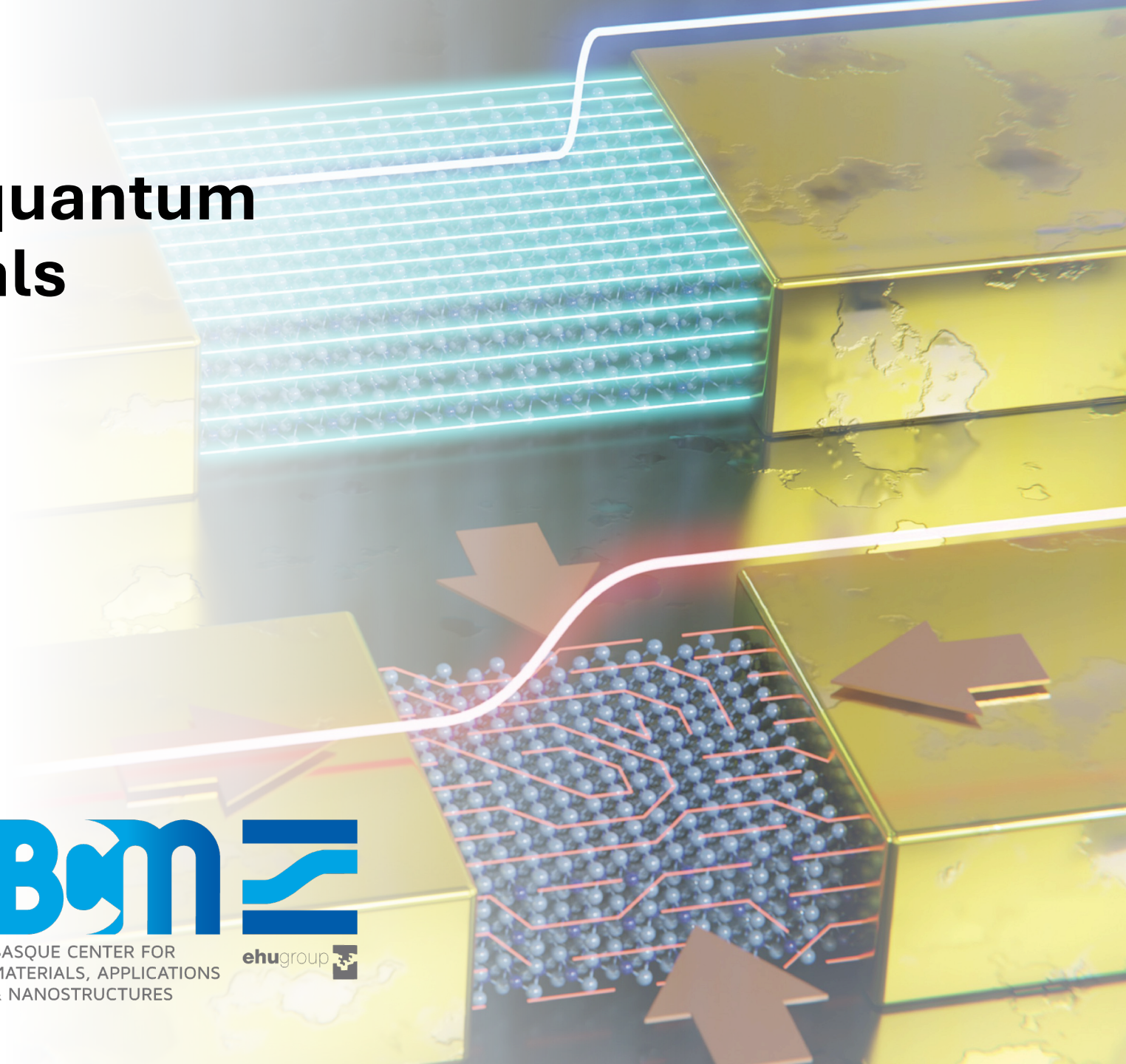
Strain engineering quantum states in 2D materials

Reyes Calvo

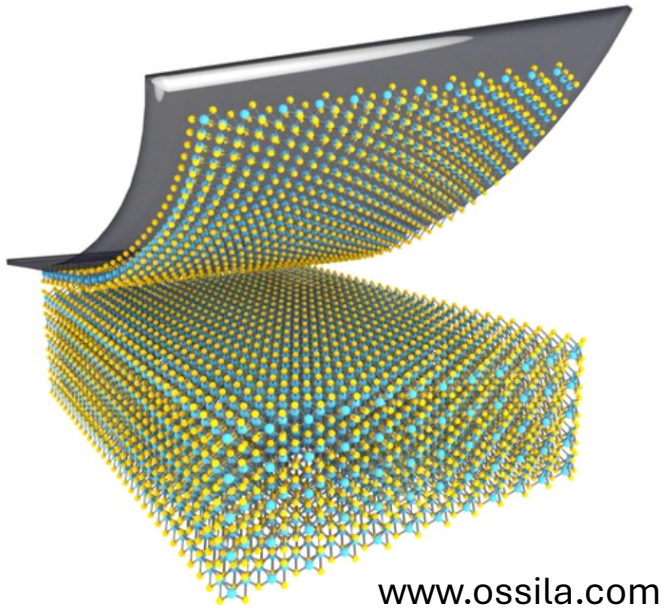
ikerbasque
Basque Foundation for Science

BASQUE CENTER FOR
MATERIALS, APPLICATIONS
& NANOSTRUCTURES

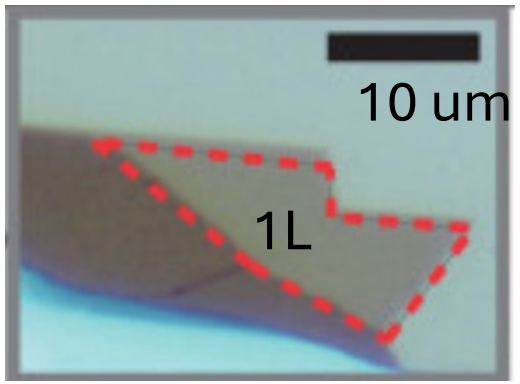
ehugroup



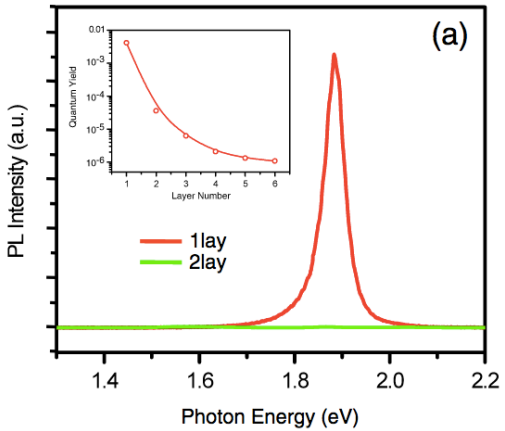
van der Waals materials



www.ossila.com

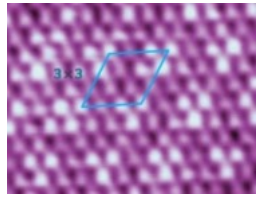


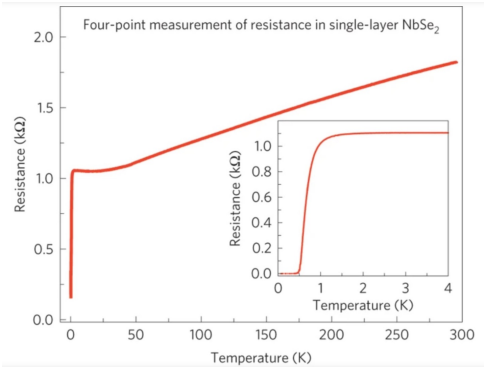
Excitonic states



Mak et al. Phys. Rev. Lett. (2010)

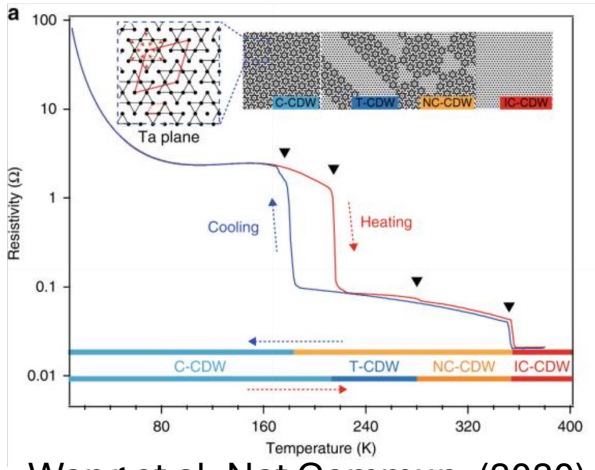
Superconductivity





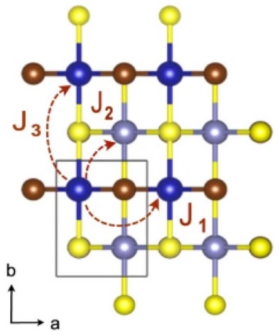
Ugeda et al. Nature Physics 12 (2016)

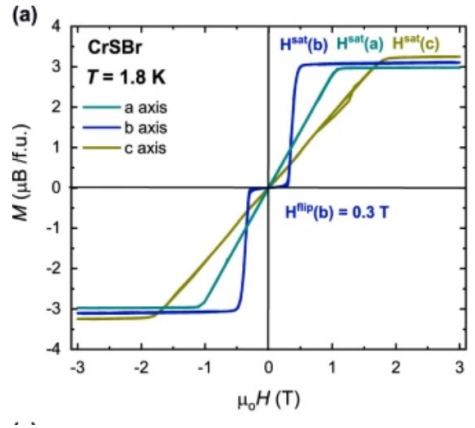
CDW phases



Wang et al. Nat Commun. (2020)

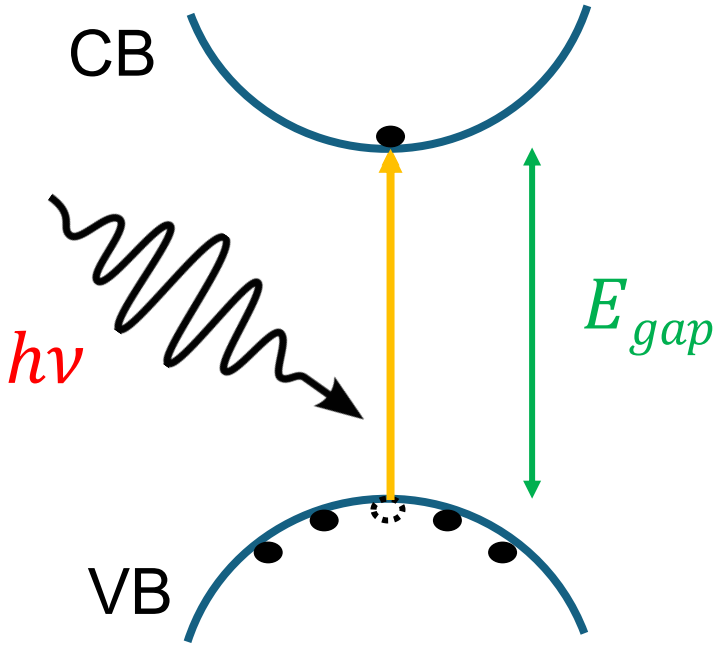
Magnetic order

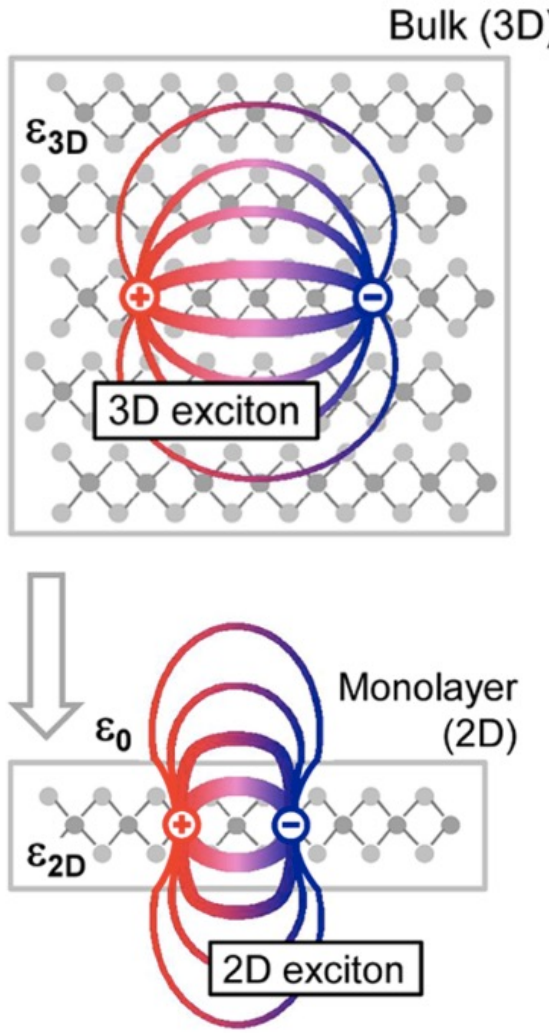




Lopez-Paz et al. Nature Communications (2022)

Excitonic properties in 2D semiconductors





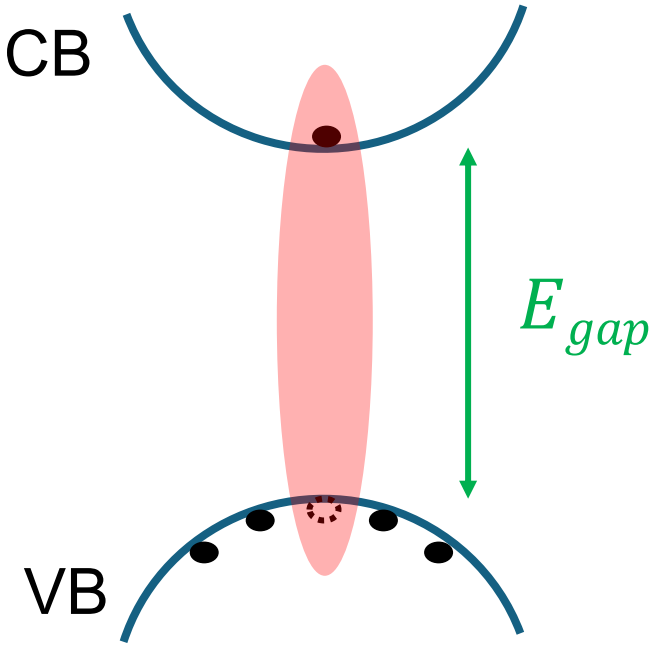
At the single layer limit:

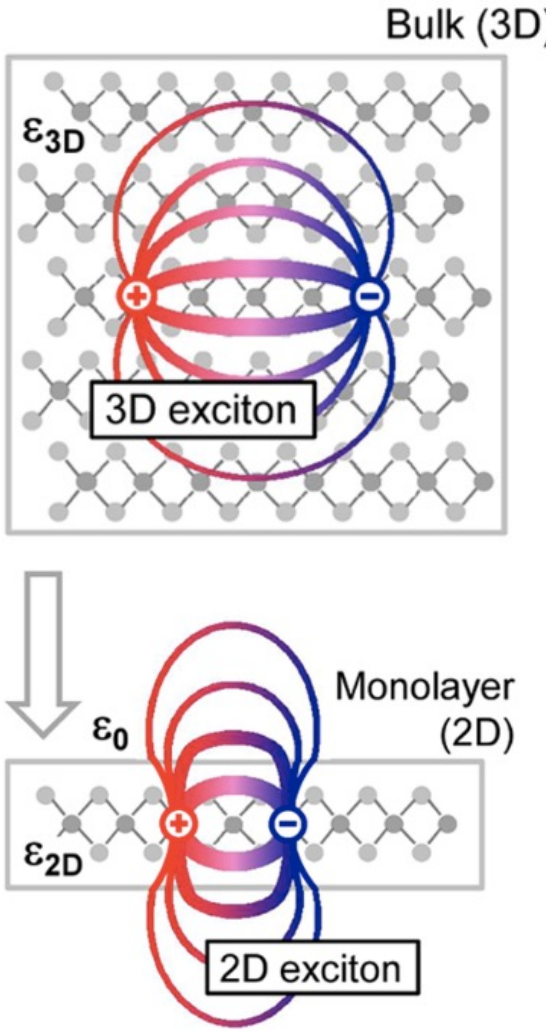
- Direct Bandgap
- Reduced dielectric screening

Splendiani et al. *Nano Lett*. 2010, 10, 127

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

Excitonic properties in 2D semiconductors





At the single layer limit:

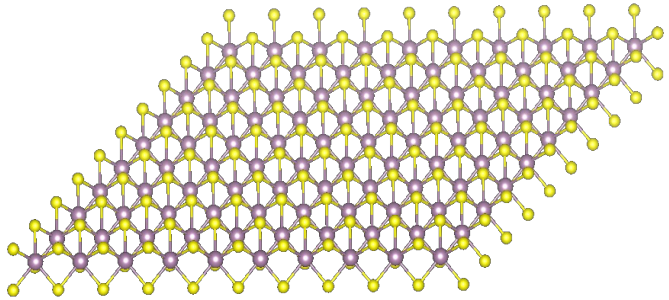
- Direct Bandgap
- Reduced dielectric screening
- Bound states: **excitons**

Splendiani et al. *Nano Lett*. 2010

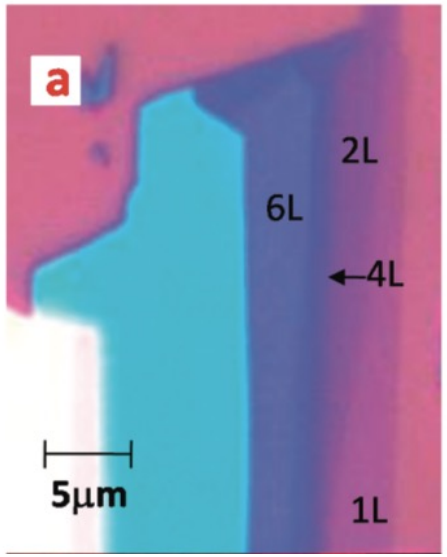
Chernikov et al. *PRL* 113 2014

Excitonic properties in 2D semiconductors

Transition Metal Dichalcogenides (TMDCs)

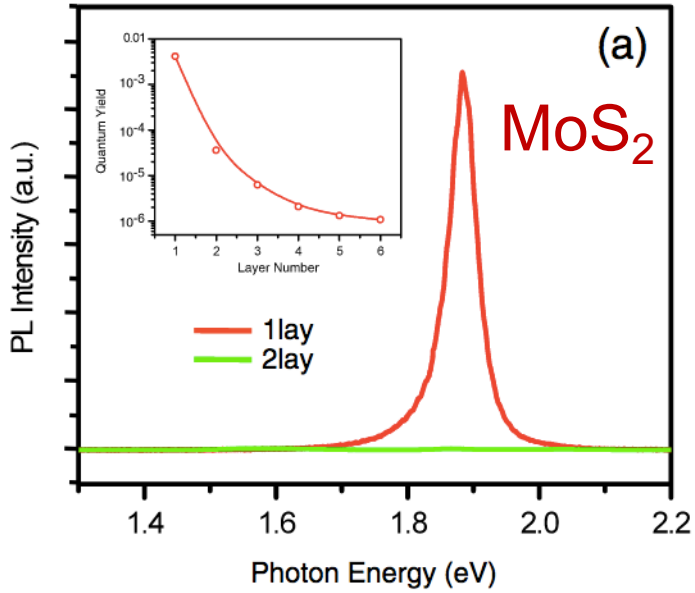


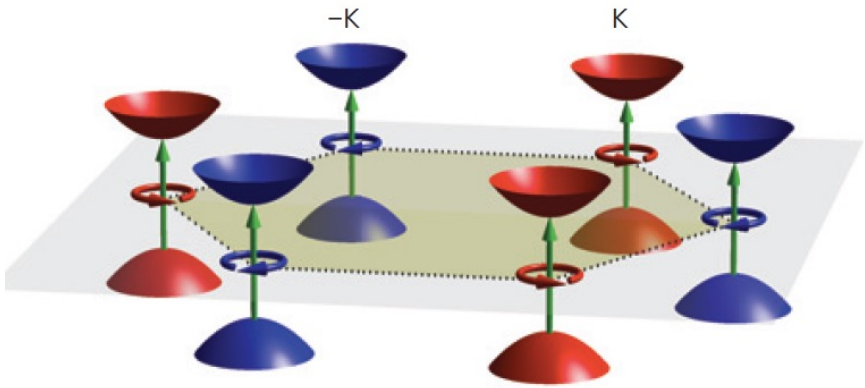
- M: Mo, W
- X: S, Se, Te



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

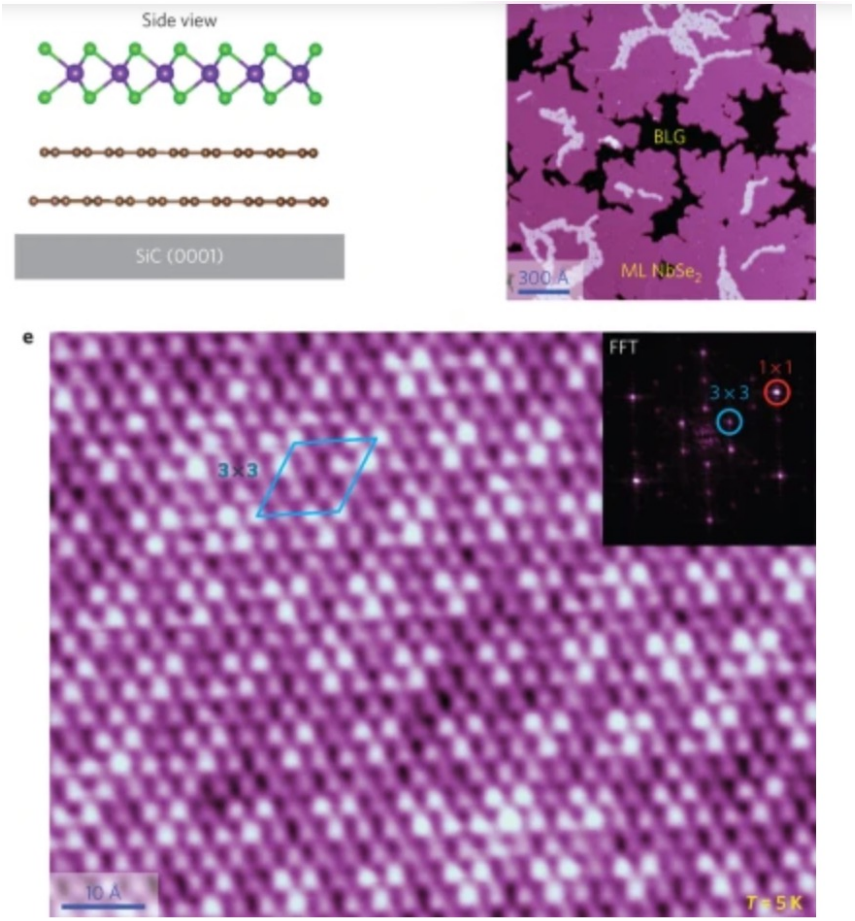
Robust optical properties



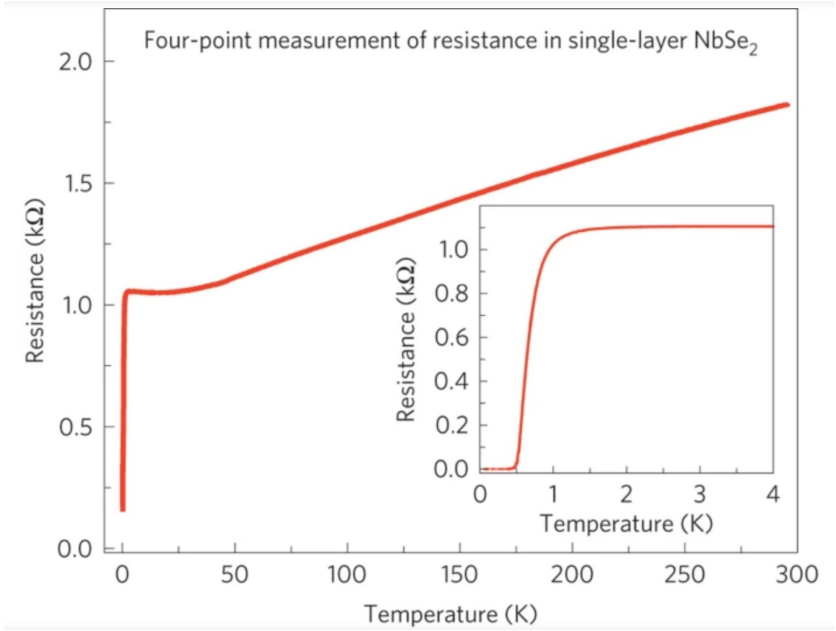


Pseudo-spin degrees of freedom

Superconductivity at the 2D limit

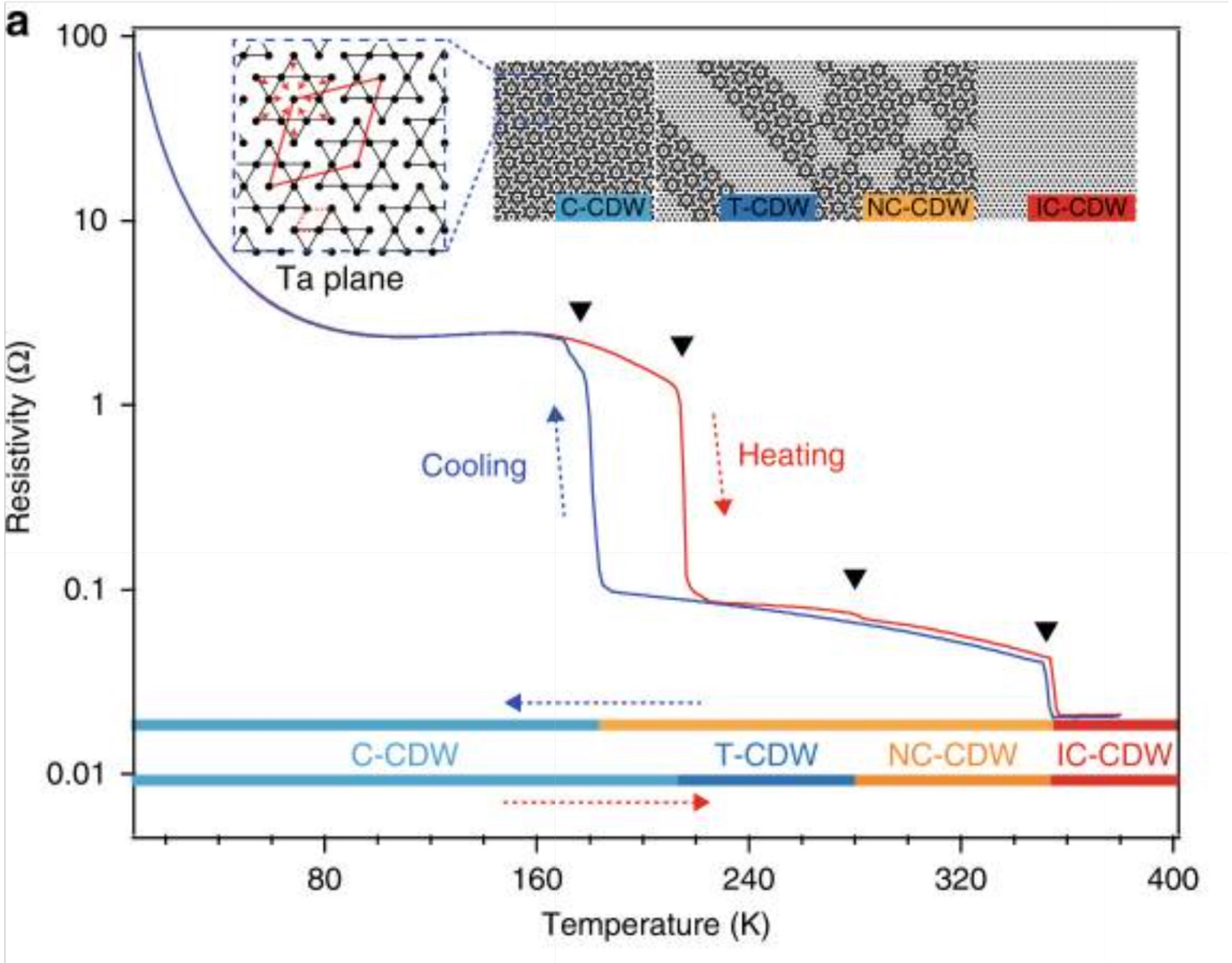


$NbSe_2$

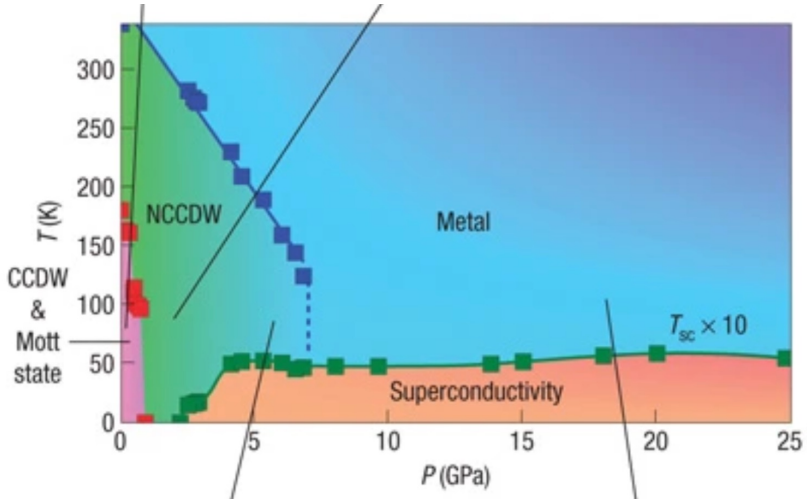


Ugeda et al. Nature Physics 12 (2016)

