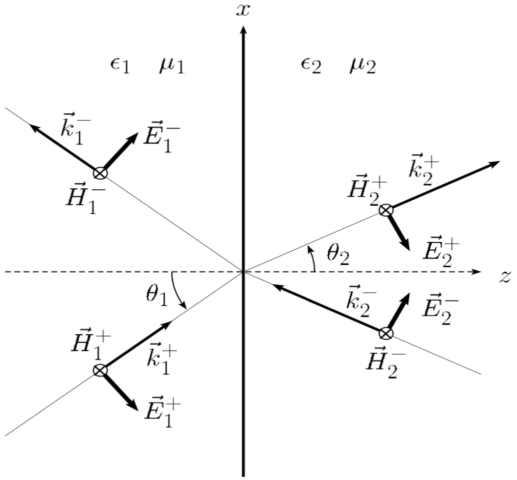
אופטיקה של חומרים דו-מימדיים

- 2D semiconductors – Transition Metal Dichalcogenides

Polaritons, DR and the TMM



$$\tilde{\mathbf{M}}^{(p)} = \frac{1}{2}\begin{pmatrix} 1+\frac{\varepsilon_1}{\varepsilon_2}\frac{k_{2z}}{k_{1z}} & 1-\frac{\varepsilon_1}{\varepsilon_2}\frac{k_{2z}}{k_{1z}} \\ 1-\frac{\varepsilon_1}{\varepsilon_2}\frac{k_{2z}}{k_{1z}} & 1+\frac{\varepsilon_1}{\varepsilon_2}\frac{k_{2z}}{k_{1z}} \end{pmatrix}$$

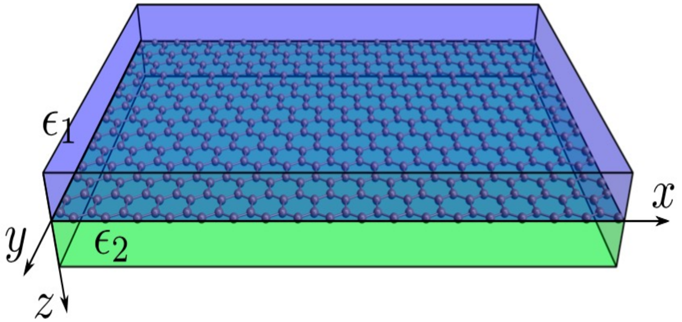
$$r = \frac{M_{21}}{M_{11}} \qquad t = \frac{1}{M_{11}}$$

$$\varepsilon_2 k_{1z} + \varepsilon_1 k_{2z} = 0 \qquad \frac{k_2}{k_1} = -\frac{\varepsilon_2}{\varepsilon_1}$$

SPP DR!

$$r = \frac{M_{21}}{M_{11}} = \frac{\varepsilon_2 k_{1z} - \varepsilon_1 k_{2z}}{\varepsilon_2 k_{1z} + \varepsilon_1 k_{2z}}$$

$$r = \frac{1 - \frac{\epsilon_1 k_{2,z}}{\epsilon_2 k_{1,z}} + \frac{\sigma_g k_{2,z}}{\omega\epsilon_0\epsilon_2}}{1 + \frac{\epsilon_1 k_{2,z}}{\epsilon_2 k_{1,z}} + \frac{\sigma_g k_{2,z}}{\omega\epsilon_0\epsilon_2}}$$



$$E_x^{(1)}(z=0) = E_x^{(2)}(z=0) \ ,$$
$$B_y^{(1)}(z=0) - B_y^{(2)}(z=0) = \mu_0\sigma_g E_x^{(1)}(z=0),$$

$$A_1 - B_1 = \frac{\epsilon_1 k_{2,z}}{\epsilon_2 k_{1,z}}(A_2 - B_2) \ ,$$
$$A_1 + B_1 = \frac{\sigma_g k_{2,z}}{\omega\epsilon_0\epsilon_2}(A_2 - B_2) + A_2 + B_2 \ .$$

$$1 + \frac{\epsilon_1 k_{2,z}}{\epsilon_2 k_{1,z}} + \frac{\sigma_g k_{2,z}}{\omega\epsilon_0\epsilon_2} = 0$$

$$k_{j,z} = i\sqrt{q^2 - \epsilon_j\omega^2/c^2} \equiv i\kappa_j$$

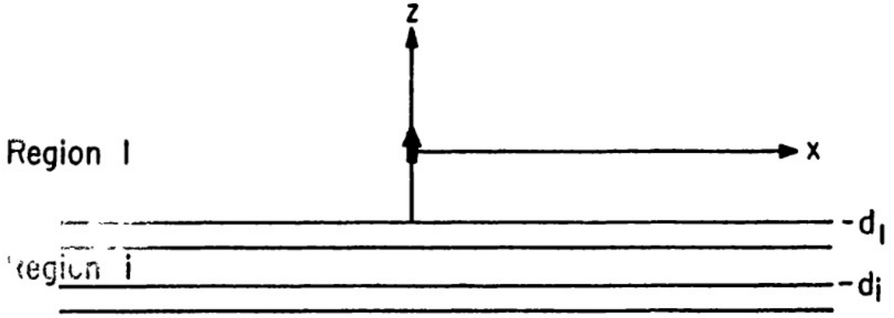
$$1 + \frac{\epsilon_1\kappa_2}{\epsilon_2\kappa_1} + \frac{i\sigma_g\kappa_2}{\omega\epsilon_0\epsilon_2} = 0$$

$$\frac{\epsilon_1}{\kappa_1} + \frac{\epsilon_2}{\kappa_2} + \frac{i\sigma_g}{\omega\epsilon_0} = 0$$

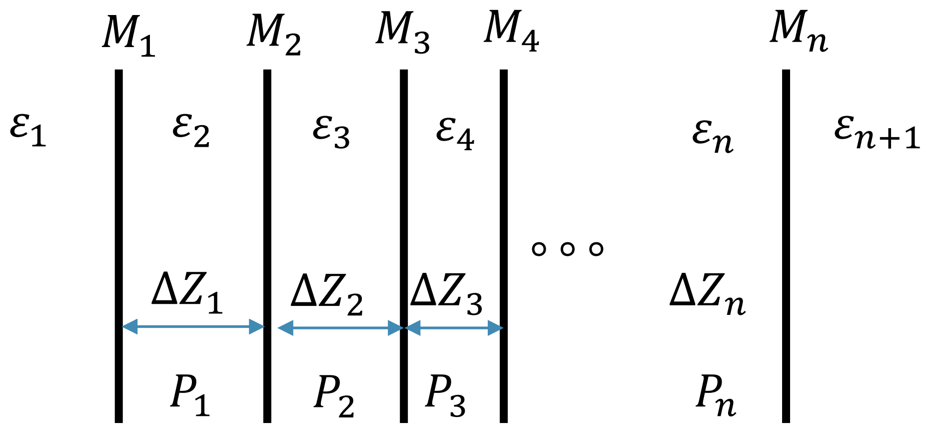
GP DR!

The poles of r give the DR!!!

Polaritons, DR and the TMM



$$E_{1z} = \frac{-I\ell}{8\pi\omega\epsilon_1}\int_{-\infty}^{\infty} dk_\rho \frac{k_\rho^3}{k_{1z}} H_0^{(1)}(k_\rho \rho)\left[e^{ik_{1z}|z|} + \tilde{R}_{12}^{TM} e^{ik_{1z}z+2ik_{1z}d_1}\right],$$



הקטבים של מקדם ההחזרה נותנים לנו את יחס הדיספרסיה!

יחס הדיספרסיה נותן לנו את כל אופני התנודה שנתמכים במערכת!

ה TMM נותן לנו את מקדם ההחזרה!

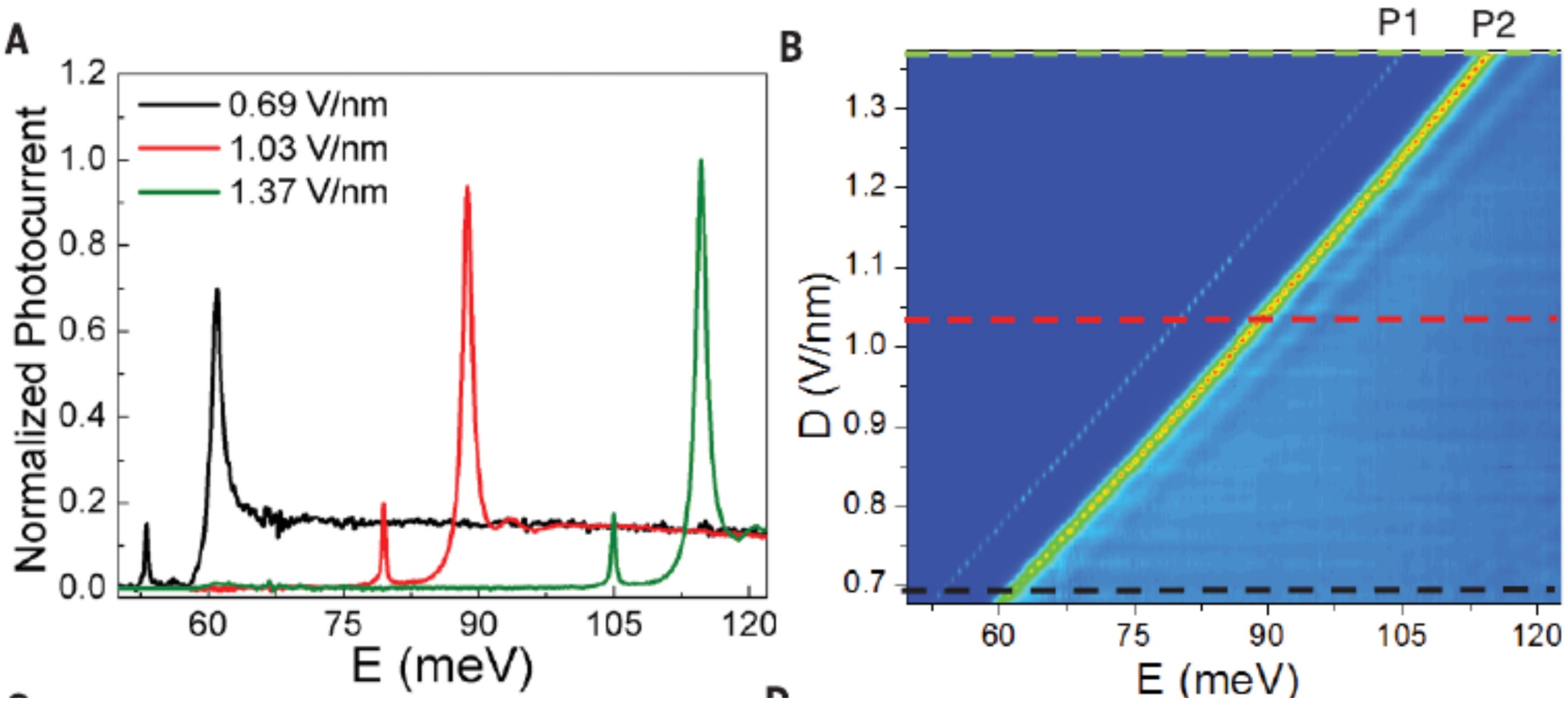
$$\begin{pmatrix} H_1^+ \\ H_1^- \end{pmatrix} = TM \begin{pmatrix} H_2^+ \\ H_2^- \end{pmatrix} \qquad TM = M_1 P_1 M_2 P_2 \cdots M_{n+1}$$

