Semiconductor Devices II

Part 2

Chapter 4: Photodetectors and LEDs

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[Outline] Chapter 4: Photodetectors and LEDs

Optoelectronics in the IT context

Optical properties of TMDCs

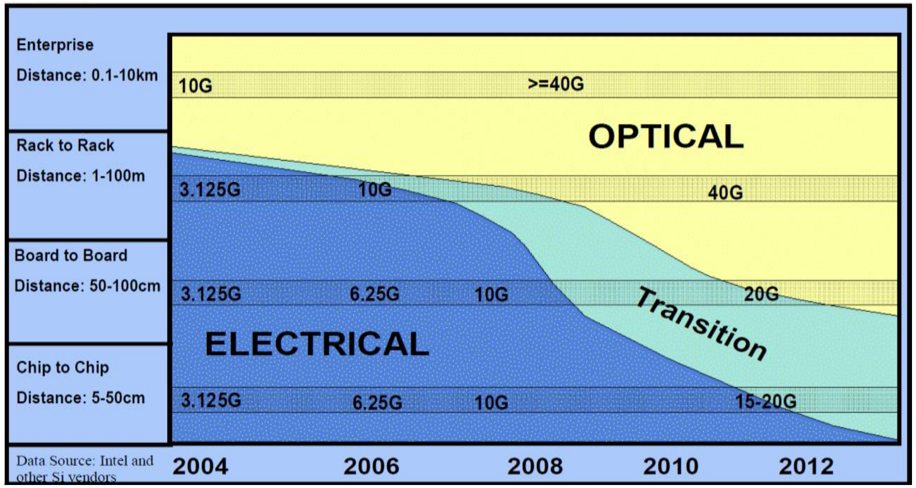
- Reflectance/absorbance
- Band structure
- Excitons – band gap, binding energy
- Tuning

Devices

- Photodetectors
- Electroluminescent devices

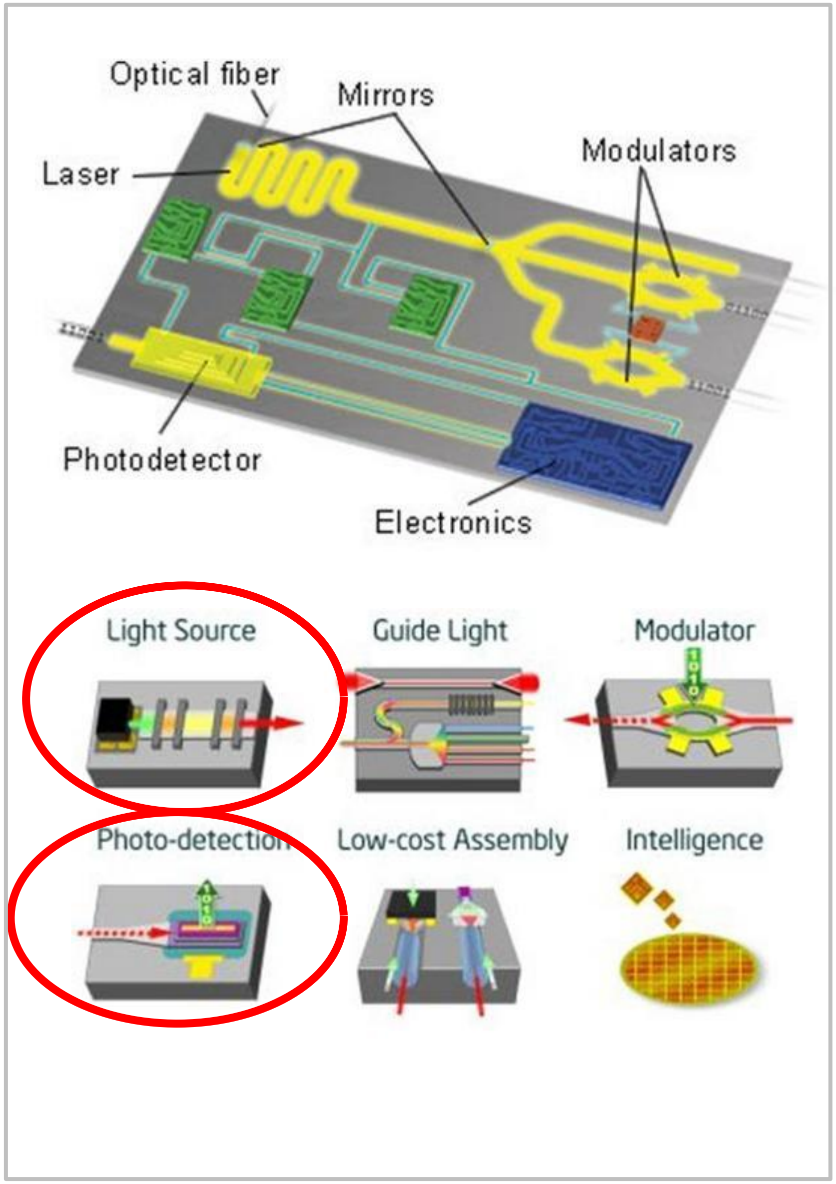
Optoelectronics and IT devices

Data load

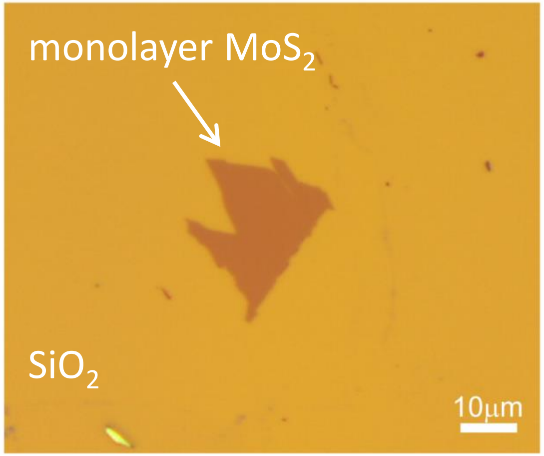


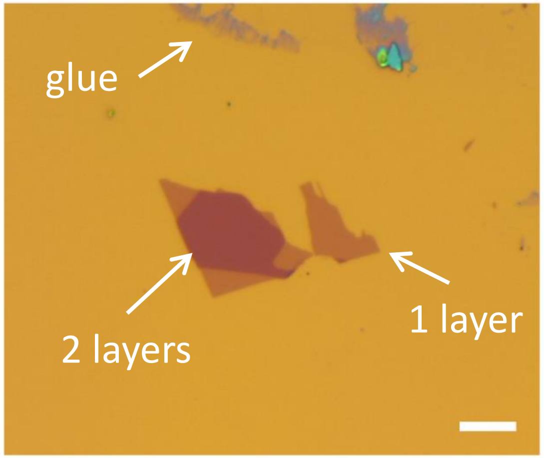
Flexible devices

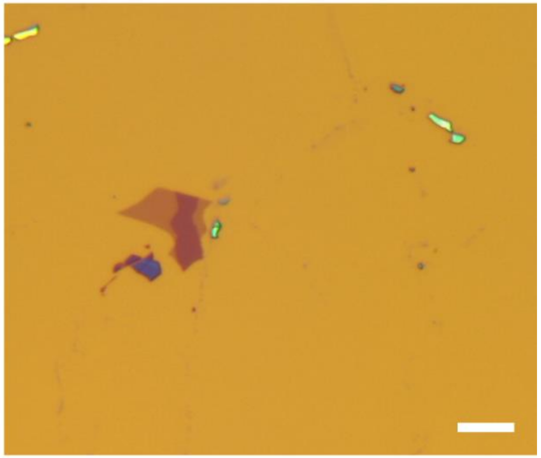
From the TV show Westworld

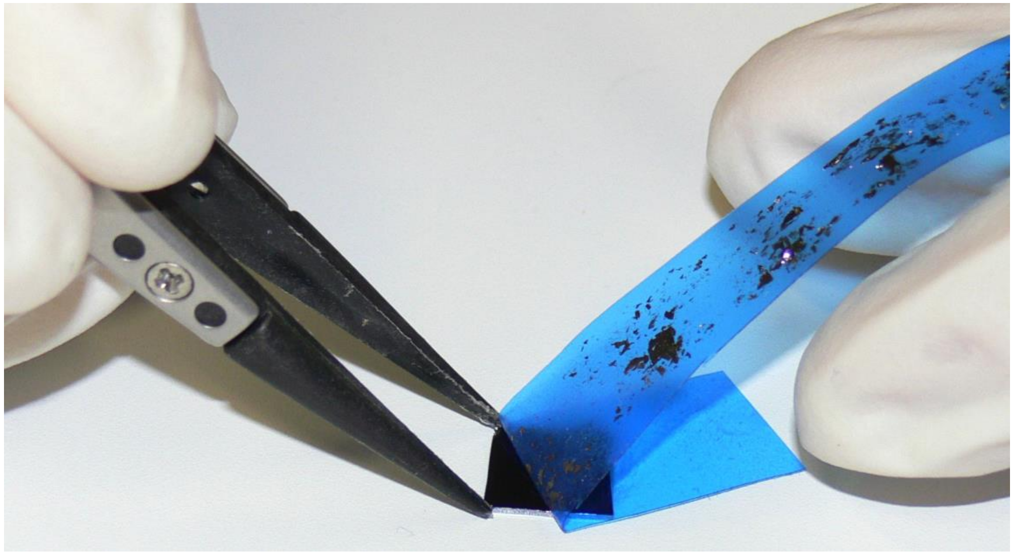


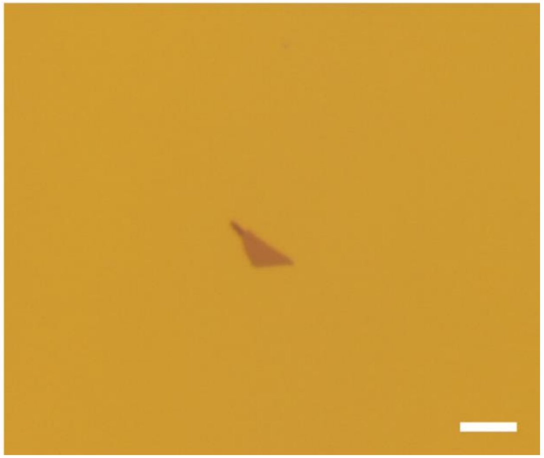
Visibility of TMDC monolayers





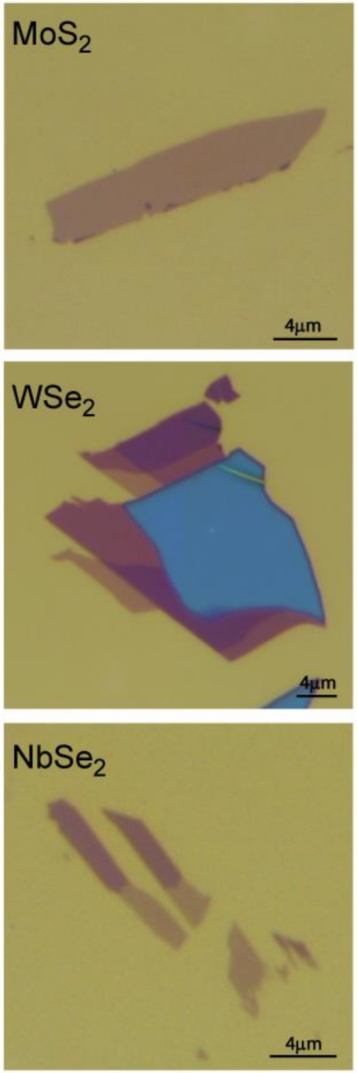


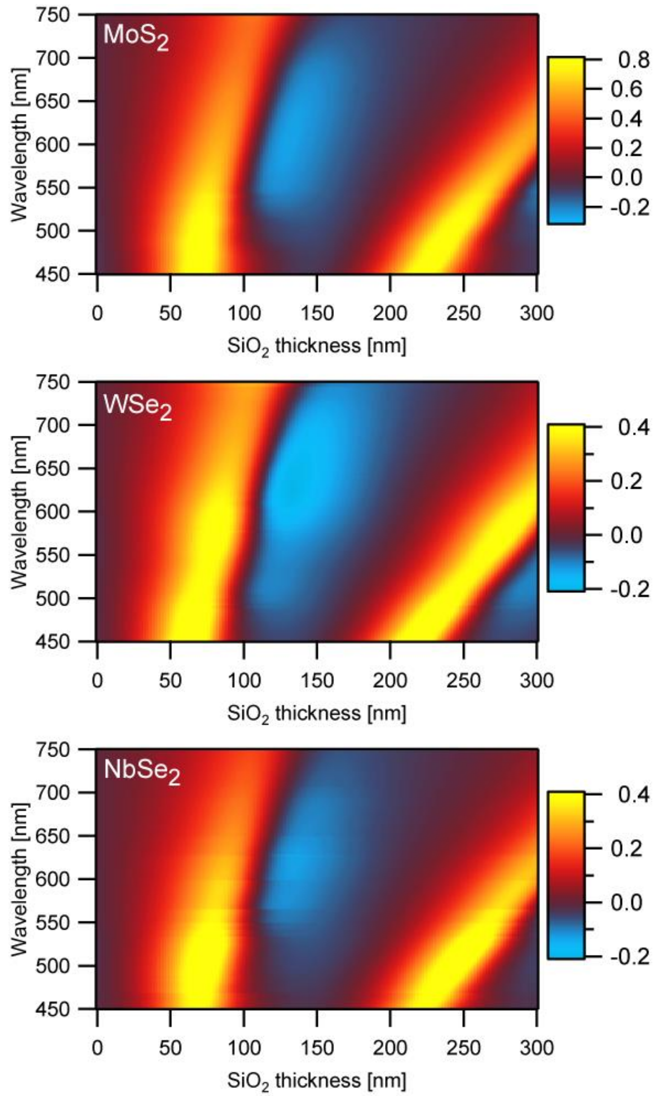


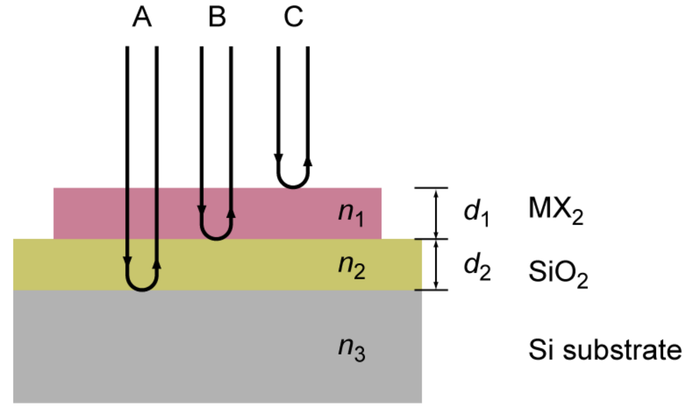


Benameur et al., Nanotechnology (2011)

Visibility of TMDC monolayers – contrast maps



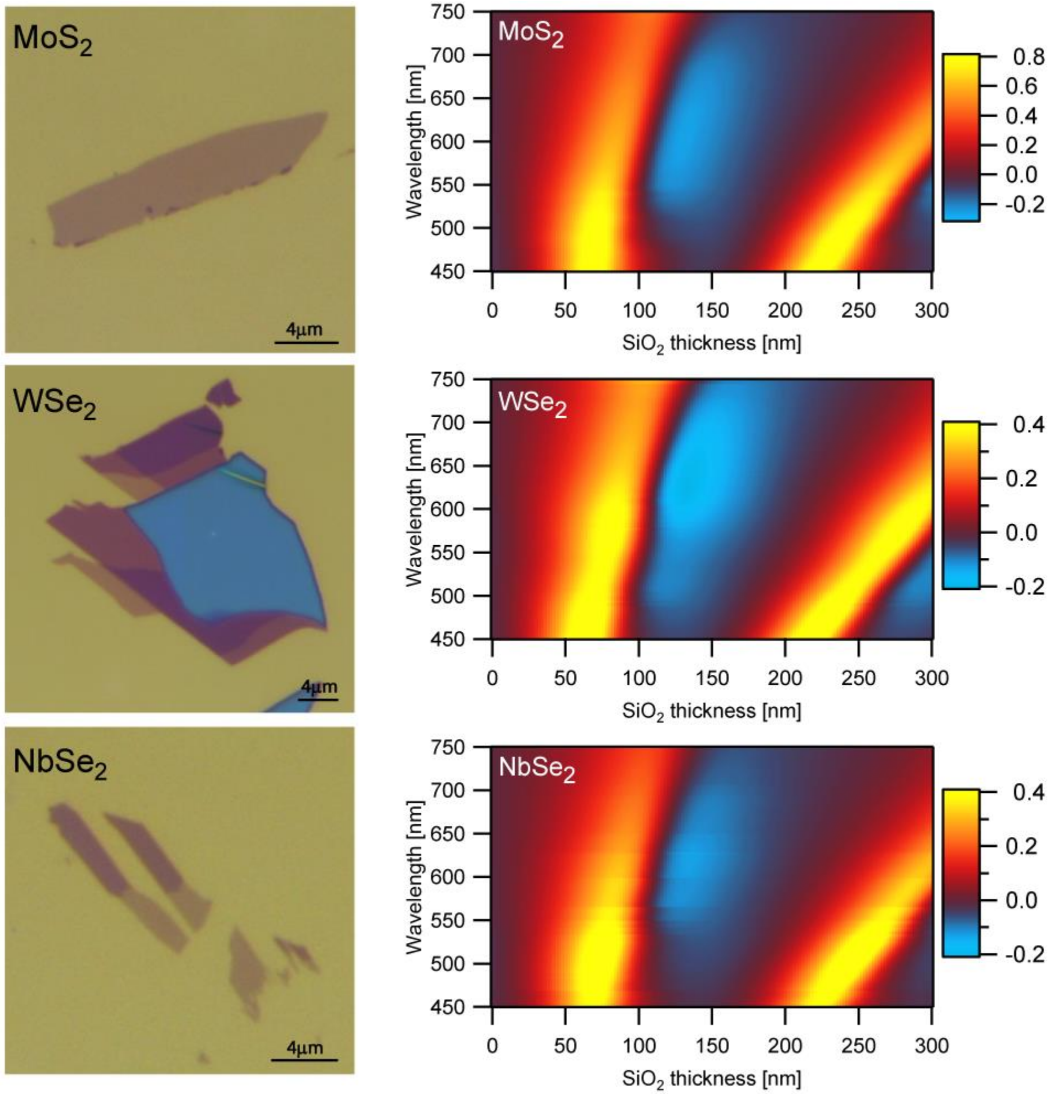


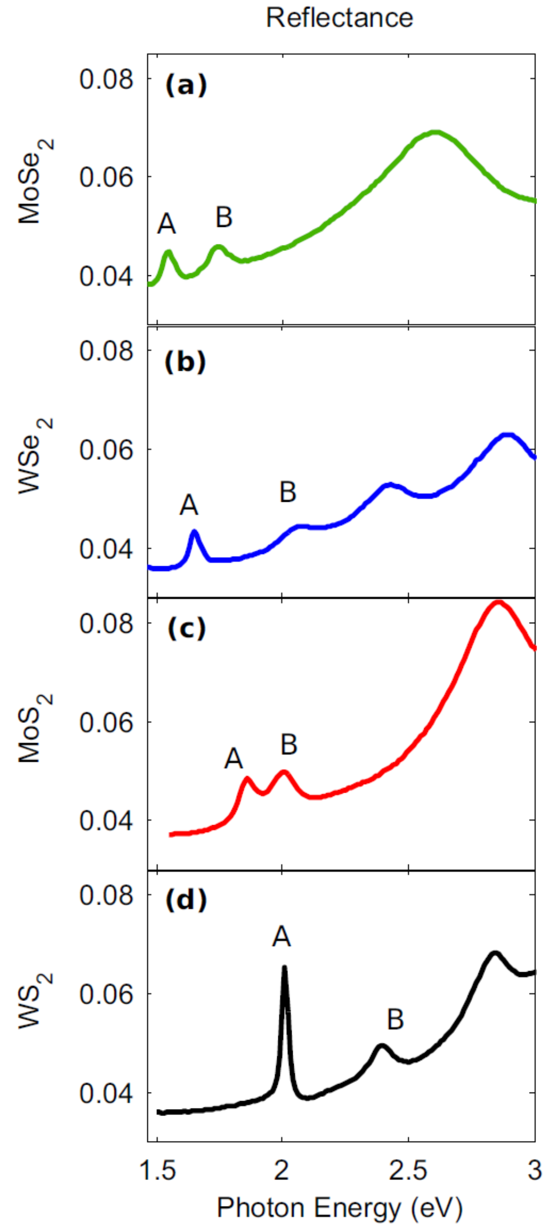


Benameur…Kis; arxiv:1006.1048 (2010)

Benameur…Kis; Nanotechnology (2011)

Visibility of TMDC monolayers – contrast maps



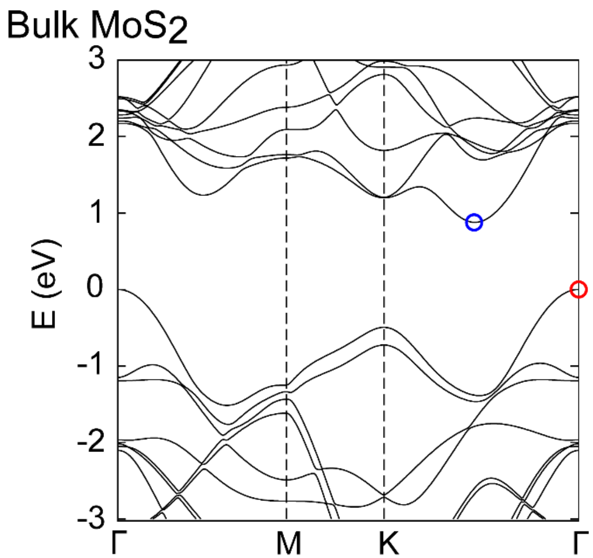


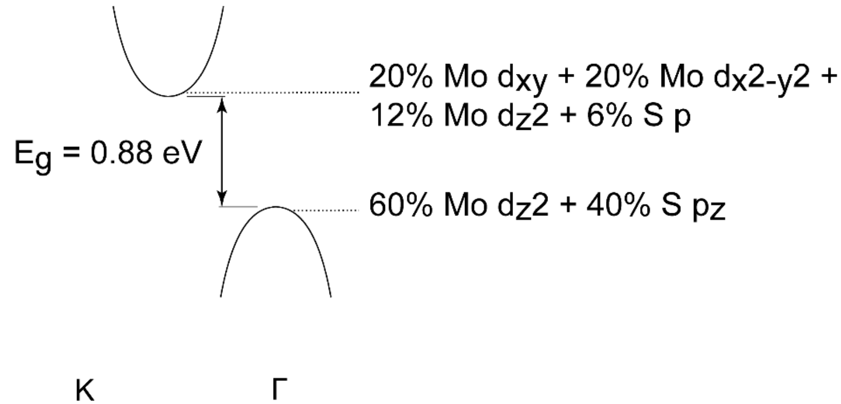
Benameur…Kis; arxiv:1006.1048 (2010)

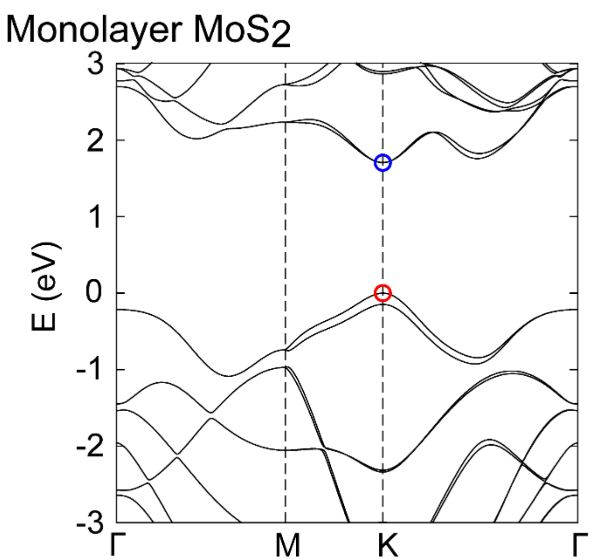
Benameur…Kis; Nanotechnology (2011)

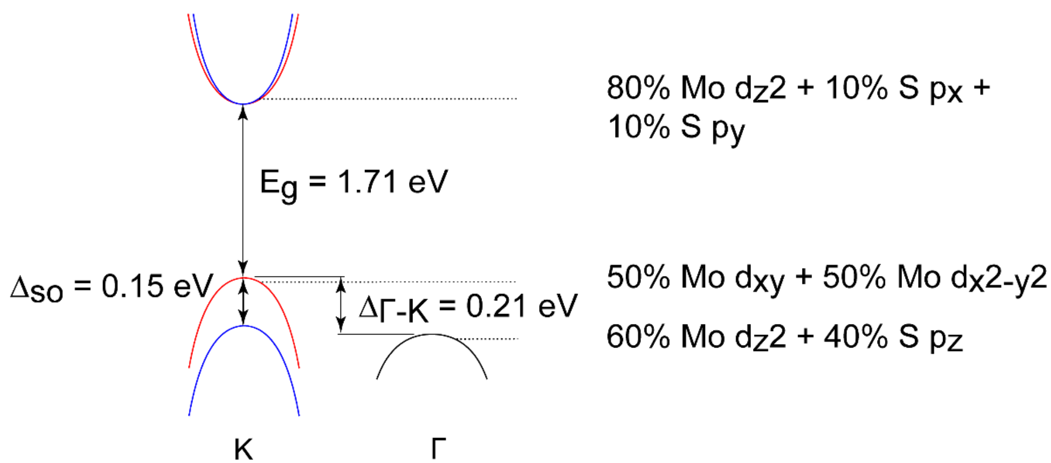
Li et al. Phys. Rev. B (2014)

Band structure of 2H MoS_2









Kuc…Heine; Physical Review B (2011)

Yazyev and Kis; Materials Today (2014)

Red, blue: spin polarized subbands

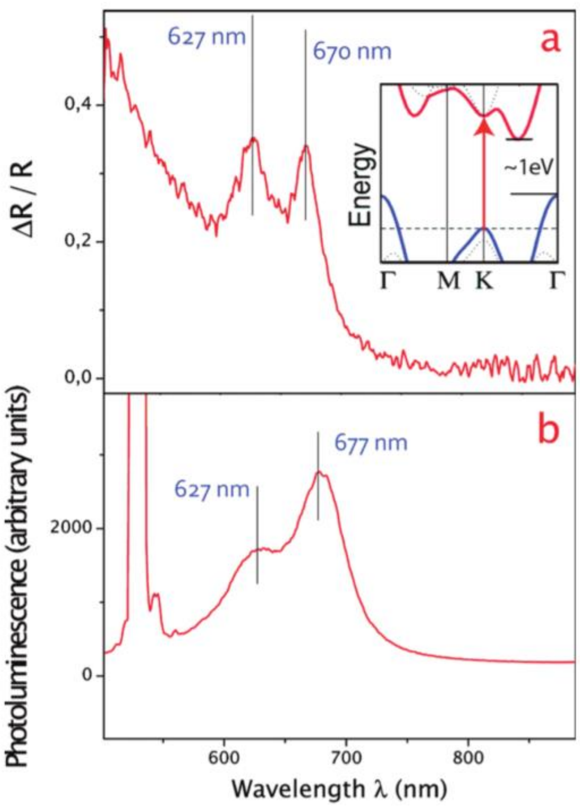
NANO LETTERS
pubs.acs.org/NanoLett

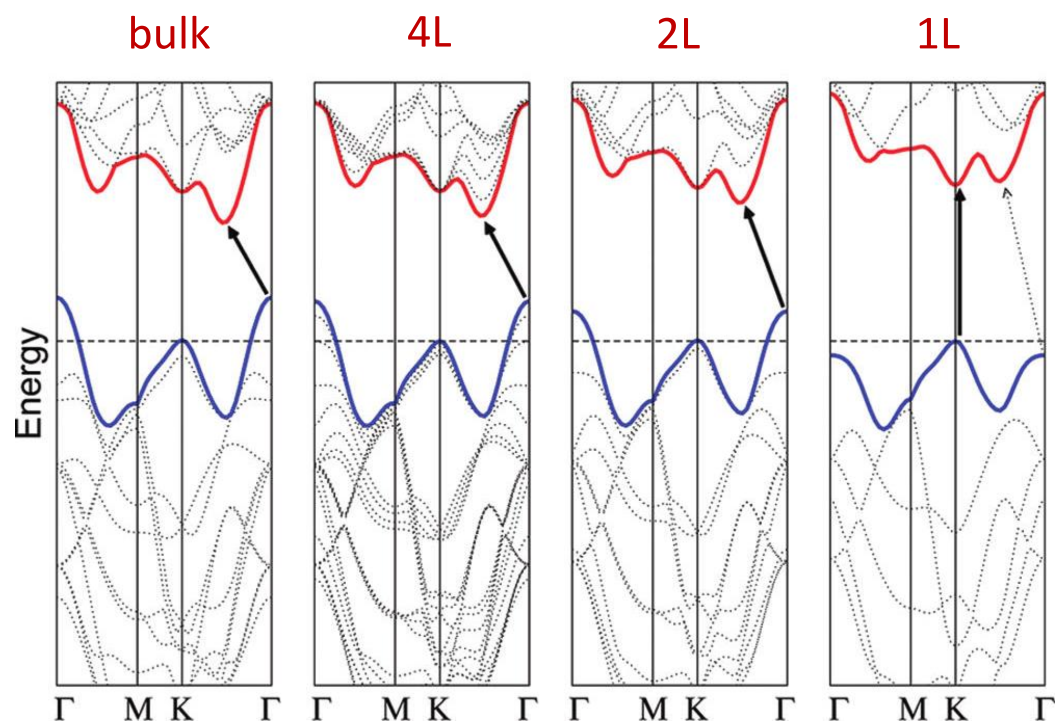
Emerging Photoluminescence in Monolayer MoS_2

