductivity Series in TMDs

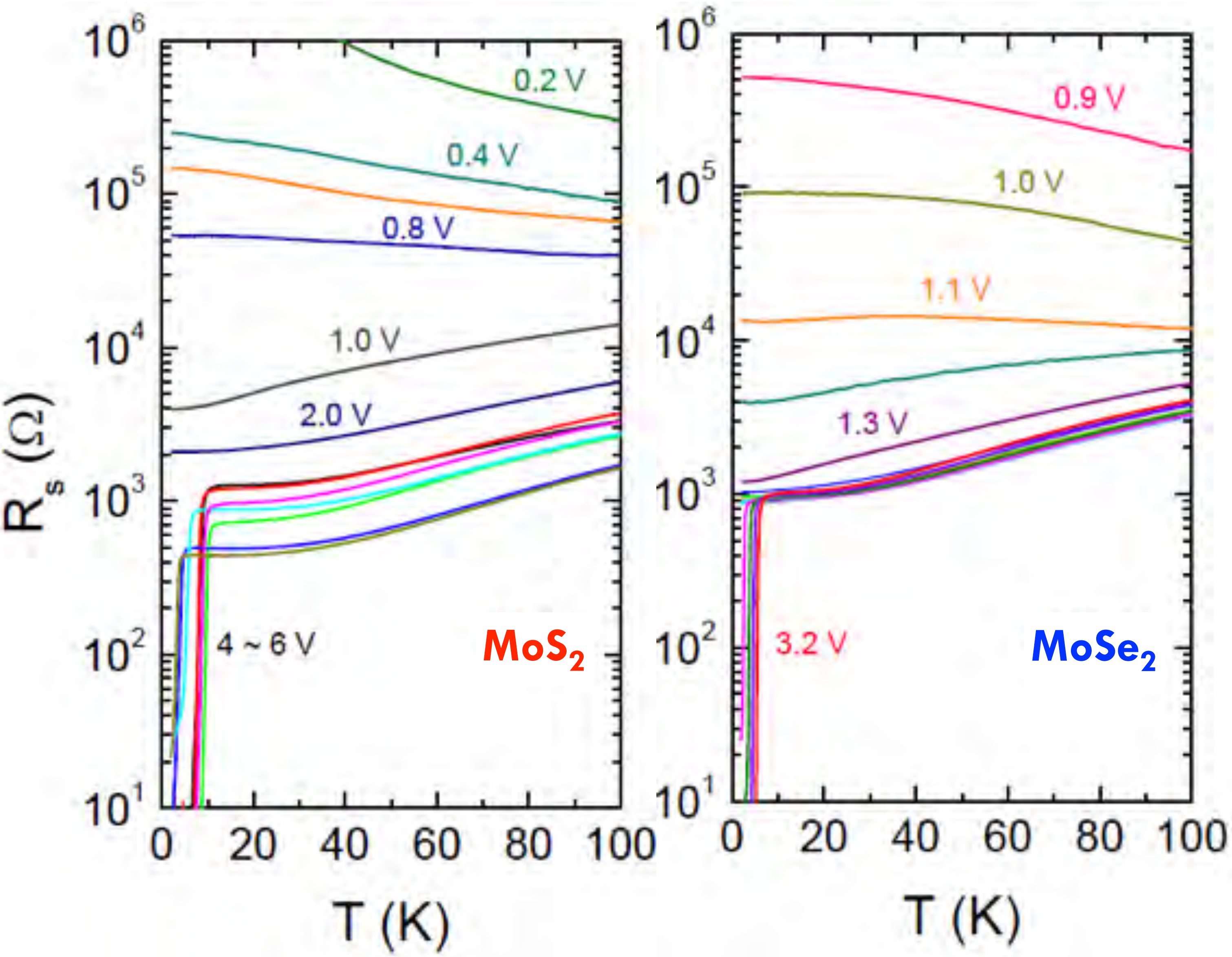
MoX_2 – by Hole Transport



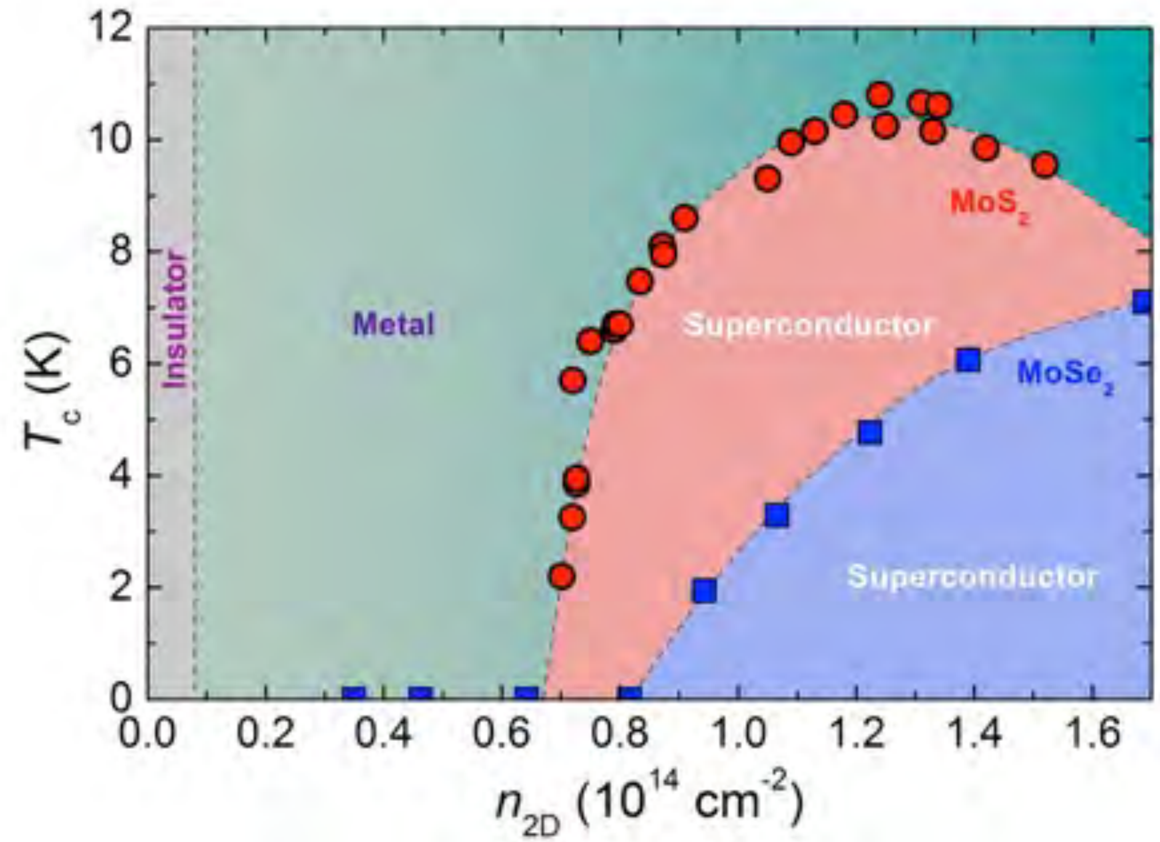
Field Induced Metal-Insulator Transition

(unpublished)

Expanding the Superconductors in TMDs



Phase diagram of MoS_2 and $MoSe_2$



- **Phase diagram is similar with a quantum critical point**
- **T_c is slightly lower**

Two-dimensional superconductors

Field-induced superconductivity

$SrTiO_3$, $KTaO_3$

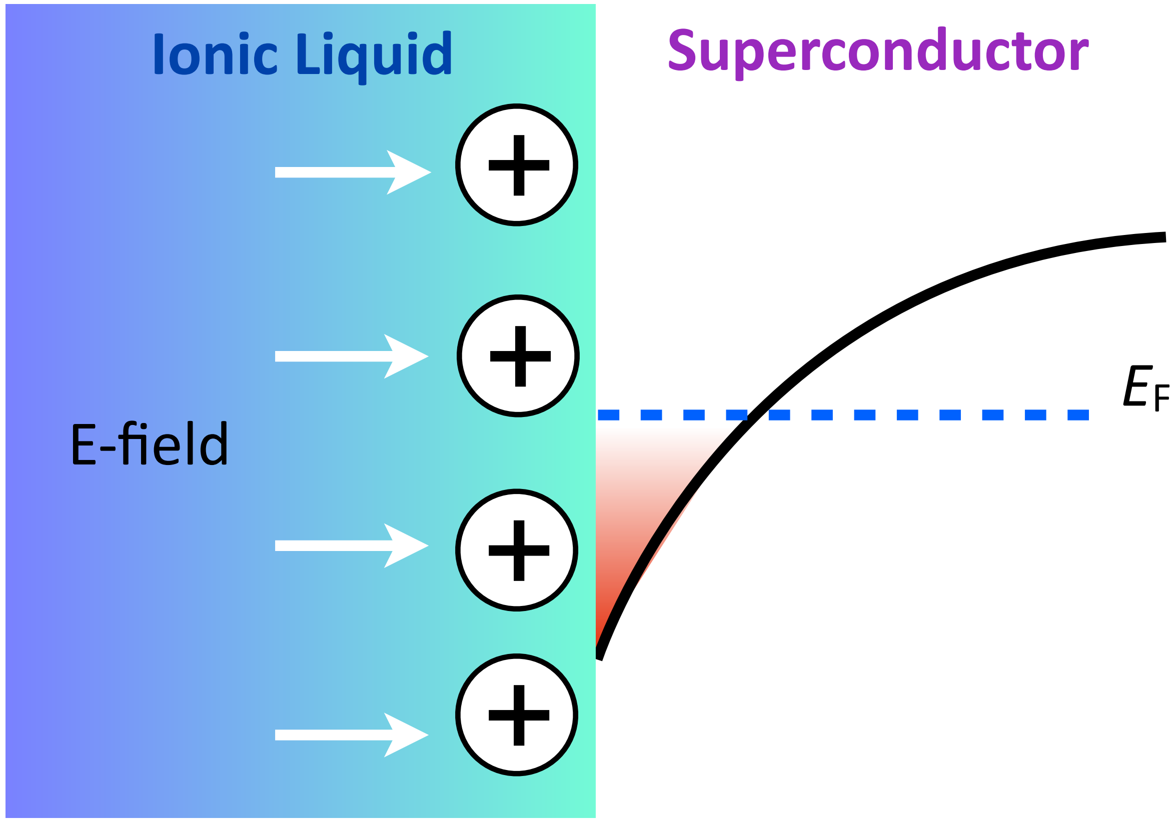
Ueno (2008,2011)

ZrNCl, MoS_2

Ye (2010, 2012)

$La_{2-x}Sr_xCuO4$, YBCO

Bozovic, Goldman (2010)



Any new phenomena different from the other system?

Ultrathin metals

Bi, Pb, Al, Sn, Be, *etc.*

monolayer Pb, In (UHV, STM)

Ultrathin films of compounds

MoGe, In_2O_3 and TiN *etc.*

Ultrathin films and interfaces of oxides

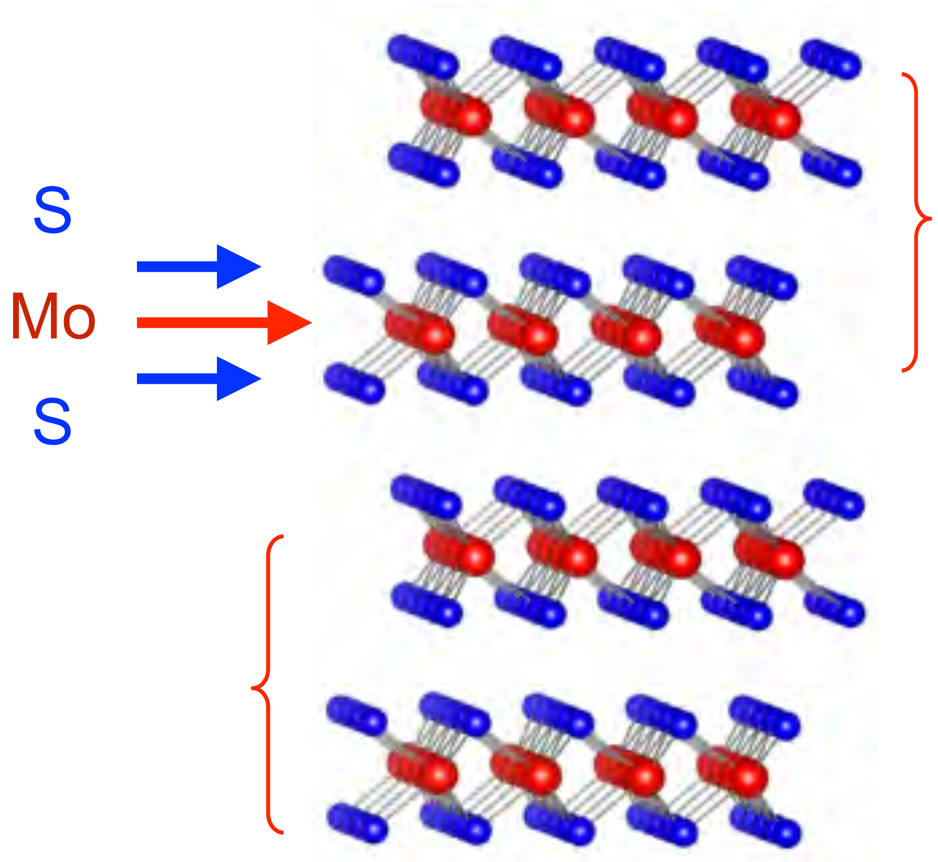
LSCO, YBCO, *etc.*

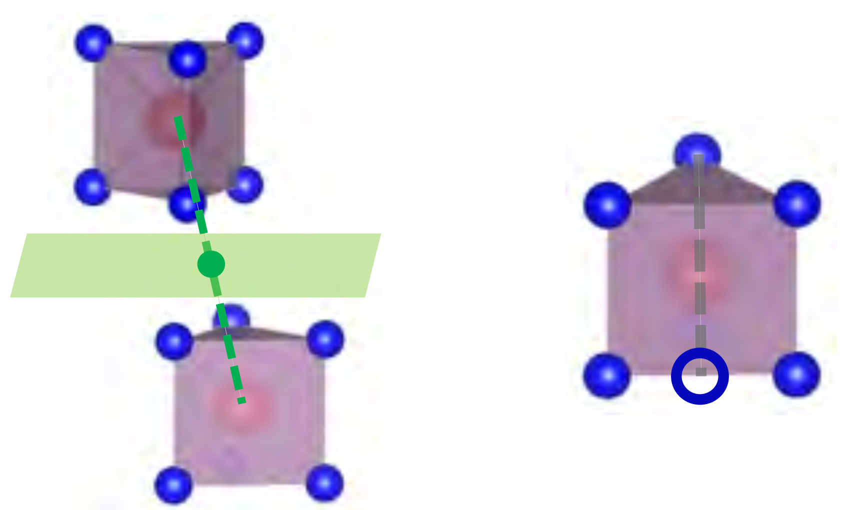
$LaAlO_3/SrTiO_3$, $SrTiO_3$ δ-doping, *etc.*

