Promise of 2D Crystals

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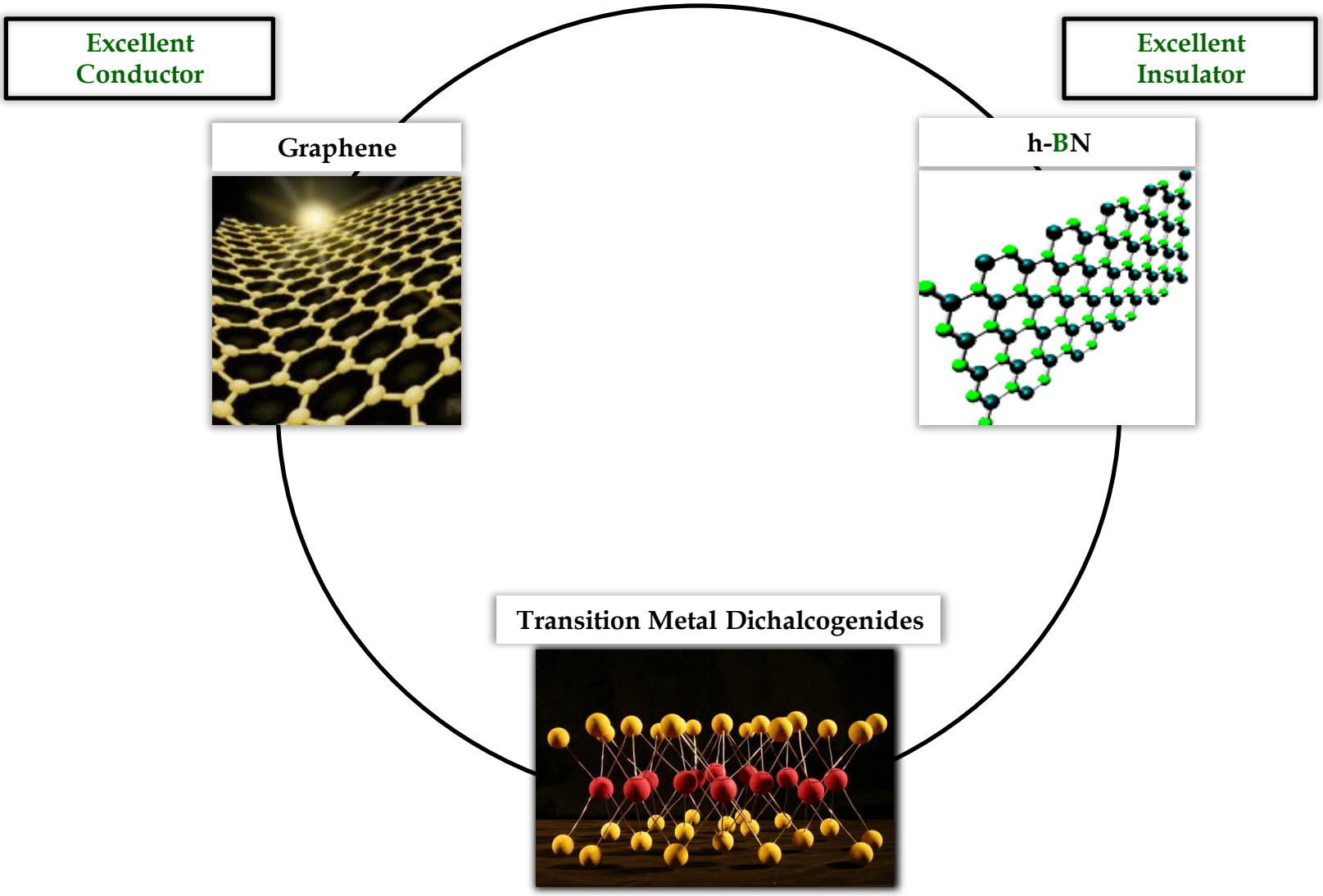
1. 2D Crystals
2. 2D Electronics
3. 2D Optoelectronics
4. 2D Engineering

1. **2D Crystals**
2. 2D Electronics
3. 2D Optoelectronics
4. 2D Engineering

Natural 2D Crystals

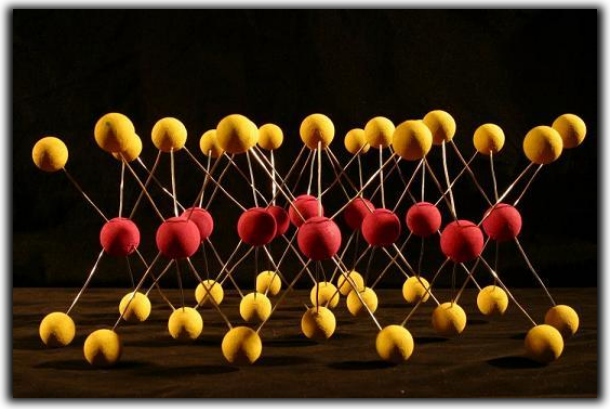
Argonne NATIONAL LABORATORY



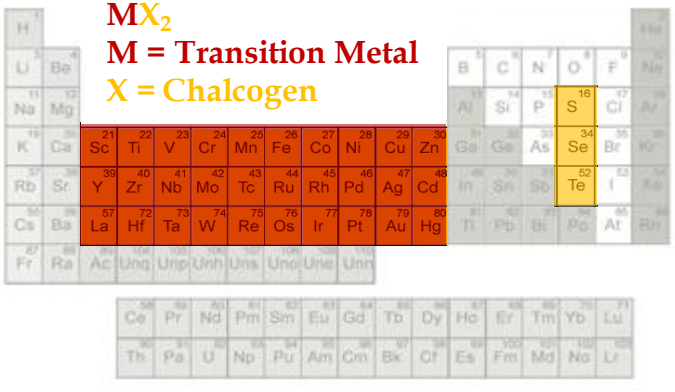
Natural 2D Crystals

Argonne NATIONAL LABORATORY

Transition Metal Dichalcogenides



Periodic Table of Elements



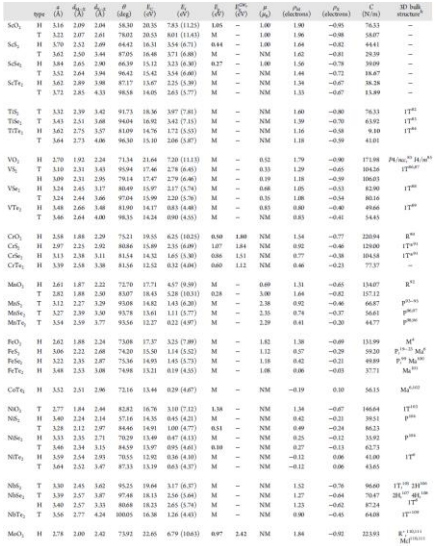
88 TMDs have been explored since 1960s

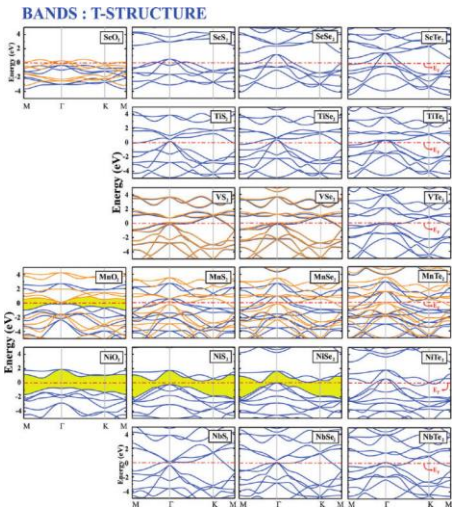
Metals: $ScTe_2$, TaS_2 , etc.

Semiconductors: WSe_2 , MoS_2, etc.

Insulators: $PtSe_2$, PdS_2 , etc.

Superconductors: VS_2 , $NbSe_2$, etc.