Charge density wave phases in van der Waals materials

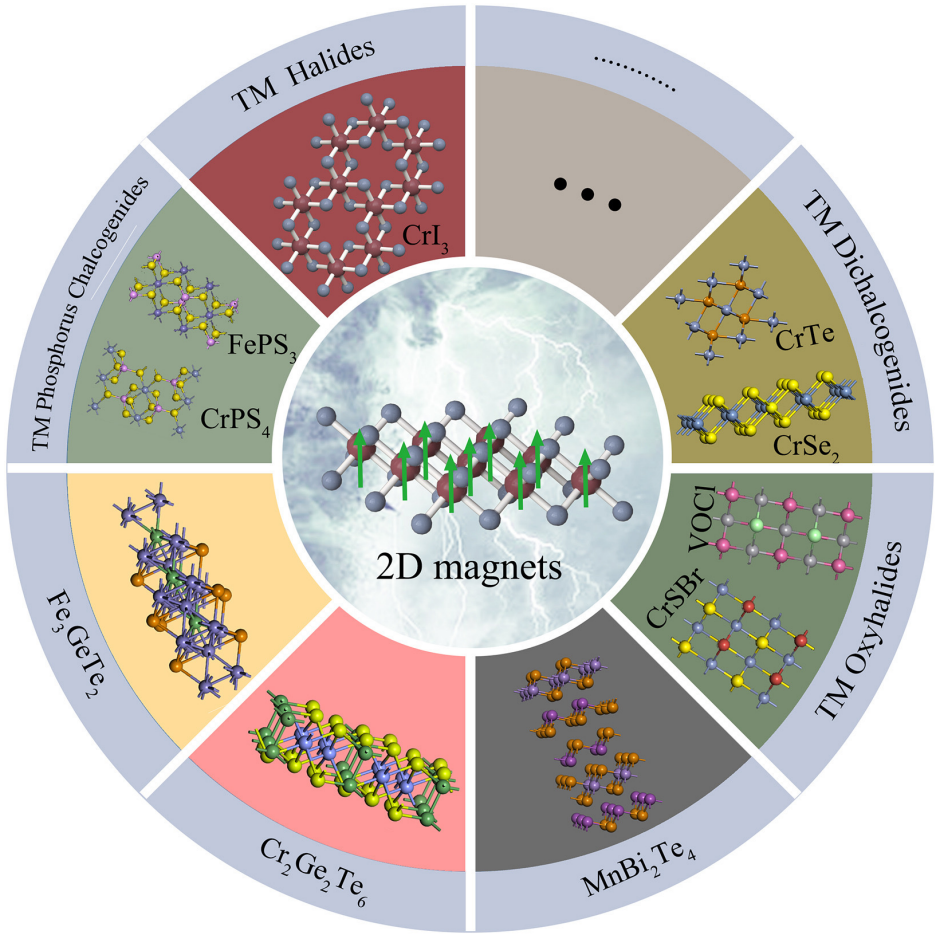


Wang et al. Nat Commun. 24, 11 (2020)

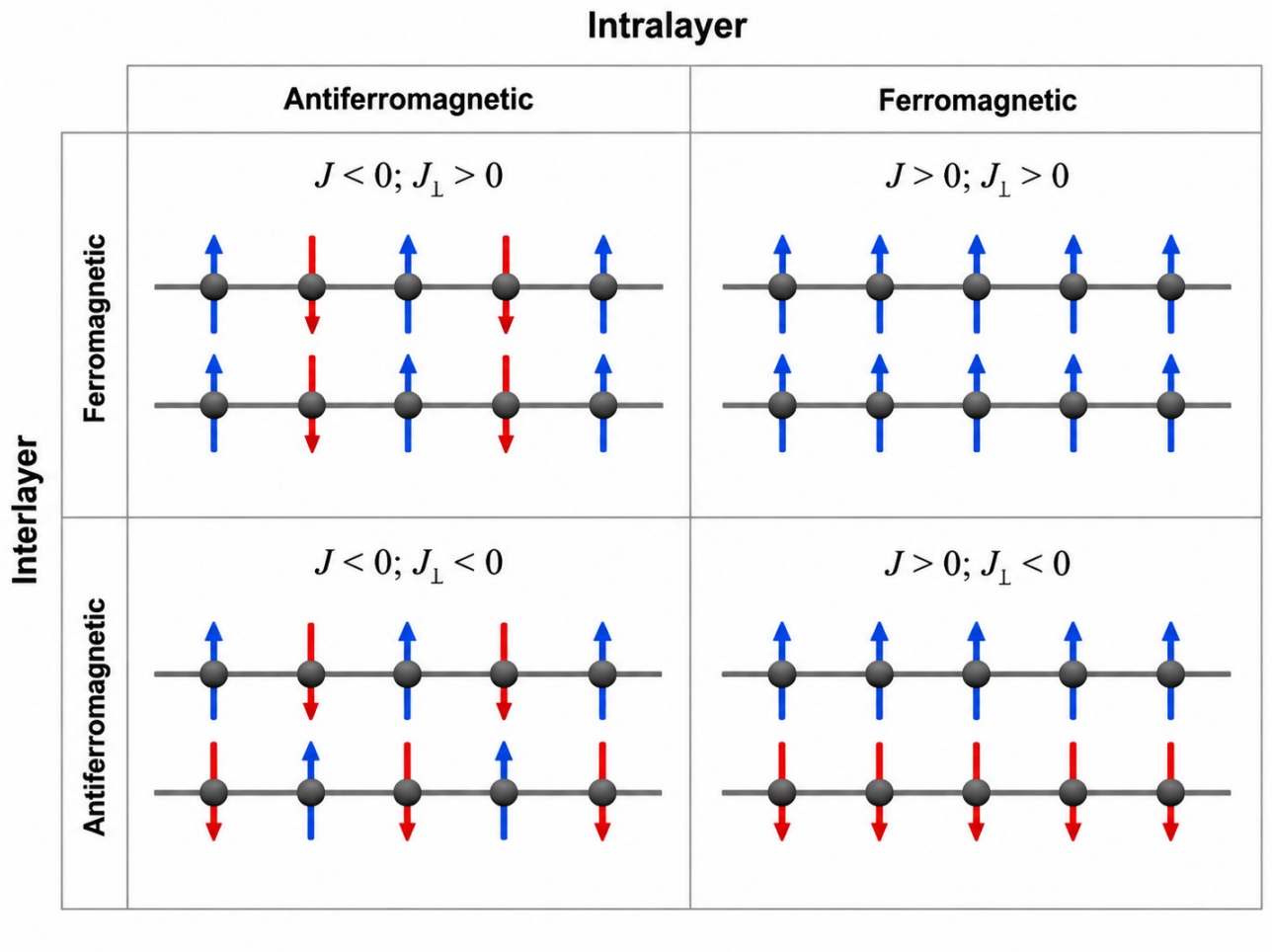


Sipos et al. Nature Materials 7, 960 (2008)

Anisotropic magnetic order in 2D magnets

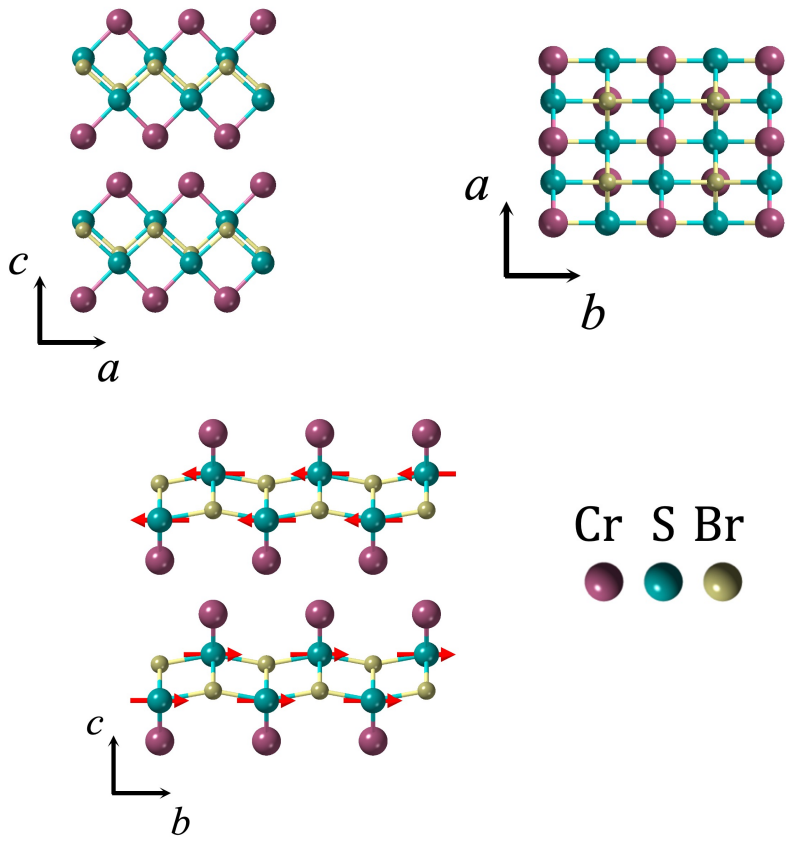


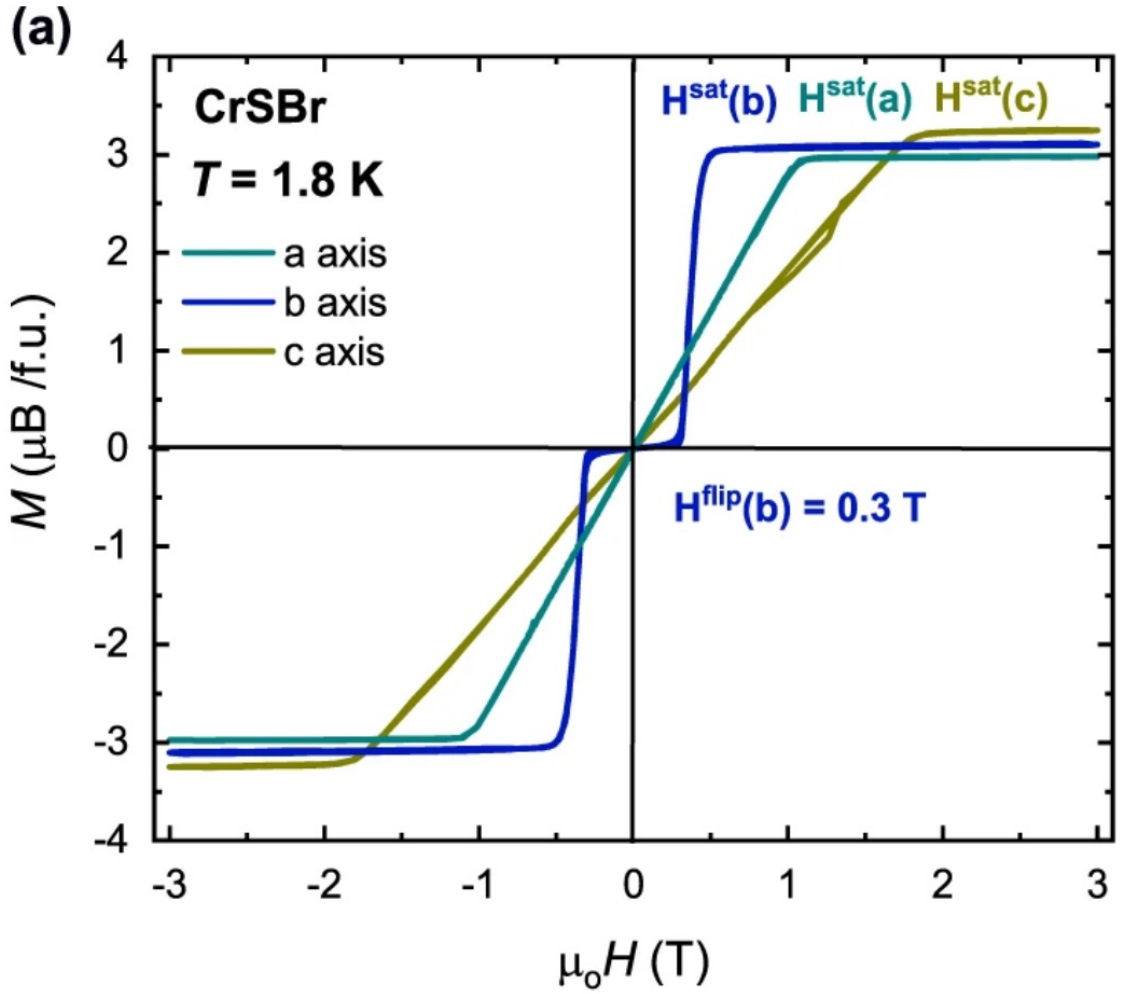
Liu et al. iScience, 26, 107584, 2023



Gilbertini et al. Nat. Nanotech. 14, 2019

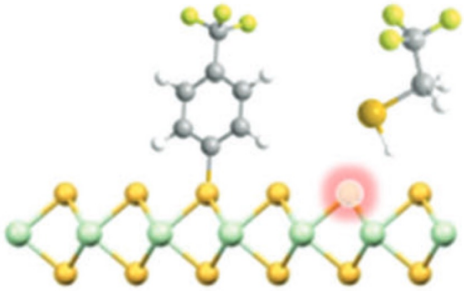
Anisotropic magnetic order in 2D magnets



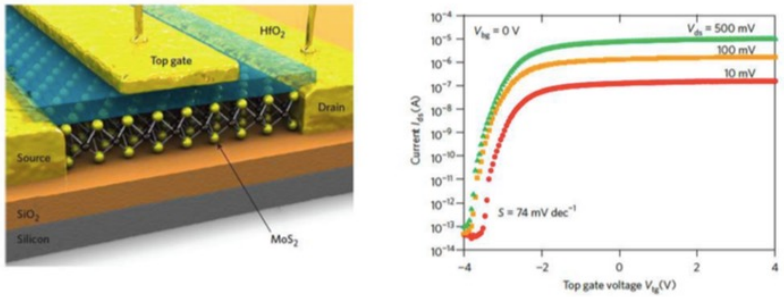


Lopez-Paz et al., Nature Communications 13, 4745 (2022)

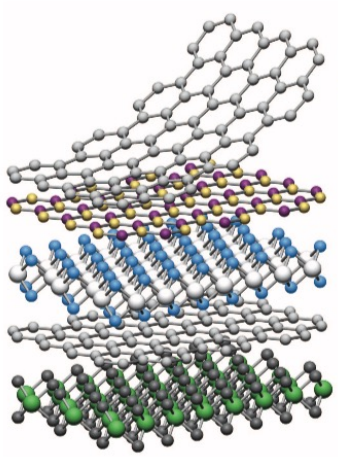
Tuning the properties of 2D materials



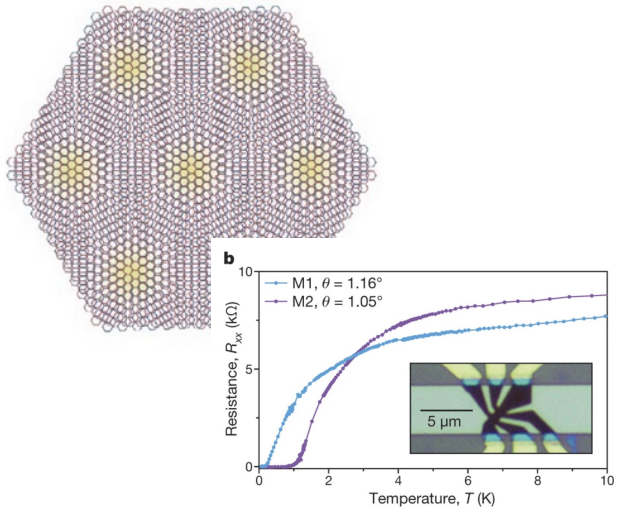
Bertolazzi, *Chem. Soc. Rev.* **47**, (2018).



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



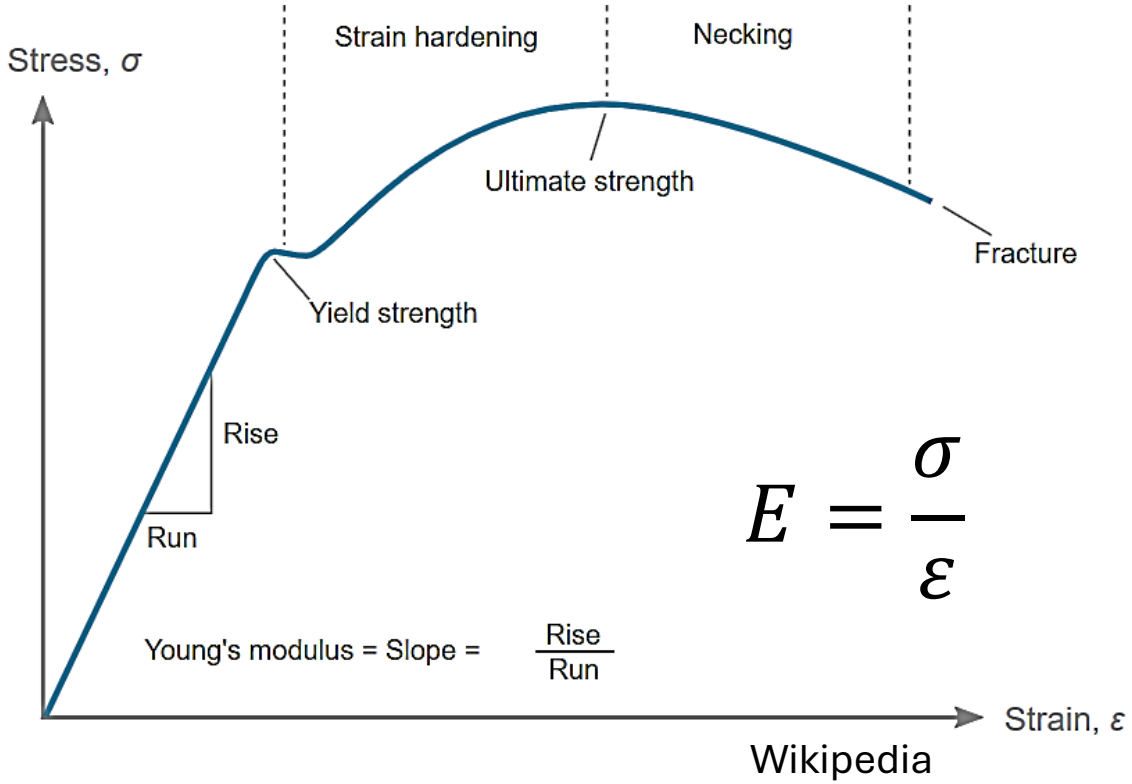
Novoselov *PNAS* **102**, (2005).



Cao et al. *Nature* **556** (2018)

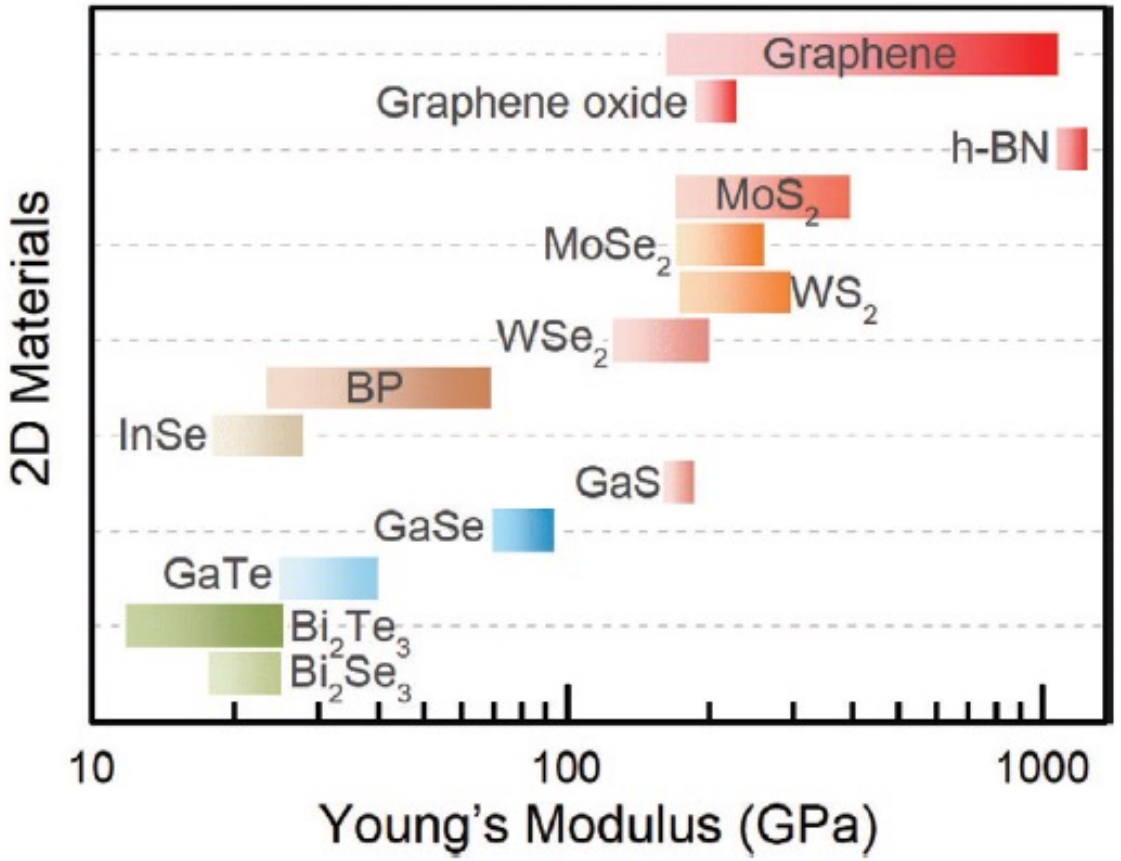
- electrostatic gating
- environment
- vdW heterostructures
- moiré superlattices
- **strain engineering**

Strain engineering 2D materials



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

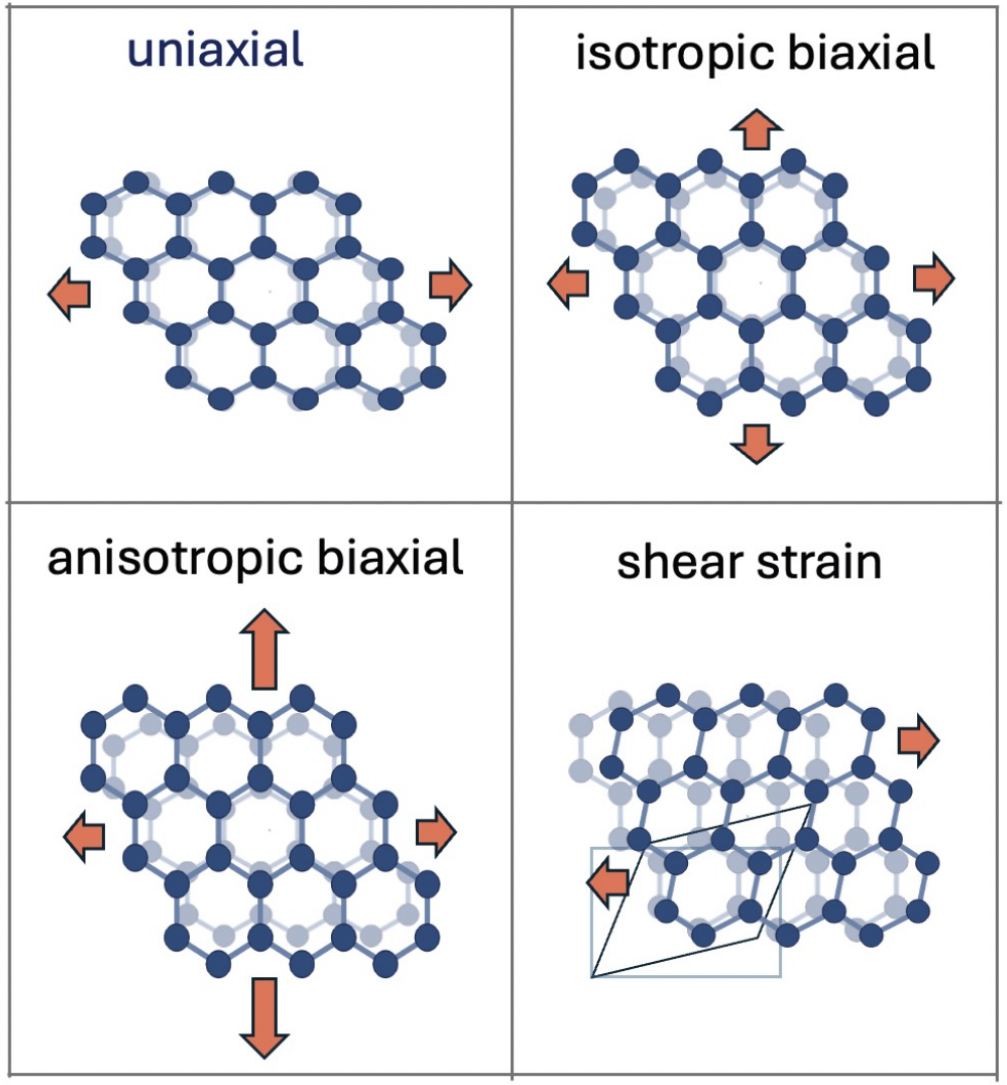
Du, J. Small Methods, 5, 2021



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

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

Strain engineering 2D materials



Mechanical deformation modifies the crystal lattice:

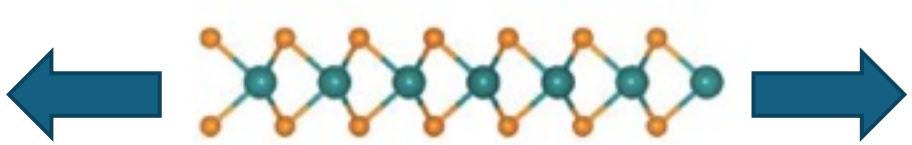
- bond lengths and angles
- orbital overlap / bandwidth
- electron–phonon coupling
- exchange interactions
- crystal symmetry