$CeCoIn_5$ superlattice, *etc.*

Bulk versus Monolayer (2D): Transition Metal Dichalcogenides

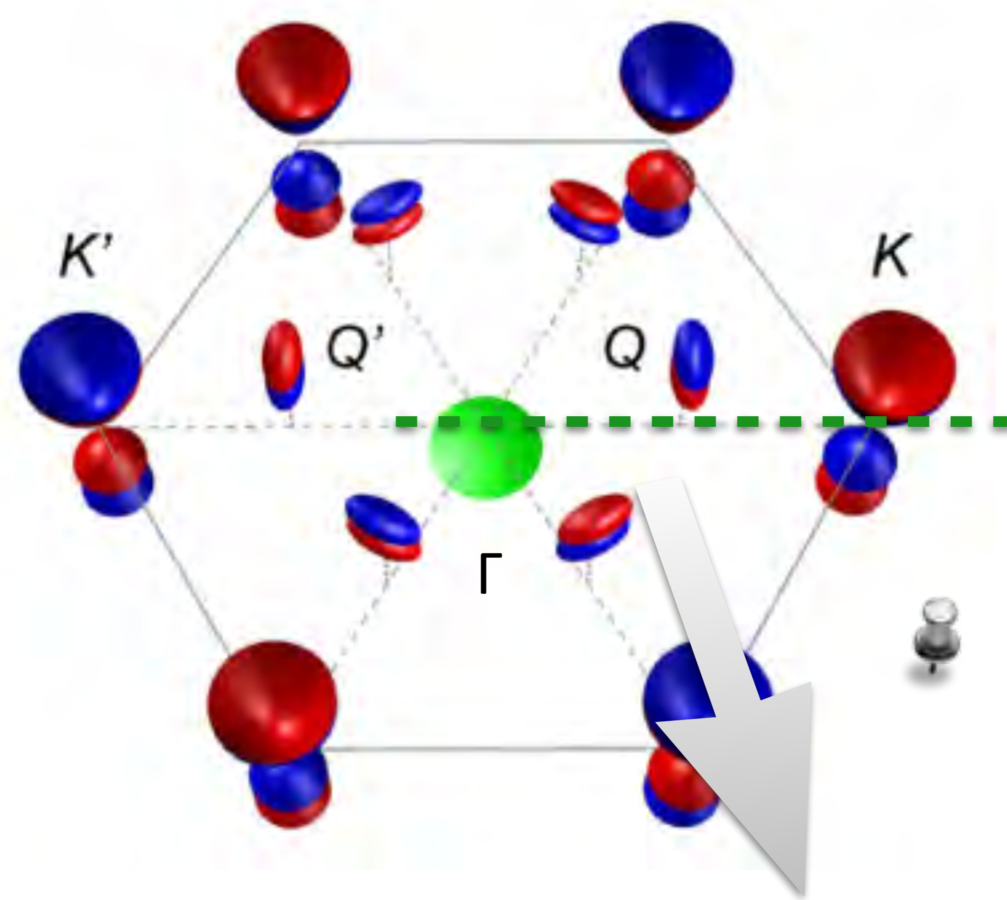
$2H$-MoS_2





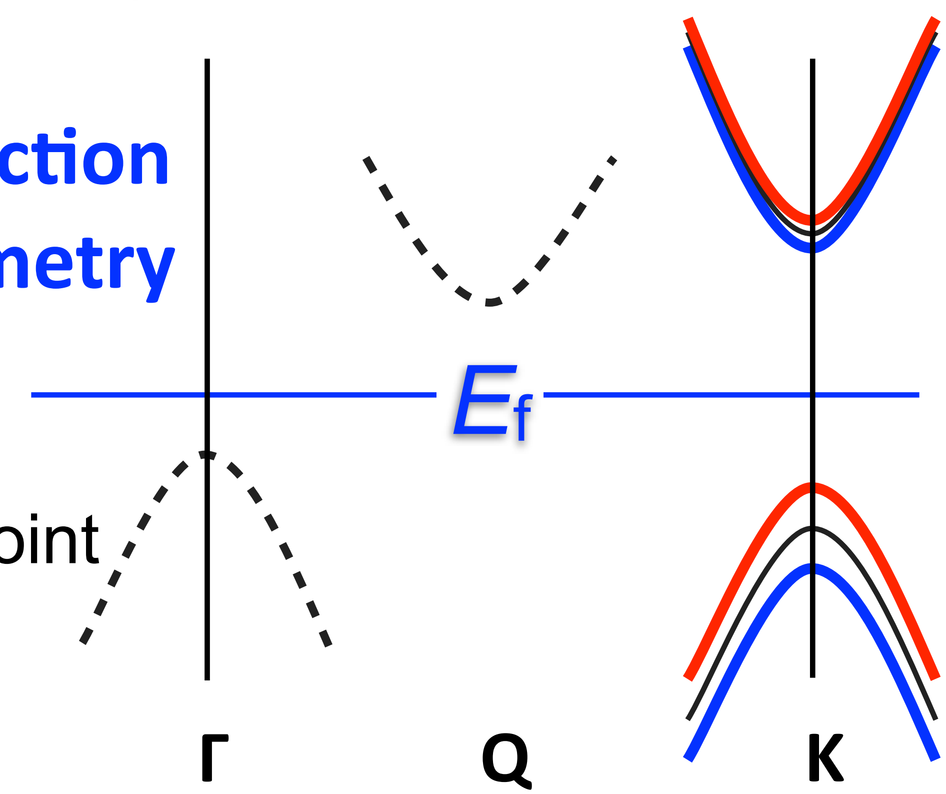
Bulk crystal

Monolayer



- **Direct Band Gap**
  Q valley rises

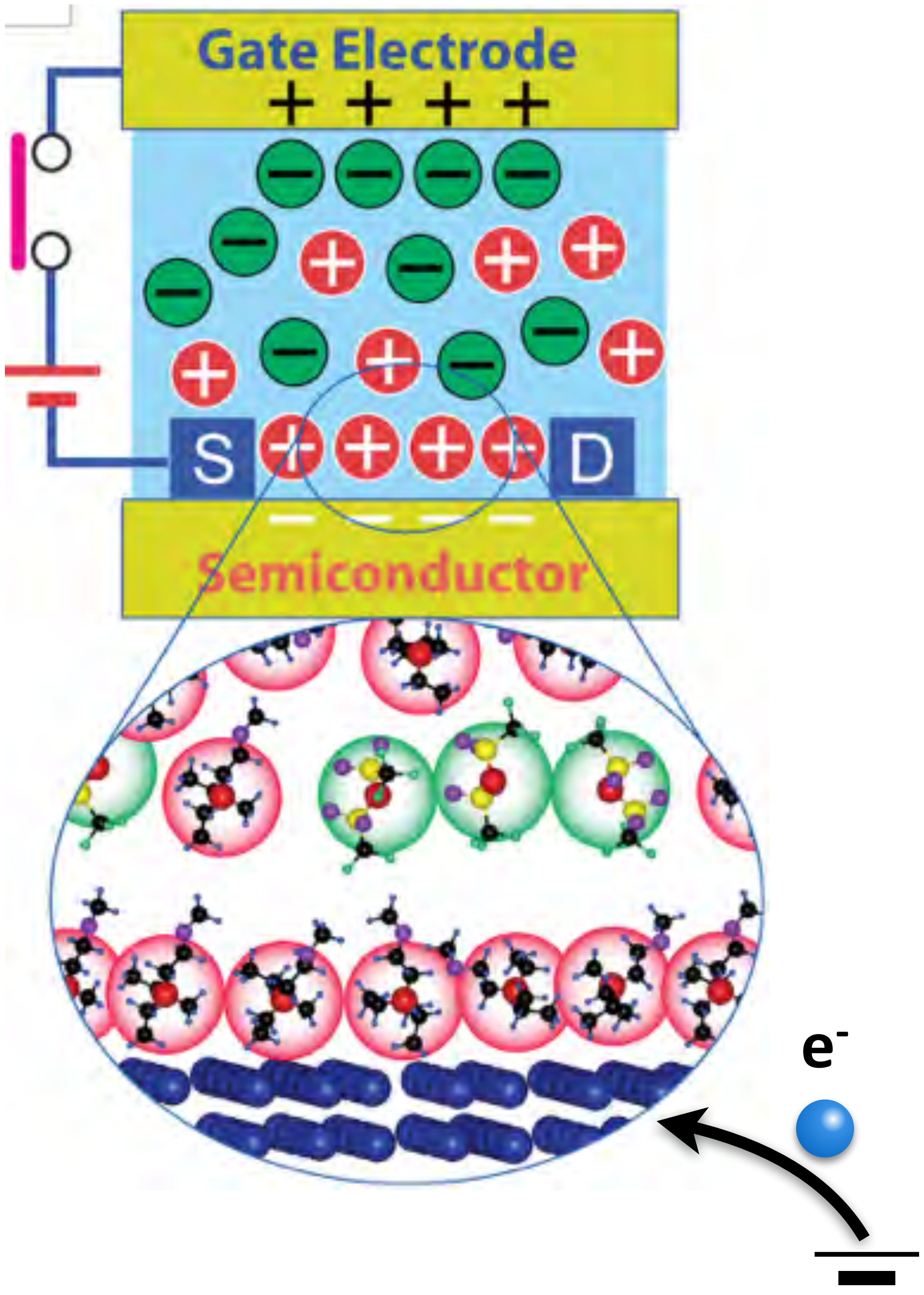
- **Spin-orbit Interaction + Inversion symmetry breaking**
  Spin splitting at high symmetry *K* point