Natural 2D Crystals

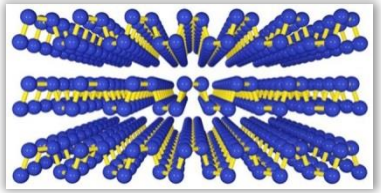
Excellent Conductor

Excellent Insulator

Graphene

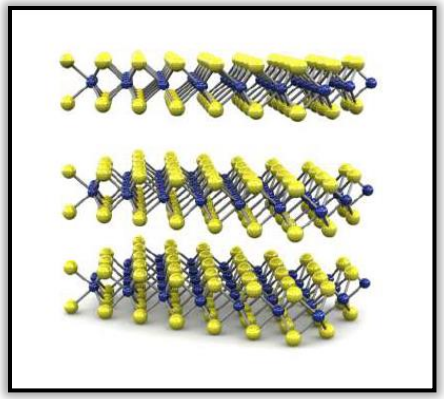
h-BN

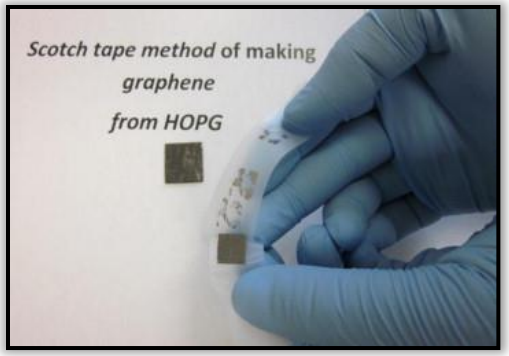
Phosphorene

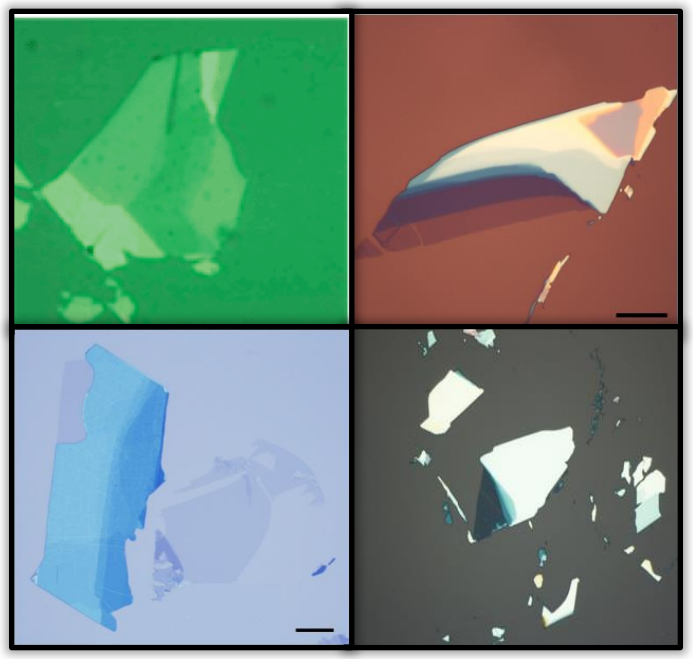


Transition Metal Dichalcogenides

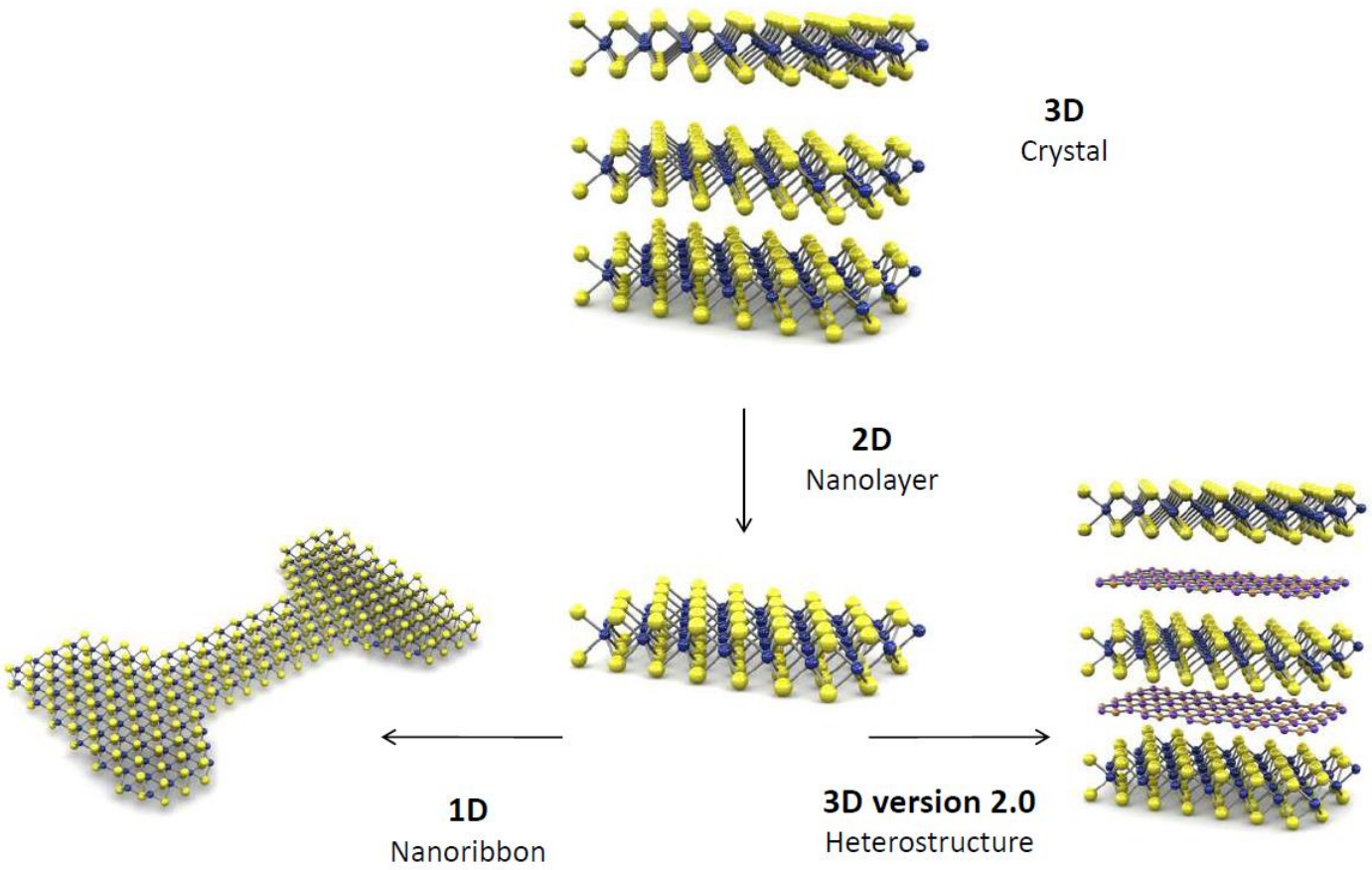
Exfoliation



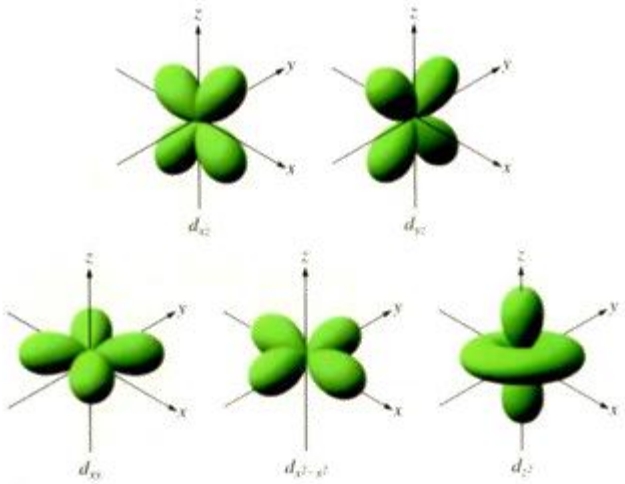




Layered Compounds



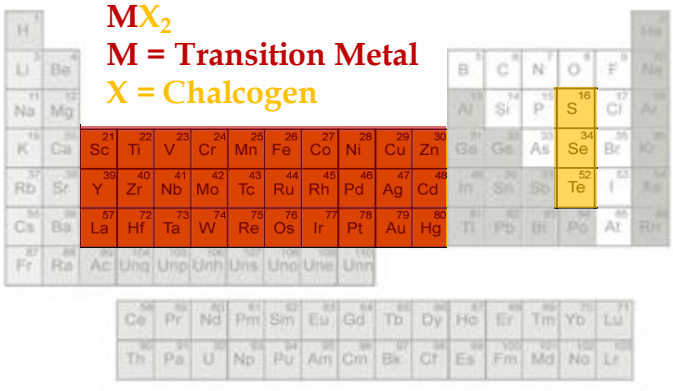
The d-orbital electronics



Mo: [Kr]. $5d^5.6s^1$
W: [Xe].$4f^{14}.5d^4.6s^2$

For the first time we have **Semiconductors** with conduction electrons contributed by **d-orbital**

Periodic Table of Elements



Band-structure Engineering

✓ Electric Field

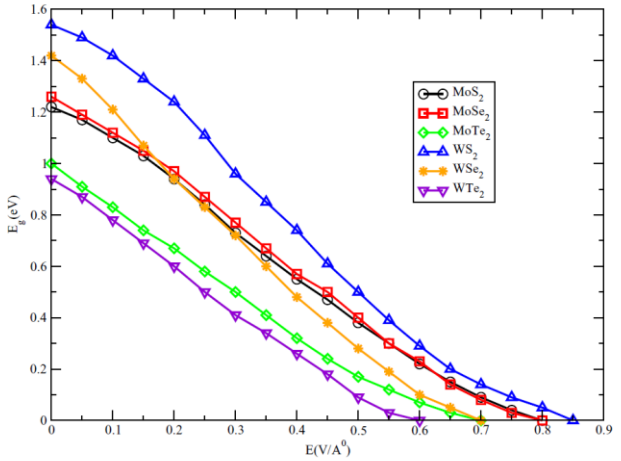
✓ Mechanical Force

✓ Temperature

Metal Insulator Transition

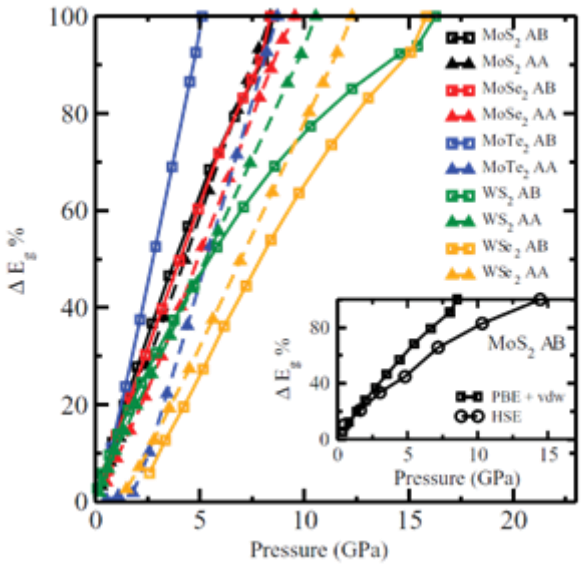
Electric Field Induced

Swastibrata Bhattacharyya, *et al*.
Physical Review B, 86, 2012



Mechanical Force Induced

Ashok Kumar, *et al*. Modeling and Simulation in Material Science and Engineering, 21, 2012



