2D materials and chalcogenides: elaboration and applications

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OUTLINE

1. Introduction to 2D and van der Waals materials

2. Growth of 2D materials and chalcogenides: from exfoliation to molecular beam epitaxy

3. Recent achievements in MBE-grown 2D materials: narrow excitonic lines, doping, alloys, superconductivity, ferroelectricity, ferromagnetism

4. 2D magnets for spintronics: $Cr_{1+\delta}Te_2$, $Fe_{3-5}GeTe_2$

5. Conclusion and perspectives

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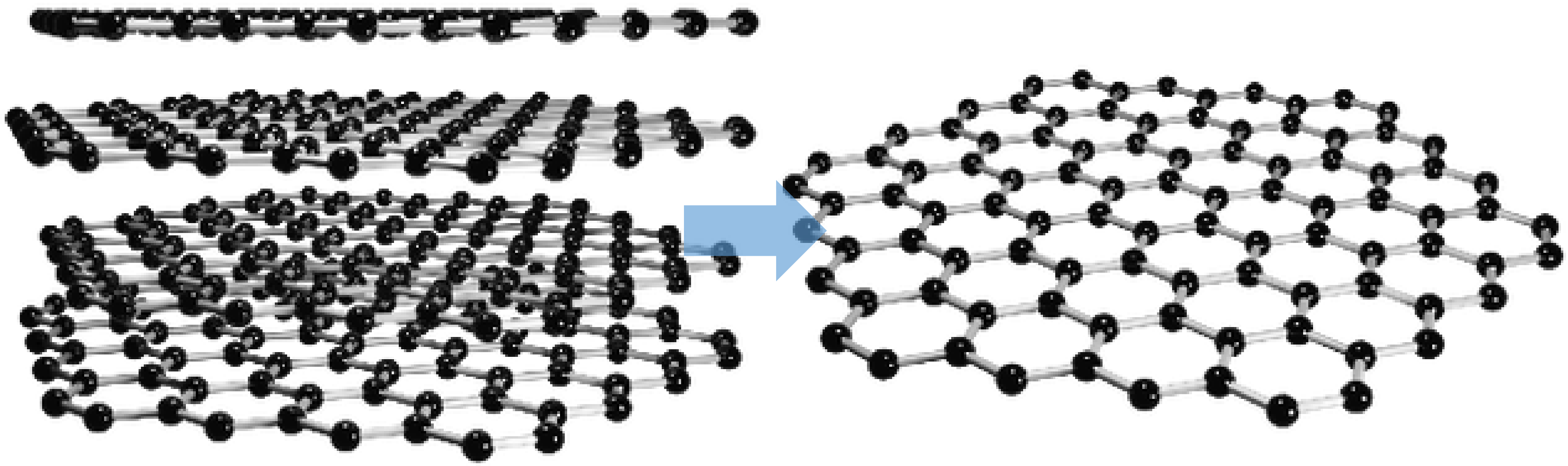
2004, GRAPHENE

Superlative material



graphite graphene

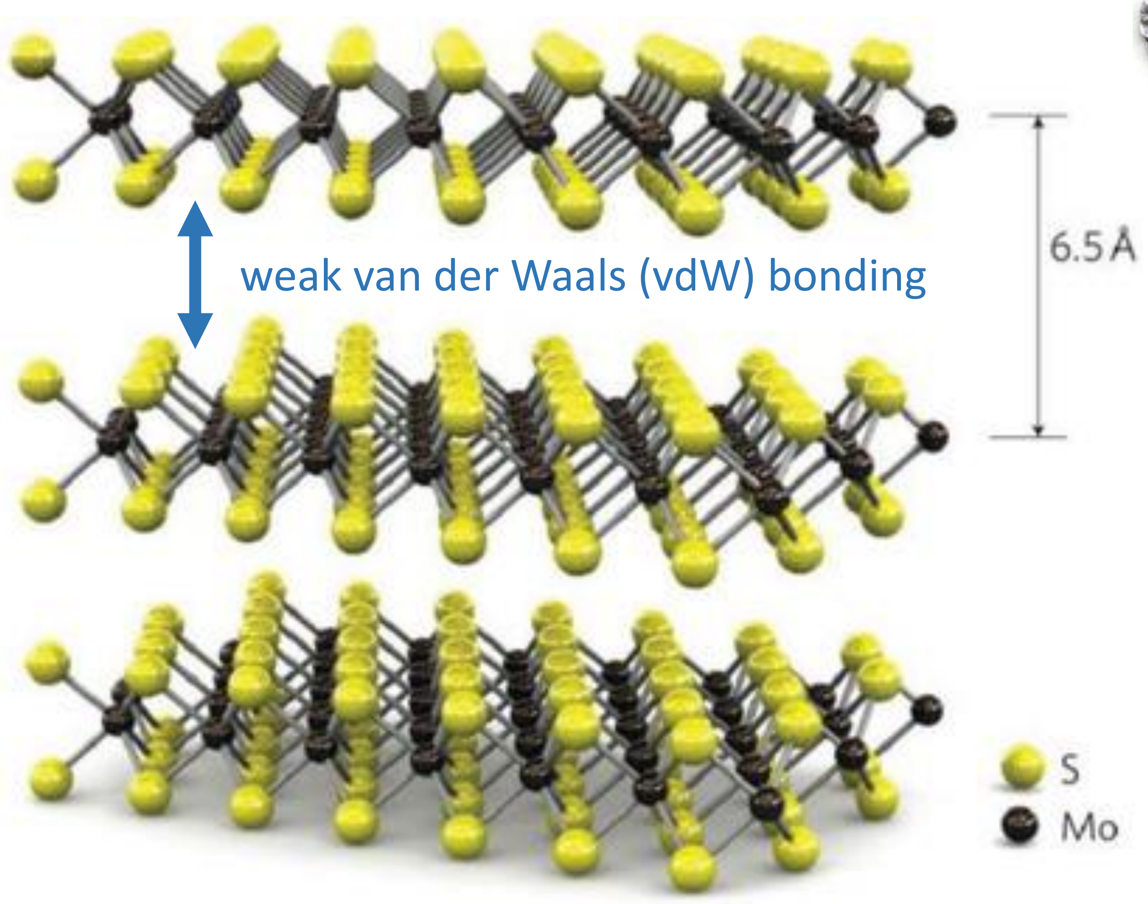
A. Geim
NOBEL PRIZE IN 2010

- 200 times stronger than steel
- 1.000.000 times thinner than a single human hair
- The world’s lightest material (1 m^2 weighs about 0,77 milligram)
- Flexible
- Transparent
- Impenetrable for molecules
- Excellent electrical and heat conduction

K. Novoselov
NOBEL PRIZE IN 2010

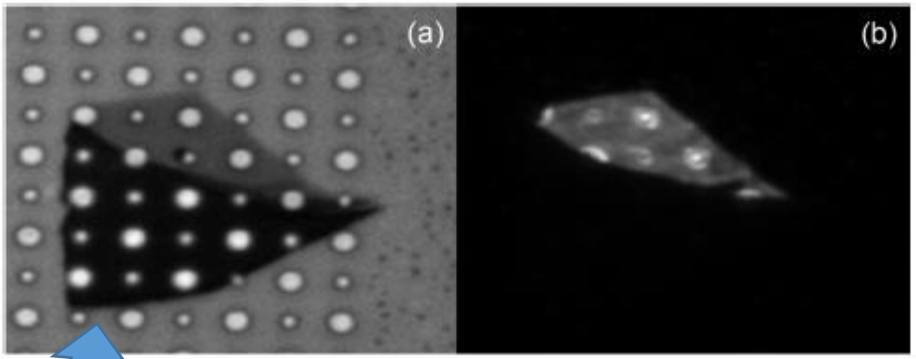
K. Novoselov and A. Geim, Nature **438**, 197 (2005)

2010, TRANSITION METAL DICHALCOGENIDES (TMD)



weak van der Waals (vdW) bonding

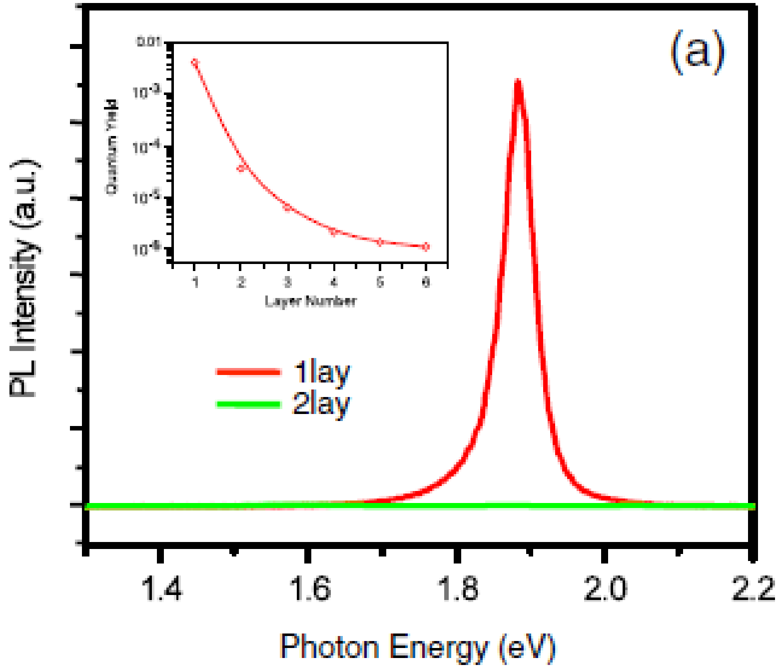
MoS_2



from the mine…to a single layer flake

MoS_2 becomes direct bandgap semiconductor in 1 monolayer

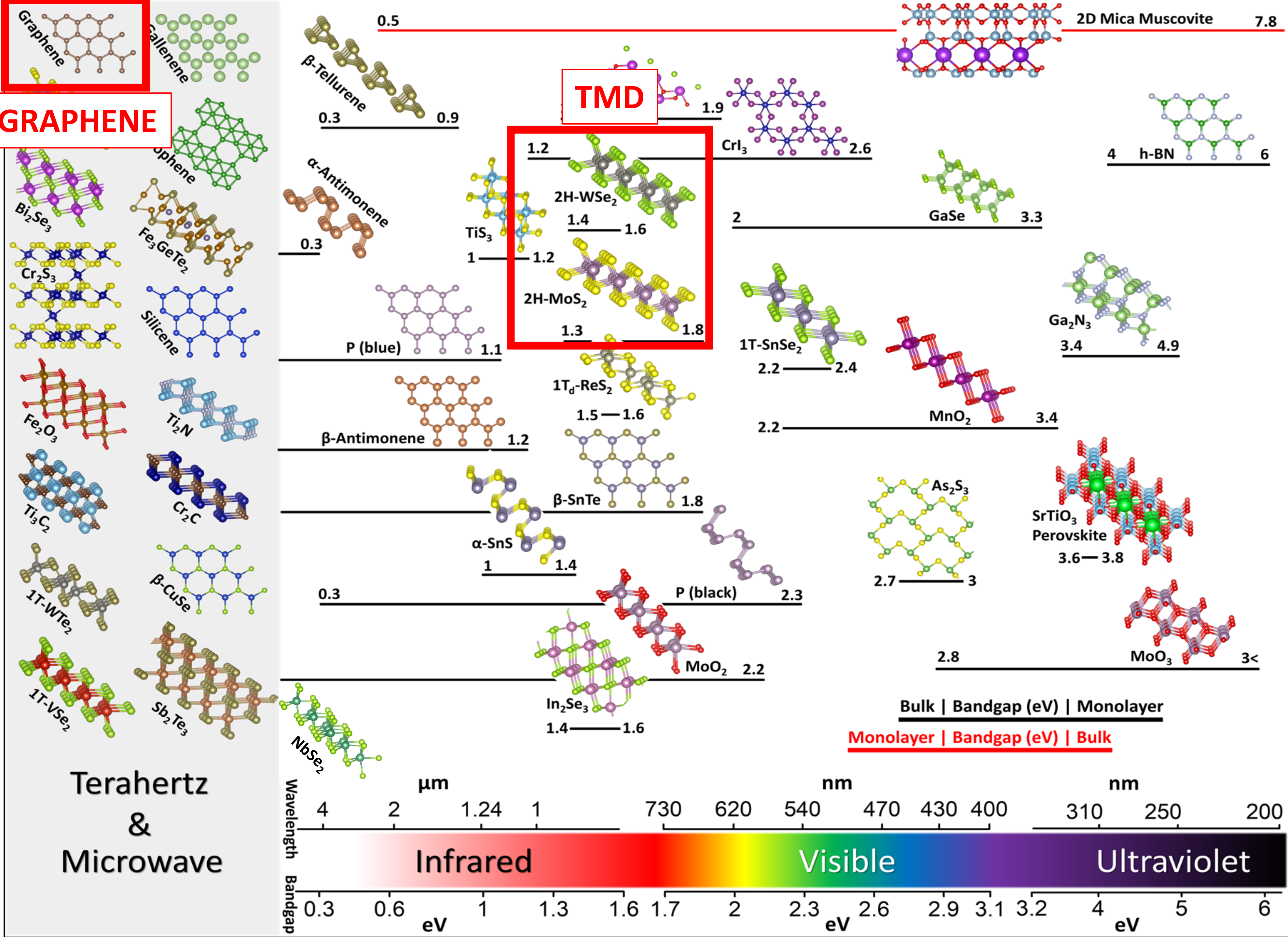
exceptional
light absorber/emitter



K. F. Mak, T. F. Heinz, Phys. Rev. Lett. **105**, 136805 (2010)

2004-2021

Boom in the number of 2D materials



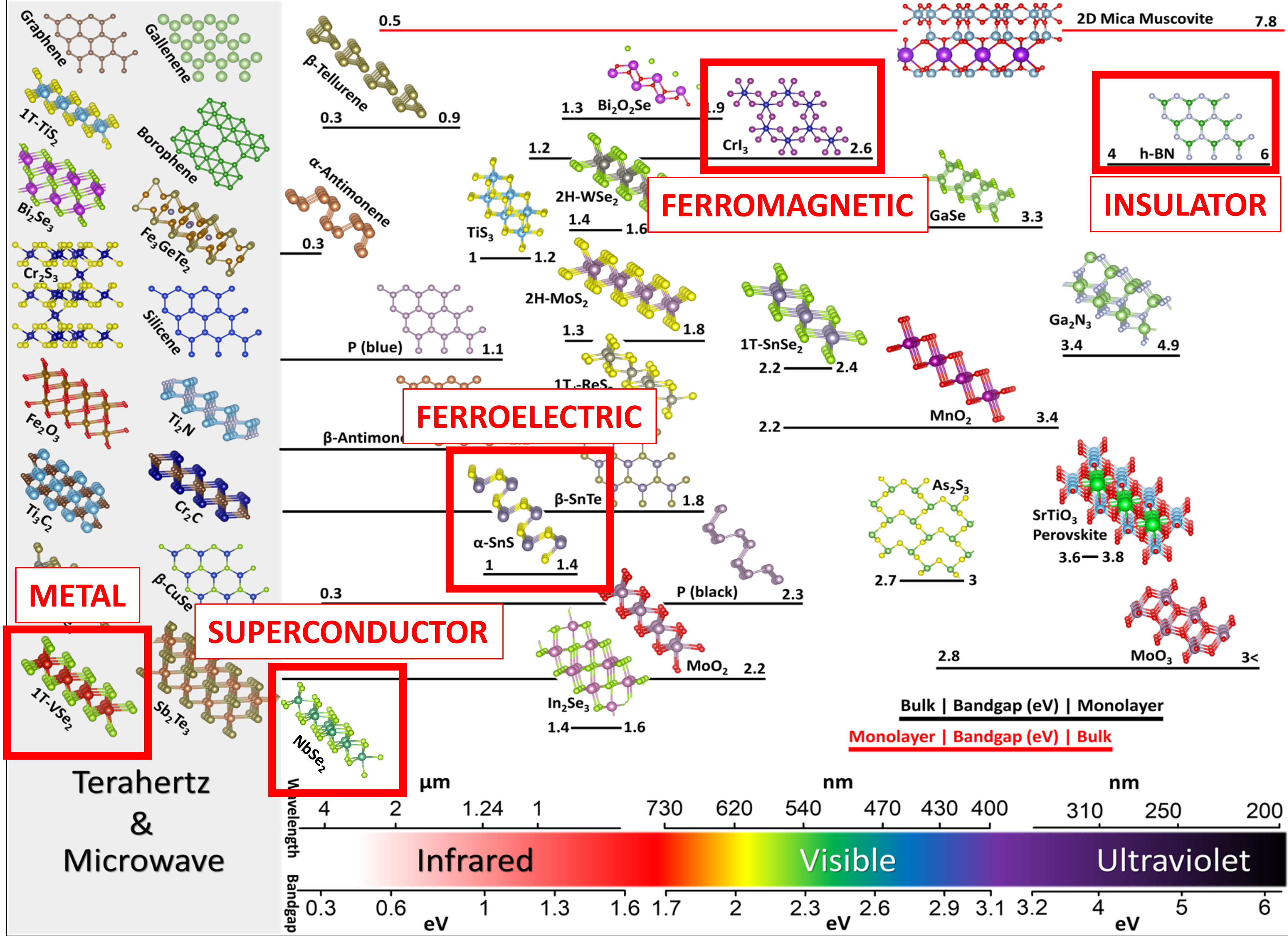
2D constellation

A. Chaves et al., npj 2D Mater. & Appl. **4**, 29 (2020)

2004-2021

Boom in the number of 2D materials

2D constellation



A. Chaves et al., npj 2D Mater. & Appl. **4**, 29 (2020)

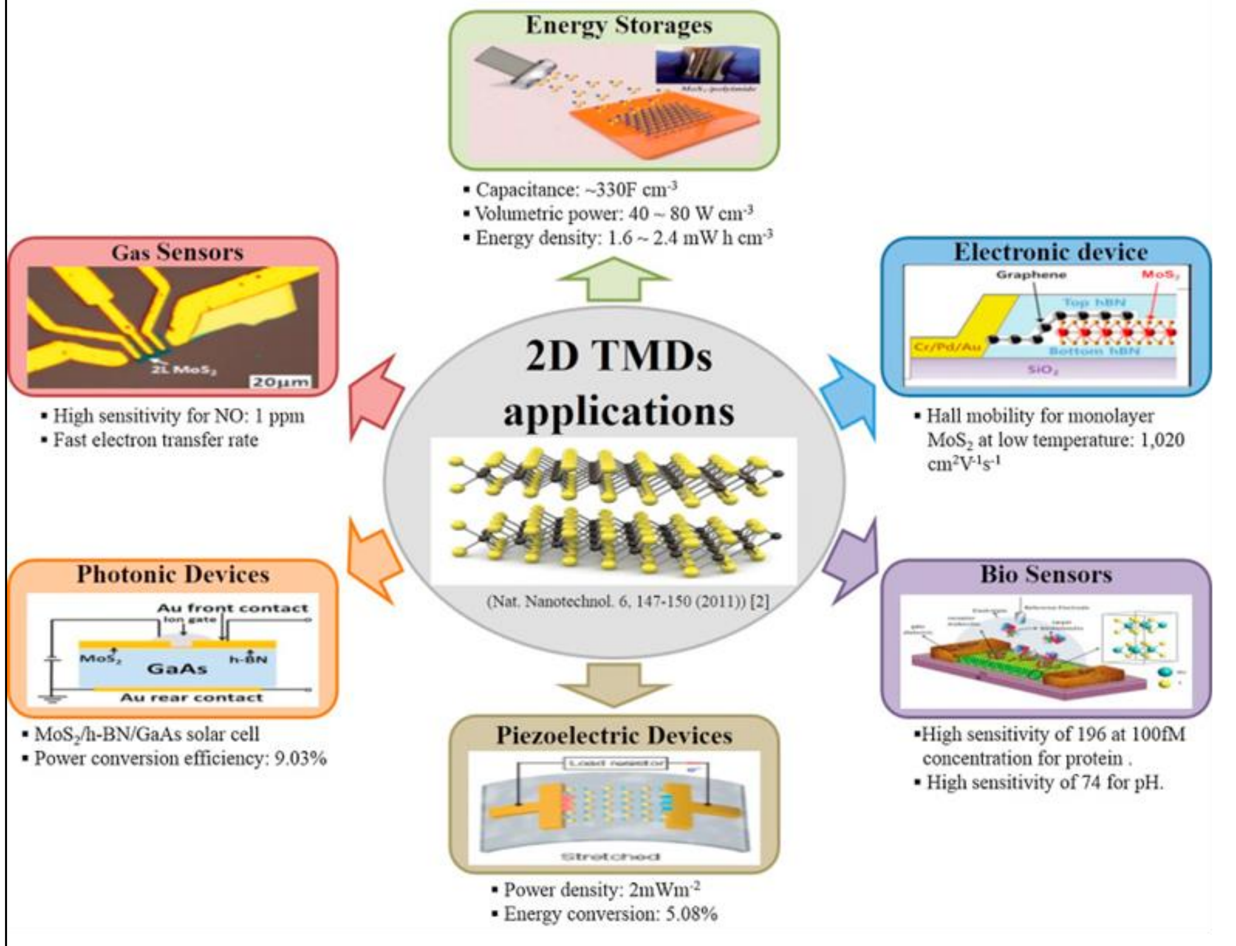
Why so much success ?

- atomically thin layers: quantum confinement effects (indirect-to-direct bandgap, high carrier mobility, excitonic effects, quantum light emitters…), high sensitivity to their environment and any stimulus (electric field, chemicals, light, stress…) + flexibility

HIGHLY TUNABLE ELECTRONIC PROPERTIES WITH LOW ENERGY COST

LESS MATERIAL FOR SUSTAINABLE ELECTRONICS

EASY TO ETCH

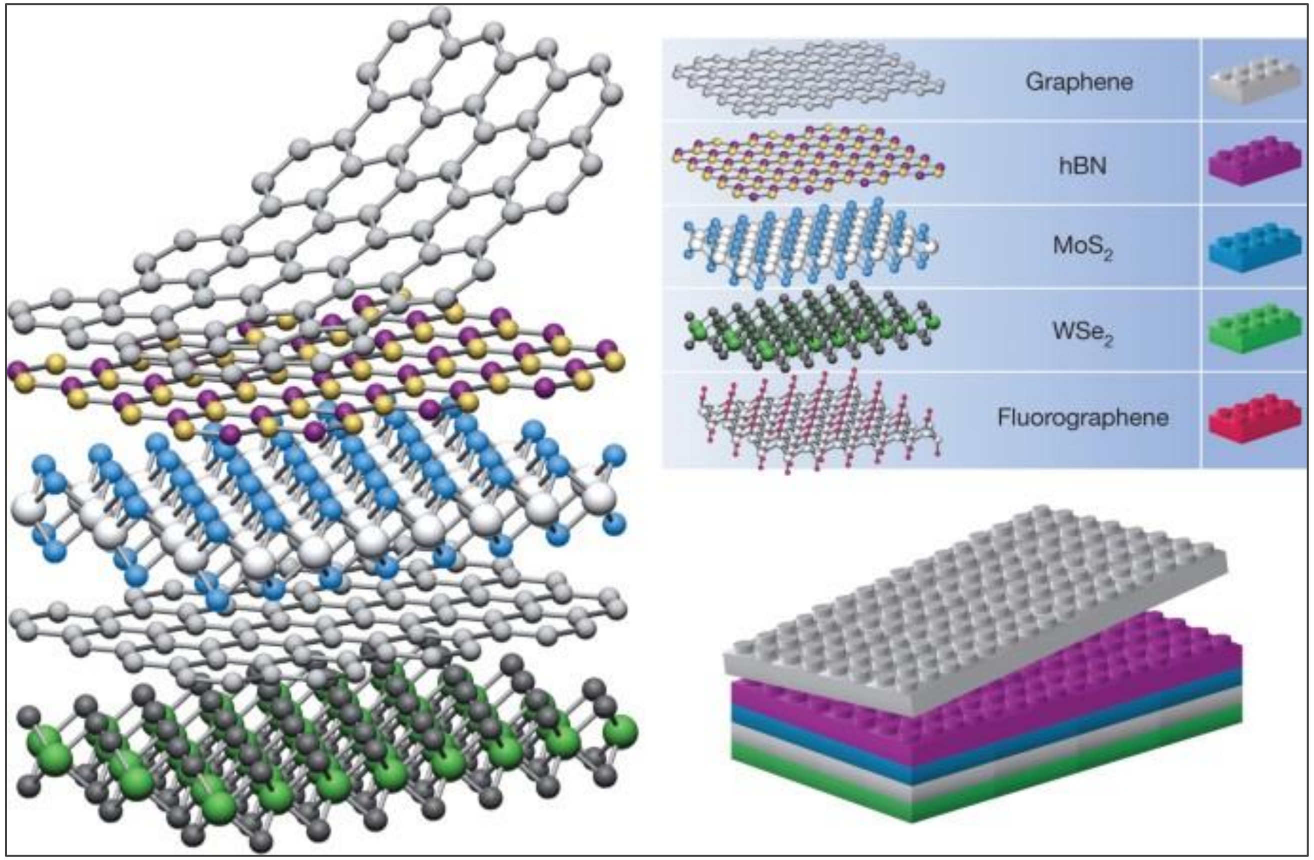


W. Choi et al. *Materials Today*, **20** (2017)

Why so much success ?