EDLT gating: tuning the bulk into a monolayer

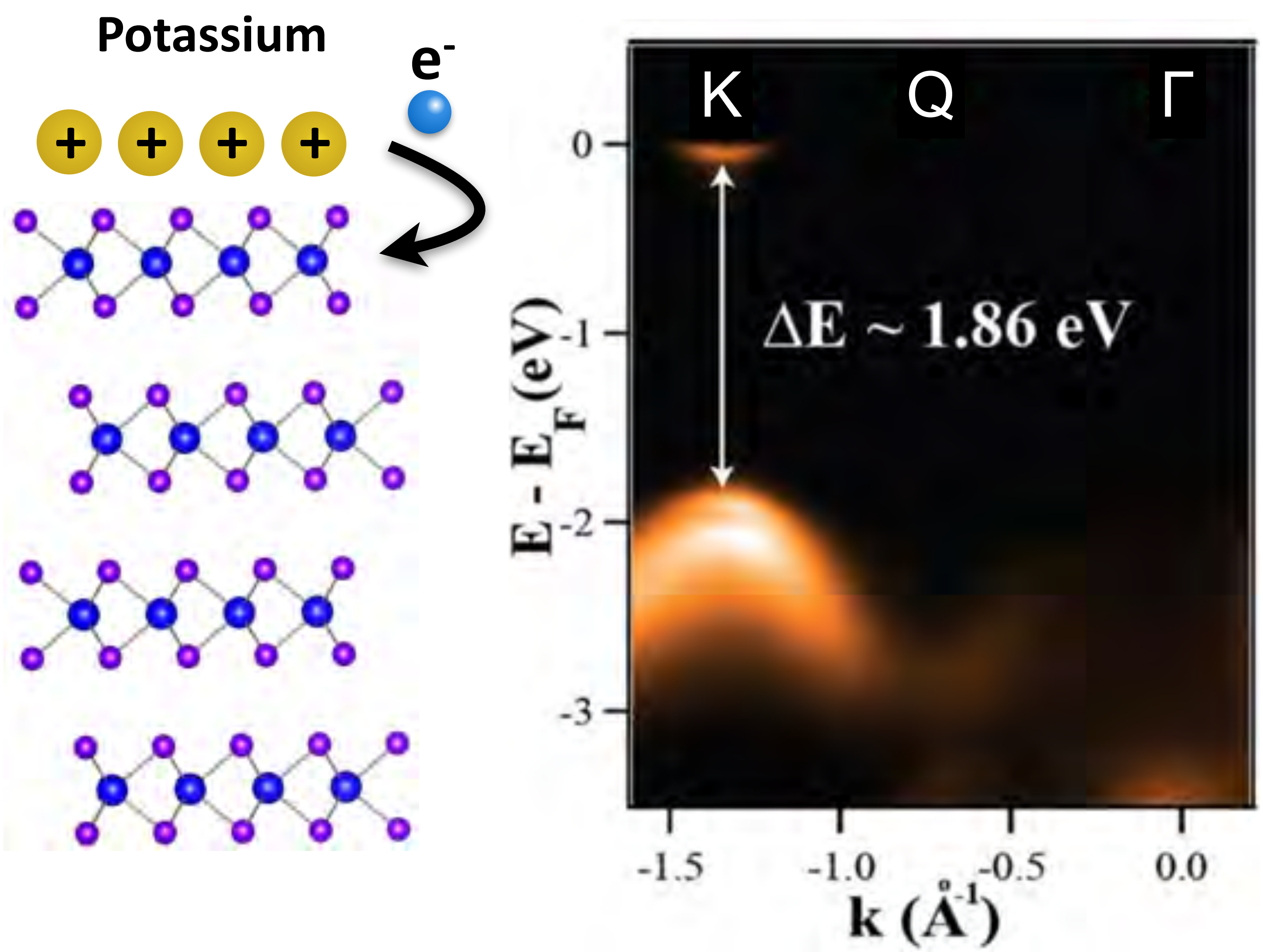
EDLT gating

physical adsorption gating



ARPES on bulk single crystal of MoS_2

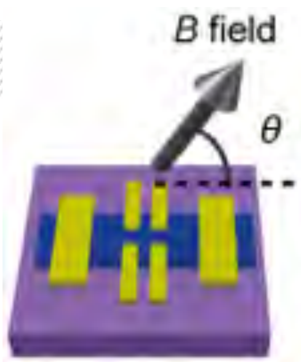
chemical doping of alkali metal



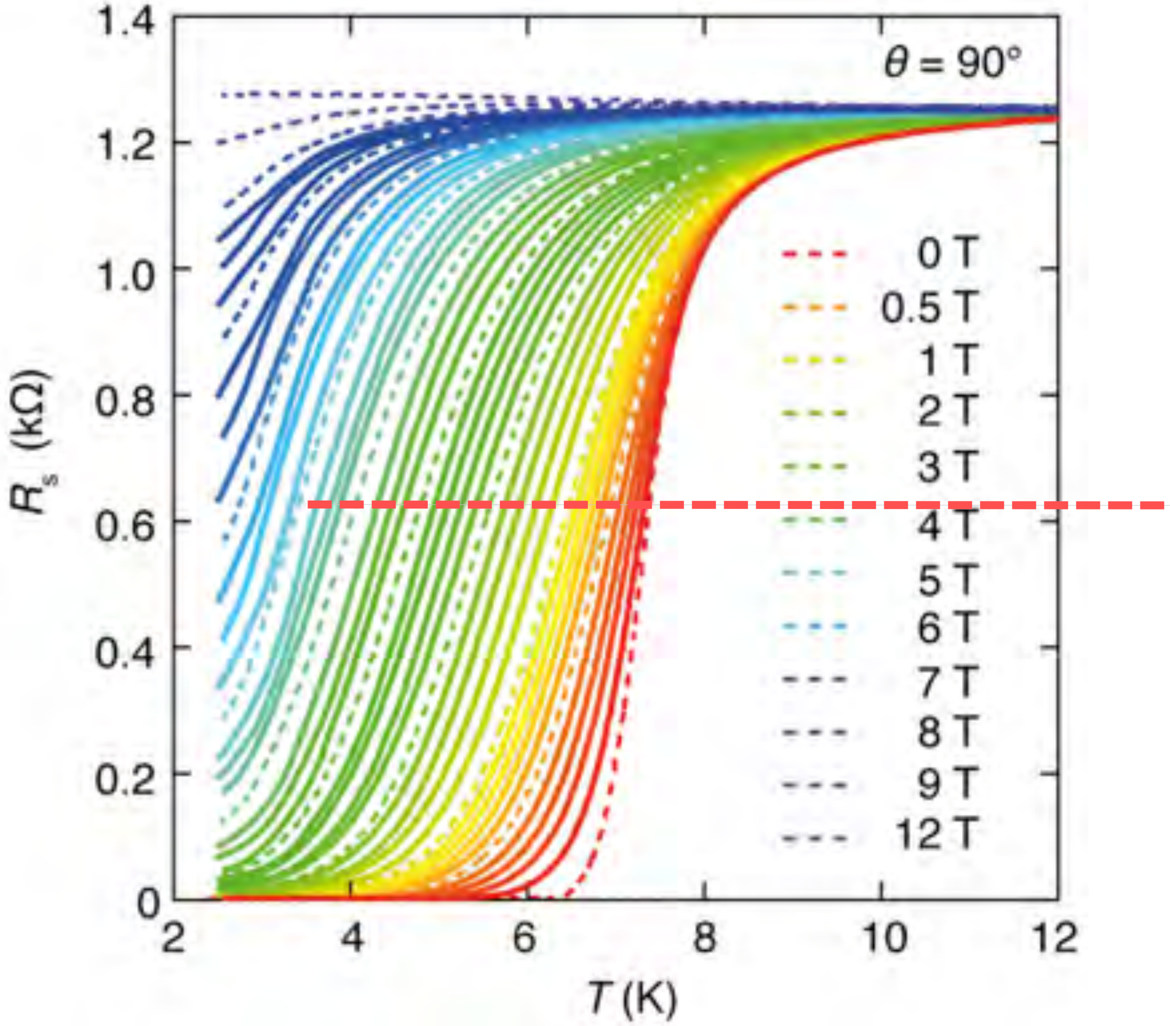
Doping start from *K* point
as if in a monolayer

High Anisotropy in critical field

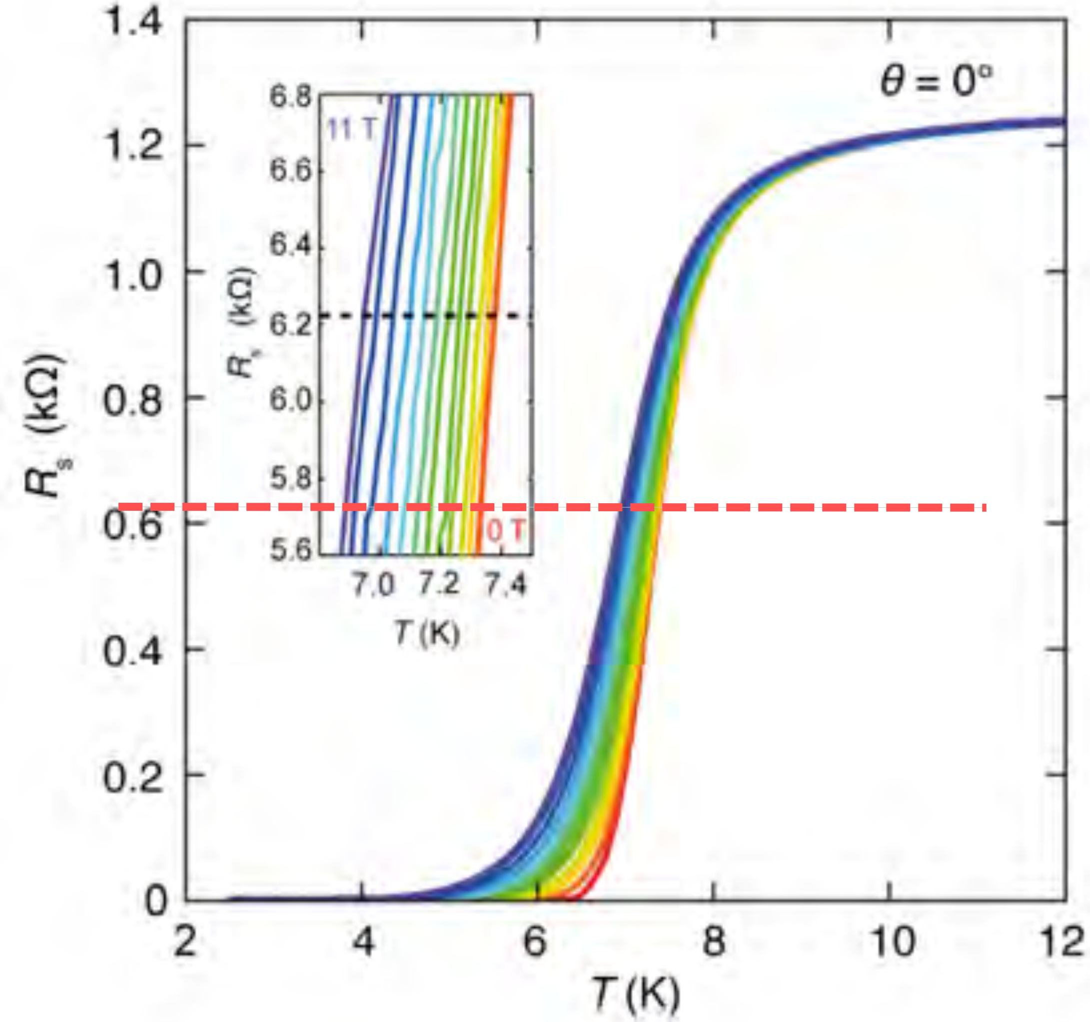
D24 sample



$H\perp$surface

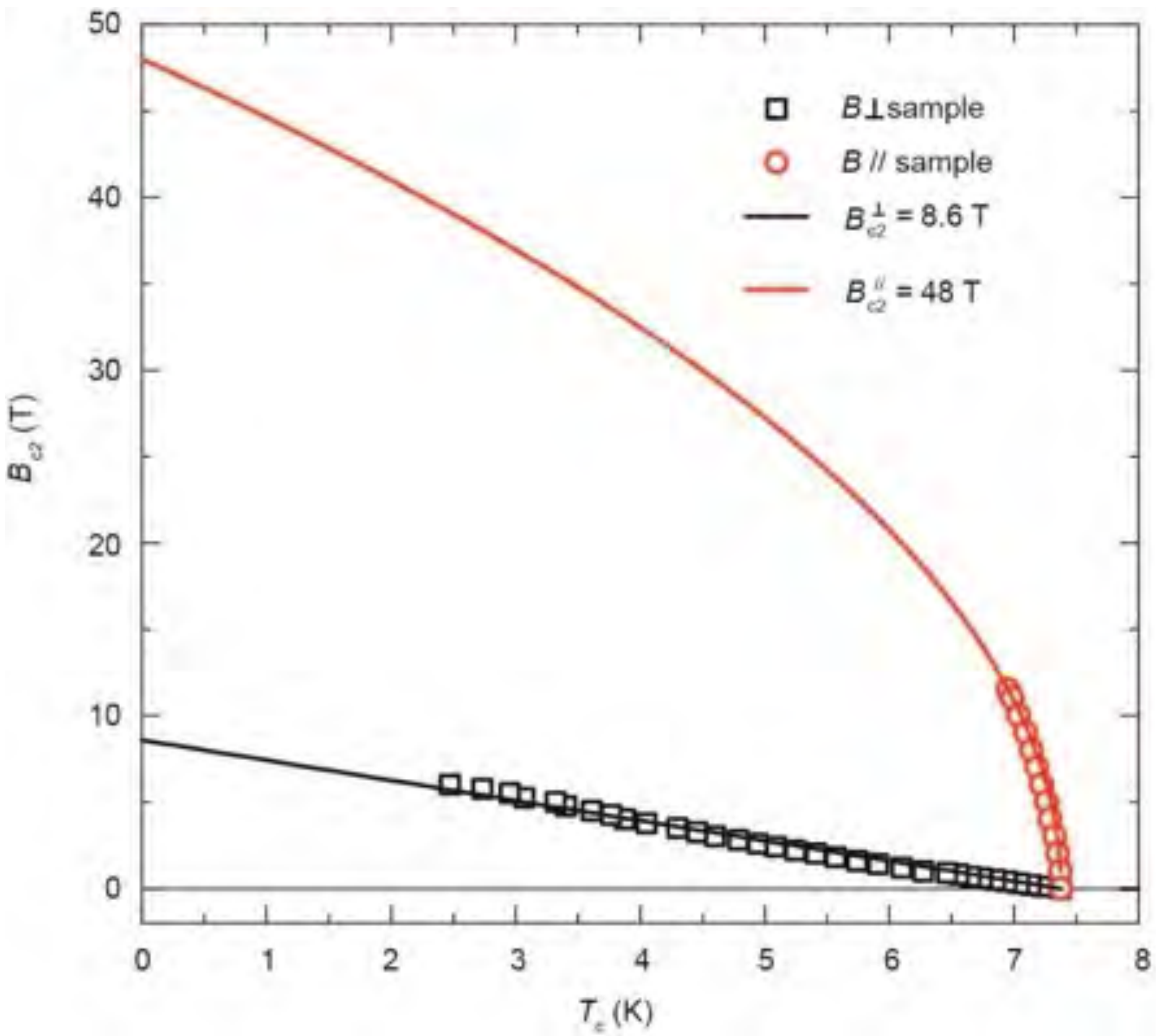


$H//$surface



$B_{c2}^{\perp} \ll B_{c2}^{//}$

Analysis of 2**D superconductivity** in EDLT of MoS_2



2D GL theory:

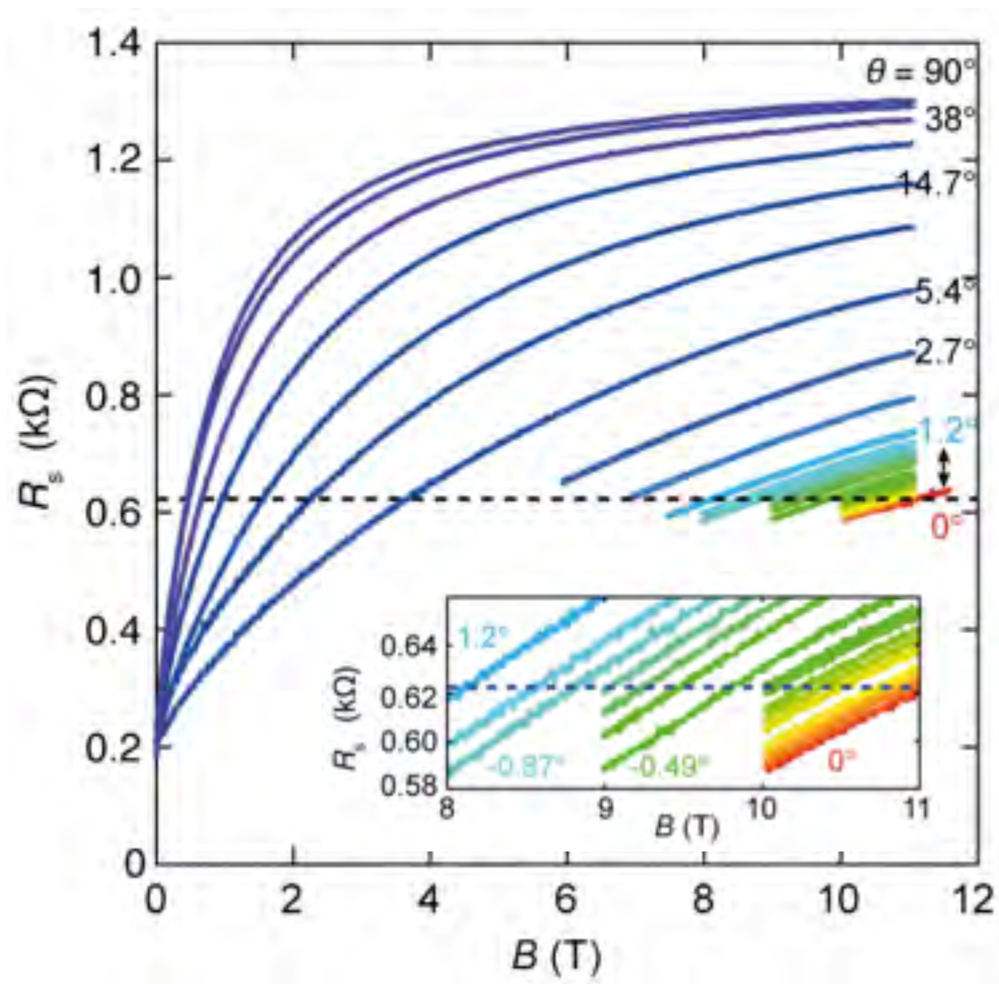
$$B_{c2}^{\perp}(t) = \frac{\Phi_0}{2\pi\xi_{GL}(0)^2}(1-t)$$

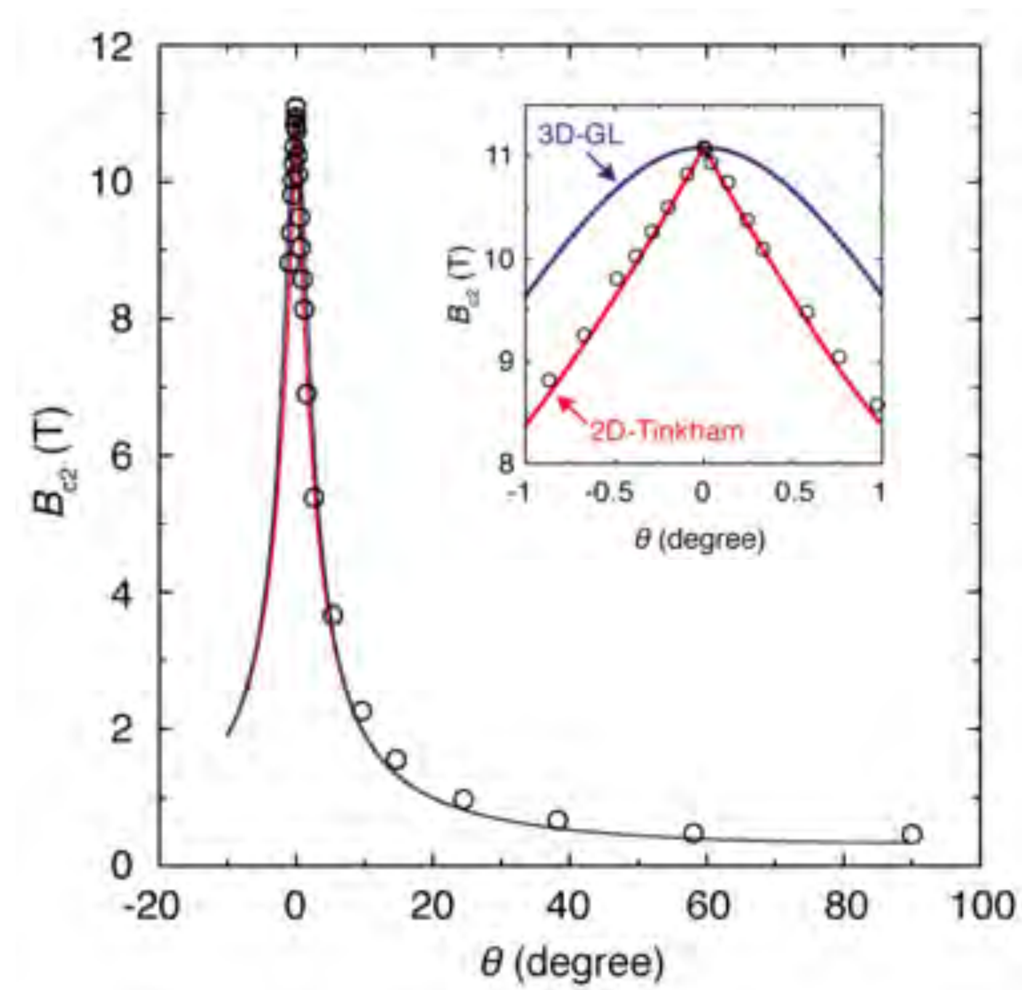
$$B_{c2}^{\parallel}(t) = \frac{\Phi_0\sqrt{12}}{2\pi\xi_{GL}(0)d_{\text{Tinkham}}}(1-t)^{1/2}$$

critical field	$B_{c2}^{\perp}(0) = 8.6$ T	$B_{c2}^{\parallel}(0) = 48$ T
coherence length	$\xi_{GL}(0) = 6.2$ nm	$d_{\text{Tinkham}} = 3.8$ nm

Sharp Cusp in Angle Dependance of B_{c2}

Cusp characteristic is a strong evidence of 2D superconductor





3D anisotropic Ginzburg-Landau model

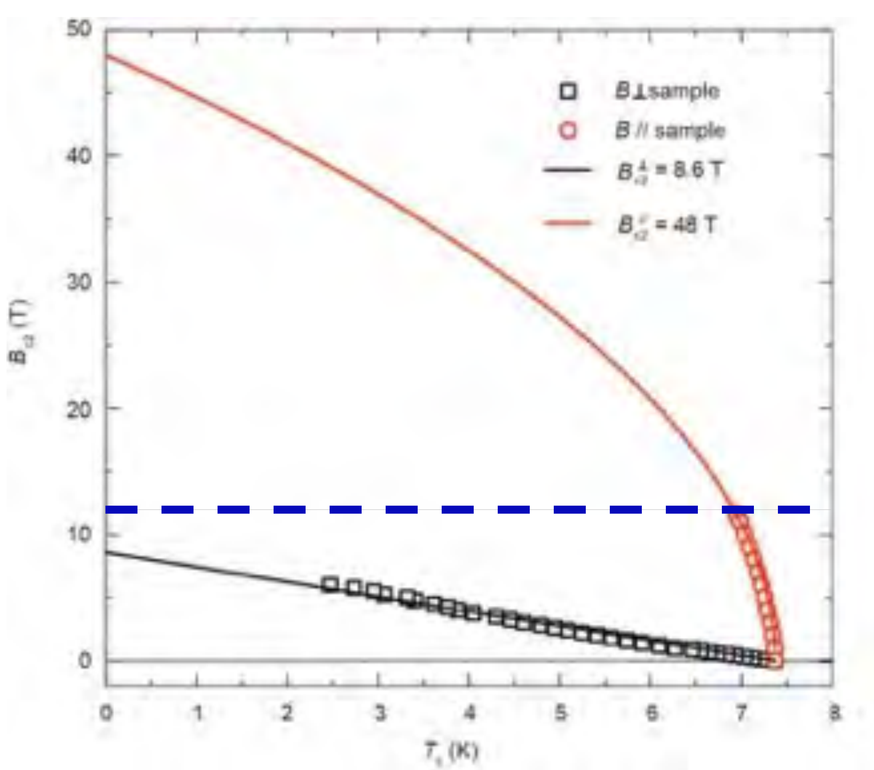
$$\left(\frac{H_{c2}(\theta)\cos\theta}{H_{c2\perp}}\right)^2+\left(\frac{H_{c2}(\theta)\sin\theta}{H_{c2//}}\right)^2=1$$

2D Tinkham model

$$\left|\frac{H_c(\theta)\cos\theta}{H_{c\perp}}\right|+\left(\frac{H_c(\theta)\sin\theta}{H_{c//}}\right)^2=1$$

2D superconductivity in EDLT of MoS_2

- ✓ High Anisotropy
- ✓ Cusp shape of angle dependence of B_{c2}
- ✓ KT transition
- ➢ **Ionic gated MoS2 flake is verified to be 2D superconductor**

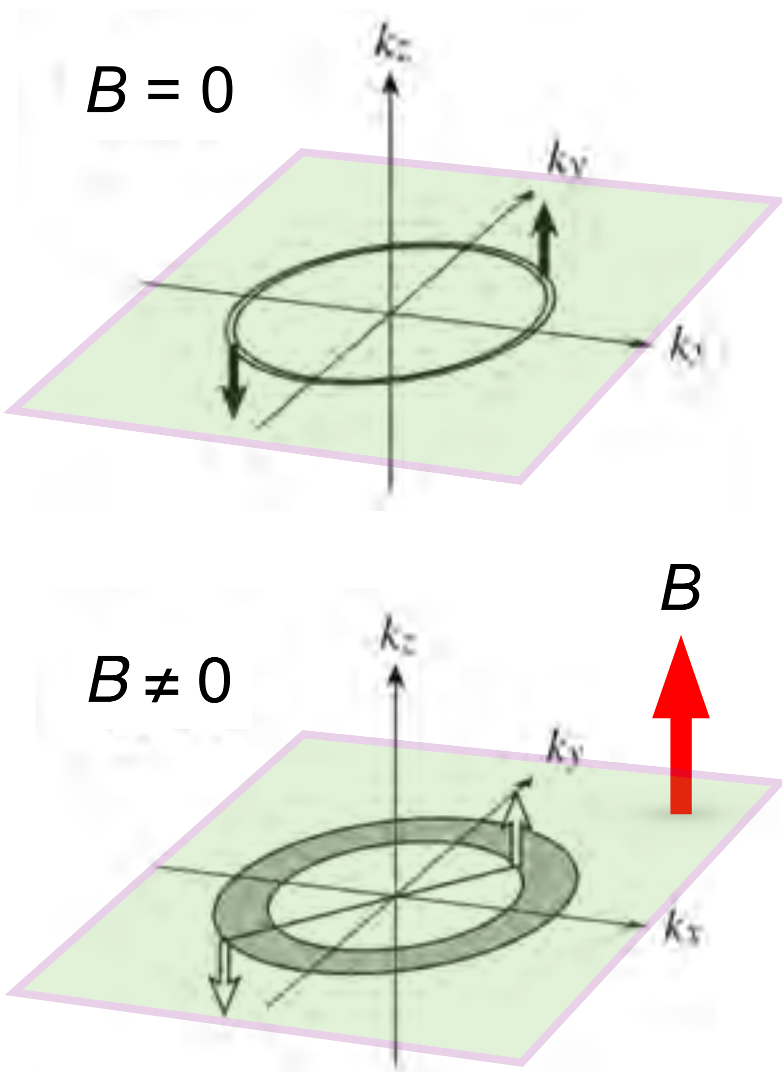


Suggesting **Huge** in-plane B_{c2}

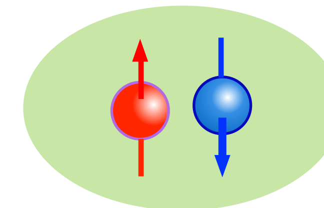
Why 2D is important?

Orbital effect

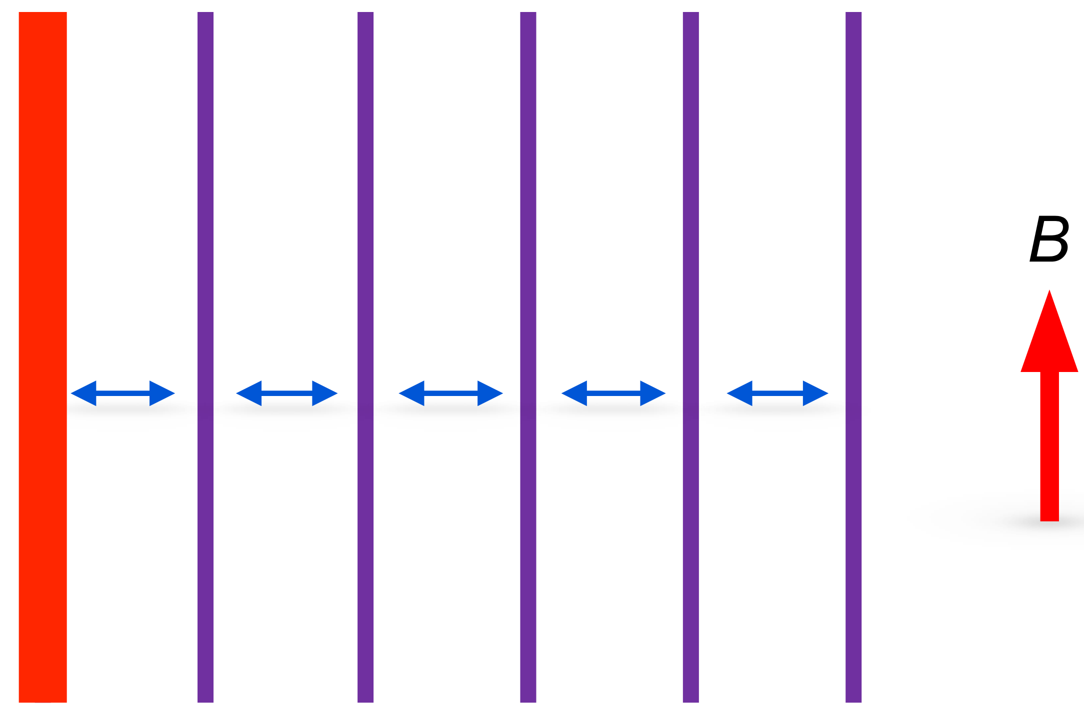
$$\boldsymbol{p} + e\mathbf{A}/c$$
$$-\boldsymbol{p} + e\mathbf{A}/c$$