Splendiani…Wang; Nano Lett. (2010)

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

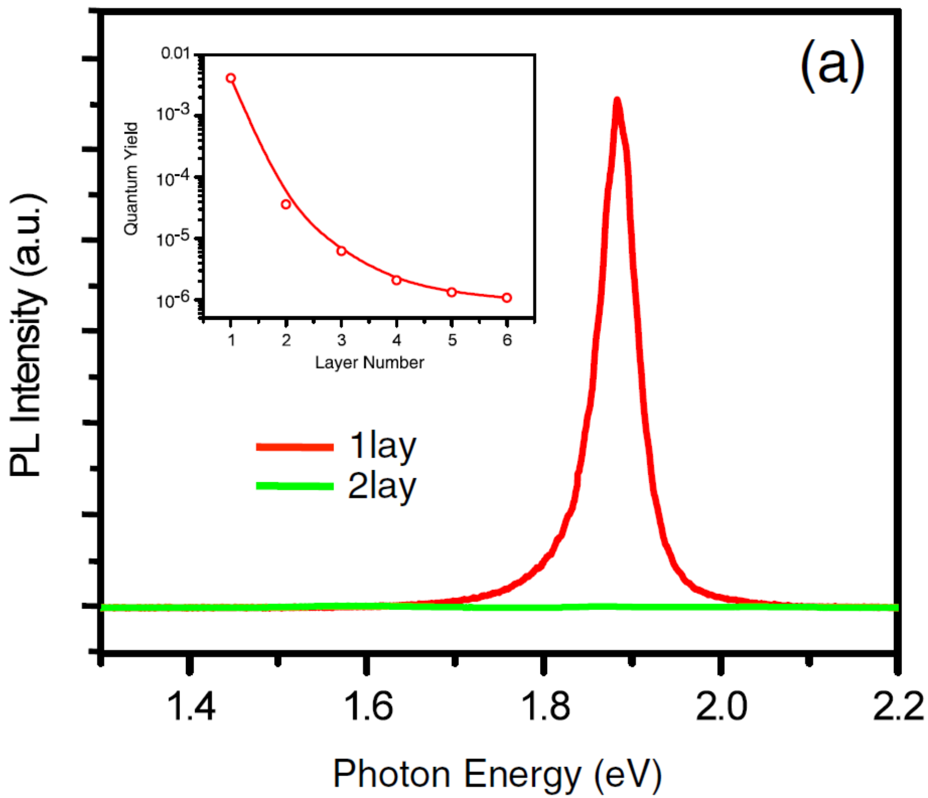
[†]Physics Department, University of California at Berkeley, Berkeley, California 94720, [‡]Scuola Galileiana di Studi Superiori di Padova, 35122 Padova, Italy, [§]Chemistry Department, University of California at Davis, Davis, California 95616, and [||]Materials Science Division, Lawrence Berkeley National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

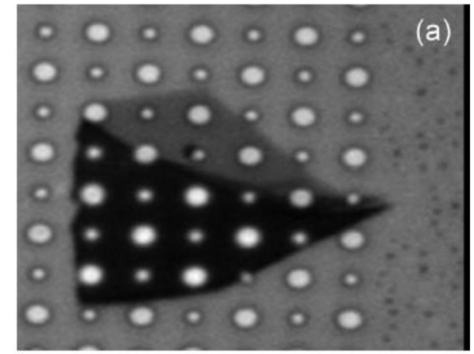


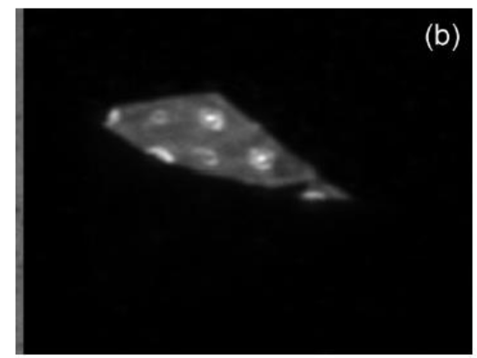


Also later work by Mak…Heinz; PRL (2010)

Photoluminescence



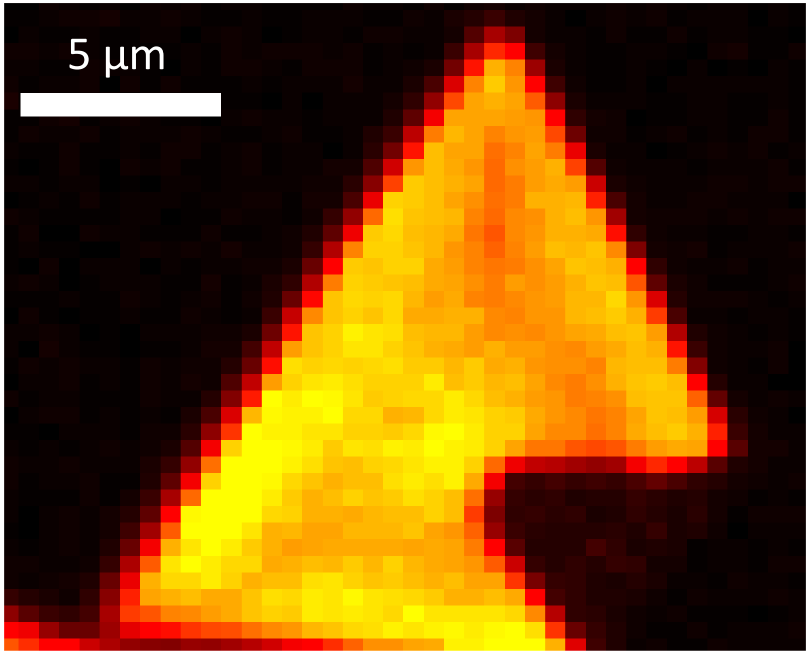


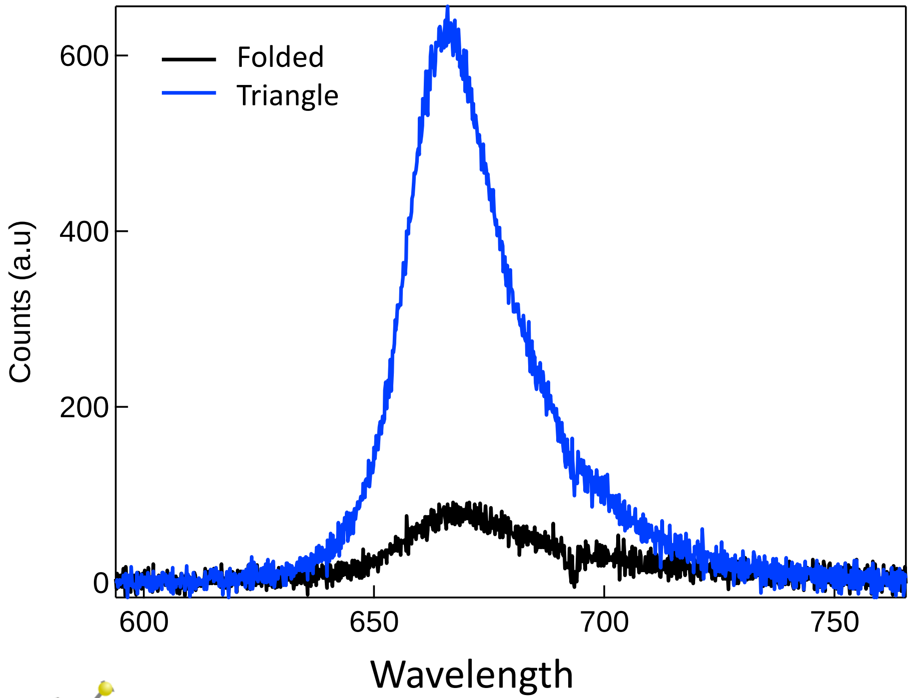


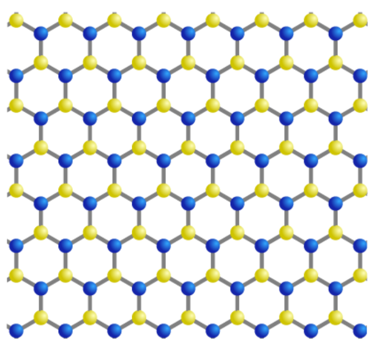
Mak et al., Physical Review Letters 2010

Photoluminescence

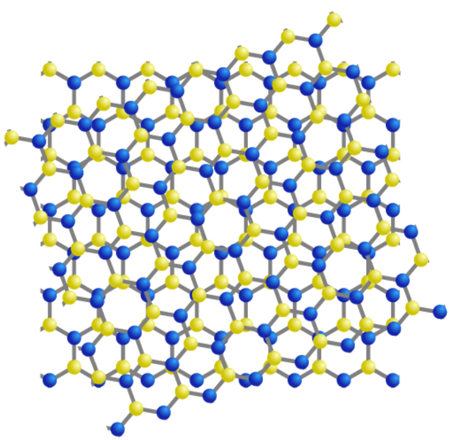
From a CVD-grown MoS_2





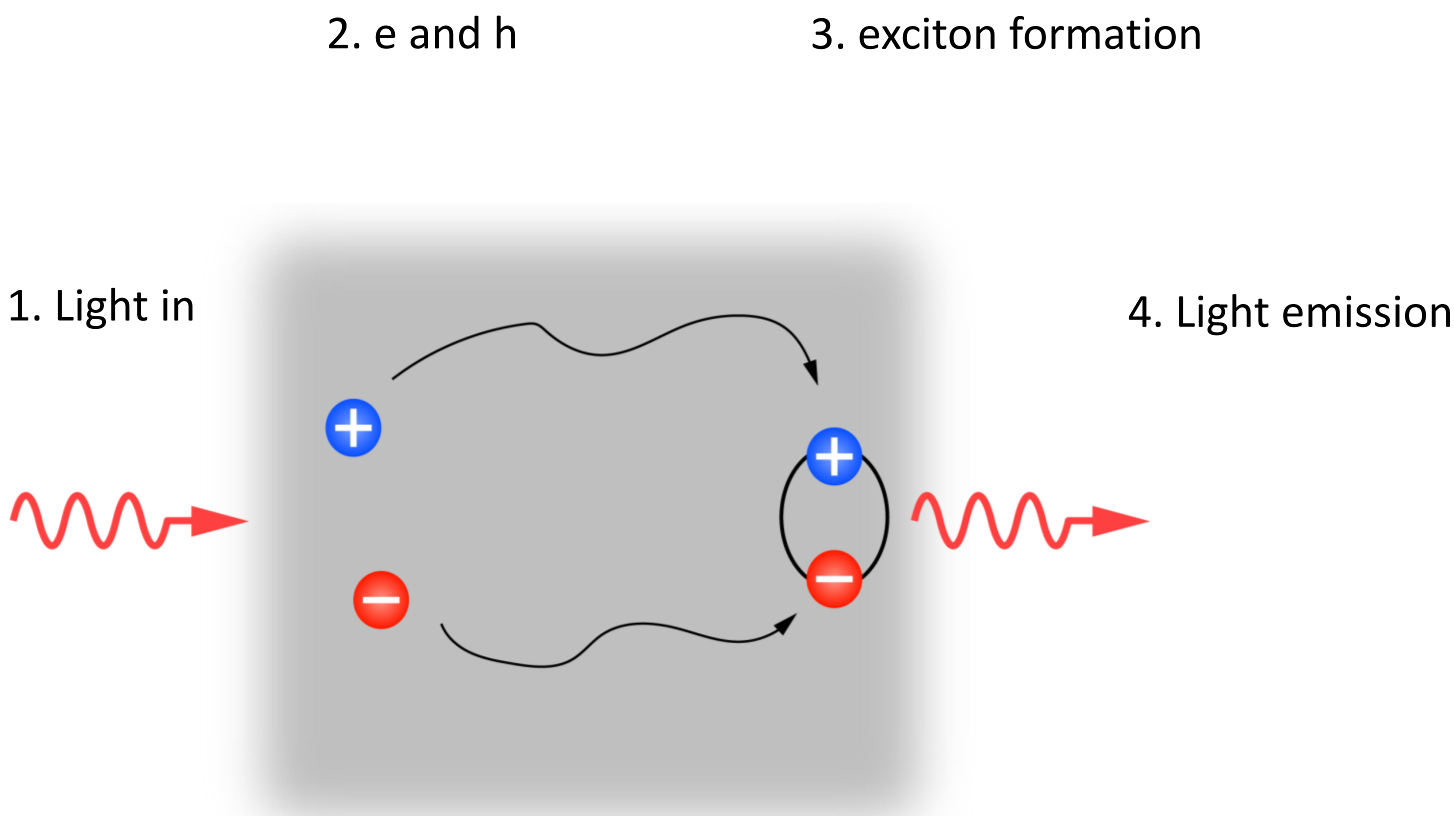


2H bilayer (natural)



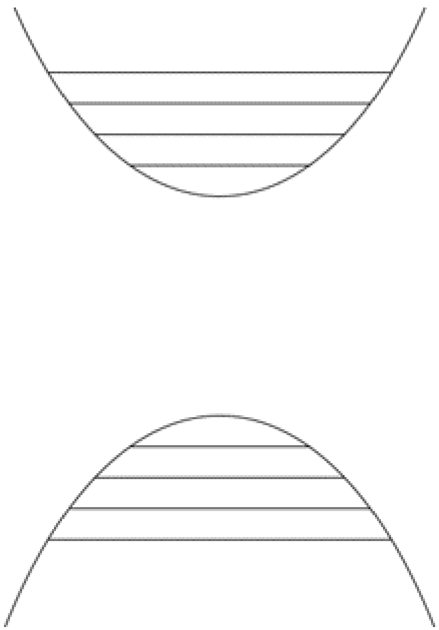
Twisted bilayer

Excitons

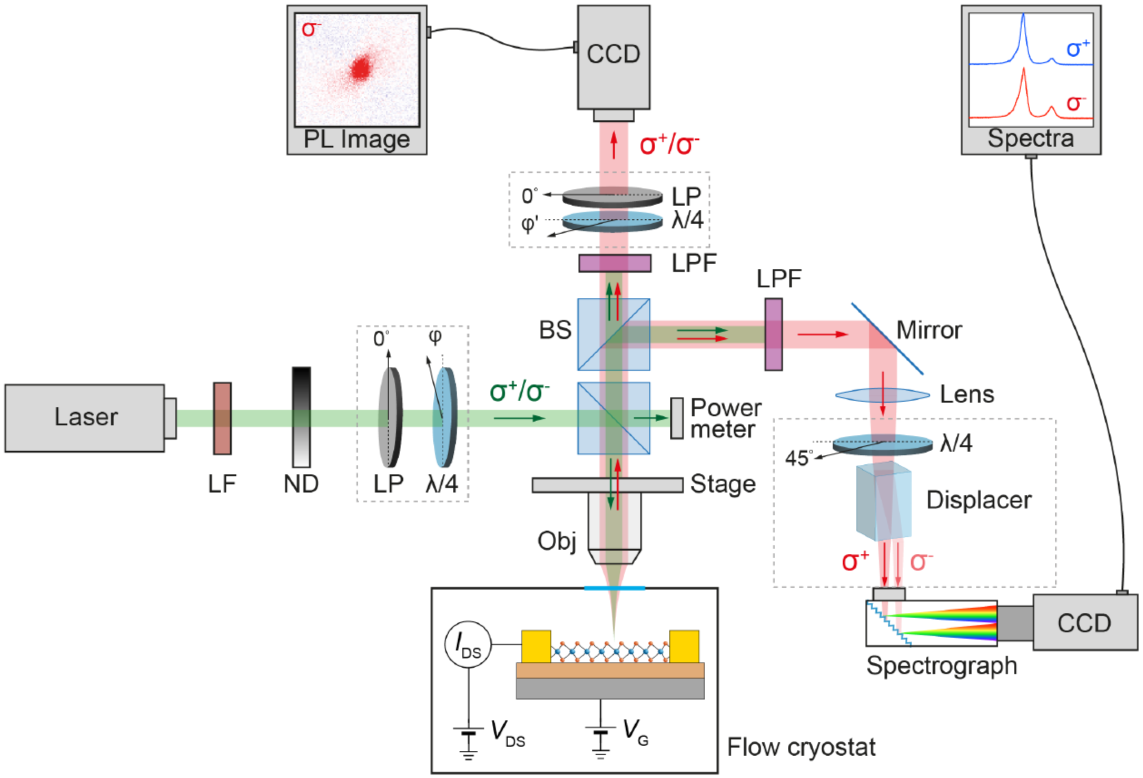


Photoluminescence

Light emission as a result of light absorption

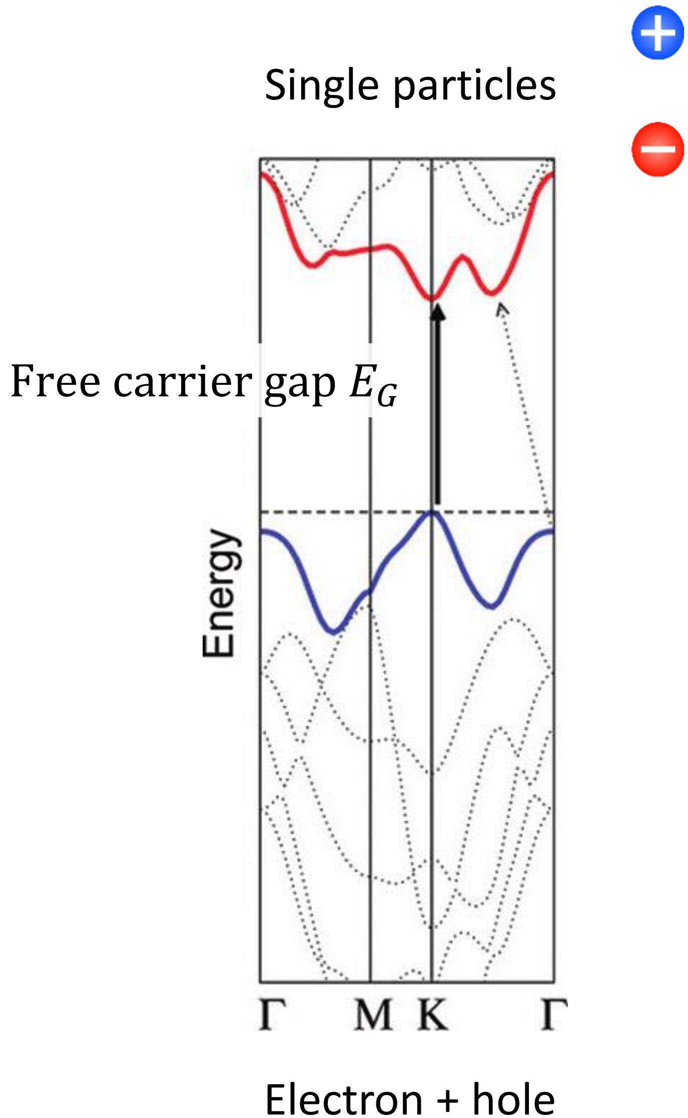


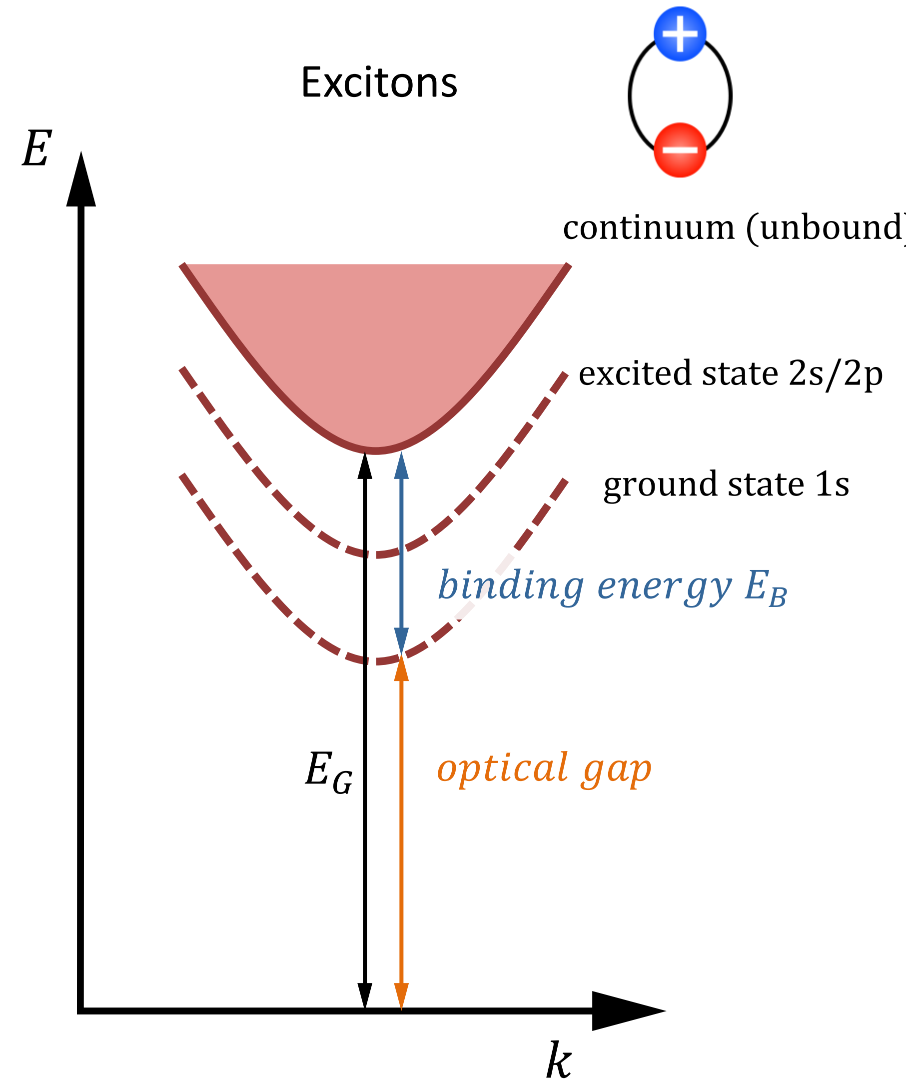
Source: Wikipedia



Source: Dmitry Unuchek, PhD dissertation (2019)

Excitons



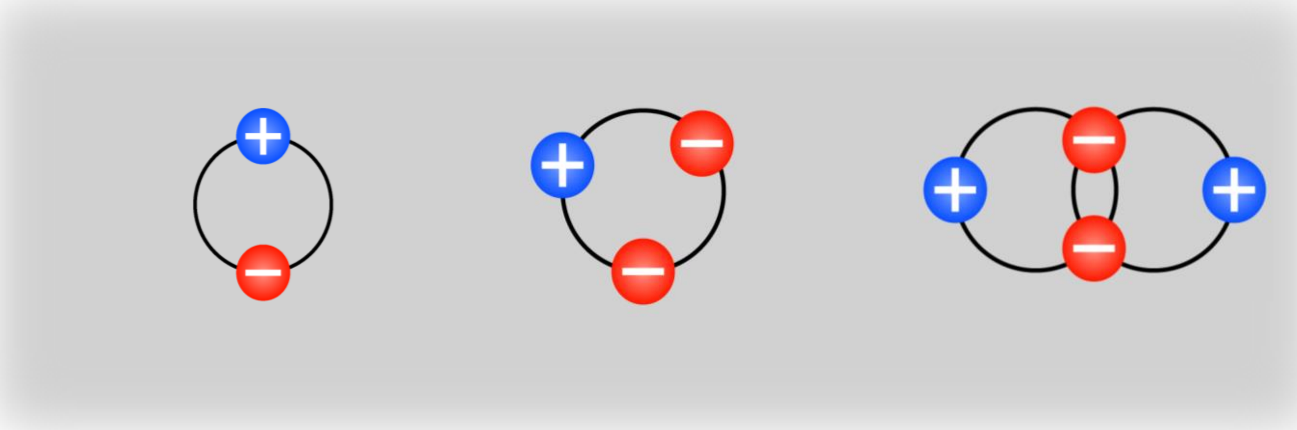


$E_B \sim 500\ meV$

Excitons visible at room temperature

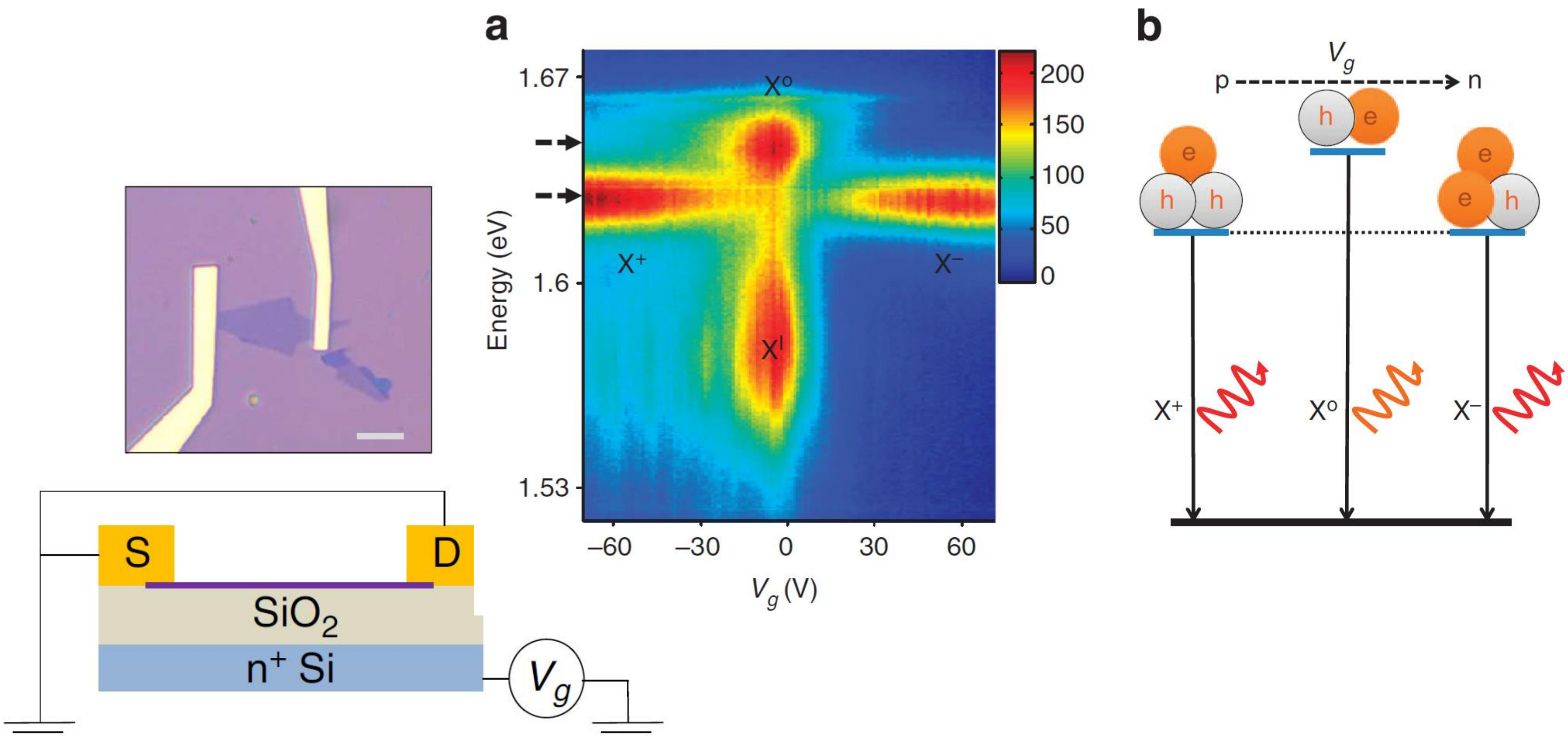
Excitonic complexes

Exciton | Trion | Biexciton



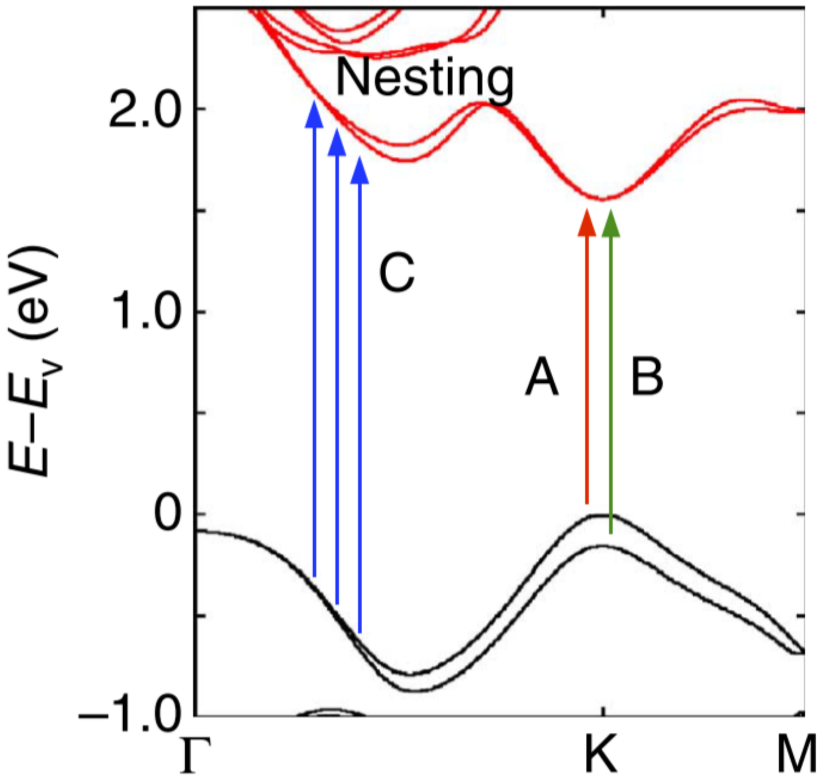
Neutral exciton X^0 | Charged exciton X^-, X^+ | Exciton molecule XX