- **vdW interfaces:** perfectly clean and sharp interfaces with no chemical reaction or atomic intermixing. Perfect control of interface effects: proximity effects (magnetism, superconductivity…), band engineering with well defined band offsets

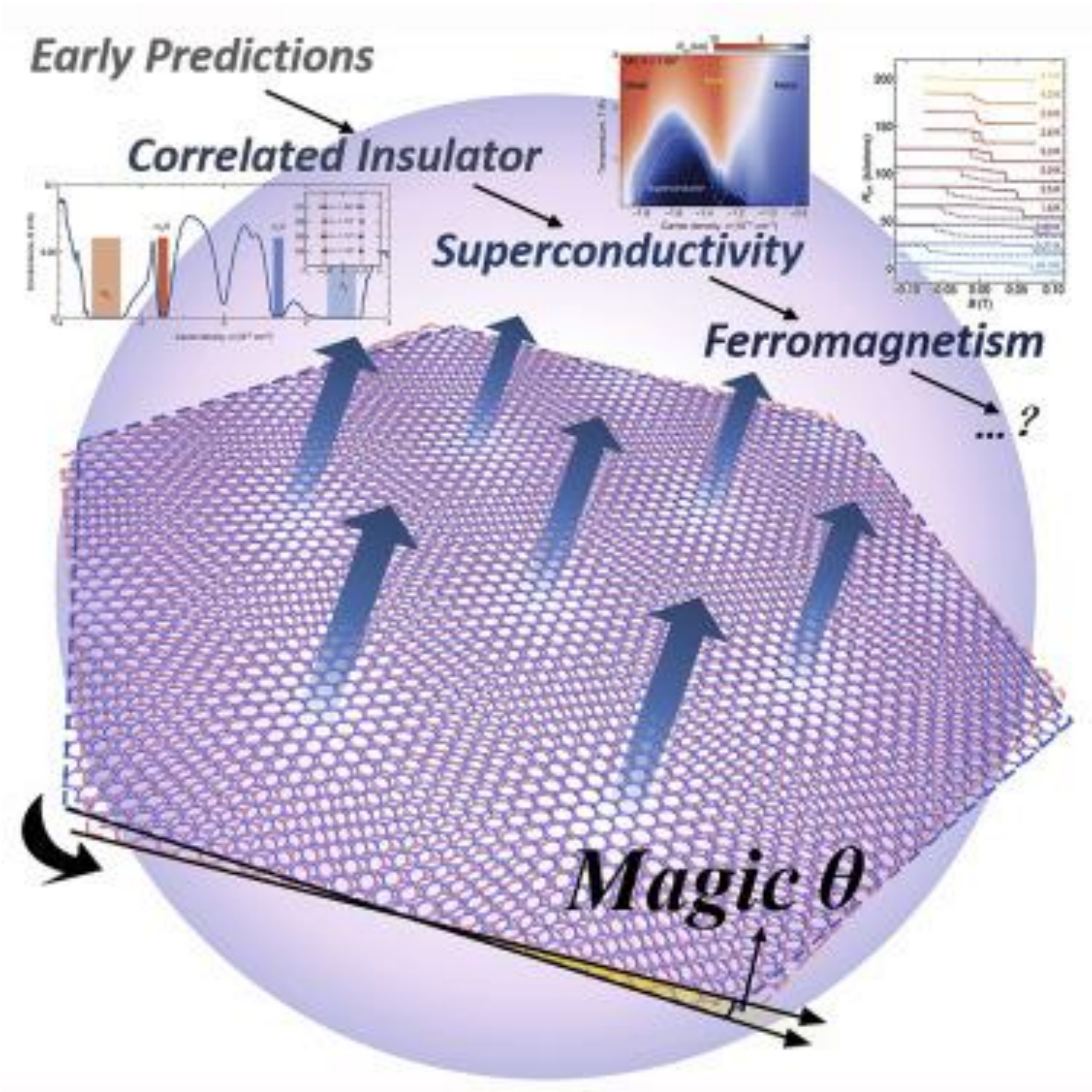
→ NEW PHYSICS AND VERTICAL DEVICES



A. K. Geim et al., Nature **499**, 419 (2013)

TWISTRONICS

the case of bilayer graphene at the magic twist angle 1.1°



Superconductivity up to T = 1.7 K,

Y. Cao et al., Nature **556**, 43 (2018)

Ferromagnetism up to T = 3.5 K,

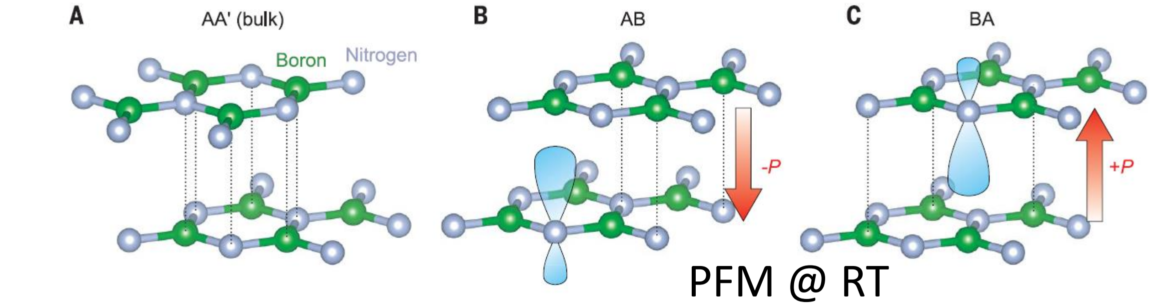
G. Chen et al., Nature **549**, 56 (2020)

Z. Sun et al., Matter **2**, 1106 (2020)

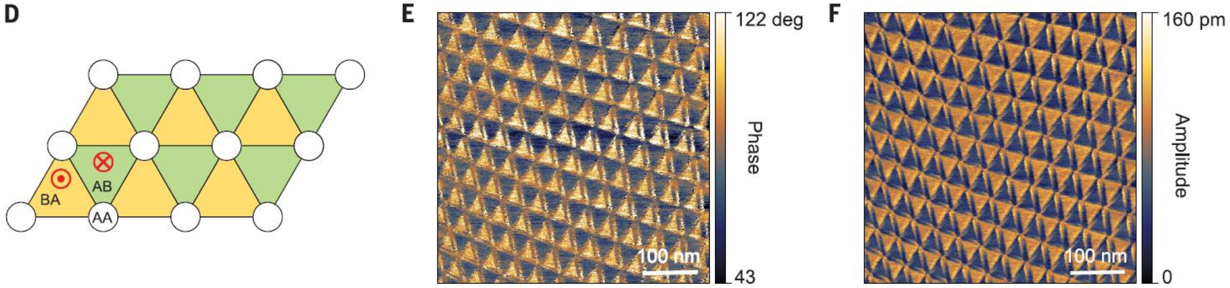
FERROELECTRICITY IN BILAYERS hBN & $MoSe_2$

tear-and-stack fabrication method

hBN

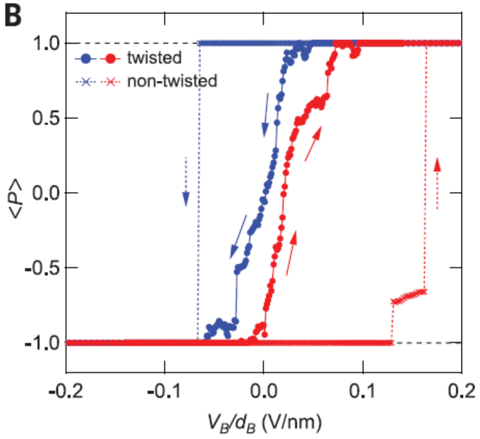


PFM @ RT

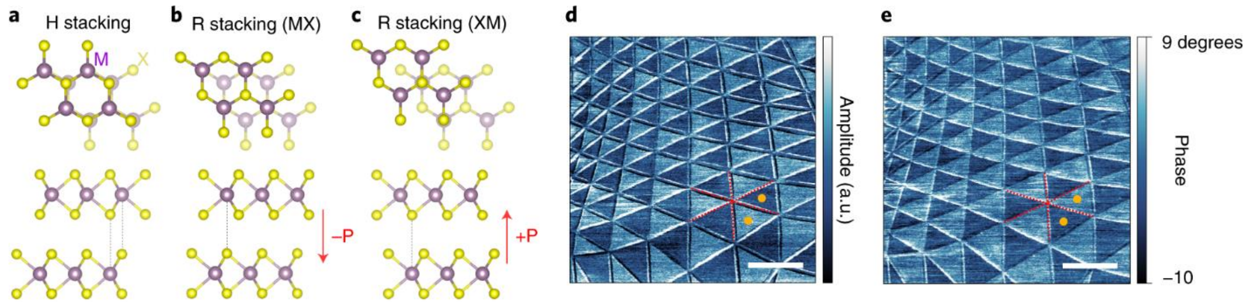


Yasuda et al., Science 372, 1458 (2021)

Hysteresis curves from electrical meas. @ 4.2K

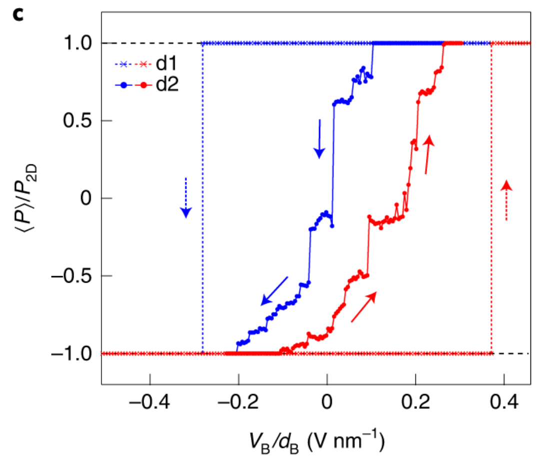


$MoSe_2$



PFM @ RT

X. Wang et al., Nat. Nanotechnol. 17, 367 (2022)



Hysteresis curves from electrical meas. @ 4.2K

Same with WSe_2, MoS_2, WS_2

Also WTe_2: Z. Fei et al., Nature 560, 336 (2018) and $MoTe_2$: A. Jindal et al., Nature 613, 48 (2023)

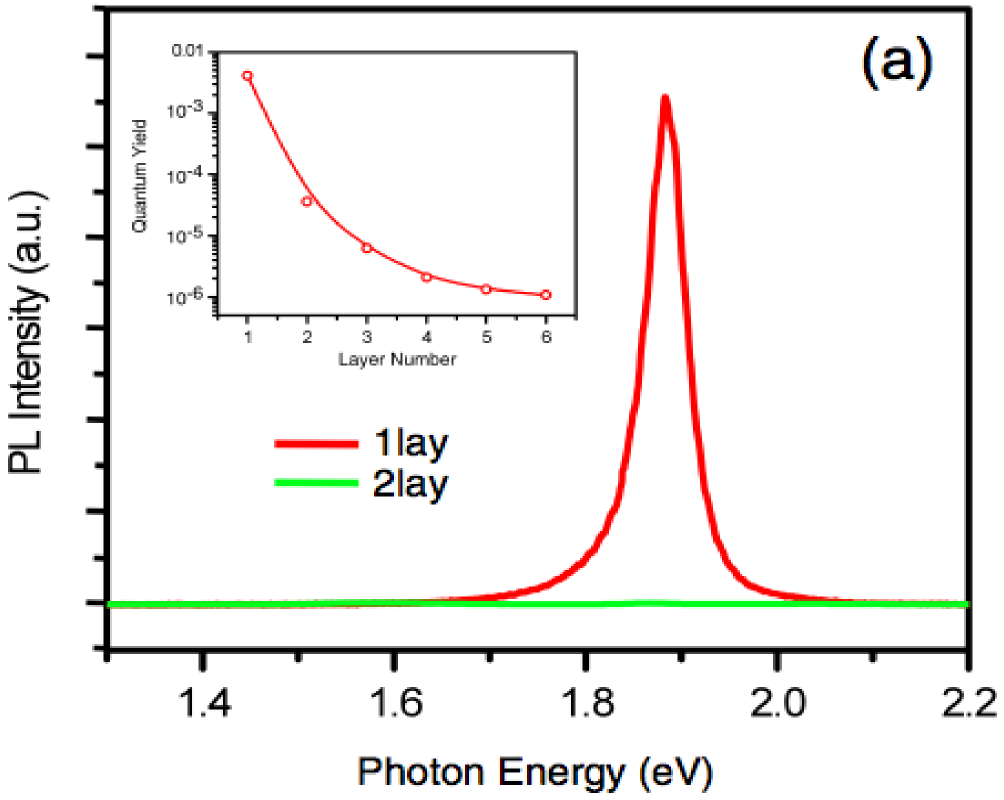
TMDs: a very specific band structure

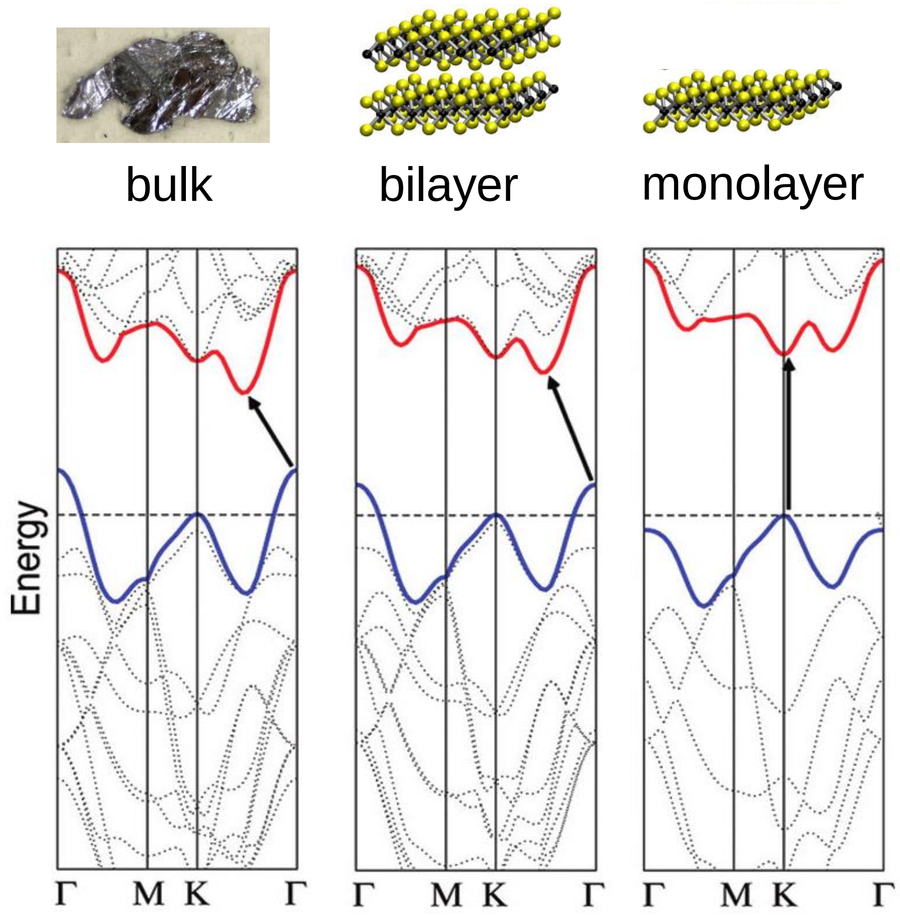
Courtesy Xavier Marie, LPCNO, INSA Toulouse, France

MoS_2 : Optical properties

Bulk MoS_2 : indirect bandgap → 1 Monolayer: direct bandgap

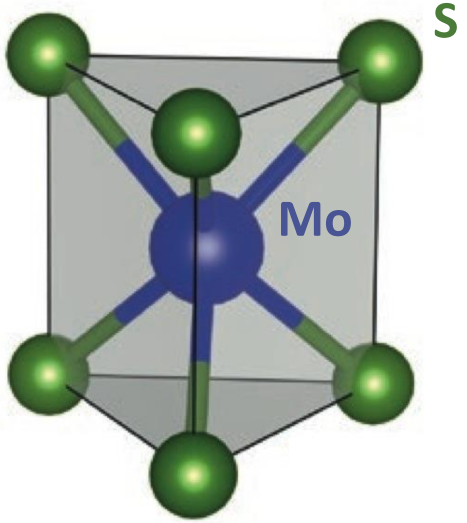
J. Phys.C : Solid State Phys. 5, 759 (1972)





Splendiani, et al, Nano Lett.10, 1271 (2010) & Mak et al, Phys. Rev. Lett. 105, 136805 (2010)

Courtesy Xavier Marie, LPCNO, INSA Toulouse, France



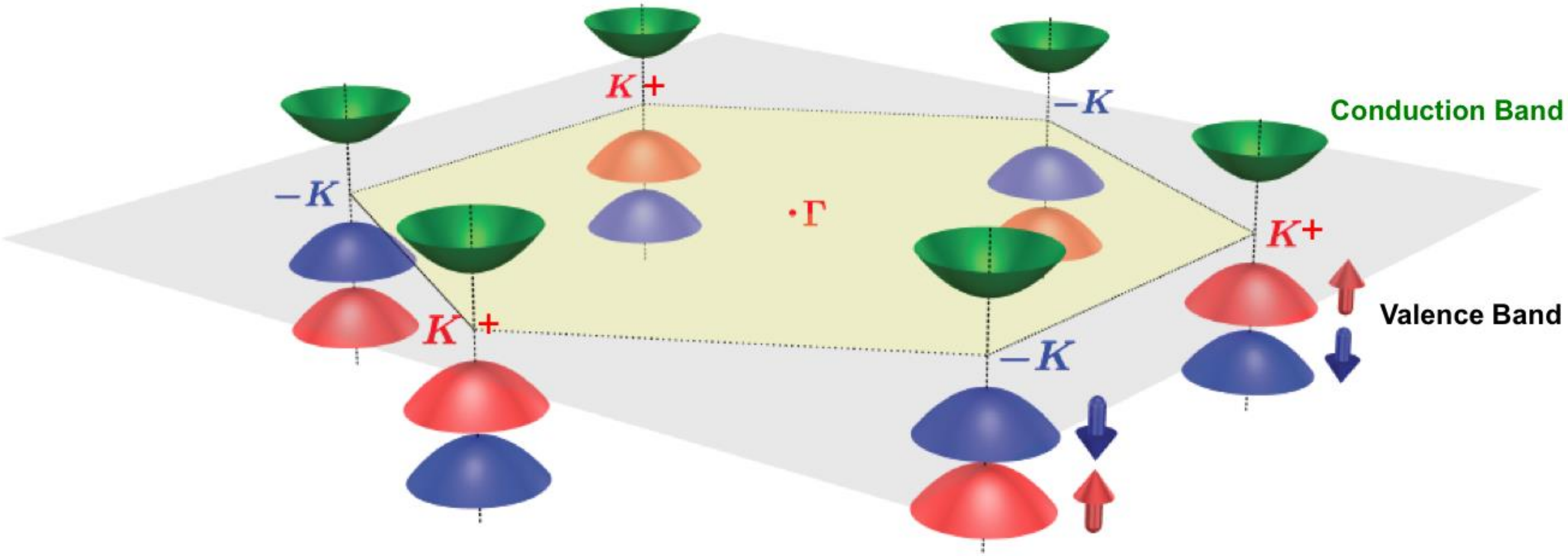
Monolayer MoS_2 band structure

Main difference to Graphene:

- direct bandgap
- broken Inversion symmetry
- strong spin-orbit coupling

} ***Spin splitting in Valence band***

CB and VB edges located at the corners (K points) of the 2D hexagonal Brillouin zone :



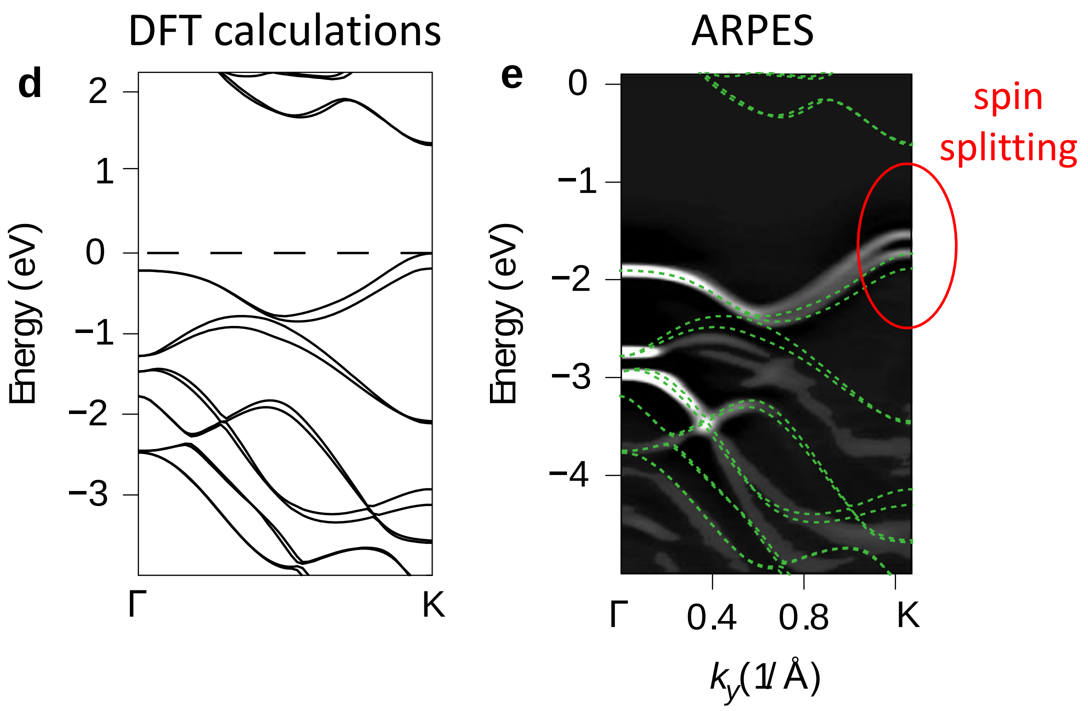
Valleytronics

(addressing –K or K+ by light, magnetism or electrically)

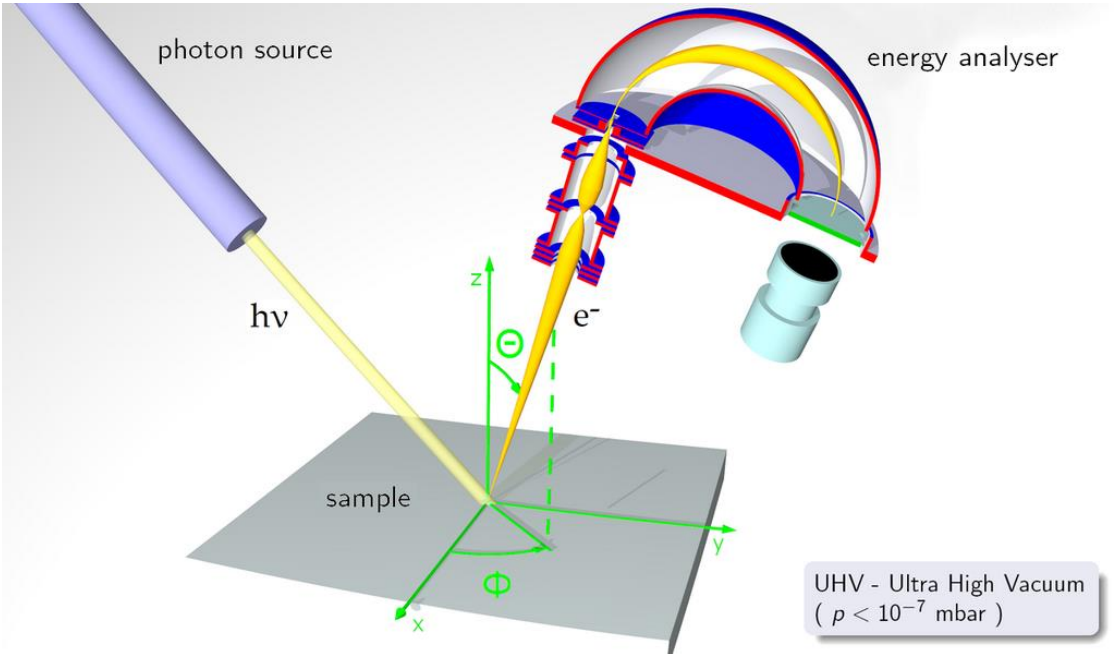
Time reversal symmetry → ***Spin splitting at different valleys is opposite***

Angle-Resolved Photoemission Spectroscopy (ARPES)

$MoSe_2$-monolayer



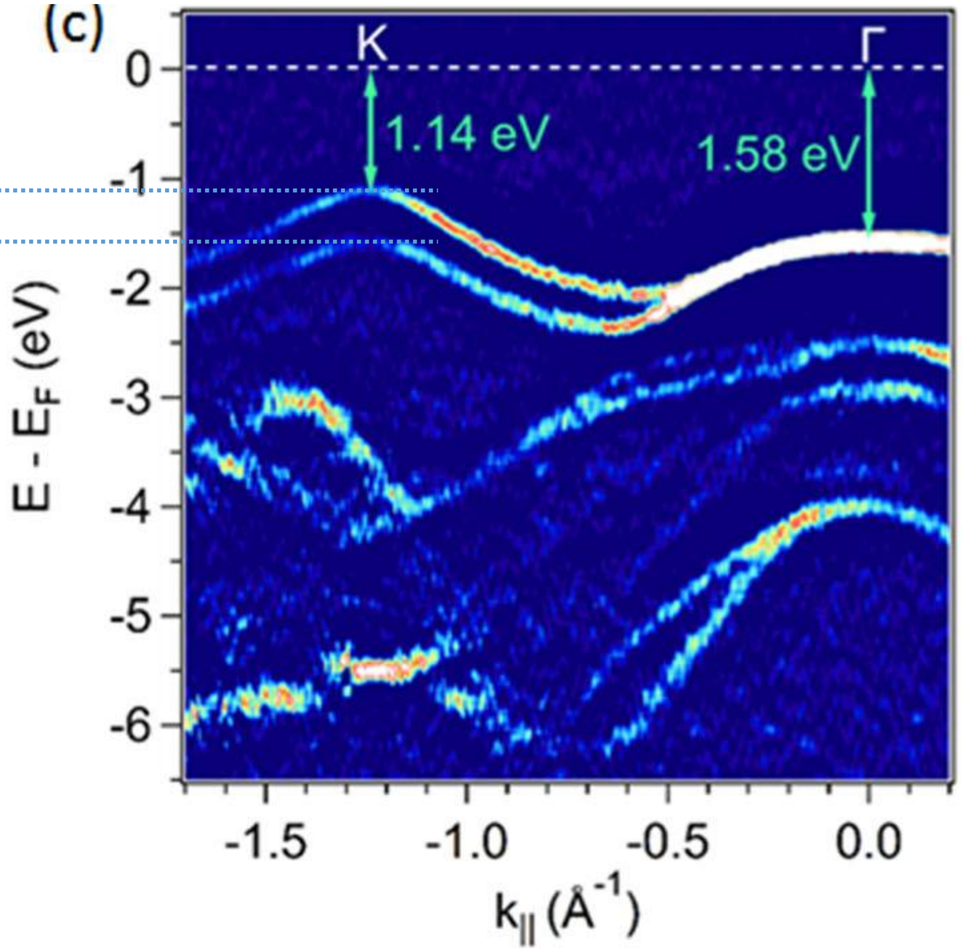
Nature Nano. **9**, 111. (2013)
PRL **111**, 106801 (2013)



