

Semiconductor Devices II

Part 2

Chapter 4: Photodetectors and LEDs

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Electrical Engineering Institute



[Outline] Chapter 4: Photodetectors and LEDs

Optoelectronics in the IT context

Optical properties of TMDCs

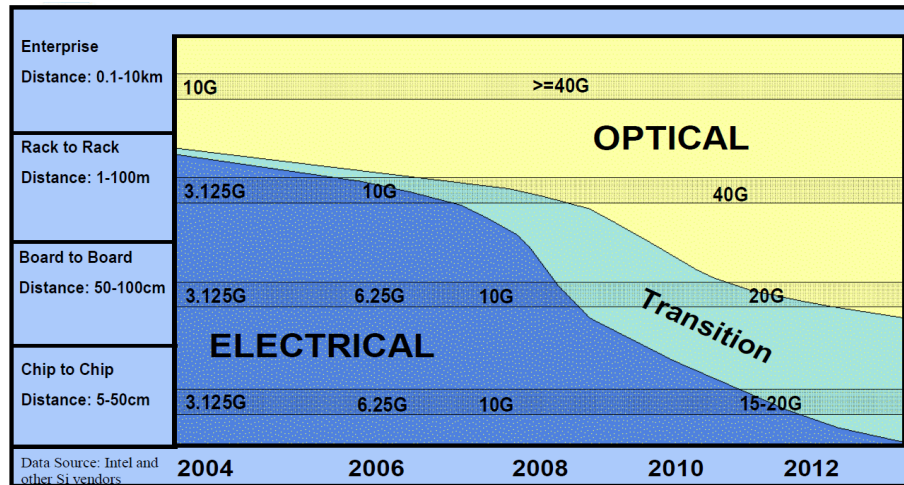
- Reflectance/absorbance
- Band structure
- Excitons – band gap, binding energy
- Tuning

Devices

- Photodetectors
- Electroluminescent devices

Optoelectronics and IT devices

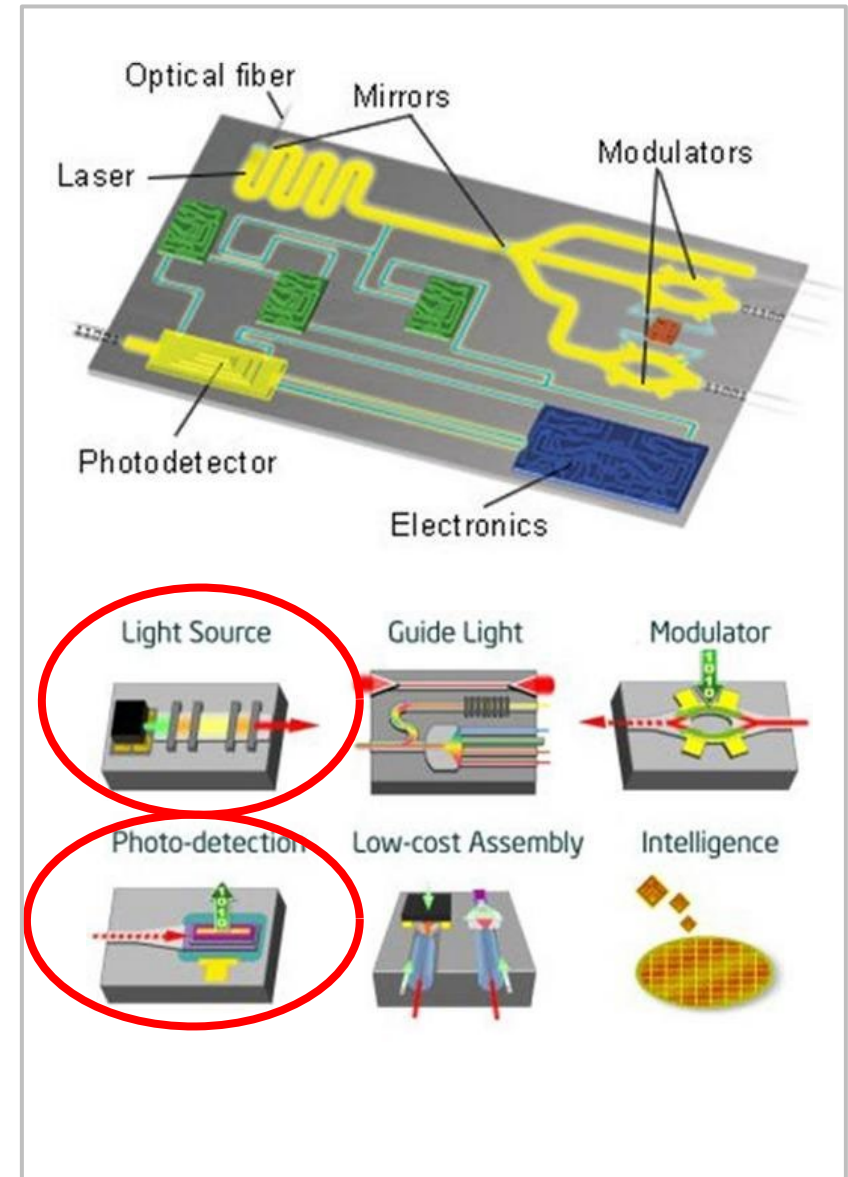
Data load



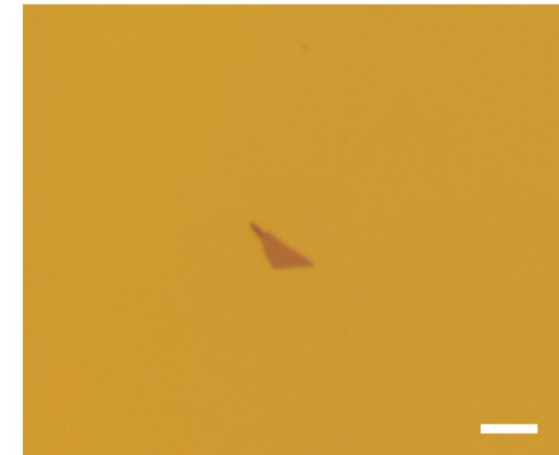
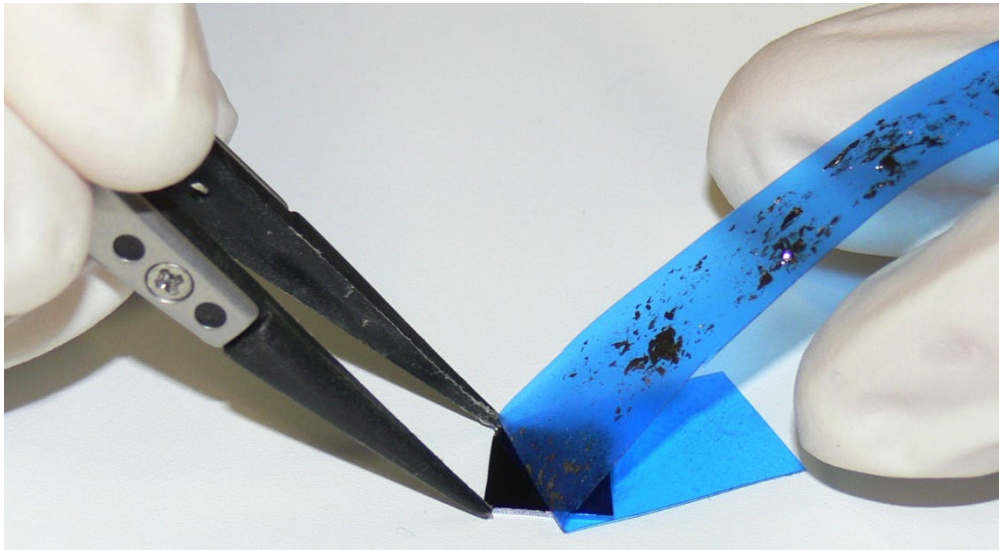
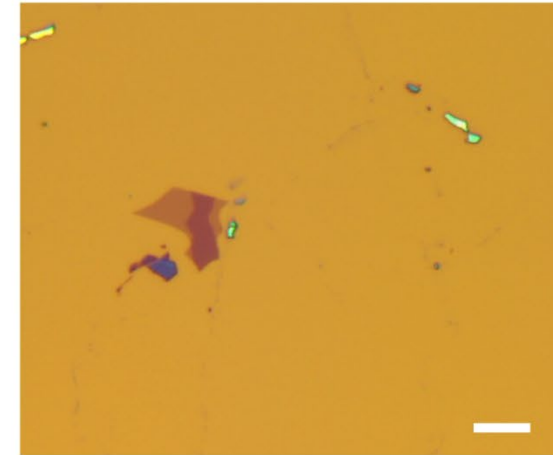
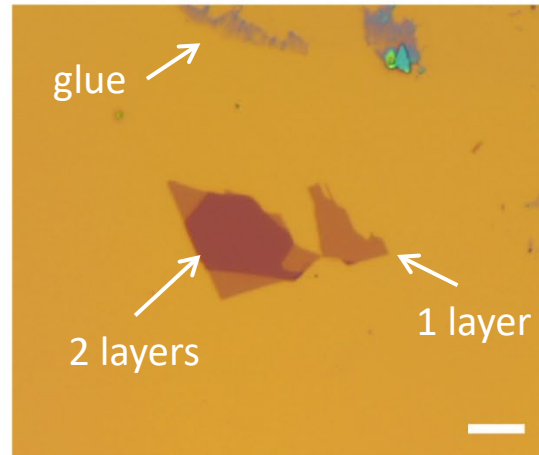
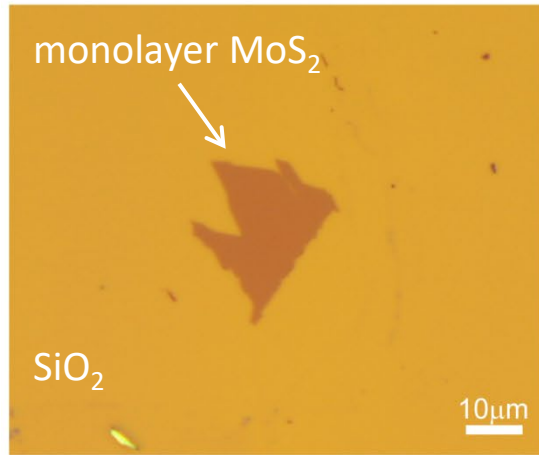
Flexible devices



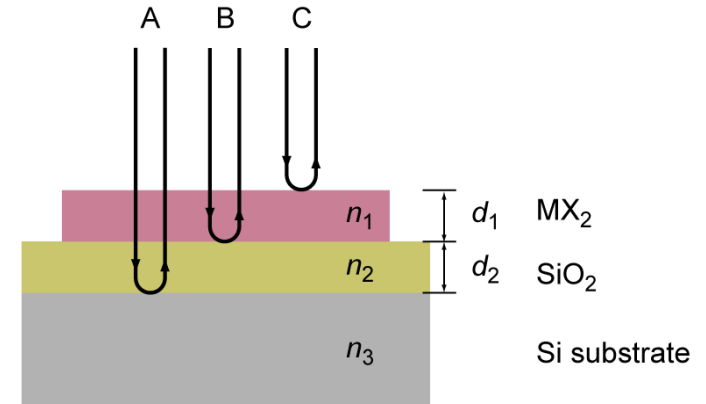
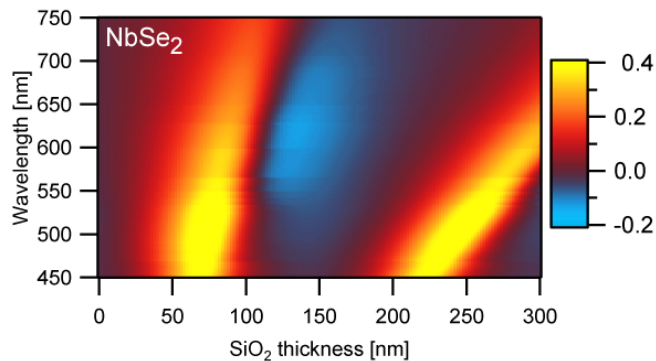
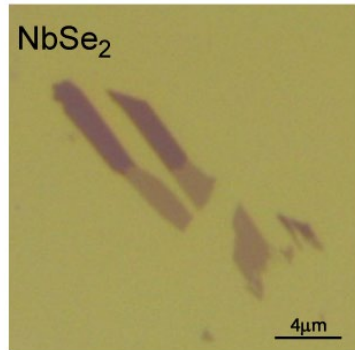
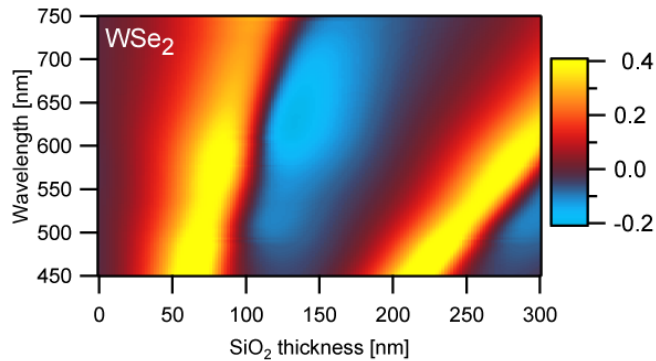
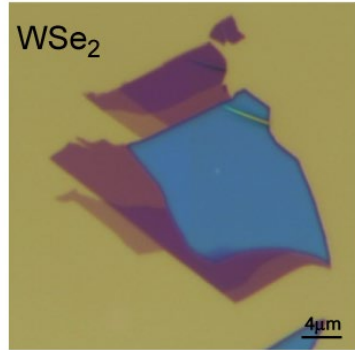
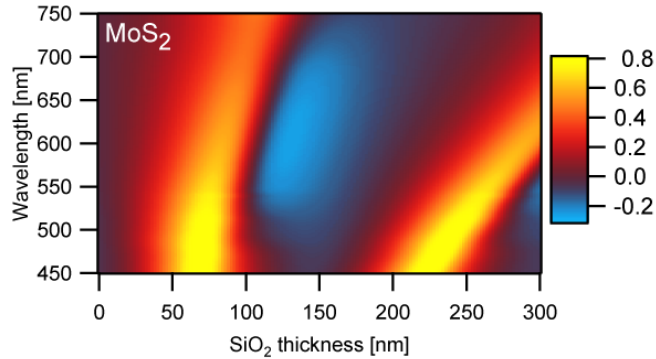
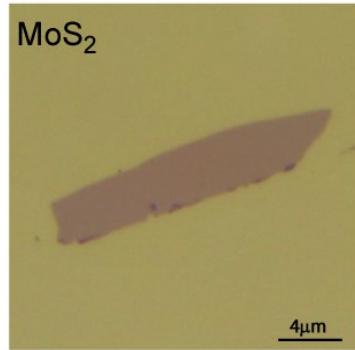
From the TV show Westworld



Visibility of TMDC monolayers



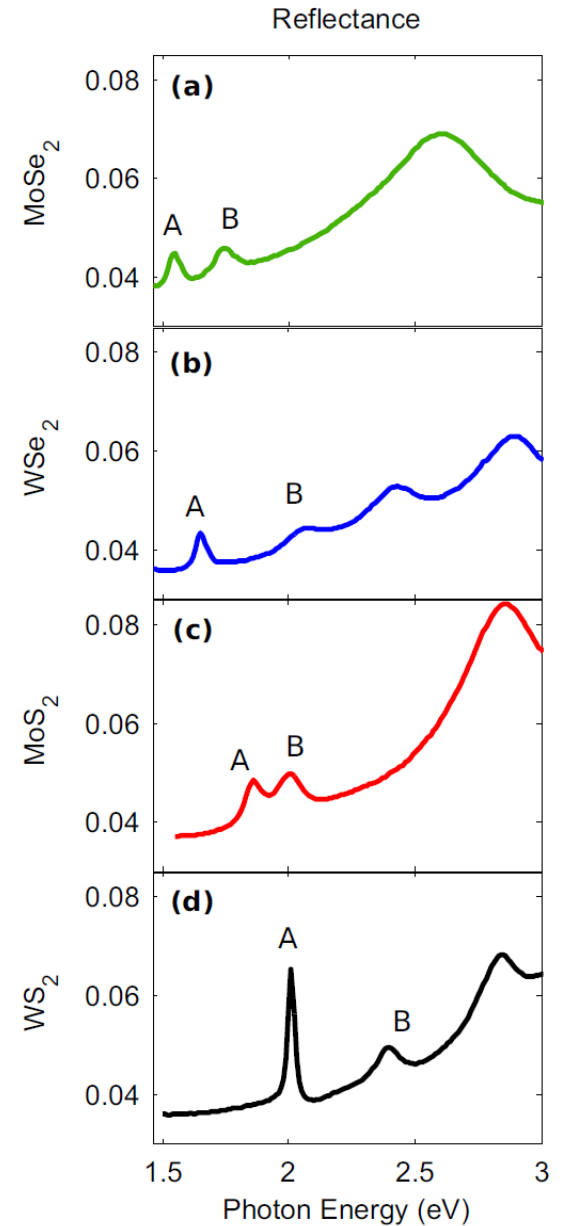
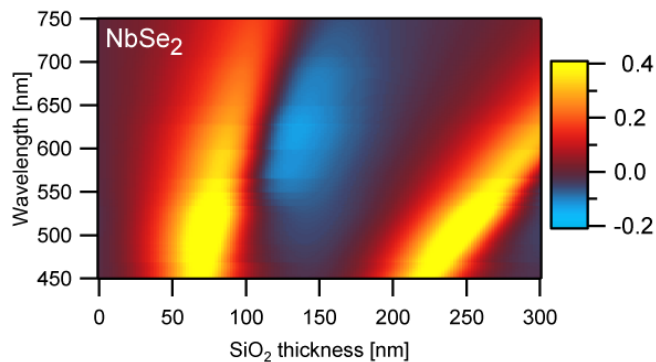
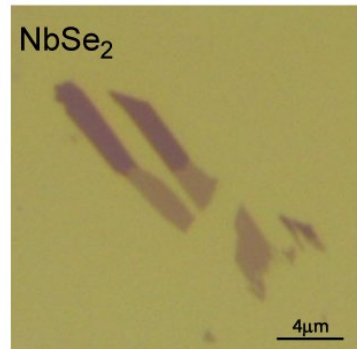
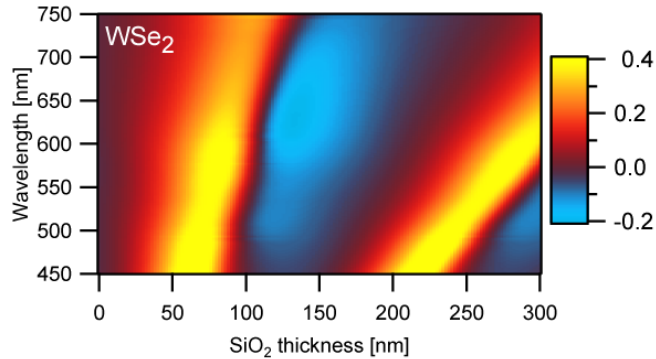
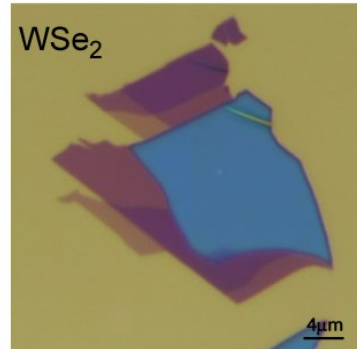
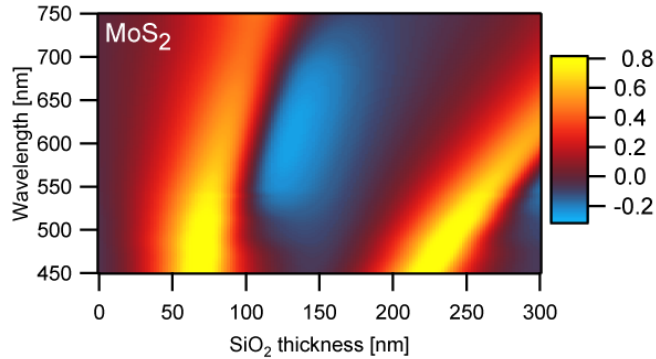
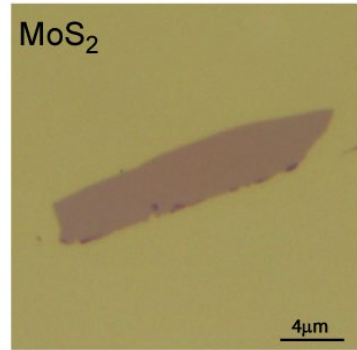
Visibility of TMDC monolayers – contrast maps



Benameur...Kis; arxiv:1006.1048 (2010)

Benameur...Kis; Nanotechnology (2011)

Visibility of TMDC monolayers – contrast maps



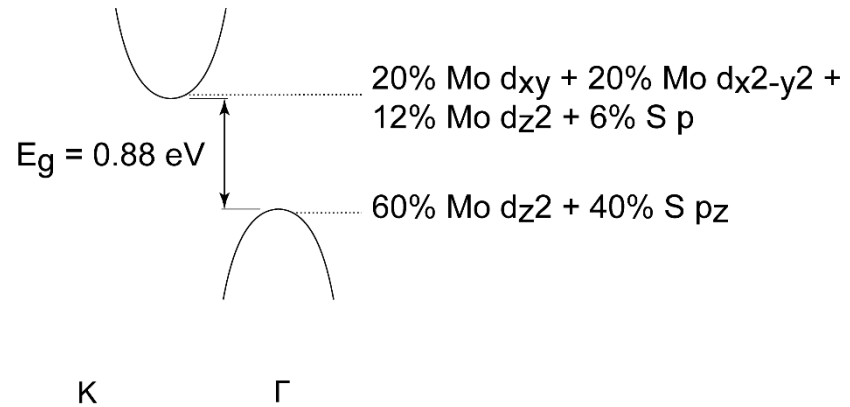
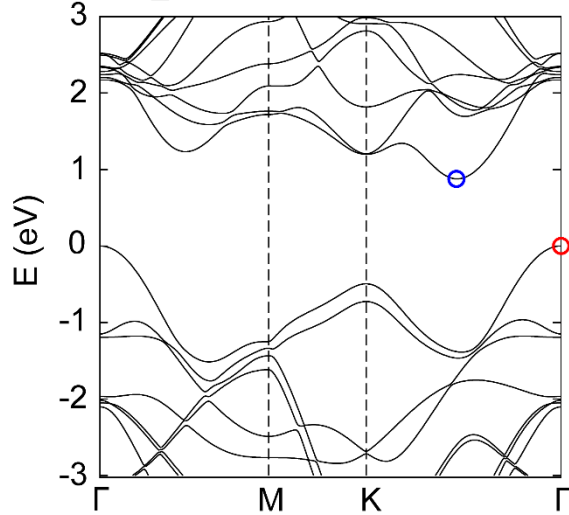
Benameur...Kis; arxiv:1006.1048 (2010)

Benameur...Kis; Nanotechnology (2011)

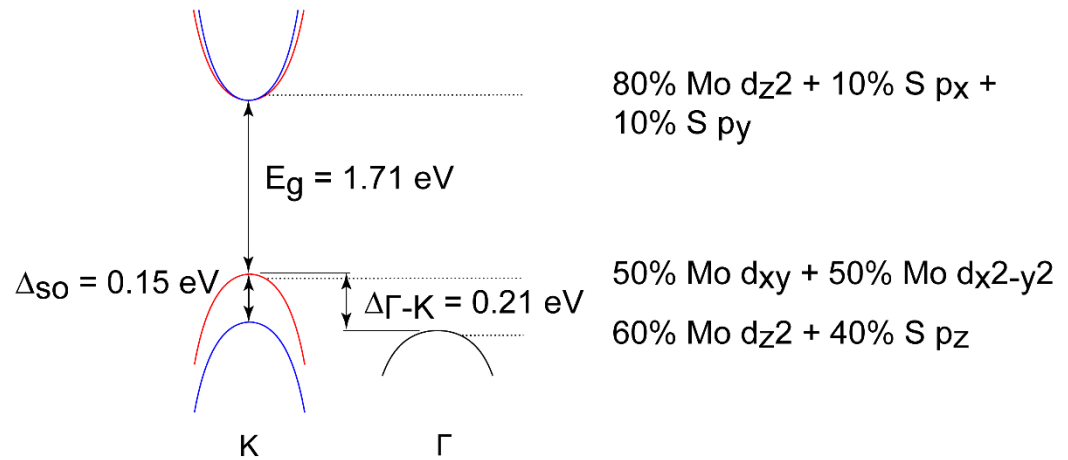
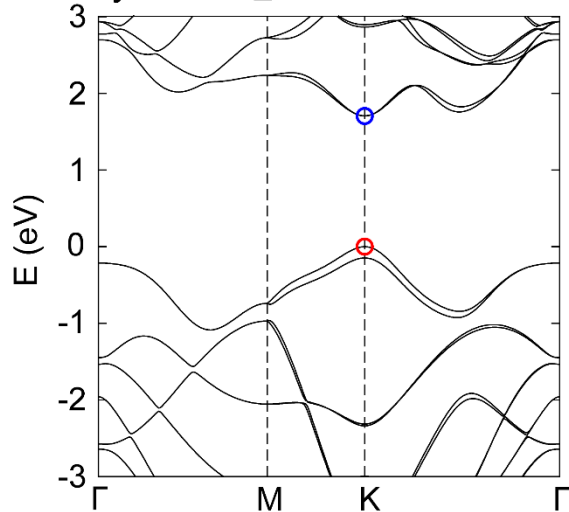
Li et al. Phys. Rev. B (2014)

Band structure of 2H MoS₂

Bulk MoS₂



Monolayer MoS₂



Kuc...Heine; Physical Review B (2011)

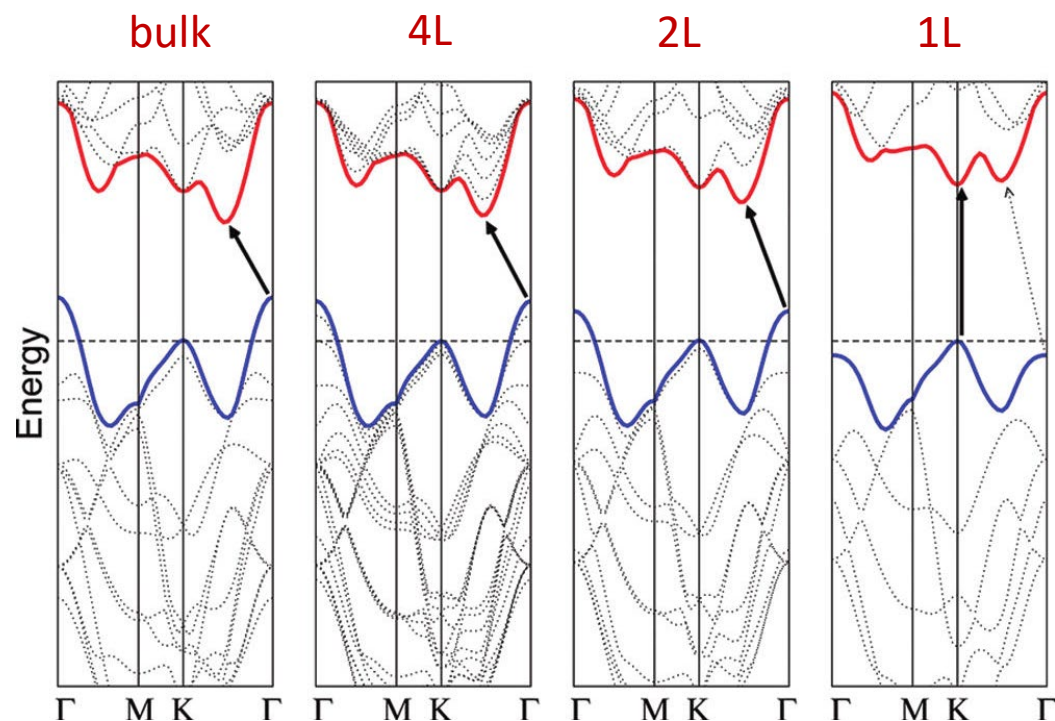
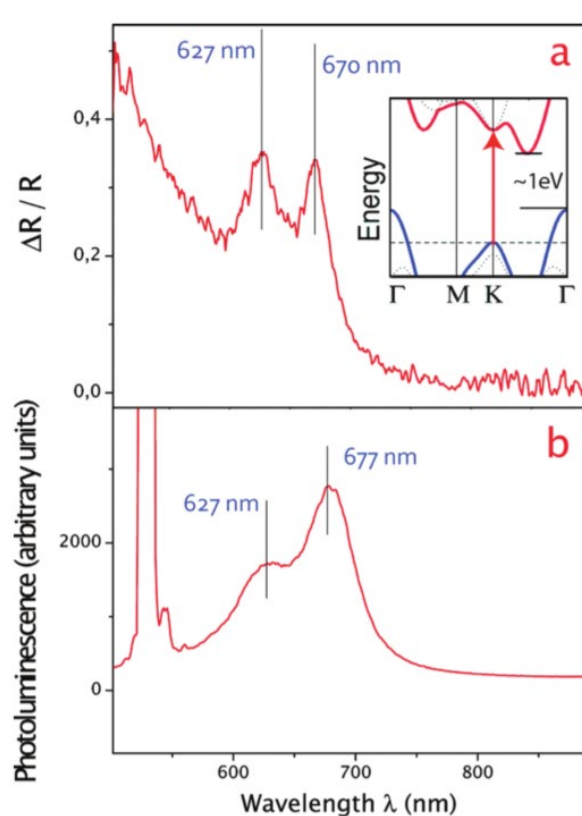
Yazyev and Kis; Materials Today (2014)

Emerging Photoluminescence in Monolayer MoS₂

Splendiani...Wang; Nano Lett. (2010)