1. 2D Crystals
2. **2D Electronics**
3. 2D Optoelectronics
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Transistor

- High Speed
- Low Power

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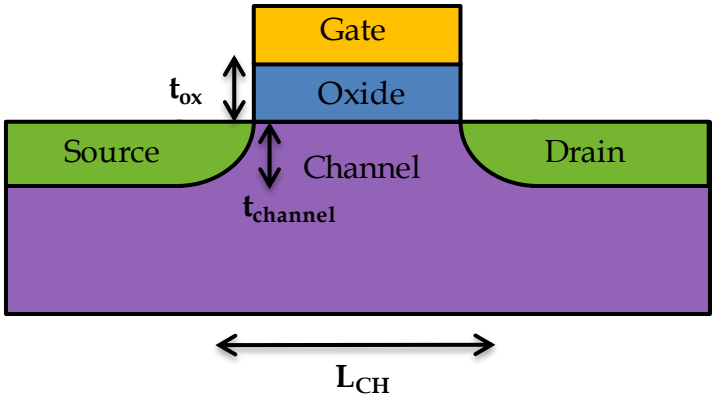
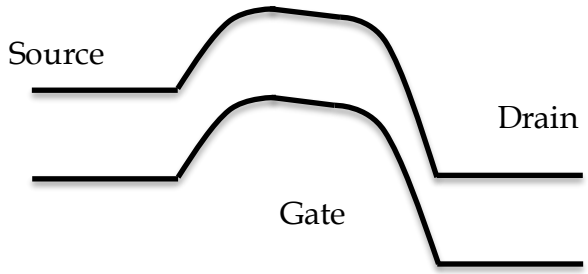
Field Effect Transistor





Transistor

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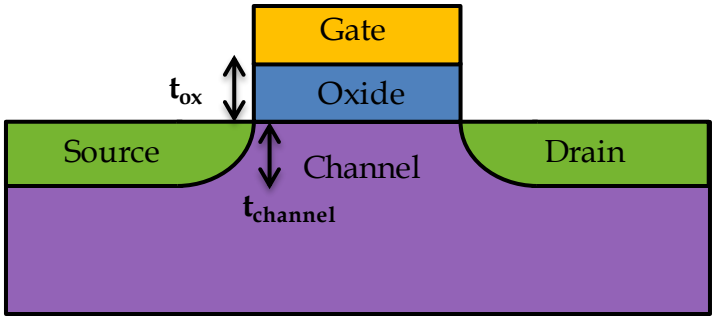
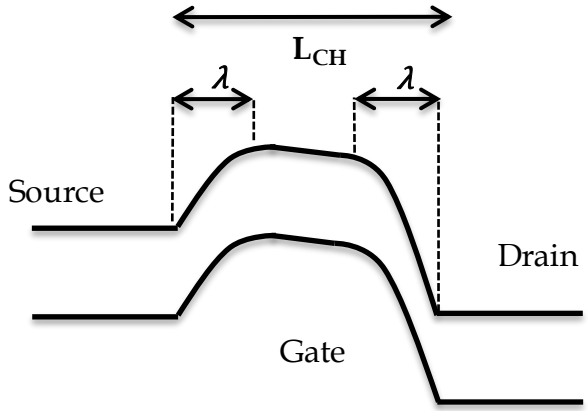
Field Effect Transistor



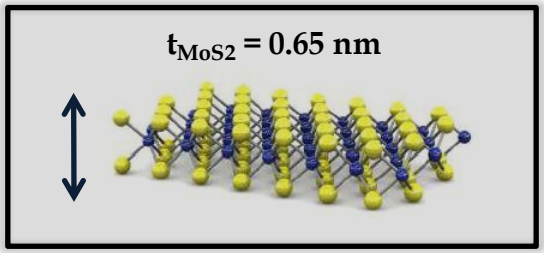


$$\lambda = \sqrt{t_{channel} t_{ox}}$$

$$L_{CH} > 3\lambda$$

Gate Leakage Current does not allow thinning down of gate Oxide

Quantum Confinement does not allow thinning down of Si channel



2D Transistor

- High Speed
- Low Power

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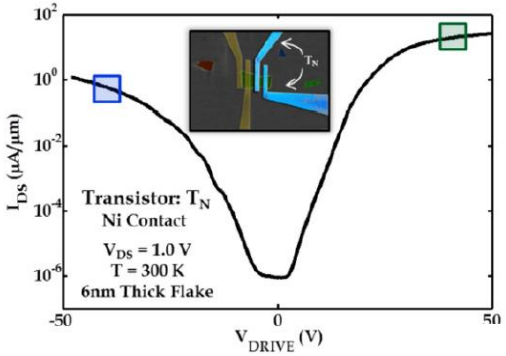
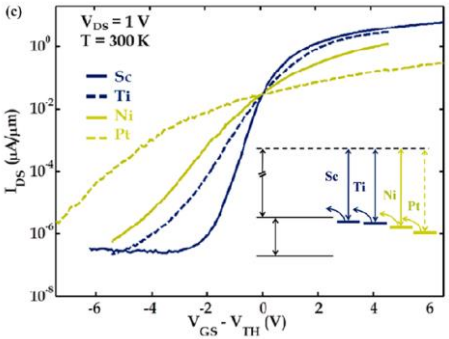
WSe_2 FET

Saptarshi. *et al.* Applied Physics Letters, 103, 2013.



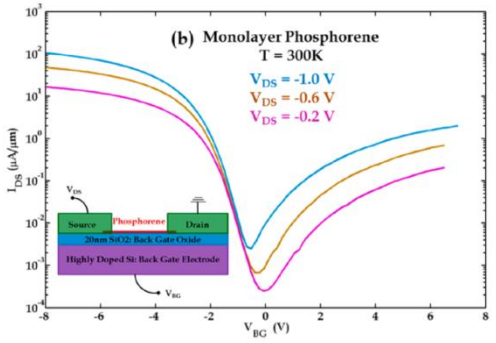
MoS_2 FET

Saptarshi. *et al.* Nano Letters, 13(1), 2013.



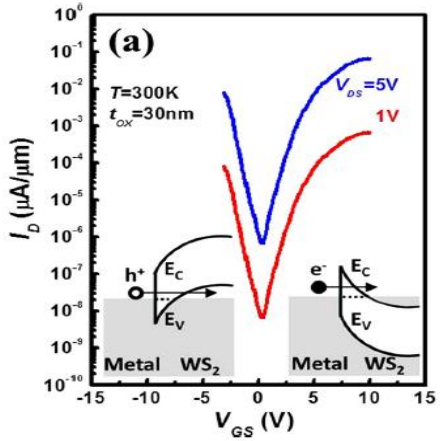
Phosphorene FET

Saptarshi. *et al.* Nano Letters, 14(10), 2014.



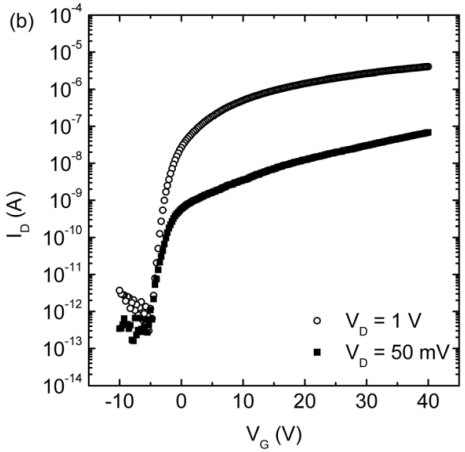
WS_2 FET

Hwang. *et al.* Applied Physics Letters, 101, 2012.



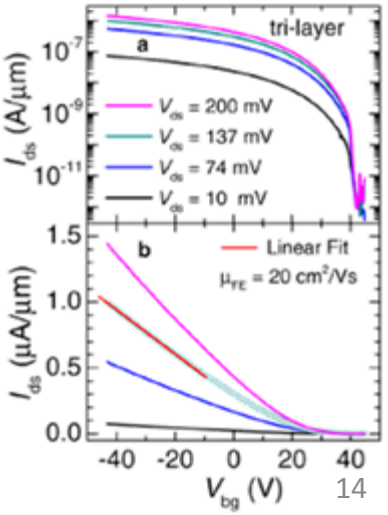
$MoSe_2$ FET

Pradhan. *et al.* ACS Nano, 8(6), 2014.



$MoTe_2$ FET

Pradhan. *et al.* ACS Nano, 8(8), 2014.