Angle-Resolved Photoemission Spectroscopy (ARPES)

WSe_2-monolayer

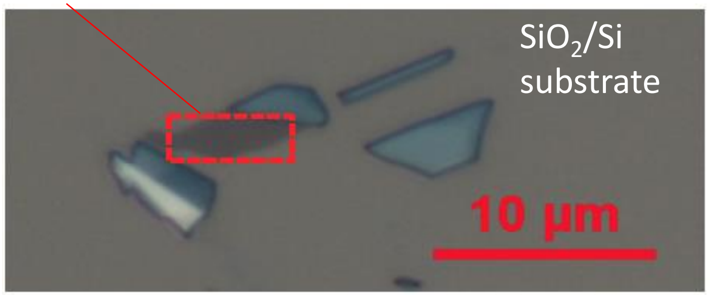
spin splitting by SOC
Δ_{SO}=480 meV



npj 2D Materials and App. **3**, 27 (2019)

Courtesy Xavier Marie, LPCNO, INSA Toulouse, France

1 ML WSe_2 sample

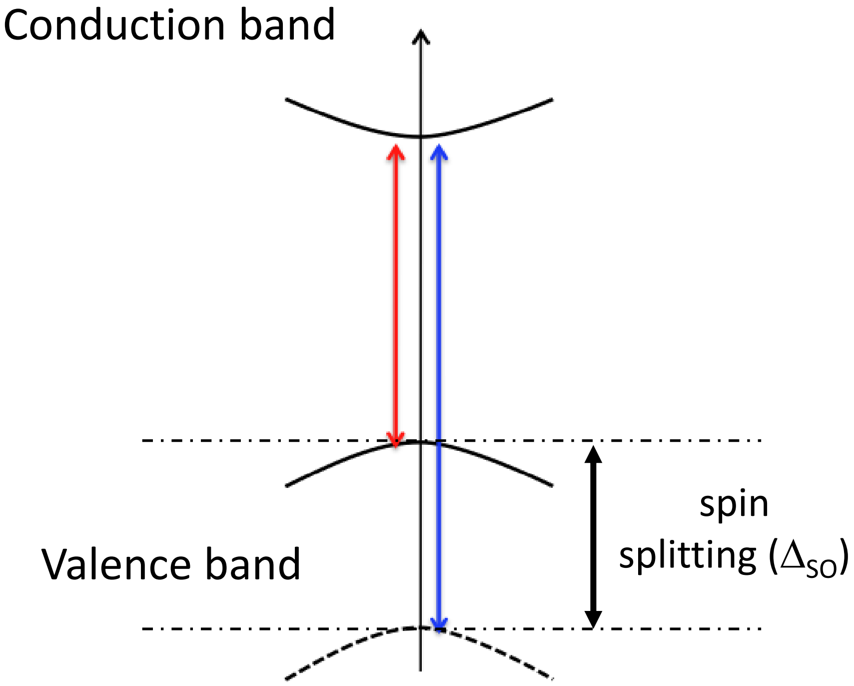


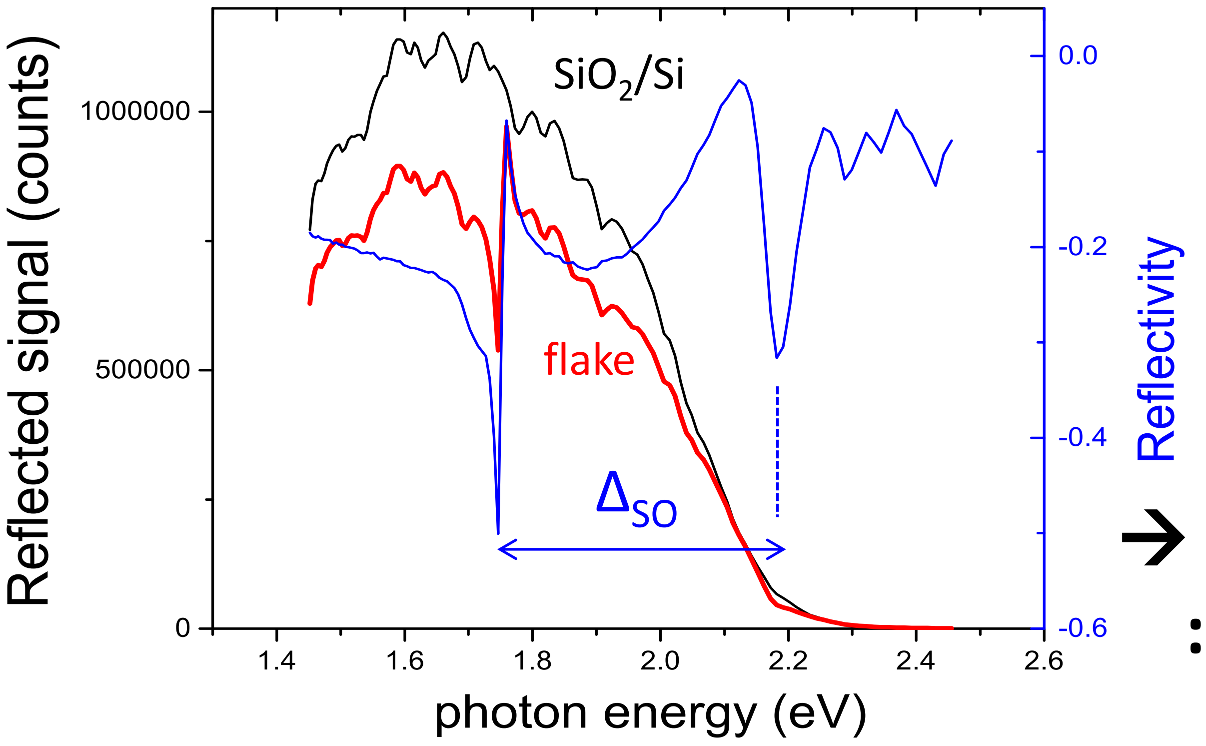
Optical detection

Excitation: *White Light source*

Detection: *reflected Light*

Strong Light ⇔ Matter Interaction





→ **Δ_{SO} energy : 410 meV**

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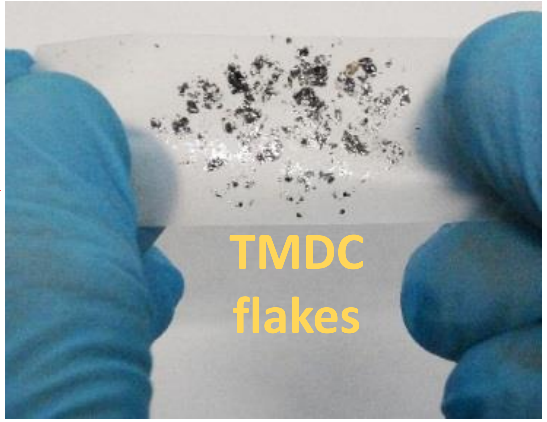
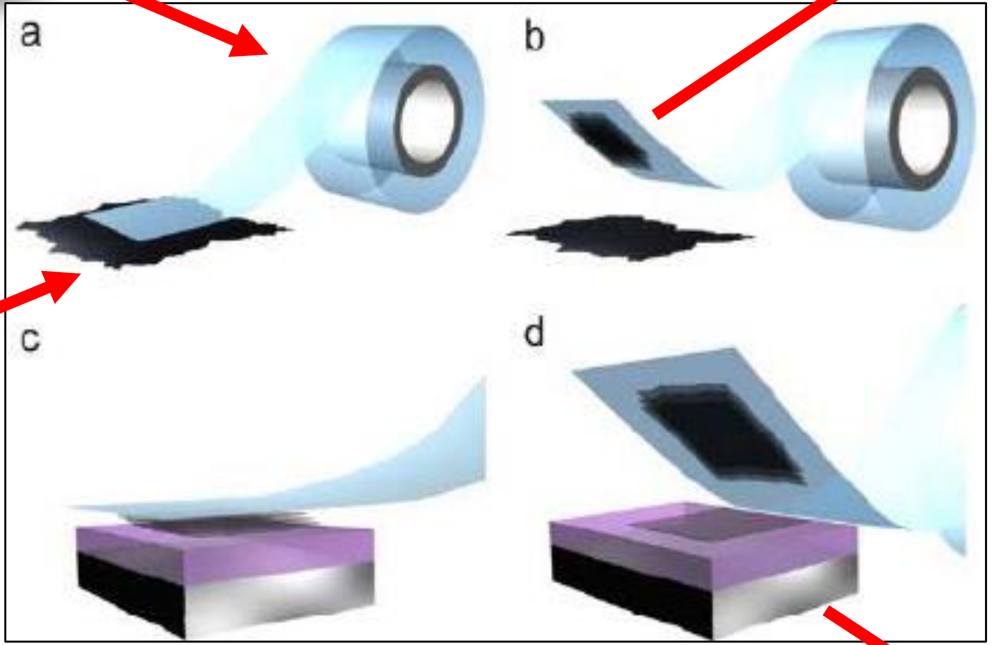
5. Conclusion and perspectives

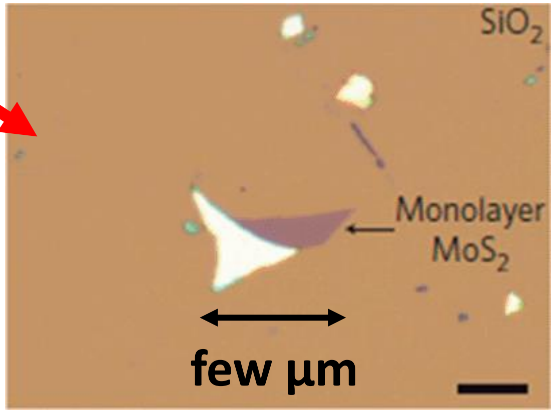
Mechanical exfoliation

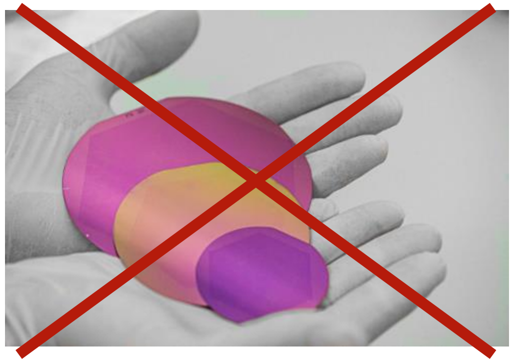
(starting in 2010 with MoS_2)





transfer to substrate

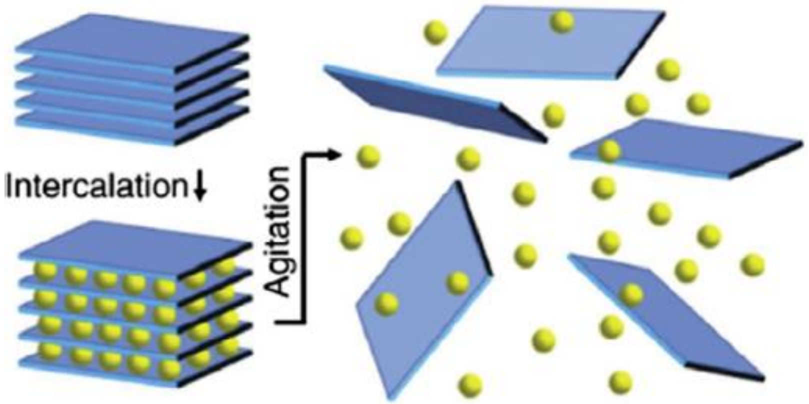


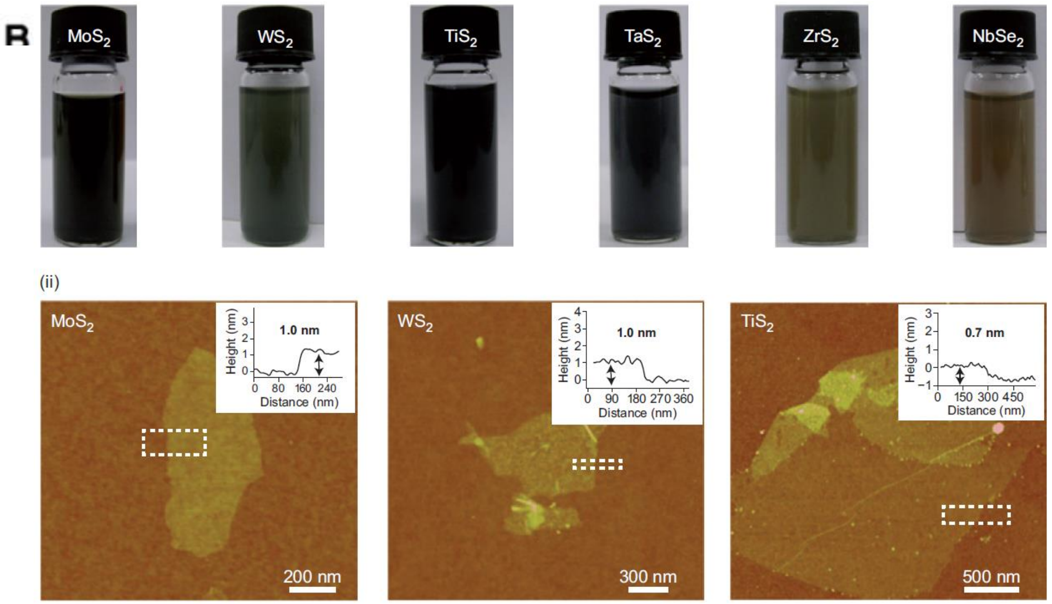


No possible upscaling

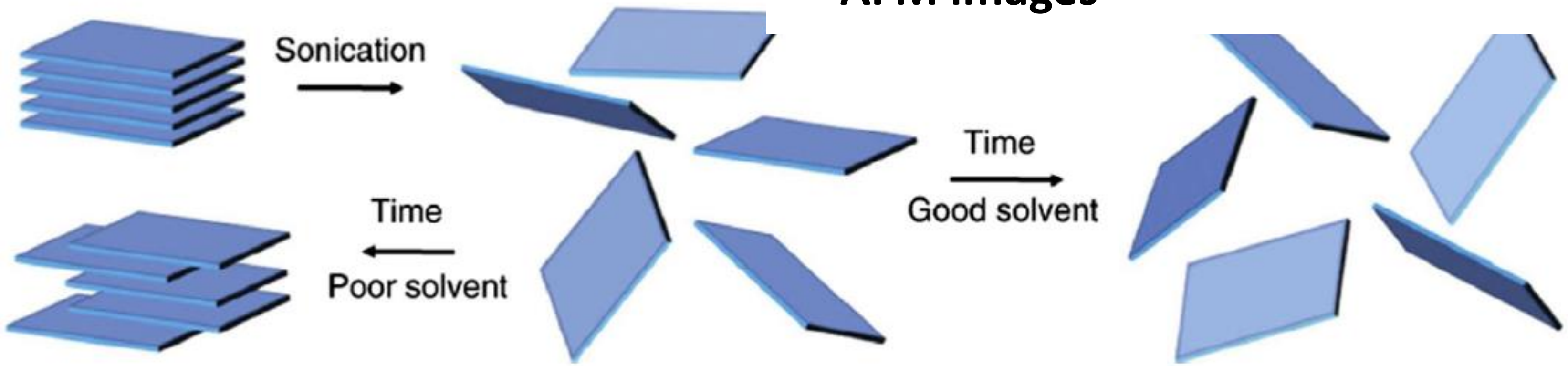
Chemical exfoliation

flakes in solution





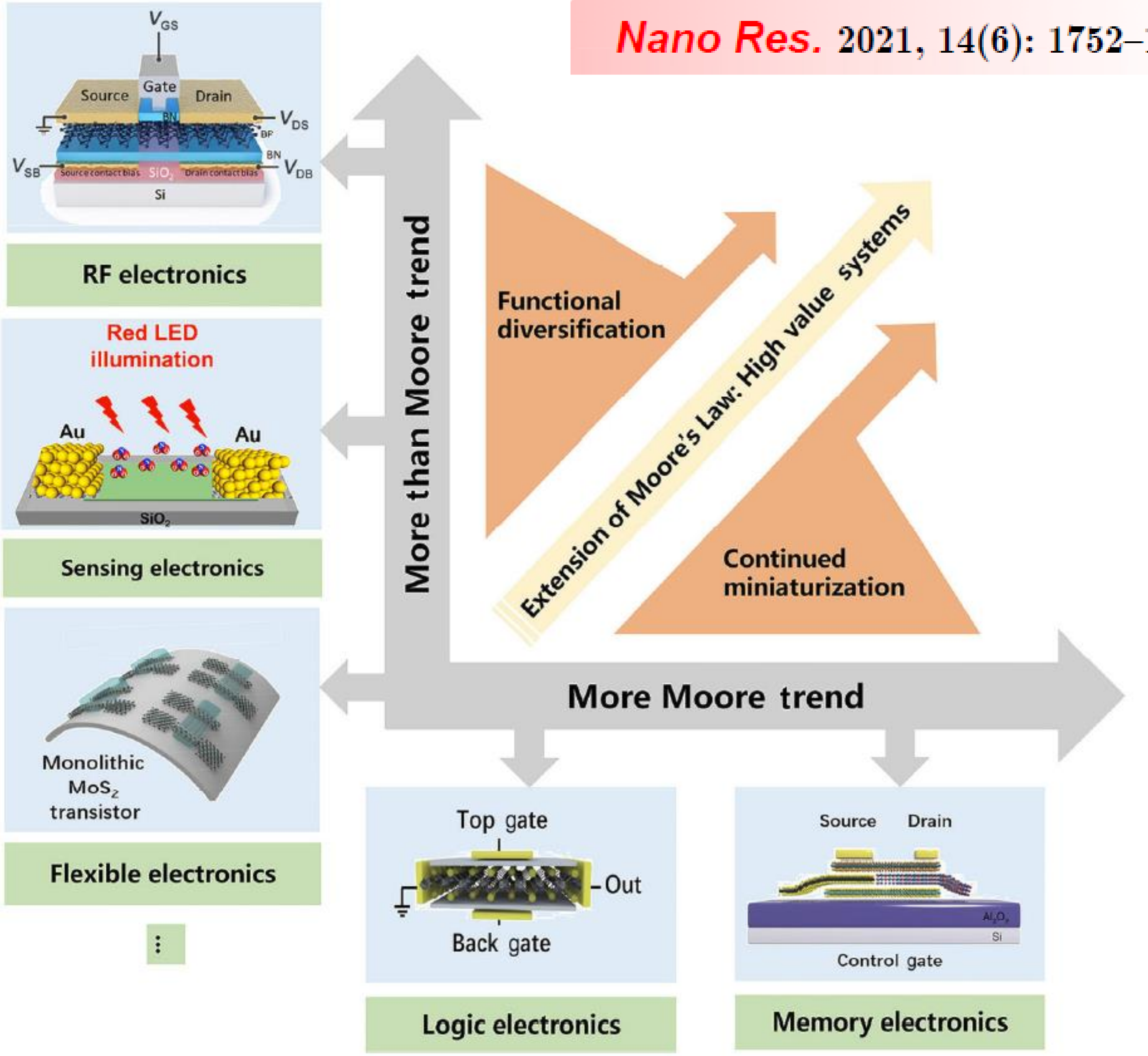
AFM images



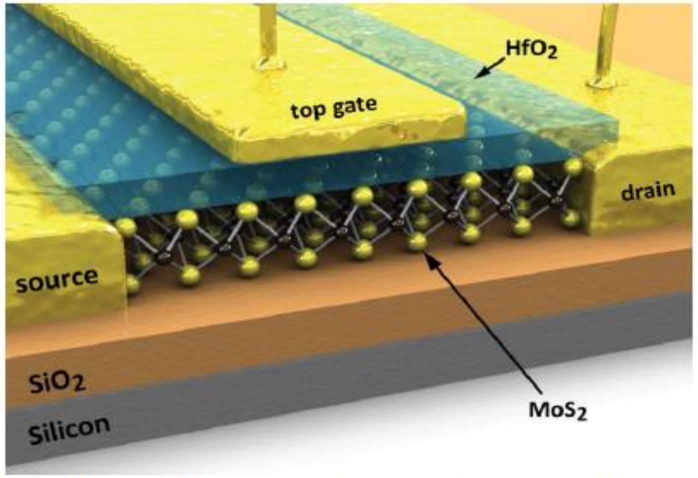
Science **340**, 1226419 (2013)
Angew. Chem. Int. Ed. **50**, 11093 (2011)

Electronics based on Single Layer TMD flake

Nano Res. 2021, 14(6): 1752–1767

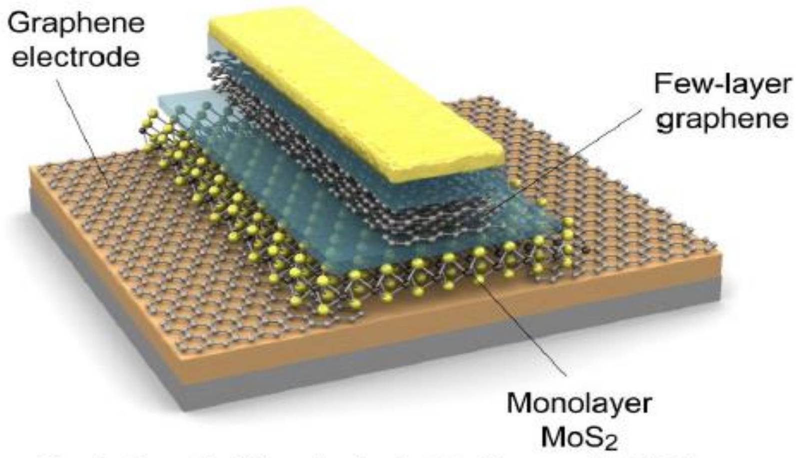


MoS_2 Transistor



Radisavljevic, Kis et al. Nature Nanotech. (2011)

MoS_2/graphene Memory Cell



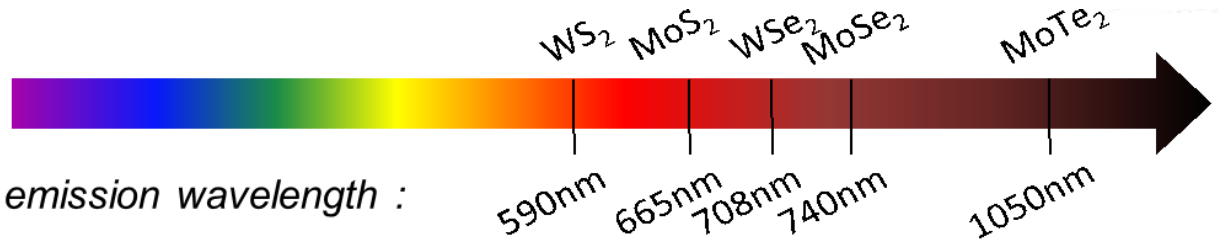
Bertolazzi, Kis et al. ACS Nano (2013)

Photodetectors based on Single Layer MoS_2 flake

MX_2 monolayers – common properties : strong interaction with light

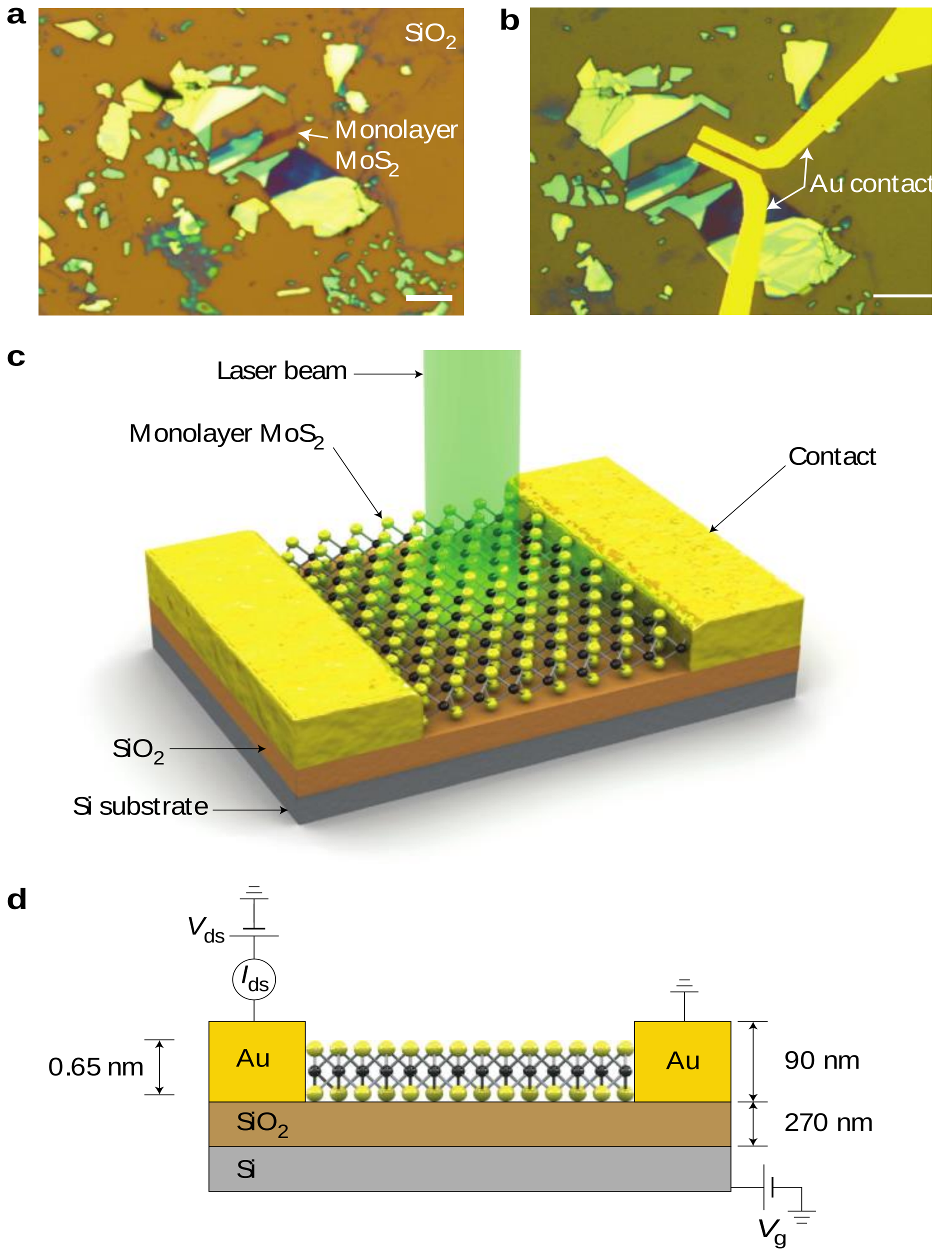
~10-15 % absorption of light for a monolayer