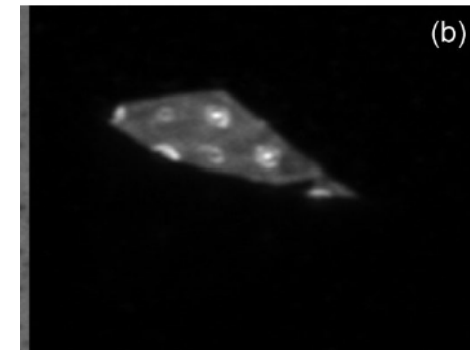
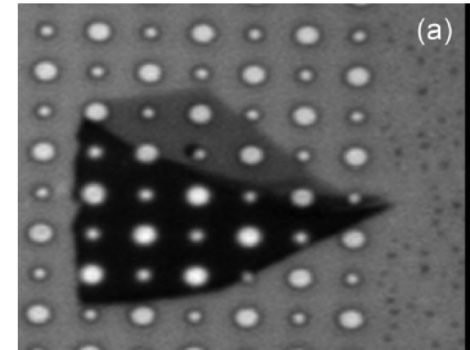
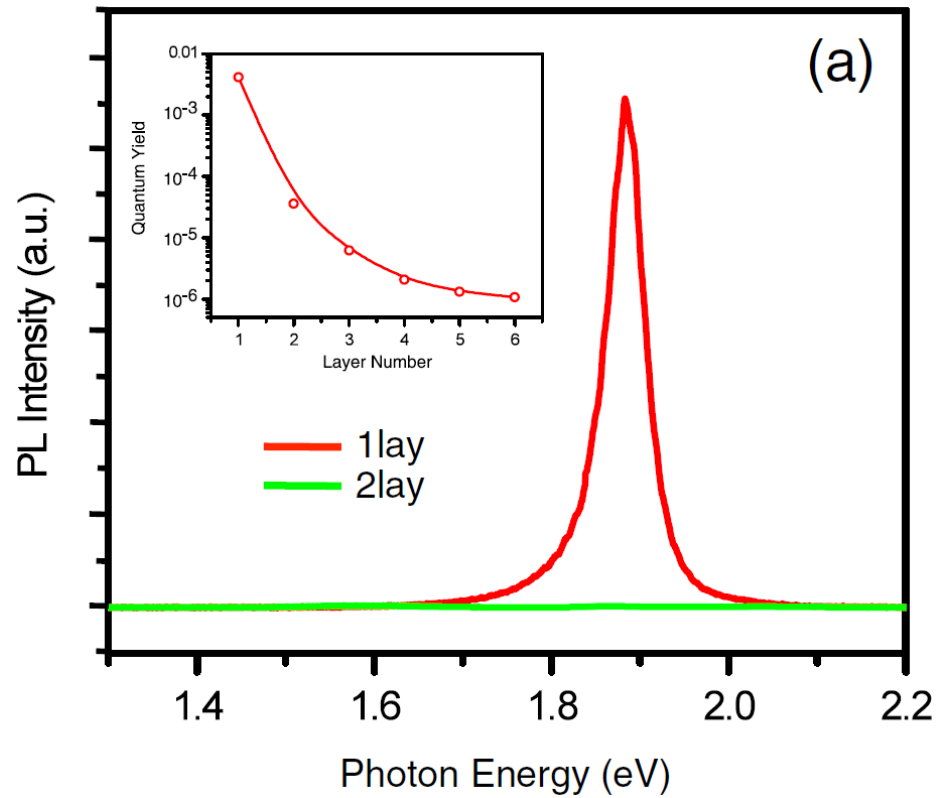
Andrea Splendiani,^{†,‡} Liang Sun,[†] Yuanbo Zhang,[†] Tianshu Li,[§] Jonghwan Kim,[†] Chi-Yung Chim,[†] Giulia Galli,[§] and Feng Wang^{*,†,||}

[†]Physics Department, University of California at Berkeley, Berkeley, California 94720, [‡]Scuola Galileiana di Studi Superiori di Padova, 35122 Padova, Italy, [§]Chemistry Department, University of California at Davis, Davis, California 95616, and ^{||}Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720



Also later work by Mak...Heinz; PRL (2010)

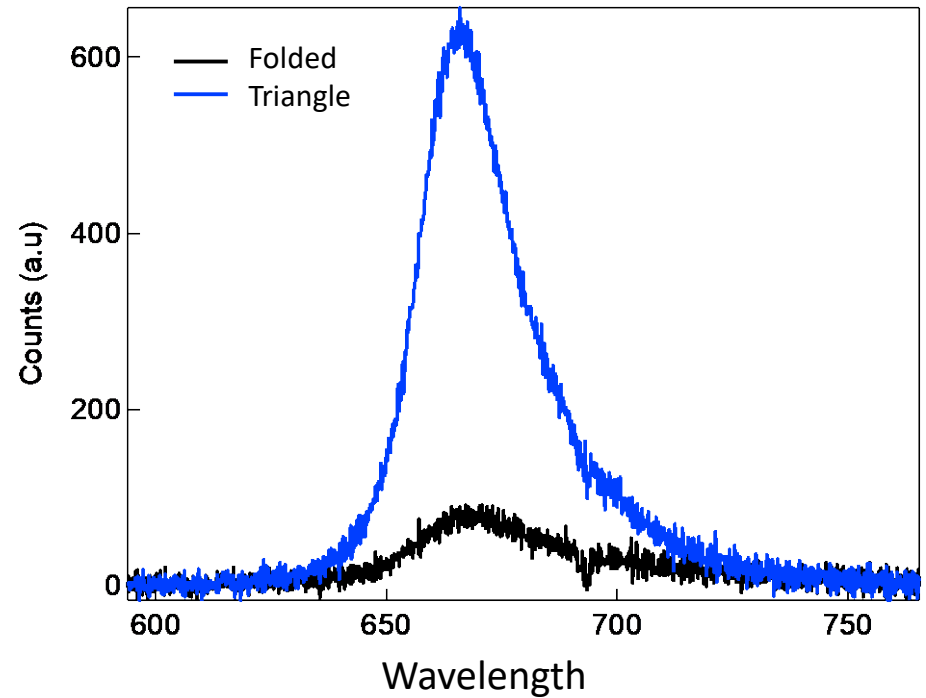
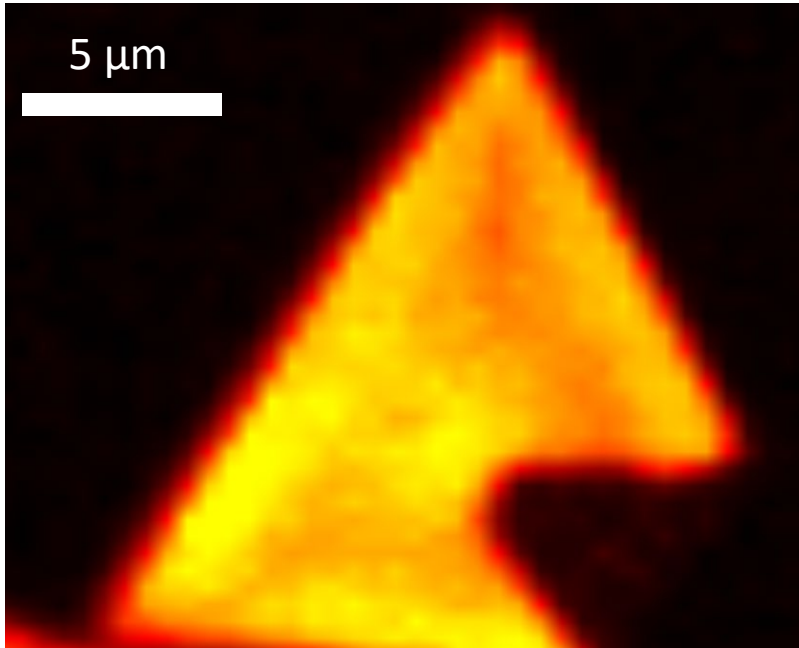
Photoluminescence



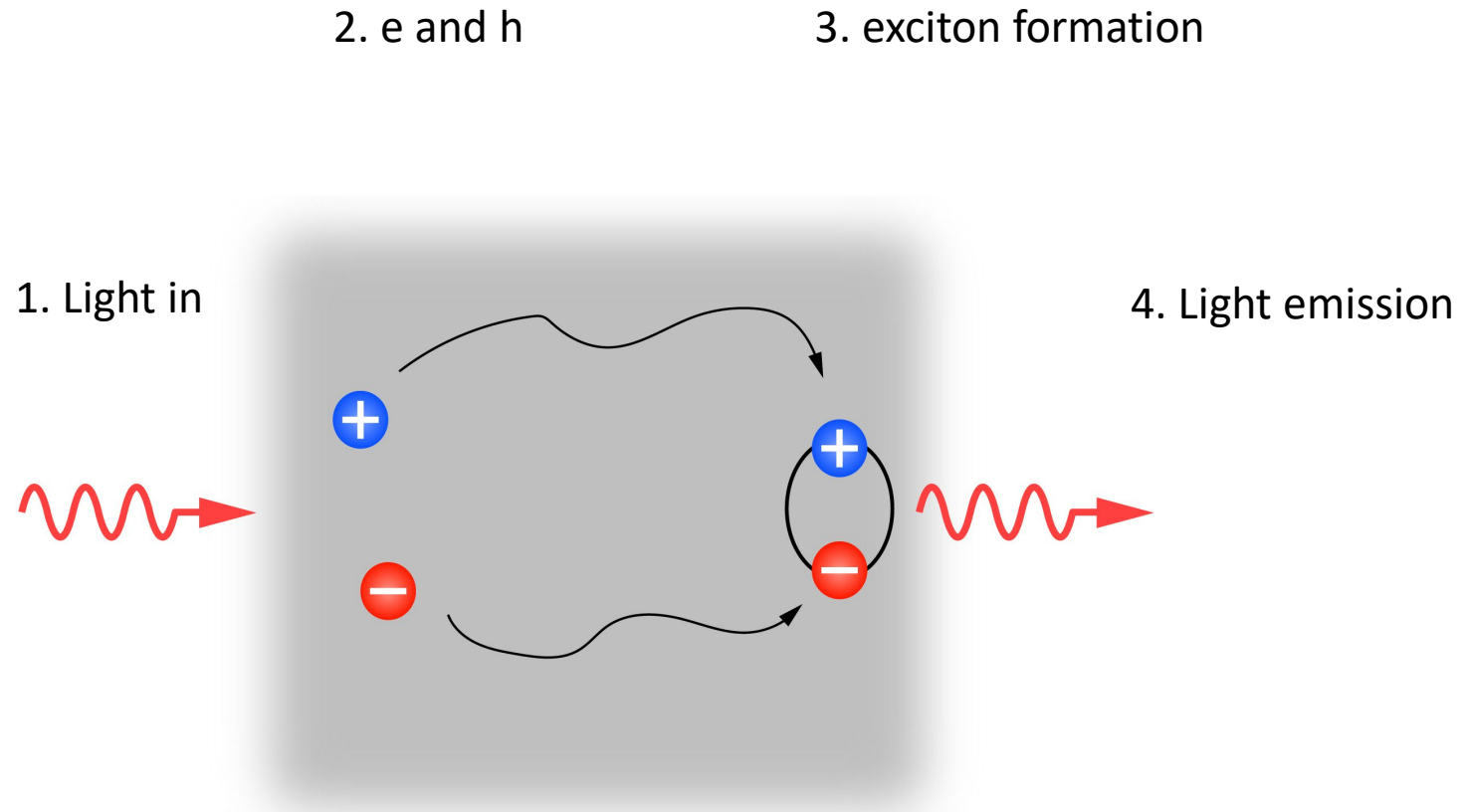
Mak et al., Physical Review Letters 2010

Photoluminescence

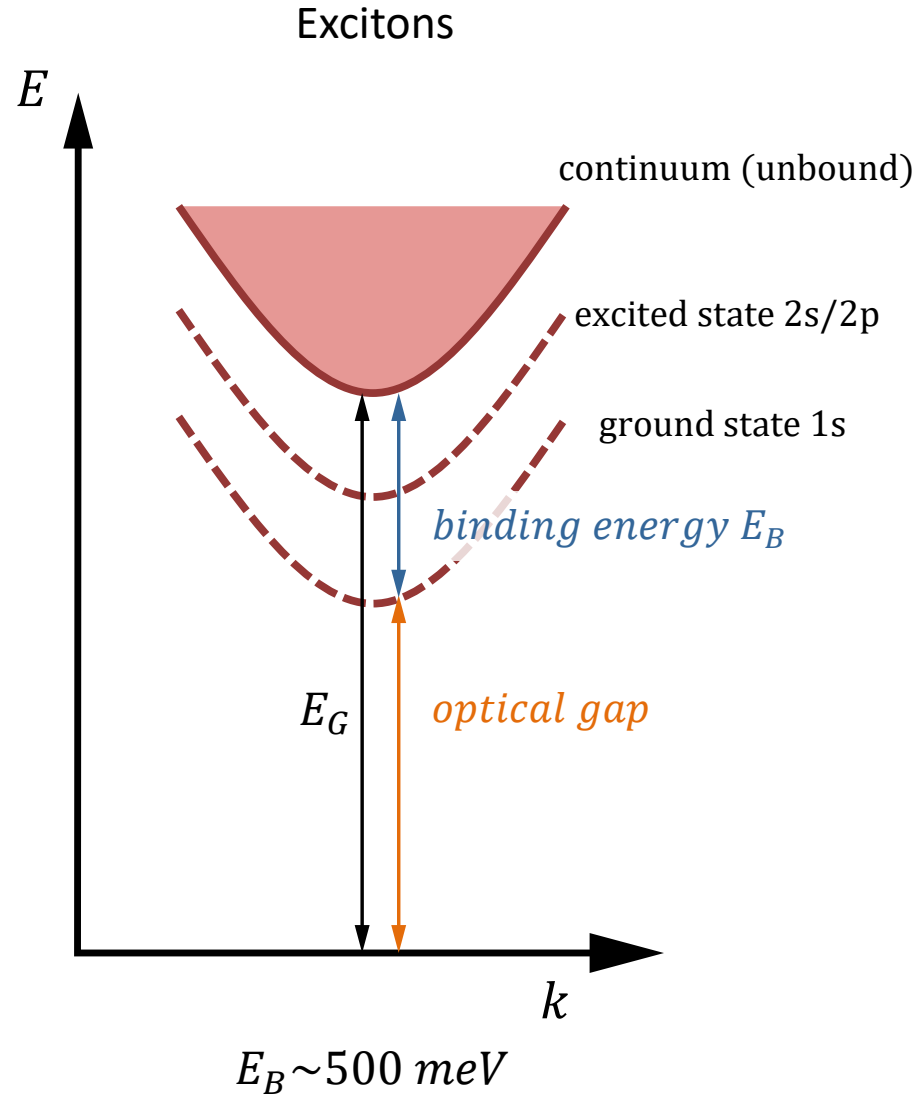
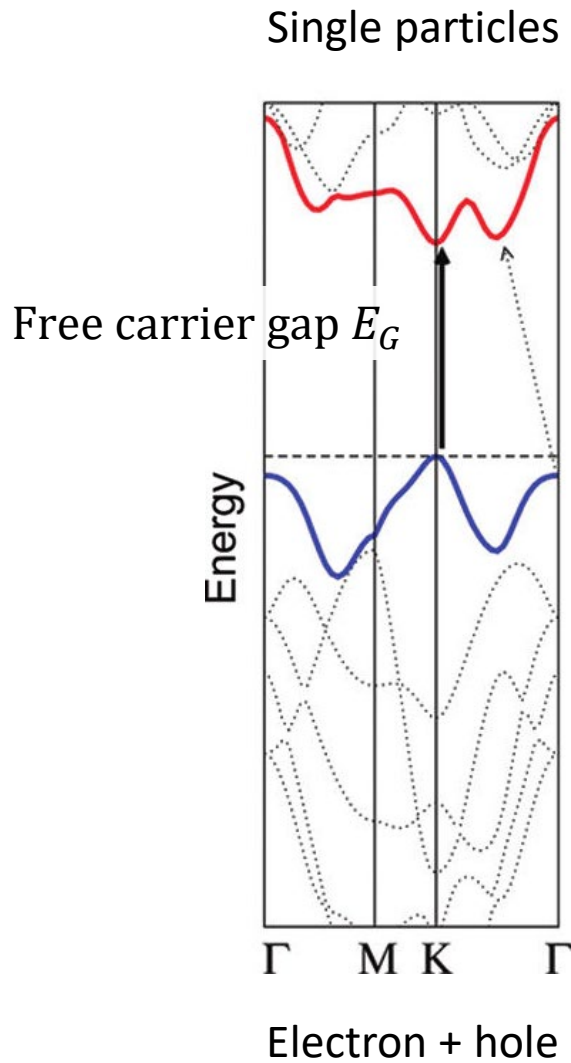
From a CVD-grown MoS_2



Excitons



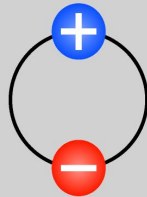
Excitons



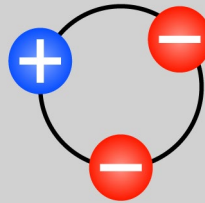
Excitons visible at room temperature

Excitonic complexes

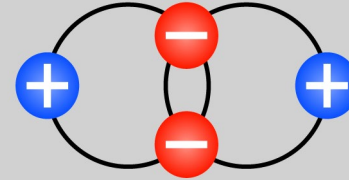
Exciton



Trion



Biexciton

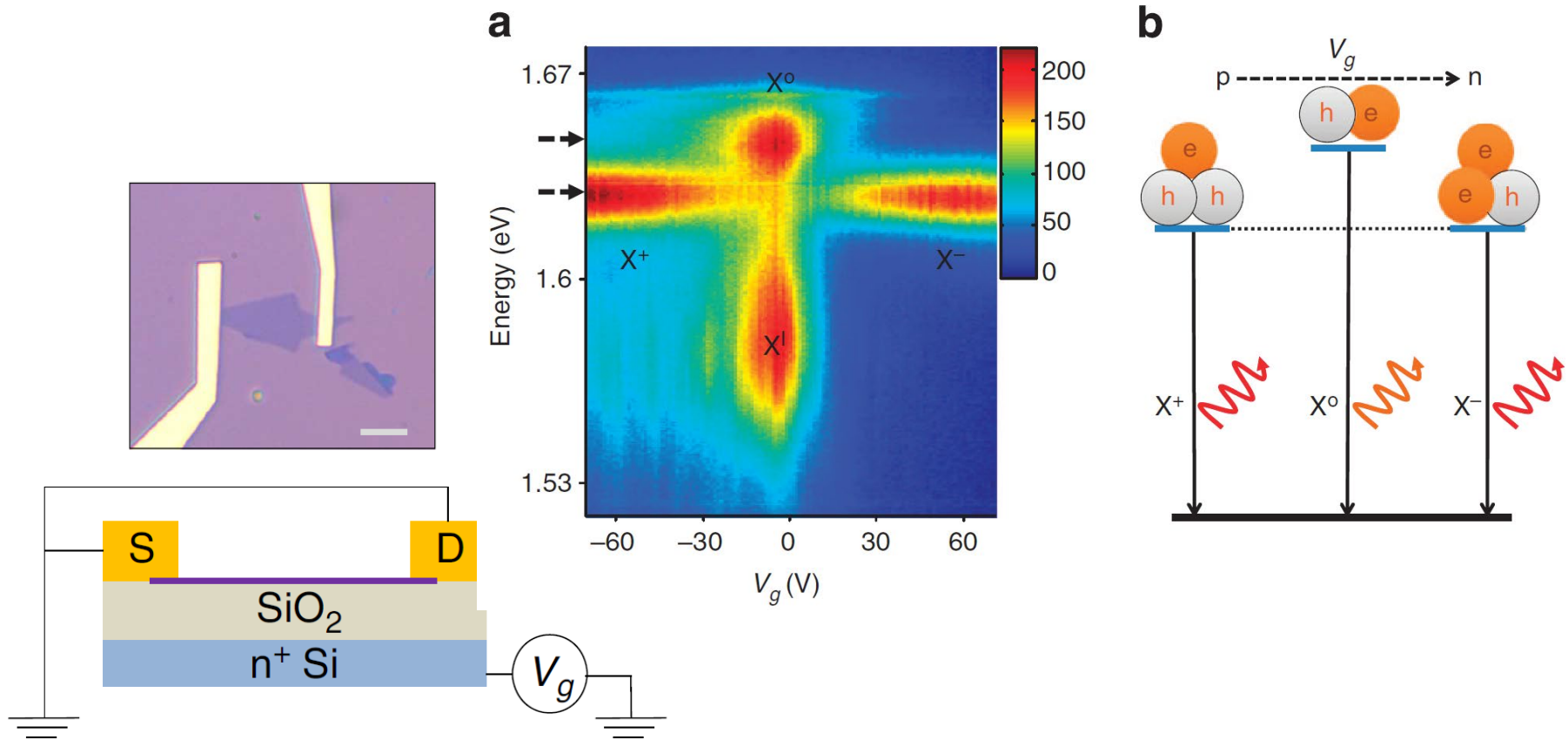


Neutral exciton
 X^0

Charged exciton
 X^-, X^+

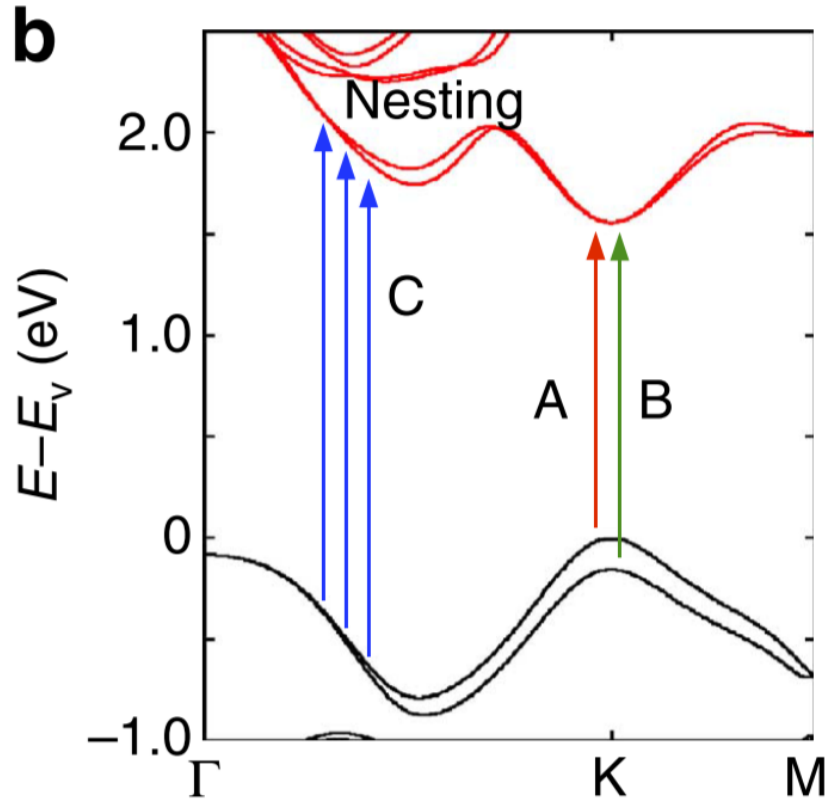
Exciton molecule
 XX

Electrostatic control of exciton charge in MoSe₂

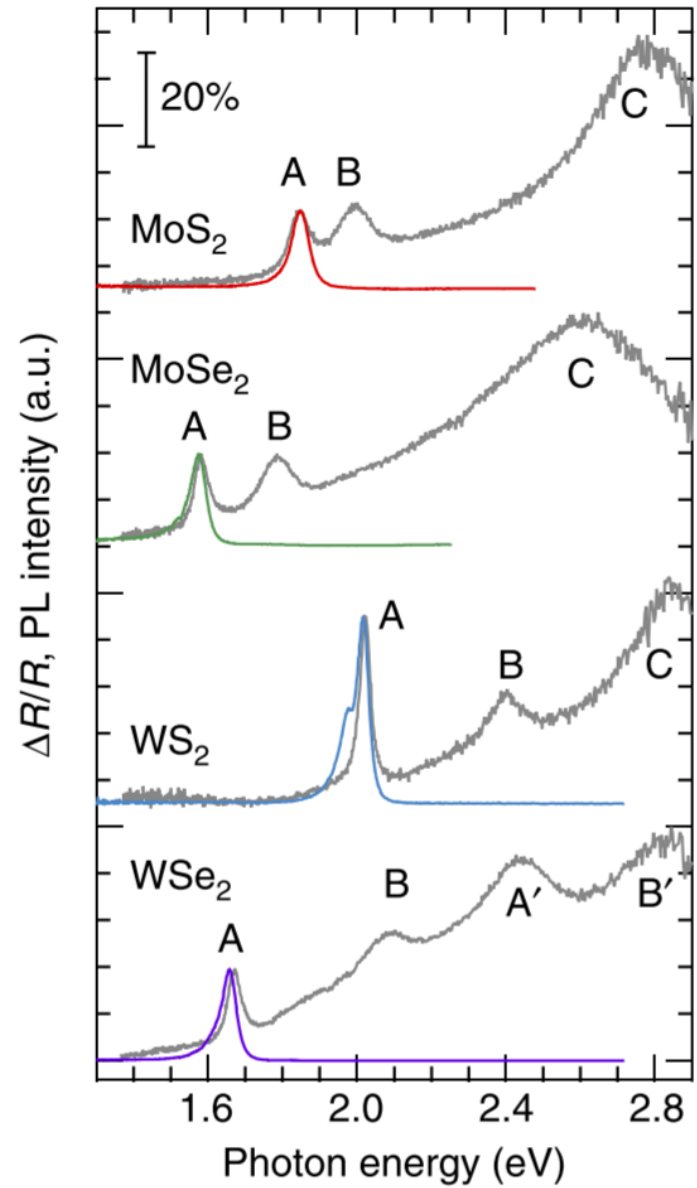


Ross et al, Nat Commun. (2013)

A, B, C of excitons



c

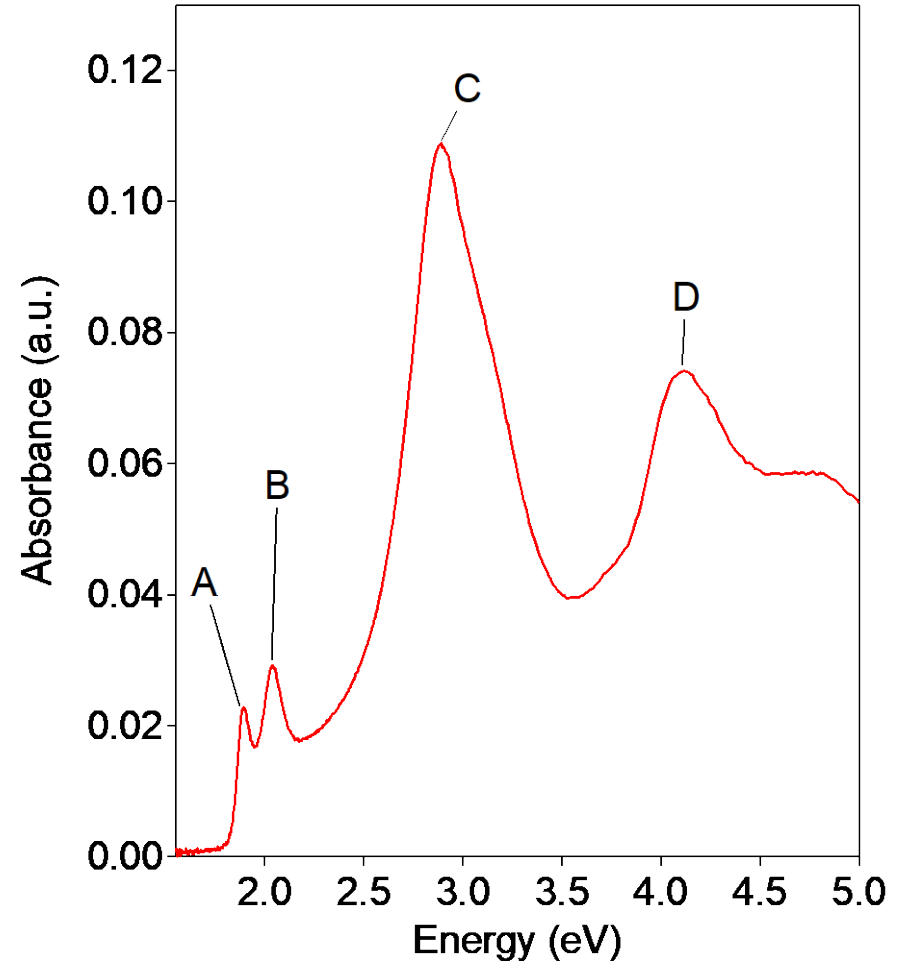


Kozawa...Eda; Nature Communications (2014)

A, B, C of excitons



Spectrophotometer

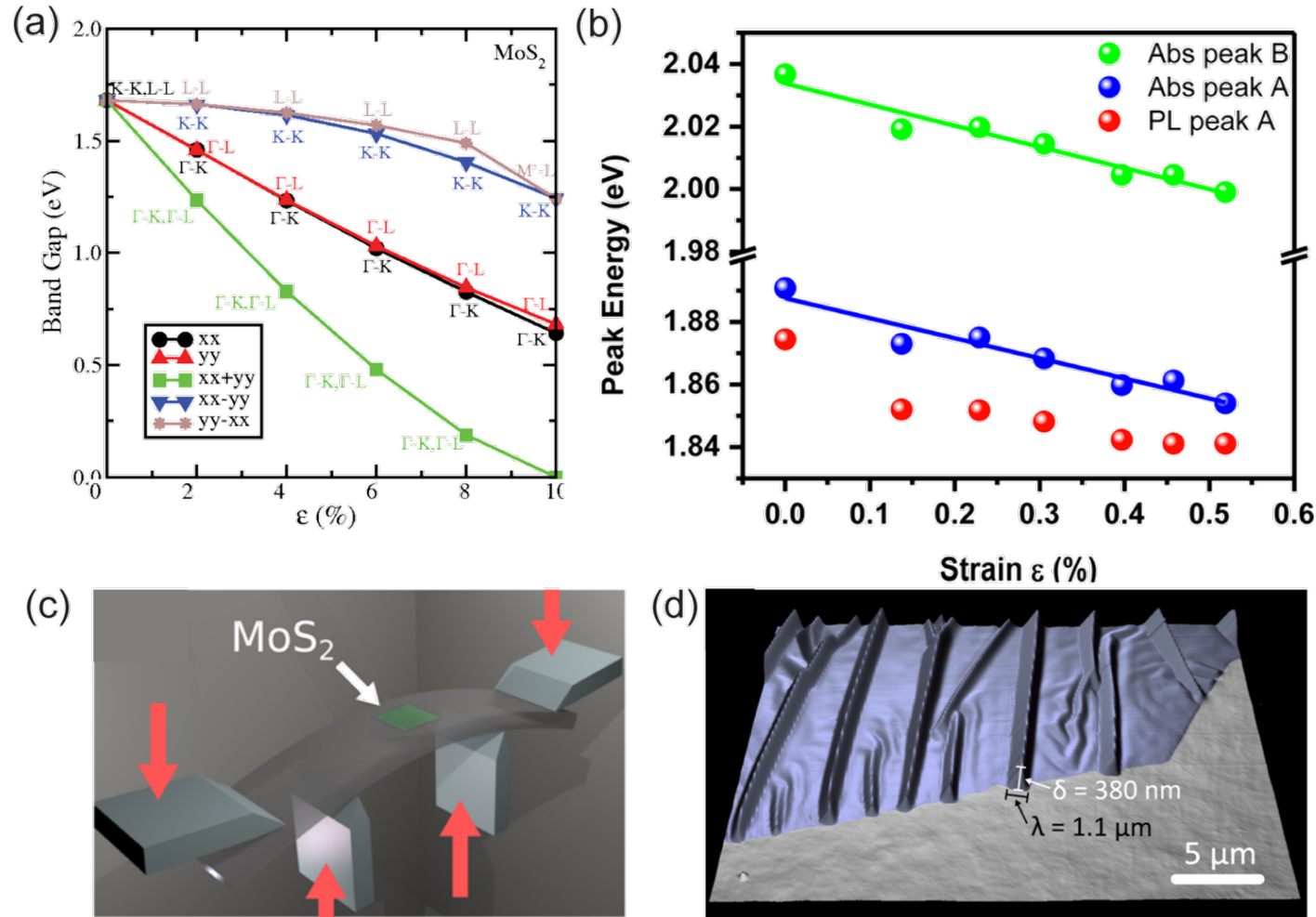


Large-area CVD MoS₂

Dumcenco...Kis; arXiv:1405.0129

Dumcenco...Kis; ACS Nano (2015)

