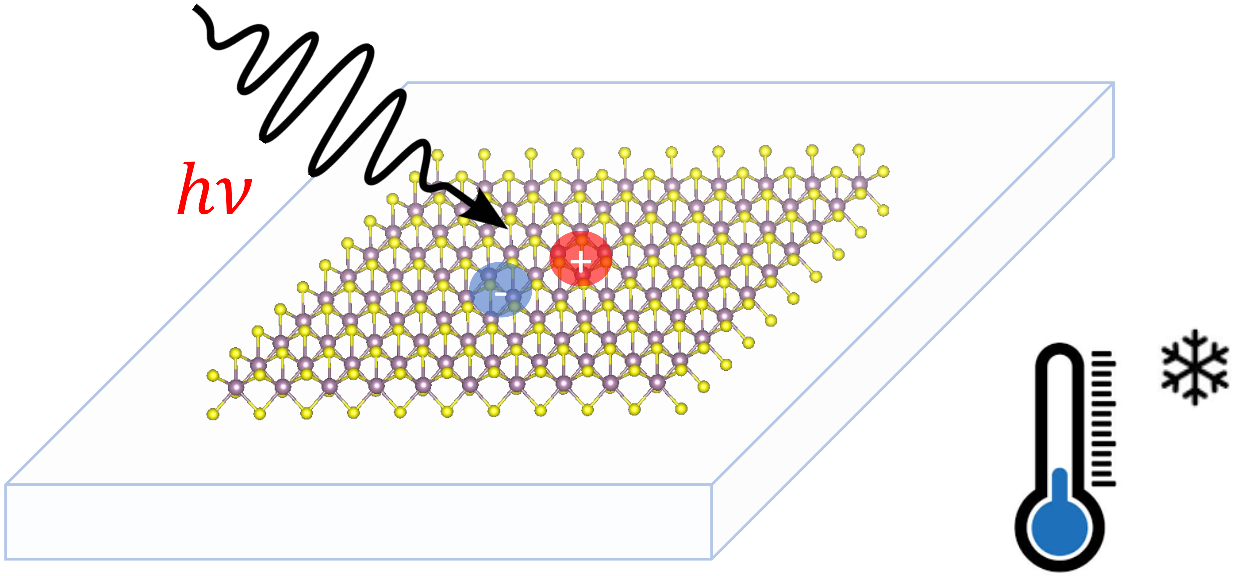
Universitat d'Alacant
Universidad de Alicante

Biaxial compressive strain tuning of neutral and charged excitons in single-layer transition metal dichalcogenides

Reyes Calvo

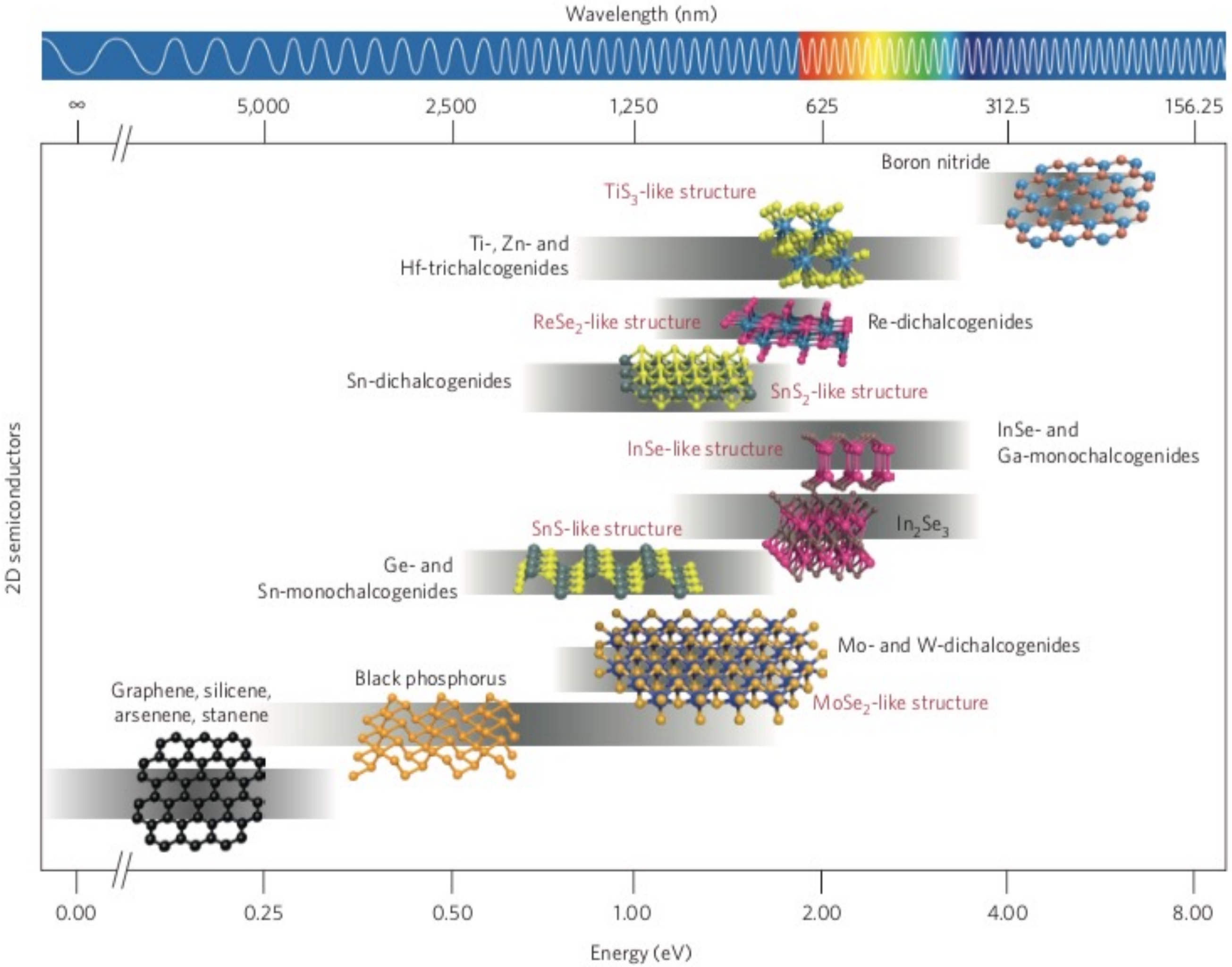
Departamento de Física Aplicada (DFA)
Instituto Universitario de Materiales (IUMA)
Universidad de Alicante



GENERALITAT VALENCIANA

Gen—T

2D semiconductors



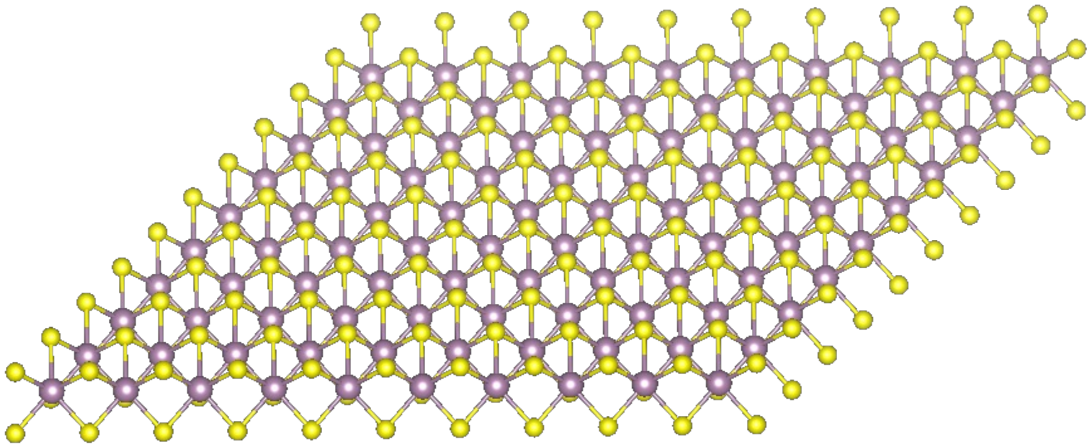
A. Castellanos-Gomez, Nature Photonics, 10, **2016**

- Emergent properties at the 2D limit
  - Excitonic states
- Tunability
  - Strain engineering

2D semiconductors

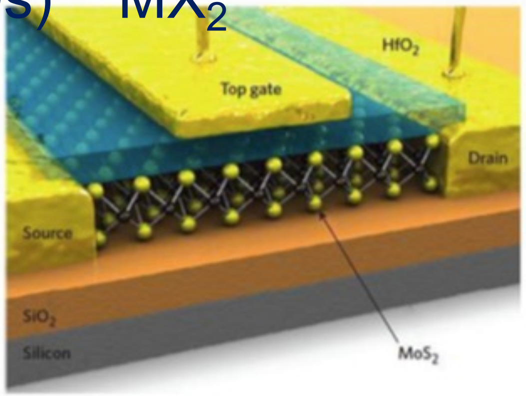
MoS_2

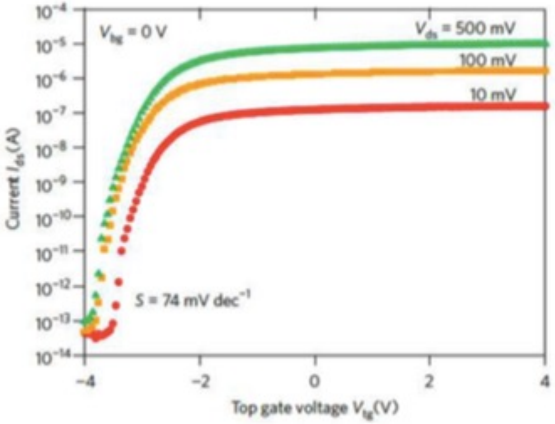
Transition Metal Dichalcogenides (TMDs) MX_2



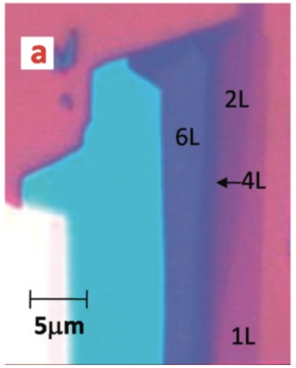
 M: Mo, W

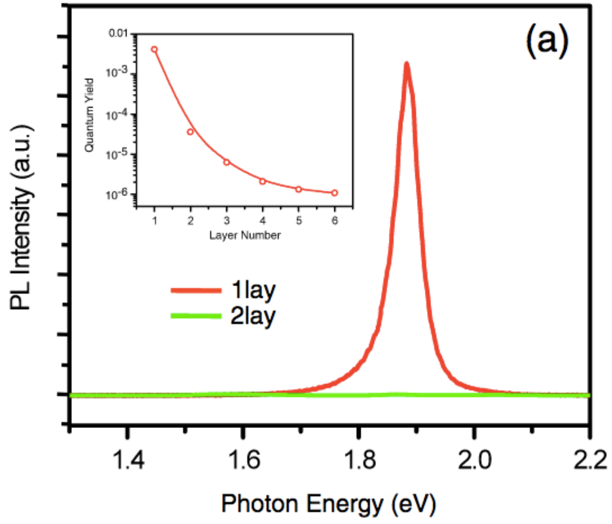
 X: S, Se, Te





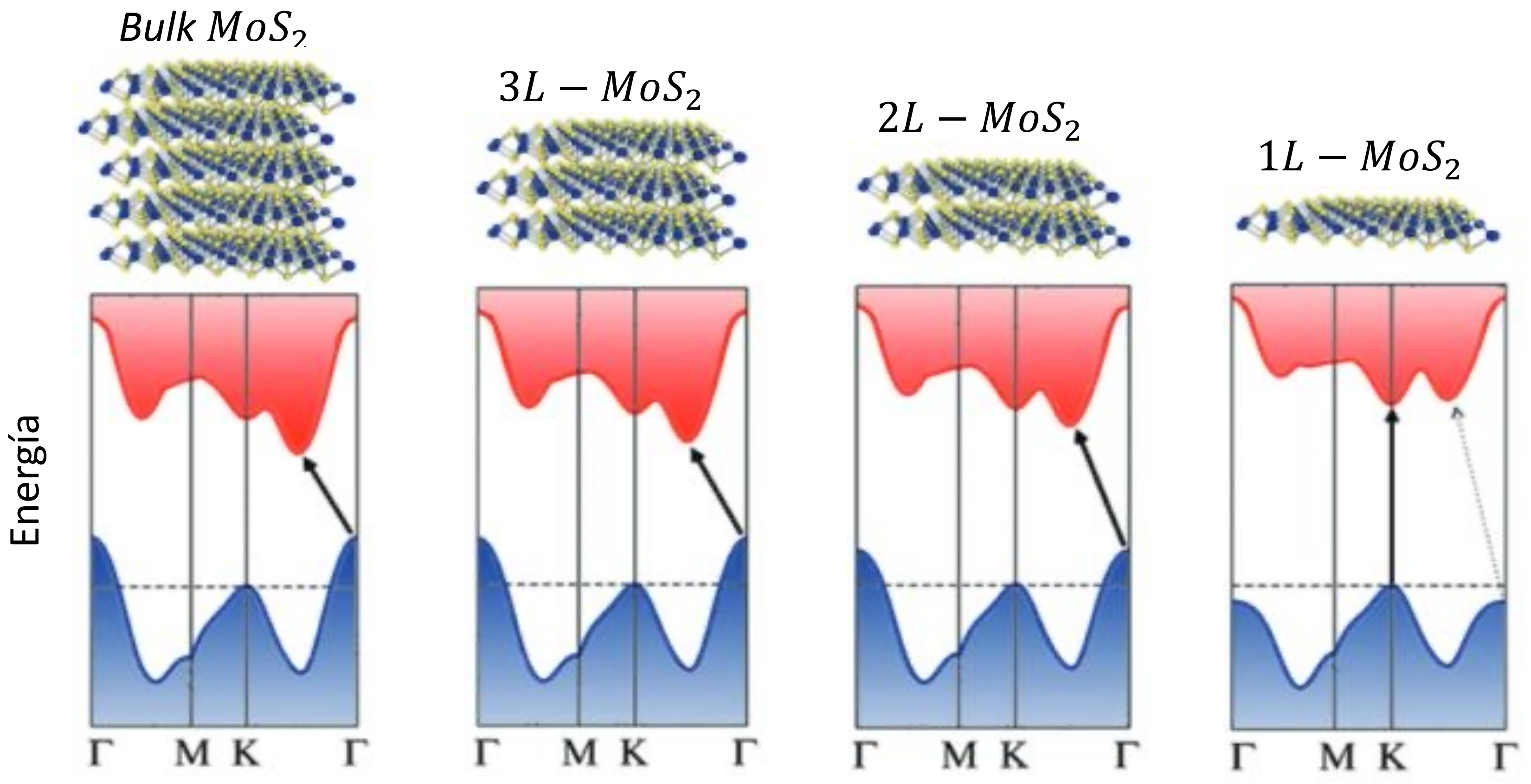
B. Radisavljevic et al., Nature Nano. 6, 147 (2011)





Mak et al. Phys. Rev. Lett. 105, 136805 (2010)

Single-layer TMDs: excitonic properties

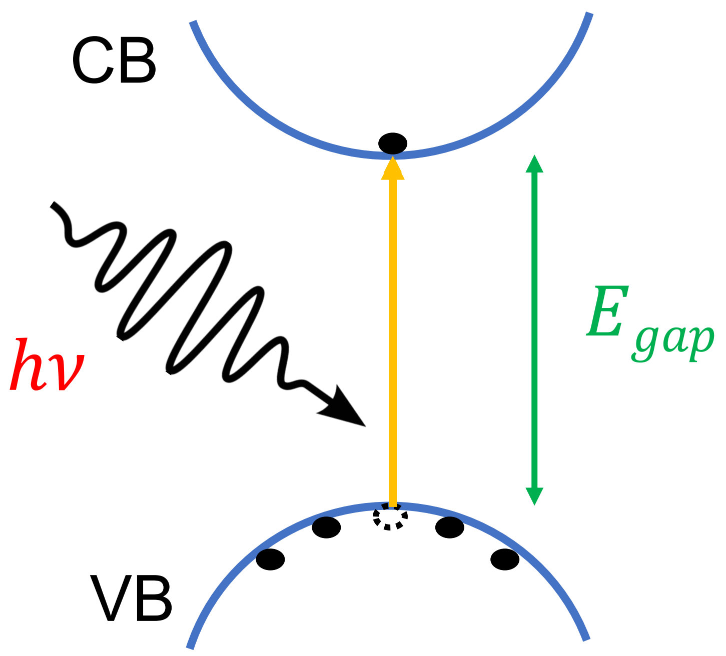


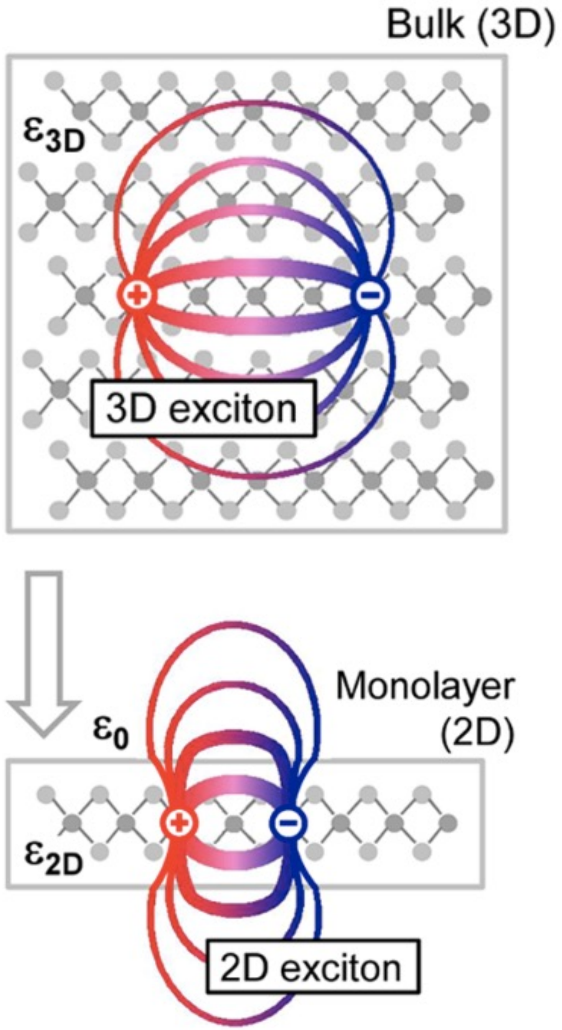
At the single layer limit:

- ➢ Direct Bandgap

F. Bonaccorso et al. (2016). *Advanced Materials,* 28(29)

Single-layer TMDs: excitonic properties





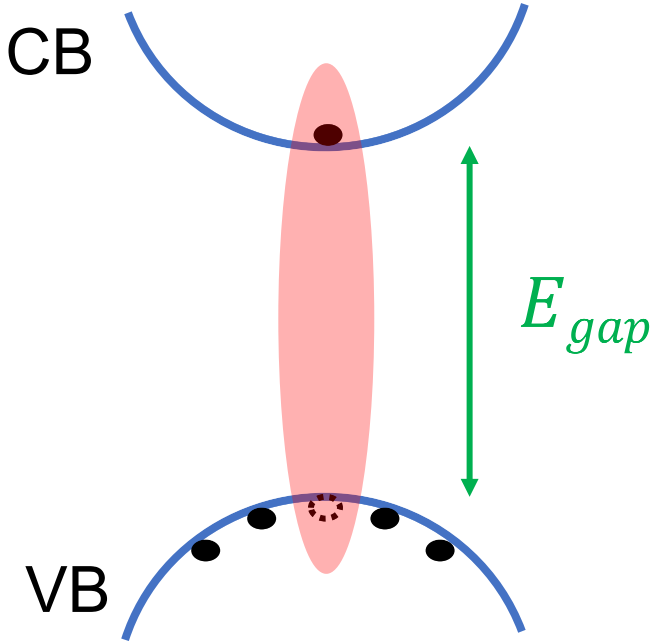
At the single layer limit:

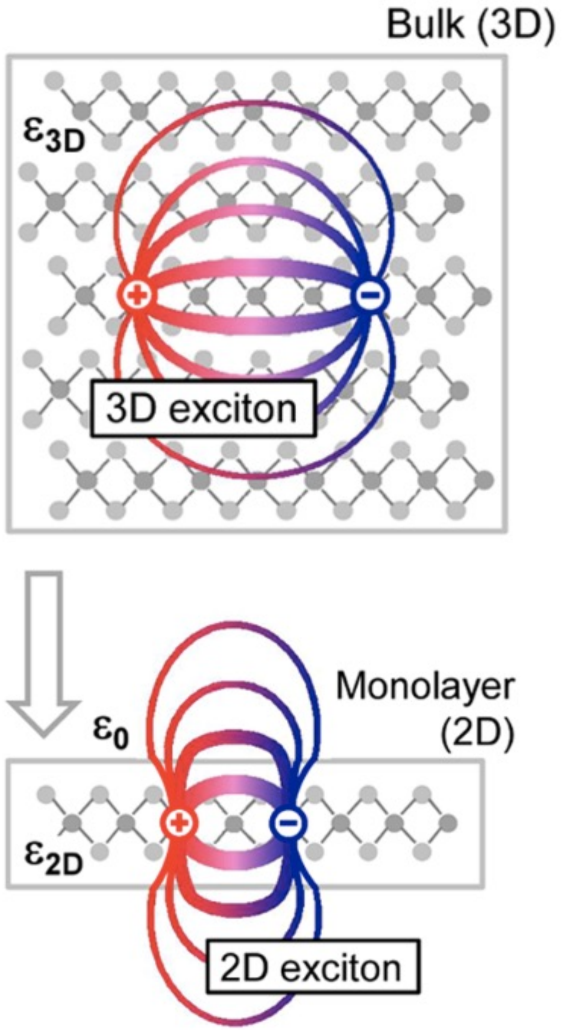
- Direct Bandgap
- Reduced dielectric screening

Splendiani et al. *Nano Lett*. 2010, 10, 1271–

Chernikov et al. *PRL* 113, 076802 (2014)

Single-layer TMDs: excitonic properties





At the single layer limit:

- Direct Bandgap
- Reduced dielectric screening
- Bound states: **excitons**

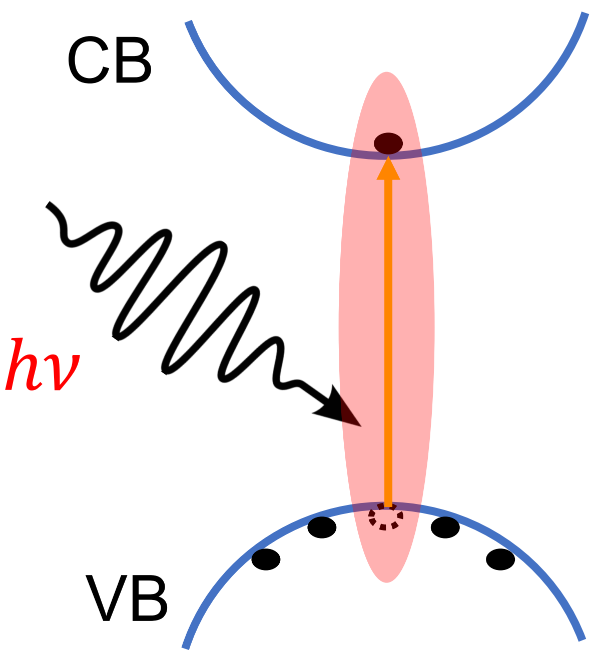
$$E_{exciton} = E_{gap} - E_{binding}$$

$E_{binding}$ (MoS_2) ~ 500 meV >> $k_B T$

Splendiani et al. *Nano Lett*. 2010, 10, 1271–

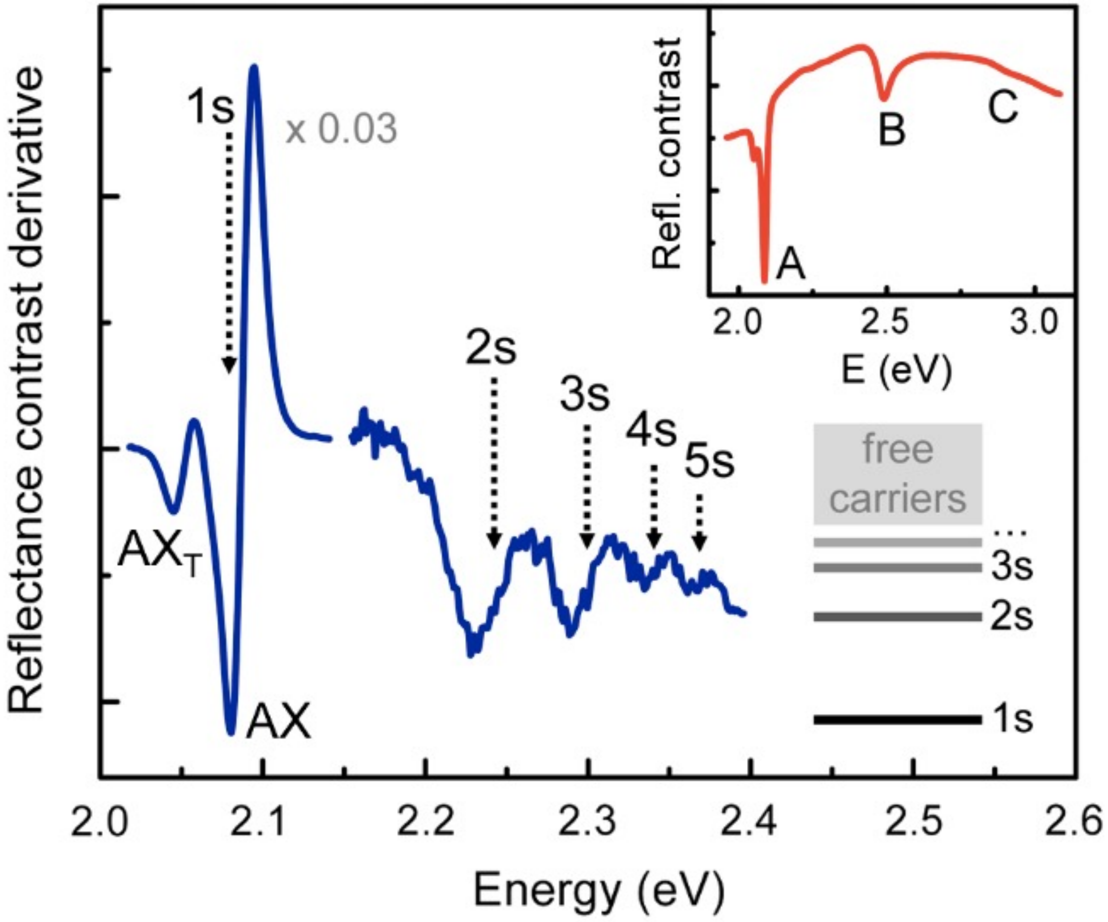
Chernikov et al. *PRL* 113, 076802 (2014)

Single-layer TMDs: excitonic properties



Absorption

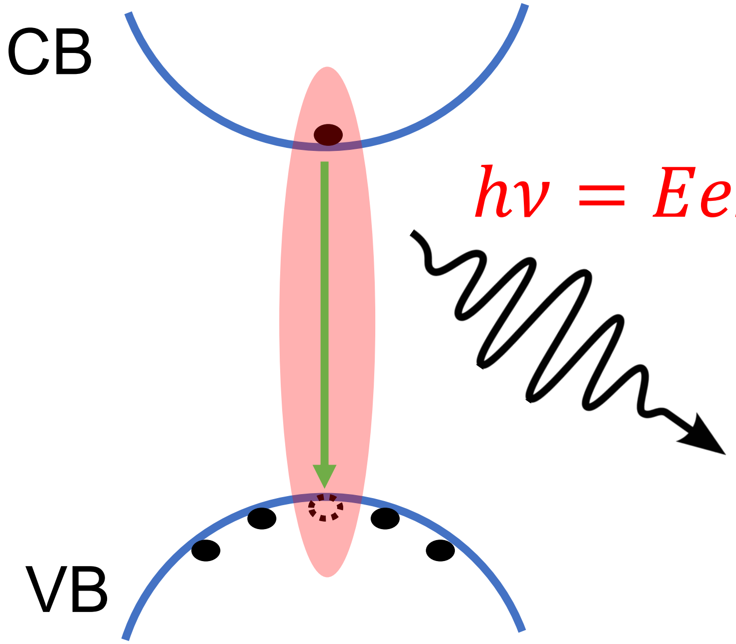
WS_2



Chernikov et al. *PRL* 113, 076802 (2014)

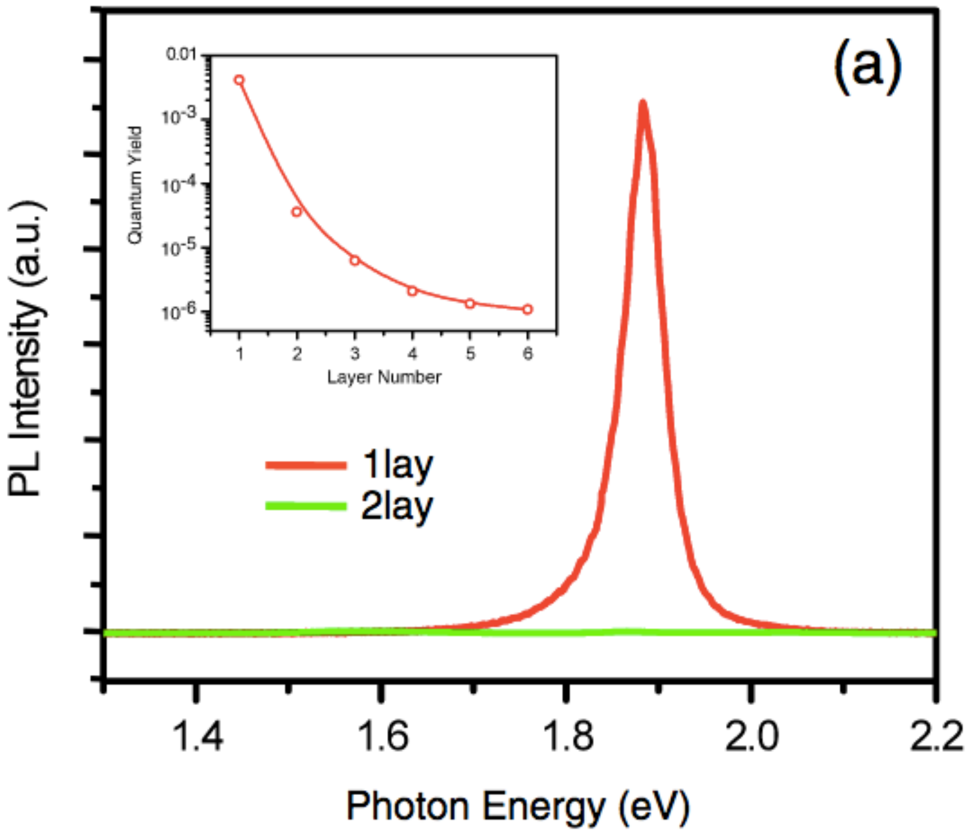
Single-layer TMDs: excitonic properties

MoS_2



$$h\nu = Eexc_{iton}$$

Photoluminescence



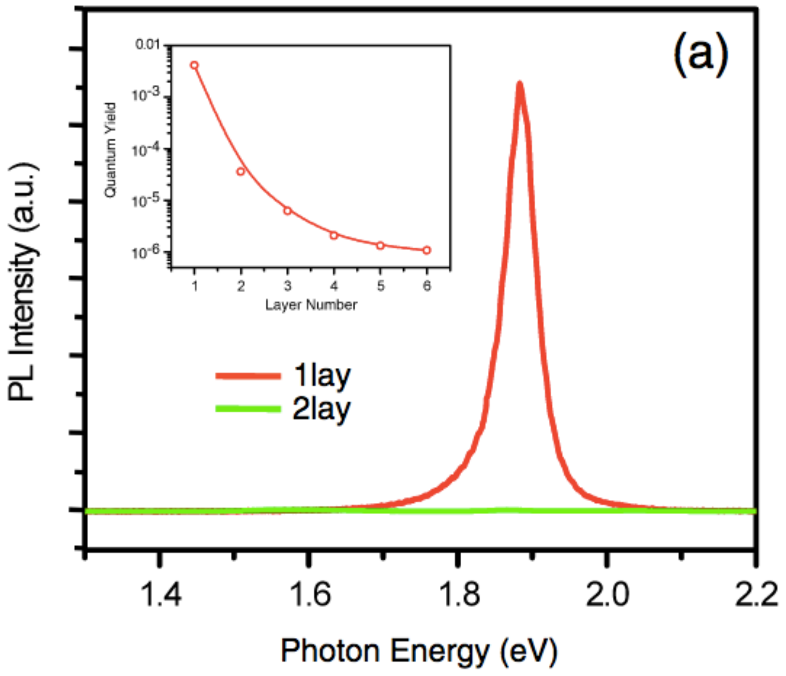
Mak et al. Phys. Rev. Lett. 105, 136805 (2010)

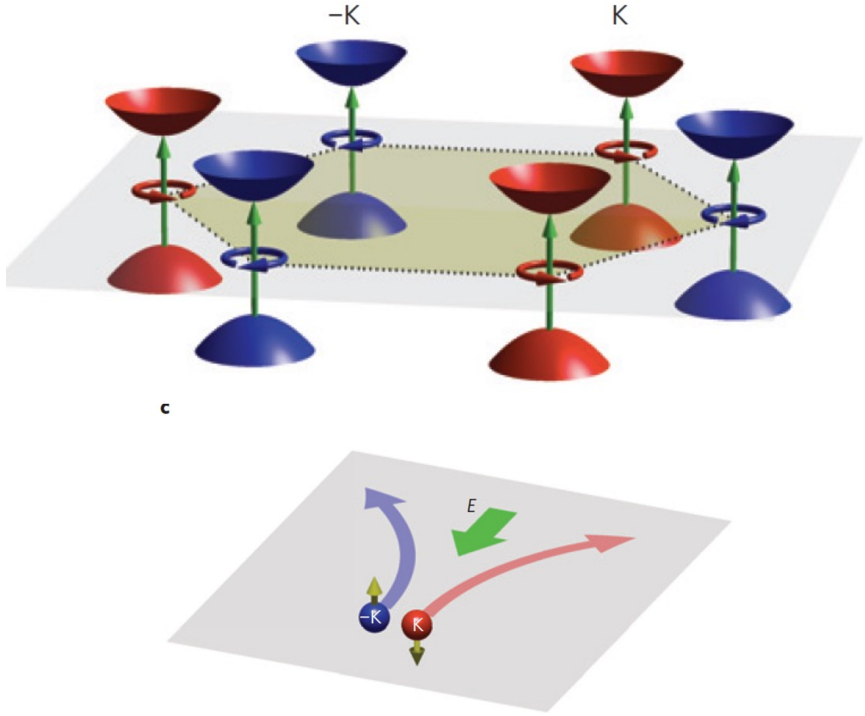
Single-layer TMDs: excitonic properties

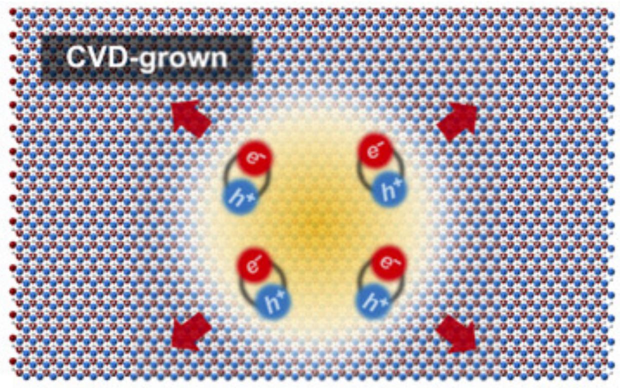
Light emission devices

Valleytronics/ Spintronics

Exciton Transport devices





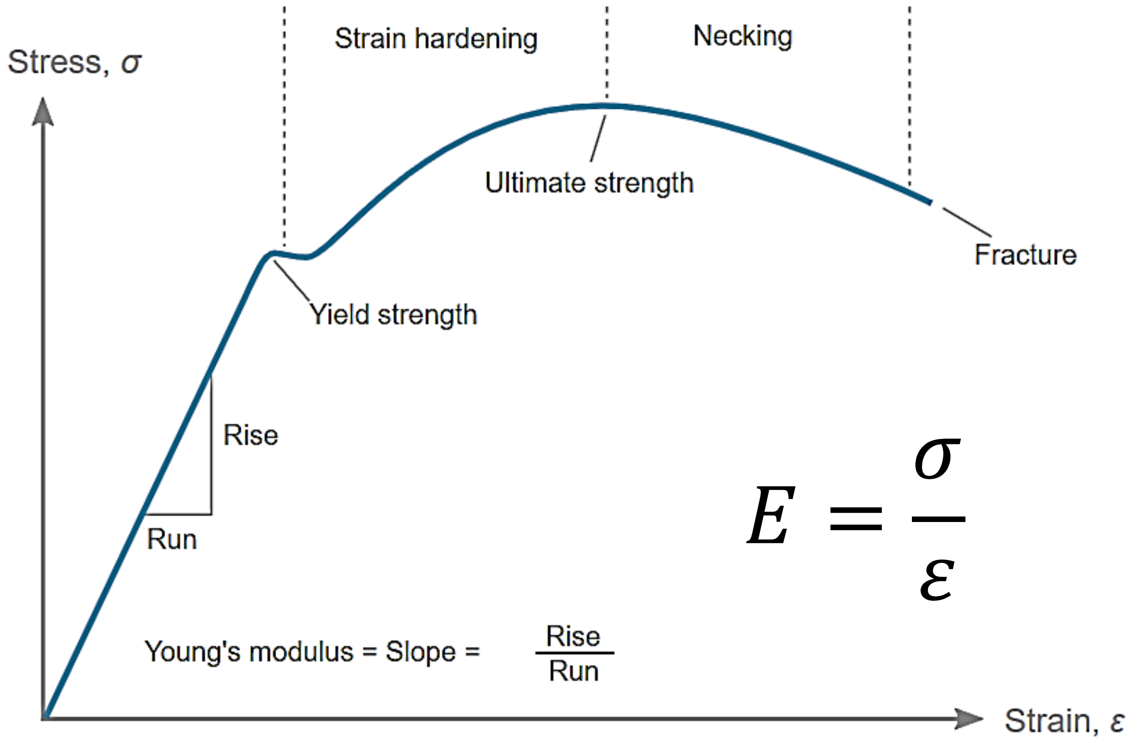


Liue et al. Adv.Mater.2020, 32, 1906540

Mak et al. Phys. Rev. Lett. 105, 136805 (2010)