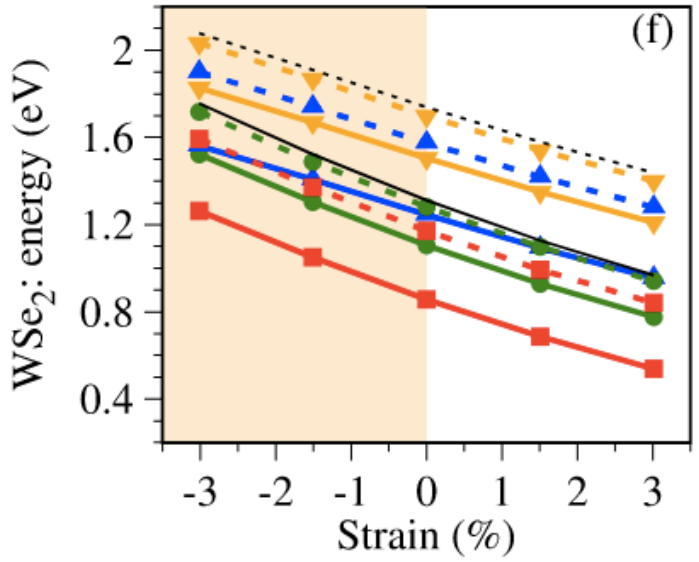
Direct control of electron interactions

Modulation of electronic phases

Strain engineering 2D materials

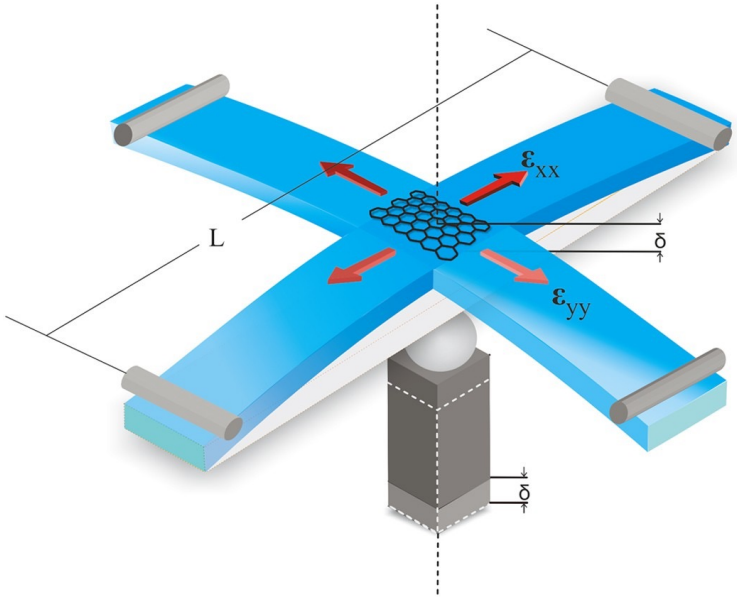
Tensile strain

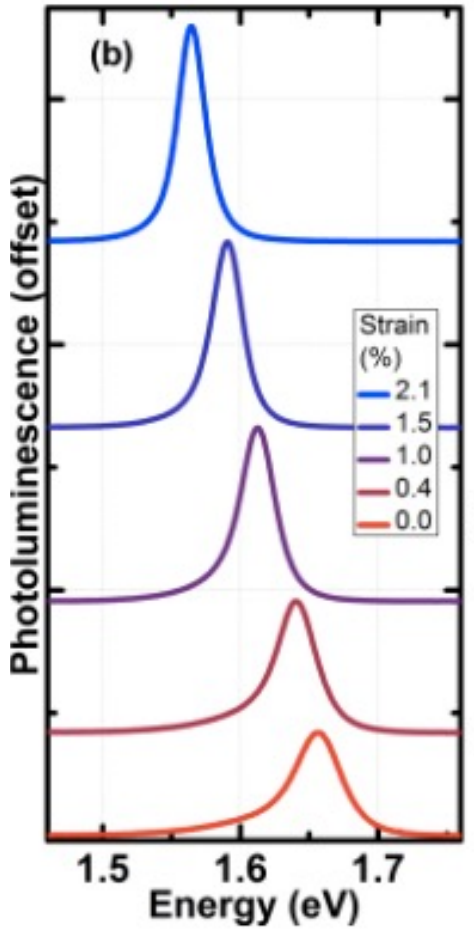




Zollner et al. Physical Review B 100 2019

Aslan et al. PRB 98 2018

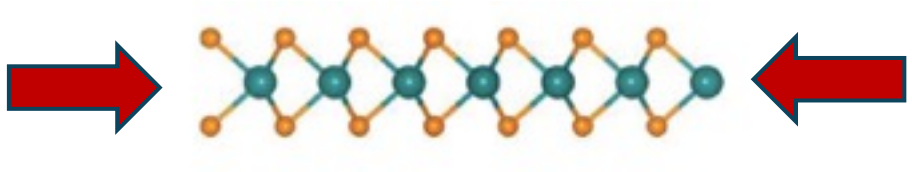


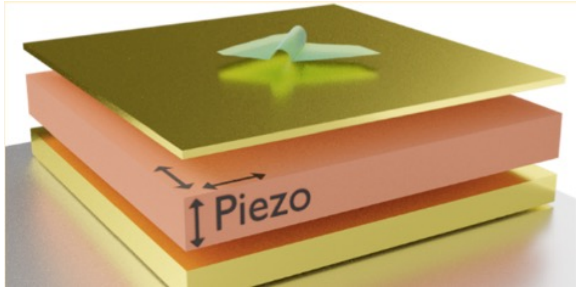


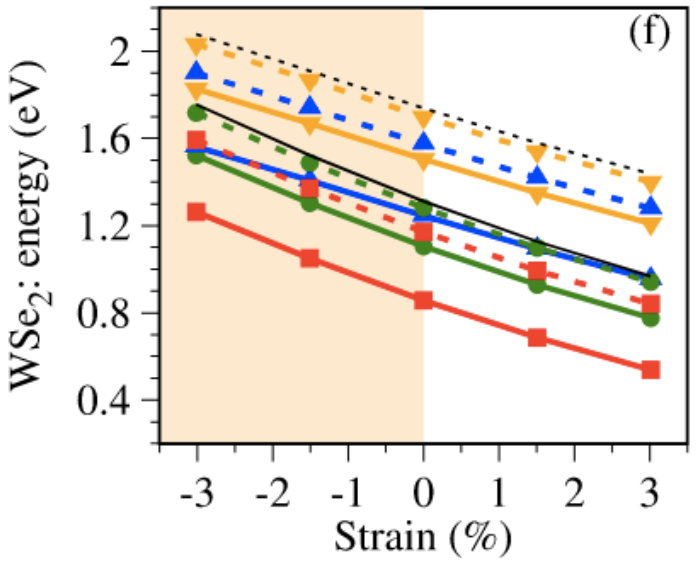
Most experimental strain engineering in 2D materials has focused on semiconductors at room temperature

Strain engineering in 2D semiconductors

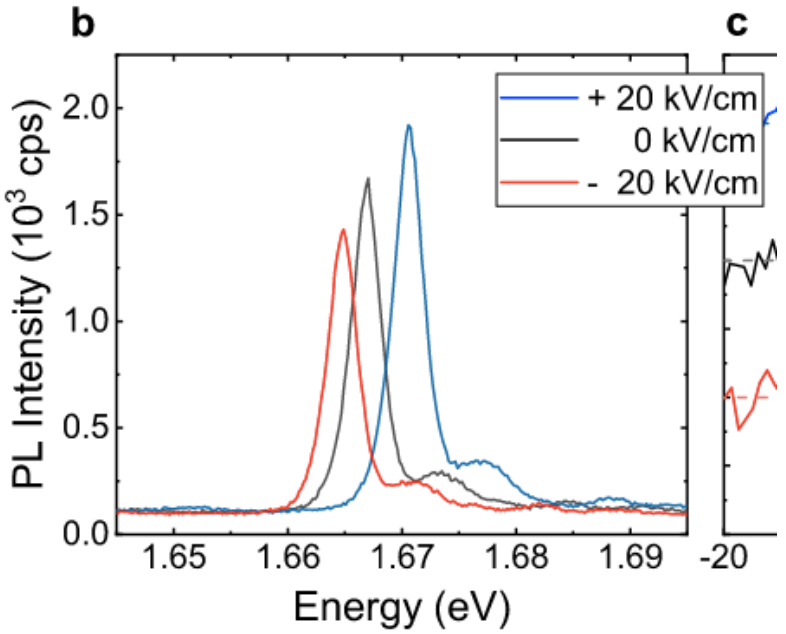
Compressive strain







Zollner et al. Physical Review B 100 2019

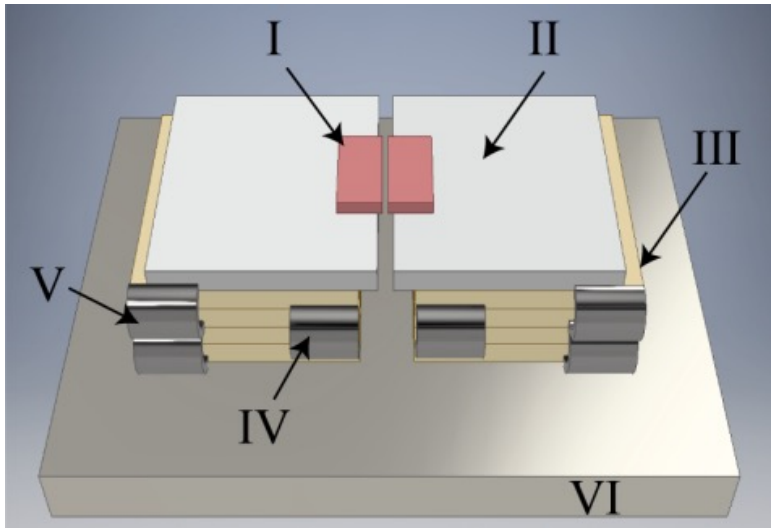


Piezo actuators

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

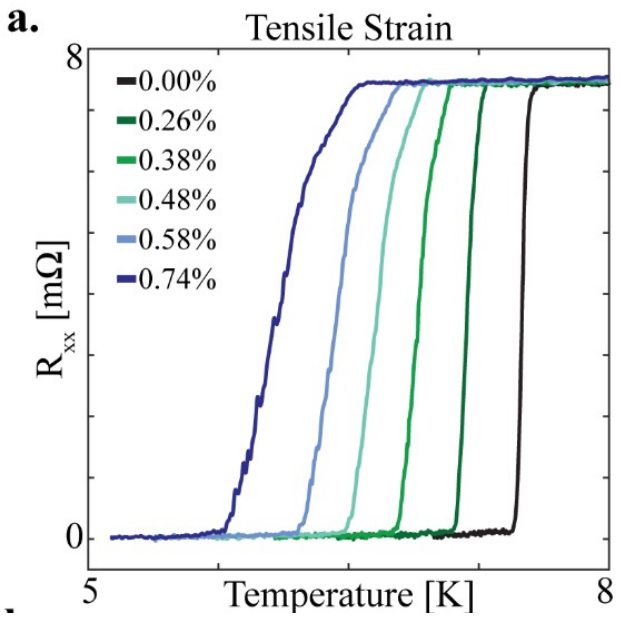
Iff et al. Nano Letters 19 2019

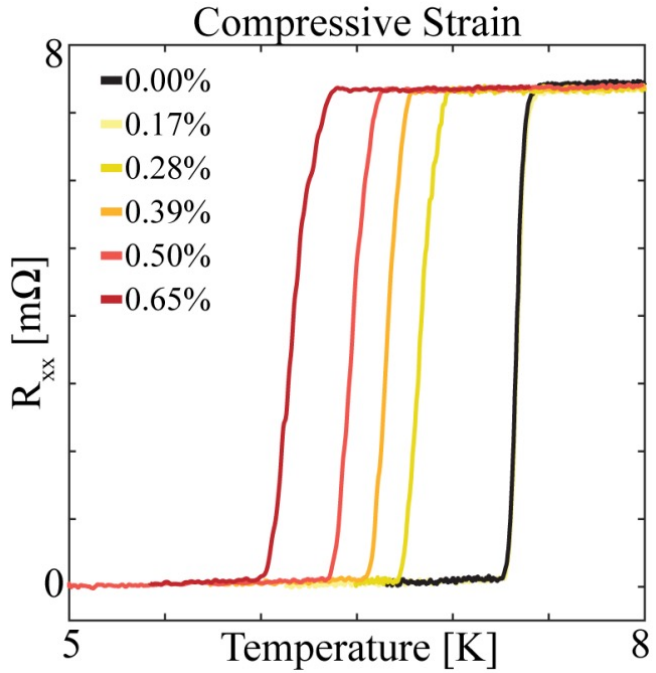
Strain engineering superconductivity in $NbSe_2$

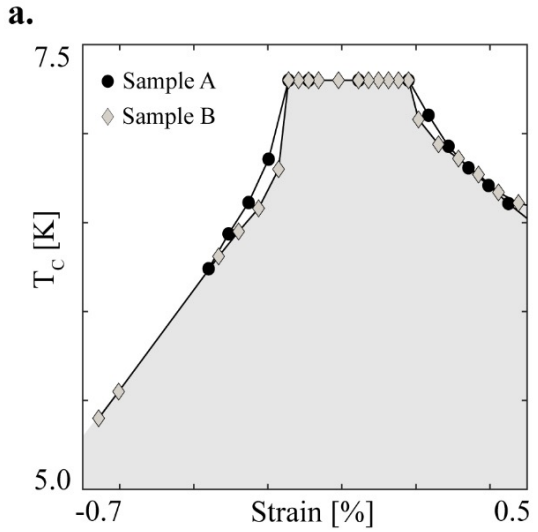


Wieteska et al. arXiv 2019

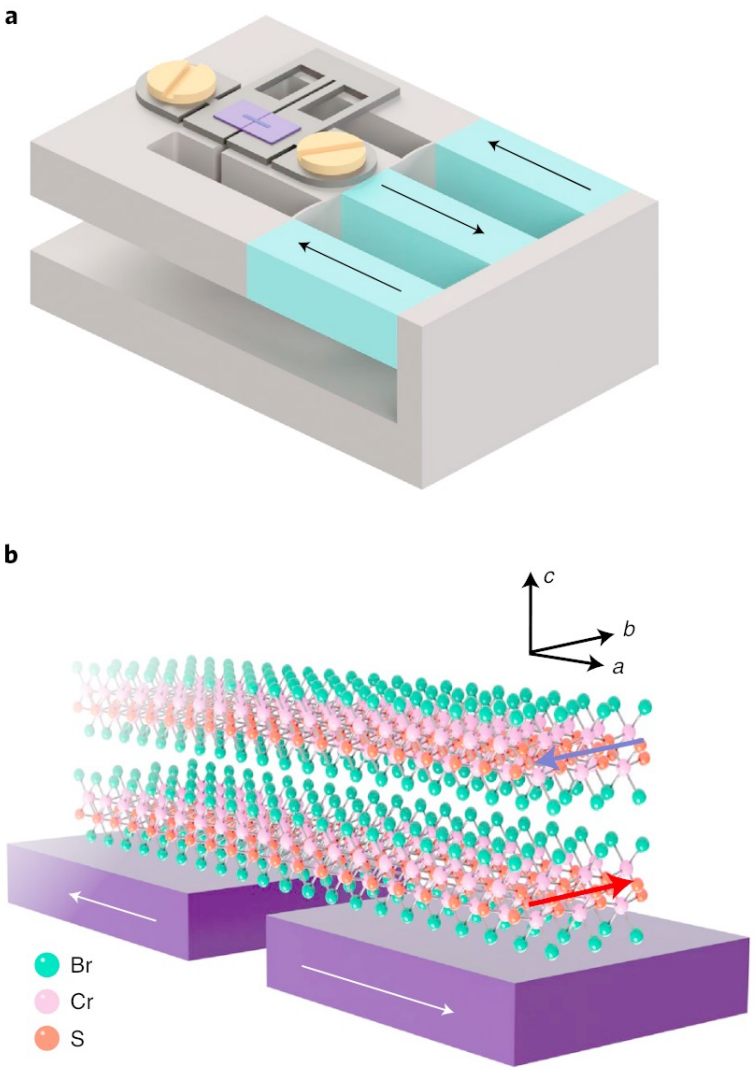
BULK $NbSe_2$ crystals
Difficult to implement with flakes







Strain engineering 2D magnetic materials



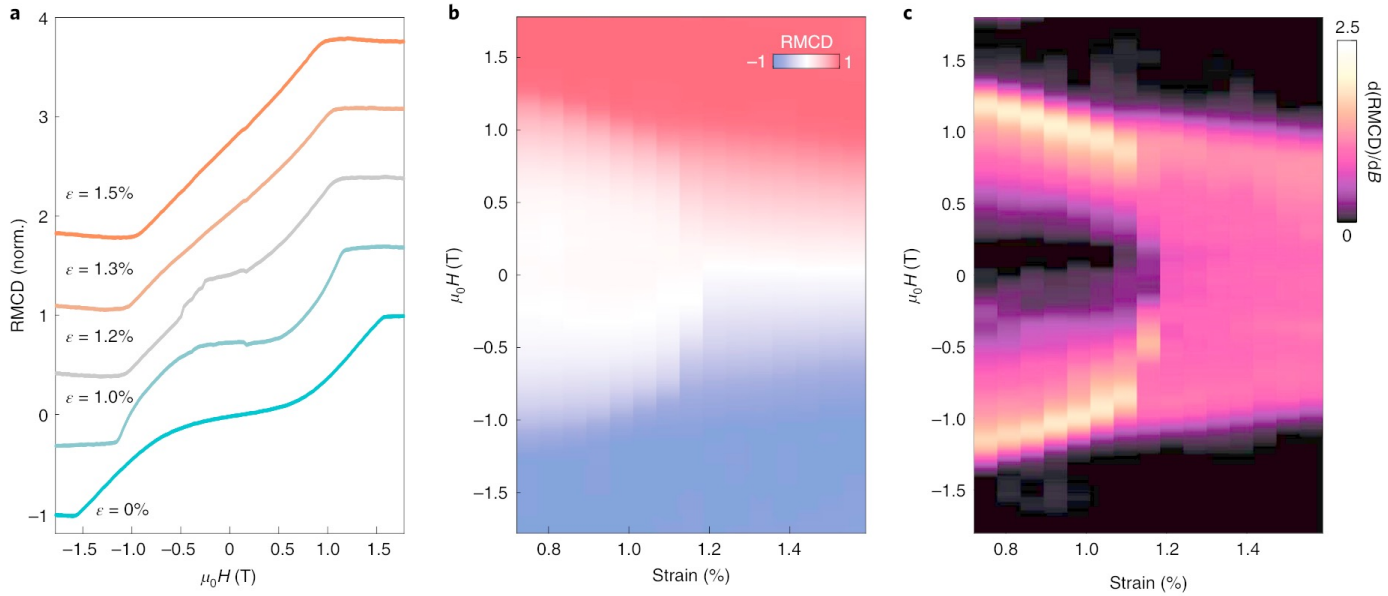
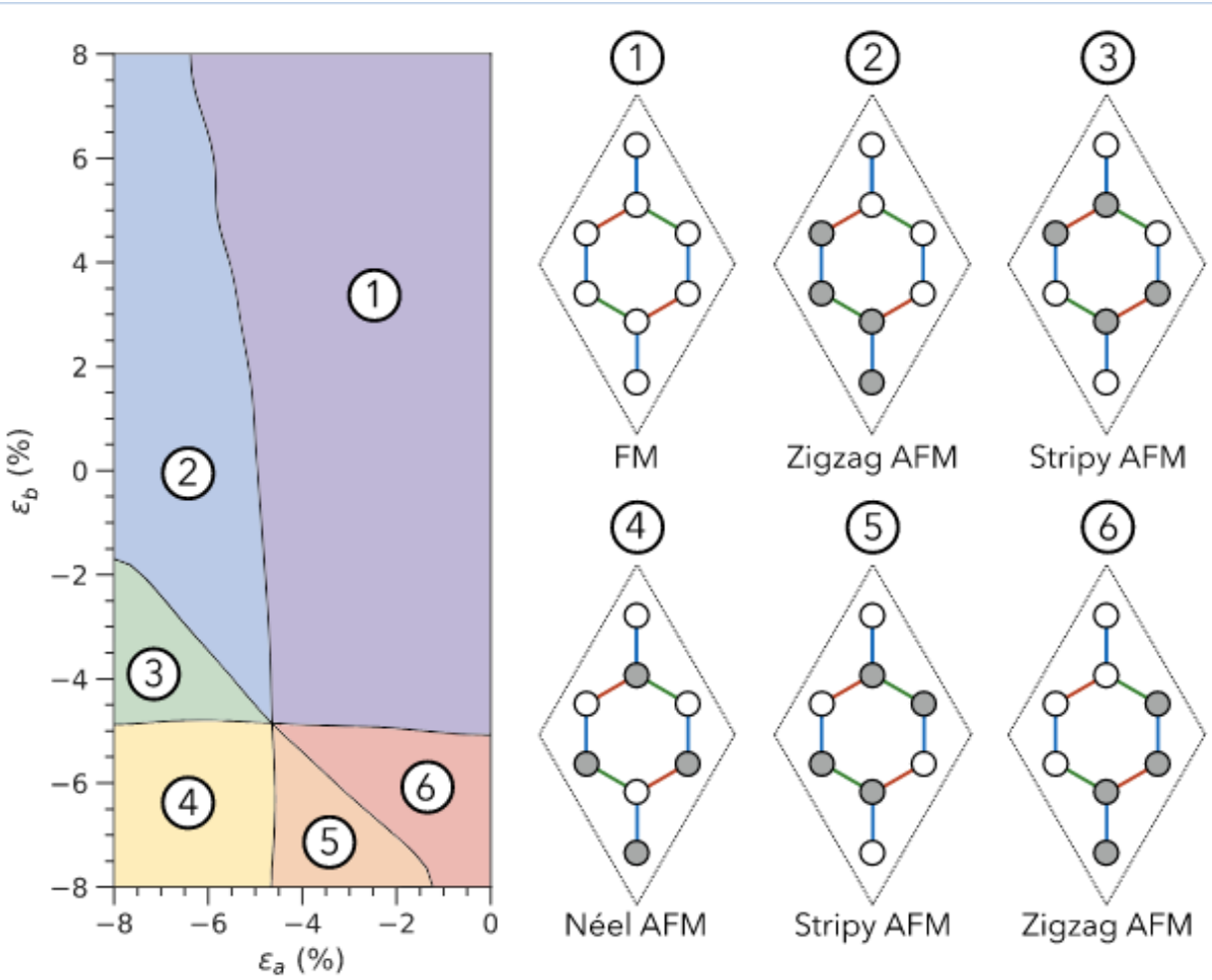


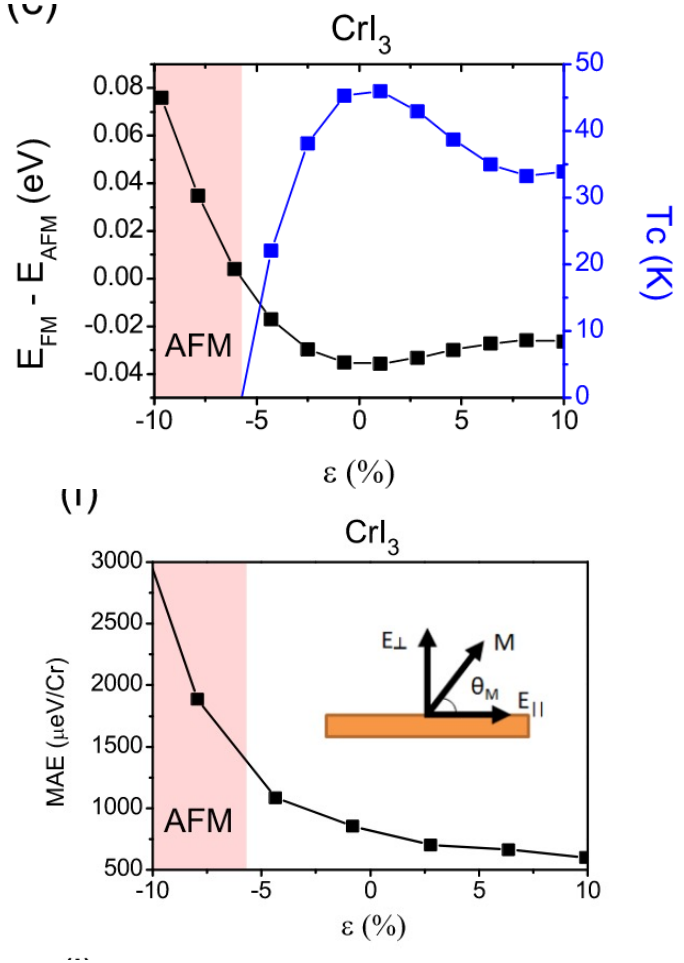
Fig. 4 | Strain tuning of the out-of-plane spin-canting process. a, Polar RMCD measurements as the out-of-plane magnetic field is swept down at select strains. RMCD sweeps are normalized at each strain value. Discrete jumps in the RMCD versus magnetic field near the critical strain (1.2% curve) imply domain effects. **b**, Colour plot of the RMCD sweeps as a function of the applied strain. **c**, Derivative of the normalized RMCD with respect to the applied magnetic field *B* as a function of strain.

Cenker et al. Nature Nanotechnology · 2022

Strain engineering 2D magnetic materials



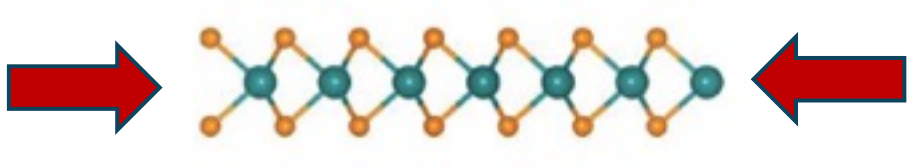
Pizzochero et al. *Phys. Chem. C* 2020, 124

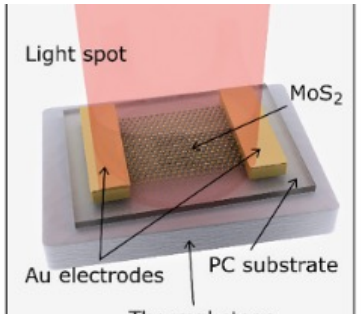


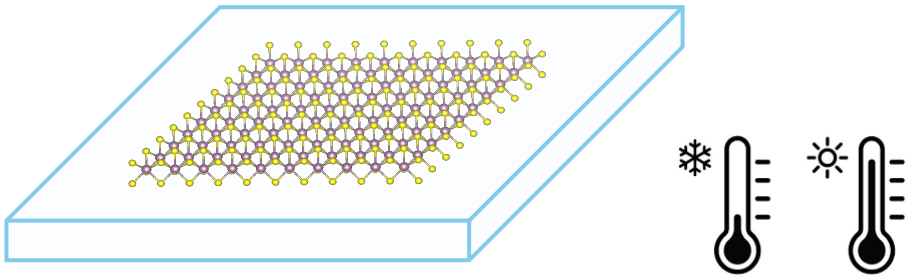
Webster *Phys. Rev. B* 98 (2018).

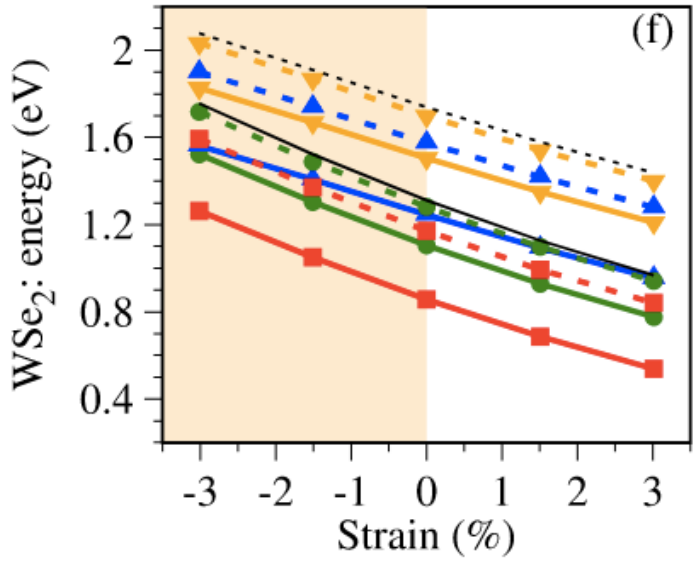
Strain engineering in 2D semiconductors: thermal mismatch

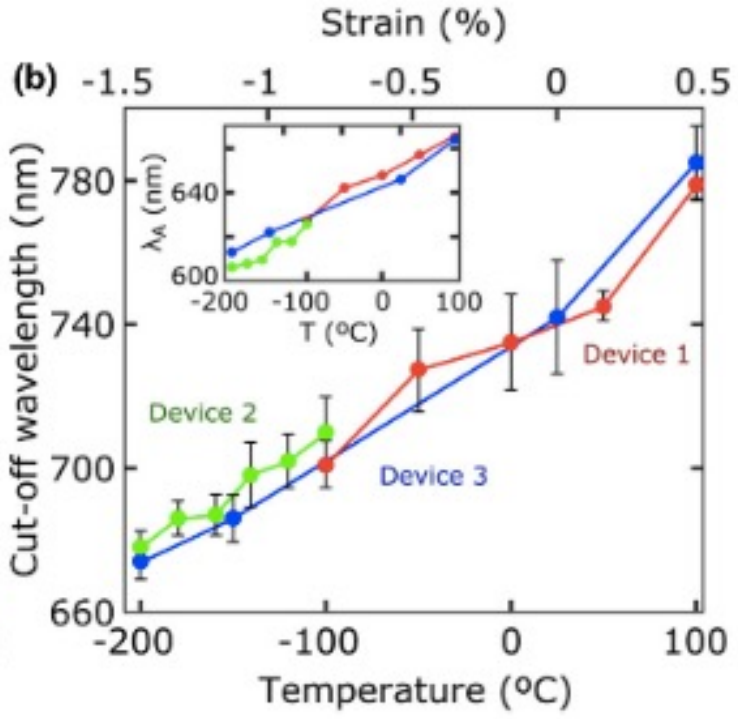
Compressive strain











Thermal expansion of Polymeric substrates:

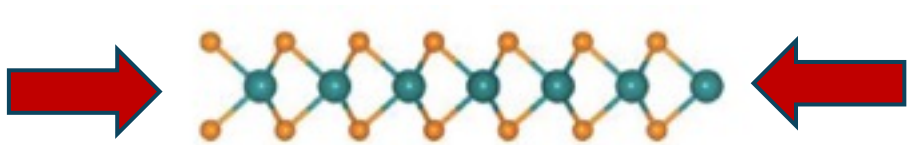
- Large thermal coefficient
- Large Young modulus
- **Expansion up to 100C**
- **Compression down to 80K**

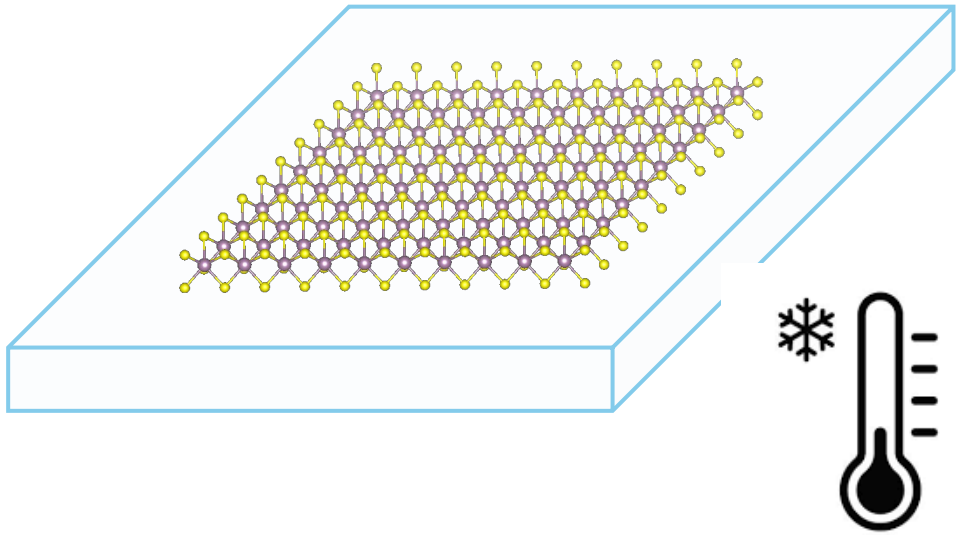
Zollner et al. Physical Review B 100 2019

