New Opportunities in Two-dimensional Materials

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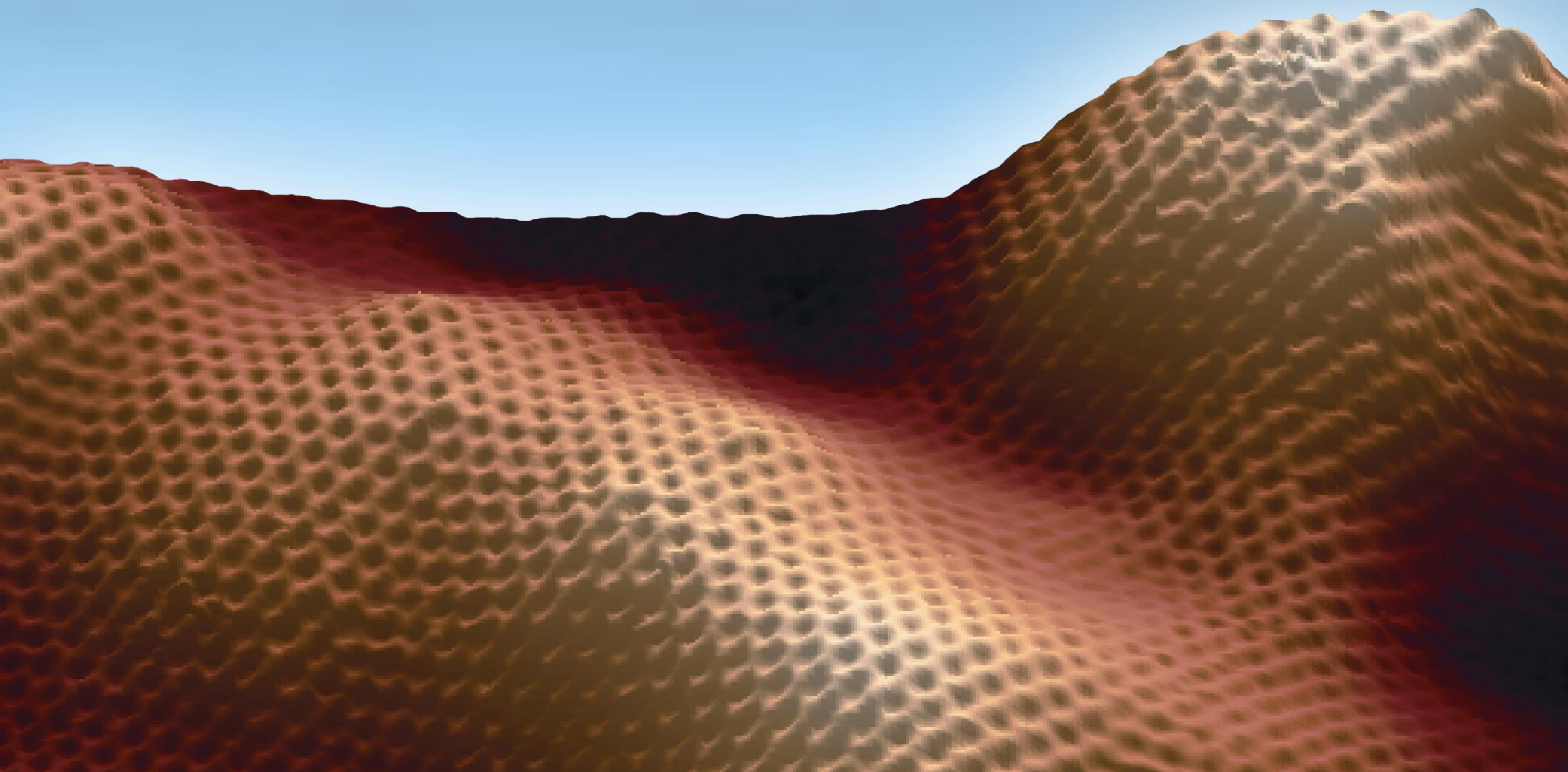
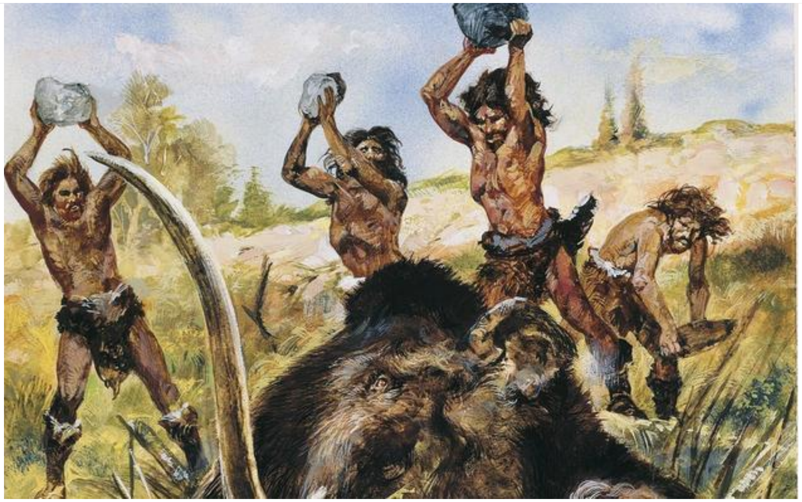
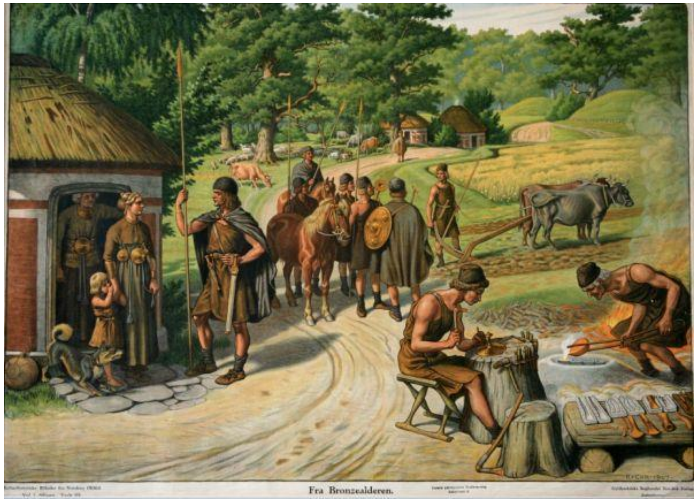


A Brief History of Materials

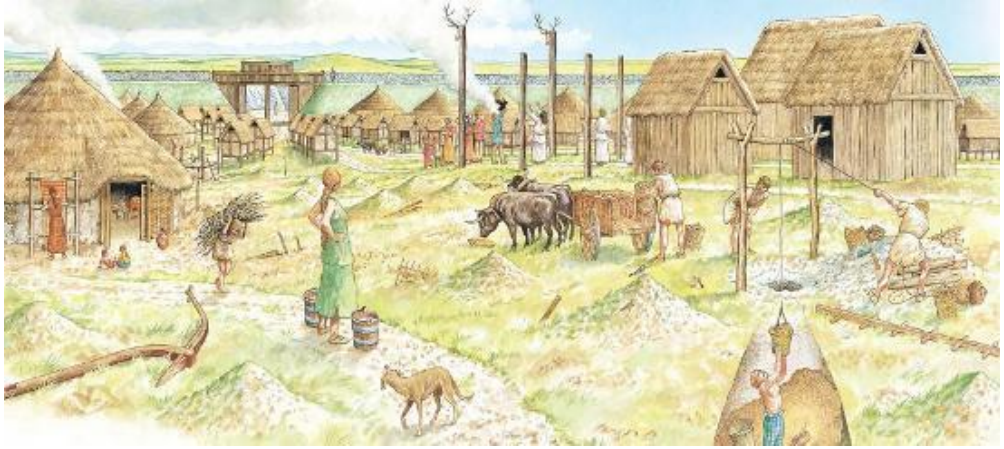
The **Stone** Age



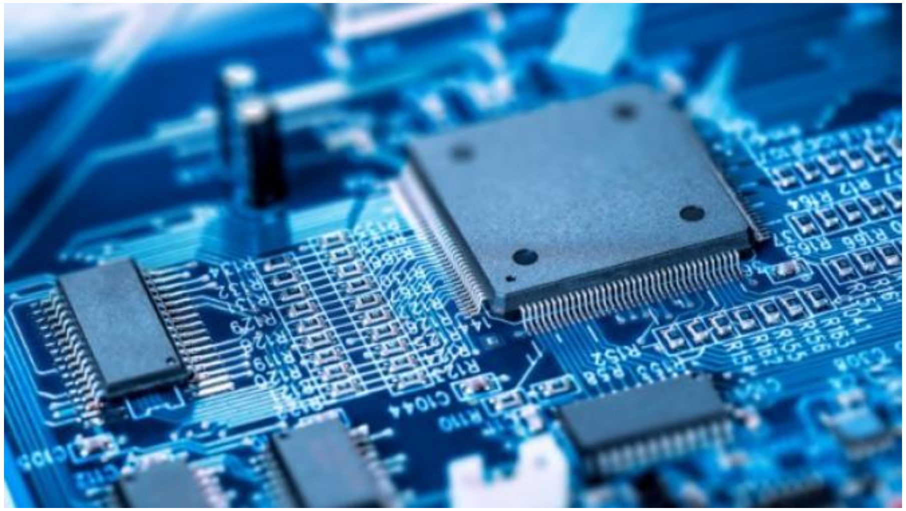
The **Bronze** Age



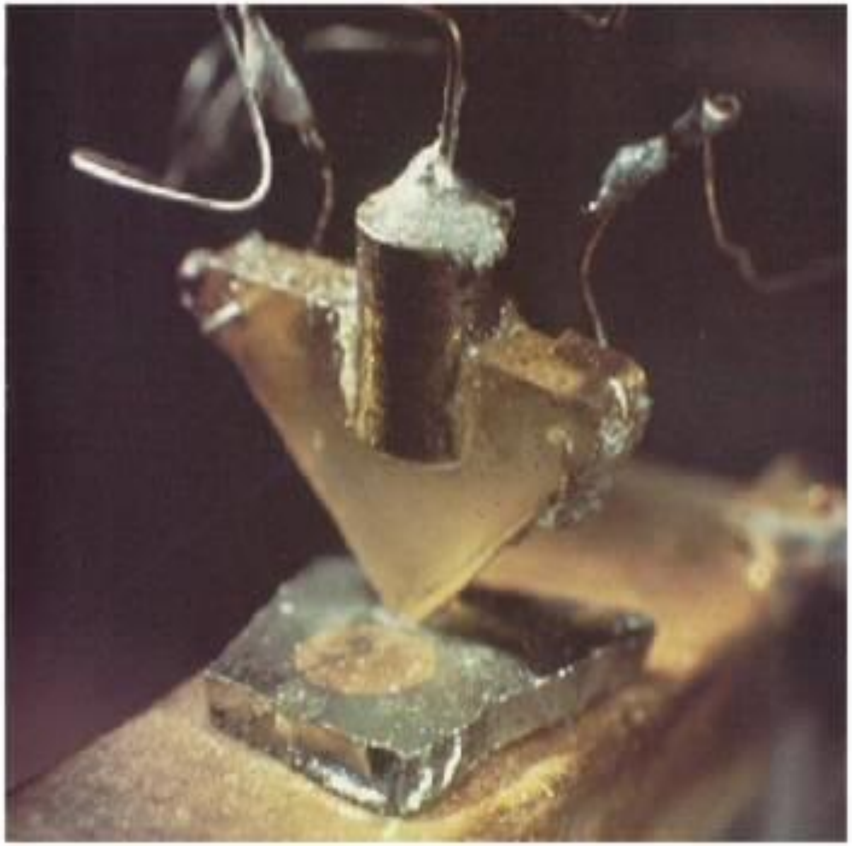
The **Iron** Age



The Silicon Age?

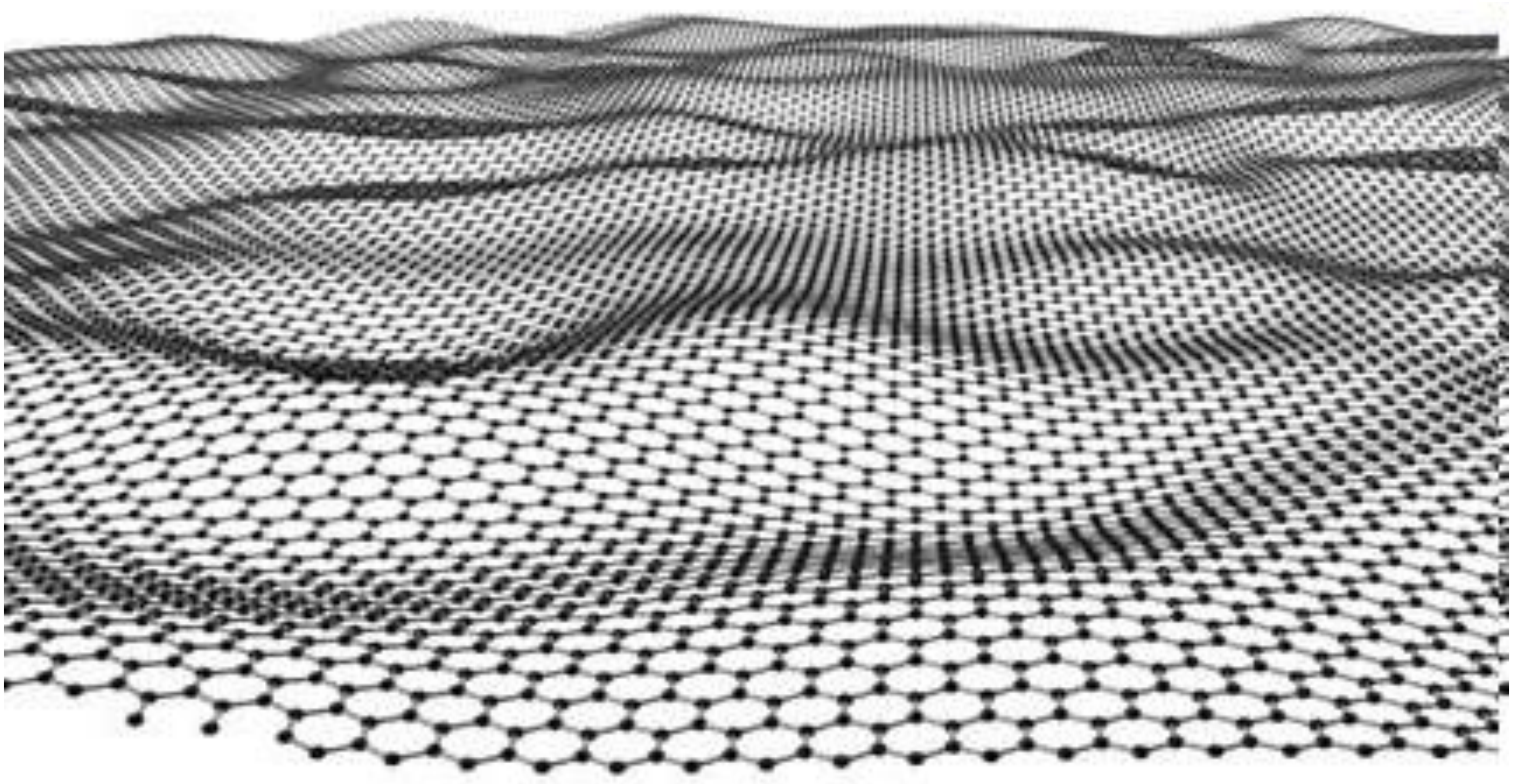


“Interface is the Device”



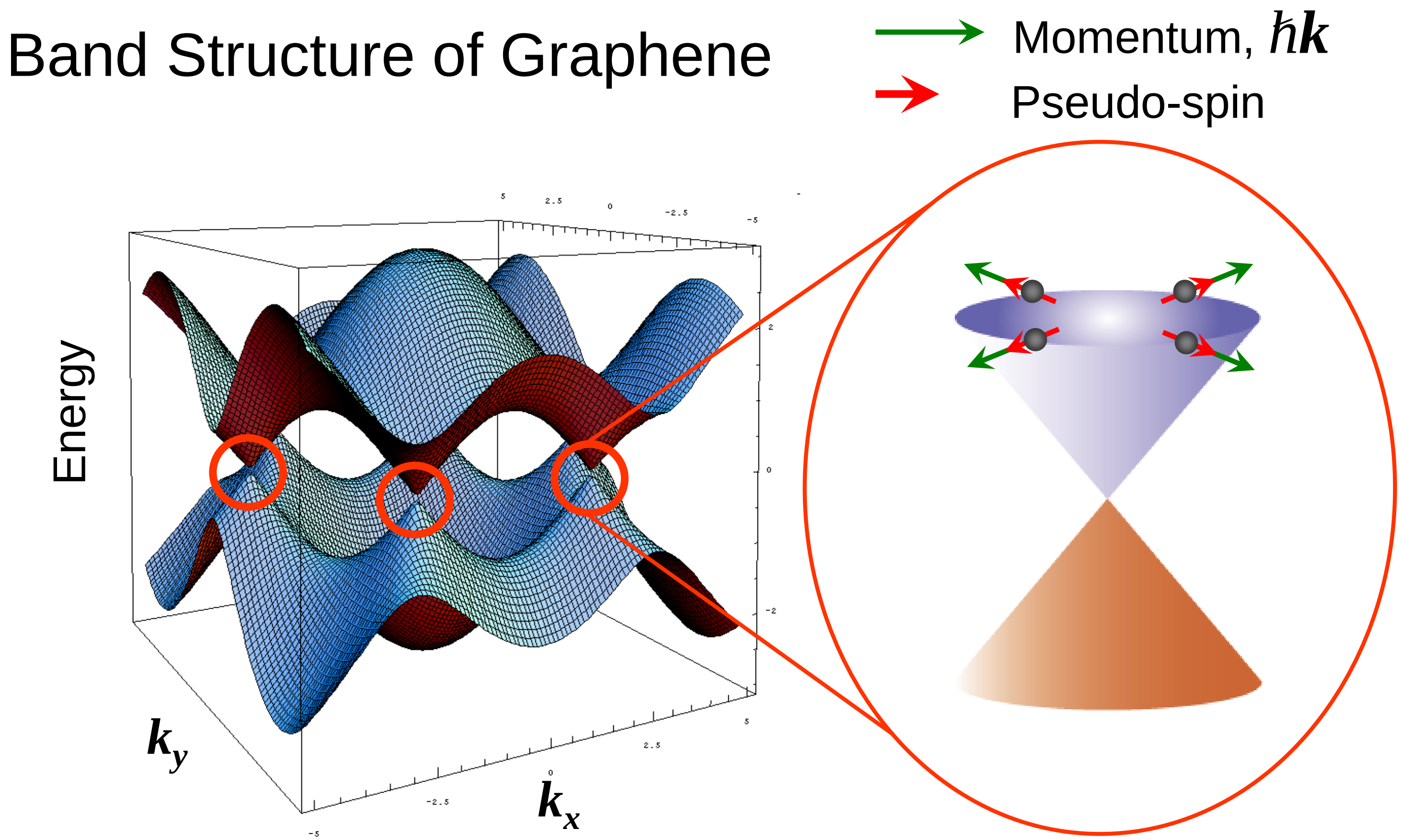
The first transistor, Bell Lab, 1947

Graphene: The Beginning of 2D Material Research



Geim group (2004)