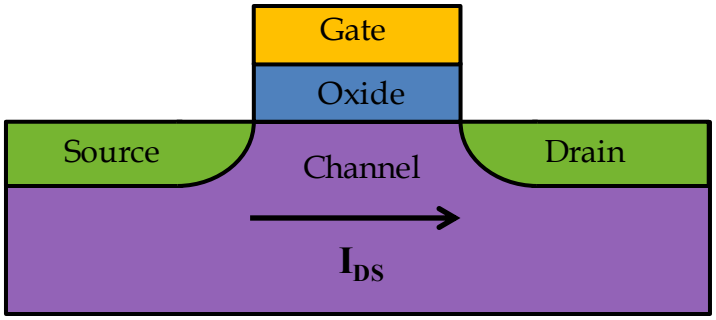


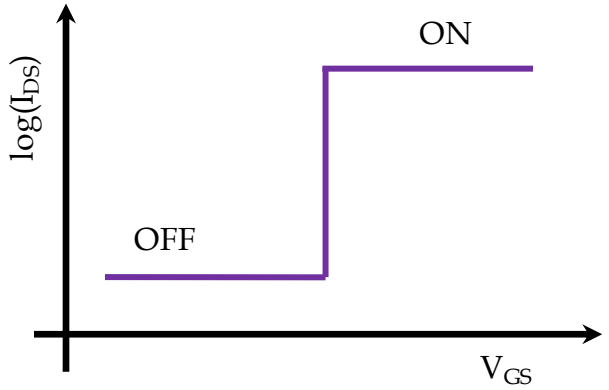
Transistor

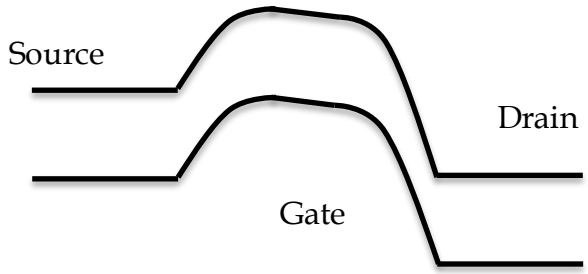
- High Speed
- **Low Power**

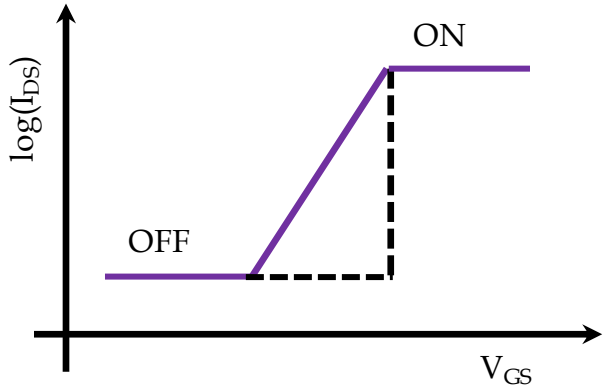
Argonne NATIONAL LABORATORY

Field Effect Transistor





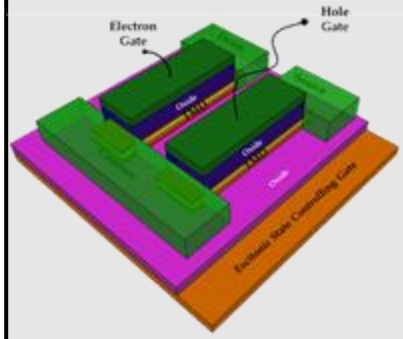




Boltzmann Statistics limits power dissipation

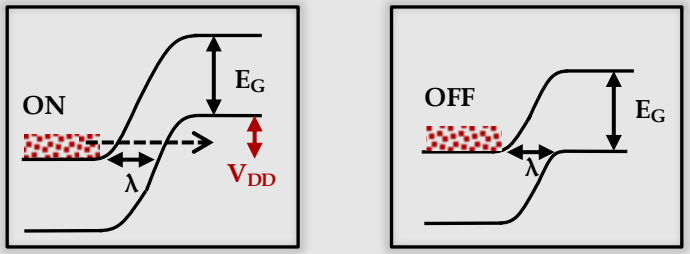
Green Transistor

Excitonic Transistors



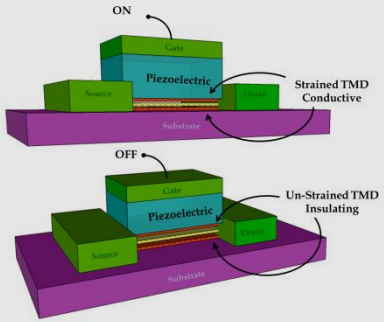
- ✓ Columbic Interaction between Electrons and Holes Resulting in Phase Transition
- ✓ Possibility of Room Temperature Superconductivity

Tunneling Transistors



$$T_{WKB} = \exp\left(-\frac{4}{3\hbar}\sqrt{2m_e E_G d_{OX} \boldsymbol{d_{BODY}}}\right)$$

Mott Transition Transistors



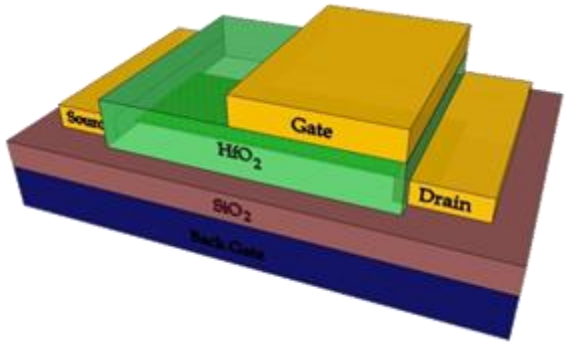
Gate Tunable

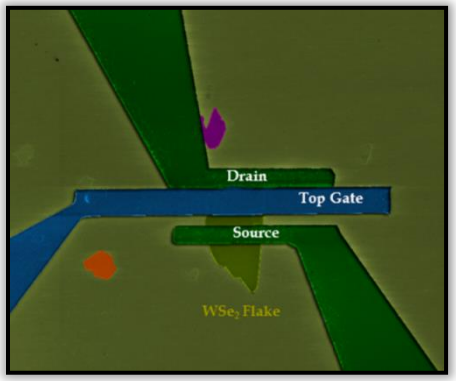
- ✓ Electronic Properties
- ✓ Photonic Properties
- ✓ Thermal Properties
- ✓ Mechanical Properties

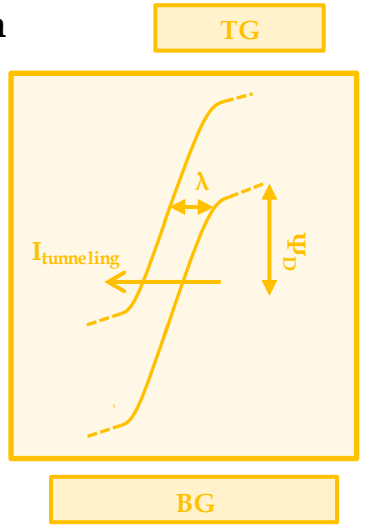
Tunneling Transistors

Electrostatically doped WSe_2 Lateral tunnel junction

Saptarshi Das. *et al.* ACS Nano, 8(2), 2014.

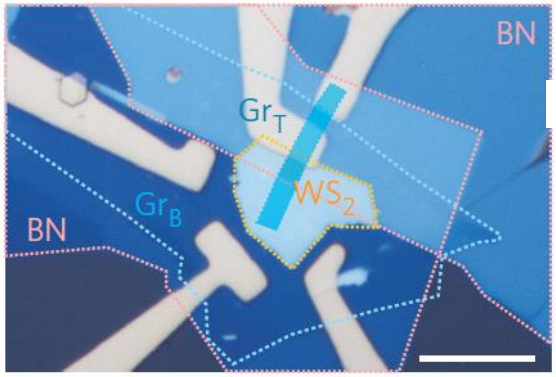


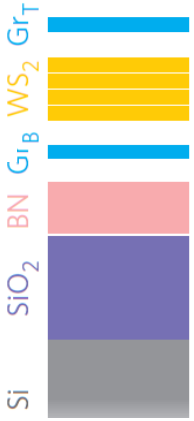


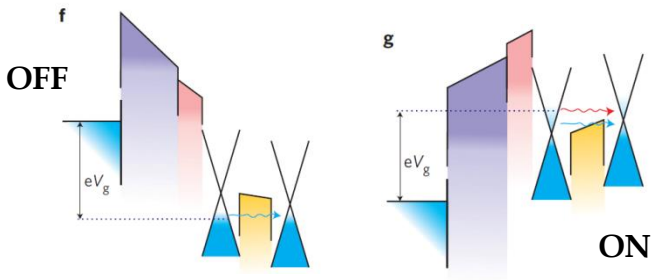


Graphene-WS_2-Graphene Vertical tunnel junction

Georgiou. *et al.* Nature Nanotechnology, 8, 2013.