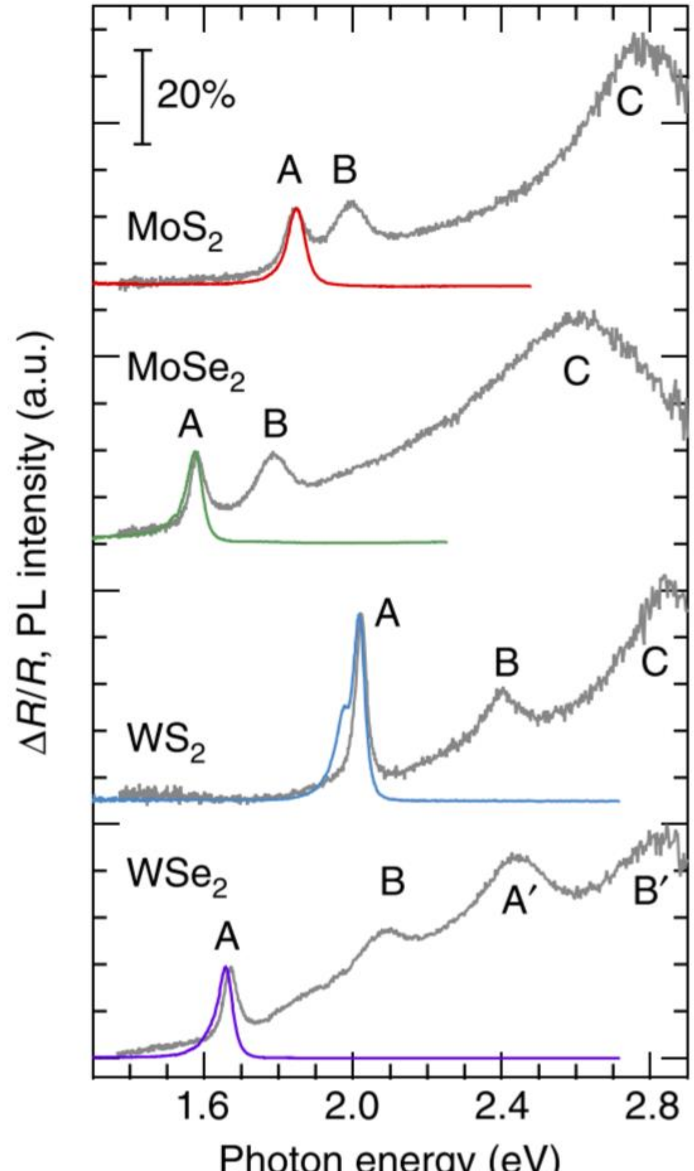
Electrostatic control of exciton charge in $MoSe_2$



Ross et al, Nat Commun. (2013)

A, B, C of excitons

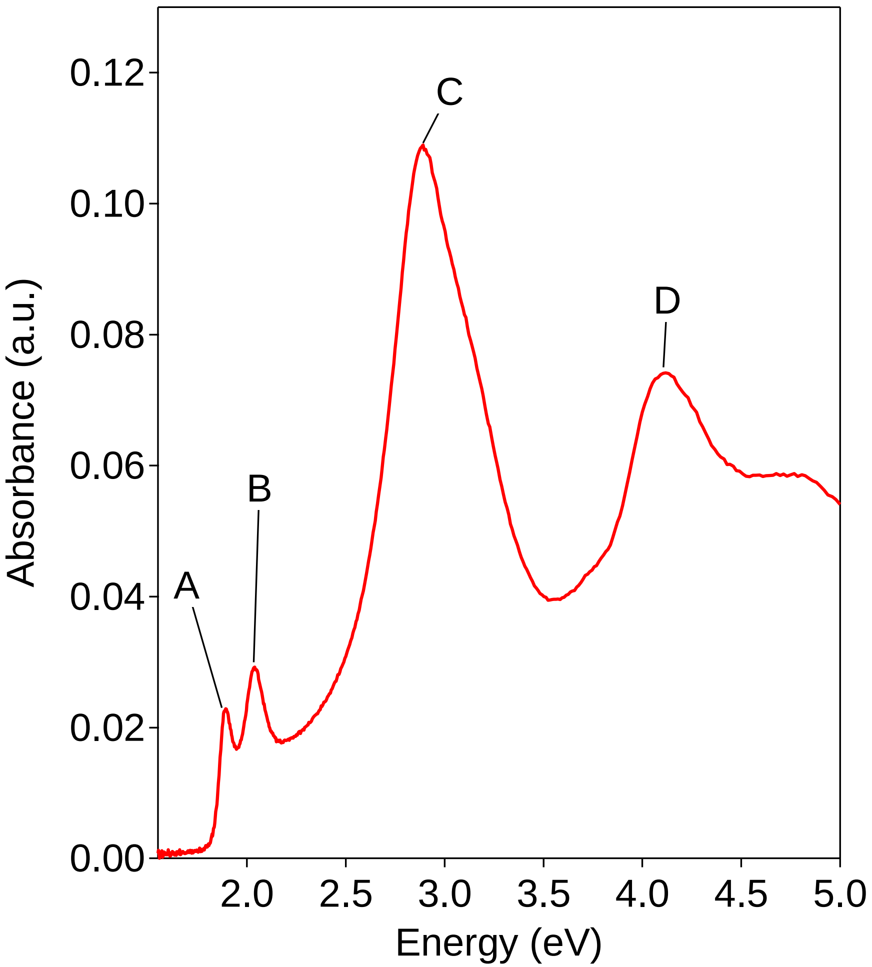




Kozawa…Eda; Nature Communications (2014)

A, B, C of excitons

Spectrophotometer



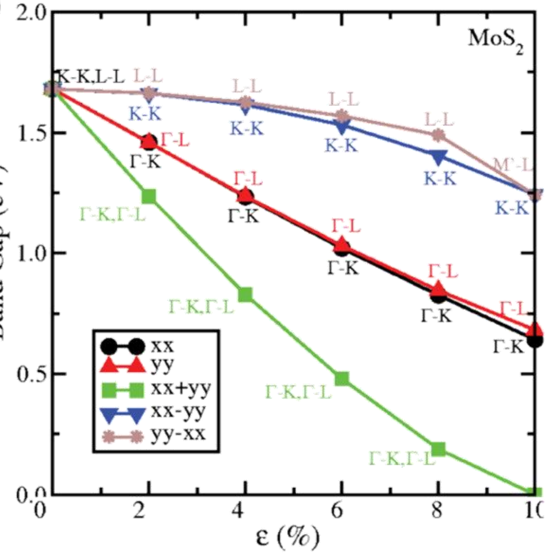
Large-area CVD MoS_2

Dumcenco…Kis; arXiv:1405.0129

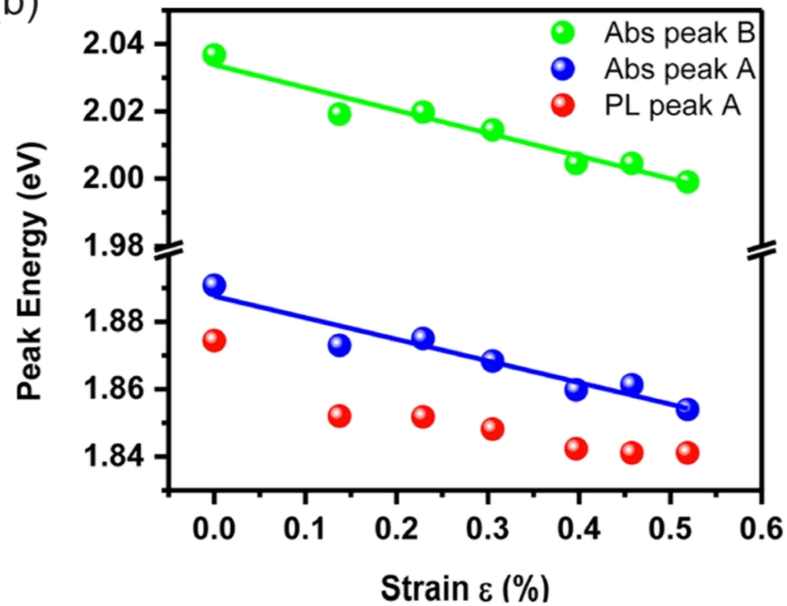
Dumcenco…Kis; ACS Nano (2015)

Band gap tuning with strain

(a)



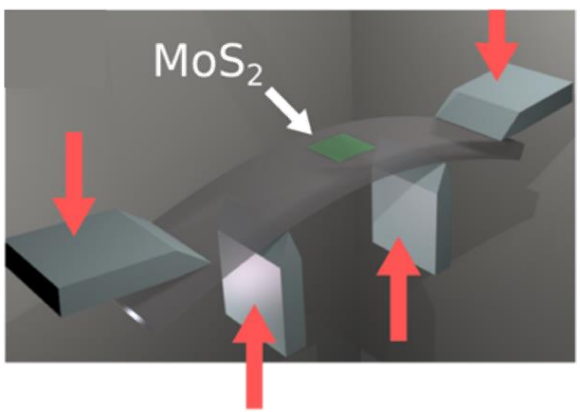
(b)



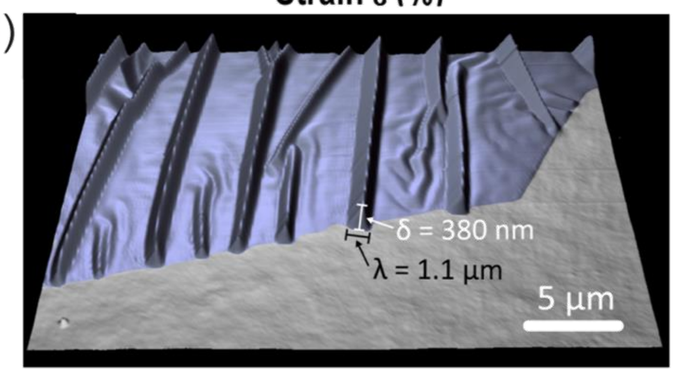
Gap tuning in 1L:

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

(c)



(d)

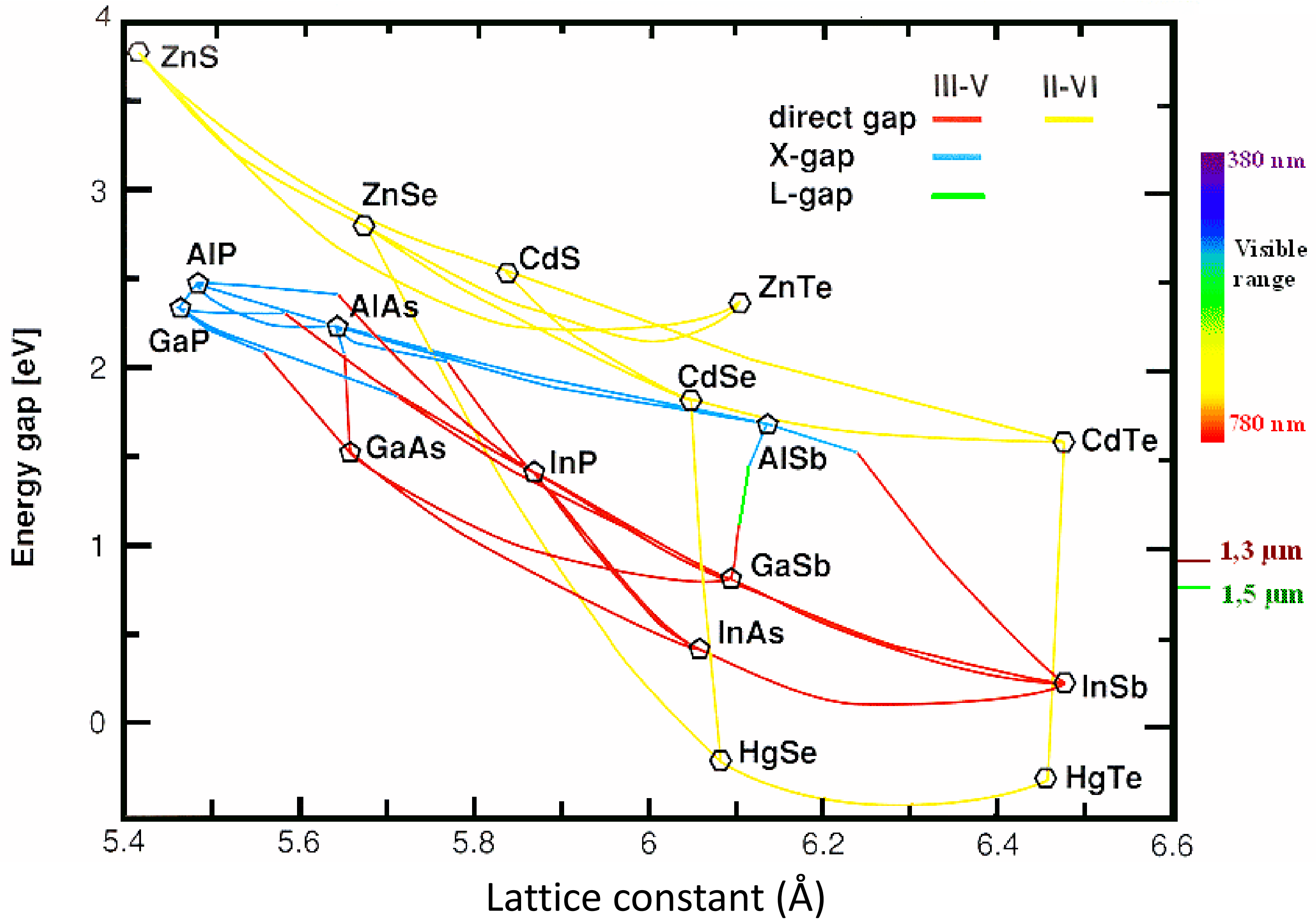


(a) Johari…Shenoy; ACS Nano (2012)
(b) He…Shan; Nano Letters (2013)
(c) Conley…Bolotin; Nano Letters (2013)
(d) Castellanos-Gomez…Steele; Nano Letters (2013)

Band gap tuning by alloying

For III-V and II-VI materials

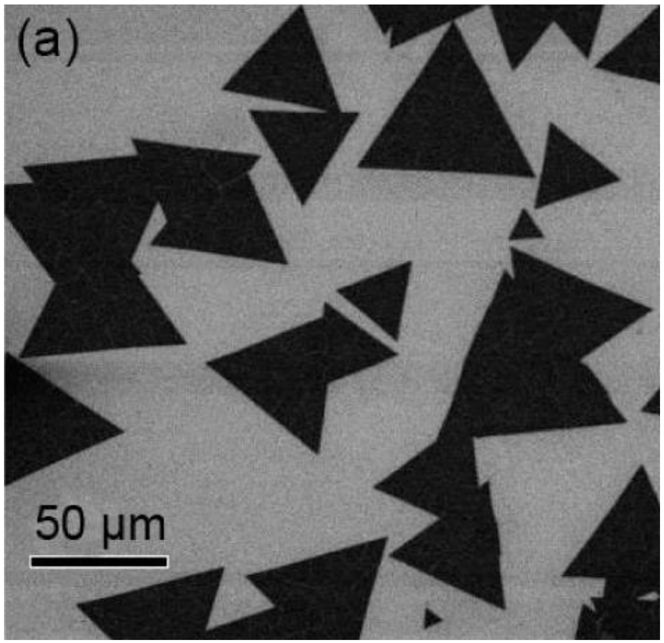
- As long as the lattice type stays the same, composition can be tuned continuously



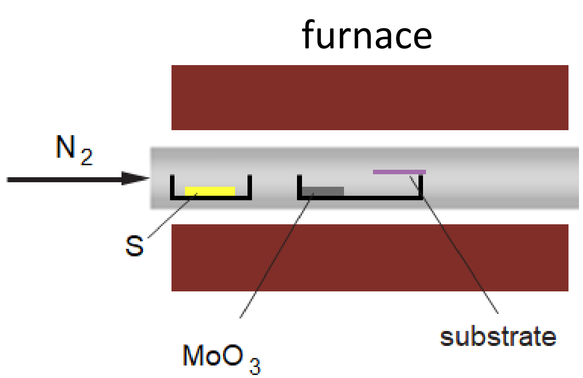
https://www.tf.uni-kiel.de/matwis/amat/semitech_en/kap_2/backbone/r2_3_1.html

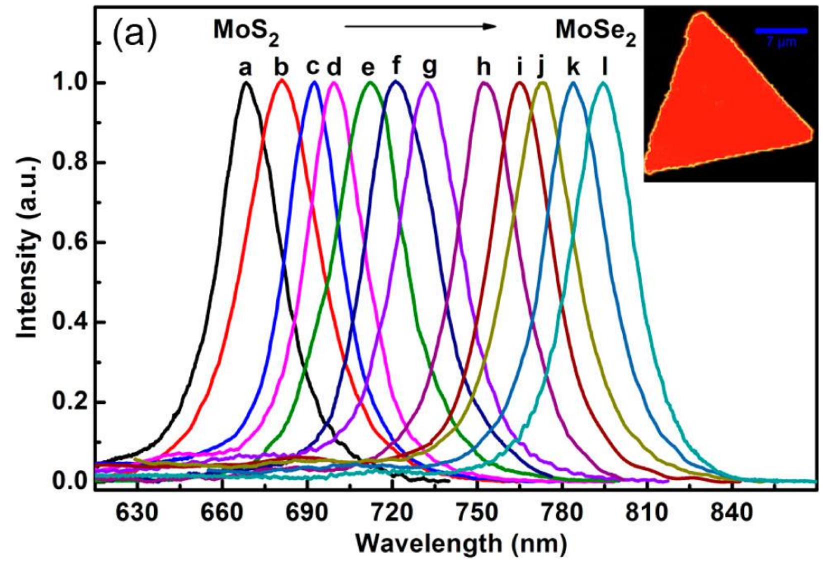
Band gap tuning by alloying

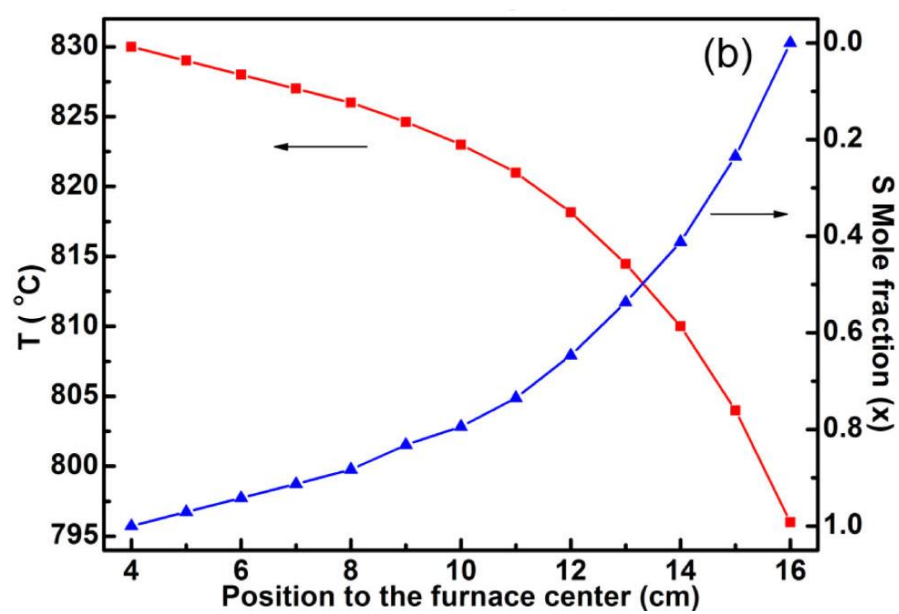
For TMDCs



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

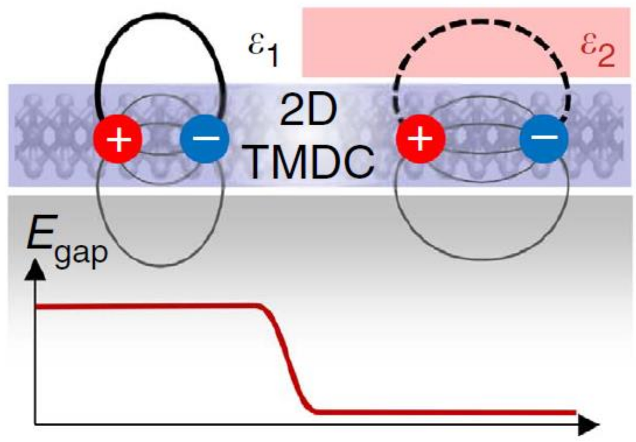




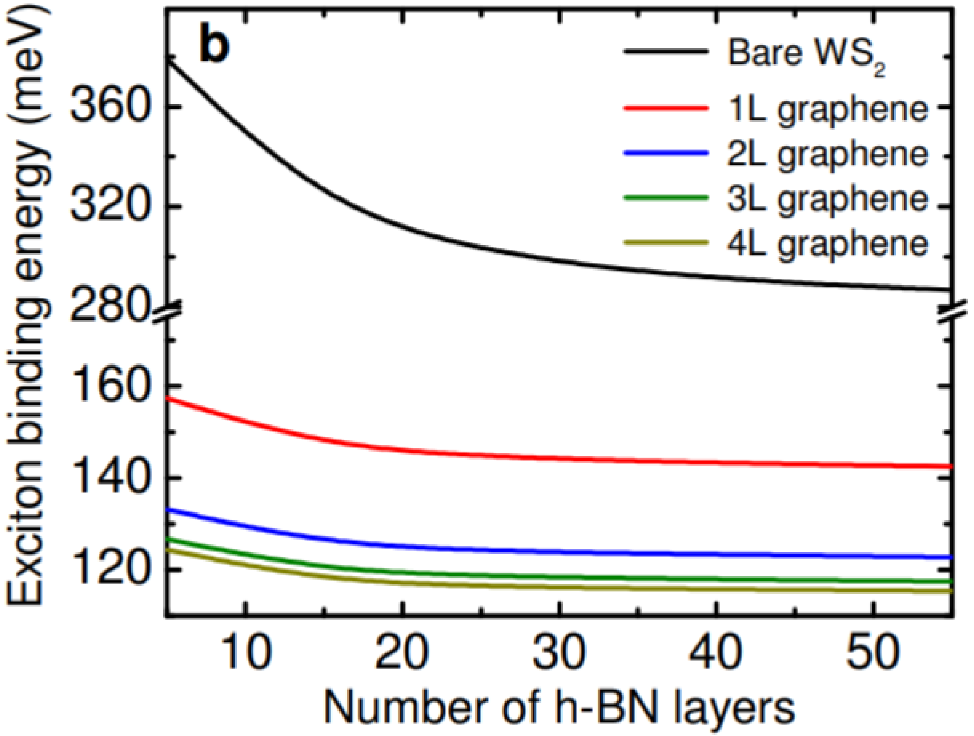


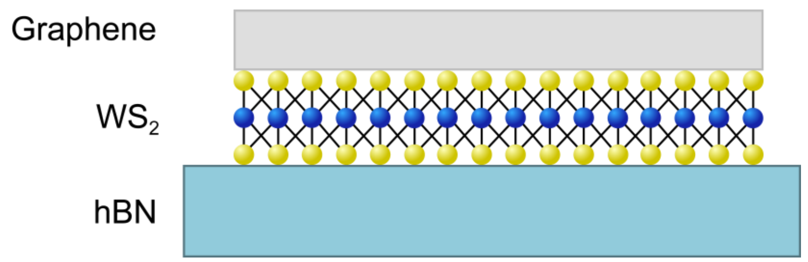
Band gap and exciton binding energy tuning

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



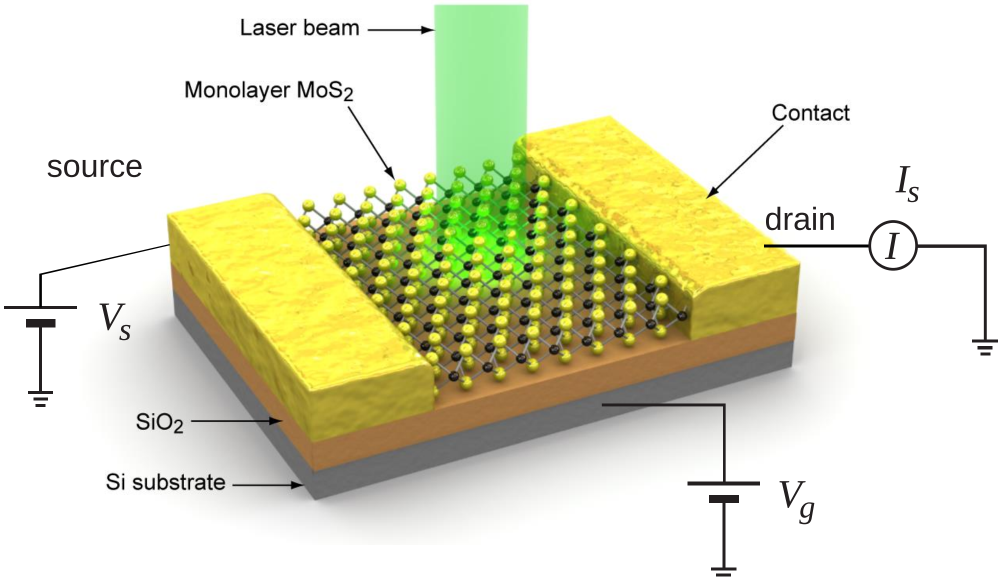
Raja et al. Nature Communications (2017)





h-BN substrate, graphene capping

Phototransistors/photodetectors

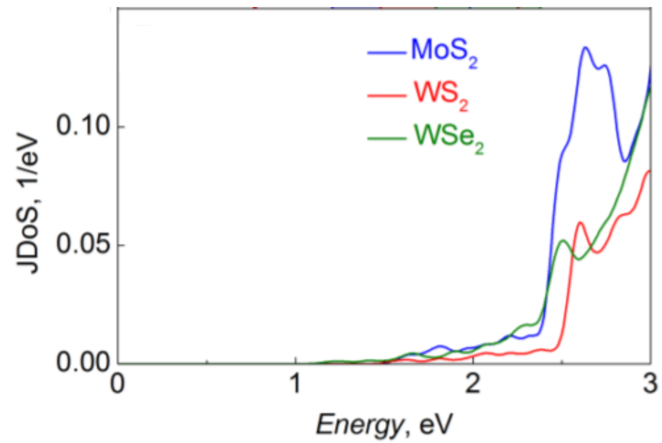


$$Joint\ density\ of\ states\ JDOS(E) = = \frac{1}{4\pi^3}\int d^3k\delta\left(E_{V,k} - E_{C,k} - E\right)$$