Monolayer emission wavelength :



- Very sensitive
- maximum external photoresponsivity of 880 A/W at a wavelength of 561 nm and a photoresponse in the 400–680 nm range

(100 mA /W silicon-based photodetectors)

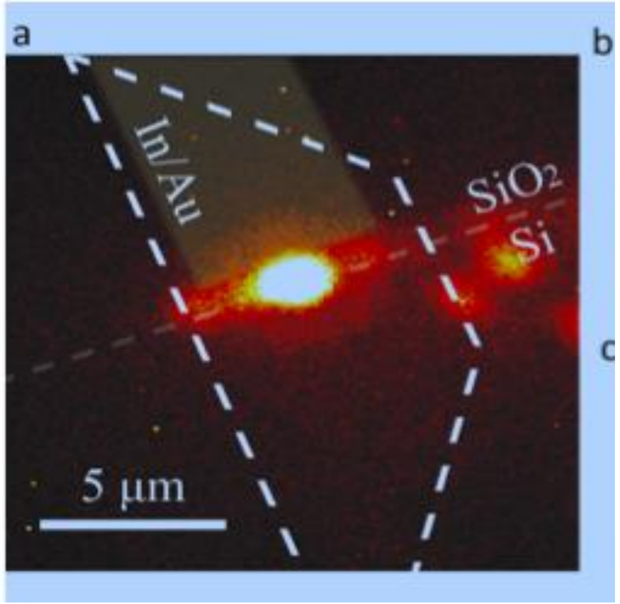


NanoLett. 12, 3695 (2012)
Nature Nanotec 8, 497 (2013
Scientific Report 4, 3826 (2014)
Sensors 21, 2758 (2021) –Review

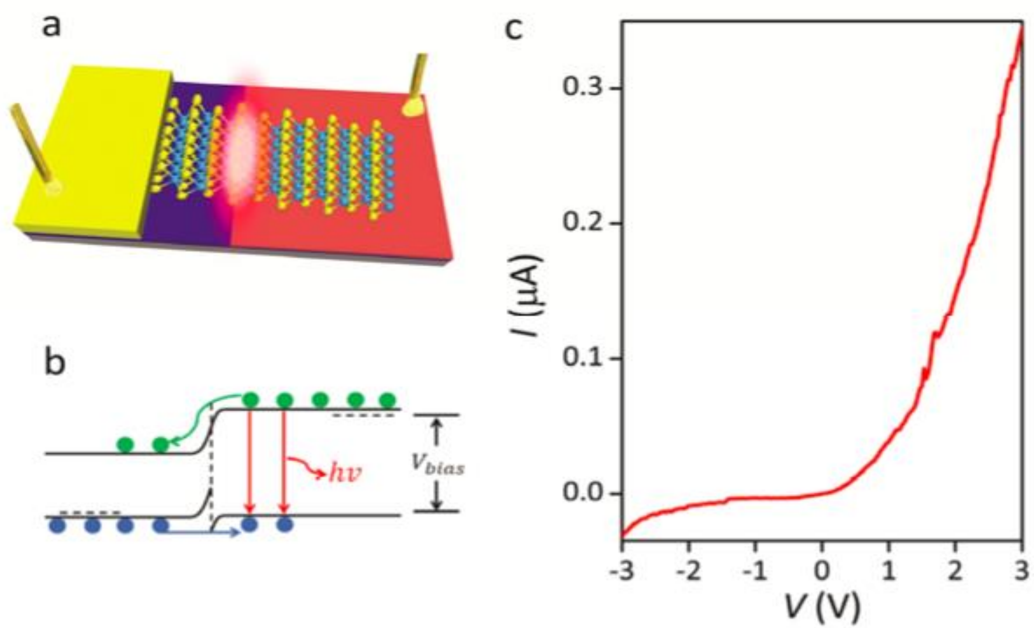
MoS_2 LED Prototypes

Electroluminescence in Single Layer MoS_2

NanoLett **13**, 1416 (2013)



APL **104**, 193508 (2014)



MoS_2 ML fabricated on a heavily p-type doped silicon substrate

WSe_2 (WS_2) monolayer laser ? : Nature **520**, 69 (2015)
Nature Phot. **9**, 733 (2015)

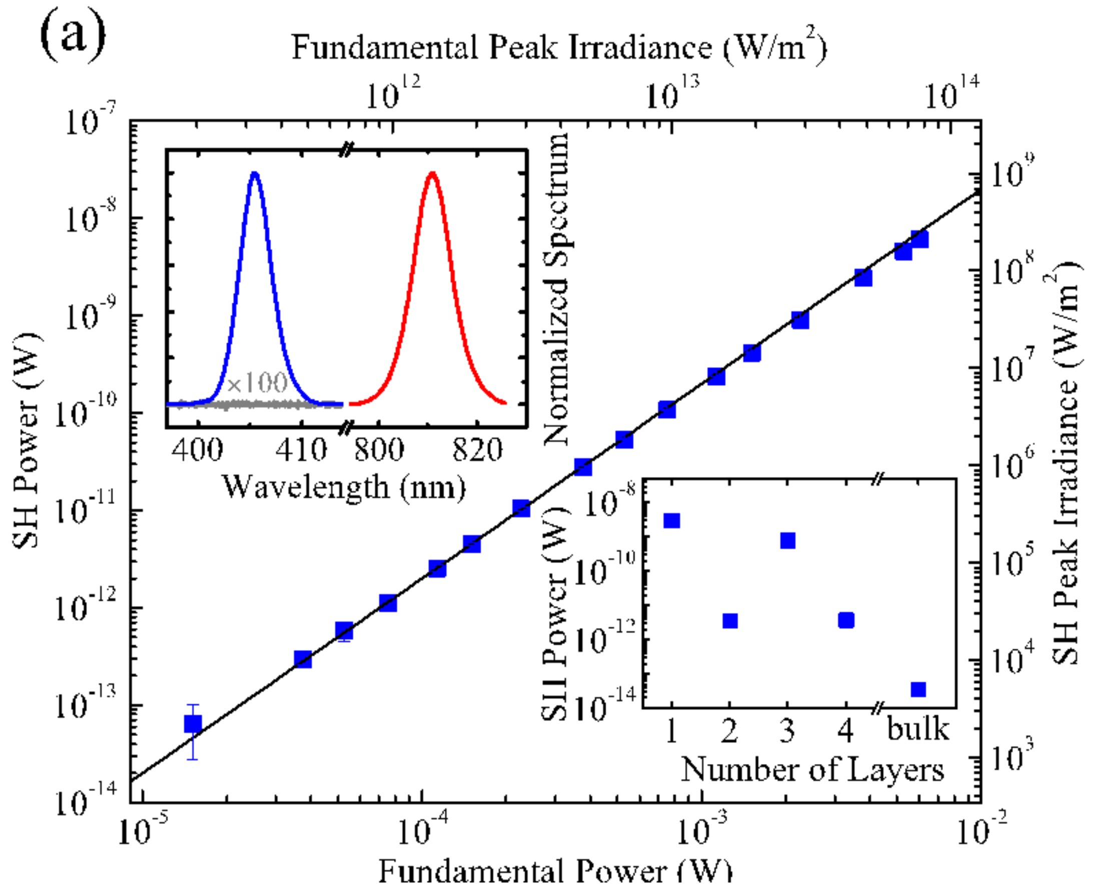
Second Harmonic Generation

MoS_2 : PRB **87**, 161403(R) (2013)
WSe_2 : PRL 114, 097403 (2015)

Second harmonic microscopy of monolayer MoS_2

Nardeep Kumar,[1] Sina Najmaei,[2] Qiannan Cui,[1] Frank Ceballos,[1] Pulickel M. Ajayan,[2] Jun Lou,[2] and Hui Zhao[1,*]
[1] *Department of Physics and Astronomy, The University of Kansas, Lawrence, Kansas 66045, USA*
[2] *Department of Mechanical Engineering and Materials Science, Rice University, Houston, Texas 77005, USA*
(Dated: April 9, 2013)

We show that the lack of inversion symmetry in monolayer MoS_2 allows strong optical second harmonic generation. Second harmonic of an 810-nm pulse is generated in a mechanically exfoliated monolayer, with a nonlinear susceptibility on the order of 10^{-7} m/V. The susceptibility reduces by a factor of seven in trilayers, and by about two orders of magnitude in even layers. A proof-of-principle second harmonic microscopy measurement is performed on samples grown by chemical vapor deposition, which illustrates potential applications of this effect in fast and non-invasive detection of crystalline orientation, thickness uniformity, layer stacking, and single-crystal domain size of atomically thin films of MoS_2 and similar materials.



→ **Lack of inversion symmetry in monolayer MoS_2 allows optical second harmonic generation**

The different growth methods

- Large scale growth of synthetic TMDCs

Chemical routes

Based on chemical reactions in the gas phase or on a substrate

- Chemical Vapor Deposition (CVD)
- Metal Organic Chemical Vapor Deposition (MOCVD)
- Atomic Layer Deposition (ALD)

VLS, plasma assisted…

Physical routes

Based on the condensation of atomic species on a substrate under vacuum or ultrahigh vacuum

- Molecular beam epitaxy in the van der Waals regime
- Sputtering: Phase Change Materials

- chalcogenization

The different growth methods

Objectives

- Growth on **centimeter scale** single crystal of TMDC monolayer (low density of defects, high mobility, electronic properties approaching the ones of flakes…)
- **Doping and Alloys** (*n*-type, *p*-type and magnetic doping, alloys for lattice parameter and bandgap tuning…)
- Vertical or lateral **heterostructures** (Band alignment tuning, heterojunctions, contacting, proximity effects…)

Criteria to assess TMDC quality

- Peak intensity and width of PL and Raman spectroscopy
- Carrier mobility
- ON/OFF ratio in a Field Effect Transistor (FET)

Depend on: film continuity, grain size and orientation (given by TEM and x-ray diffraction), grain boundaries, density of point or extended defects, substrate, contamination, oxidation/pollution

For each growth technique

- Basic principle
- Key parameters
- Review of recent advances

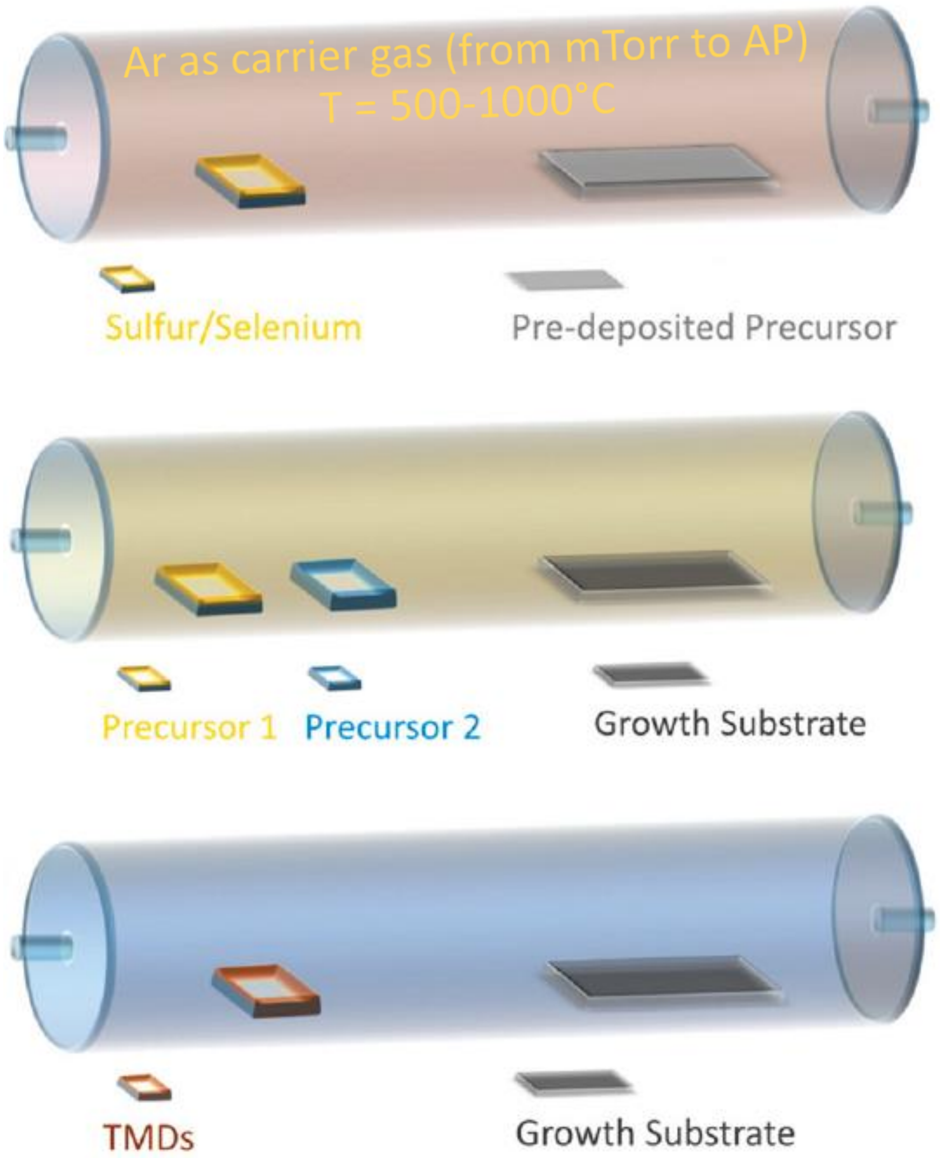
The different growth methods: CVD

Review of reviews on Chemical Vapor Deposition:

- Materials Today 20, 116 (2017)
- Small 13, 1700098 (2017)
- Crystals 8, 35 (2018)
- Chem. Soc. Rev. 44, 2587 (2015) and 2744 (2015)
- RSC Adv. 5, 75500 (2015)
- Chem. Rev.: DOI: 10.1021/acs.chemrev.7b00212 and 7b00536 (2017)
- Electronics 4, 1033 (2015)
- Nature Chem. 5, 263 (2013)
- Nature Nanotech. 7, 699 (2012)

The different growth methods: CVD

- **SOLID PRECURSORS**



Two-step method:

- Deposition of the TM (Mo, MoO_3, W, WO_3)
- Sulfurization/selenization in the CVD reactor

One-step method:

Both the TM (MoO_3, $MoCl_5$, WO_3, WCl_5) and S, Se powders are evaporated in the CVD reactor

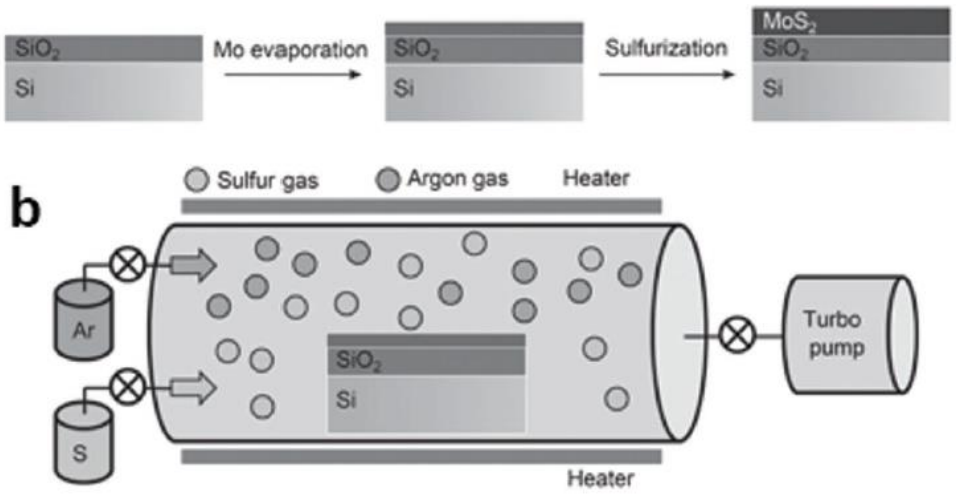
Direct evaporation of the TMDC

<u>Adjusting parameters:</u> T, p, carrier gas (Ar, H_2/Ar), substrate (single crystal, presence of defects, patterning, functionalization, liquid substrate…)

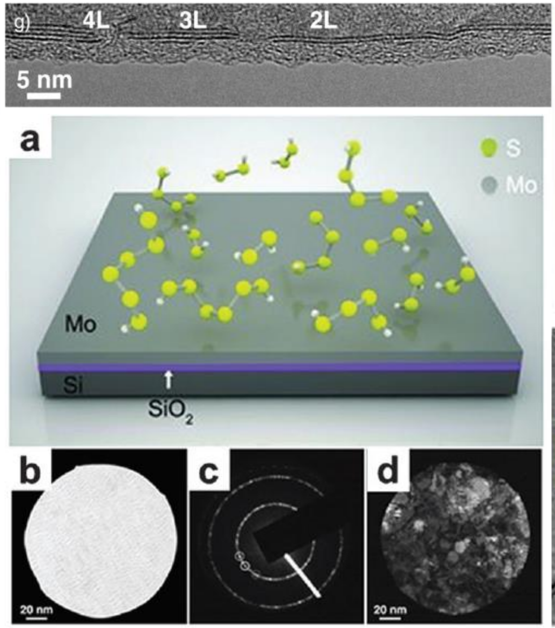
The different growth methods: CVD

Two-step CVD method

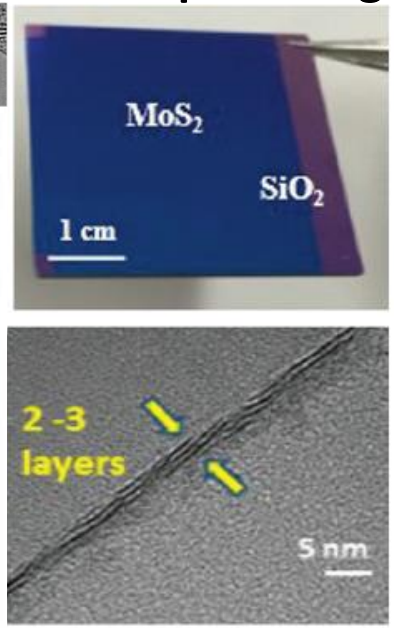
The thickness of pre-deposited Mo, MoO_2 or MoO_3 (by e-beam, sputtering, ALD for WO_3) determines the TMDC thickness



e-beam



sputtering



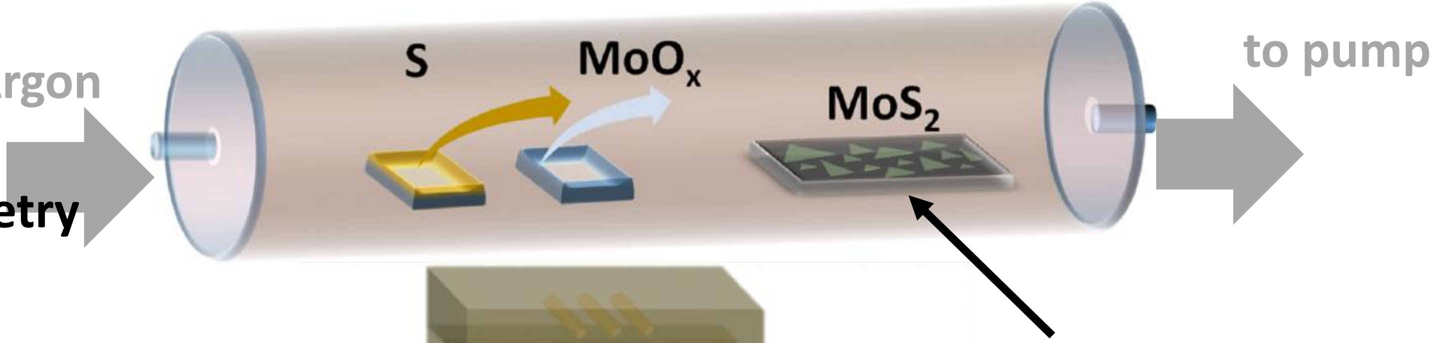
$$M(s) + 2S(g) \rightarrow MS_2(s)$$

Continuous films on large area **BUT** very small randomly oriented grains (10 nm), metallic character for Mo (low ON/OFF ratios), semiconducting character for MoO_3 (ON/OFF ratio 10^4), distribution of thicknesses (1-20 ML), defective layers. Mobility ≤ 1 $cm^2/(V.s)$, (max exp. 100; theory 300).

The different growth methods: CVD

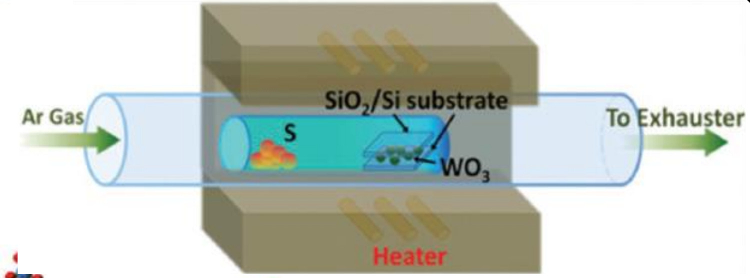
- One-step CVD method

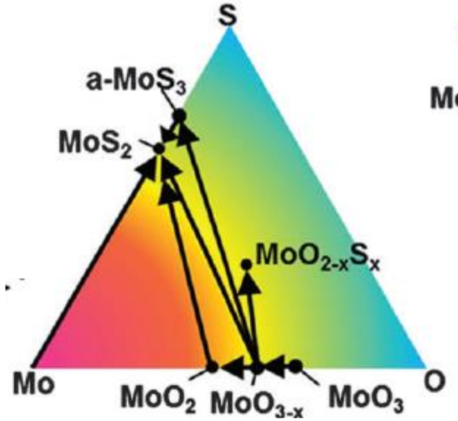
horizontal geometry



substrate

or vertical geometry:





- Growth T: 650°C-1000°C

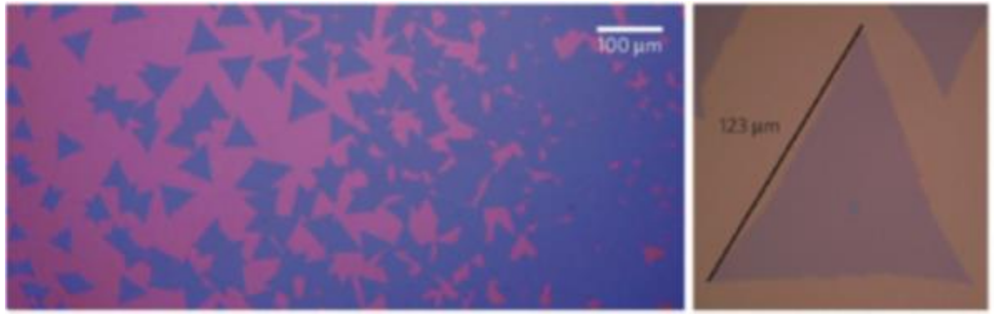
- Gas phase and surface reactions:

(1) $2MoO_3 + xS \rightarrow 2MoO_{3-x}(g) + xSO_2$;

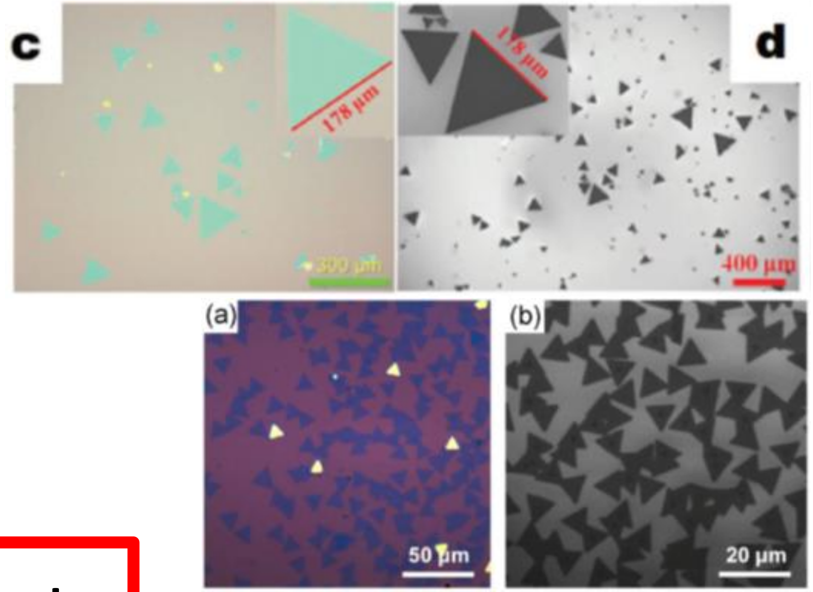
(2) $2MoO_{3-x} + (7-x)S \rightarrow 2MoS_2 + (3-x)SO_2$