Band gap tuning with strain



Gap tuning in 1L:

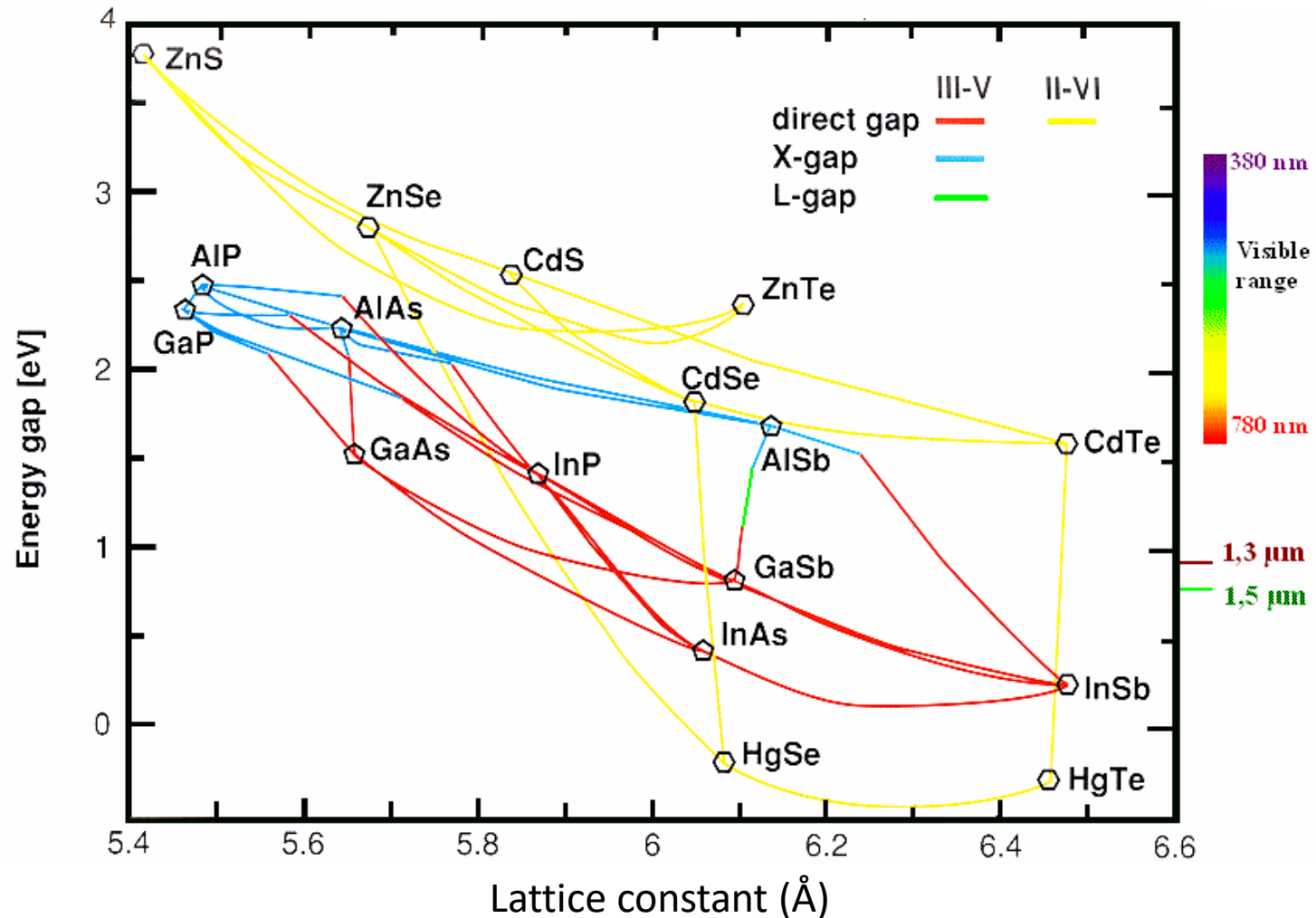
$$\frac{dE_g}{d\epsilon} = -70 \text{ meV}/\%$$

- (a) Johari...Shenoy; ACS Nano (2012)
 (b) He...Shan; Nano Letters (2013)
 (c) Conley...Bolotin; Nano Letters (2013)
 (d) Castellanos-Gomez...Steele; Nano Letters (2013)

Band gap tuning by alloying

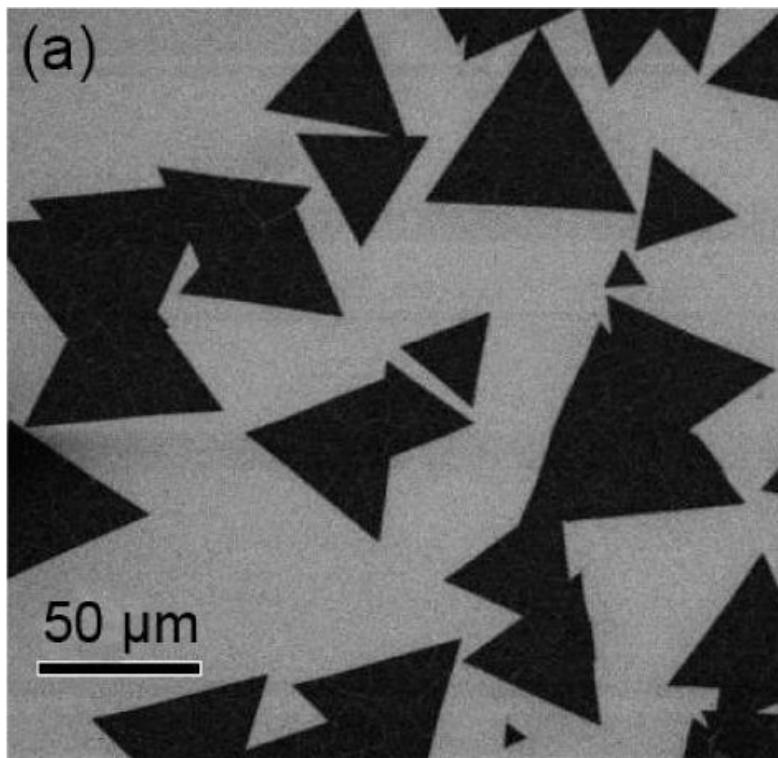
For III-V and II-VI materials

- As long as the lattice type stays the same, composition can be tuned continuously

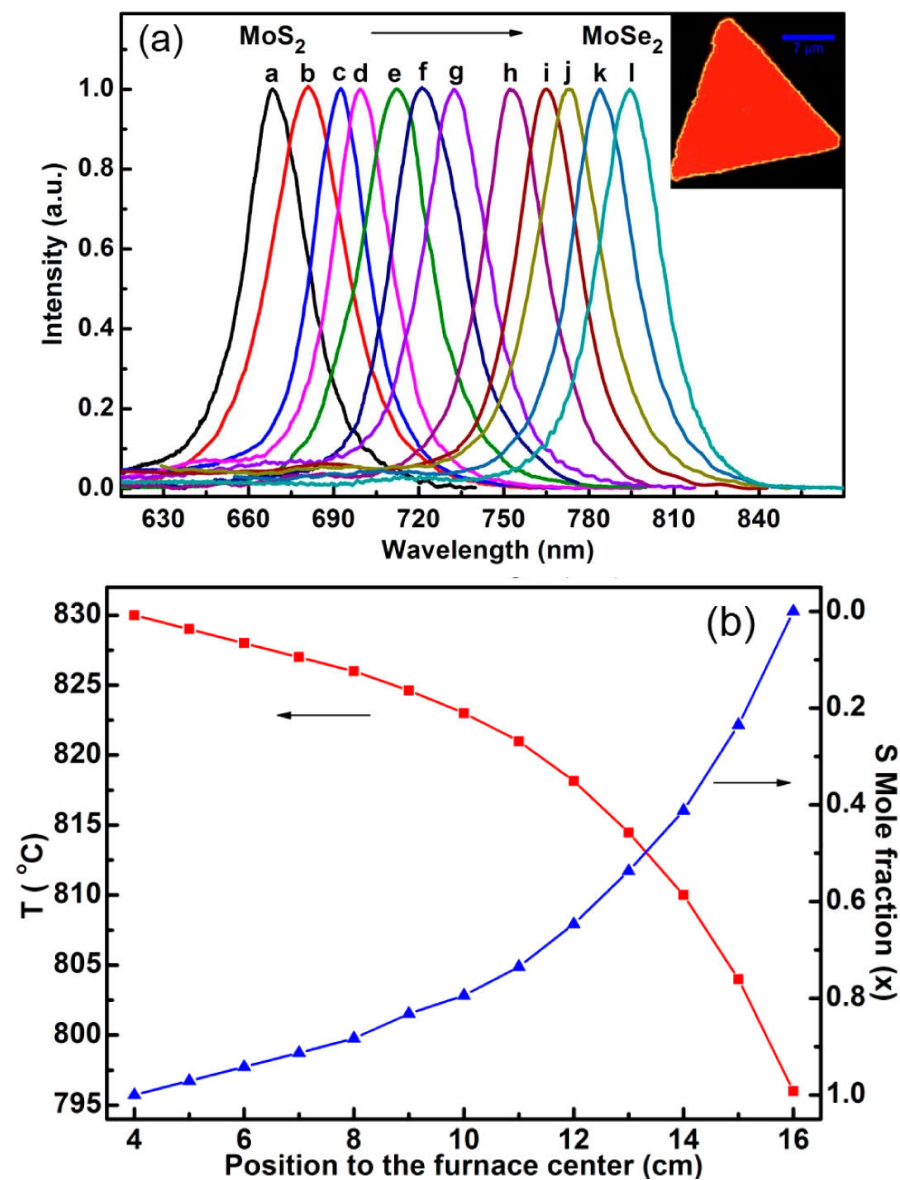


Band gap tuning by alloying

For TMDCs

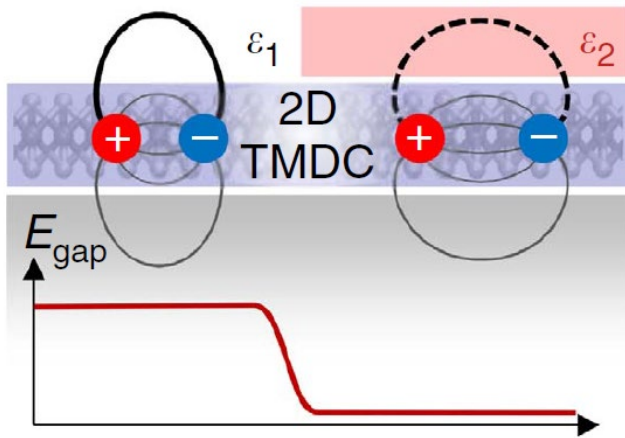


Li et al. J. Am. Chem. Soc. (2014)

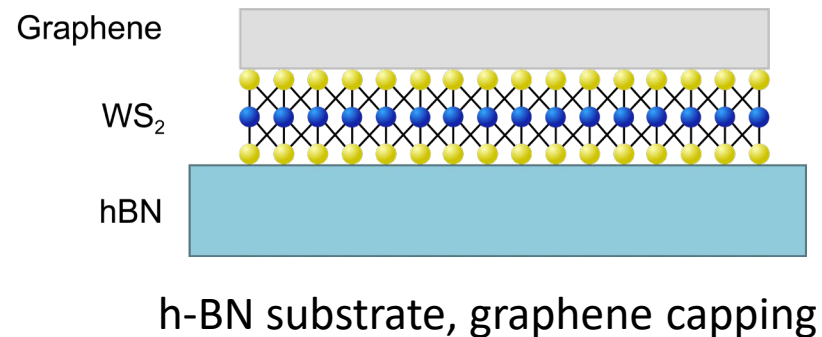
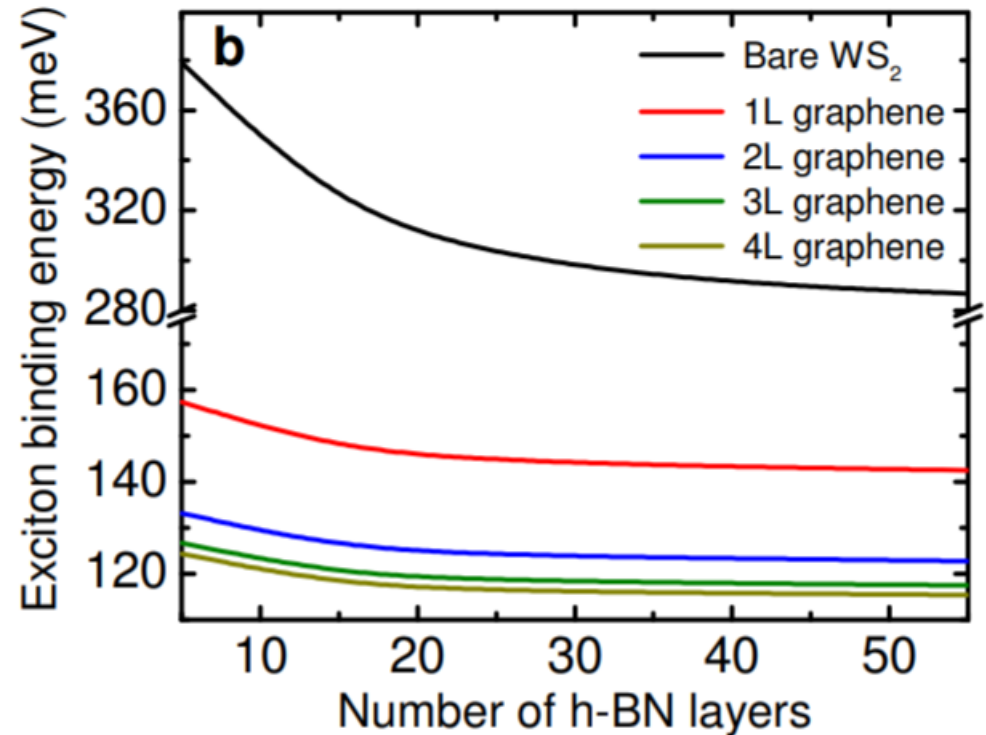


Band gap and exciton binding energy tuning

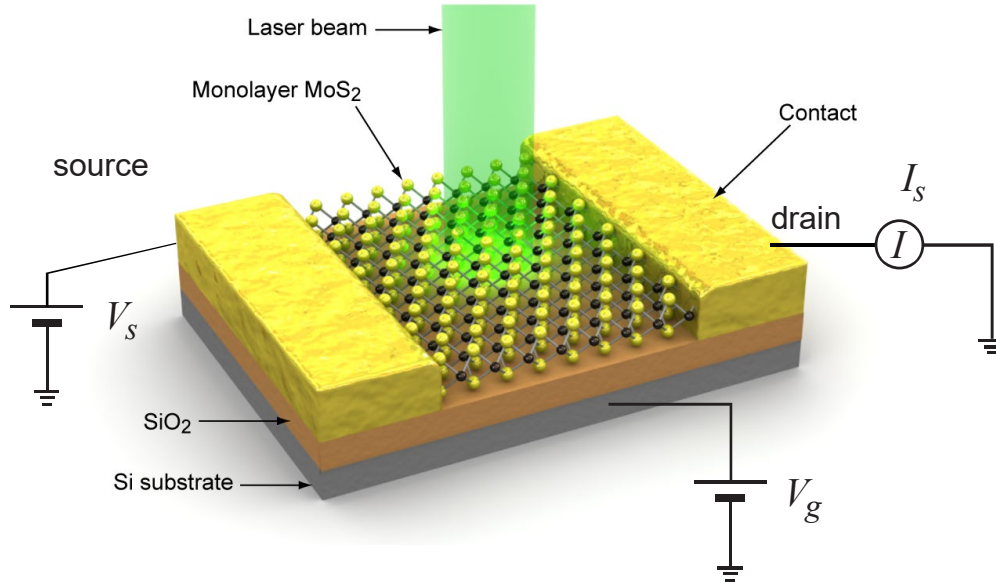
Dielectric constant of the environment affect the band gap E_G and exciton binding energy E_B



Raja et al. Nature Communications (2017)



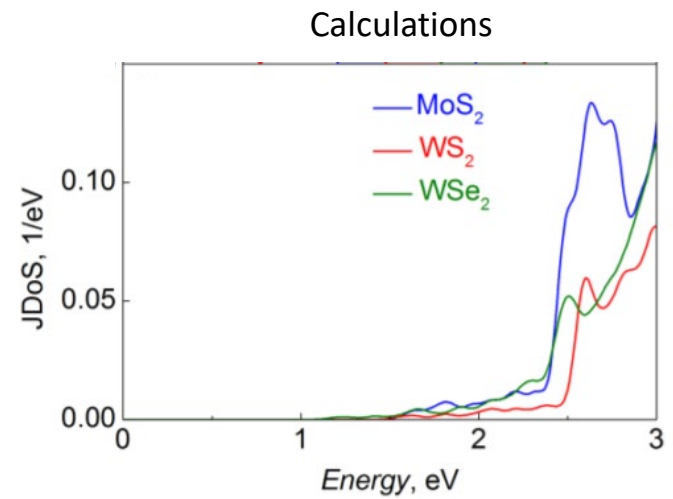
Phototransistors/photodetectors



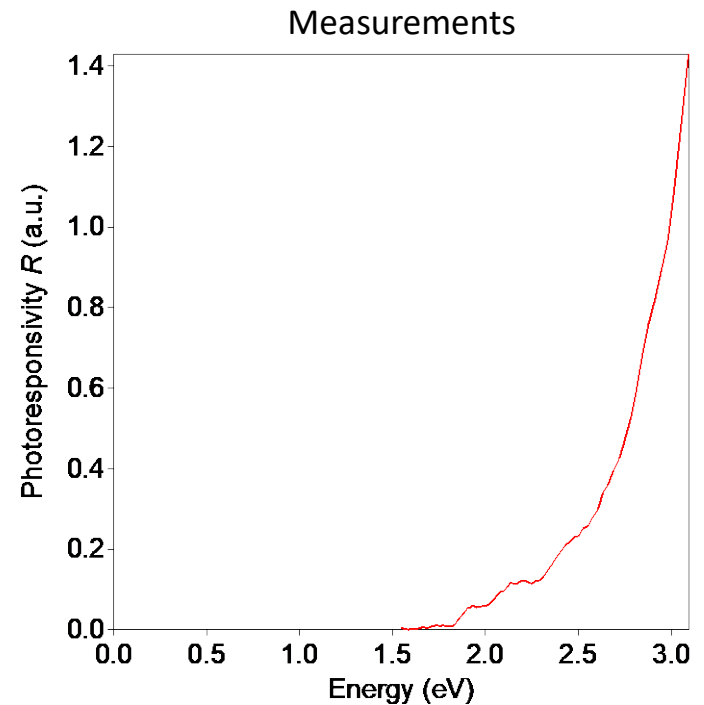
$$\text{Joint density of states } JDOS(E) = \frac{1}{4\pi^3} \int d^3k \delta(E_{V,k} - E_{C,k} - E)$$

$$\text{Photocurrent } I_{ph} = I_{light} - I_{dark}$$

$$\text{Responsivity } R = \frac{I_{ph}}{P_{inc}}$$



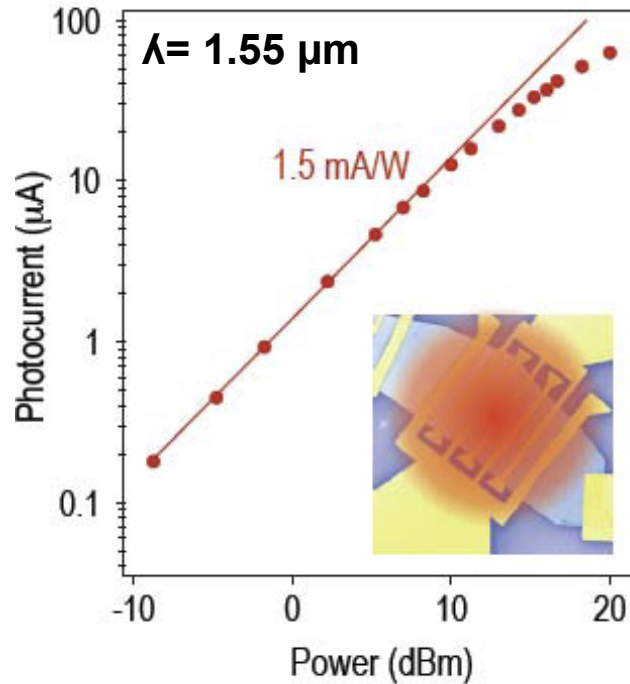
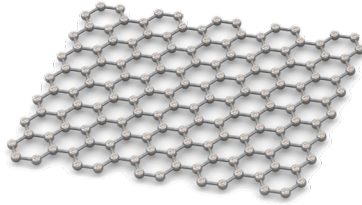
Britnell...Novoselov; Science (2013)



Lopez Sanchez...Kis; Nat. Nanotech. (2013)

Early graphene and MoS₂ photodetectors

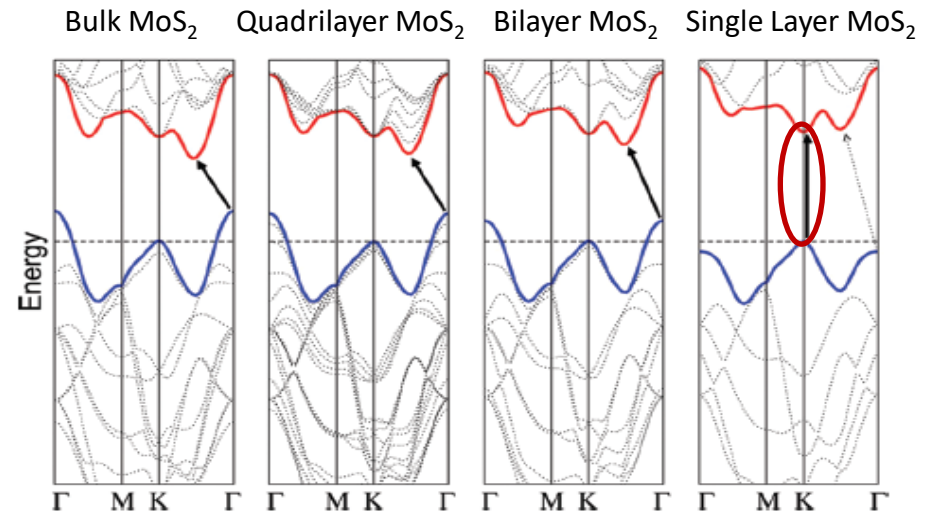
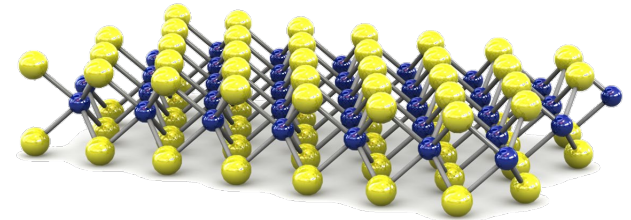
Graphene



Zero band gap: small response
wide spectral range

High mobility: fast response

MoS₂



$$E_G = 1.8 \text{ eV} \Rightarrow \lambda = 680 \text{ nm}$$

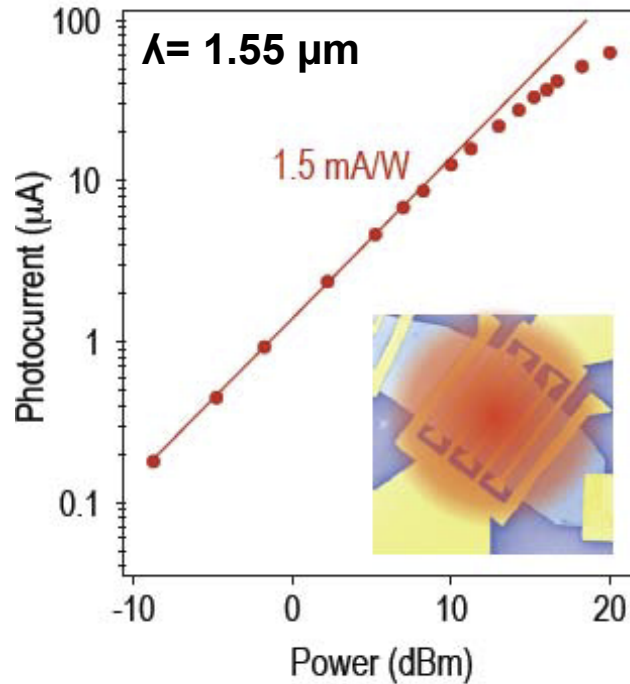
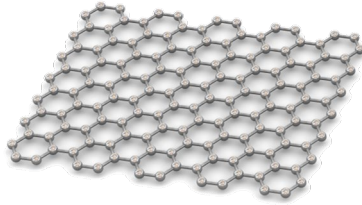
Direct band gap: large response
efficient photoconversion

Low mobility: slow response

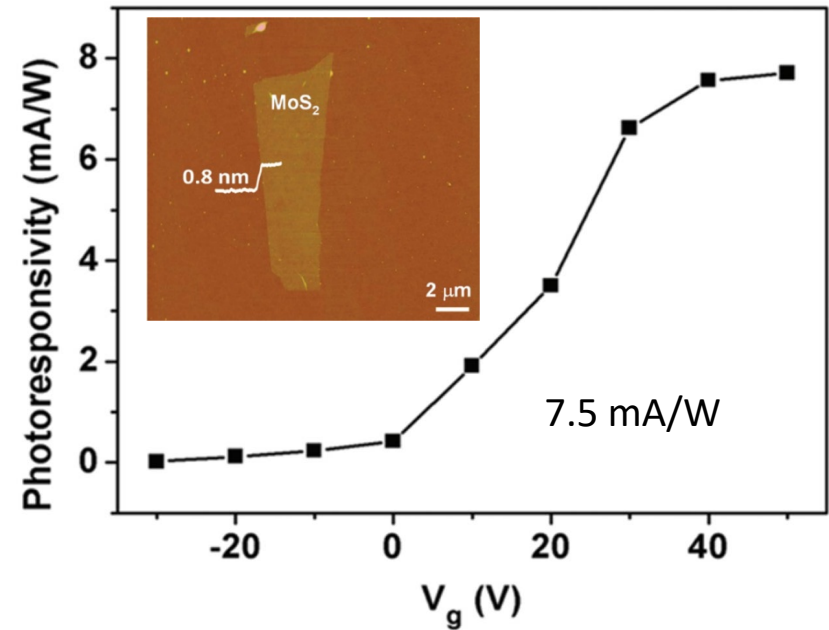
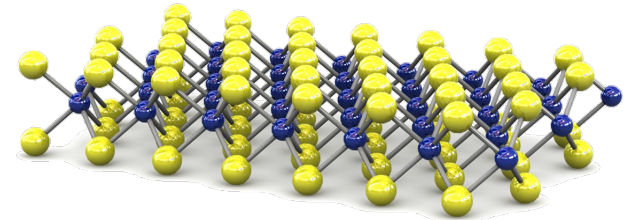
Mueller et al., Nature Photonics (2010)
Splendiani et al., Nano Letters (2010)
Echtermeyer et al., Nature Com. (2011)

Early graphene and MoS₂ photodetectors

Graphene



MoS₂



Zero band gap: small response
wide spectral range

High mobility: fast response

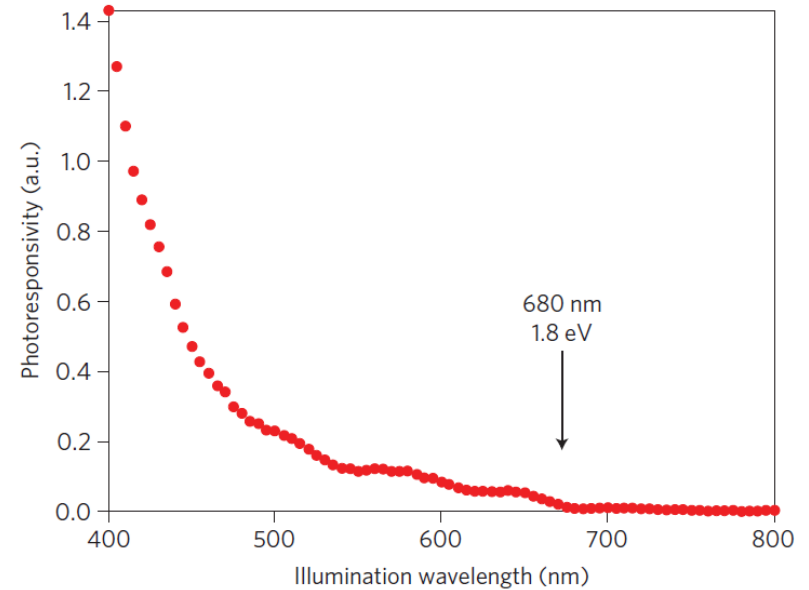
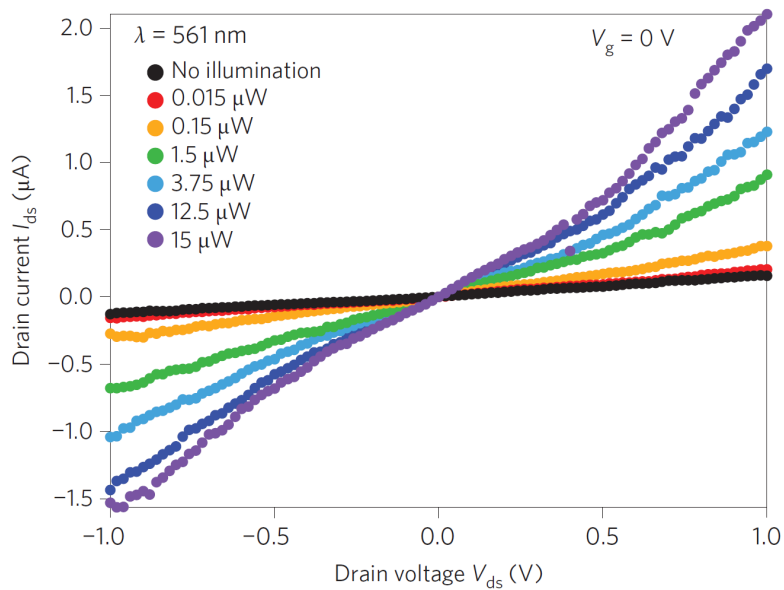
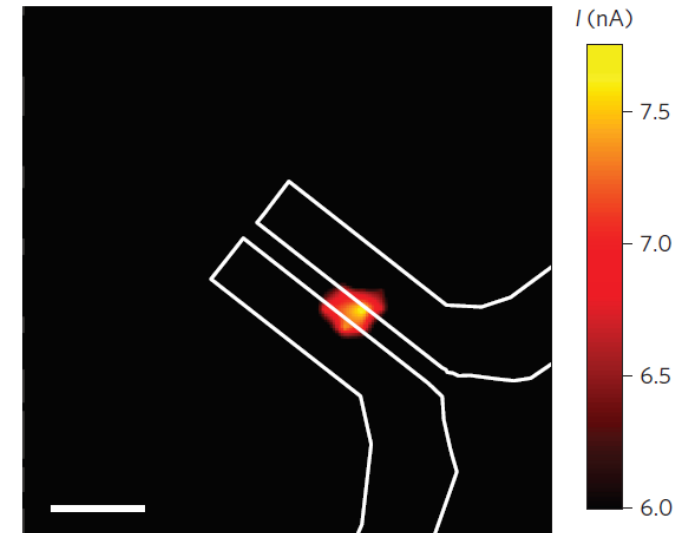
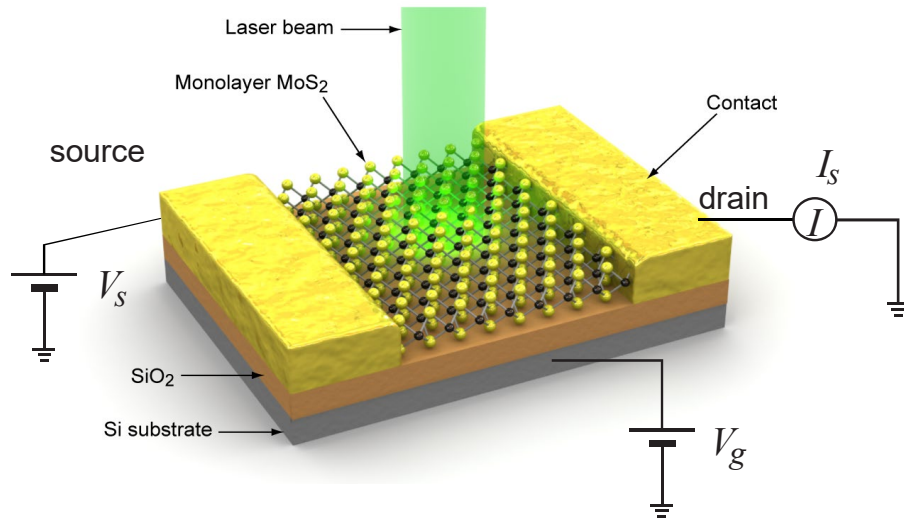
Yin et al.; ACS Nano 6 (1) 74-80 (2011)

