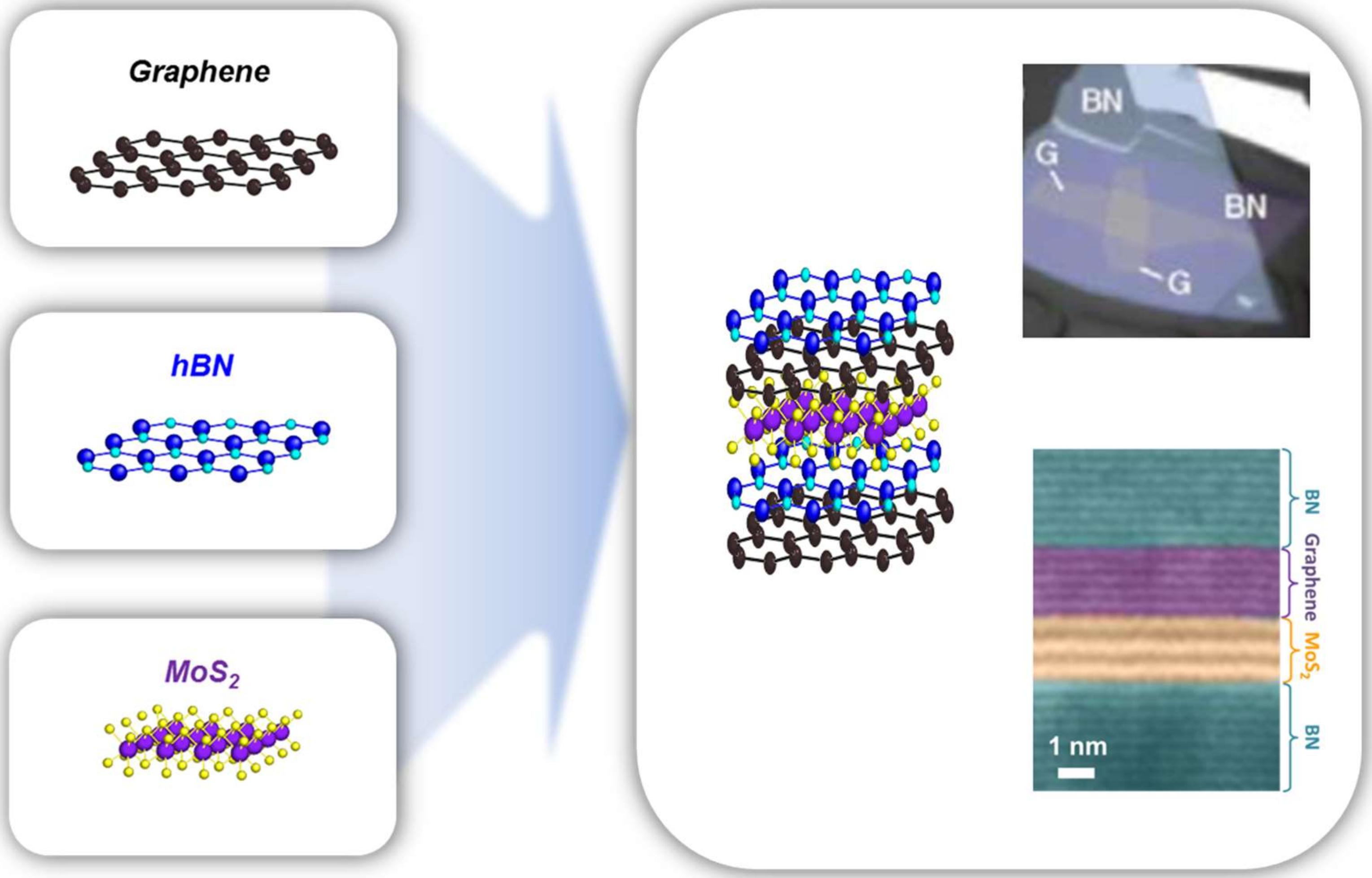
8. van der Waals Heterostructures

서울대학교
SEOUL NATIONAL UNIVERSITY

van der Waals Heterostructures

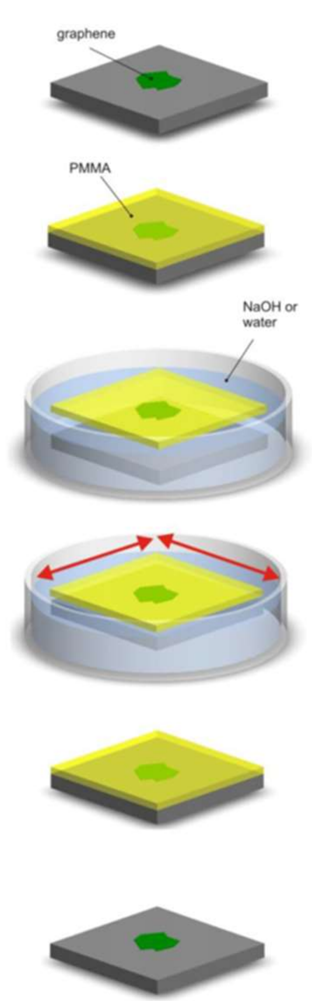


Ultrathin devices for flexible & transparent

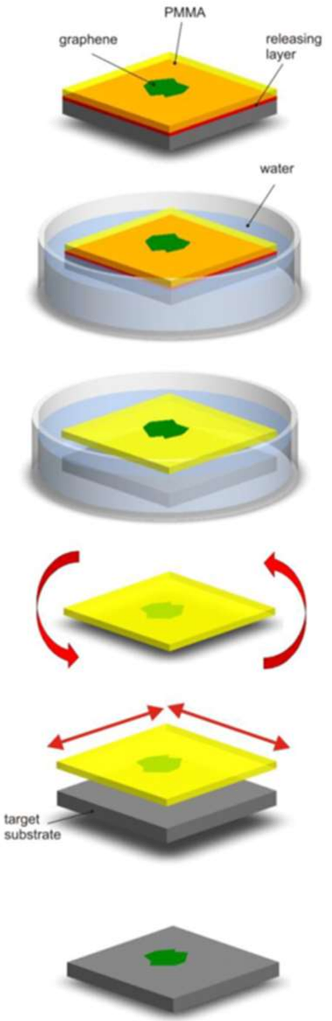
Ultrasharp heterointerface formed through vdW force

Stacking Technique for 2D Heterostructures

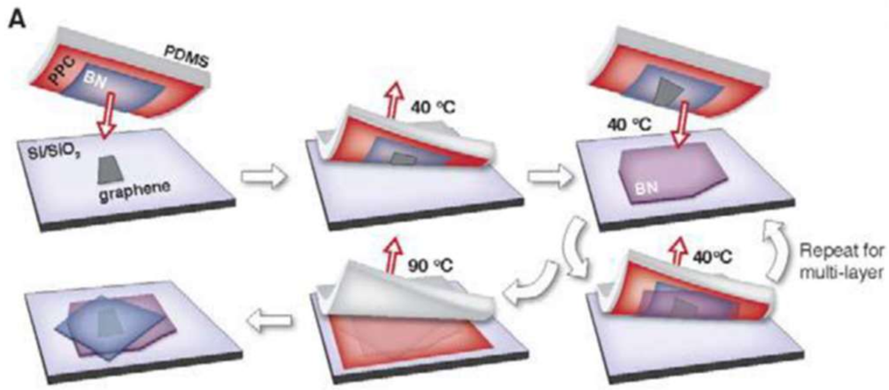
Wet Transfer



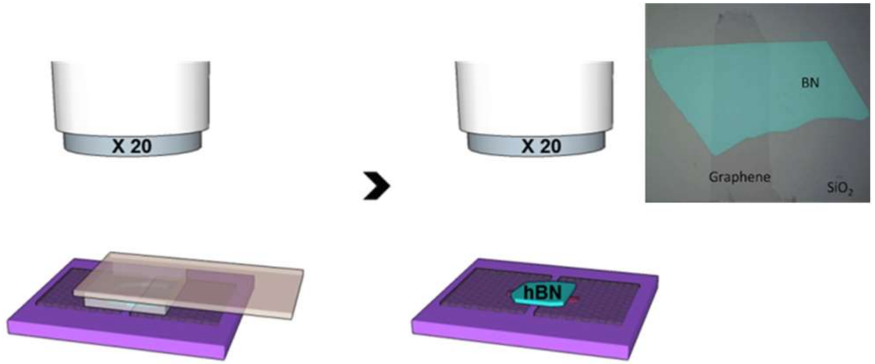
Dry Transfer



Pick-up Transfer



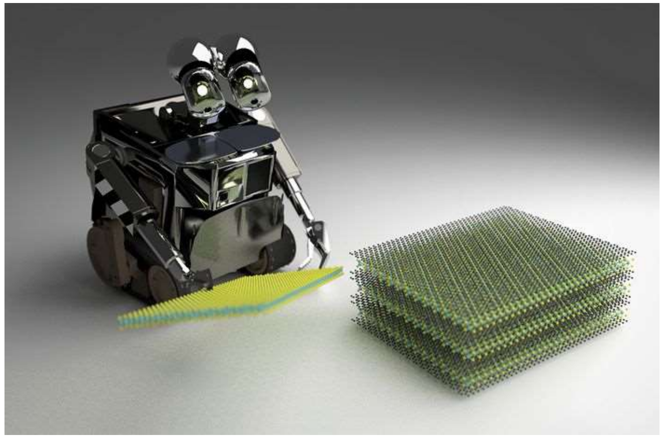
Elastomer Stamp Transfer



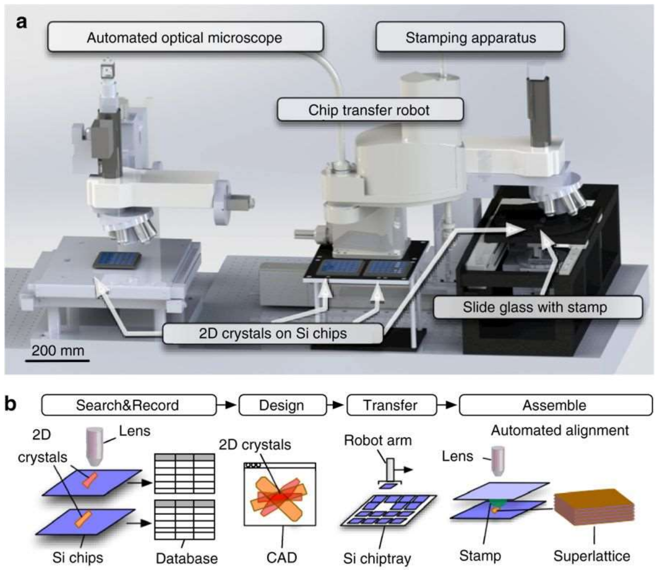
<u>G.H. Lee</u>, *J. Hone et al. ACS Nano (2013). APL Materials (2014)*

Stacking Technique for 2D Heterostructures

Robotic assembly of artificial nanomaterials



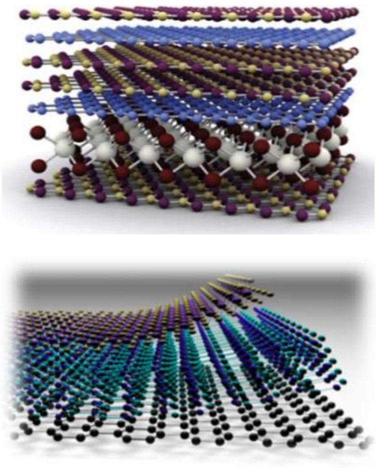
A. Castellanos-Gomez et al. Nat. Nanotechnol. (2018)

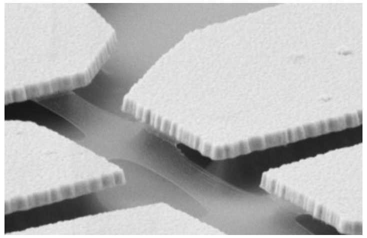


T. Machida et al. Nat. Commun. (2018)

van der Waals Heterostructures

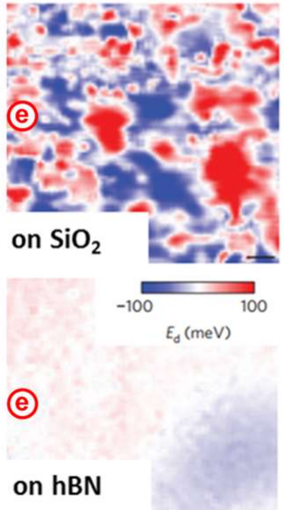
Effect of hBN on Electrical Transport of Graphene



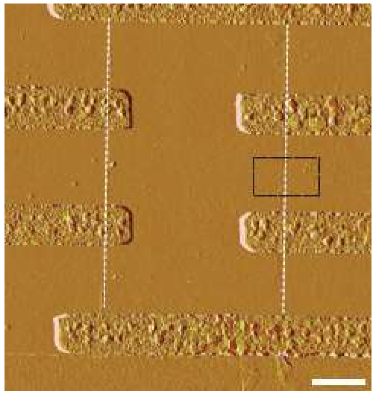


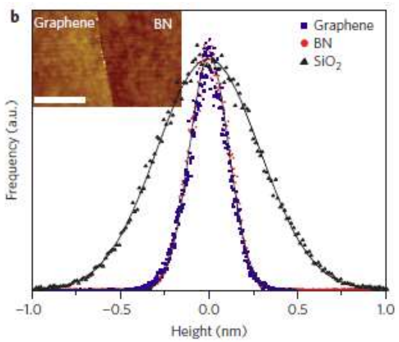
Graphene on SiO_2

Graphene on hBN



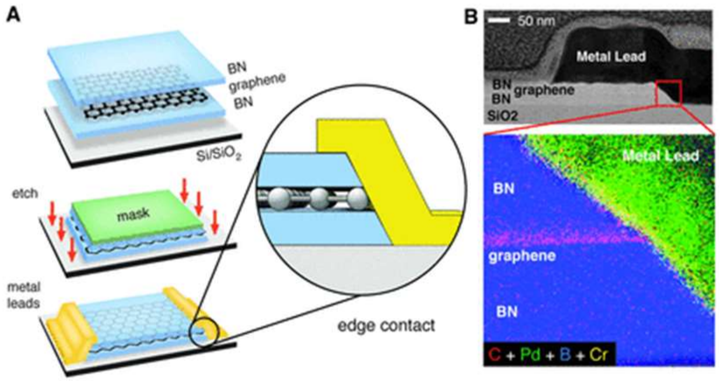
J. Xue et al. Nat. Mater. (2011)





40,000 $cm^2/V\cdot s$ at 300K

C. Dean et al. Nat. Nanotech. (2010)

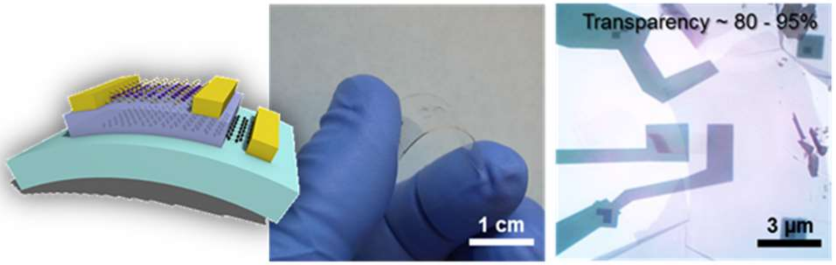


Room-temperature mobility > 140,000 cm^2/Vs

L. Wang et al. Science (2014)

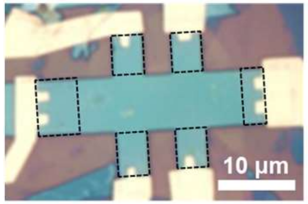
Advantages of van der Waals Heterostructures

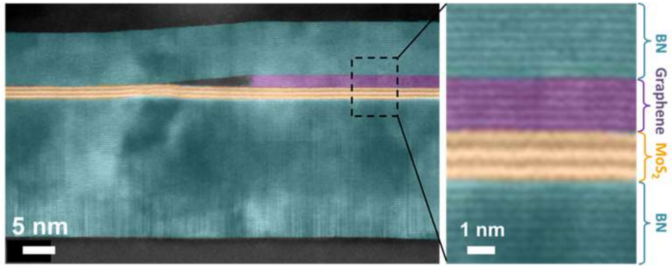
1. Ultrathin devices for flexible & transparent electronics

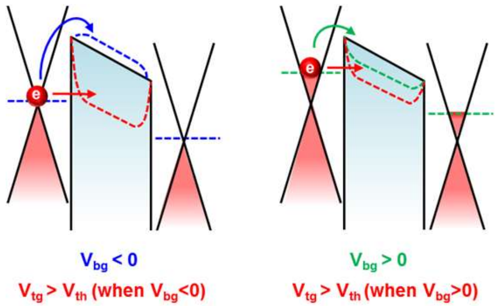


G.H. Lee et al. ACS Nano (2013)

2. Ultrasharp heterointerface

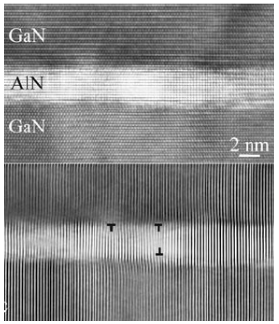




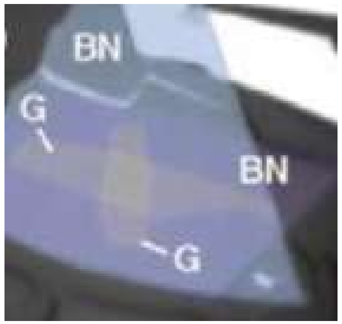


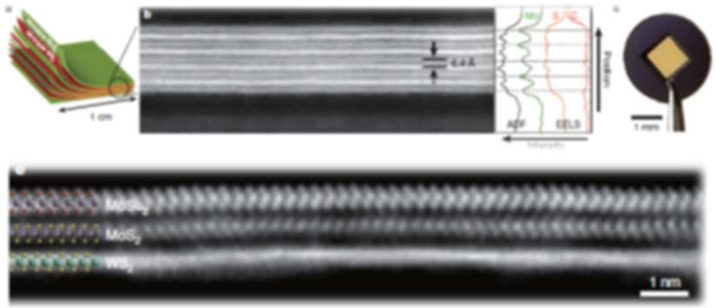
G.H. Lee et al. Nat. Nanotechno. (2015)

3. Arbitrary stacking



vs.

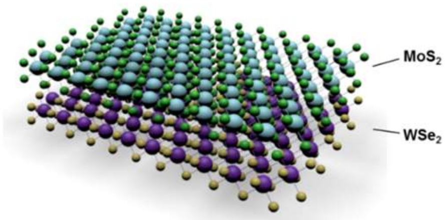




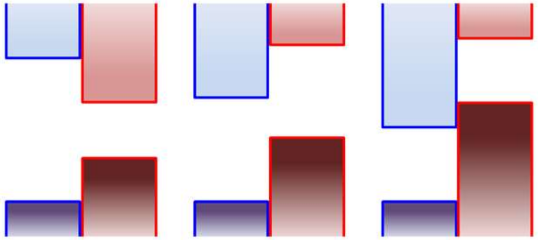
J. P et al. Nature (2017)

Advantages of van der Waals Heterostructures

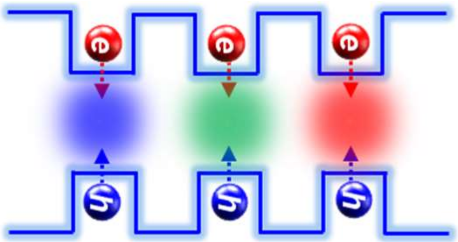
4. Band engineering



C.H. Lee, et al. Nature Nanot. (2015)

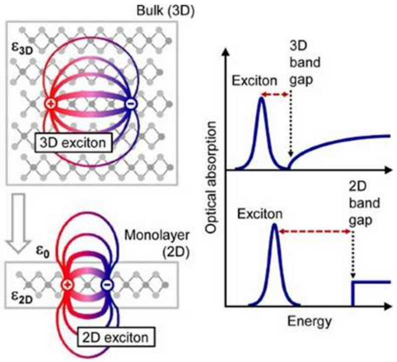


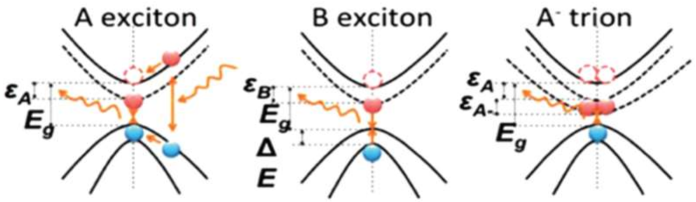
Type I   Type II   Type III



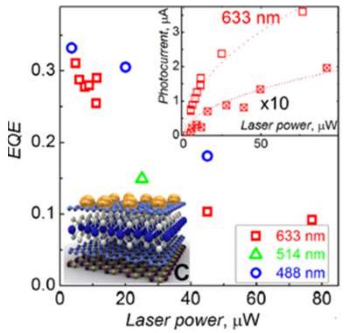
Quantum well structure

5. Strong light-matter interaction



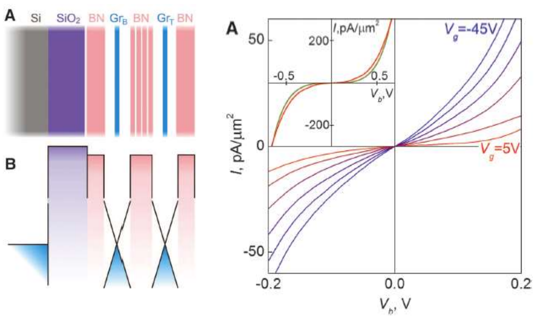


Phys. Rev. Lett. (2014)

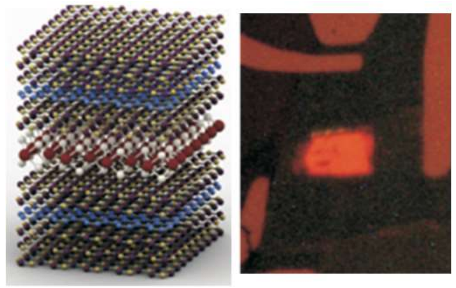


L. Britnell et al. Science (2013)

6. Vertical confinement in 2D space (quantum well structure)



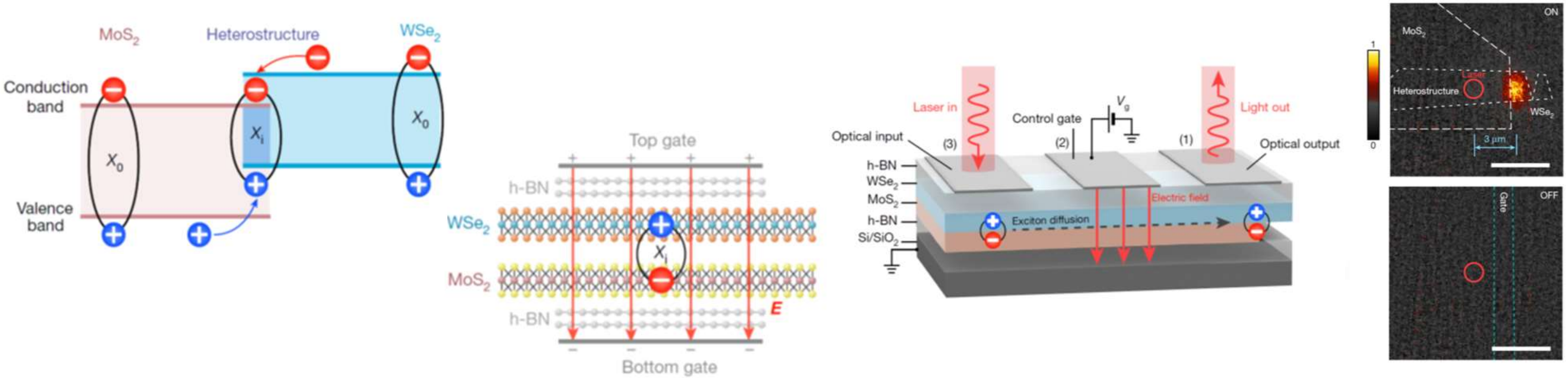
R. V. Gorvachev et al. Science (2012)



F. Withers et al., Nat. Mater. (2015)

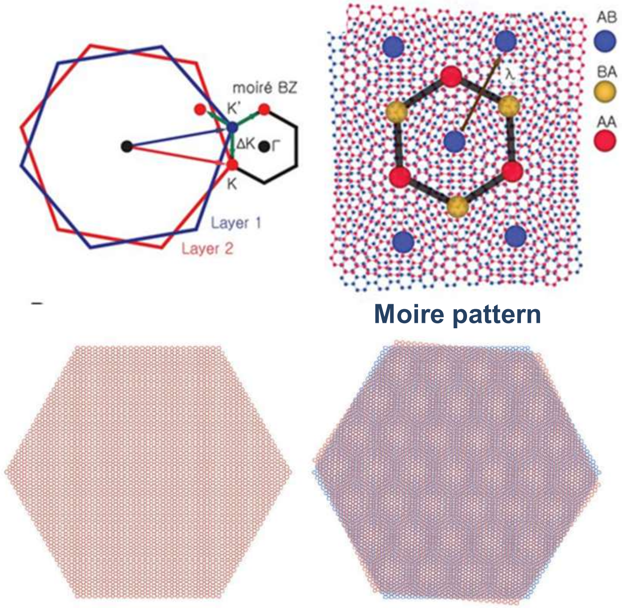
Advantages of van der Waals Heterostructures

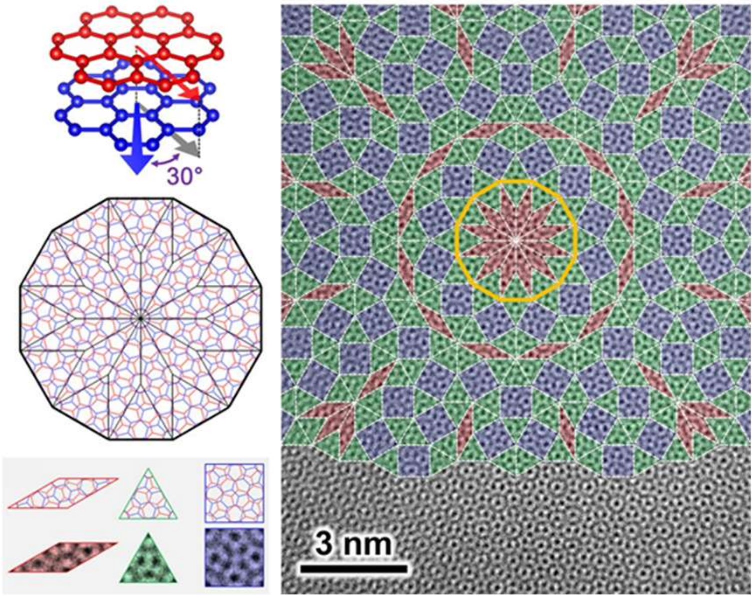
7. Interlayer interaction (interlayer exciton)