The different growth methods: CVD

- Some examples

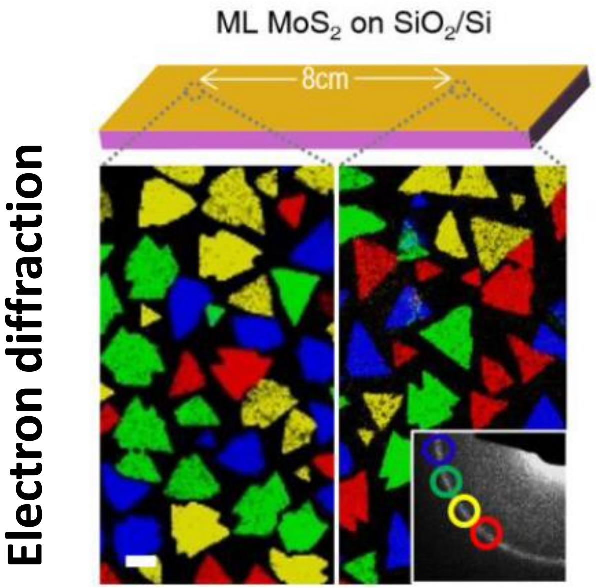


$MoS_2/SiO_2/Si$

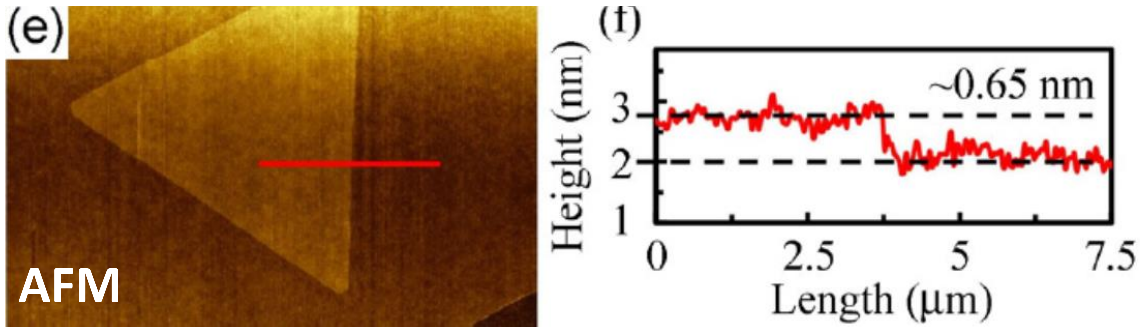


$WS_2/SiO_2/Si$

≈100 μm triangles



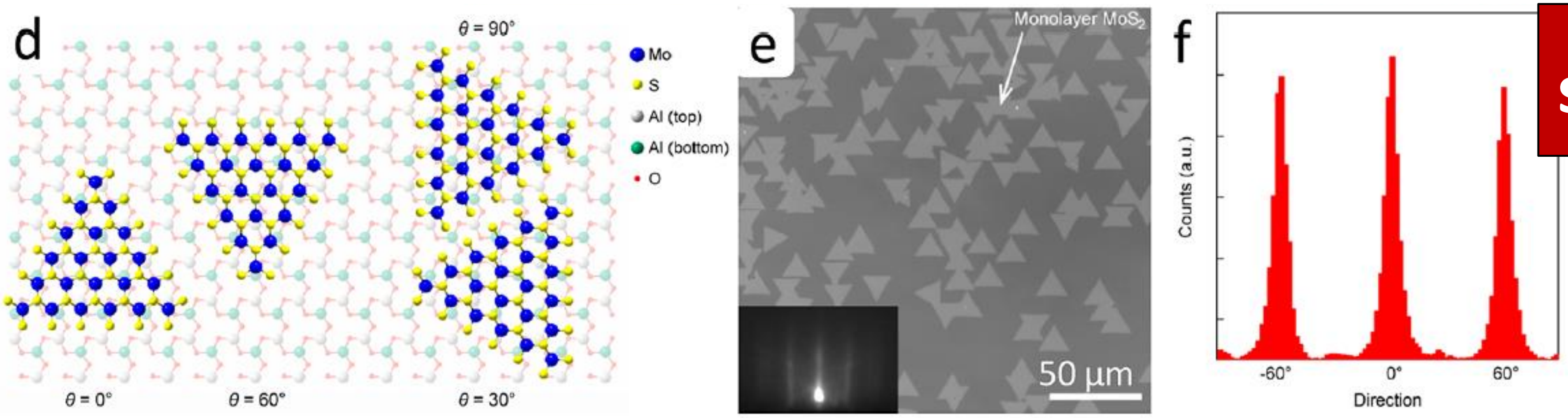
Randomly oriented flakes



VdW gap

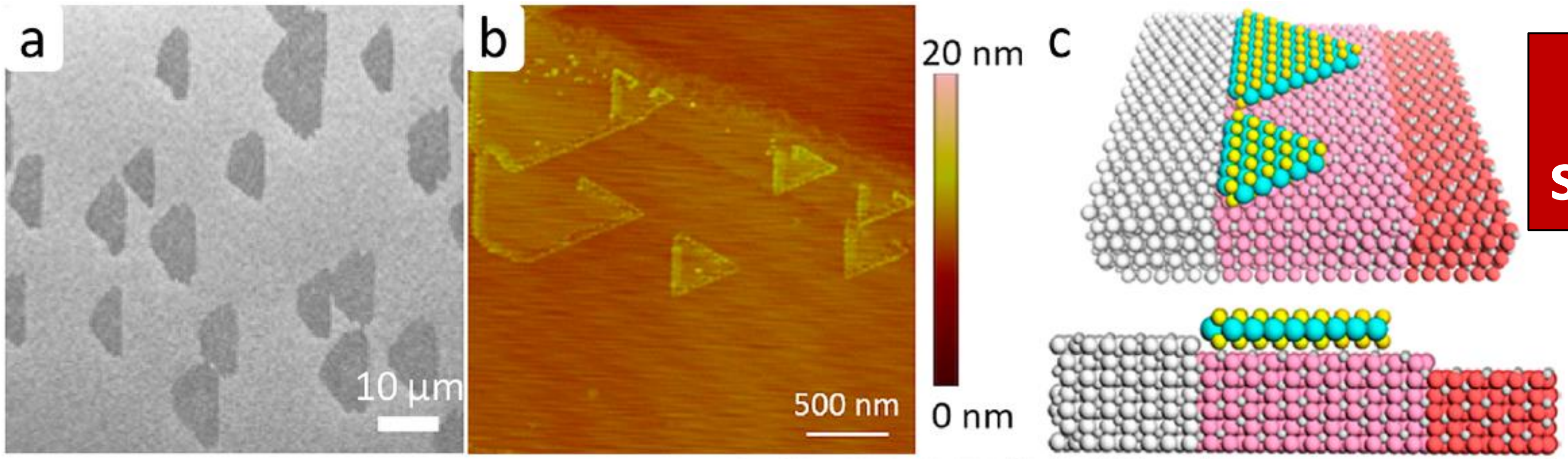
The different growth methods: CVD

- Grain orientation



sapphire

MoS_2



vicinal sapphire

WSe_2

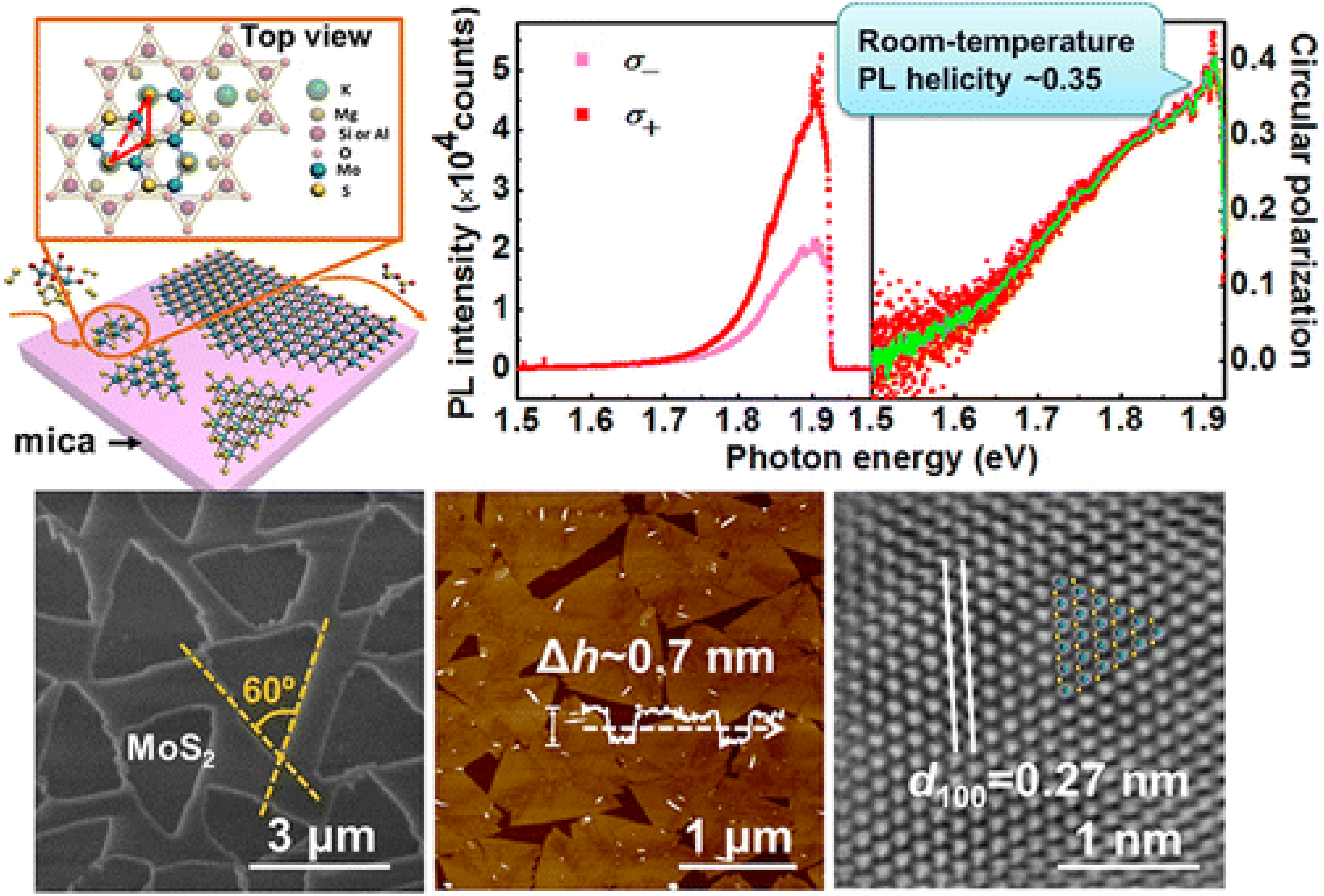
Growth at 950°C

The different growth methods: CVD

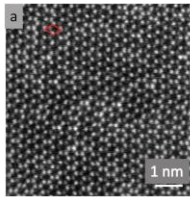
- Grain orientation

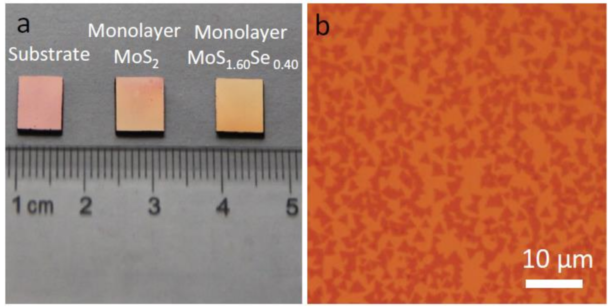
LPCVD: 30 Pa; 50 sccm; 530°C; 1 hour

mica



The different growth methods: CVD



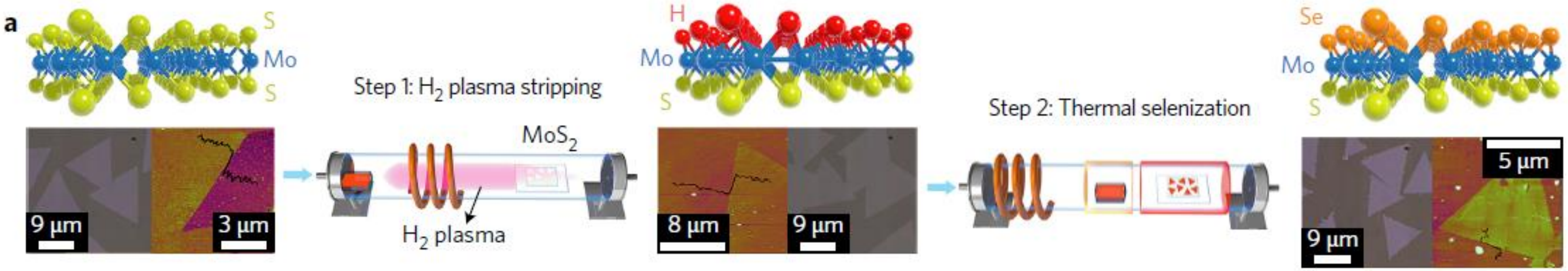


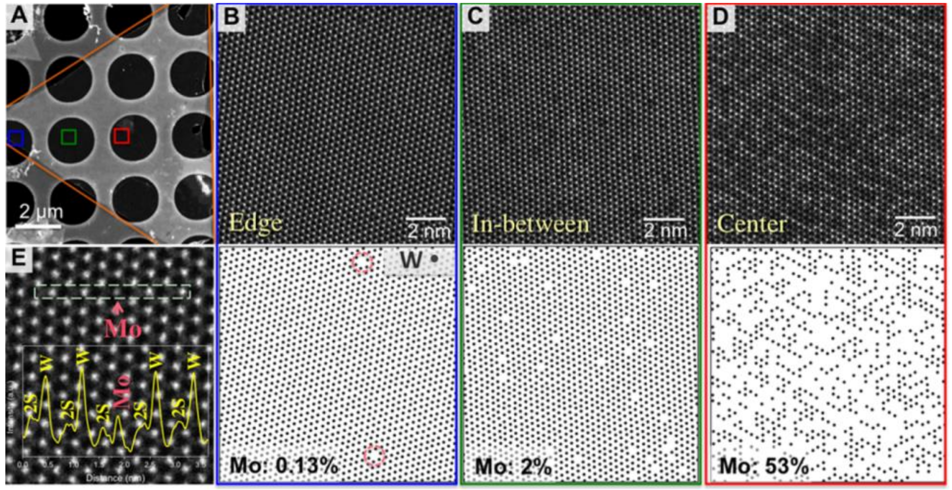
- **Alloys MoSeS (random)**

Adv. Mater. **26**, 2648 (2014)

- **Alloys MoSeS (Janus)**

Nature Nanotech. **12**, 744 (2017)





- **Alloys $MoWS_2$**

Nano Lett. **16**, 6982 (2016)
Nano Lett. **17**, 2802 (2017)

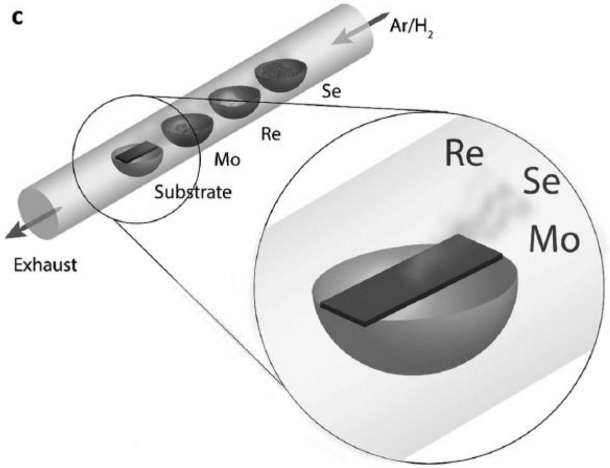
The different growth methods: CVD

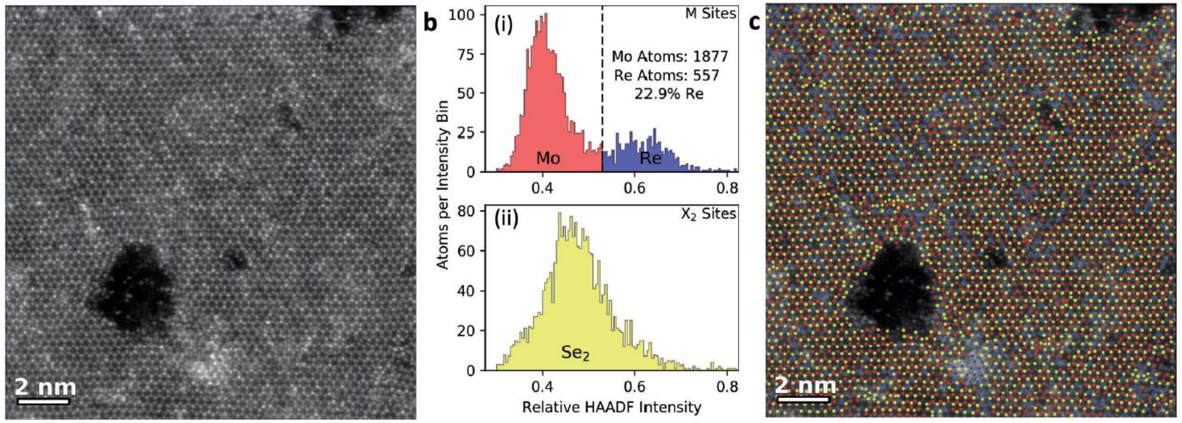
Electrical and magnetic doping

(Substitutional ≠ S, Se vacancies, chemical doping or electrostatic gating using polymer electrolytes or ionic liquids)

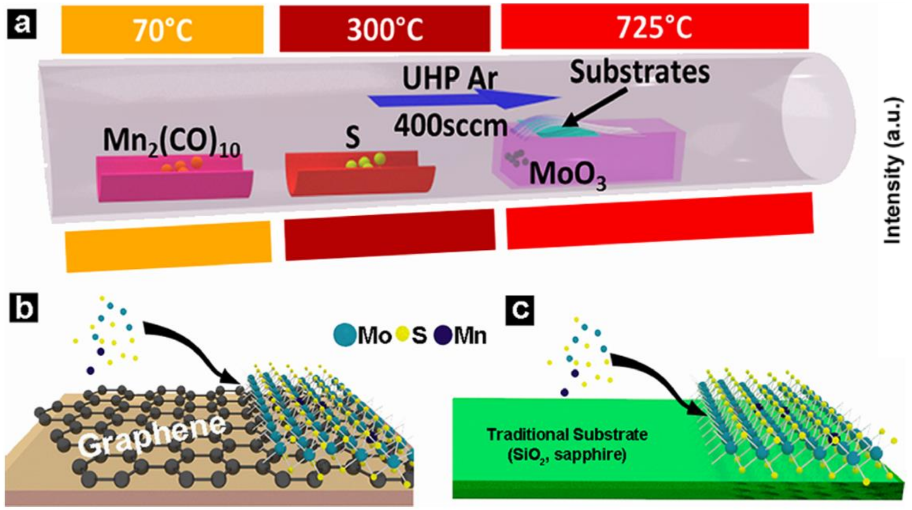
n-type Re doping

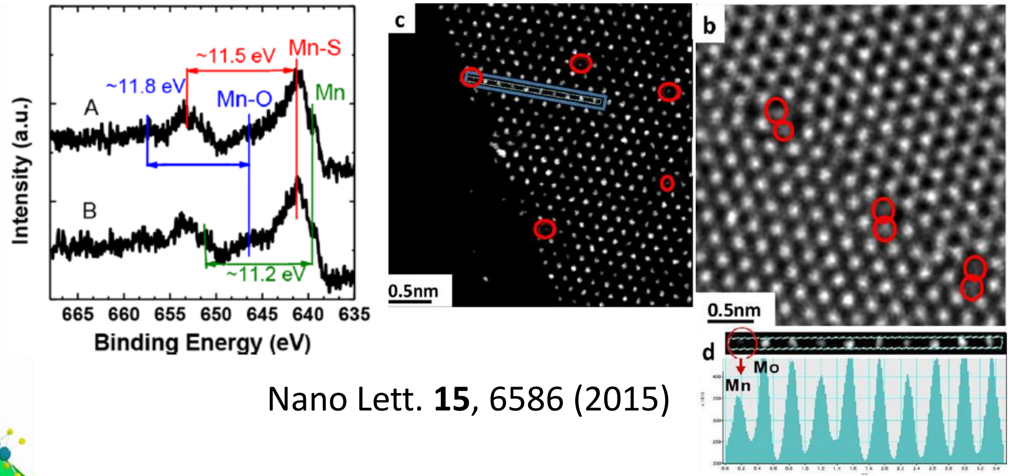
Adv. Mater. **29**, 1703754 (2017)





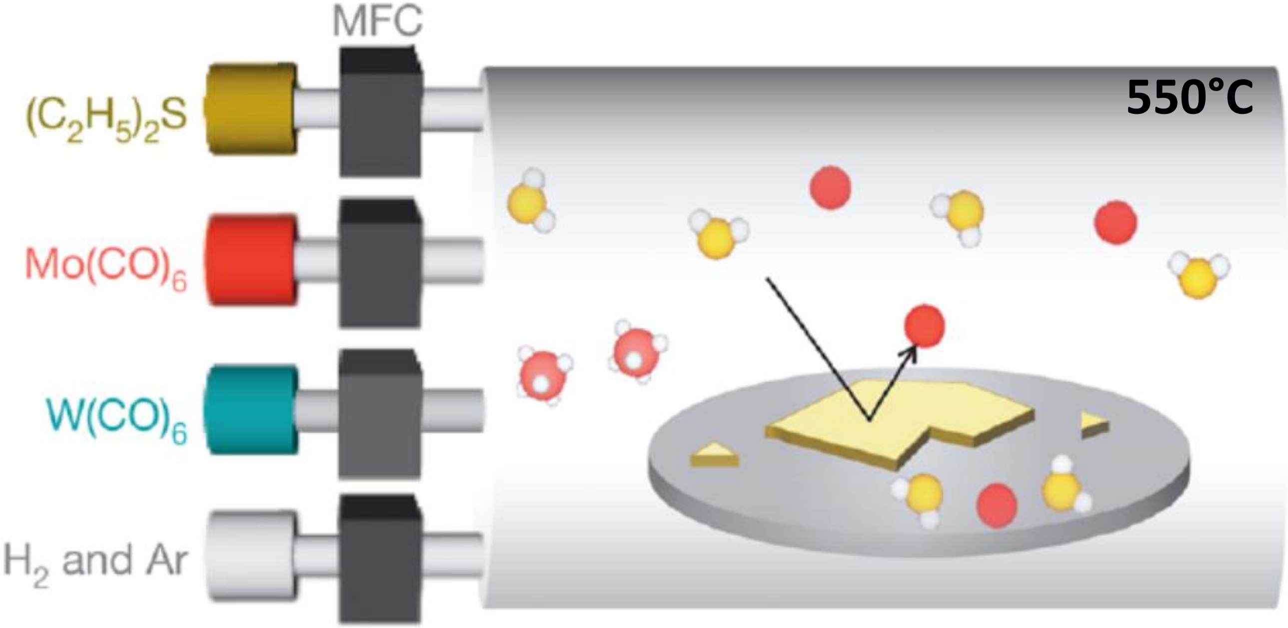
Mn-doping (incorporation depends on the substrate)



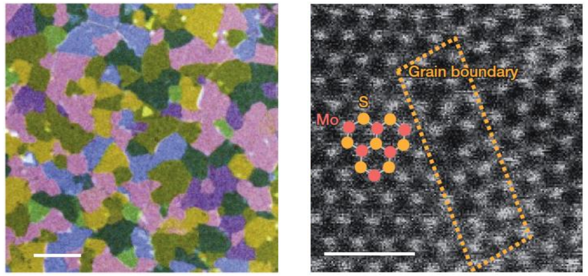


Nano Lett. **15**, 6586 (2015)

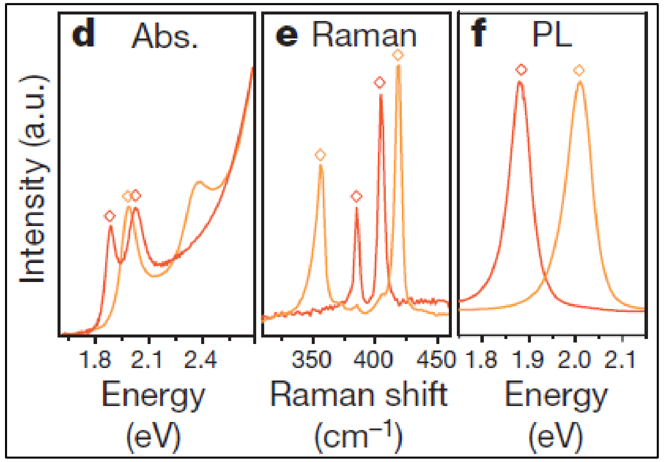
The different growth methods: MOCVD



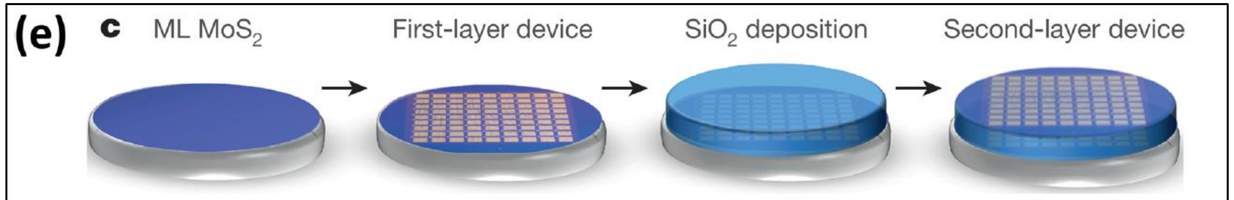
- **MOCVD**

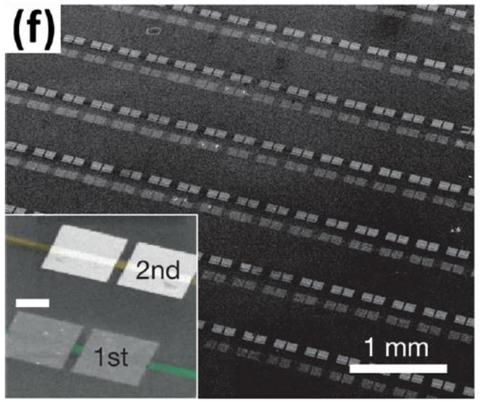


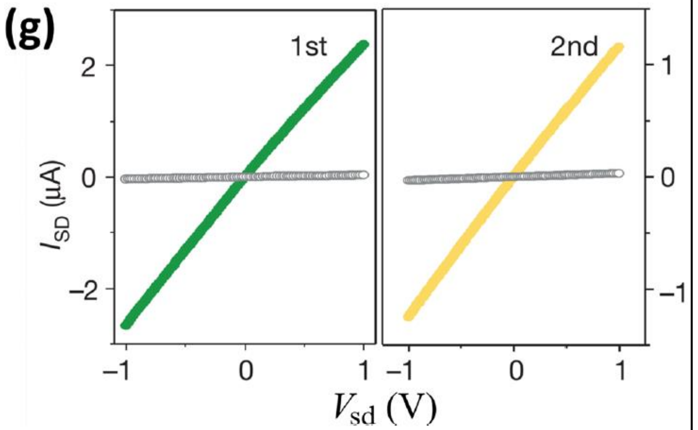
100% coverage, randomly oriented small grains 10-20 nm, 26 hours growth for 1 ML