Xu et al. Nature Physics **10**, 343–350 (2014)

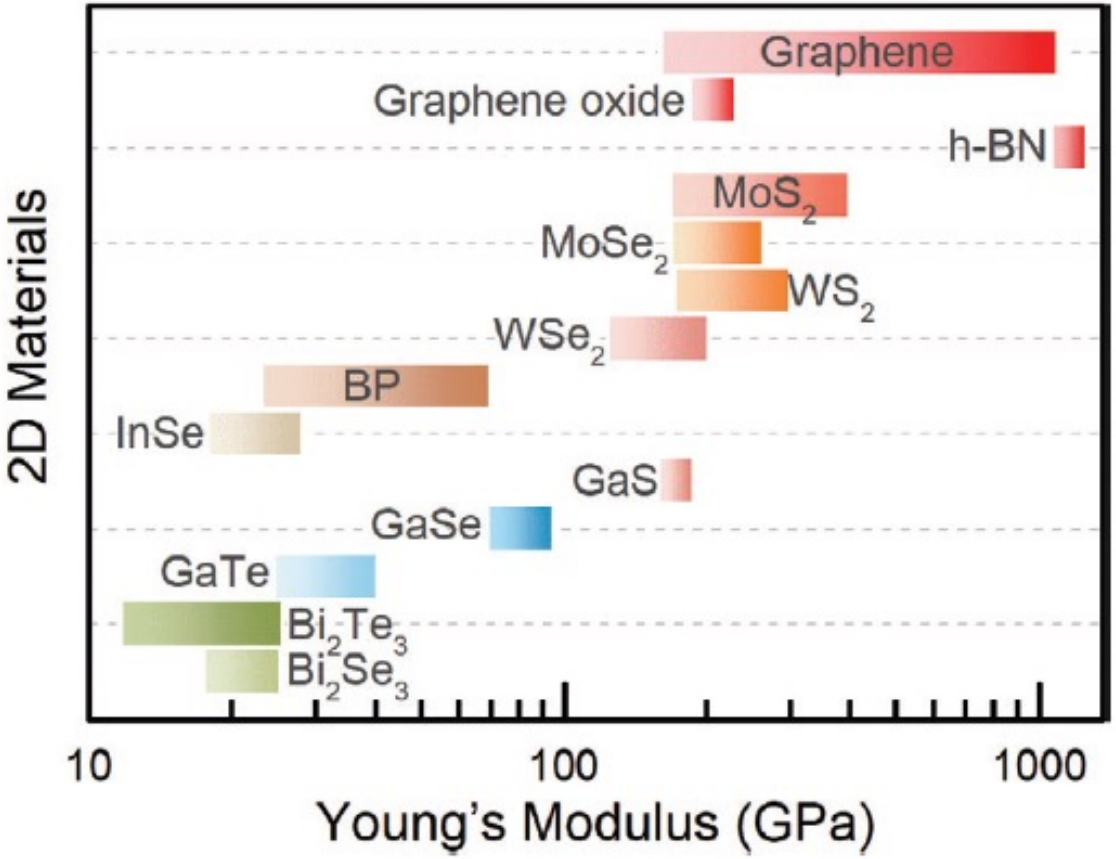
Strain engineering in 2D materials



$$E = \frac{\sigma}{\varepsilon}$$

Wikipedia

Du, J (2021). Small Methods, 5(1), 2000919.v



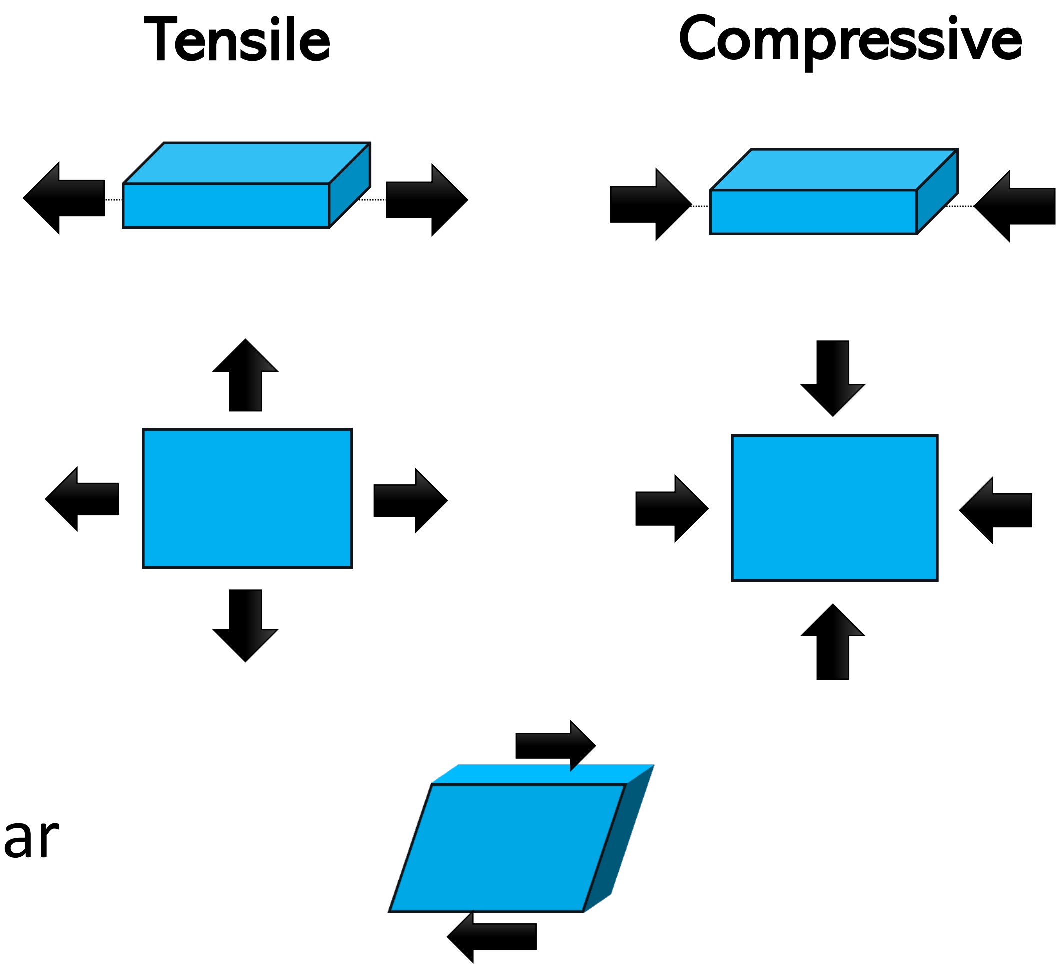
$$K = E \times \frac{A}{L}$$

- Single-layer TMDs exhibit a remarkable resilience to mechanical deformation.

Strain engineering in 2D materials

Depending on degrees of freedom

- ❑ Uniaxial
- ❑ Biaxial
- ❑ Shear

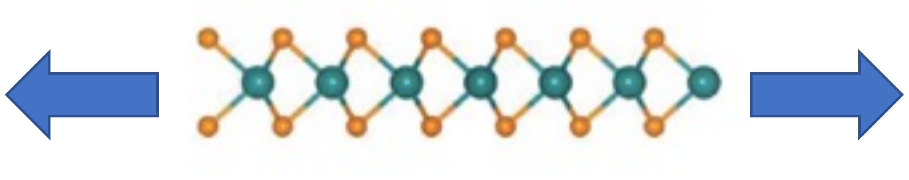


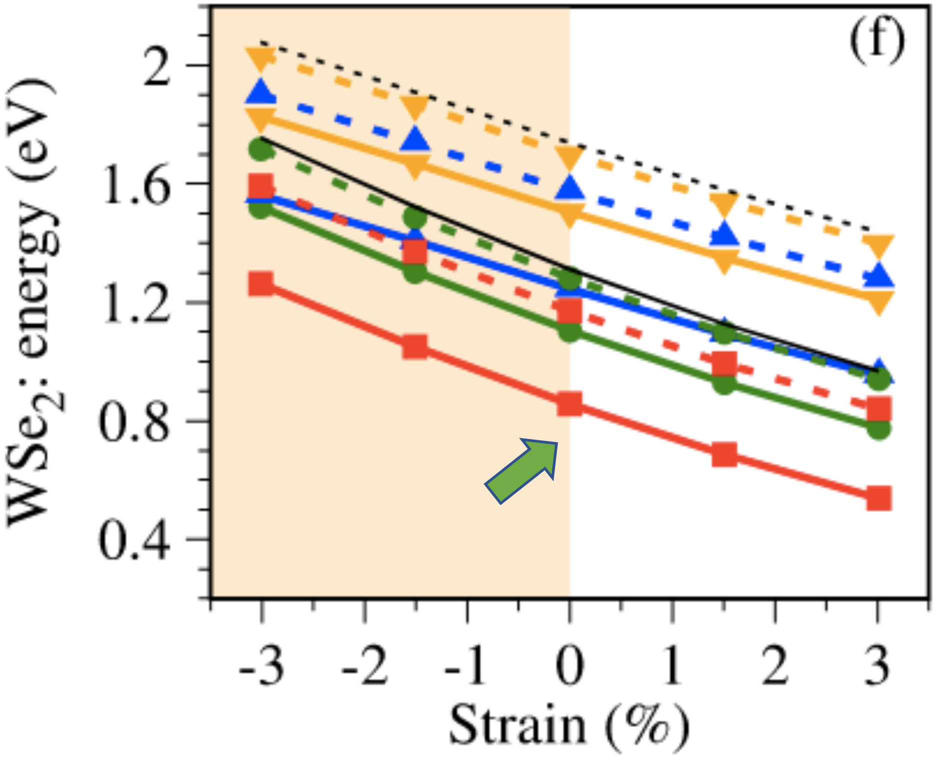
$$S = \frac{L - L_o}{L_o} 100\%$$

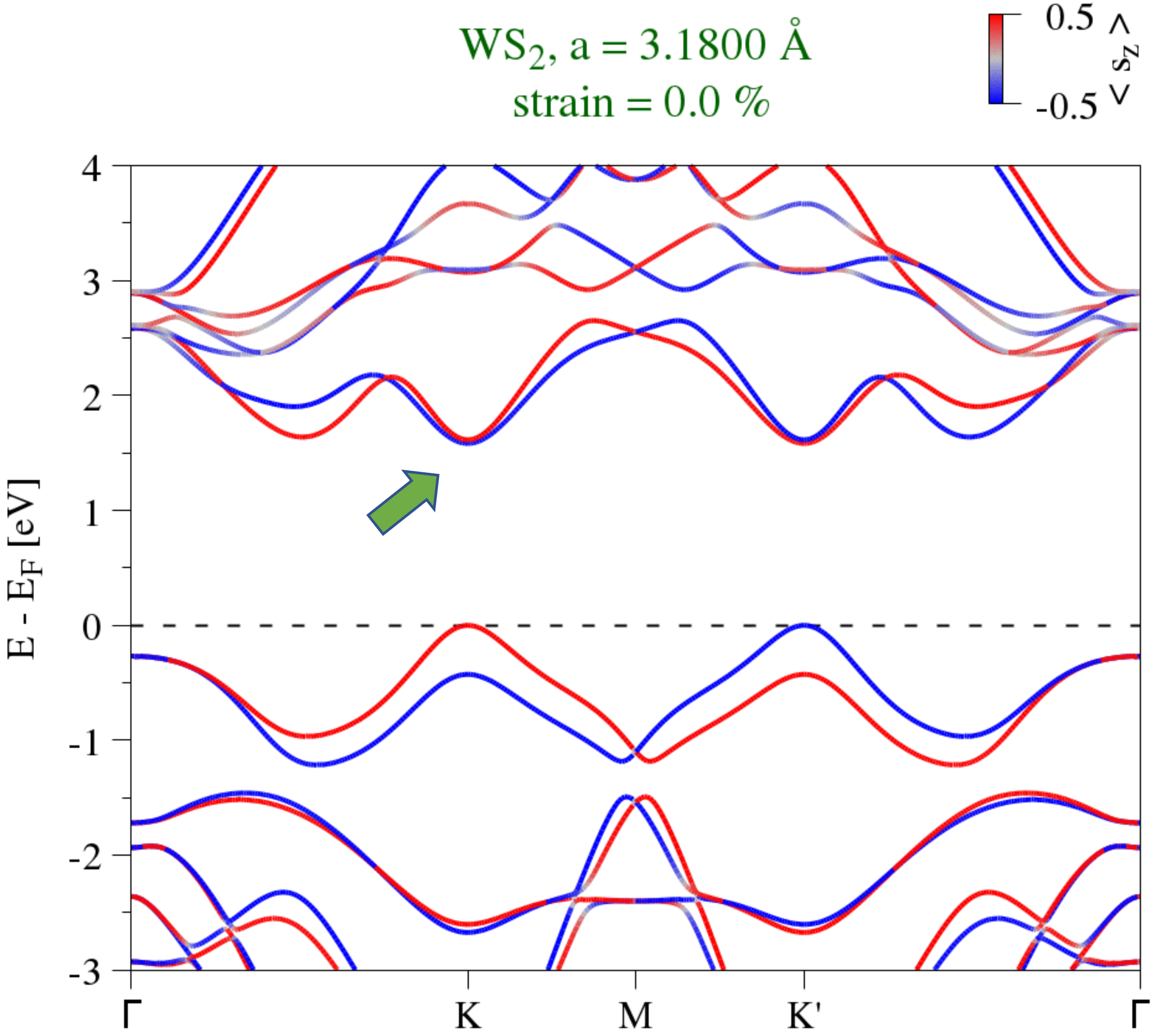
Strain engineering in 2D materials

Zollner, K., Junior, P. E. F., & Fabian, J. (2019). Physical Review B, 100(19), 195126.

Tensile strain







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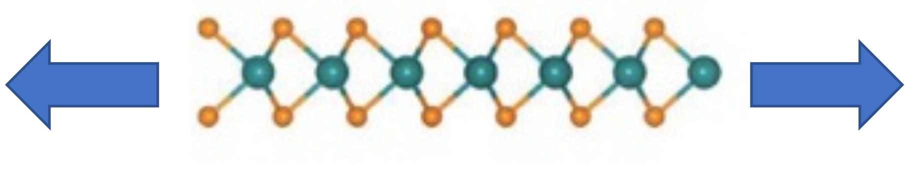