A. Kis et al. Nature (2018)

8. Periodic potential modulation / Novel symmetry material systems (Quasicrystal)



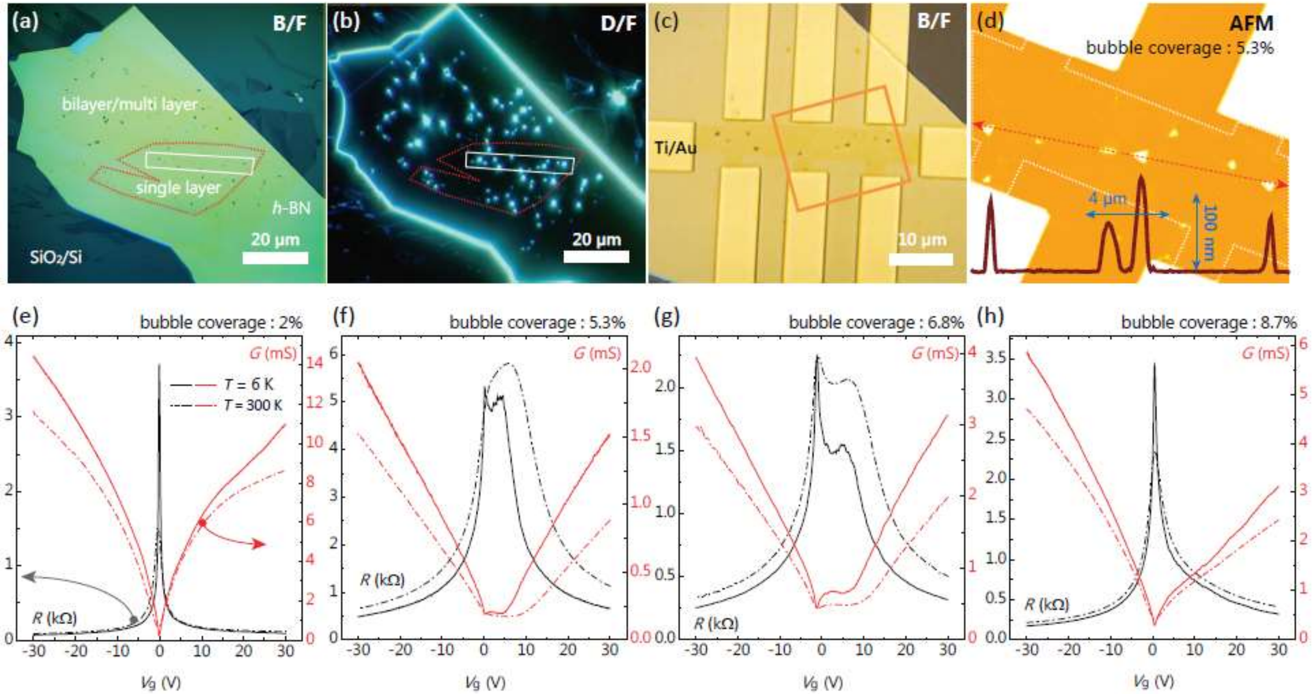


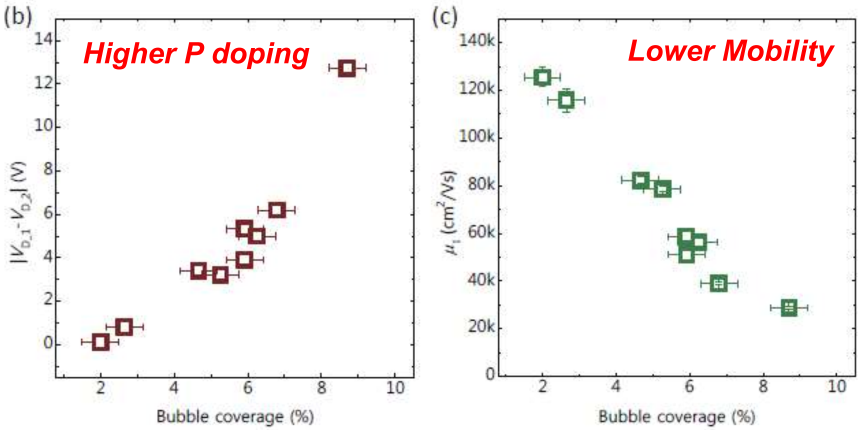
L. A. Ponomarenko et al. Science (2019)

Y.W. Son et al. Science (2018)

Issue in Stacking

Formation of bubbles



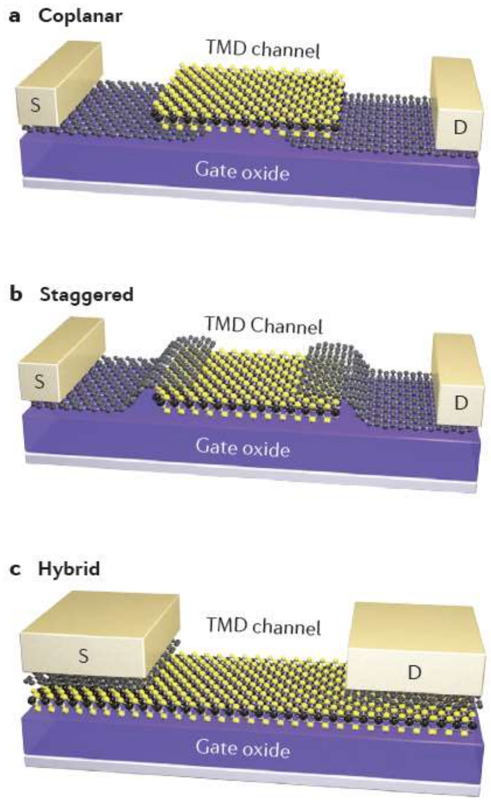


- ❑ Contaminant inside graphene bubbles are mostly hydro-carbon. And hydrocarbons behave like p-type dopants
- ❑ Low mobility attribute to scattering effects from long and short range disorders induced by bubble graphene

S. Jeong et al. Nanoscale (2017)

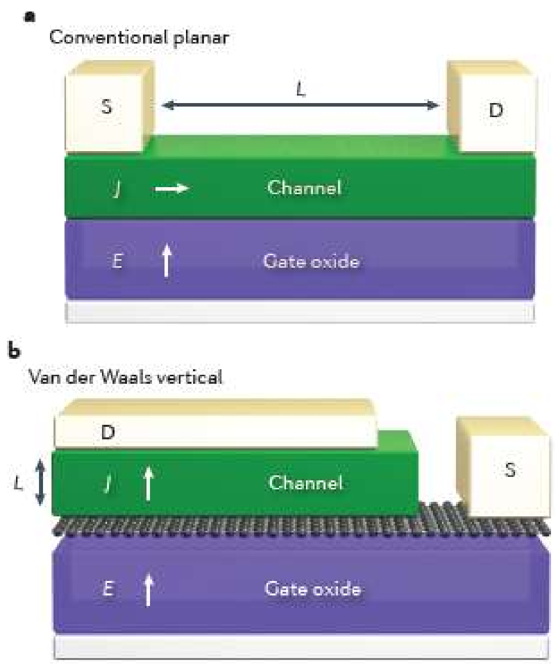
Various Types of vdW Heterostructure Devices

1. Vertical contact



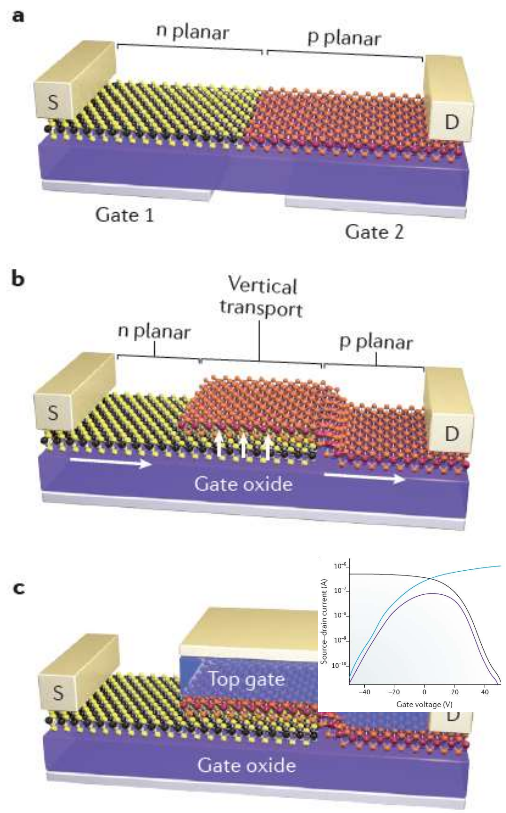
- Versatile work-function tunable contact
- Less contamination
- Non-damaging interface between metal and 2D channel

2. Vertical transistors



- High-speed, low-power and flexible
- Tunneling vertical transistors

3. Vertical diodes

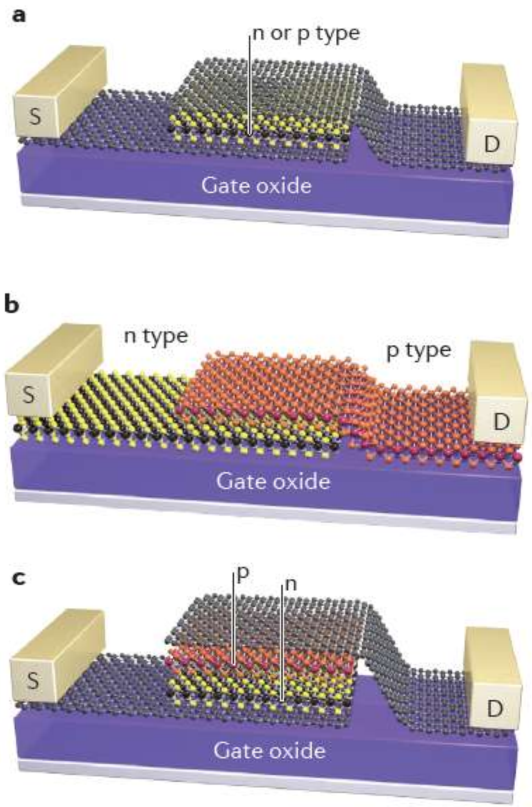


- Unique E-field controlled p-n diodes
- Anti-ambipolar behavior

X. Duan et al. Nat Rev. Mate. (2016)

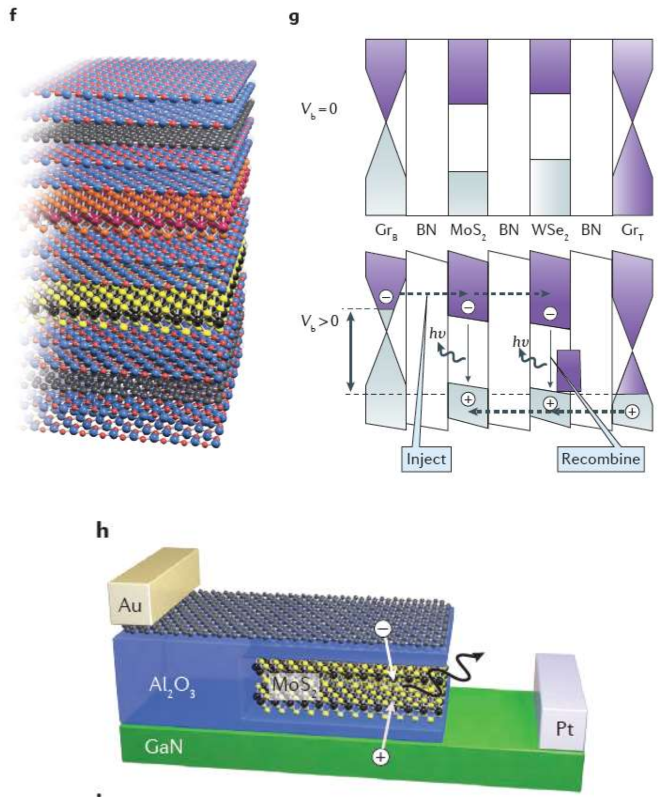
Various Types of vdW Heterostructure Devices

4. Light harvesters and detectors



- Gate-dependent photoresponse (tunable carrier density)
- Dynamic modulation of diode characteristics
- Rapid extraction of exciton

5. Light emitting devices

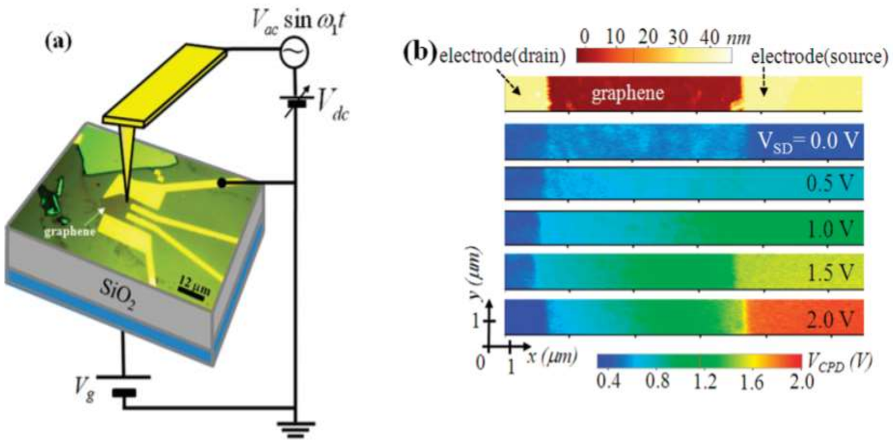


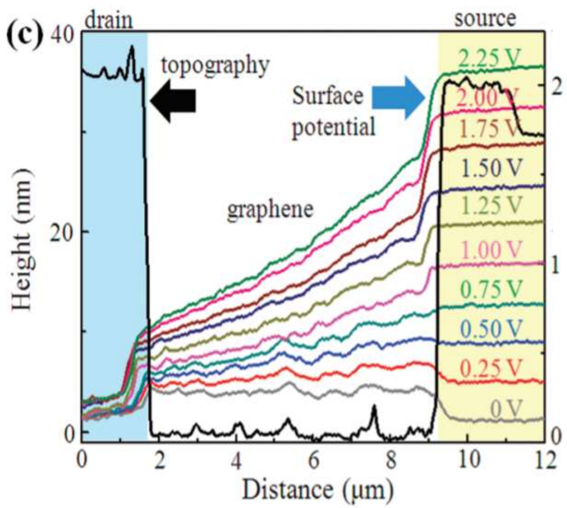
- Vertical device structure
- Vertical current injection
- Quantum well structure

X. Duan et al. Nat Rev. Mate. (2016)

Heterostructure of Graphene/hBN

Tunable Schottky barrier in graphene

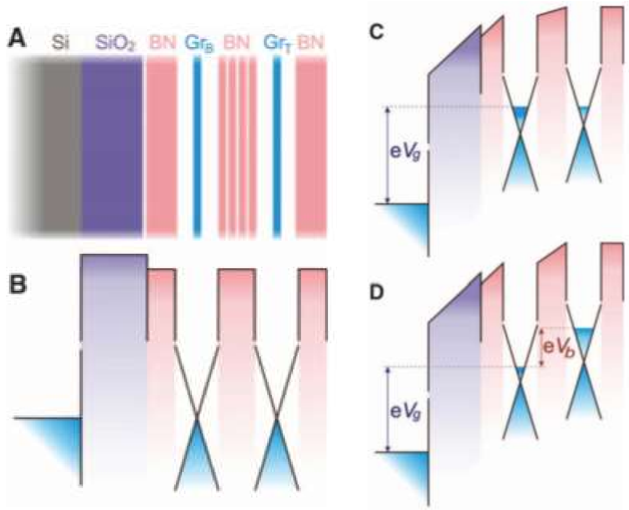


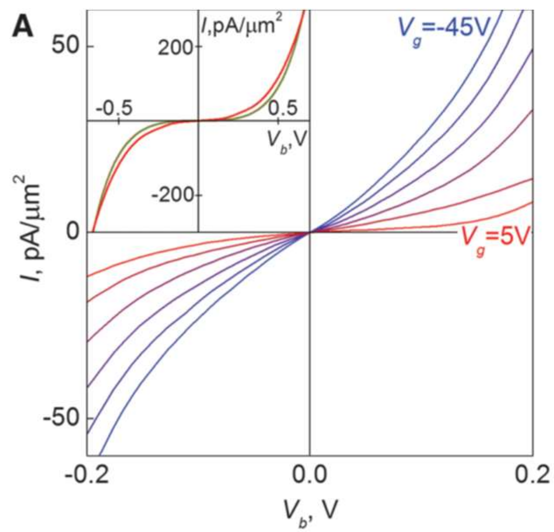


Tuning the graphene work function by electric field

P. Kim et al. Nano. Lett. (2009)

Field-effect tunneling transistor

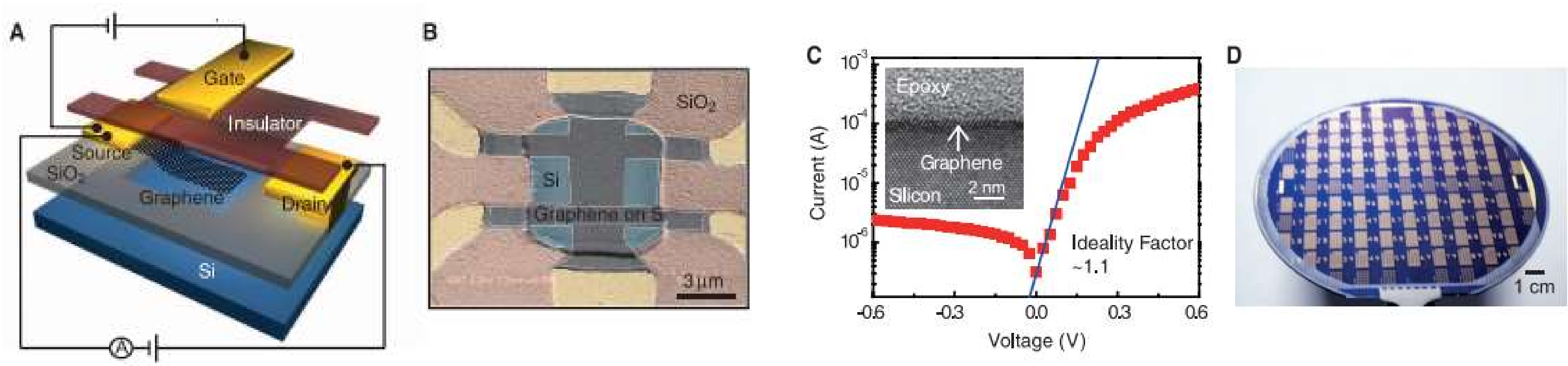




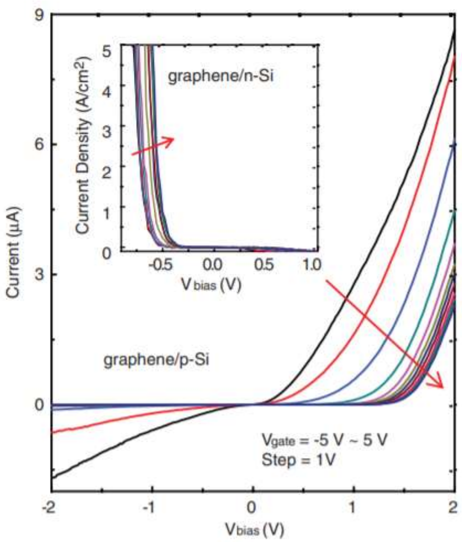
L. A. Ponomarenko et al. Science (2012)

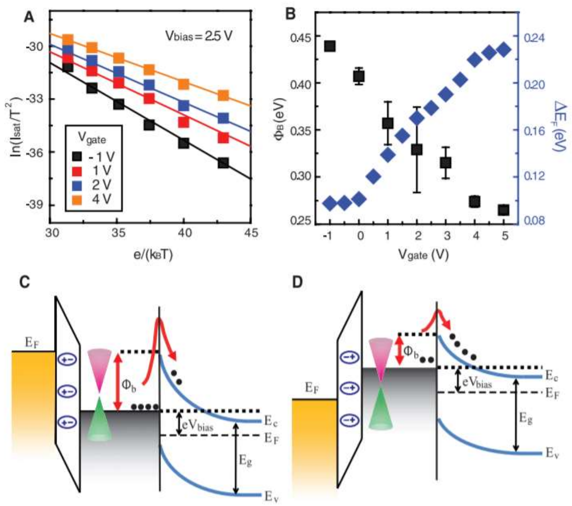
Barristor

Graphene barristor



Tunable Schottky barrier

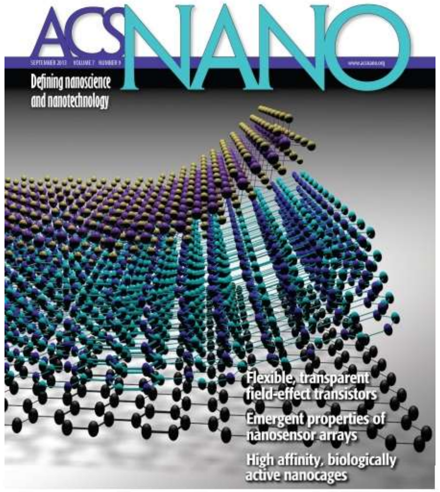


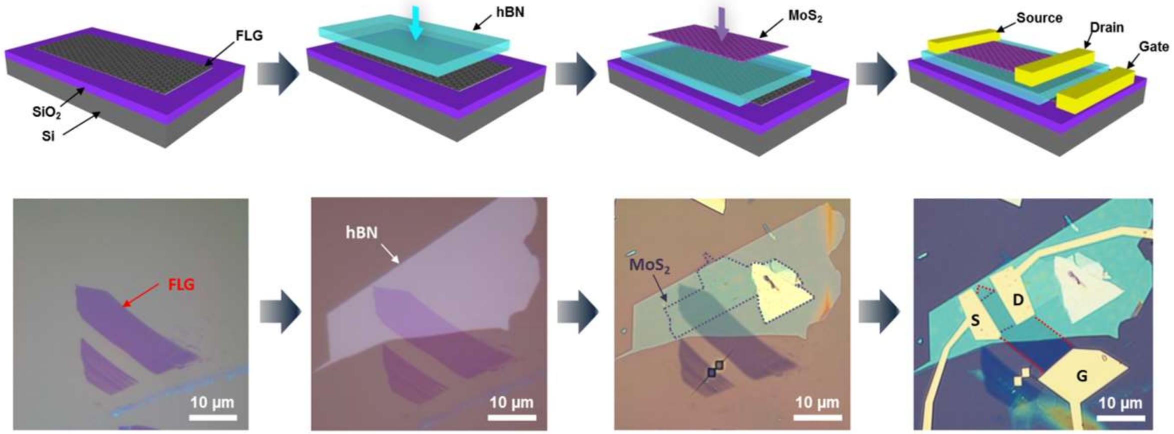


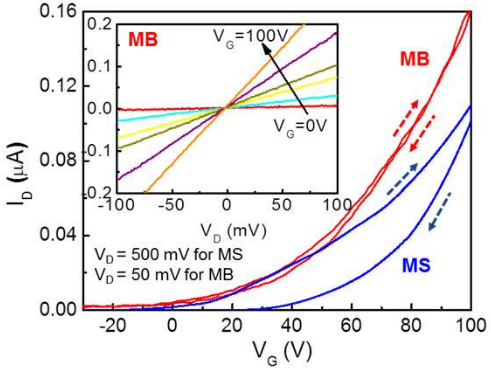
- ❑ Barristor = Barrier + transistor
- ❑ Barristor is a device that controls the on-off ratio by changing the Schottky barrier of graphene and silicon via the applied gate voltage.