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

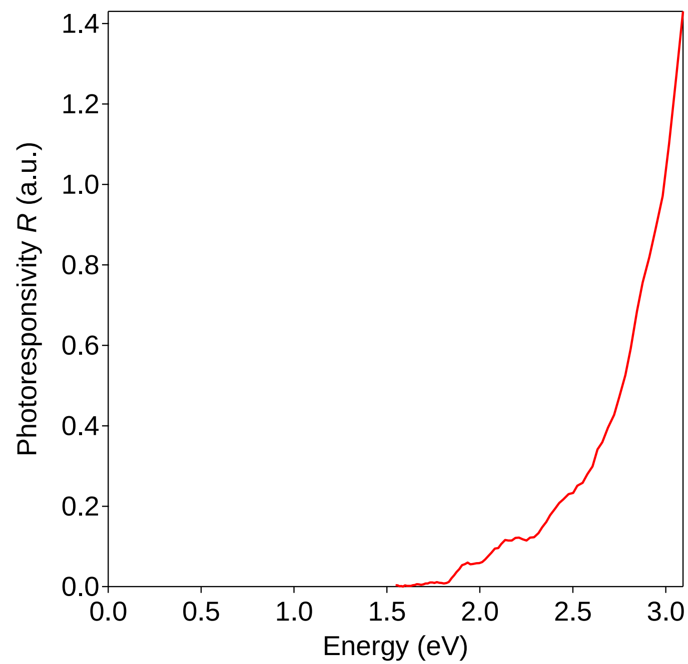
$$Responsivity\ R = \frac{I_{ph}}{P_{inc}}$$

Calculations



Britnell…Novoselov; Science (2013)

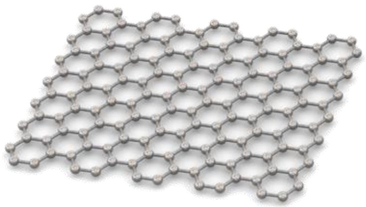
Measurements

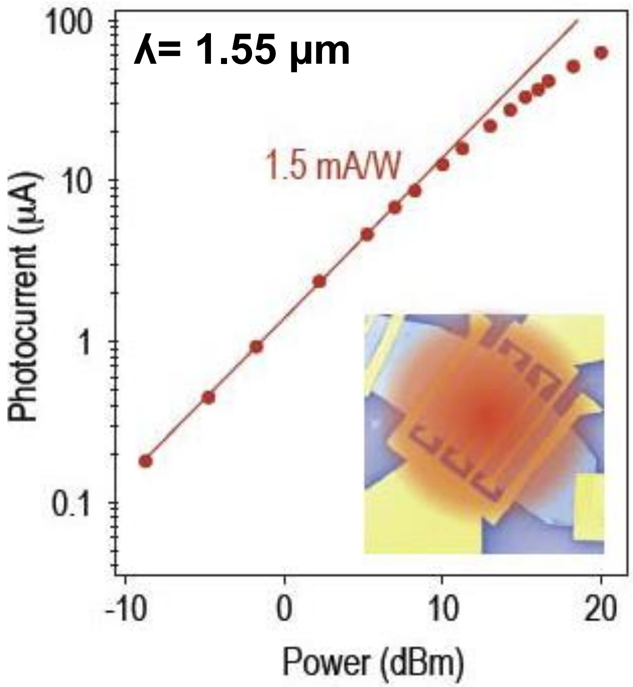


Lopez Sanchez…Kis; Nat. Nanotech. (2013)

Early graphene and MoS_2 photodetectors

Graphene

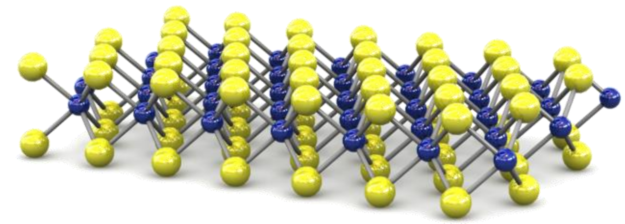


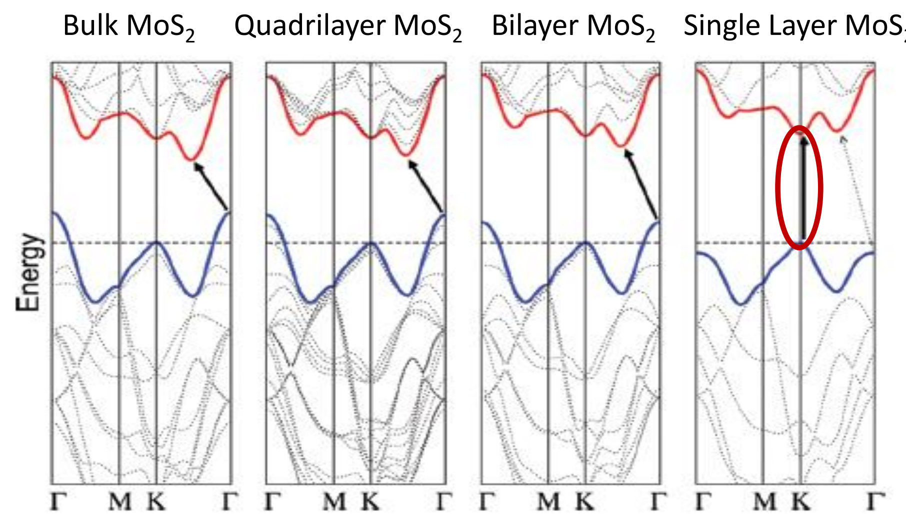


Zero band gap: small response
wide spectral range

High mobility: fast response

MoS_2





E_G = 1.8 eV => λ= 680nm

Direct band gap: large response
efficient photoconversion

Low mobility: slow response

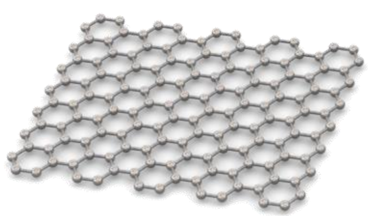
Mueller et al., Nature Photonics (2010)

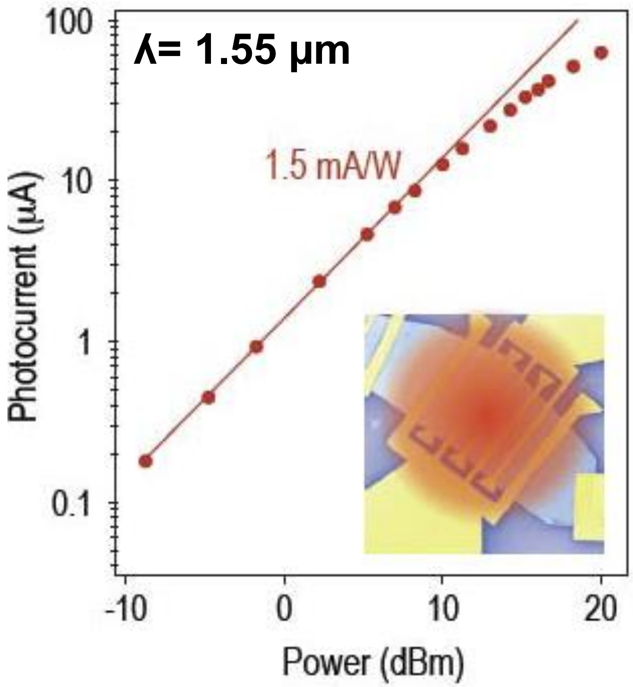
Splendiani et al , Nano Letters (2010)

Echtermeyer et al, Nature Com. (2011)

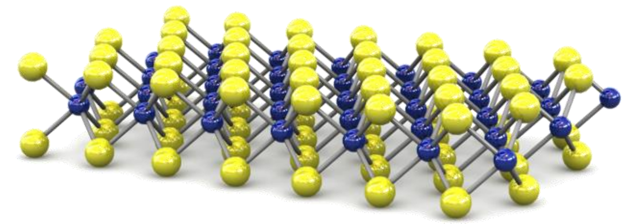
Early graphene and MoS_2 photodetectors

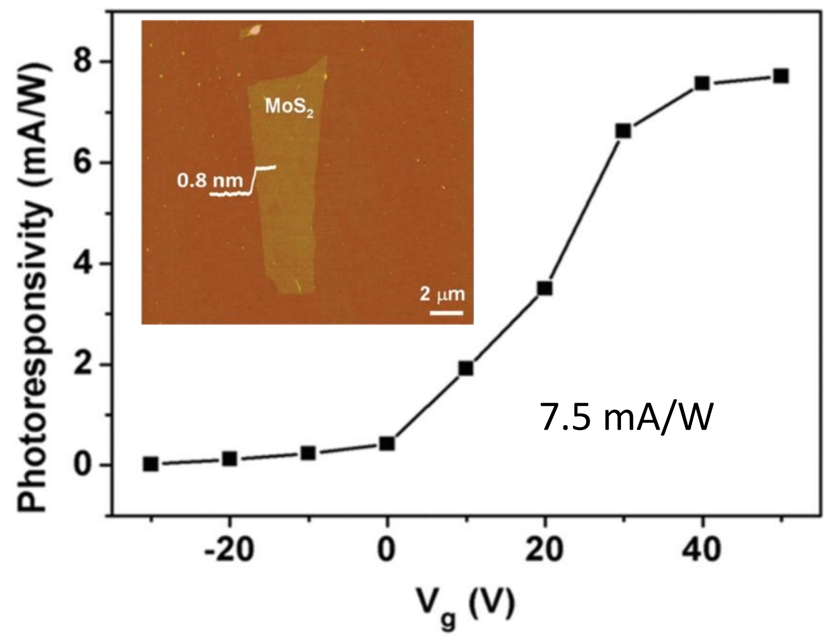
Graphene





MoS_2





Zero band gap: small response
wide spectral range

High mobility: fast response

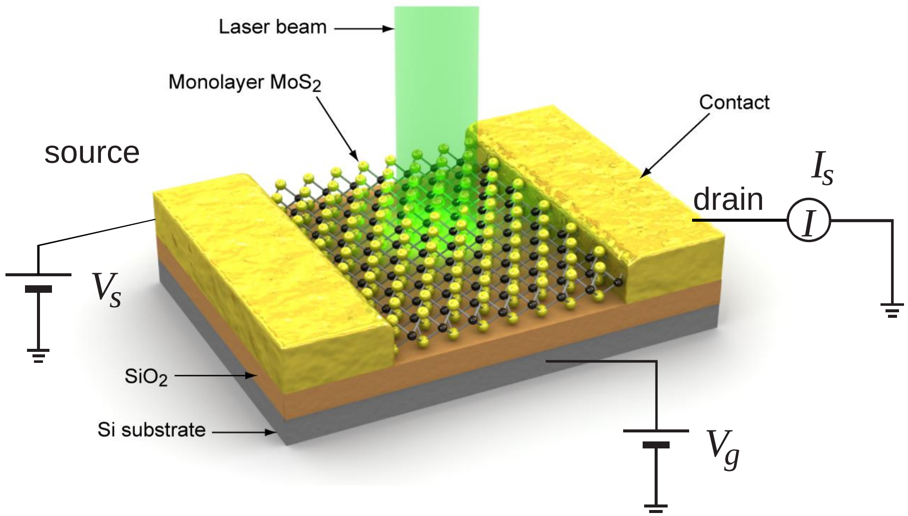
Yin et al.; ACS Nano 6 (1) 74-80 (2011)

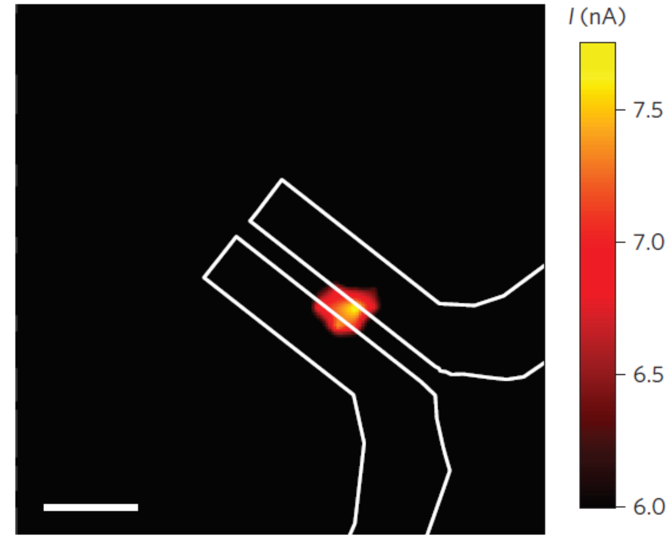
Mueller et al., Nature Photonics (2010)

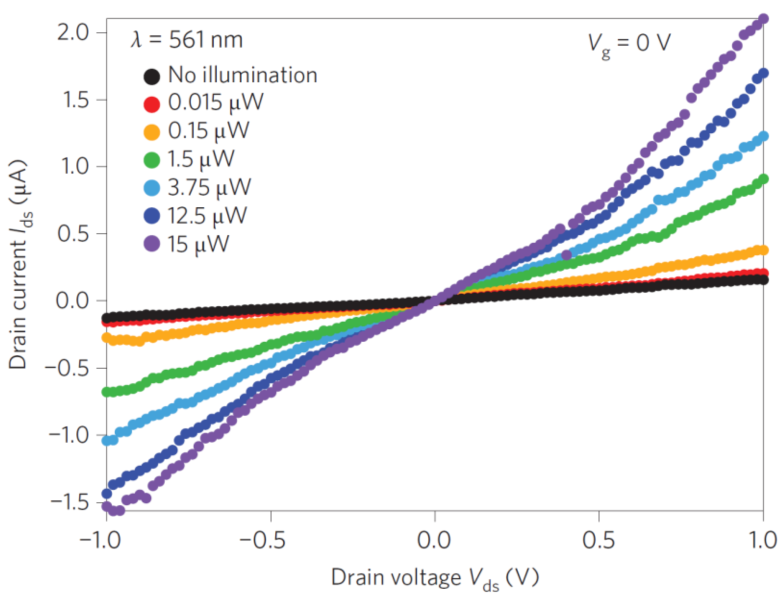
Splendiani et al , Nano Letters (2010)

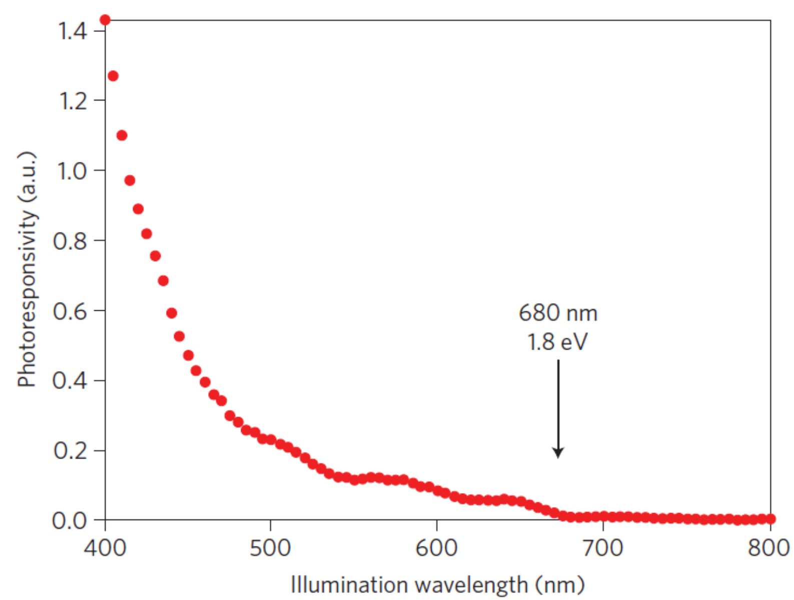
Echtermeyer et al, Nature Com. (2011)

Sensitive MoS_2 photodetectors





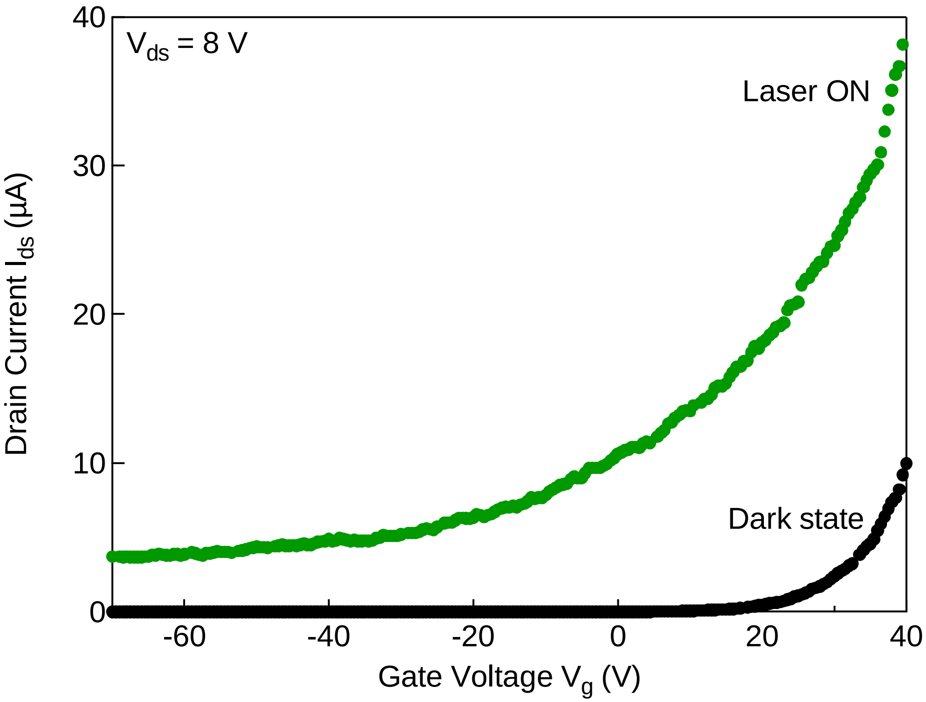


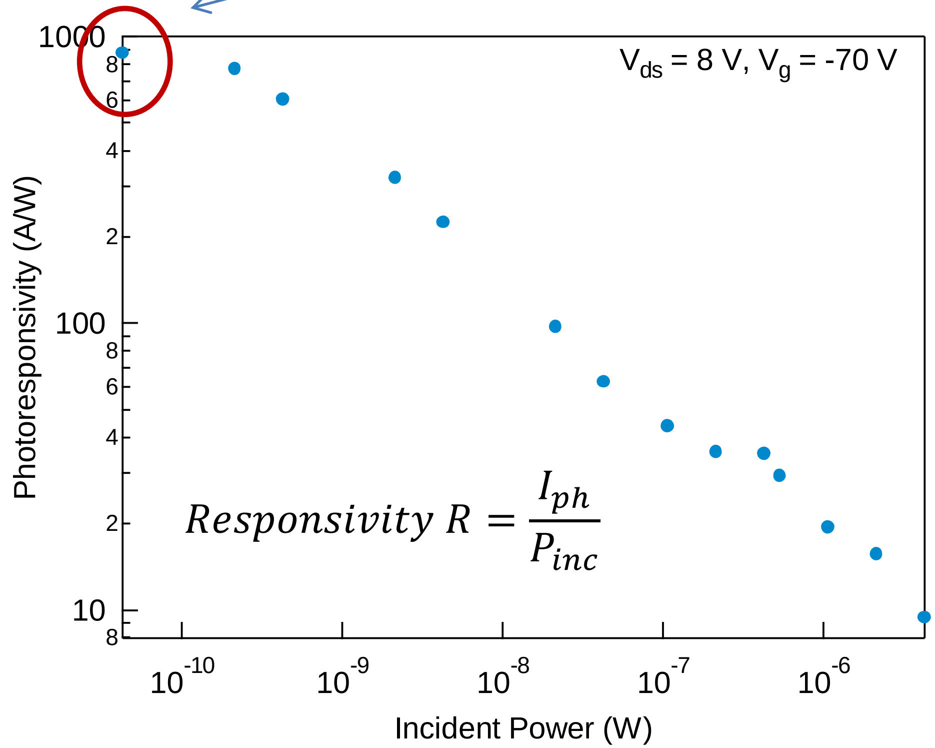


Lopez-Sanchez, Nature Nanotechnology (2013)

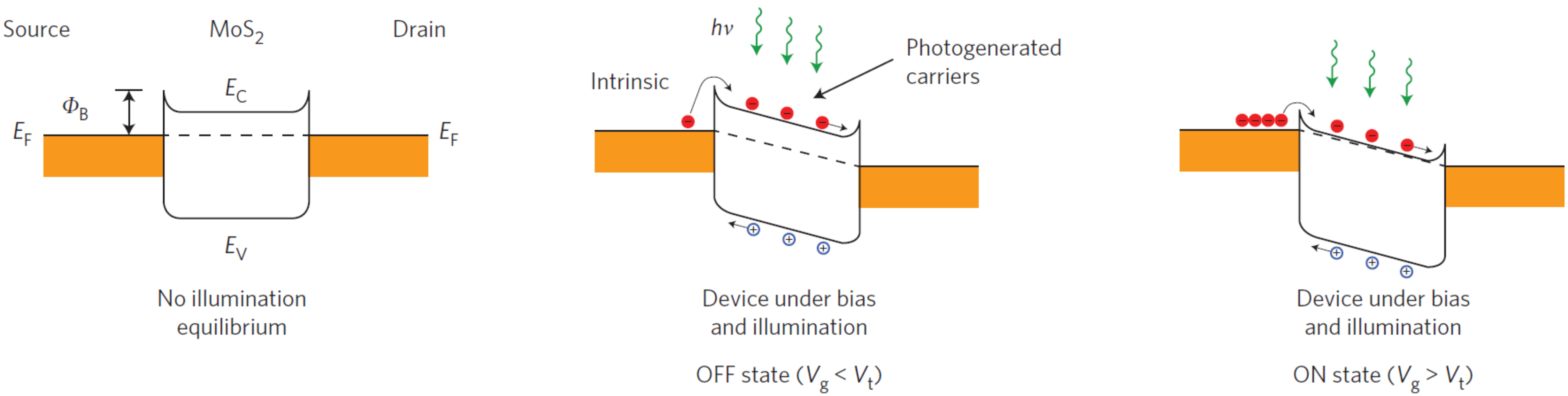
Sensitive MoS_2 photodetectors

880 A/W



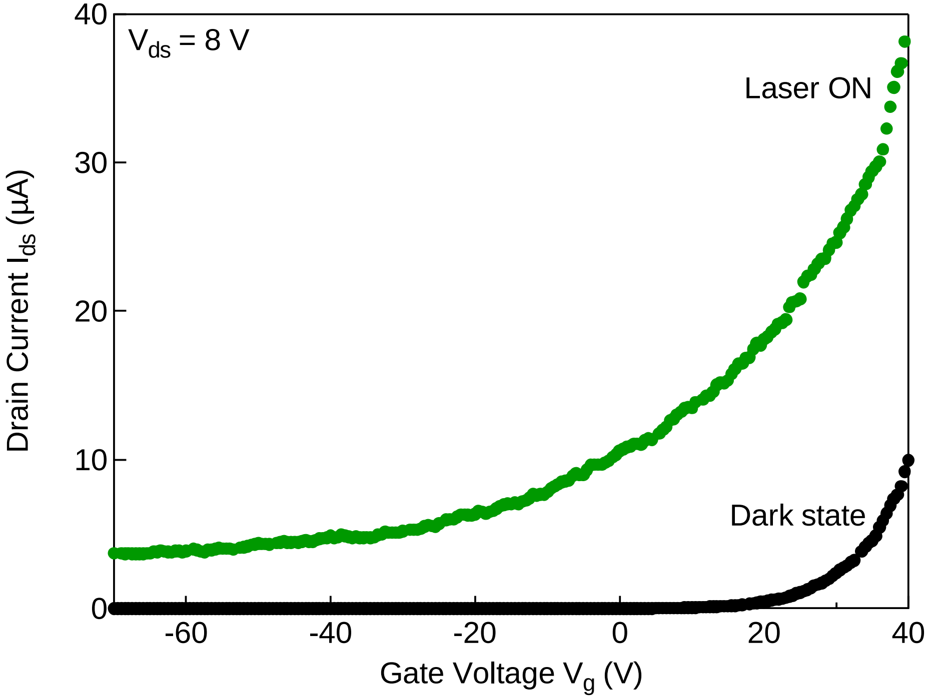


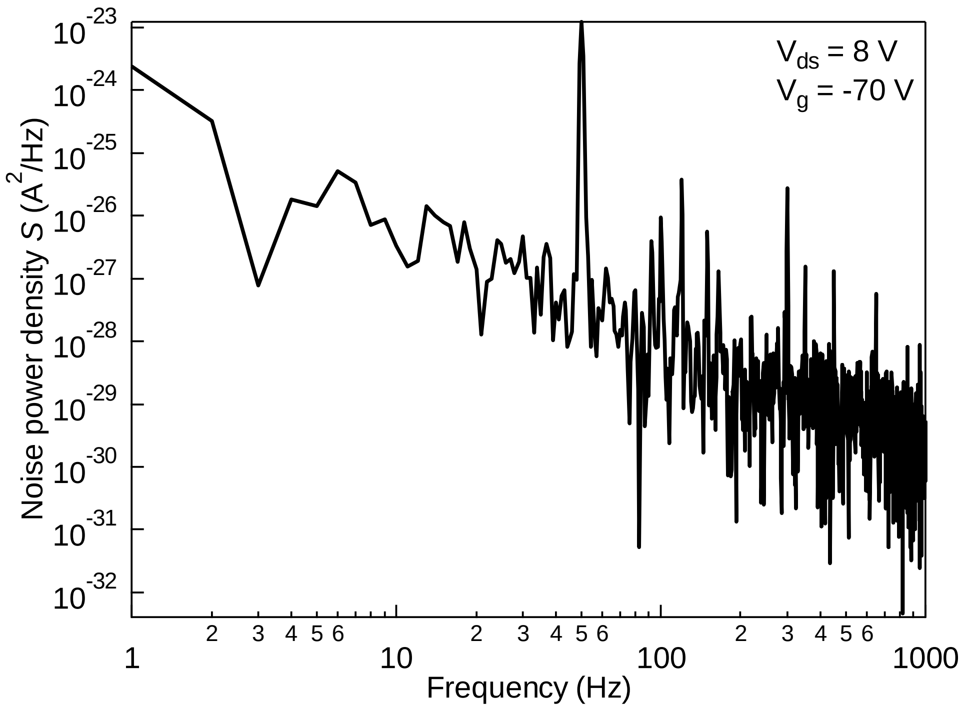
$$Responsivity\ R = \frac{I_{ph}}{P_{inc}}$$



Lopez-Sanchez, Nature Nanotechnology (2013)