$$r = \frac{M_{21}}{M_{11}}$$

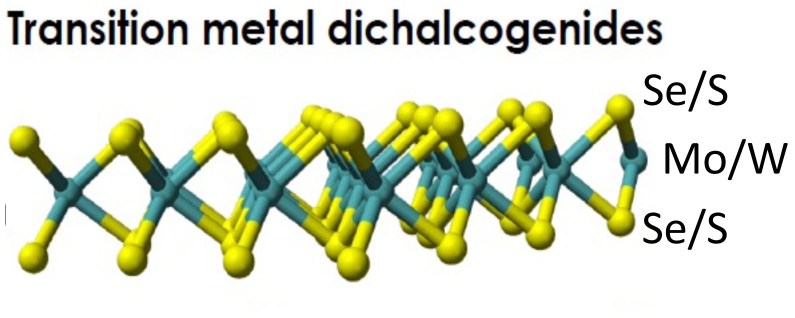
The loss function $L_r(q,\omega) = \Im\mathrm{m}\,\{r\}$

Needs to cover all the relevant momentum/frequency space

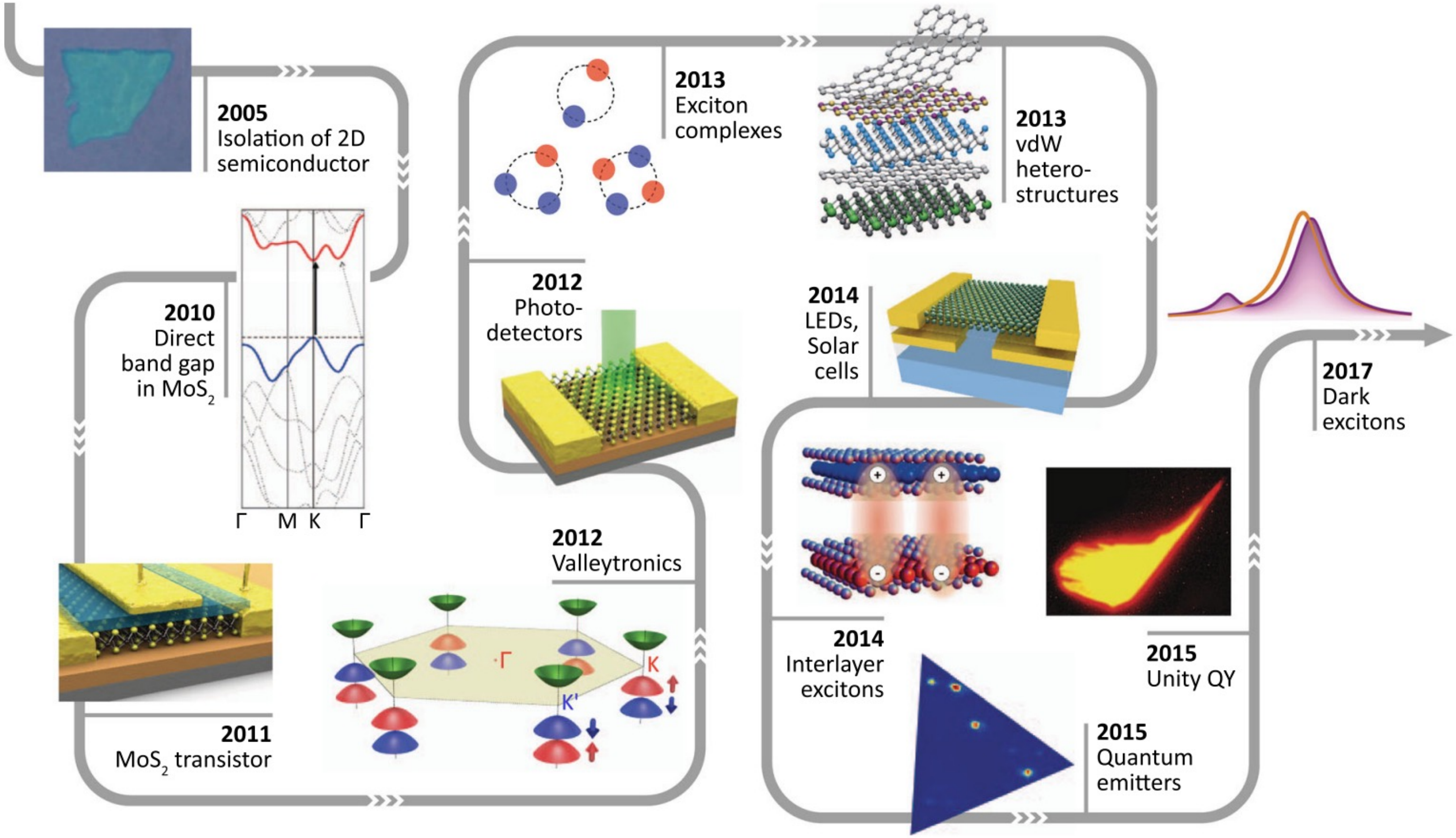
Polaritons, DR and the TMM - examples



Transition-Metal-Dichalcogenides (TMDs)



WS2, WSe2, MoS2, MoSe2



Transition-Metal-Dichalcogenides (TMDs)

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Emerging Photoluminescence in Monolayer MoS_2

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

View Author Information

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https://doi.org/10.1021/nl903868w

SUBJECTS: Monolayers, Photoluminescence, Luminescence, Electrical conductivity, Layers

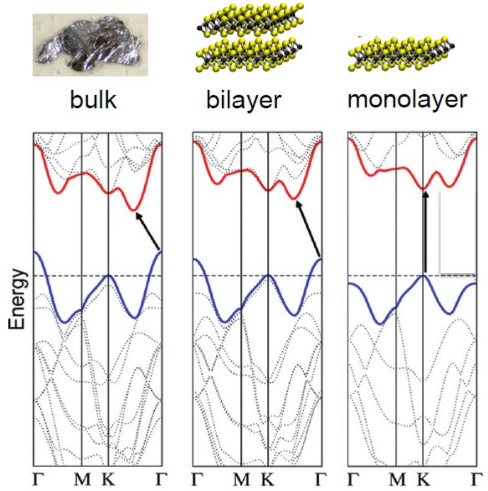
Atomically Thin MoS_2: A New Direct-Gap Semiconductor

Kin Fai Mak, Changgu Lee, James Hone, Jie Shan, and Tony F. Heinz

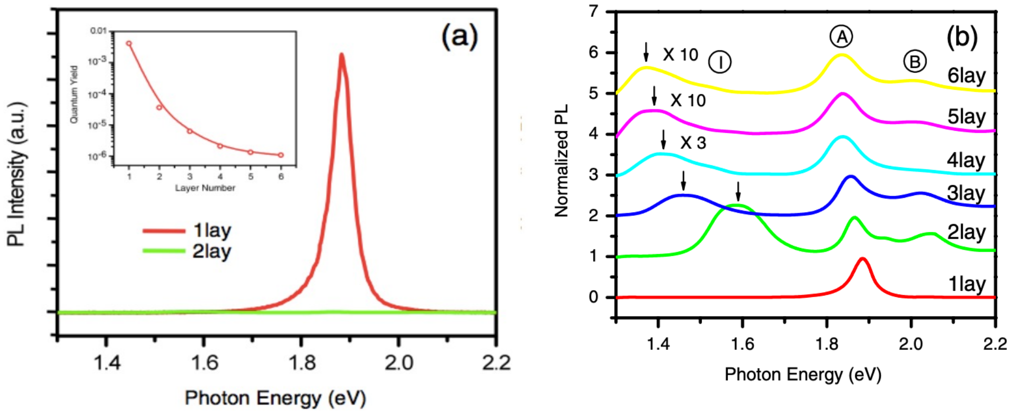
Phys. Rev. Lett. **105**, 136805 – Published 24 September 2010

ABSTRACT

The electronic properties of ultrathin crystals of molybdenum disulfide consisting of $N = 1, 2, \ldots, 6$ S-Mo-S monolayers have been investigated by optical spectroscopy. Through characterization by absorption, photoluminescence, and photoconductivity spectroscopy, we trace the effect of quantum confinement on the material's electronic structure. With decreasing thickness, the indirect band gap, which lies below the direct gap in the bulk material, shifts upwards in energy by more than 0.6 eV. This leads to a crossover to a direct-gap material in the limit of the single monolayer. Unlike the bulk material, the MoS_2 monolayer emits light strongly. The freestanding monolayer exhibits an increase in luminescence quantum efficiency by more than a factor of 10^4 compared with the bulk material.