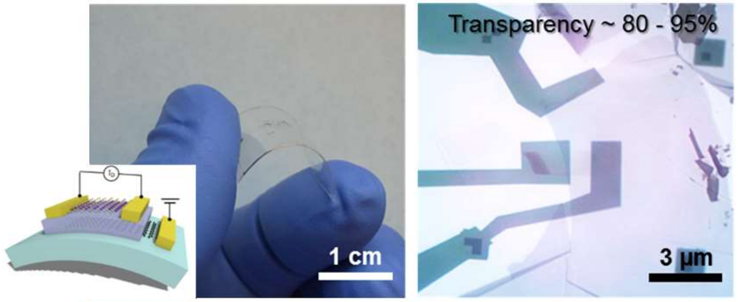
H. Yang et al. Science (2012)

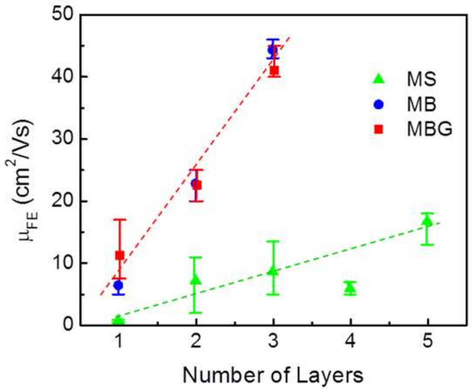
Flexible and Transparent Heterostructure Devices

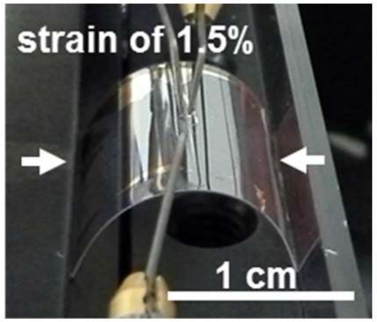


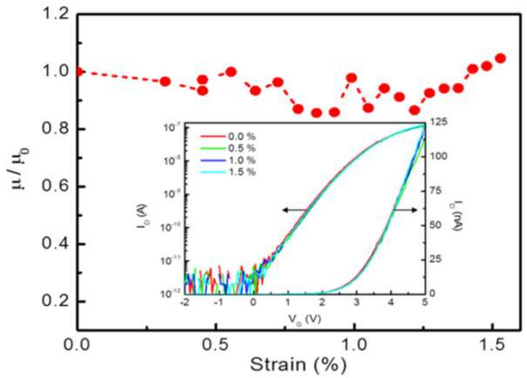




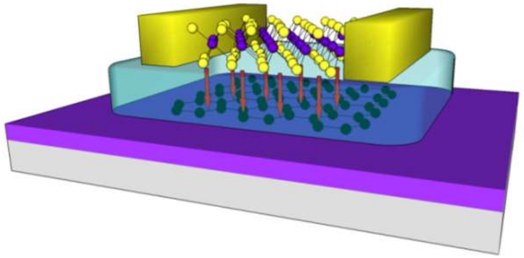


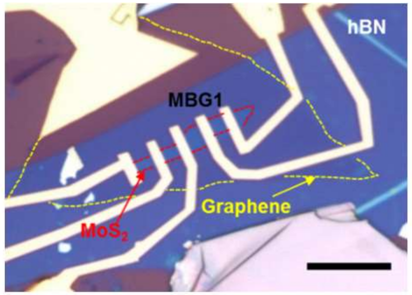


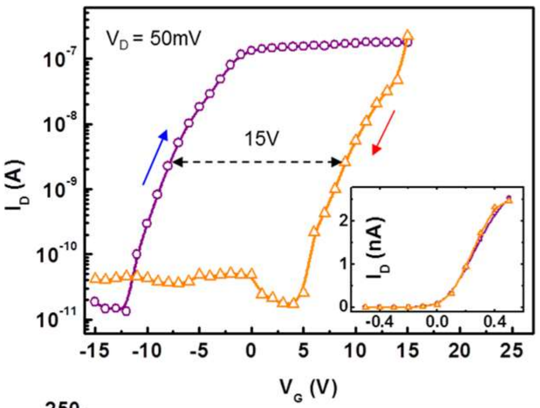


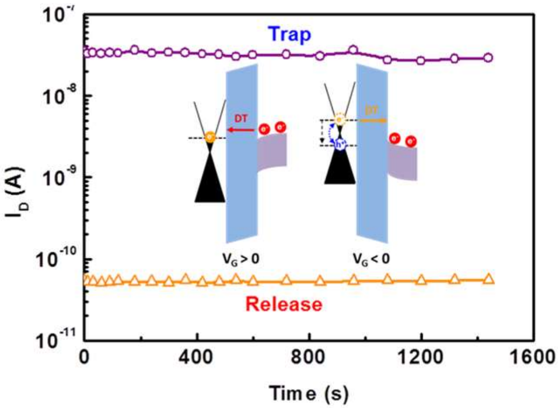


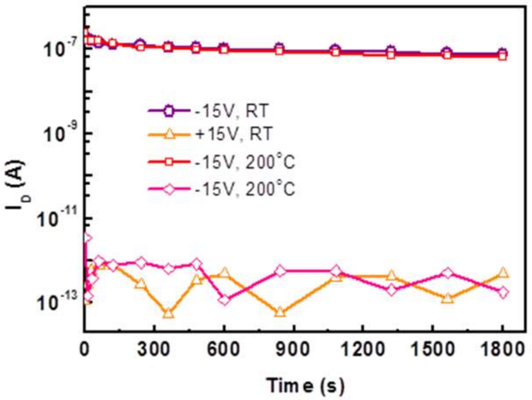
ACS Nano *7, 7931–7936 (2013)*

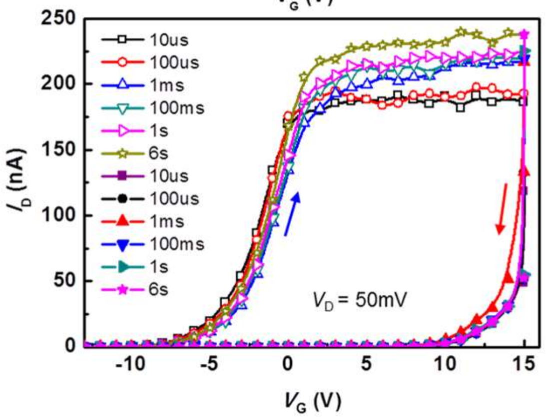


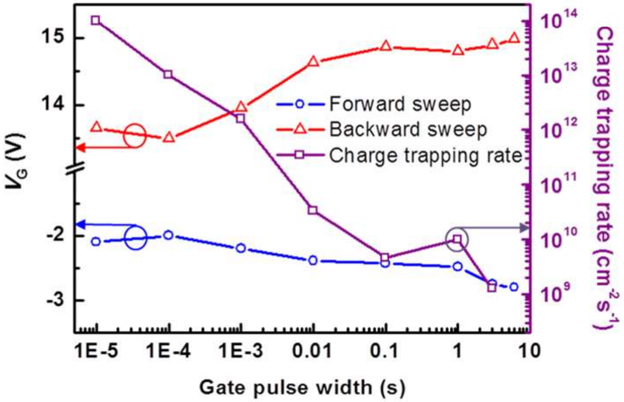












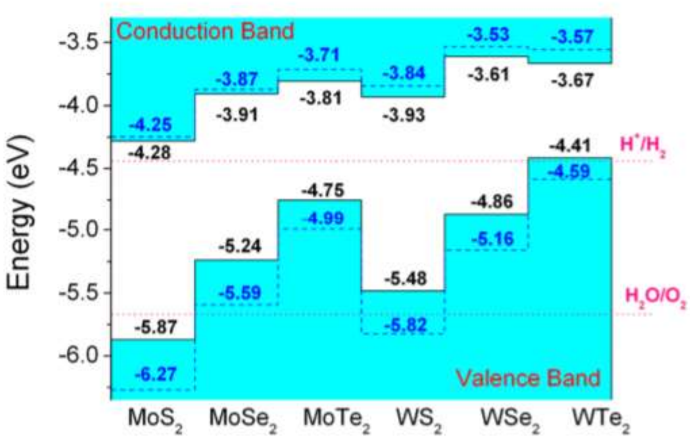
- ***High stability***
- ***High carrier mobility***
- ***high on/off ratio***
- ***Large memory window***
- ***Low operating voltage***
- ***Small dimension***
- ***Transparency and flexibility***

Nature Communications *4, 1624-1628 (2013)*

Heterostructure of TMD/TMD

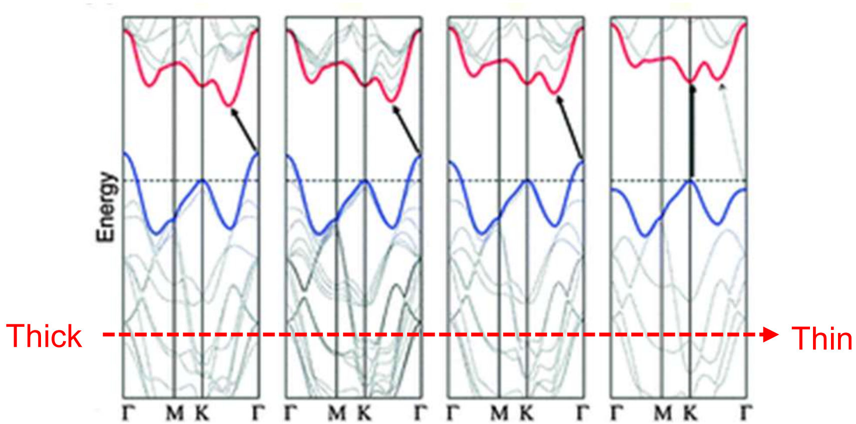
Band engineering

Various band structure of TMD



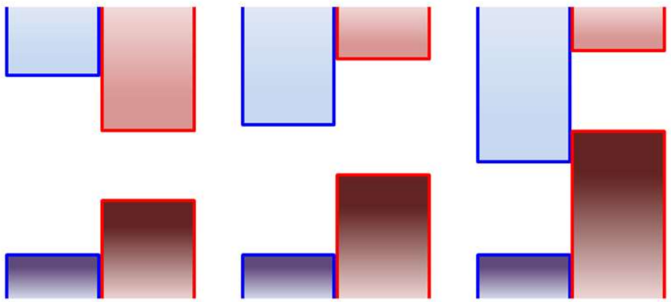
J. Wu et al. Appl. Phys. Lett (2013)

Band structure dependent on TMD thickness



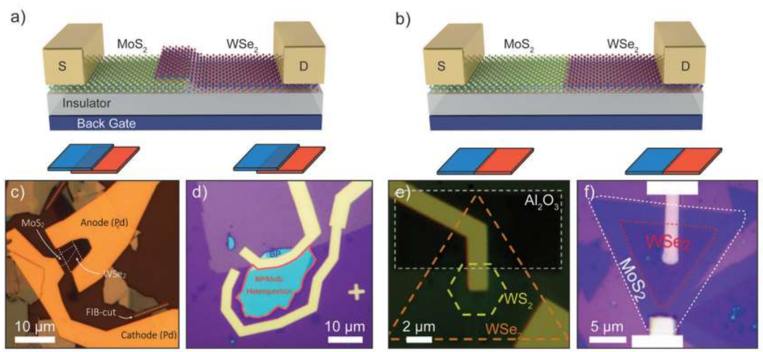
F. Wang et al. Nano Lett. (2010)

Type of band alignment



Type I (Stradding gap)
Type II (Staggered gap)
Type III (Broken gap)

Type of heterojunction

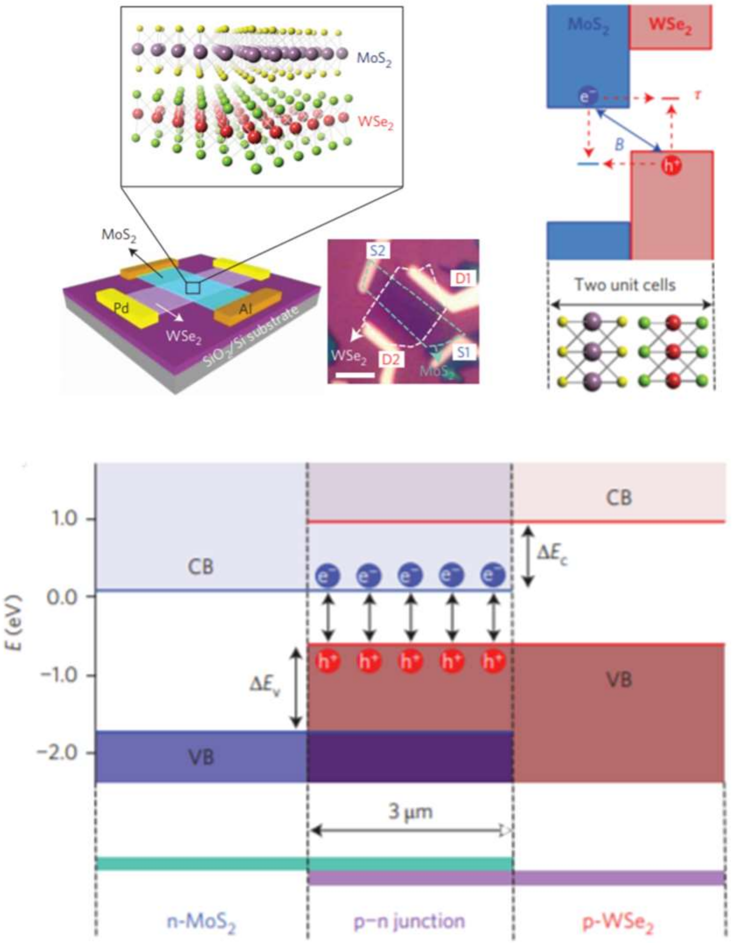


Vertical Junction
Lateral Junction

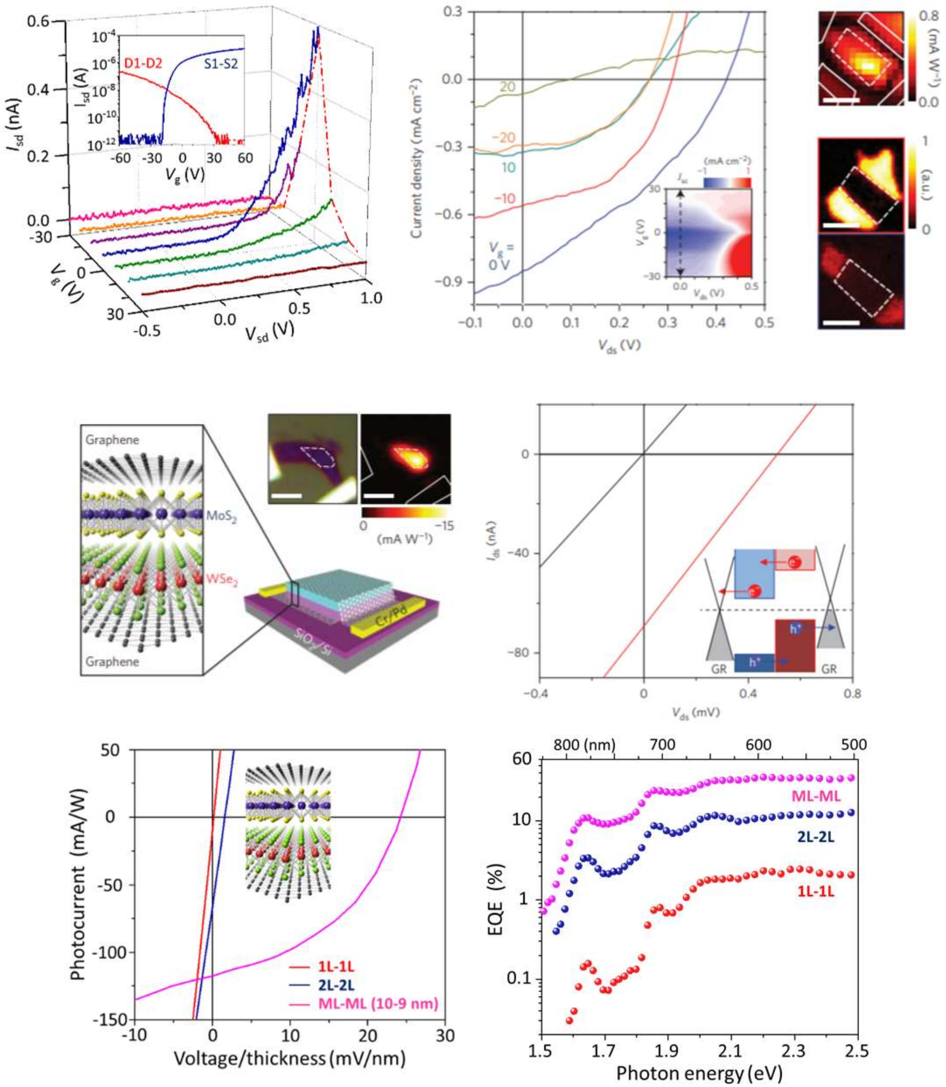
H. S. J. van der Zant et al Chem. Soc. Rev. (2018)

Heterostructure of TMD/TMD

Atomically PN junction



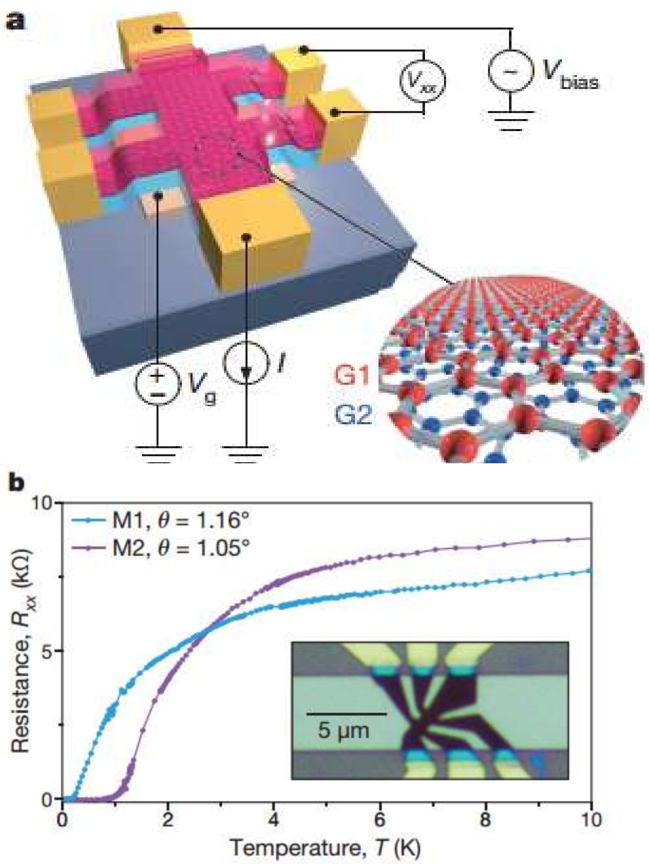
PN Junction device



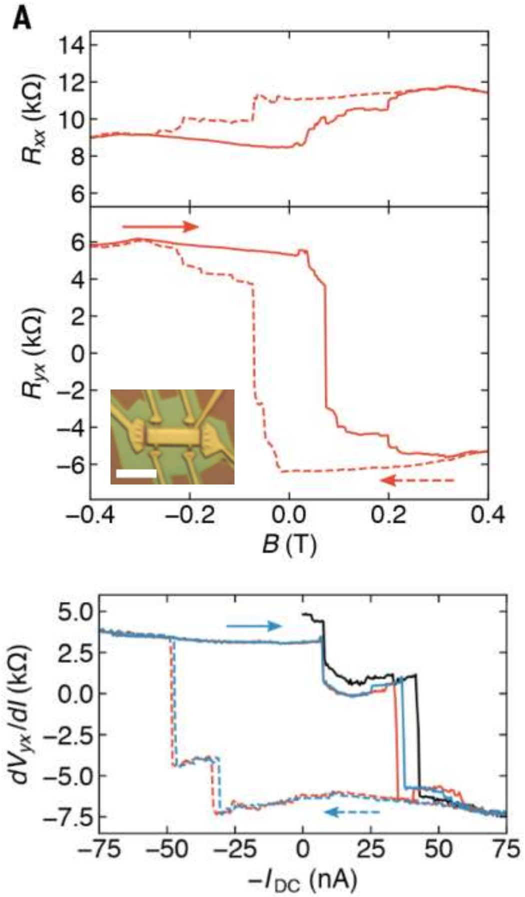
C.H. Lee, G.H. Lee et al. Nat. Nanotechno. (2014)

Heterostructure of Graphene/Graphene

Twisted bilayer graphene

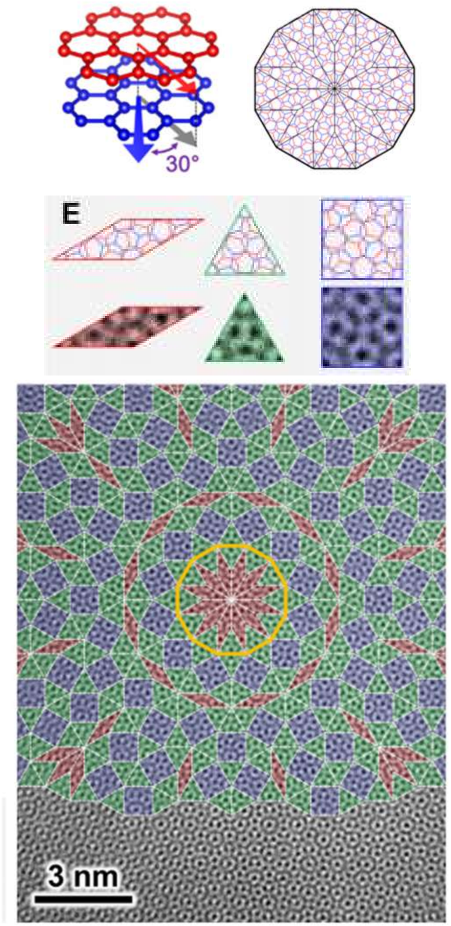


Superconductivity



Ferromagnetism

Graphene quasi-crystal

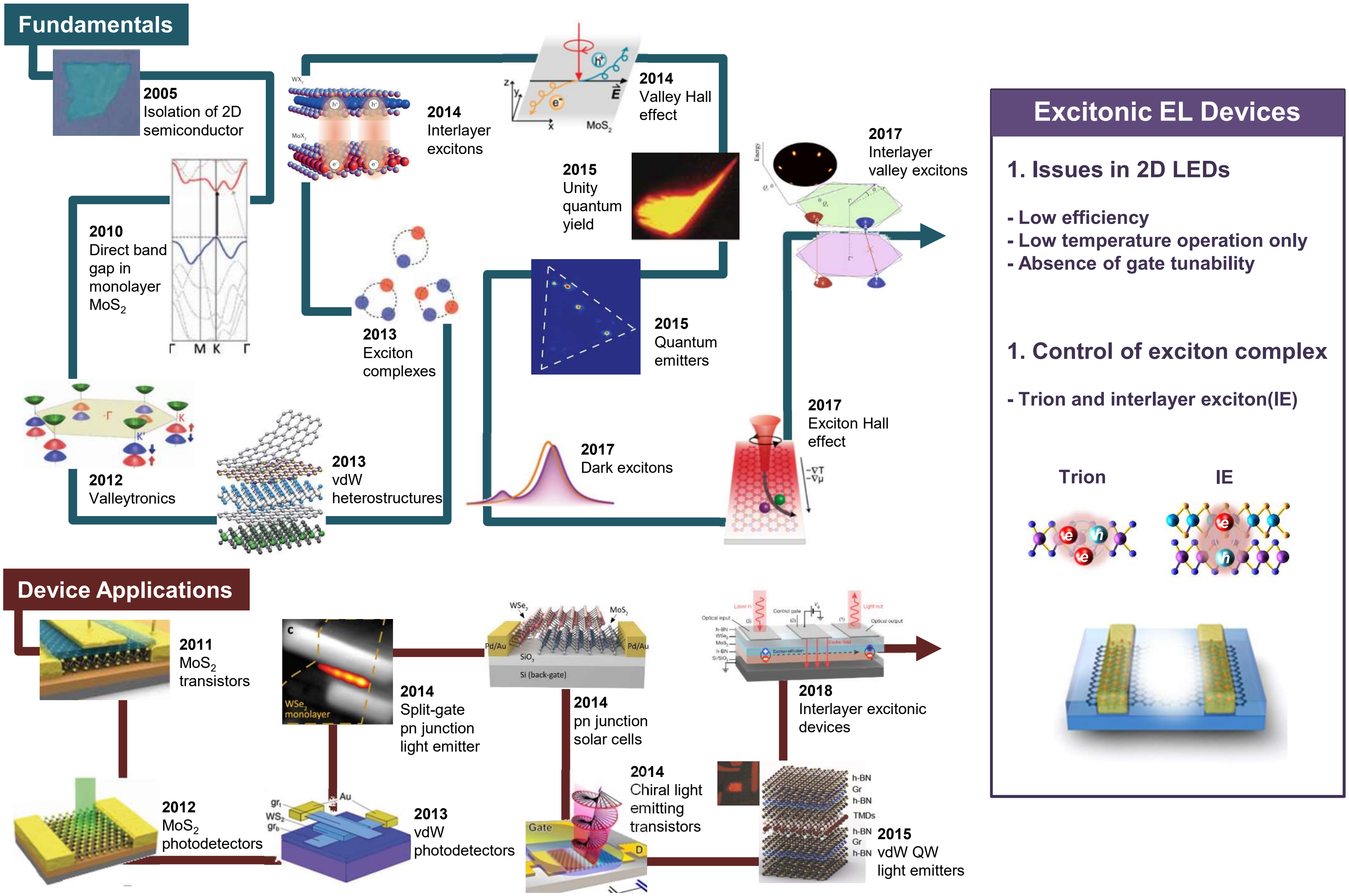


P Jarillo-Herrero et al. Nature. (2018)

L. A. Ponomarenko et al. Science (2019)

Y.W. Son et al. Science (2018)

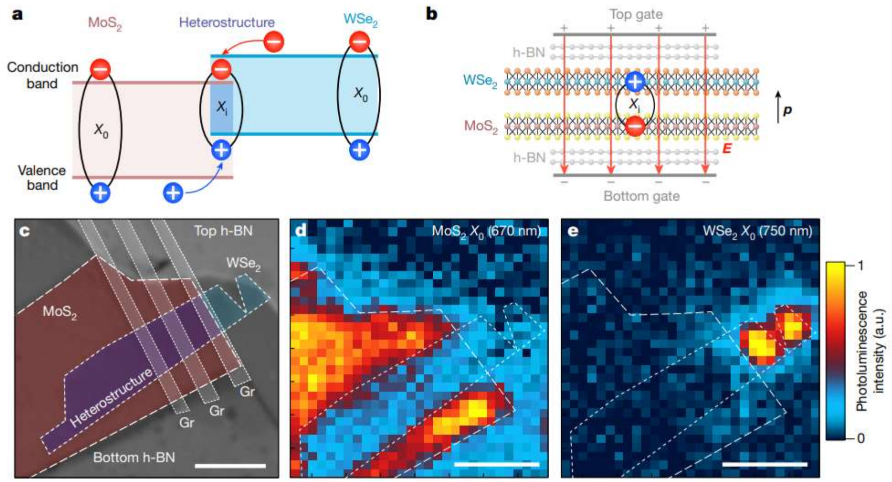
Excitons and Excitonic Devices



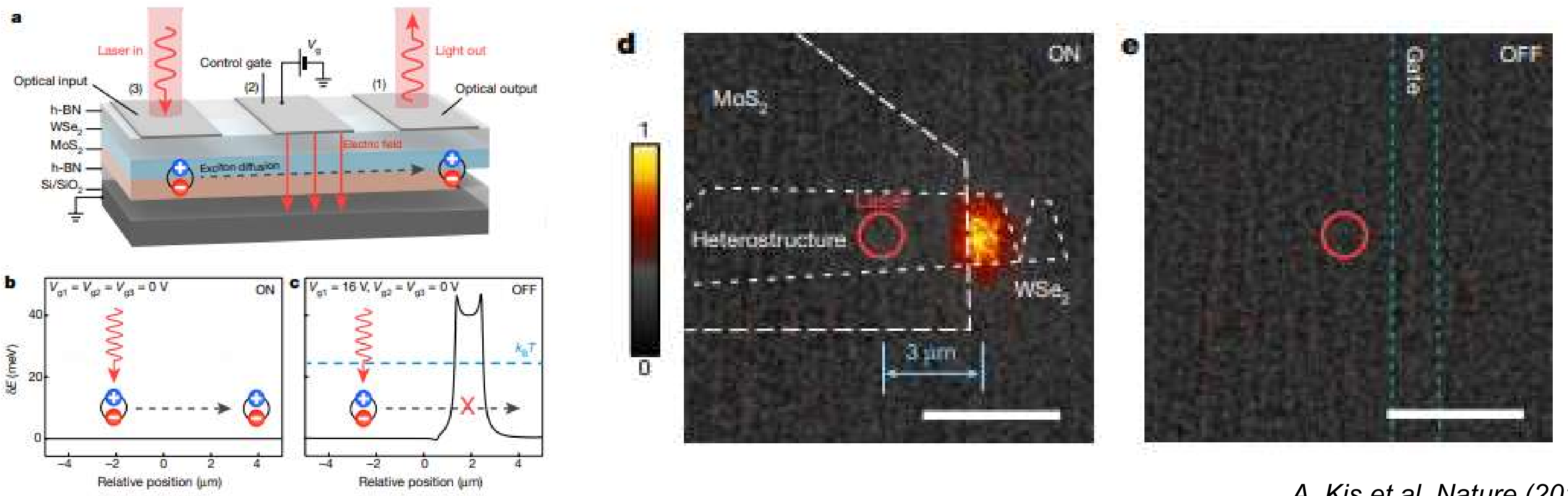
Interlayer exciton

Interlayer exciton	
Charge	Neutral Charge
Transport mechanism	Diffusion
Control parameter	Exciton density