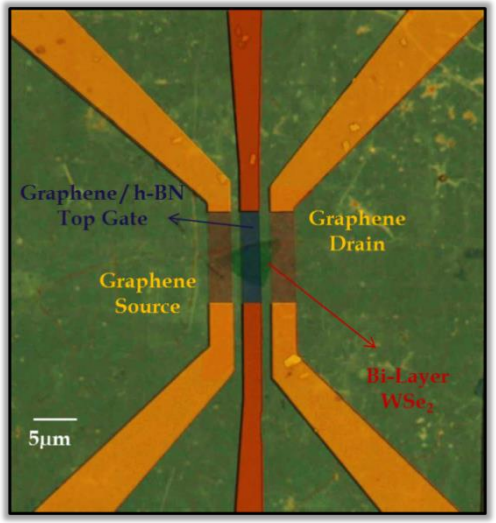


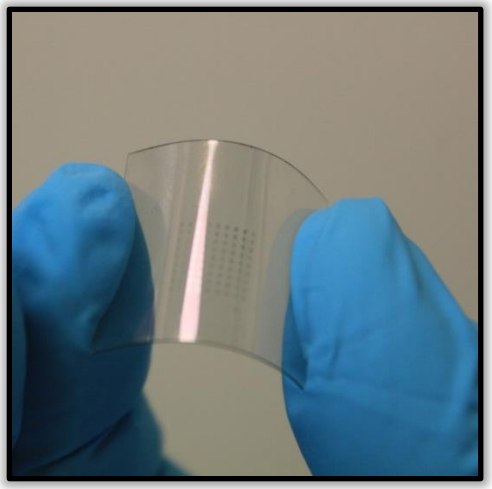


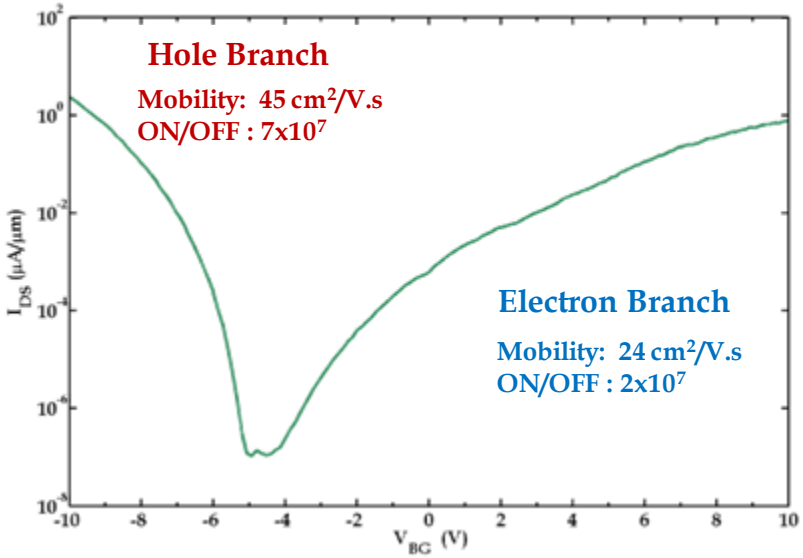


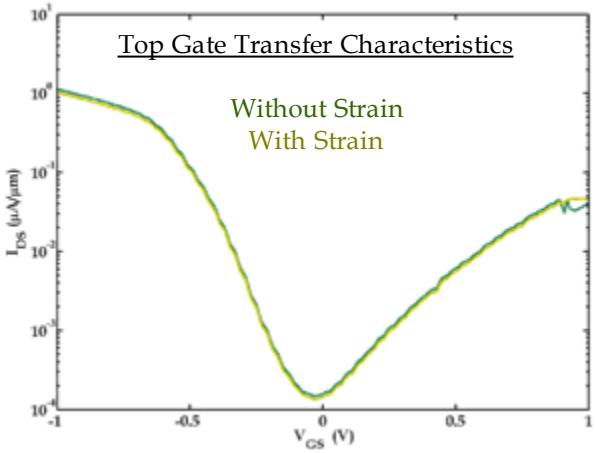
Integration: All 2D Transistor

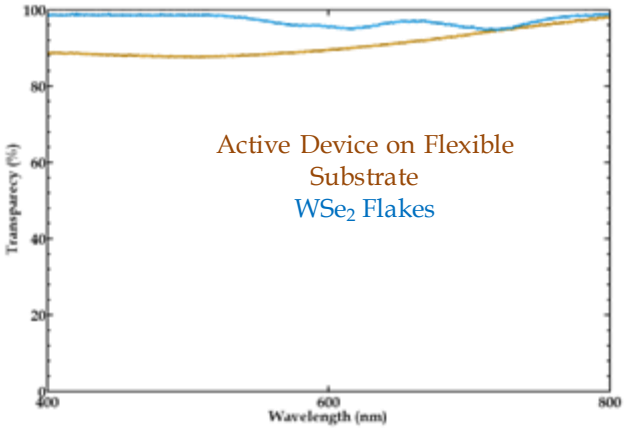
Saptarshi, *et al.*
Nano Letters 14 (5), 2014.







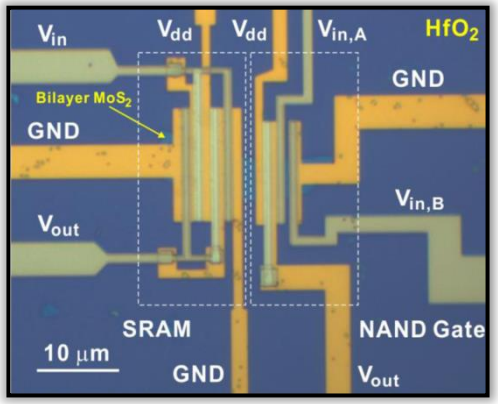




2D Circuits and Sensors

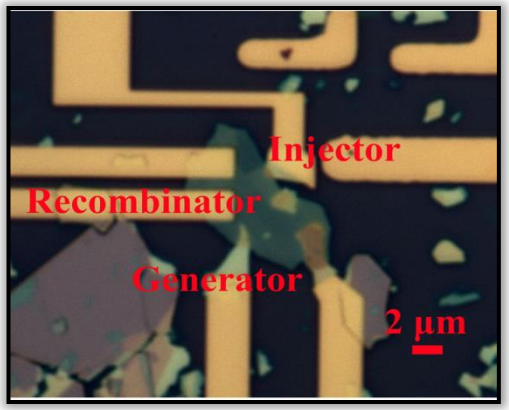
Integrated circuit based on MoS_2

Wang. *et al*. Nano Letters, 12(9), 2012.



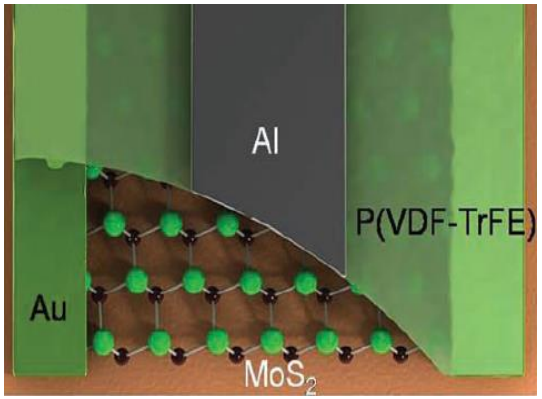
Analog small signal generator

Tan. *et al*. Applied Physics Letters, 103, 2013.



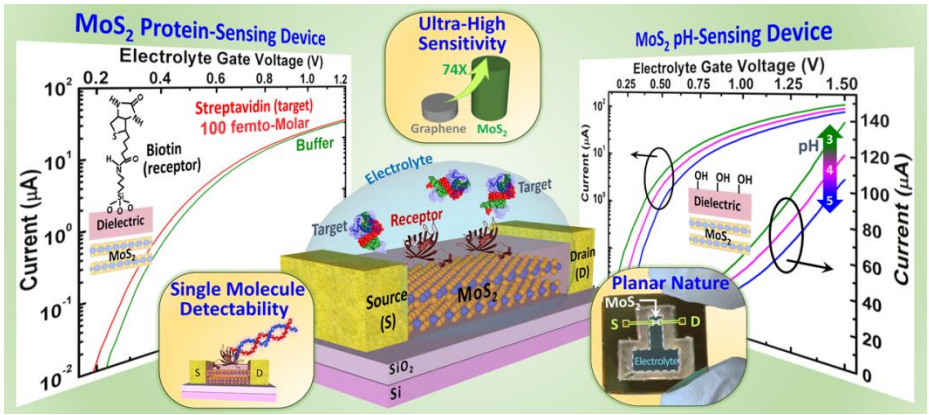
Memory transistor with MoS_2

Lee. *et al*. Small, 8(20), 2012.



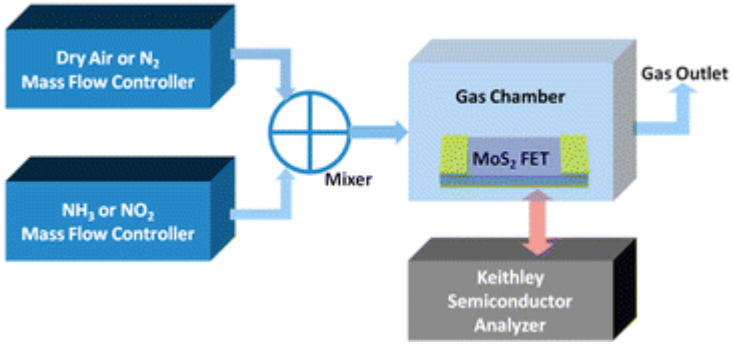
MoS_2 FET based bio-sensor

Late. *et al*. ACS Nano, 7(6), 2013.



MoS_2 FET based gas-sensor

Sarkar. *et al*. ACS Nano, 8(4), 2014.