μ = 114 cm/(Vs) @ 90 K

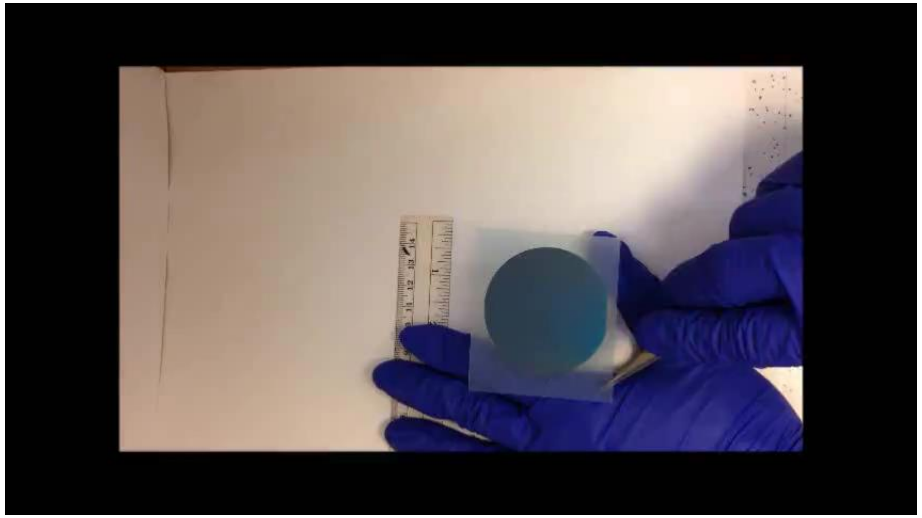


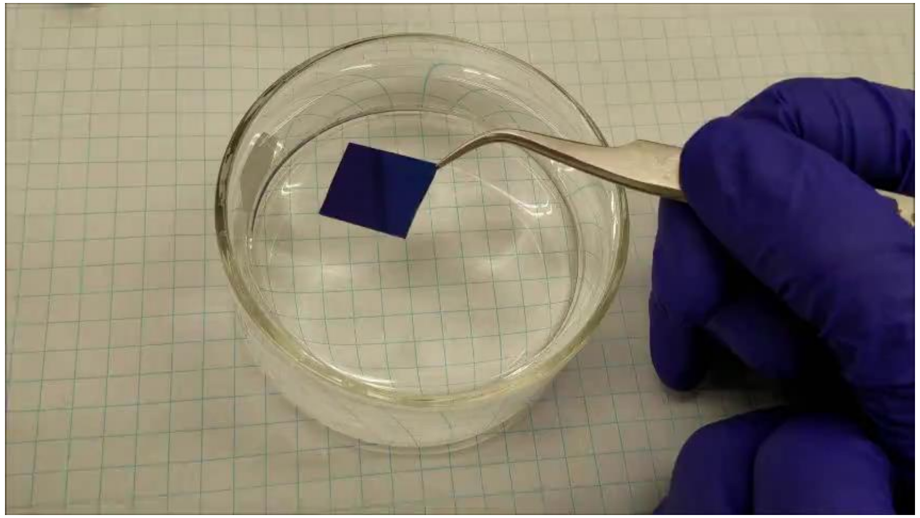




The different growth methods: MOCVD

- **Layer transfer**





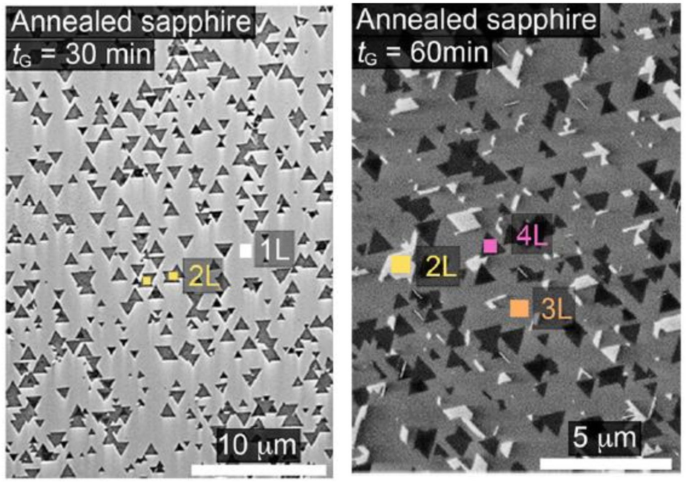
Kang et al., Nature **520**, 656 (2015)

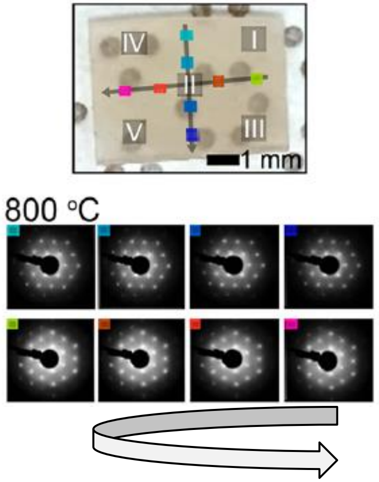
<u>Also:</u>
J. Cryst. Growth **464**, 100 (2017)
ACS Nano **9**, 2080 (2015)

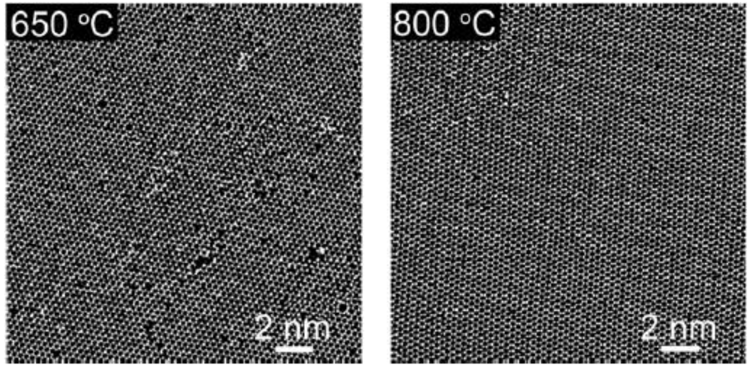
The different growth methods: MOCVD

- **Last achievement by MOCVD:** single crystalline WSe_2/Sapphire (Aixtron: WS_2/sapphire)

ACS Nano **12**, 965 (2018)





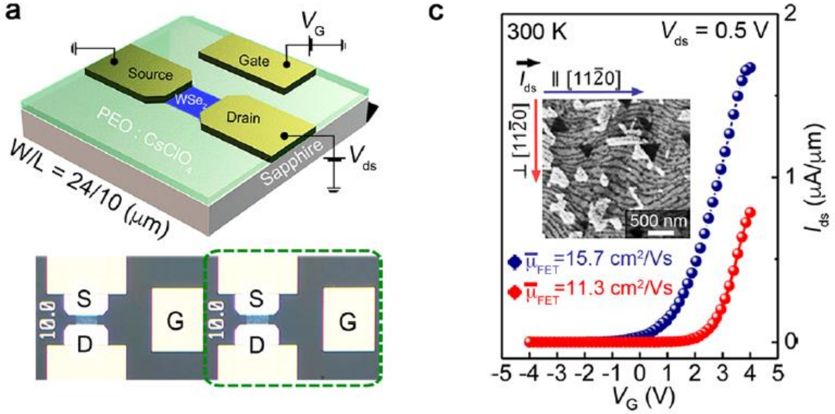


3-step process

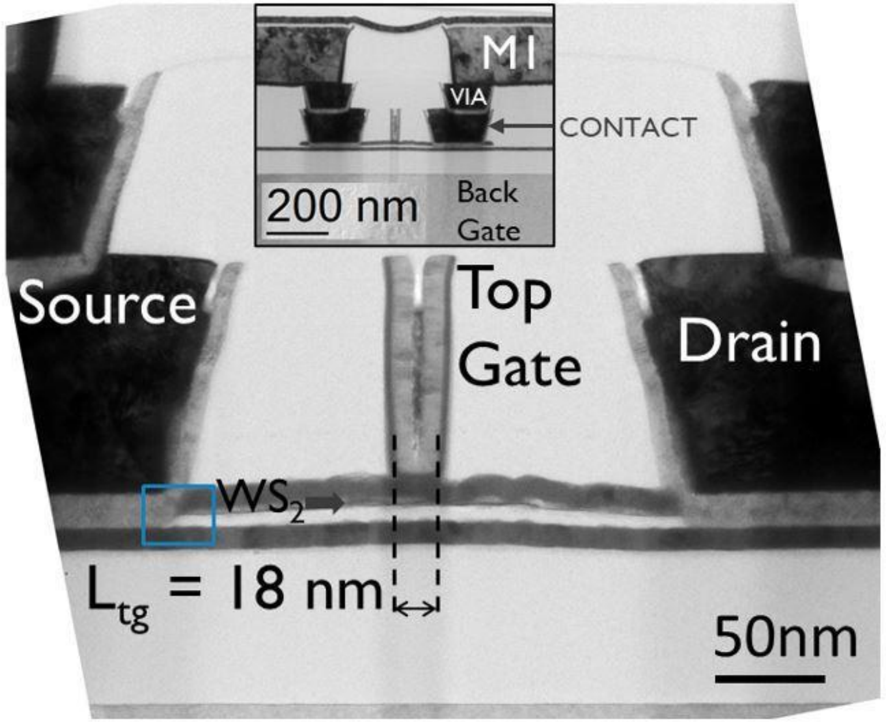
(1) Single crystalline, flat substrate with high surface energy (Sapphire)

(2) Short nucleation step with high flow rates of precursors (W and Se)

(3) Postgrowth annealing at 800°C under H_2Se



FETs (TMDs for digital electronics)



300 mm WS_2 integration @ IMEC (MOCVD)
IEDM 2020

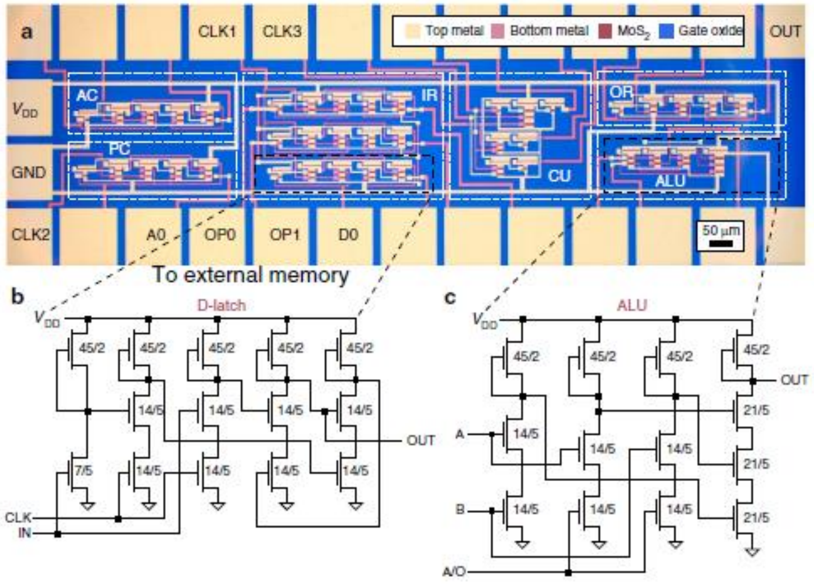
ON/OFF ratios > Silicon
MoS_2 n-channel 10^8, WS_2 p-channel 10^6

SS ≤ Silicon
MoS_2 74 mV/dec, WS_2 60 mV/dec

Better scalability (down to 0.7nm channel)

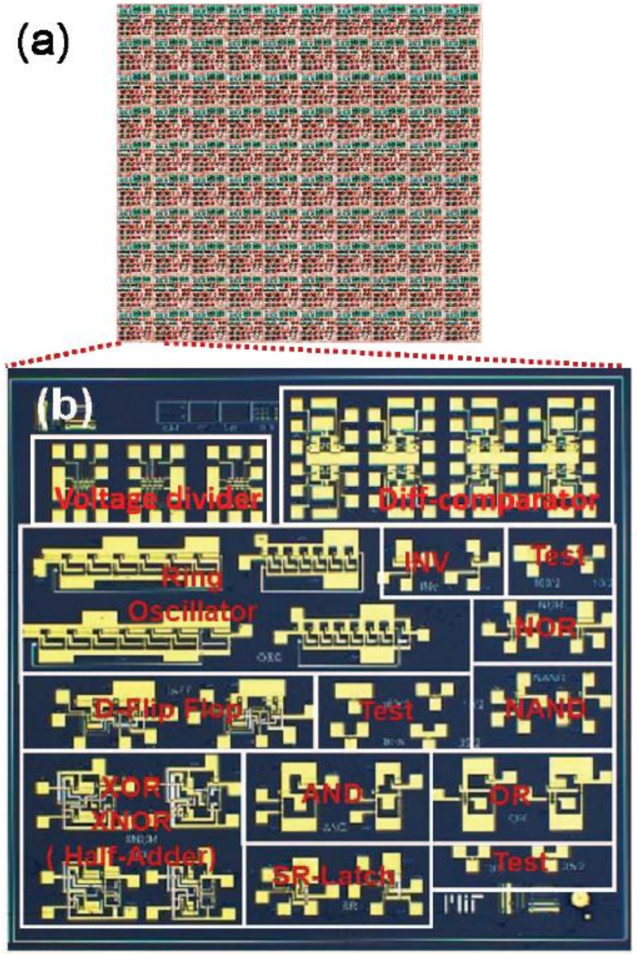
Cadence < Silicon (to improve: reduce channel length, improve carrier mobility, electrical doping, contacts)

115 transistors processor (2017)



+ INTEL
(MoS_2 CVD growth and transfer)

NATURE COMMUNICATIONS | 8:14948 | DOI: 10.1038/ncomms14948 | www.nature.com/naturecommunications

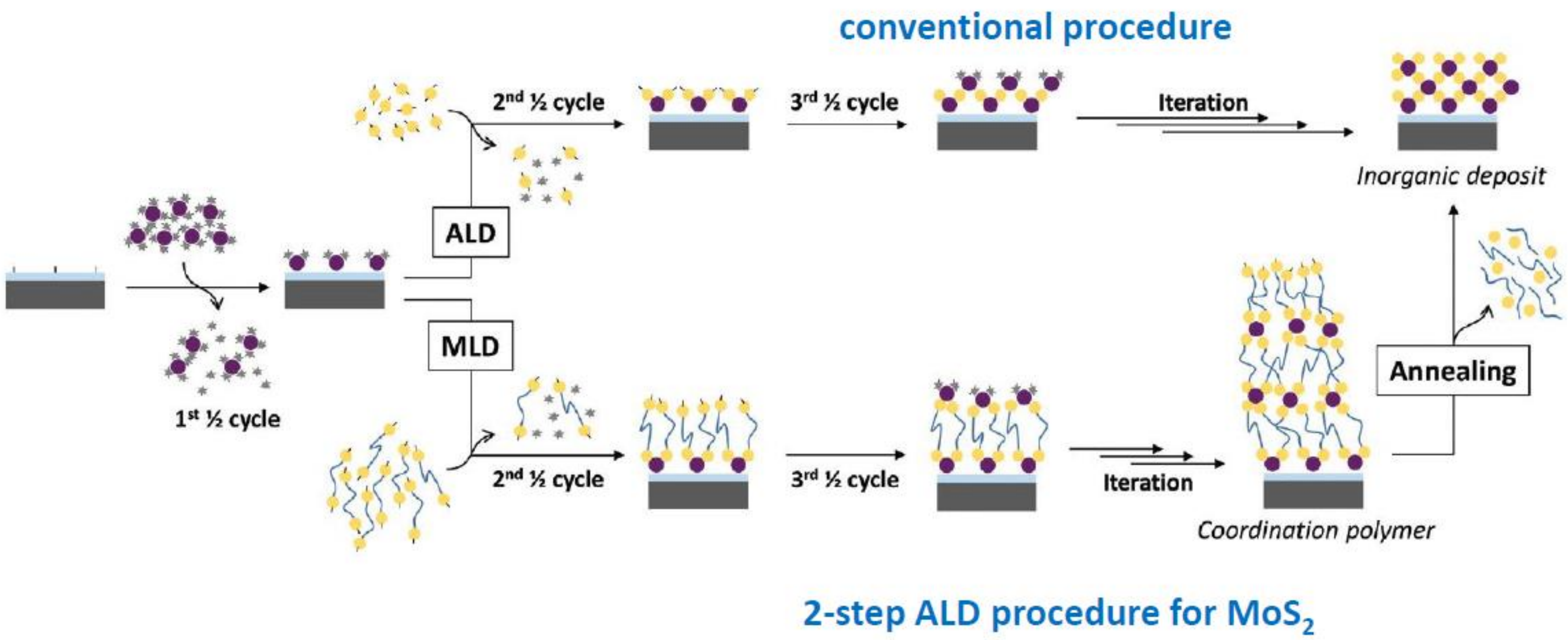


MIT, IEDM2015

The different growth methods: ALD

- **ALD or « pulsed MOCVD »**

- **Principle of Atomic Layer Deposition and Molecular Layer Deposition**



The different growth methods: ALD

State of the art Atomic Layer Deposition of MoS_2

- **Metal-halides as metal precursor ($MoCl_5$, WF_6)**

- Well known issue with byproducts (HCl, HF)
  - Substrate etching
  - Protective layer required on SiO_2 (e.g. ZnS)

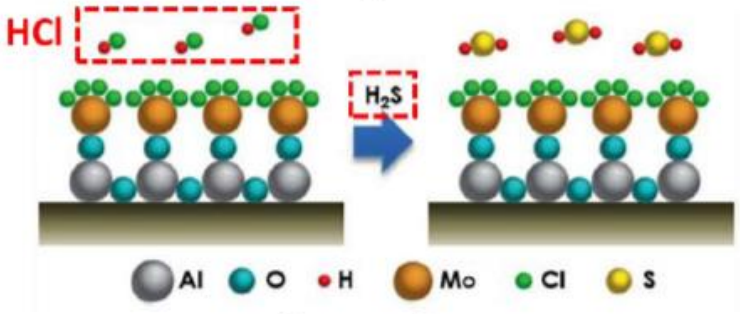
- Monolayer MoS_2 target = high uniformity

→ **Alternative to molybdenum halides ?**

- **H_2S as sulfur precursor**

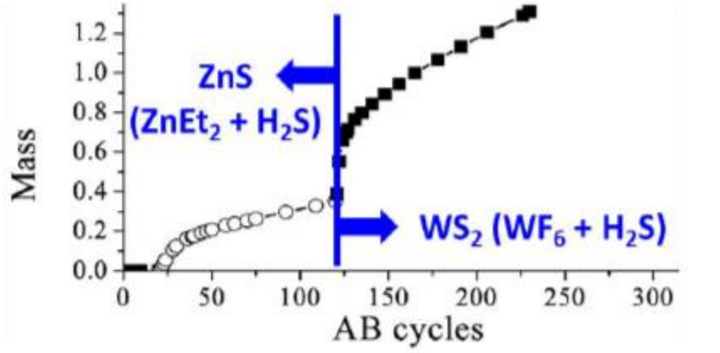
- Highly toxic and flammable gas (bp = -60°C)
- Handling and storage issues…

ALD with $MoCl_5$ and H_2S



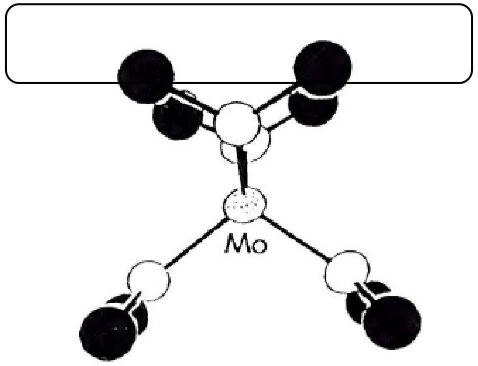
K. P. Loh, ***Nanoscale***, 2014, 6, 10584-10588

ALD with WF_6 and H_2S (thick film for tribology)



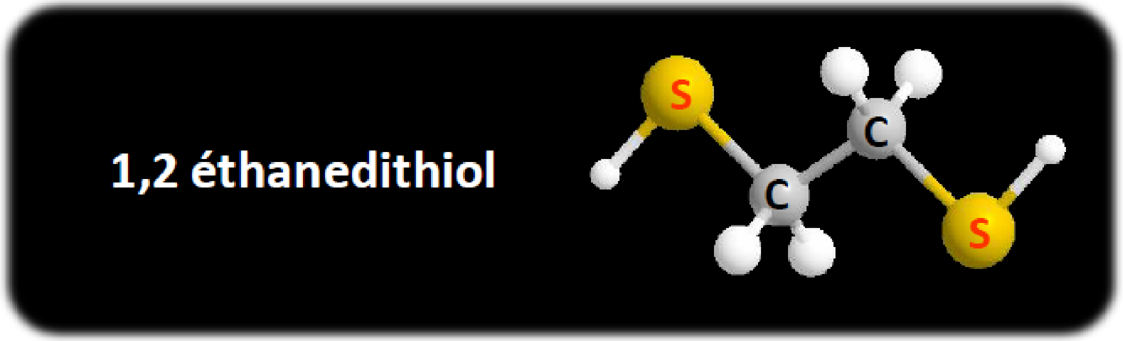
T.W. Scharf, **J. Mater. Res.**, 2002, 19 (12), 3443-3446

The different growth methods: ALD

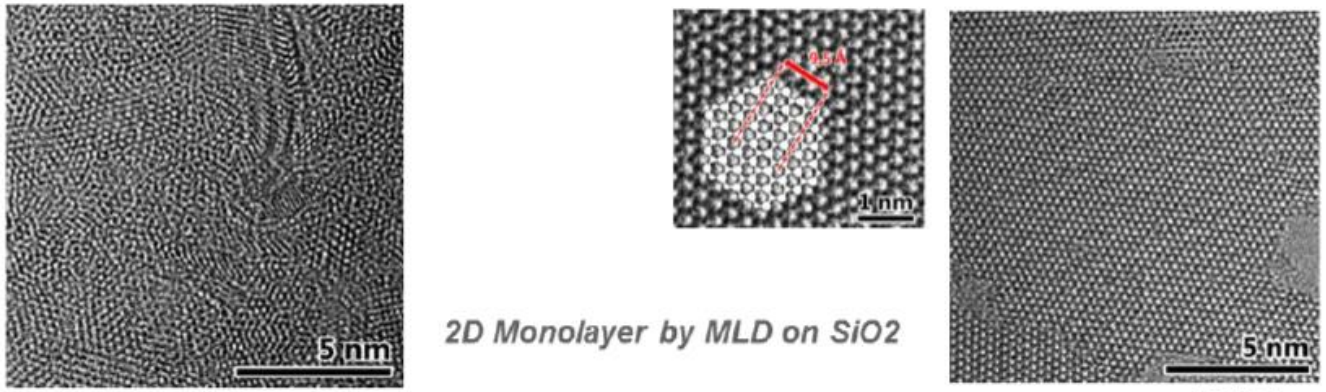


$Mo(NMe_2)_4$

+



- Evidence of in-plane film organization above 450°C



450°C

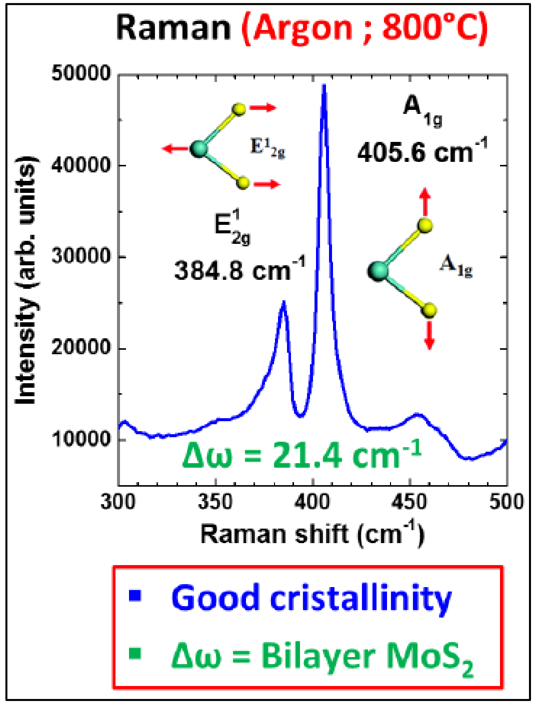
2D Monolayer by MLD on SiO2

800°C

S.Cadot , H.Okuno et al, Nanoscale 2016

DOI: 10.1039/c6nr06021h

also ACS Nano **7**, 11333 (2013)



The different growth methods: CVD, MOCVD, ALD

To summarize:

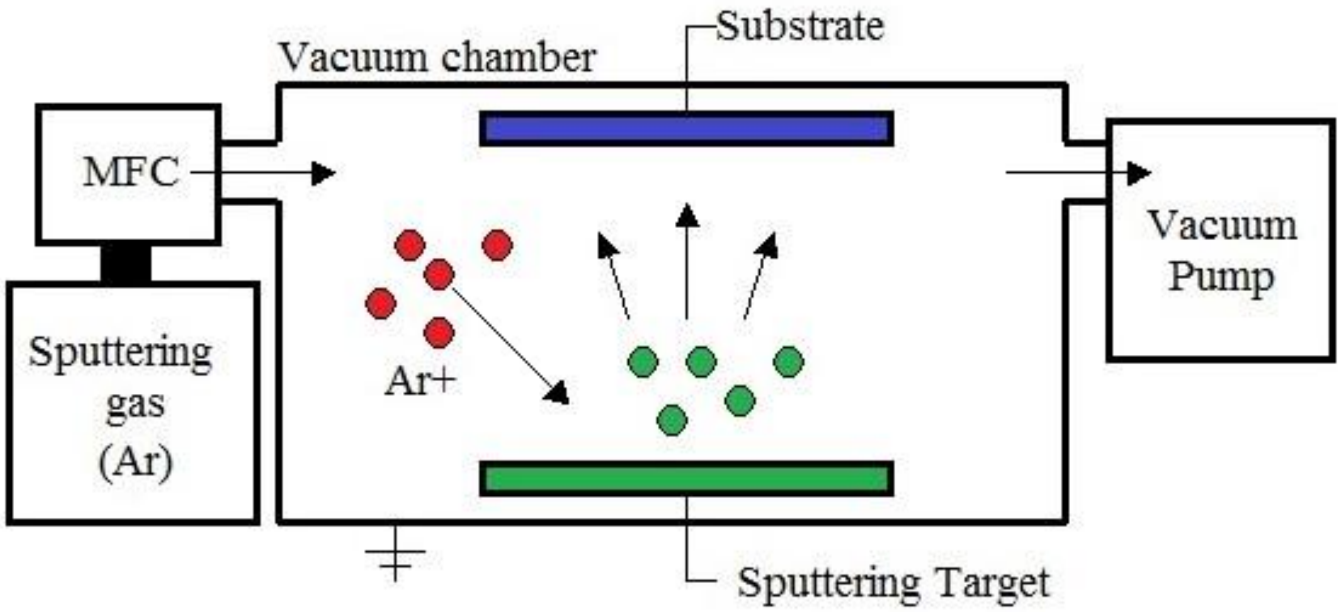
CVD with solid precursors: simple set-up BUT non-uniformity, non-continuous layers, poor control of the number of layers. Poor control of alloys, doping and heterostructures. Good mobility, PL on triangular flakes.