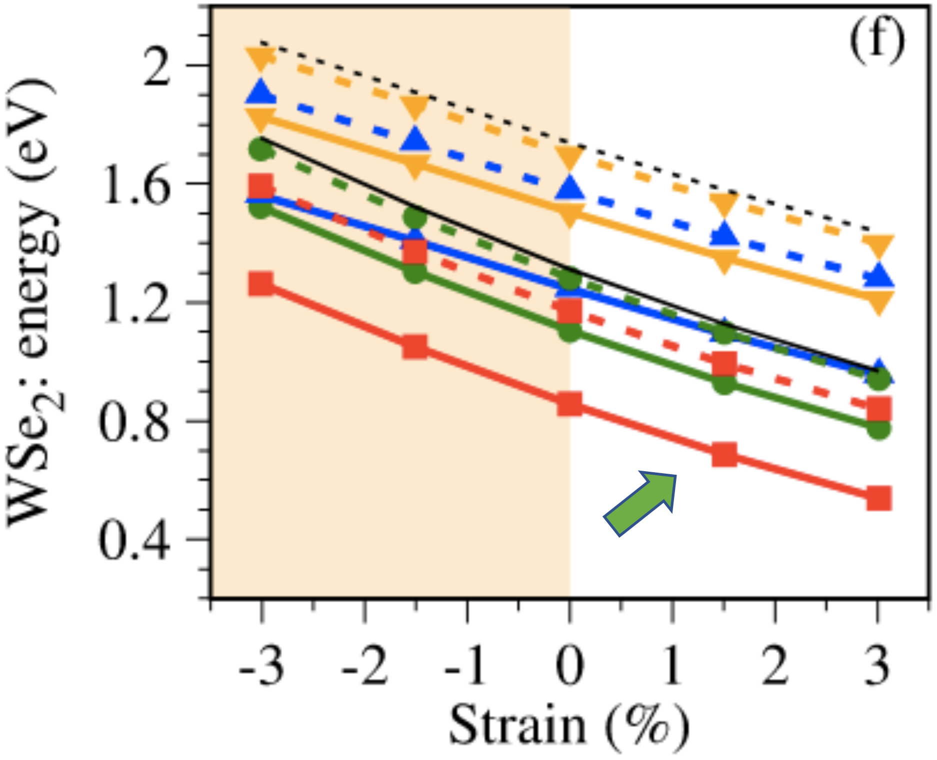

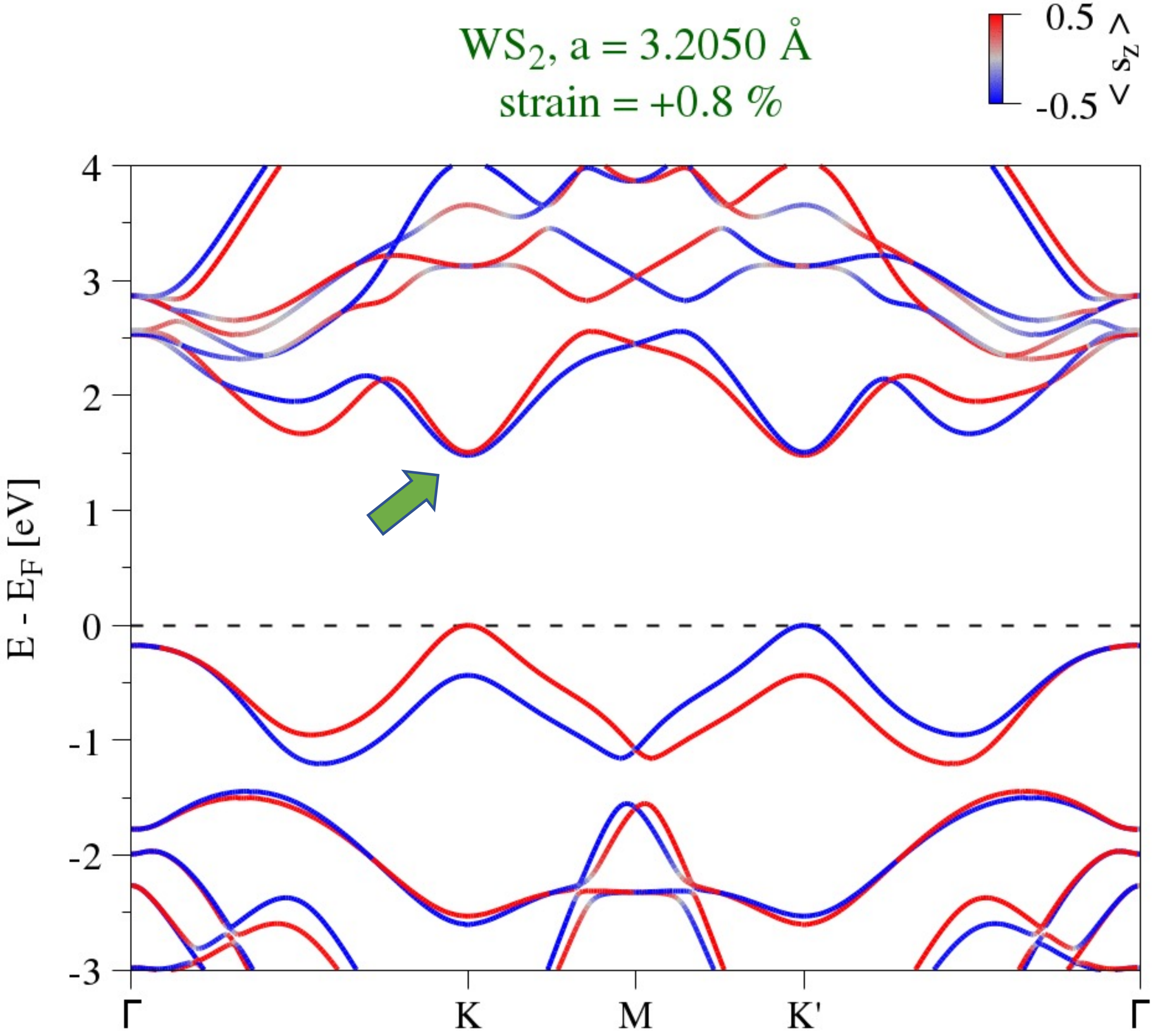

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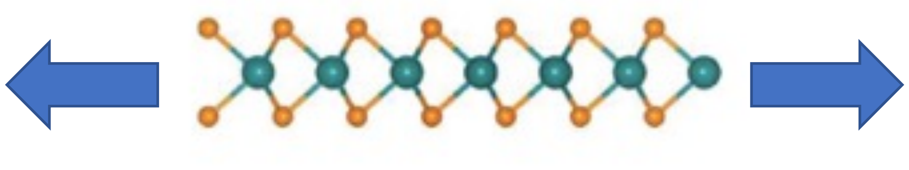

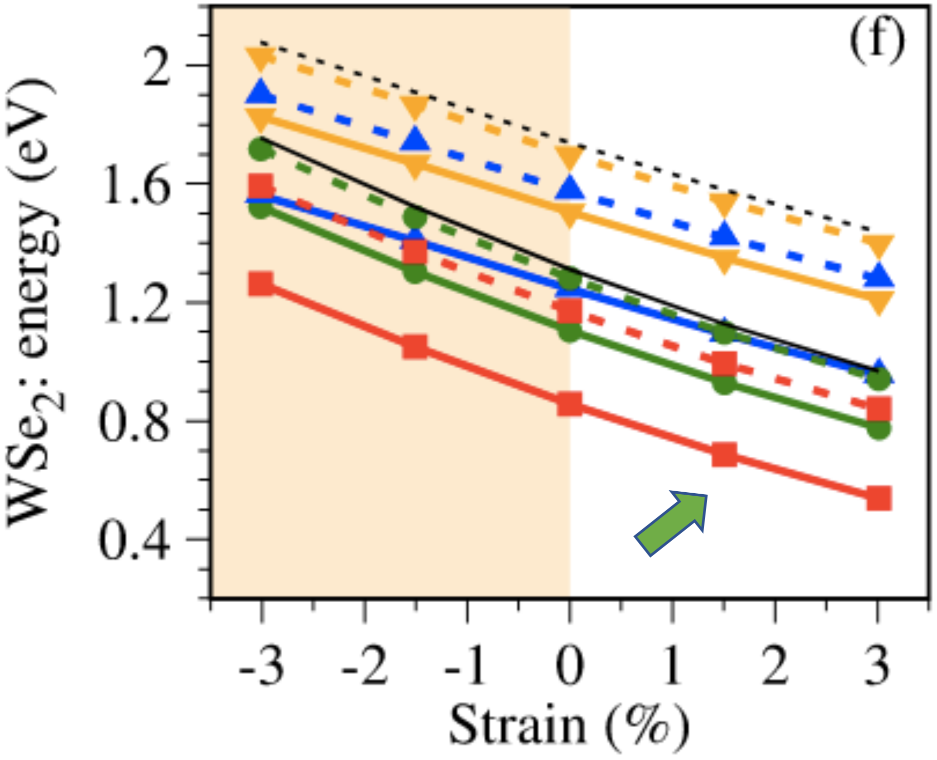

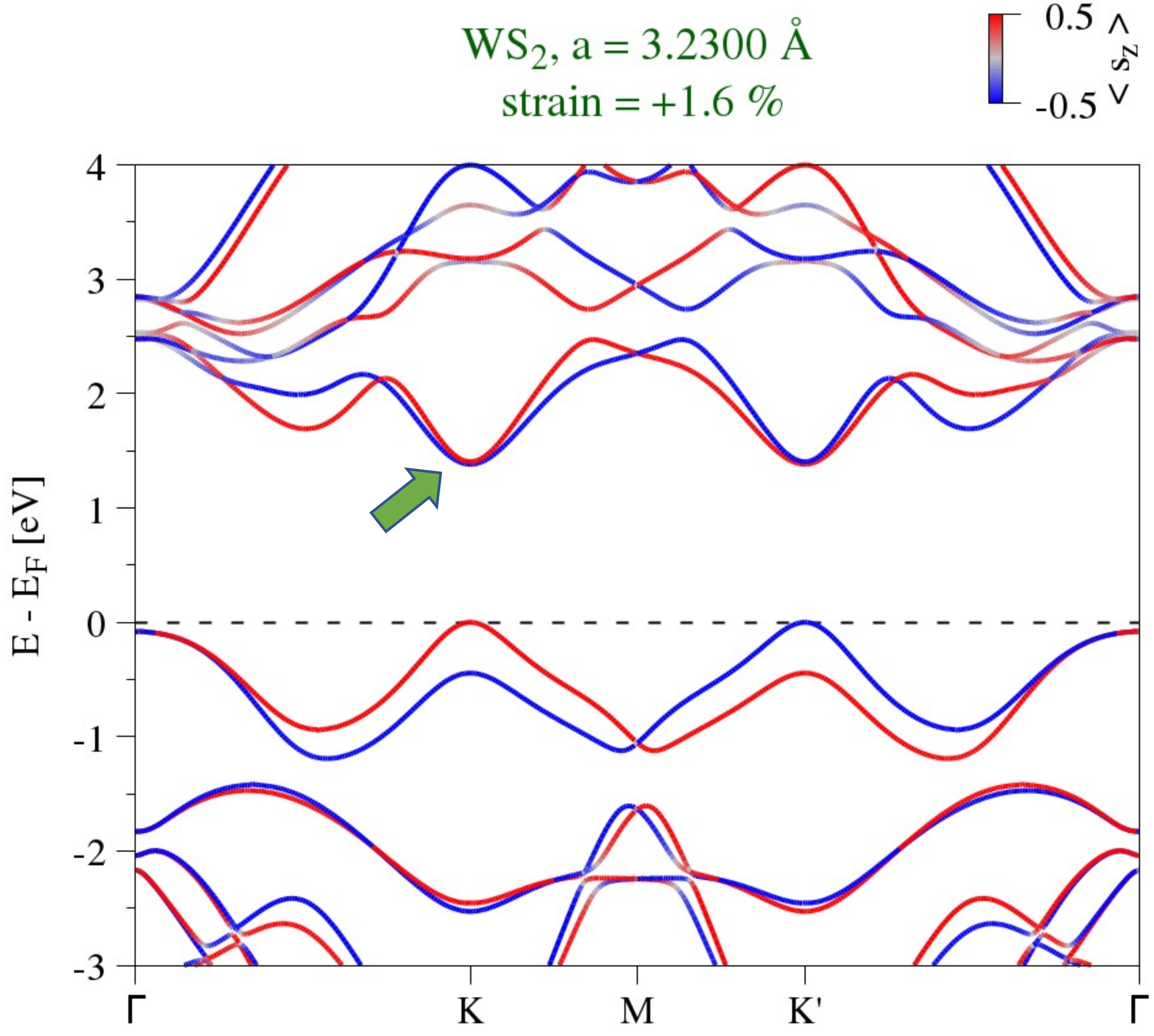

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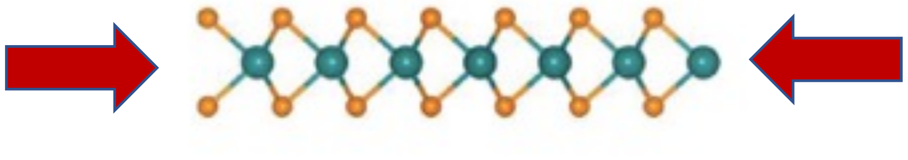
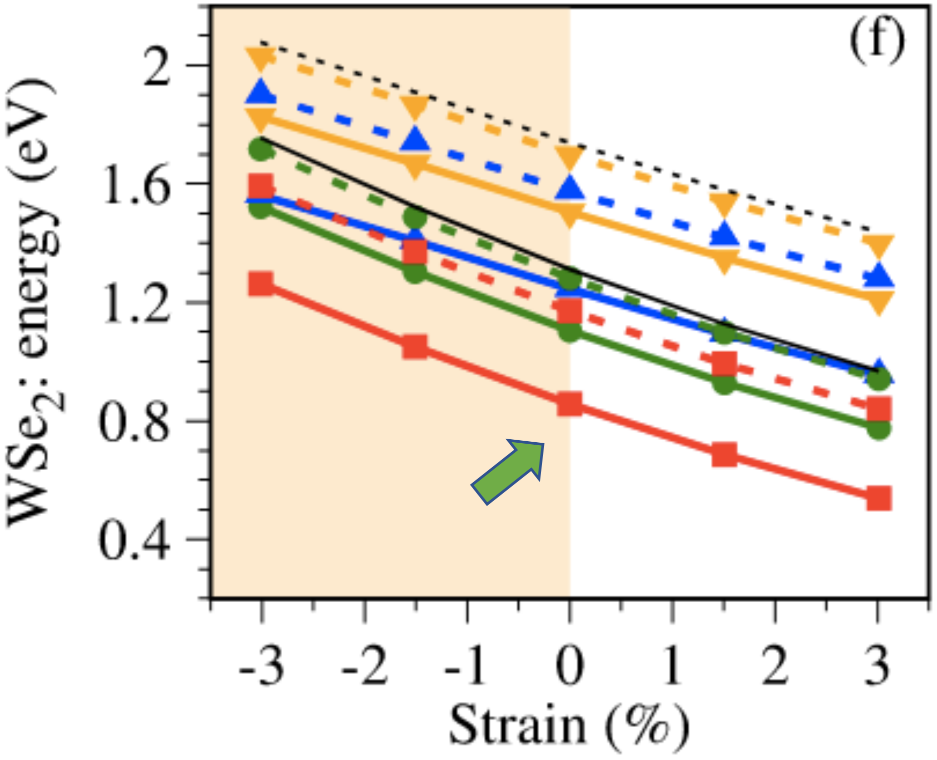
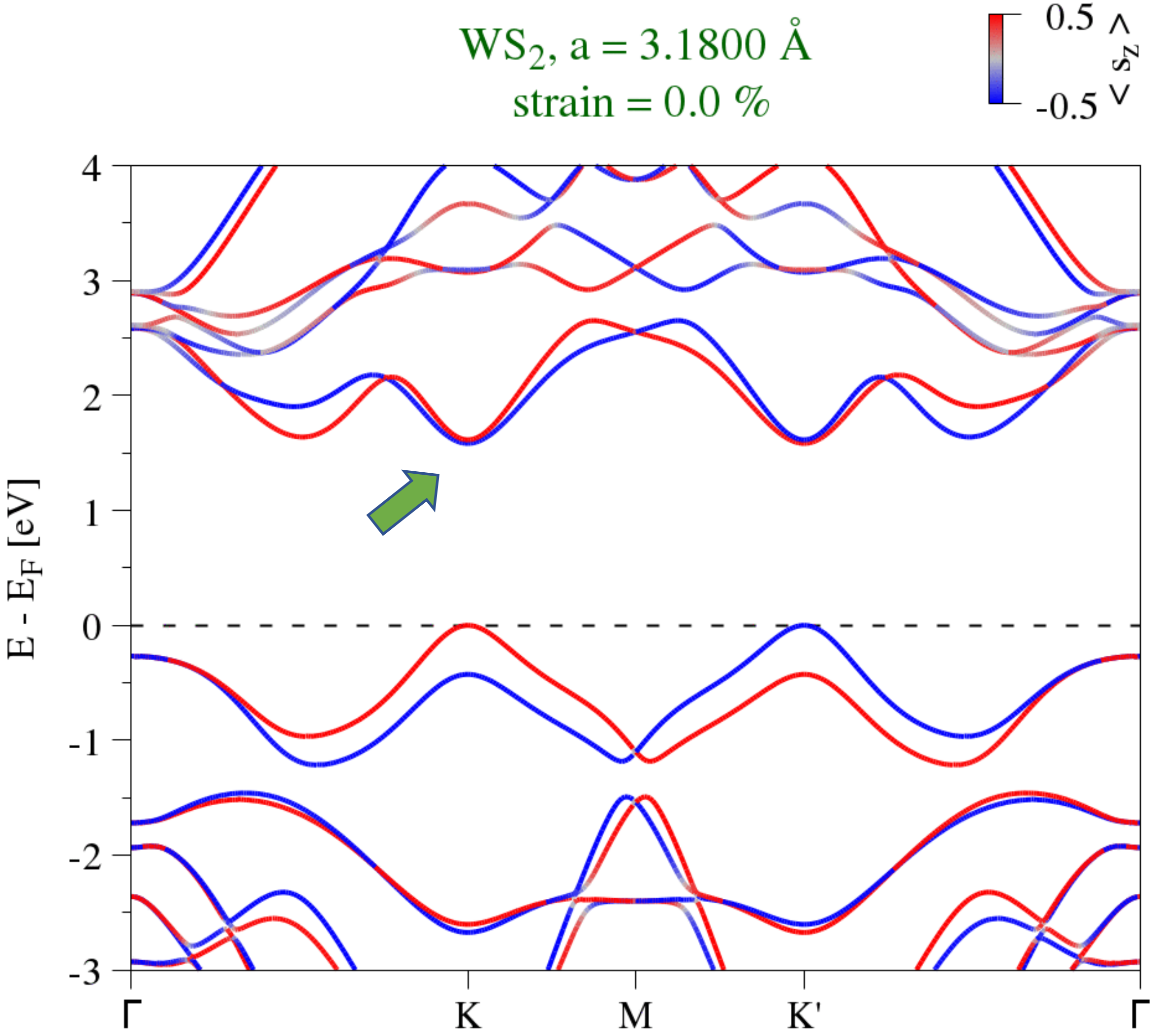
Compressive strain







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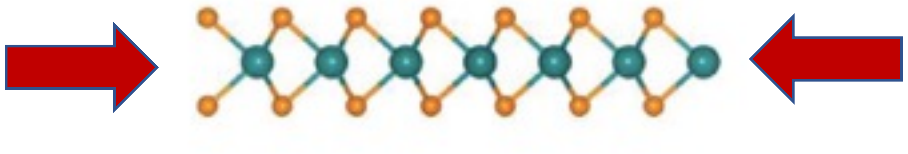