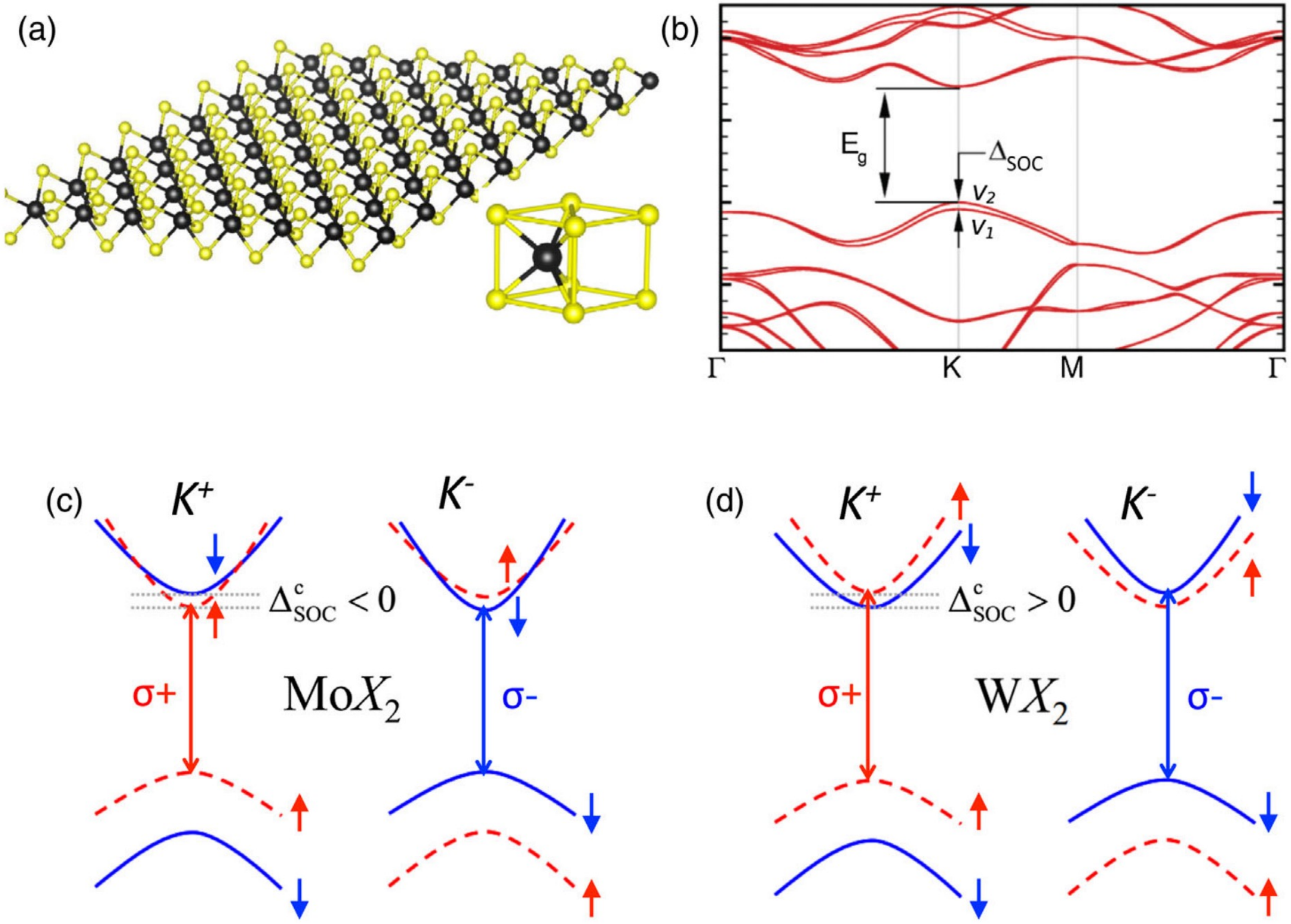


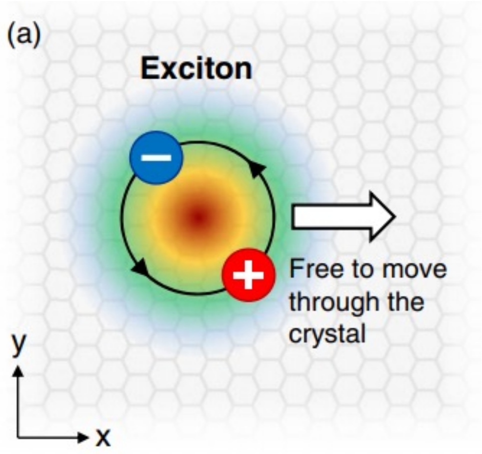
Spaldiani et al, Nano Lett. 10, 1271-1275(2010)



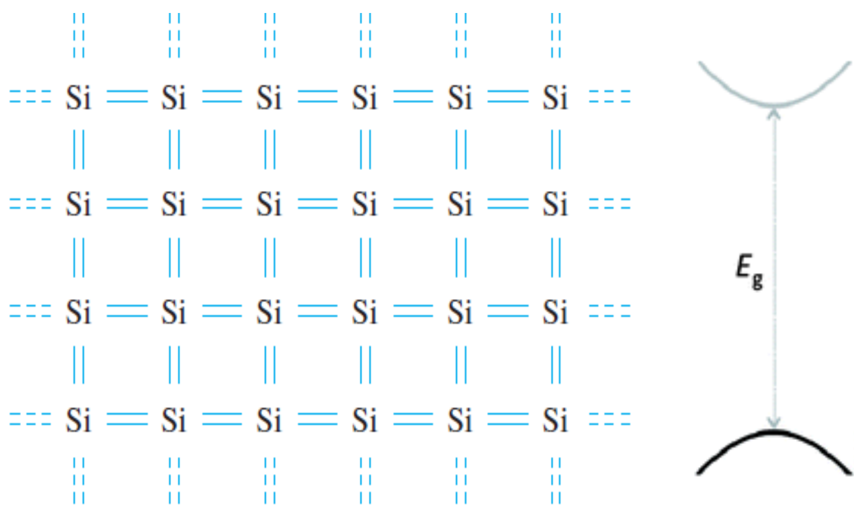
Mak et al, PRL 105, 136805 (2010)

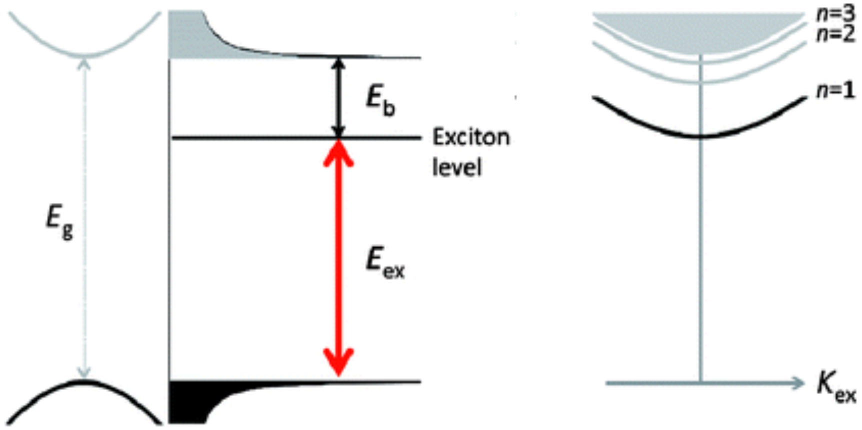
Transition-Metal-Dichalcogenides (TMDs)