Spin paramagnetism



$$+g\boldsymbol{\mu}\cdot\boldsymbol{B}$$
$$-g\boldsymbol{\mu}\cdot\boldsymbol{B}$$



2D samples

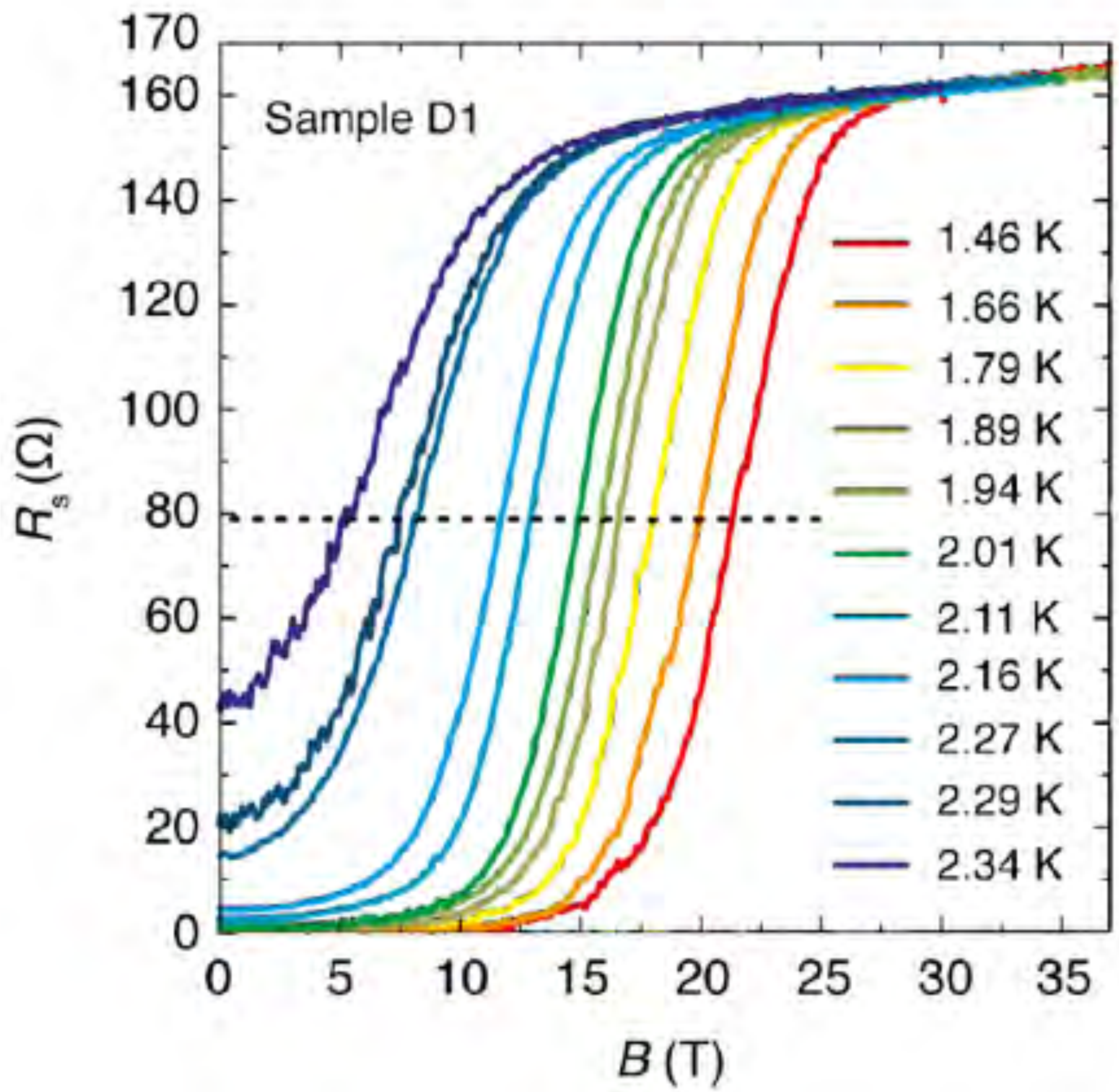
Zeeman Energy = Paring Energy

Pauli limit: $B_p = 1.86\ T_c$

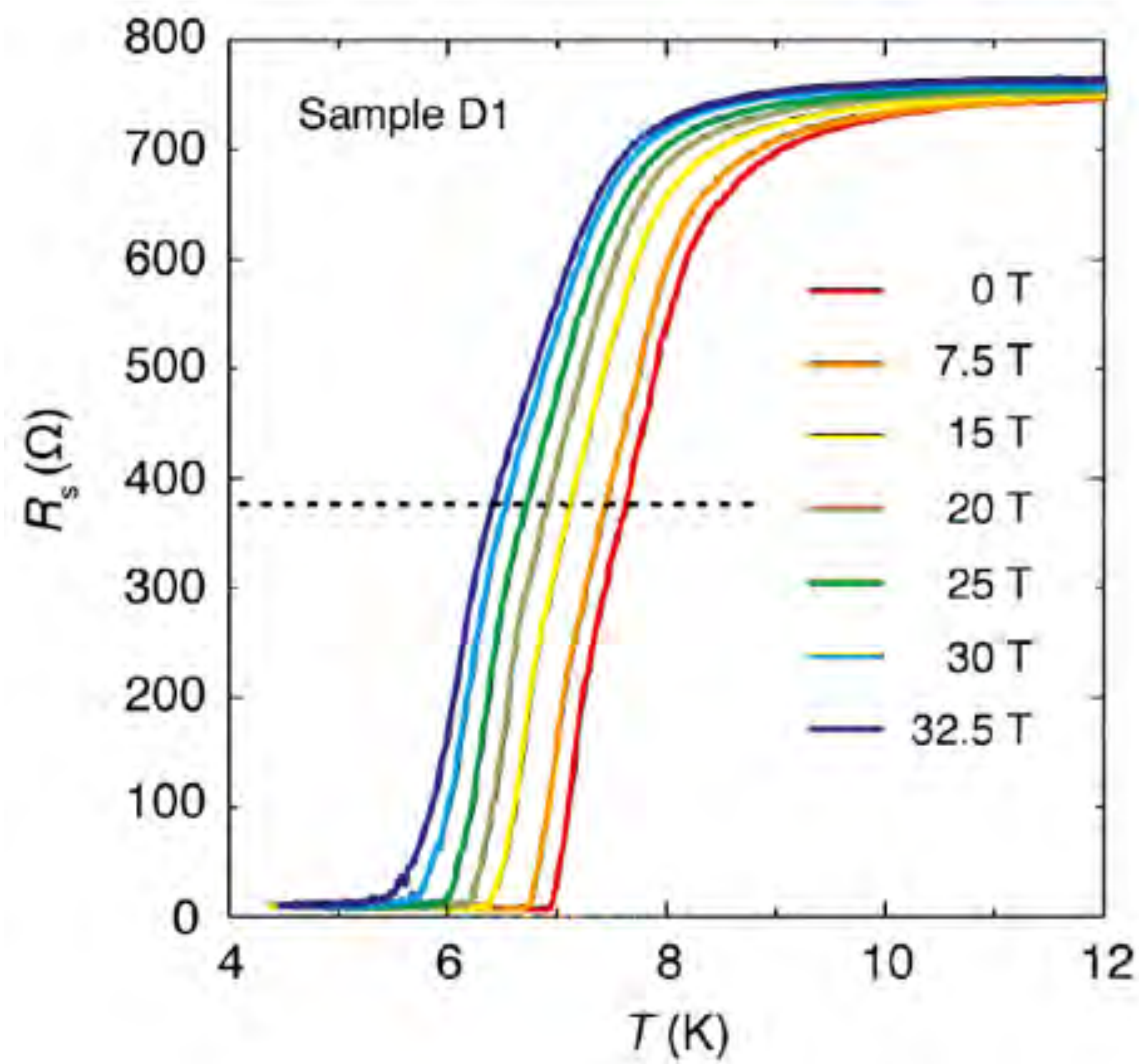
Huge in-plane B_{c2}

D1 sample

Low carrier density T_c = 2.3 K

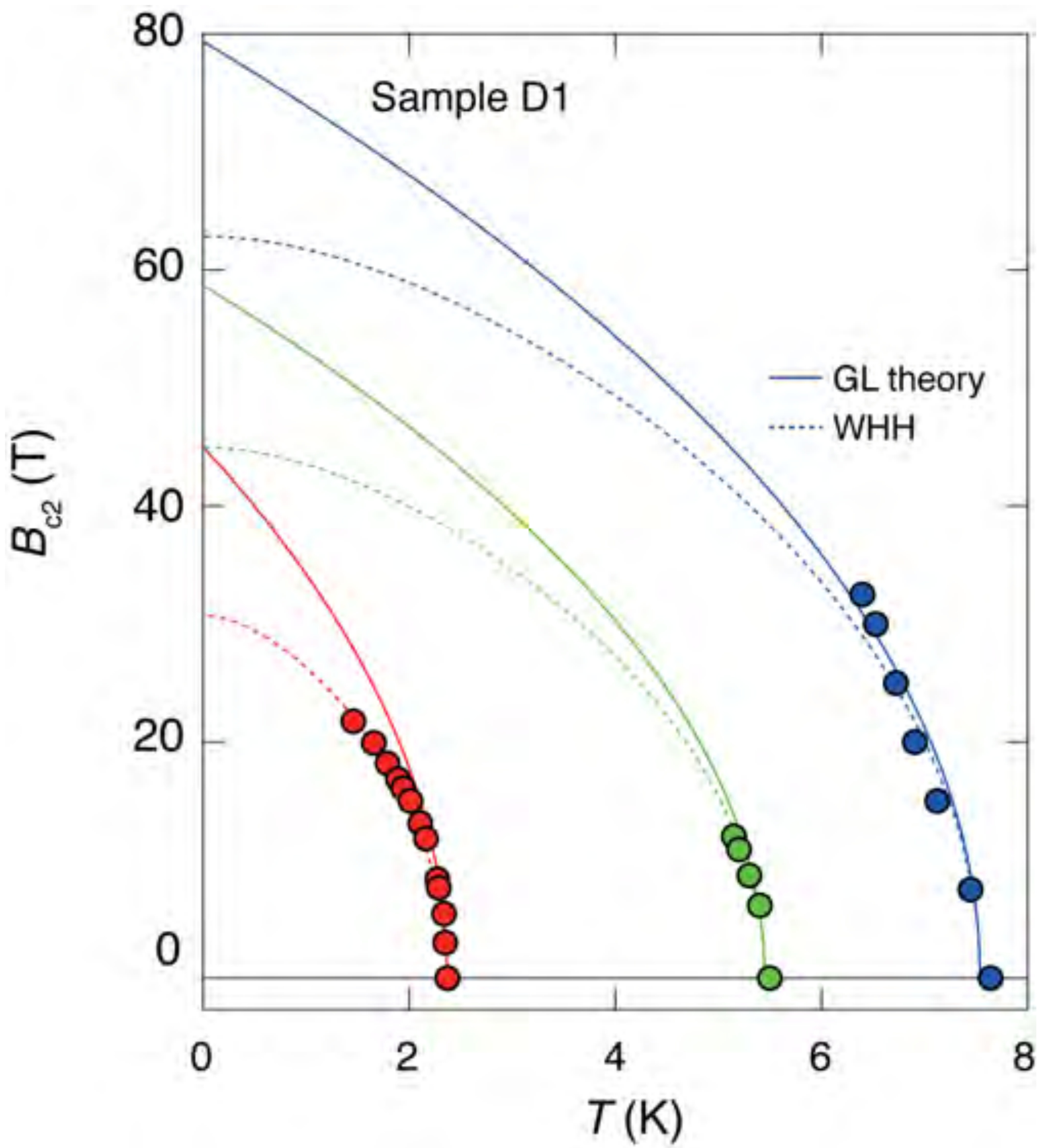


High carrier density T_c = 7 K



High Magnetic Field Lab (**HMFL**) in Nijmengen

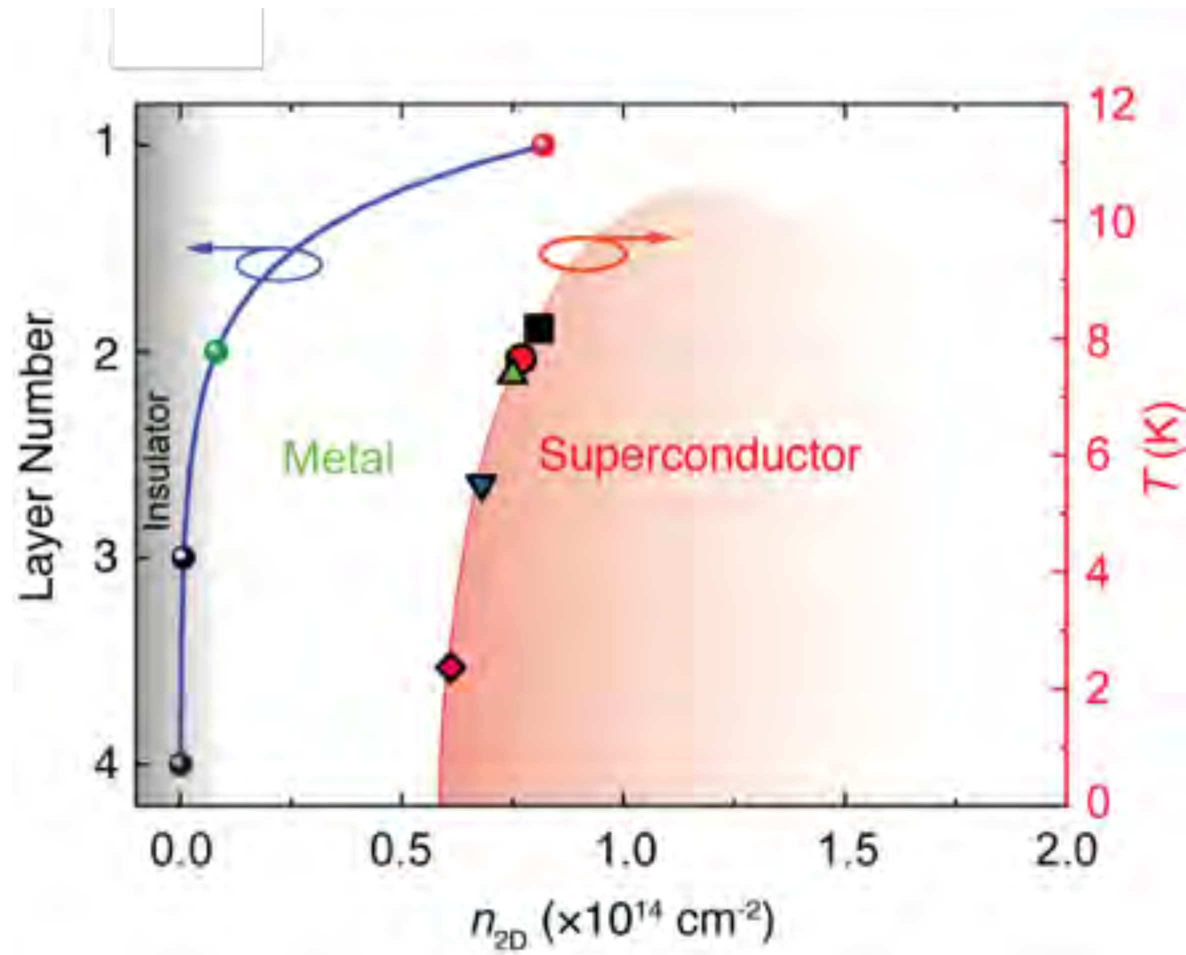
Huge in-plane B_{c2}



Ionic gated MoS_2 flake

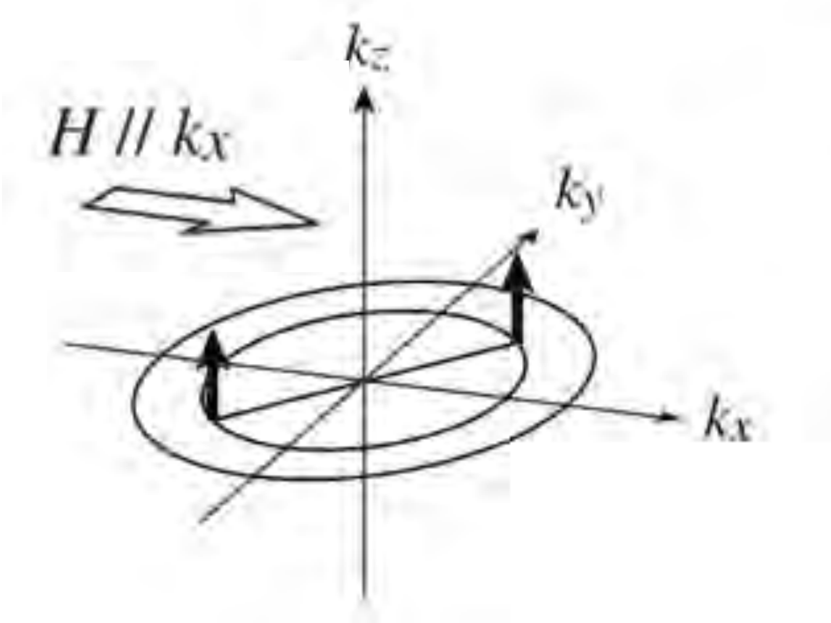
very larger B_{c2}

Significantly above the Pauli limit

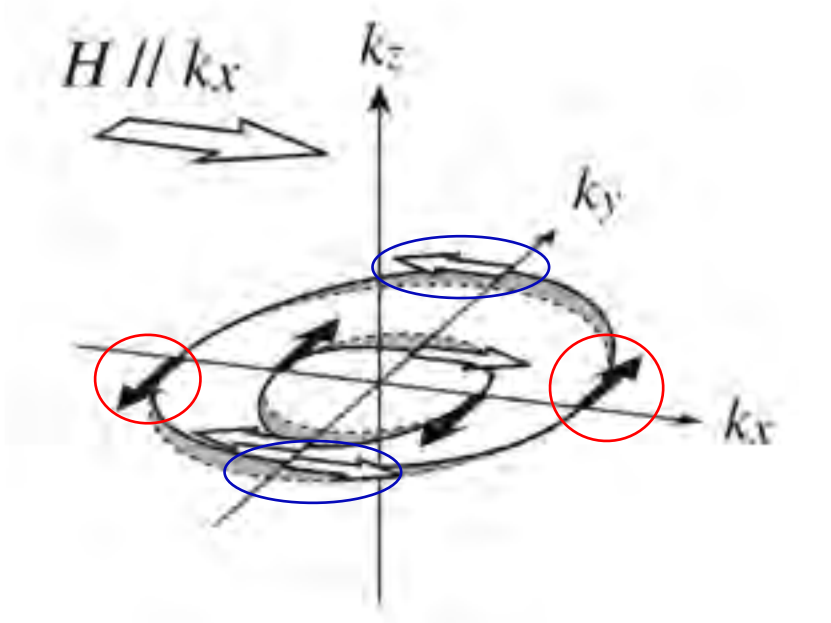


Why this superconductivity is so robust?