Mueller et al., Nature Photonics (2010)

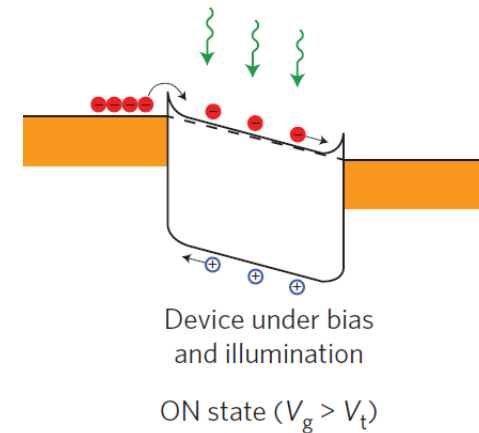
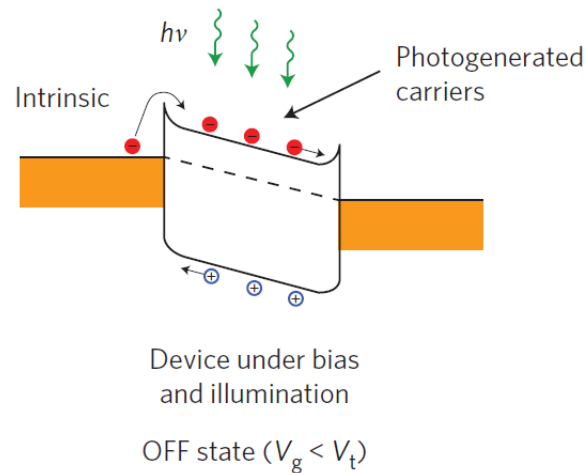
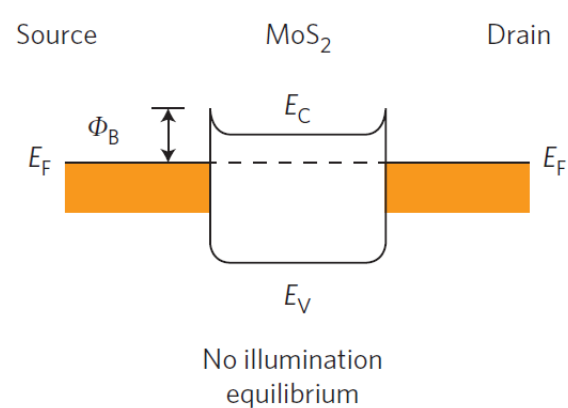
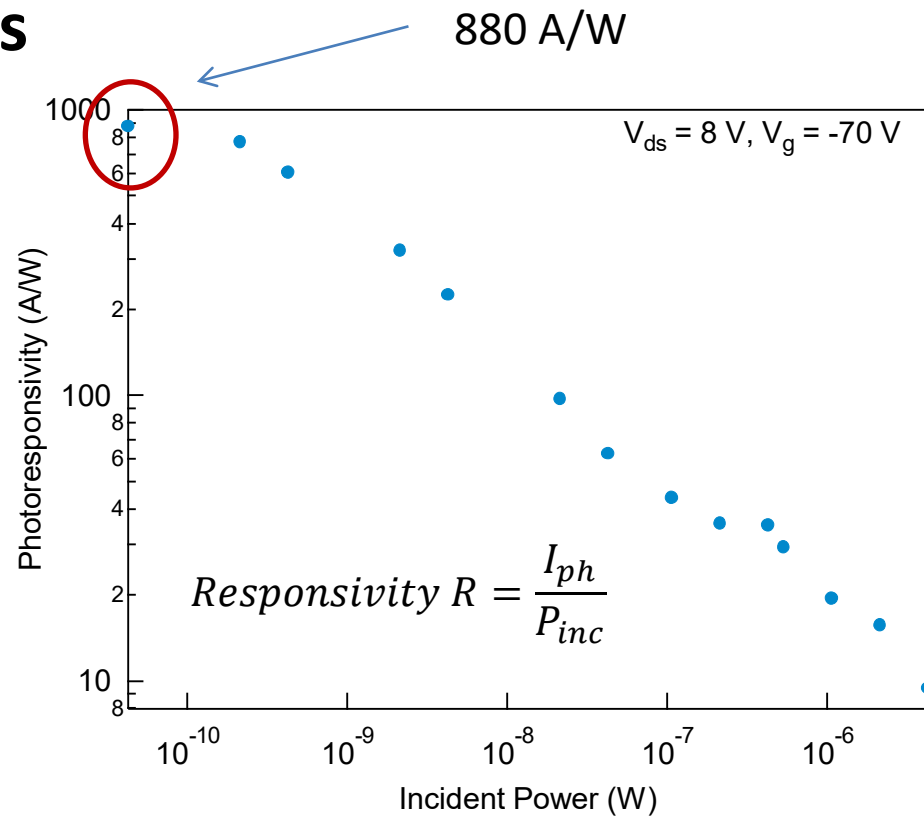
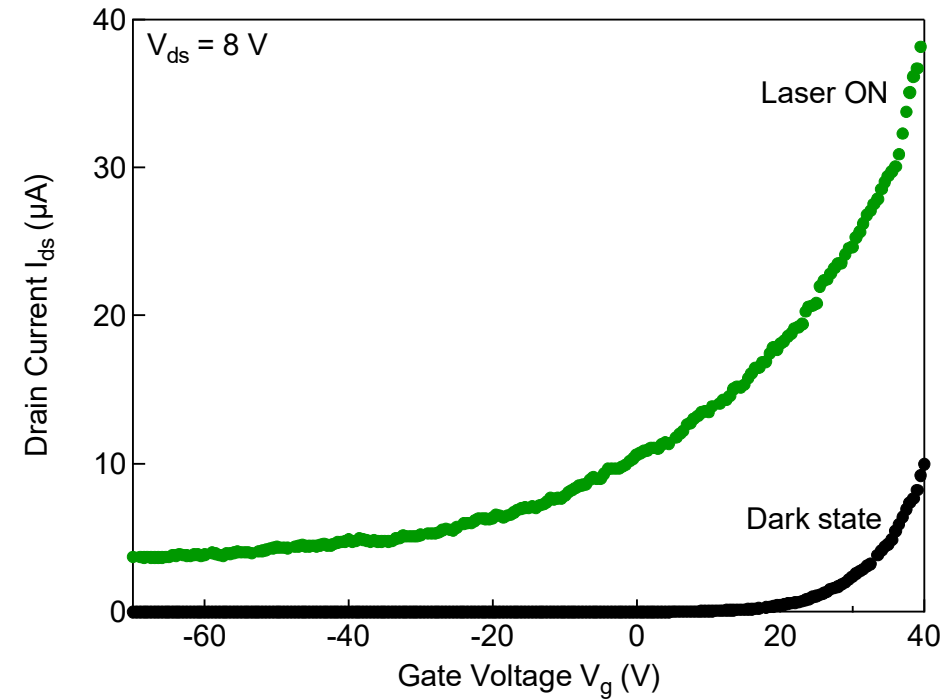
Splendiani et al, Nano Letters (2010)

Echtermeyer et al, Nature Com. (2011)

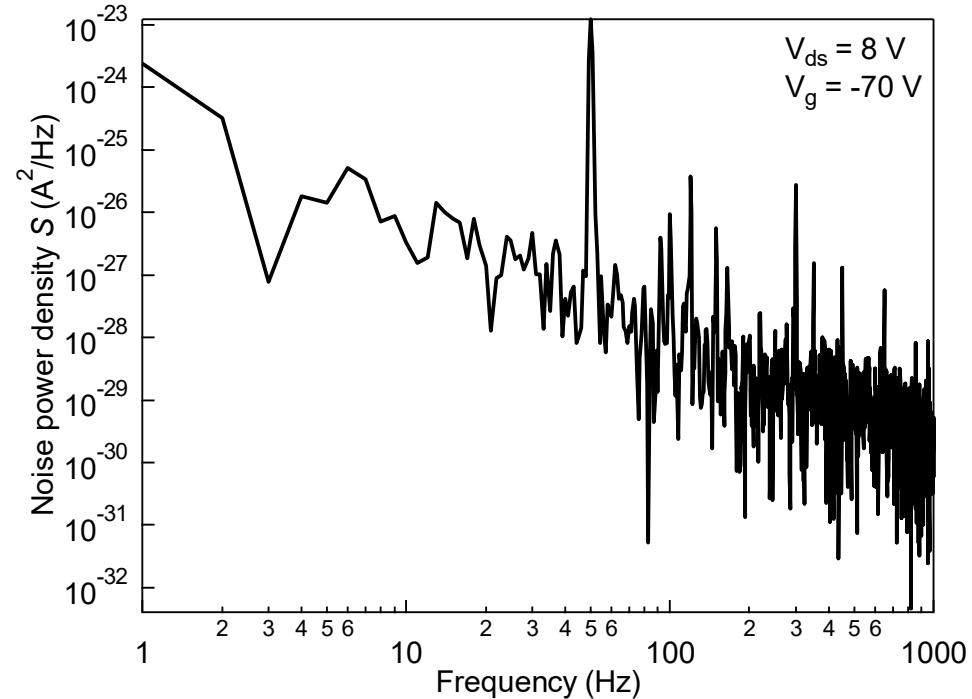
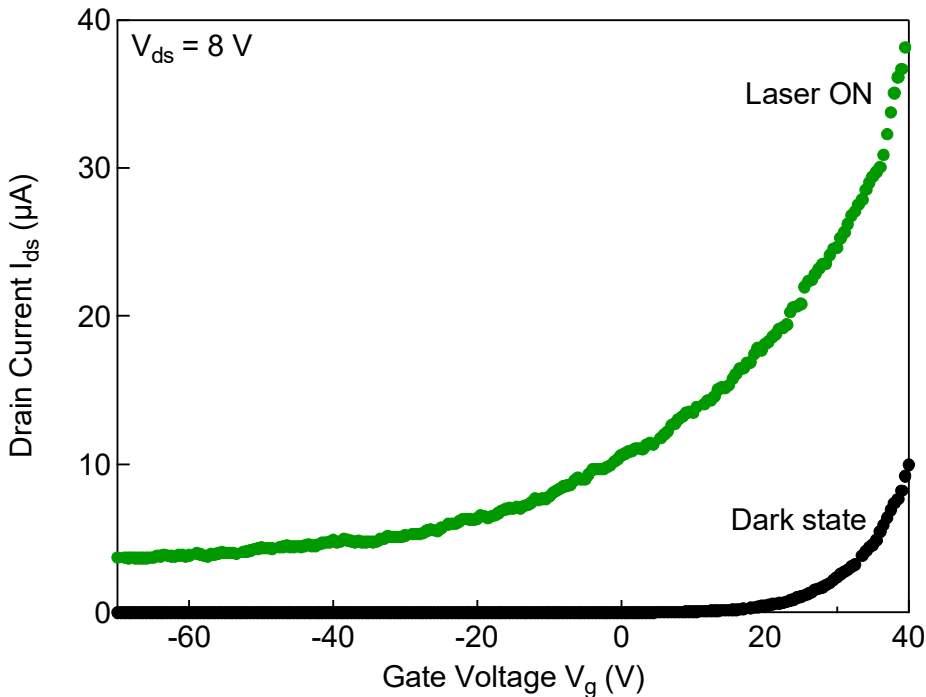
Sensitive MoS₂ photodetectors



Sensitive MoS₂ photodetectors



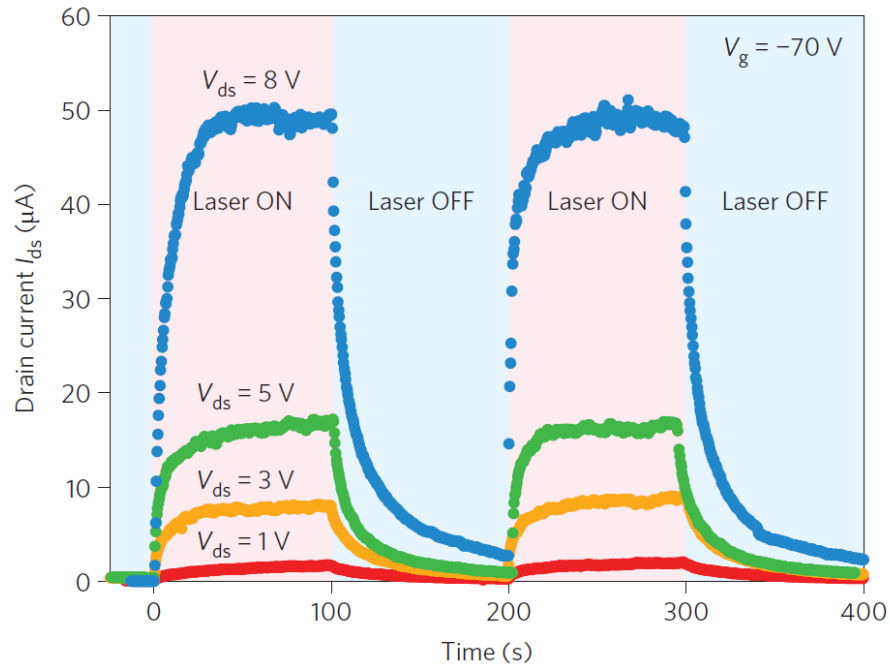
Noise-equivalent power



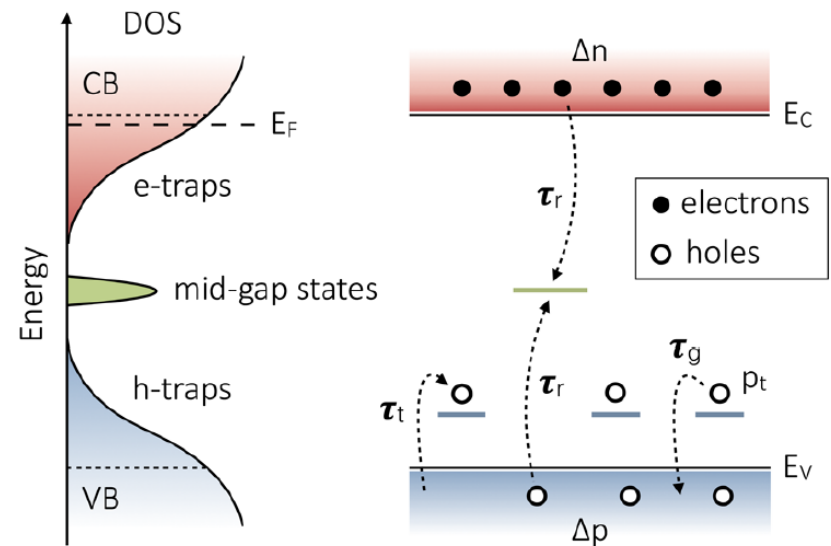
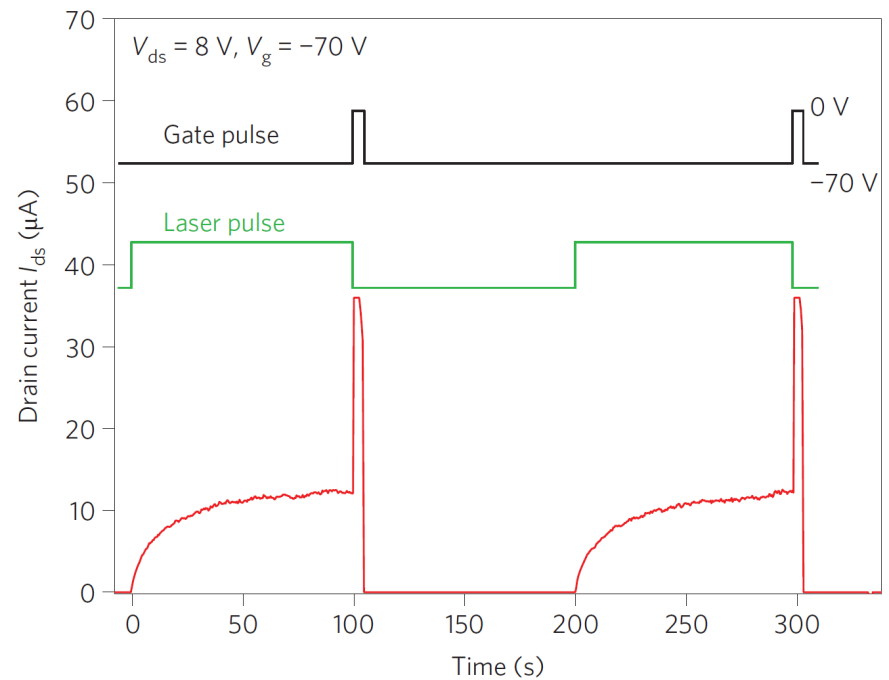
Photoresponsivity: 880 A/W
NEP: $1.8 \times 10^{-15} \text{ W/Hz}^{1/2}$

Si photodiodes: 1 A/W
NEP: $3 \times 10^{-14} \text{ W/Hz}^{1/2}$

Photocurrent dynamics

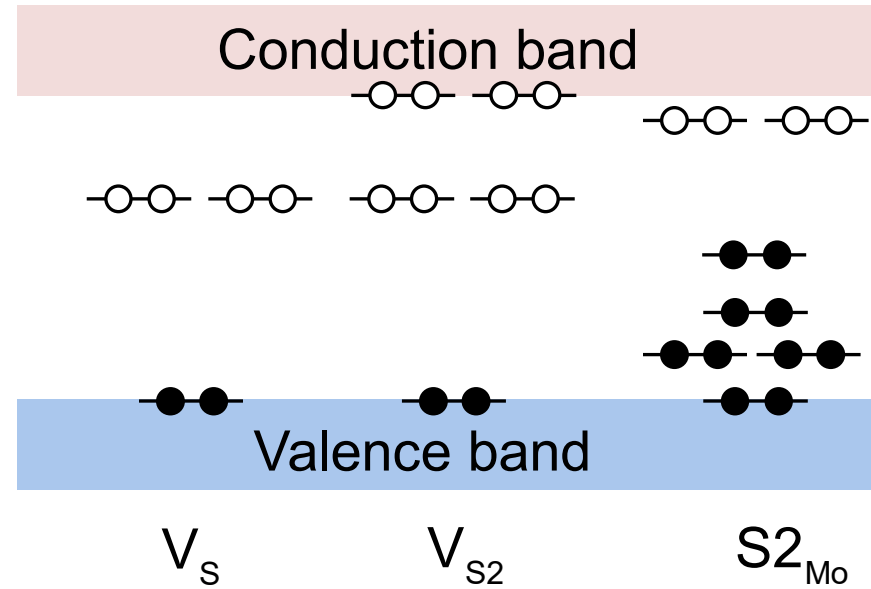
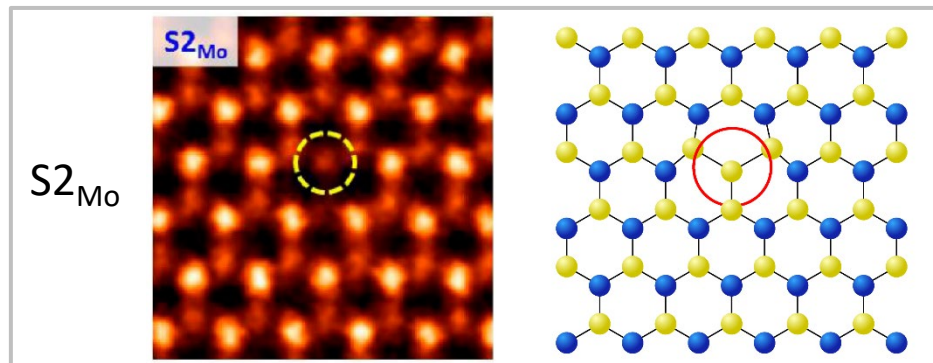
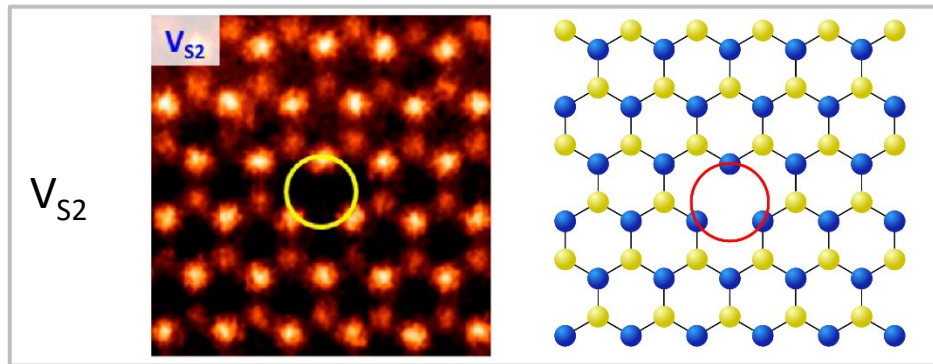
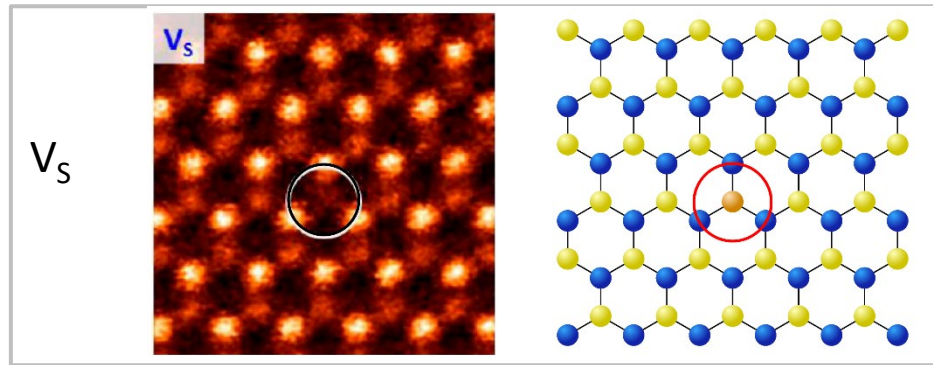


Lopez-Sanchez, Nature Nanotechnology (2013)



Furchi et al. Nano Lett. (2014)

From Ch. 2: most common point defects in MoS₂

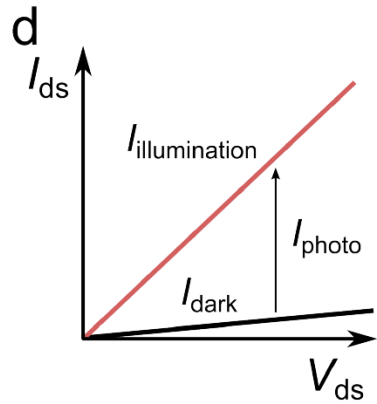
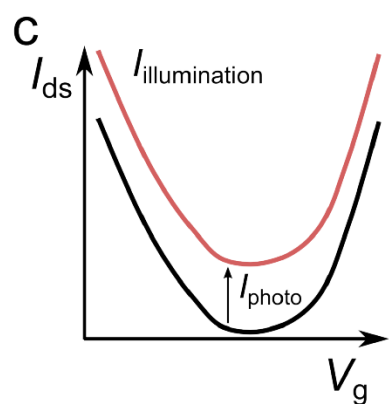
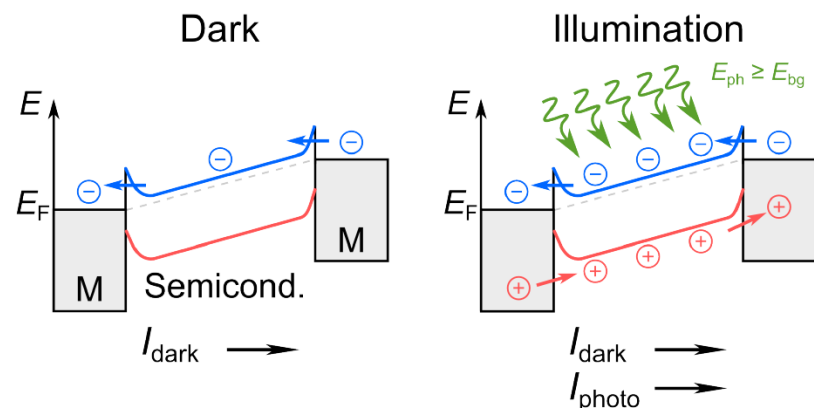


Zhou et al. Nano Letters (2013)

Mechanisms of photoconductivity

Photoconductive (PC)

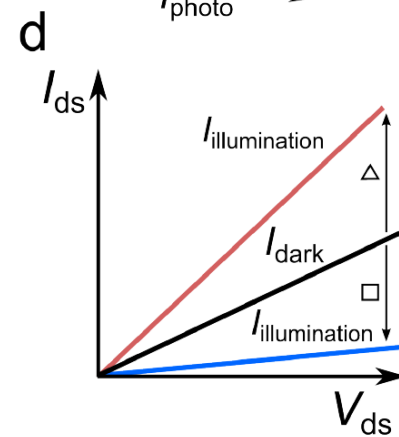
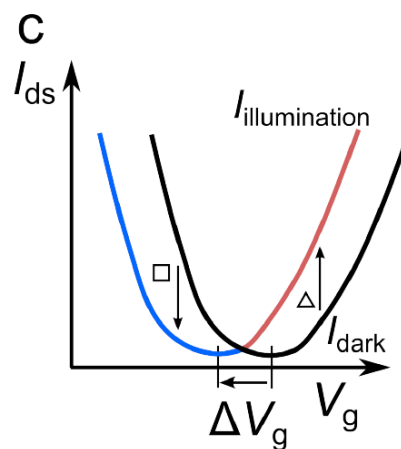
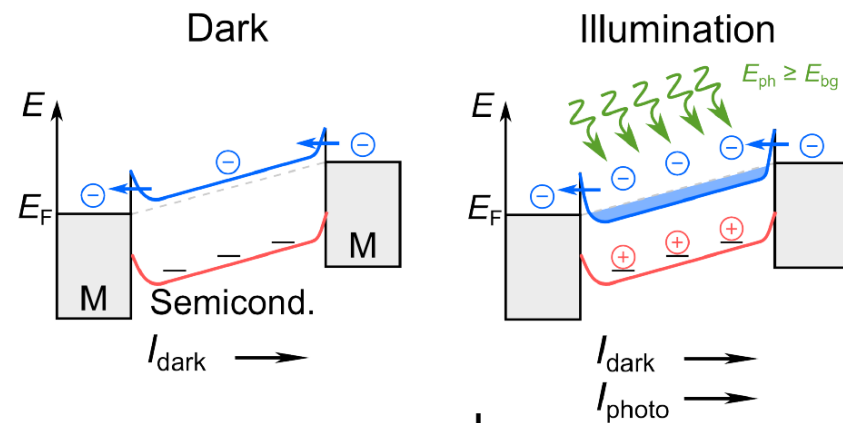
$$I_{ph,PC} = \frac{W}{L} V_D \Delta\sigma$$