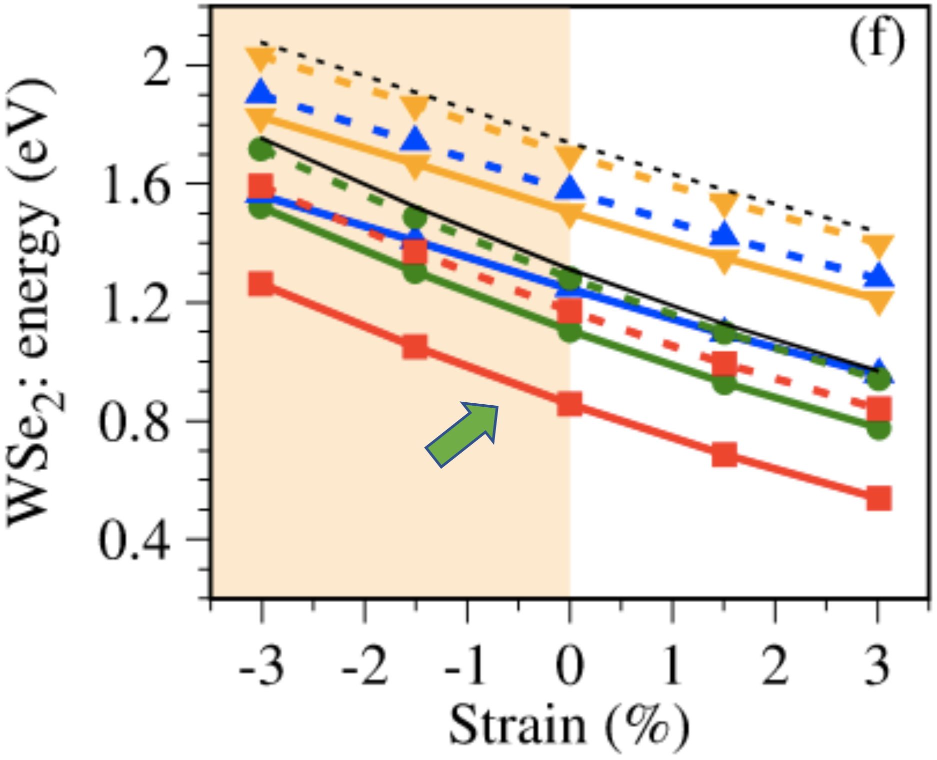

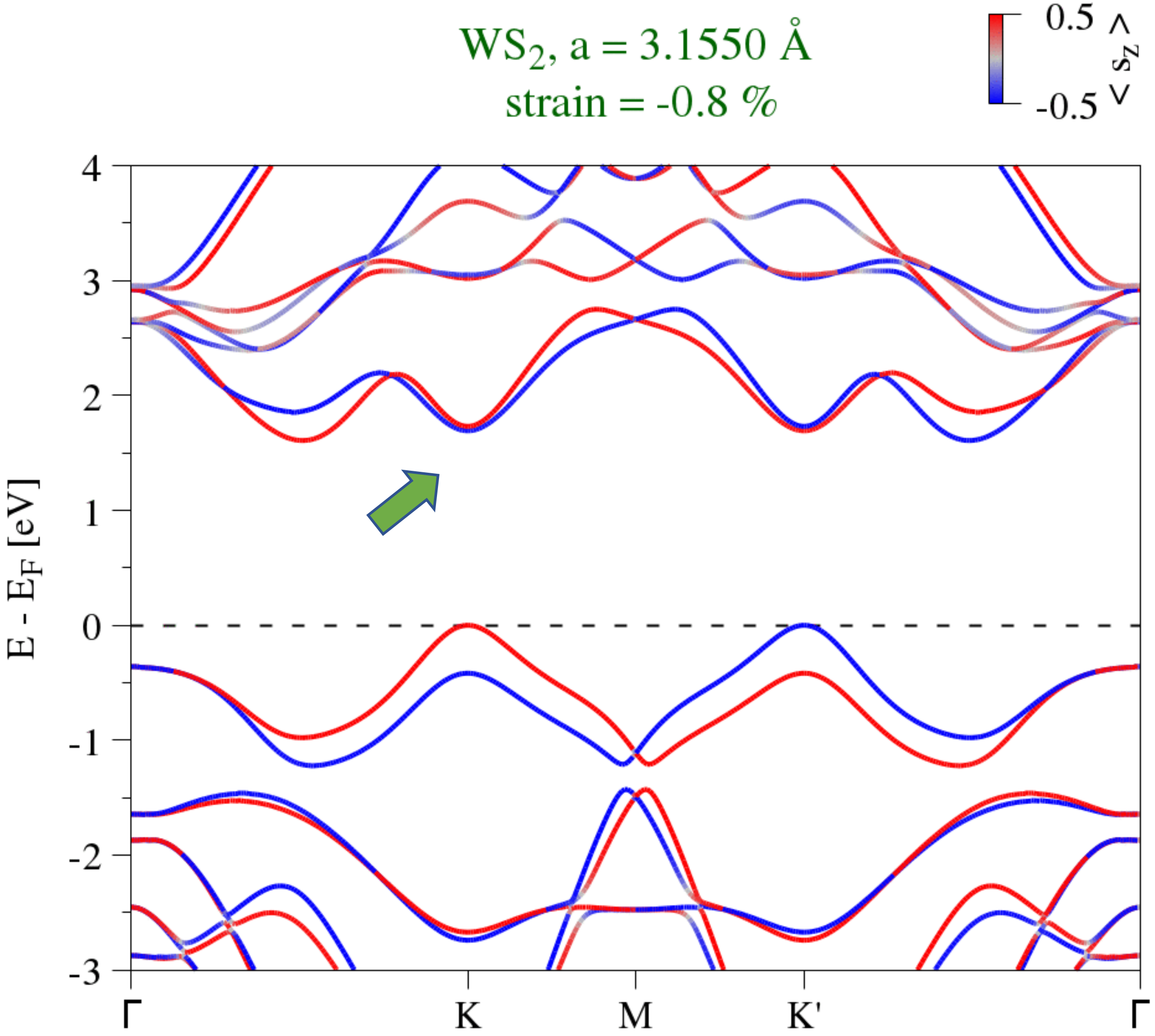

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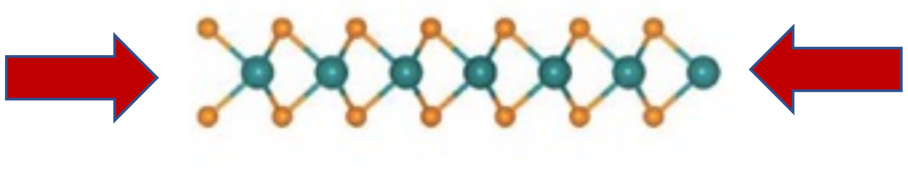
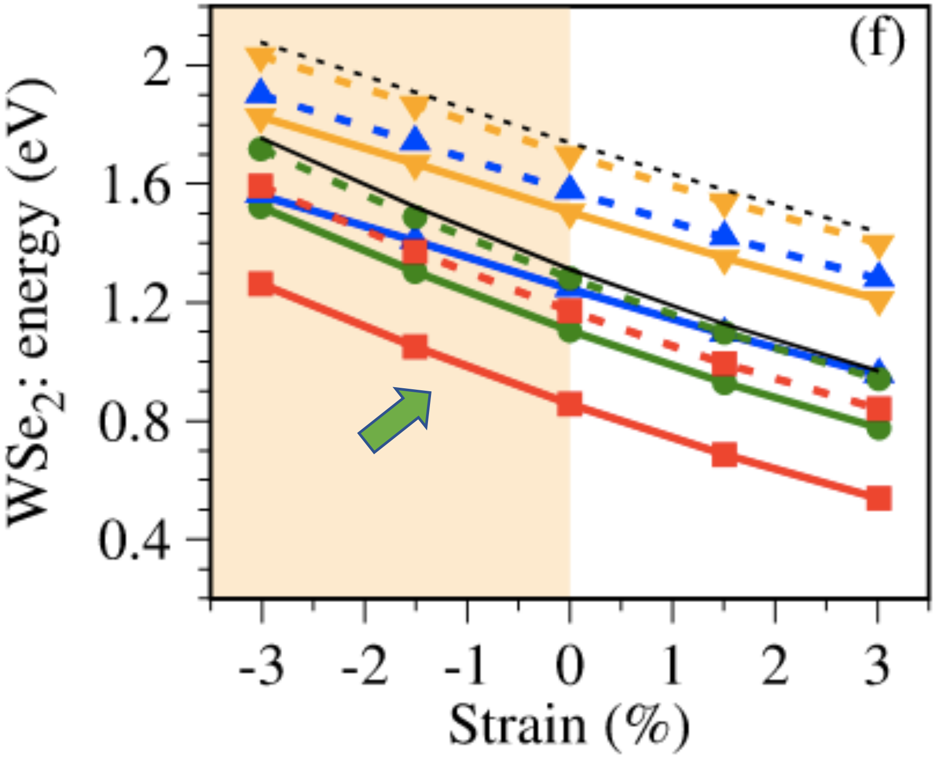
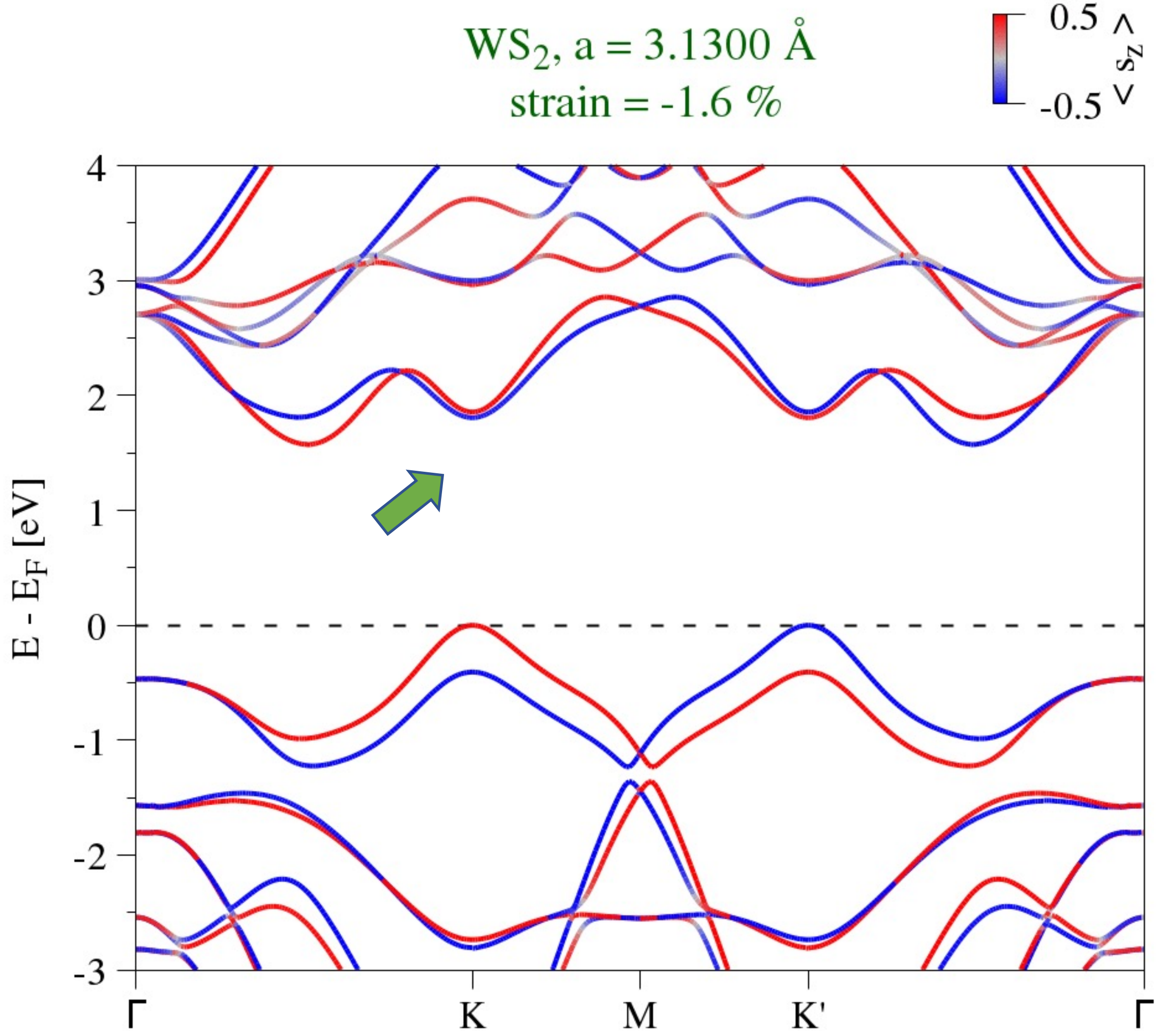
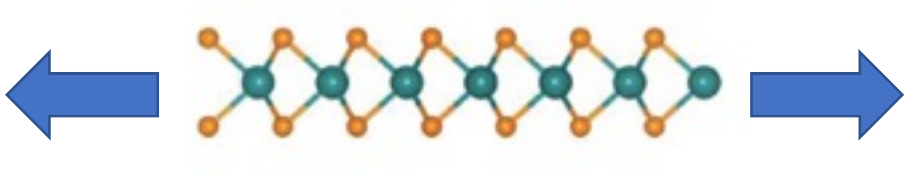


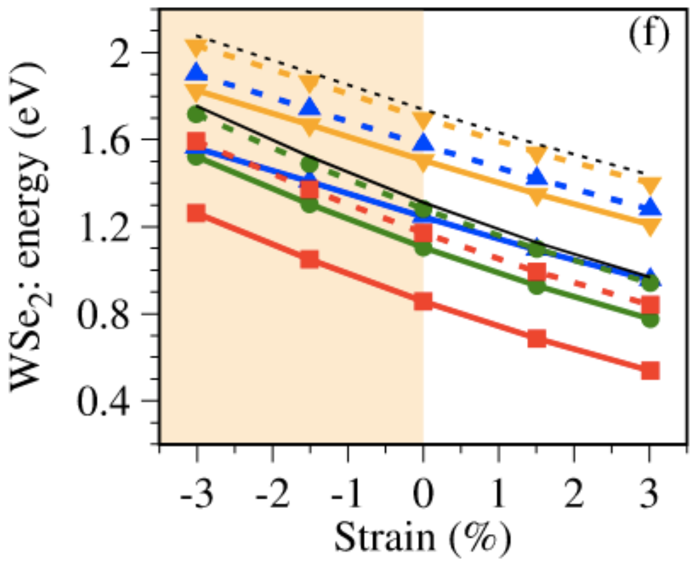


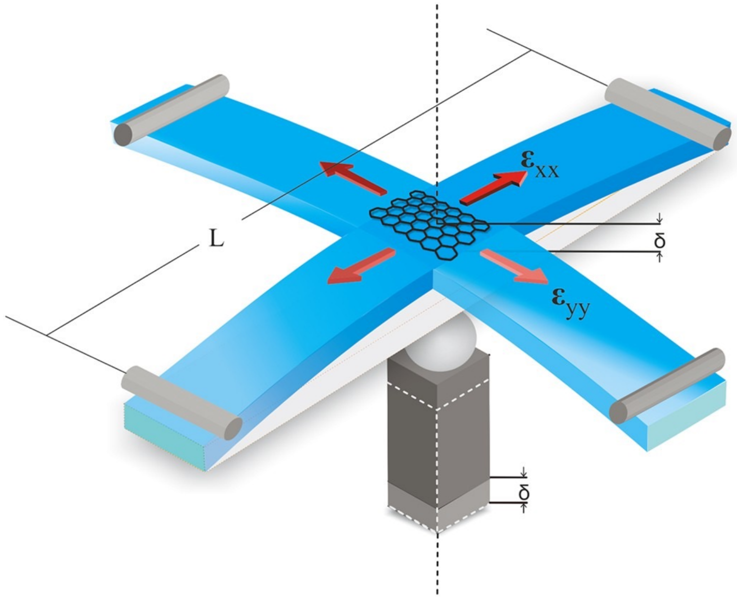


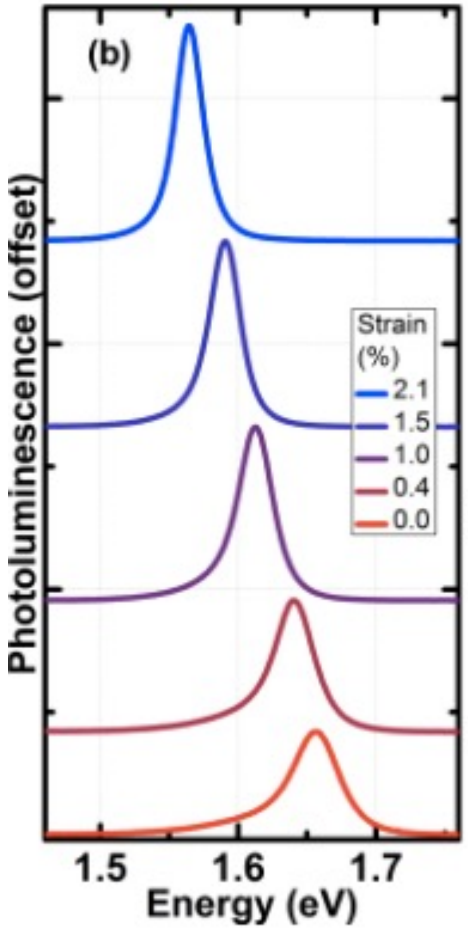
Strain engineering in 2D materials

Tensile strain









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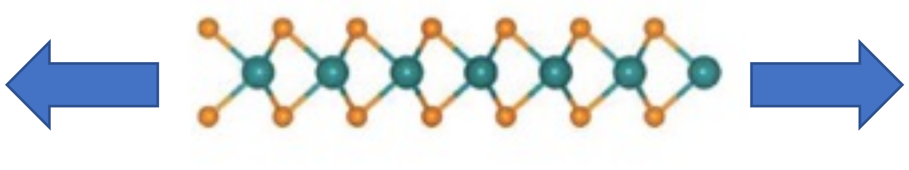
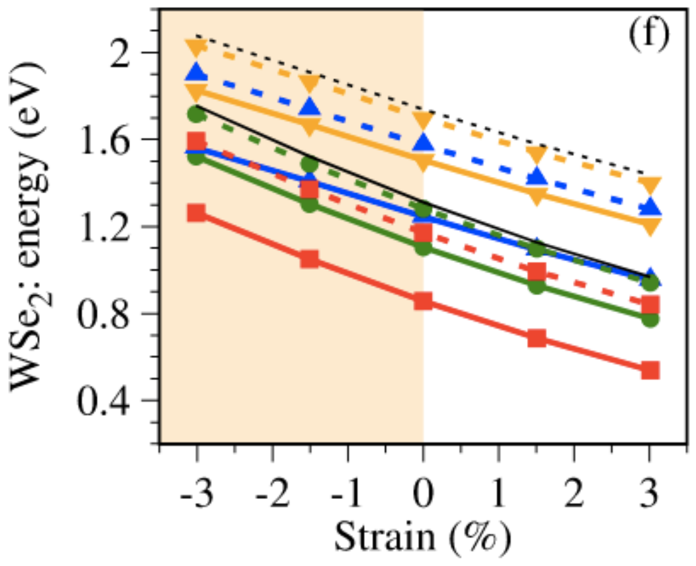
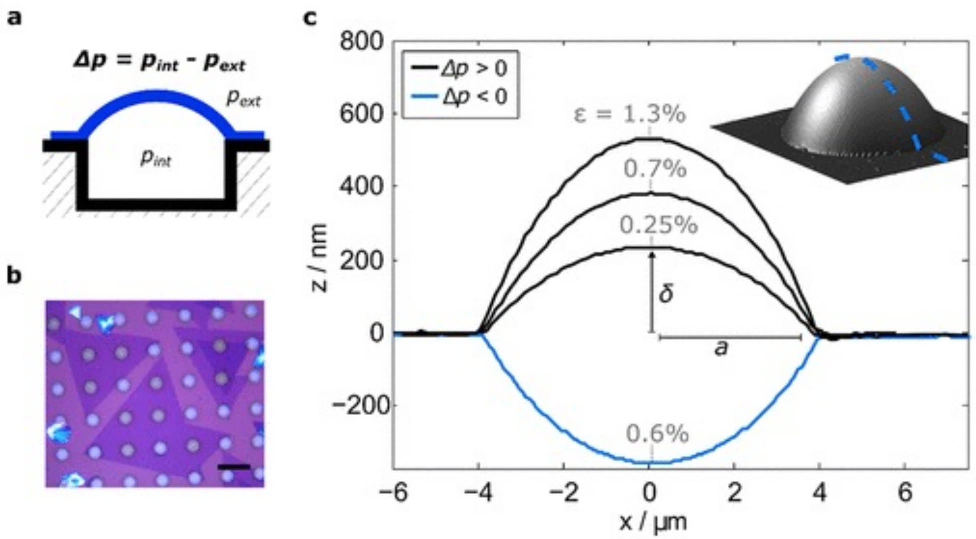
Aslan et al. PRB 98,115308 (2018)
Lloyd et al. Nano Lett. 2016, 16, 5836−5841