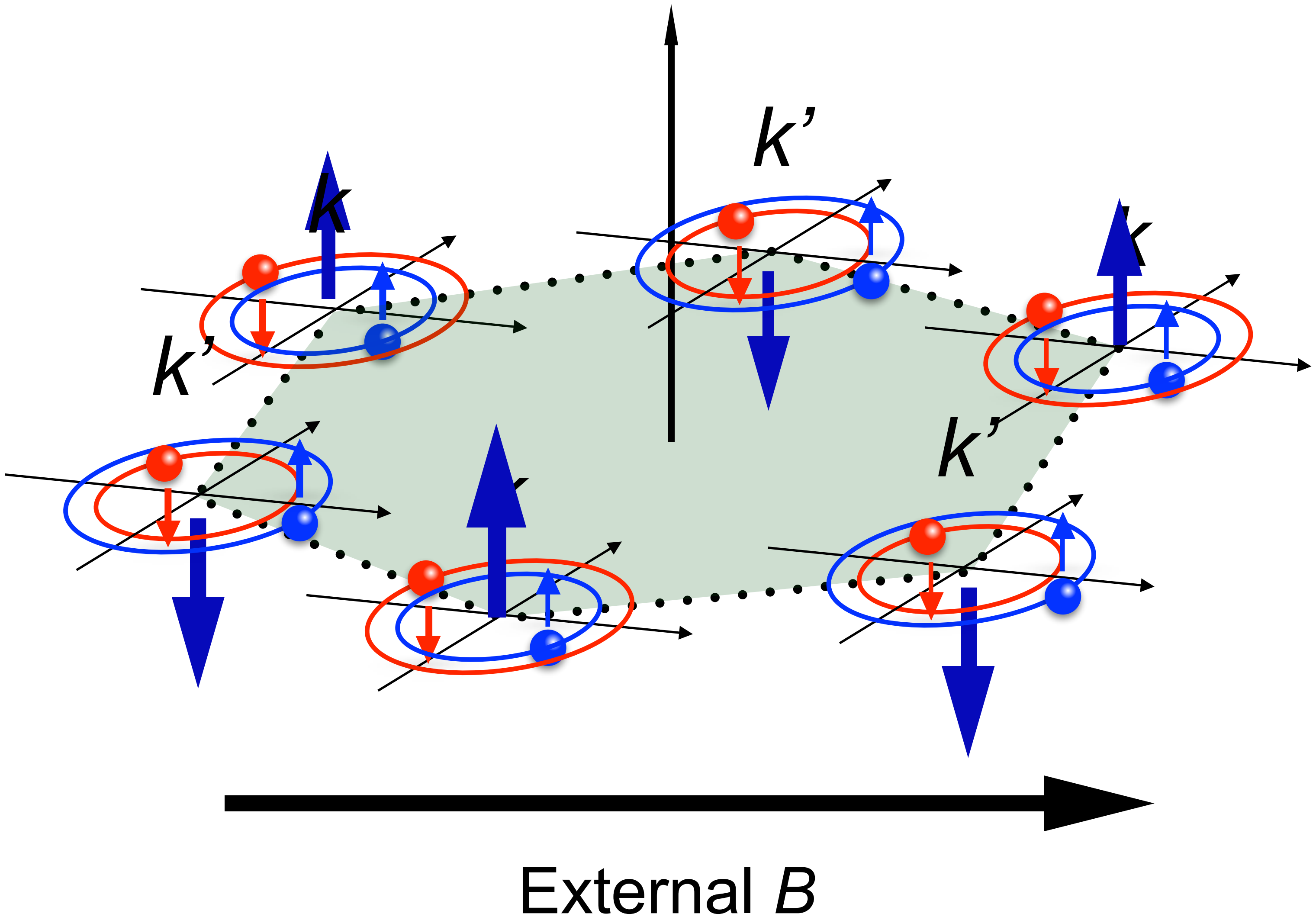
Triplet Cooper pair



Rashba SOC Protected

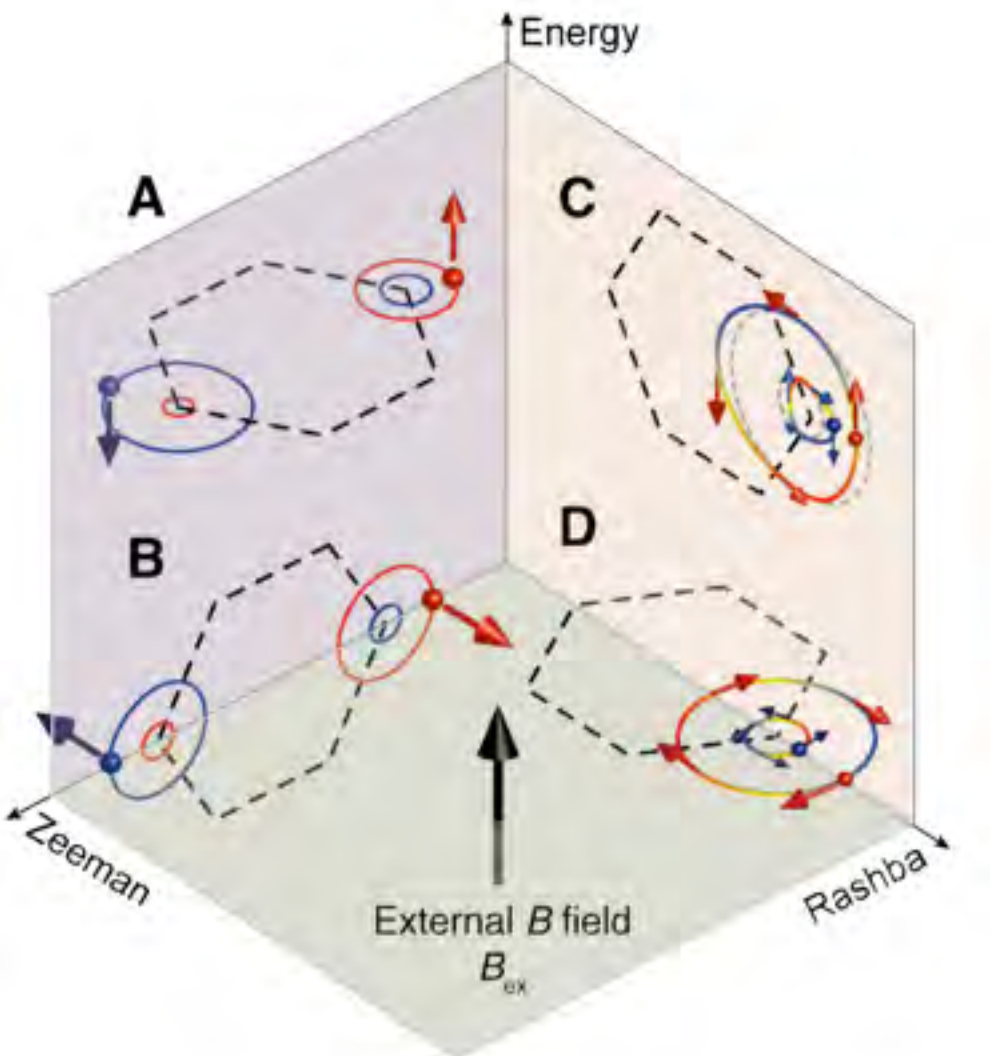


Zeeman SOC: Effective *B = 100 Tesla!*



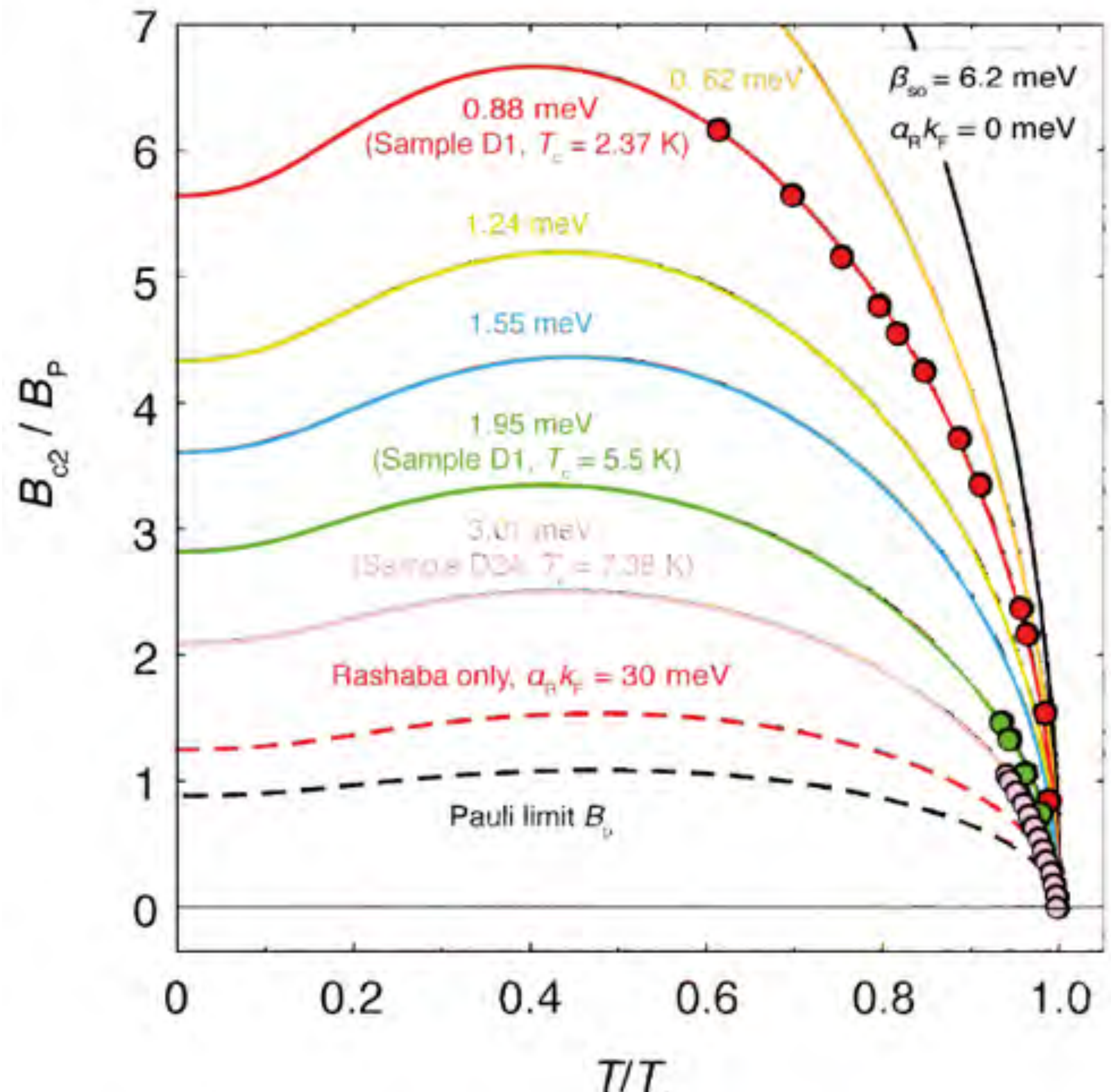
If external *B* ⊥ spin,
orthogonal protection is effective!