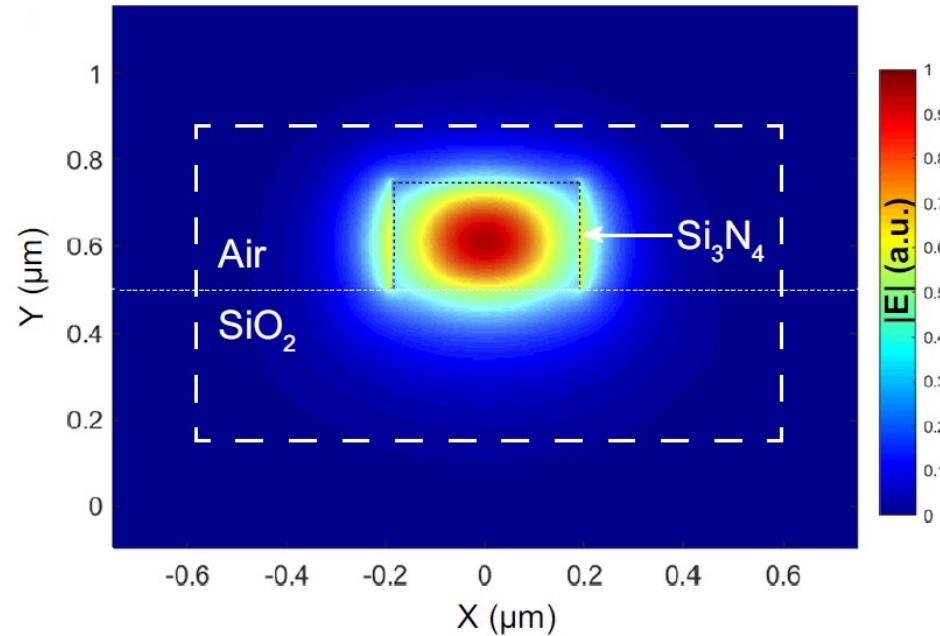
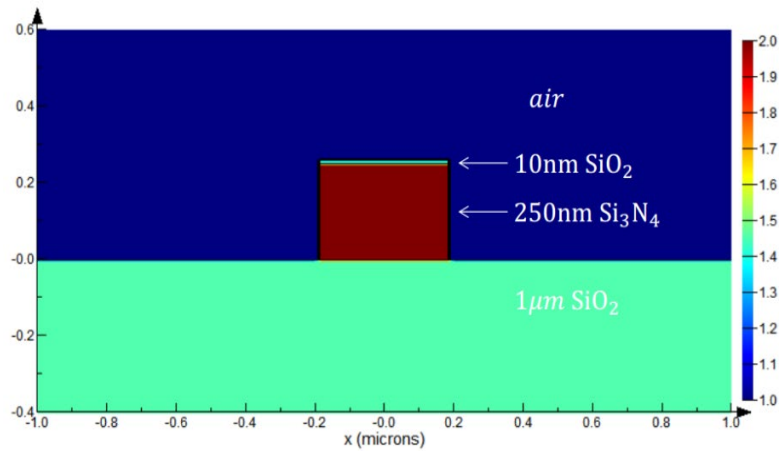
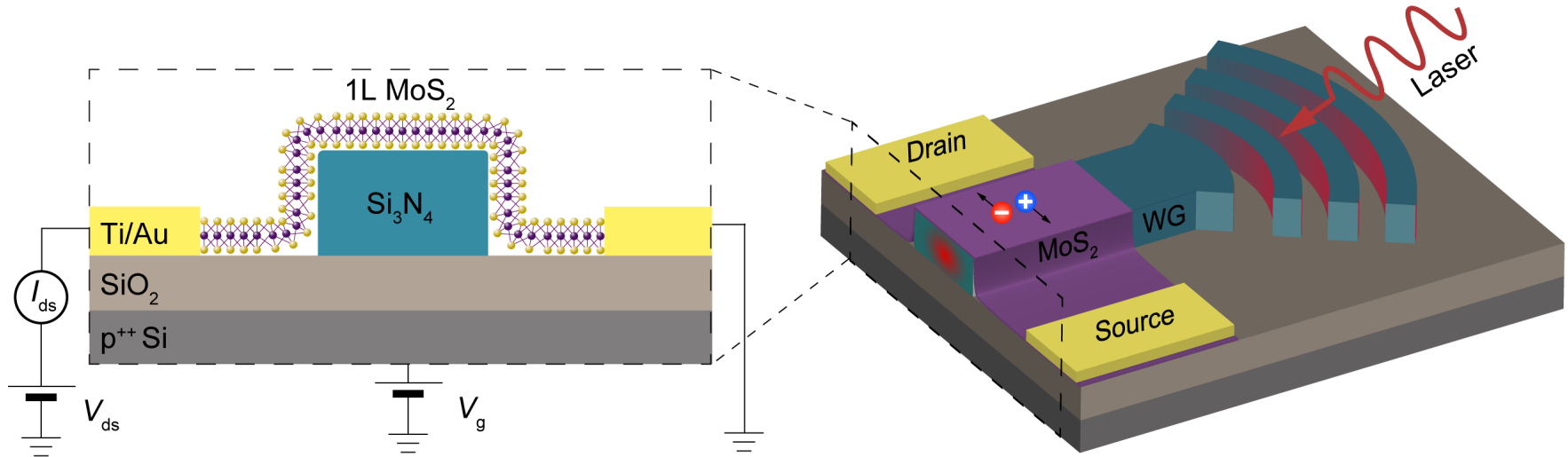
Photogating (PG)

$$I_{ph,PG} \approx g_m \Delta V_T$$

$$g_m = dI_D/dV_G$$



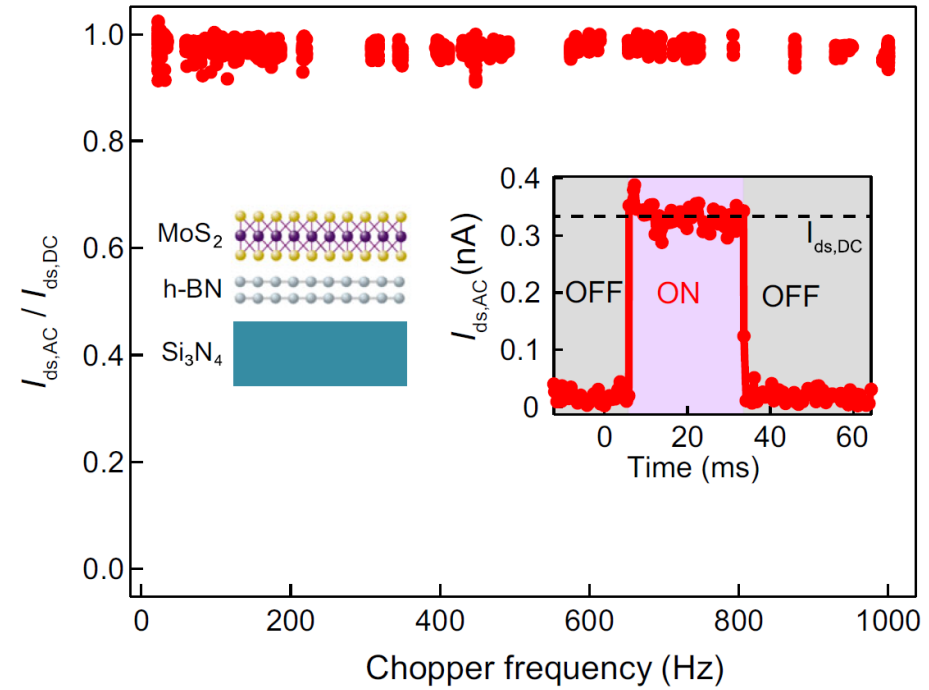
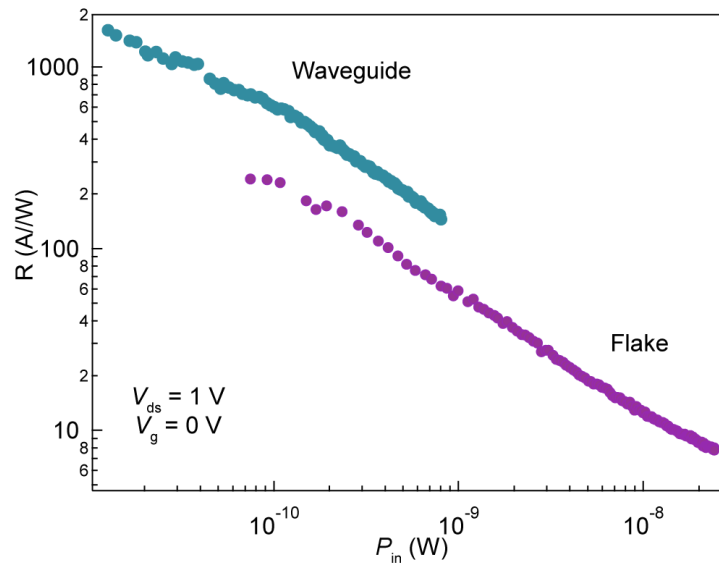
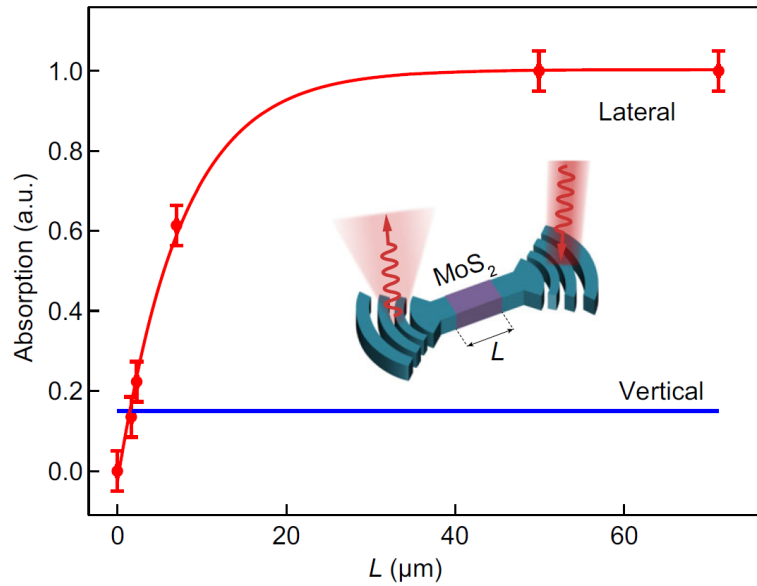
Photonic circuit integration



Gonzalez Marin et al.; npj 2D materials and applications (2019)

Integrated photodetectors

Light absorption



[Repeated] Chapter 4: Photodetectors and LEDs

Optoelectronics in the IT context

Optical properties of TMDCs

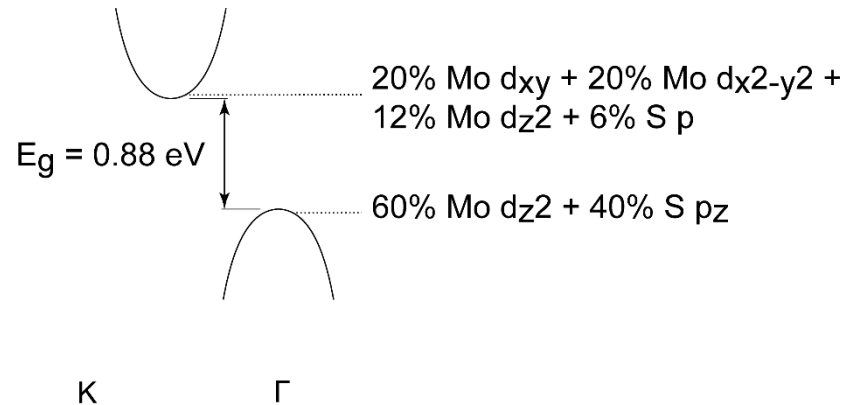
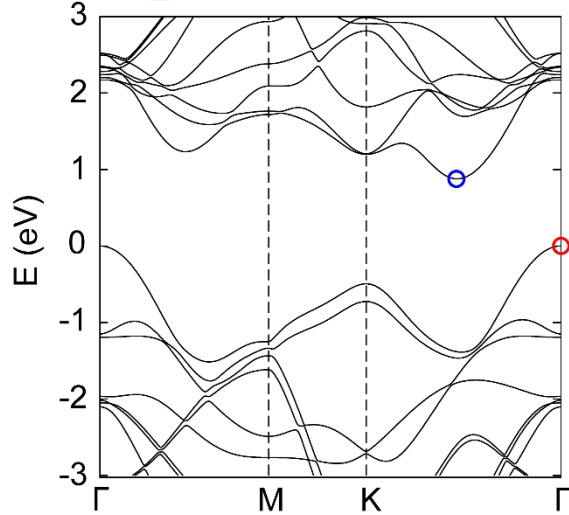
- Reflectance/absorbance
- Band structure
- Excitons – band gap, binding energy
- Tuning

Devices

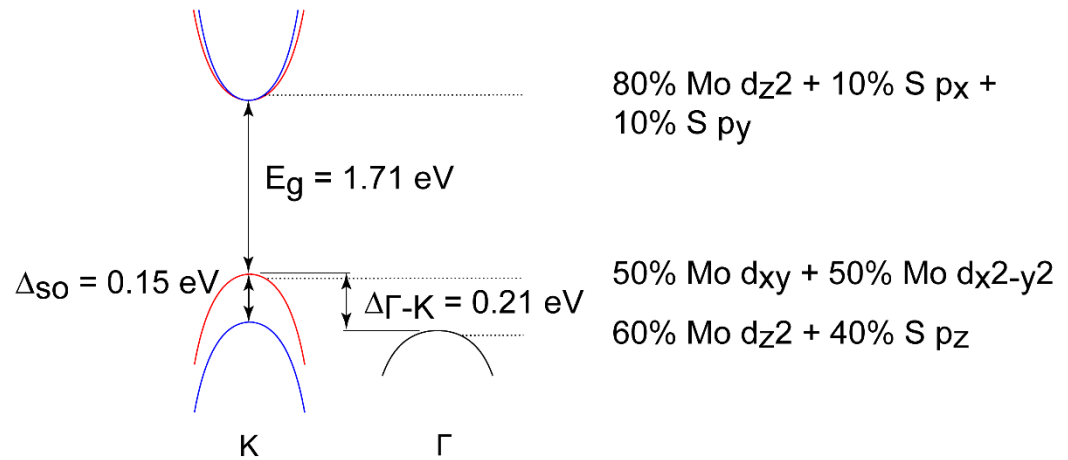
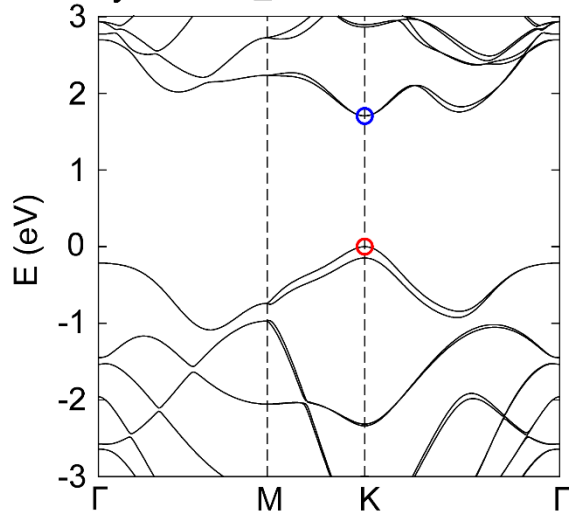
- Photodetectors
- Electroluminescent devices

[Recap] Band structure of 2H MoS₂

Bulk MoS₂



Monolayer MoS₂



Kuc...Heine; Physical Review B (2011)

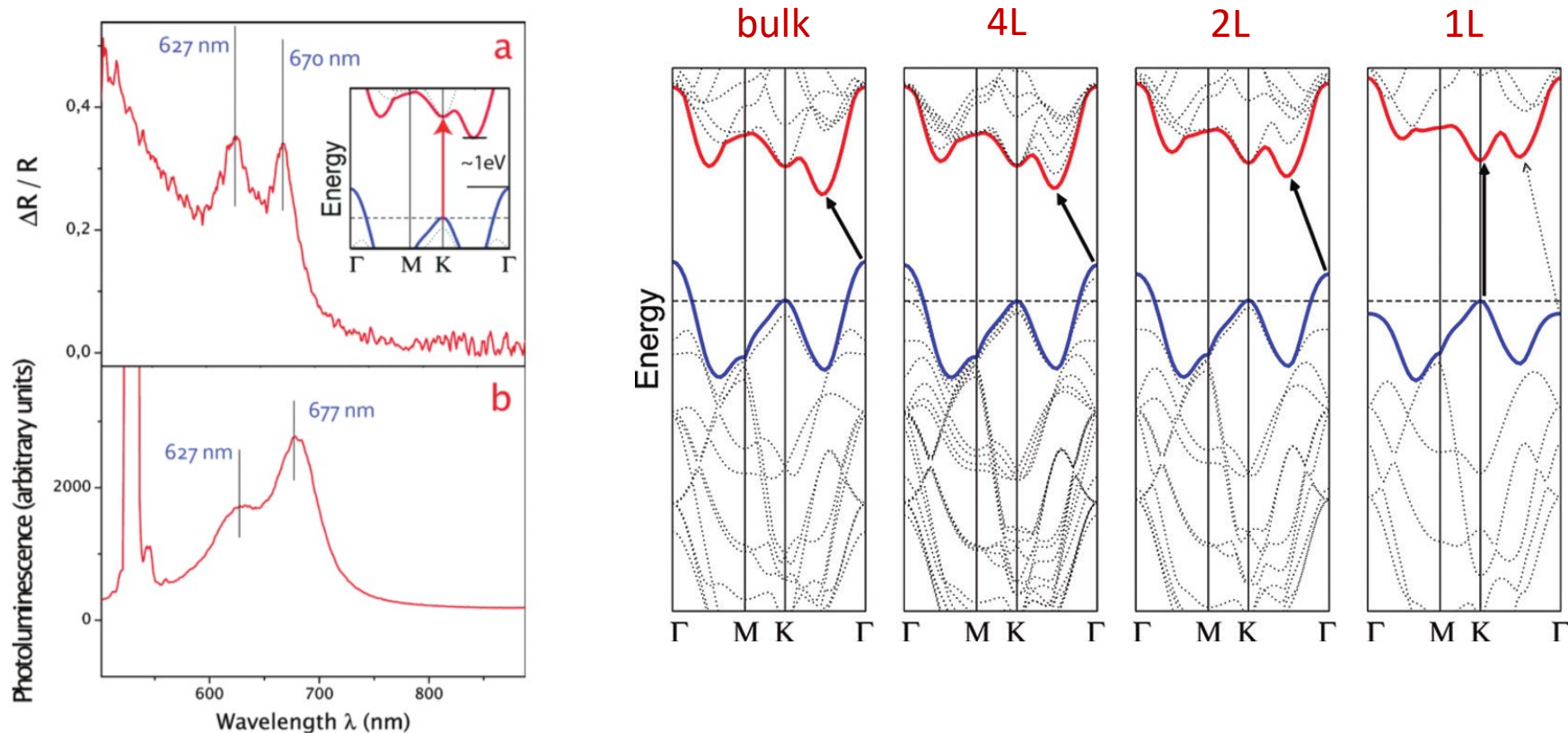
Yazyev and Kis; Materials Today (2014)

Emerging Photoluminescence in Monolayer MoS₂

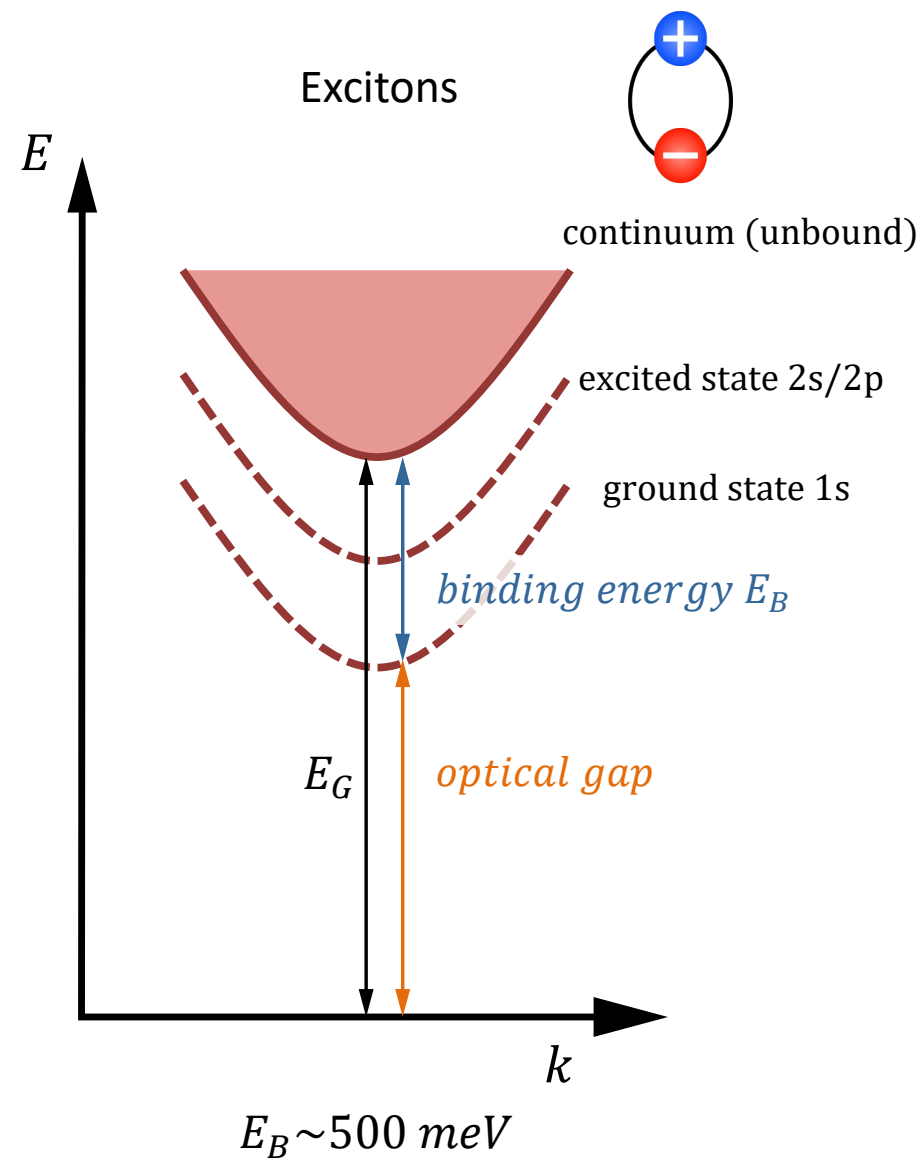
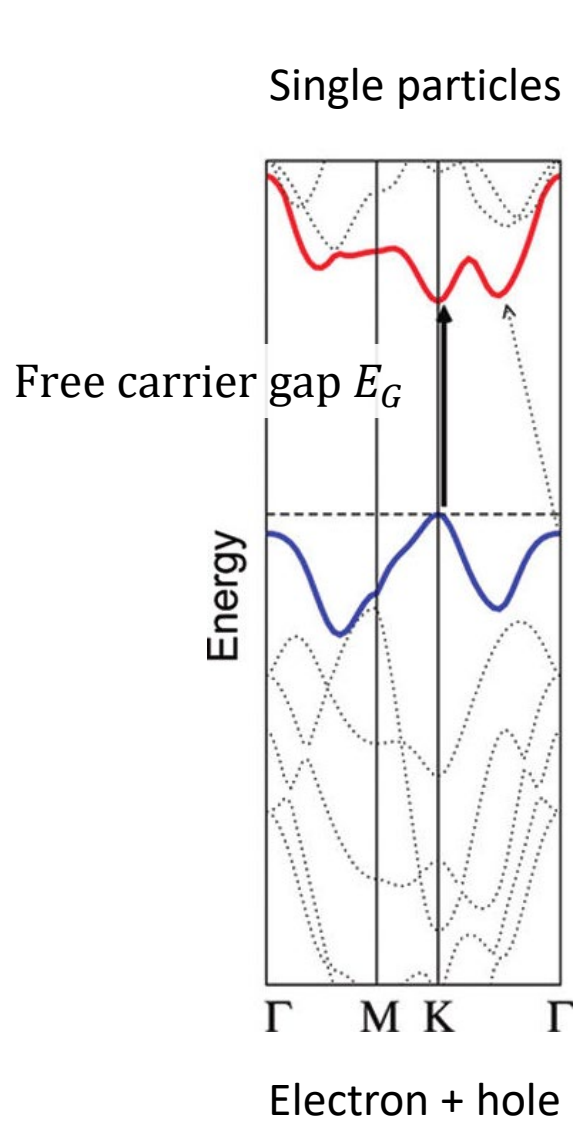
Splendiani...Wang; Nano Lett. (2010)

Andrea Splendiani,^{†,‡} Liang Sun,[†] Yuanbo Zhang,[†] Tianshu Li,[§] Jonghwan Kim,[†] Chi-Yung Chim,[†] Giulia Galli,[§] and Feng Wang^{*,†,||}

[†]Physics Department, University of California at Berkeley, Berkeley, California 94720, [‡]Scuola Galileiana di Studi Superiori di Padova, 35122 Padova, Italy, [§]Chemistry Department, University of California at Davis, Davis, California 95616, and ^{||}Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720



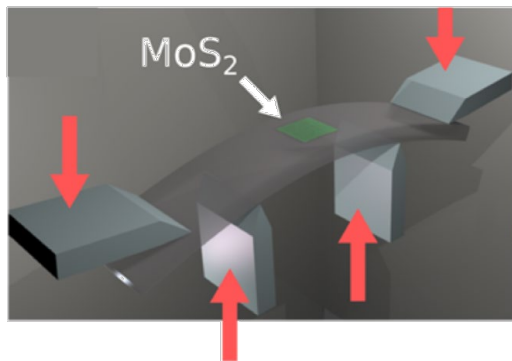
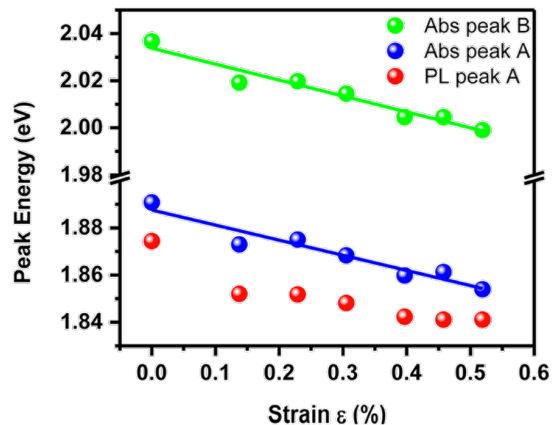
[Recap] Excitons



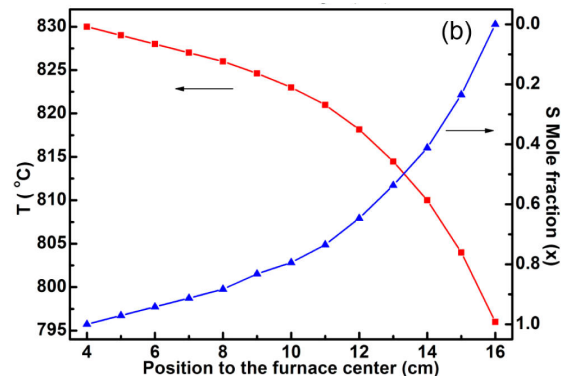
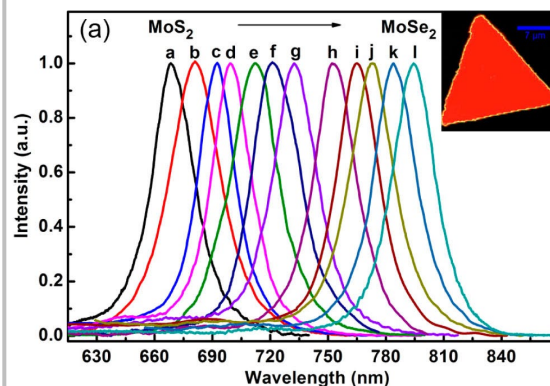
Excitons visible at room temperature

Band gap tuning

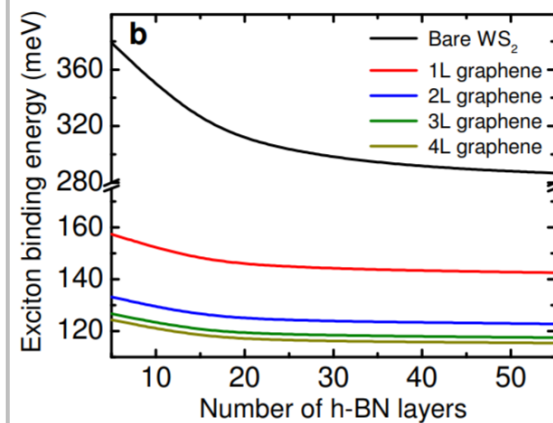
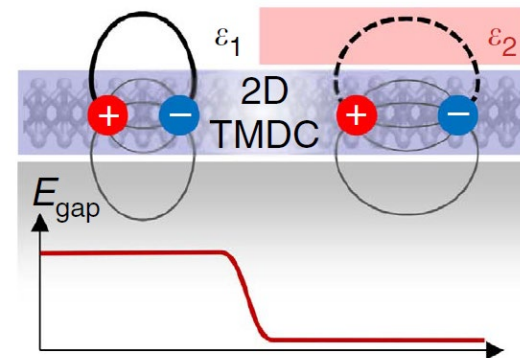
Strain



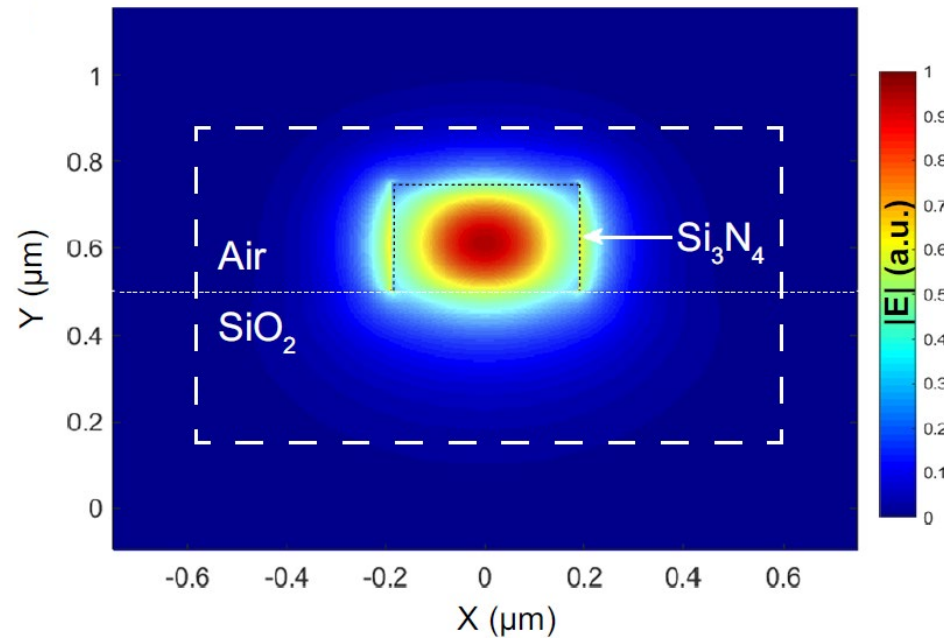
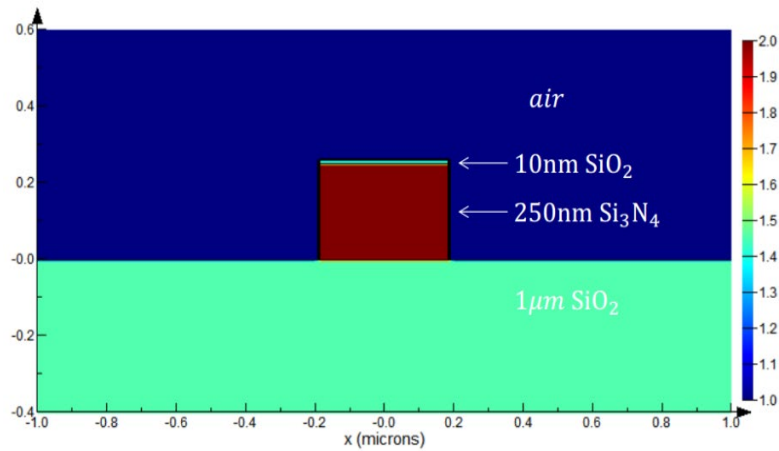
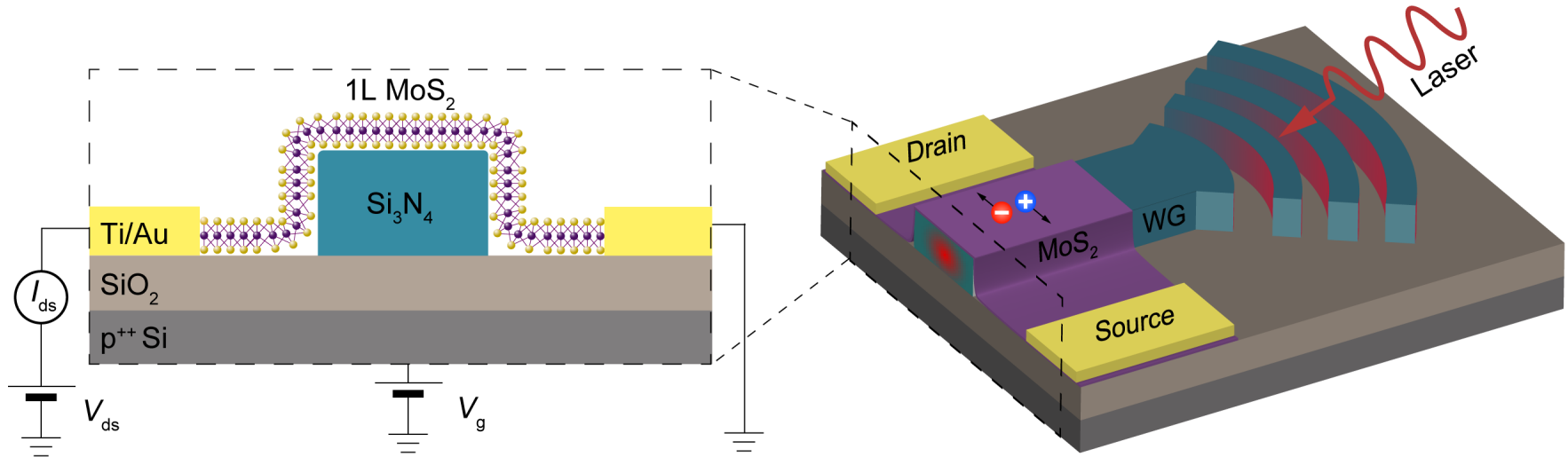
Alloying