Gant, …. Castellanos Materials Today 2019

Thermal compression at cryogenic temperatures

Compressive strain





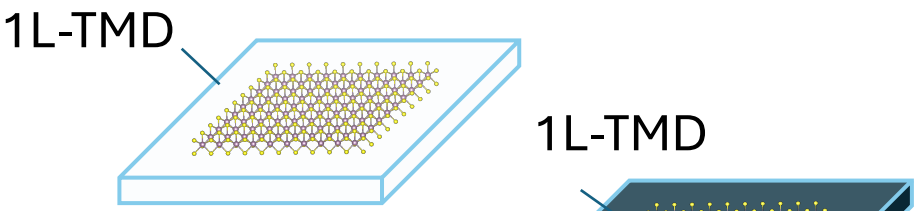
Simple preparation

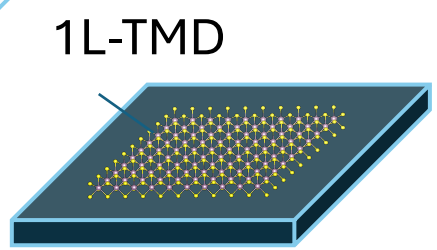
Large biaxial *compressive* strain

Strain-tuning of low temperature physics in 2D materials

- **excitonic phenomena in 2D TMDCs**
- **superconductivity in few-layered $NbSe_2$**
- **magnetic anisotropy in CrSBr**
- **CDW phase transitions in 1T-TaS_2**

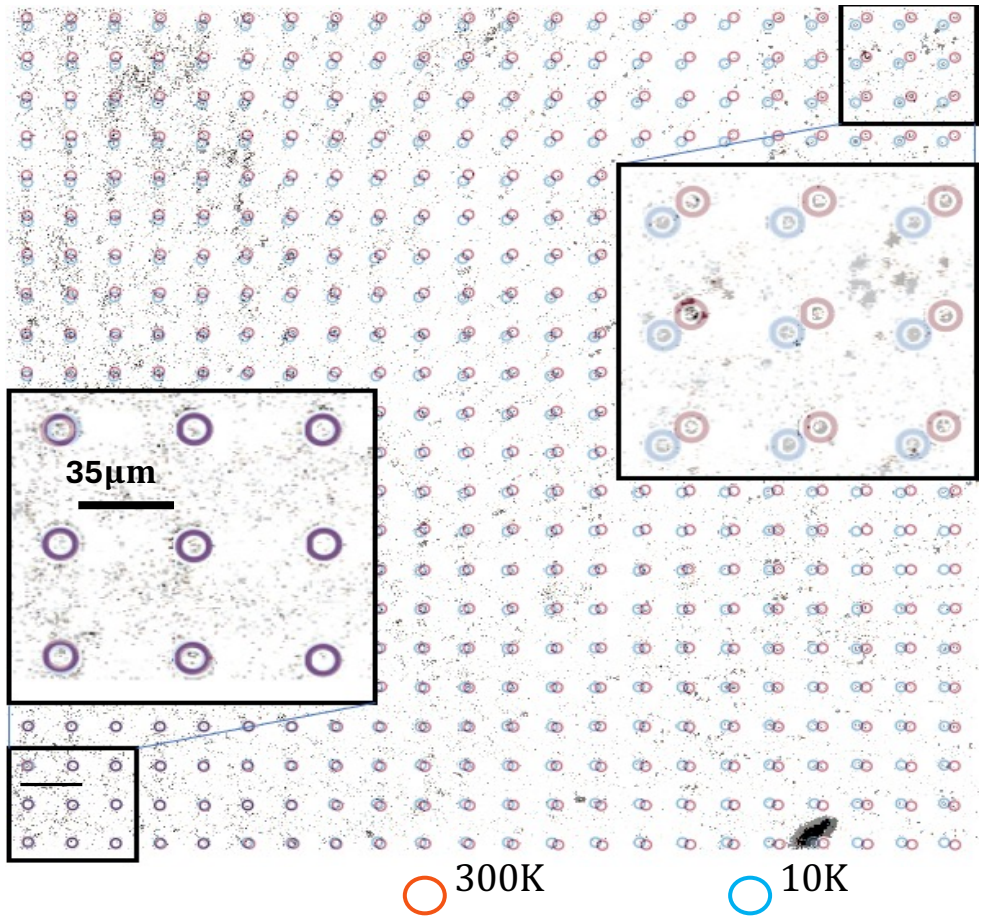
Strain engineering single-layer TMDCs

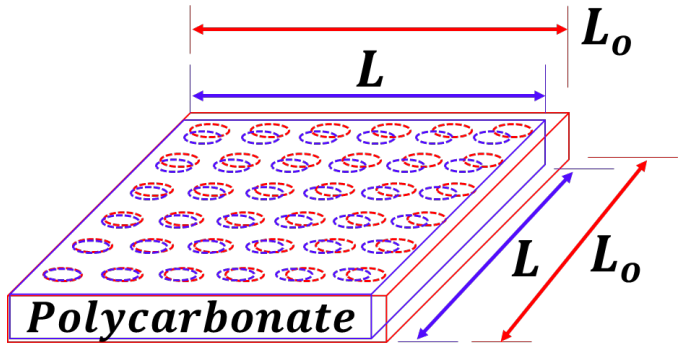




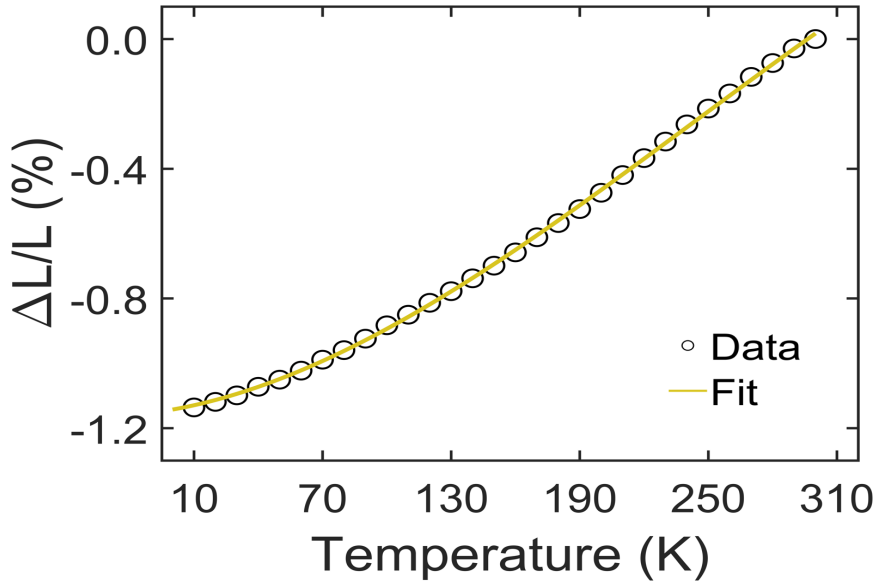
Polycarbonate substrate deformation

α ~ 6.5 10^{-5} 1/K



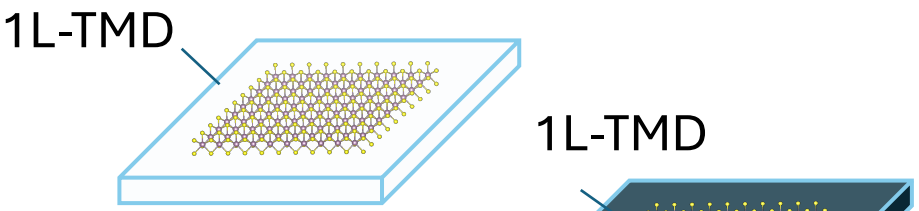


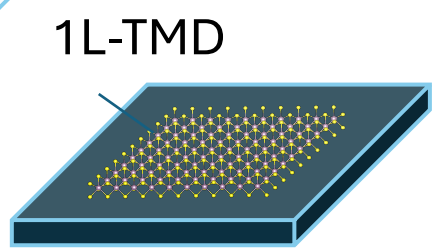
$$\frac{\Delta L}{L}(\%) = \frac{L - L_o}{L_o}\ 100\%$$



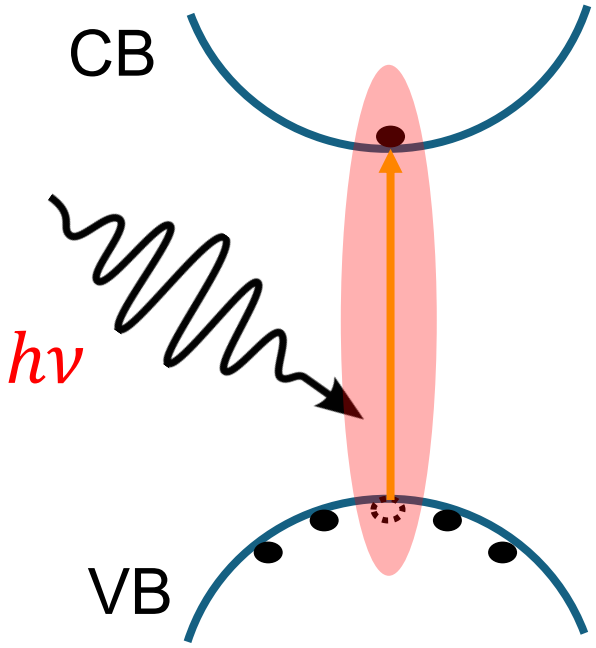
$$\frac{\Delta L}{L}(T) = aT^3 + bT^2 + cT + d$$

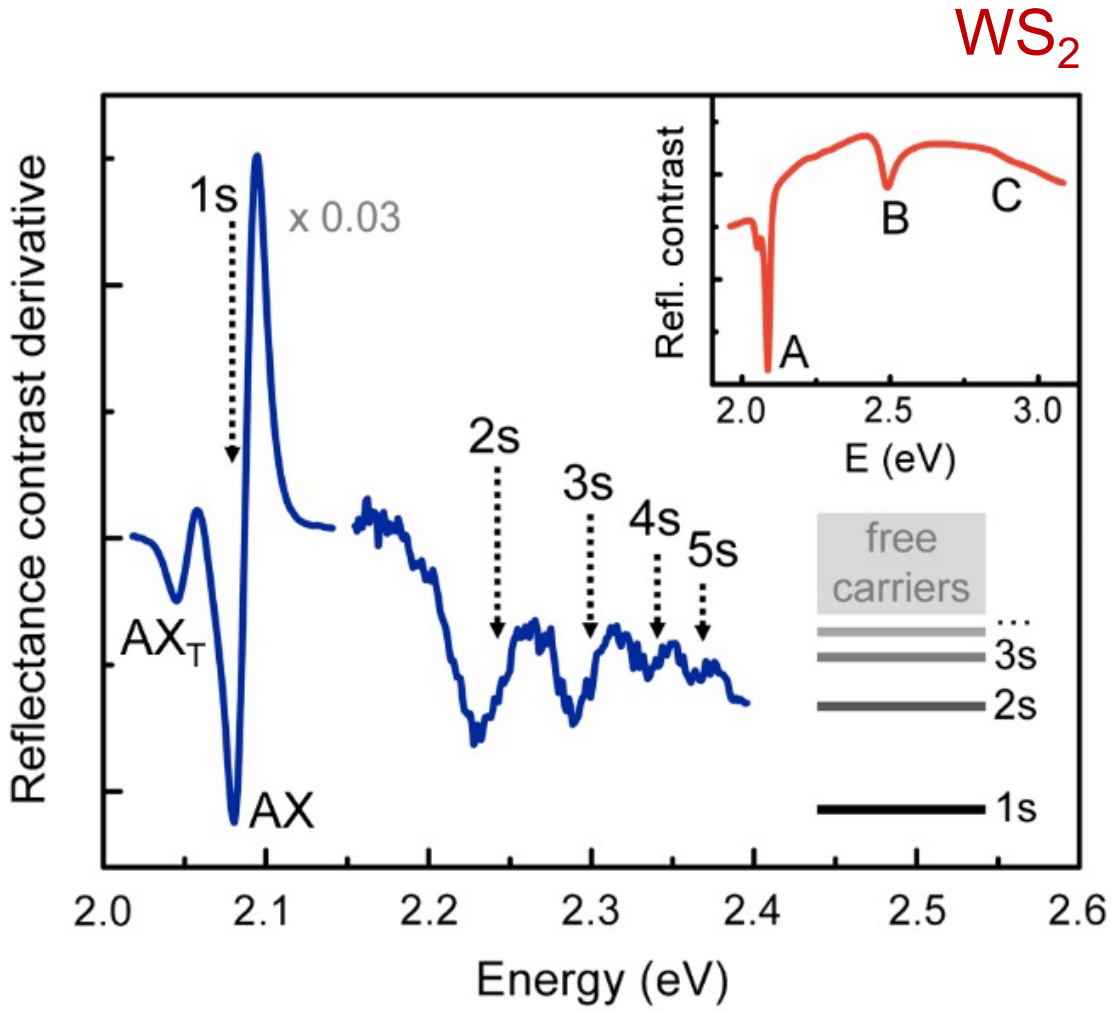
Strain engineering single-layer TMDCs





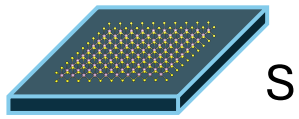
Single-layer TMDCs: excitonic properties



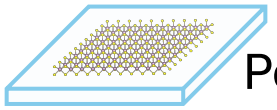


Chernikov et al. *PRL* 113 2014

Micro-reflectance spectroscopy

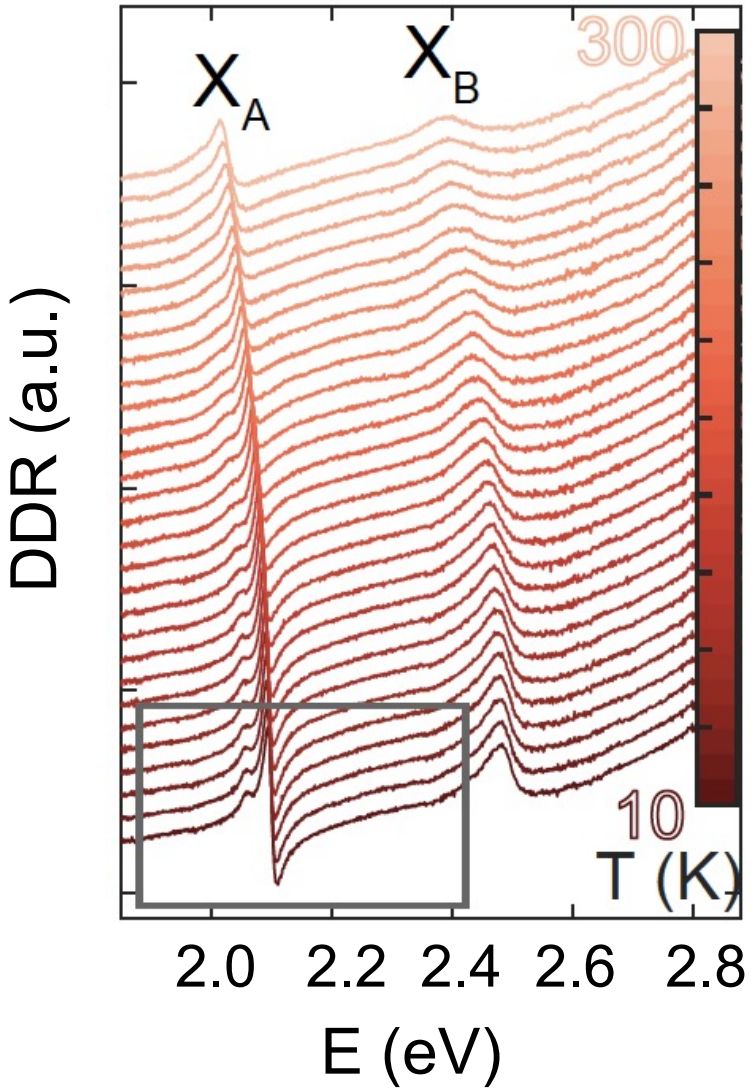


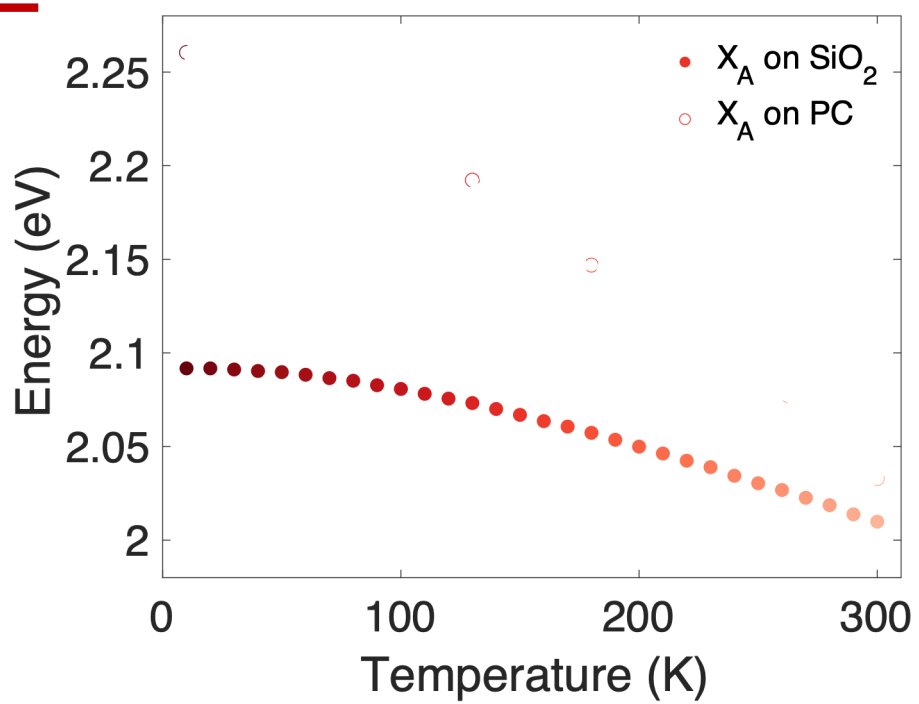
Si/SiO_2



Polycarbonate

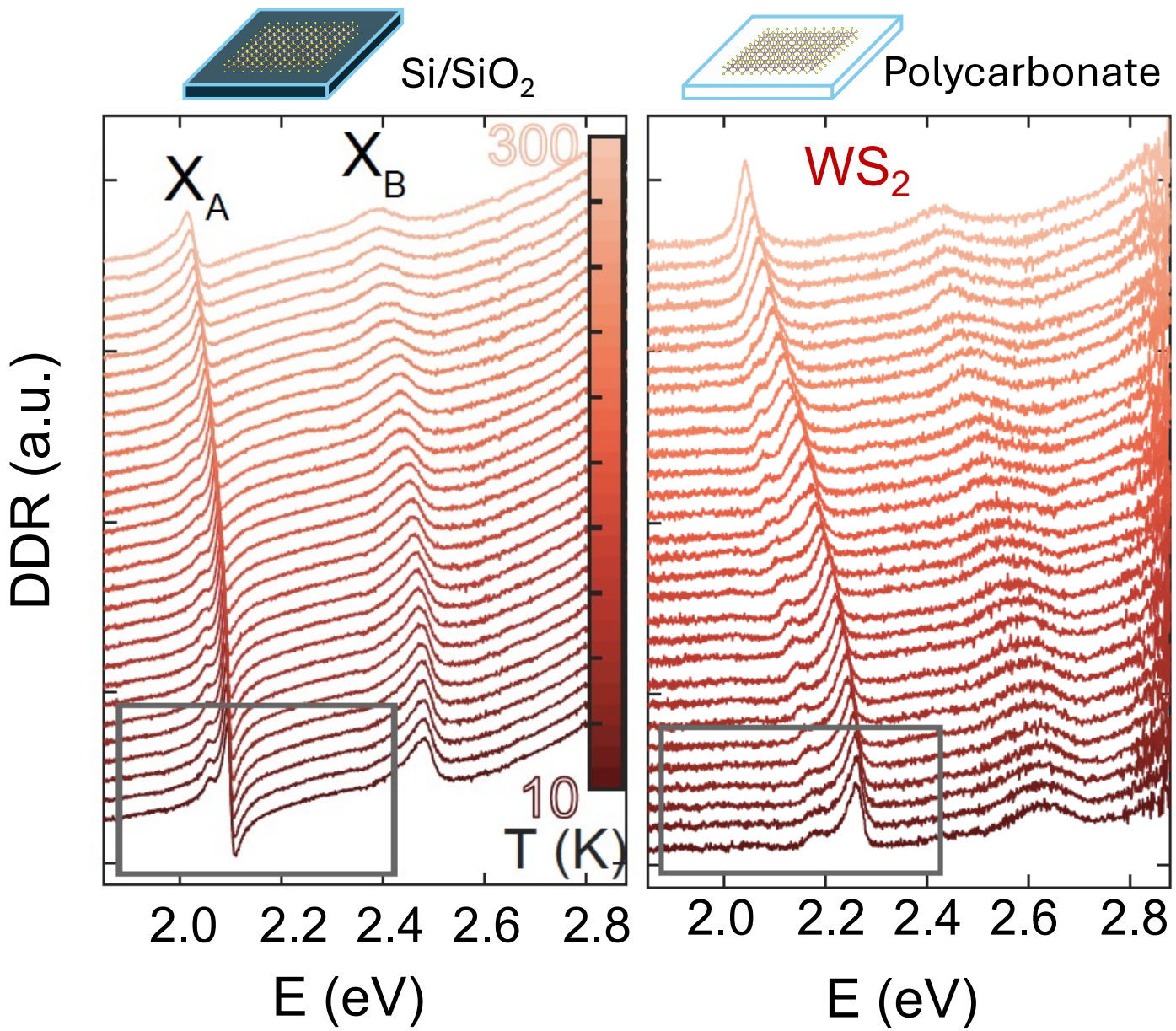
WS_2

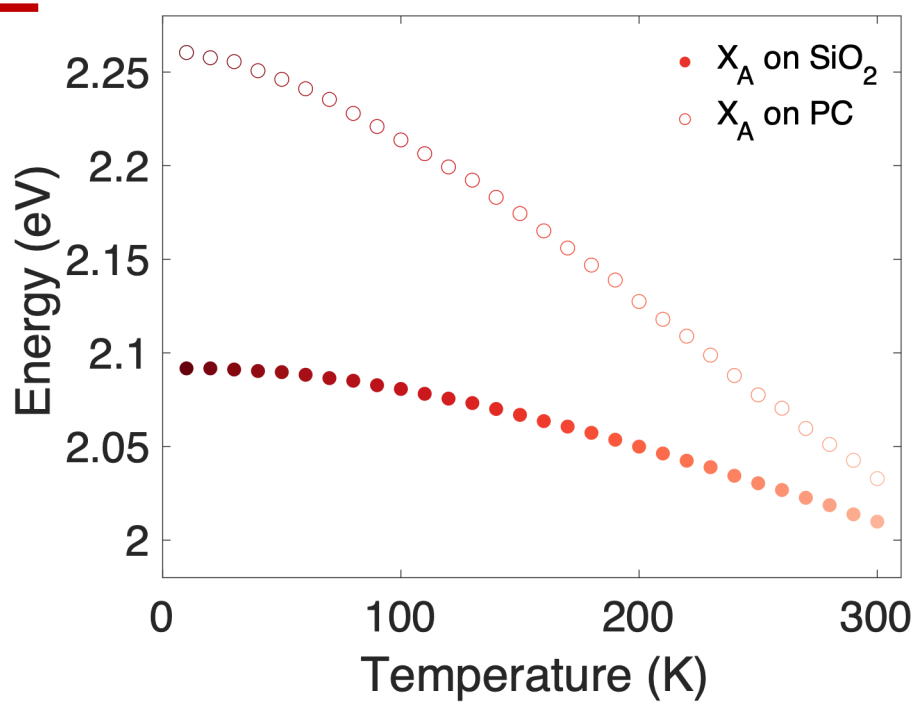




Henríquez-Guerra, ..., Castellanos-Gomez, Calvo. ACS Appl. Mater. Interfaces 2023

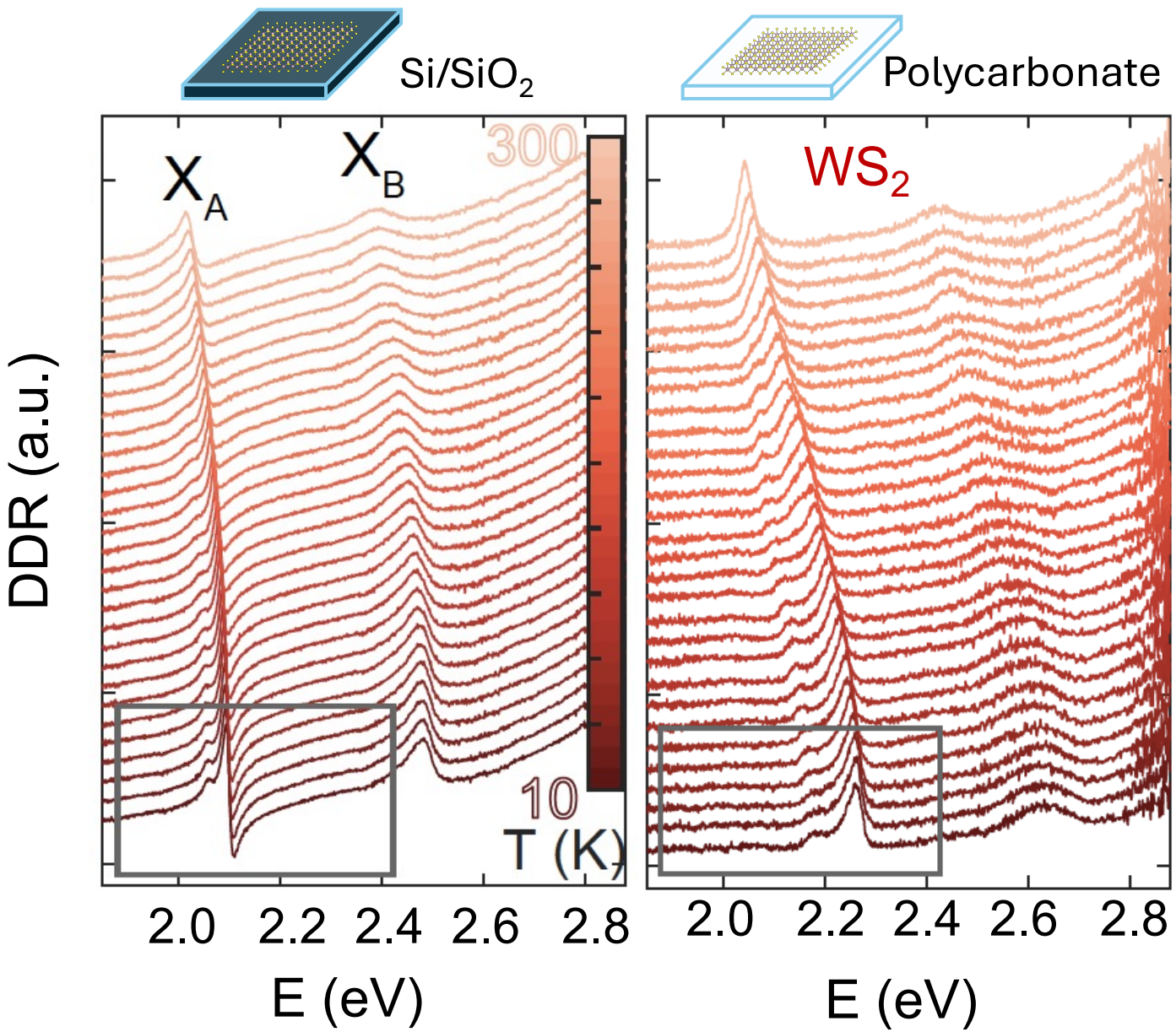
Strain engineering in single-layer TMDCs