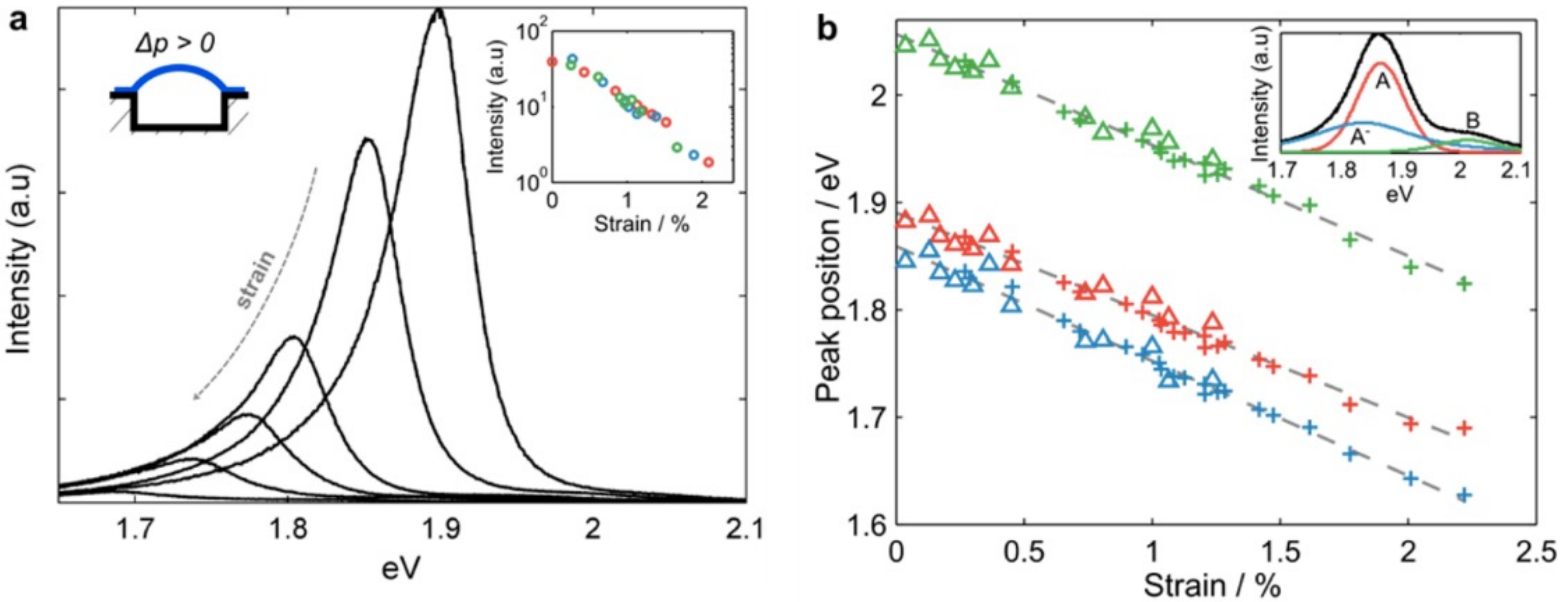
Strain engineering in 2D materials

Tensile strain









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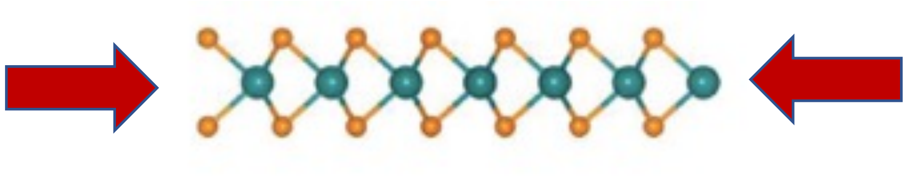
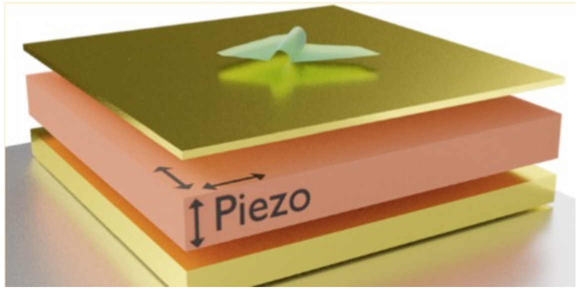
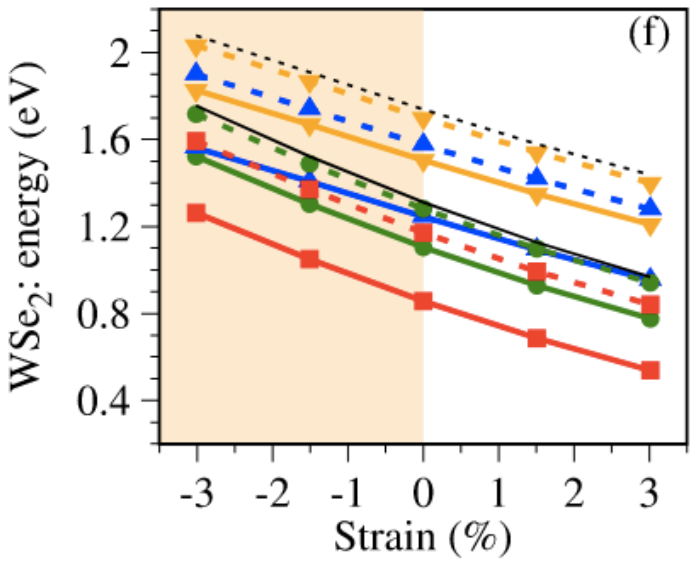
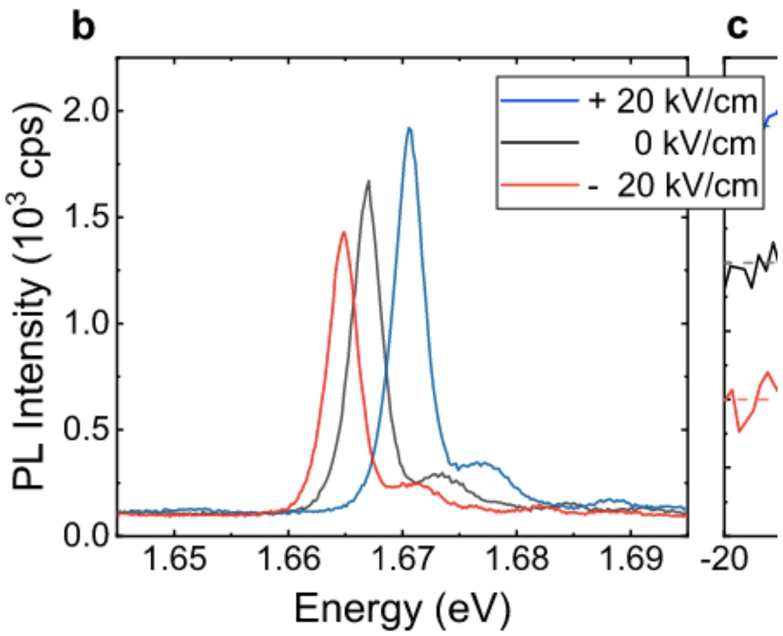
Strain engineering in 2D materials

Compressive strain









Piezo actuators

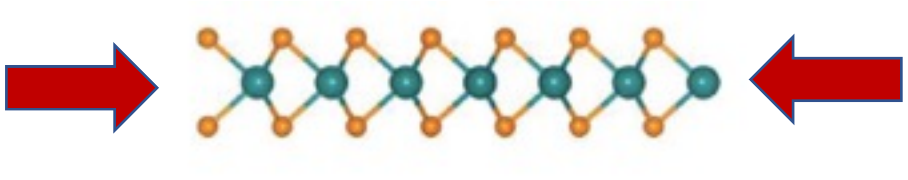
- ➢ Small ammounts of compressive strain
- ➢ Suitable for low temperature studies

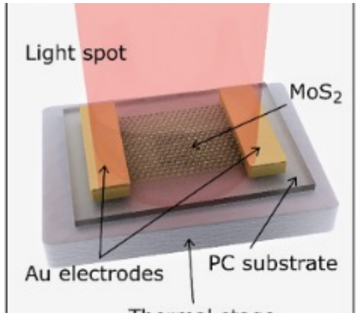
Zollner, K., Junior, P. E. F., & Fabian, J. (2019). Physical Review B, 100(19), 195126.

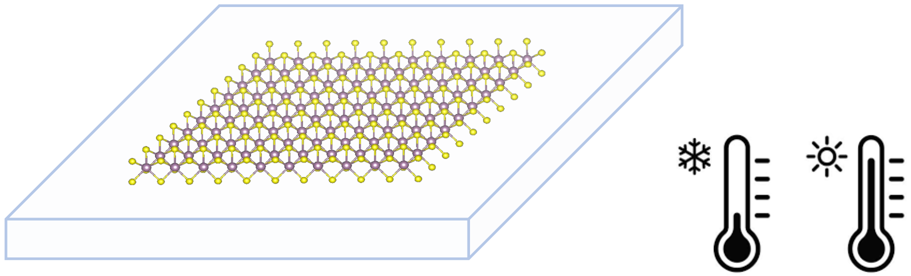
Iff et al. Nano Lett. 2019, 19, 6931−6936

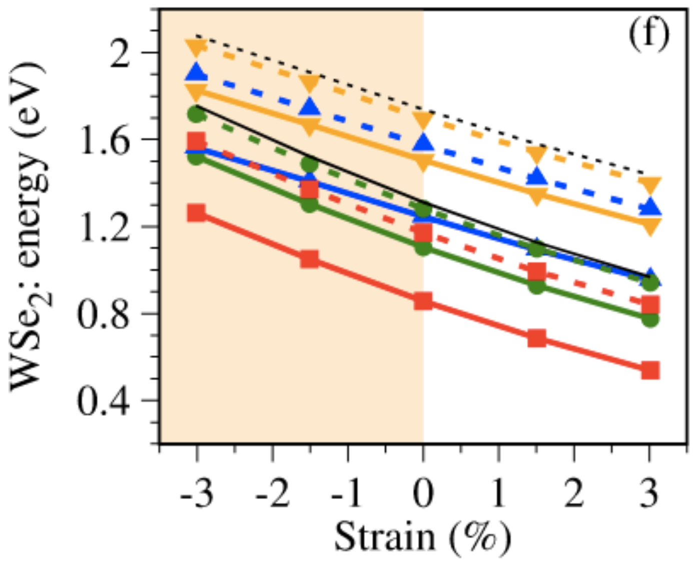
Strain engineering in 2D materials

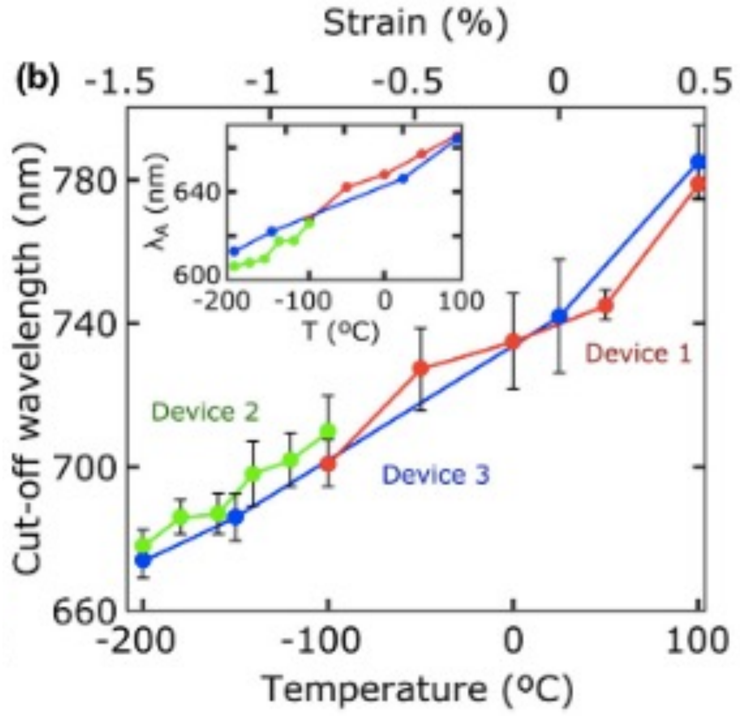
Compressive strain











Thermal expansion of Polymeric substrates:

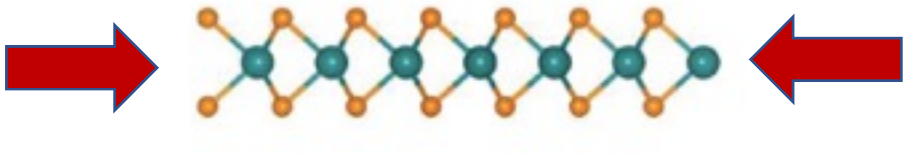
- Large thermal coefficient
- Large Young modulus
- **Expansion up to 100C**
- **Compression down only to 80K**

Zollner, K., Junior, P. E. F., & Fabian, J. (2019). Physical Review B, 100(19), 195126.

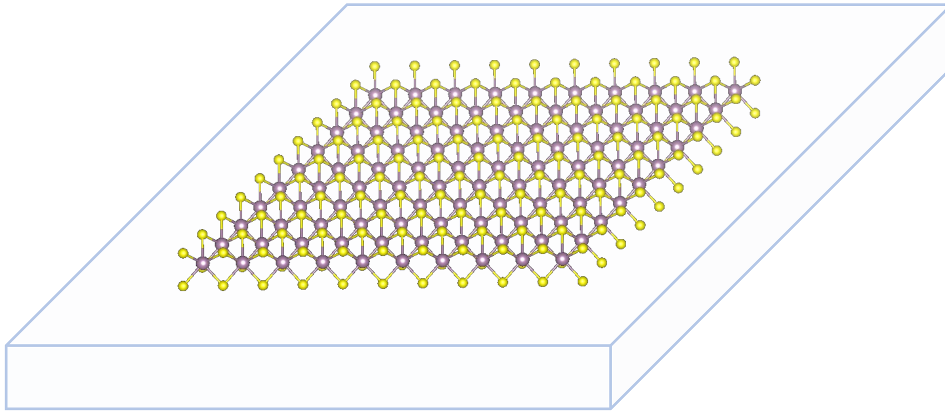
Gant et al. Materials Today 2019

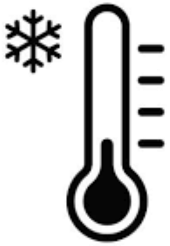
Thermal compression at lower temperatures

Compressive strain



Would this work at lower *T*?



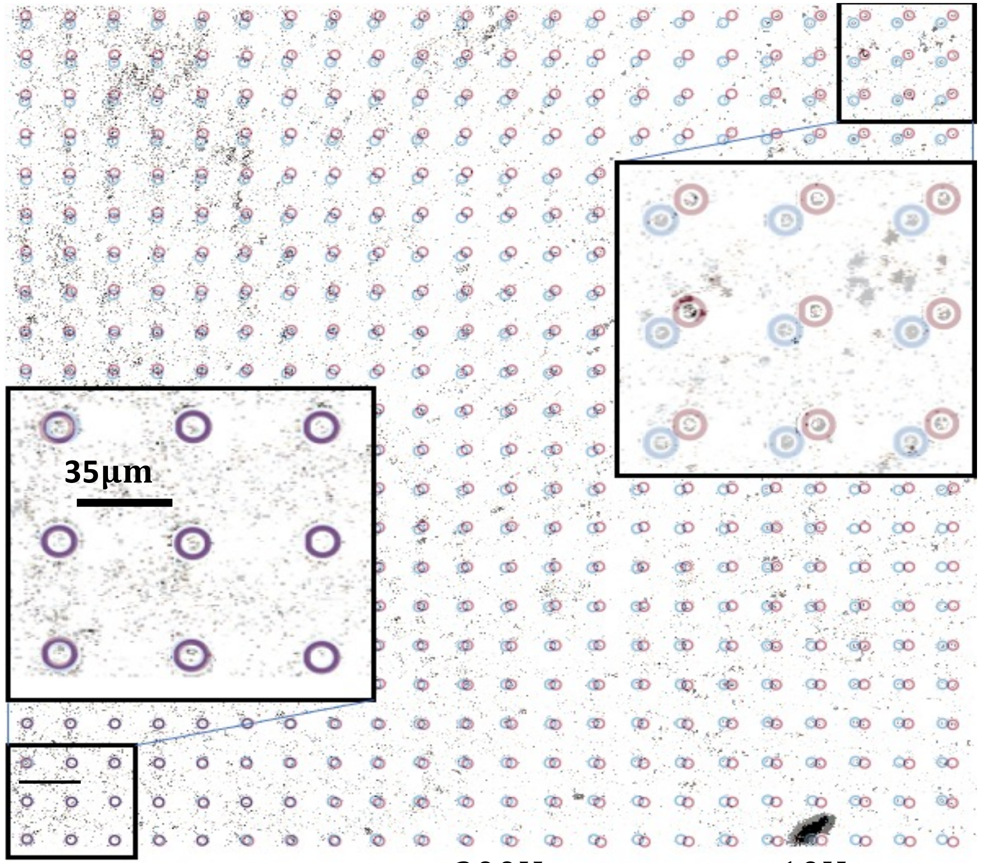


Advantages:

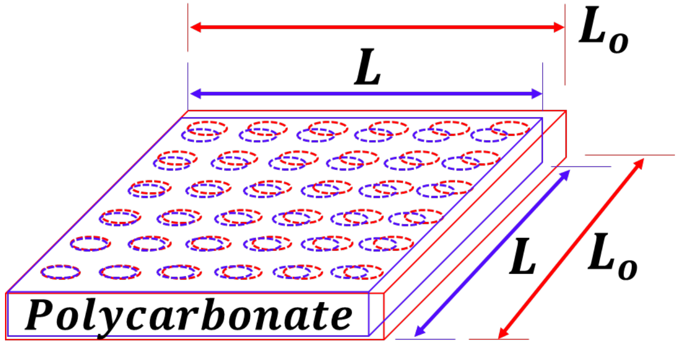
❖ Simple preparation
❖ Large biaxial compressive strain
❖ Low temperature phenomena