Dielectric environment



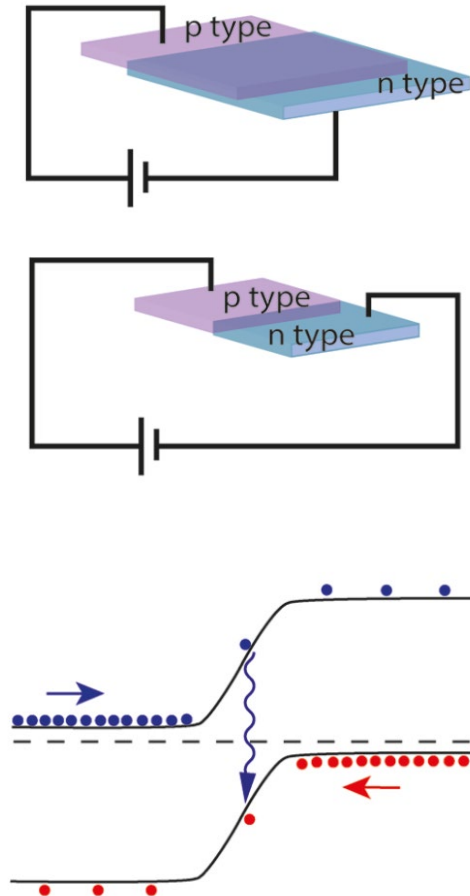
[Recap] Integrated photodetectors



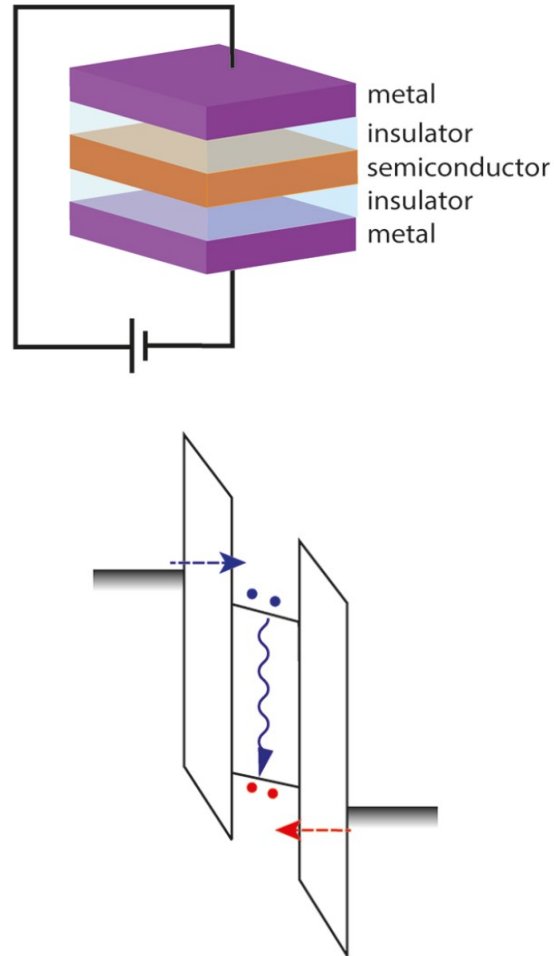
Gonzalez Marin et al.; npj 2D materials and applications (2019)

[Overview] Electroluminescent devices

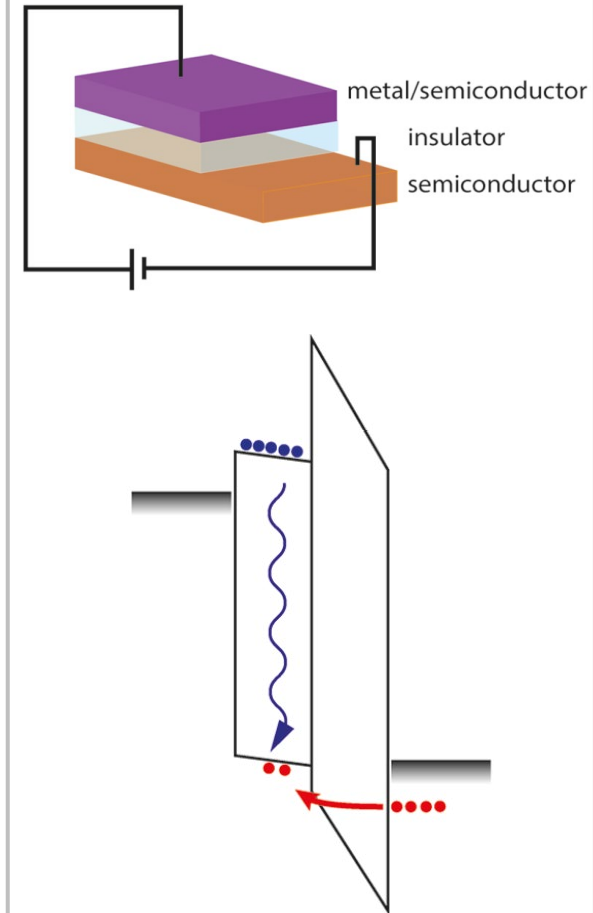
pn junctions



Quantum wells

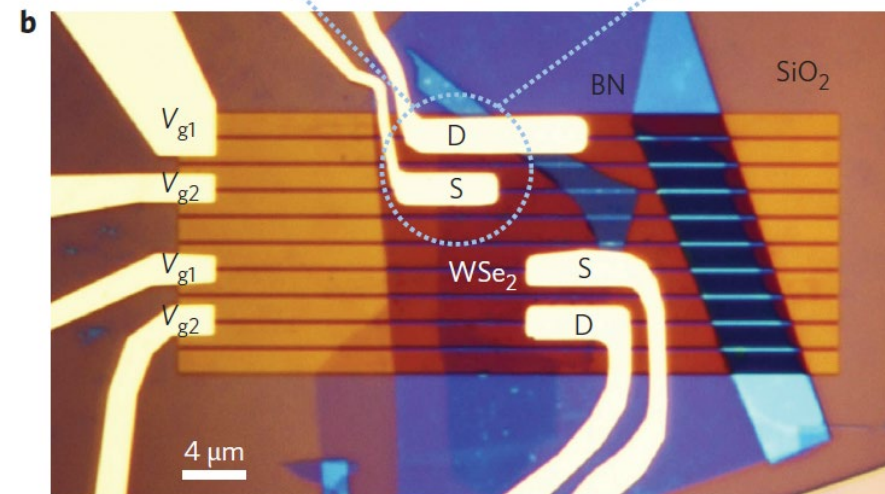
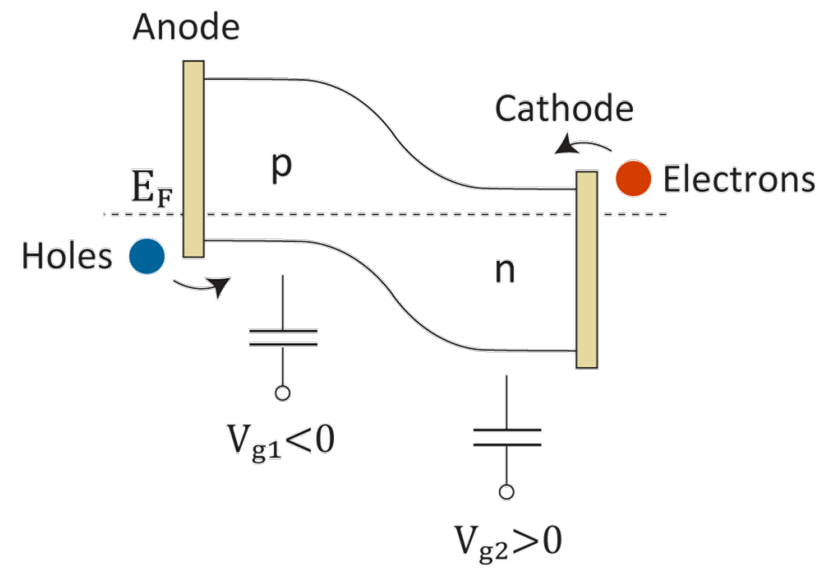
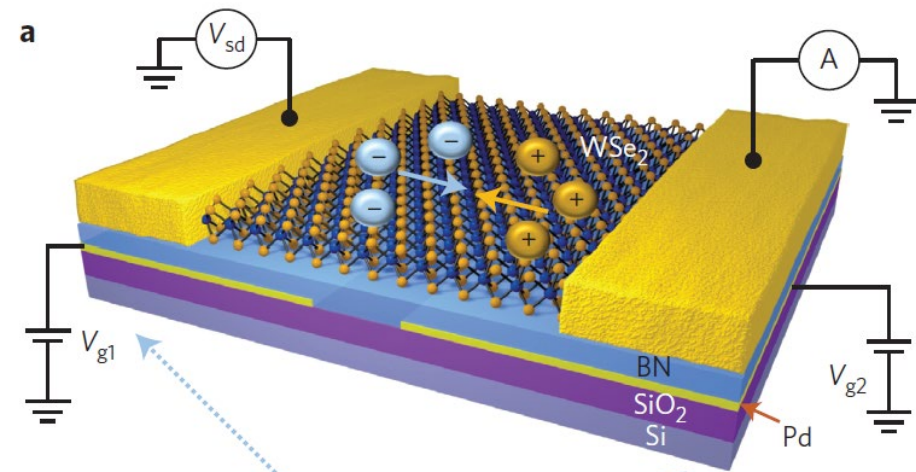


MIS/SIS structure

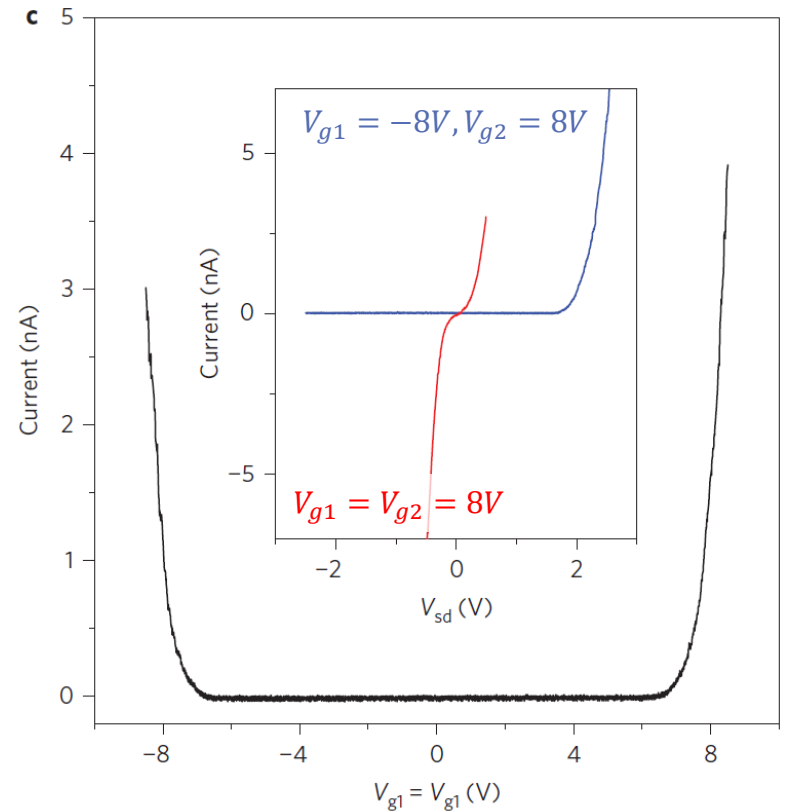


Adapted from Wang et al. Advanced Materials (2018)

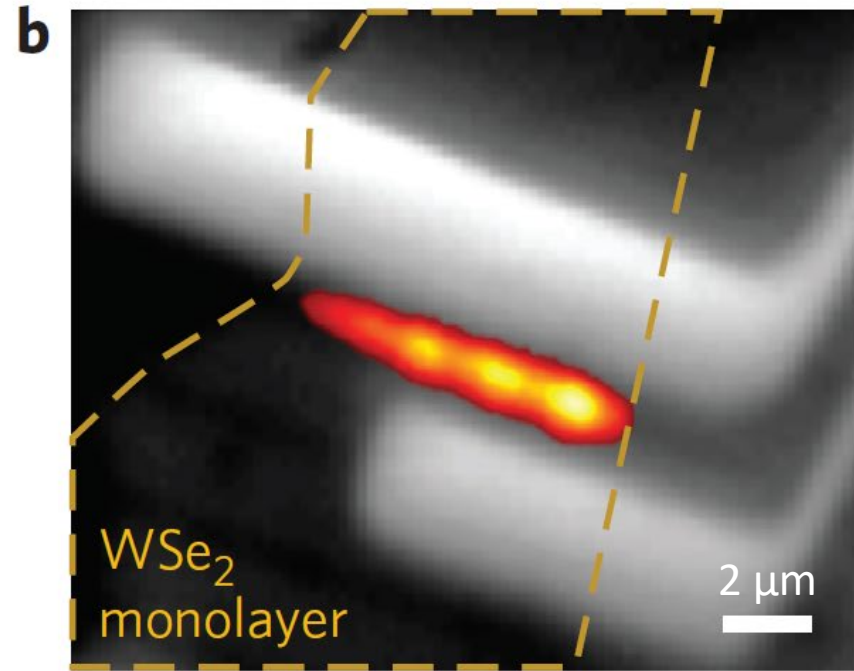
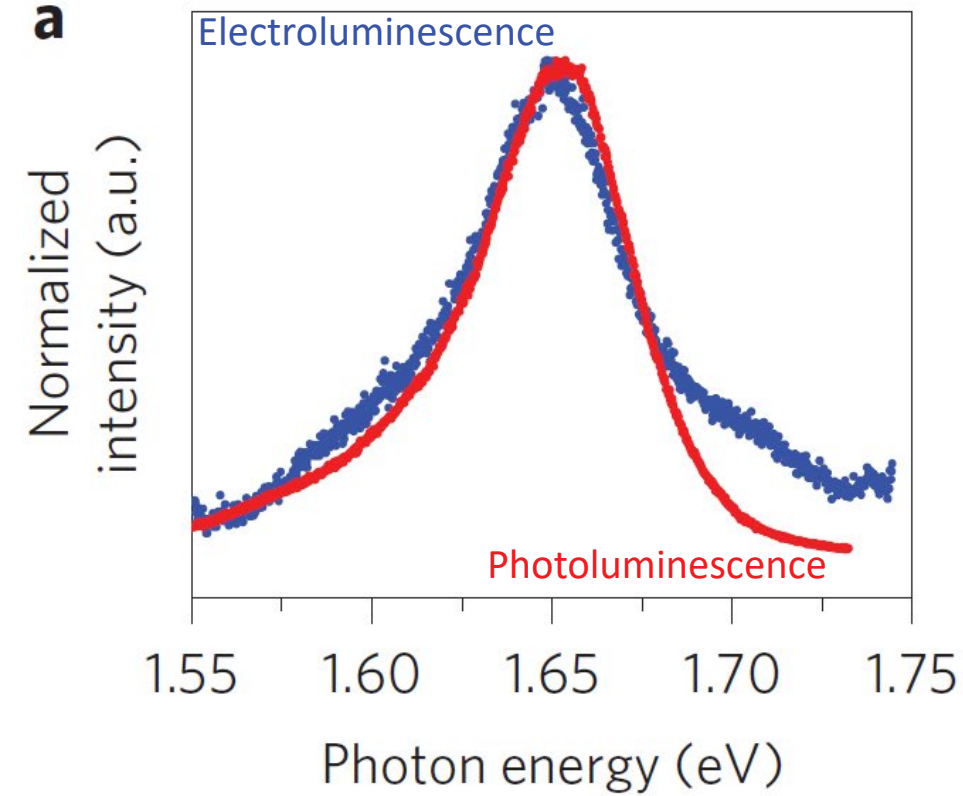
Lateral heterojunction LEDs



Ross et al. Nat Nano (2014),
Pospischil et al. Nat Nano (2014)

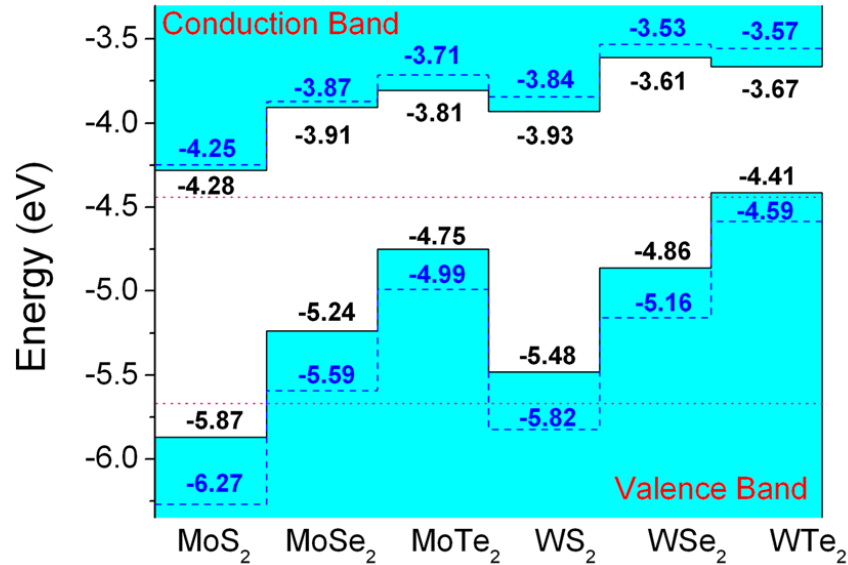


Lateral heterojunction LEDs

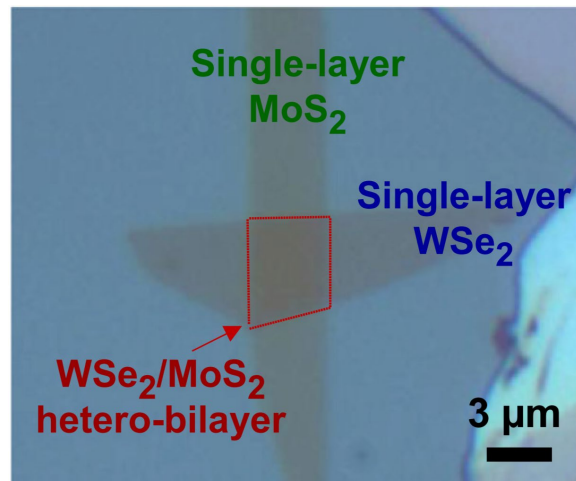


Ross et al. Nat Nano (2014)

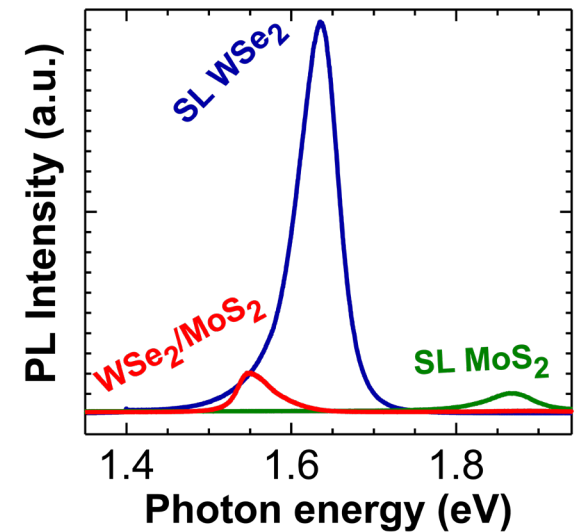
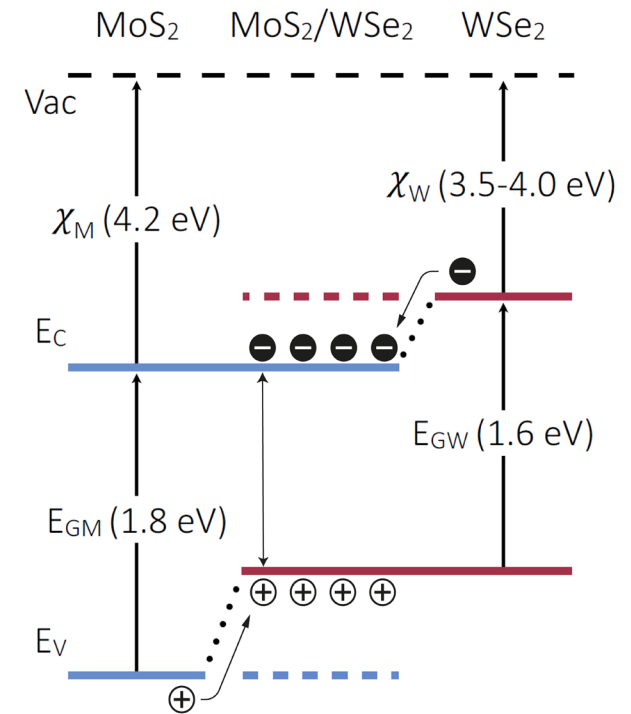
Vertical heterojunctions



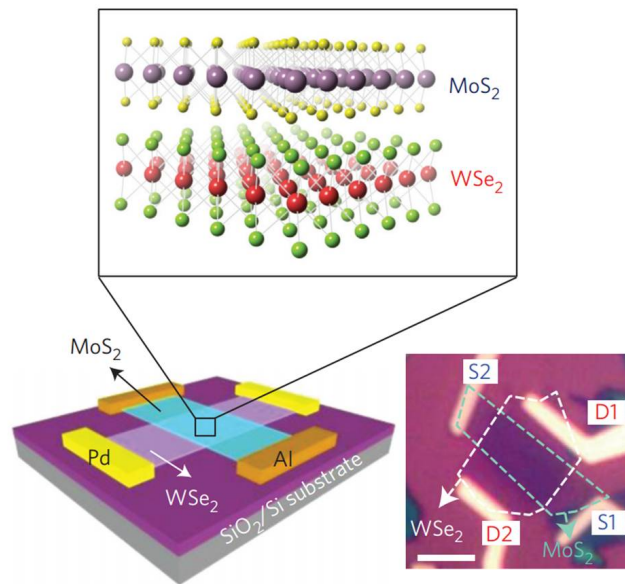
Kang, Jun, et al, APL (2013)



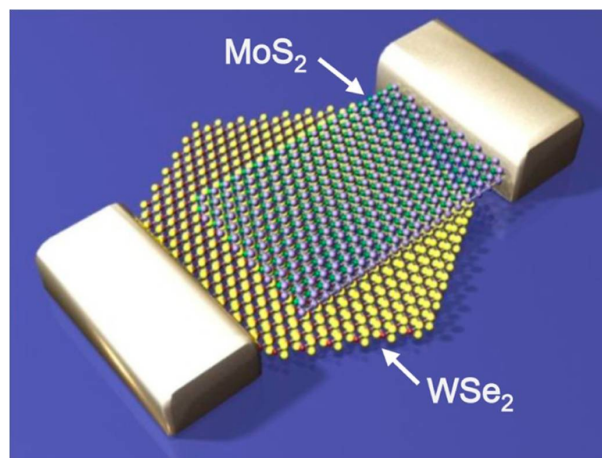
Fang...Javey; PNAS (2014)



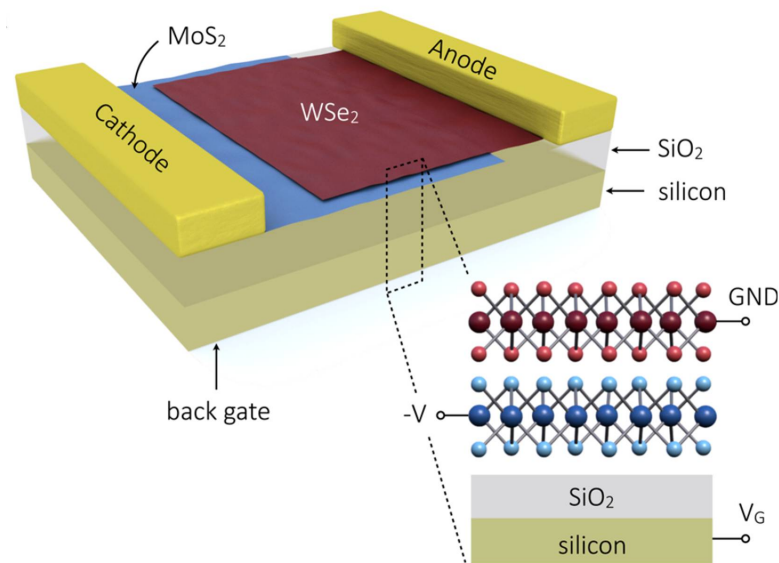
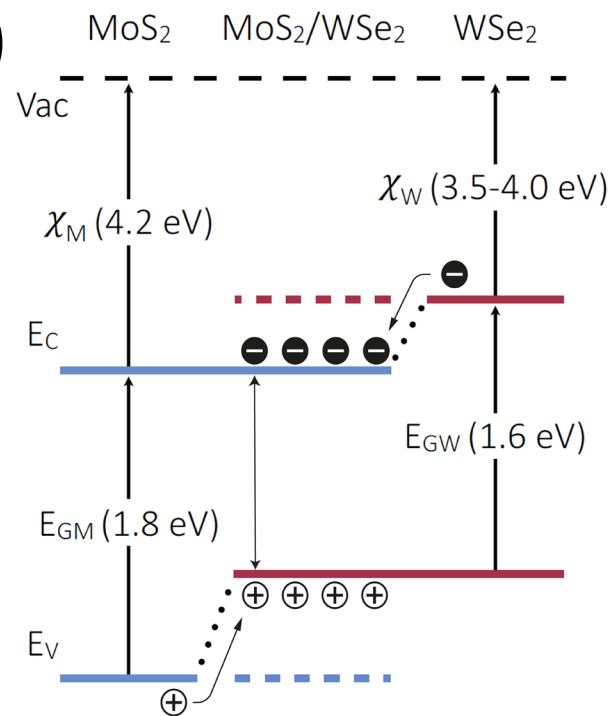
Vertical heterojunction devices (2D/2D)



Lee...Kim; Nat. Nanotechnology (2014)

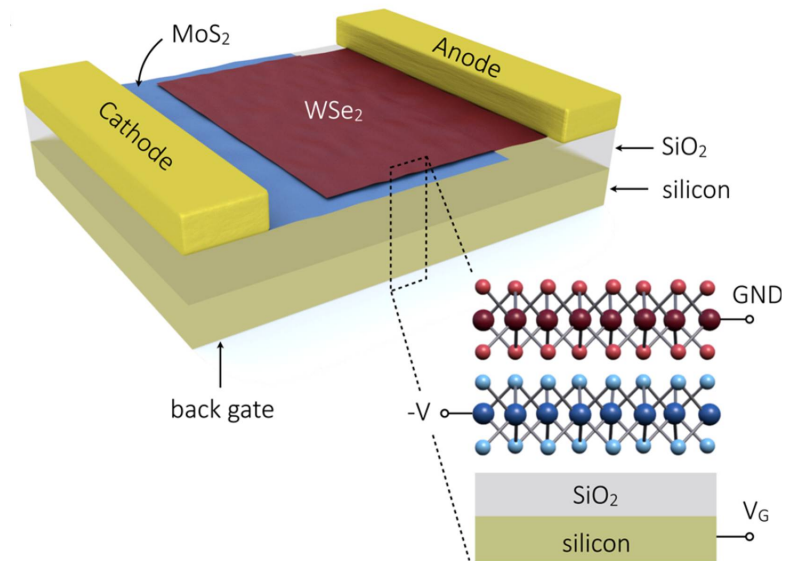
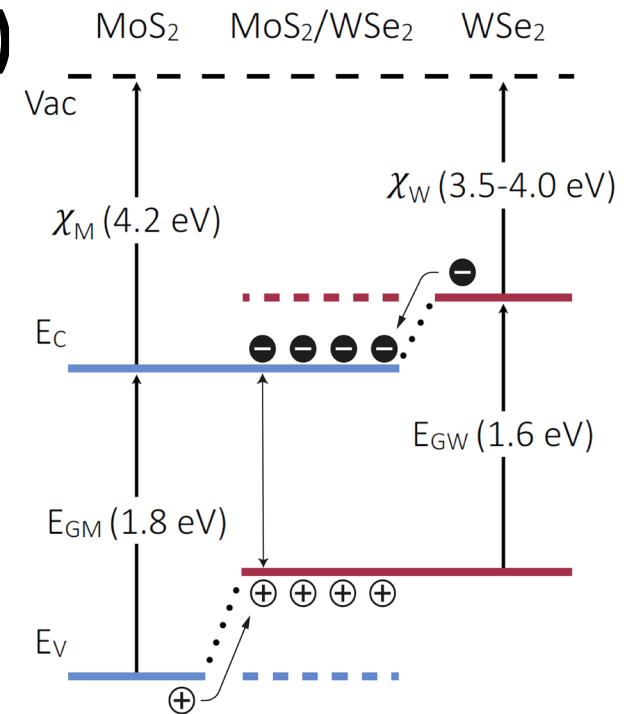
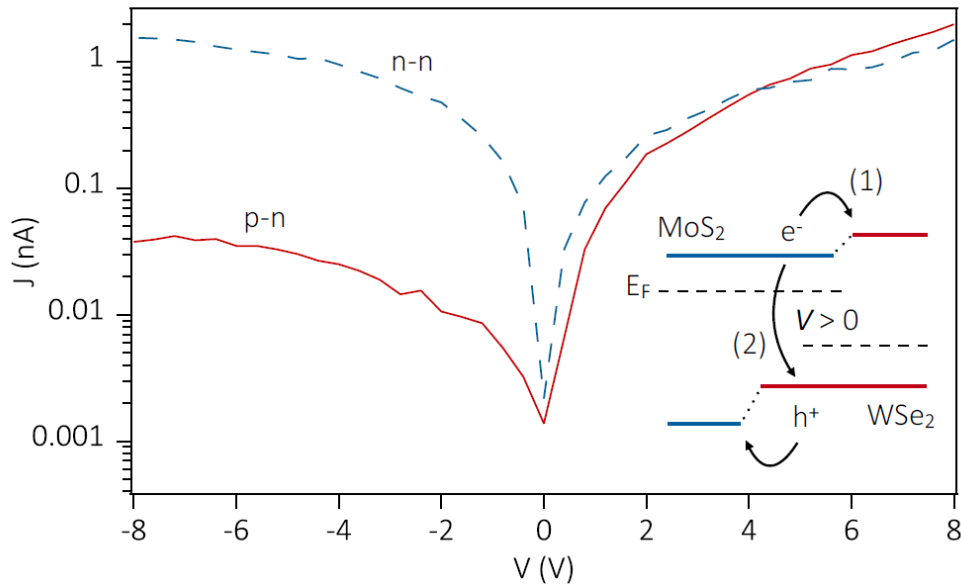
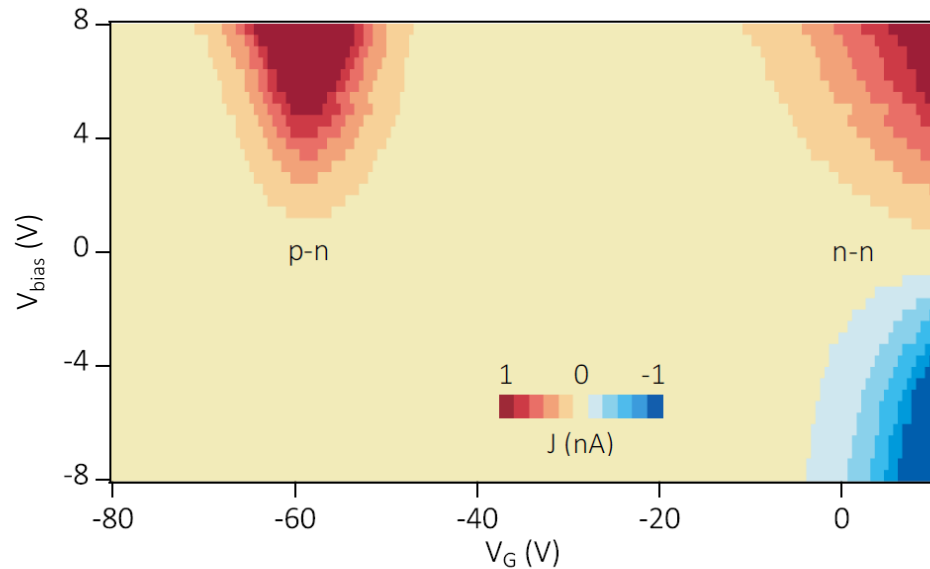