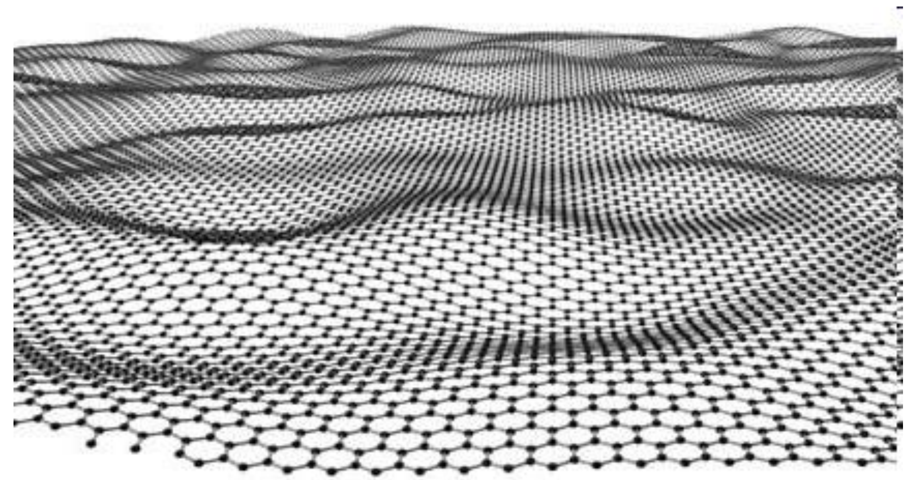
Graphene : Dirac Fermions in 2D



$$E = \hbar k v_F$$

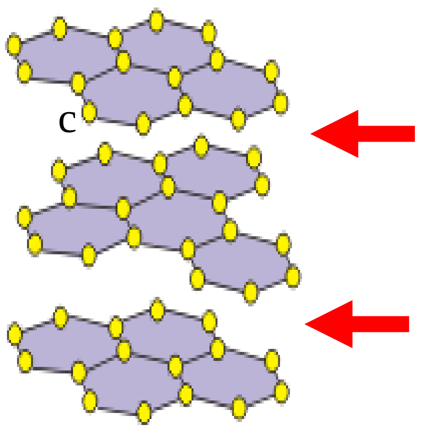
$$E = pc$$

P. R. Wallace, *Phys. Rev.* 71, 622 (1947).
T. Ando et al, *J. Phys. Soc. Jpn* 67, 2857 (1998).

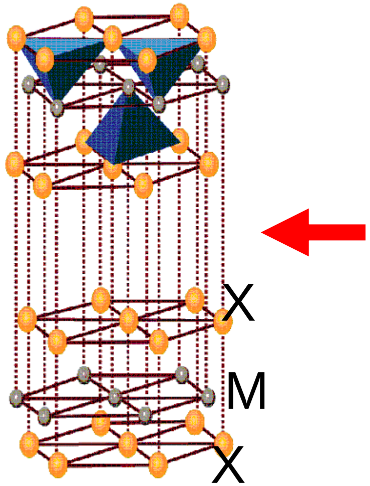


Less is different

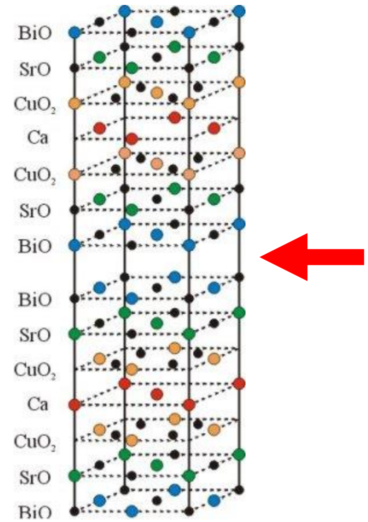
Families of New Materials in 2D



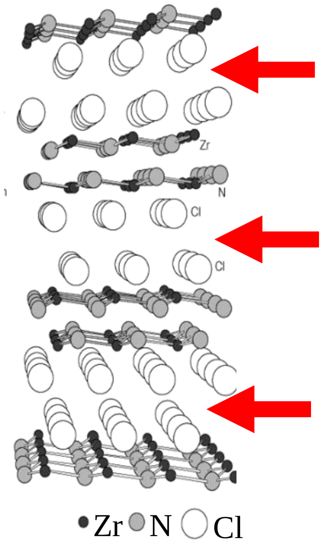
Graphite



Metal Chalcogenides (M= Nb, Ta, Va, … X= S, Se, Te)



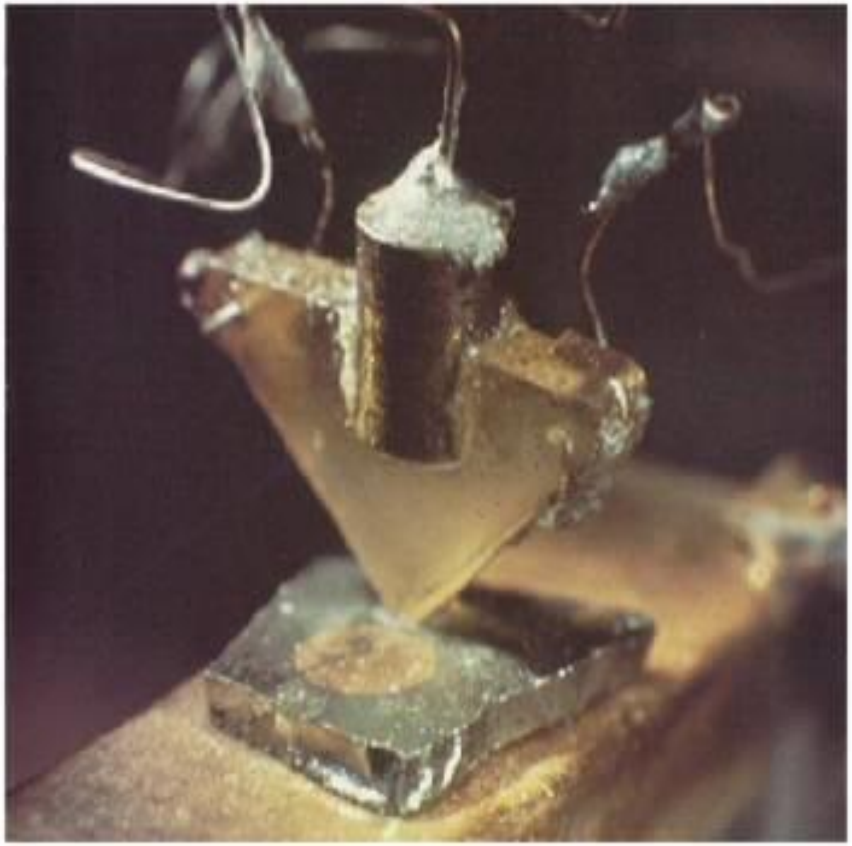
High Tc Materials Such as $Bi_2Sr_2CaCu_2O_{8-x}$



β- ZrNCl

Hundreds of 2D crystals waiting to be explored

Opportunities to Tune the Material Properties in 2D

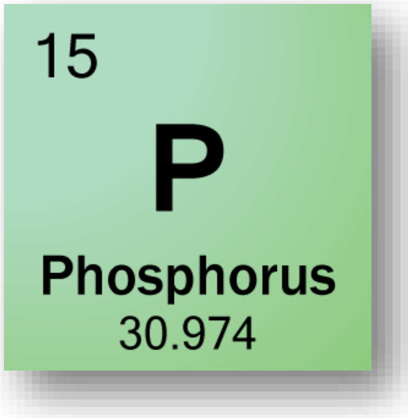


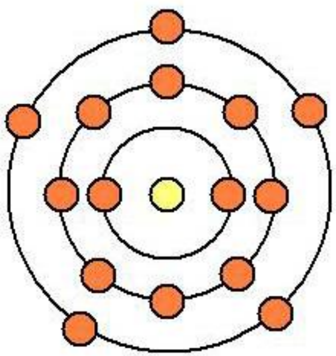
New device paradigm?

Outline

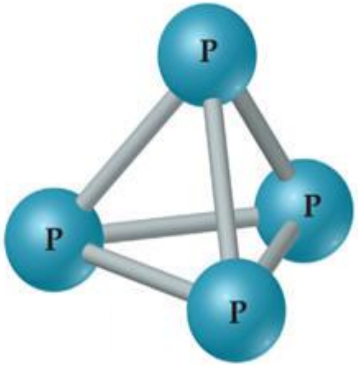
- Black phosphorus (semiconductor)
- 1T-TaS_2 (metal)
    - Gate-controlled intercalation
    - Tunable Phase in 1T-TaS_2

Allotropes of Phosphorus

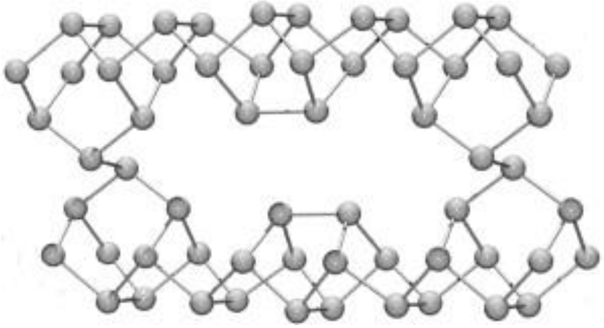




White Phosphorus



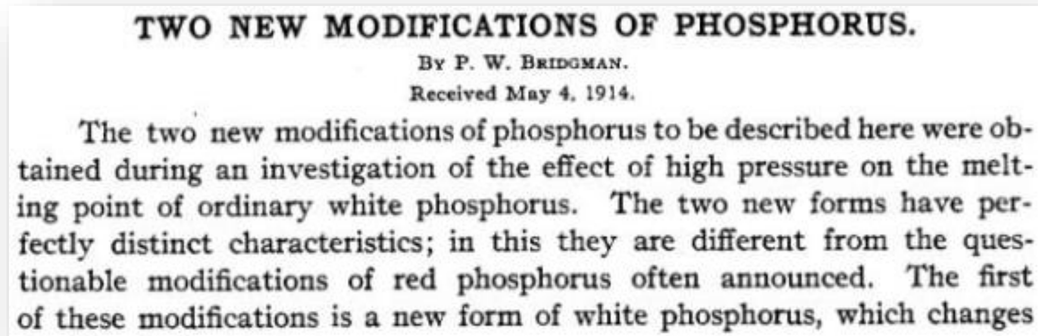
Red Phosphorus



Allotropes of Phosphorus: Black Phosphorus

Black Phosphorus

P. W. Bridgman, JACS 36,1344 (1914)



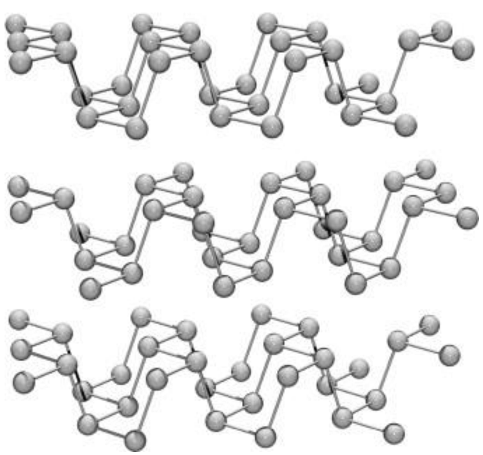
TWO NEW MODIFICATIONS OF PHOSPHORUS.

By P. W. Bridgman.

Received May 4, 1914.

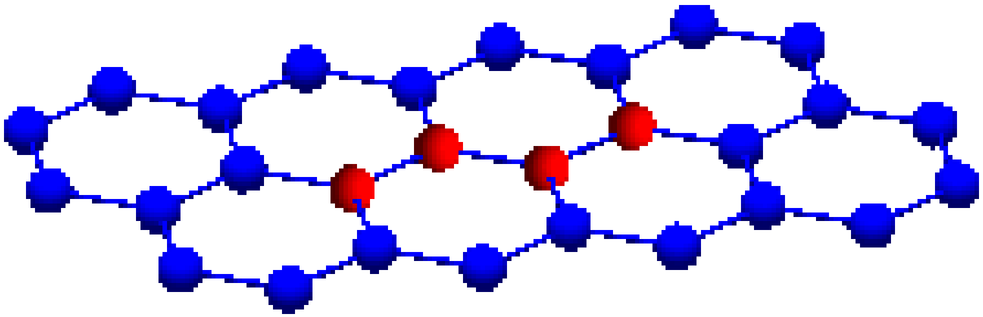
The two new modifications of phosphorus to be described here were obtained during an investigation of the effect of high pressure on the melting point of ordinary white phosphorus. The two new forms have perfectly distinct characteristics; in this they are different from the questionable modifications of red phosphorus often announced. The first of these modifications is a new form of white phosphorus, which changes

Layered crystal structure



Review:
Morita, *Applied Physics A* **39,** 227–242 (1986).

Phosphorene v.s. Graphene



Graphene

- ***Planar*** honey-comb lattice
- ***4*** valence electrons
- ***Half-filled*** conduction band
- ***Zero-gap*** semiconductor

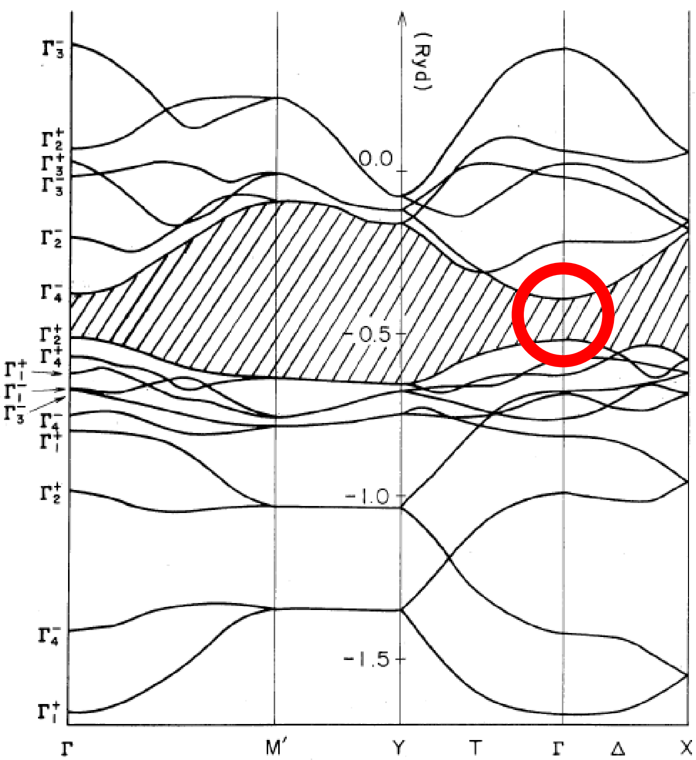
Phosphorene

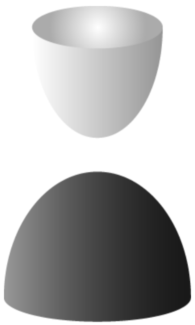
- ***Puckered*** honey-comb lattice
- ***5*** valence electrons
- ***Fully filled*** valence band
- ***Gapped*** semiconductor

Phosphorene v.s. Graphene

Phosphorene

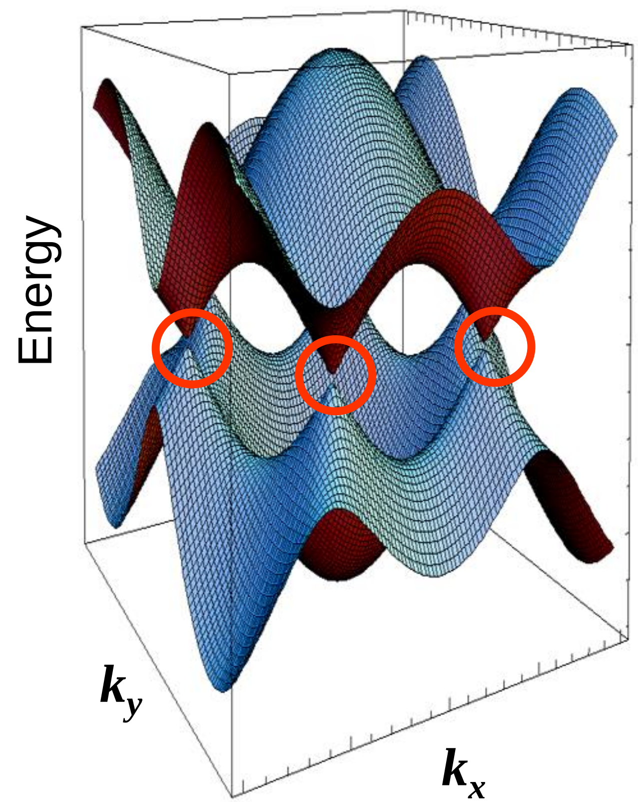
Band gap ~ 2 eV





Y. Takao, et al., *J. Phys. Soc. Jpn.* 50, 3362 (1981)

Graphene

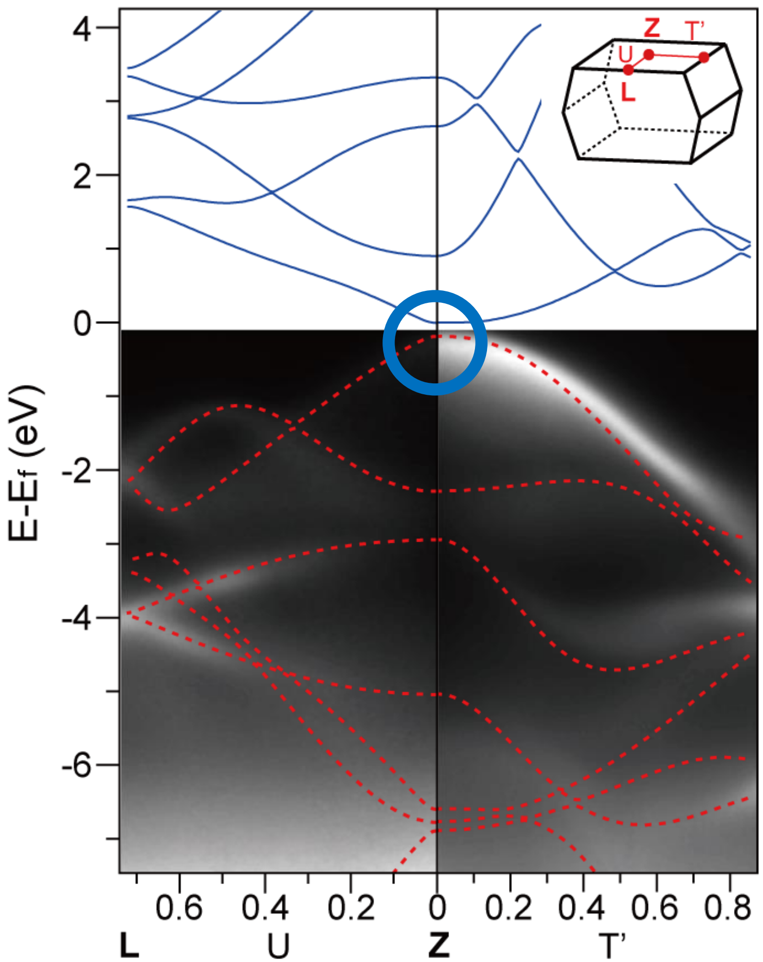


P. R. Wallace, *Phys. Rev.* 71, 622 (1947).

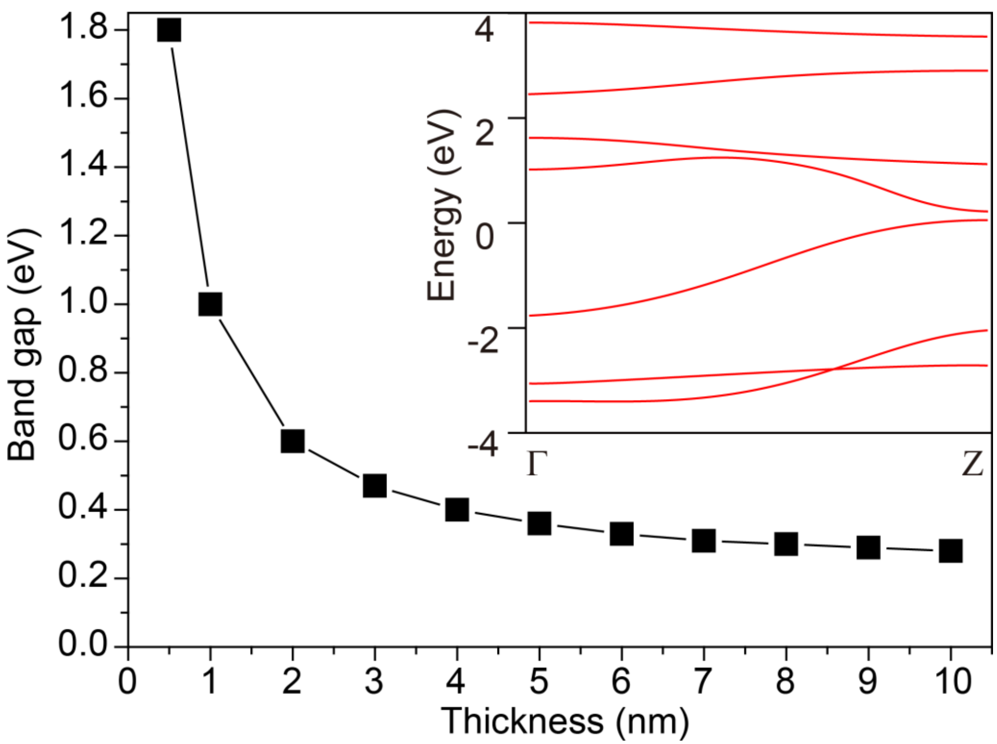
Thickness-dependent Bandgap in few-layer Phosphorene