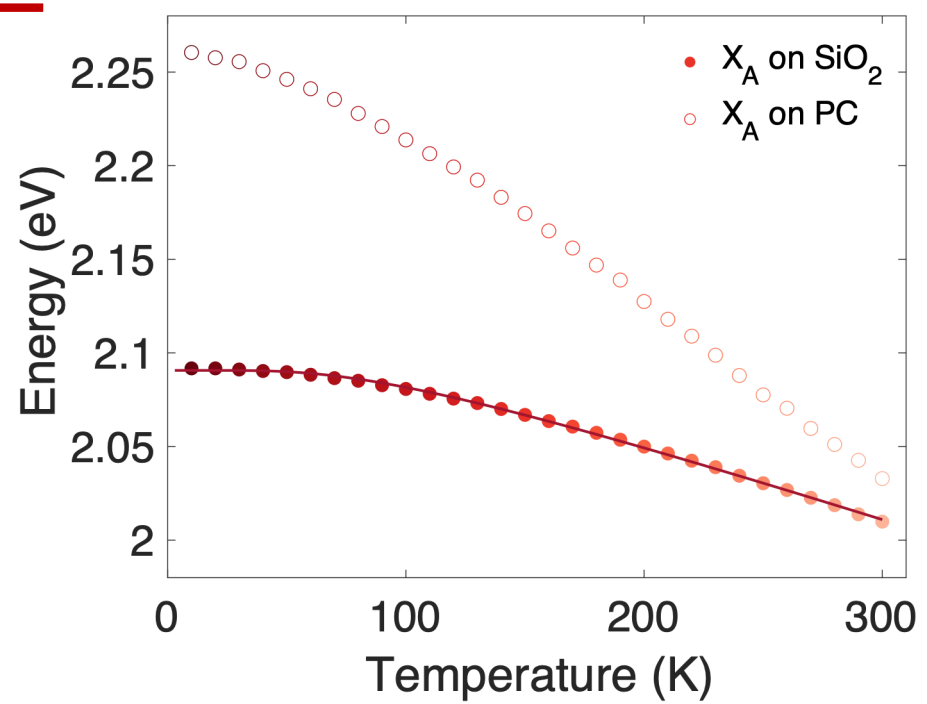


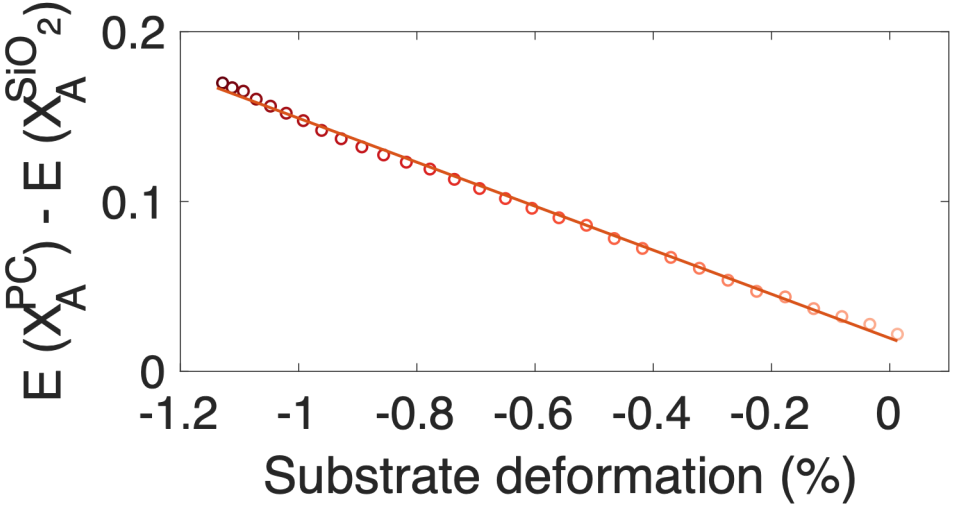


Henríquez-Guerra, …, Castellanos-Gomez, Calvo. *ACS Appl. Mater. Interfaces* 2023

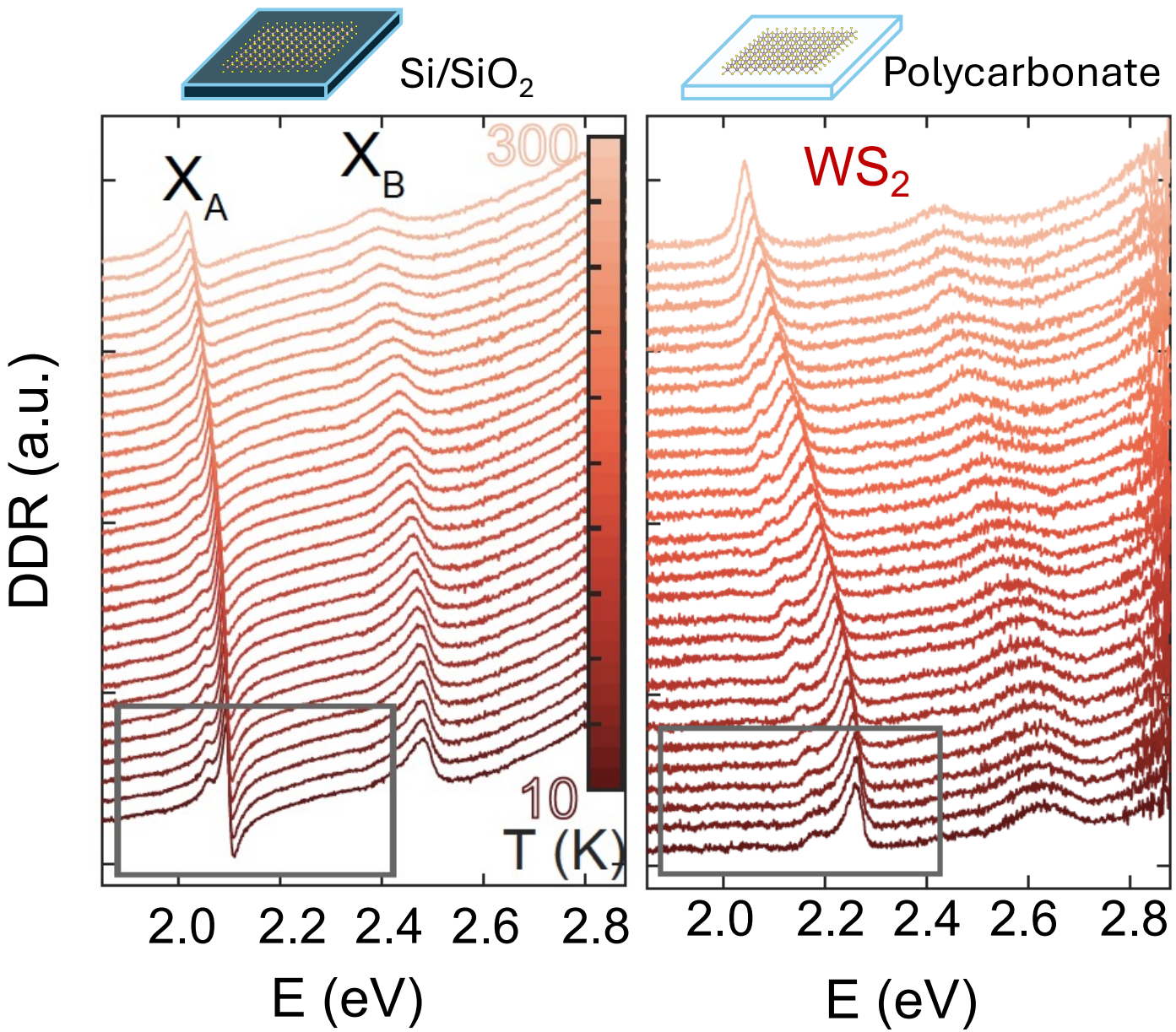
Strain engineering in single-layer TMDCs

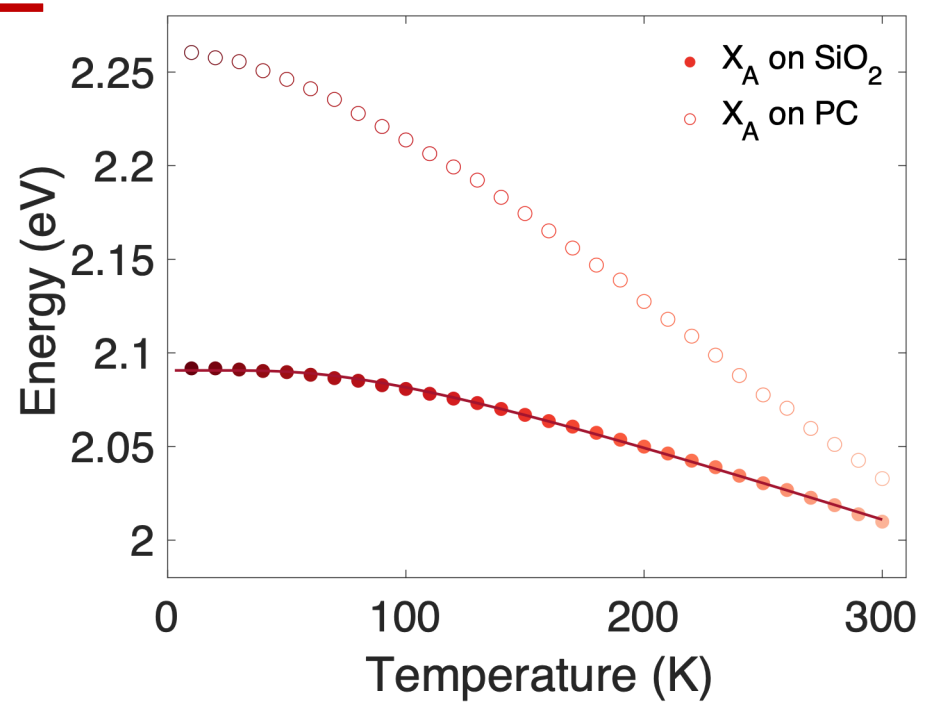


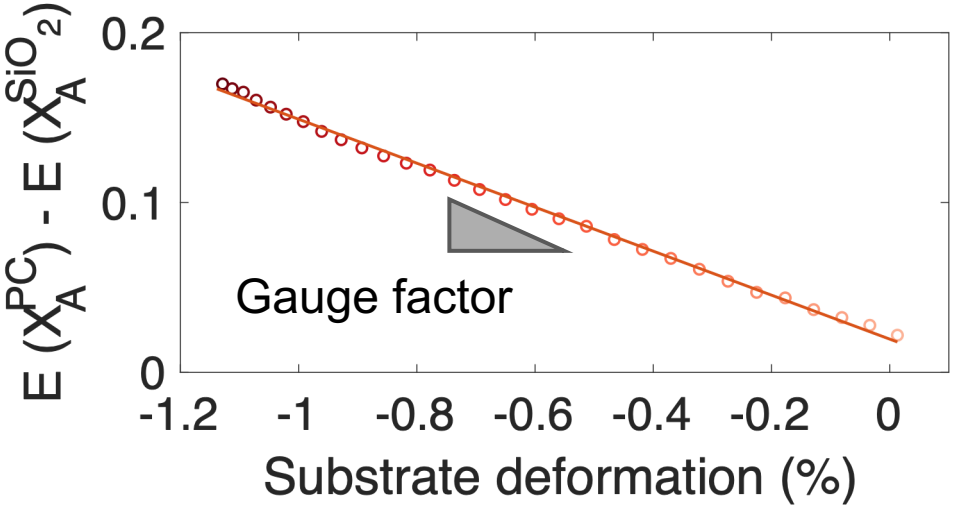




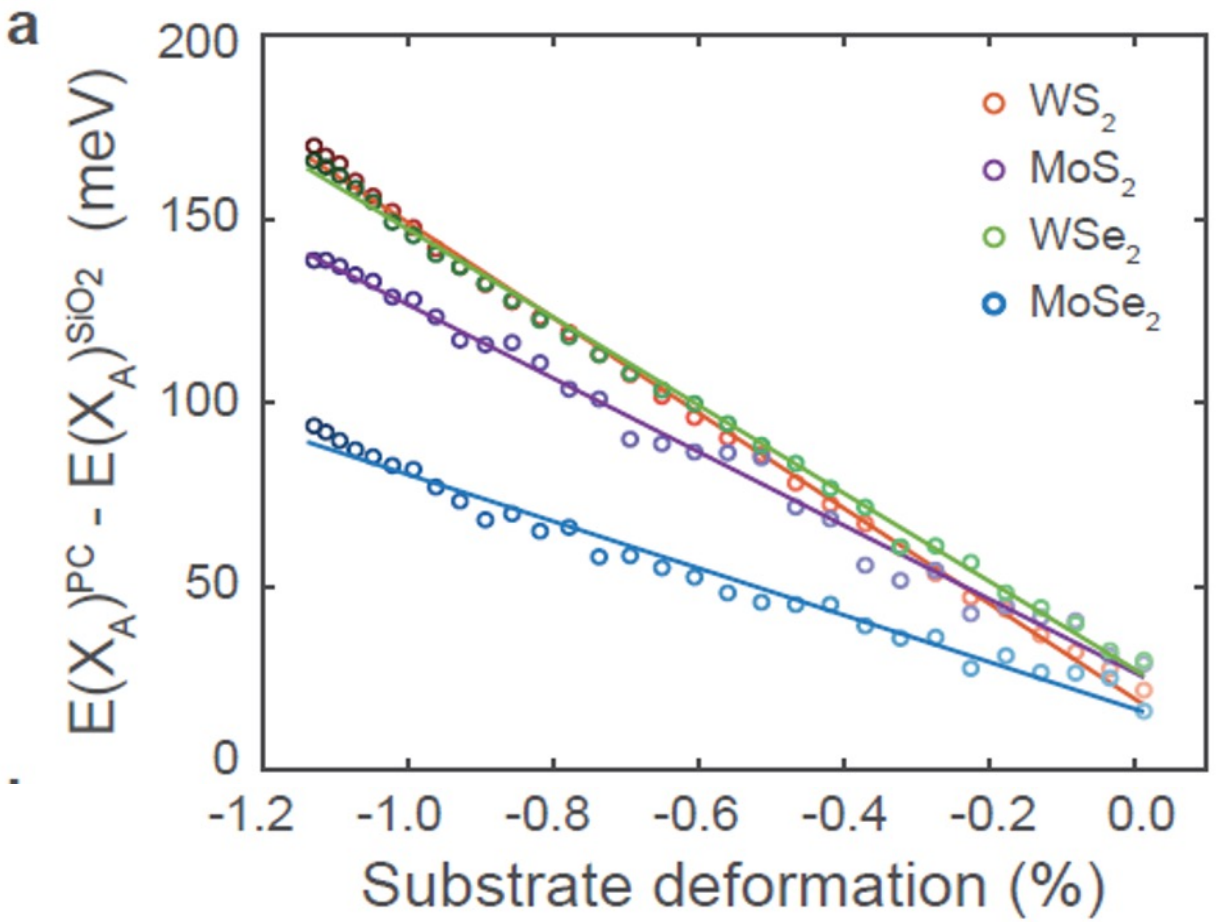
Strain engineering in single-layer TMDCs

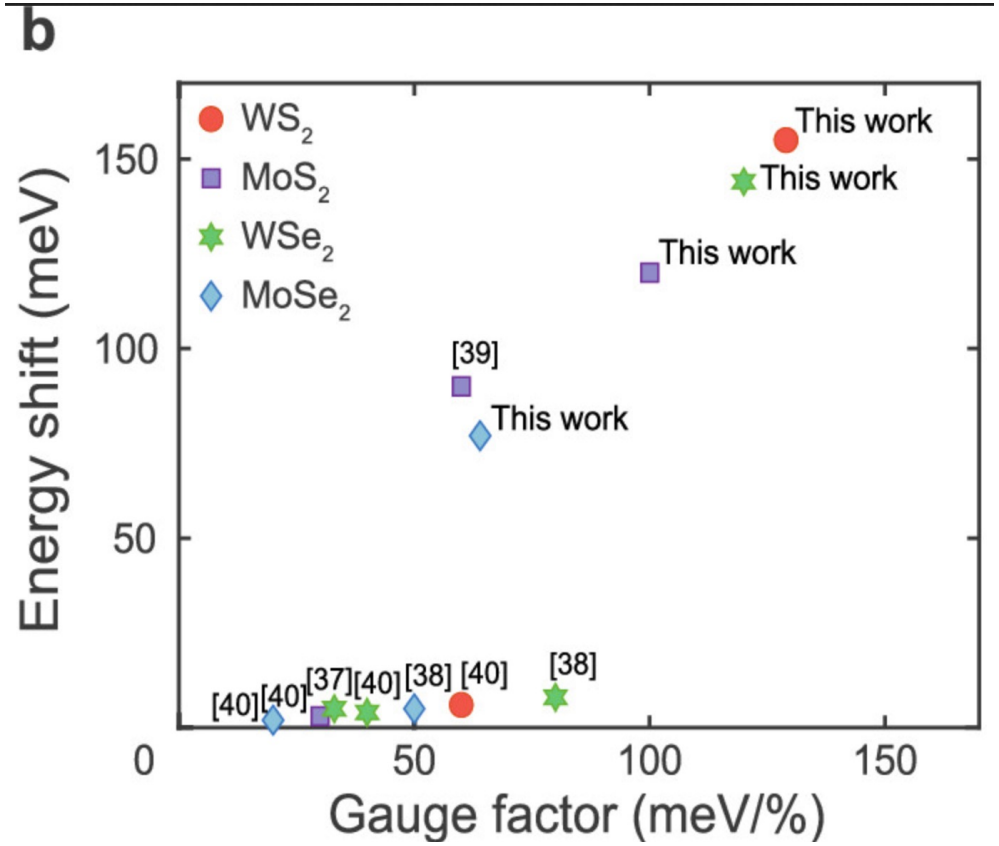






Strain engineering in single-layer TMDCs

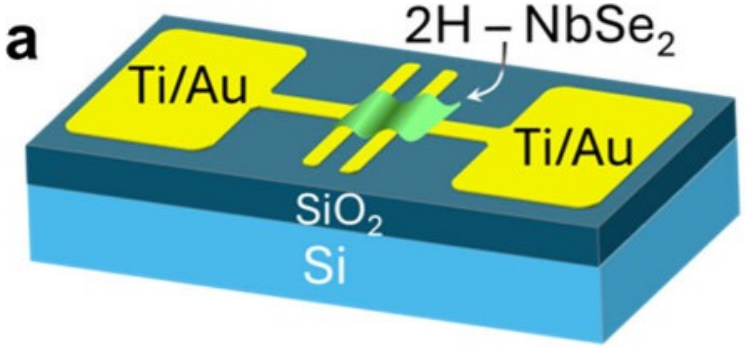


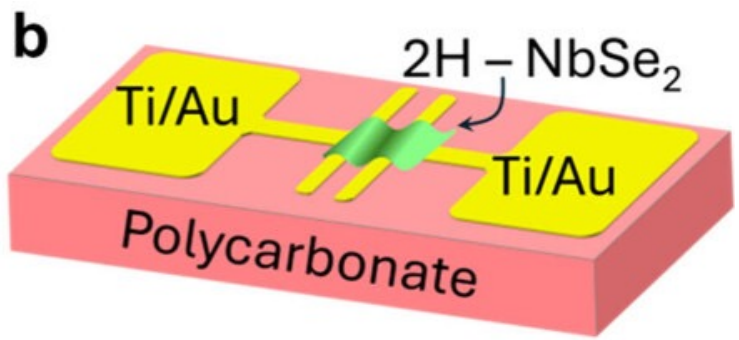


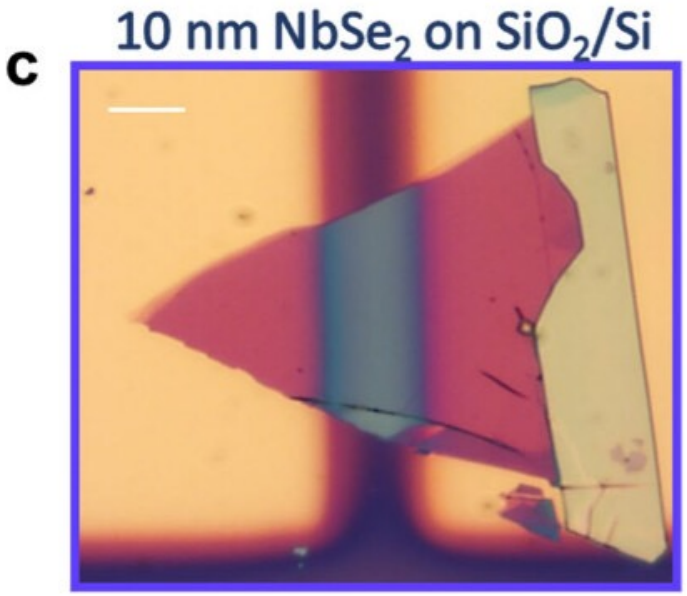
Henríquez-Guerra, ..., Castellanos-Gomez, Calvo. *ACS Appl. Mater. Interfaces* 2023

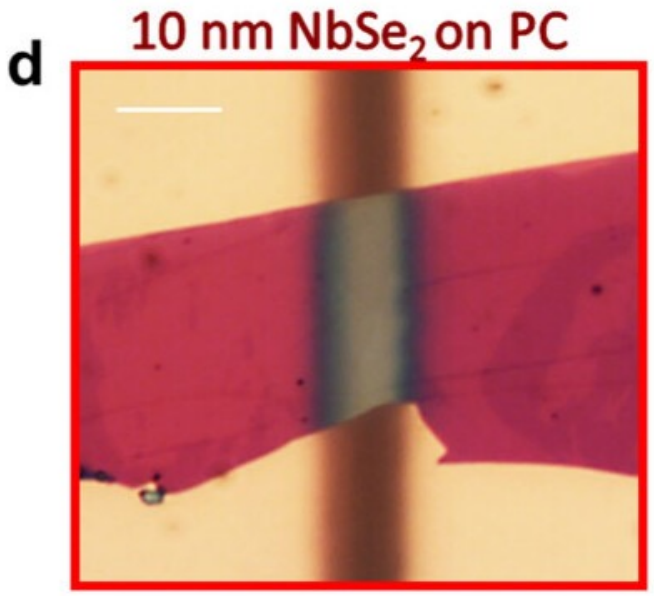
- Very good strain transfer
- Unprecedent ammount of biaxial compressive strain (~1.2%)

Strain modulation of superconductivity in $NbSe_2$









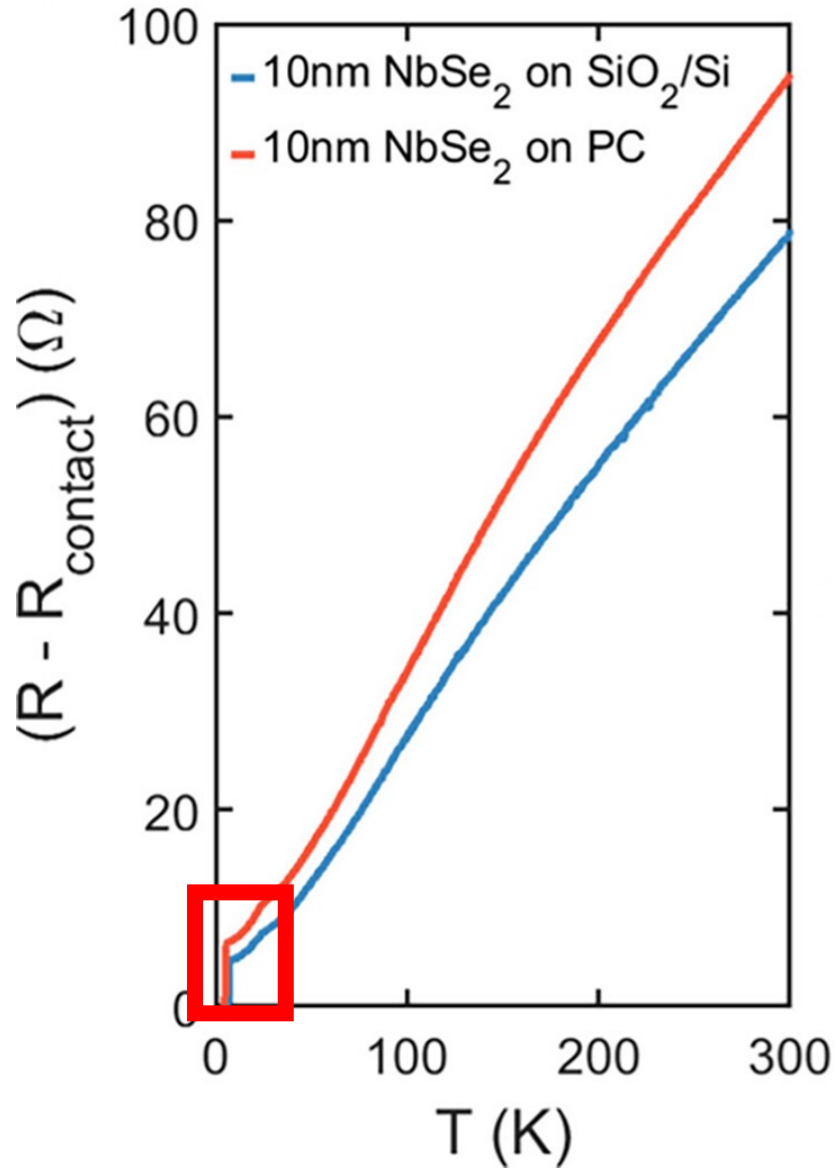
Henríquez-Guerra, …, Calvo, Castellanos-Gomez. *Nano Letters* 2024

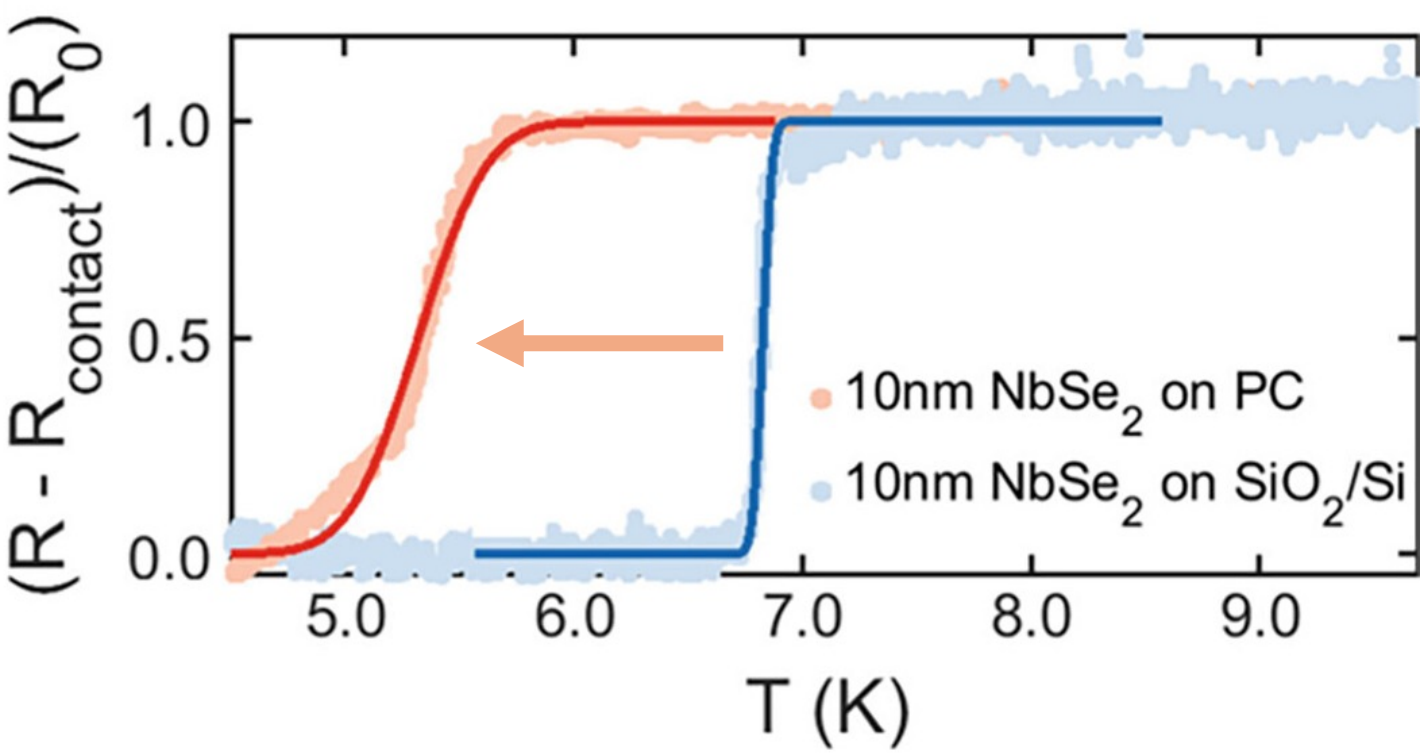
NANO LETTERS

LETTER | July 30, 2024

Modulation of the Superconducting Phase Transition in Multilayer 2H-$NbSe_2$ Induced by Uniform Biaxial Compressive Strain