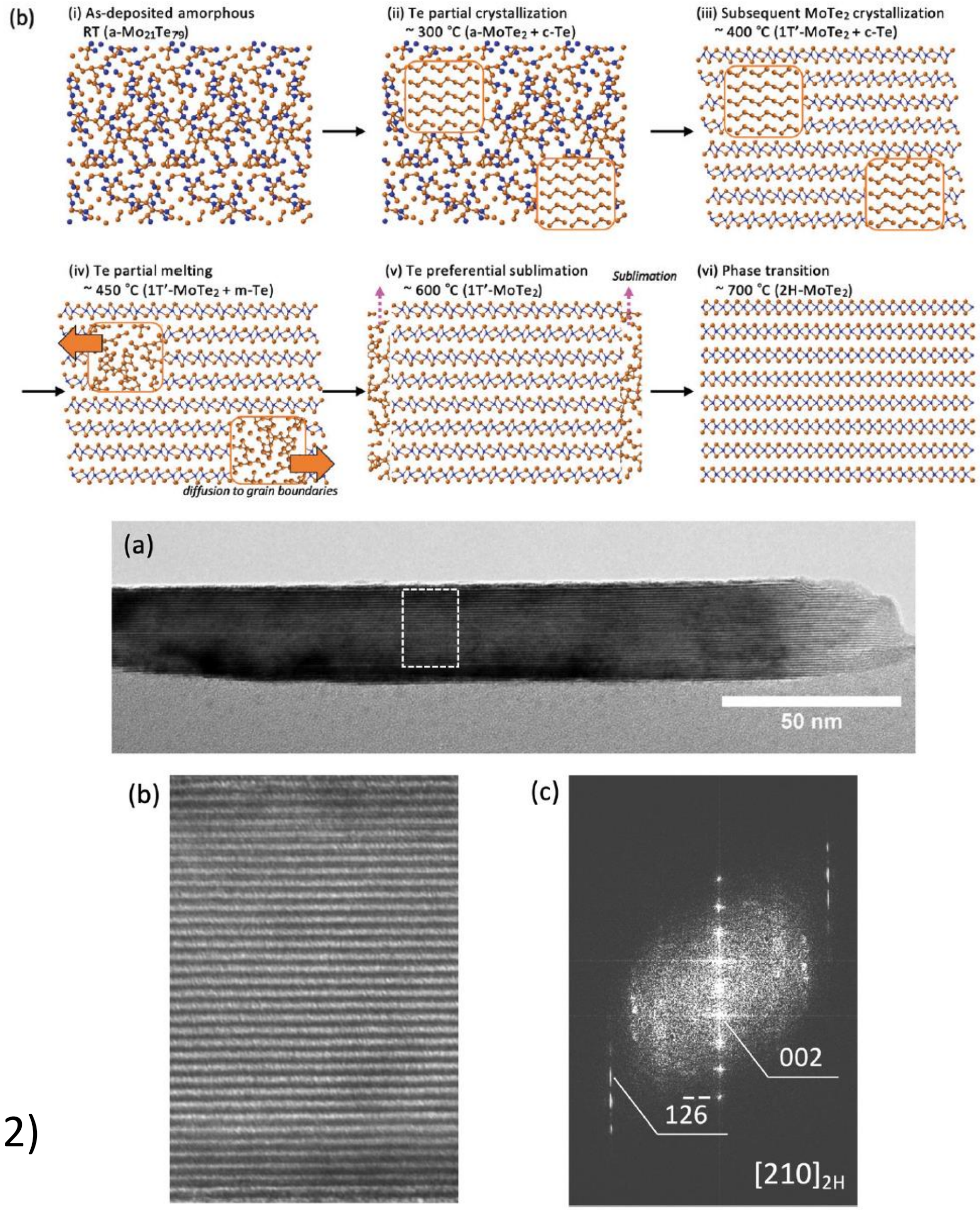
MOCVD including ALD: large area growth, continuity, uniformity, single crystalline on sapphire (2018). Very long growth. To develop: alloying, doping and heterostructures.

The different growth methods: sputtering

Example: $MoTe_2$

PRINCIPLE

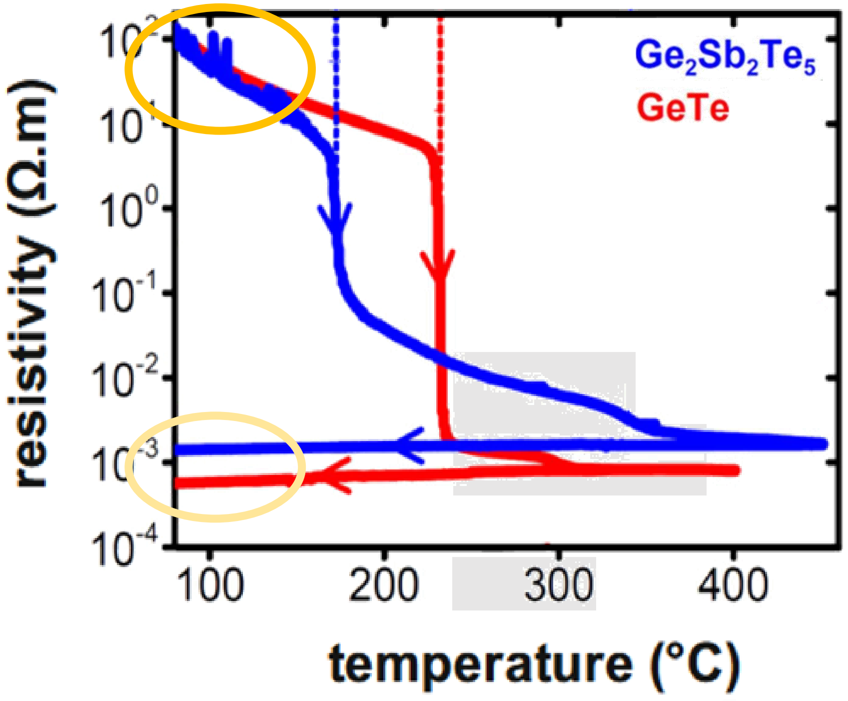




S. Hatayama et al., *J. Mater. Chem. C* **10**, 10627 (2022)

Courtesy Pierre Noé, CEA LETI, Grenoble

Phase change chalcogenides (PCM)



Crystalline phase

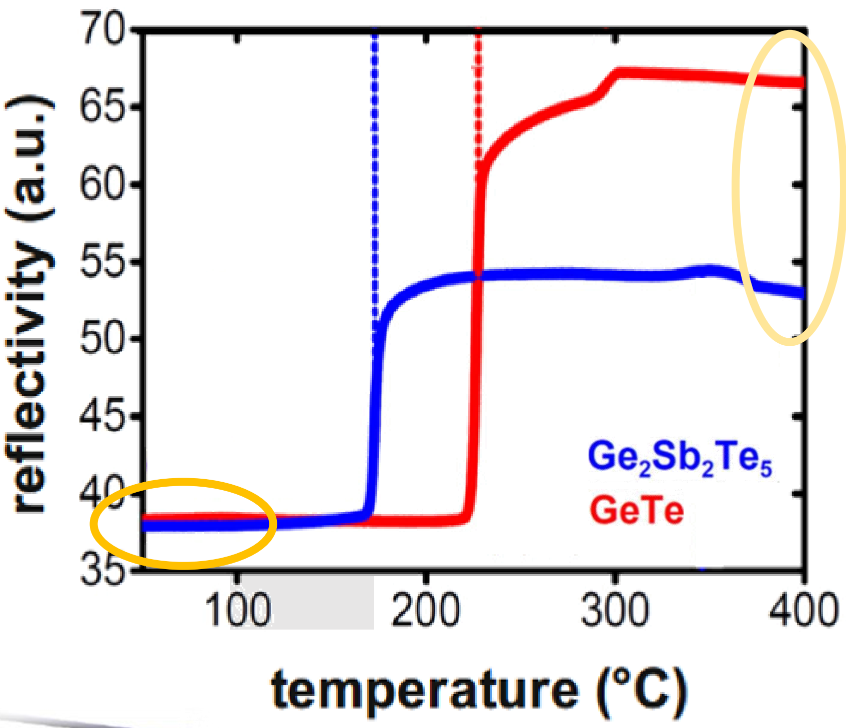
High reflectivity

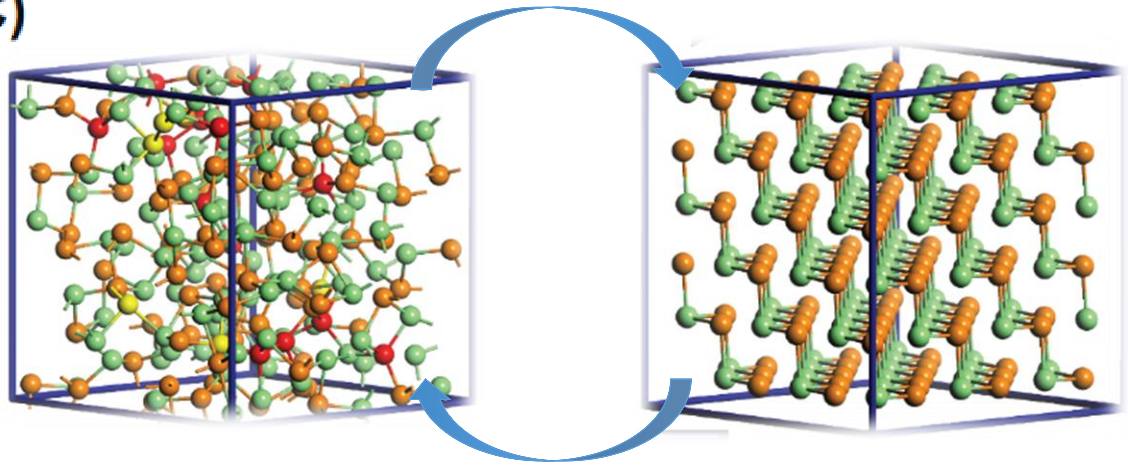
Low resistivity

Amorphous phase

Low reflectivity

High resistivity

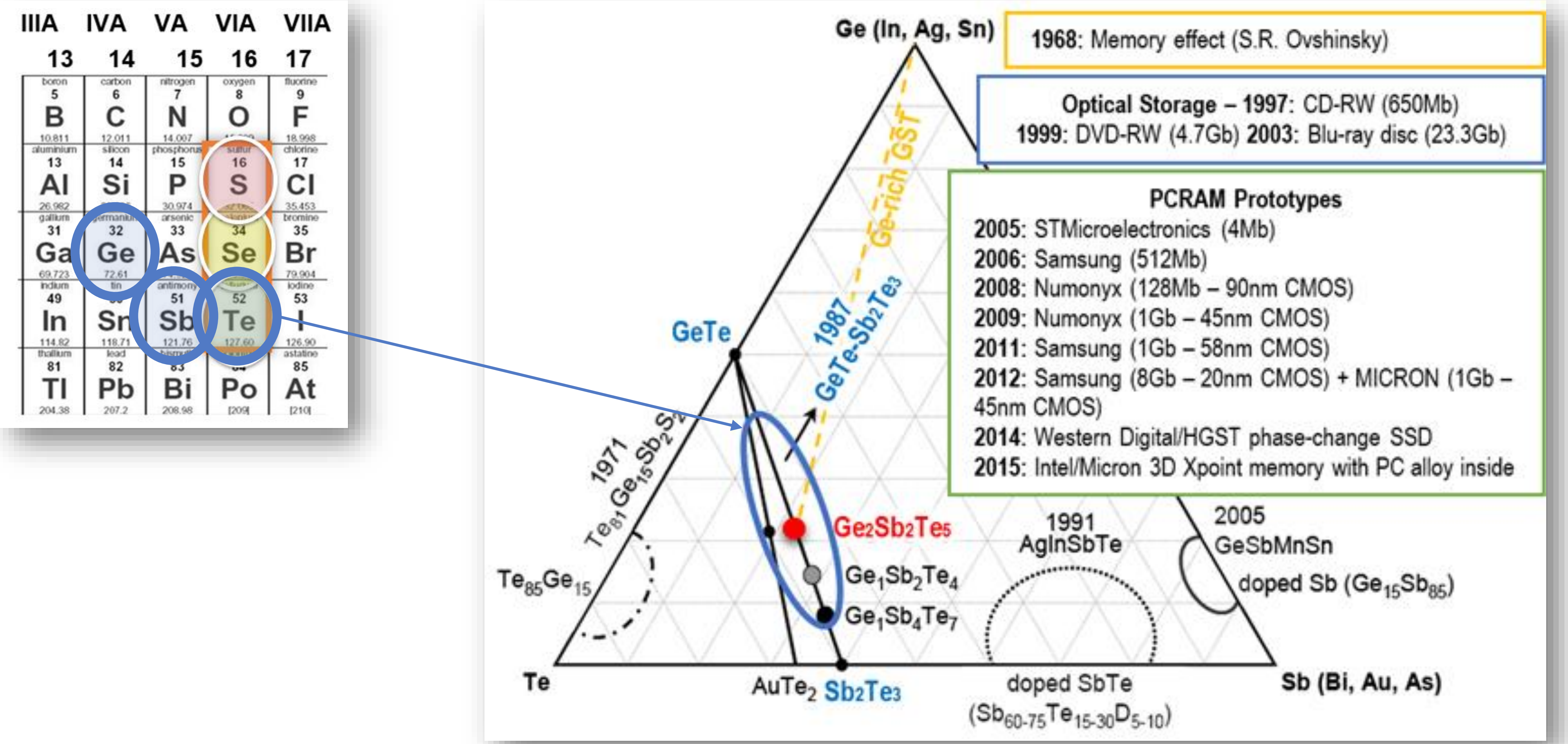




P. Noé, C. Vallée, F. Hippert, F. Fillot, J.-Y. Raty, Semicond. Sci. Technol. 2018, 33, 013002

Courtesy Pierre Noé, CEA LETI, Grenoble

PHASE CHANGE CHALCOGENIDES (PCM)



P. Noé, C. Vallée, F. Hippert, F. Fillot, J.-Y. Raty, Semicond. Sci. Technol. 2018, 33, 013002.;

Courtesy Pierre Noé, CEA LETI, Grenoble

PHASE CHANGE CHALCOGENIDES (PCM)

Physics of PCM : Metavalent Bonding (MVB) mechanism

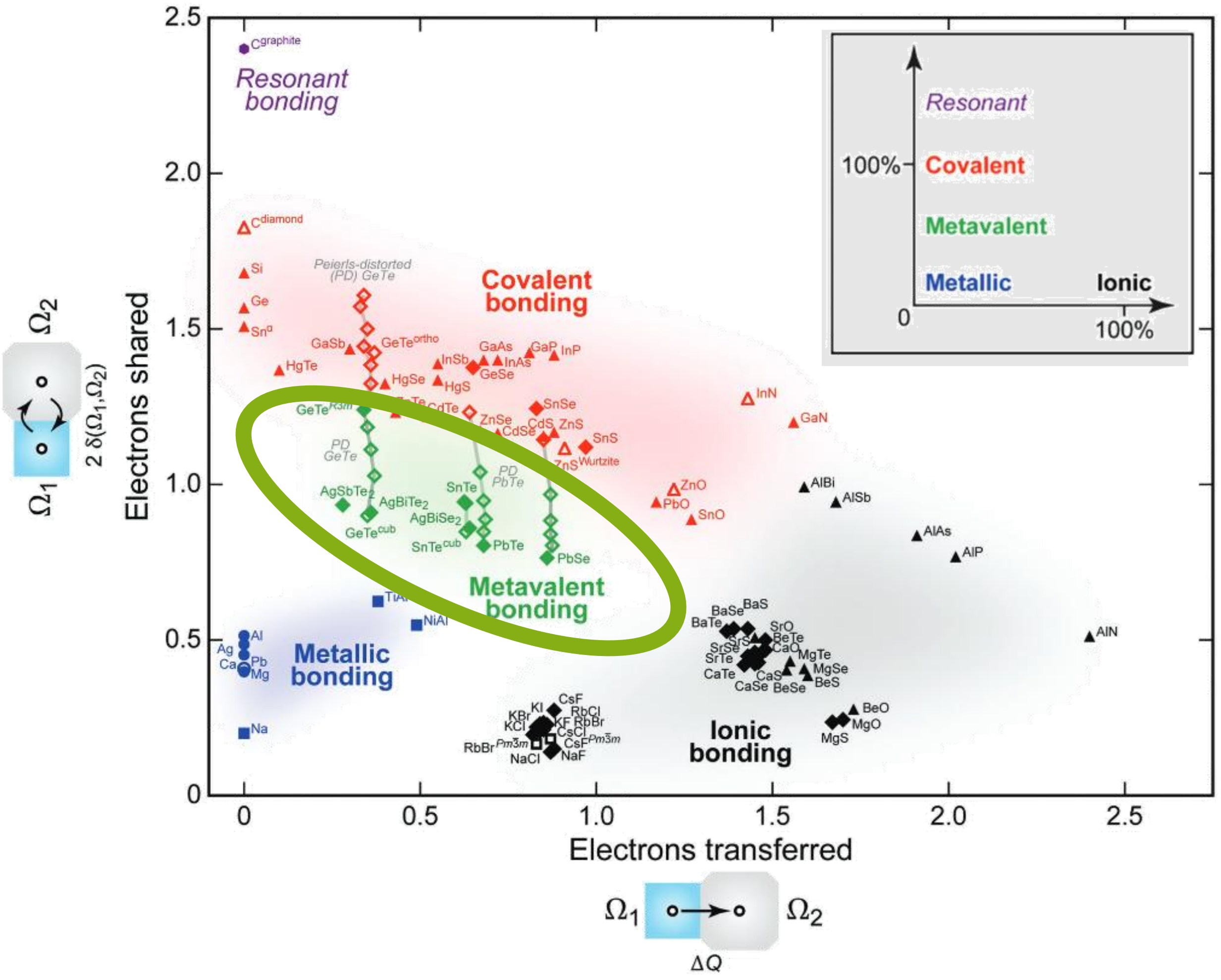
Huge contrast in optical and electronic properties
between
amorphous et crystalline phases !

COVALENT — **METAVALENT**

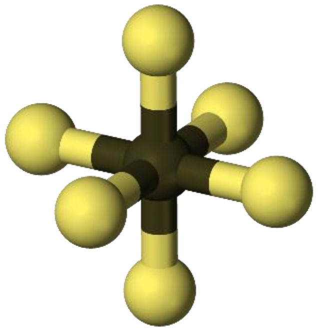
⟷

Difference in the bonding mechanism
Between amorphous and crystalline phases

METAVALENT BONDING
Unique bonding mechanism prensent in the CRYSTALLINE PHASE OF PCM
(« INCIPIENT METALS »).



- IV-VI chalcogenides
- *p*-bonded materials
- Octahedral atomic arrangement



J-Y Raty et al., Adv. Mater. 2019, 31, 1806280; B. Kooi, M. Wuttig, Adv. Mater. 2020, 32, 1908302

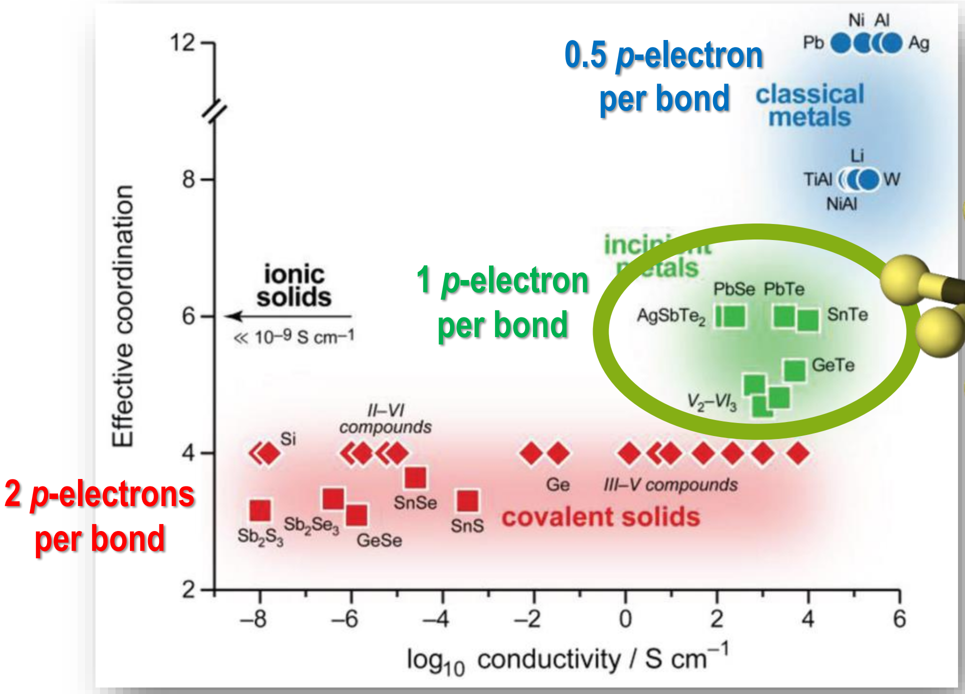
Courtesy Pierre Noé, CEA LETI, Grenoble

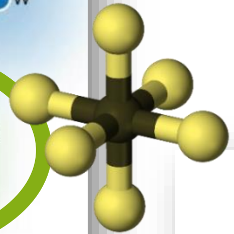
PHASE CHANGE CHALCOGENIDES (PCM)

Physics of PCM : Metavalent Bonding (MVB) mechanism

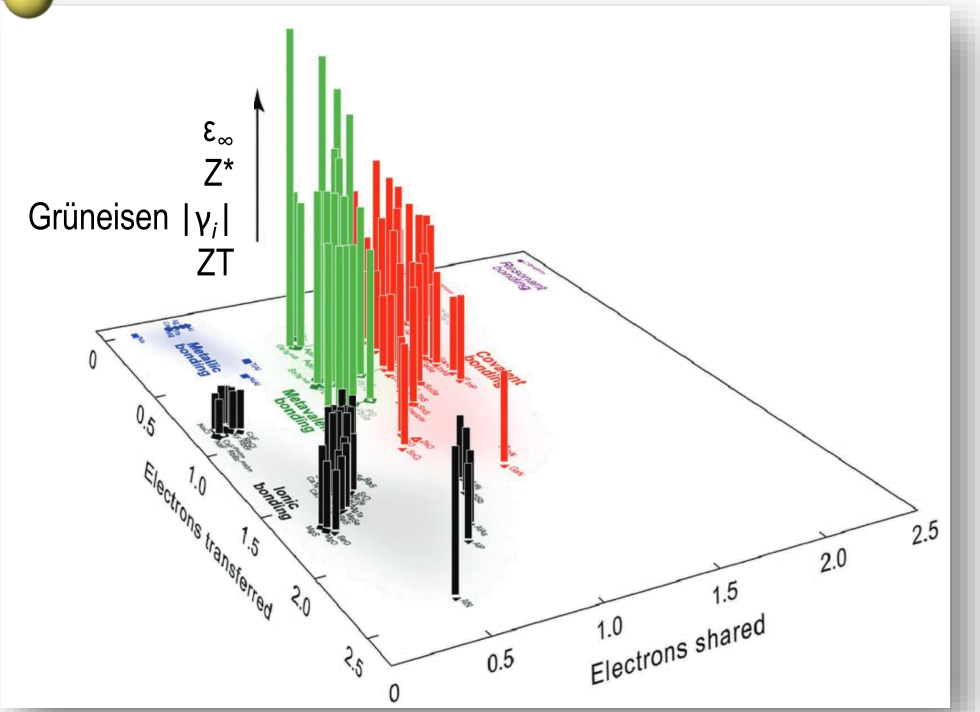
Signatures and properties of MVB :