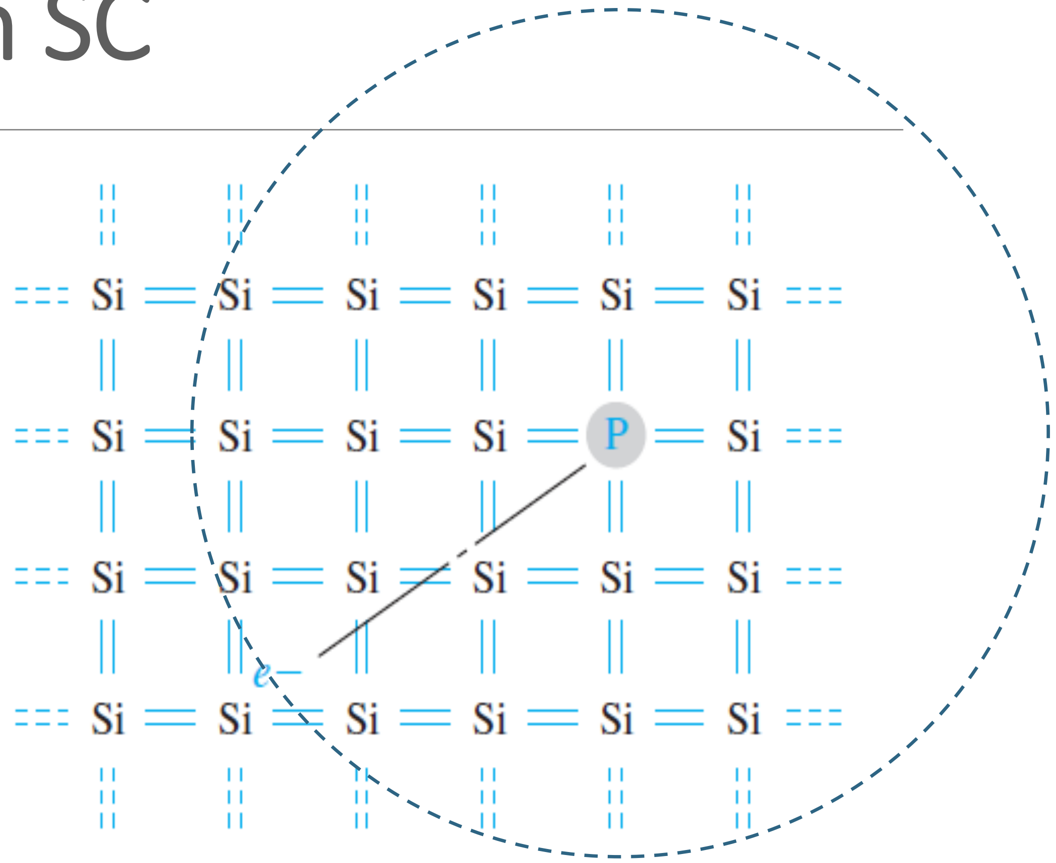




Excitons in SC

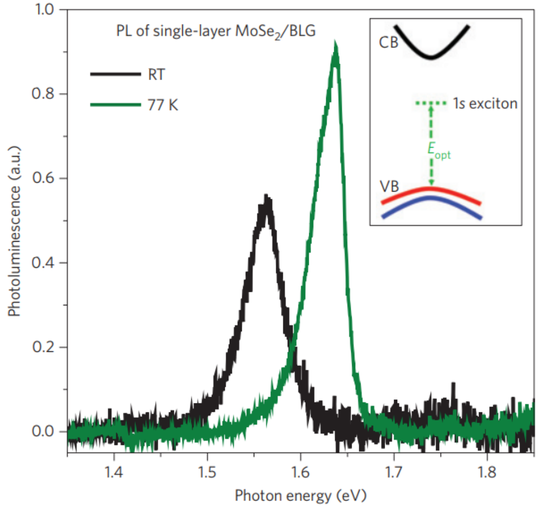




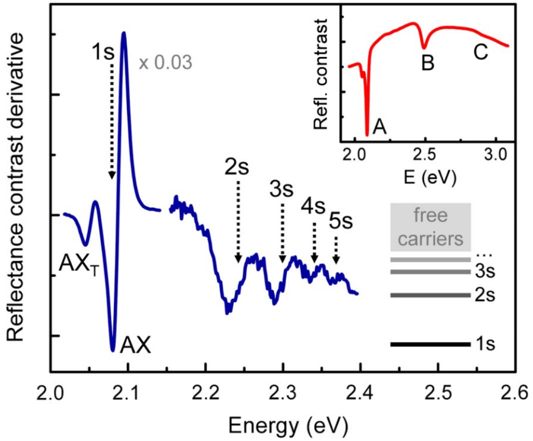


Excitons in monolayer TMDs

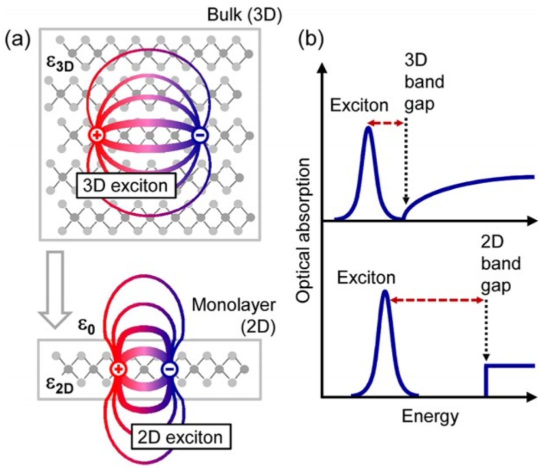
Ugeda et al, Nat. Mat. 13, 1091 (2014)



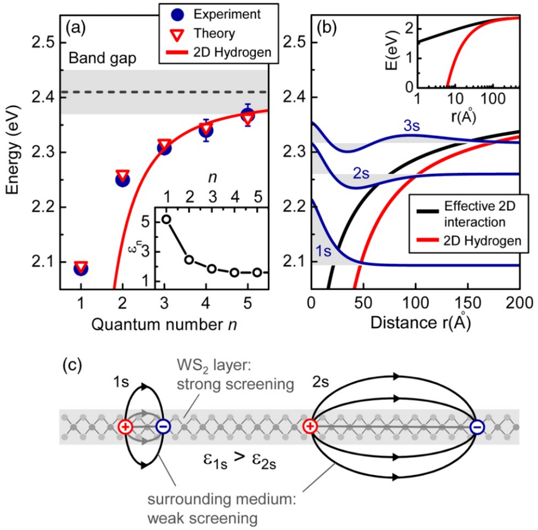
Material	Sample (temperature)	Experimental technique	Binding energy (eV)	Band gap (eV)	Reference
WSe_2	Exf. on SiO_2/Si (RT)	Refl., 2P-PLE	0.37	2.02	He *et al.* (2014)
	CVD on HOPG (79 K)	STS, PL	0.5	2.2 ± 0.1	C. Zhang *et al.* (2015a)
	Exf. on SiO_2/Si (4 K)	PLE, 2P-PLE, SHG	0.6 ± 0.2	2.35 ± 0.2	Wang, Marie, Gerber *et al.* (2015)
	Exf. on SiO_2/Si (4–300 K)	Refl.	0.887	2.63	Hanbicki *et al.* (2015)
	CVD on HOPG (77 K)	STS, PL	≈0.4[a]	2.08 ± 0.1	Chiu *et al.* (2015)
	Exf. on diamond (RT)	Mid-IR pump probe	0.245	1.9[b]	Poellmann *et al.* (2015)
WS_2	Exf. on SiO_2/Si (5 K)	Refl.	0.32 ± 0.04	2.41 ± 0.04	Chernikov *et al.* (2014)
	Exf. on fused silica (10 K)	2P-PLE	0.7	2.7	Ye *et al.* (2014)
	Exf. on SiO_2/Si (RT)	2P-PLE	0.71 ± 0.01	2.73	B. Zhu *et al.* (2014)
	Exf. on SiO_2/Si (4–300 K)	Refl.	0.929	3.01	Hanbicki *et al.* (2015)
	Exf. on fused silica (RT)	Refl., PLE	0.32 ± 0.05	2.33 ± 0.05	Hill *et al.* (2015)
	Exf. on fused silica (RT)	STS, Refl.	0.36 ± 0.06	2.38 ± 0.06	Rigosi *et al.* (2016)
	CVD on SiO_2 (4 K)	Magnetoreflection	0.26–0.48	2.31–2.53[b]	Stier, McCreary *et al.* (2016)
$MoSe_2$	MBE on 2*L* graphene/SiC (5 K)	STS, PL	0.55	2.18	Ugeda *et al.* (2014)
	CVD on HOPG (79 K)	STS, PL	0.5	2.15 ± 0.06	C. Zhang *et al.* (2015a)
MoS_2	CVD on HOPG (77 K)	STS, PL	0.2 (or 0.42)	2.15 ± 0.06	C. Zhang *et al.* (2014)
	Exf., suspended (77 K)	PC	≥ 0.57	2.5	Klots *et al.* (2014)
	Exf. on hBN/fused silica (RT)	PLE	0.44 ± 0.08[c]	2.47 ± 0.08[c]	Hill *et al.* (2015)
	CVD on HOPG (77 K)	STS, PL	≈0.3[a]	2.15 ± 0.1	Chiu *et al.* (2015)
	Exf. on fused silica (RT)	STS, Refl.	0.31 ± 0.04	2.17 ± 0.1	Rigosi *et al.* (2016)



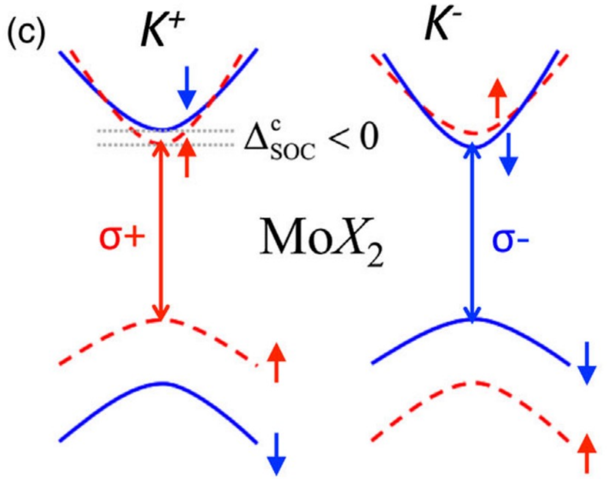
Chernikov et al, PRL 113, 076802 (2014)



Direct bandgap + large binding energy = Excitons dominate the optical response of TMDS!!!