Band structure of the bulk

Direct band gap ~ 0.3 eV



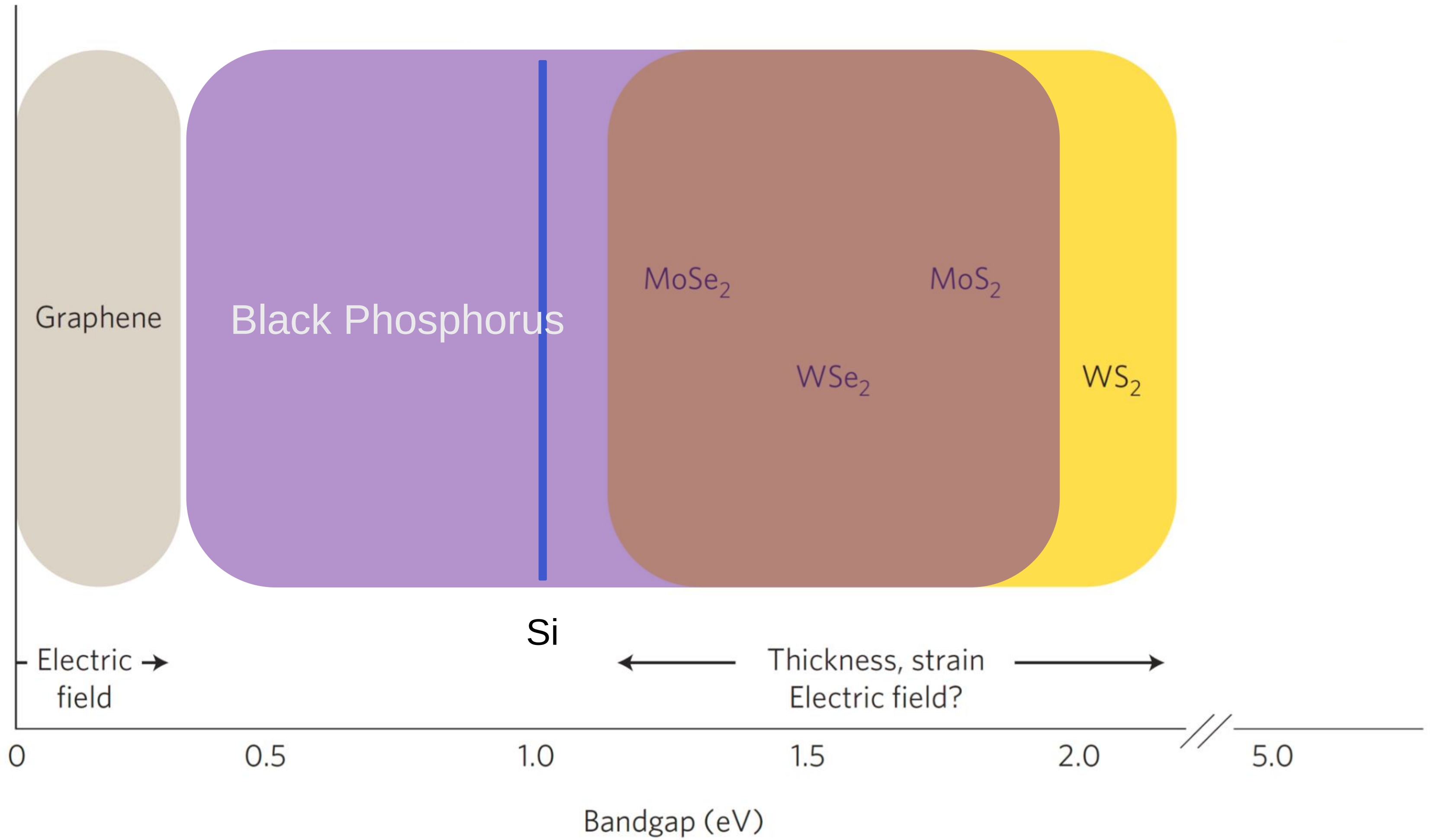
Thickness-dependent bandgap



Direct bandgap tunable by varying thickness

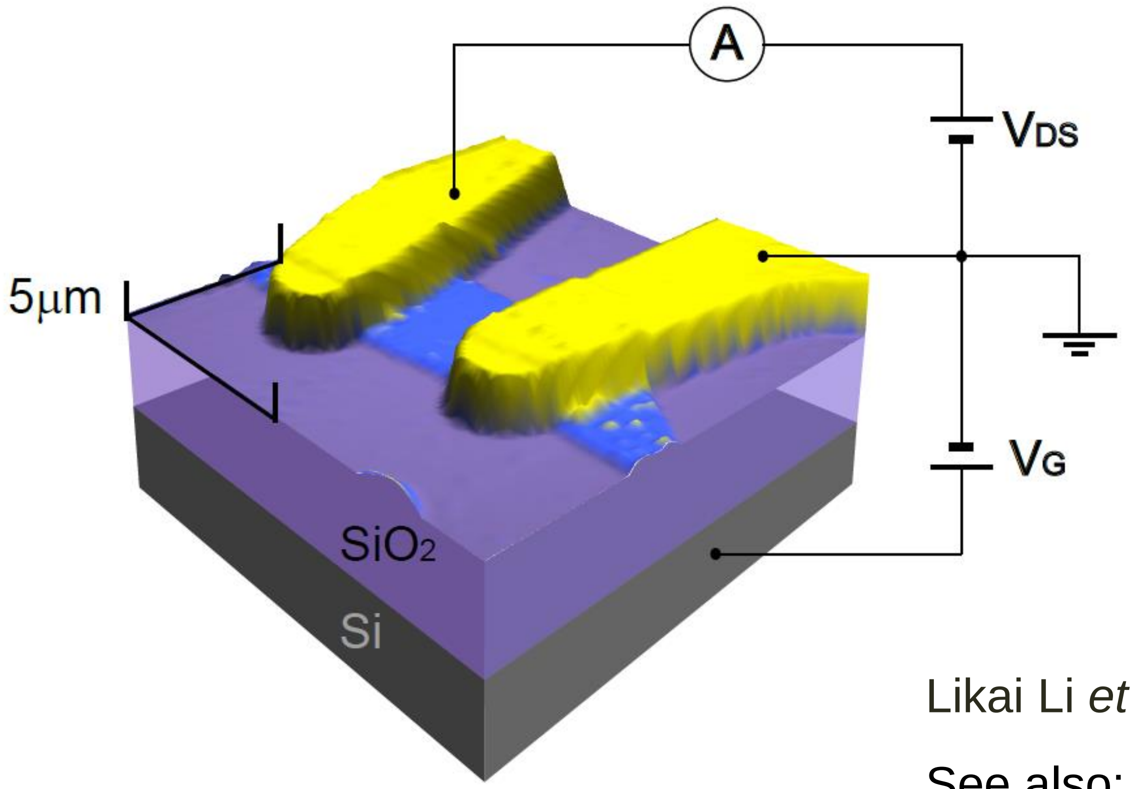
Thickness-dependent Band Gap

Bridging the gap



Churchill and Jarillo-Herrero, Nature Nano. (2014)

Black Phosphorus Field-effect Transistor



Likai Li

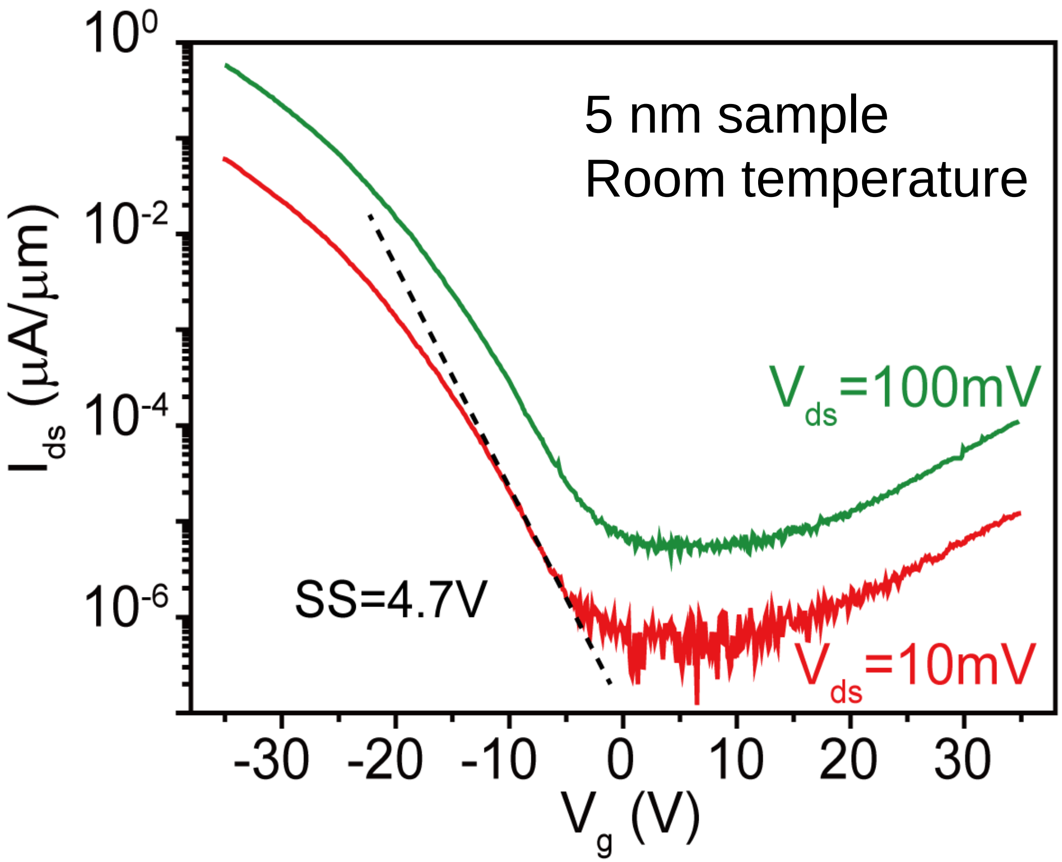
Fangyuan Yang

Likai Li *et al.* Nature Nano. **9**, 372 (2014).

See also:
Liu, H. et al. ACS Nano 8, 4033 (2014).
Koenig, S. P. et al., APL 104, 103106 (2014).
Xia, F. et al., Nature Comm. 5, 4458 (2014).