Noise-equivalent power



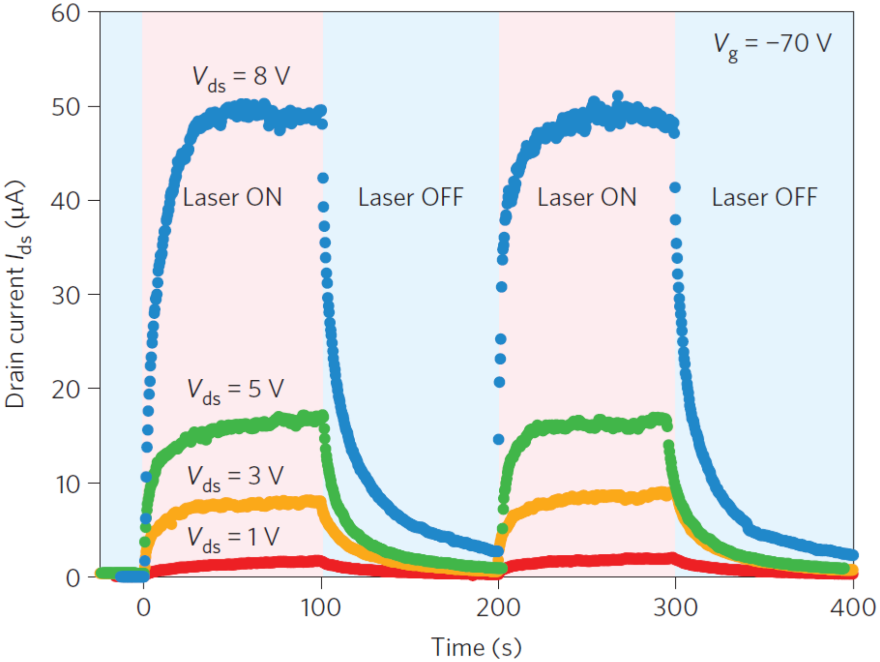


Photoresponsivity: 880 A/W
NEP: 1.8×10^{-15} W/Hz$^{1/2}$

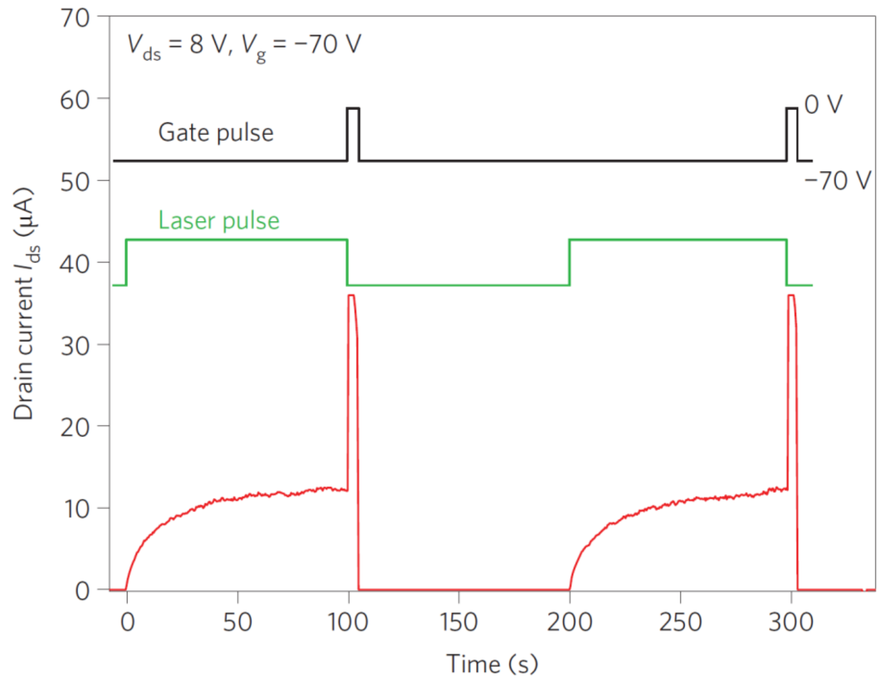
Si photodiodes: 1 A/W
NEP: 3×10^{-14} W/Hz$^{1/2}$

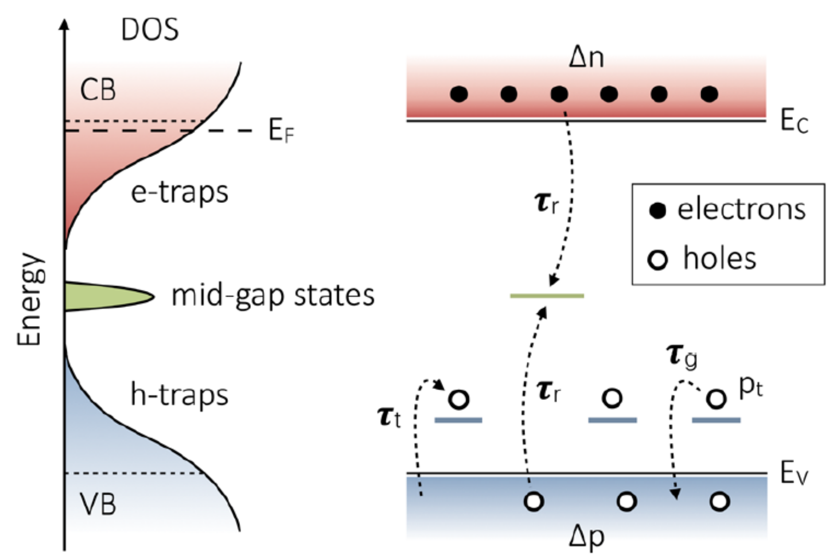
Lopez-Sanchez, Nature Nanotechnology (2013)

Photocurrent dynamics



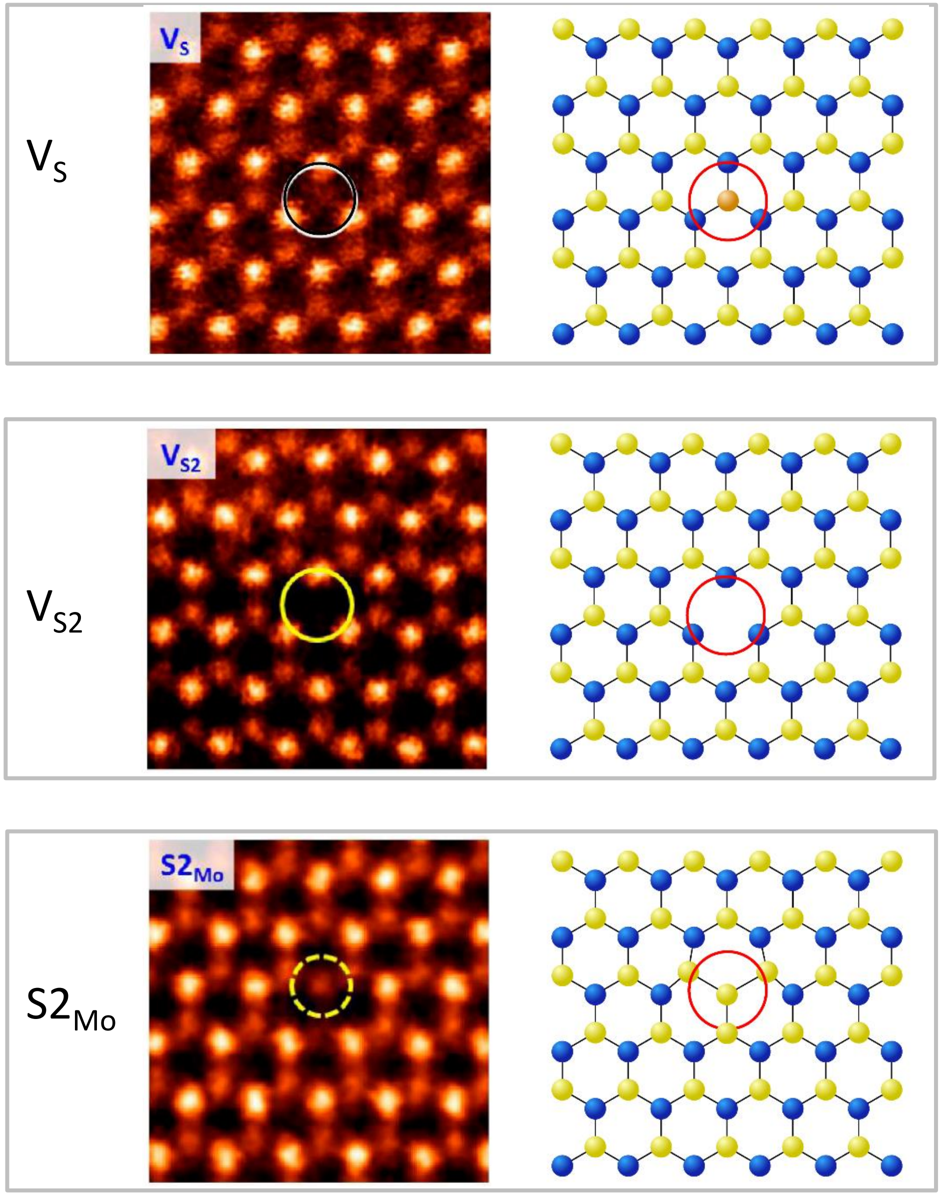
Lopez-Sanchez, Nature Nanotechnology (2013)



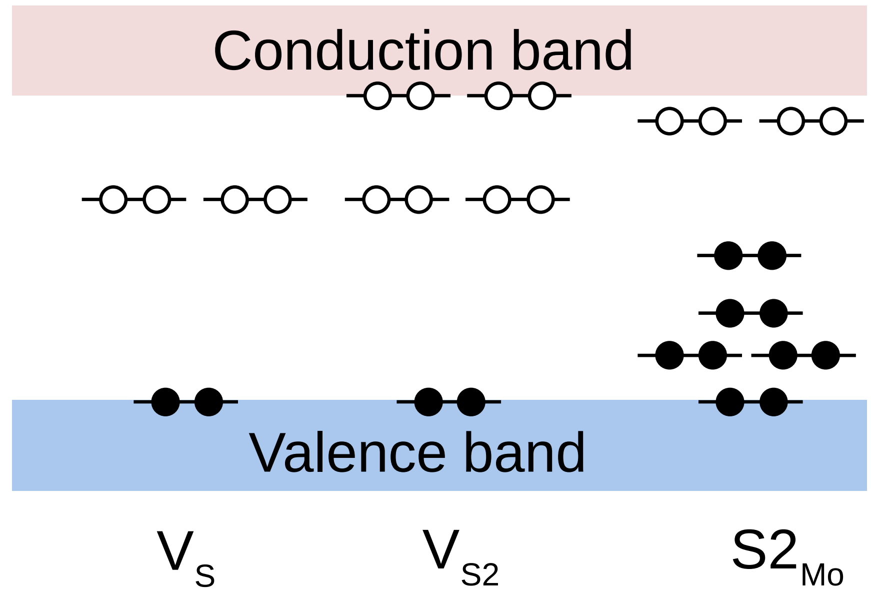


Furchi et al. Nano Lett. (2014)

From Ch. 2: most common point defects in MoS_2



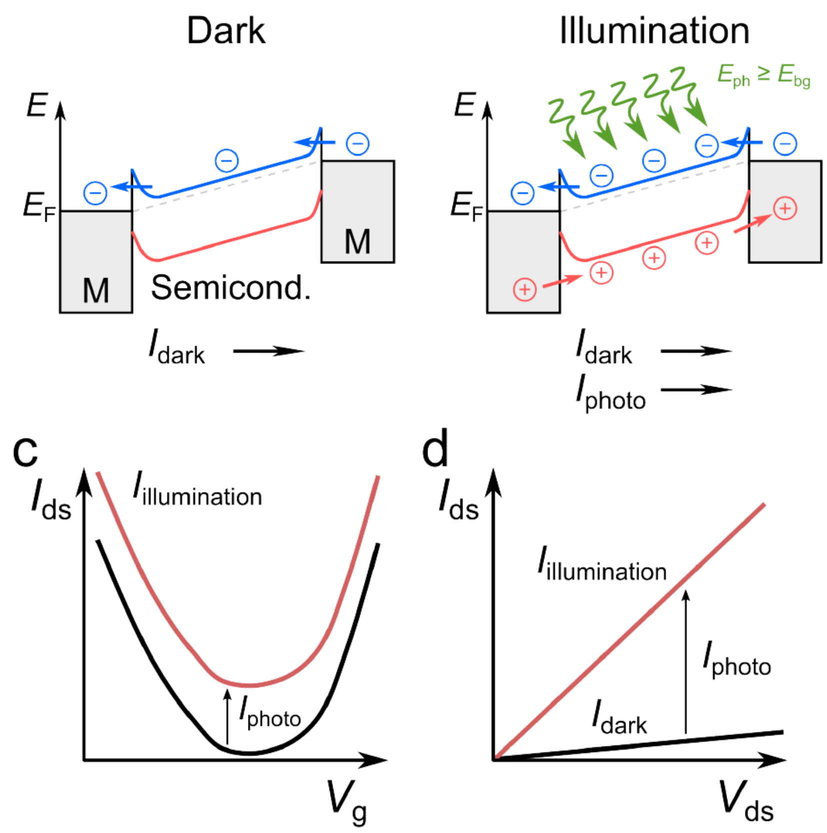
Zhou et al. Nano Letters (2013)



Mechanisms of photoconductivity

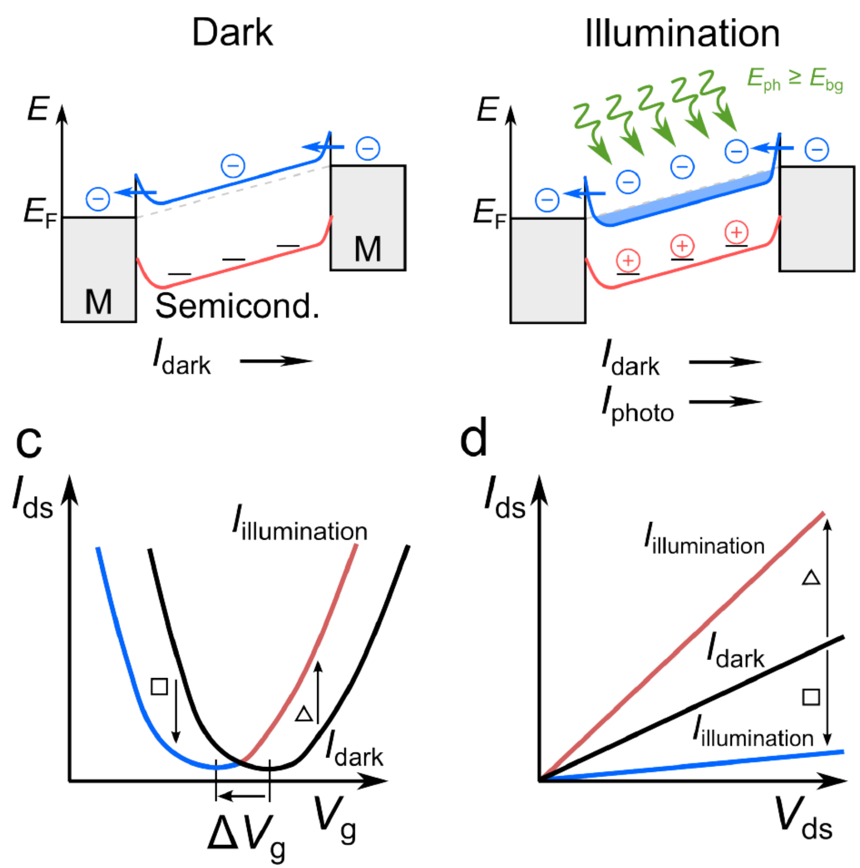
Photoconductive (PC)

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



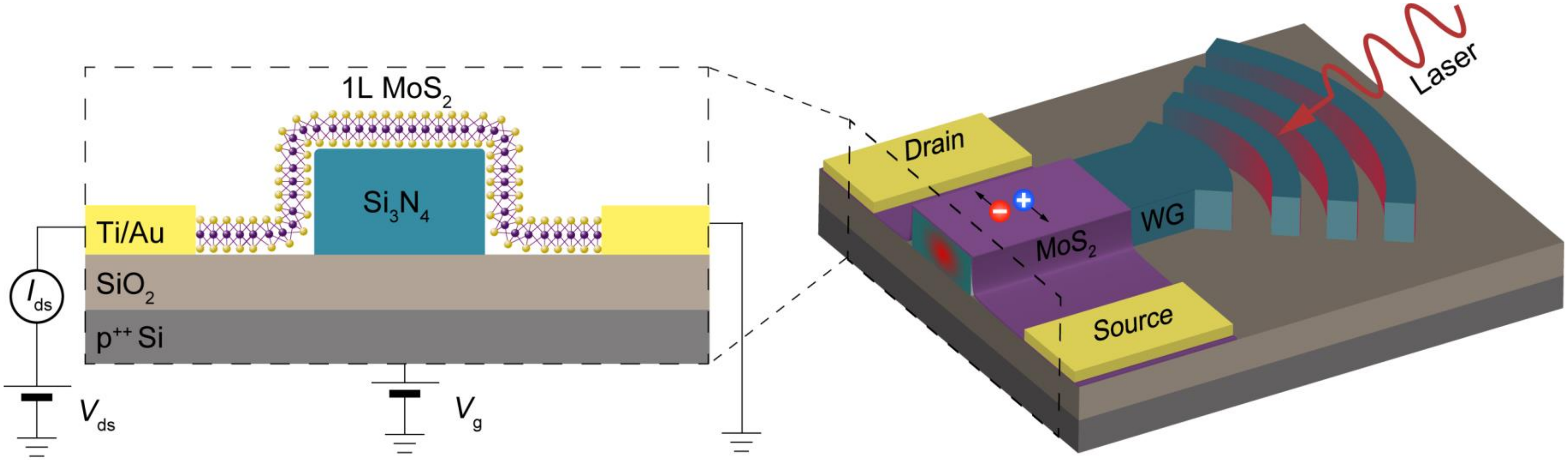
Photogating (PG)

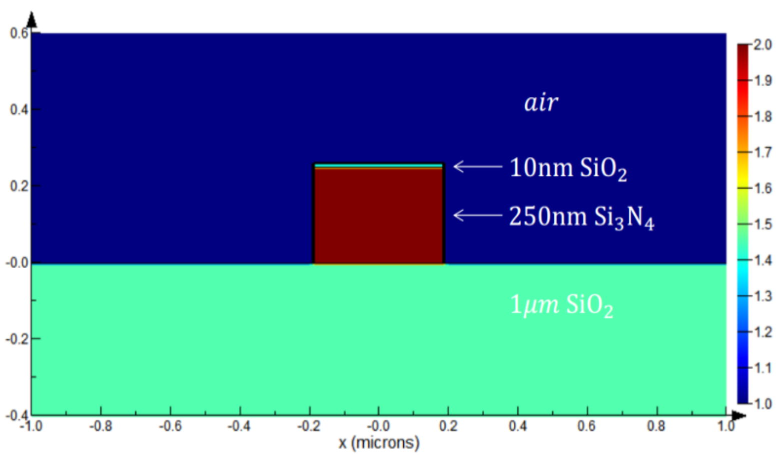
$$I_{ph,PG} \approx g_m \Delta V_T$$
$$g_m = dI_D/dV_G$$

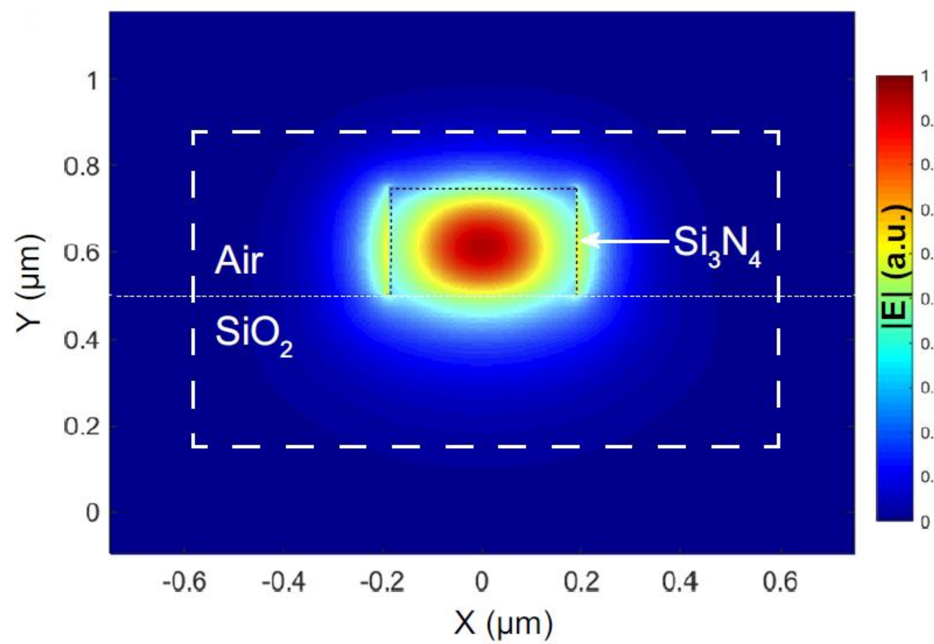


Buscema et al. Chem. Soc. Rev. (2015)

Photonic circuit integration



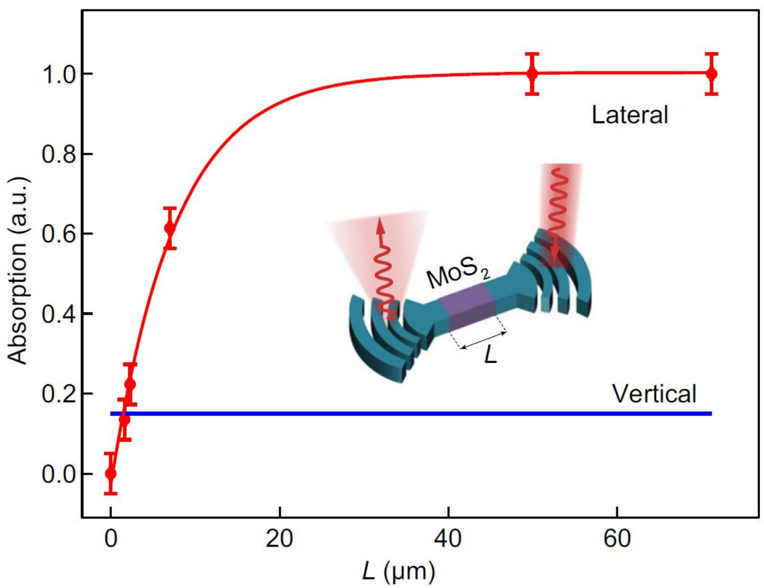


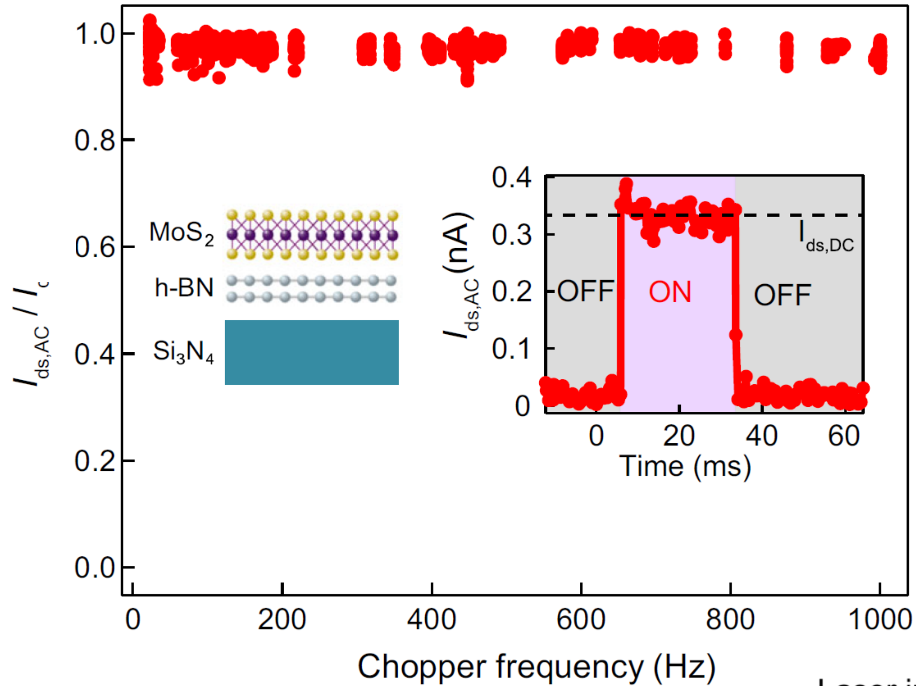


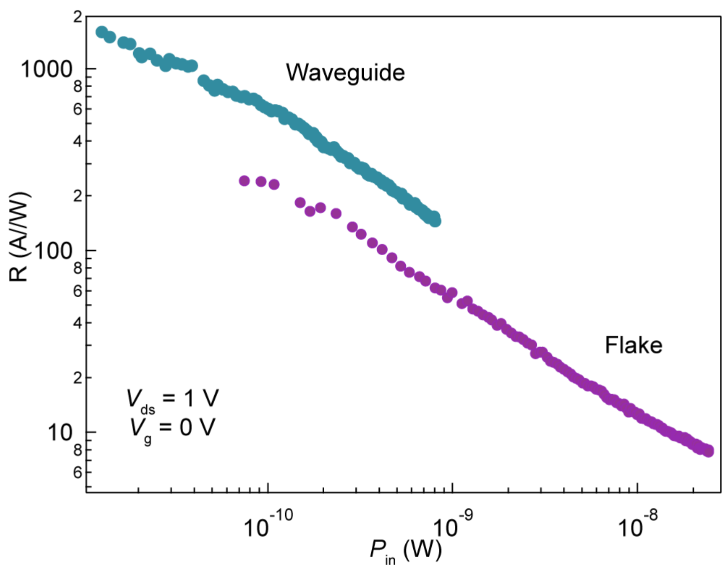
Gonzalez Marin et al.; npj 2D materials and applications (2019)