Valley polarization



nature nanotechnology

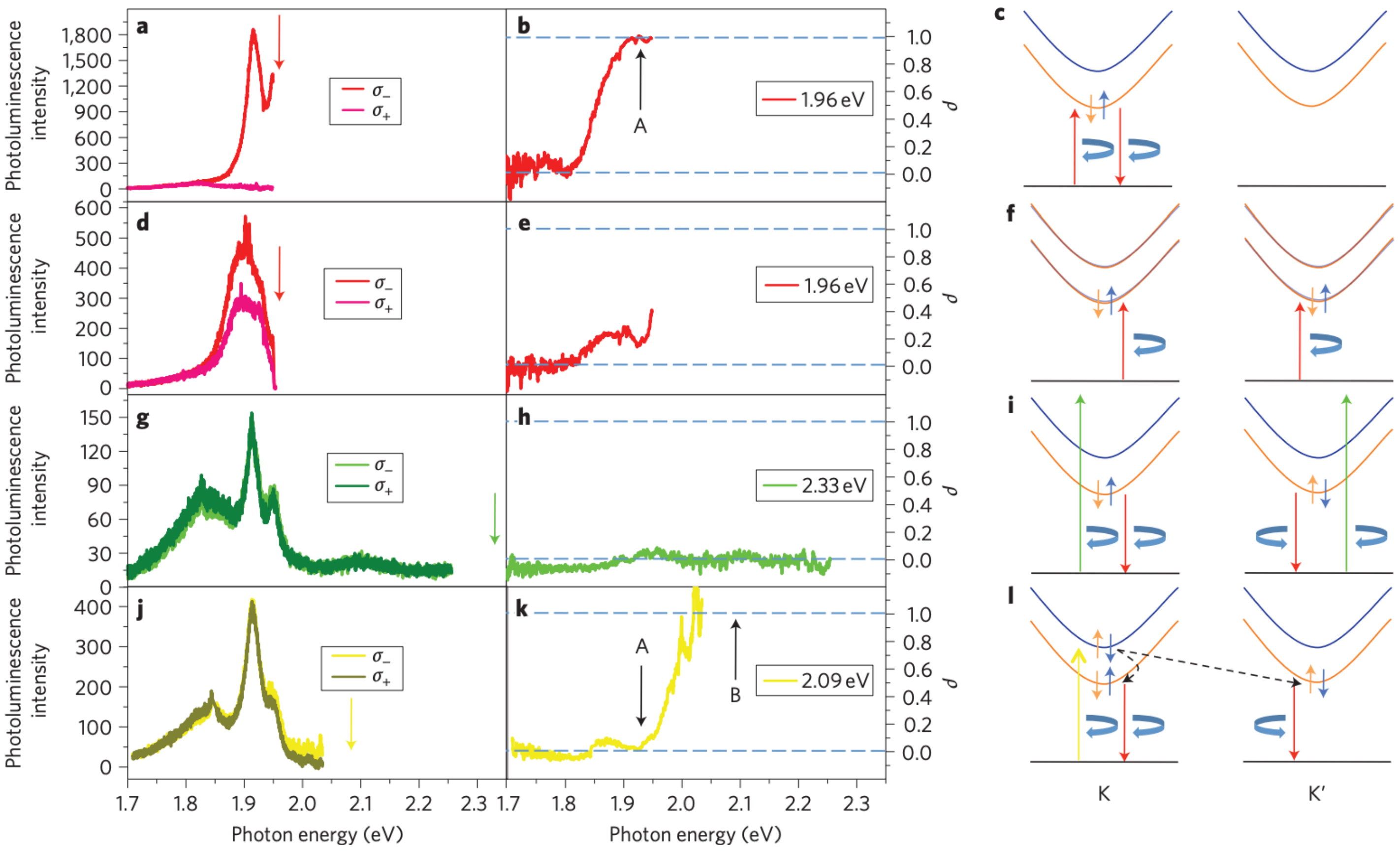
Published: 17 June 2012

Control of valley polarization in monolayer MoS_2 by optical helicity

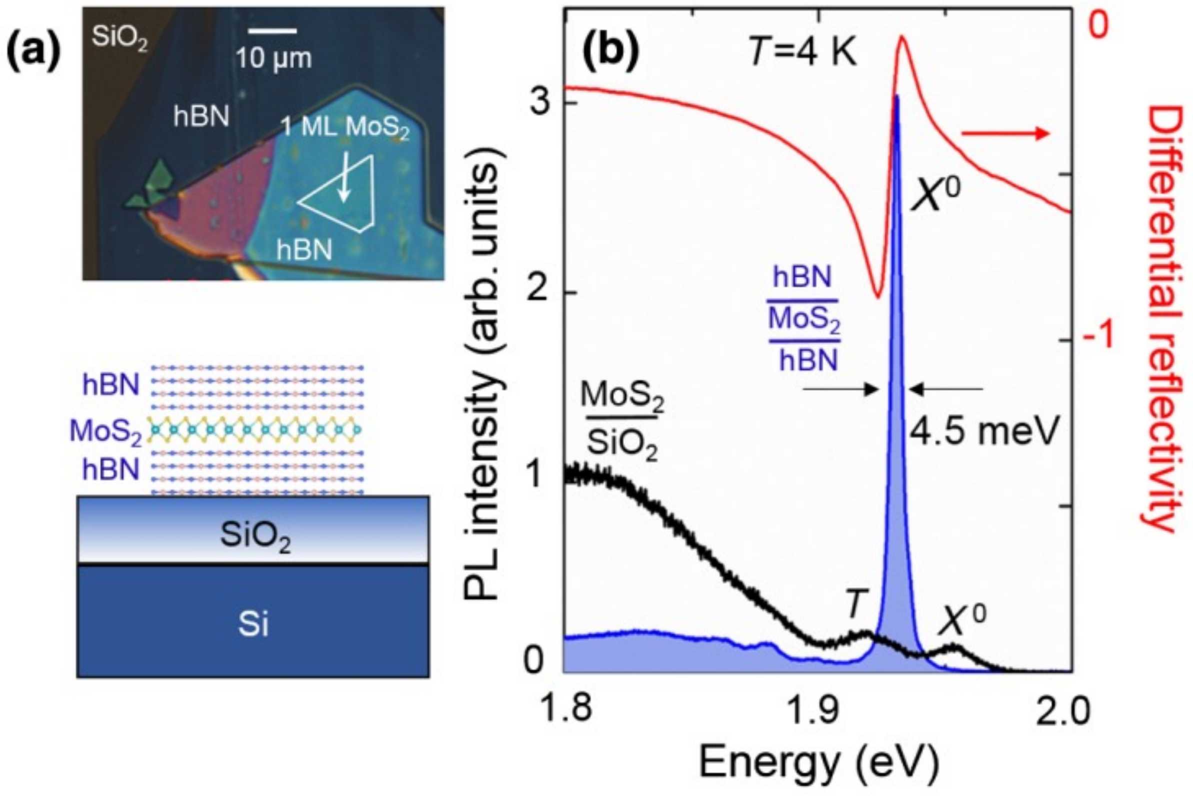
Kin Fai Mak, Keliang He, Jie Shan & Tony F. Heinz

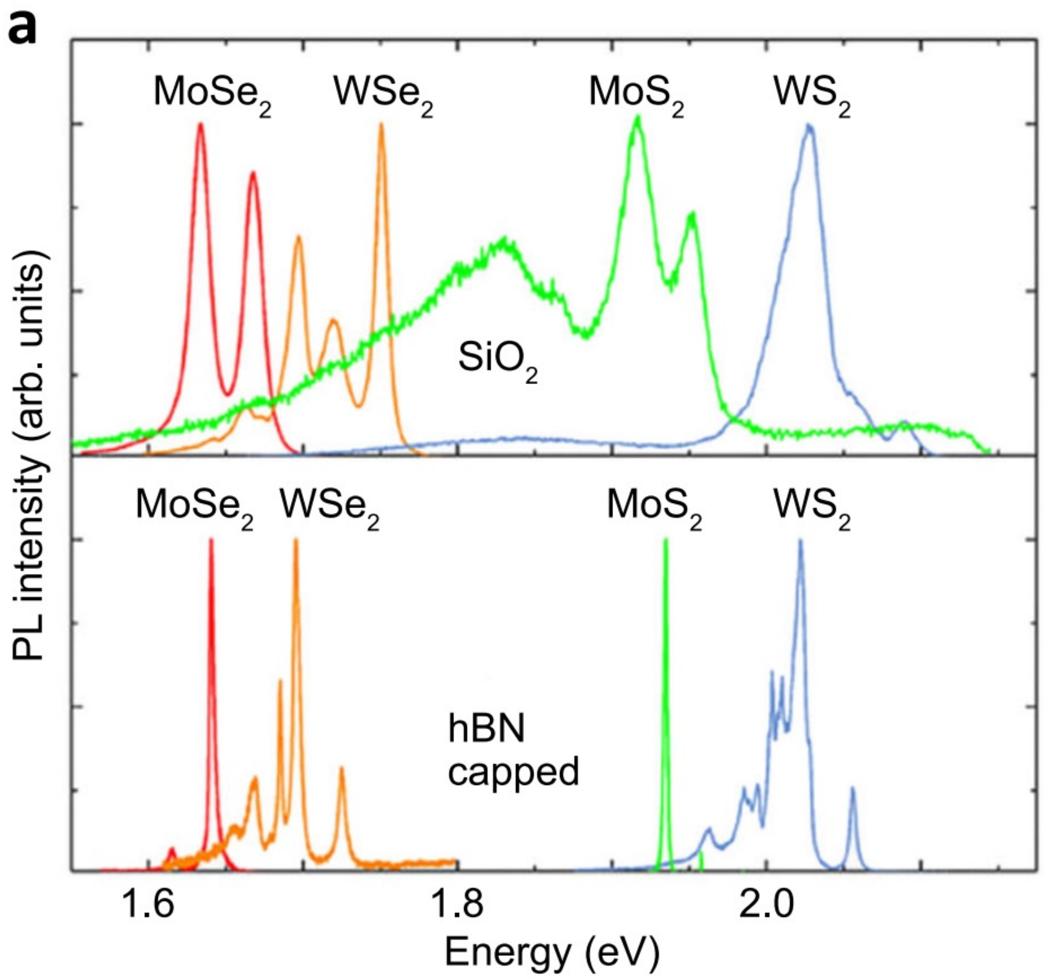
Nature Nanotechnology 7, 494–498 (2012) | Cite this article