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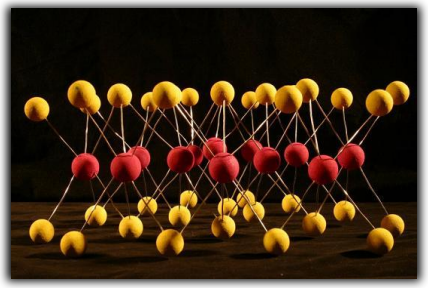
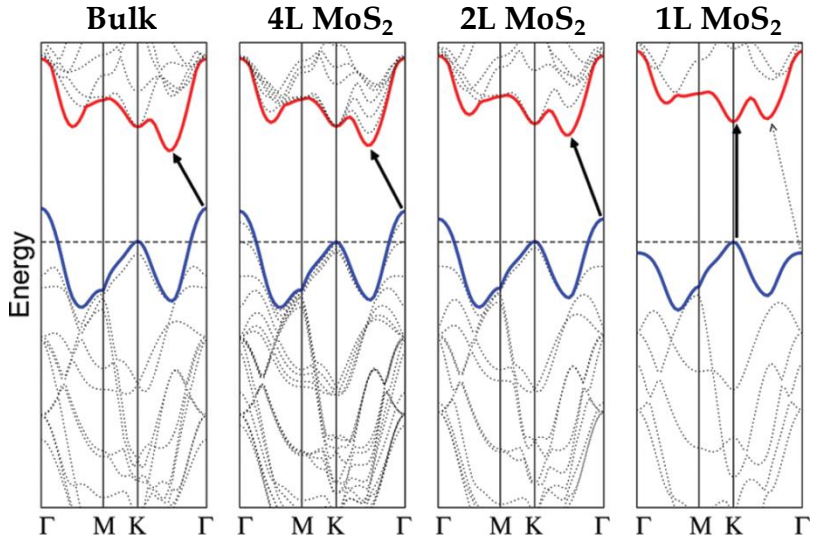
4. 2D Engineering

Photoluminescence



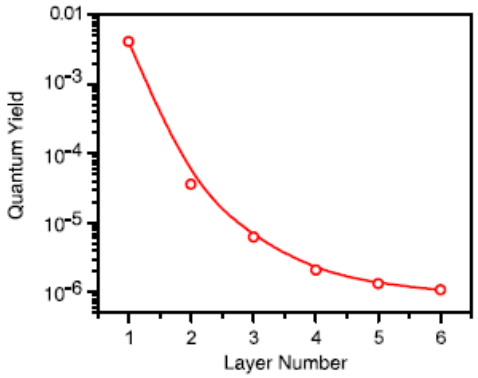
K point: localized d orbitals at the Mo atom

Γ point: linear combination of d orbitals on the Mo atoms and anti-bonding p_Z orbitals on the S atoms

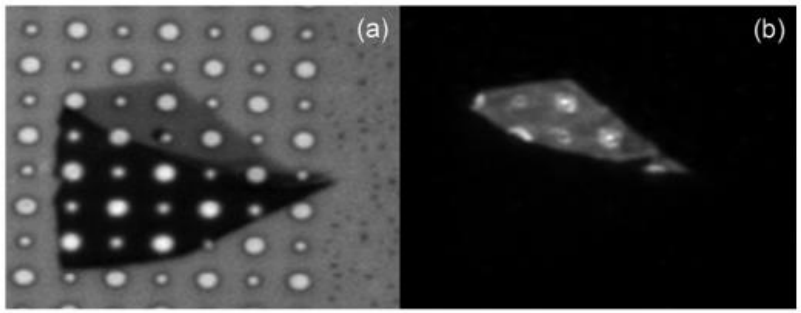


Photoluminescence in MoS_2

Splendiani. *et al*. Nano Letters, 10(4), 2010.



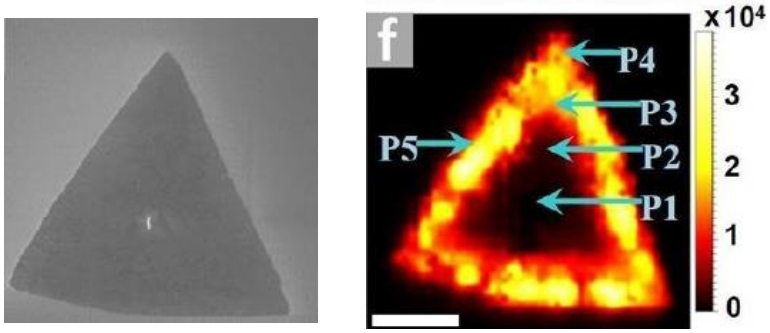
Photoluminescence from suspended flakes



Photoluminescence

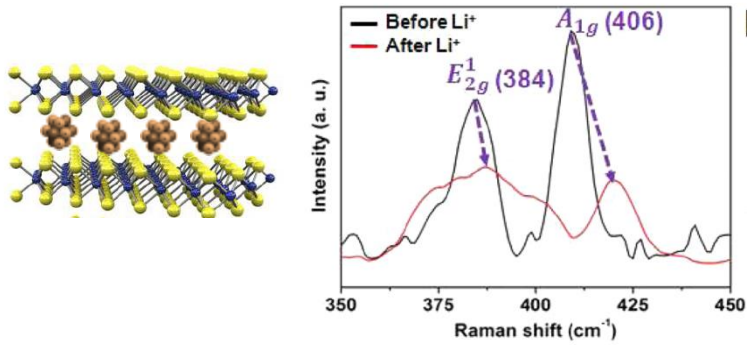
Enhanced photoluminescence from edges of WS_2

Gutierrez. *et al*. Nano Letters, 13(12), 2013.



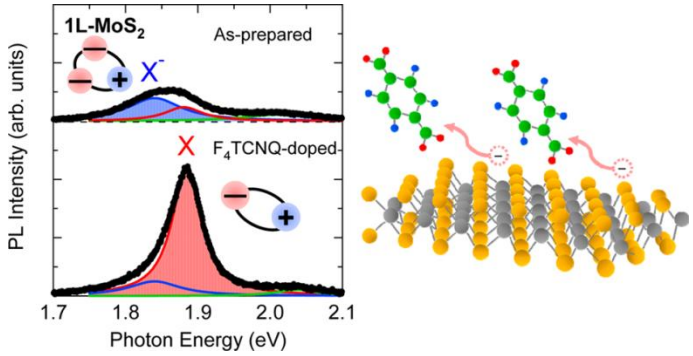
Photoluminescence modulation through intercalation

Wang. *et al*. ACS Nano, 7(11), 2013.



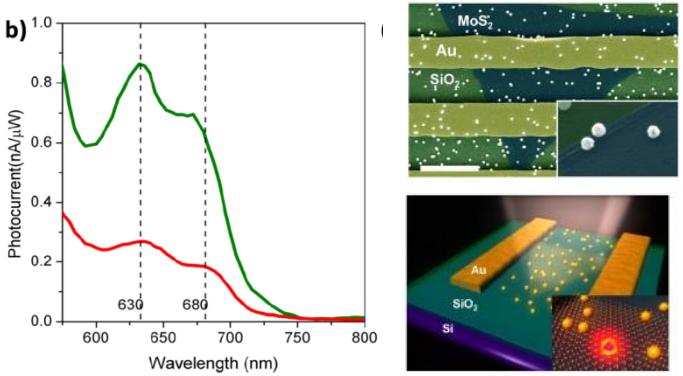
Photoluminescence modulation through doping

Mouri. *et al.* Nano Letters, 13(12), 2013.

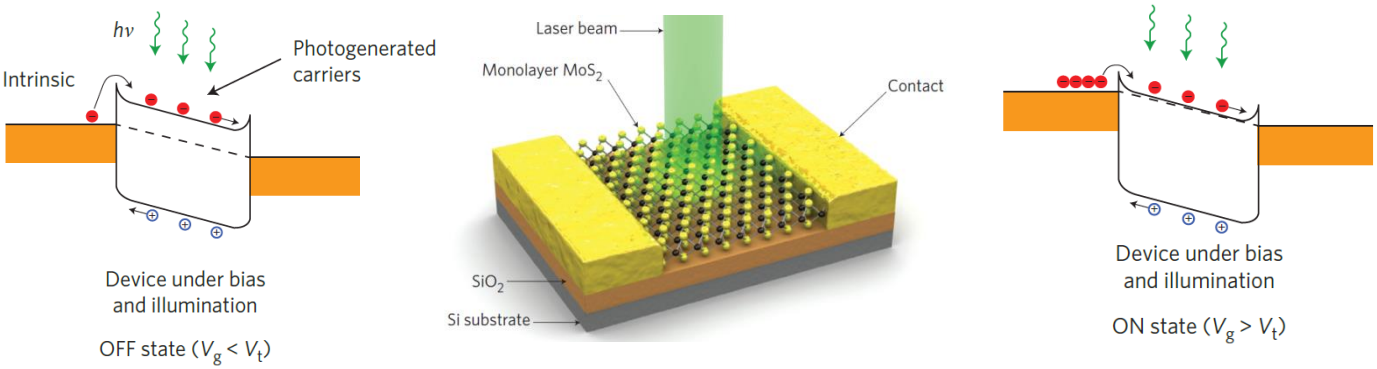


Photoluminescence modulation through plasmon

Shovani. *et al.* Applied Physics Letters, 104, 2014.



Phototransistor



Photoresponsivity ($\gamma = I_{photo}/P_{laser}$)

Mobility

Exfoliated monolayer MoS_2 : 7.5mA/W
Exfoliated few-layer MoS_2 : 120mA/W

Lopez. *et al*. Nature Nanotechnology, 8, 2013.

Ambience

CVD monolayer MoS_2 : 780mA/W (air)
CVD monolayer MoS_2 : 2200mA/W (high vacuum)

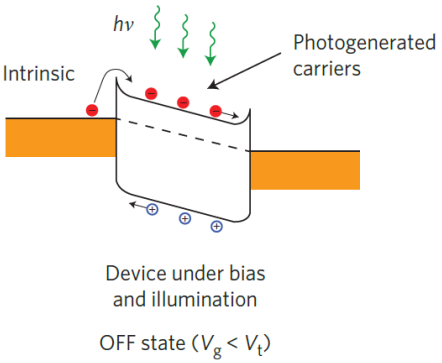
Zhang. *et al*. Advanced Materials, 25, 2013.

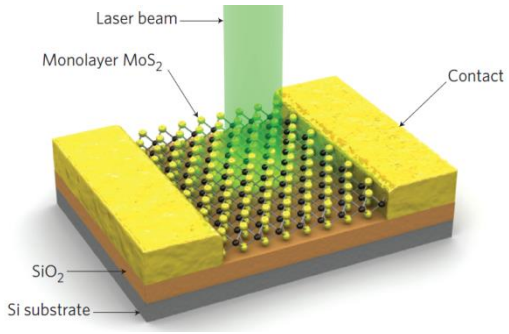
Contact Resistance

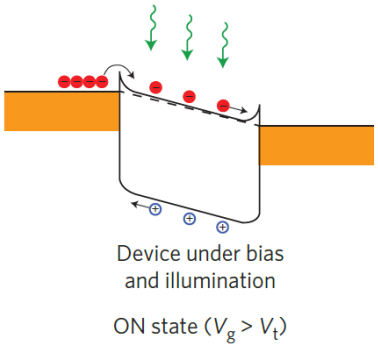
Ohmic contacted monolayer WSe_2 : ~1.8×10^5A/W

Zhang. *et al*. ACS Nano, 8(8), 2014.

Phototransistor



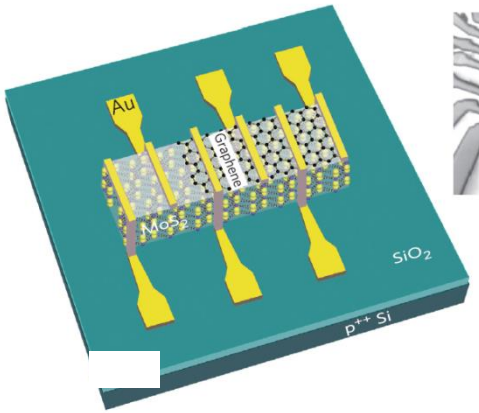


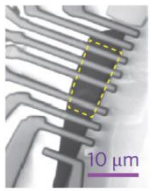


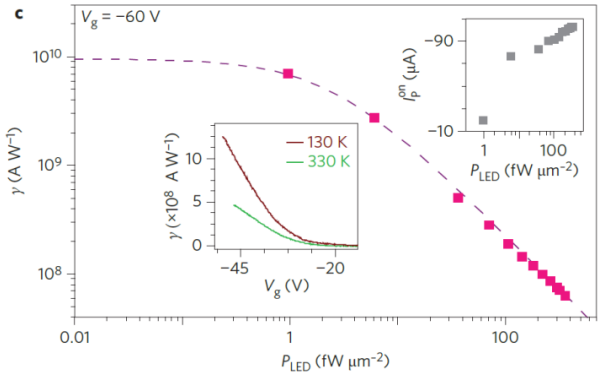
Photoresponsivity ($\gamma = 5x10^8 A/W$)

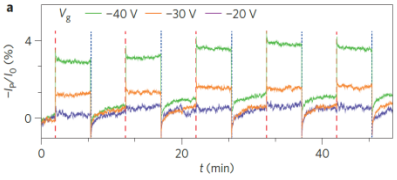
Graphene - MoS_2 heterojunction phototransistor

Roy. *et al*. Nature Nanotechnology, 8, 2013.



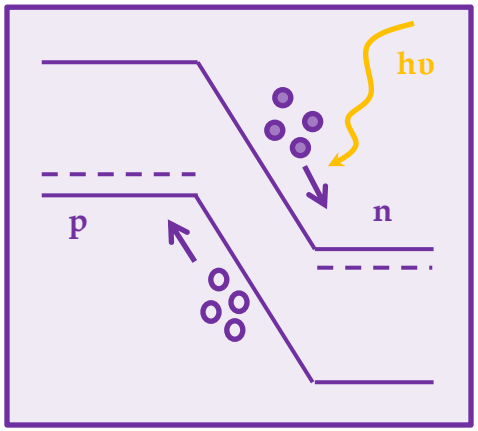




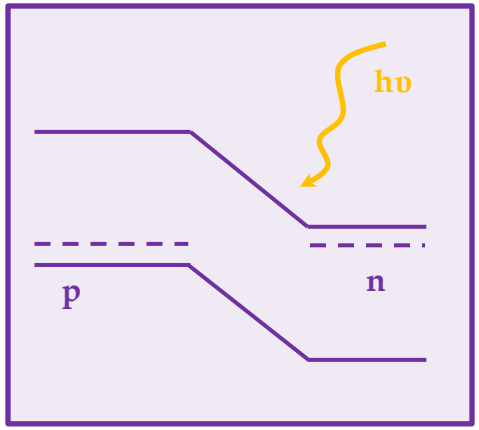


Photodiode

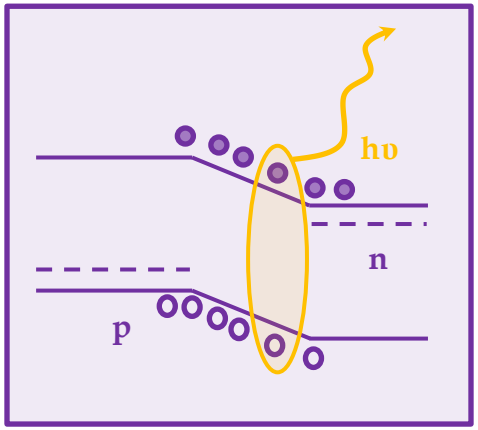
Photodetector: I_{ph}



Photovoltaic (solar cells): $I_{sc,}V_{oc}$



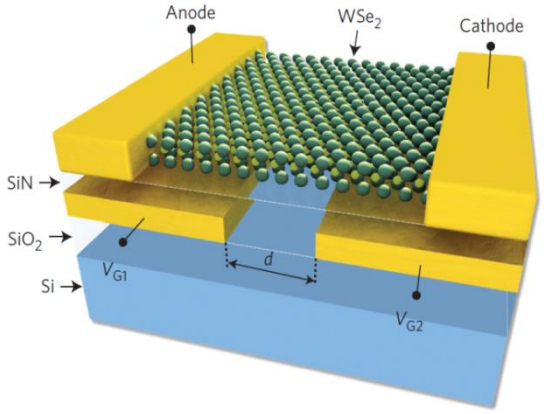
Electroluminescence (LEDs) : hυ

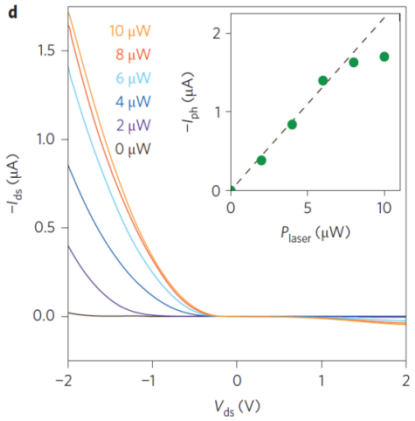


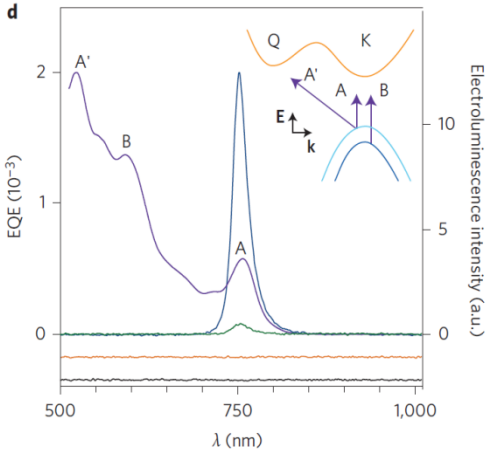
Photodiode

Electrostatically doped WSe_2 p-n diodes

Baugher. *et al.* Nature Nanotechnology, 9, 2014.
Ross. *et al.* Nature Nanotechnology, 9, 2014.
Pospischil. *et al.* Nature Nanotechnology, 9, 2014.

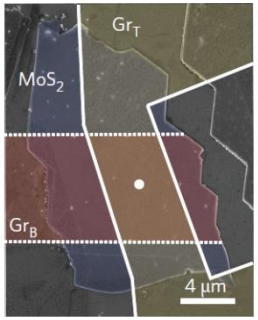


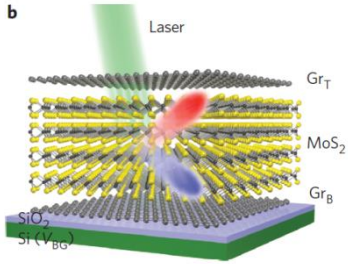


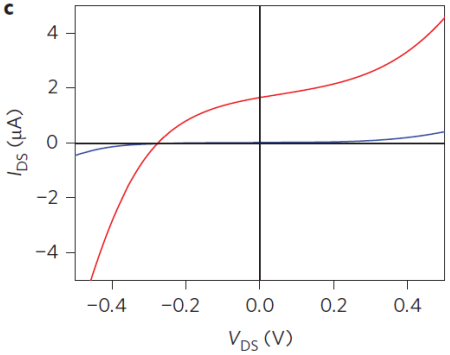


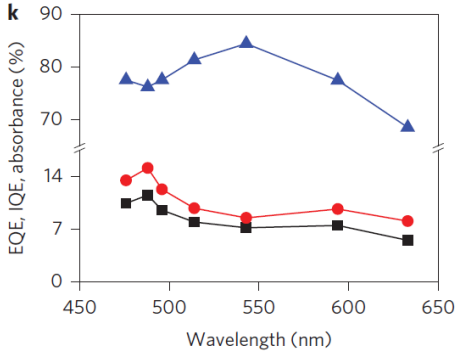
Graphene - MoS_2 – Graphene heterojunction photodiode

Yu. *et al.* Nature Nanotechnology, 8, 2013.