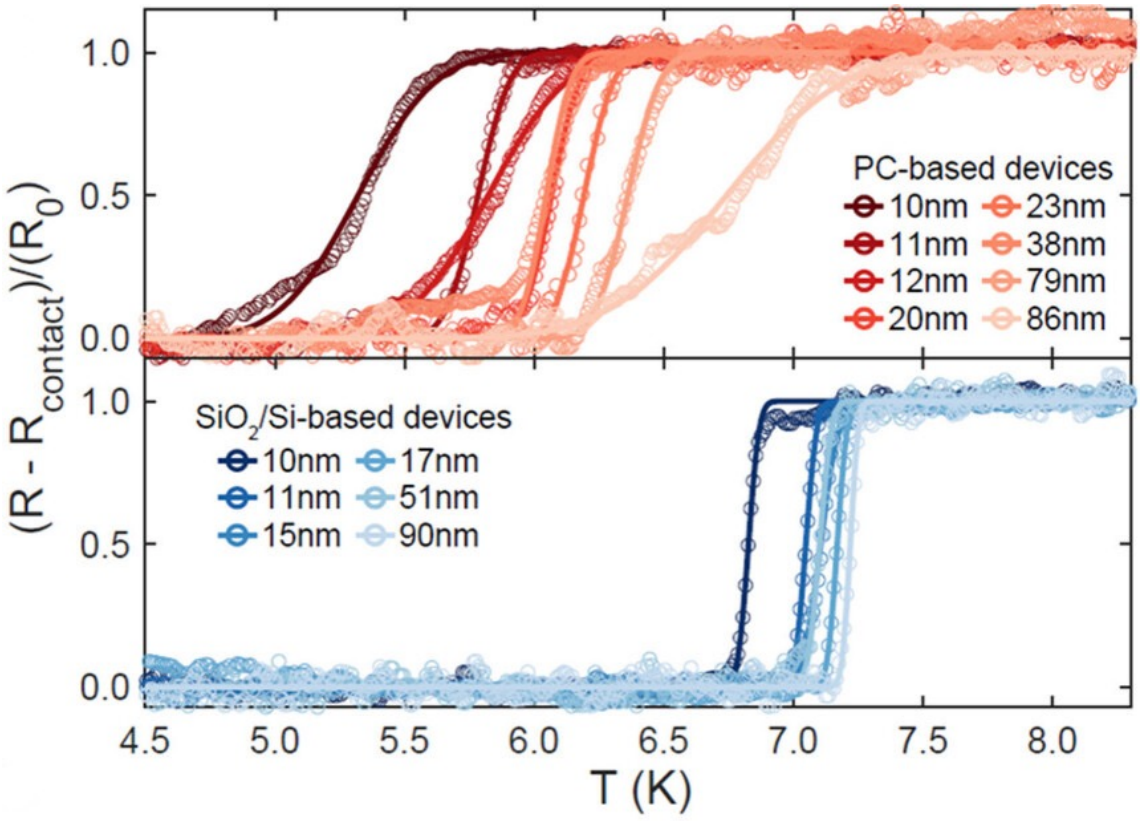
Strain modulation of superconductivity in $NbSe_2$





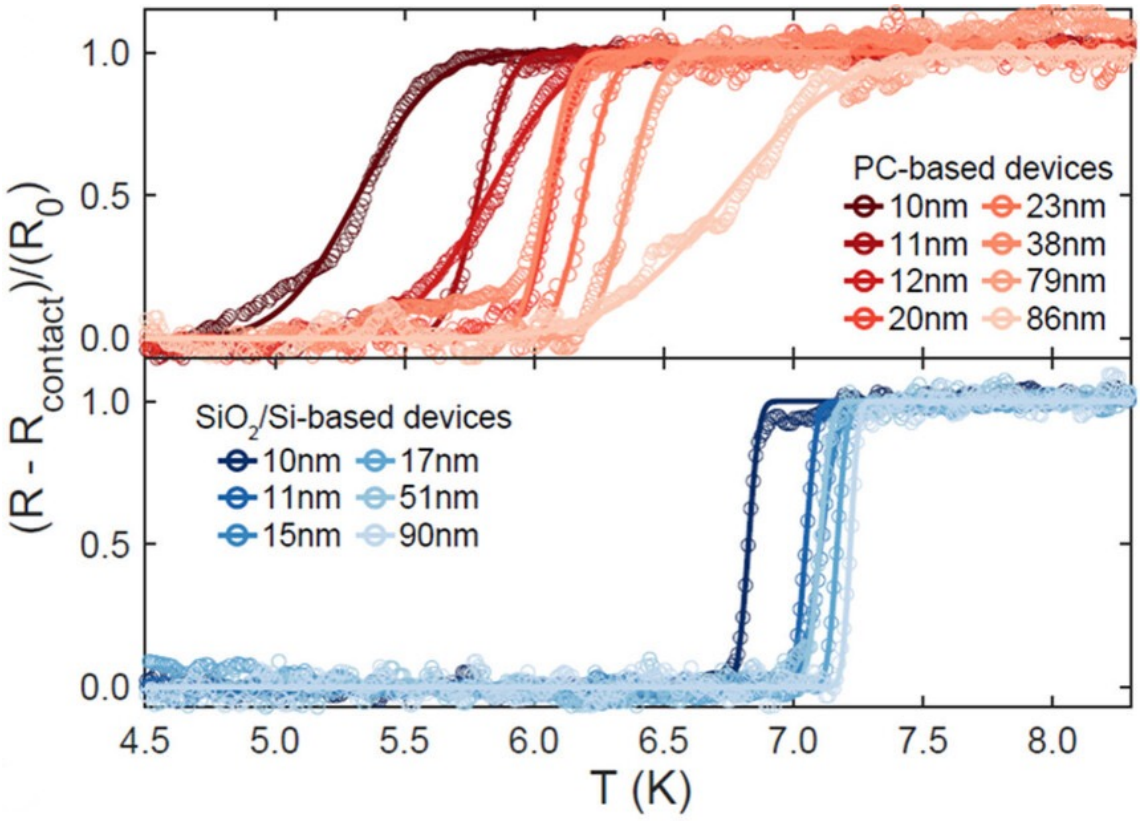
Henríquez-Guerra, …, Calvo, Castellanos-Gomez. *Nano Letters* 2024

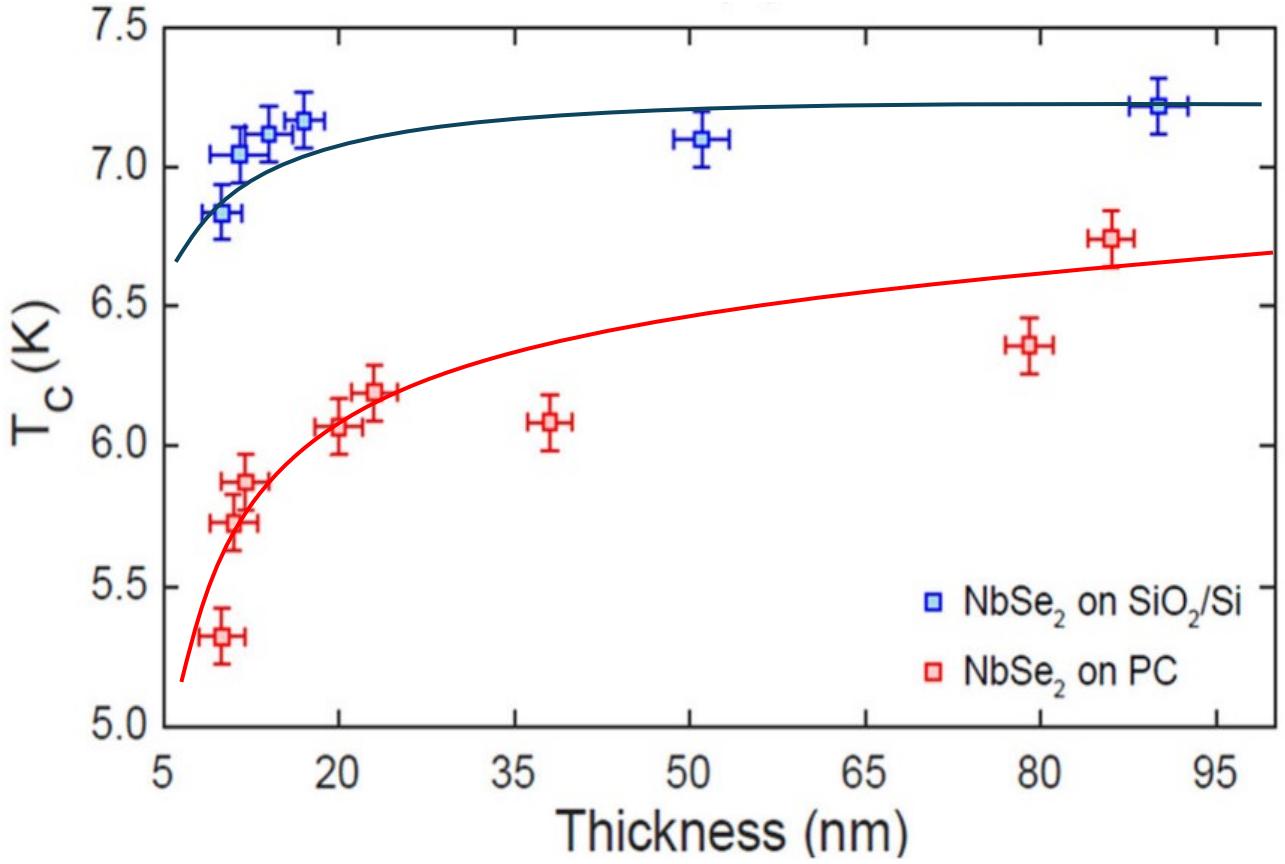
Strain modulation of superconductivity in $NbSe_2$



Henríquez-Guerra, ..., Calvo, Castellanos-Gomez. *Nano Letters* 2024

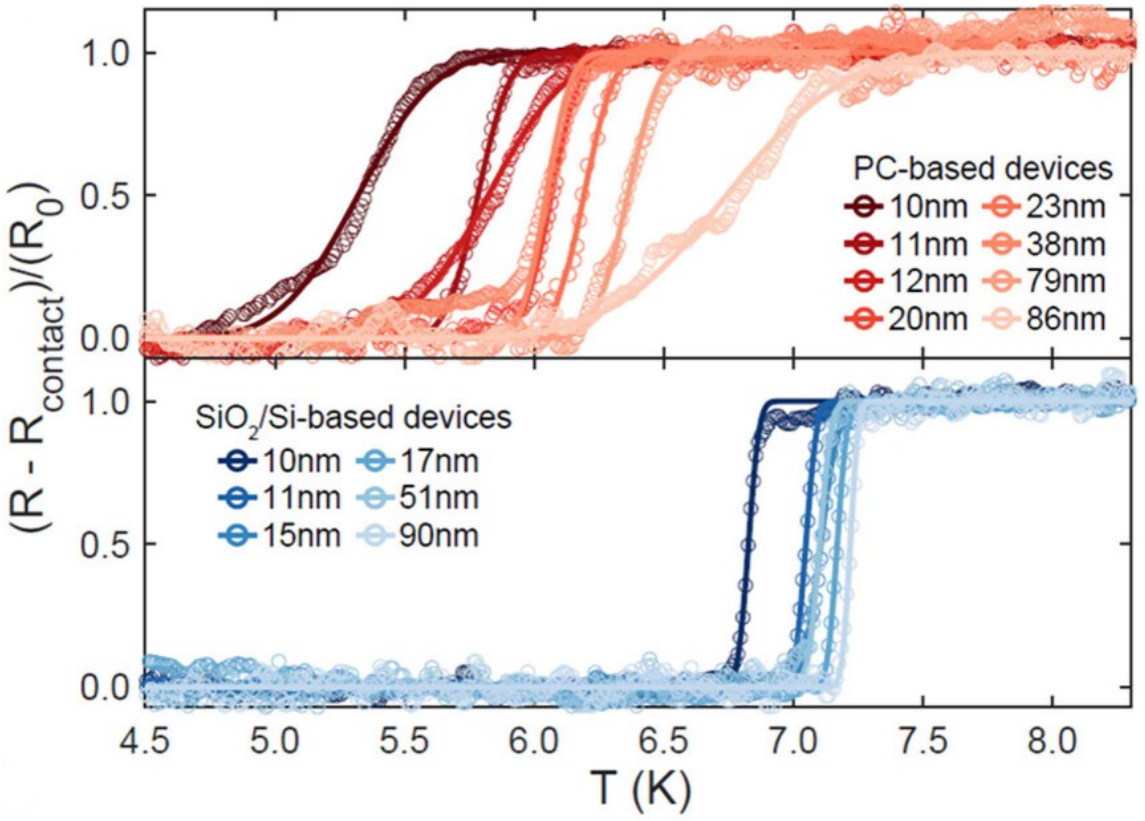
Strain modulation of superconductivity in $NbSe_2$

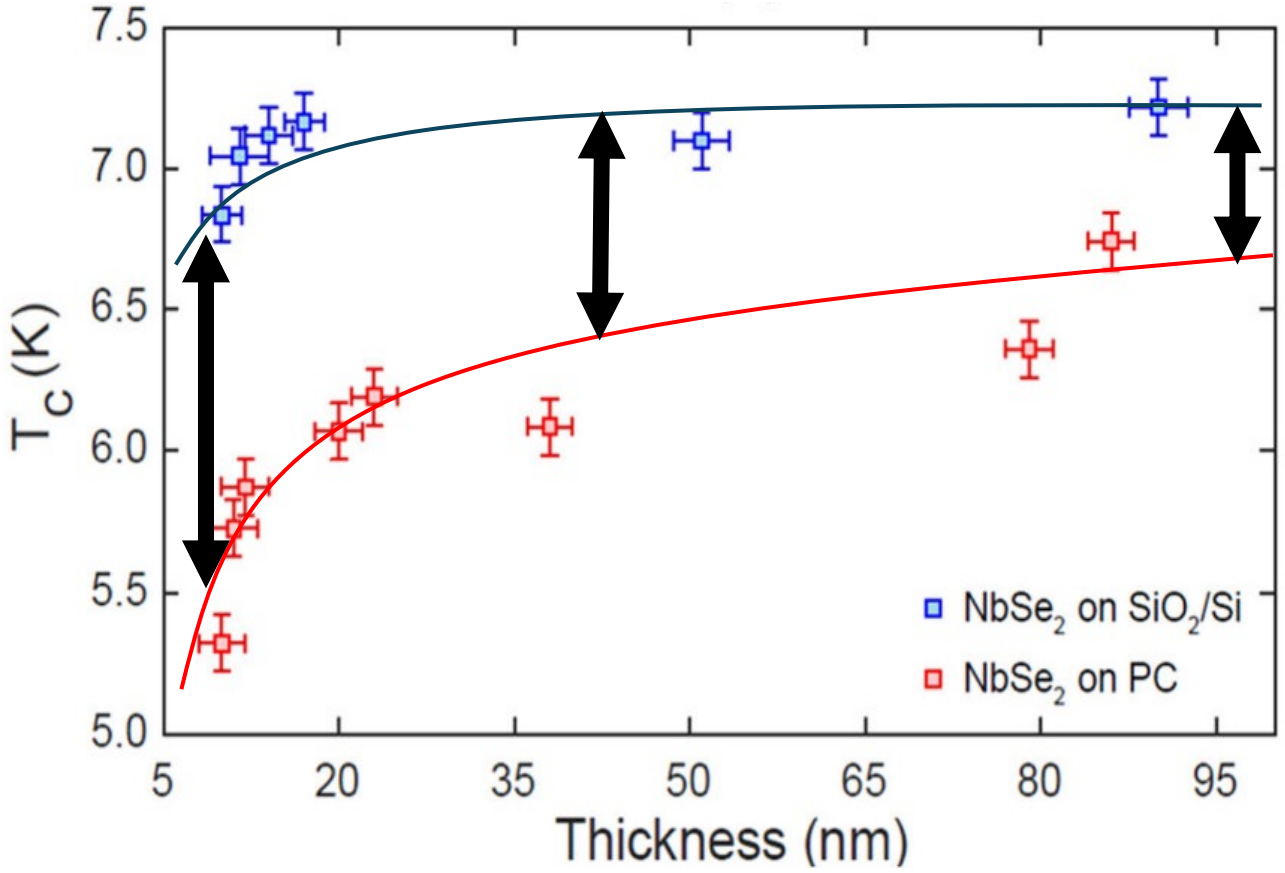




Henríquez-Guerra, …, Calvo, Castellanos-Gomez. *Nano Letters* 2024

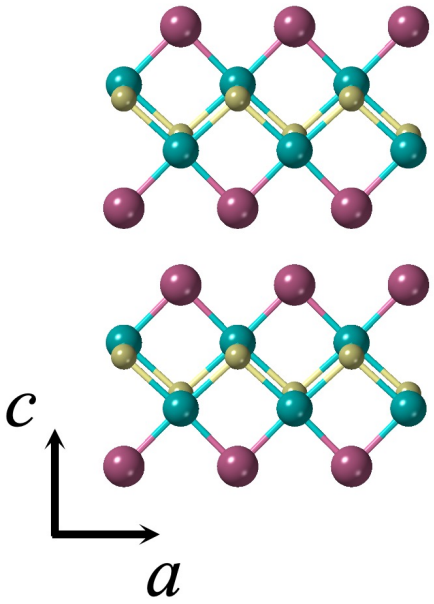
Strain modulation of superconductivity in $NbSe_2$

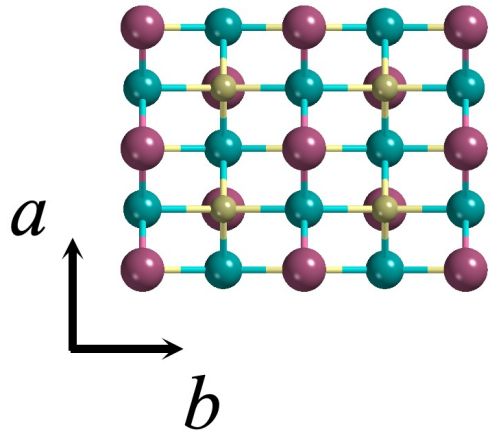


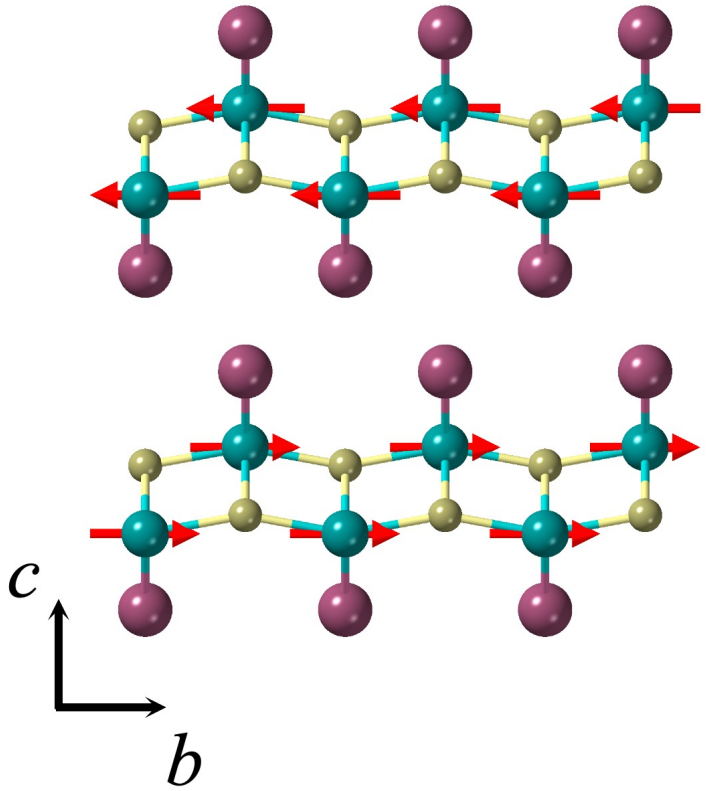


Henríquez-Guerra, …, Calvo, Castellanos Nano Letters 2024

Strain modulation of magnetoresistance in CrSBr





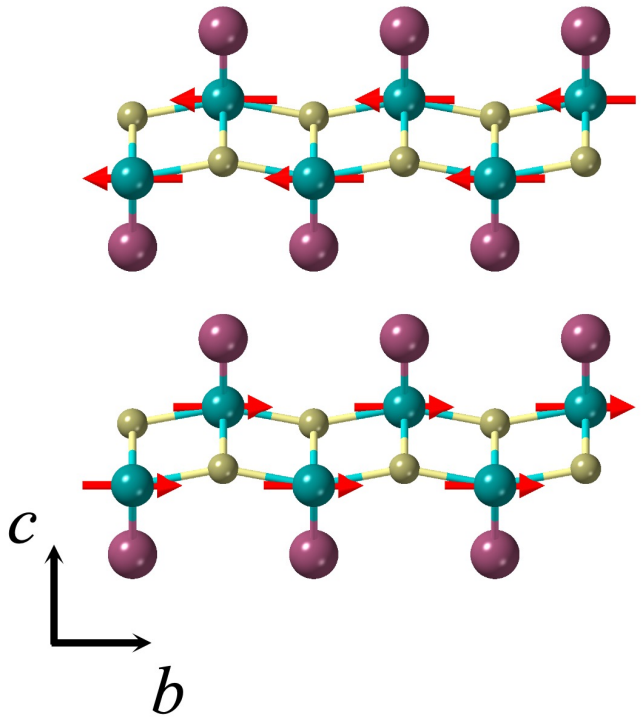


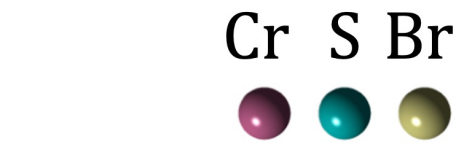
Cr S Br

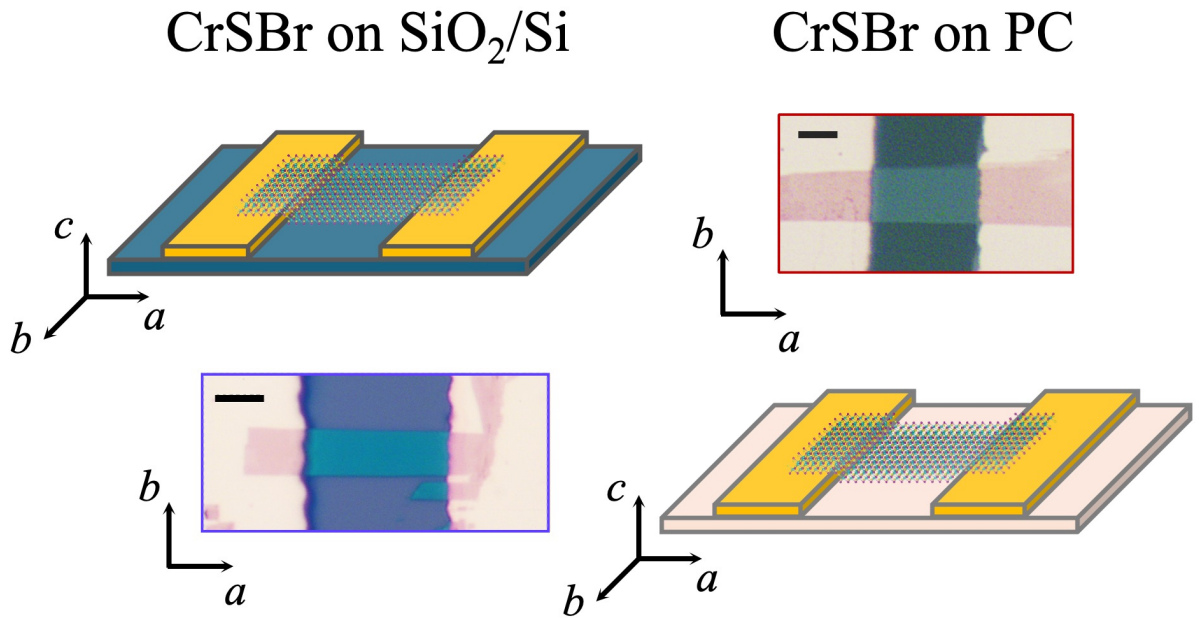
T_N~132 K

Henríquez-Guerra, …, ***Calvo.*** Adv. Mater. 2025

Strain modulation of magnetoresistance in CrSBr

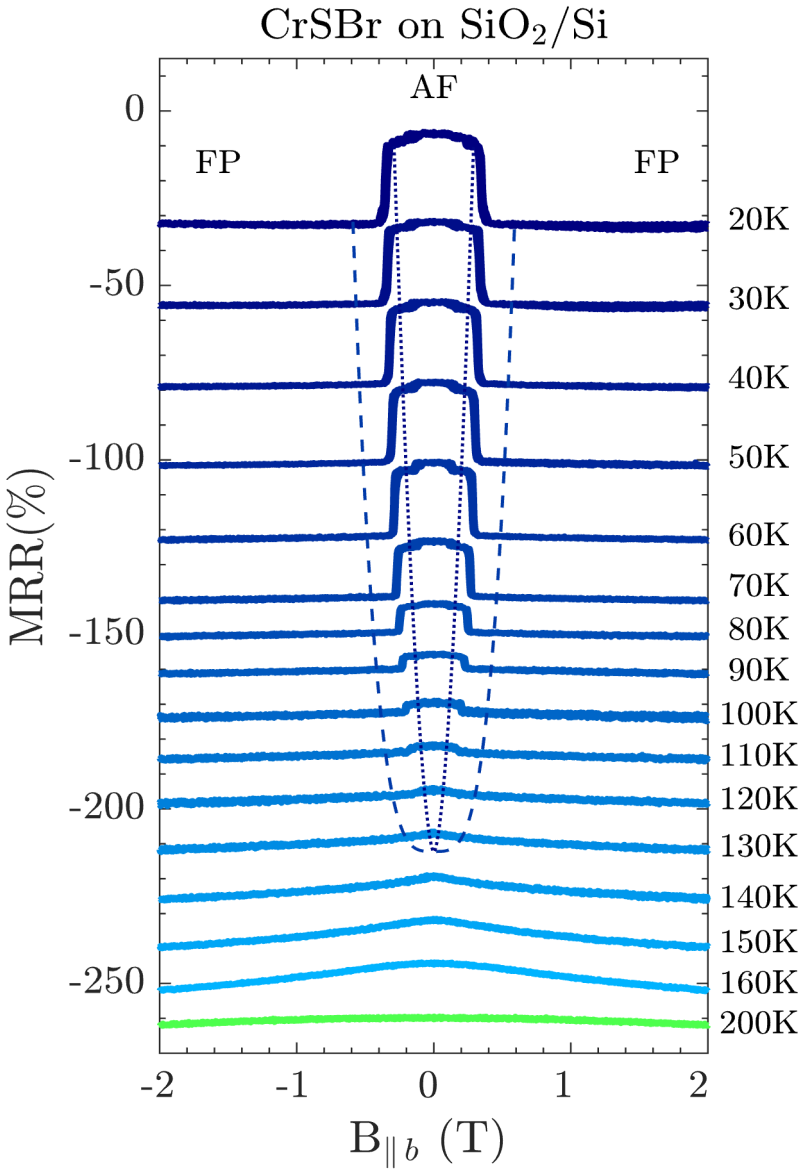


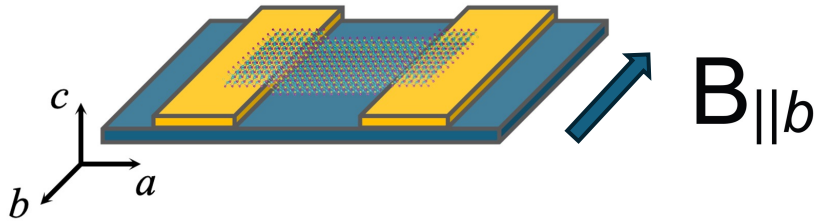




Henríquez-Guerra, …, ***Calvo.*** Adv. Mater. 2025

Strain modulation of magnetoresistance in CrSBr

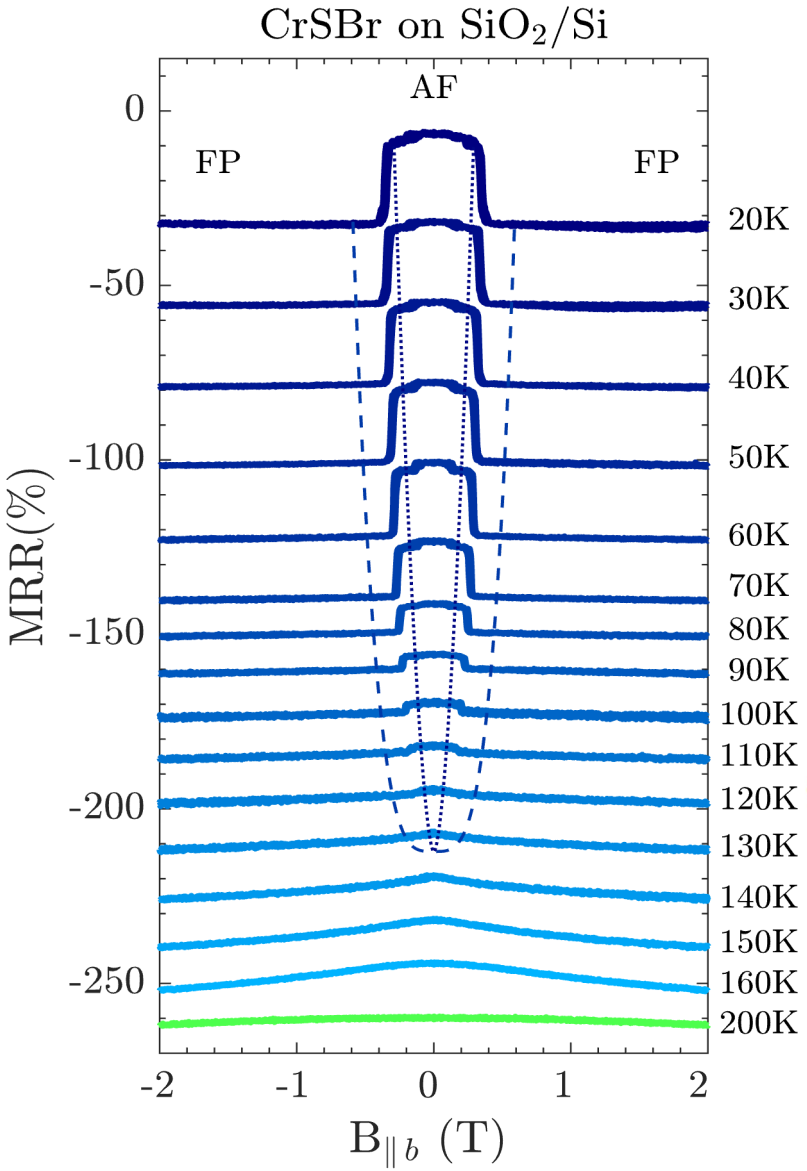


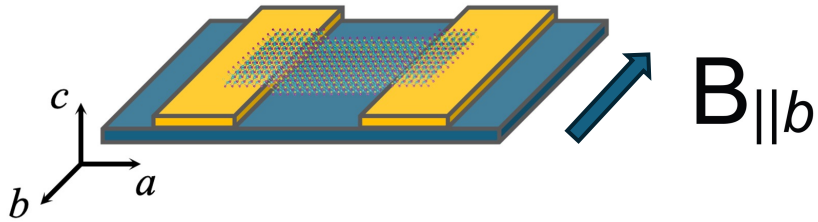


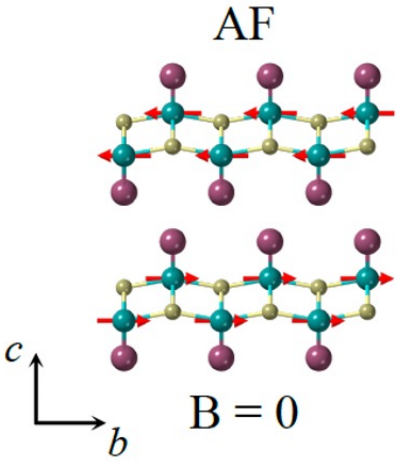
$$MRR = \frac{R(B) - R\,(B=0)}{R(B=0)} \times 100$$

Henríquez-Guerra, …, ***Calvo.*** Adv. Mater. 2025

Strain modulation of magnetoresistance in CrSBr

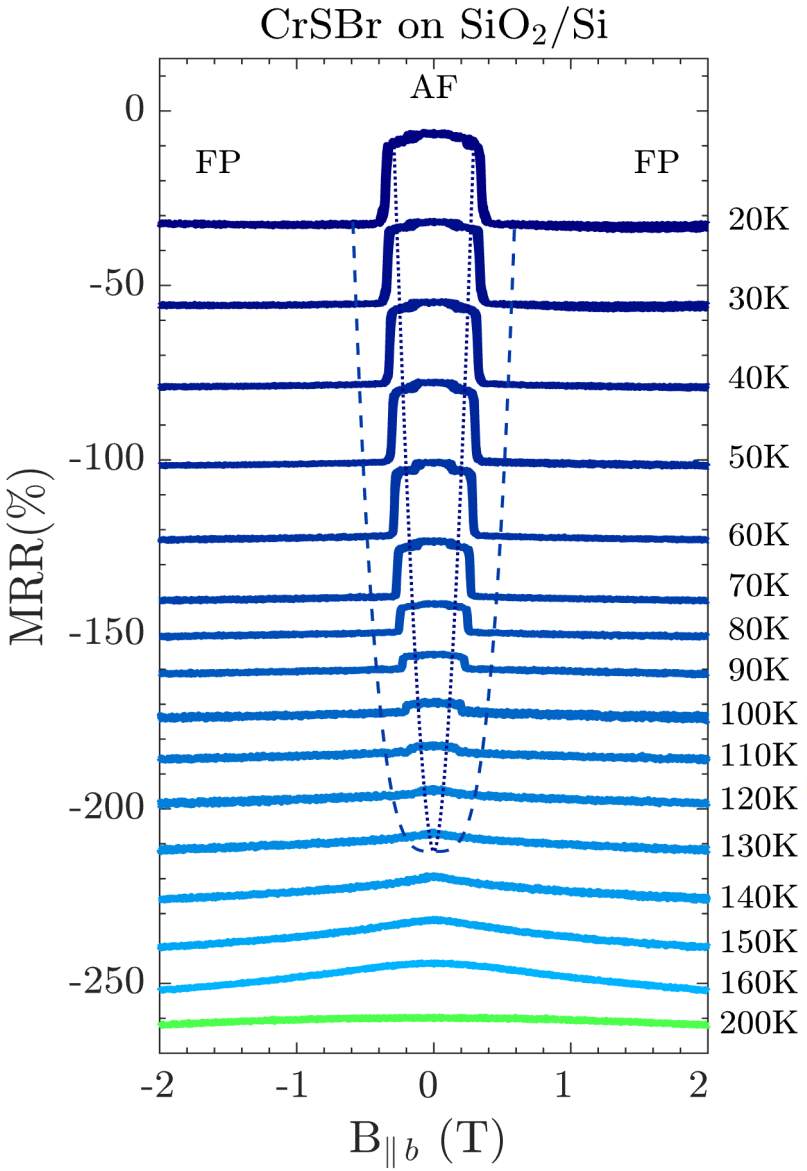


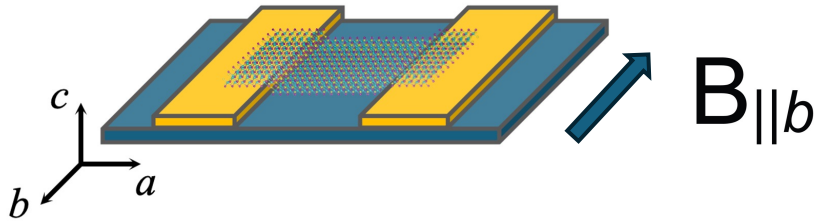


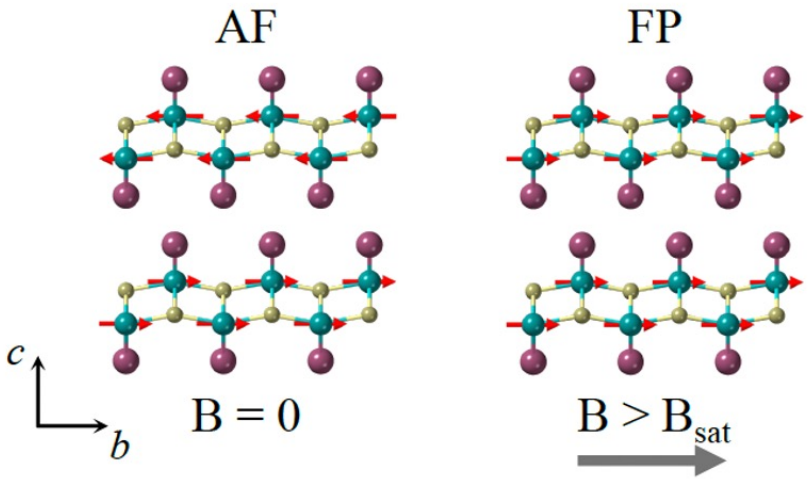


Henríquez-Guerra, …, ***Calvo.*** Adv. Mater. 2025

Strain modulation of magnetoresistance in CrSBr

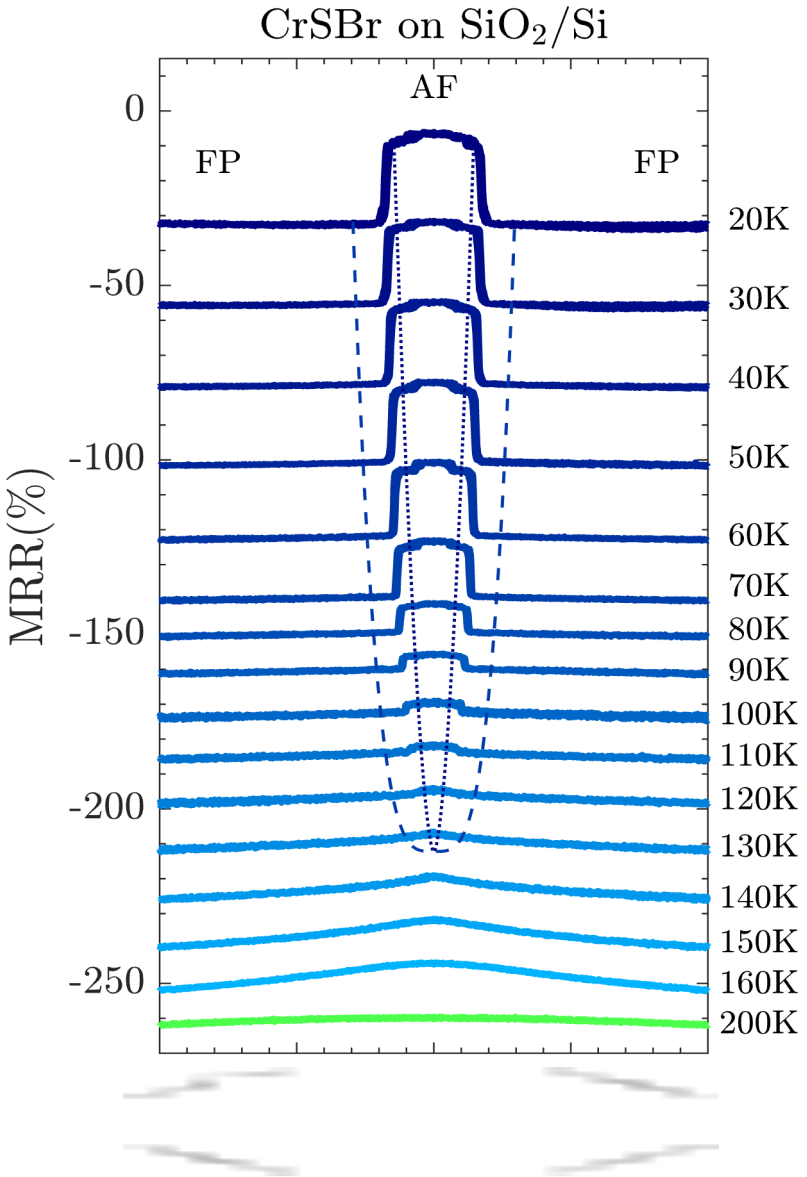


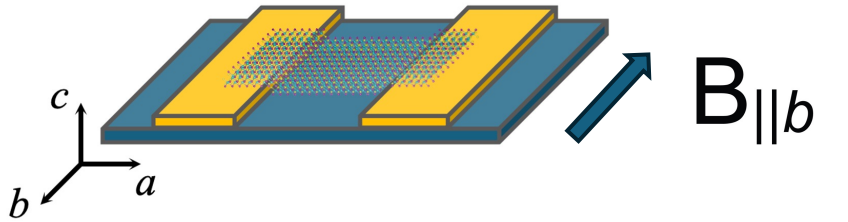


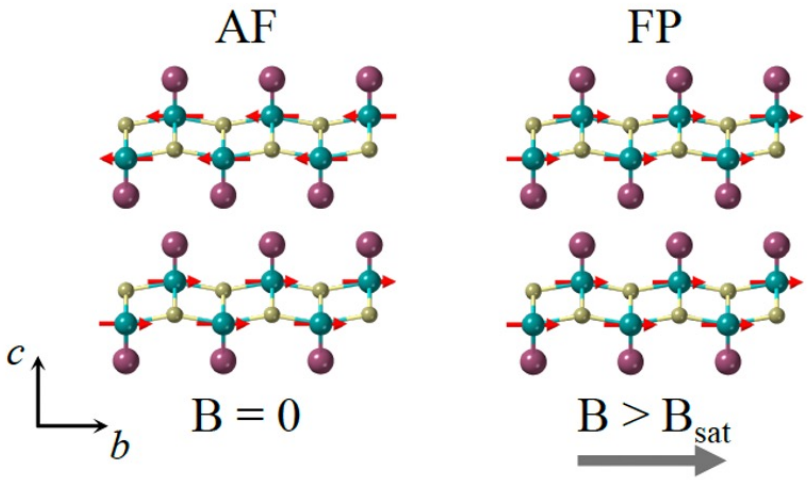


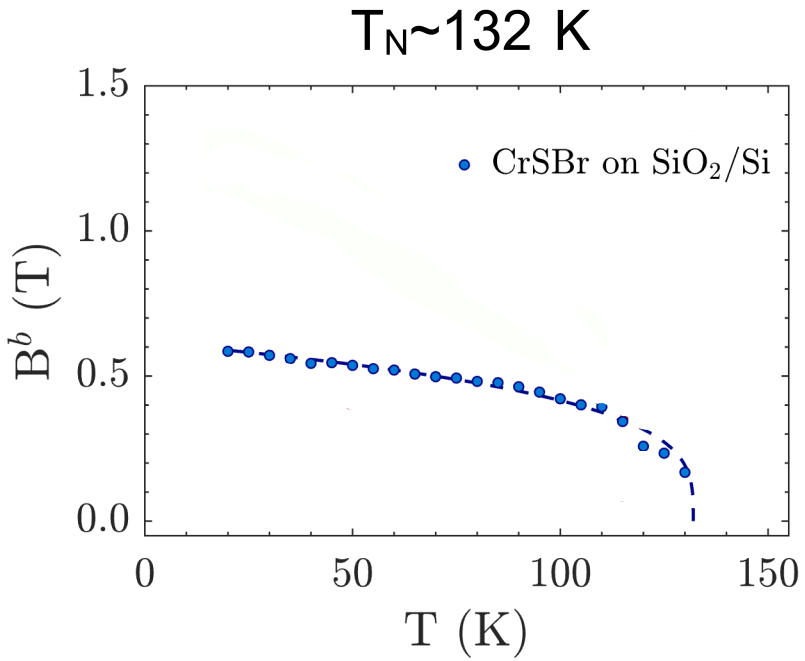
Henríquez-Guerra, …, ***Calvo.*** Adv. Mater. 2025

Strain modulation of magnetoresistance in CrSBr



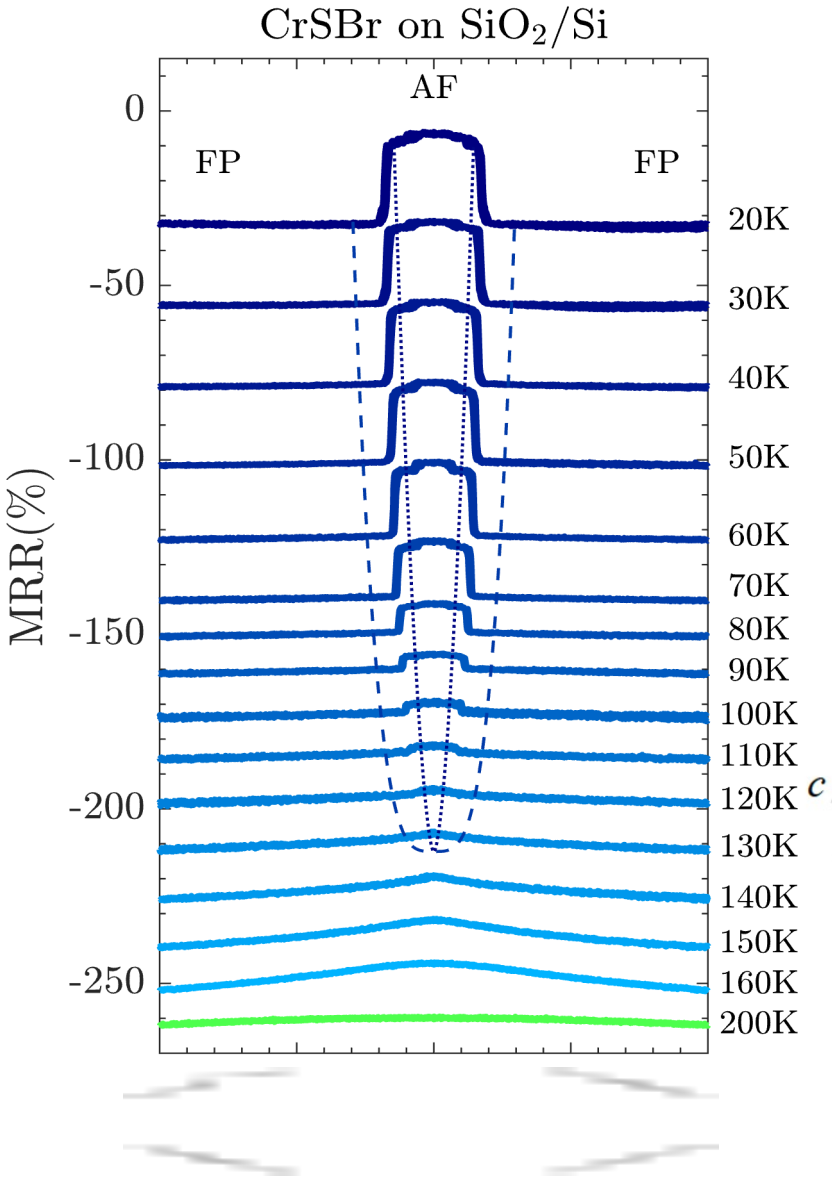


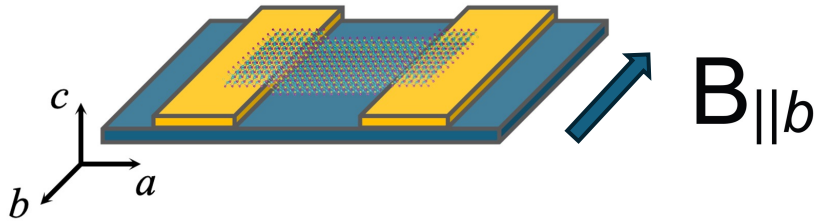


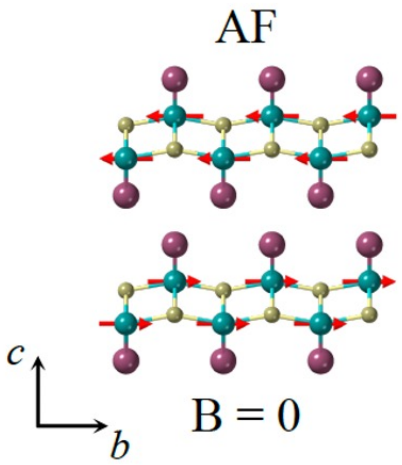


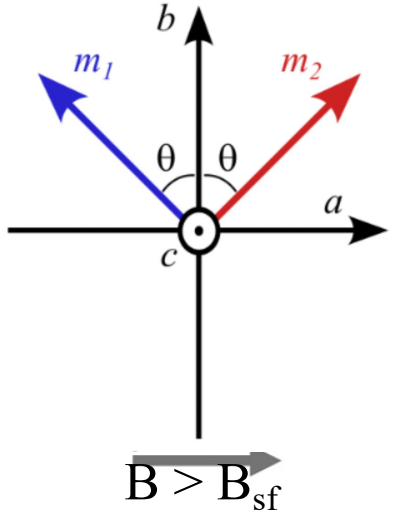
Henríquez-Guerra, …, ***Calvo.*** Adv. Mater. 2025

Strain modulation of magnetoresistance in CrSBr



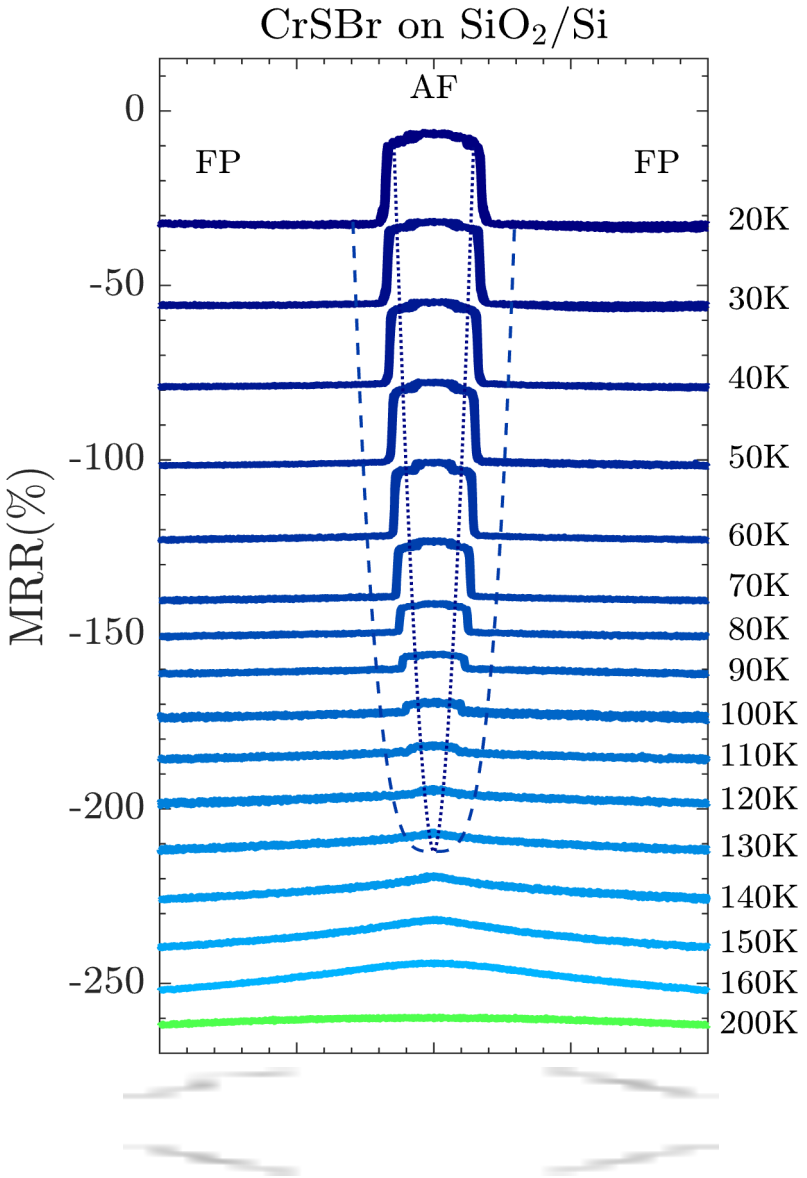


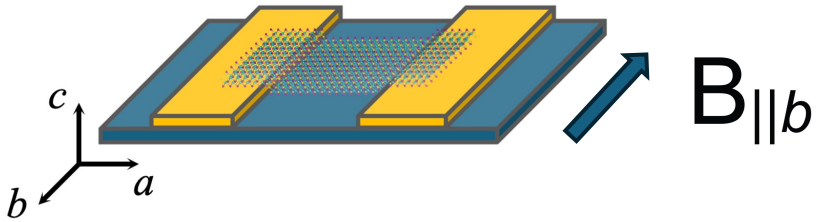


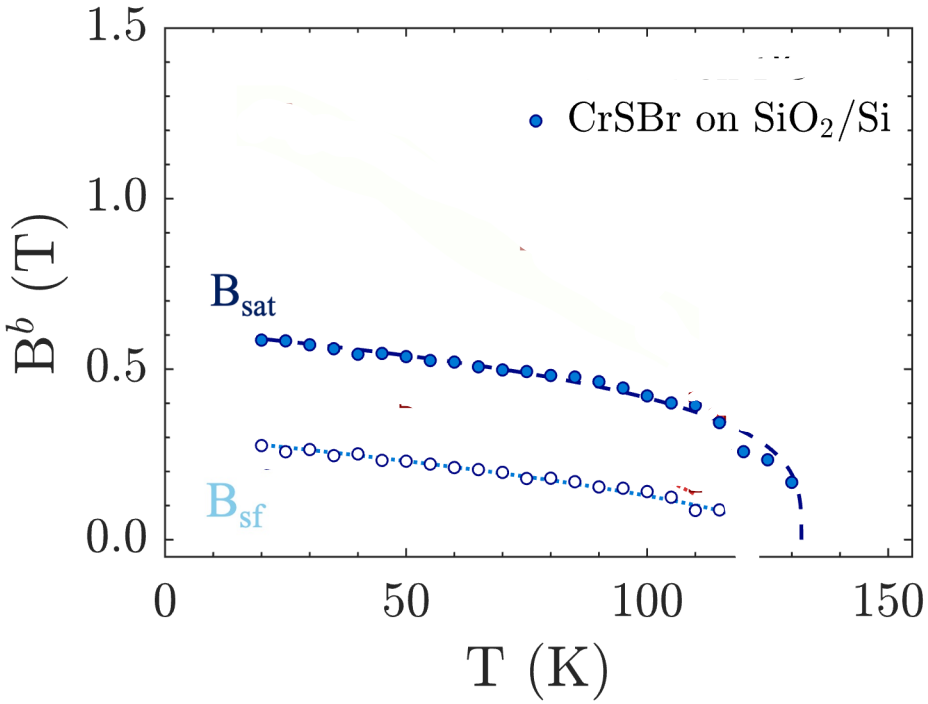


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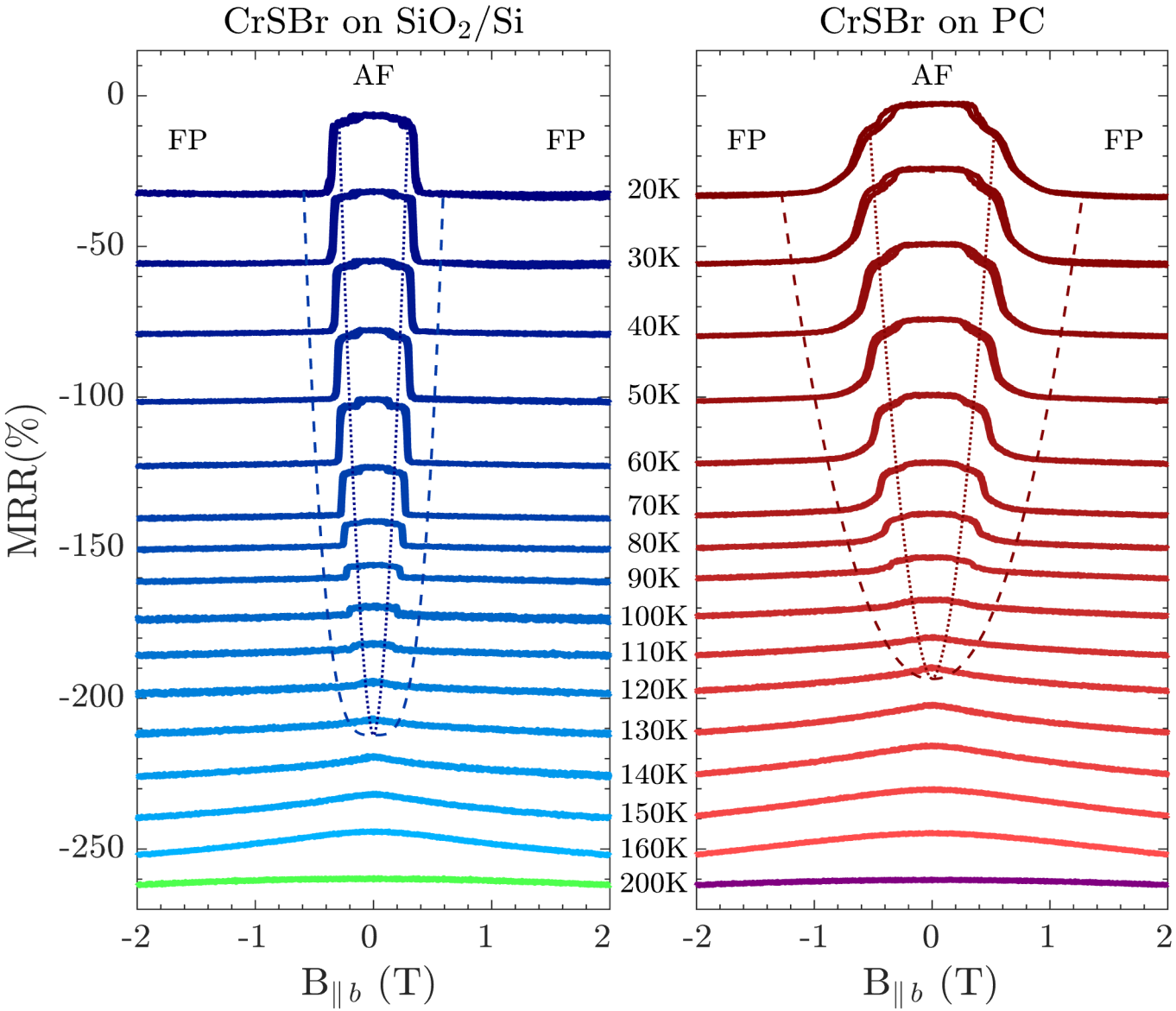