$$\rho = \frac{I(\sigma_-) - I(\sigma_+)}{I(\sigma_-) + I(\sigma_+)}$$



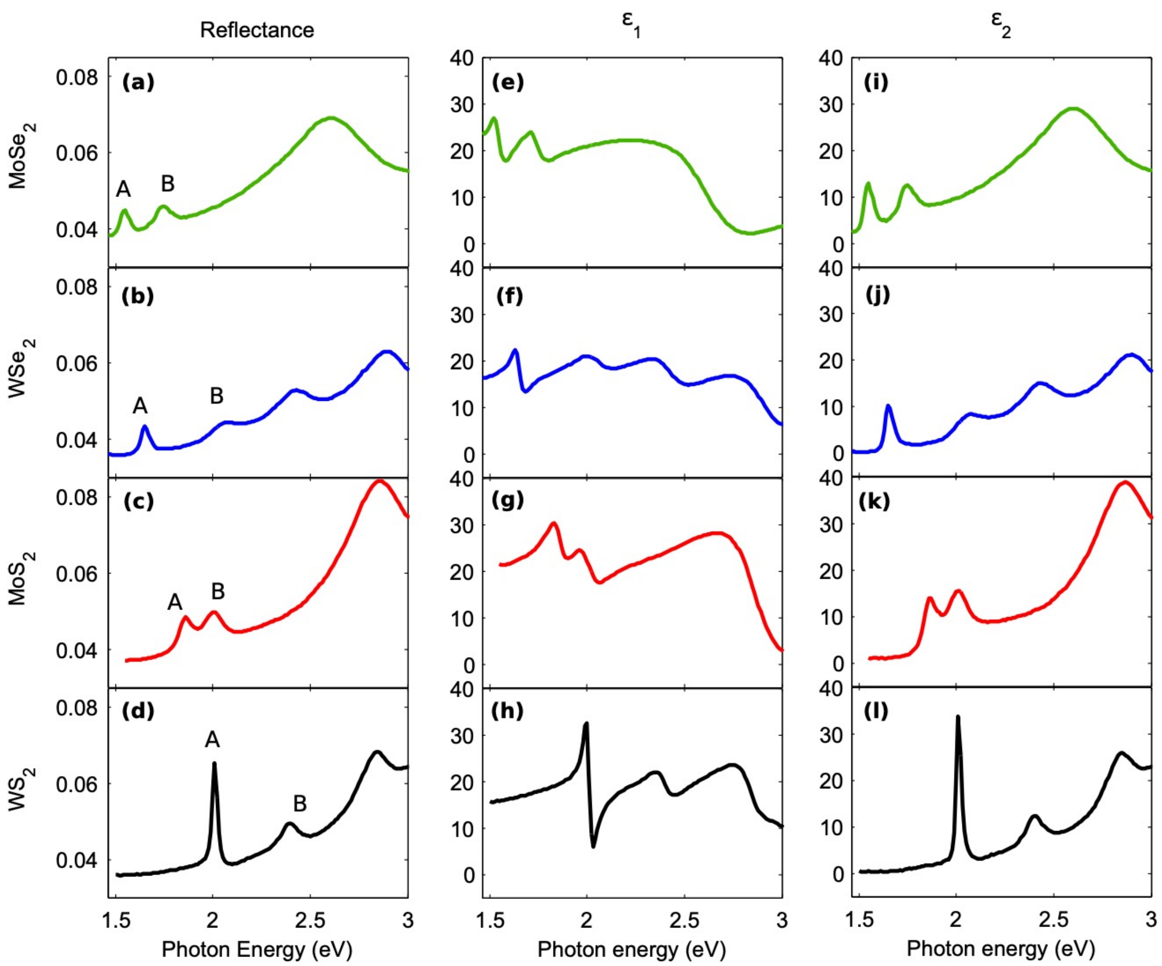
Excitons linewidth

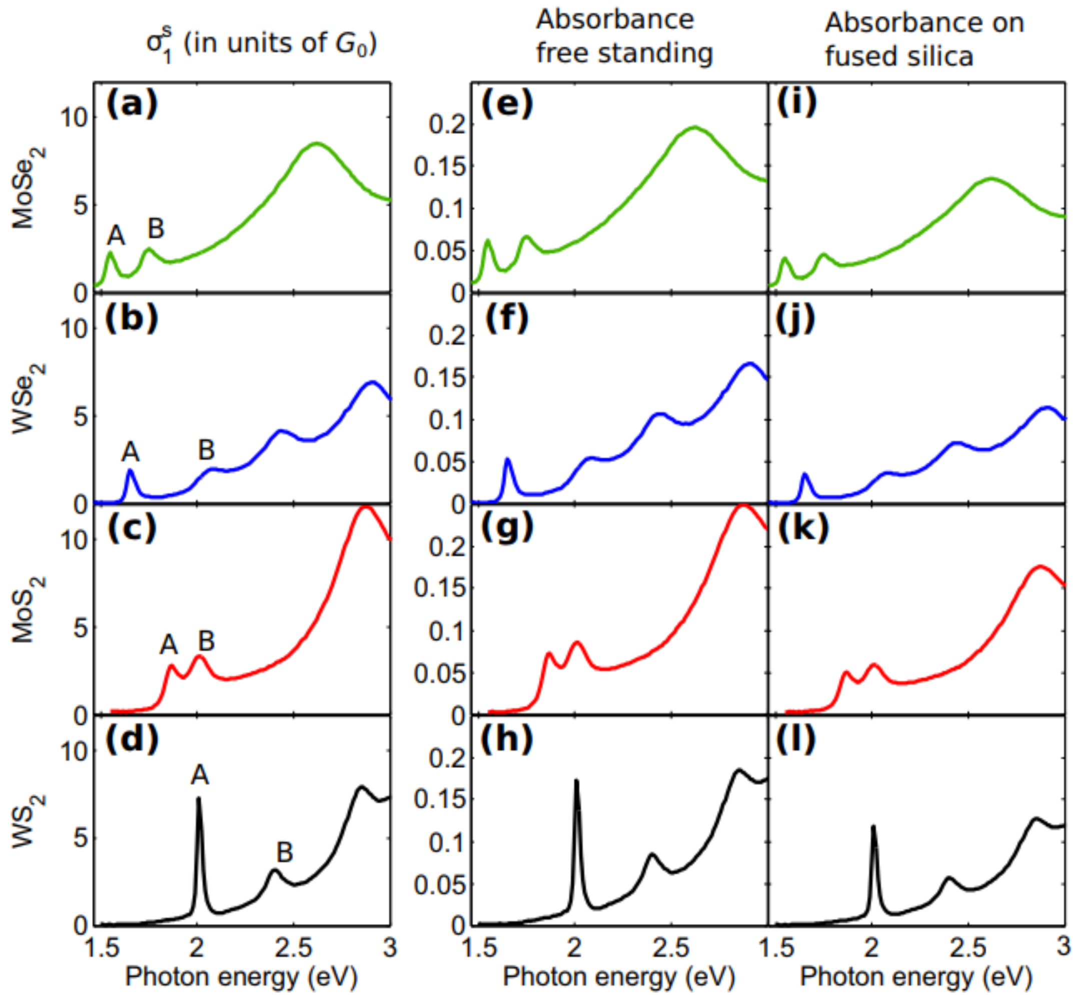




Cadiz et al, PRX 7, 021026 (2017)
Ajayi et al, 2D Mater. 4, 031011 (2017)

Optical properties



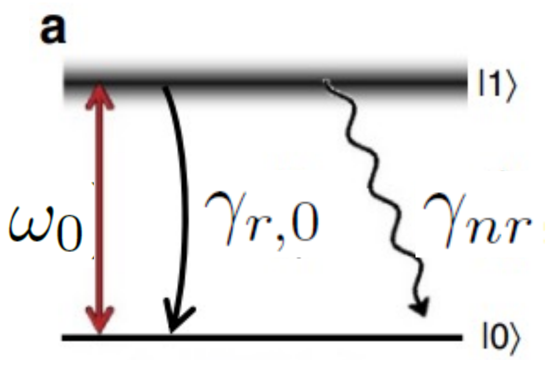


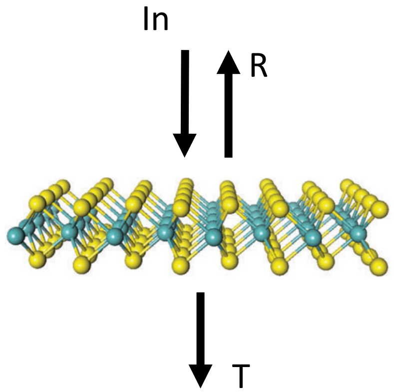
Li et al, PRB 90, 205422 (2014)

Monolayer TMD - Optical modeling

$$\tilde{\varepsilon}_r(\omega) = \tilde{\varepsilon}_r(\infty) + \omega_p^2 \sum_{m=1}^{M} \frac{f_m}{\omega_{0,m}^2 - \omega^2 - j\omega\Gamma_m}$$

$$\chi_{\text{in-plane}} = \chi_{bg} - \frac{c}{\omega_0 d_0} \frac{\gamma_{r,0}}{\omega - \omega_0 + i\frac{\gamma_{nr}}{2}} \qquad \varepsilon = 1 + \chi$$





$$A(\omega) = \frac{2\gamma_{nr}\gamma_{r,0}}{4(\omega-\omega_0)^2 + (\gamma_{nr}+\gamma_{r,0})^2}$$

$\gamma_{r,0} \gg \gamma_{nr}$ → $A(\omega) = 0$

$\gamma_{r,0} = \gamma_{nr}$ → $\boxed{A(\omega) = 50\%}$

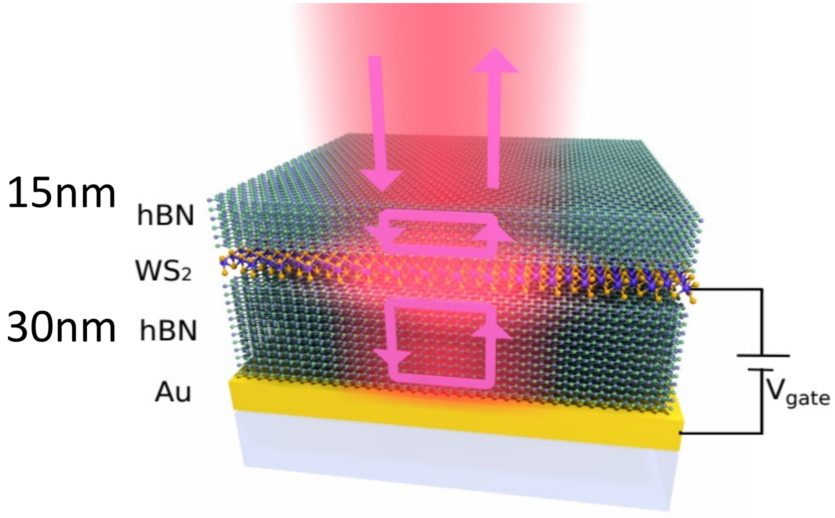
$\gamma_{r,0} \ll \gamma_{nr}$ → $A(\omega) = 0$

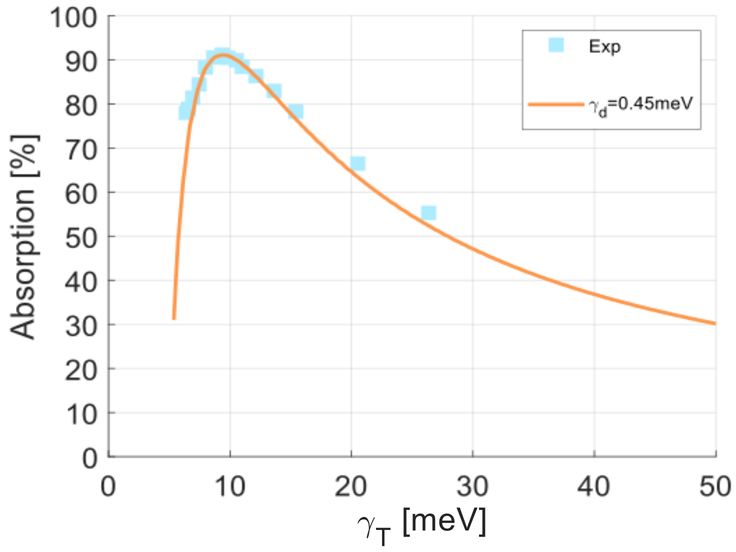
$$R(\omega) = \frac{\gamma_{r,0}^2/4}{(\omega-\omega_0)^2 + (\gamma_{nr}+\gamma_{r,0})^2/4}$$

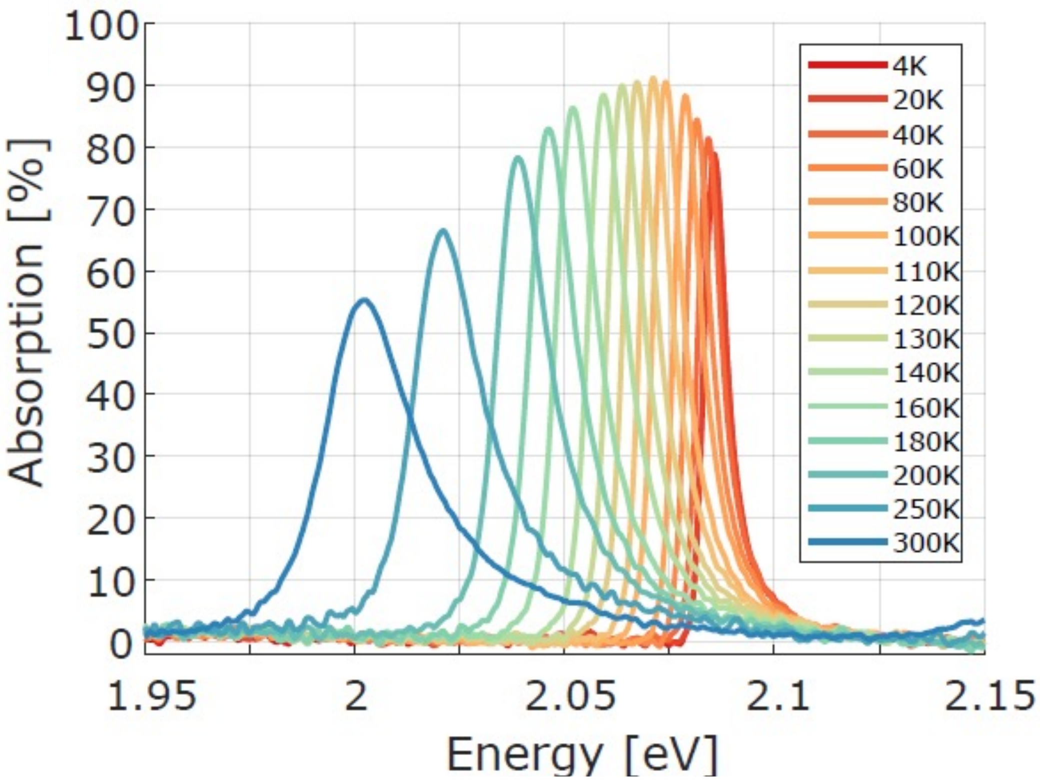
$\gamma_{r,0} \gg \gamma_{nr}$ → $R(\omega) = 1$

$\gamma_{r,0} \ll \gamma_{nr}$ → $R(\omega) = 0$

Controlling Optical properties of monolayer TMD



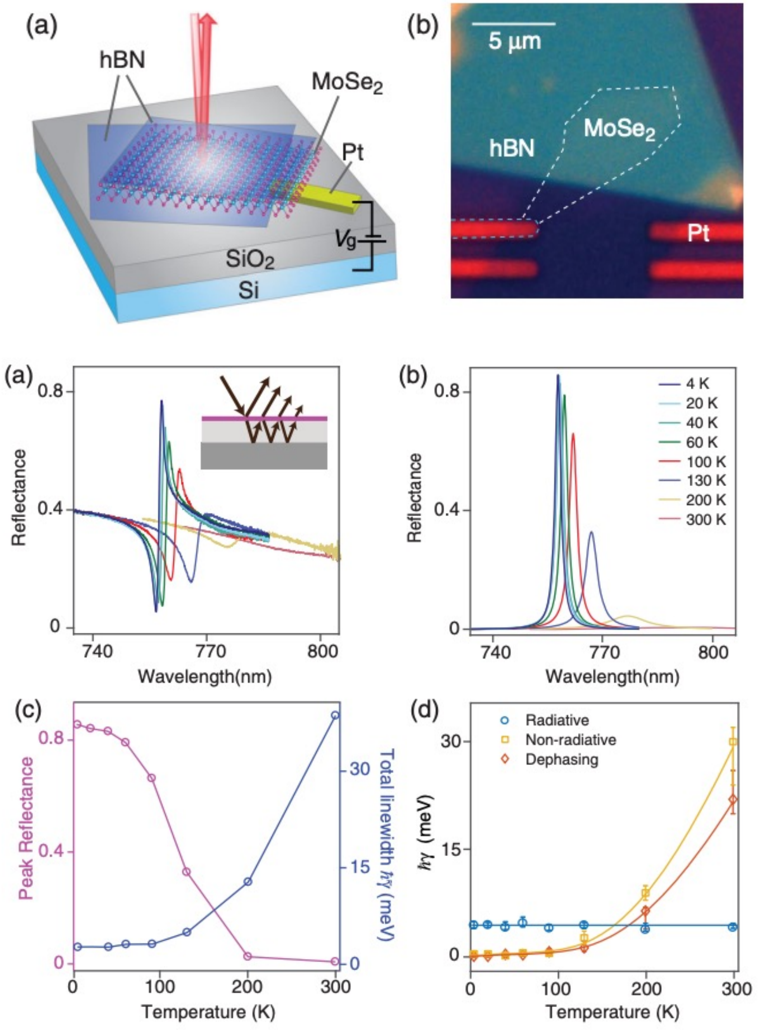




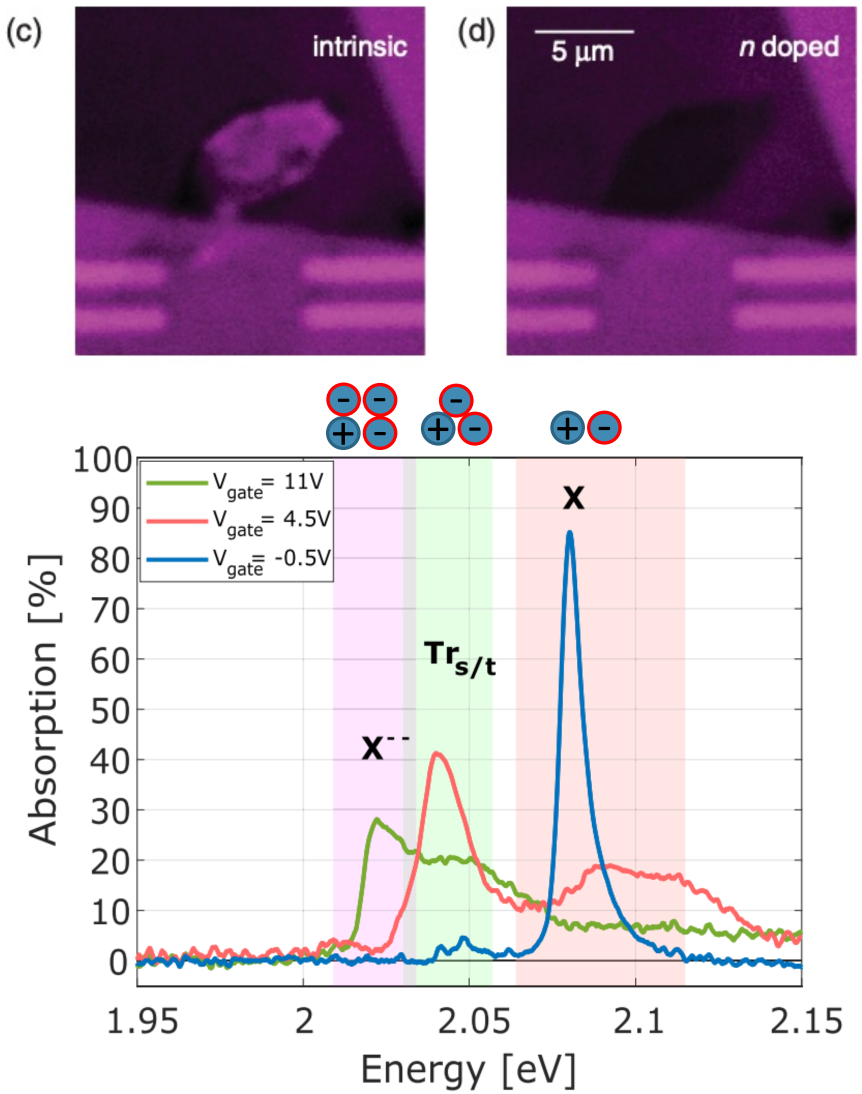
For TMM:

$$\chi_{\text{in-plane}} = \chi_{bg} - \frac{c}{\omega_0 d_0} \frac{\gamma_{r,0}}{\omega - \omega_0 + i(\frac{\gamma_{nr}}{2} + \gamma_d)}$$

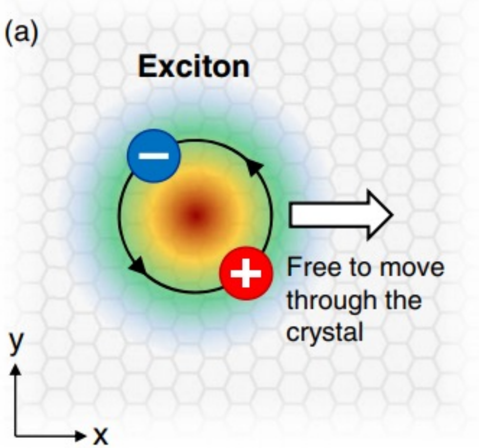
Controlling Optical properties of monolayer TMD

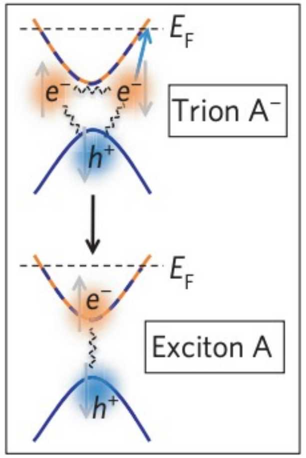


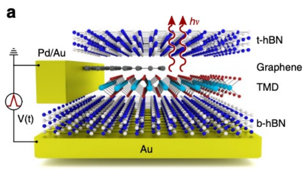
PHYSICAL REVIEW LETTERS 120, 037402 (2018)

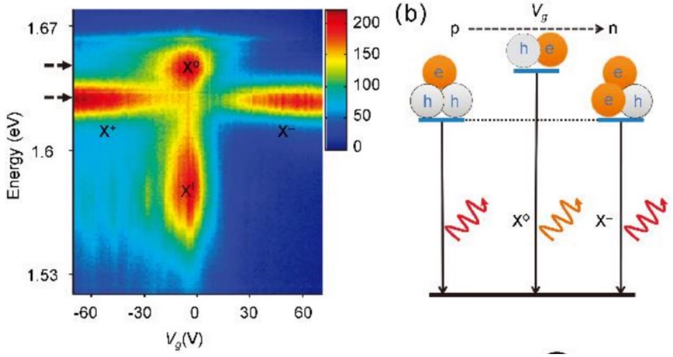


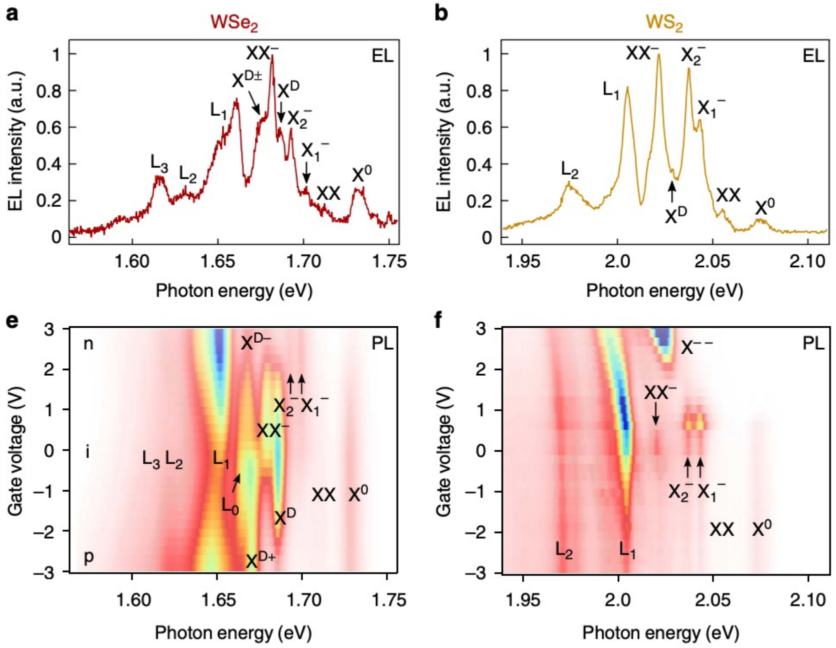
Exciton complexes





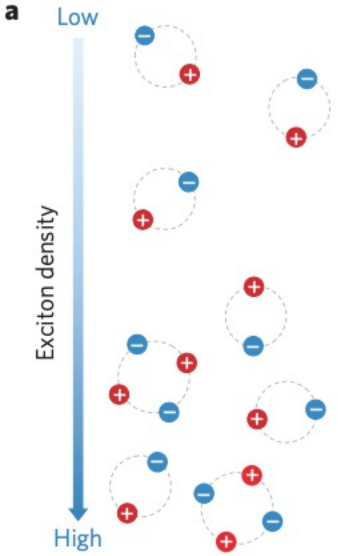


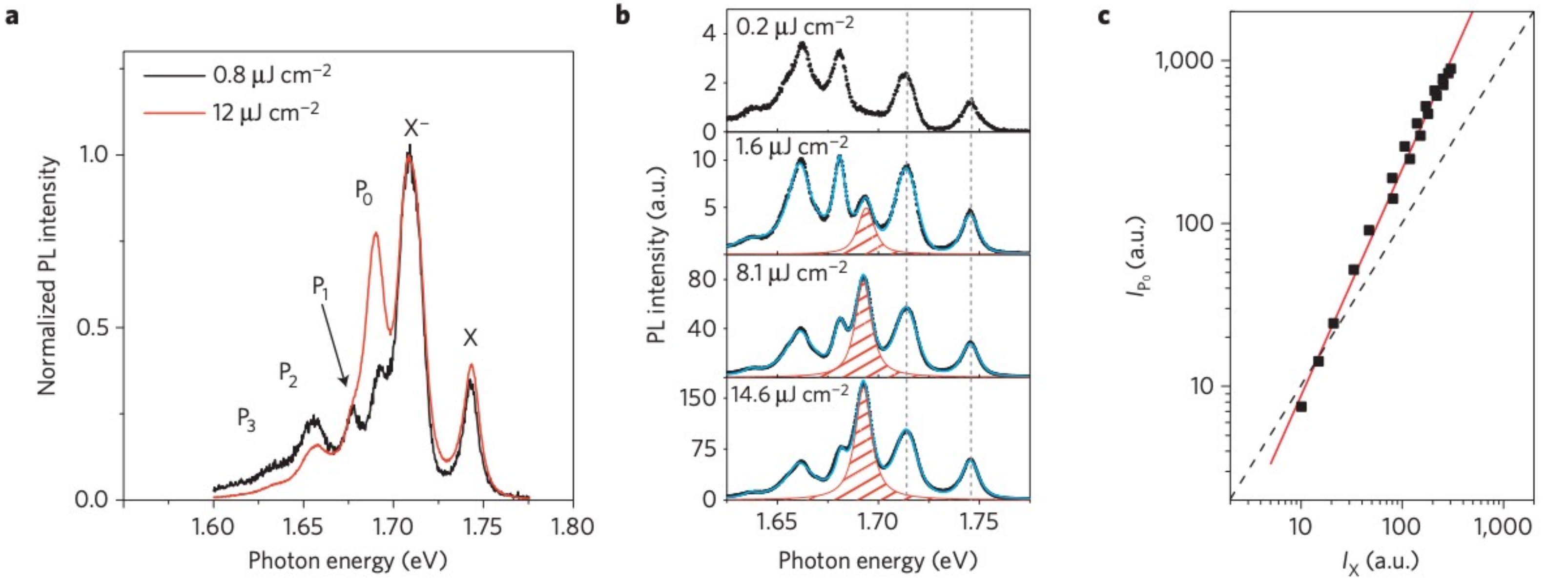




Exciton complexes

Biexcitons





$$I_{XX} \propto I_X{}^{\alpha} \text{ with } \alpha = 2$$