Interlayer excitons in the vdW heterostructure



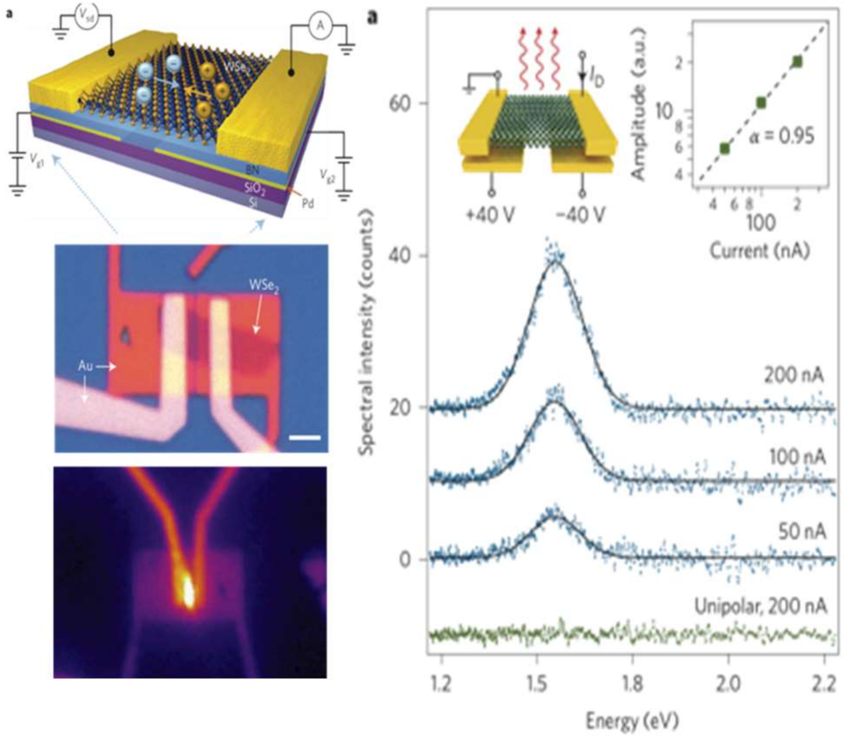
Excitonic transistor operation by electric field



A. Kis et al. Nature (2018)

Light Emitting Devices

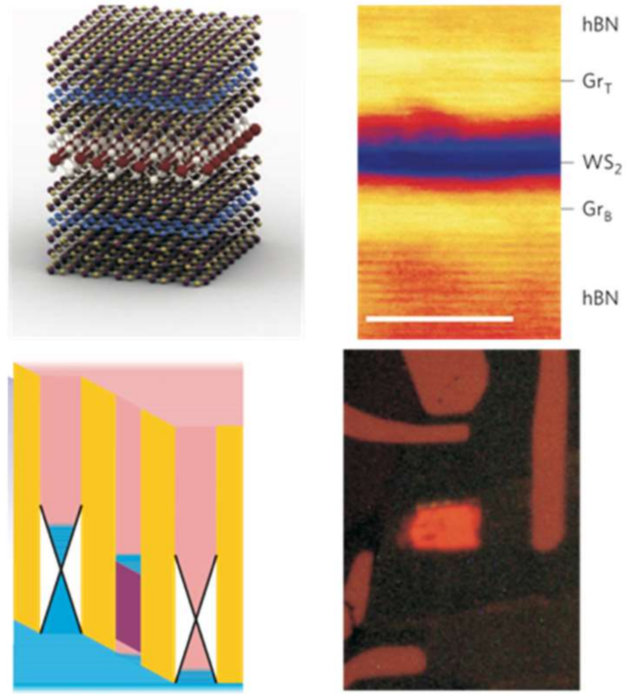
TMDC Light Emitter



- Atomically thin LEDs (pn junction by split gate) from WSe_2, MoS_2, WS_2
- EQE: ~ 0.2 % (limited by contact and thickness)

A. Pospischil et al. Nature Nanotech. 9, 257 (2015)
B. W. H. Baugher et al. Nature Nanotech. 9, 262 (2015)
J. S. Ross et al. Nature Nanotech. 9, 268 (2015)

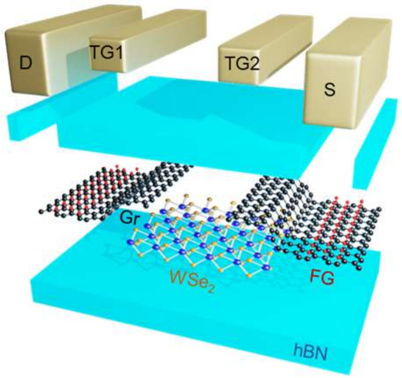
van der Waals Light Emitter

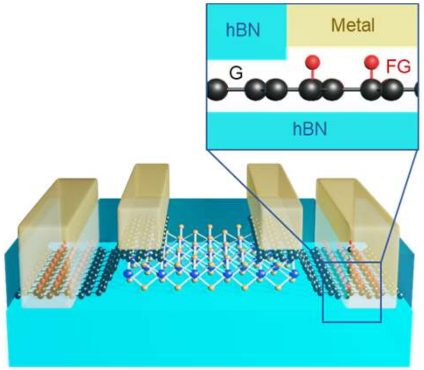


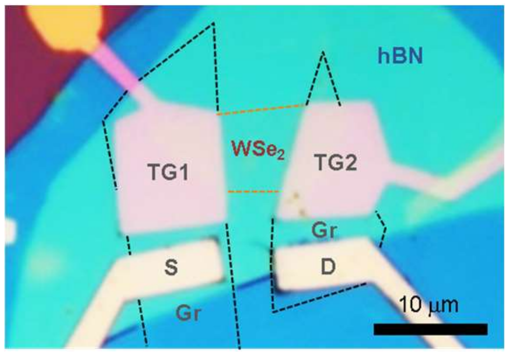
- Atomically thin quantum well with van der Waals heterostructure
- Efficient electron and hole injection by tunneling through hBN
- Flexible and transparent light emission devices
- EQE: 2.0 ~ 8.4 % (at low T)

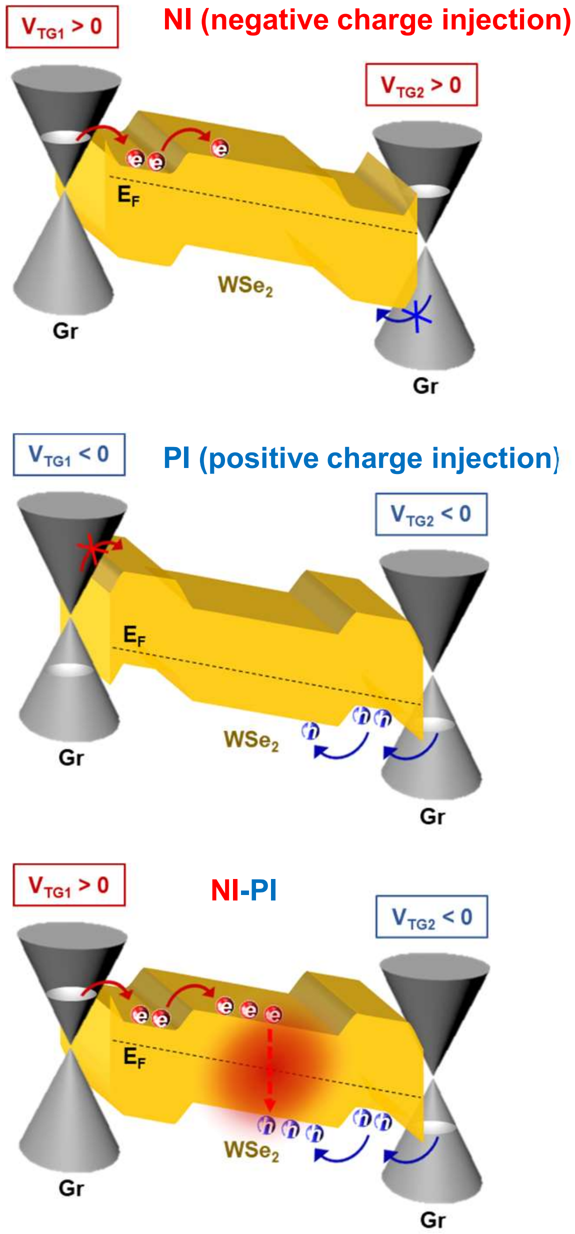
F. Withers et al. Nature Materials 14, 301 (2015)

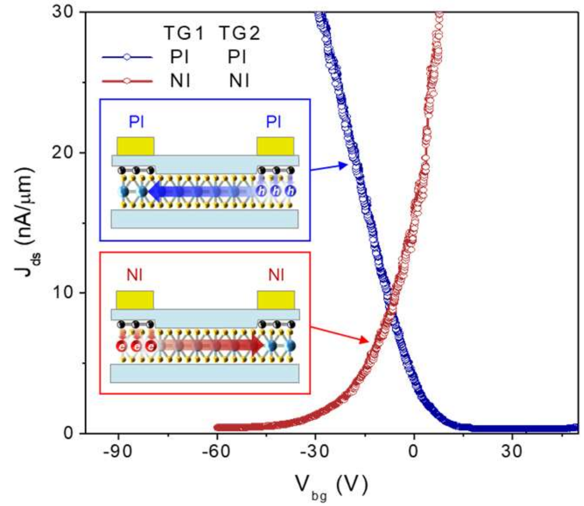
Monolayer WSe_2 LETs with Tunable Schottky Barrier

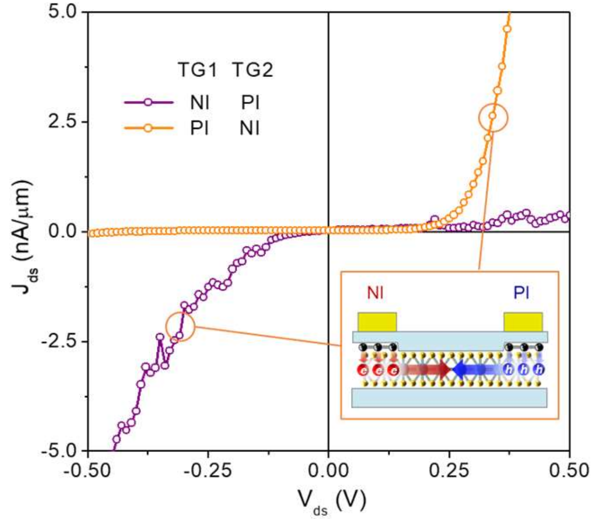






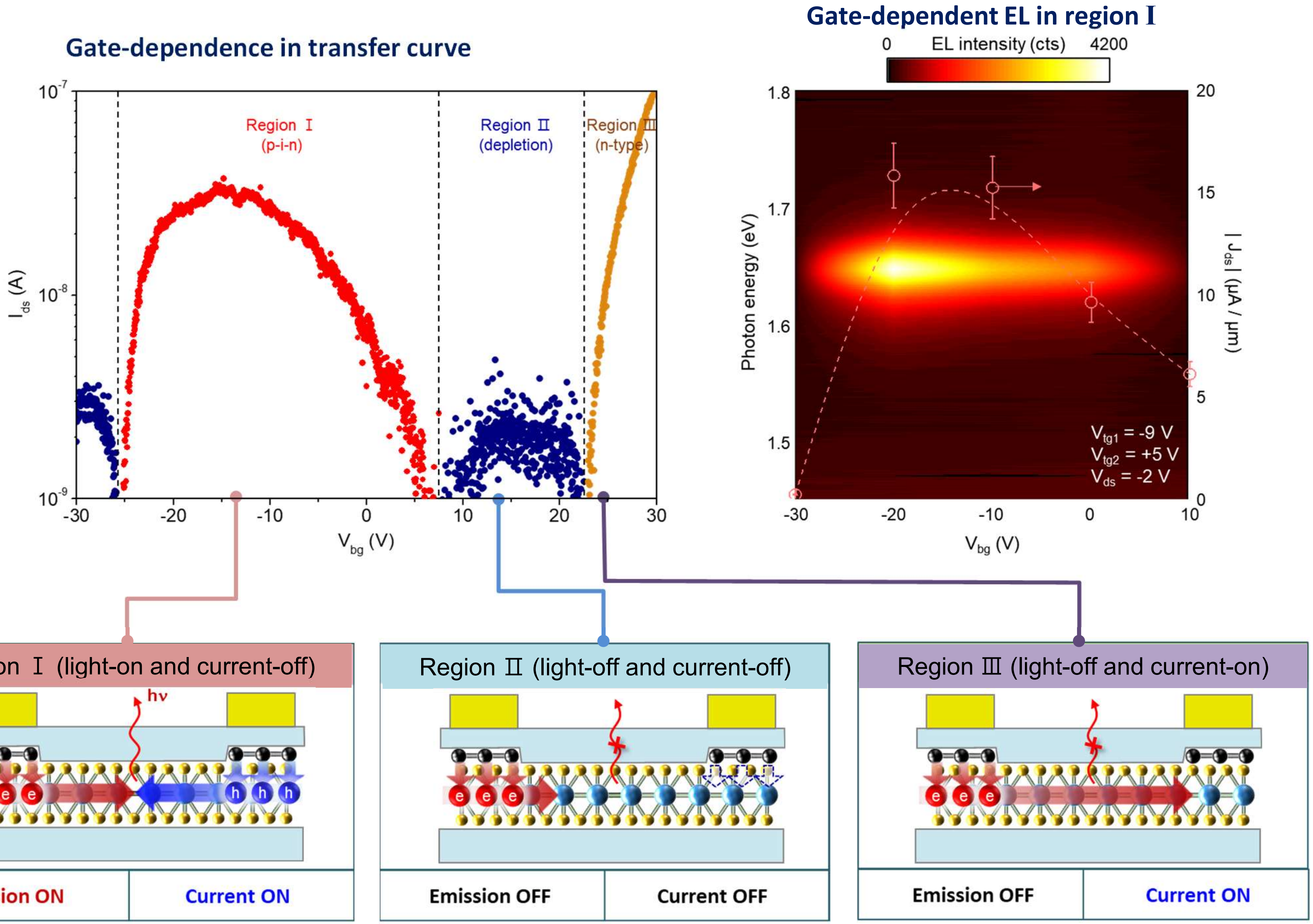






J. Kwon, C. H. Lee, G. H. Lee **Advanced Materials** (2020)

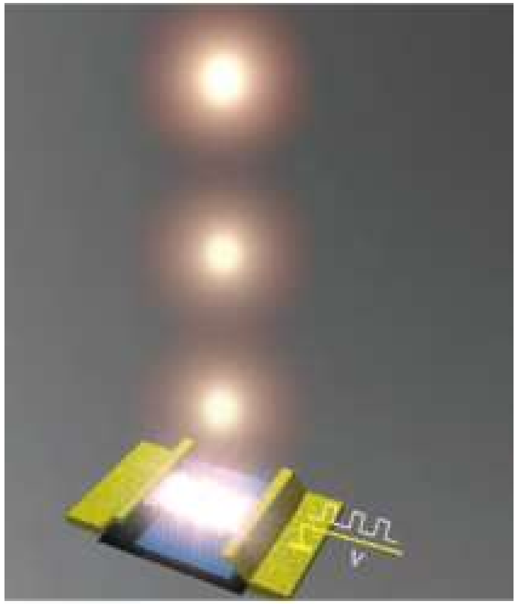
Multi-operation Modes of WSe_2 LETs

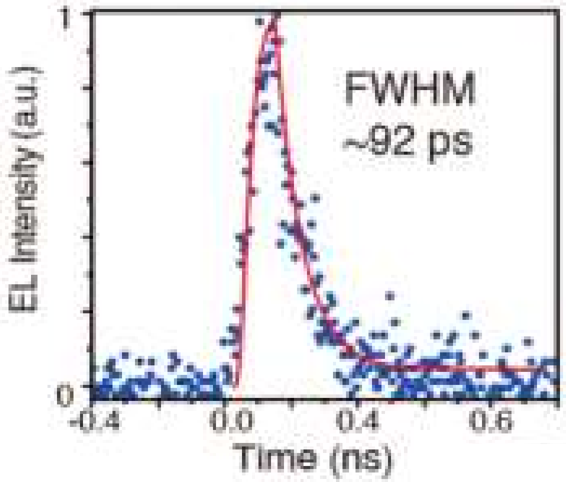


J. Kwon, C. H. Lee, G. H. Lee **Advanced Materials** (2020)

Light Emitting Devices

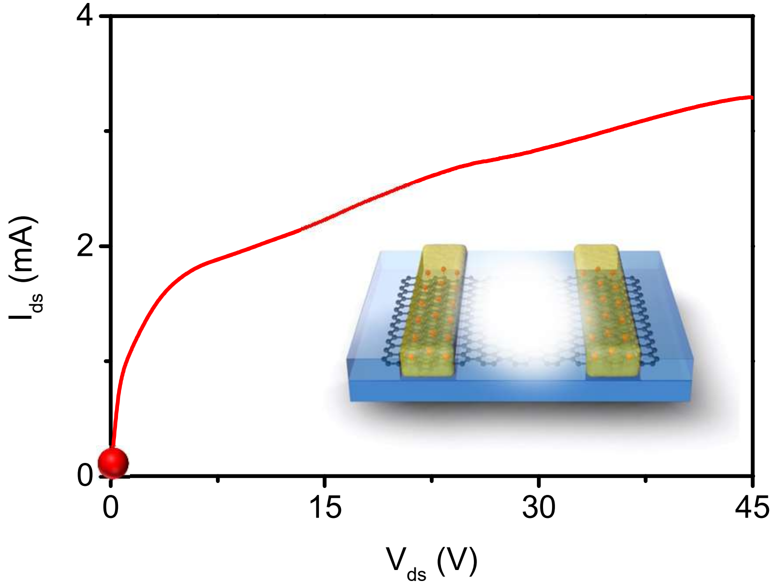
Graphene light emitting device



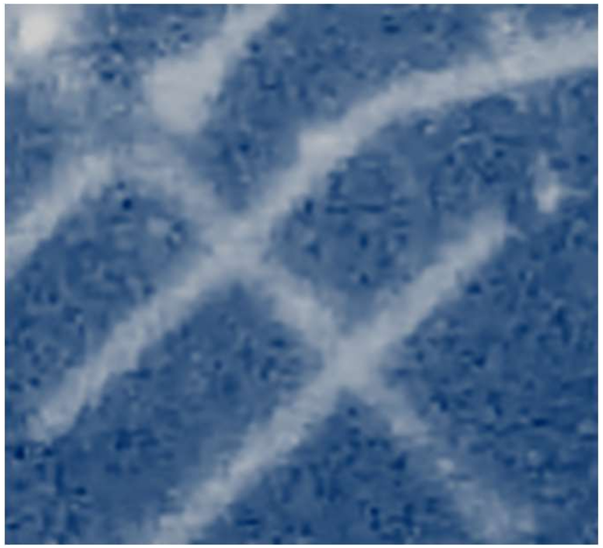


J. Hone. et al. Nano Lett. (2018)

High breakdown current

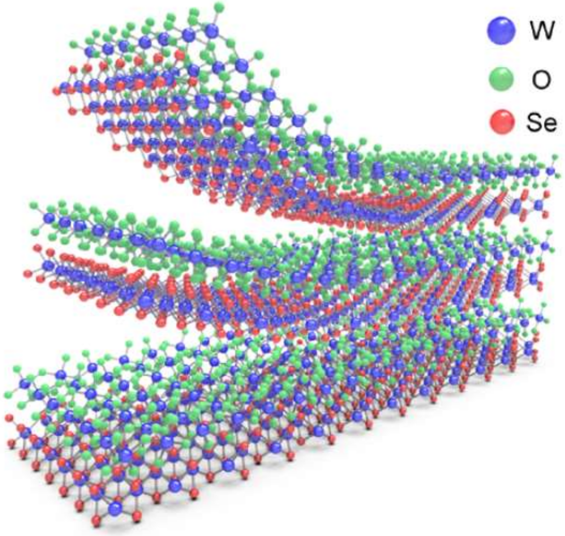


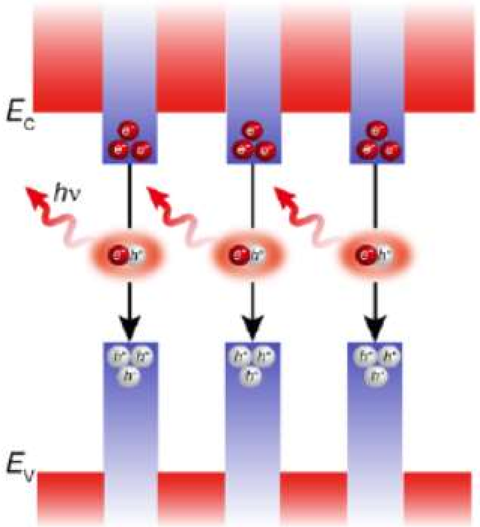
Light emission from graphene

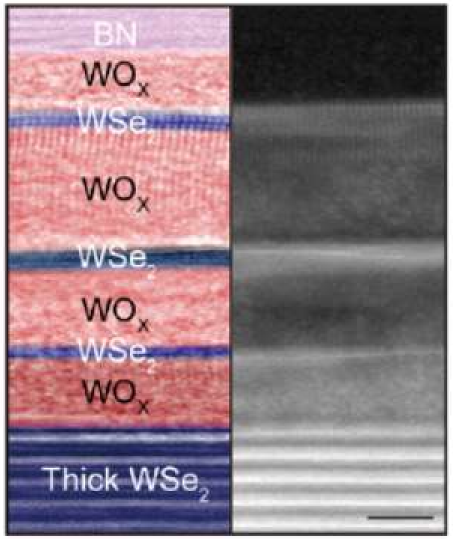


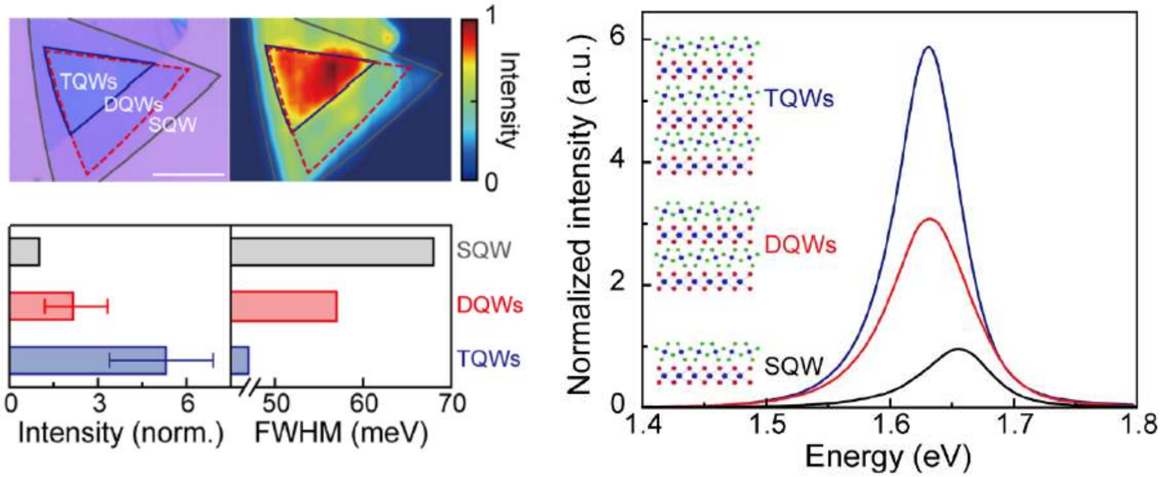
Multiple Quantum Well of TMDs

Fabrication process of $WO_x/WSe_2/WO_x/WSe_2$ by Layer-by-layer oxidation





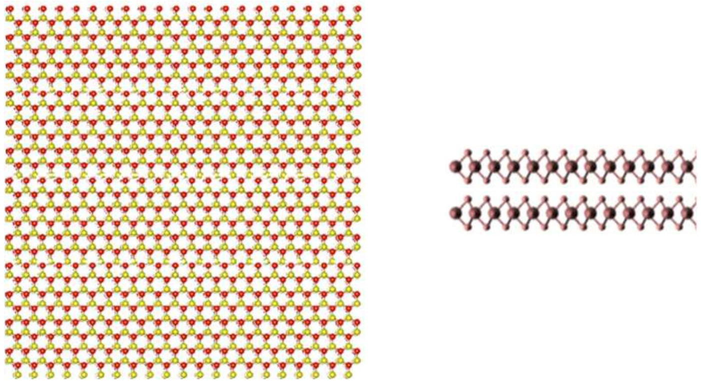




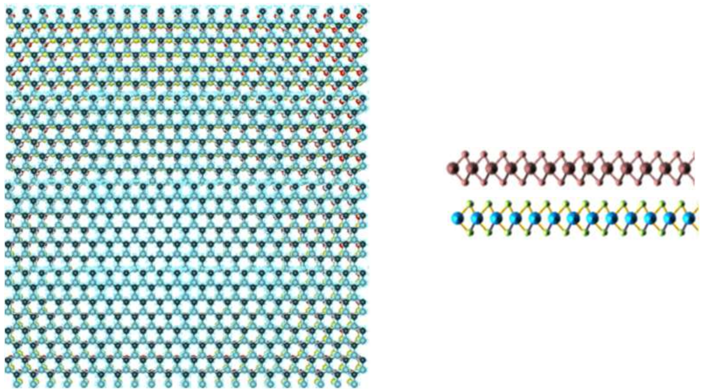
Y. S. Kim† , S. Kang†, G. H. Lee*, C. H. Lee* **Science Advances** 7, eabd7921 (2021)