Why B_{c2} exceeds Pauli limit?



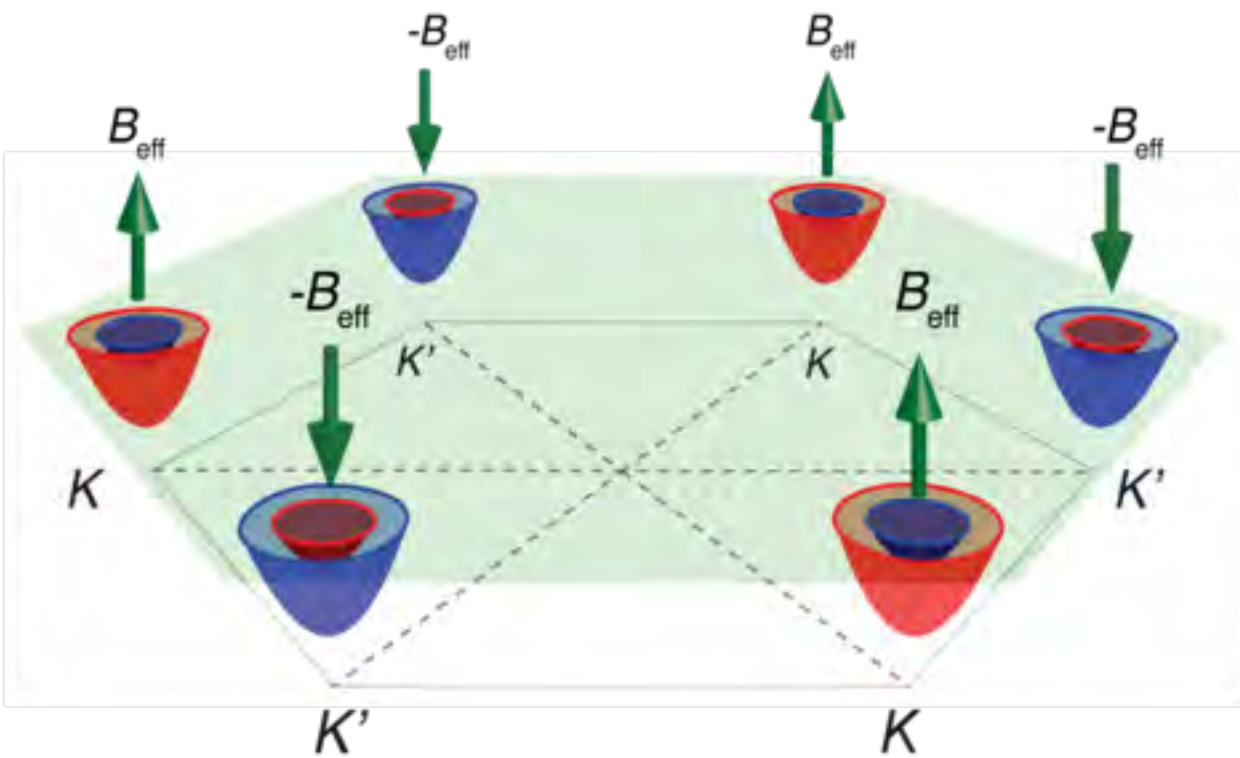
Zeeman SOC align spin along out-of-plane

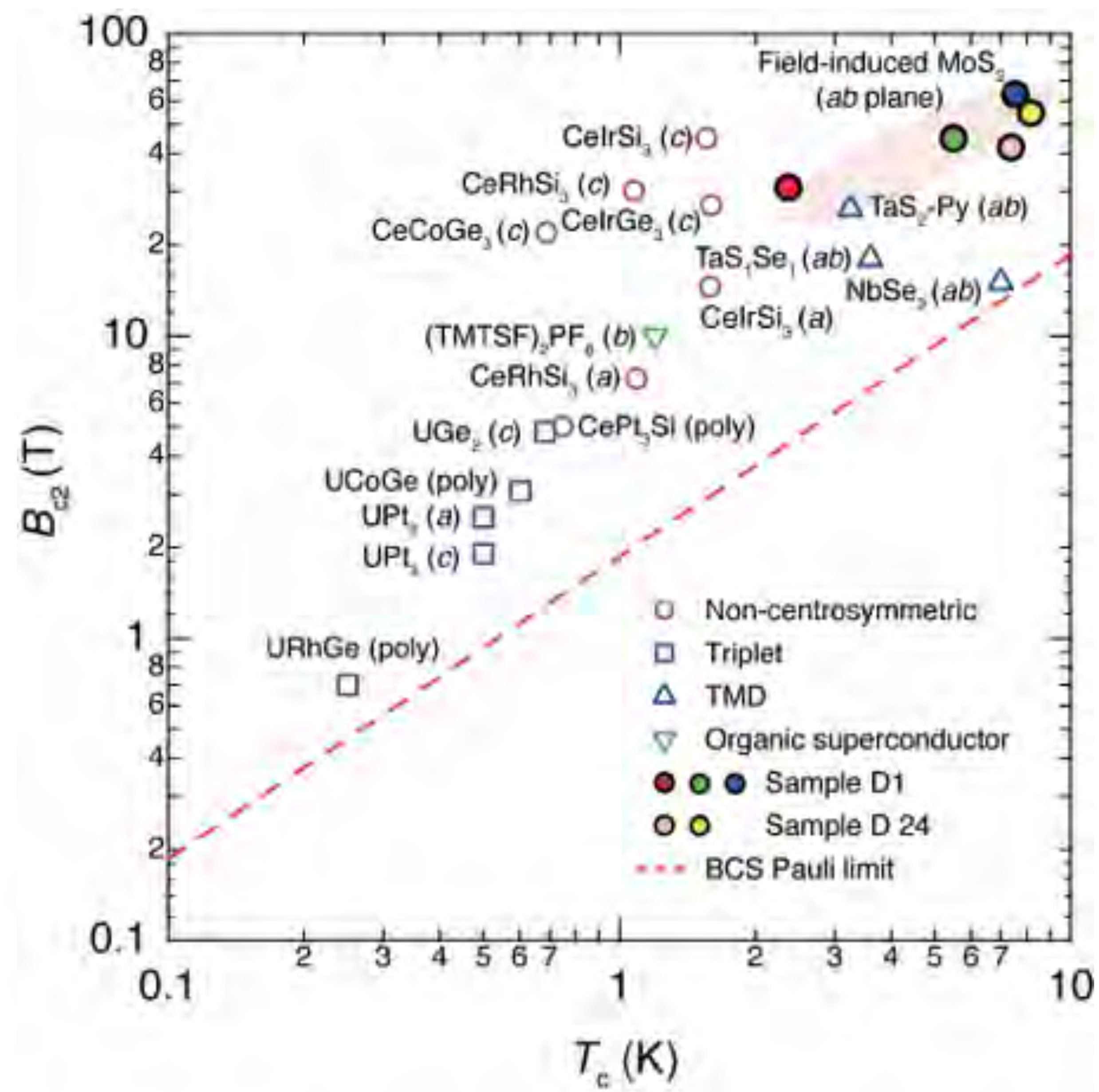
Rashba SOC align spin in in-plane

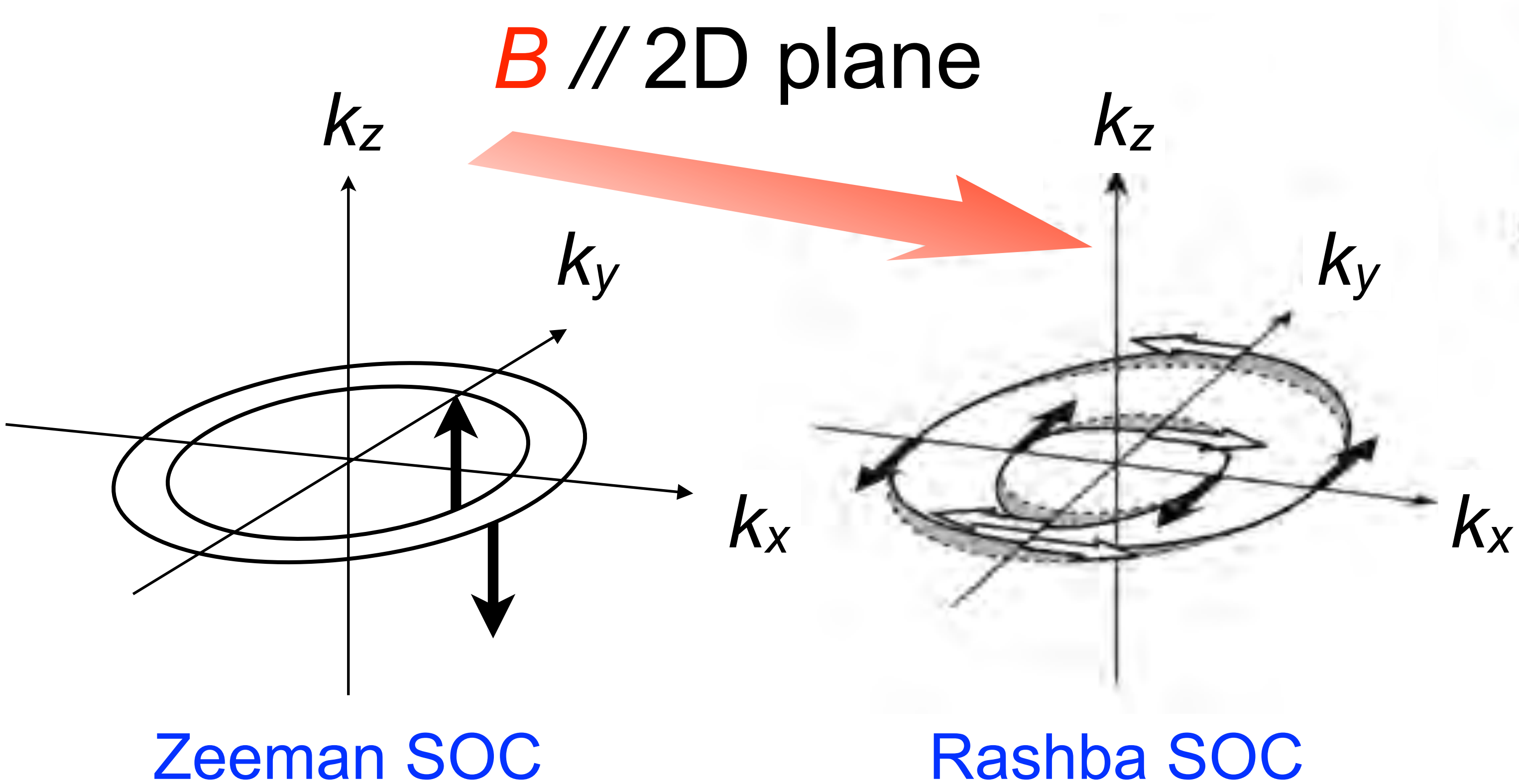


arXiv:1506.07620 [cond-mat.supr-con]

Ising Superconductivity

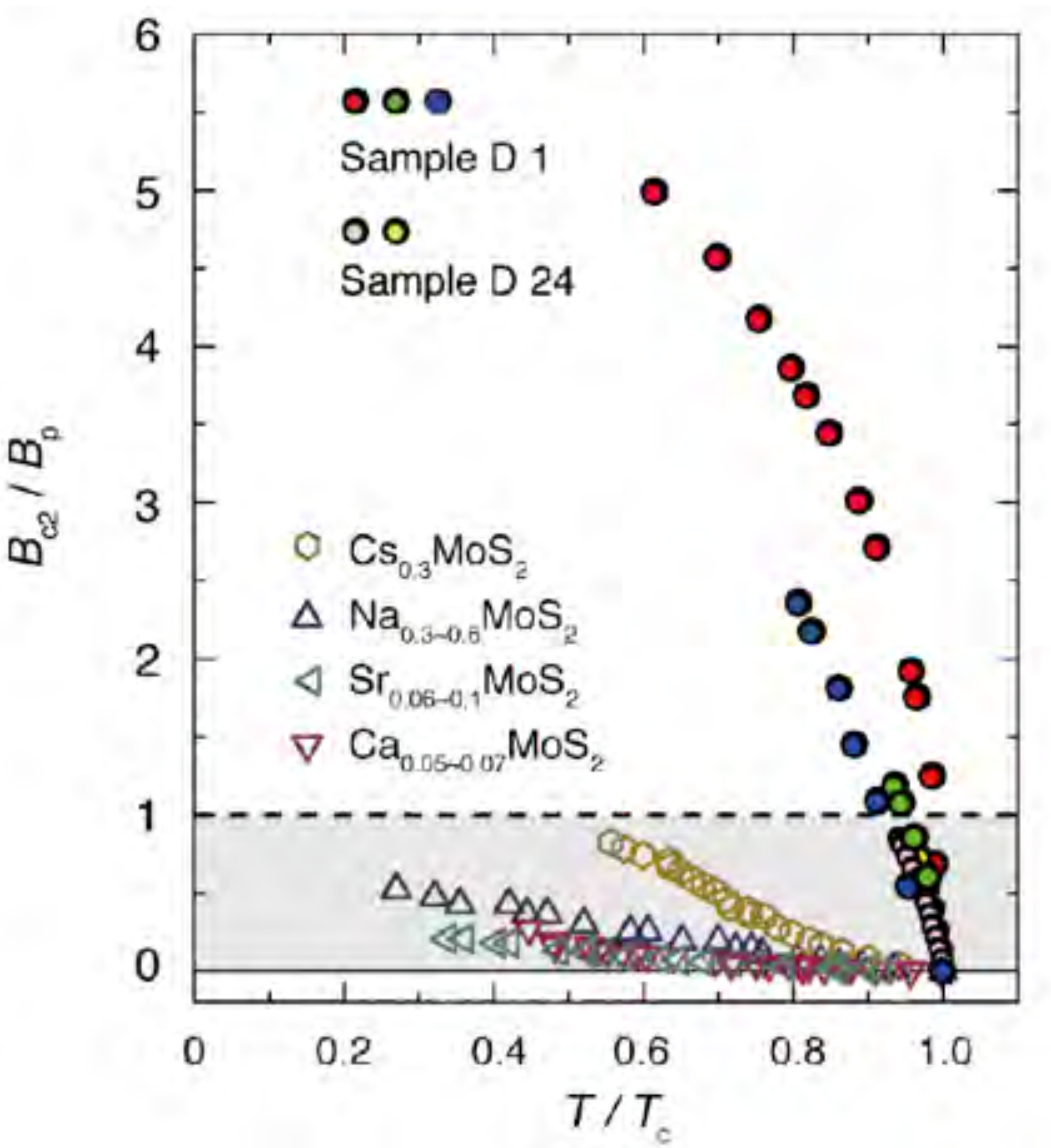






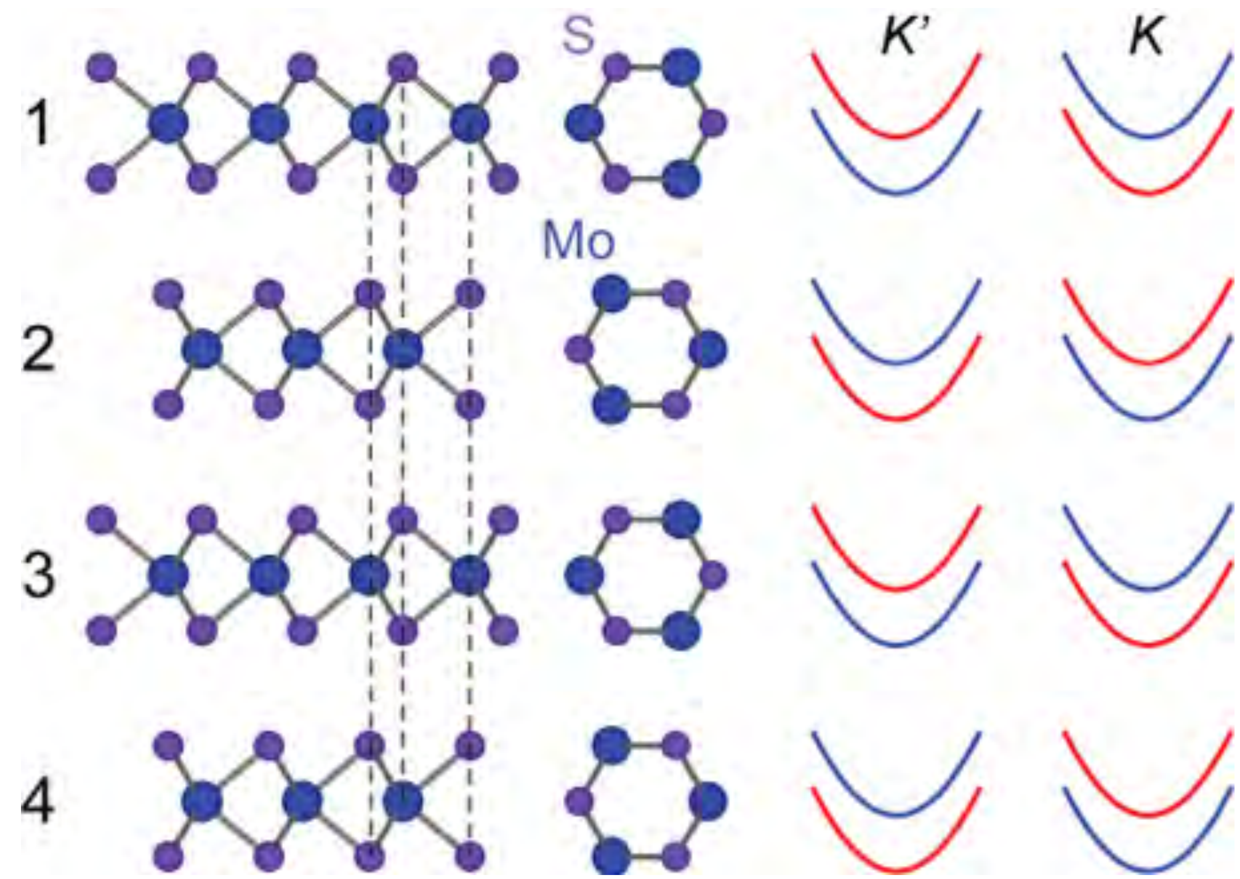
Zeeman-type protection
very robust superconductor!

Bulk Versus Field Induced Superconductivity



Bulk Phase: Zeeman SOC Cancellation

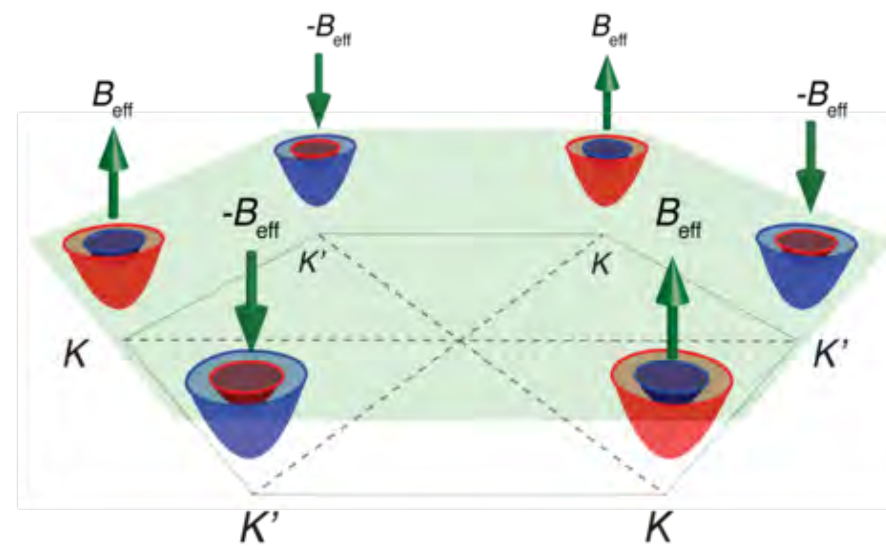
Gated Phase: Zeeman SOC 100 Tesla



- Ionic gated flake shows much larger B_{c2}, compared to chemical doped bulk MoS_2
- The former easily exceeds Pauli limit, but the latter falls below the limit.

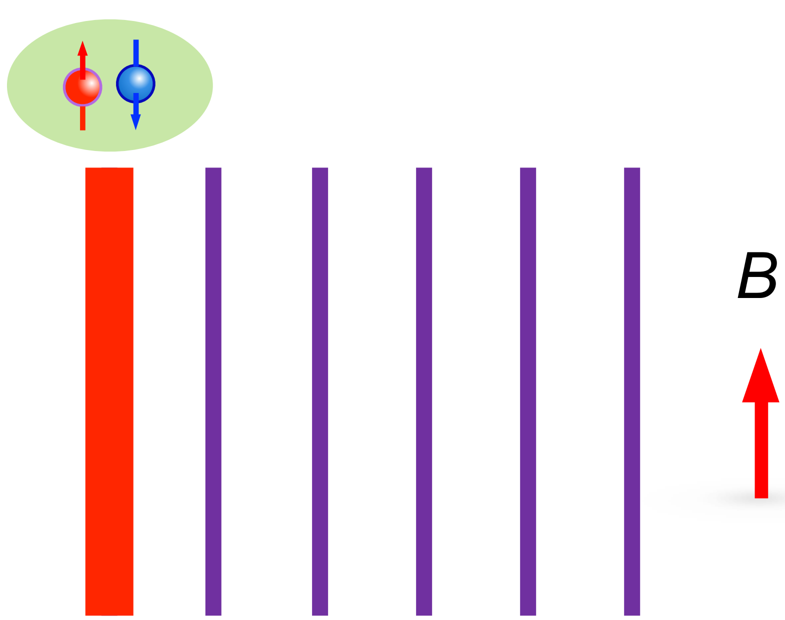
How to prepare an Ising superconductor

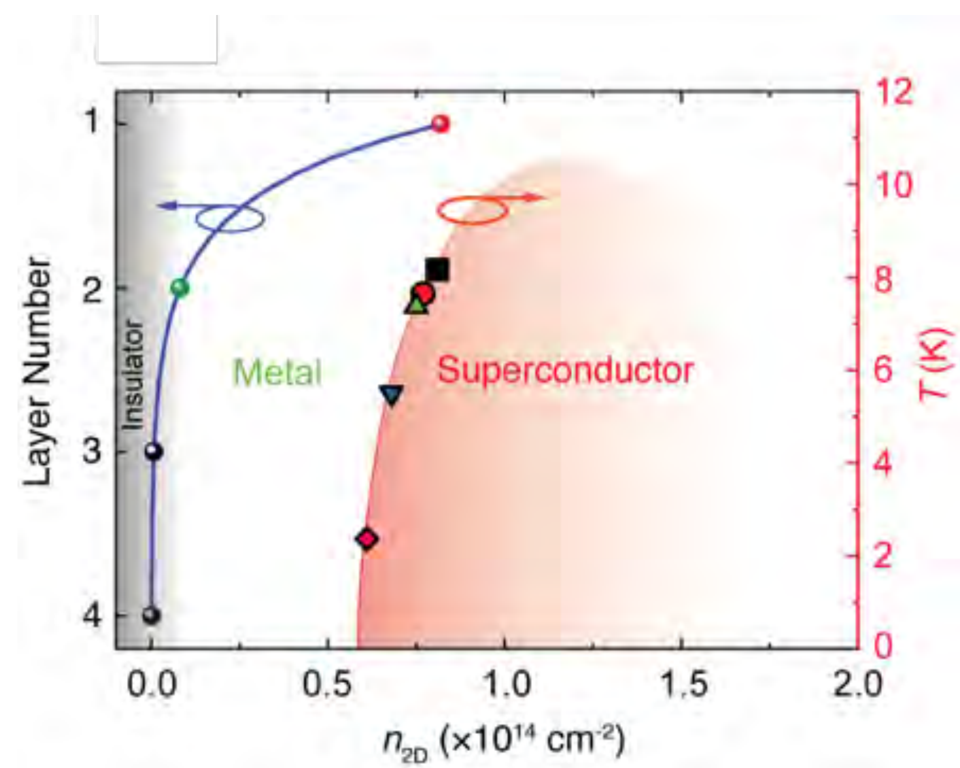
- Zeeman SOC at *K* and *K*' point
  Superconductivity exist



- Extreme two dimensionality

- Field effect doping
  Accumulating carrier for inducing different T_c
  Breaking inversion symmetry for Zeeman type SOC
  Inducing Rashba SOC





Summary

- Introduction to ion-gated transistors

  Ion-gating: a device physics with multidisciplinary taste on many materials

  Super efficient tool with rich variations

- Field control of electronic phases

  Metal-insulator transition, superconductivity, valley, ferromagnetic transitions, etc.

  More phenomena and functionalities appeared!

Gate Control of Electronic Properties and Functionalities