Polycarbonate substrate deformation

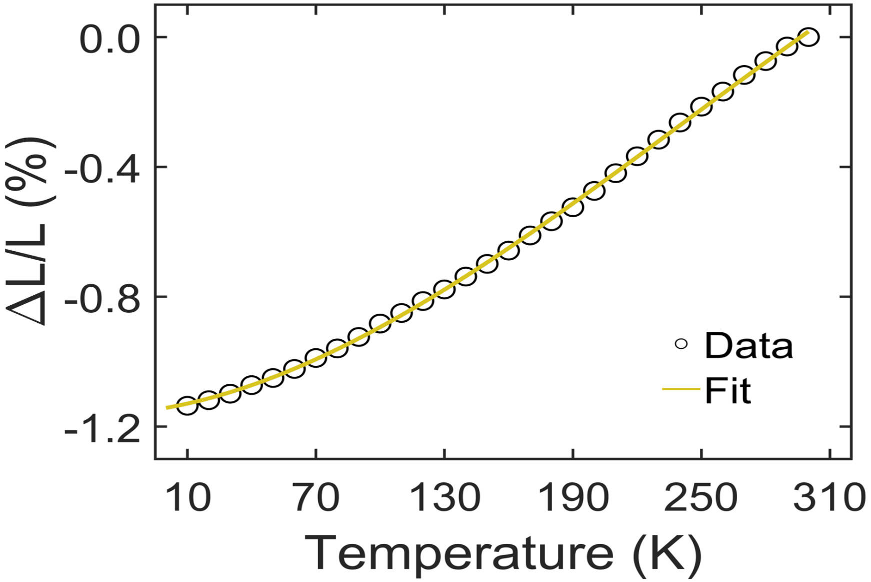
α ~ 6.5 10^{-5} 1/K



300K
10K



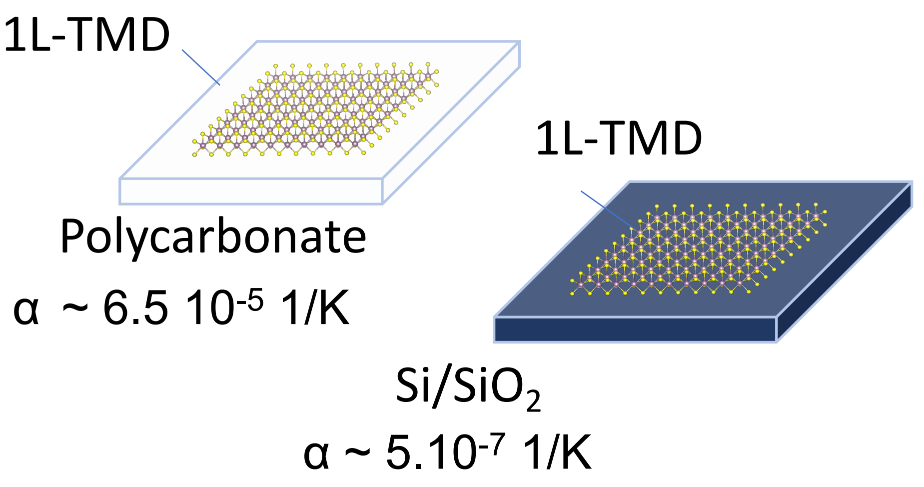
$$\frac{\Delta L}{L}(\%) = \frac{L - L_o}{L_o}\,100\%$$

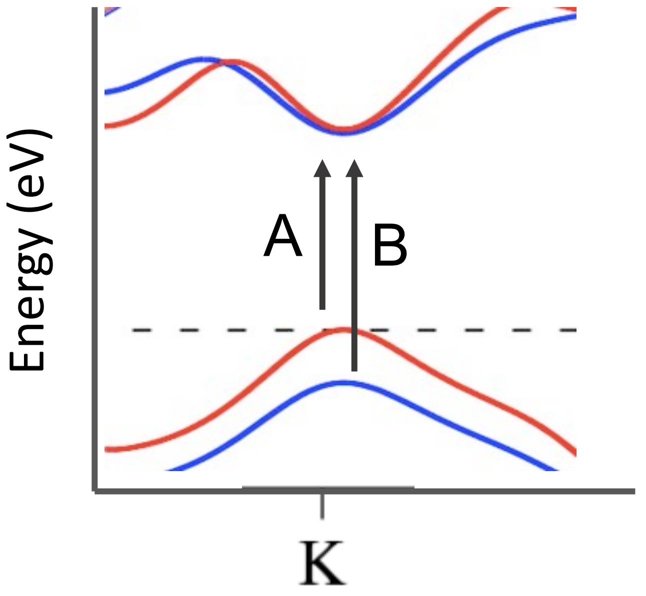


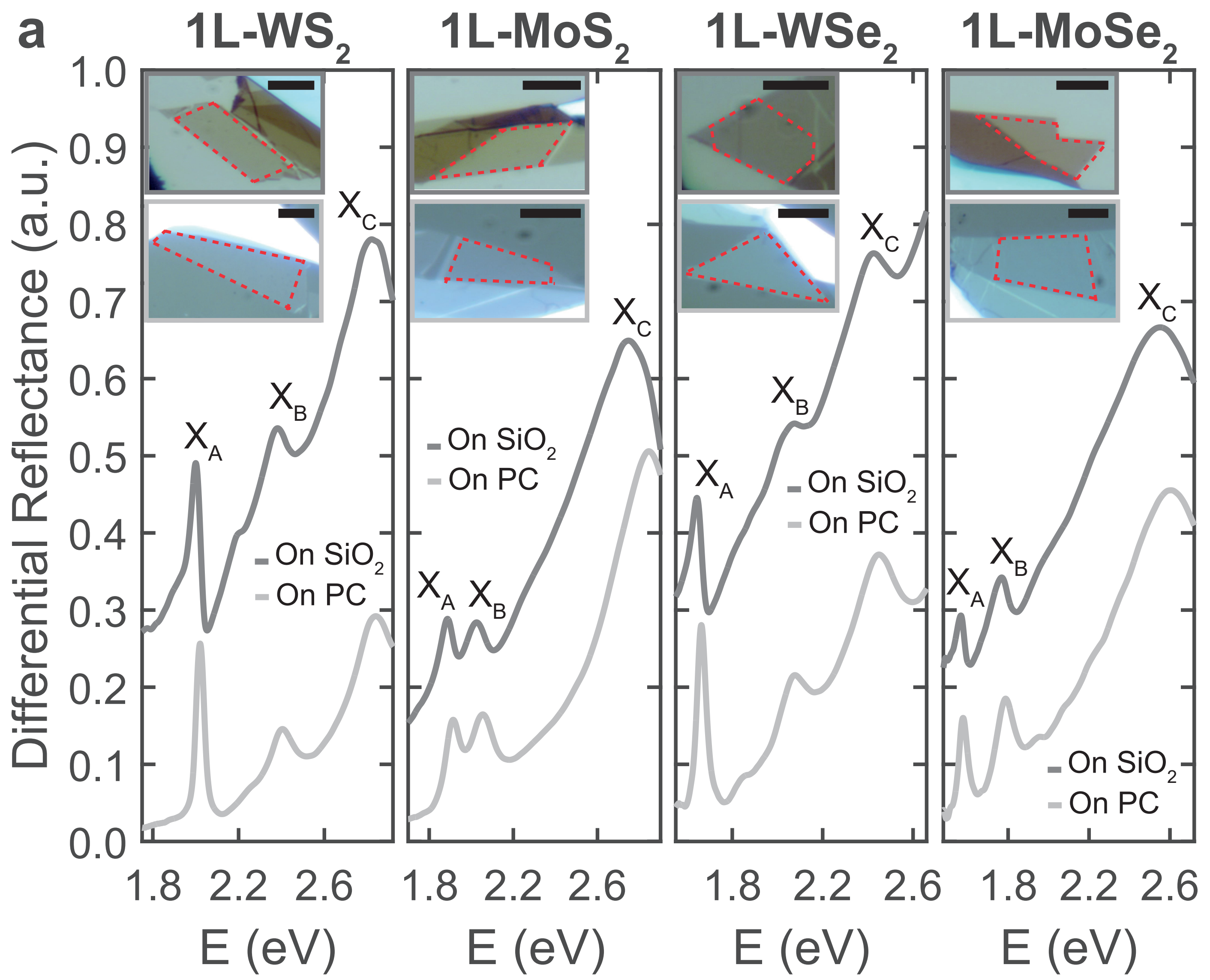
$$\frac{\Delta L}{L}(T) = aT^3 + bT^2 + cT + d$$

Micro-reflectance spectroscopy

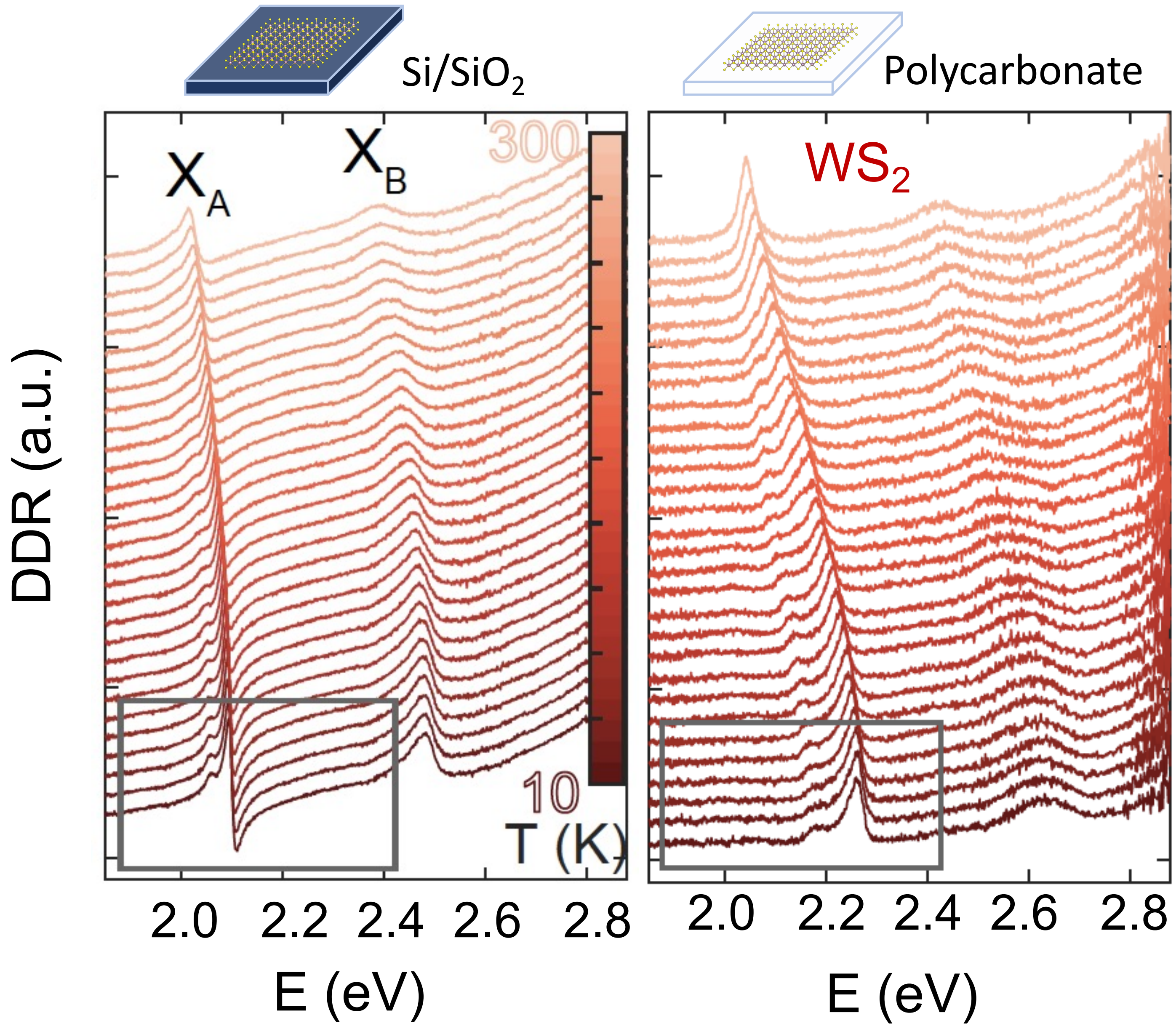
Room temperature

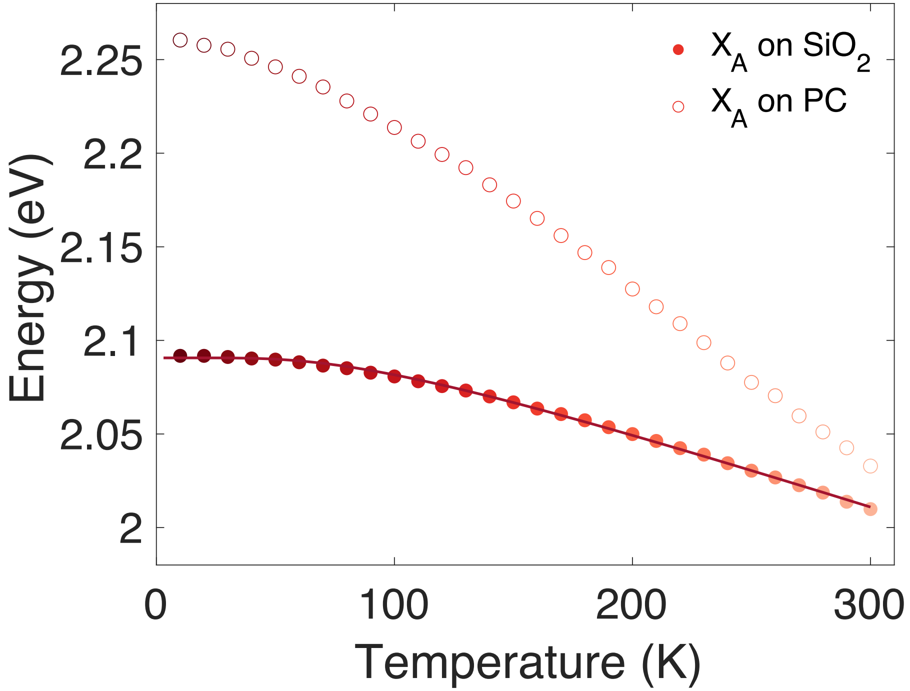






Micro-reflectance spectroscopy

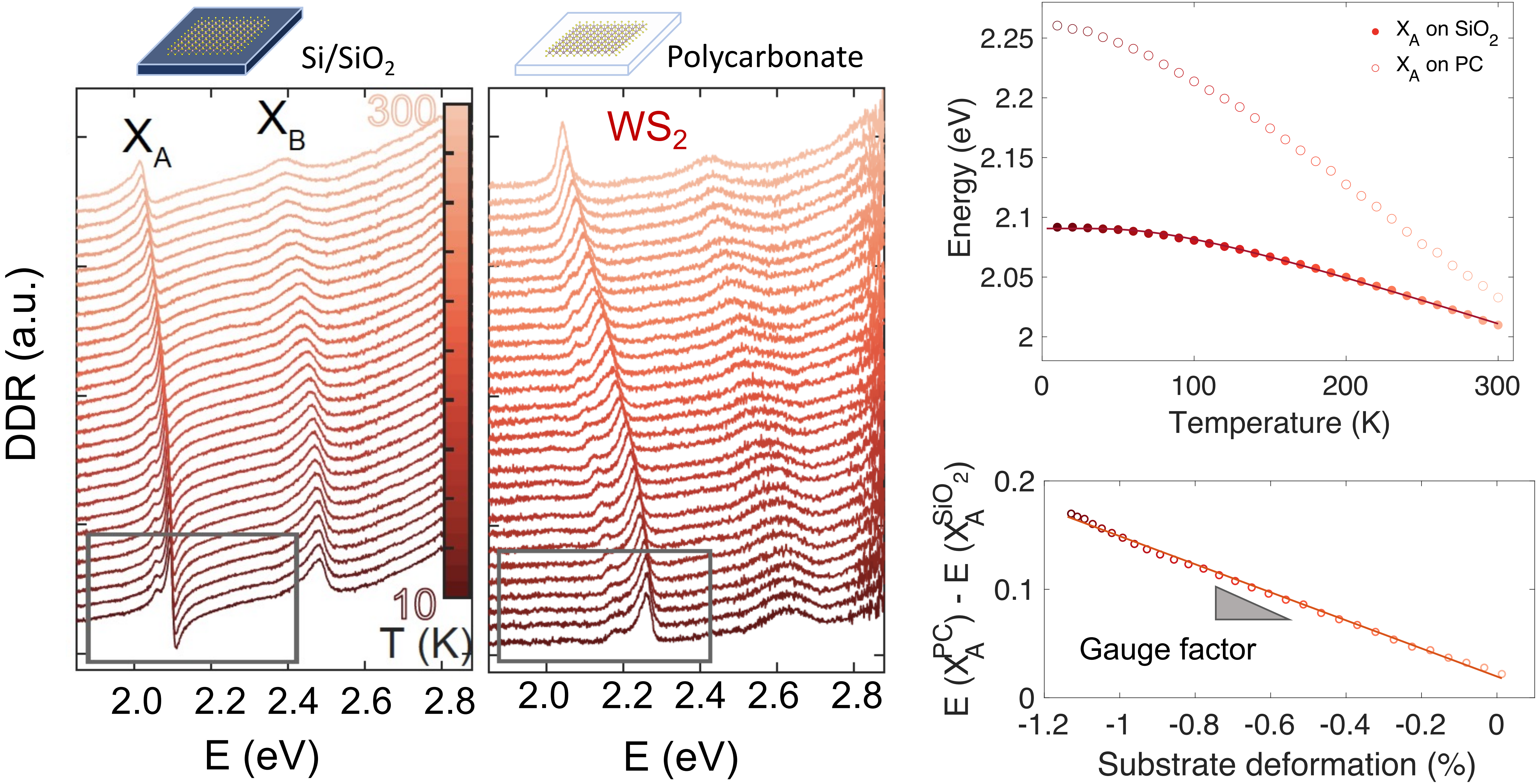




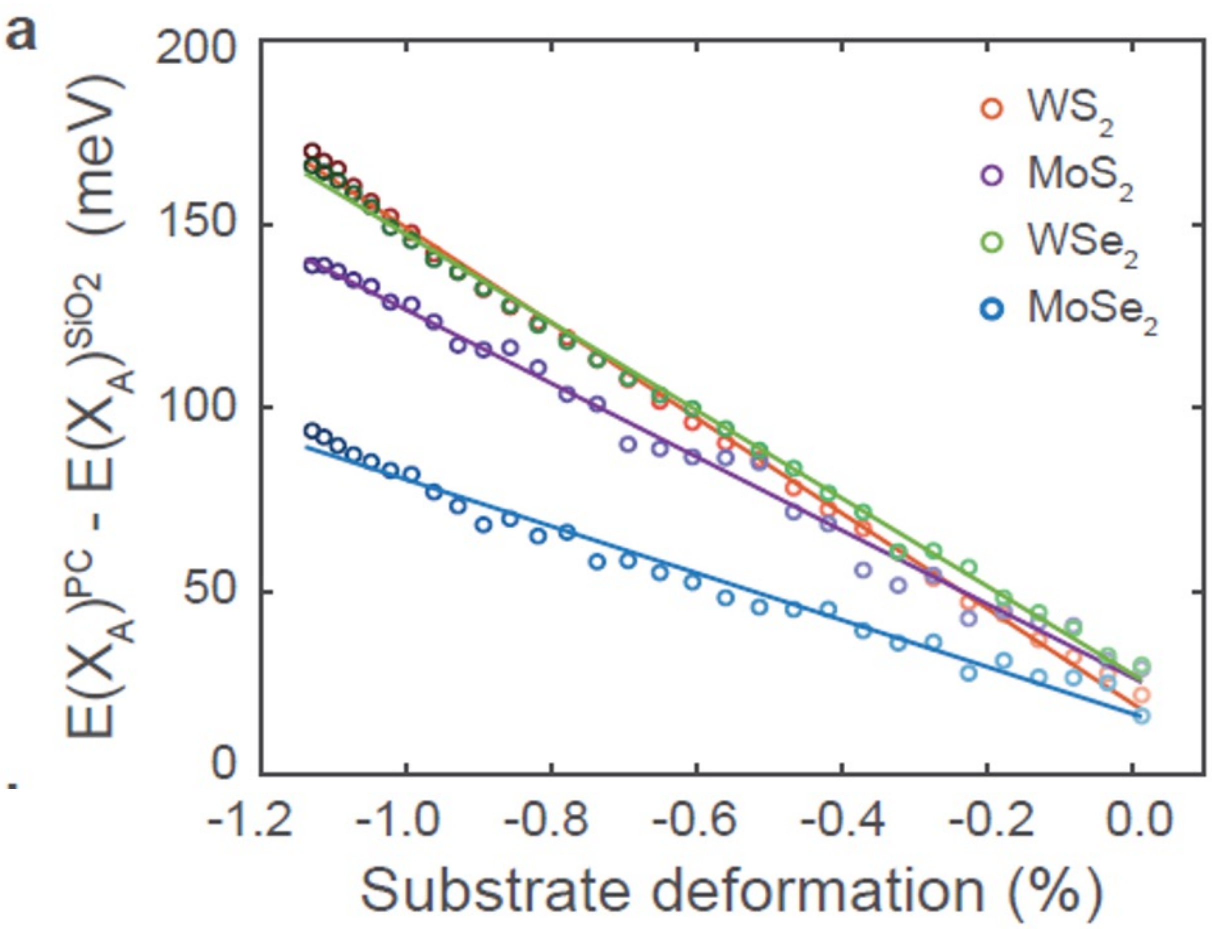
$$Eg(T) = Eg(0) - S\langle\hbar\omega\rangle[\coth(\langle\hbar w\rangle/2kT) - 1]$$