Twist Angle of Stacked 2D Layers

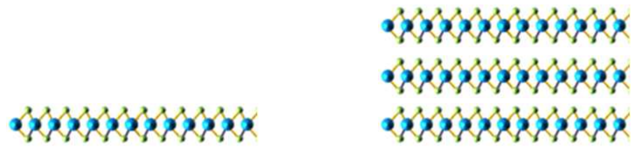
MoS_2/MoS_2



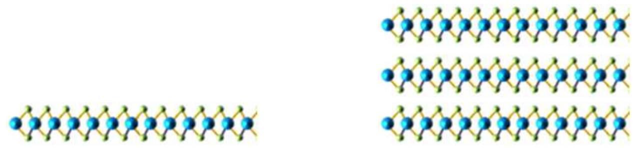
MoS_2/WSe_2



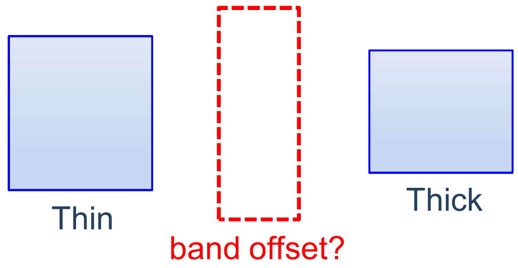
Lateral junction



Vertical junction



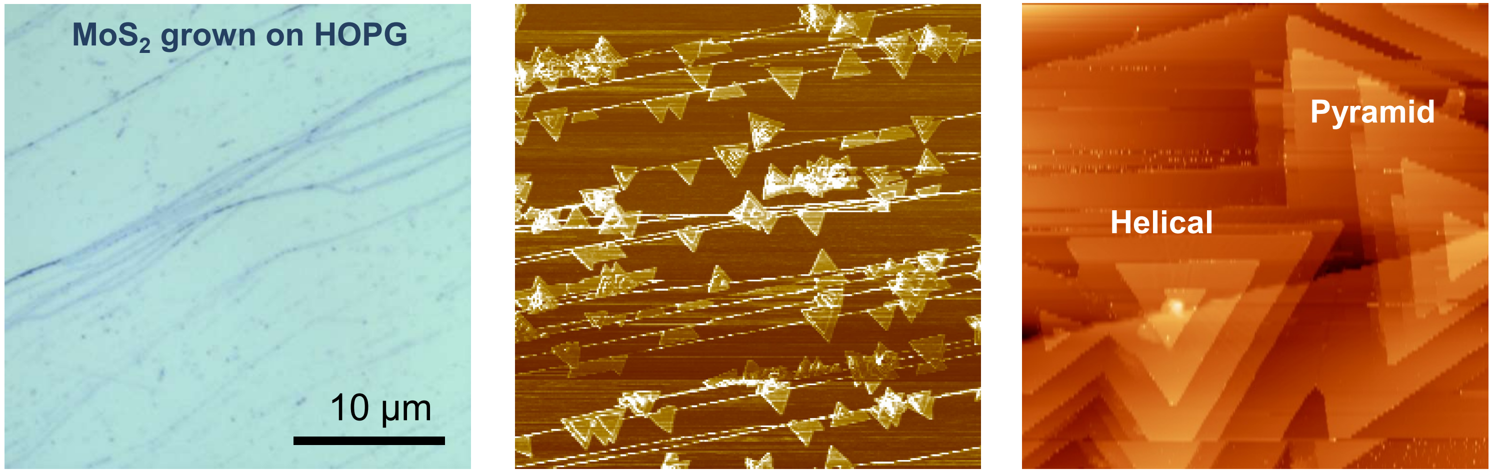
Junction band structure

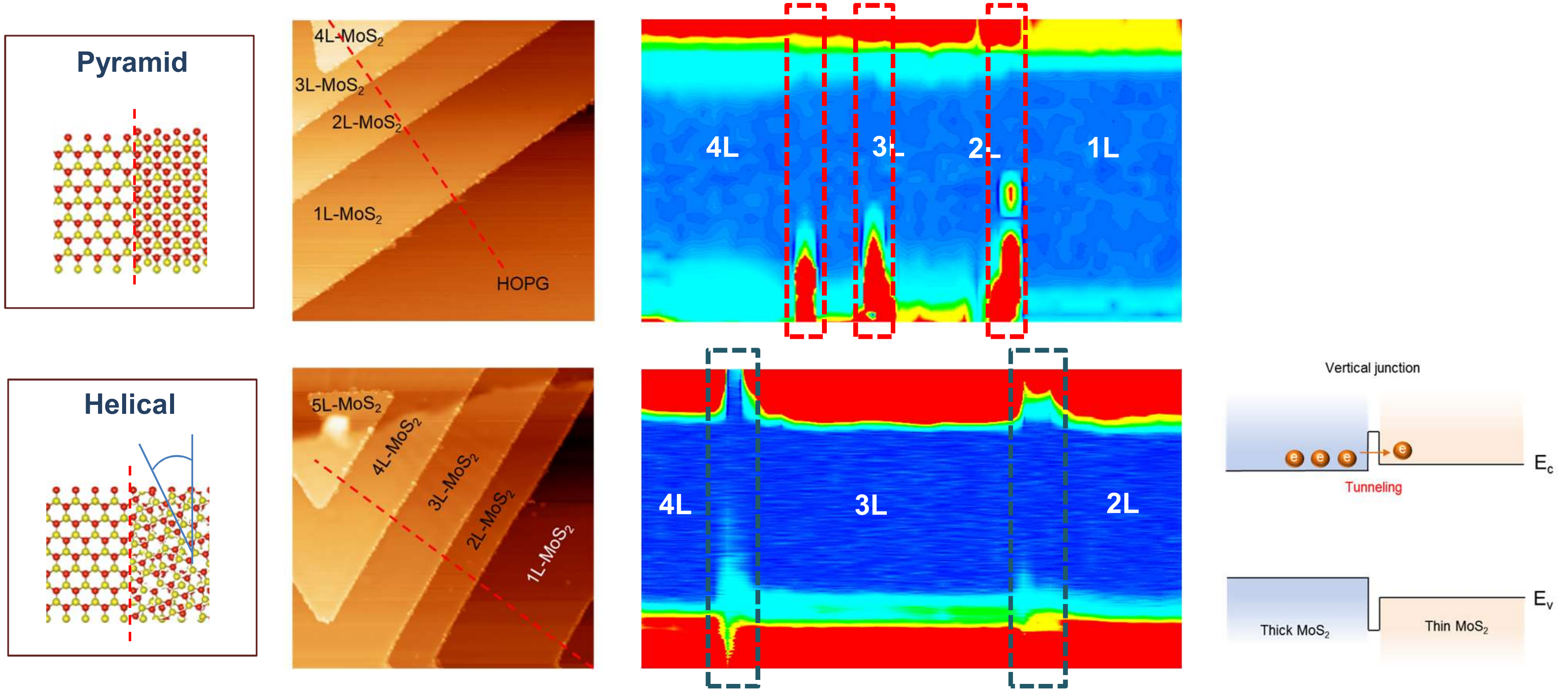


Charge transfer at interface of stacked 2D layers

- Electrical properties are influenced by stacking angle?
- The stacked layers are coupled or decoupled?
- Can we modify interfacial properties and band structure with twist angle and stacking structure?

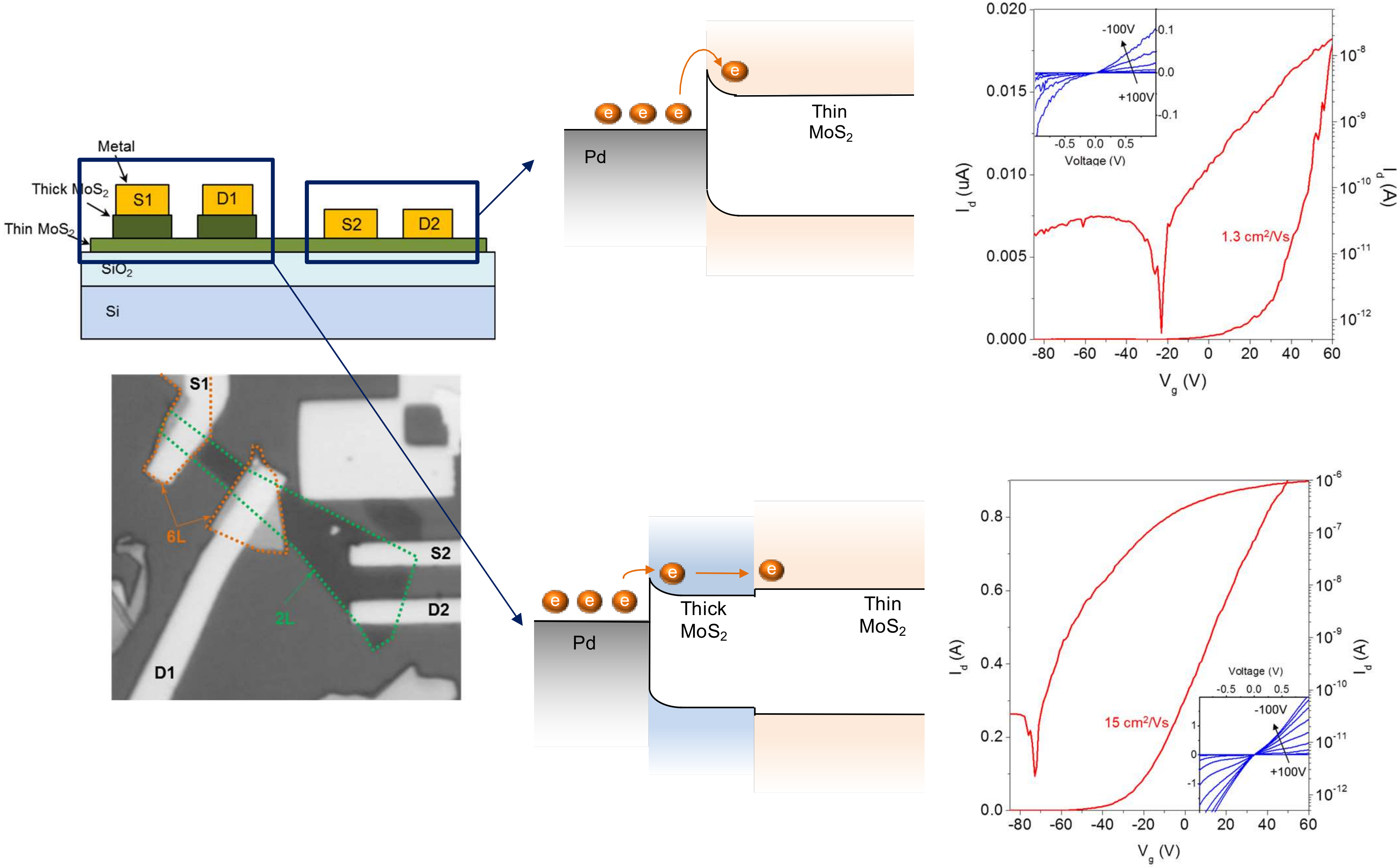
Band Offset at Heterointerface





J.H. Kim, G.H. Lee Unpublished

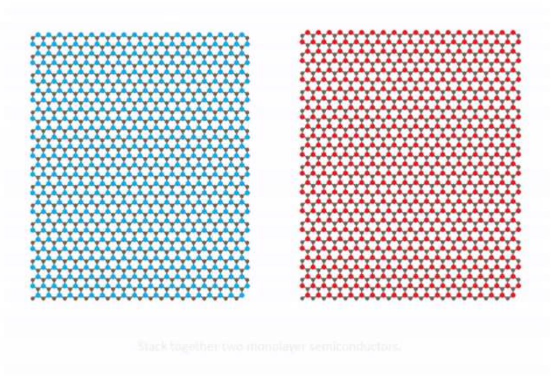
Hetero-structured Contacts with Low Resistance



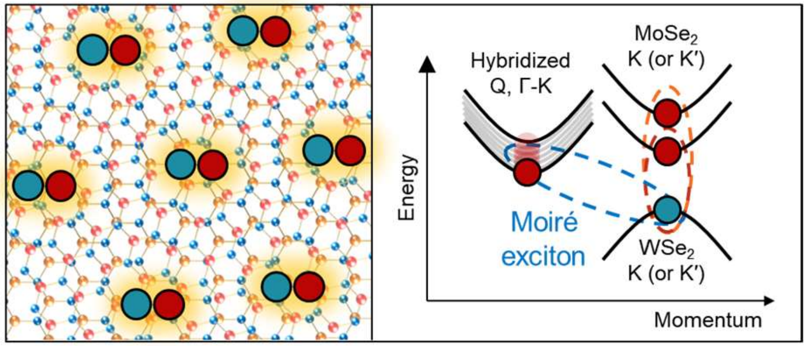
H. Yoon, G.H. Lee, S.C. Jun et al. NPG Asia Mater. (2019)

Moiré Crystals

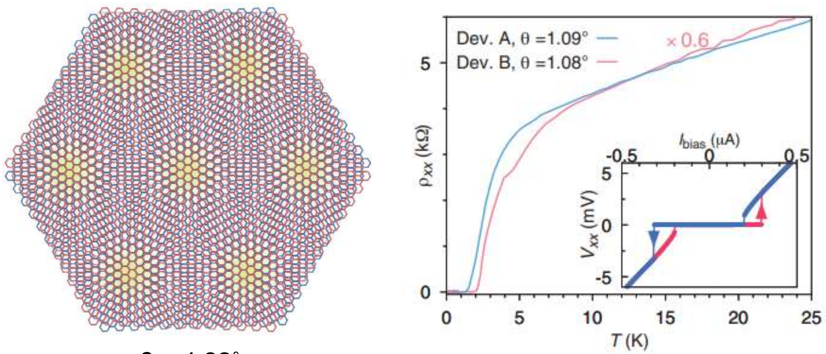
Moiré superlattice



Moiré potential trapped interlayer exciton



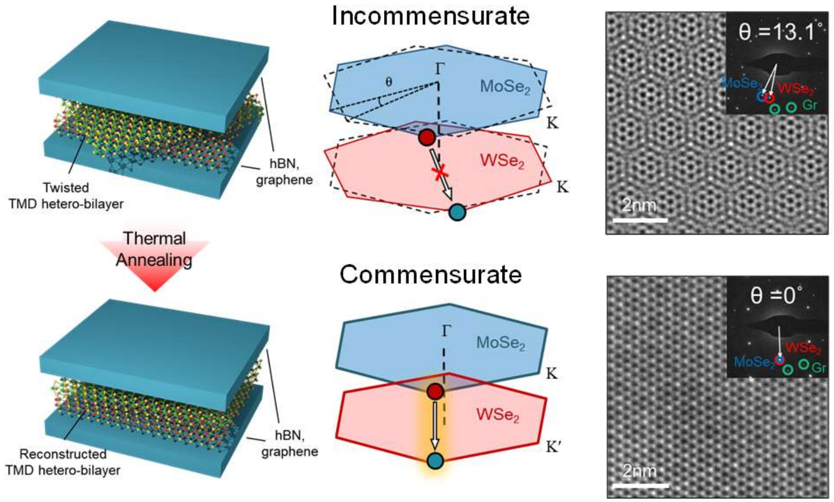
Superconductivity in magic angle graphene



θ = 1.09°

Science (2018)

Twist angle control in TMDs heterobilayers



J. Baek, G.H. Lee ***In preparation***

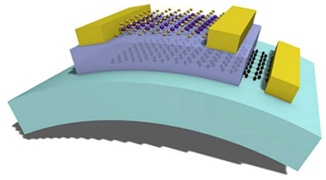
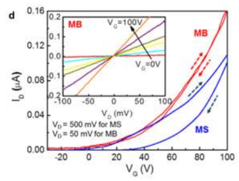
- ❑ Moiré potential trapped charge carriers contribute to novel quantum physics in 2D materials.
- ❑ Twisted bilayer graphene shows superconducting behavior at specific angle (θ ≒ 1.1˚).

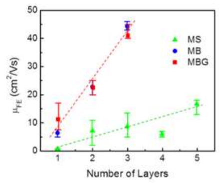
- ❑ Interlayer excitons are laterally confined from the moiré potential
- ❑ Atomic reconstruction occurred in twisted TMDs heterobilayer by thermal annealing.

Type of van der Waals heterostructure

1.Heterostructure of Graphene-hBN / TMD-hBN

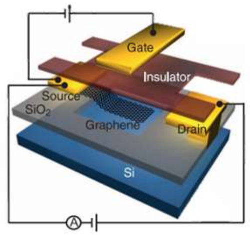
- High mobility
- No hysteresis

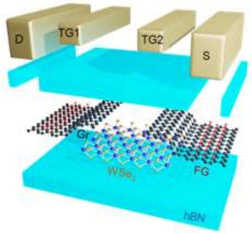



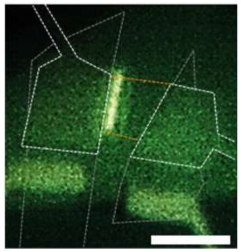


2. Heterostructure of Graphene-TMD-hBN

- Tunable Schottky barrier
- Fast charge transfer
- Barristor / LET

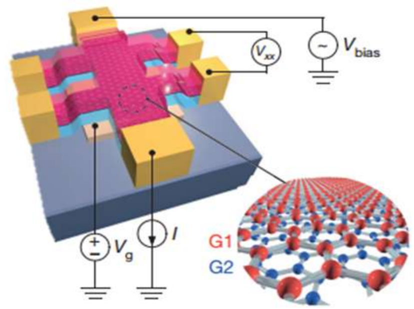


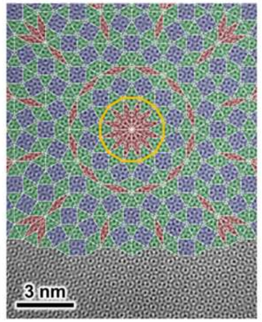




3. Heterostructure of Graphene – Graphene

- Twisted bilayer graphene
- Quasi crystal



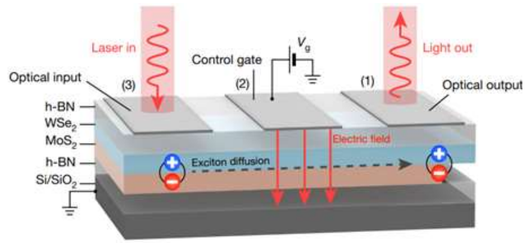


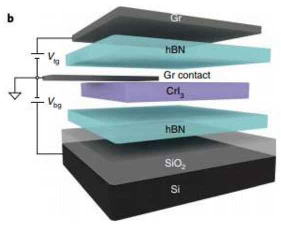
4. Heterostructure of TMD-TMD

- Band engineering
- PN junction
- Interlayer exciton

5. Heterostructure of various 2D material

- 2D magnetic : spin
- 2D ferroelectric : NC transistor

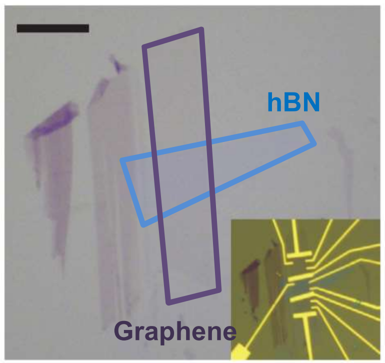


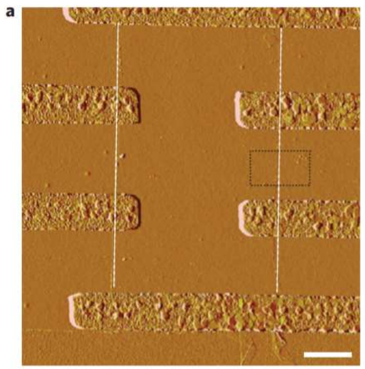


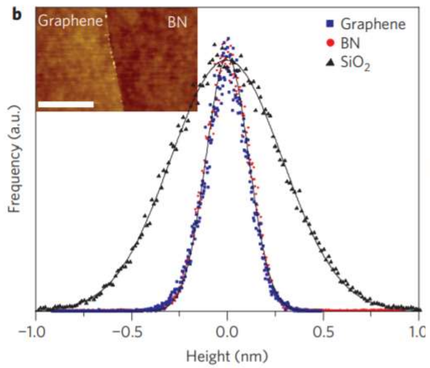
Heterostructure of Graphene-hBN / TMD-hBN

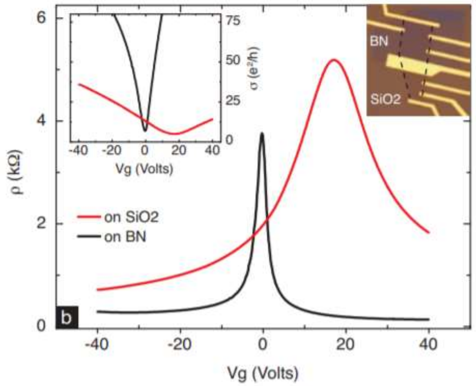
1-1. Heterostructure of Graphene-hBN

μ_{hall} for 1L Gr on hBN = 25000 cm^2/Vs
μ_{hall} for 2L Gr on hBN = 40000 cm^2/Vs
μ_{hall} for 1L Gr on SiO2 = 2500 cm^2/Vs



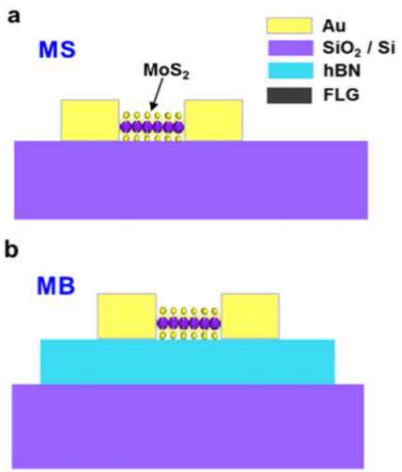


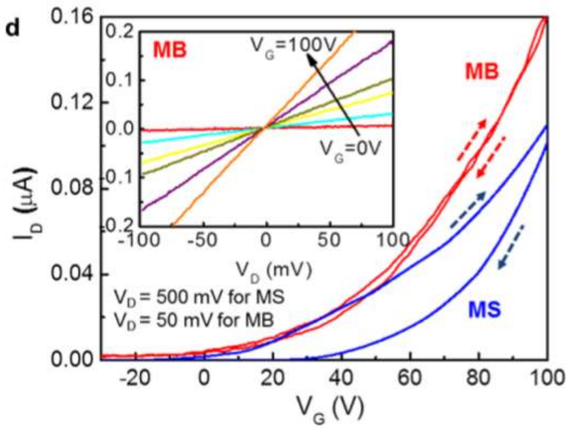


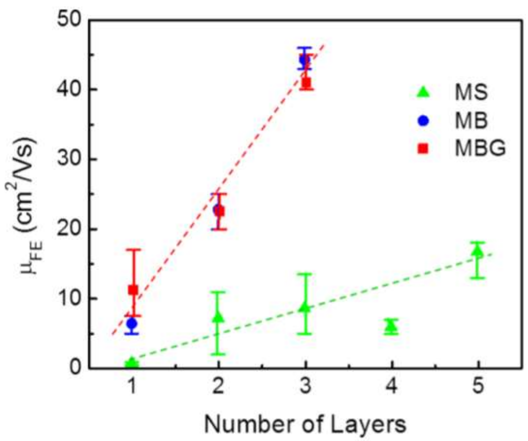


J. Hone et al. Nat. Nanotechnol (2010)

1-2. Heterostructure of TMD-hBN



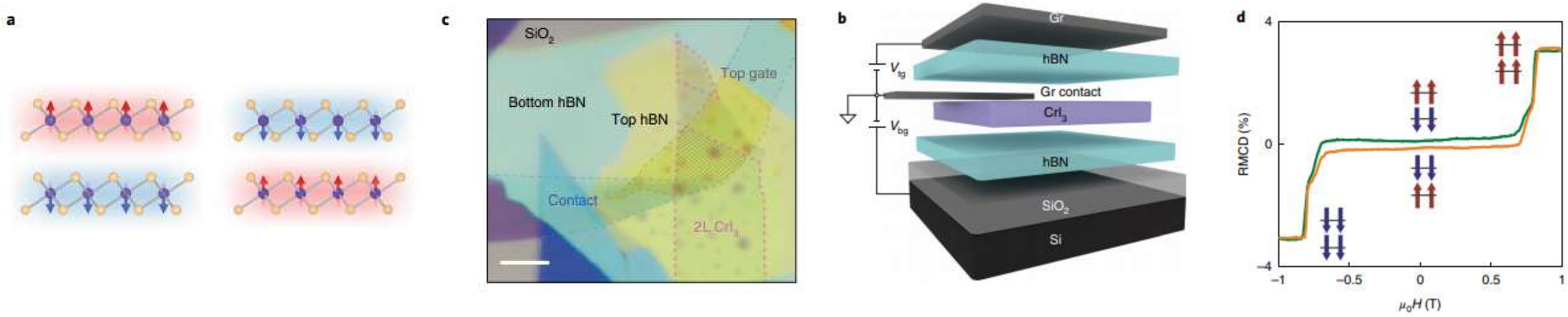




G.H. Lee, J. Hone et al Nat. Nanotech (2013)

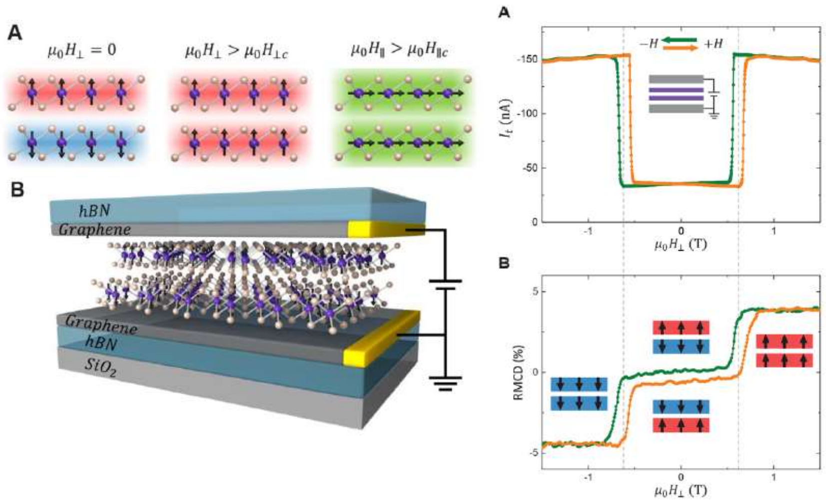
Heterostructure of magnetic material

2D magnetic material CrI3



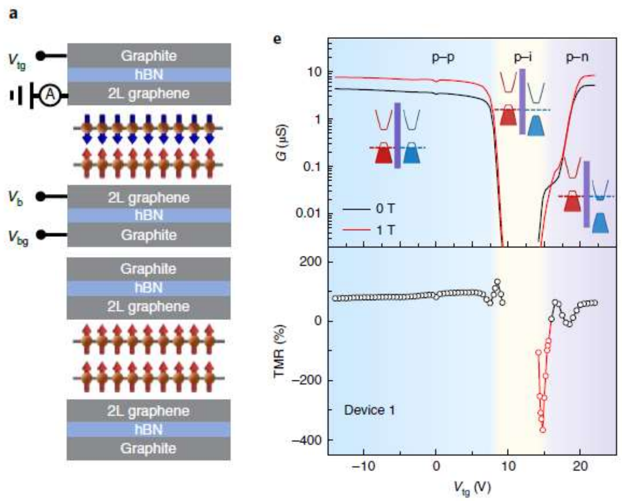
X. Xu et al. Nat. Nanotechno. (2018)

Giant tunneling magnetoresistance in spin filter



X. Xu et al. Science (2018)

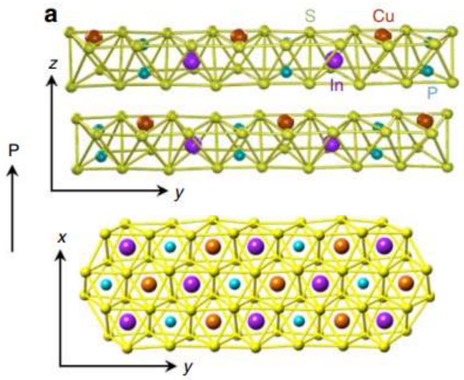
Spin tunnel field effect transistor

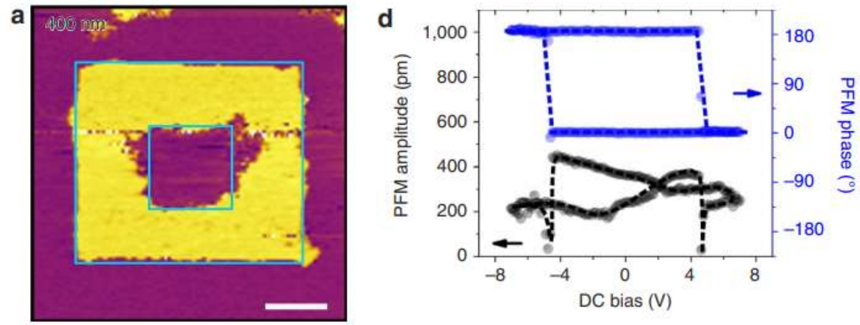


K.F. Mak et al. Nat. Electro. (2019)

Heterostructure of ferroelectricity material

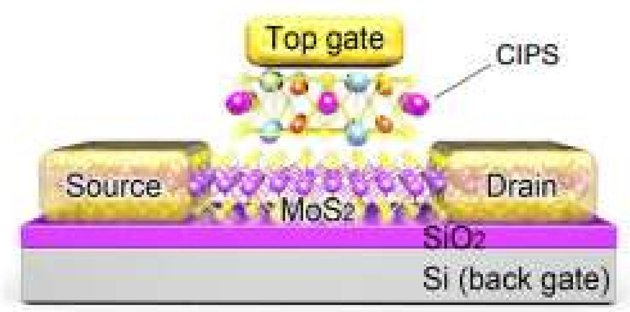
2D ferroelectric material $CuInP_2S_6$

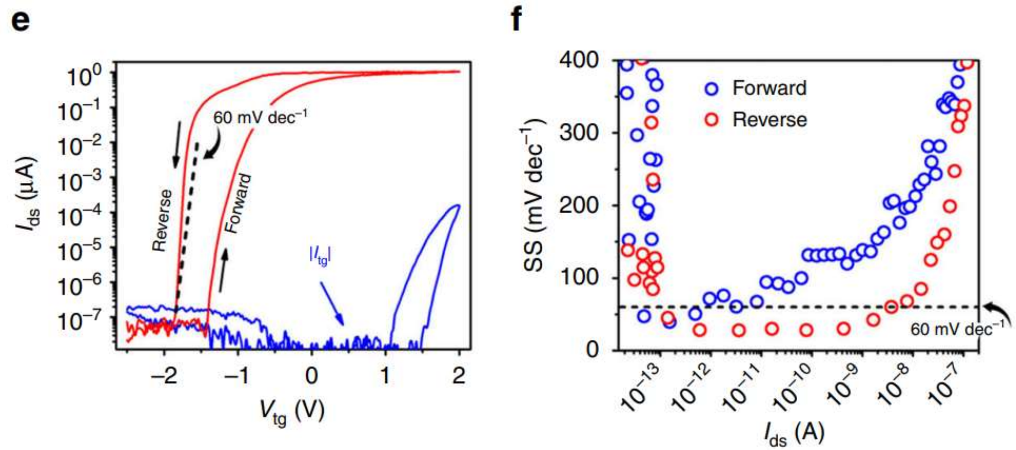




Z. Liu et al. Nat. Commun. (2016)

Negative capacitance transistor



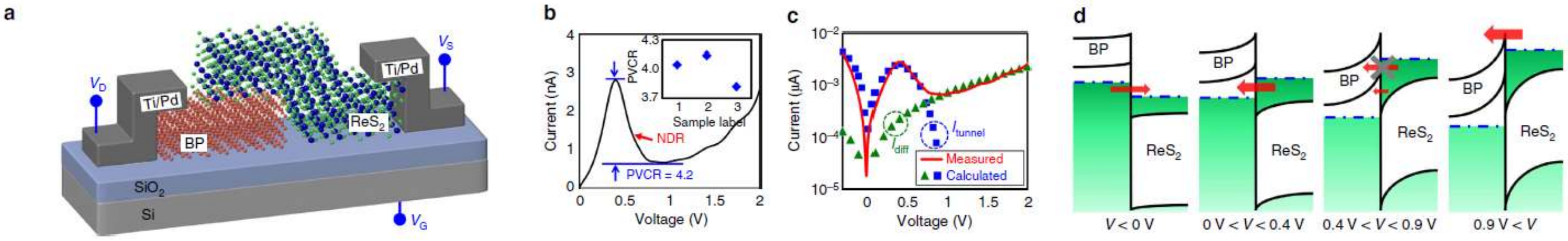


- vdW NC transistor has 28 mV dec^{-1} subthreshold swing(SS) and can overcome theoretically thermionic limit of 60 mV dec^{-1}

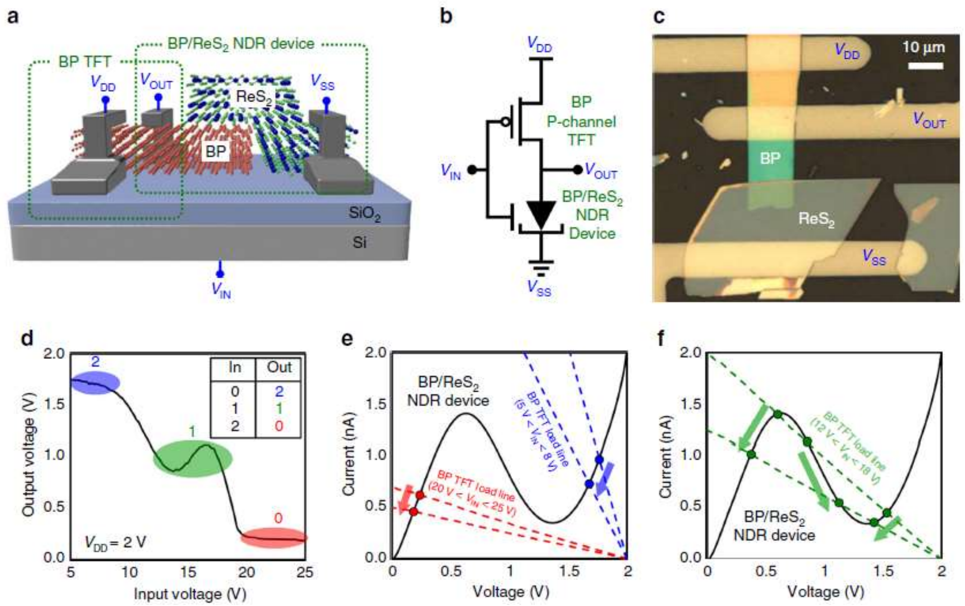
Z. Liu et al. Nat. Commun. (2019)

Negative differential resistance device

NDR device



Ternary inverter with three logical states

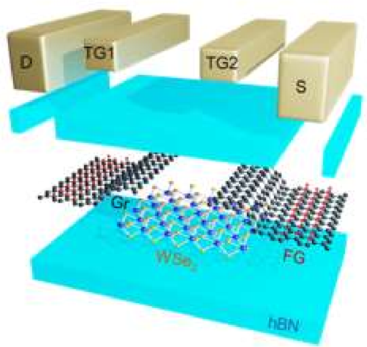


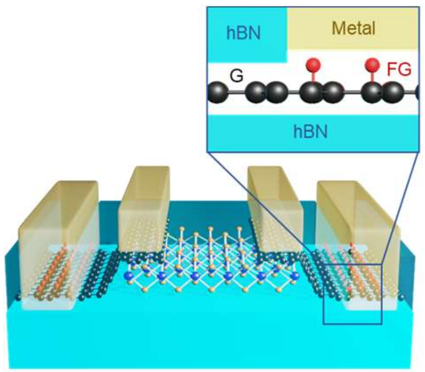
- NDR device using band engineering of vdW heterostructure
- NDR charactersistric can be attributed to change types of band alignment from type Ⅲ to type Ⅱ.
- Multi-value level can be demonstrated, as ternary inverter fabricated using NDR characteristics

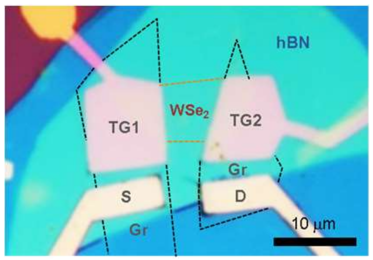
J. H. Park et al. Nat. Commun. (2016)

Light emitting transistor with tunable Schottky barrier

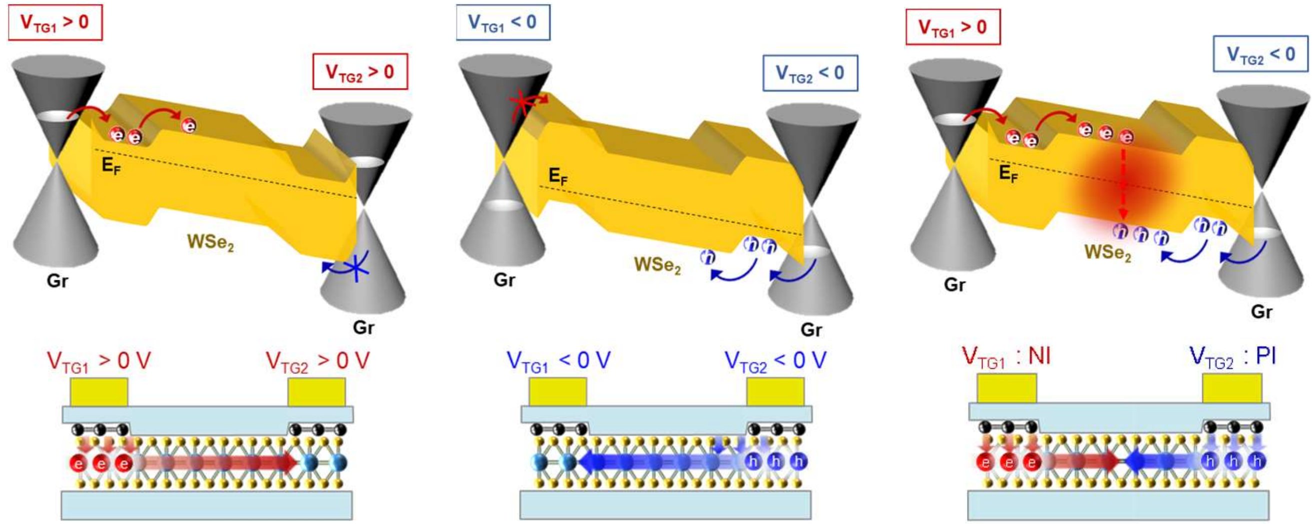
Device geometry



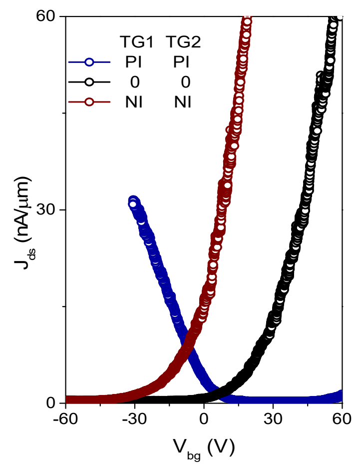


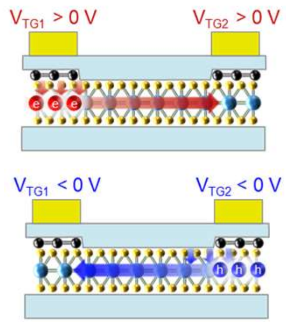


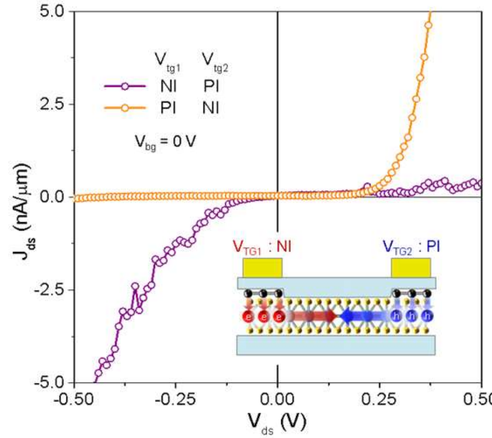
Working principle



Polarity Control



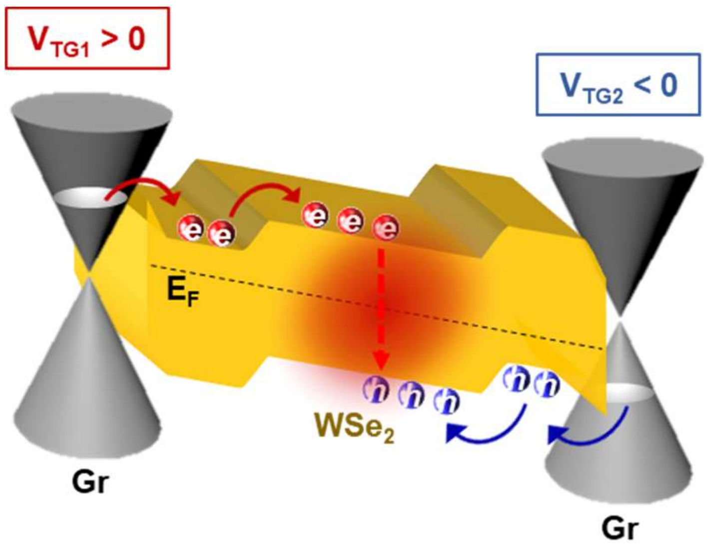


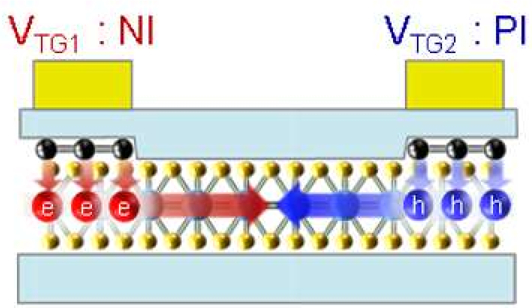


J. Kwon, G.H. Lee In preparation

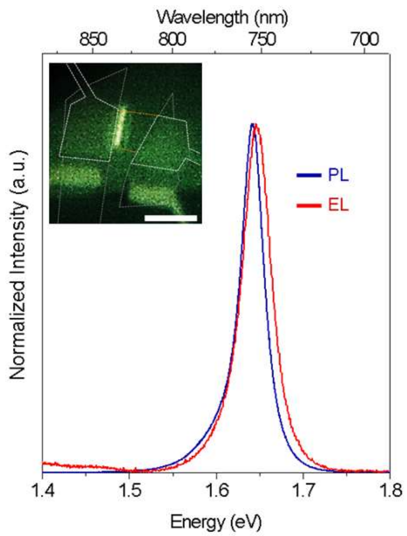
Light emitting transistor with tunable Schottky barrier

Light emission

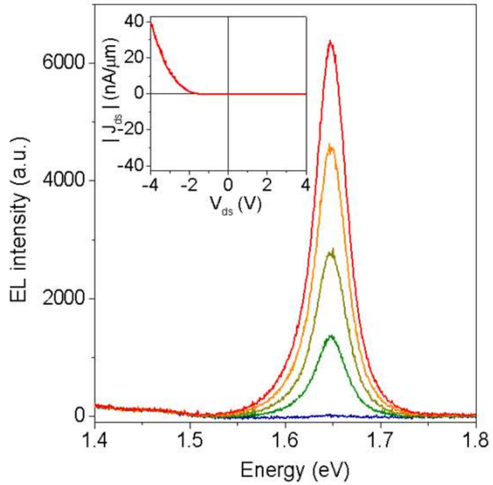




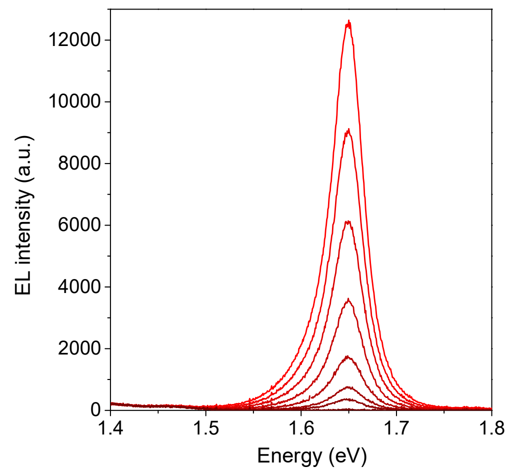
EL vs PL



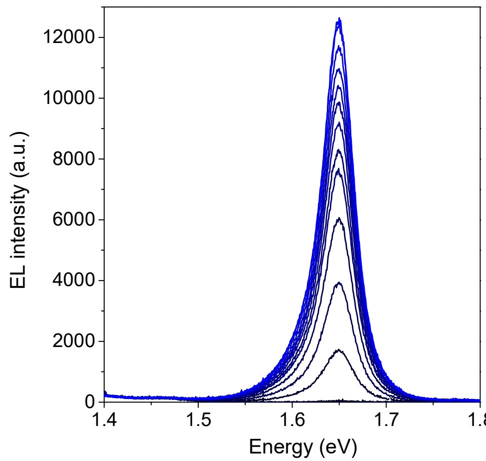
V_{ds} dependence of EL



Control of hole injection (V_{tg1} modulation)



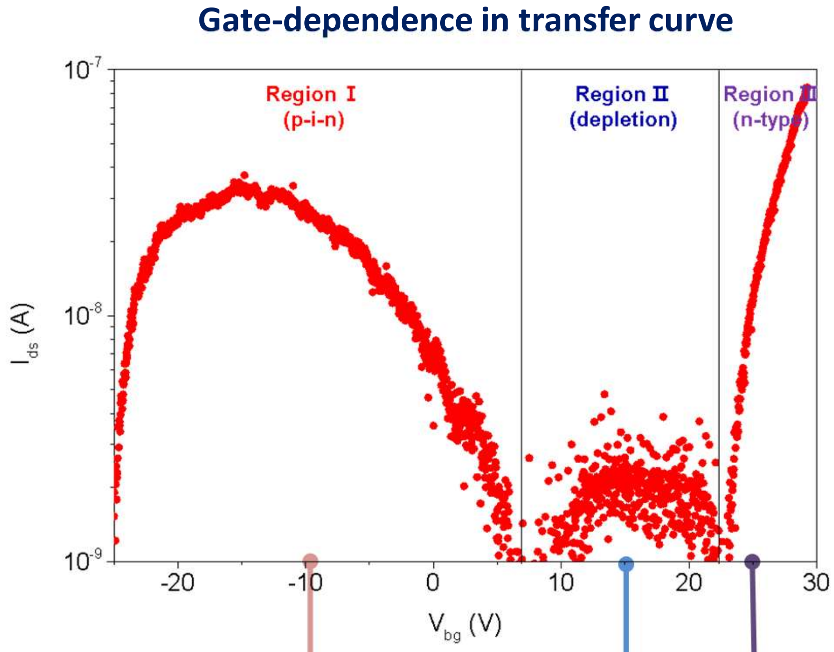
Control of electron injection (V_{tg2} modulation)

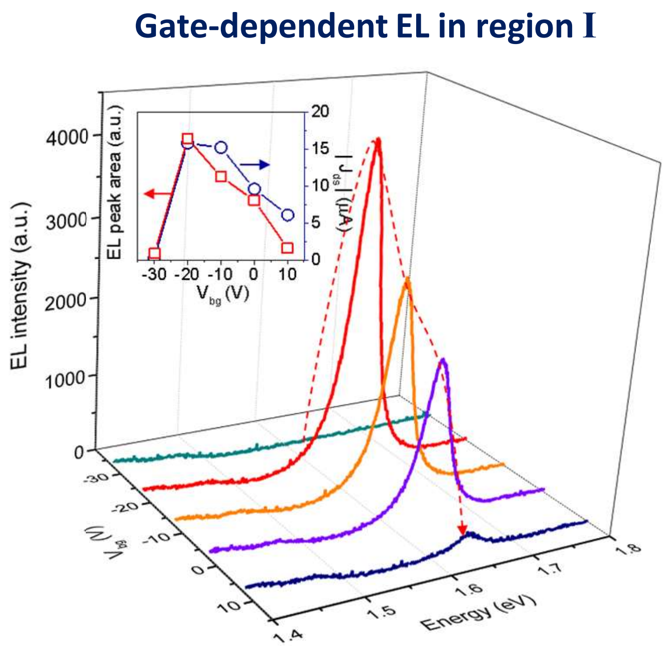


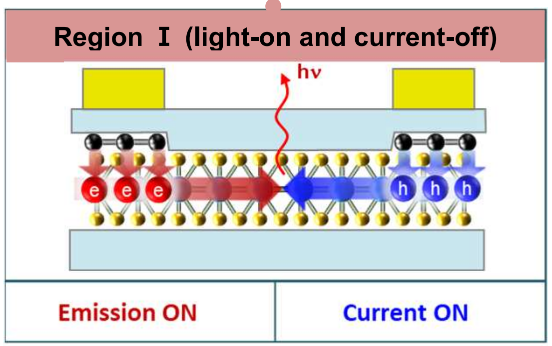
J. Kwon, G.H. Lee In preparation

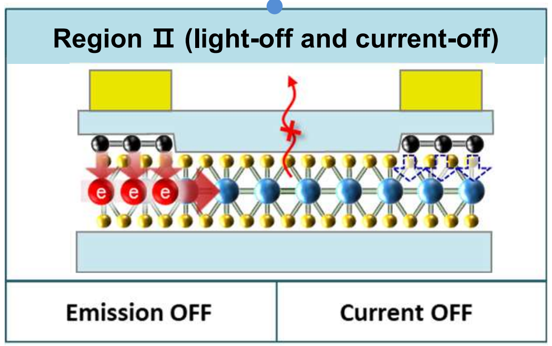
Light emitting transistor with tunable Schottky barrier

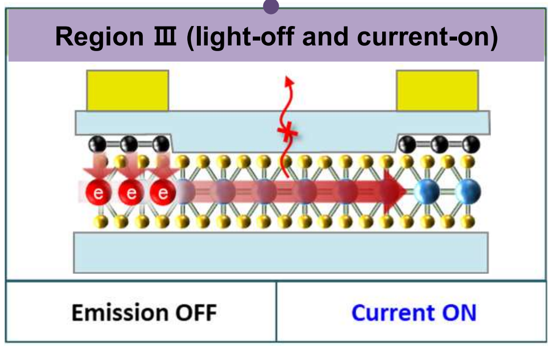
Multi-mode Operation





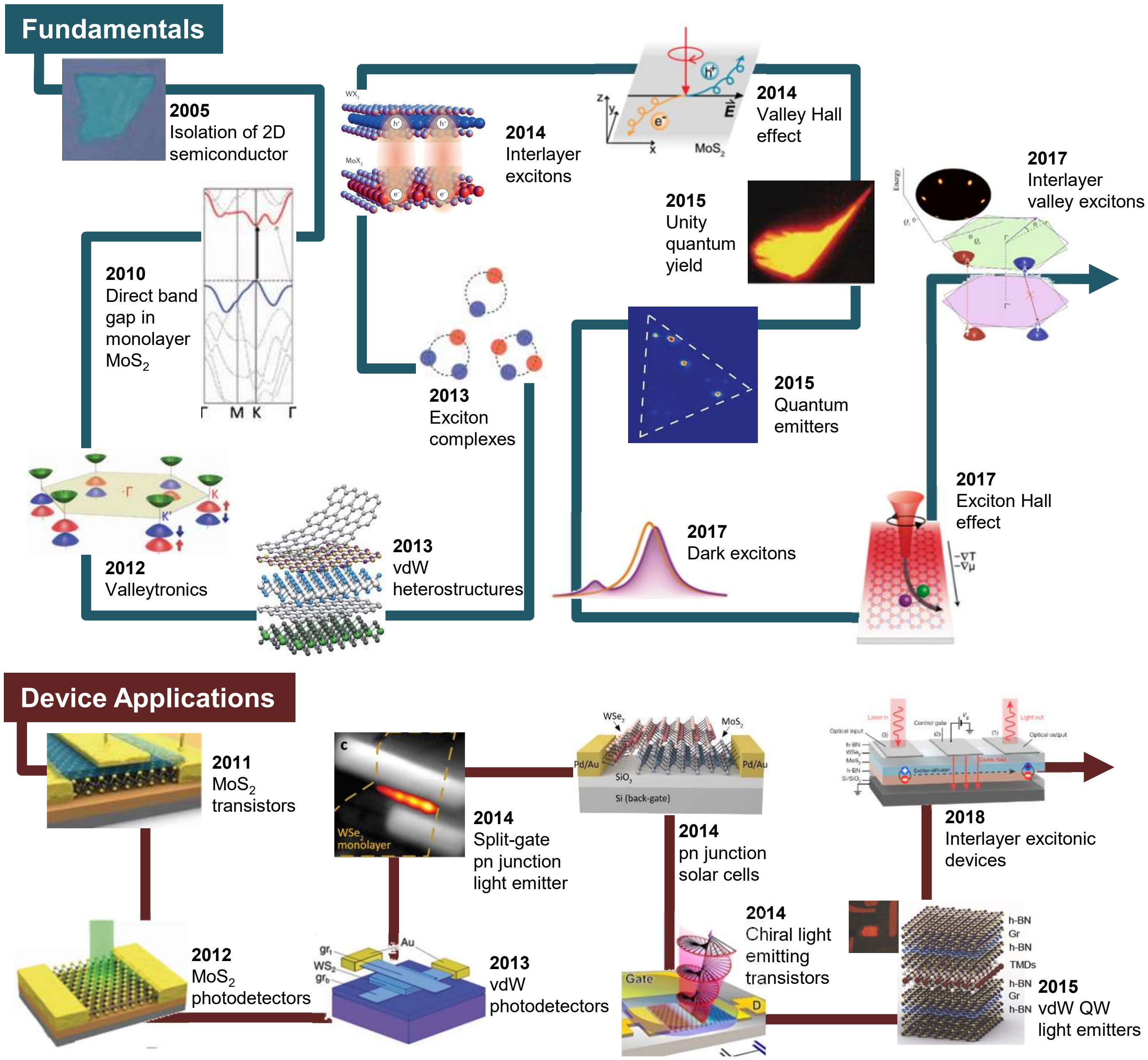






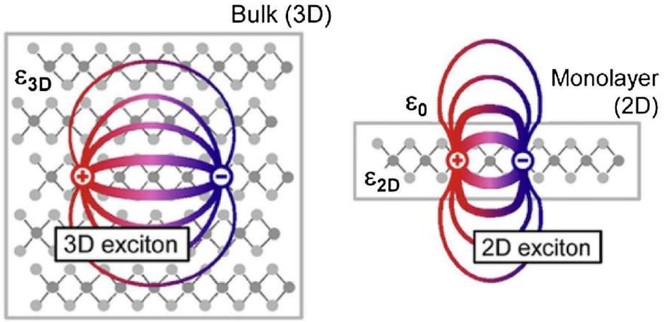
J. Kwon, G.H. Lee In preparation

Excitonic Light Emitting Devices



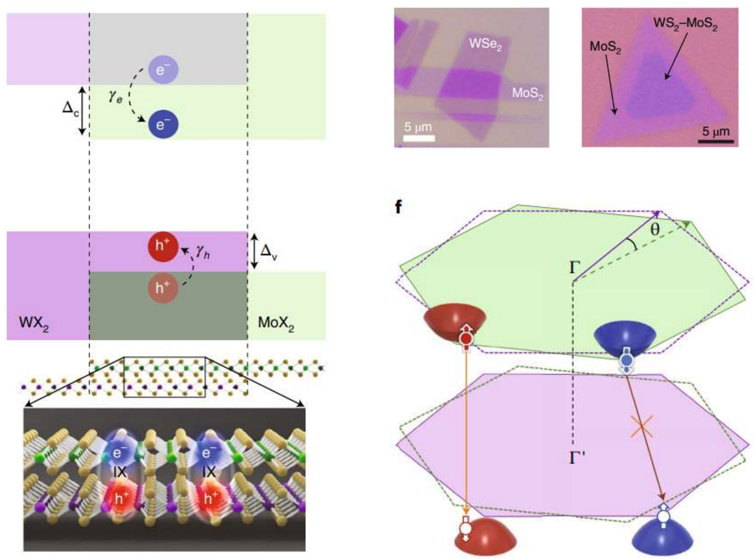
Interlayer exciton

Strong light-matter interaction of TMD



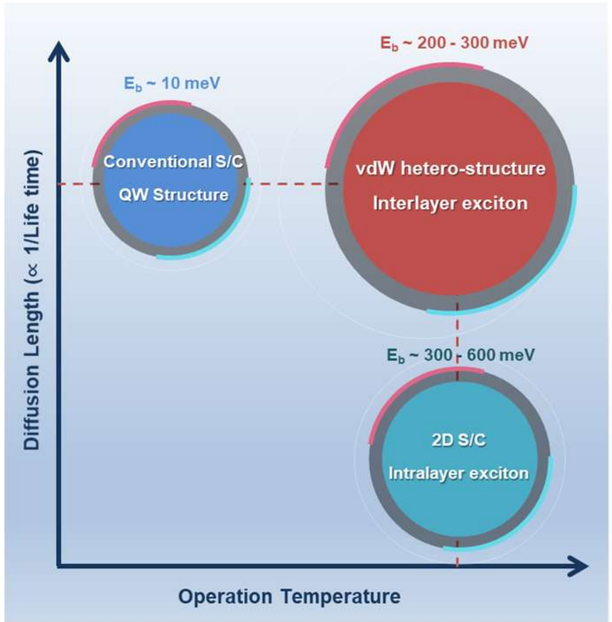
P. S. Toth et al. Appl. Mater. Today (2017)

Interlayer excition generation



X. Xu et al. Nat. Nanotechno. (2018)

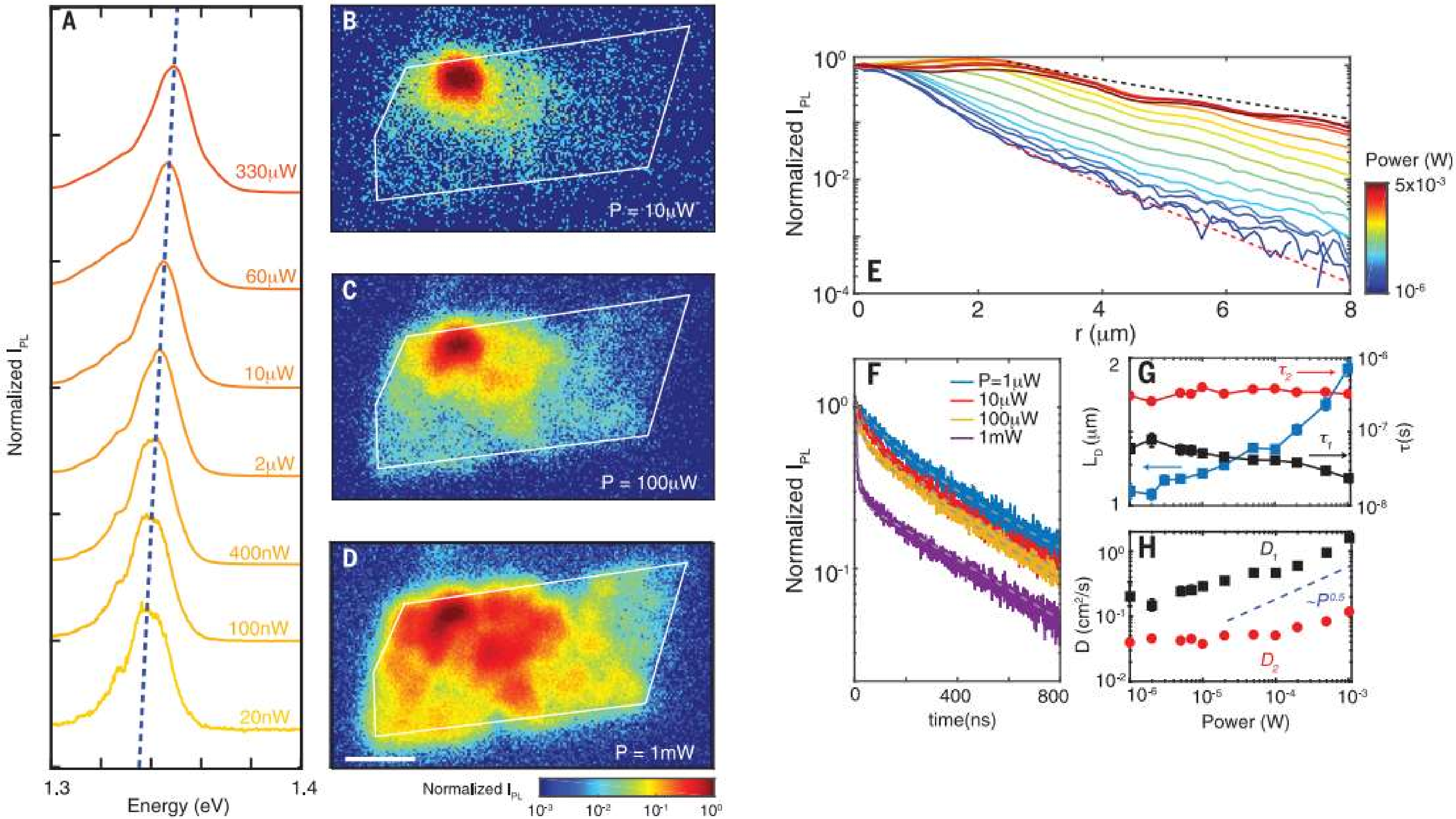
Possibility of interlayer excition



TMD	Binding energy	Life time
Conventional S/C	1~20meV	300ns
2D S/C	300~500meV	0.001~20ns
Vdw heterostructure	200~300meV	100ns

Interlayer exciton

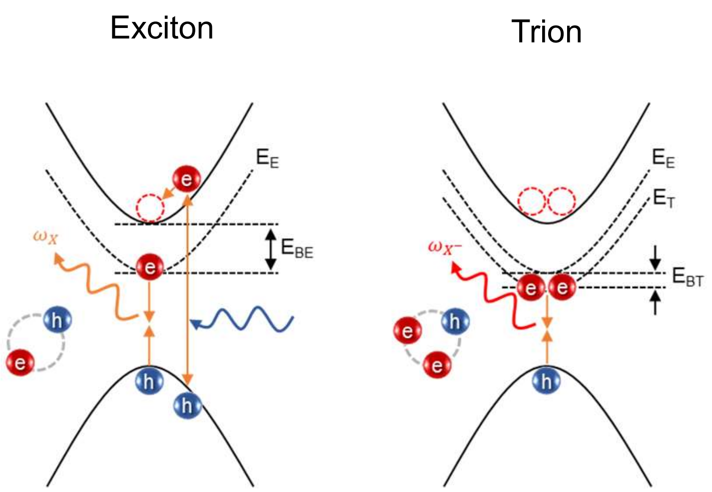
Diffusion of Interlayer exciton



P. Kim et al. Science (2019)

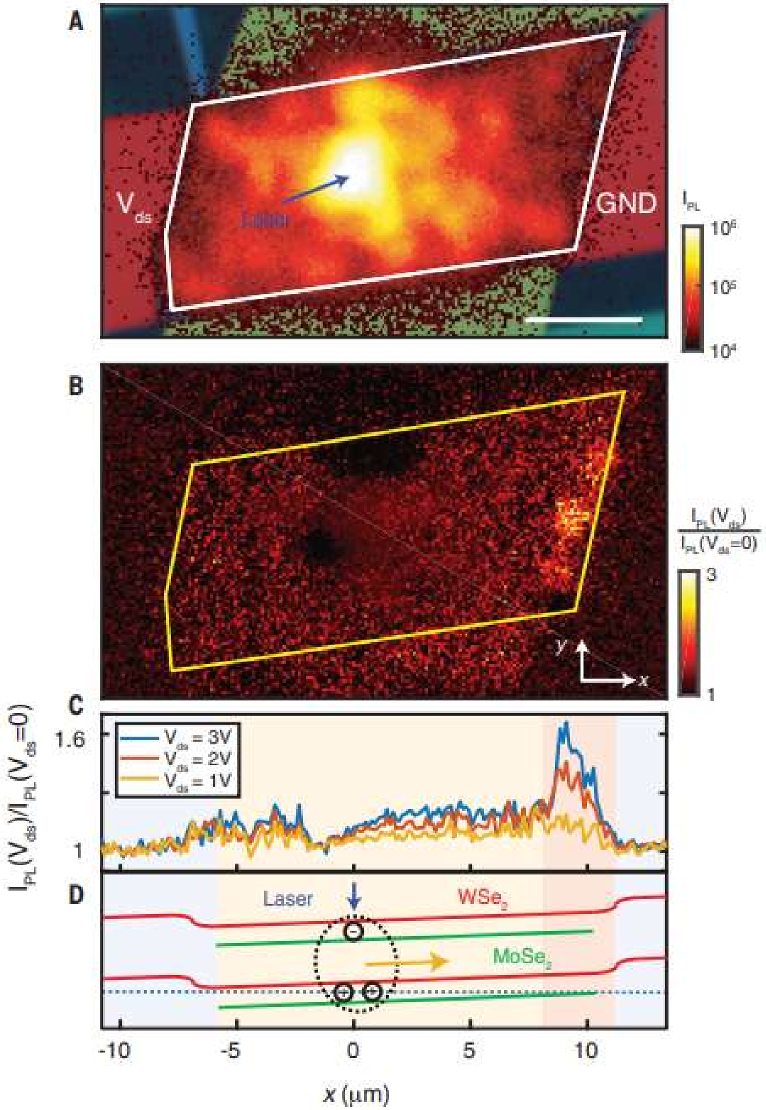
Interlayer trion

Exciton vs Trion



Interlayer trion	
Charge	Positive Charge Negative Charge
Transport mechanism	Drift (+Diffusion)
Control parameter	Electric field

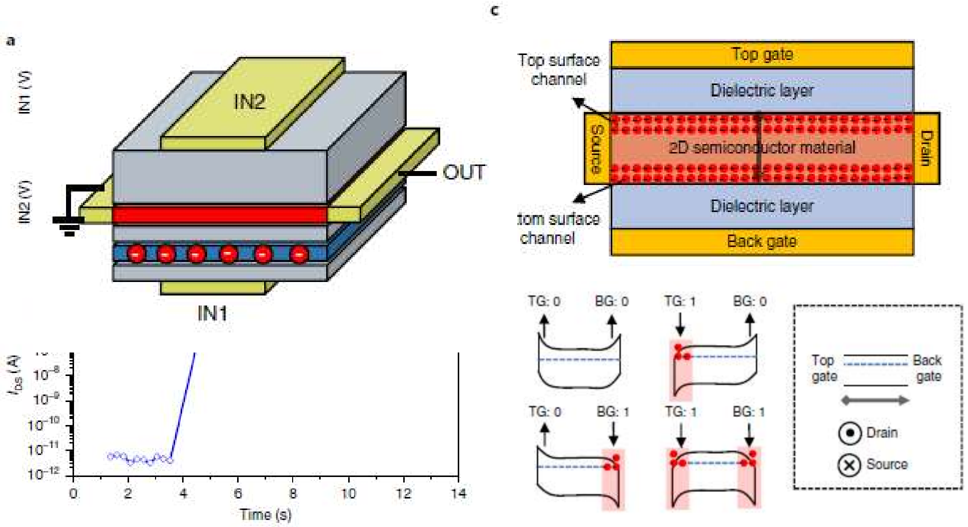
Diffusion of Interlayer trion



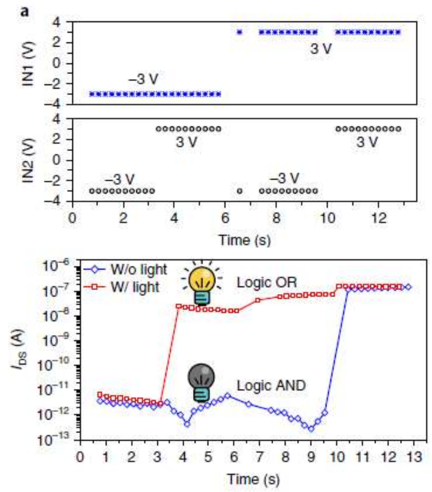
P. Kim et al. Science (2019)

Photoswitching logic and memory

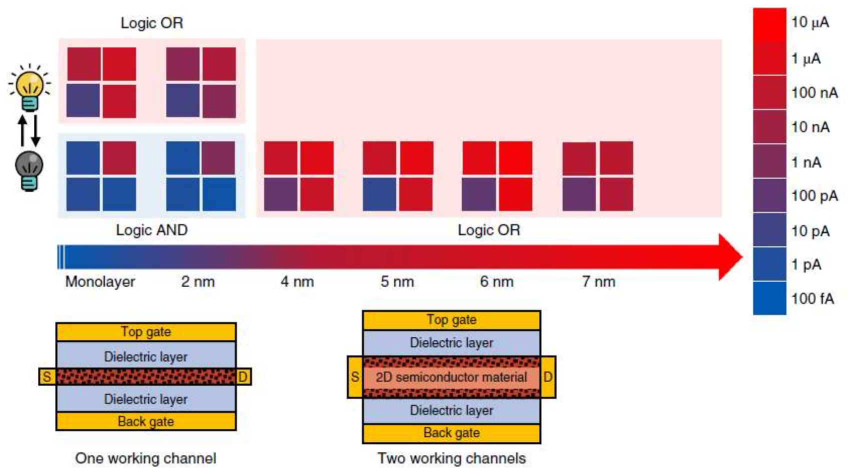
OR gate



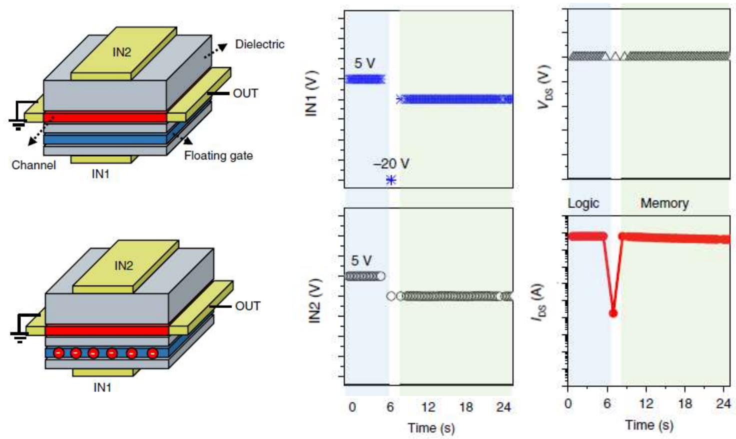
AND gate



Different operation depend on channel thickness

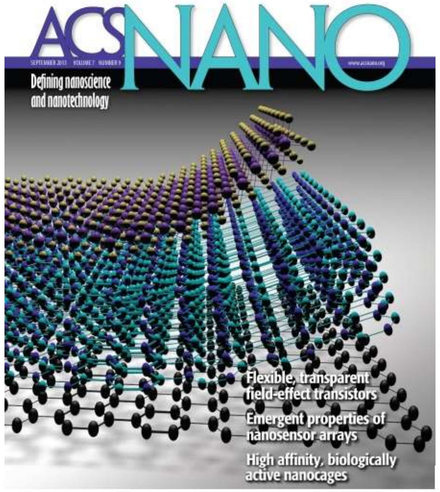


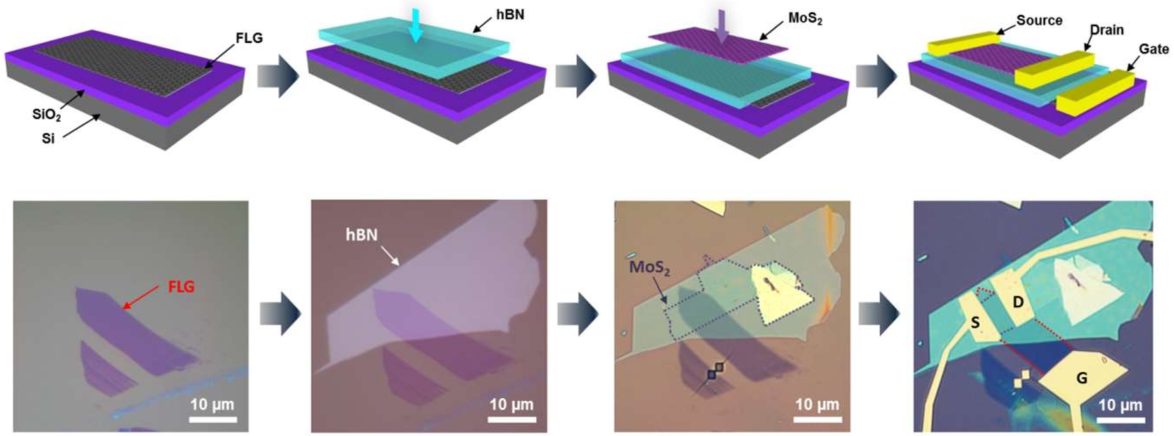
Memory using floating gate

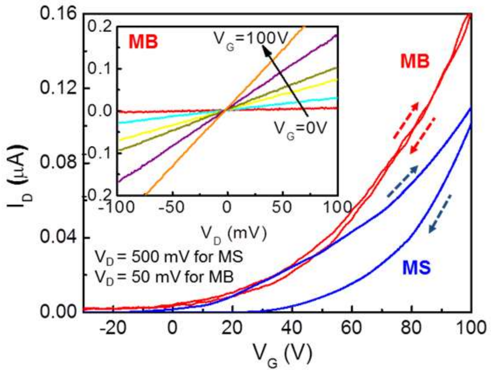


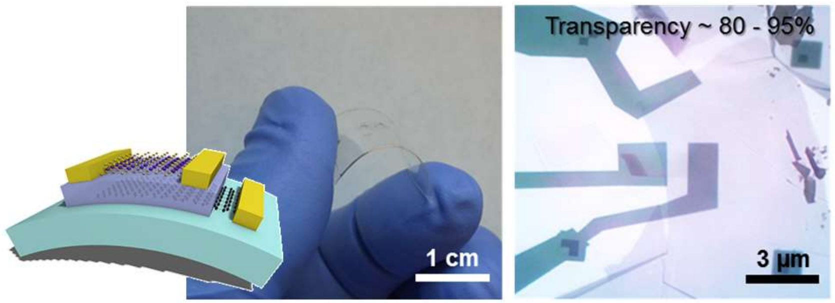
P. Zhou et al. Nat. Nanotechno (2019)

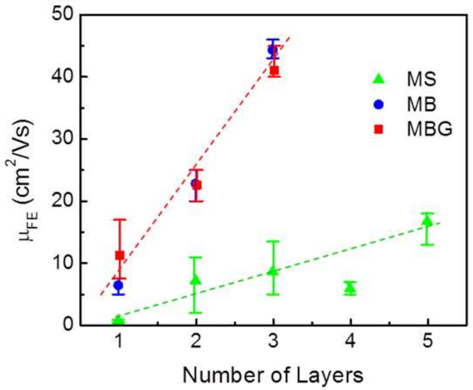
Flexible and Transparent Heterostructure Devices

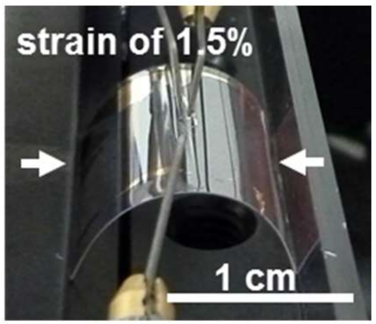


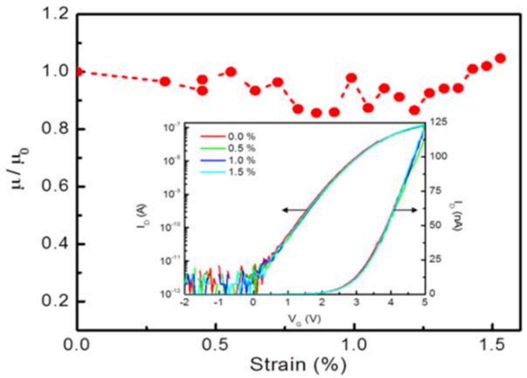








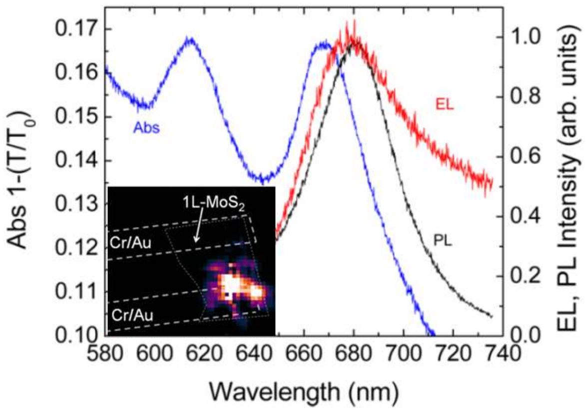




G.H. Lee et al. *ACS Nano 7, 7931–7936 (2013)*

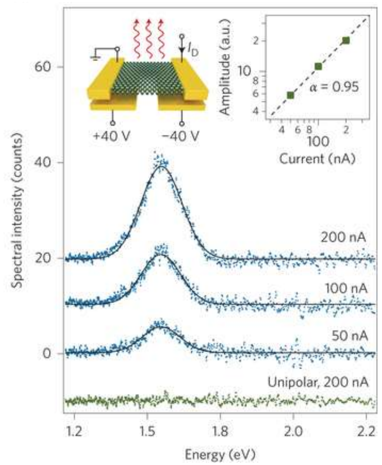
Light Emitting Devices based on 2D Materials

Thermionic emission



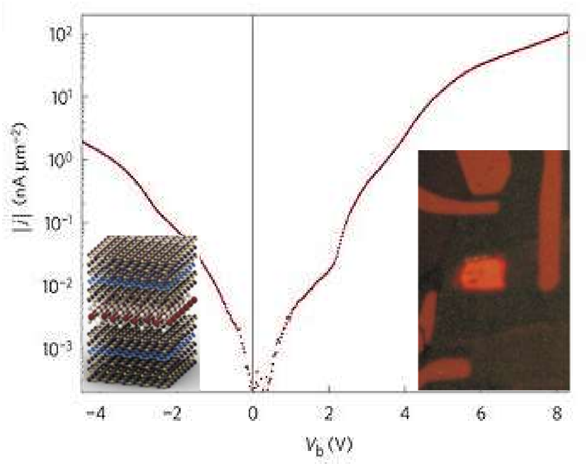
M. Steiner et al. Nano Lett. (2013)

Lateral p-n diode

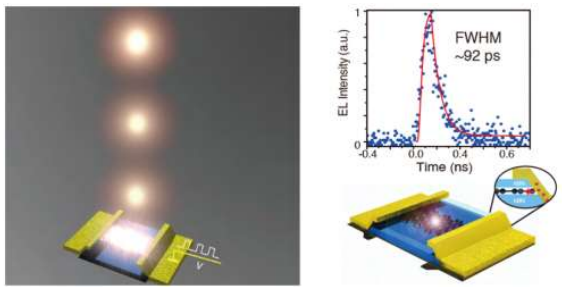


A. Pospischil et al. Nat. Nanotech. (2015)

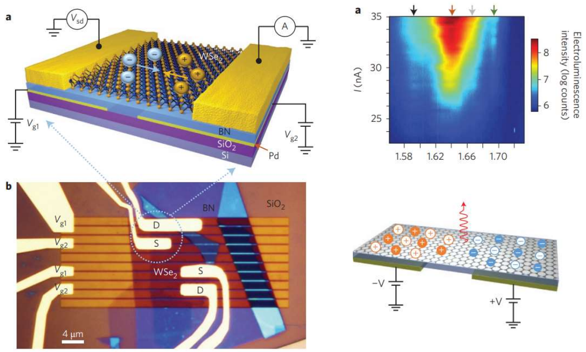
Tunnel device



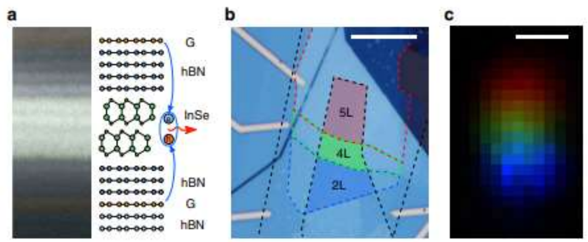
F. Withers et al. Nat. Mater. (2015)



J. Hone. et al. Nano Lett. (2018)

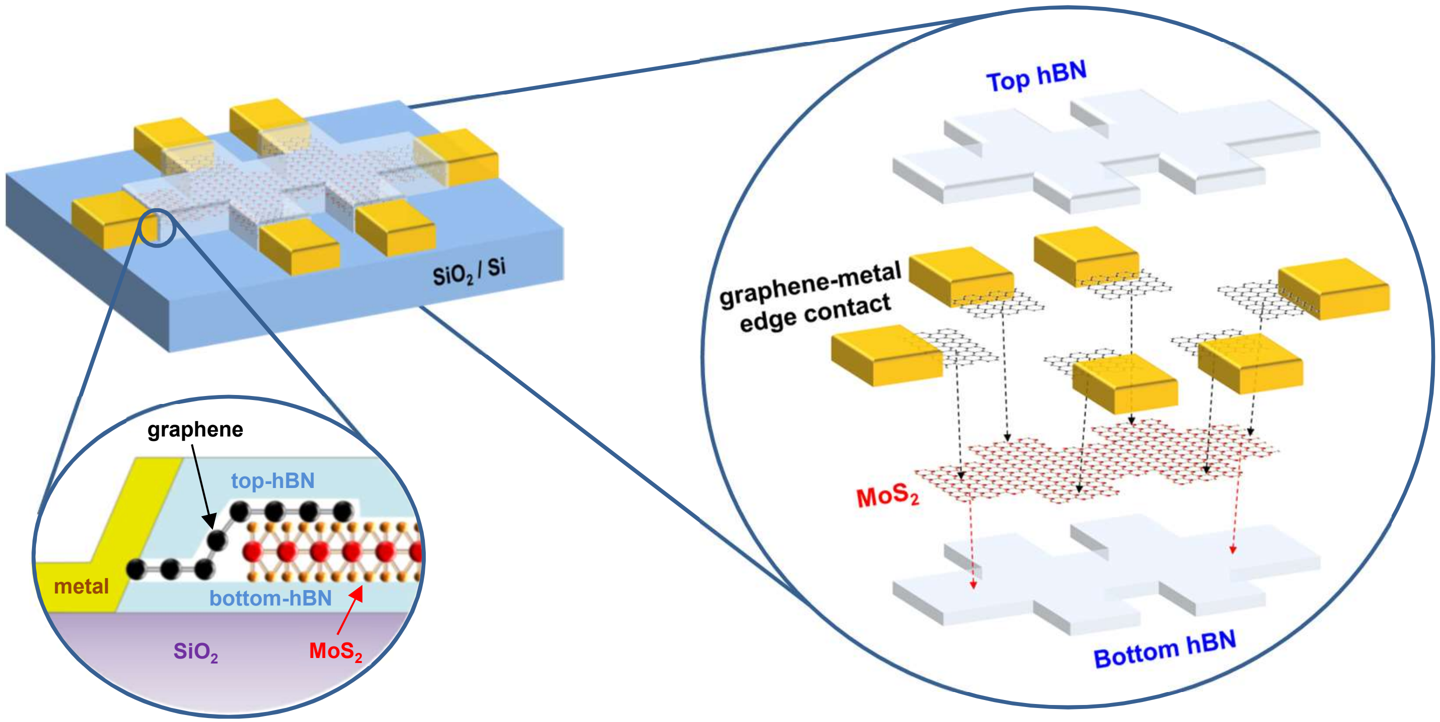


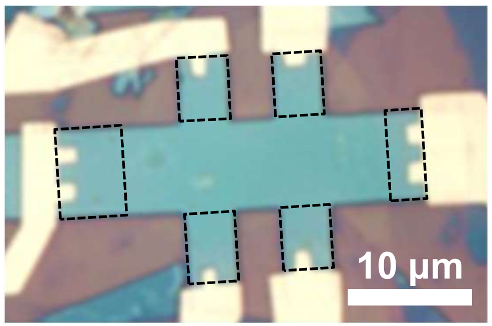
X. Xu. et al. Nat. Nanotechno. (2014)

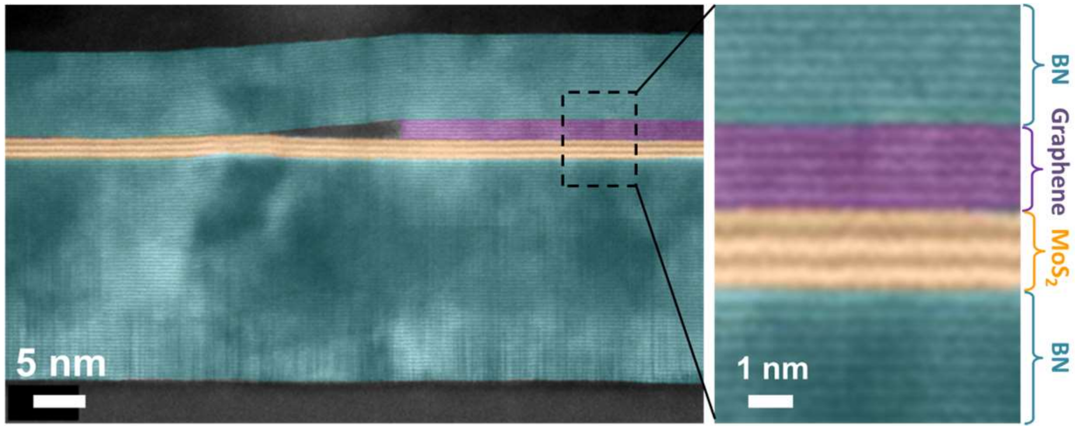


R. Gorbachev et al. Nat. Commun. (2020)

vdW Heterostructure Device Platform



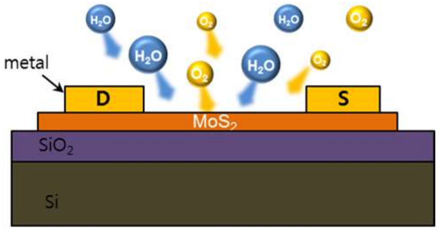




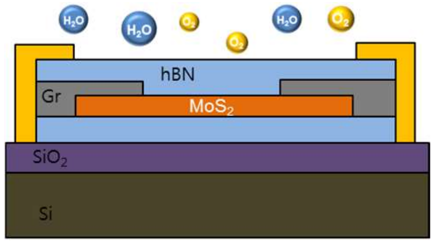
<u>G.H. Lee</u>, *X. Cui, Y.D. Kim Nat. Nanotechno. (2015)*

High Stability and Low Contact Resistance

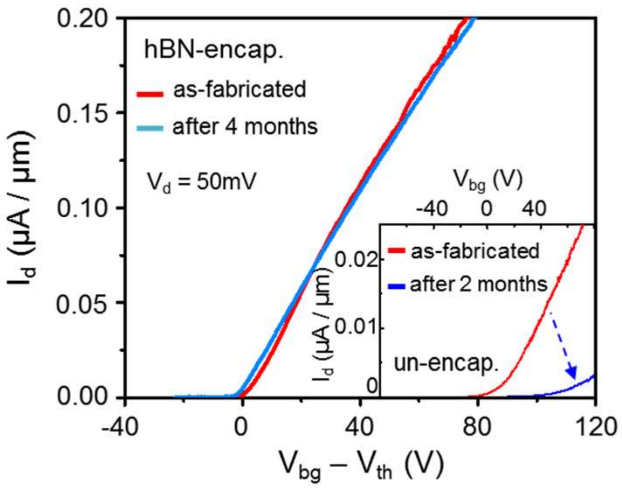
Open structure device

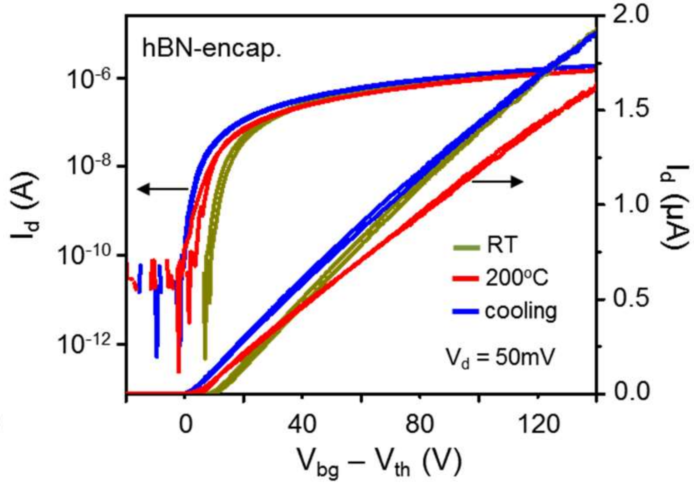


Encapsulated Device

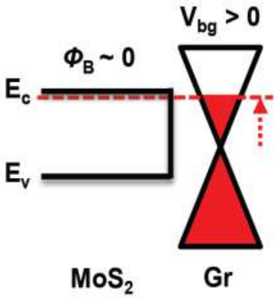


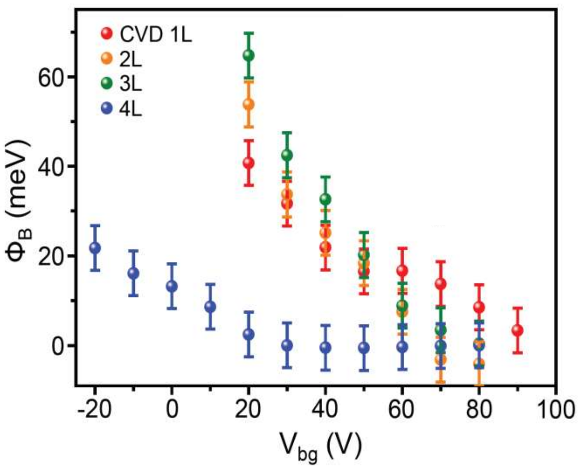
Perfect protection from environment

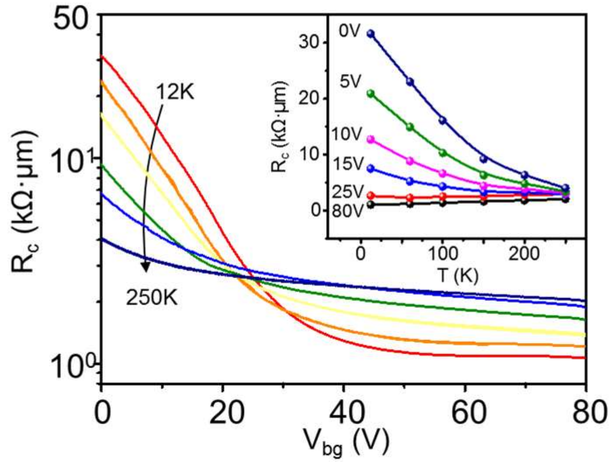




Gate-tunable graphene electrodes

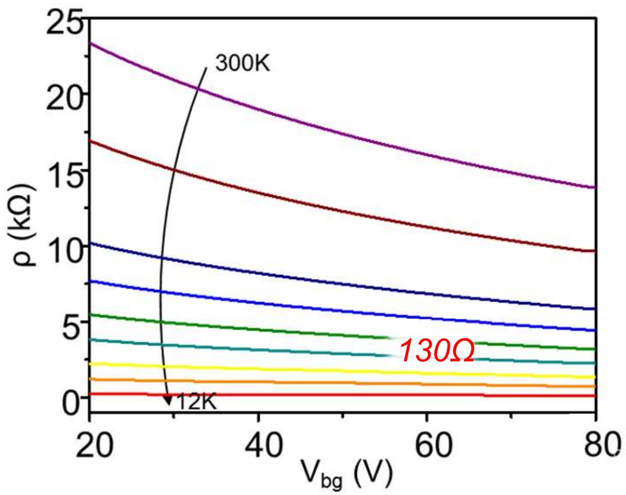


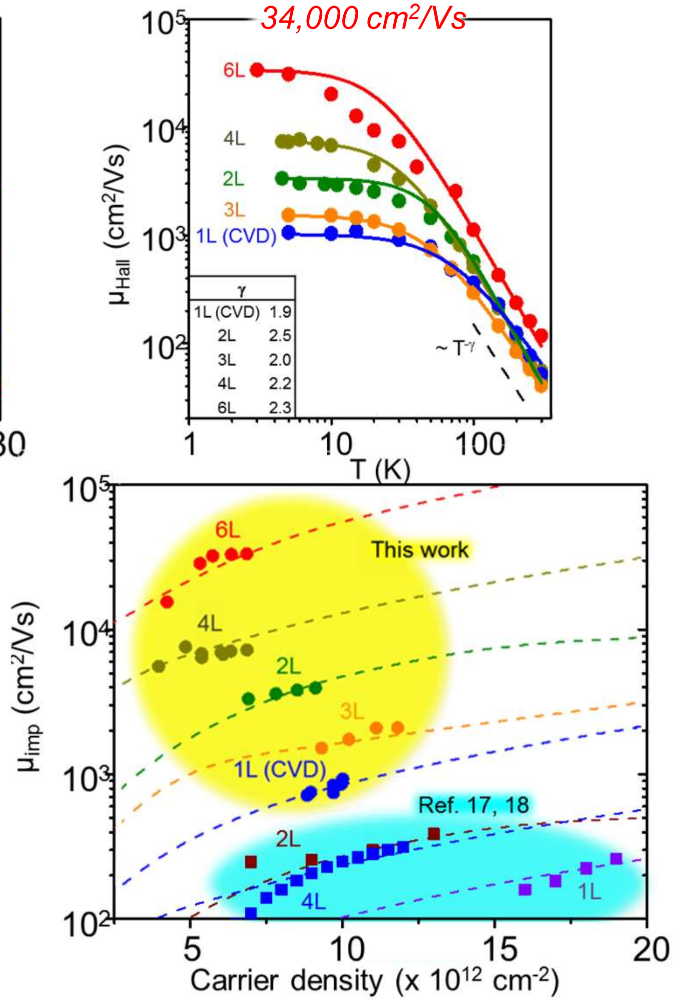


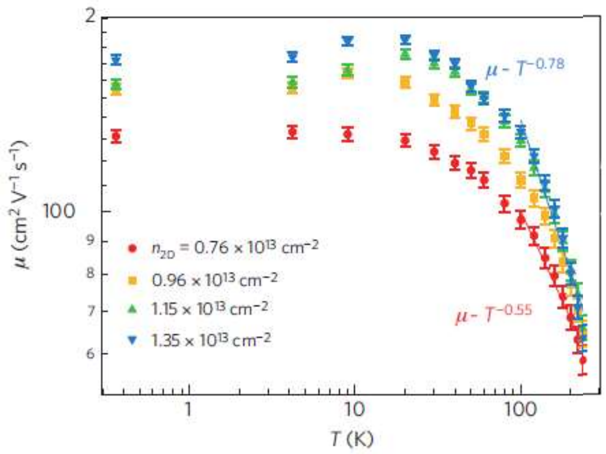


G.H. Lee, X. Cui, Y.D. Kim et al. Nat. Nanotechno. (2015)

Ultrahigh Mobility of MoS_2





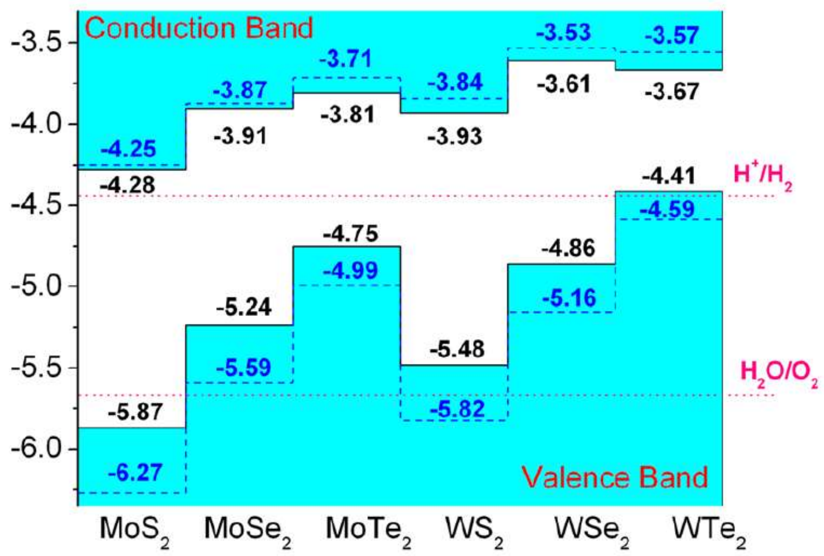


B. Radisavjevic et al. Nature Mater. (2014)

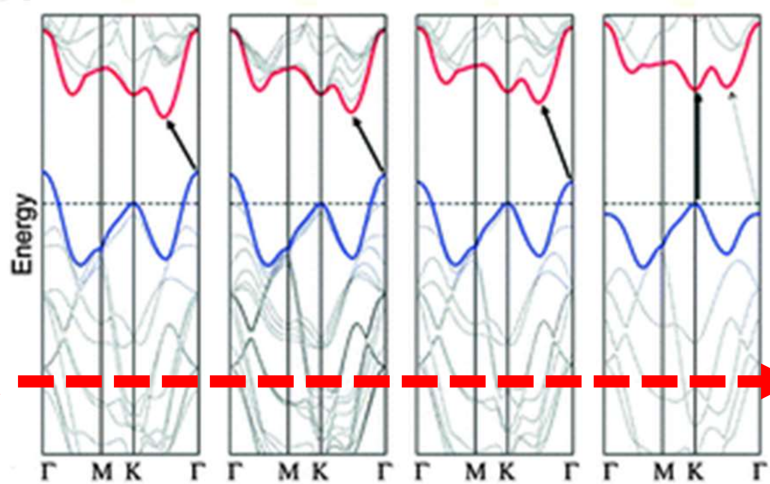
- ❑ Promising carrier mobility of 2D semiconductors
- ❑ Device platform for measurement of intrinsic electrical properties of 2D materials

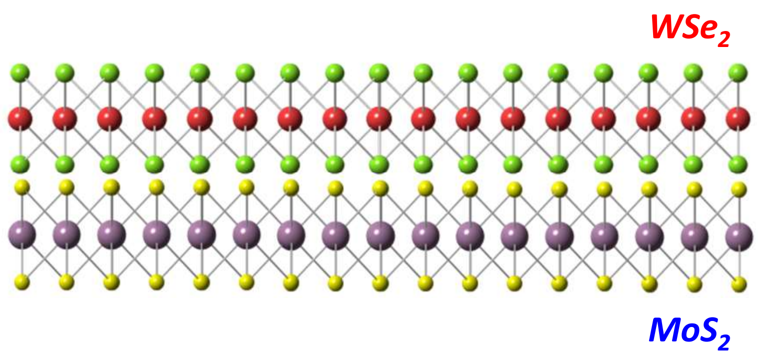
G.H. Lee, X. Cui, Y.D. Kim et al. Nat. Nanotechno. (2015)

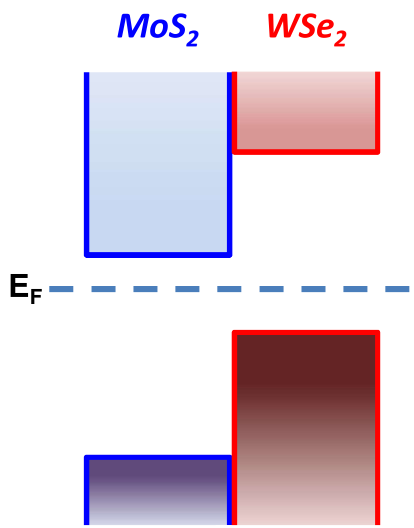
Heterostructures of p-type and n-type



Appl. Phys. Lett. **102**, 012111 (2013)



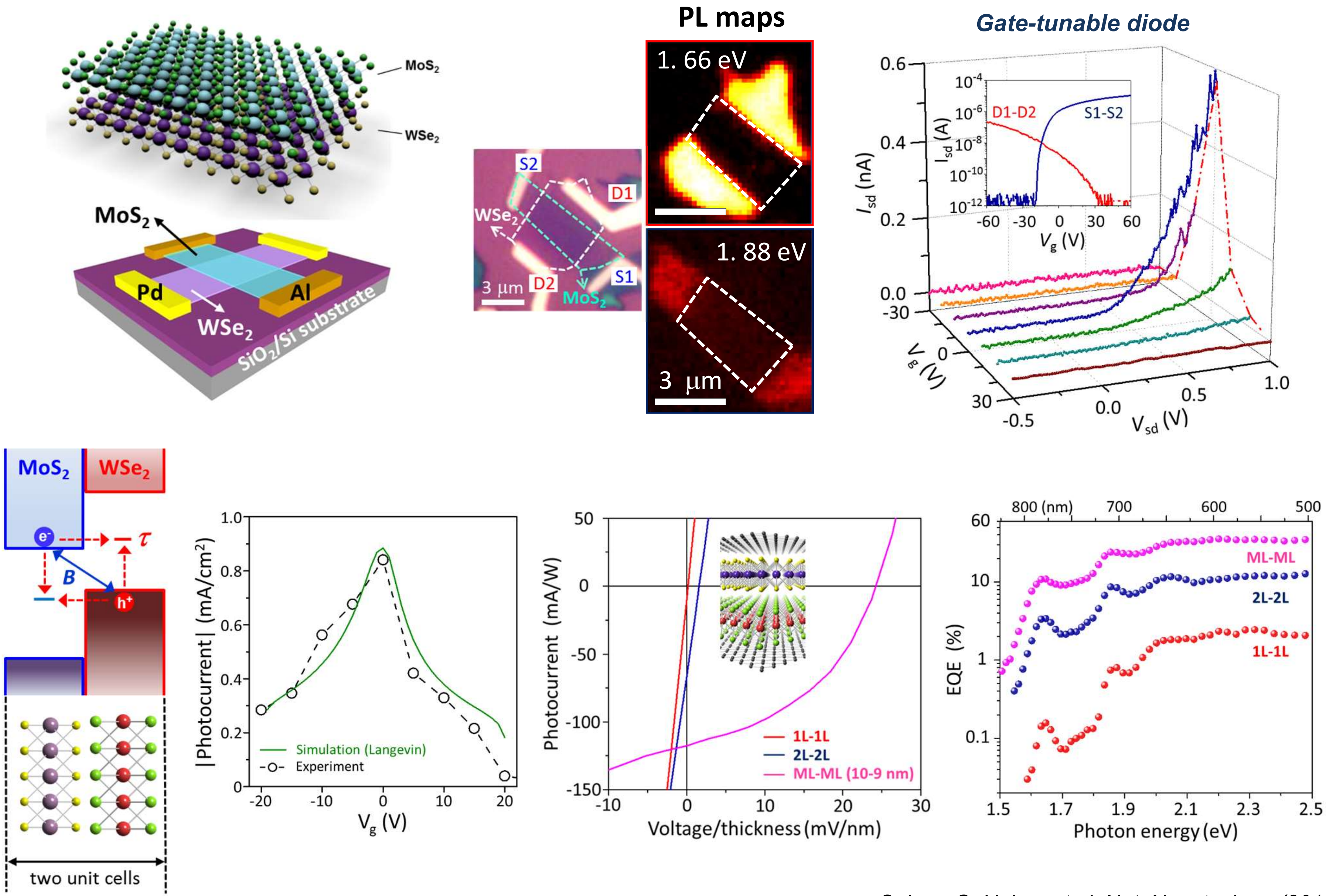




Tunable photovoltaic effect?
Light-emitting?
New band structure at the interface?

C. Lee, G. H. Lee et al. Nat. Nanotechno. (2014)

Ultra-thin p-n Junction Devices



C. Lee, G. H. Lee et al. Nat. Nanotechno. (2014)