Cheng...Duan; Nano Letters (2014)

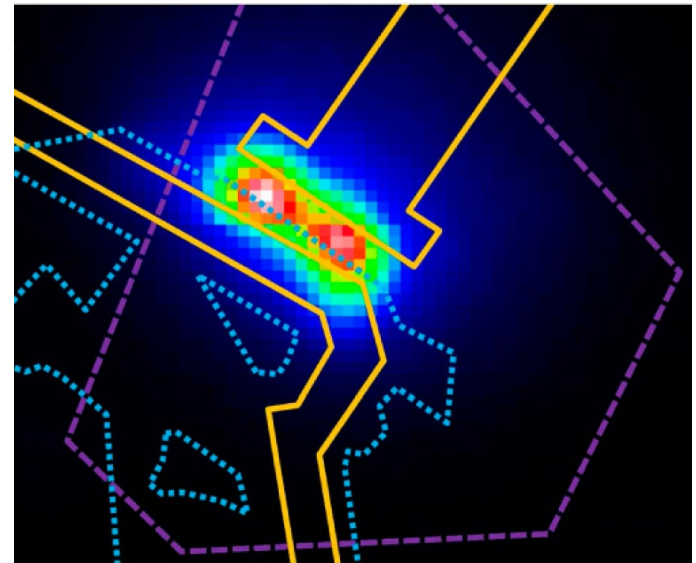
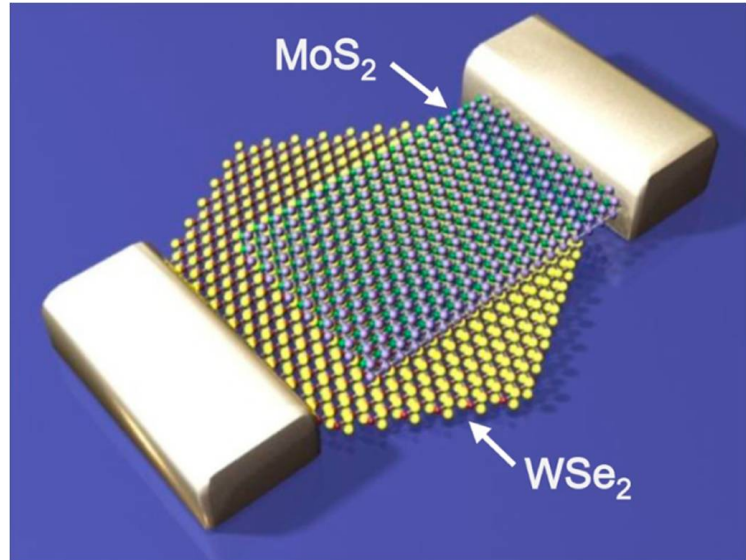
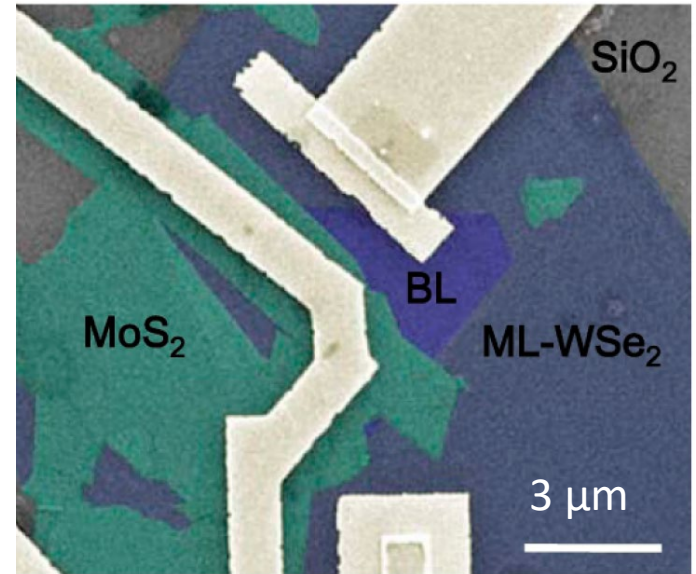
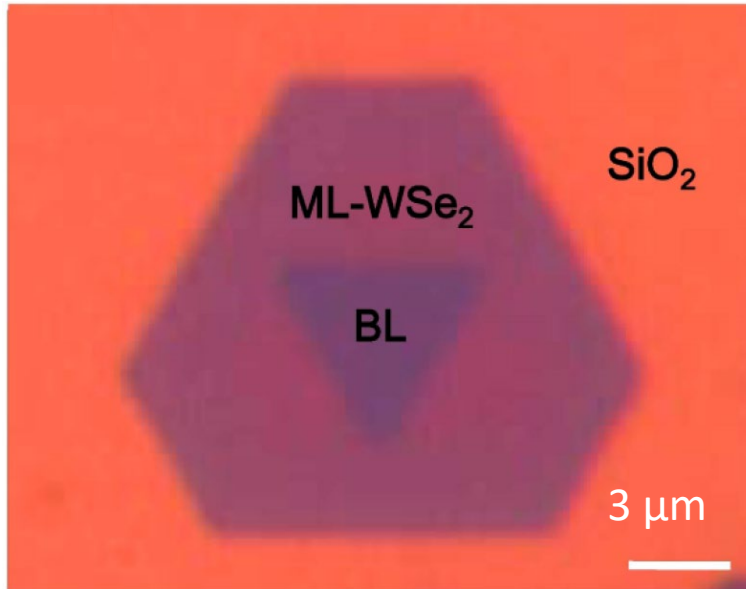


Furchi...Müller; Nano Letters (2014)

Vertical heterojunction devices (2D/2D)

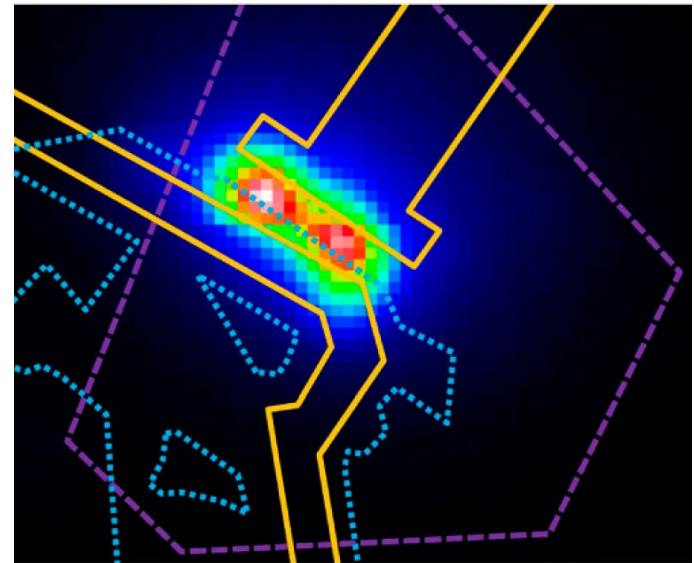
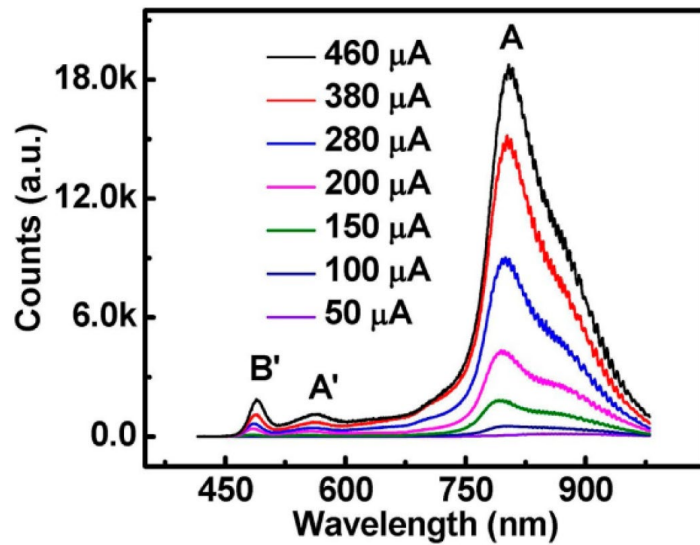
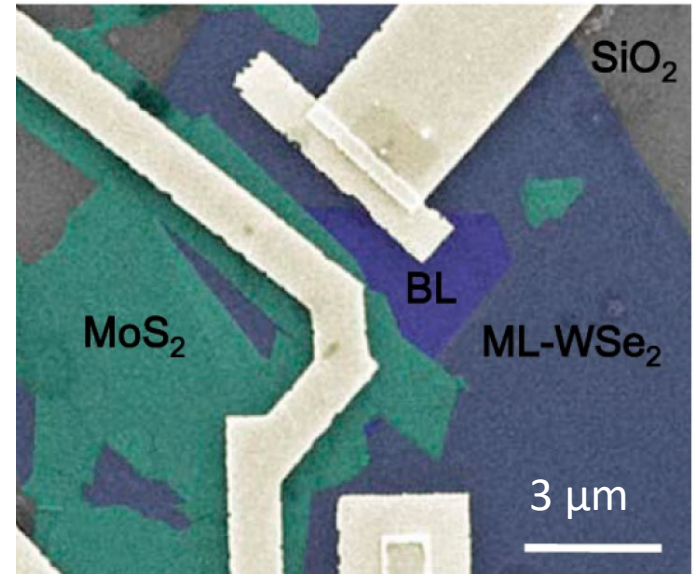
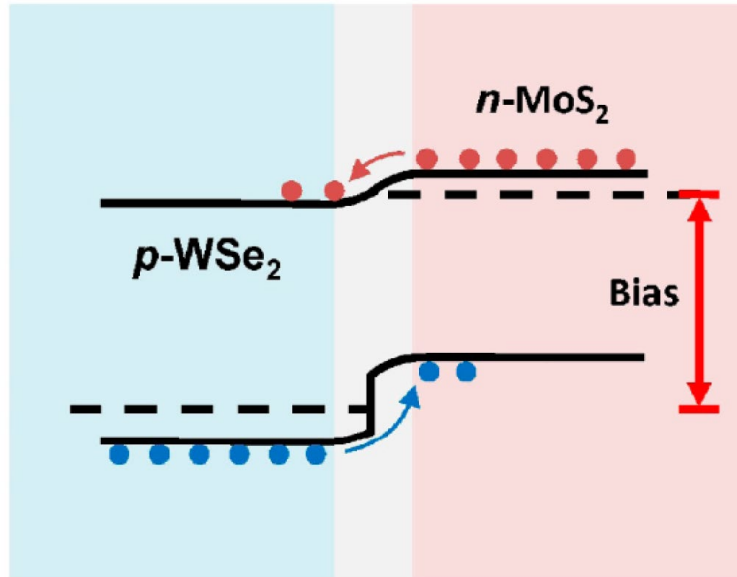


Vertical heterojunction LEDs



Cheng...Duan; Nano Letters (2014)

Vertical heterojunction devices (2D/2D)

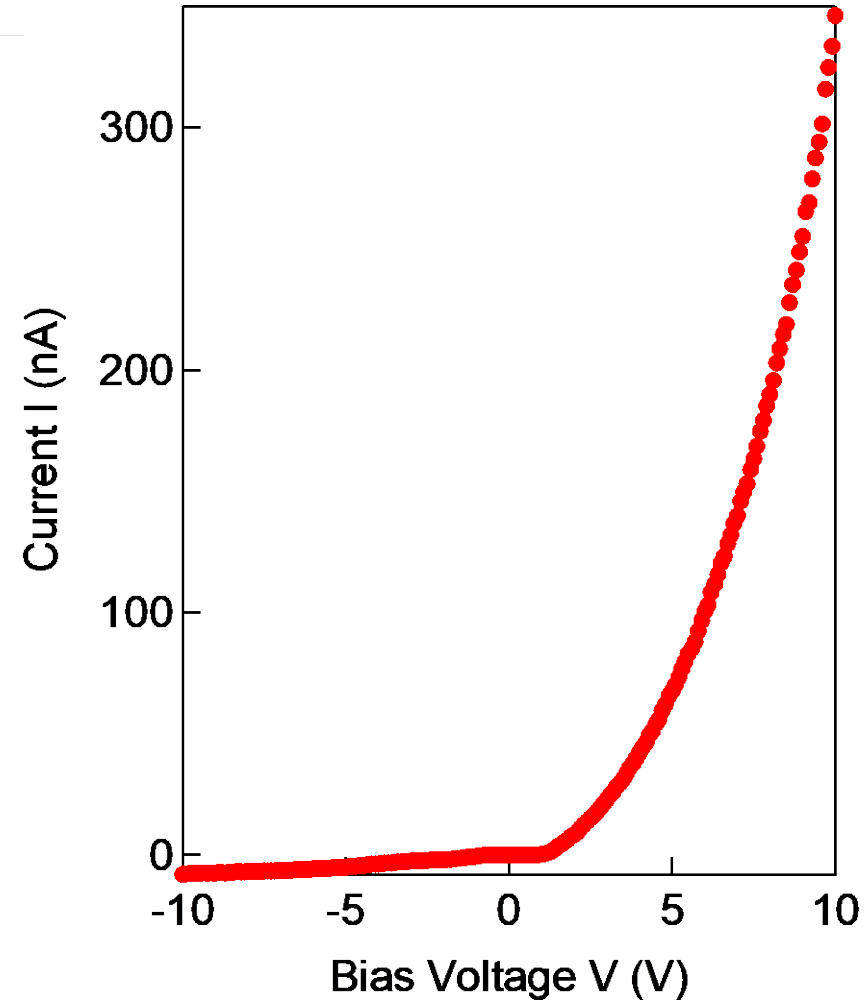
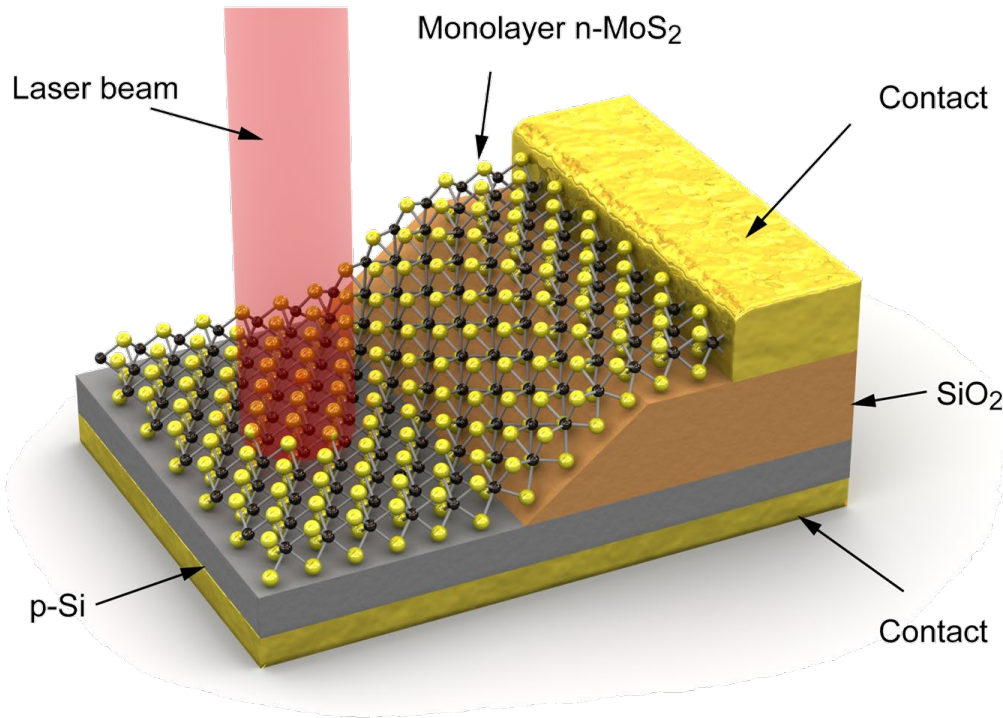


Cheng...Duan; Nano Letters (2014)

Vertical heterojunction devices 2D/3D MoS₂/p-Si

Diode characteristic

Device structure

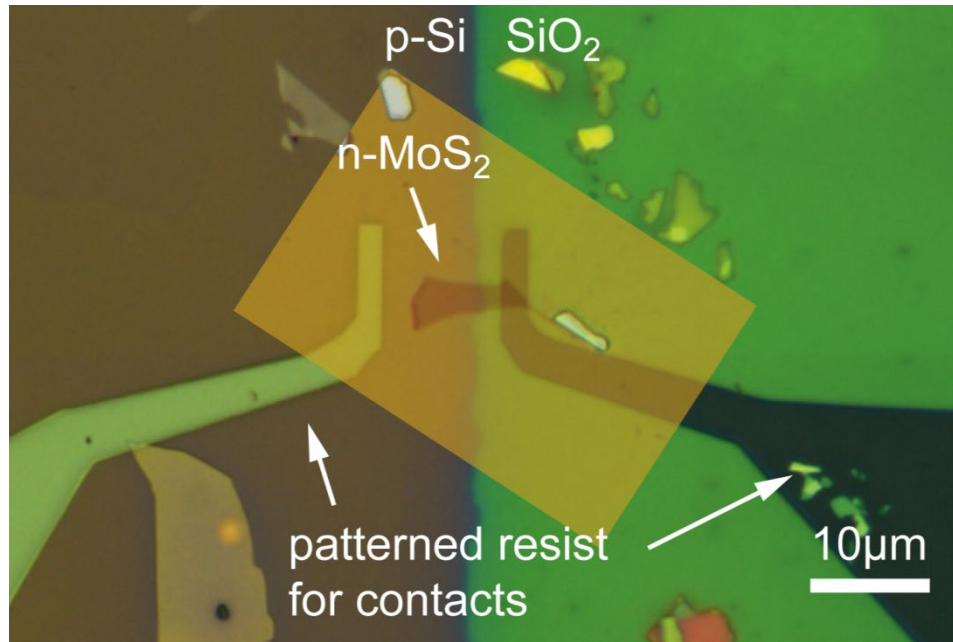


Lopez-Sanchez, Kis et al. ACS Nano (2014)

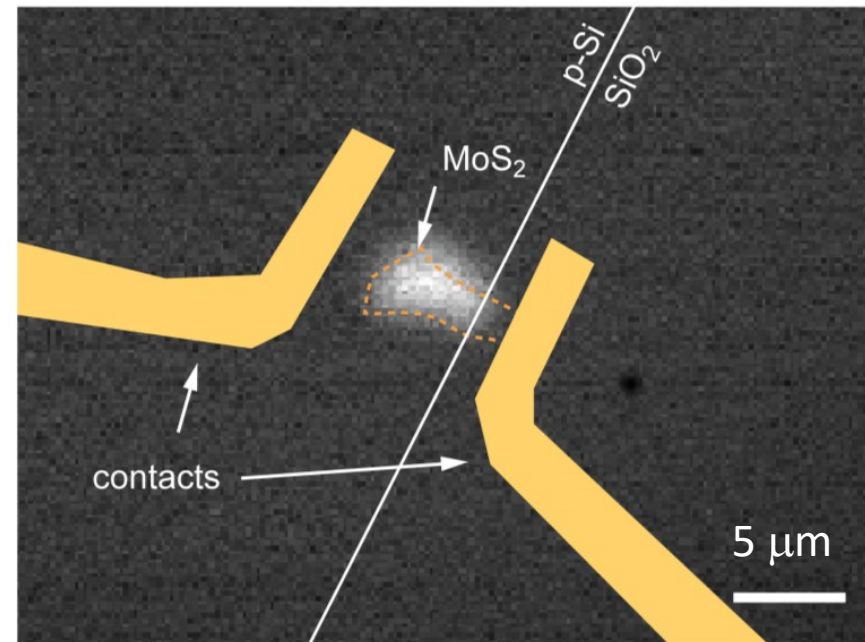
See also: Yim, Lemme, Duesberg et al, Scientific Reports (2014)

MoS₂/Si heterojunctions: light emission

Device structure



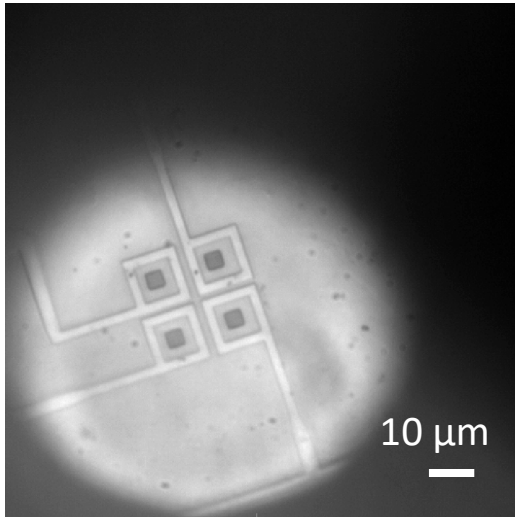
Emitted light intensity map



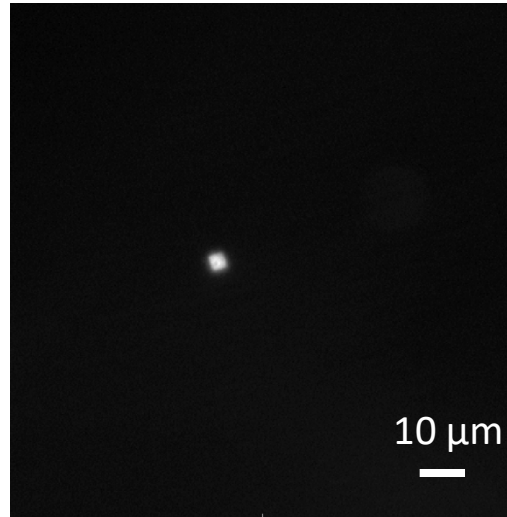
MoS₂/p-Si heterojunctions: light emission

CVD material

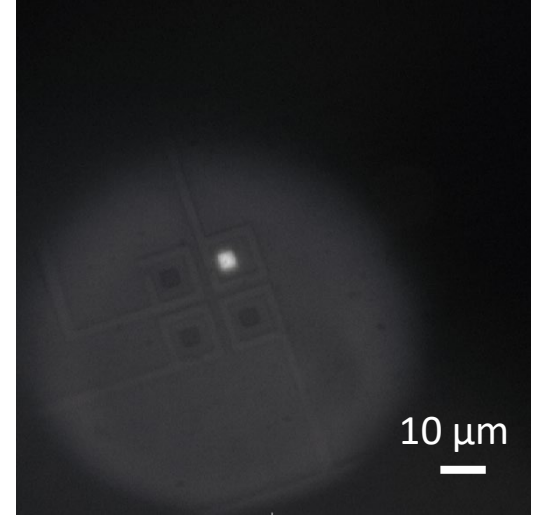
Reflected light



Emitted light

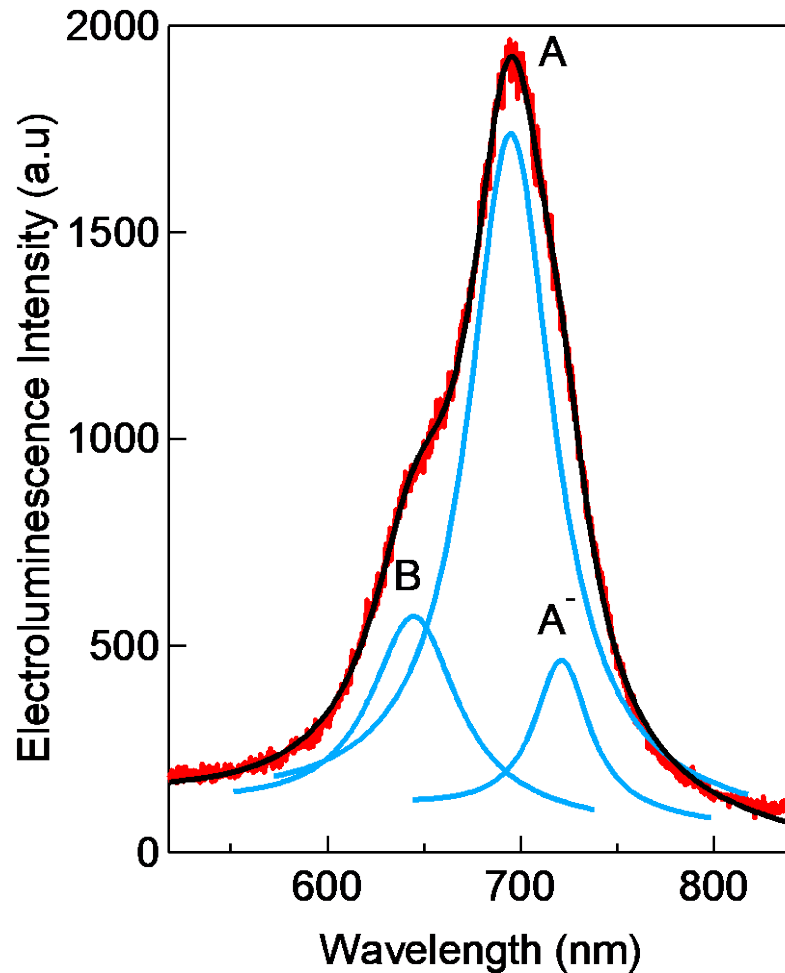


Superposition

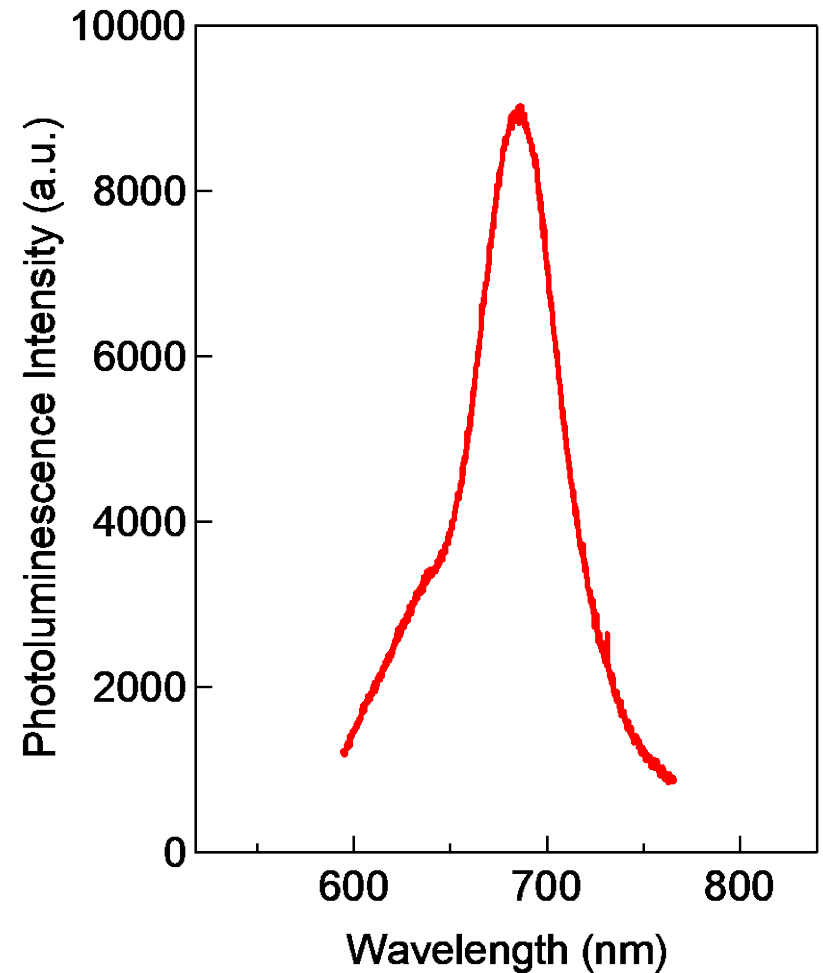


MoS₂/Si heterojunctions: light emission

Electroluminescence spectrum

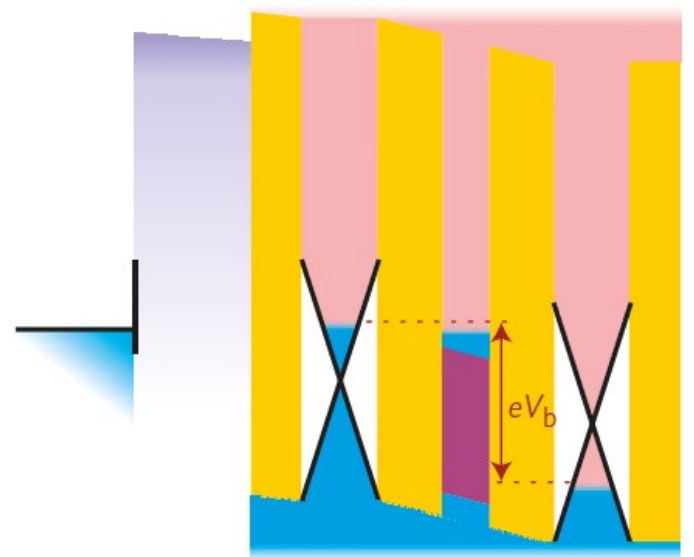
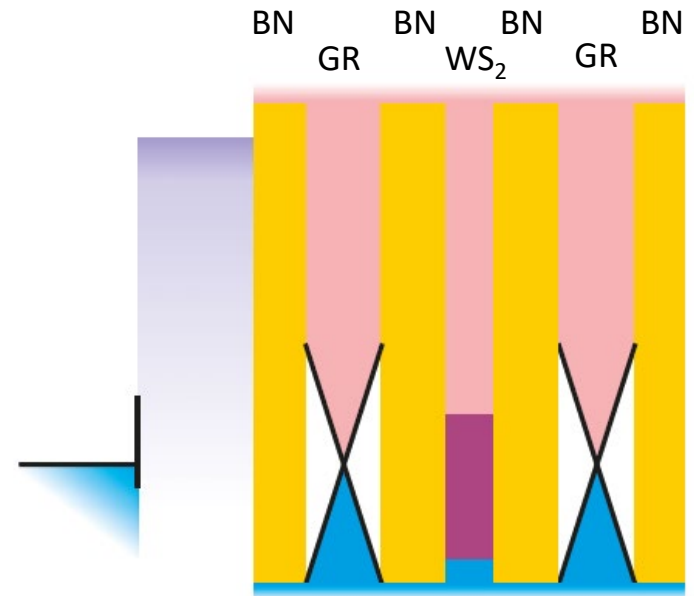
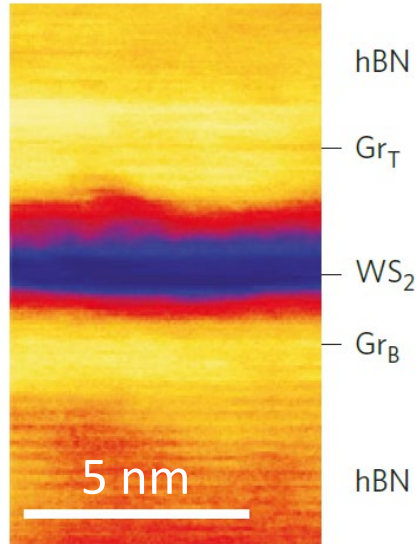
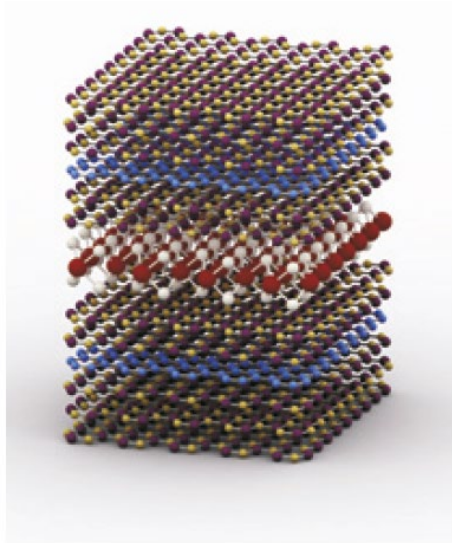


Photoluminescence spectrum



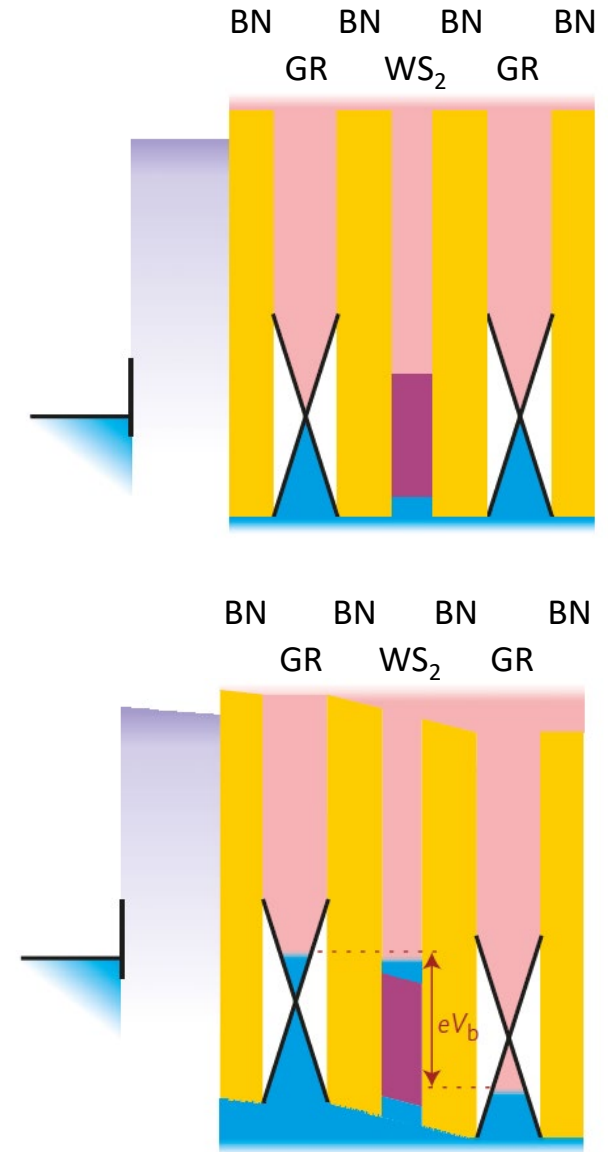
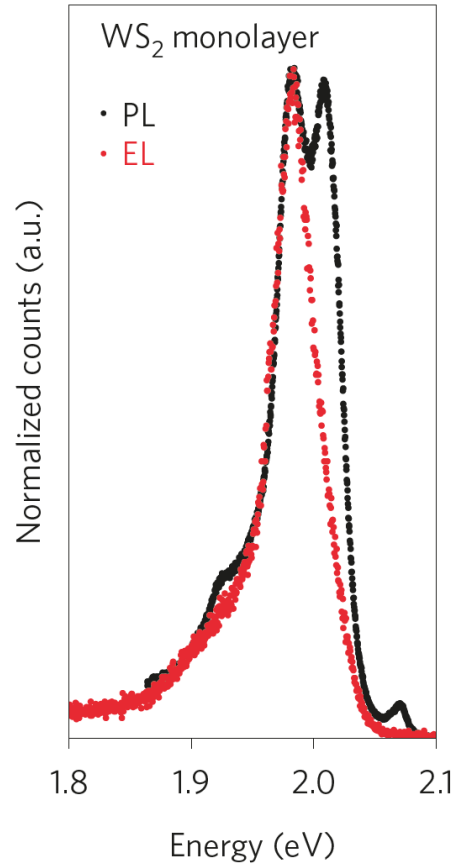
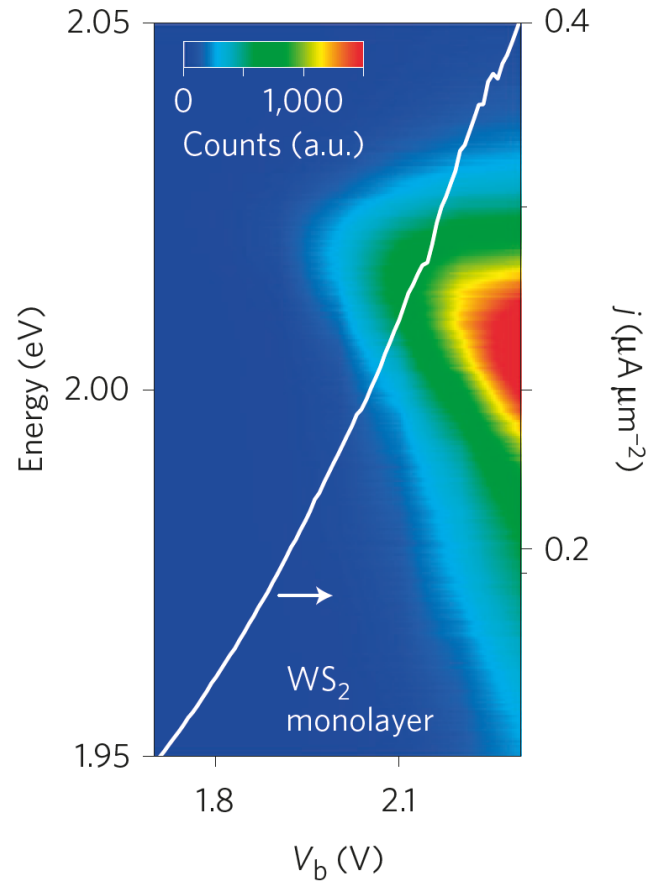
Lopez-Sanchez, Kis et al. ACS Nano (2014)

Quantum well EL devices

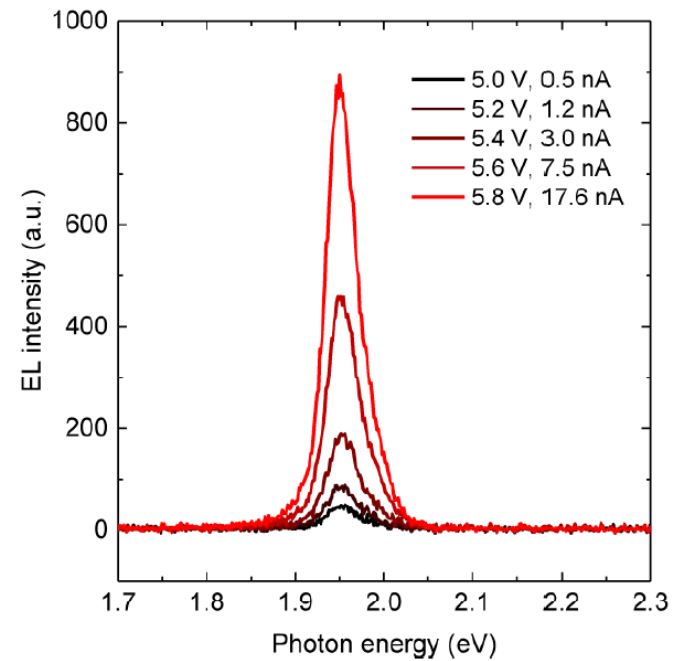
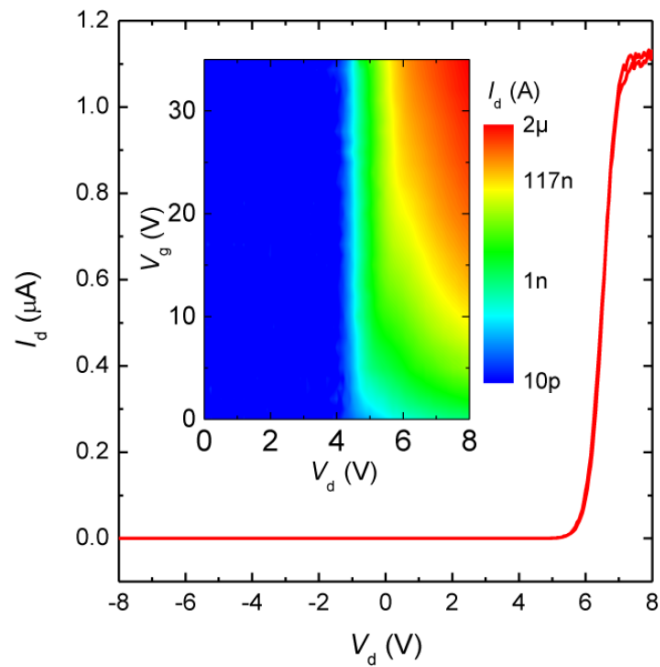
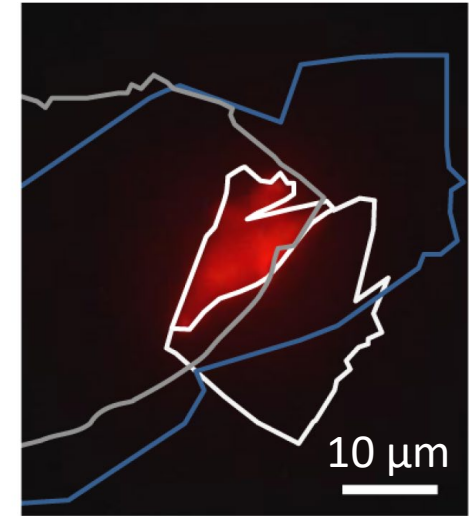
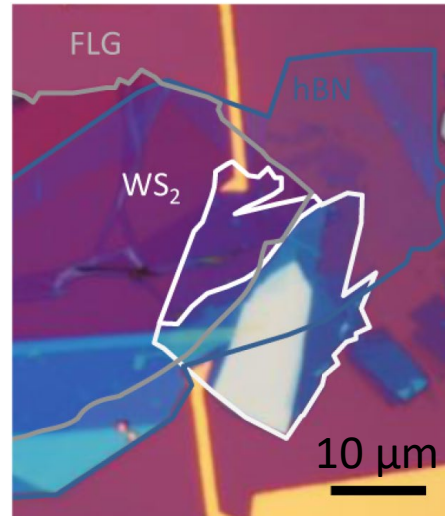
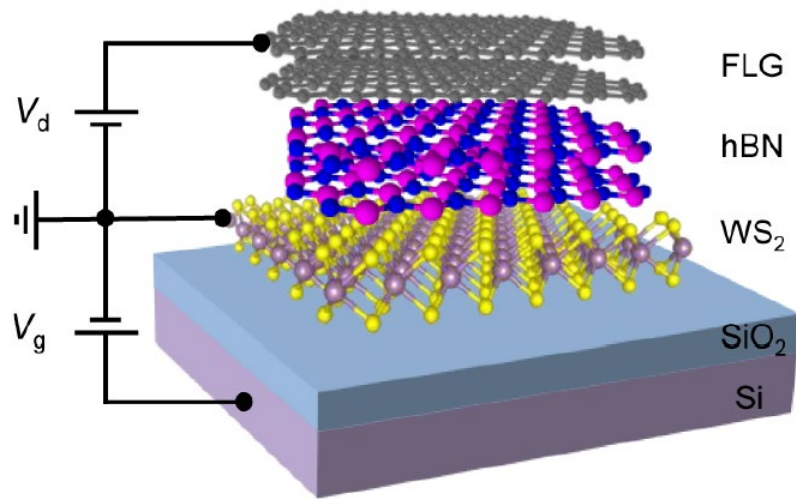


Withers et al. Nature Materials(2015)

Quantum well EL devices

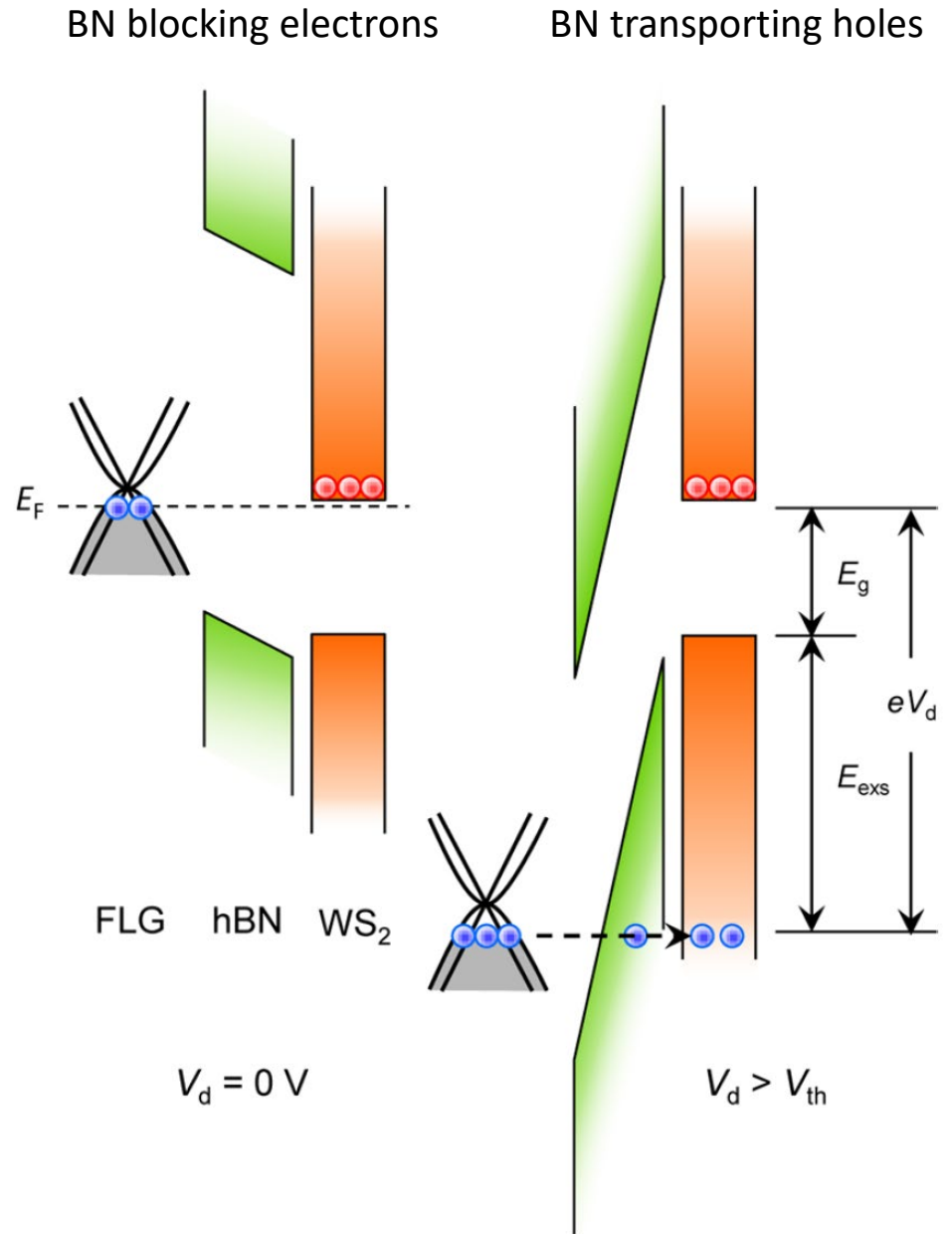
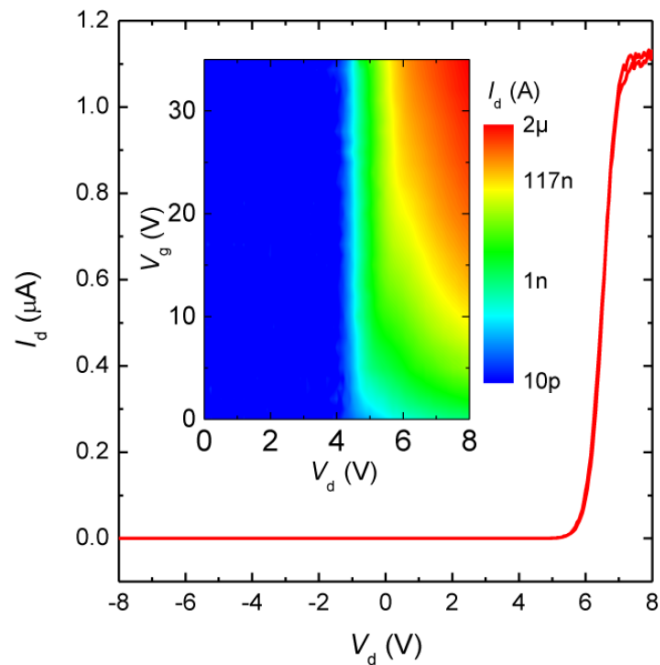
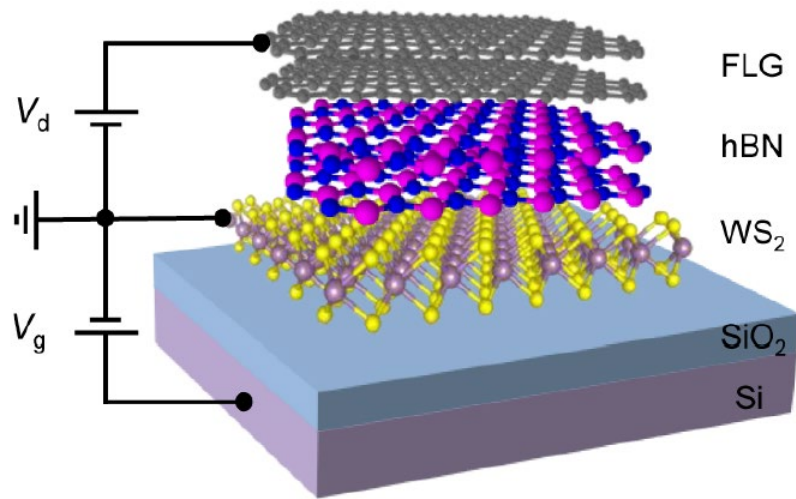


Metal-insulator-semiconductor (MIS) EL devices



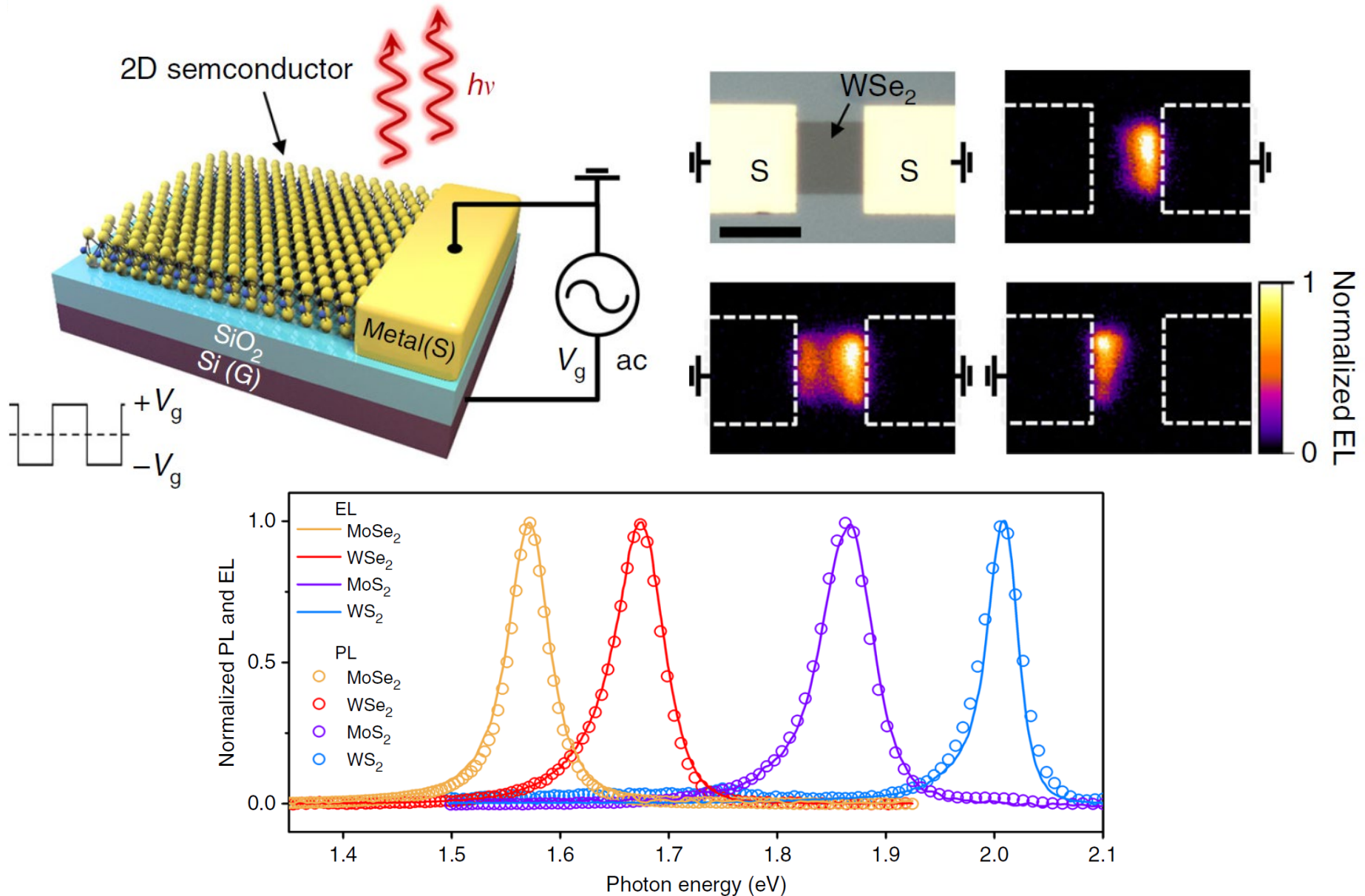
Wang et al. Nano Letters (2017)

Metal-insulator-semiconductor (MIS) EL devices

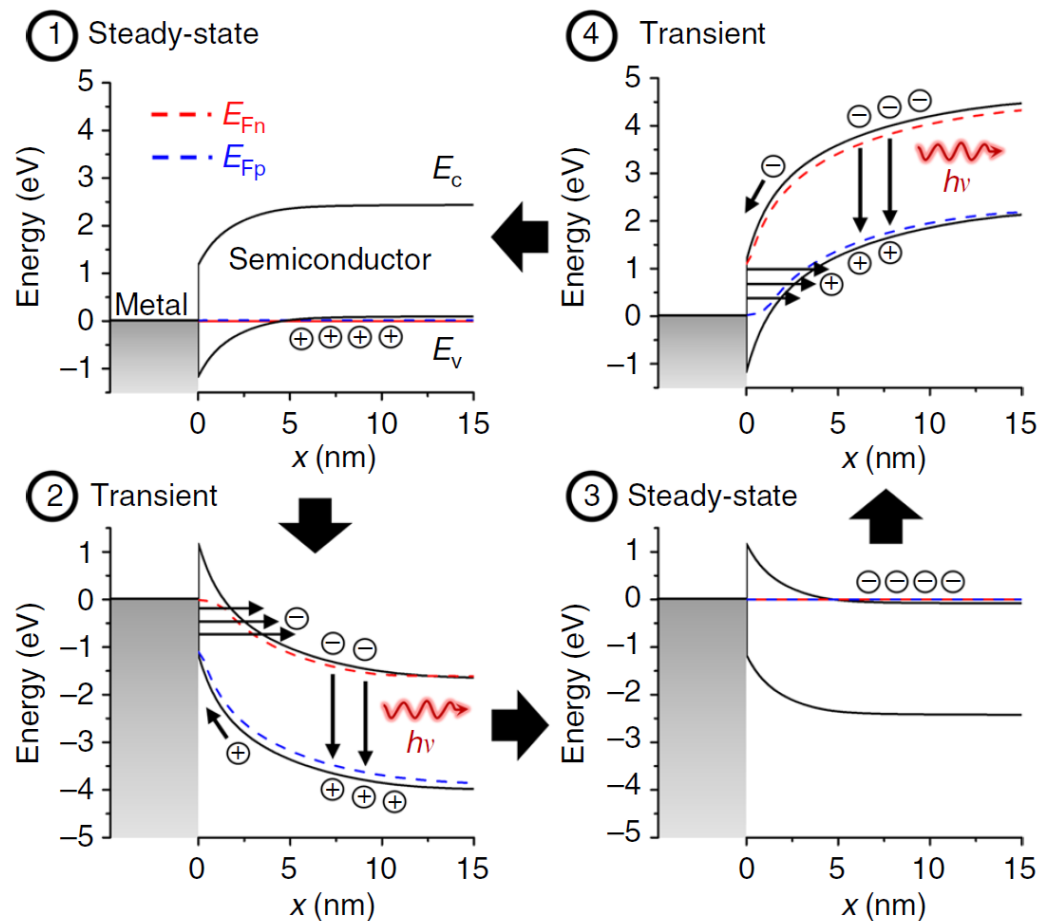
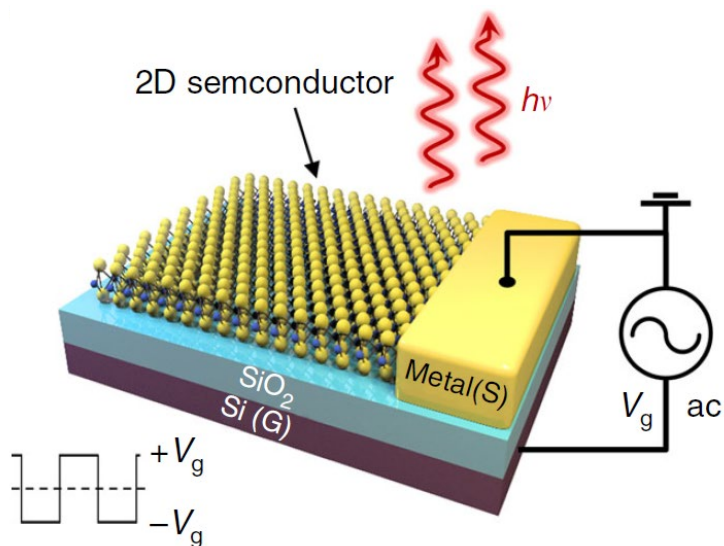
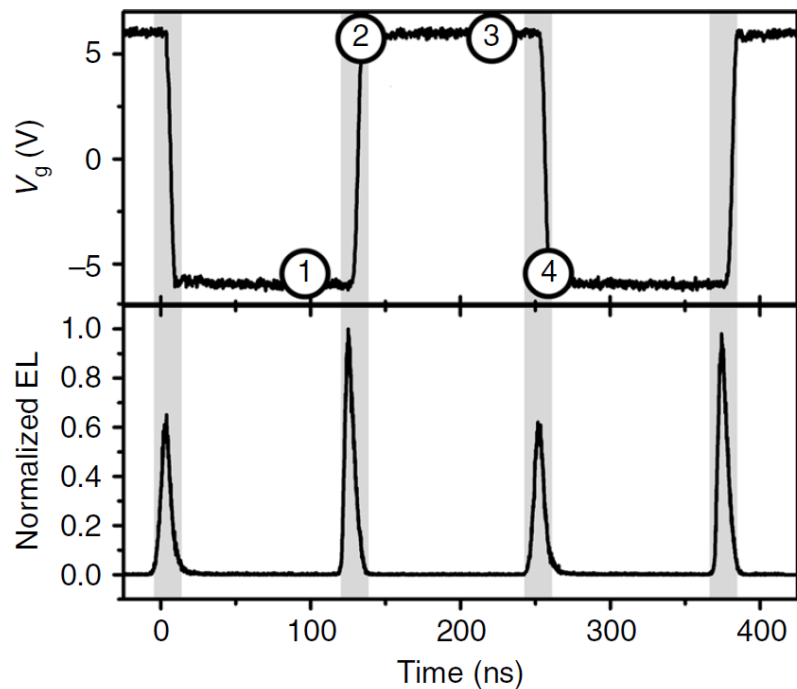


Wang et al. Nano Letters (2017)

Pulsed EL device



Pulsed EL device



Lien et al. Nature Communications (2018)

Recapitulation

Optoelectronics in the IT context

- Integrated sources, modulators and detectors for data transmission

Optical properties of TMDCs

- Strong absorbance, excitons, nesting
- Can be tuned via strain, composition, environment
- Joint density of states
- Photodetector speed limited by traps

Devices

- Joint density of states
- Photodetector speed limited by traps
- Integration with waveguides for on-chip devices possible
- Lateral and vertical heterostructures for LEDs