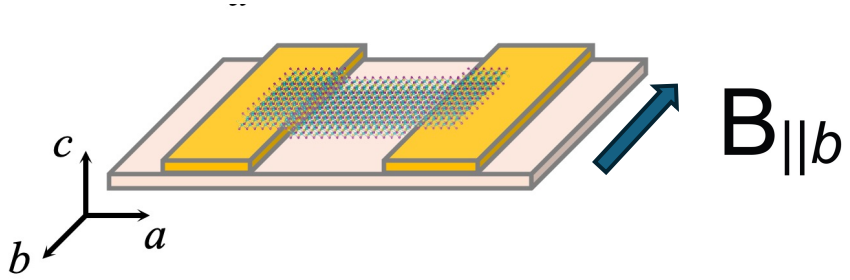




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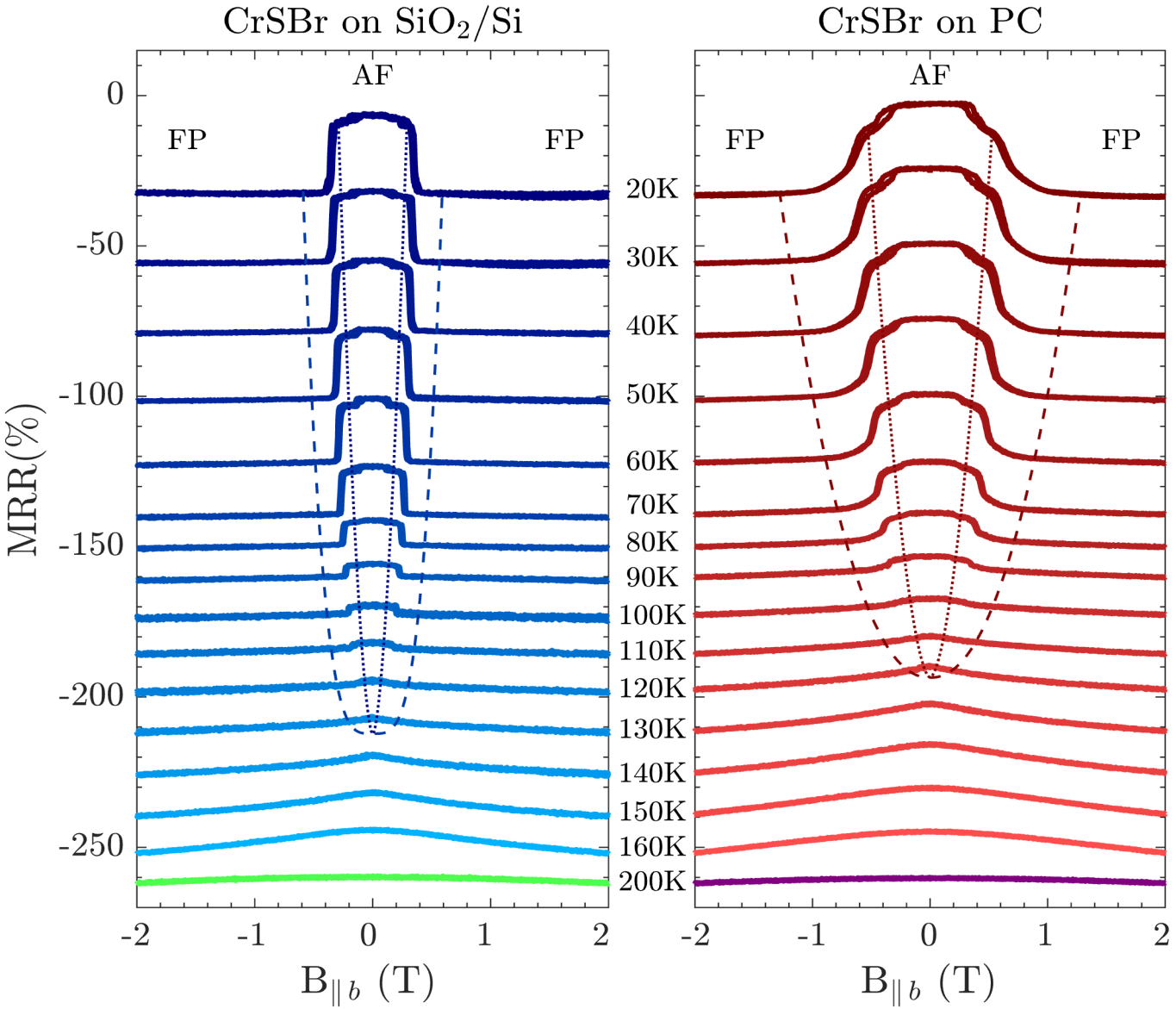
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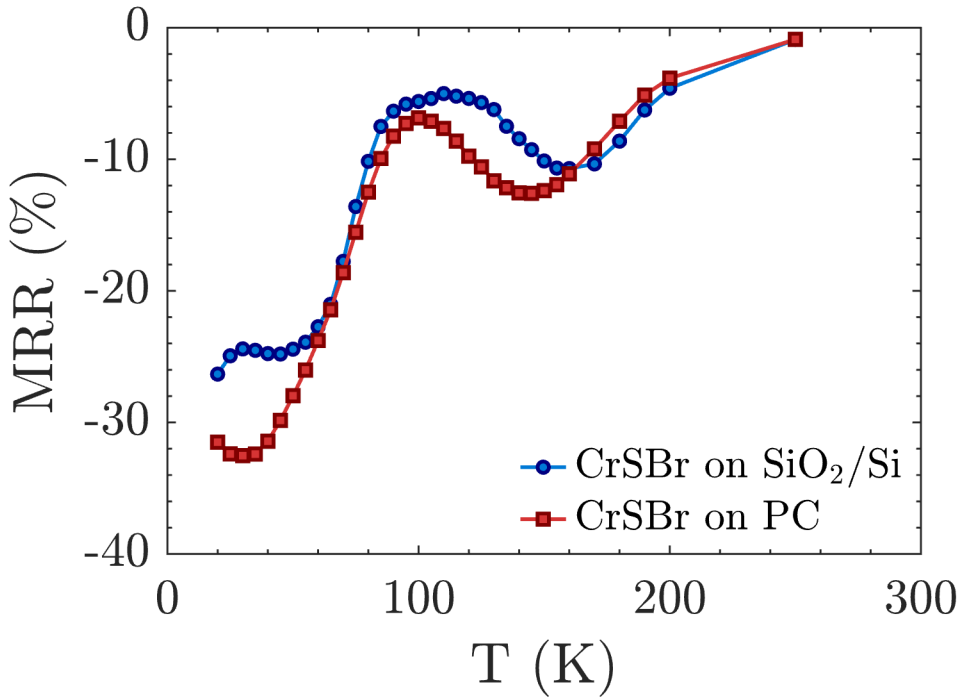




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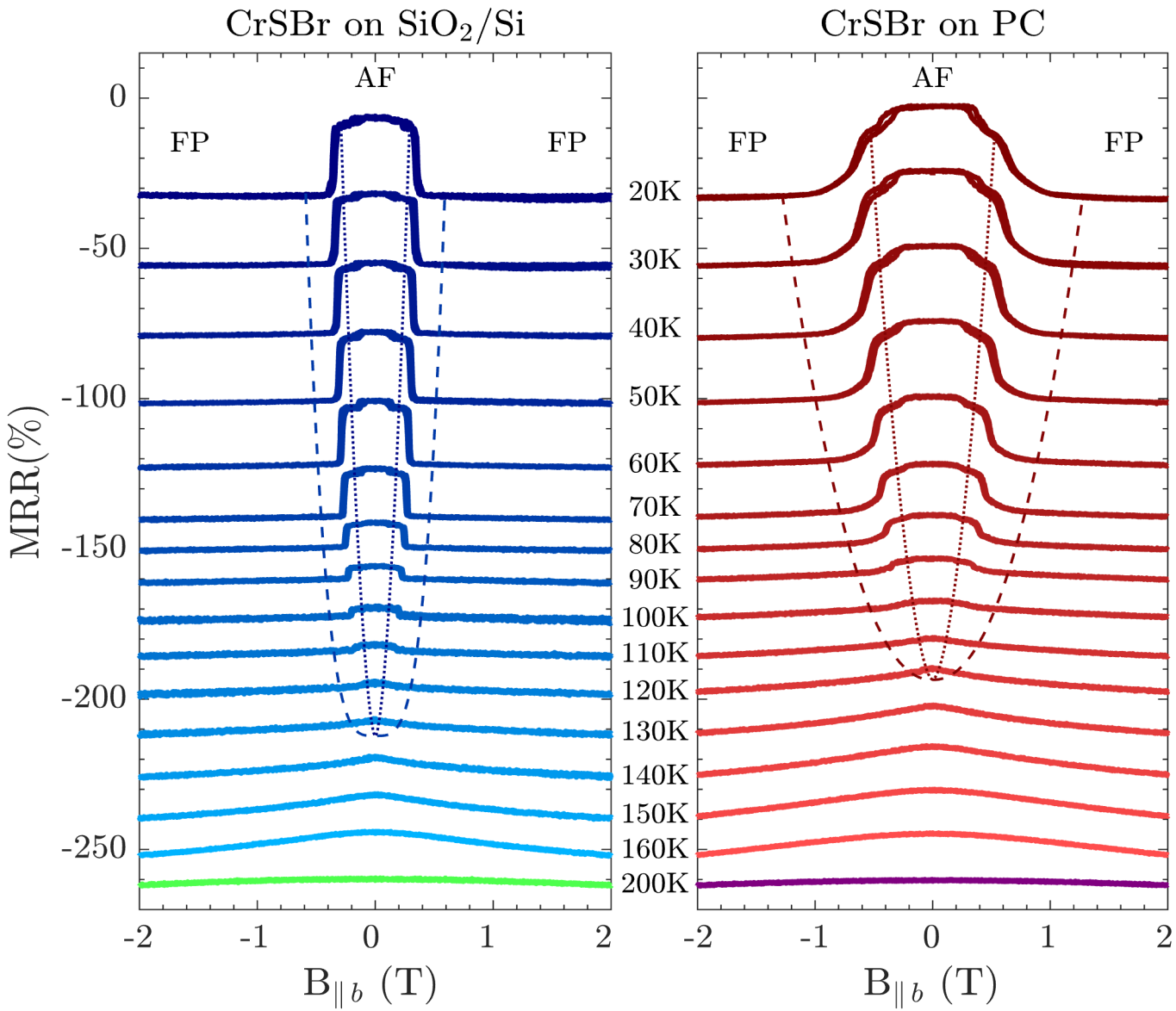
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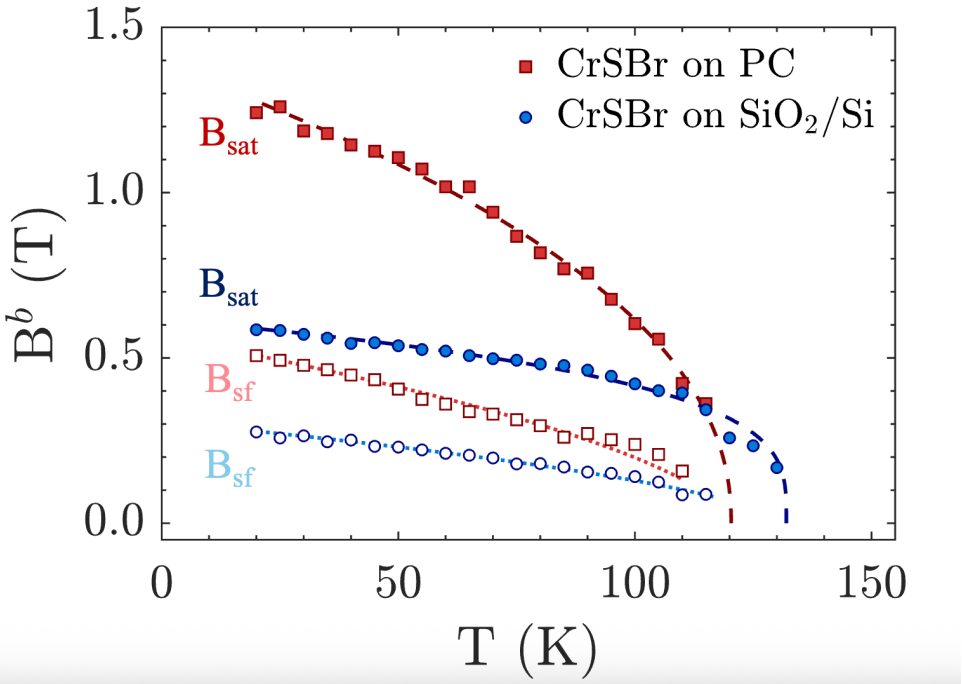




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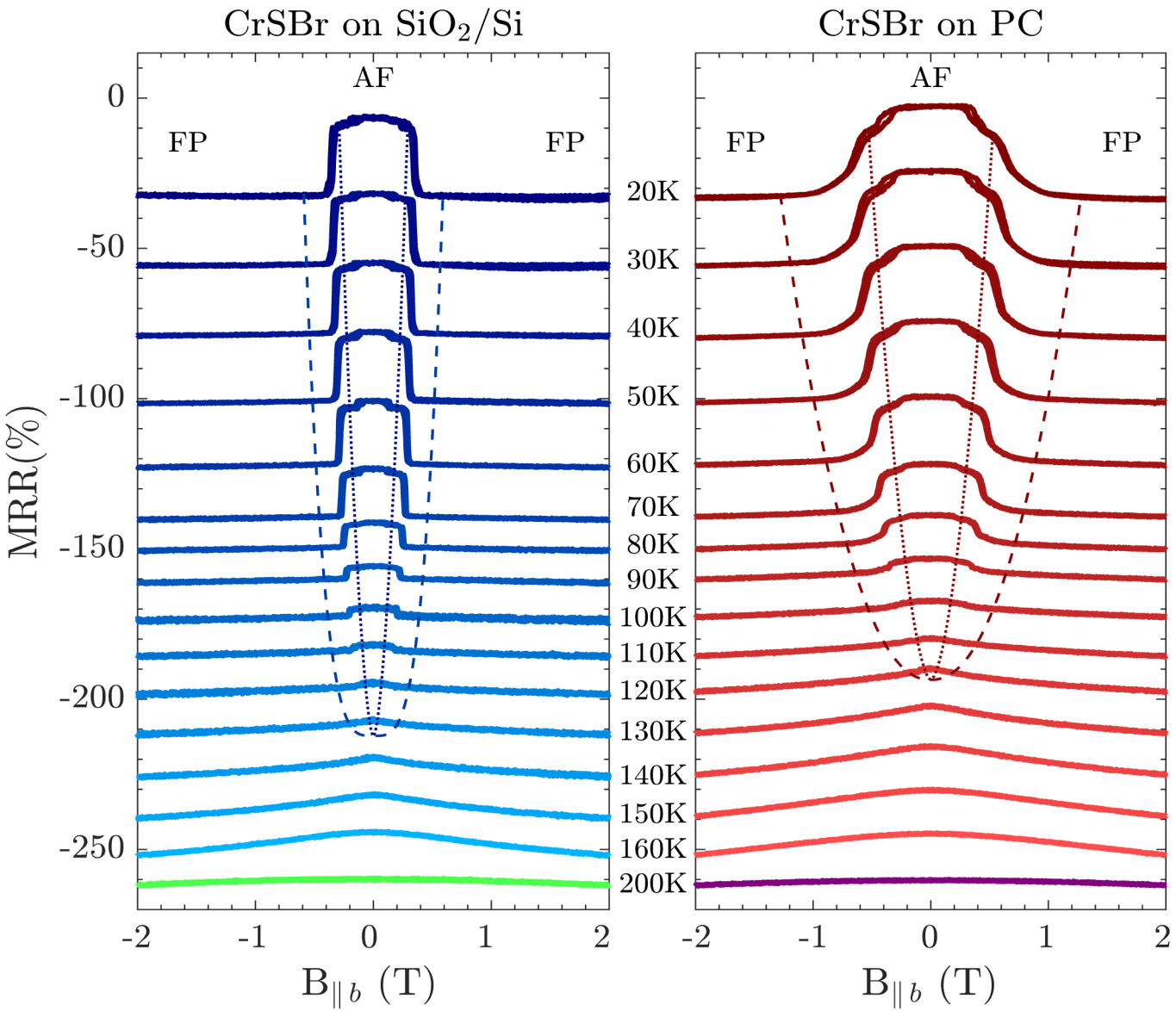
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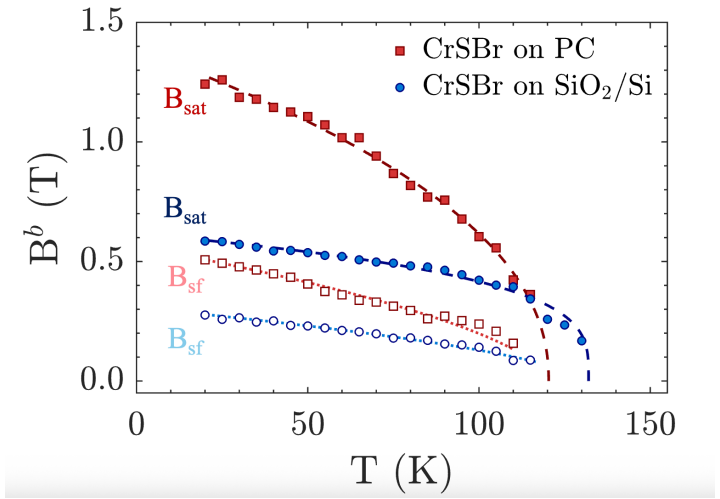




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Strain modulation of magnetoresistance in CrSBr



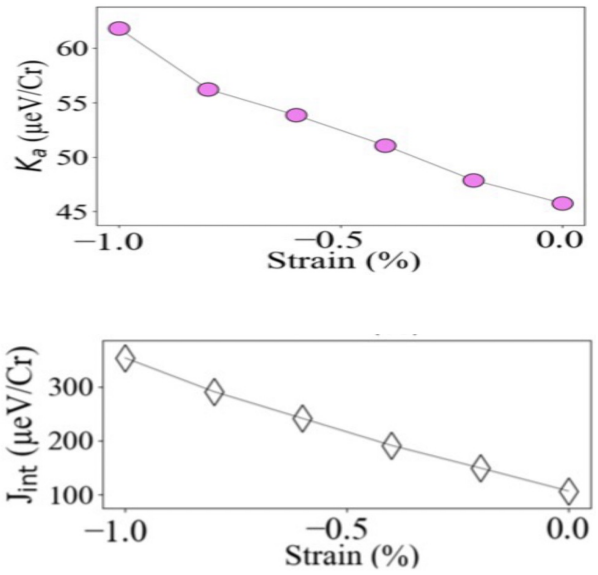


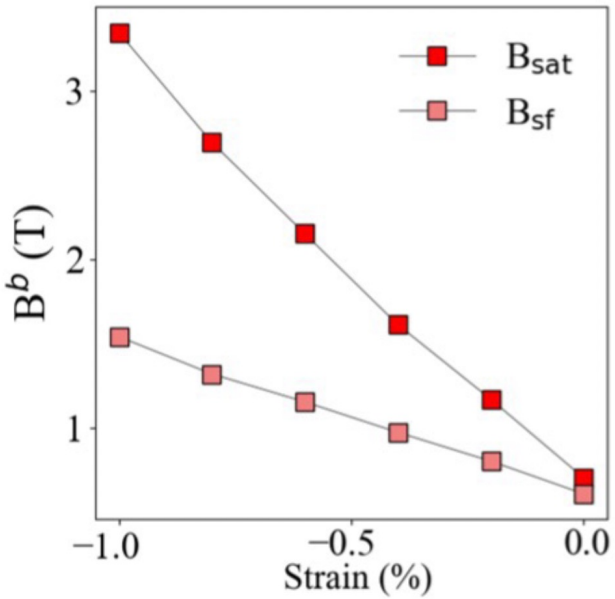
$$B_{sf}^{b} = \frac{2\sqrt{K_a(J_{int} - K_a)}}{M_0} \qquad (2)$$

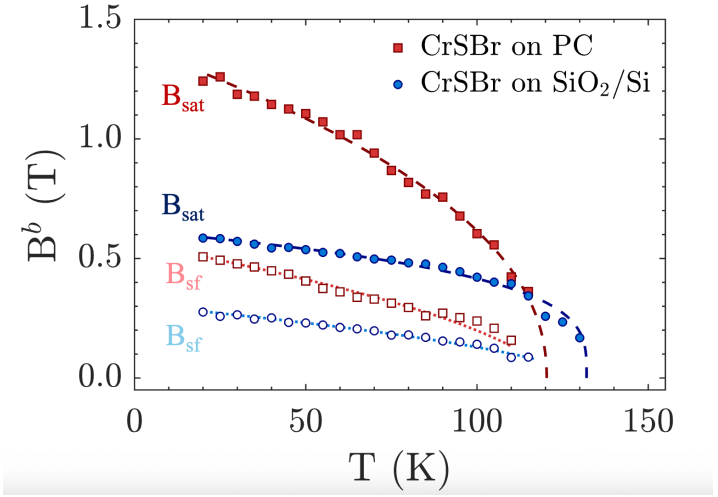
$$B_{sat}^{b} = 2\frac{J_{int} - K_a}{M_0} \qquad (3)$$

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Strain modulation of magnetoresistance in CrSBr





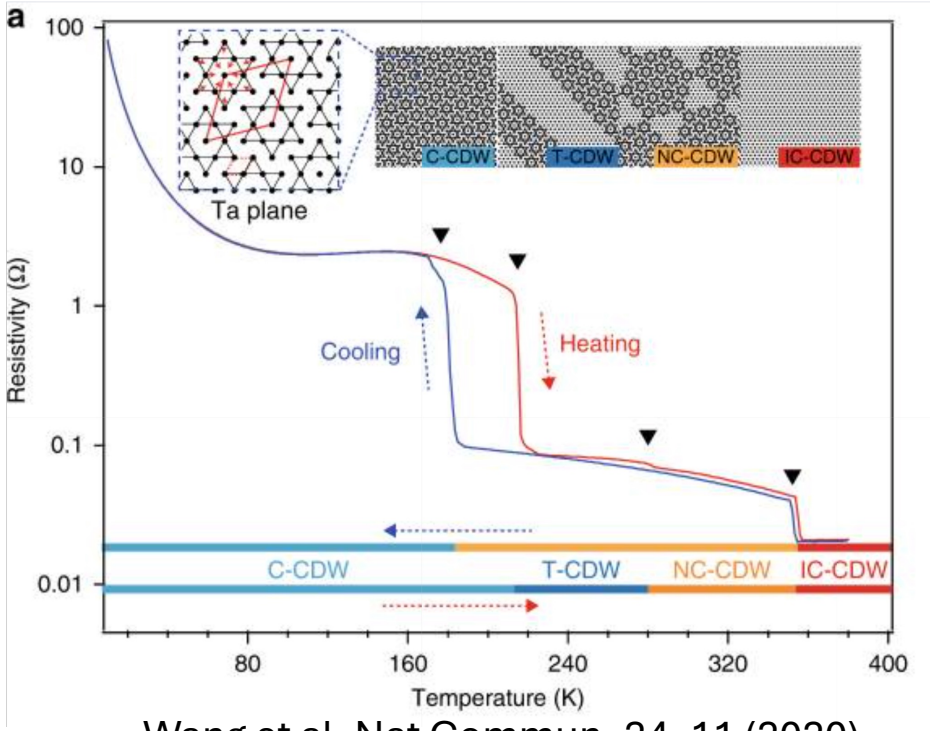


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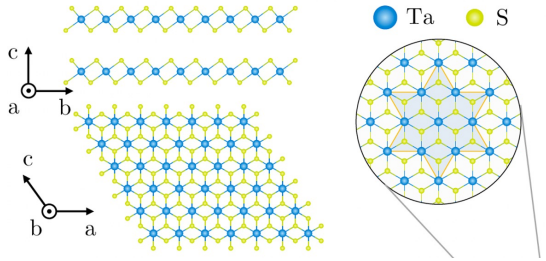
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Henríquez-Guerra, …, ***Calvo.*** Adv. Mater. 2025

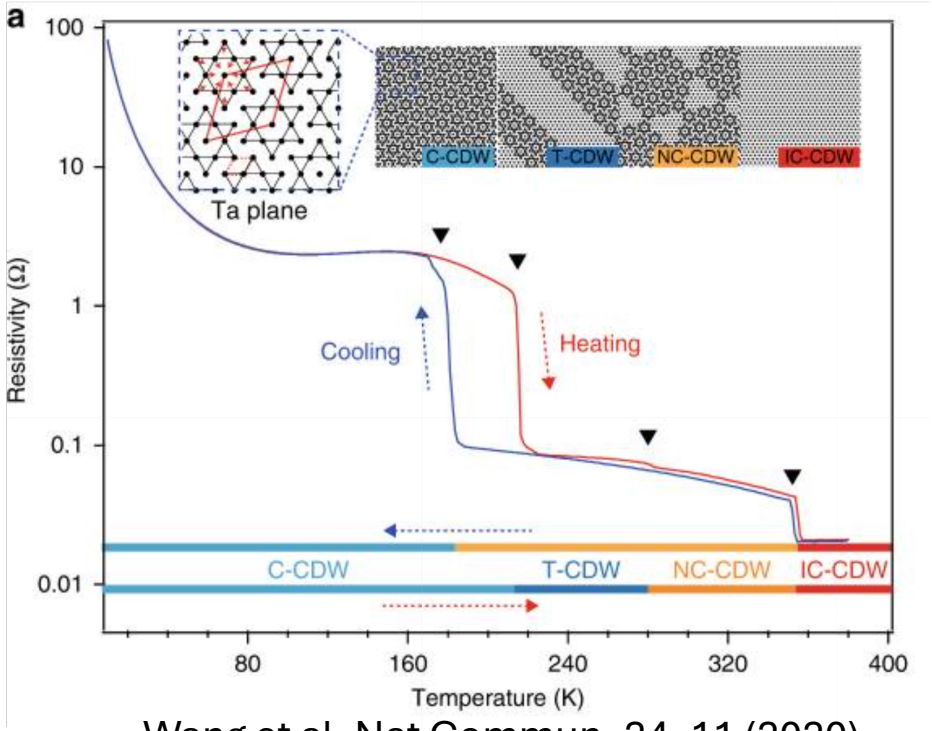
Strain control of CDW phases in 1T-TaS_2



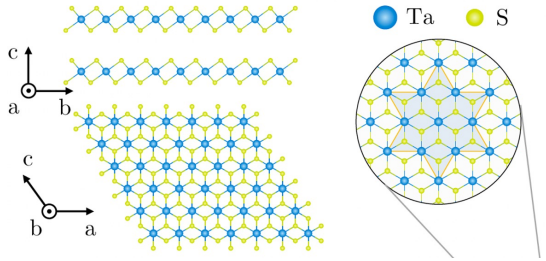
Wang et al. Nat Commun. 24, 11 (2020)

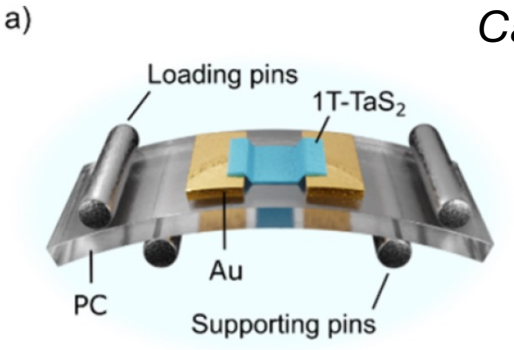


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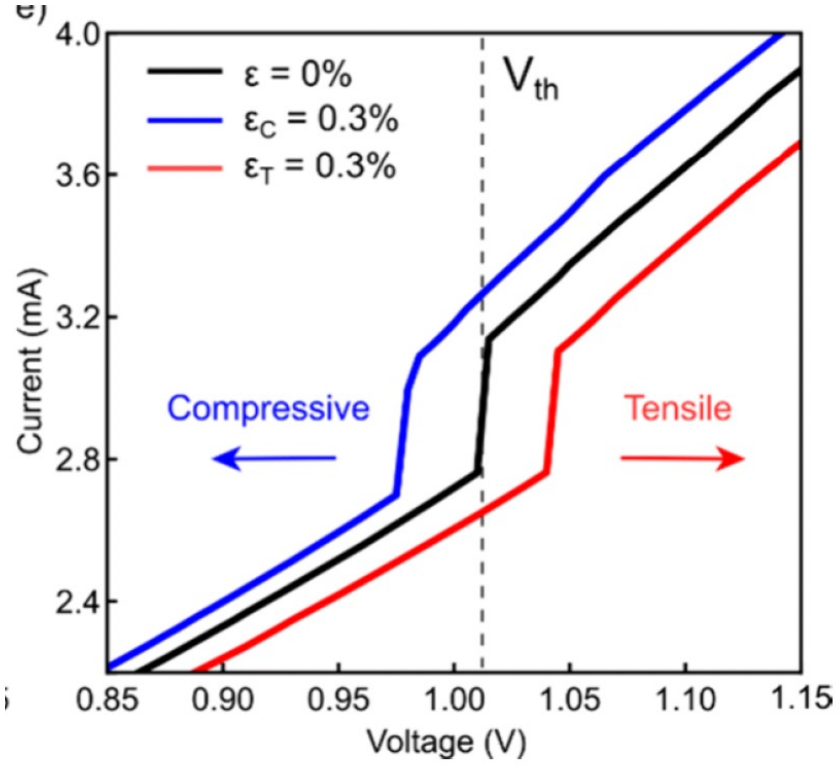


Wang et al. Nat Commun. 24, 11 (2020)





Luque-Merino, … , Henríquez-Guerra, Calvo, … Castellanos-Gomez, Nano Lett 25 16379 (2025)



Uniaxial strain reversibly tunes the switching threshold for the NC → IC phase transition

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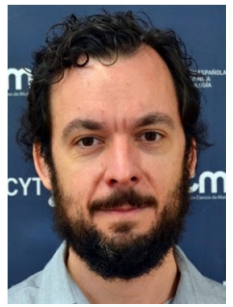
Efrén Navarro



Jose J. Baldoví



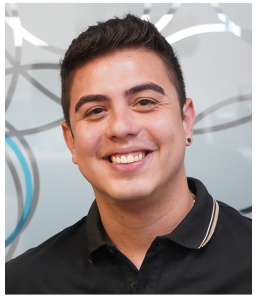
Hao Li



Andrés Castellanos



Lisa Almonte



Juan David Cortes



Daniel Gosálbez



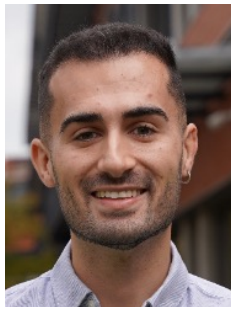
Roberto D'Agosta



Mario Amado



Marta Galbiati



Alberto M. Ruiz

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