O'Donell et al Appl. Phys. Lett. 58, 2924 (1991)

Micro-reflectance spectroscopy



Strain gauge factors for excitons

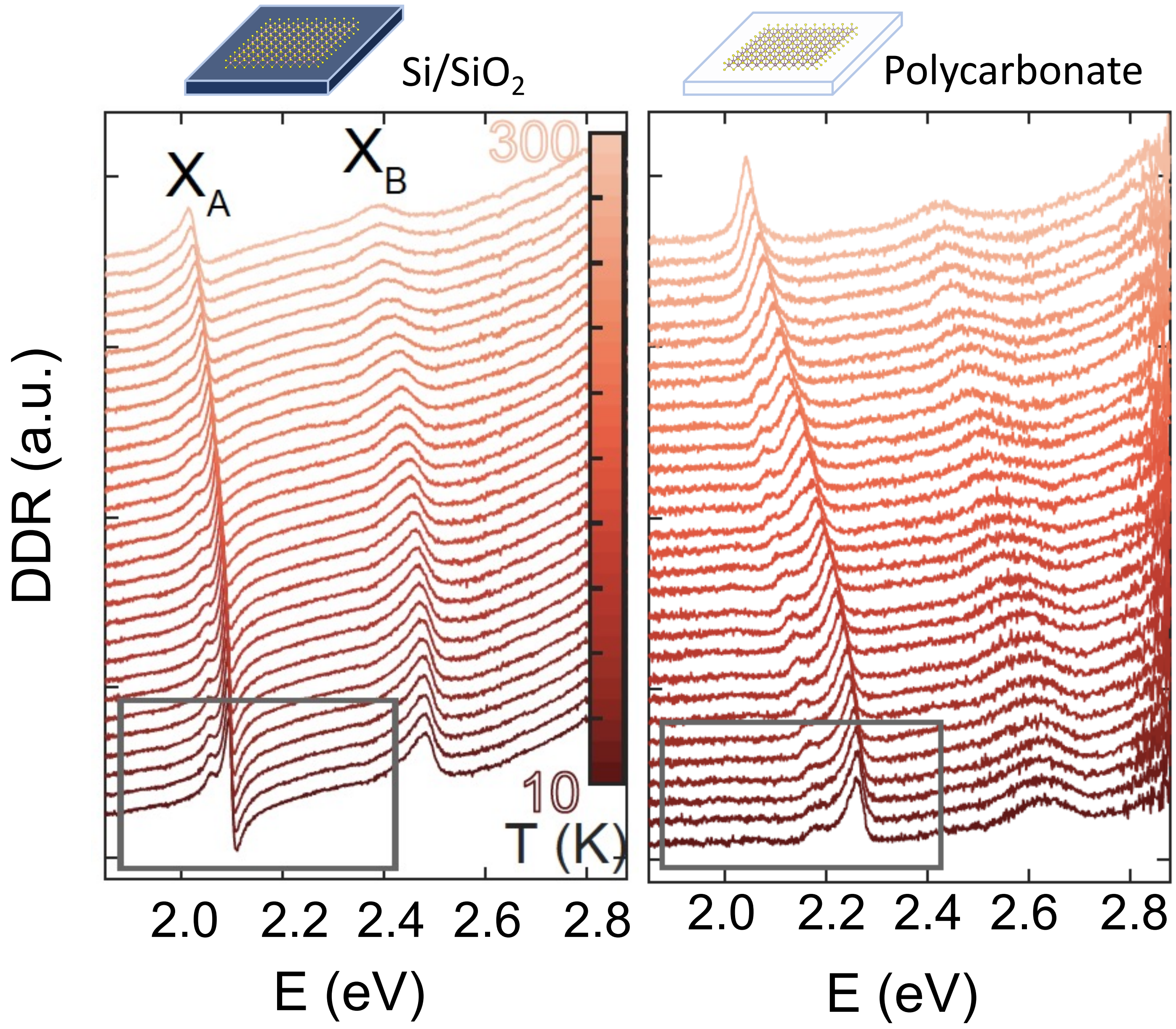


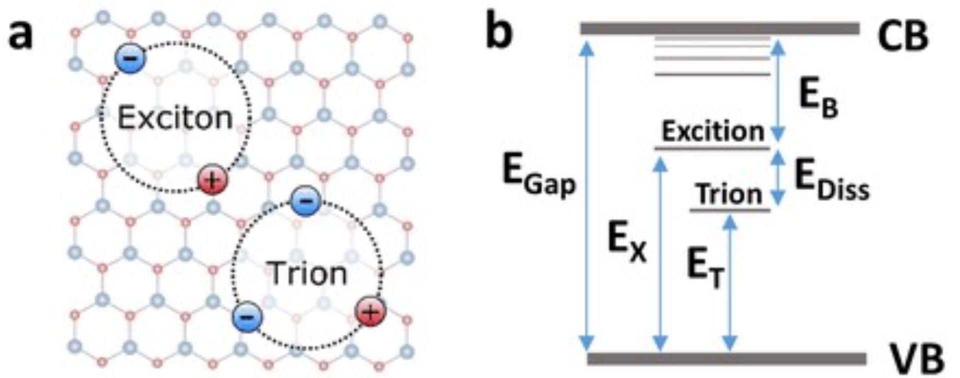
Gauge factor (meV/%)	X_A This work	X_A Theory	X_B This work	X_B Theory
$1L\text{-}WS_2$	**-129 ± 3**	-151[1] -144.0[2]	-112 ± 10	-130[1] -123.8[2]
$1L\text{-}MoS_2$	-100 ± 3	-110[1] -112.5[2]	-90 ± 5	-107[1] -109.8[2]
$1L\text{-}WSe_2$	-120 ± 3	-134[1] -131.2[2]	-129 ± 10	-111[1] -109.7[2]
$1L\text{-}MoSe_2$	-64 ± 4	-90[1] -98.6[2]	-66 ± 4	-89[1] -97.2[2]

1: Frisenda, NPJ 2D materials,2017 2: Zollner,PRB, 2019

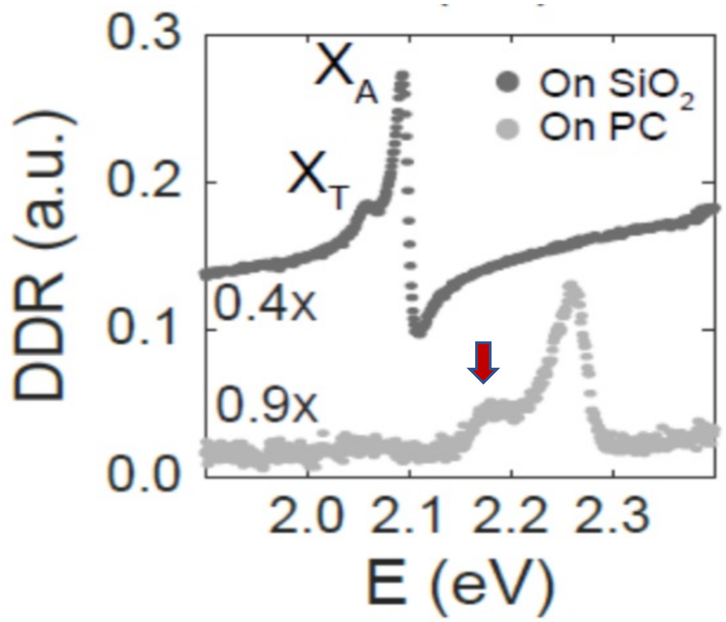
- Very good strain transfer
- Unprecedent ammount of biaxial compressive strain (~1.2%)

Micro-reflectance spectroscopy

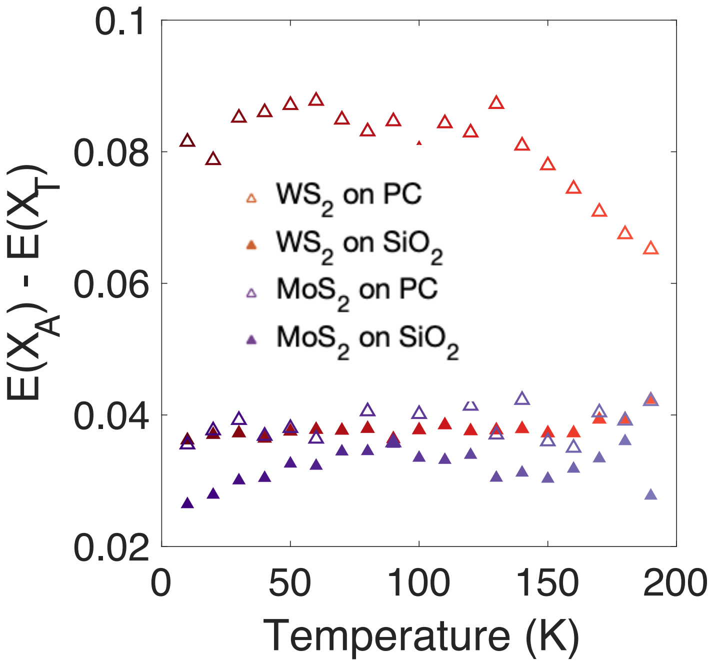


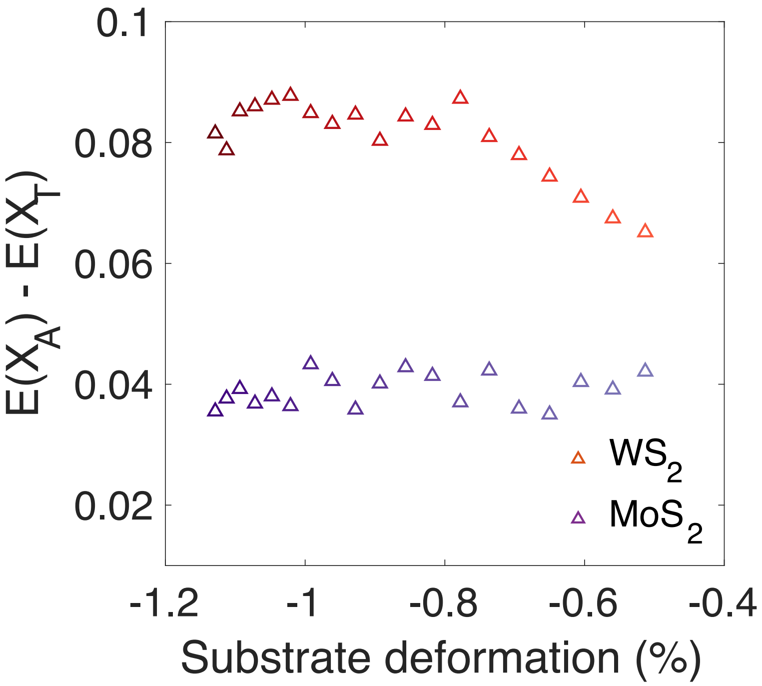


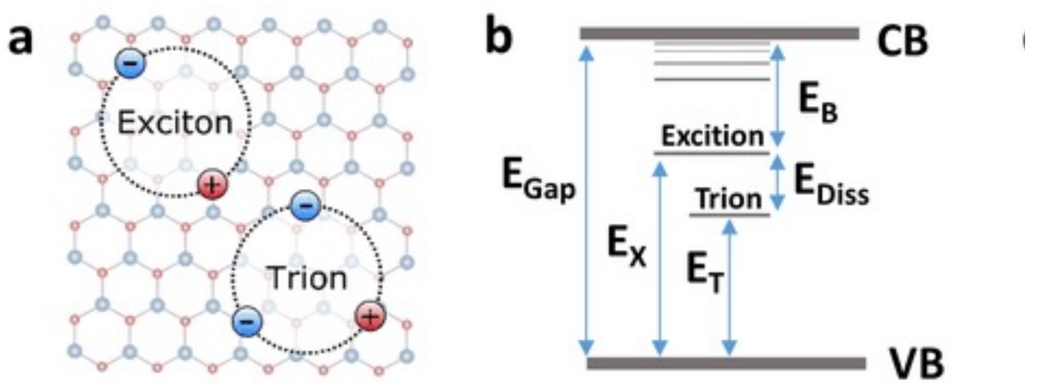
N. Lundt PhD thesis 2019



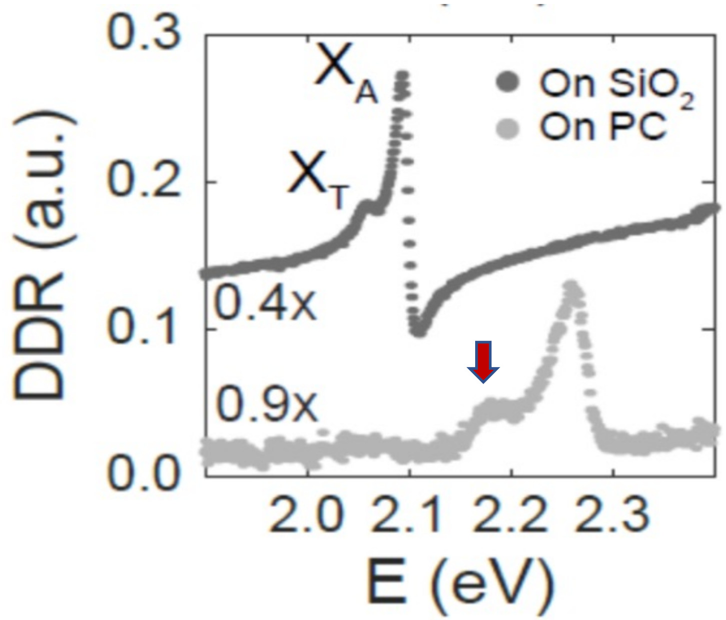
Micro-reflectance spectroscopy







N. Lundt PhD thesis 2019

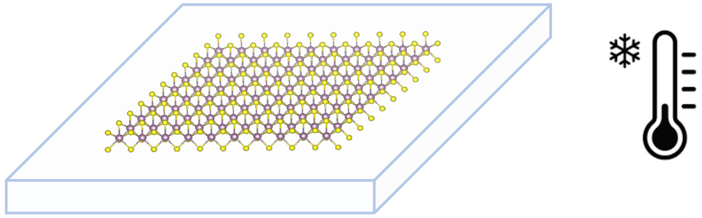


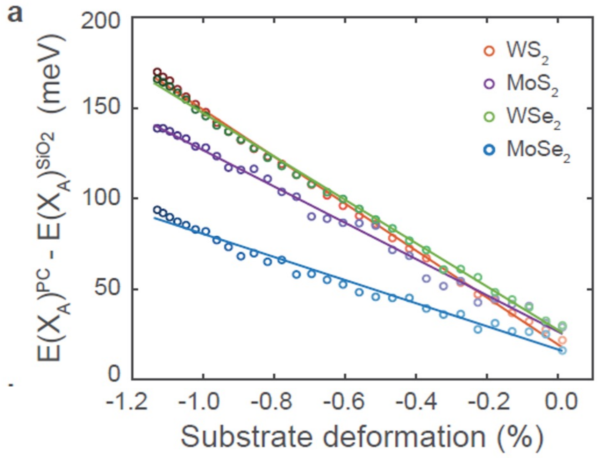
E_b (X_T) (meV)	on SiO2	On PC
MoS_2	~25	~40
WS_2	~40	~80

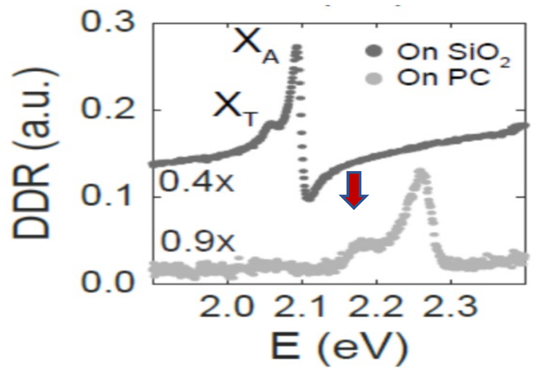
Binding energies for exciton and trions depend on

- Effective masses
- Dielectric screening
- Doping levels

Conclusions and outlook







- Thermal compression suitable methods to study effects of compressive biaxial strain in 2D materials

- Low temperature regime enables high spectroscopy resolution, allow study of excitonic complexes under strain: interest for valleytronics and exciton transport

- Strain engineering for many other quantum properties in low temperature phases: from phase transition to other quantum properties tuned or induced by strain

Eudomar Henriquez

Marcos Gadea

Daniel Gosalbez

Roberto D'Agosta

Li Hao

Andres Castellanos

Lisa Almonte

Juan David Cortes

Universitat d'Alacant
Universidad de Alicante

Universidad del País Vasco
Euskal Herriko Unibertsitatea

icmm

CSIC
Consejo Superior de Investigaciones Científicas

Q2D@UA

Universitat d'Alacant
Universidad de Alicante

GENERALITAT VALENCIANA

Gen—T

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES