2D Materials Beyond Graphene

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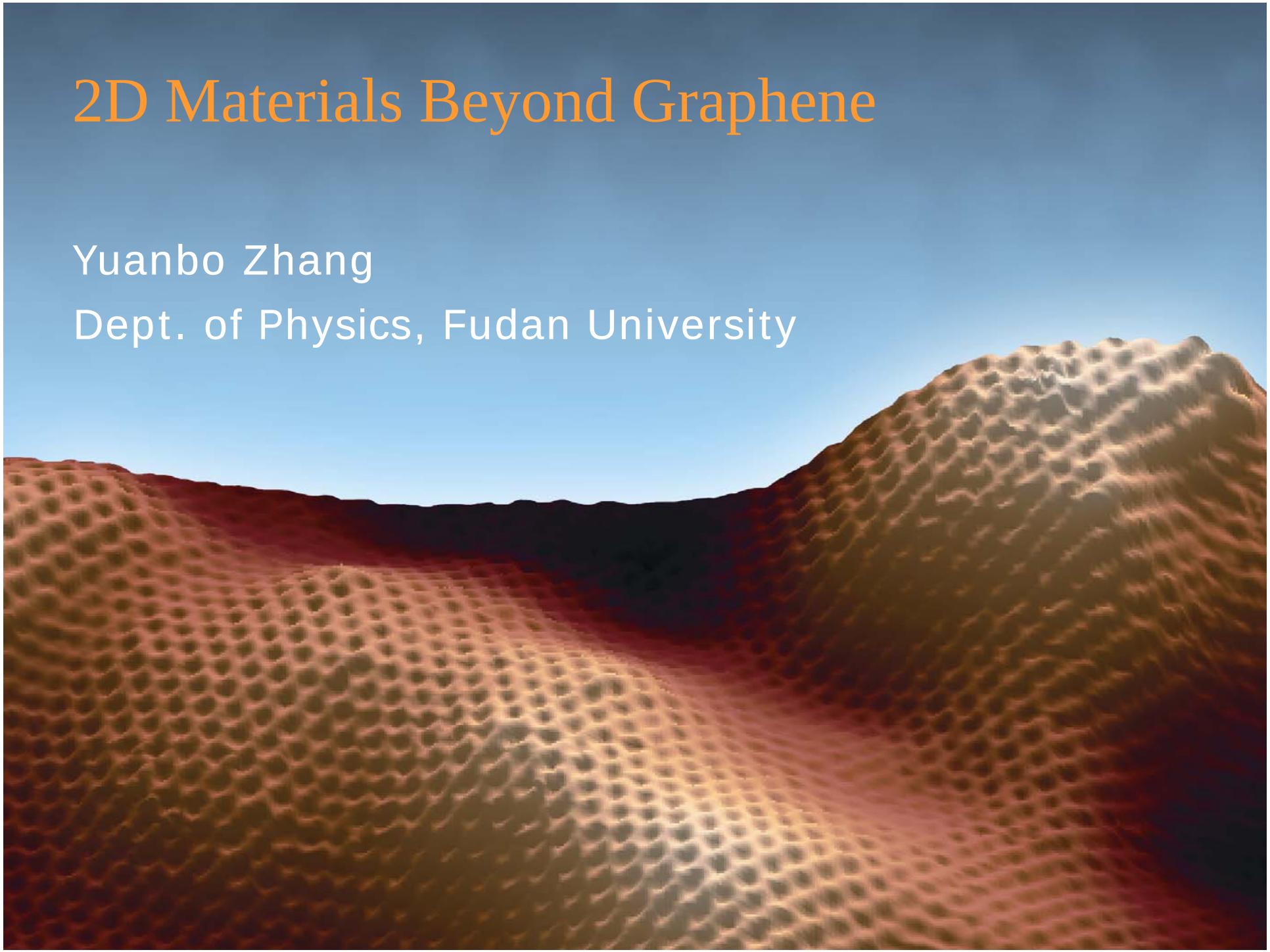


Why 2D Crystal?

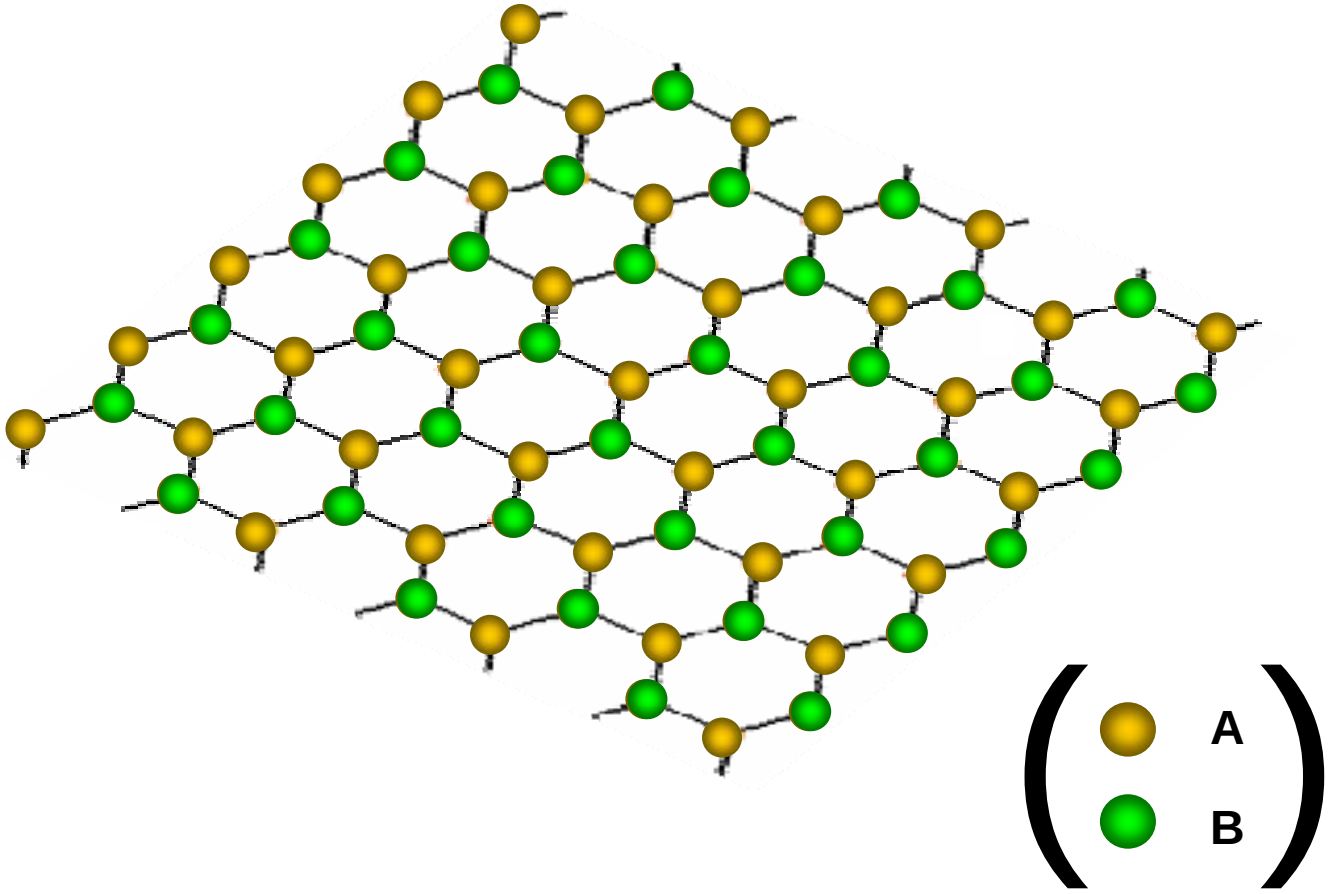
- **Technologically important**

  “interface is the device”

- **Interesting new physics**

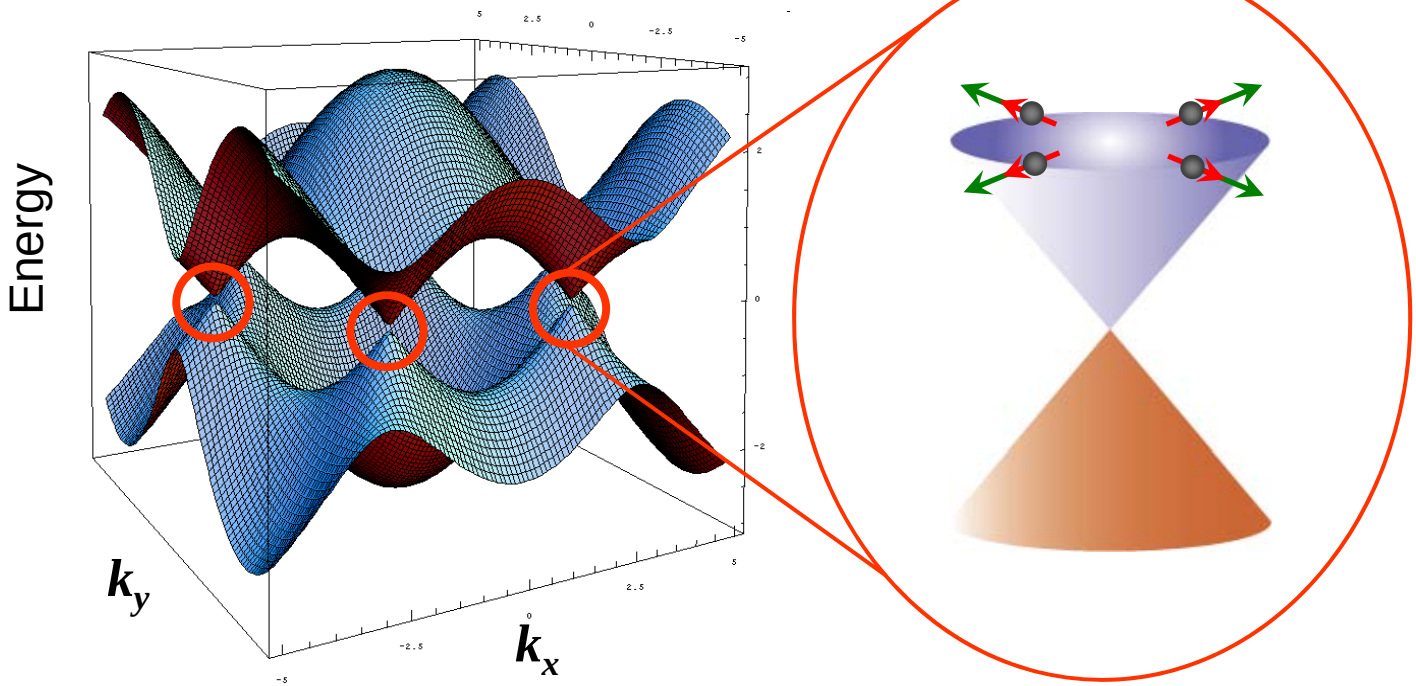
  Quantum Hall effect
  Fractional quantum Hall effect
  Anyon physics
  2D superconductivity
  …

Graphene



Graphene : Dirac Fermions in 2D

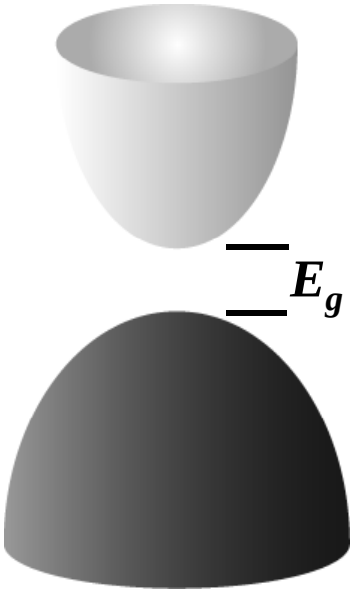
Band Structure of Graphene



Momentum, $\hbar \boldsymbol{k}$

Pseudo-spin

Semiconductor Band Structure



Massless Dirac Fermions with effective speed of light $v_F \sim c/300$.

$$E = \hbar k v_F$$

$$E = pc$$

$$E = \frac{\hbar^2 k^2}{2m^*}$$

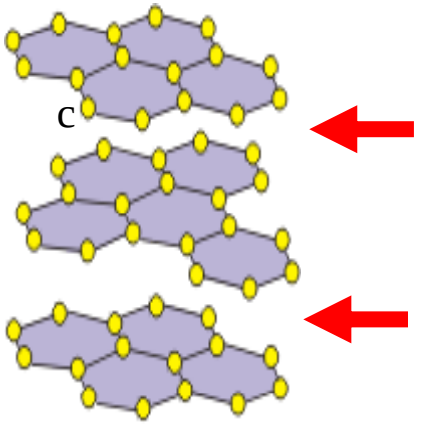
P. R. Wallace, *Phys. Rev.* 71, 622 (1947).

T. Ando et al, *J. Phys. Soc. Jpn* 67, 2857 (1998).

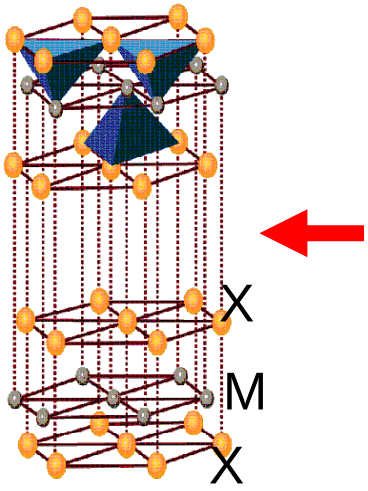
What Makes Graphene Great?

- **Peculiar Band Structure (Interesting Physics)**
- **High Quality**
- **Ease of Fabrication**
- **Widely Tunable**

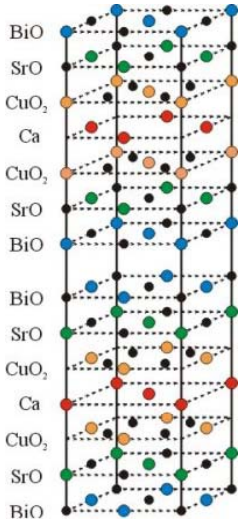
Other 2D Crystals



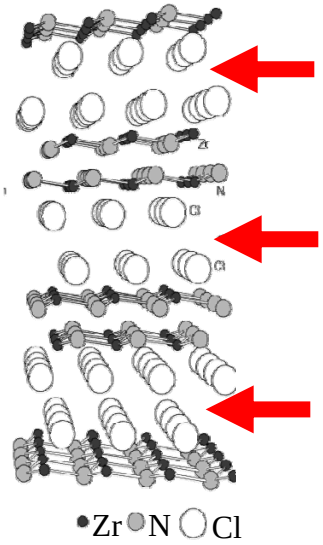
Graphite



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



High Tc Materials
如$Bi_2Sr_2CaCu_2O_{8-x}$

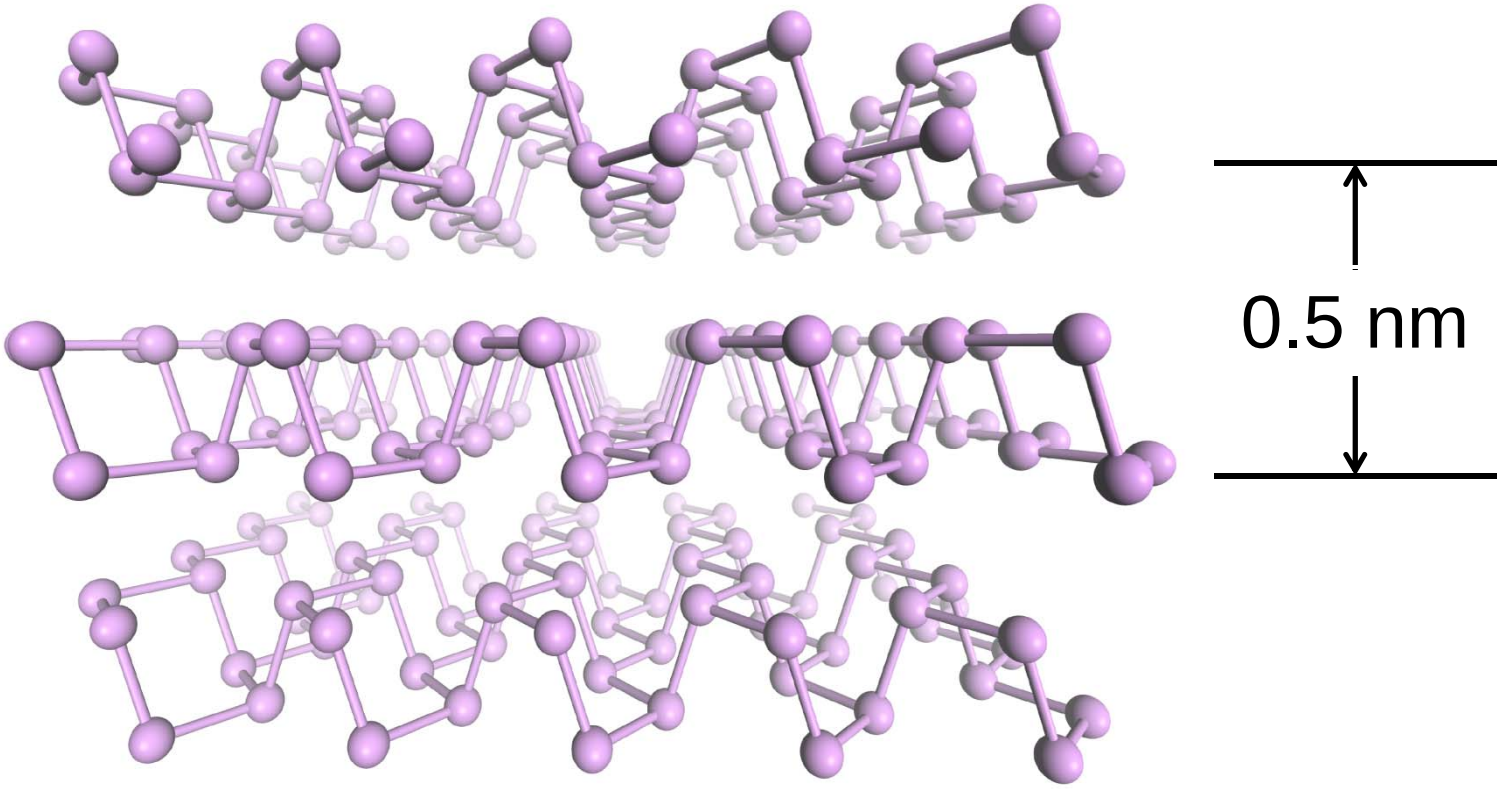


β- ZrNCl

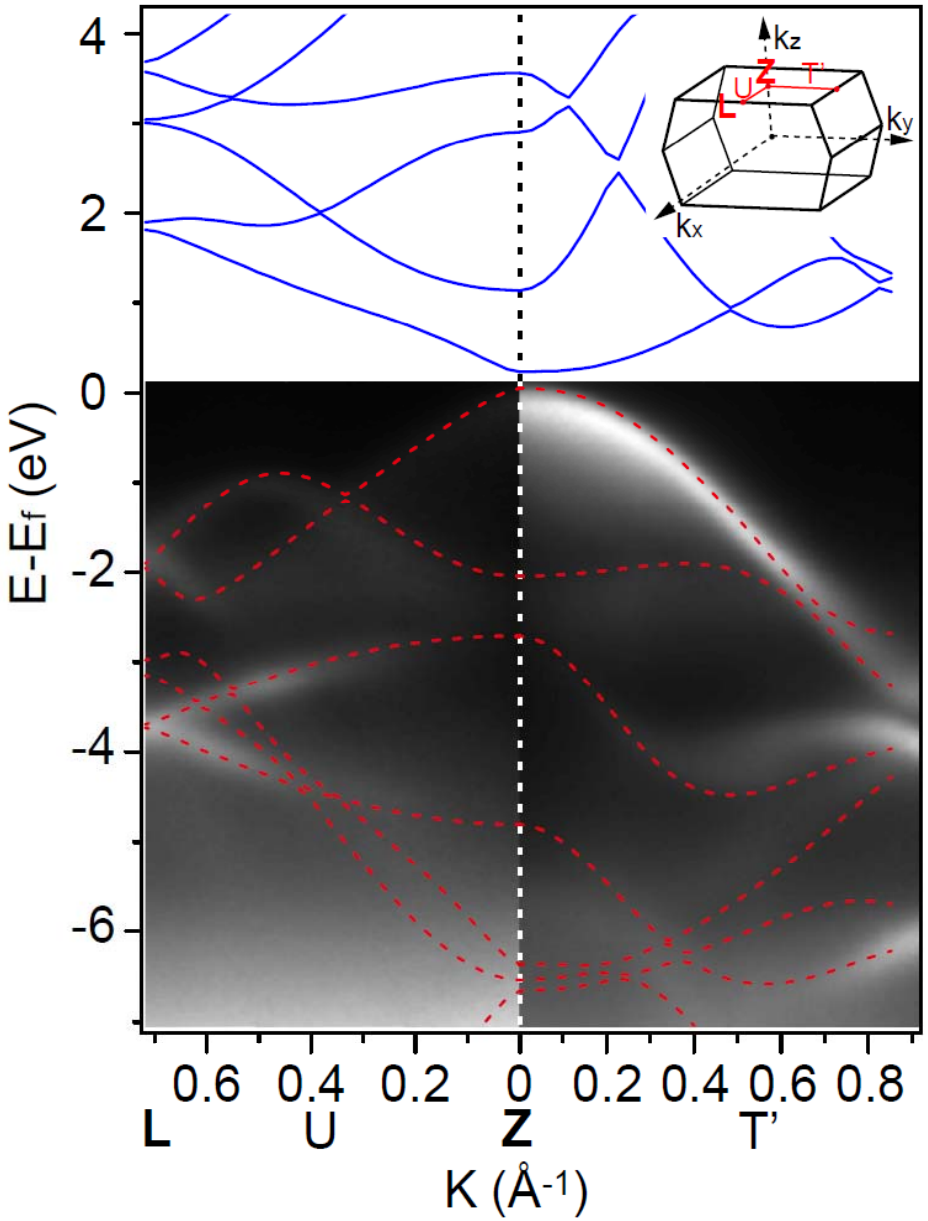
92 two-dimensional compounds recently identified by Lebe`gue et al. (PRL, 2013)

Black Phosphorus

Atomic structure of Black Phosphorus



Black Phosphorus – Bulk Band Structure



Bulk Phosphorus:

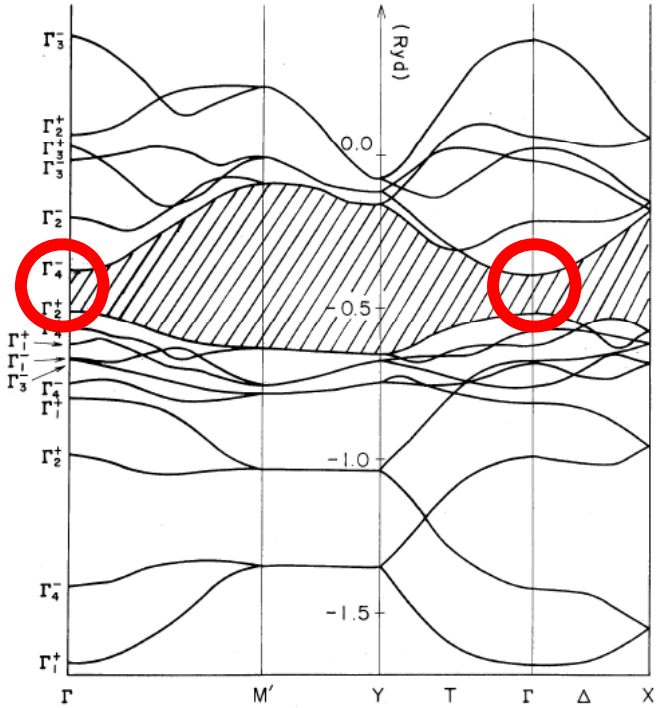
Semiconductor with direct bandgap

~ 0.3 eV

Black Phosphorus – Monolayer and Bulk

Single atomic layer

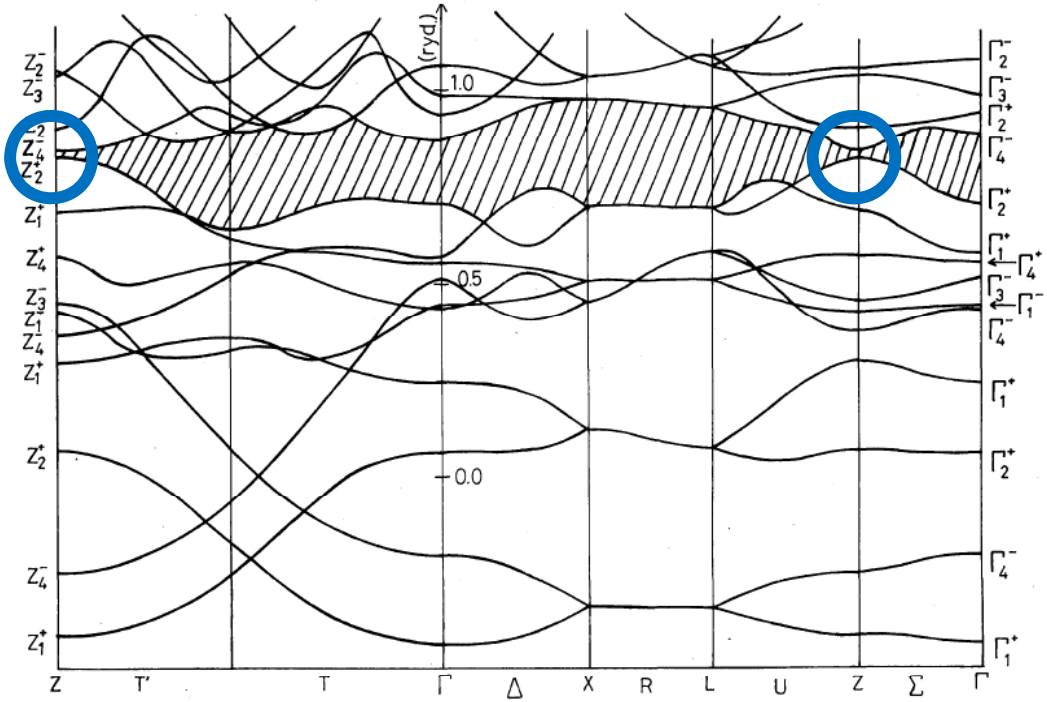
Band gap ~ 2 eV



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

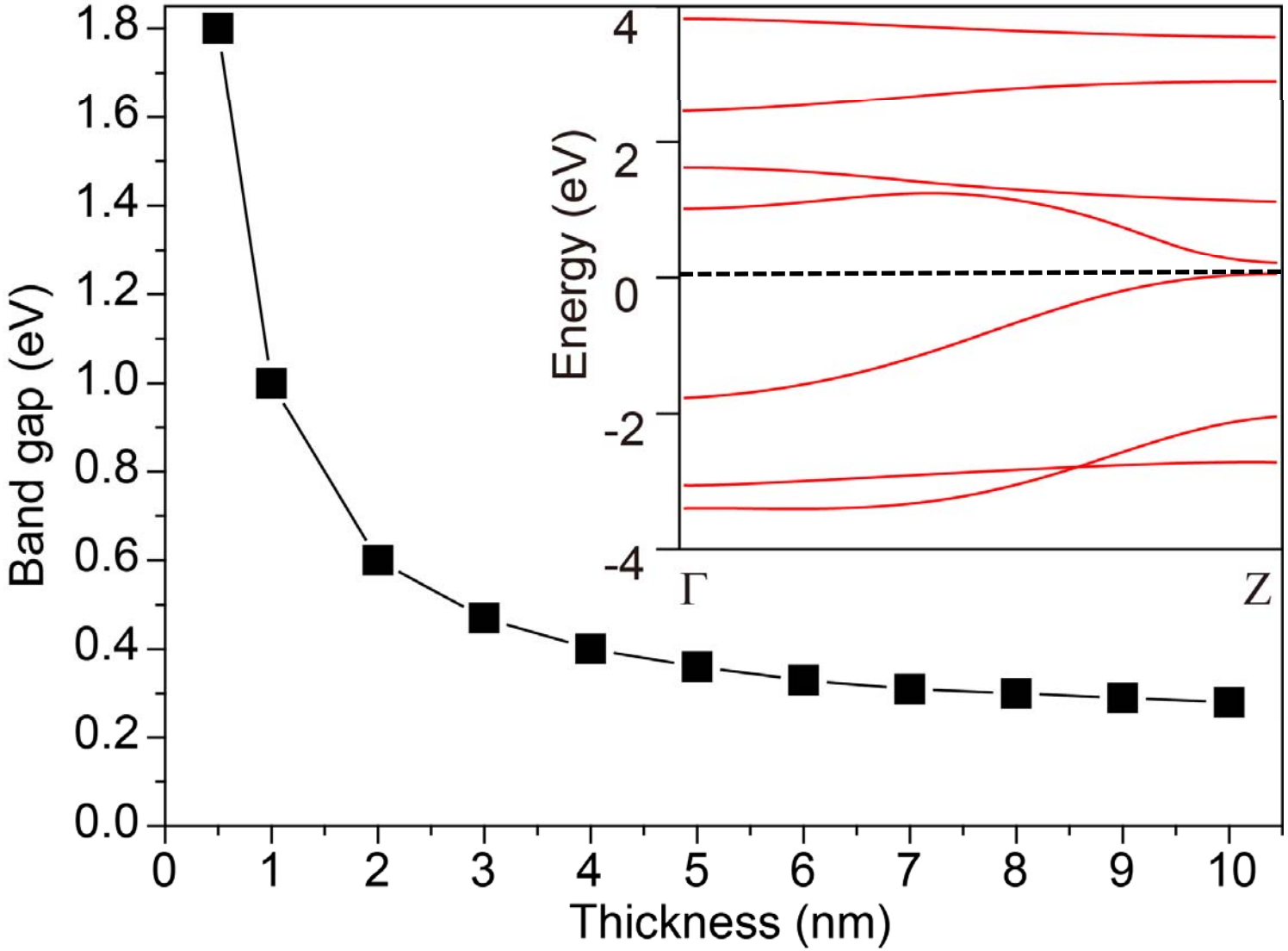
Bulk crystal

Band gap ~ 0.3 eV

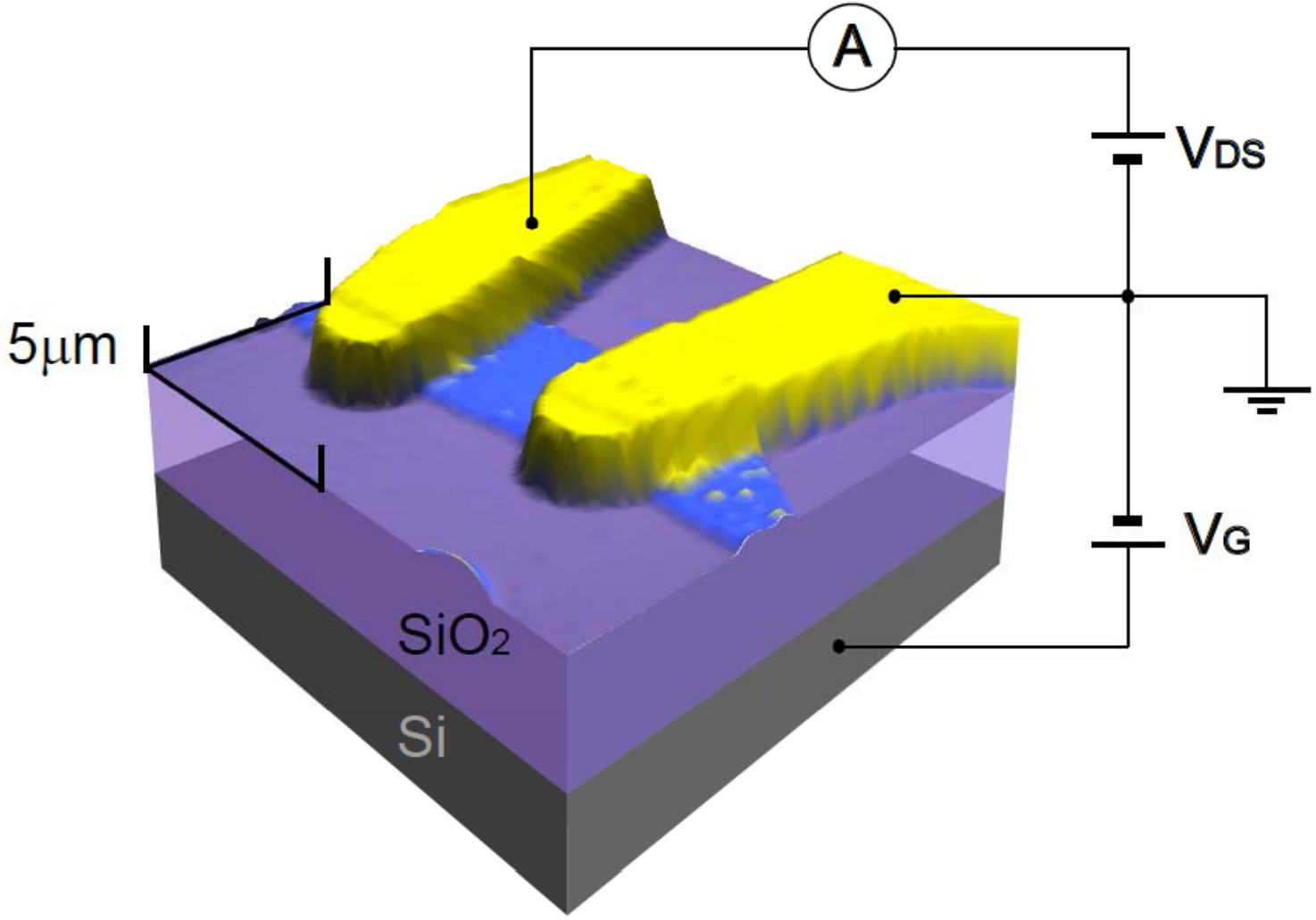


H. Asahina et al.,J. Phys. Soc. Jpn. 51, 1192 (1982)

Black Phosphorus Band Gap

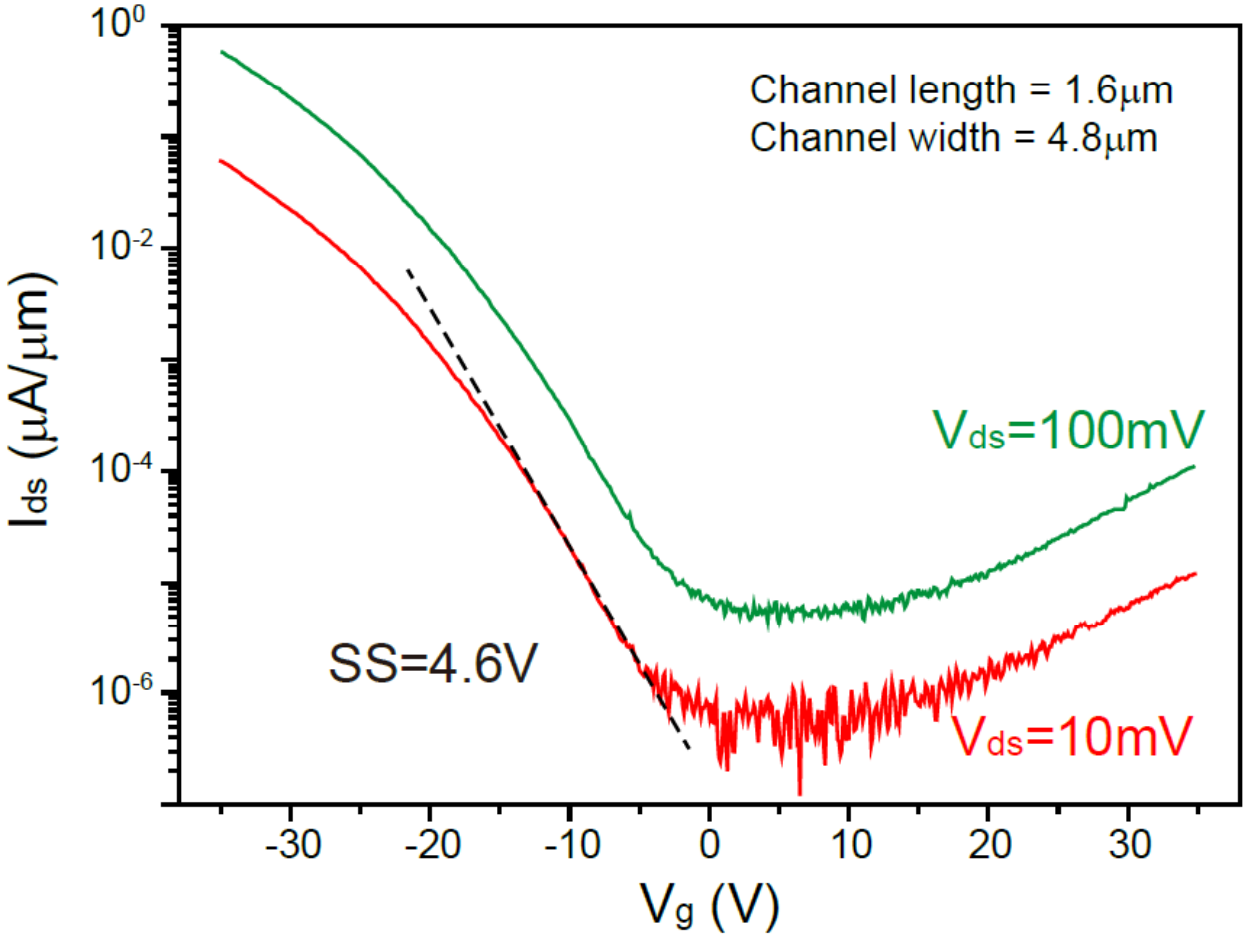


Sample Fabrication



Black Phosphorus transistor performance
Field effect properties

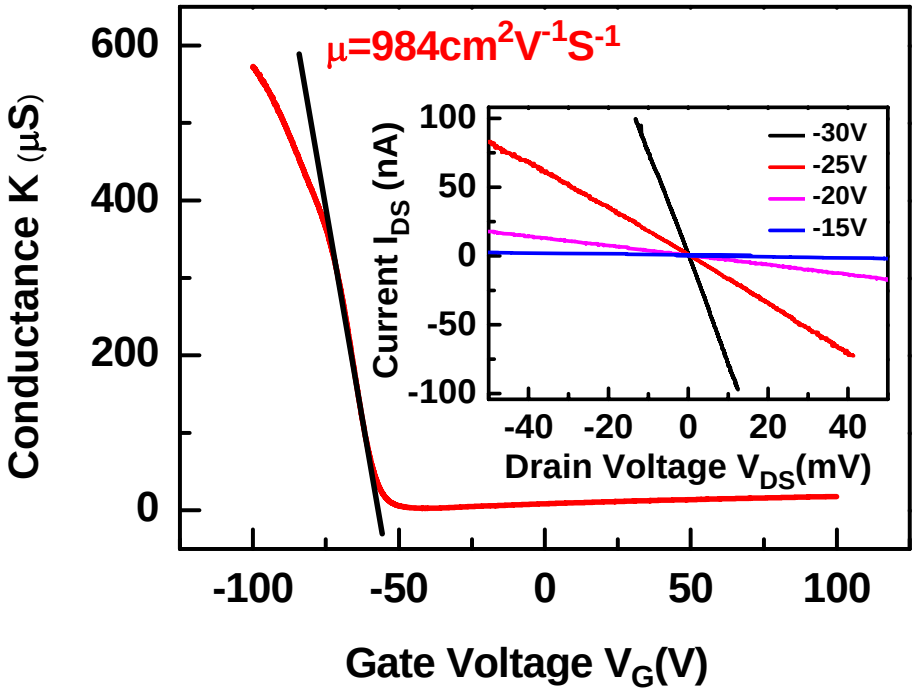
- **10^5 on-off ratio (5 nm sample)**
- **Ambipolar field effect**



Black Phosphorus transistor performance
High Mobility & Ohmic Contact

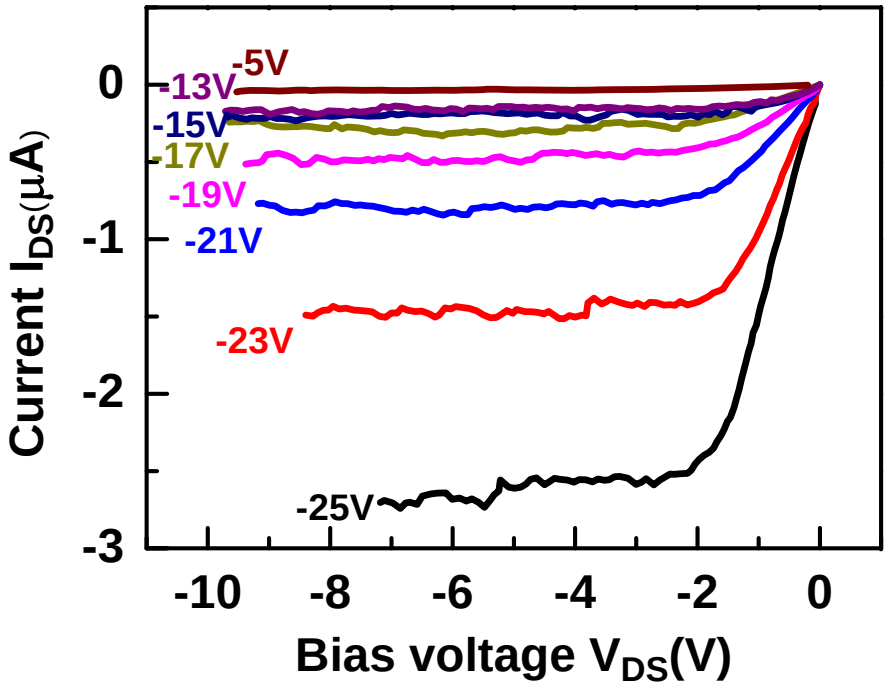
- $\mu = \frac{L}{W}\frac{1}{eV_{DS}C_{BG}}\left(\frac{dI_{DS}}{dV_{BG}}\right)$

High field effect mobility
& I-V property (inset)



- **Ohmic contact**
- **Saturation region**

Saturation region in
I-V curve



Acknowledgement

Fudan Univ.

Guorui Chen

Mengqiao Sui

Fangyuan Yang

Fan Liu

Yijun Yu

Likai Li

Qiong Wu

Liguo Ma

Prof. Donglai Feng

Qinqin Ge

Prof. Hua Wu

USTC

Prof. Xianhui Chen

Guojun Ye

IoP, CAS

Prof. Guangyu Zhang

Wei Yang

NIMS Japan

Prof. Takashi Taniguchi

Kenji Watanabe

Rutgers Univ., USA

Prof. Sang-Woo Cheong