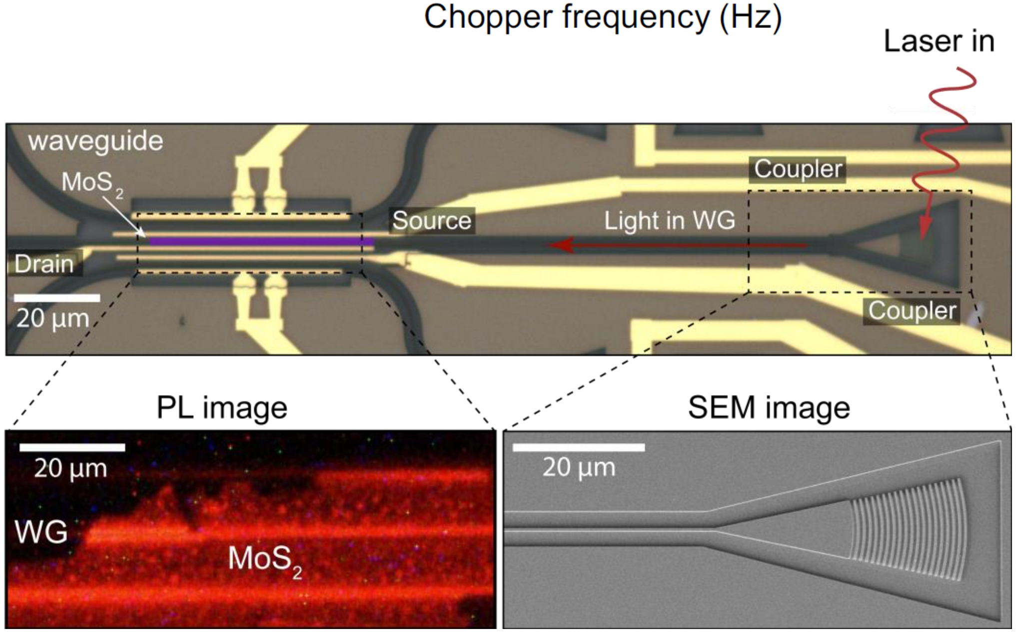
Integrated photodetectors

Light absorption

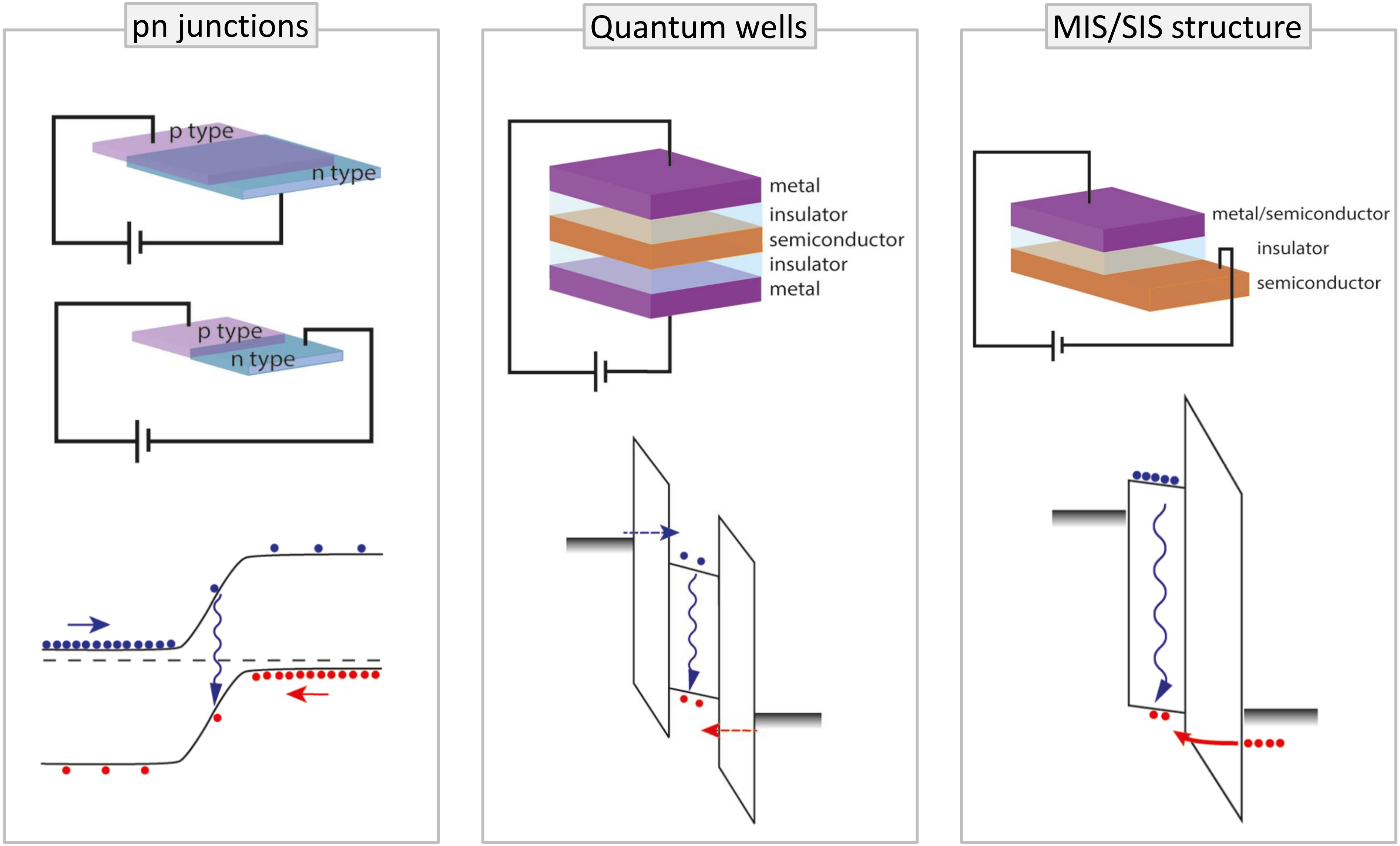






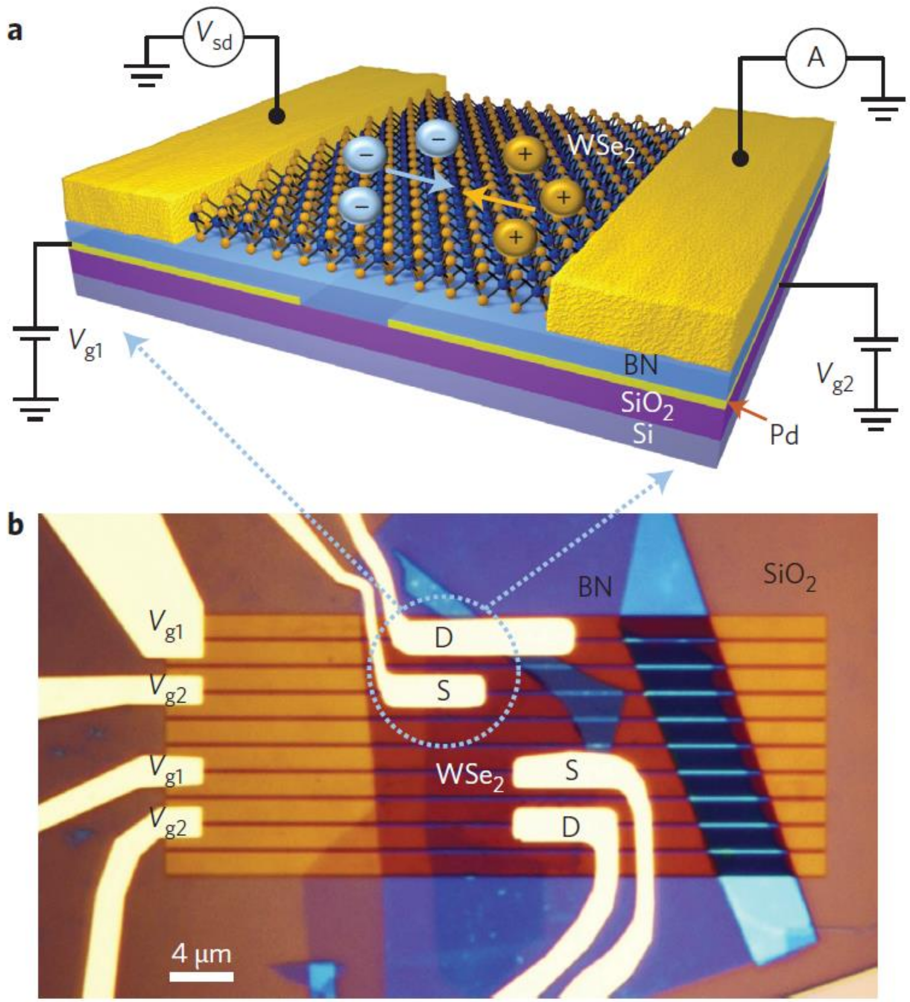


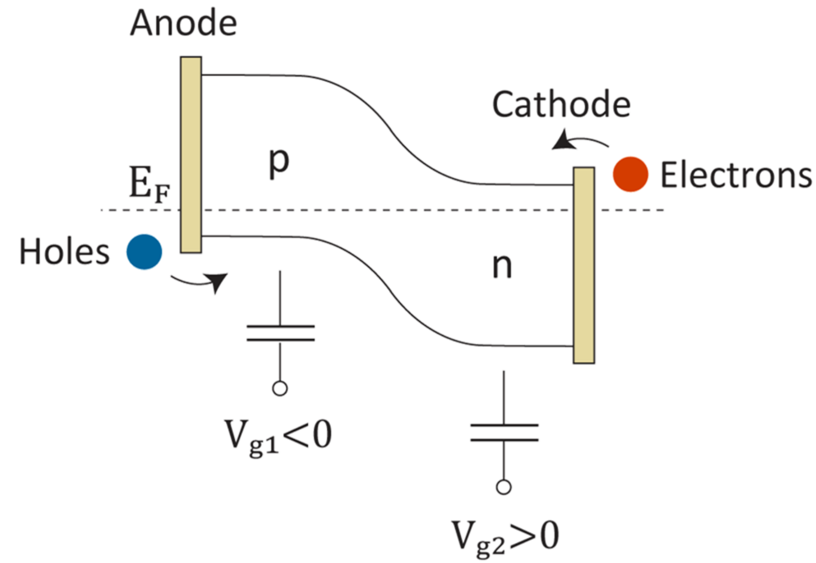
[Overview] Electroluminescent devices

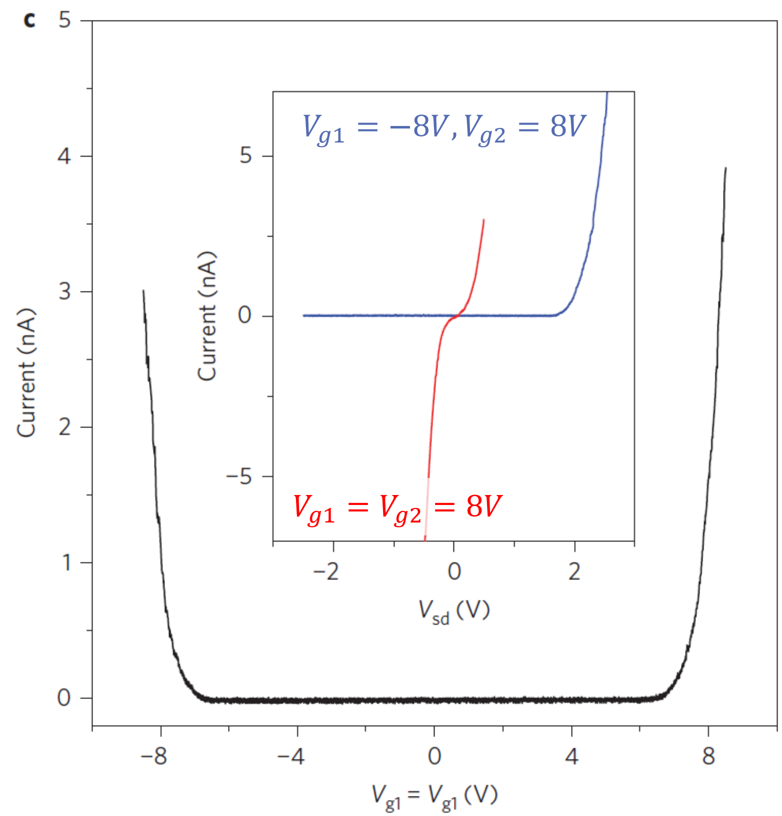


Adapted from Wang et al. Advanced Materials (2018)

Lateral junction LEDs



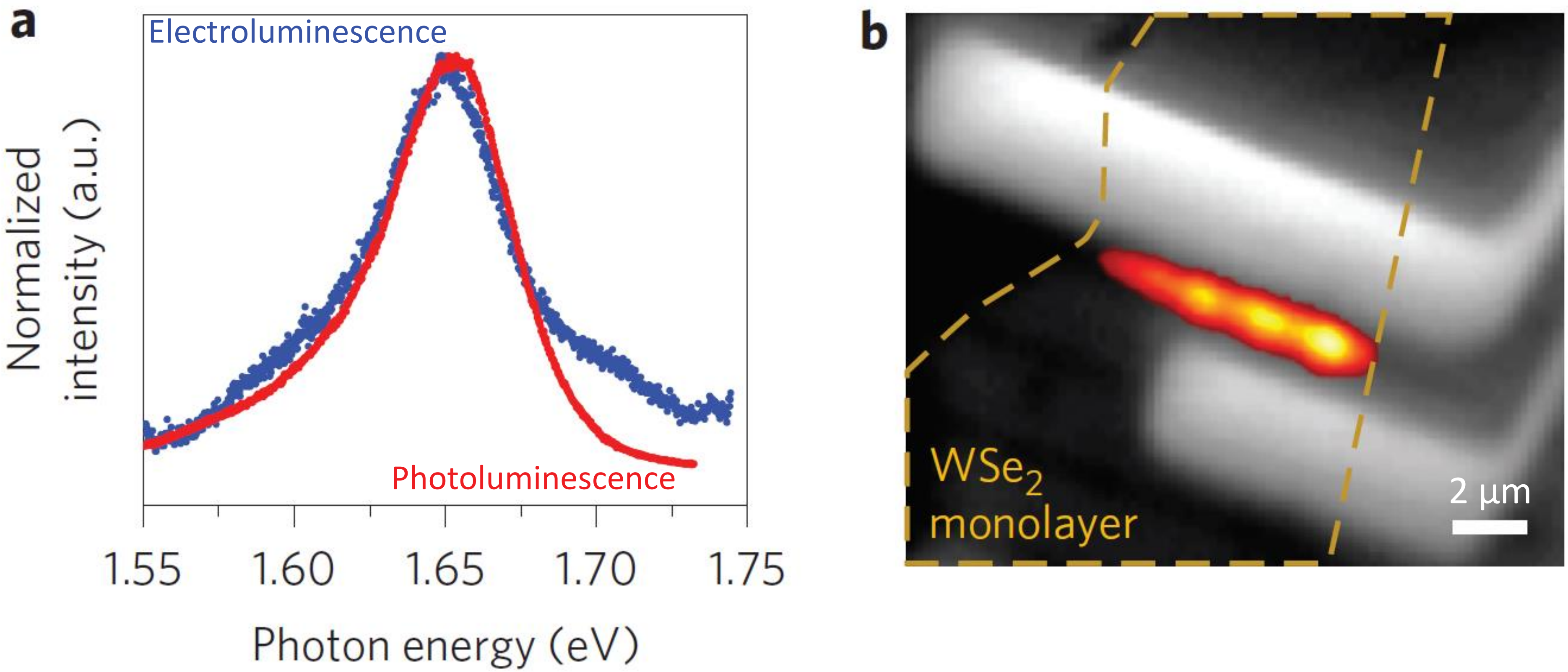




Ross et al. Nat Nano (2014),

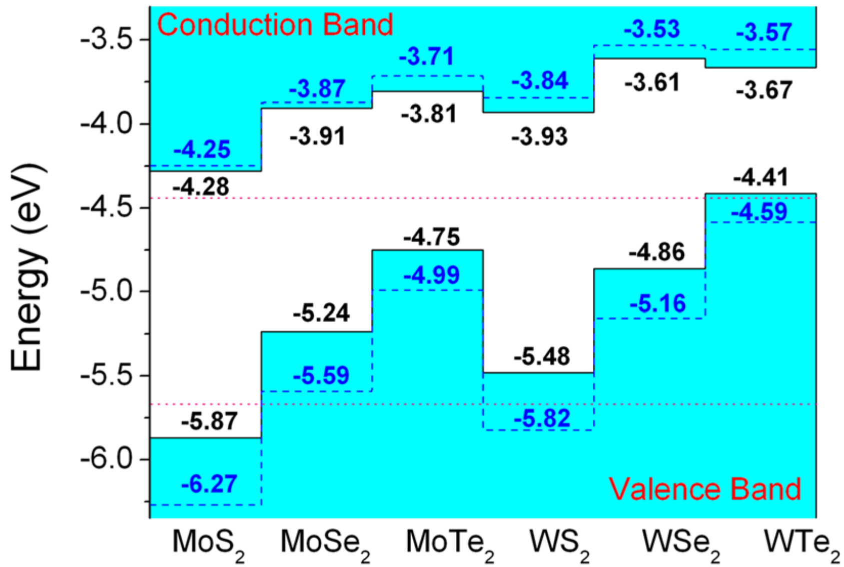
Pospischil et al. Nat Nano (2014)

Lateral junction LEDs

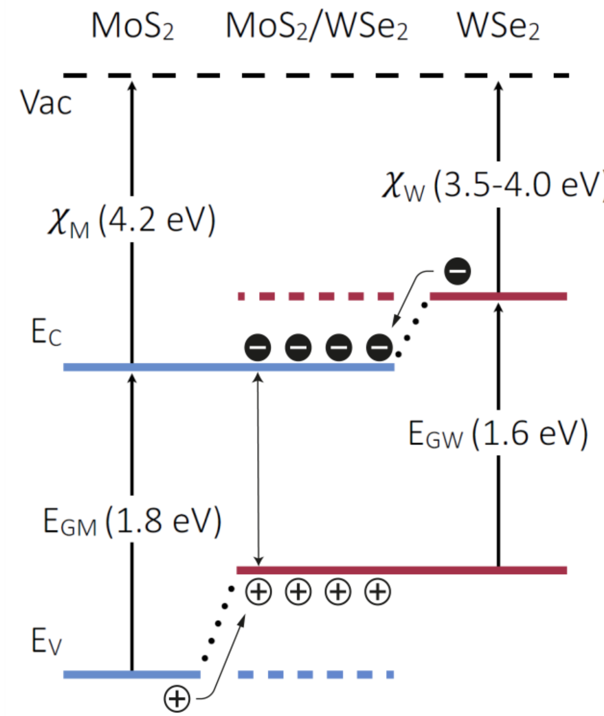


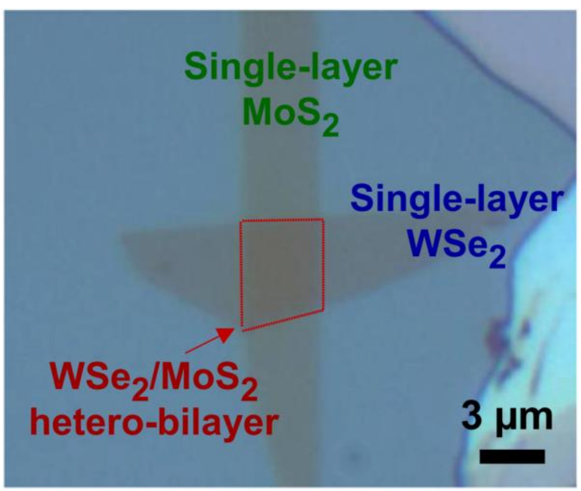
Ross et al. Nat Nano (2014)

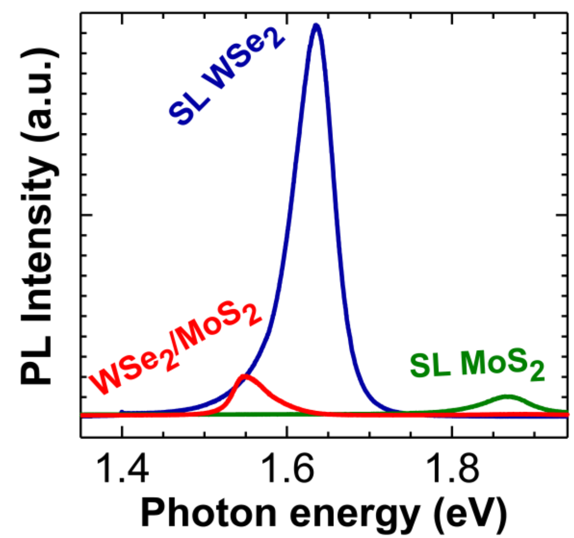
Vertical heterojunctions



Kang, Jun, et al, APL (2013)

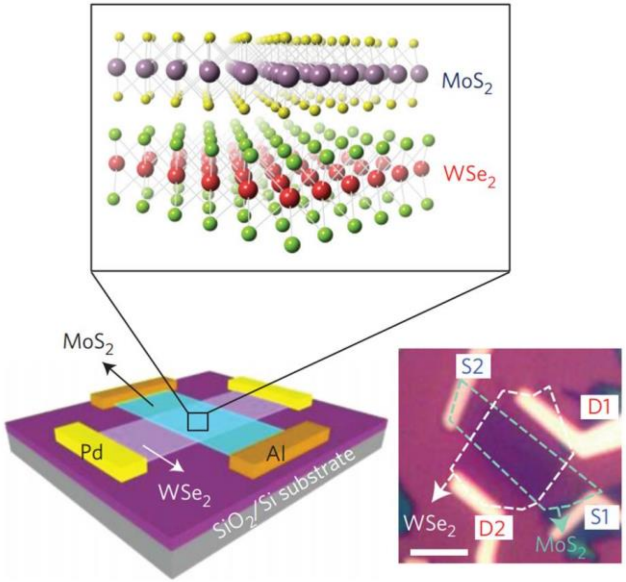




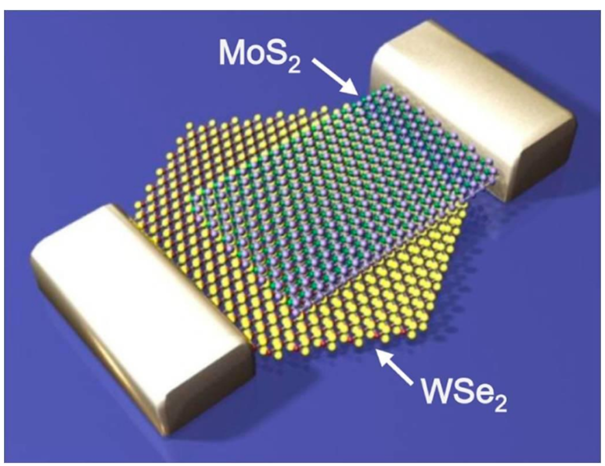


Fang…Javey; PNAS (2014)

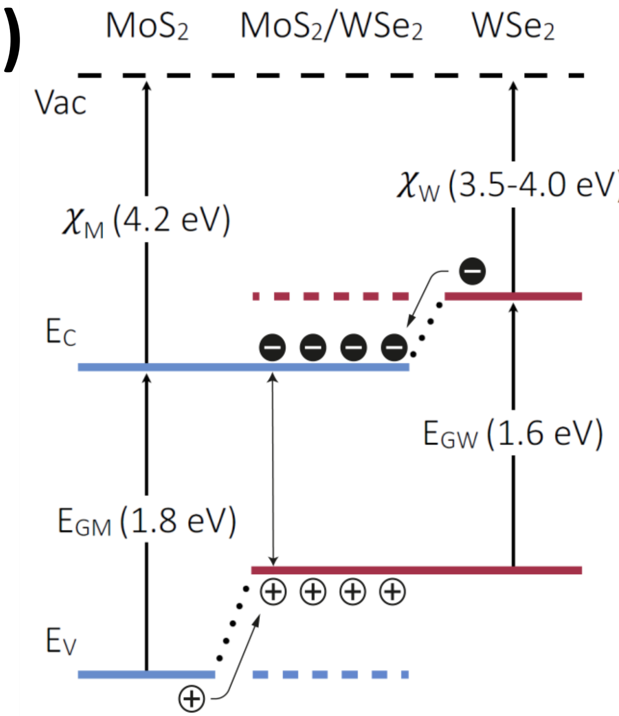
Vertical heterojunction devices (2D/2D)

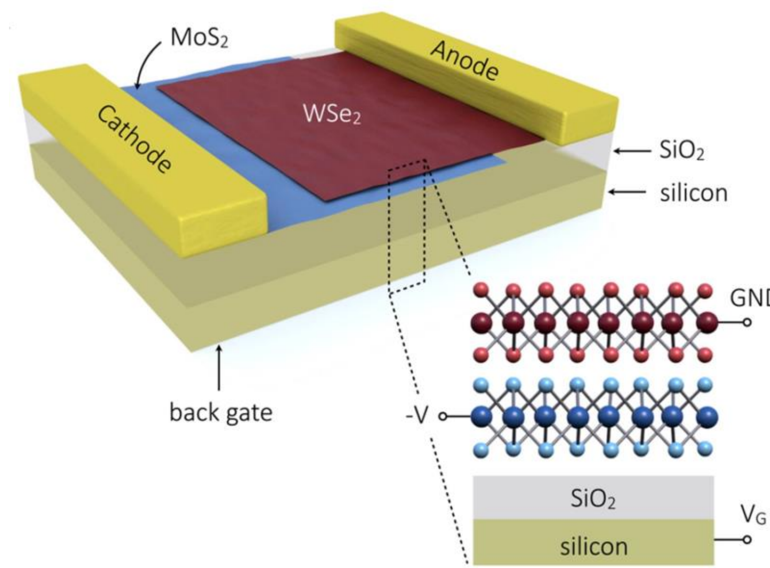


Lee…Kim; Nat. Nanotechnology (2014)



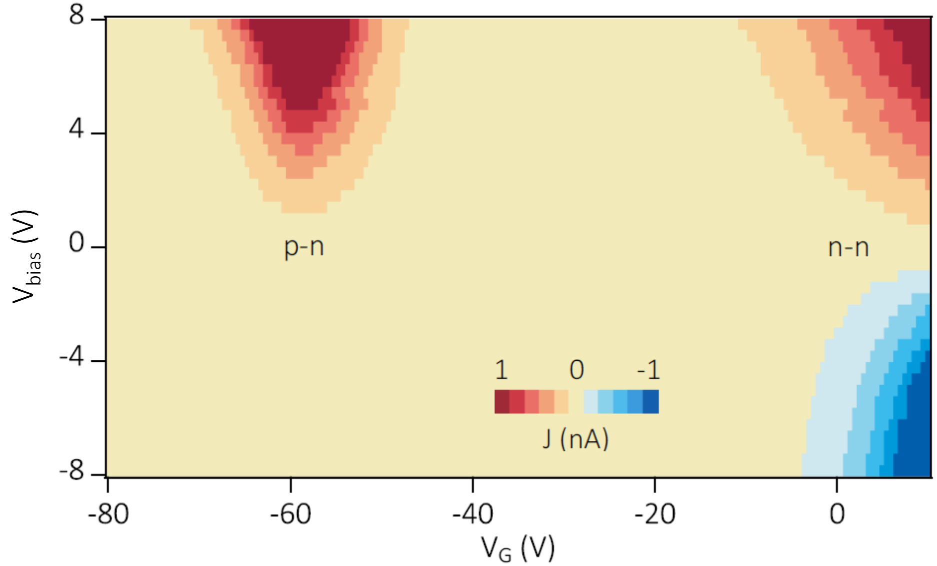
Cheng…Duan; Nano Letters (2014)

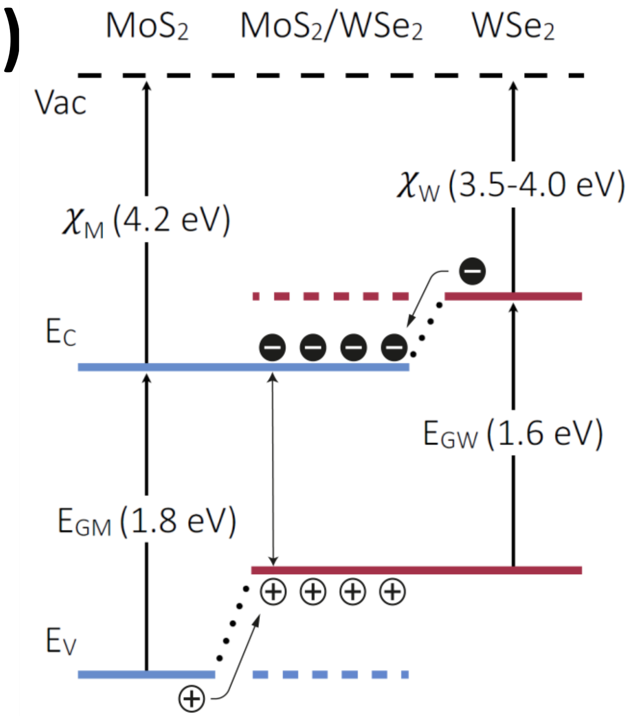


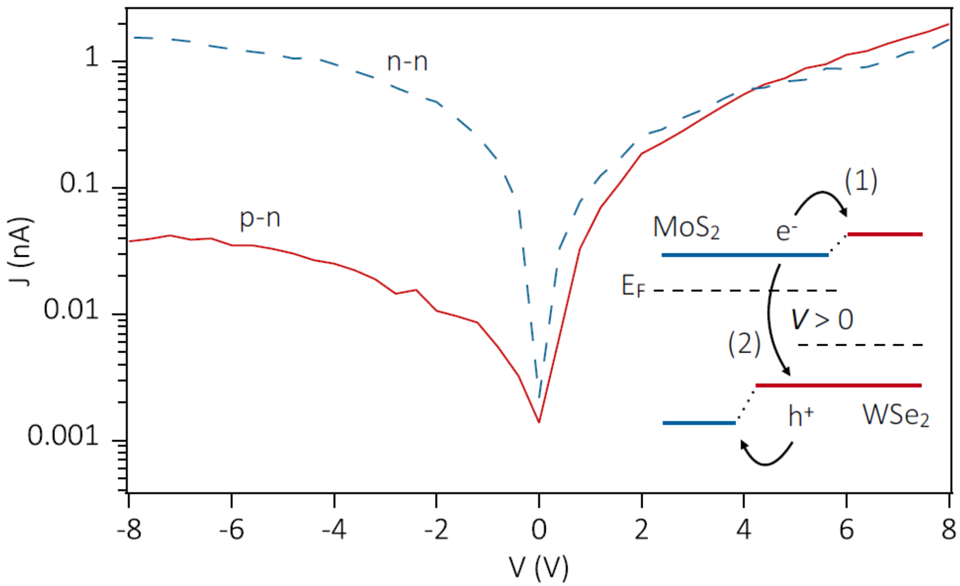


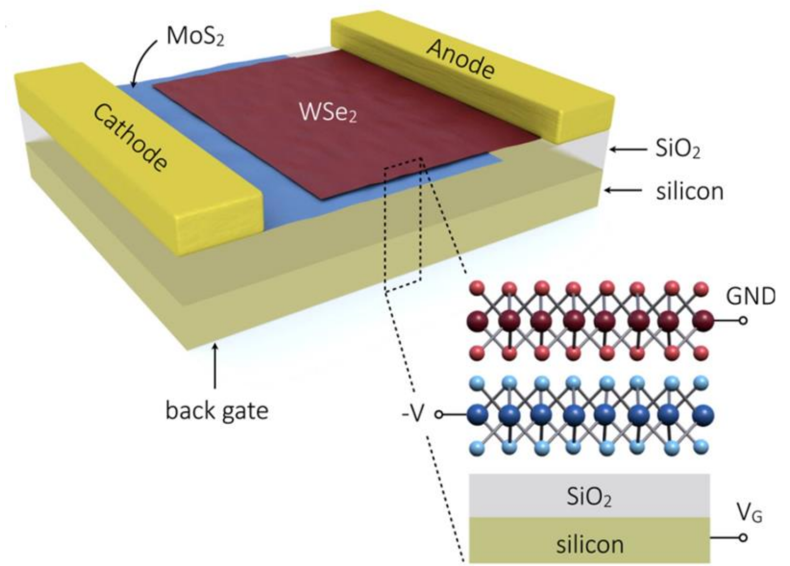
Furchi…Müller; Nano Letters (2014)

Vertical heterojunction devices (2D/2D)



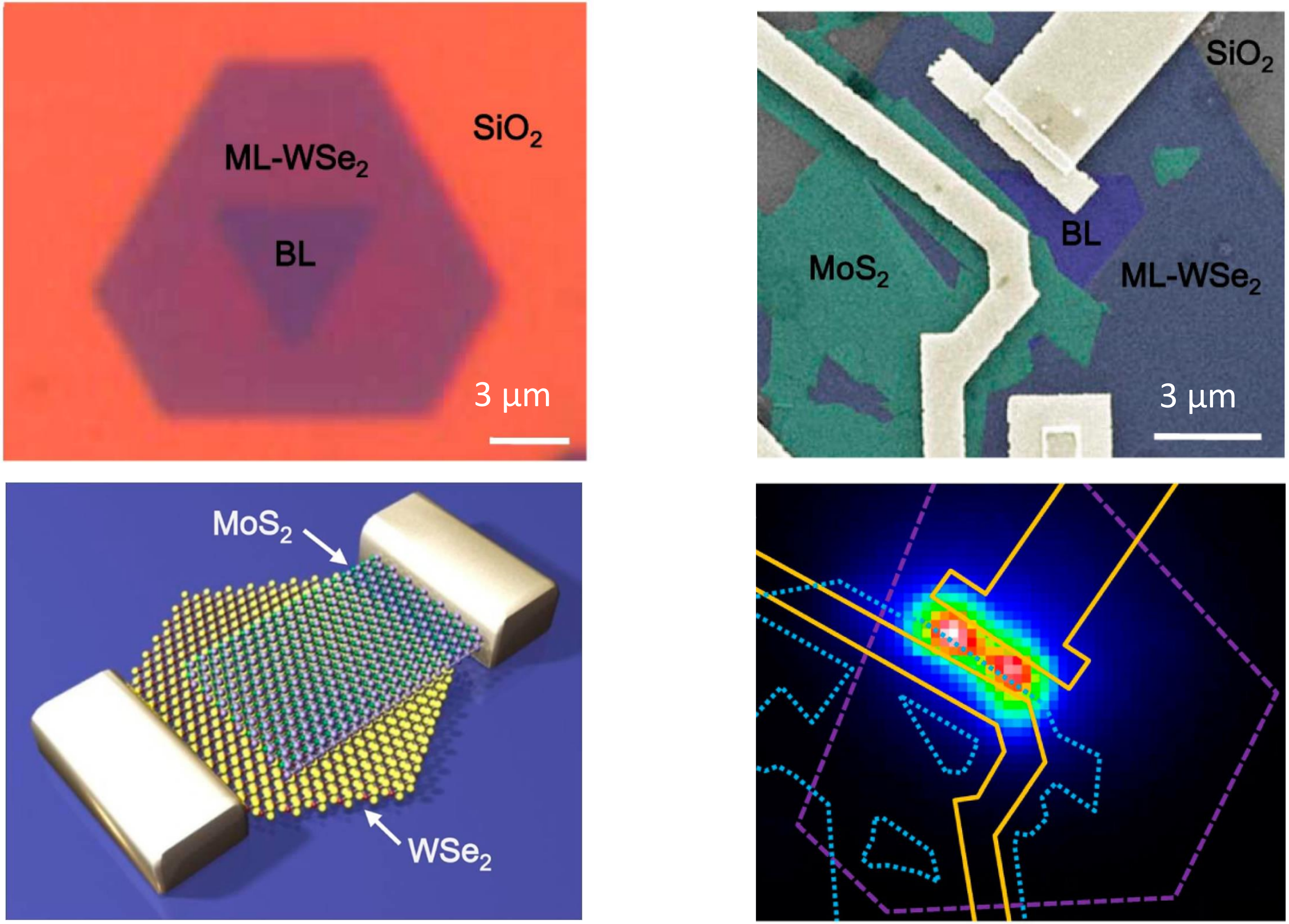






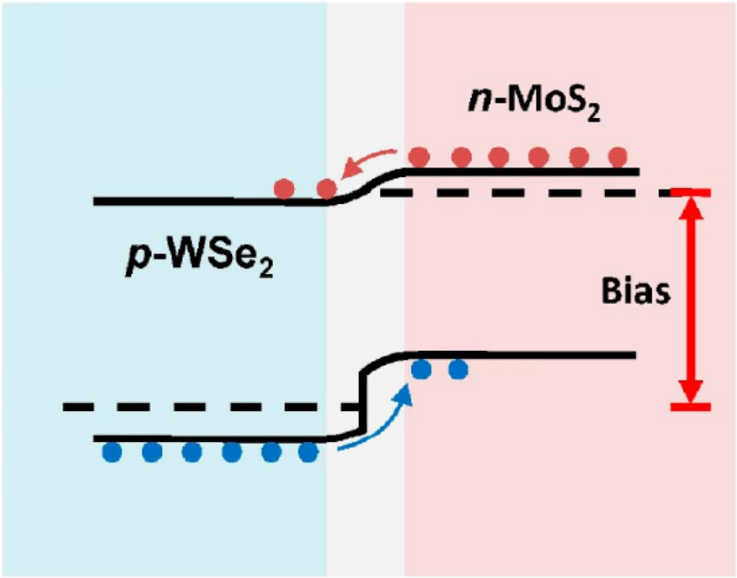
Furchi…Müller; Nano Letters (2014)

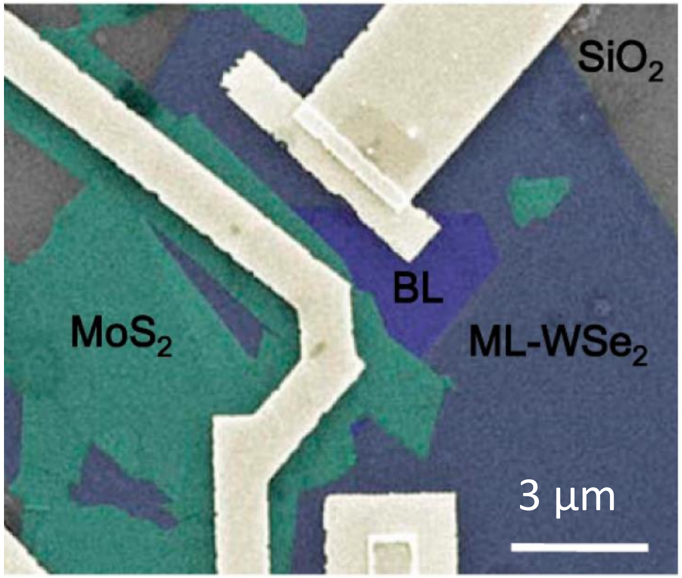
Vertical heterojunction LEDs

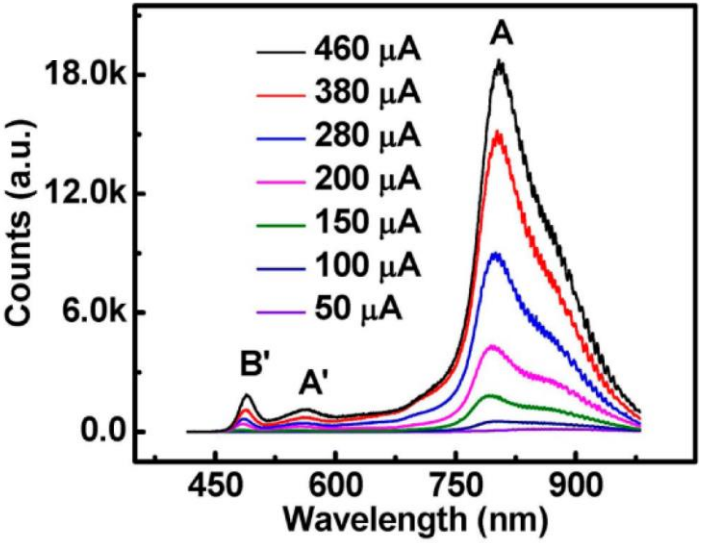


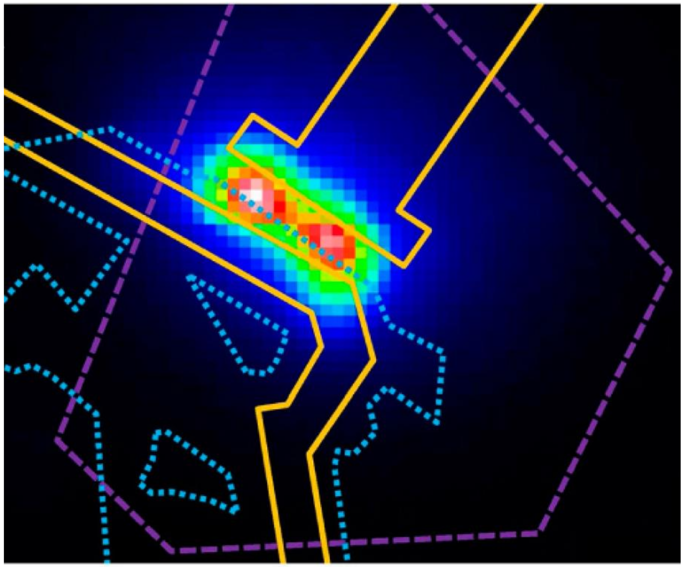
Cheng…Duan; Nano Letters (2014)

Vertical heterojunction devices (2D/2D)





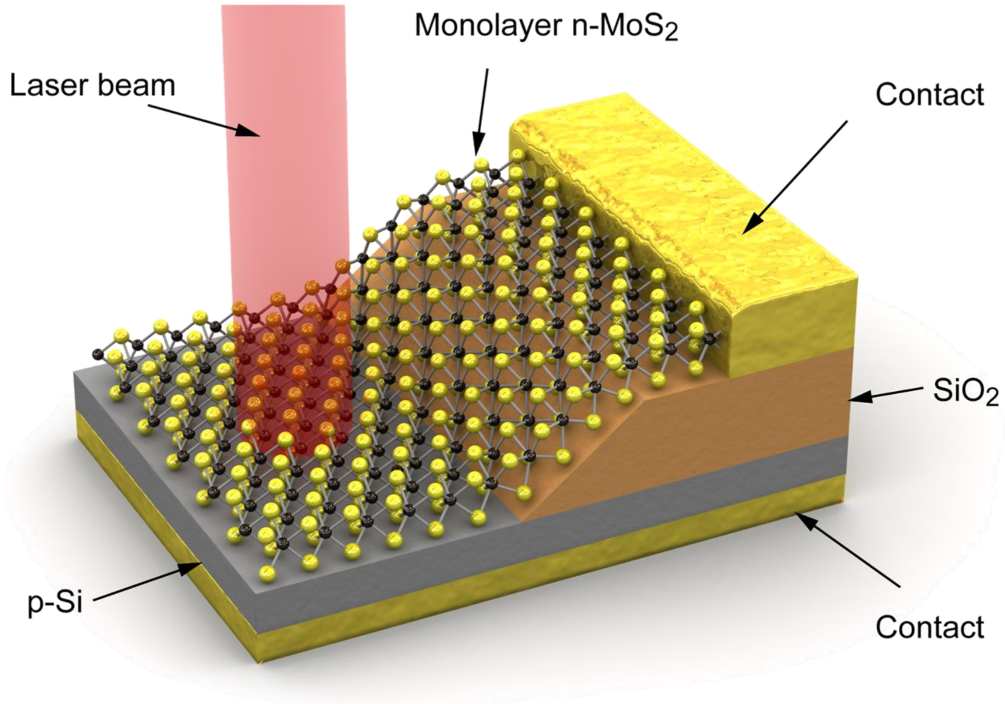




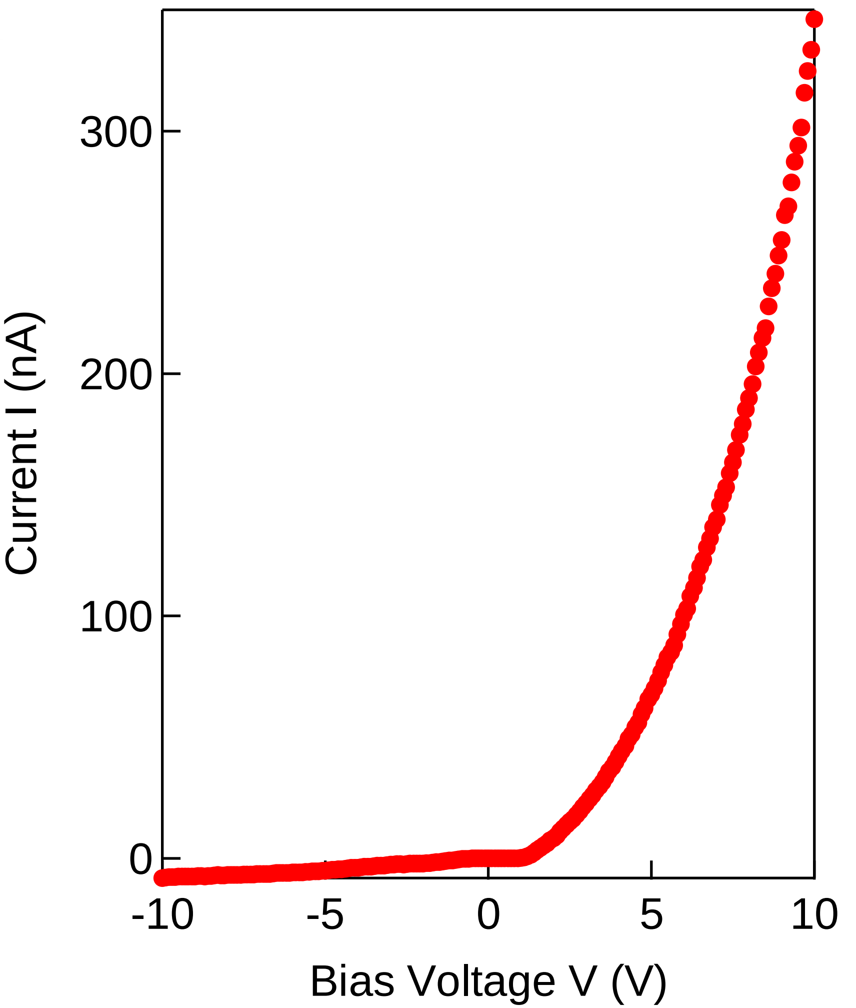
Cheng…Duan; Nano Letters (2014)

Vertical heterojunction devices (2D/3D) MoS_2/p-Si

Device structure



Diode characteristic

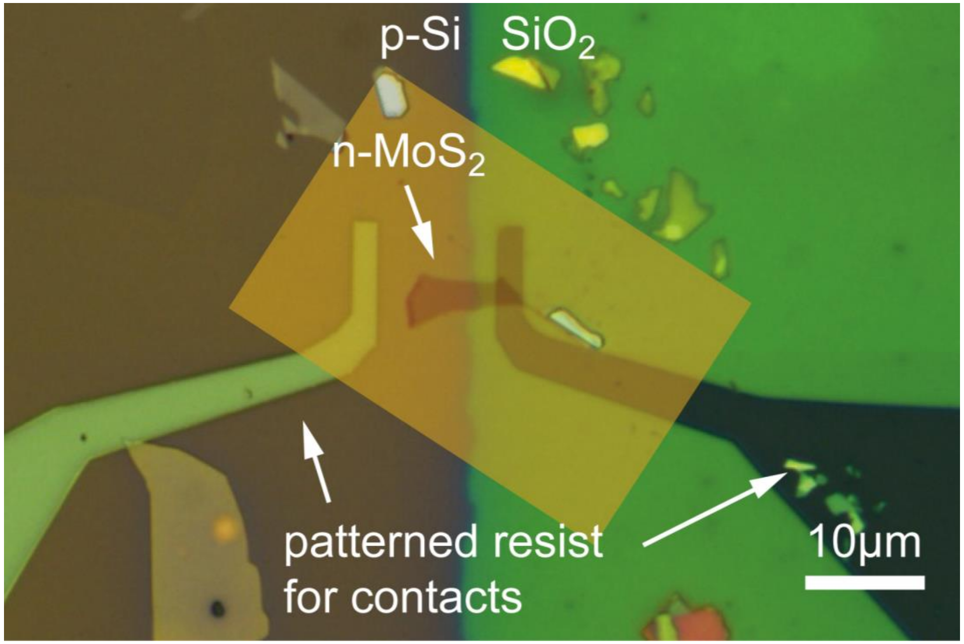


Lopez-Sanchez et al. ACS Nano (2014)

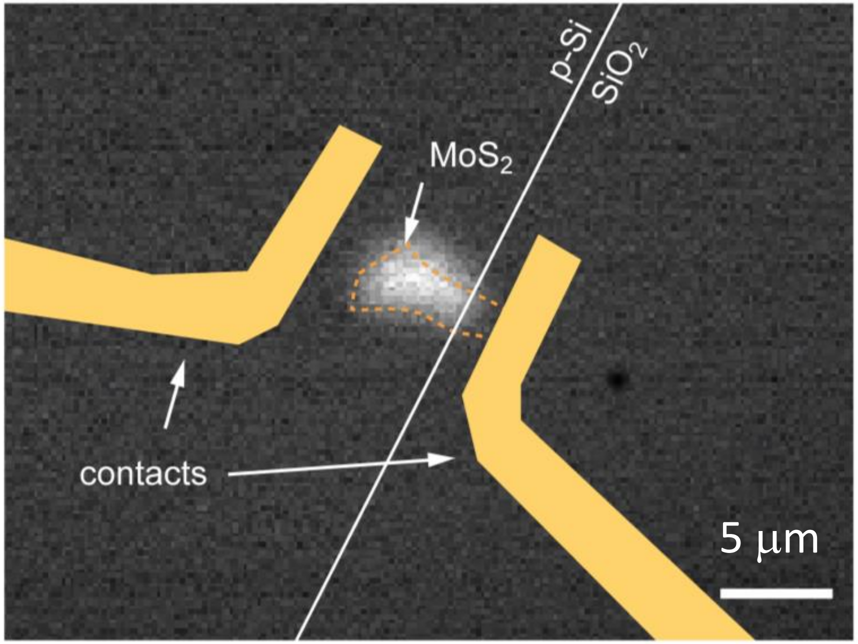
See also: Yim, Lemme, Duesberg et al, Scientific Reports (2014)

MoS_2/p-Si heterojunctions: light emission

Device structure



Emitted light intensity map

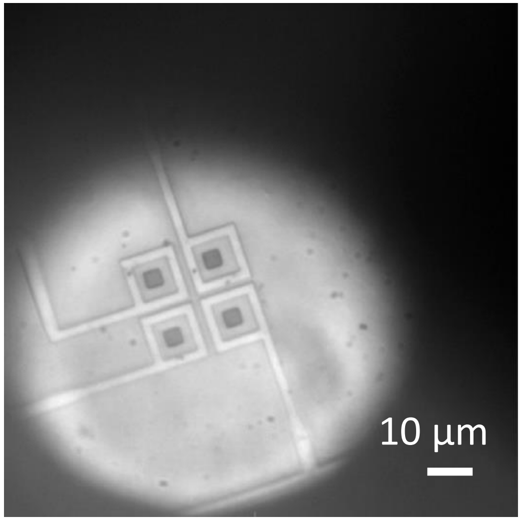


Lopez-Sanchez et al. ACS Nano (2014)

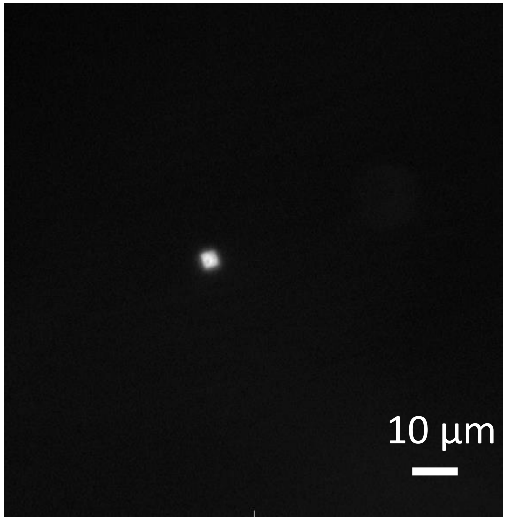
MoS_2/p-Si heterojunctions: light emission

CVD material

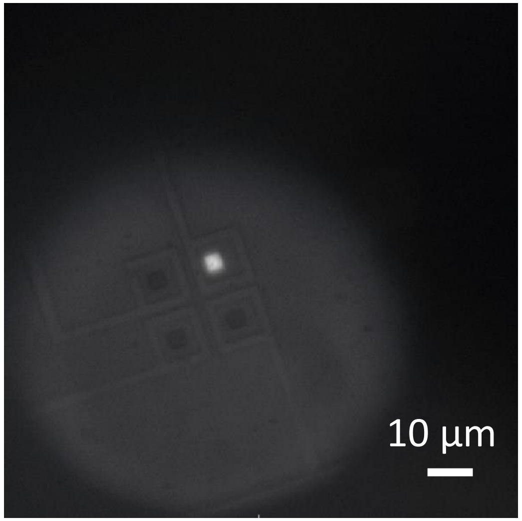
Reflected light



Emitted light

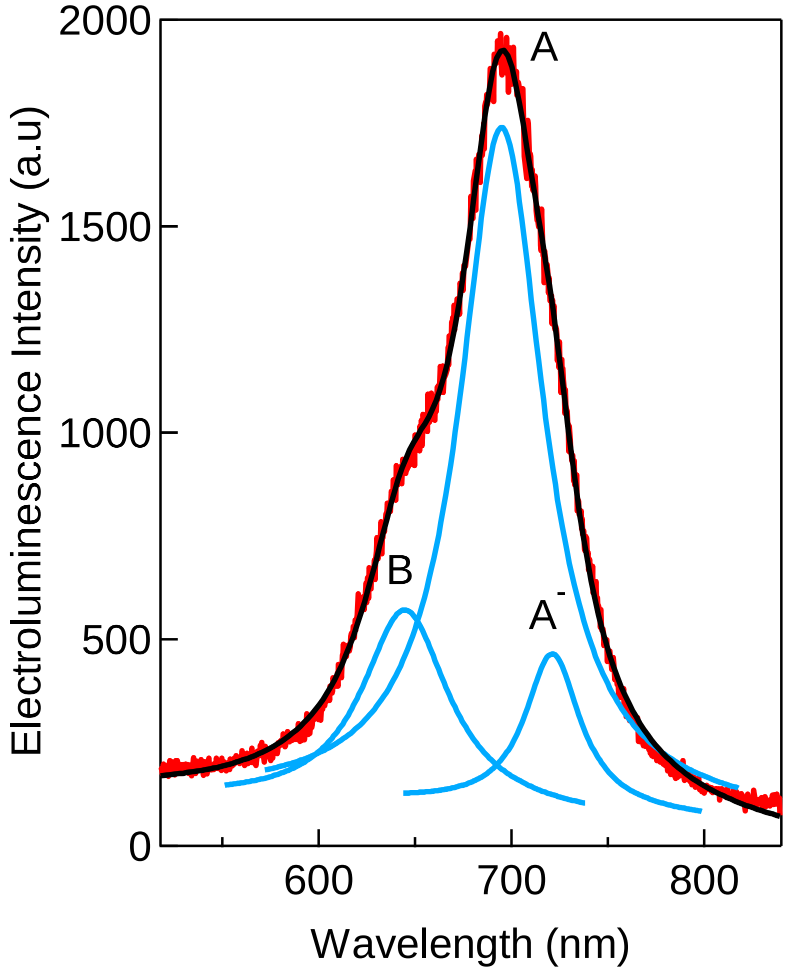


Superposition

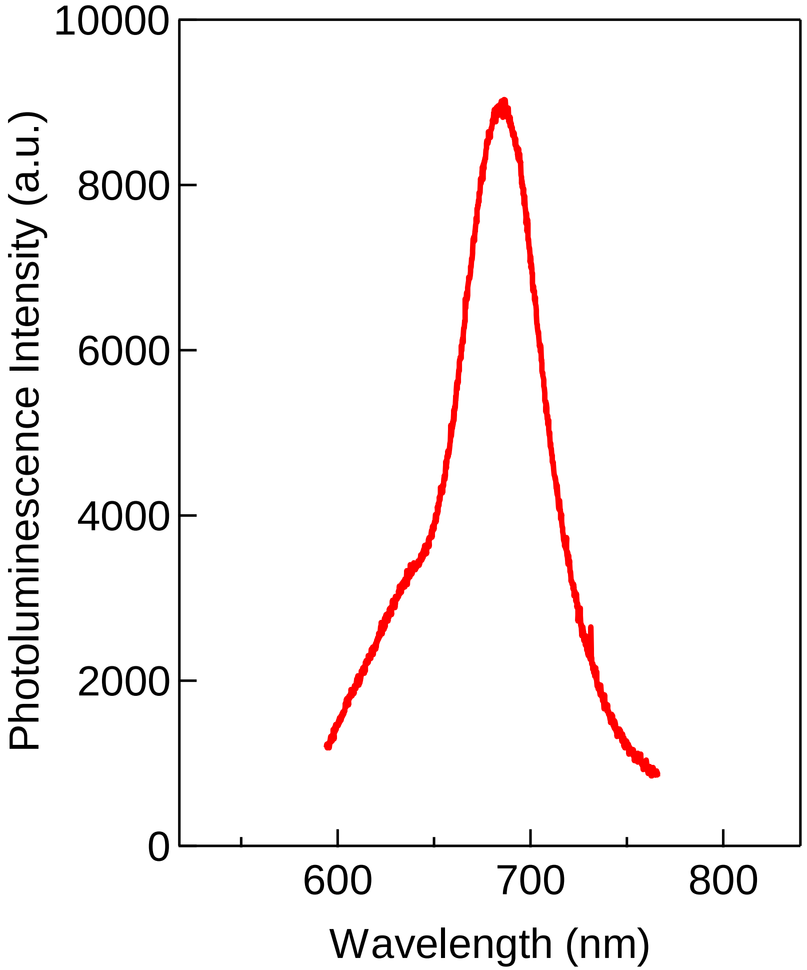


MoS_2/p-Si heterojunctions: light emission

Electroluminescence spectrum

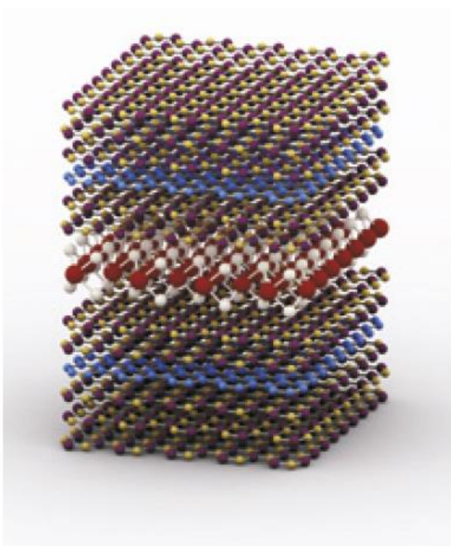


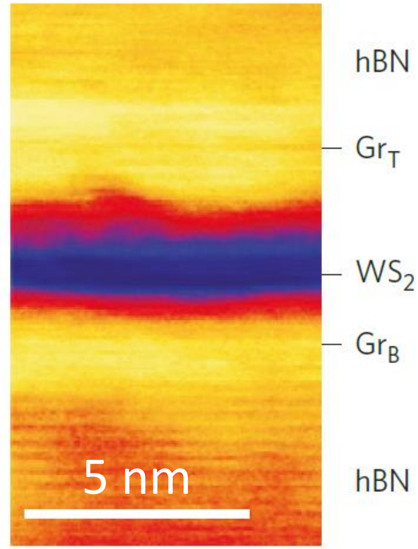
Photoluminescence spectrum

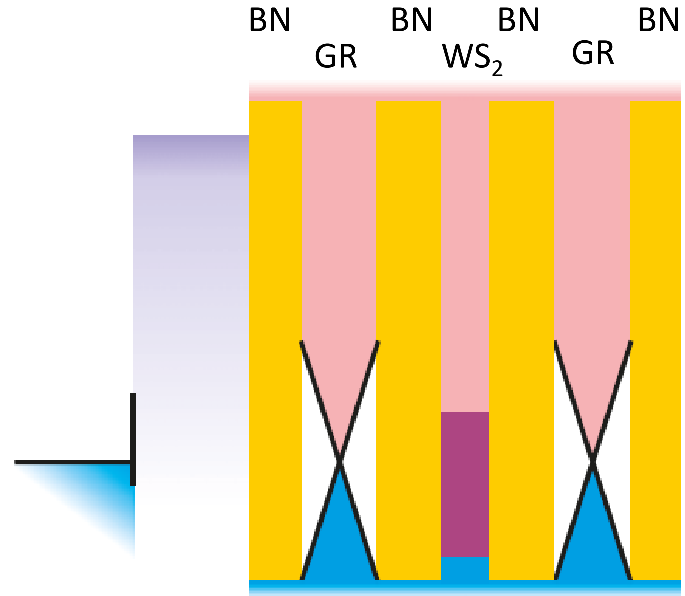


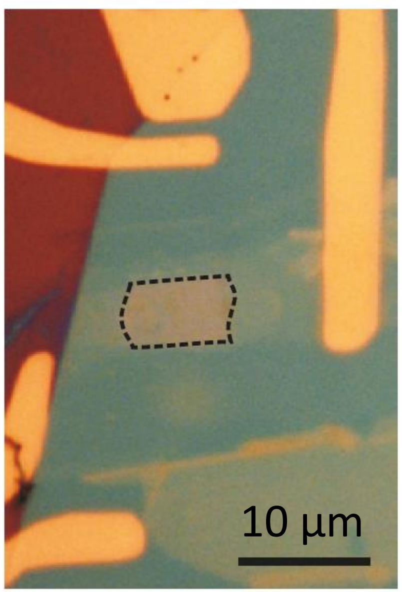
Lopez-Sanchez et al. ACS Nano (2014)