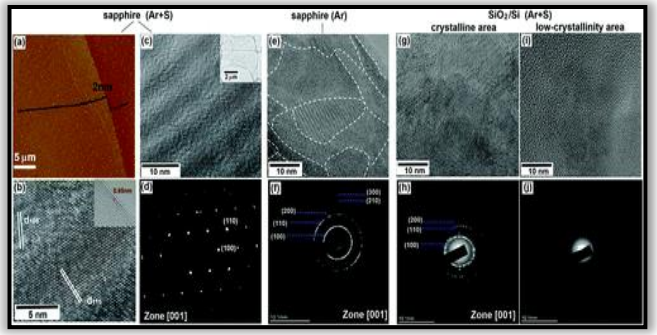


1. 2D Crystals
2. 2D Electronics
3. 2D Optoelectronics
4. **2D Engineering**

Large Area Growth: Homogeneous

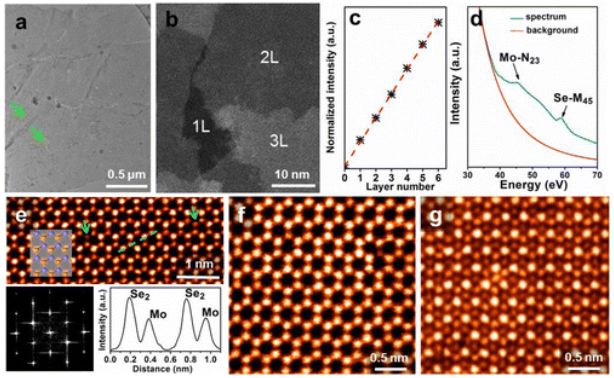
Physical Vapor Transport

Liu, *et al*.. Nano Letters, 12(3), 2012



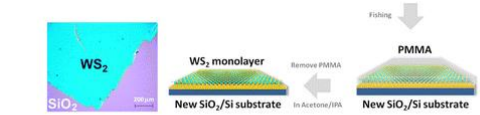
Chemical Vapor Deposition

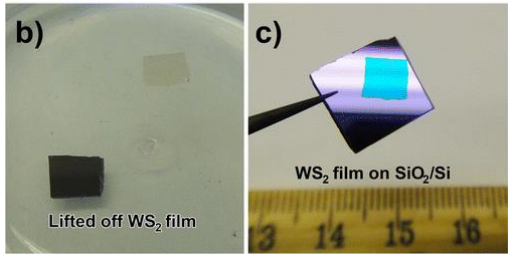
Lu, *et al*. Nano Letters, 14(5), 2014



Thermal Reduction

Elias, *et al*. ACS Nano, 7(6), 2013





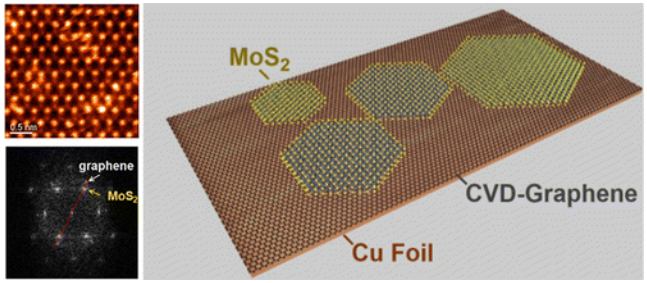
Atomic Layer Deposition

Molecular Beam Epitaxy

Large Area Growth: Heterogeneous

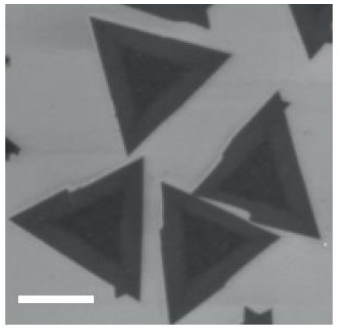
Vertical Heterostructure: MoS_2 on Graphene

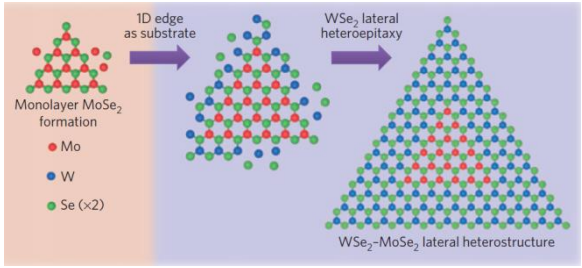
Shi, *et al* Nano Letters, 12(6), 2012



Lateral Heterostructure: $MoSe_2$ - WSe_2

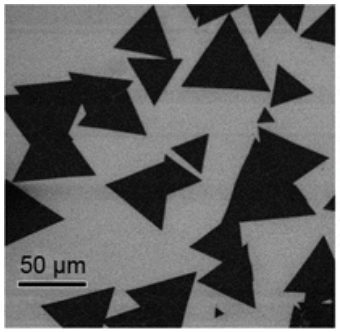
Huang. *et al*. Nature Material, 2014.

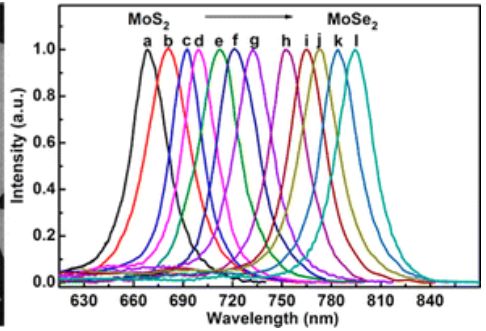




Stoichiometric Heterostructure: $MoS_{2x}Se_{2(1-x)}$

Shi, *et al* Journal of American Chemical Society, 136(10), 2014

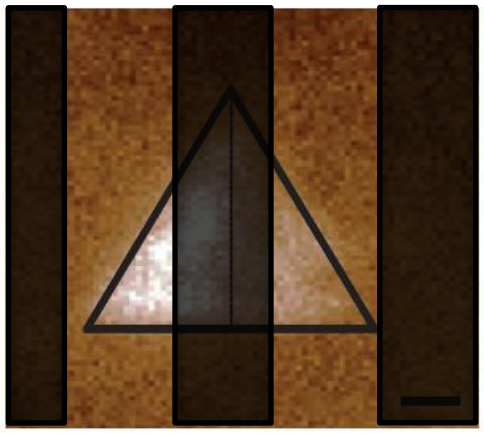




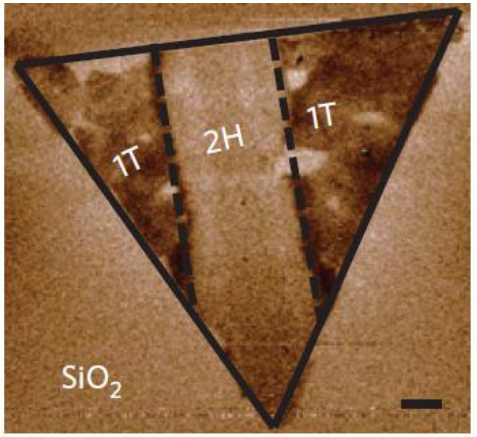
Phase Engineering

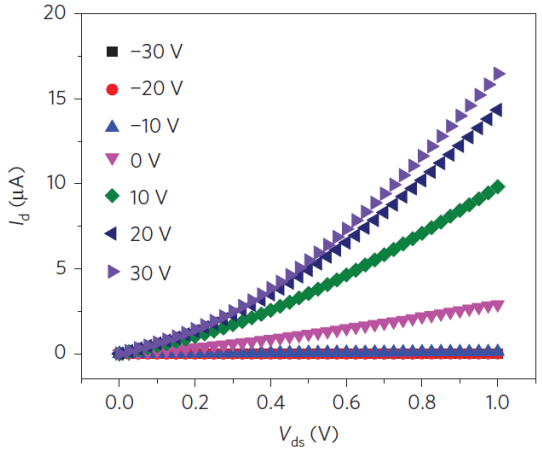
1T MoS_2 : Metallic
2H MoS_2 : Semiconducting

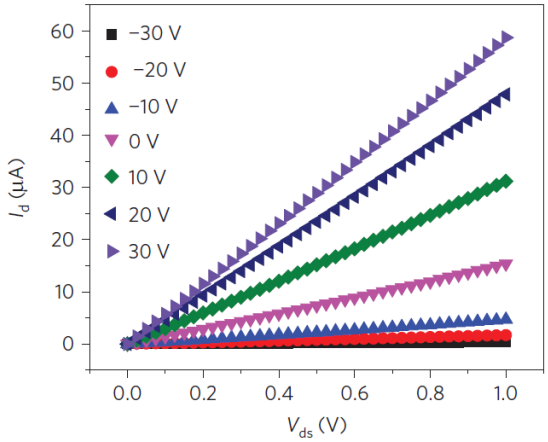
Kappera. *et al.* Nature Materials, 2014.



n-butyl lithium







Conclusion

2D Crystals show a lot of promises and a lot of scope for innovative scientific thinking

Acknowledgement

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Madan Dubey (ARL)
Abhijith Prakash (Purdue)

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Thank You