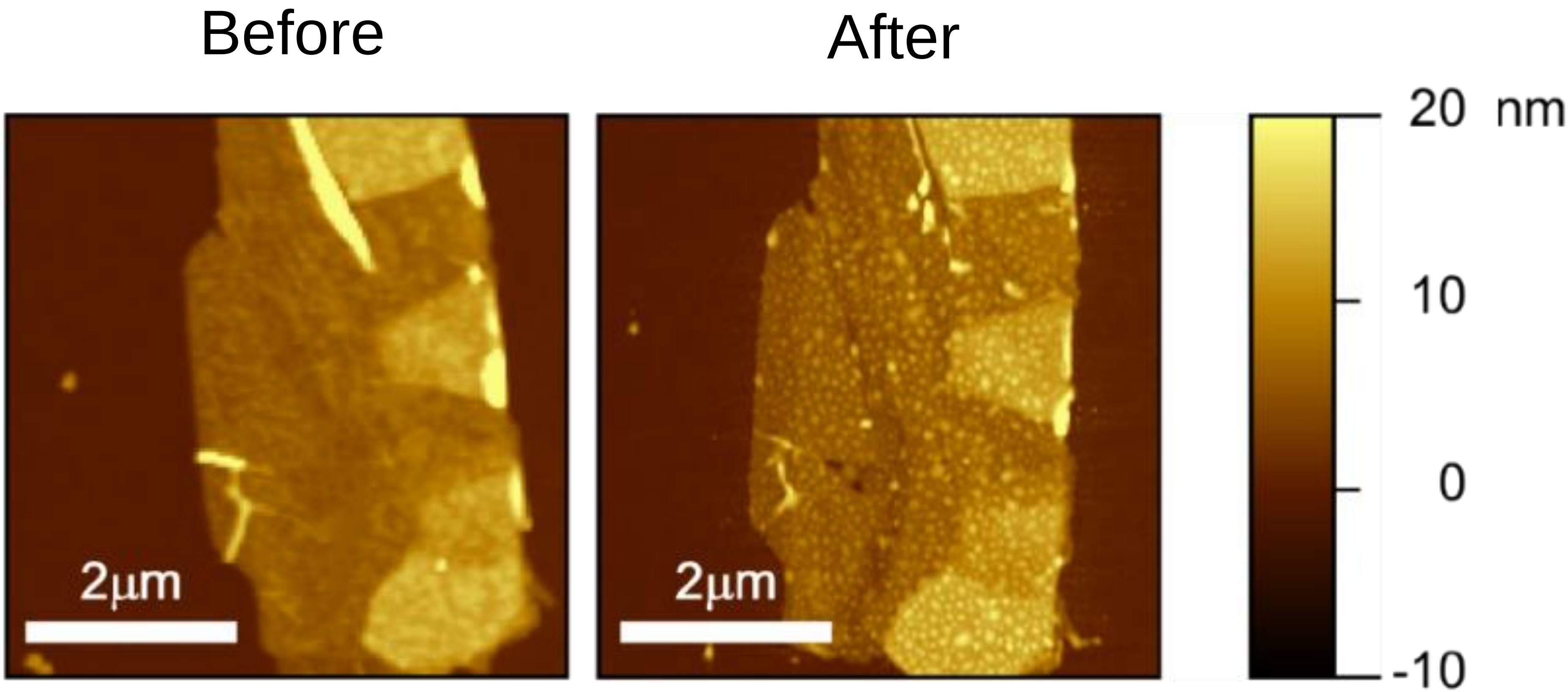
Black Phosphorus FET

Highest on-off ratio ~ 10^5



- High mobility up to 1000 cm^2/Vs
- Saturation in I-V Characteristics

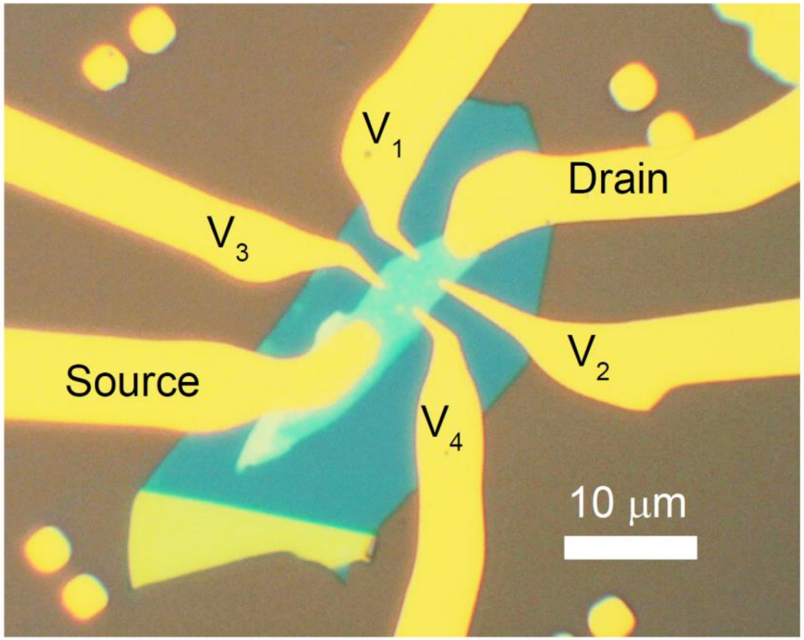
Limiting Factors of Carrier Mobility



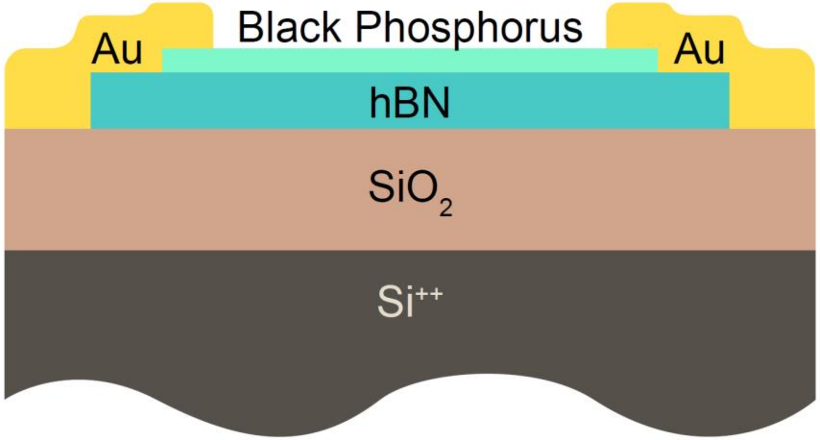
Sample left in air for 3 days

Black Phosphorus on Hexagonal Boron Nitride

Optic Image of
Black Phosphorus on BN



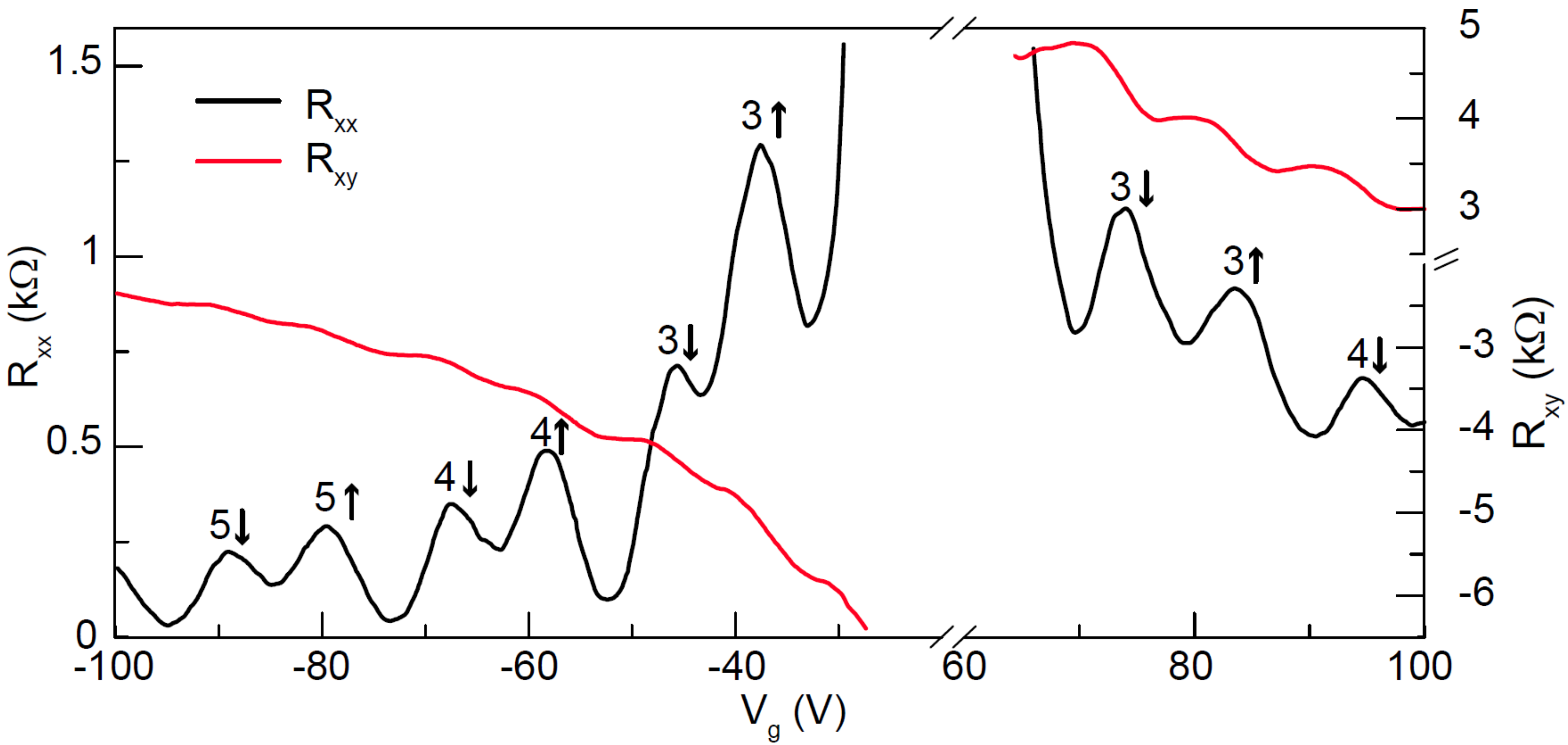
Cross-sectional View



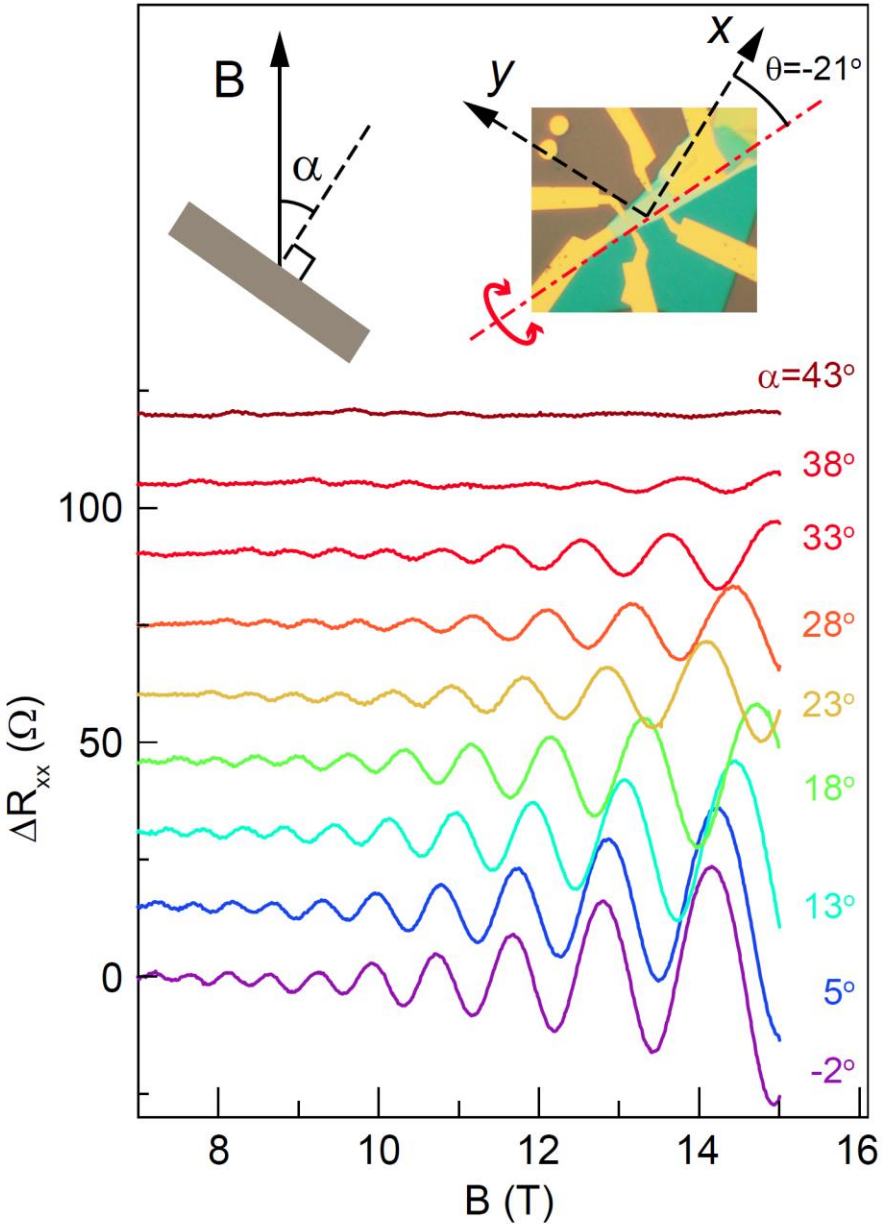
Protecting the bottom surface with hBN

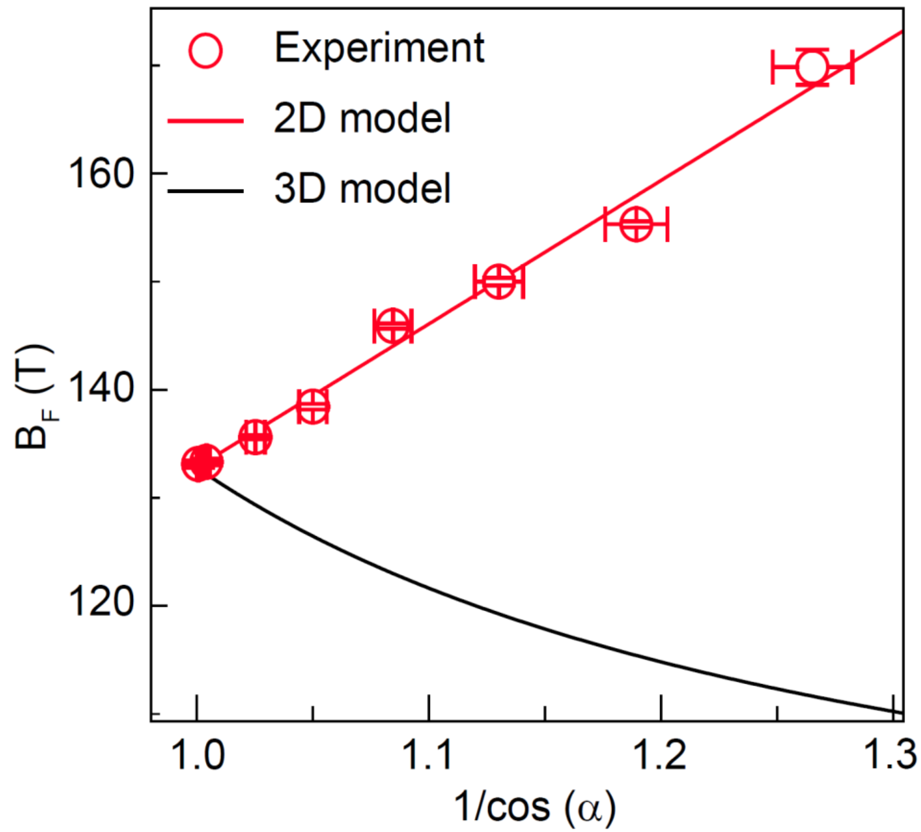
Quantum Oscillations in Black Phosphorus on hBN

B = 31T, T = 0.3K



2D Electron and Hole Gases in Black Phosphorus

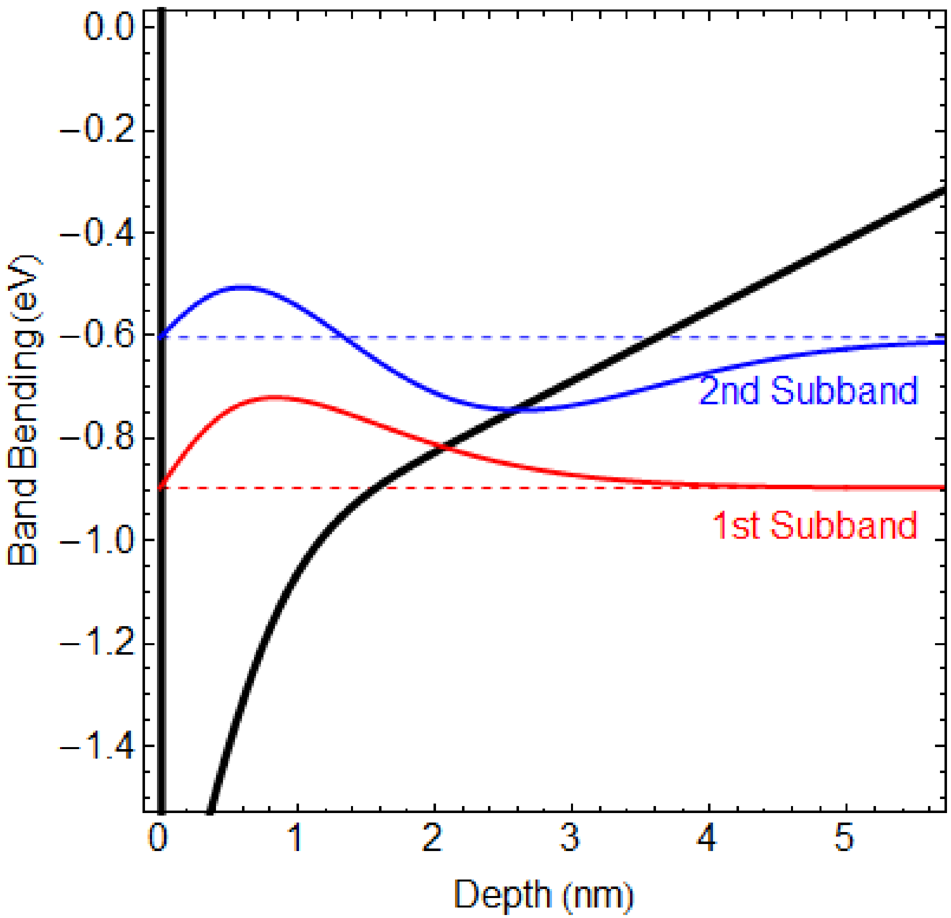




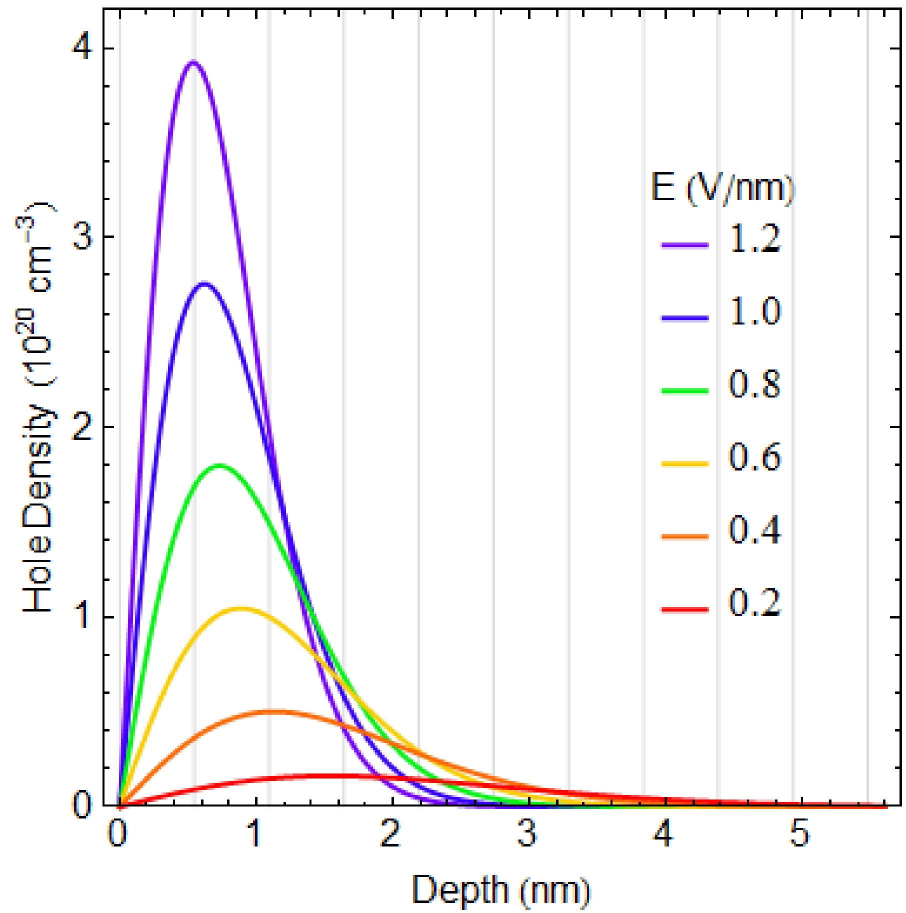
2D instead of 3D Fermi surface

2D Electron and Hole Gases in Black Phosphorus

2D confinement at the surfave

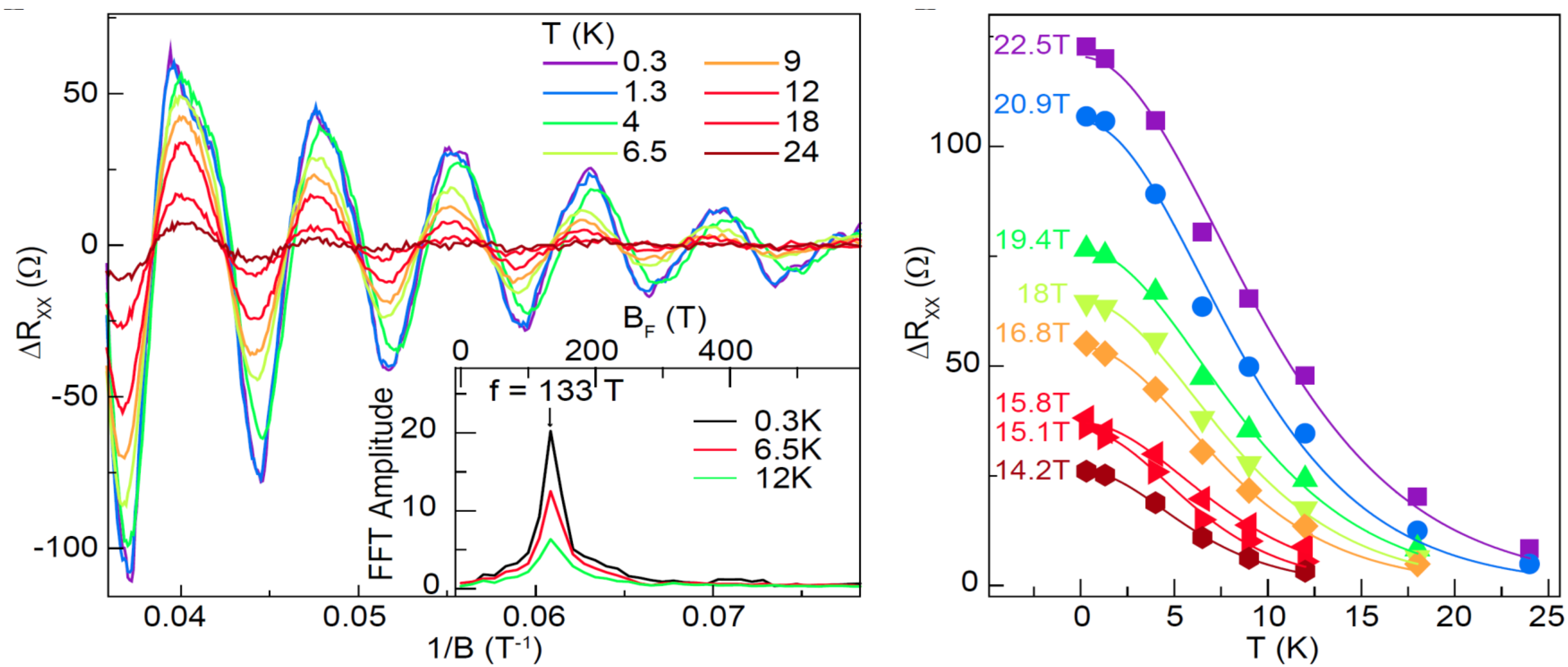


Charge distribution



2D electron and hole gases are confined to ~ 2 atomic layers

2D Electron and Hole Gases in Black Phosphorus



Crucial information obtained from the quantum oscillations

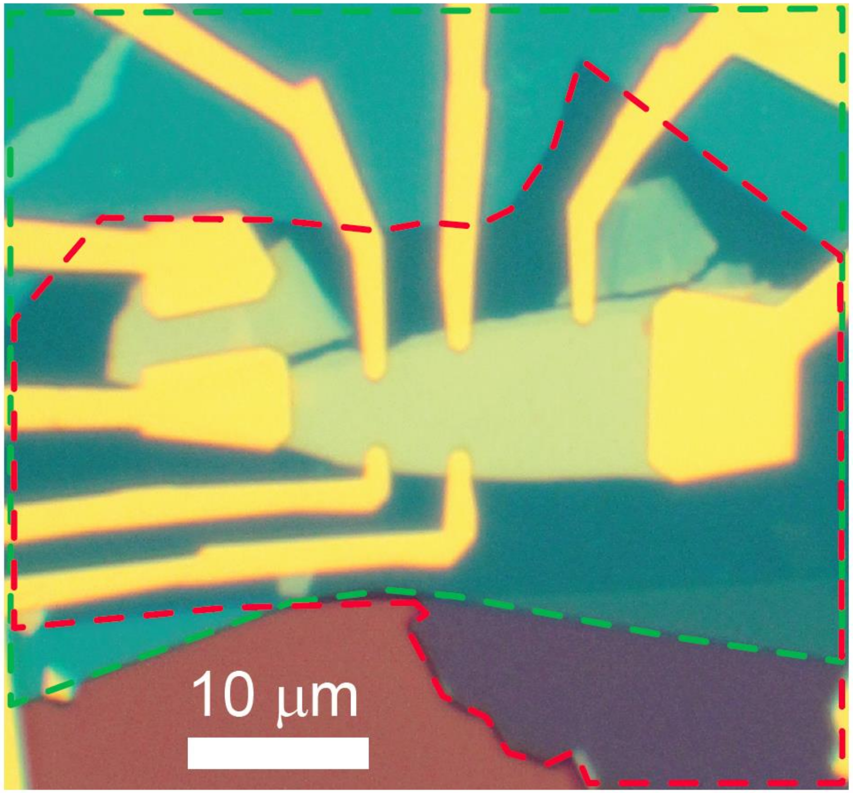
Likai Li *et al.* Nature Nano., Advance Online Publication (arXiv:1411.6572).

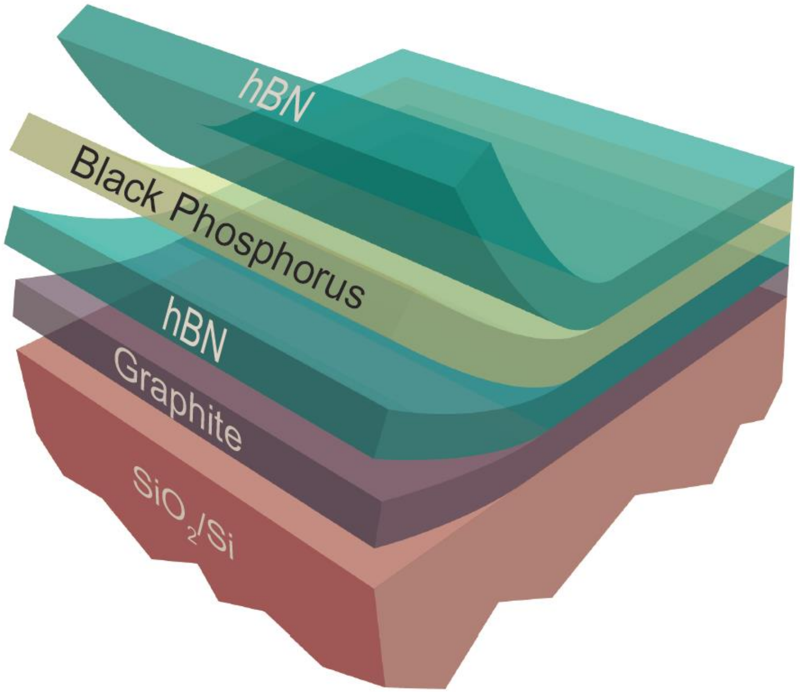
See also:
Tayari, V. et al., arXiv:1412.0259 (2014).
Chen, X. et al., arXiv:1412.1357 (2014).
Gillgren, N. et al., 2D Mater. 2, 011001 (2015).

Even Higher Mobility?

Top View

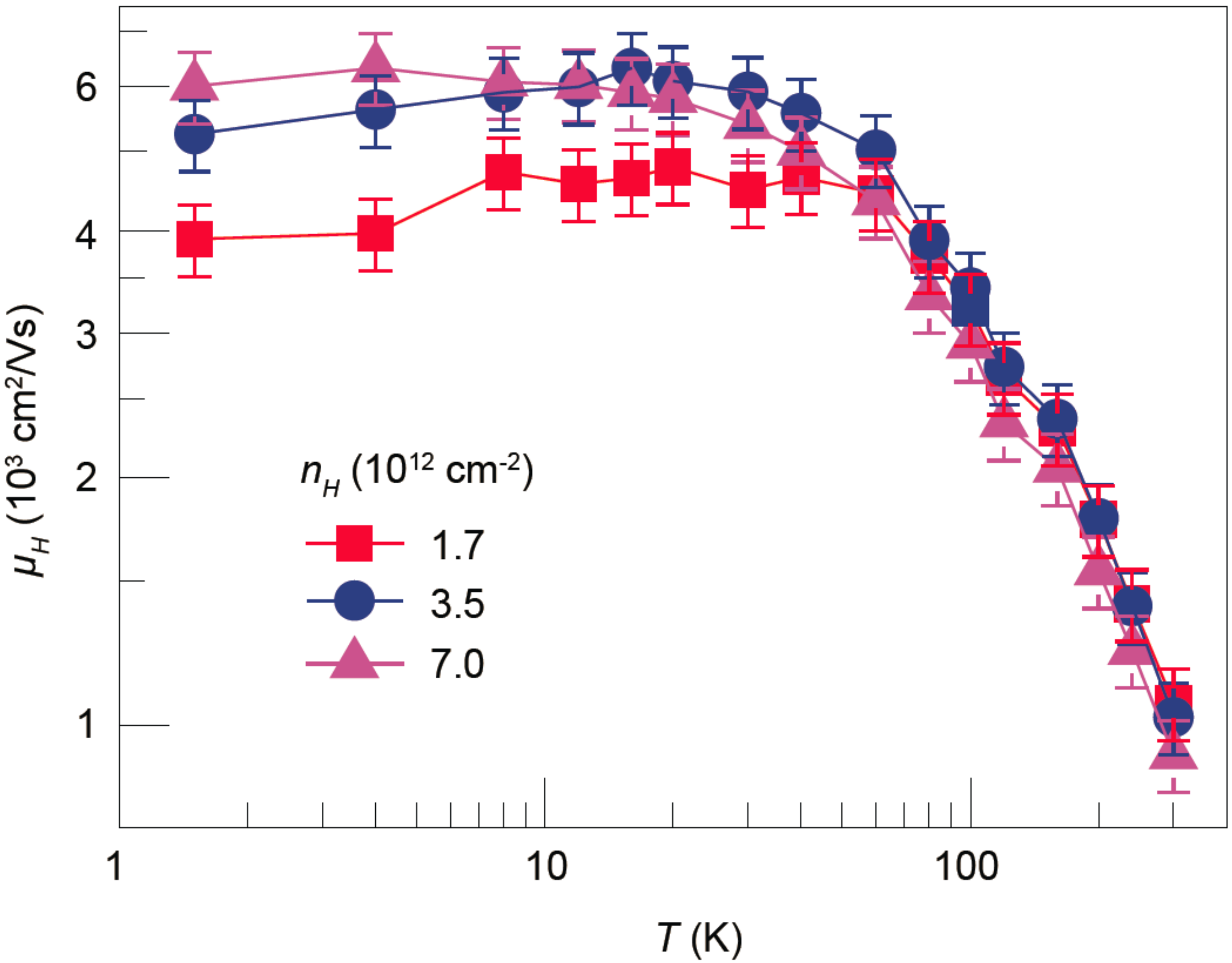
Side View





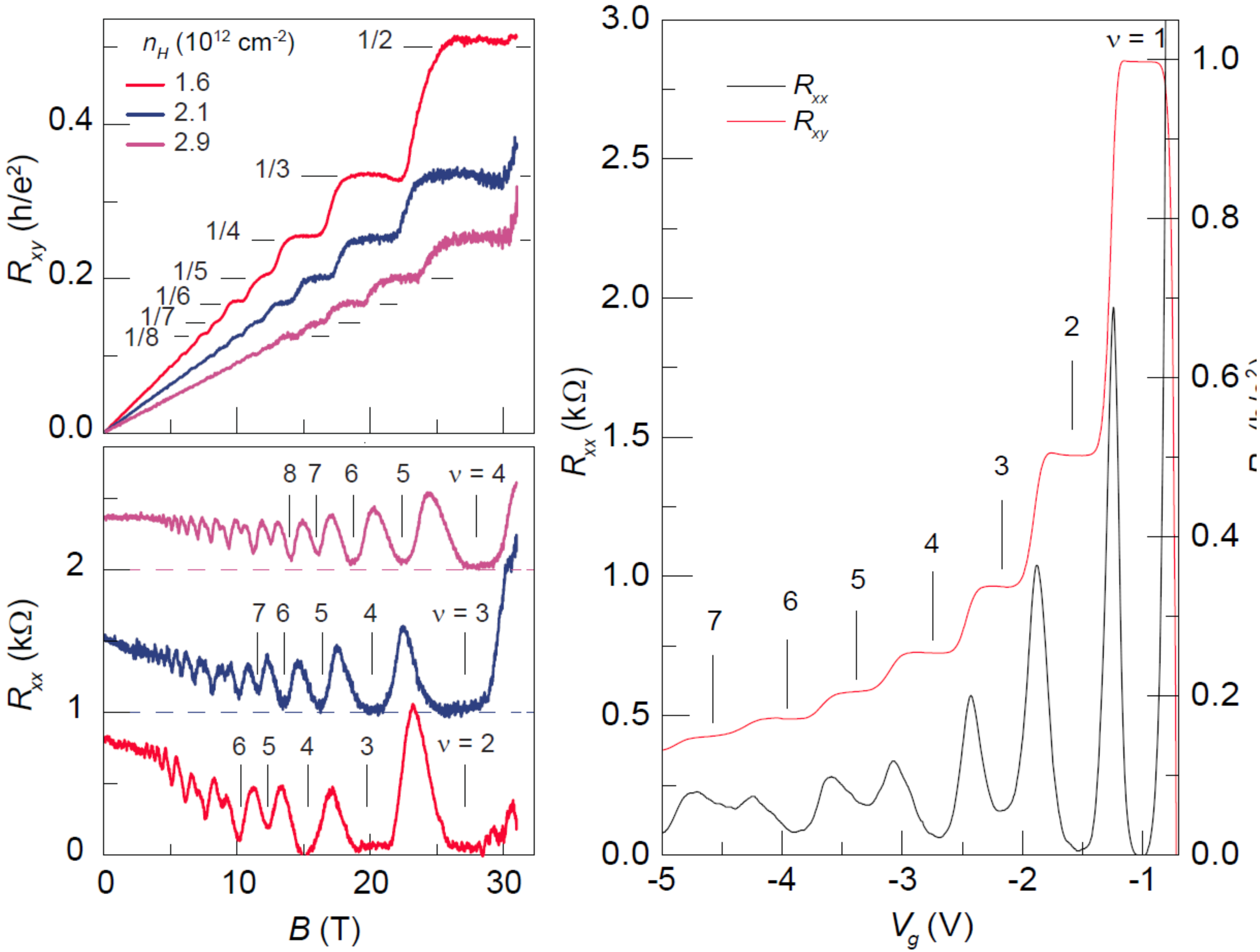
Graphite local gate screens impurity potential, leads to high mobility

High Mobility Black Phosphorus 2DEG



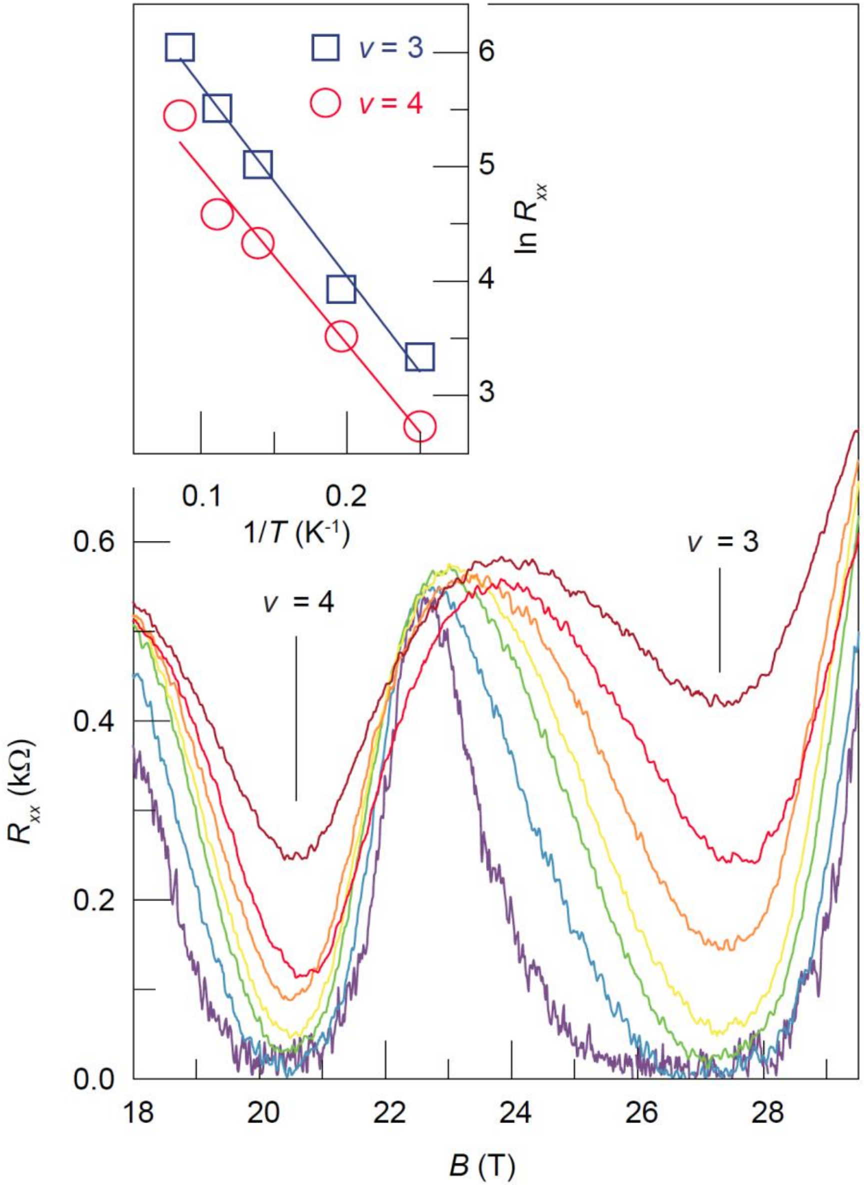
Factor of 3 increase in mobility

Quantum Hall Effect in Black Phosphorus 2DEG



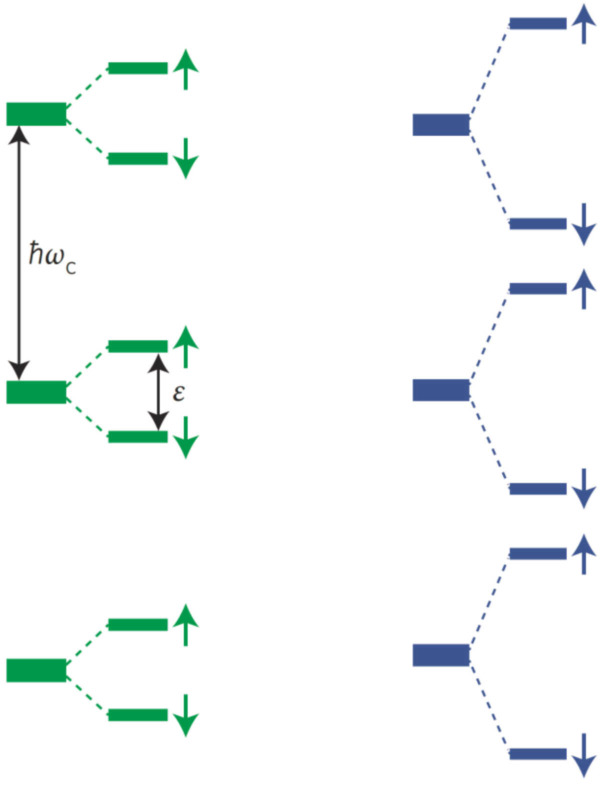
Likai Li *et al.* arXiv:1504.07155 (2015)

Landau Level Energy Landscape



$$E_Z/E_C = m^* g^* / 2\, m_0$$

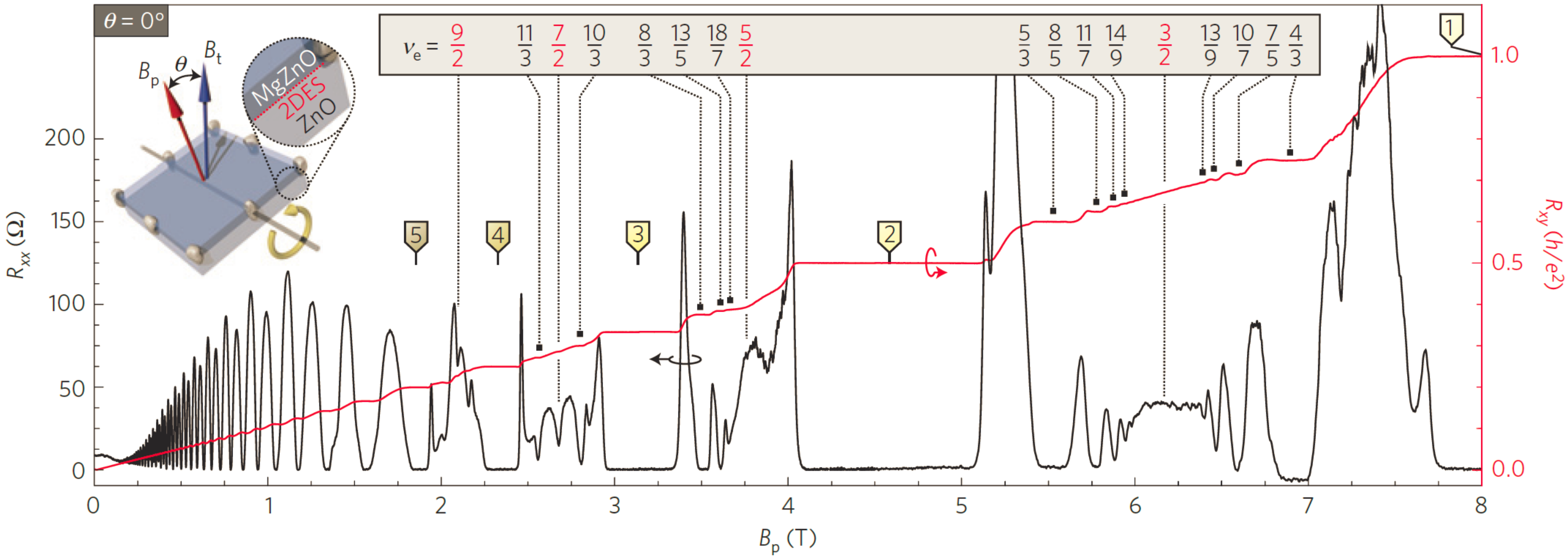
E_Z/E_c=0.35 E_Z/E_c>0.5



Holes **Electrons**

Anyons in Black Phosphorus 2DEG?

Even-denominator fractional quantum Hall states in ZnO



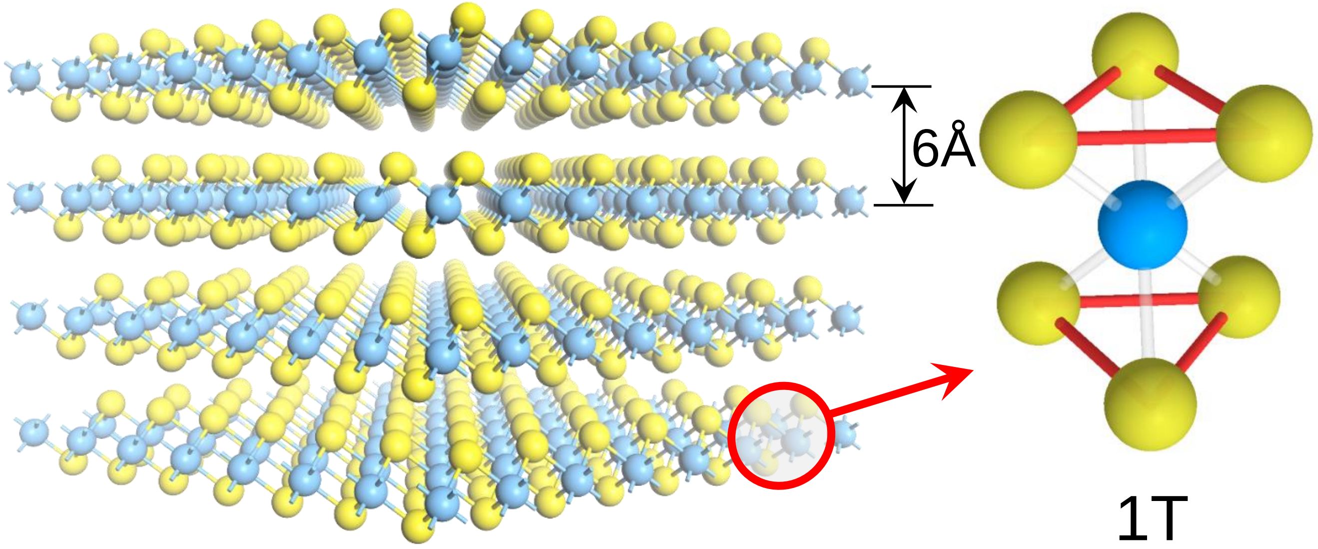
Falson, J. *et al.* Nature Physics **11,** 347 (2015)

Black phosphorus potentially harbors similar FQH states

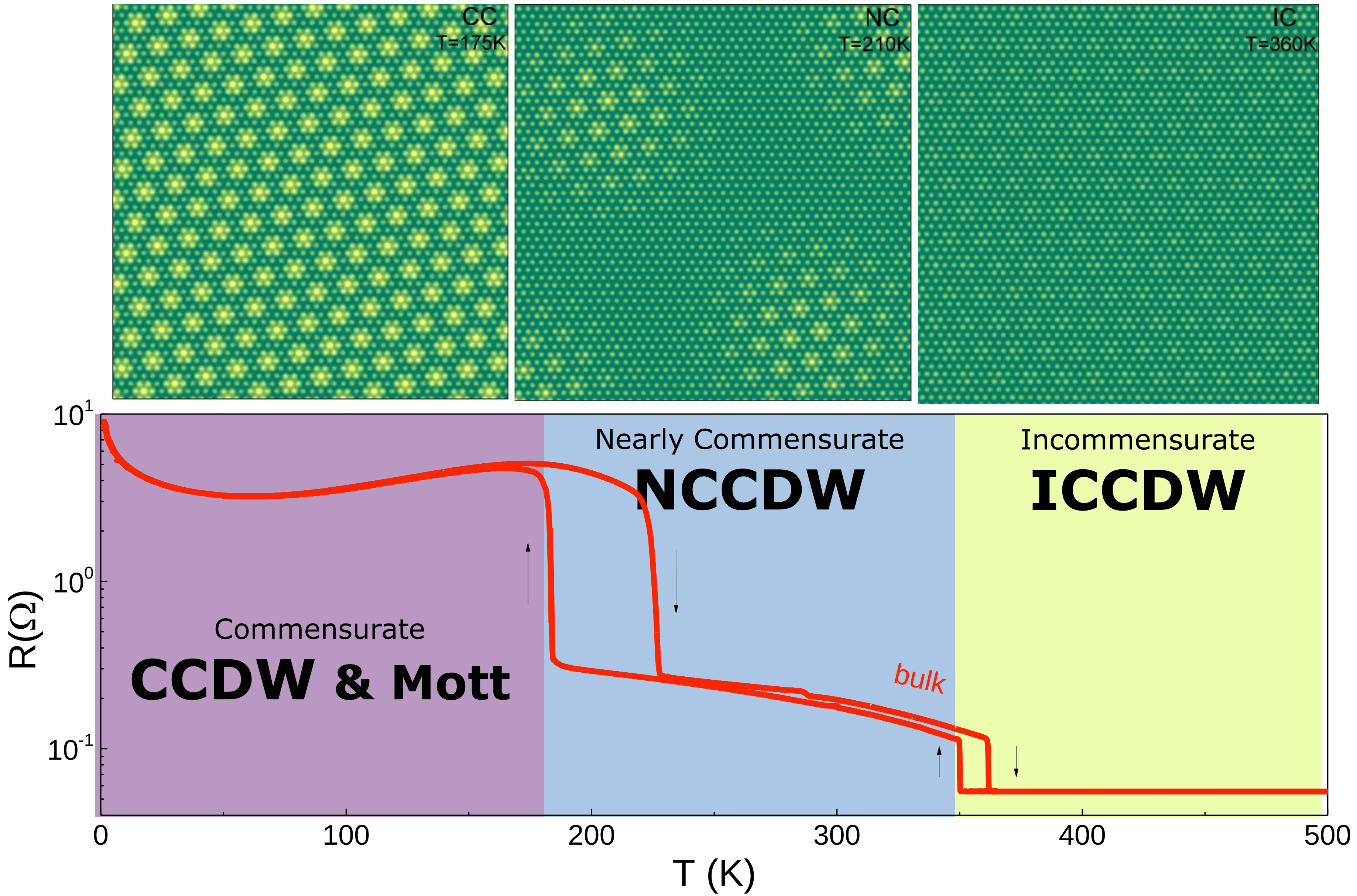
1T-TaS_2 : a Strongly Correlated 2D Material

Yijun Yu

Crystal structure of 1T-TaS_2

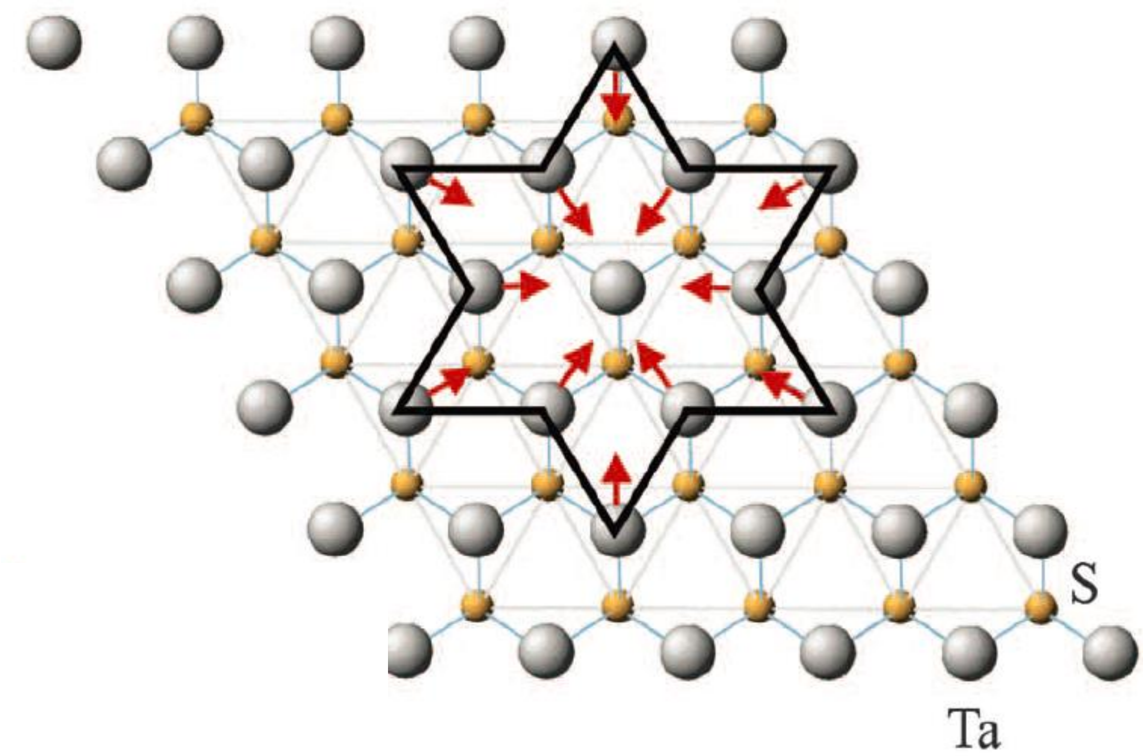


Various CDW Phases in 1T-TaS_2



Various CDW Phases in 1T-TaS_2

Commensurate CDW and Mott Insulator State



Wilson et al., *Adv. Phys.* (1975)

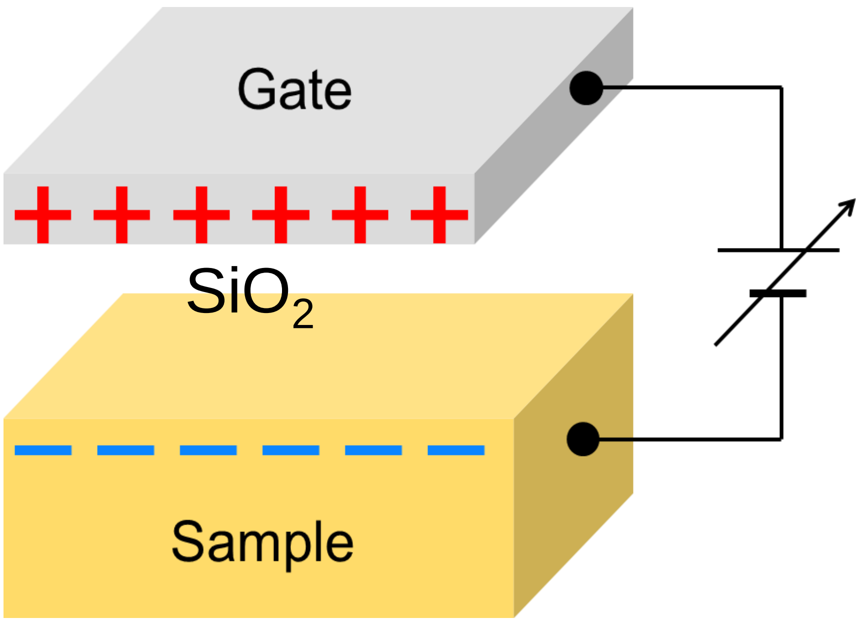
Fazekas, P. & Tosatti, E. *Philos. Mag. B* (1979)

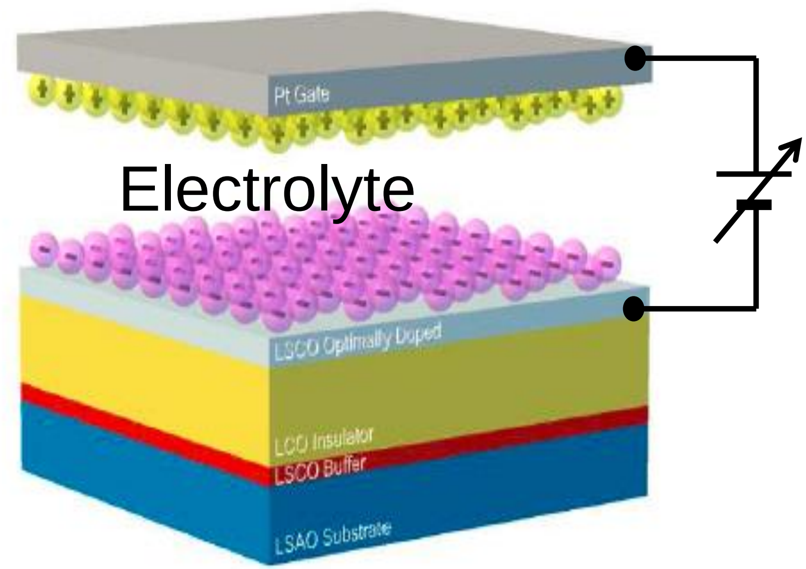
Sipos, *et al. Nat. Mater.* (2008).

Gate Doping Limits

Conventional Dielectric Gating

Ion Liquid Gating





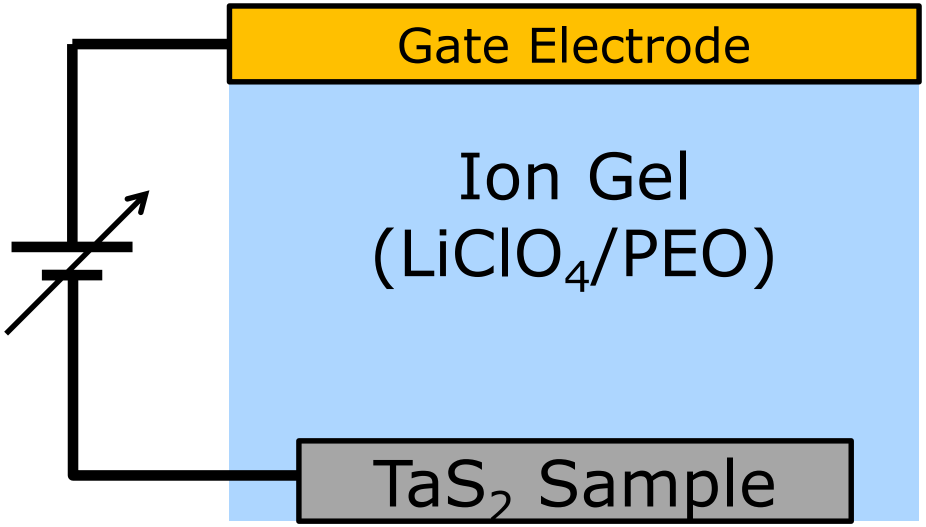
Maximum n ~ 10^{13} cm^{-2}

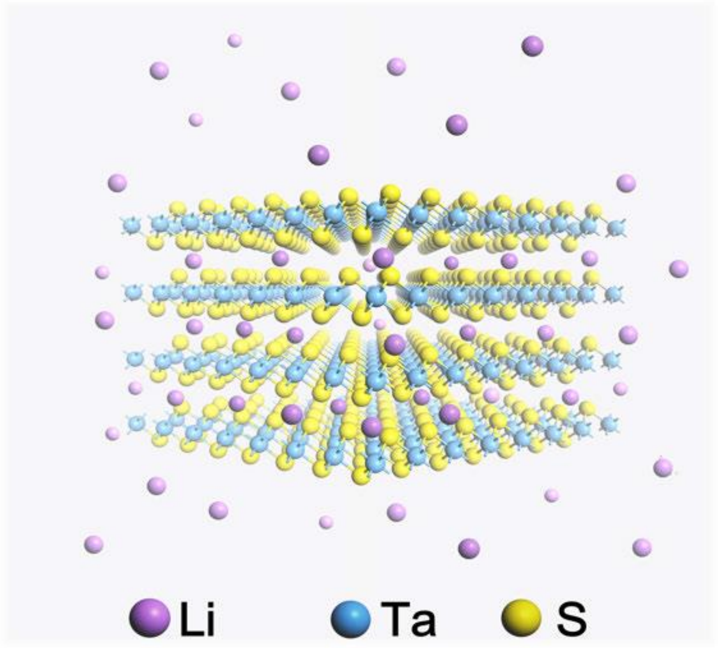
Maximum n ~ 10^{14}-10^{15} cm^{-2}
Only top atomic layer

K.Ueno,*Nat.Mater.*(2008); D.K.Efetov,*Phys.Rev.Lett.*(2010); J.T.Ye,*Nat.Mater.*(2010); J.G.Checkelsky,*Nat.Phys.*(2012); Nakano,*Nature*(2012); J.T.Ye,*Science*(2013)

Tuning TaS_2 through Gate-controlled intercalation

Gate-controlled intercalation in TaS_2

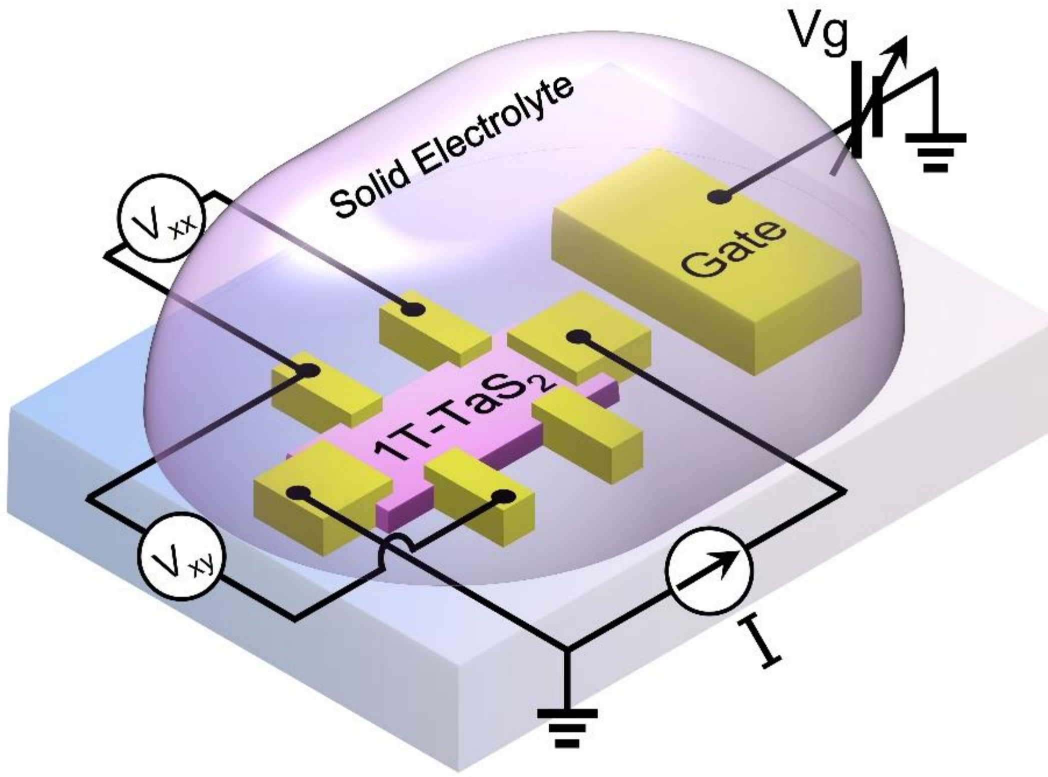




n ~ 10^{15} cm^{-2} for EACH atomic layer

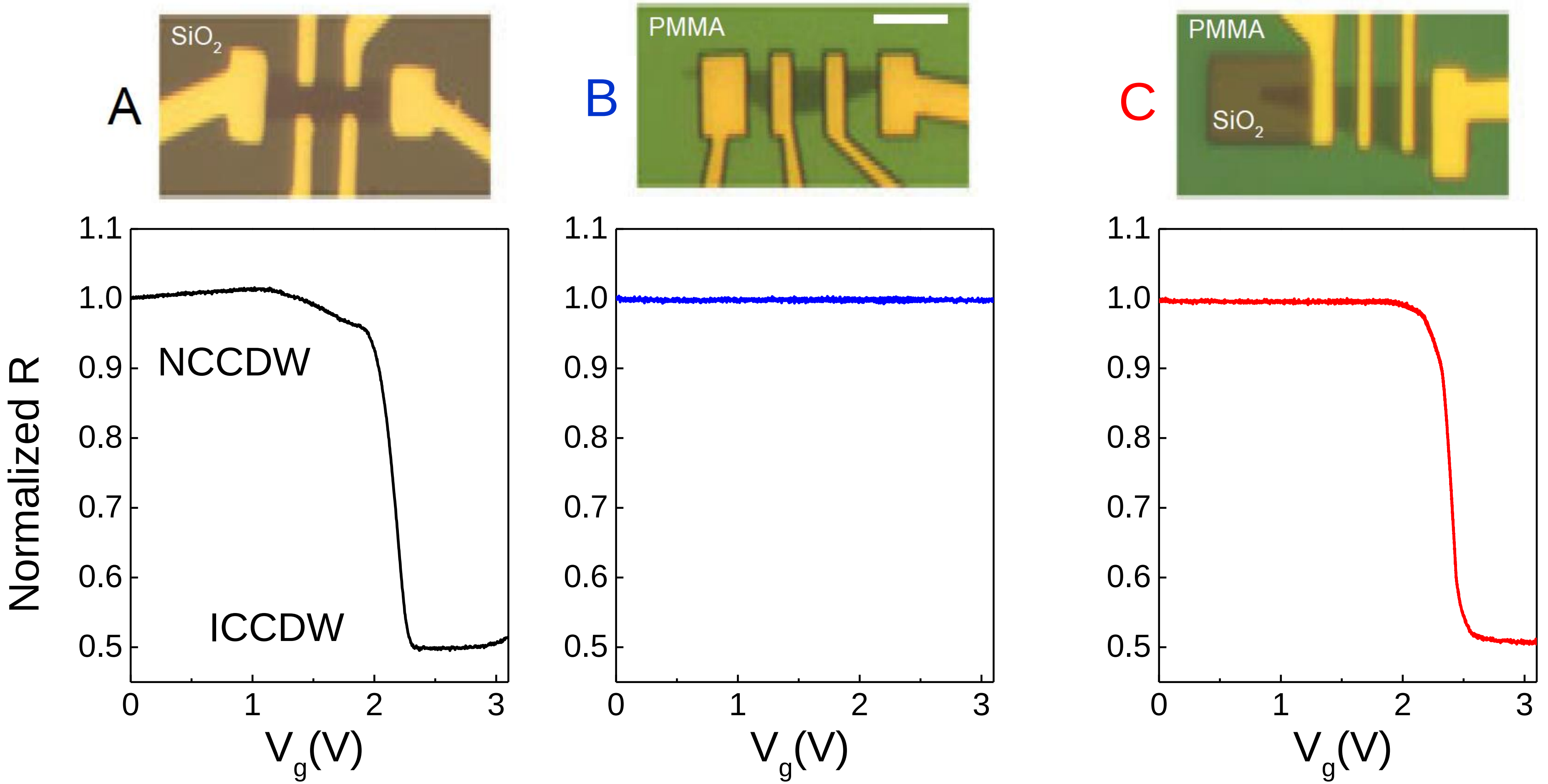
Gate-controlled Doping by Intercalation

Device Structure



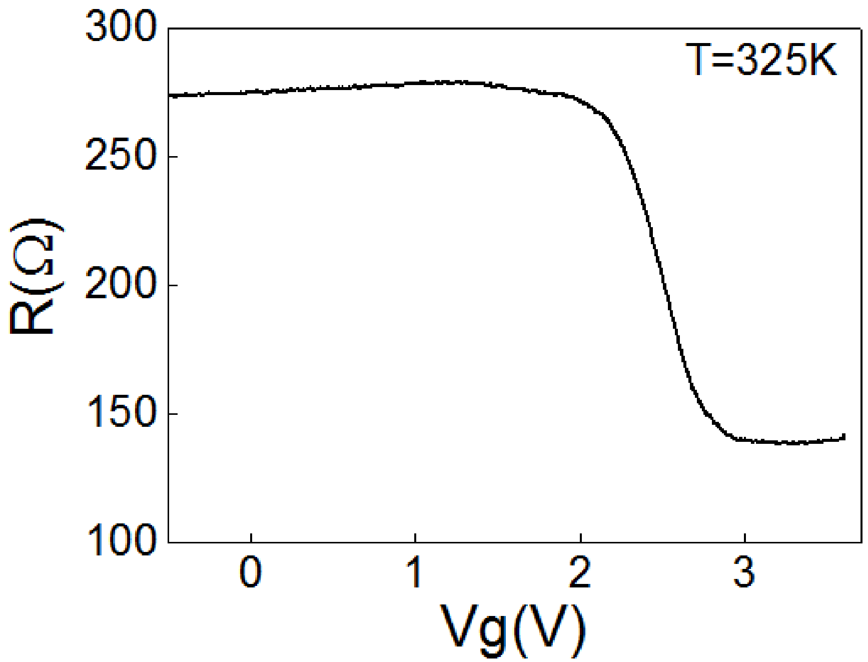
Yijun Yu *et al.* Nature Nano., 10, 270 (2015).

$1T\text{-}TaS_2$ Ionic Field-effect Transistors (iFET)

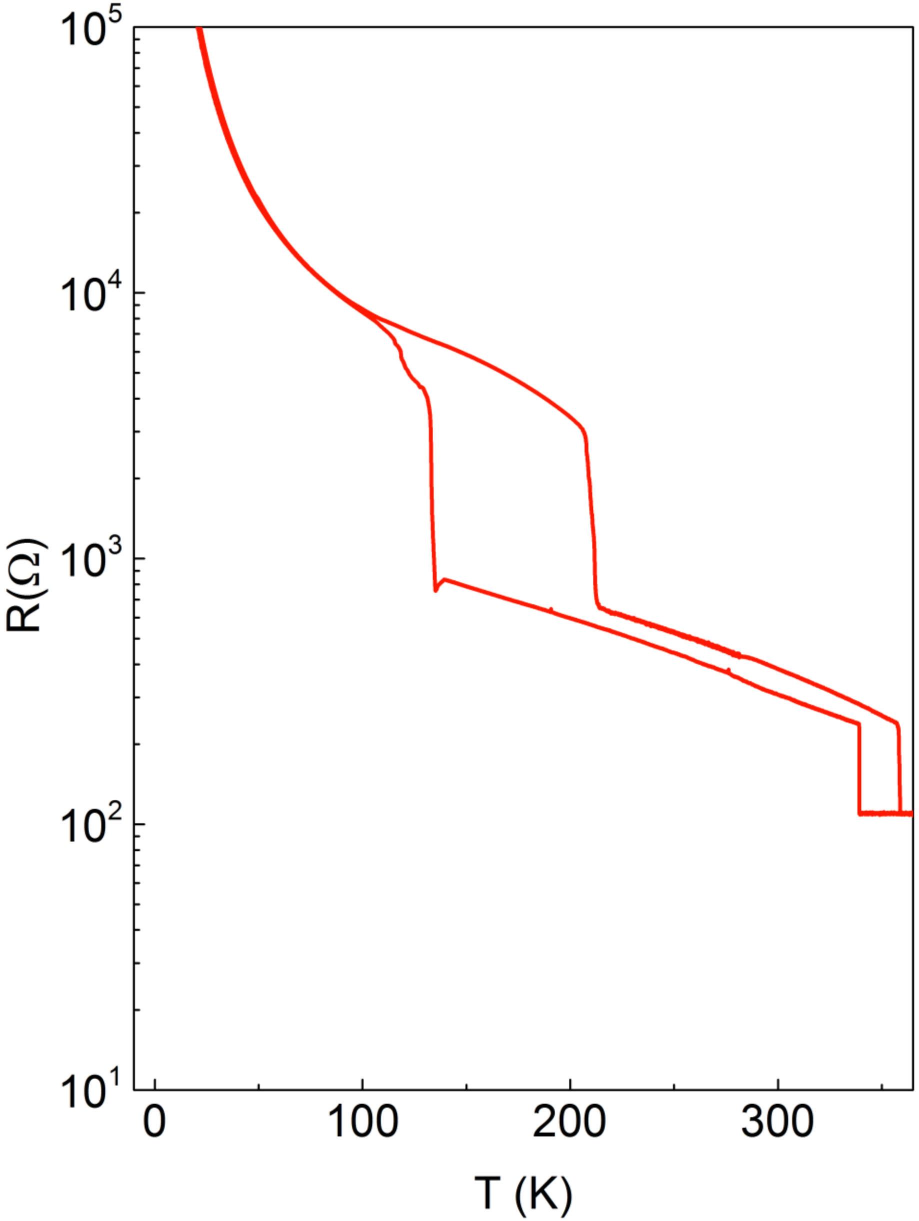


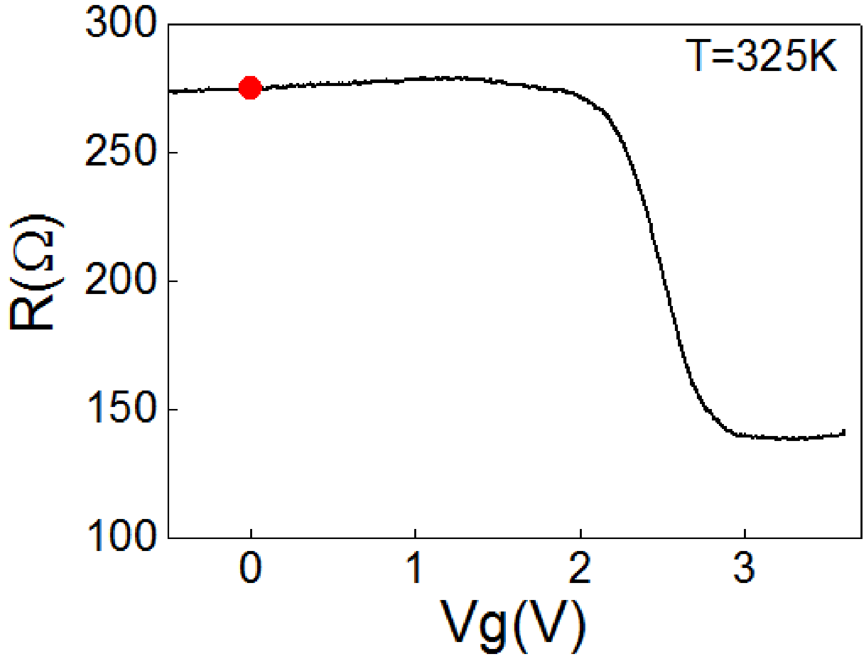
iFET operates through ion diffusion

Gate-controlled Doping by Intercalation

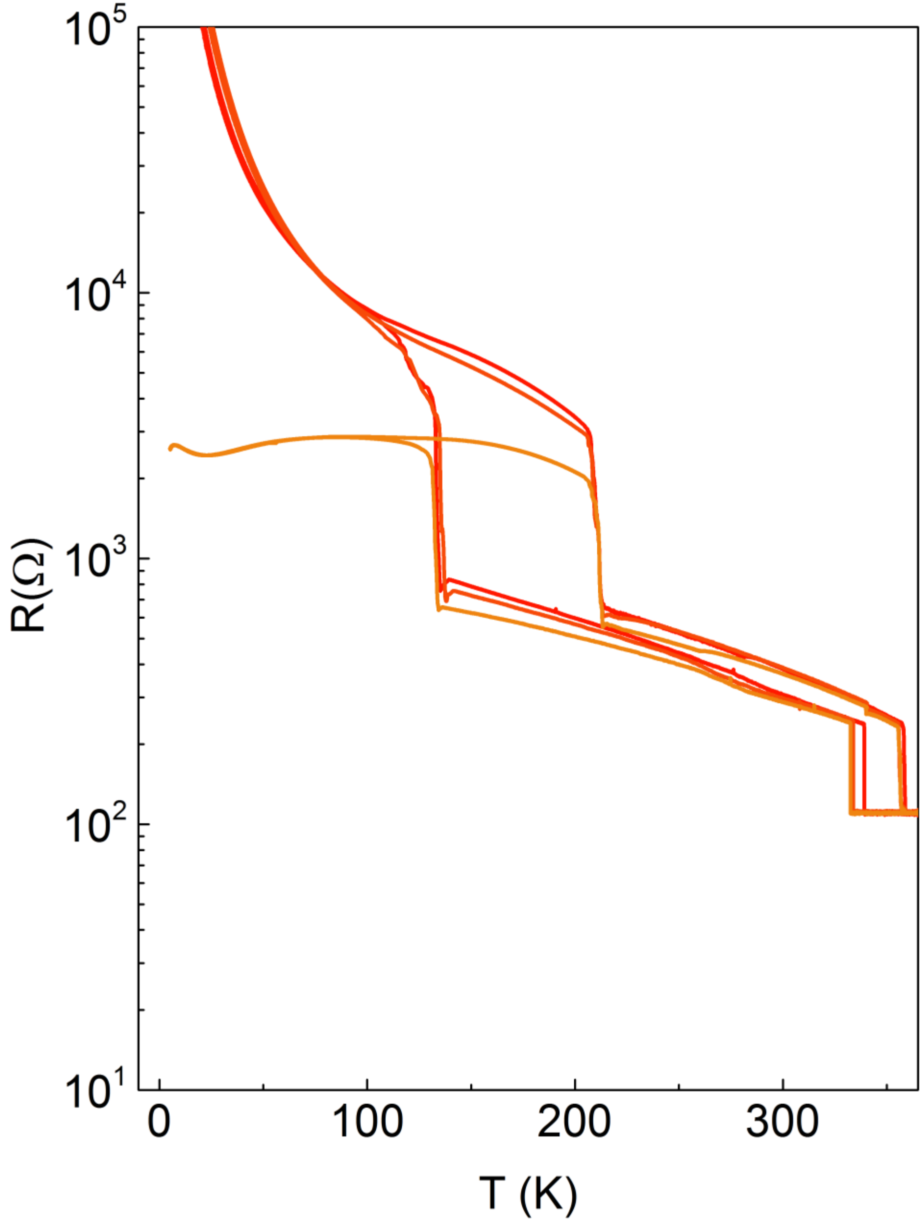


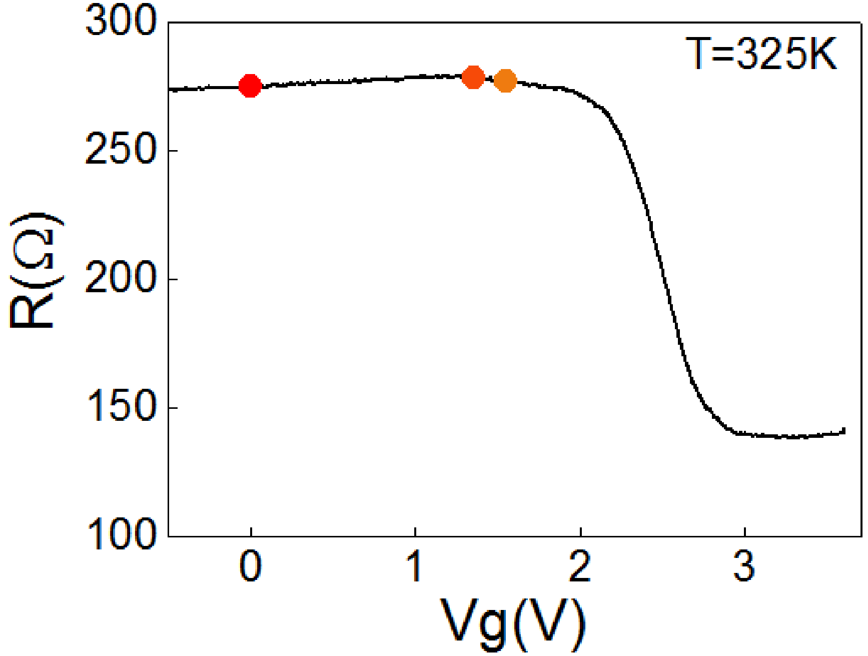
Gate-controlled Doping by Intercalation



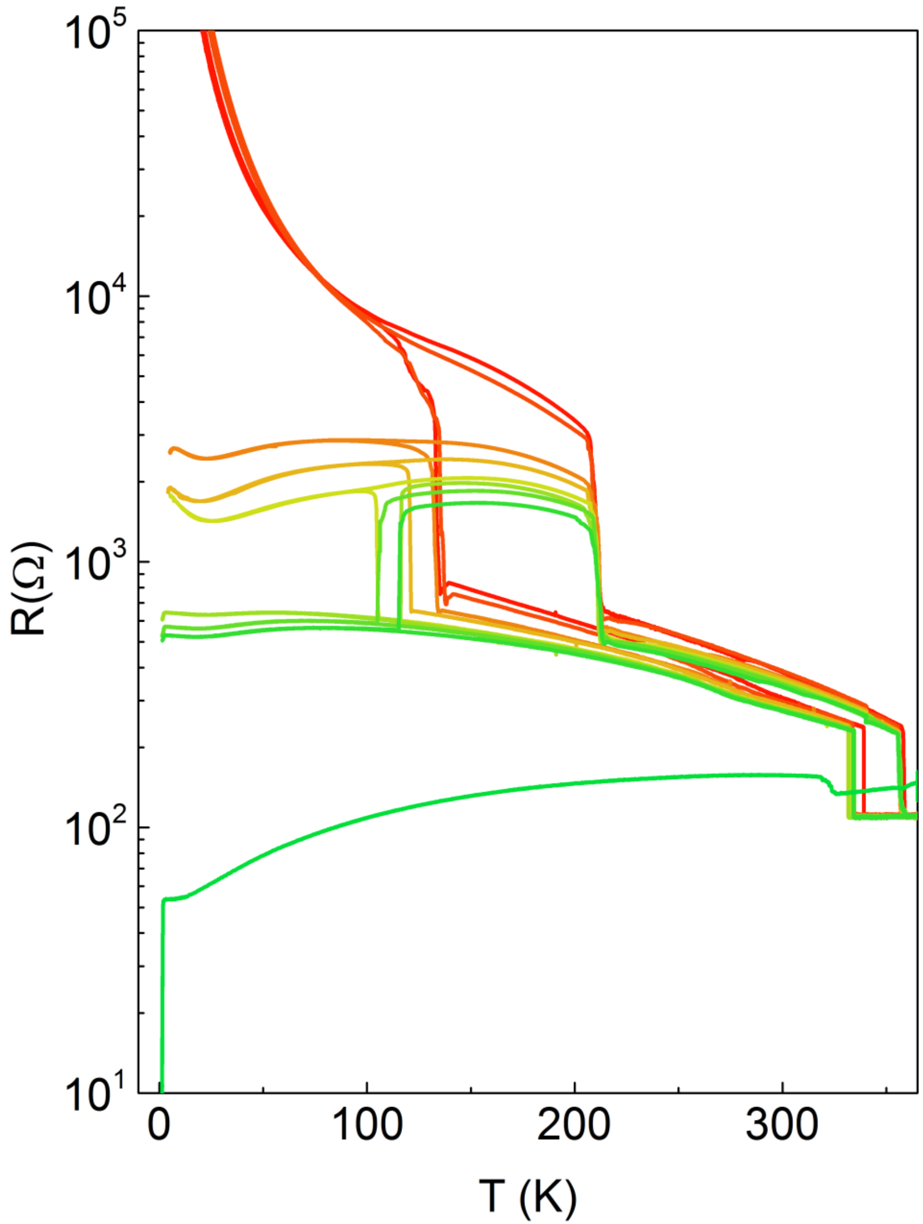


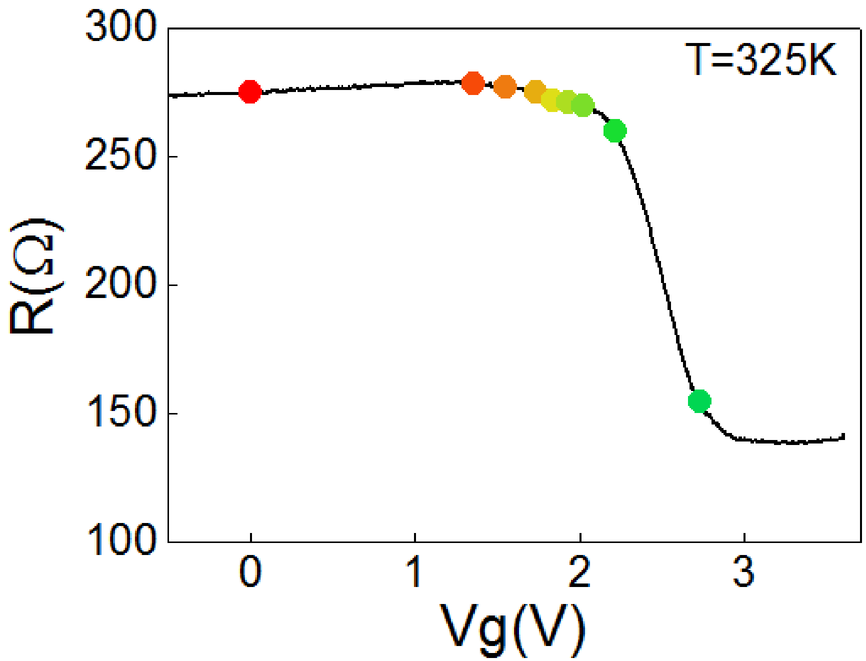
Gate-controlled Doping by Intercalation

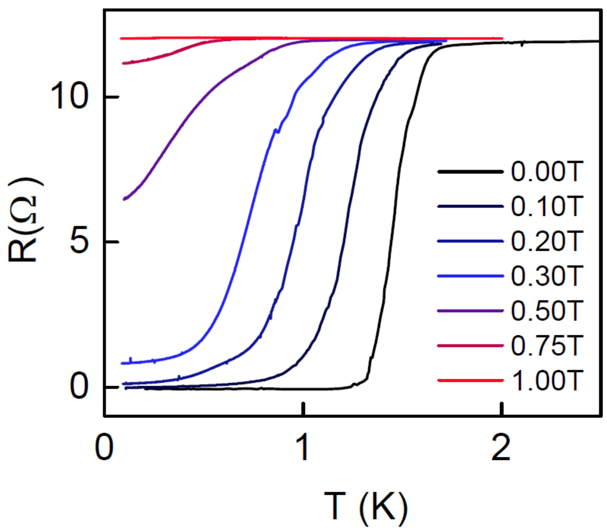




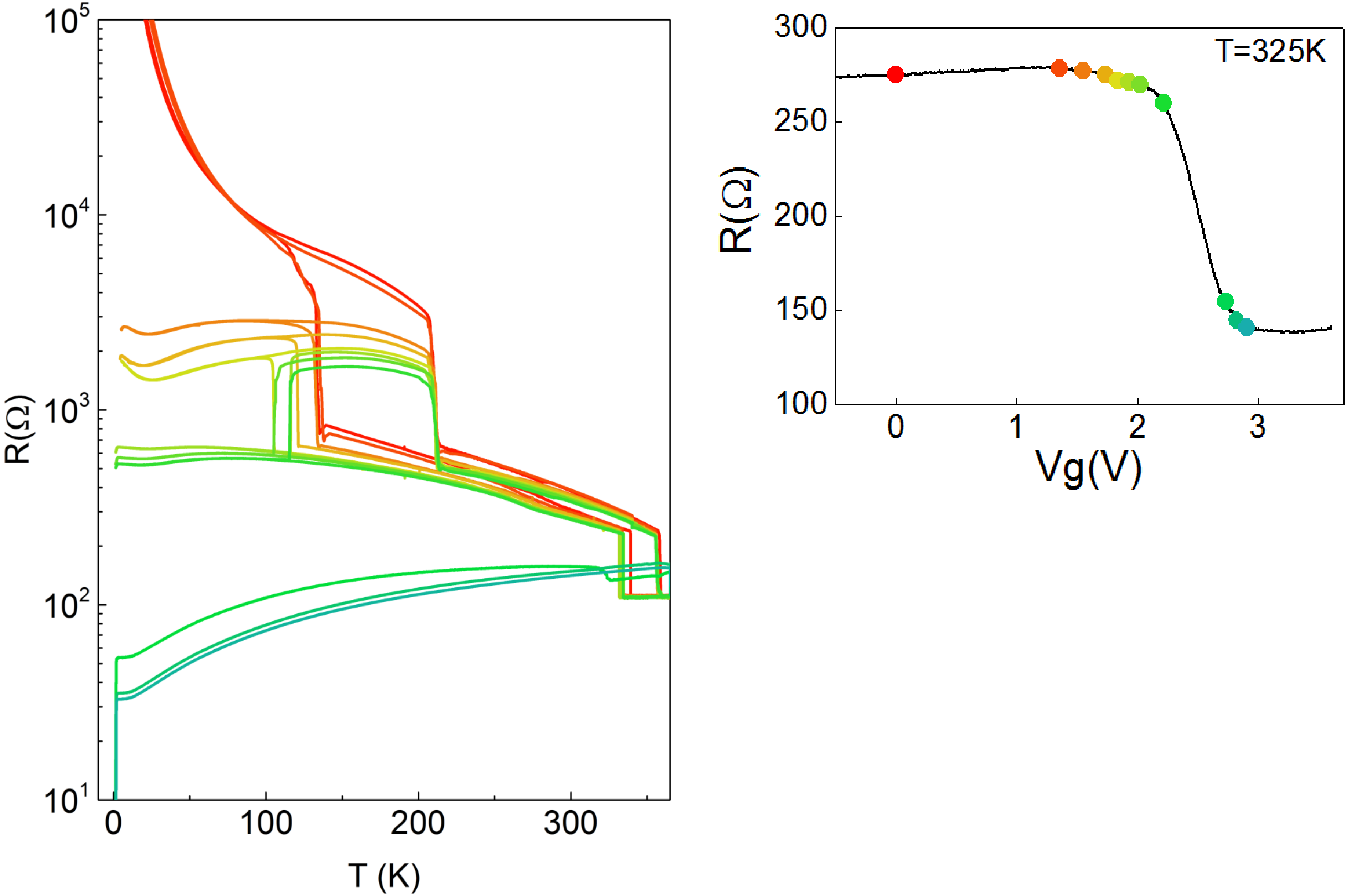
Gate-controlled Doping by Intercalation







Gate-controlled Doping by Intercalation



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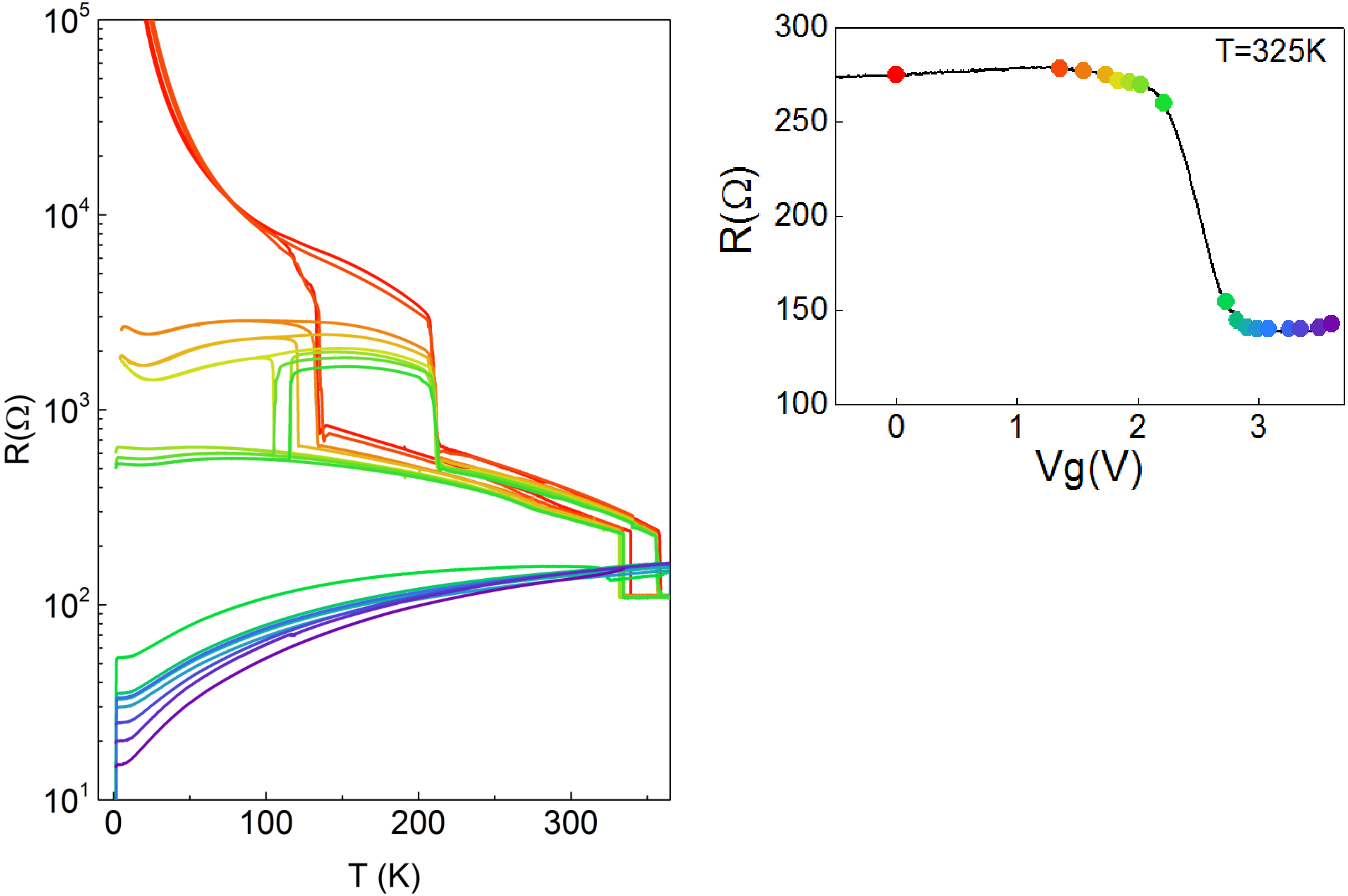
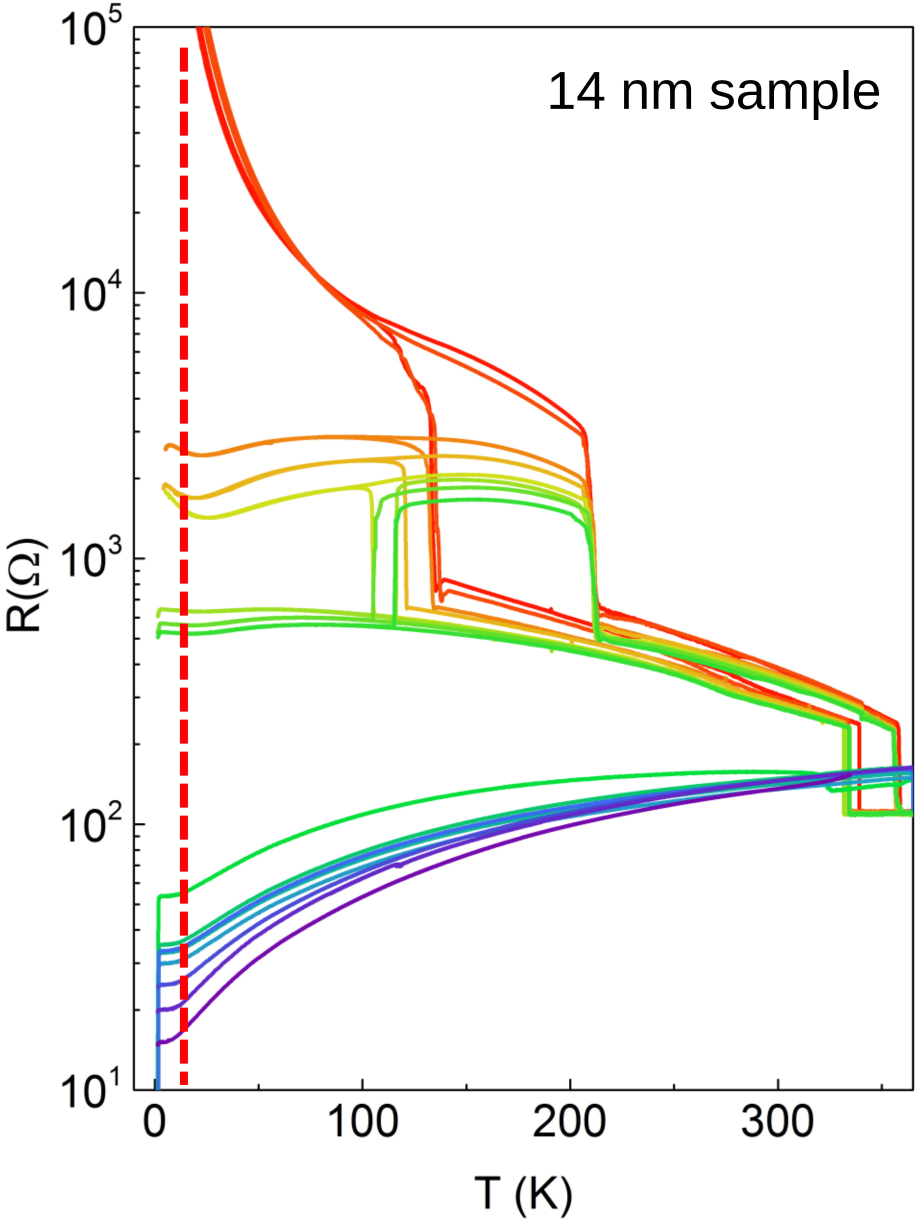
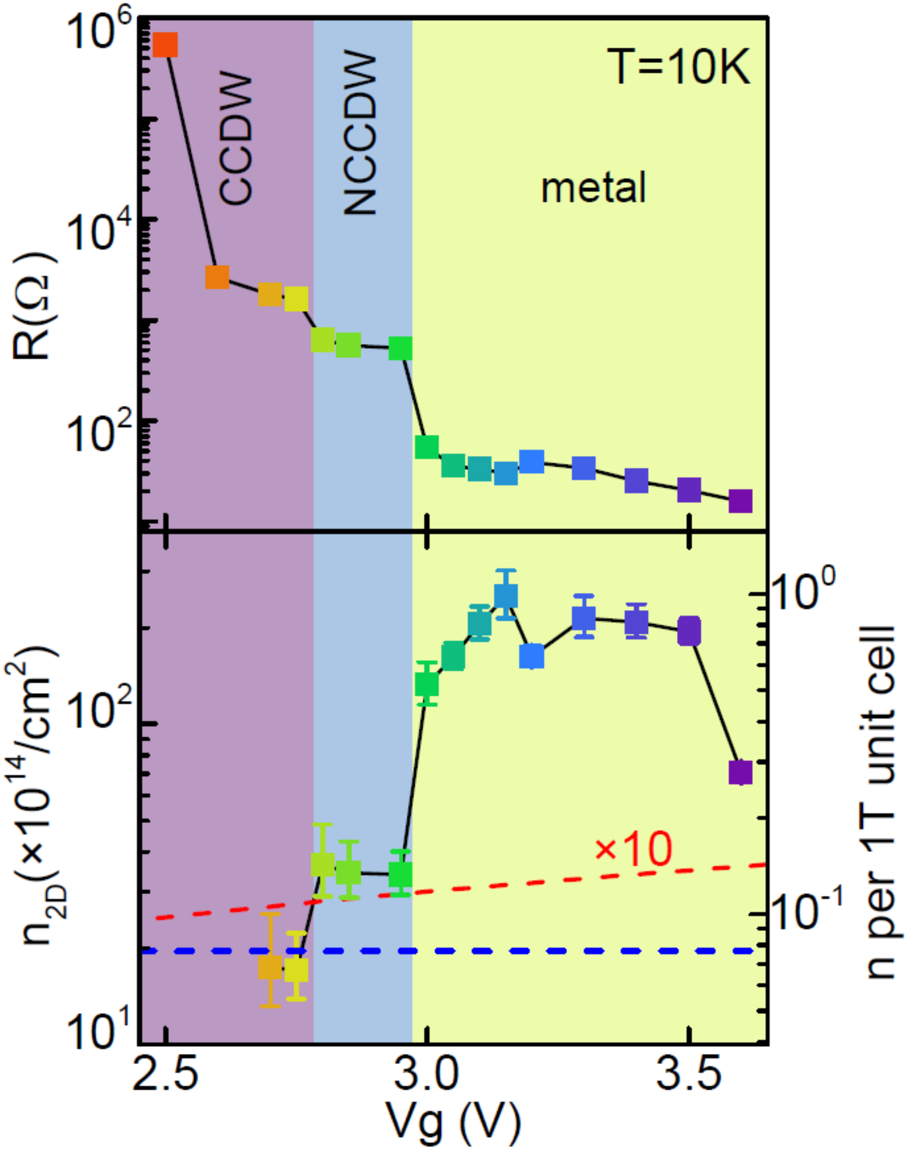
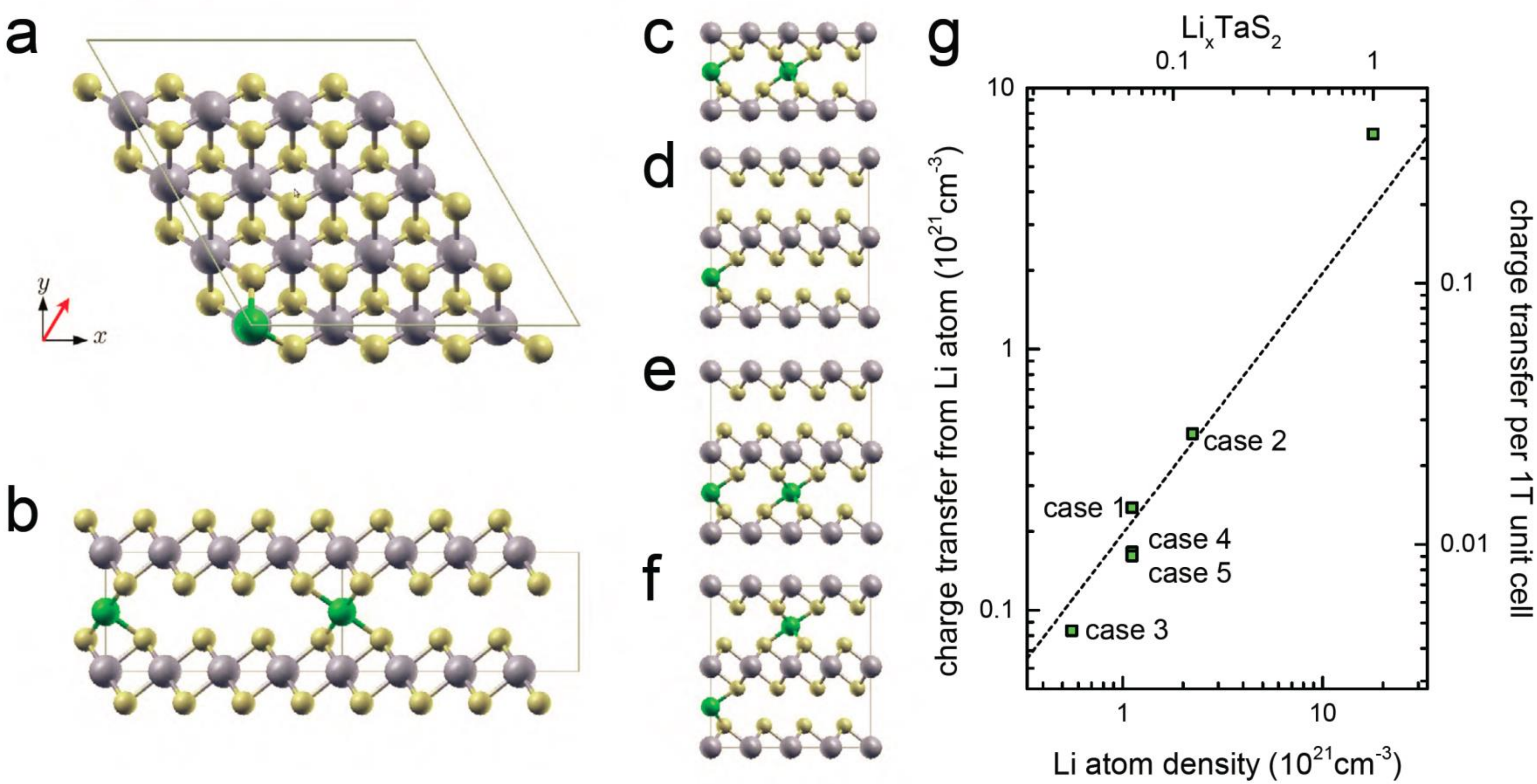


Gate-controlled Doping by Intercalation



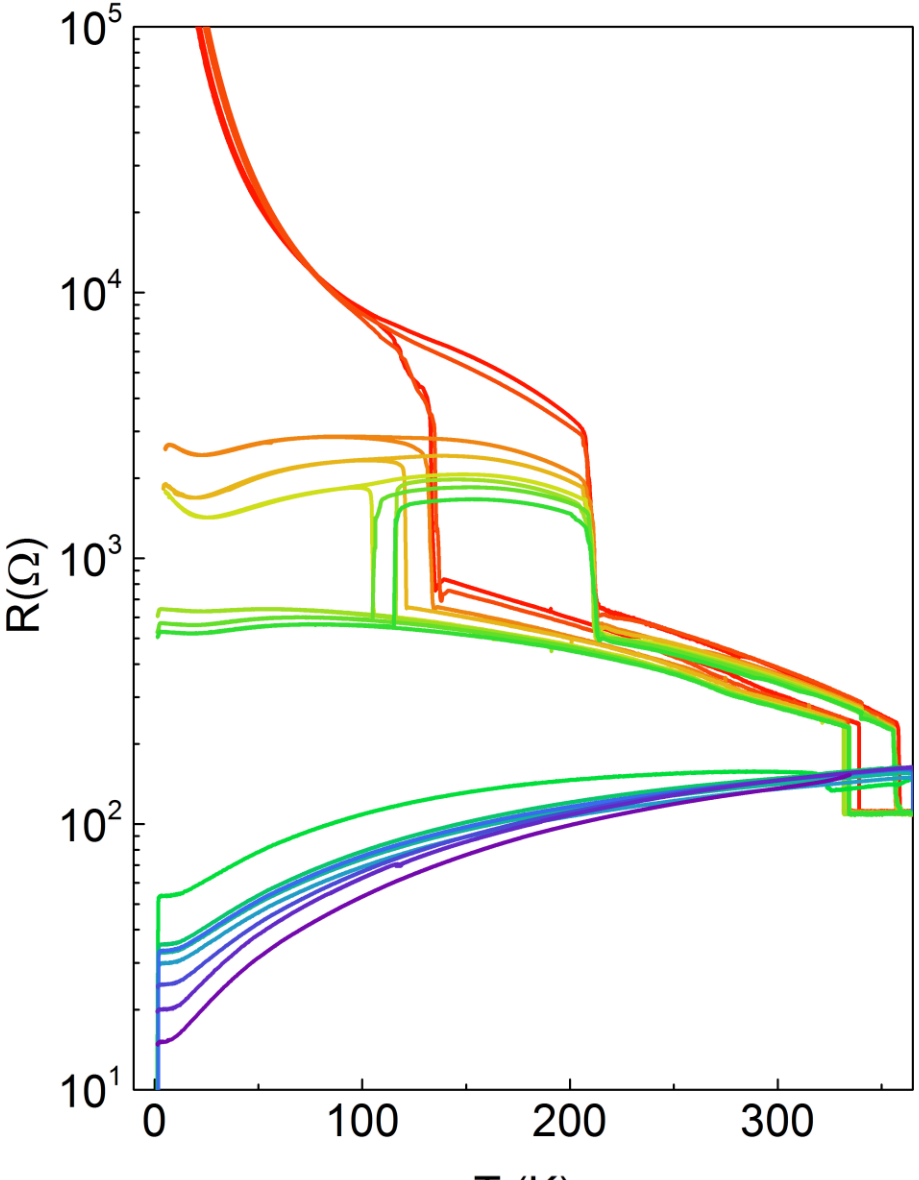


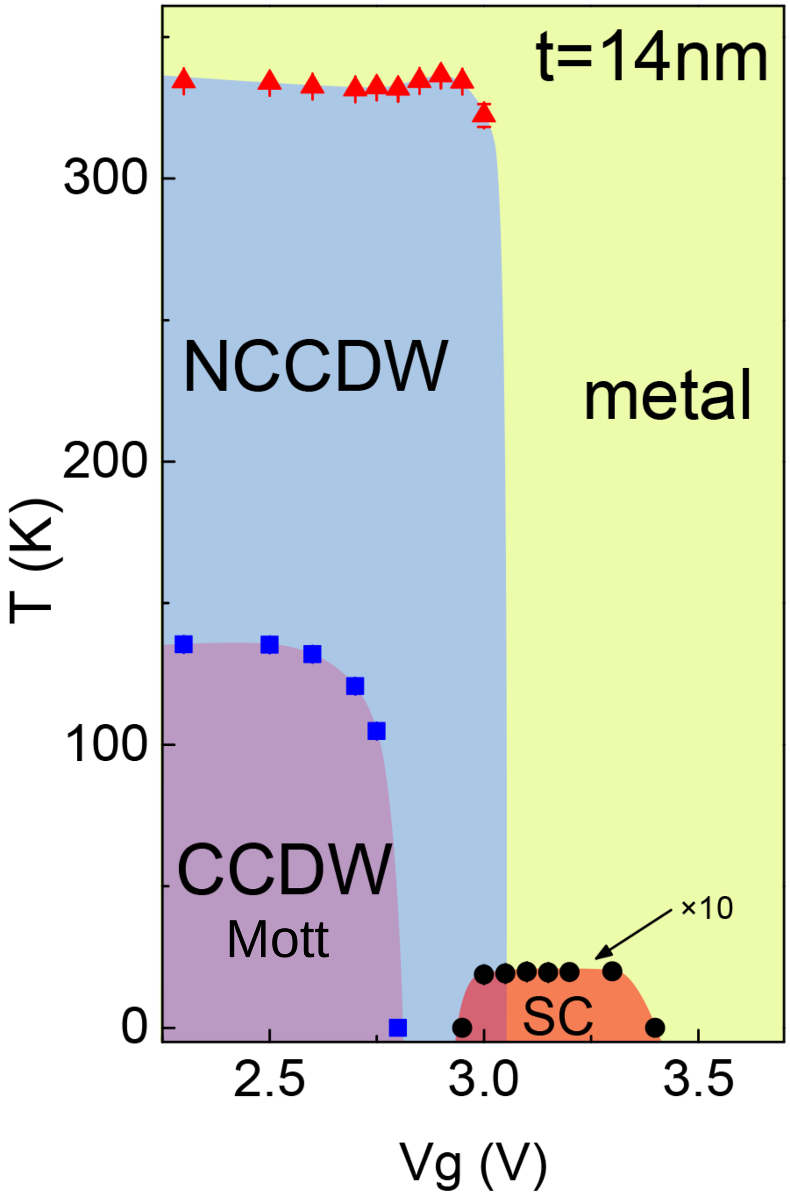
Electron Doping from Charge Transfer



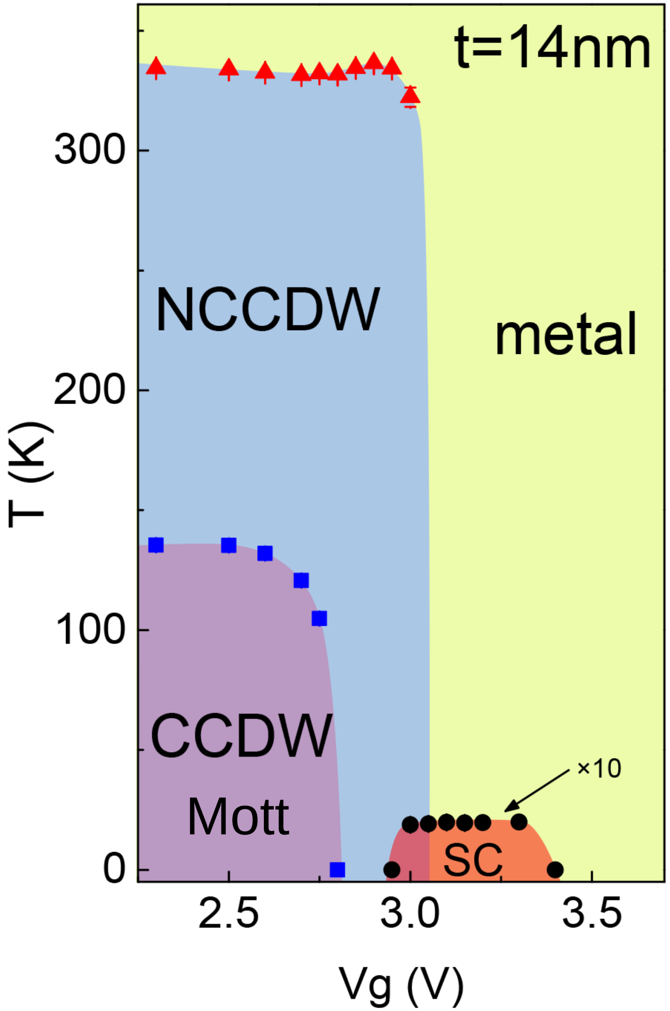
~ 20% electron doping from charge transfer from Li

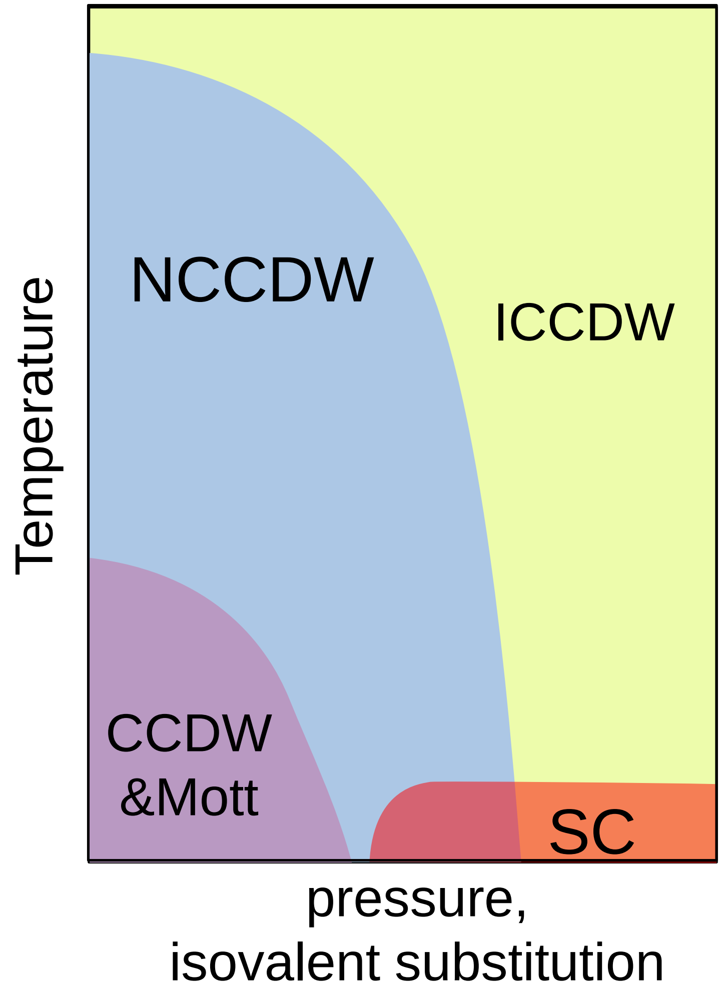
Tunable Phases in 1T-TaS_2 iFET





Intercalation Compared with Pressure and Isovalent Substitution





Connection btw intercalation and pressure/isovalent substitution??

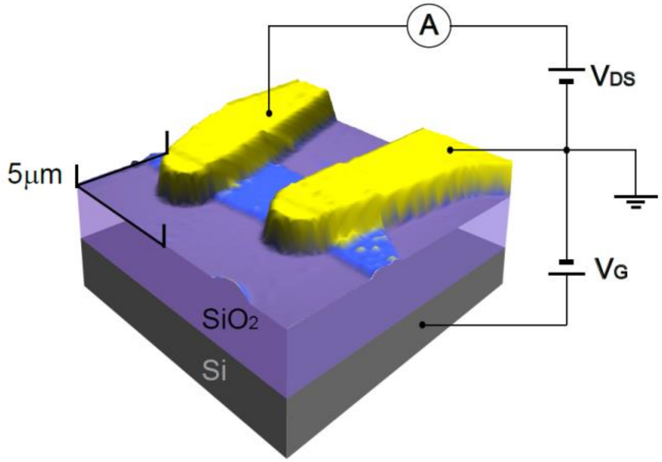
Sipos, *et al. Nat. Mater.* (2008).

L. J. Li *et al. EPL* (2012)

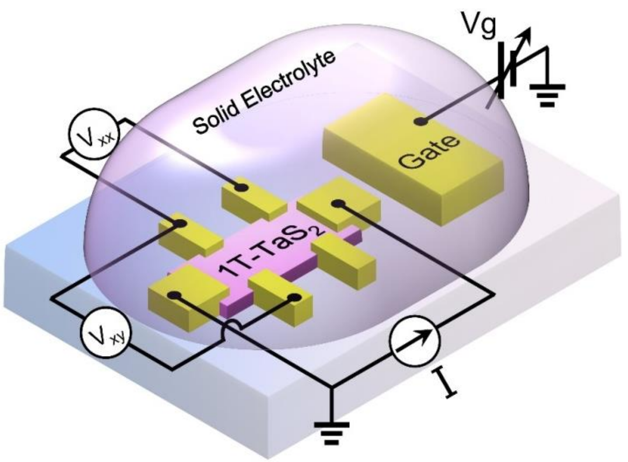
R. Ang *et al. PRL* (2012)

Summary

- Black Phosphorus Transistor



- Tunable Phases in 1T-TaS_2



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