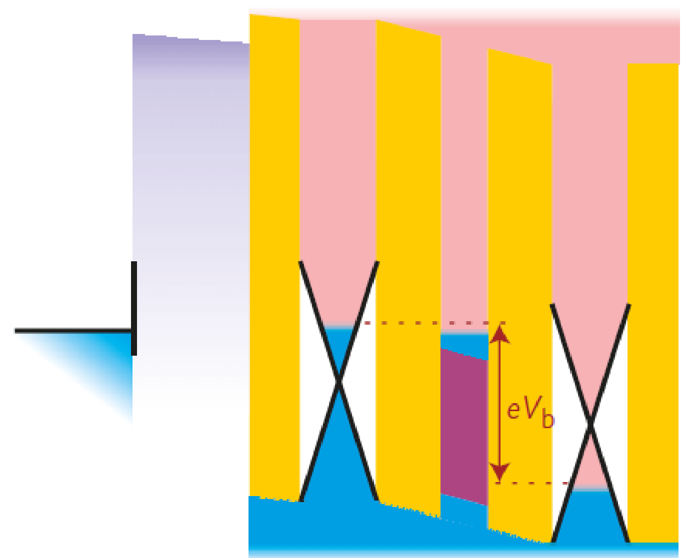
Quantum well EL devices





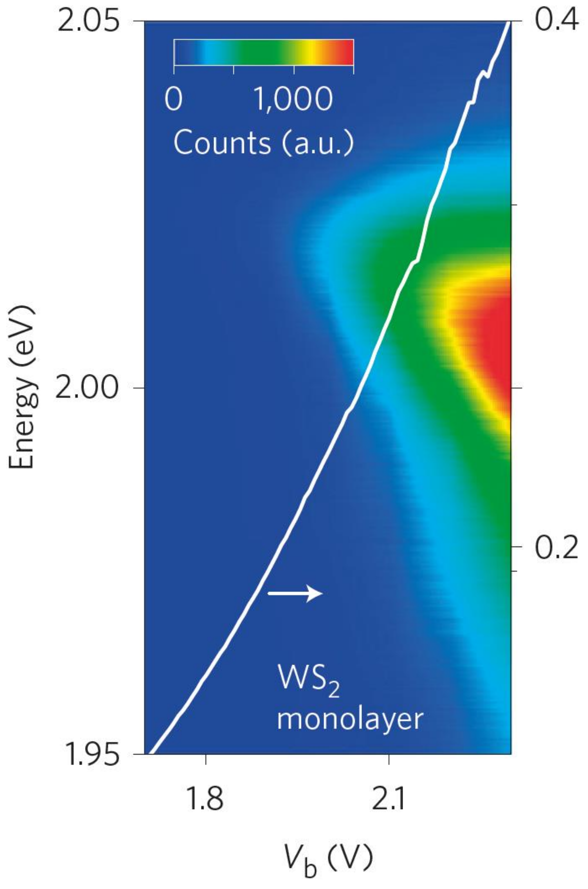


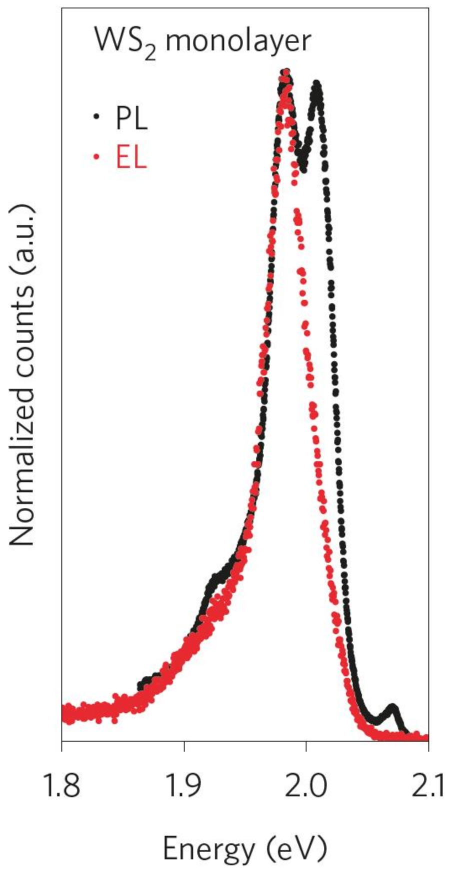


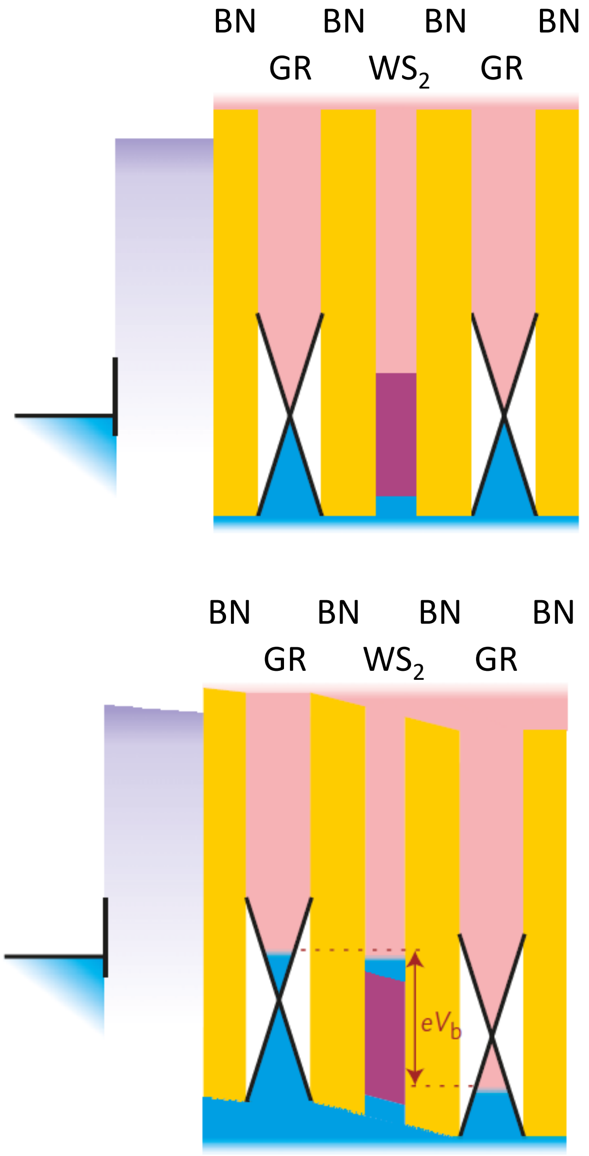


Withers et al. Nature Materials (2015)

Quantum well EL devices

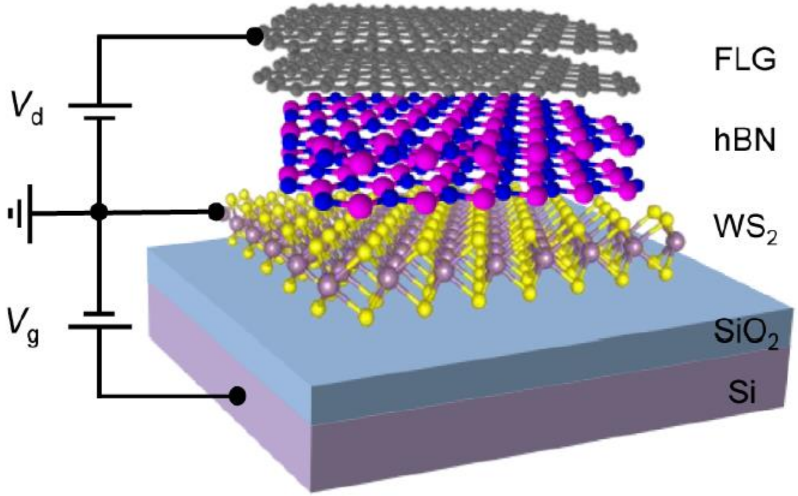


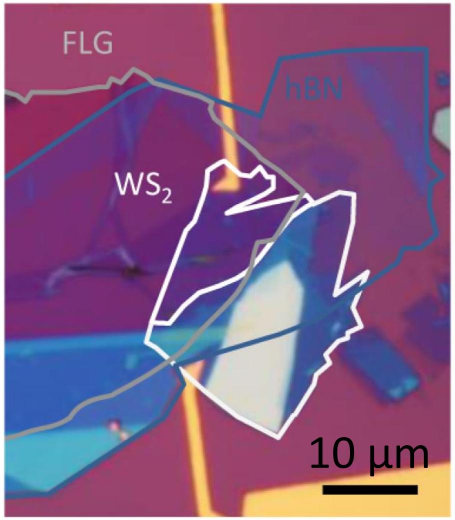


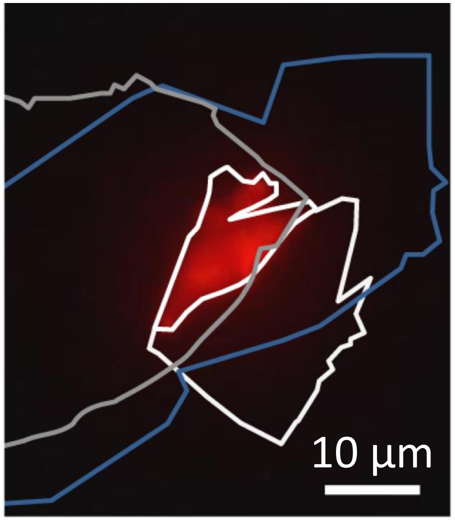


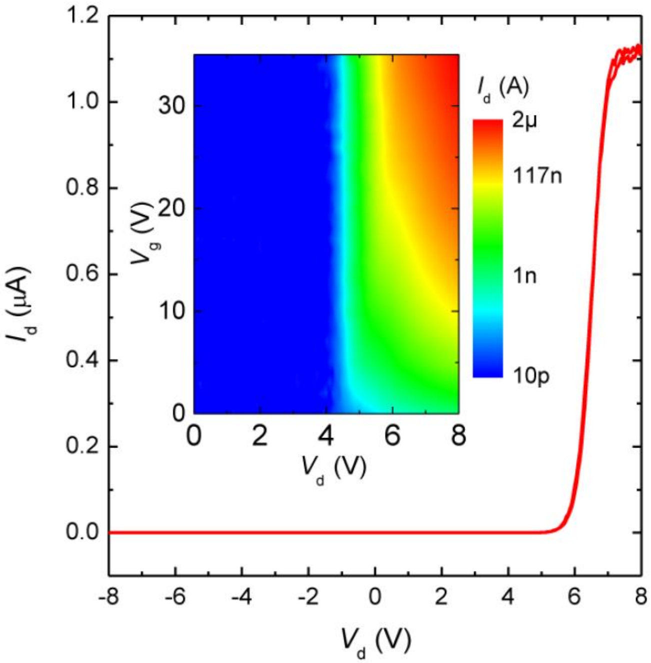
Withers et al. Nature Materials (2015)

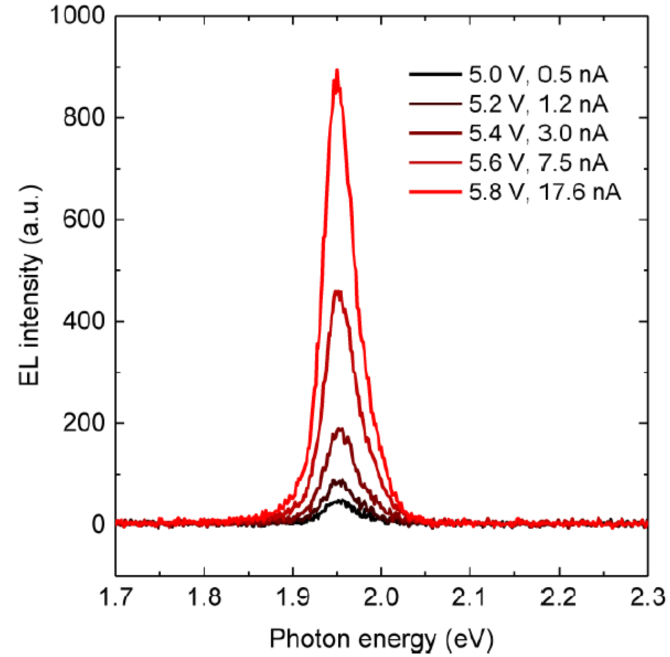
Metal-insulator-semiconductor (MIS) EL devices





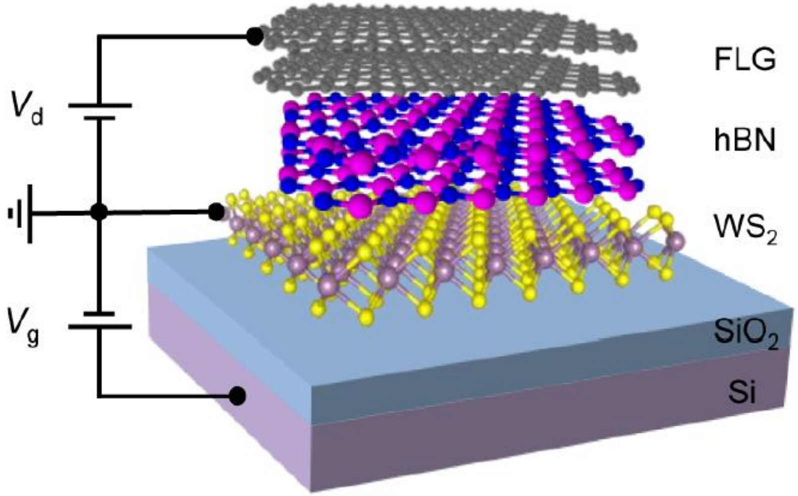


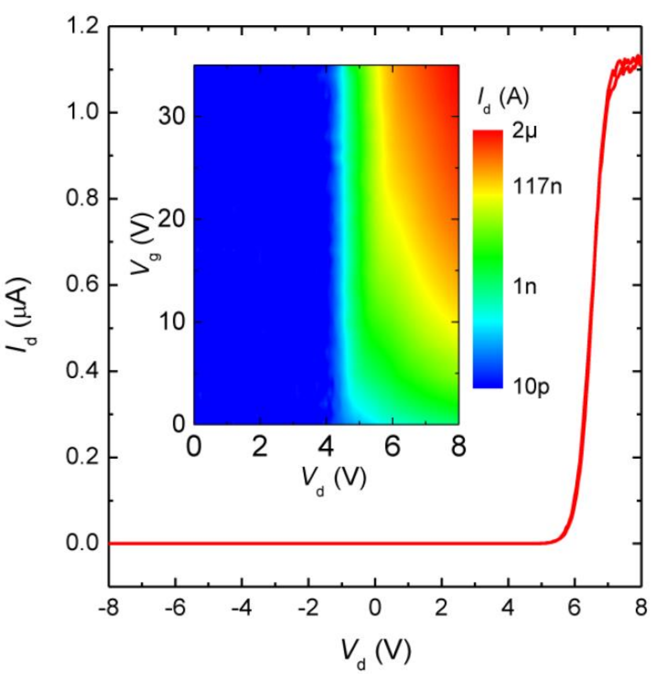




Wang et al. Nano Letters (2017)

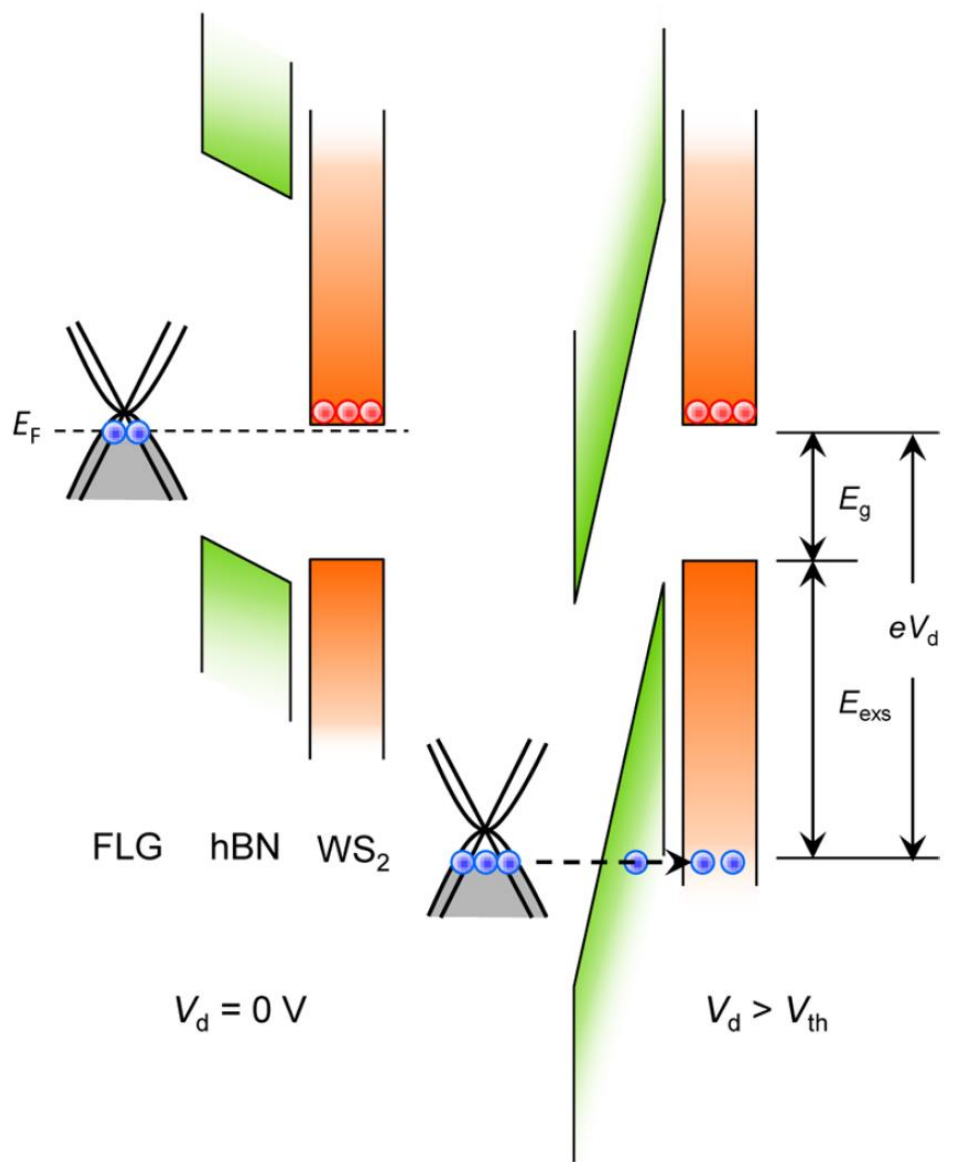
Metal-insulator-semiconductor (MIS) EL devices





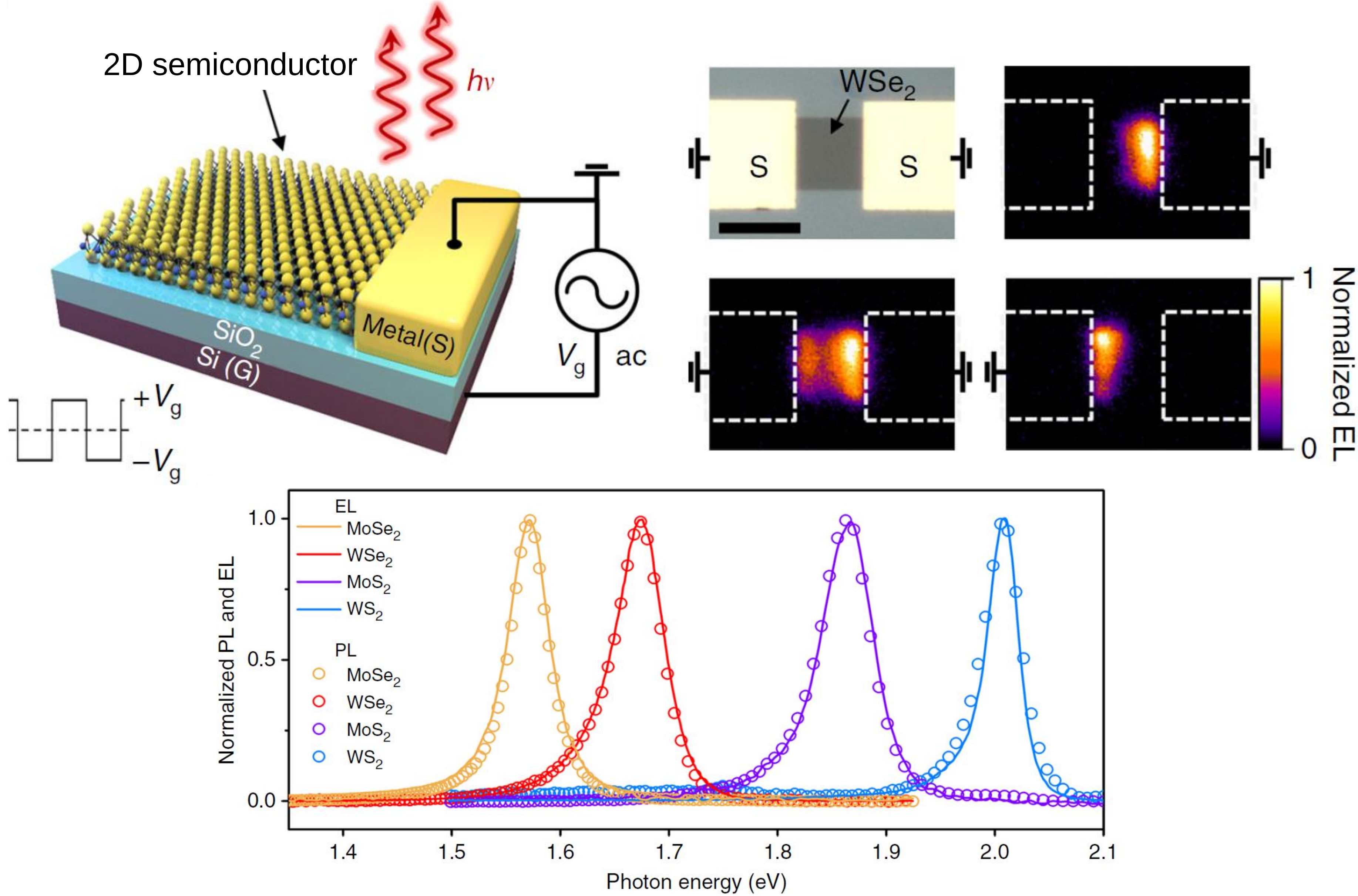
BN blocking electrons

BN transporting holes



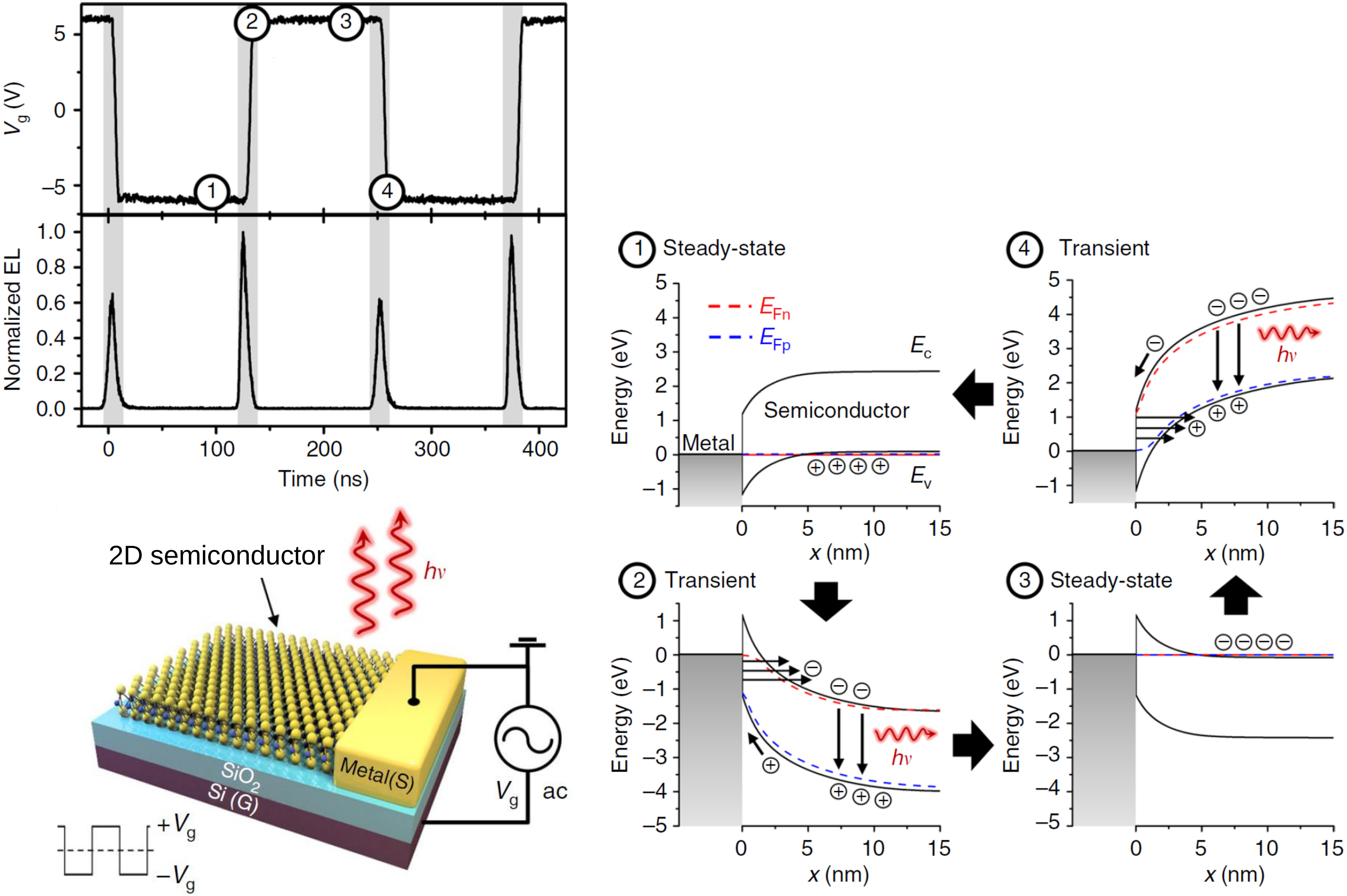
Wang et al. Nano Letters (2017)

Pulsed EL device



Lien et al. Nature Communications (2018)

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

Devices

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