- **Coordination excess:**
Half filled orbitals (or non-saturated covalent bond)





In MVB solids
→ Electrons are « locally » delocalized along certain bonds



- **Moderate degree of distorsion of the lattice :**
To favor the alignment and overlap of *p* orbitals

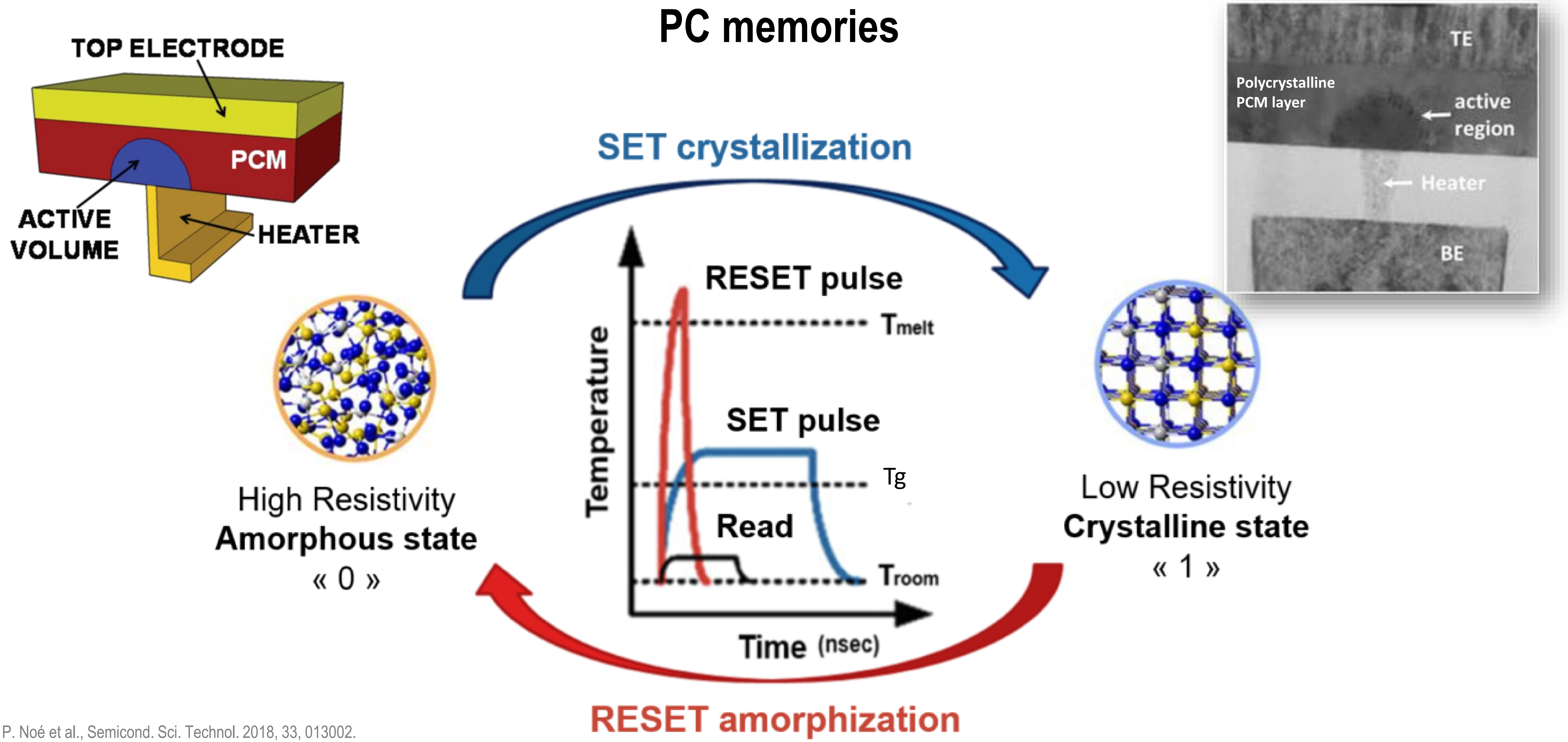
- **Large electronic polarizability and anharmonicity of the lattice :**
Very large dielectric constant, Grüneisen parameters very large + high effective Born charge Z*.

J-Y Raty et al., Adv. Mater. 2019, 31, 1806280; B. Kooi, M. Wuttig, Adv. Mater. 2020, 32, 1908302

Courtesy Pierre Noé, CEA LETI, Grenoble

PHASE CHANGE CHALCOGENIDES (PCM) AND PHASE CHANGE MEMORIES

PC memories

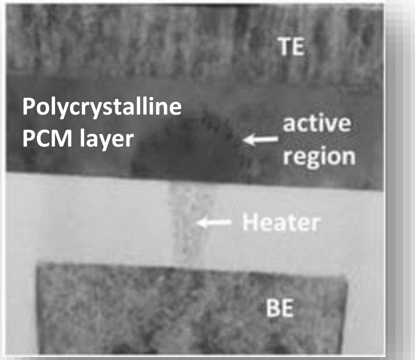


P. Noé et al., Semicond. Sci. Technol. 2018, 33, 013002.

Courtesy Pierre Noé, CEA LETI, Grenoble

PHASE CHANGE CHALCOGENIDES (PCM) AND PHASE CHANGE MEMORIES

Still several scientific and technological challenges !



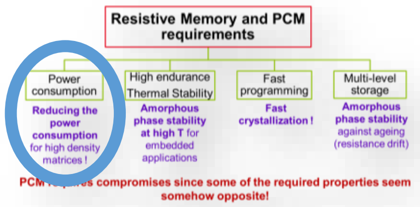
Resistive Memory and PCM requirements

- **Power consumption** — **Reducing the power consumption** for high density matrices !
- **High endurance / Thermal Stability** — **Amorphous phase stability at high T** for embedded applications
- **Fast programming** — **Fast crystallization !**
- **Multi-level storage** — **Amorphous phase stability** against ageing (resistance drift)

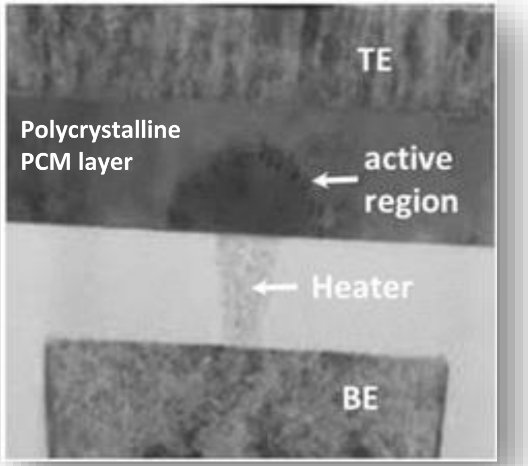
P. Noé, C. Vallée, F. Hippert, F. Fillot, and J.-Y. Raty, Semicond. Sci. Technol. **33**, 013002 (2018).

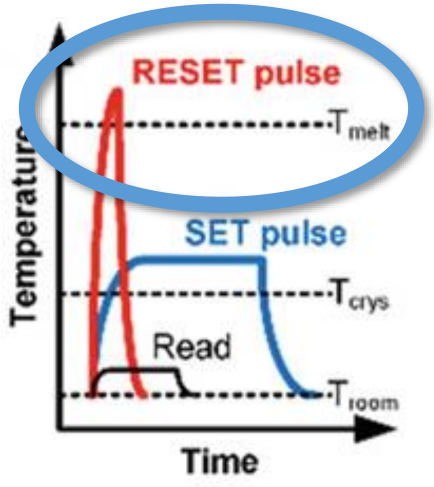
Courtesy Pierre Noé, CEA LETI, Grenoble

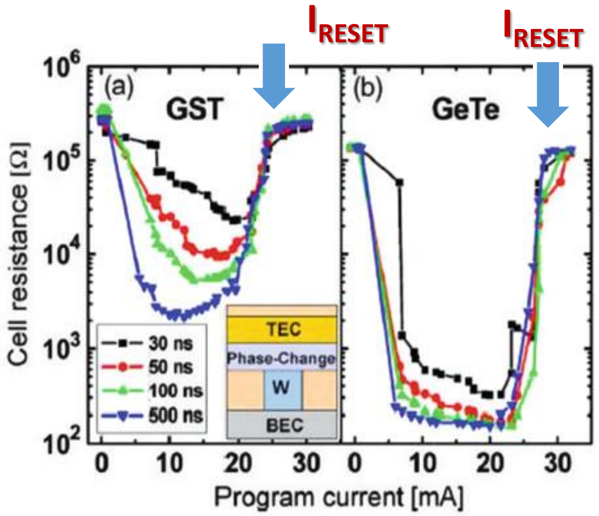
PHASE CHANGE CHALCOGENIDES (PCM) AND PHASE CHANGE MEMORIES



Reduce the energy consumption of PC memories: confinement !

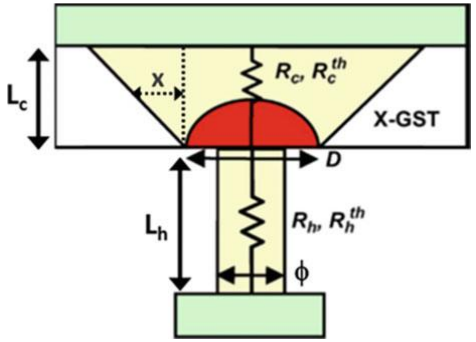


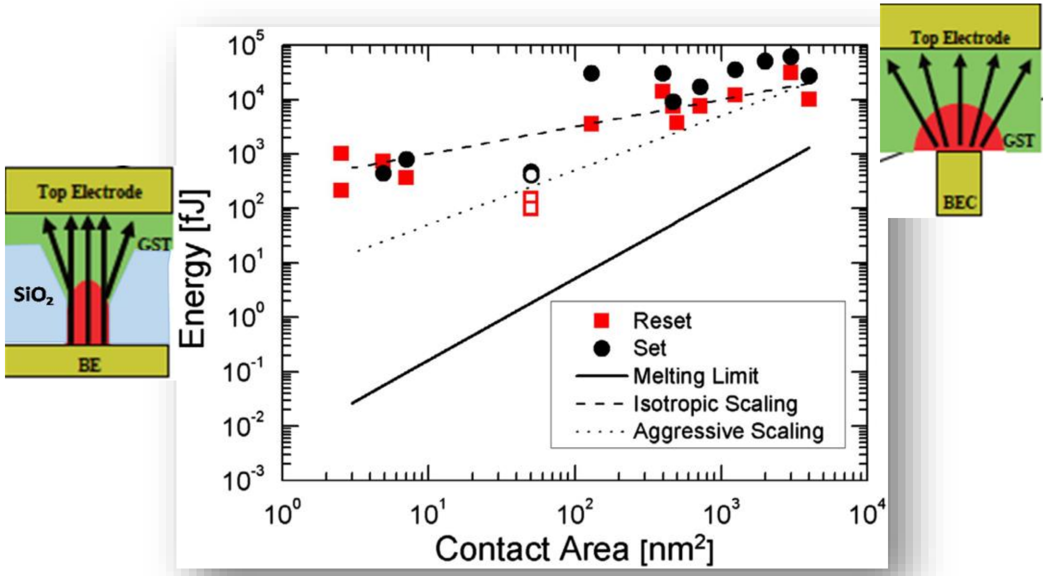




Thermal optimization of the PC memory cell
to limit energy and heat losses
<u>during RESET operation</u>
(Melting of the PC material at high T followed by quenching).

Confining heat in the PC memory cell by using a confinement structure as small as possible !

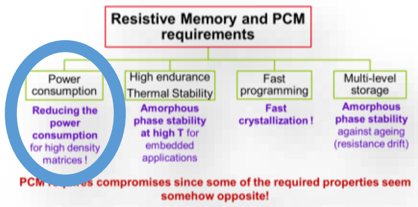




A. Redaelli, editor , *Phase Change Memory* (Springer International Publishing, Cham, 2018).

Courtesy Pierre Noé, CEA LETI, Grenoble

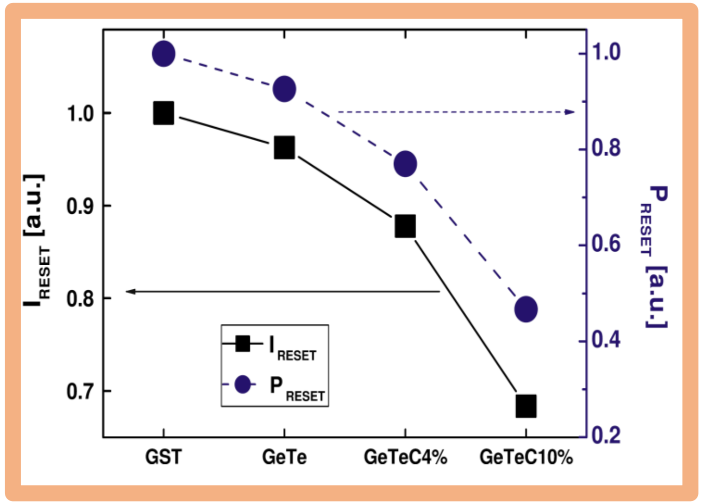
PHASE CHANGE CHALCOGENIDES (PCM) AND PHASE CHANGE MEMORIES



Reduce the energy consumption of PC memories: confinement !

Extra gain thanks to the reduction of the thermal conductivity of the polycrystalline phase of the PCM !

	Thermal conductivity of thin PCM films @ 300K K_{th} (W/(m.K))	
	Amorphous phase	**Crystalline phase**
GeTe	~0.2-0.25	**~3 to 5.5 [1]**
GST compounds	~0.2-0.25	**~0.4 to 5 (cubic to hex)**
C-doped GeTe	~0.2-0.25	**0.95-1.44 [1]**



G. Betti Beneventi *et al.*, Solid-state electronics 65-66, 197–204 (2011).

[1] J. Paterson, phD thesis, Grenoble Alpes University (2020).
K. Ghosh et al., PRB **101**, 214305 (2020).
R.J. Warzoha et al APL **115**, 023104 (2019).
D. Campi et al PRB 95, 024311 (2017).
K S Siegert et al Rep. Prog. Phys. **78** 013001 (2015).
R. Fallica et al Phys. Status Solidi RRL 7, No. 12, 1107–1111 (2013).
J. M. Yanez-Limon, PRB **52** 16321 (1995),

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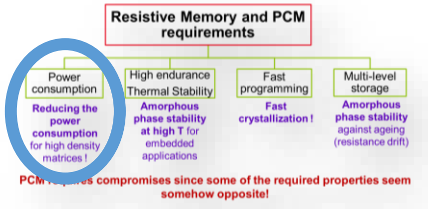
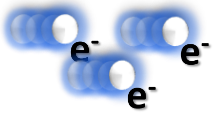
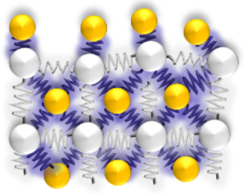


Reduce the energy consumption of PC memories: confinement !

How can we still decrease the thermal conductivity K_{th} of the polycrystalline phase of the PCM ?

$$k_{Th} = k_{el} + k_{ph}$$





Heat transport by electrons - Wiedemann-Franz law for metals

$$L = \frac{\kappa}{\sigma T} = \frac{\pi^2 k_B^2}{3e^2} = 2,4428\ldots \times 10^{-8} W \cdot \Omega \cdot K^{-2}$$

- ❑ Electronic conductivity σ (carrier type/concentration/mobility)
- ❑ Lorentz factor $L \propto |S|$ (Seebeck coefficient)

$$L = 1.5 + \exp\left[-\frac{|S|}{116}\right]$$

Ex. GeTe: $L \approx 2.4\ 10^{-8}\ V^2K^{-2}$

Heat transport by phonons

- ❑ Umklapp anharmonic diffusion (3 phonons process)
- ❑ Diffusion on point defects (vacancies, defects ...)
- ❑ Diffusion at grain boundaries or at chemical heterogeneities
- ❑ Electron or magnon diffusion

Reduction of K_{th} by introducing diffusion centers for phonons and/or electrons !

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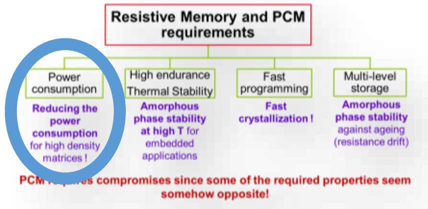
PHASE CHANGE CHALCOGENIDES (PCM) AND PHASE CHANGE MEMORIES



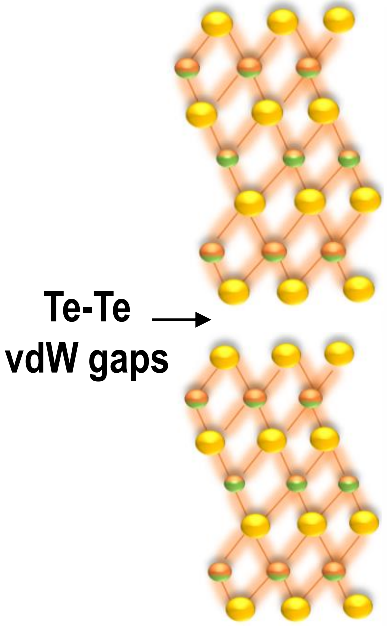
Reduce the energy consumption of PC memories: confinement !

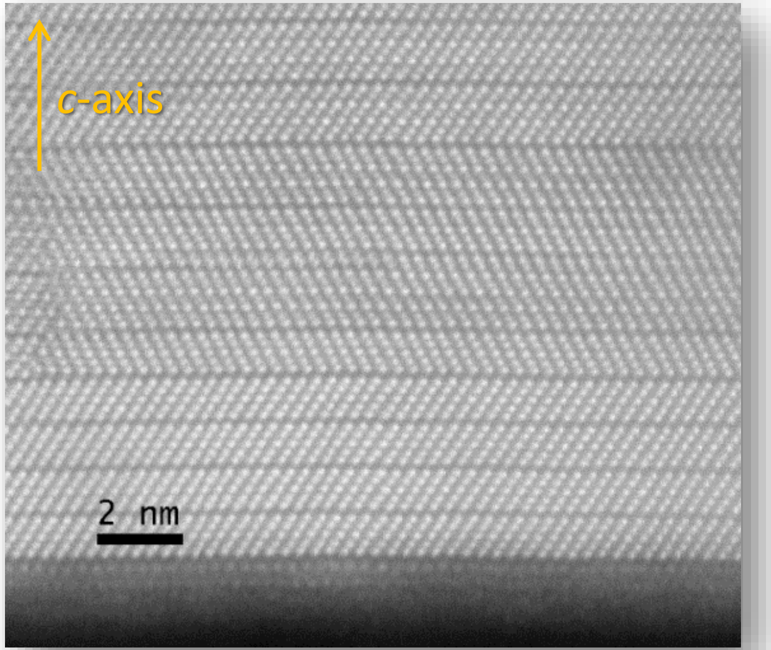
How can we still decrease the thermal conductivity K_{th} of the polycrystalline phase of the PCM ?

Introduction of diffusion centers for phonons and/or electrons !

GST 2D & super-lattices (SL) van der Waals $[(GeTe)_2/(Sb_2Te_3)_m]_n$

Modify electronic transport *along the c-axis with vdW Te-Te gaps*

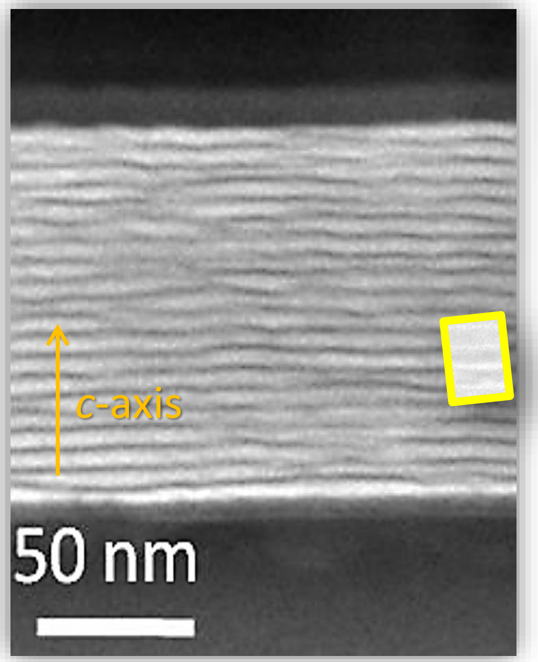


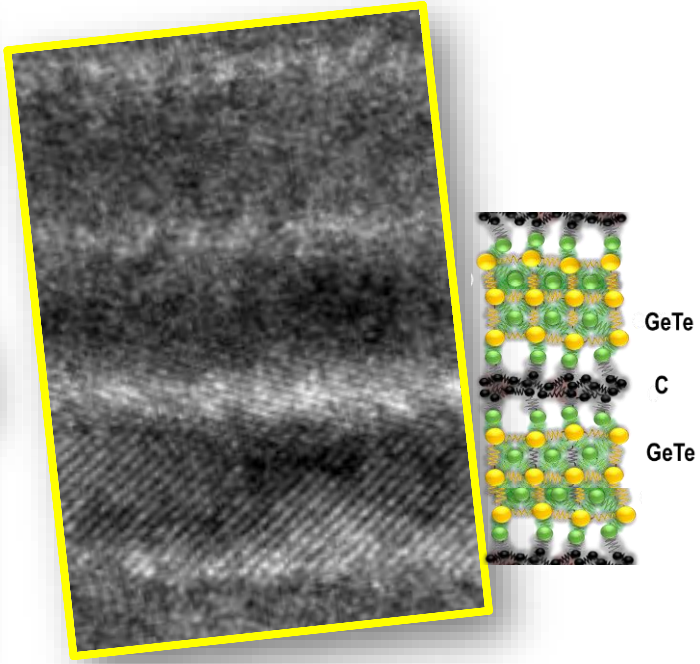


D. Térébénec, et al., Physica Status Solidi (RRL) – Rapid Research Letters **15**, 2000538 (2021).

Nanocomposites PCM → GeTe/C multilayers

Modify phonon propagation *along the c-axis by introducing heterogeneities of elastic constants*





D. Térébénec, et al., Physica Status Solidi (RRL) – Rapid Research Letters 2200054 (2022).

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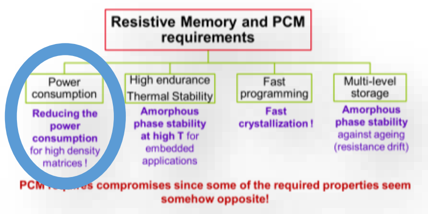

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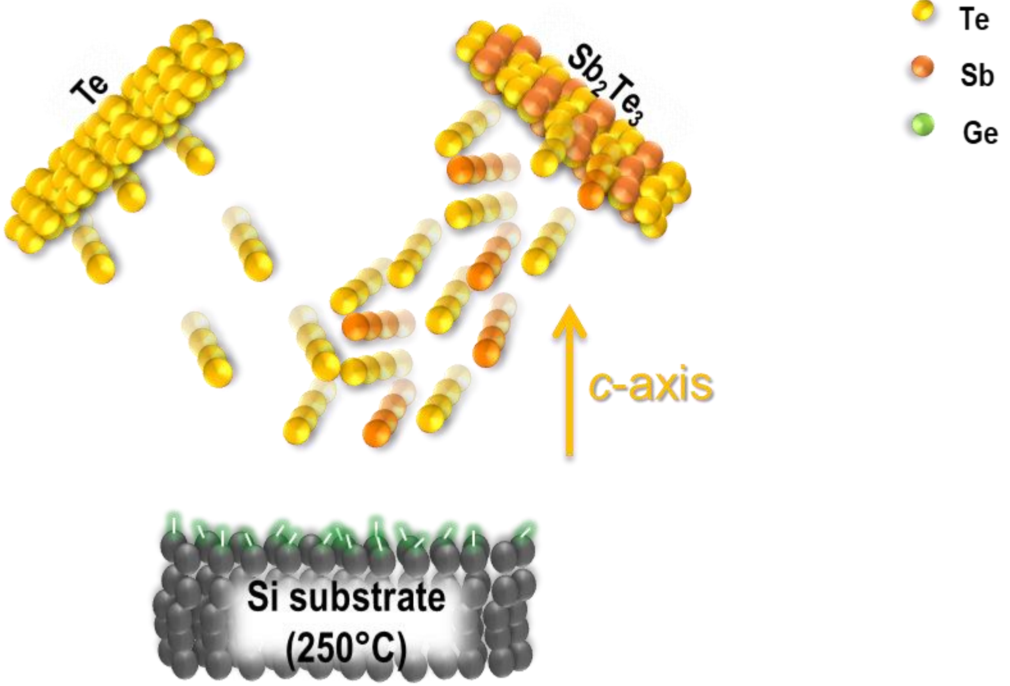

P. Kowalczyk at al., *Small* **2018**, *14*, 1704514.

F. Hippert, et al., *J. Phys. D: Appl. Phys.* **2020**, *53*, 154003.

Courtesy Pierre Noé, CEA LETI, Grenoble

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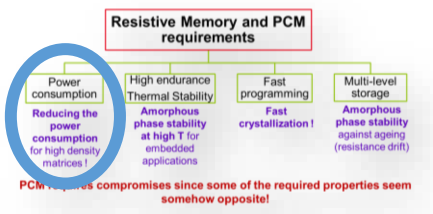

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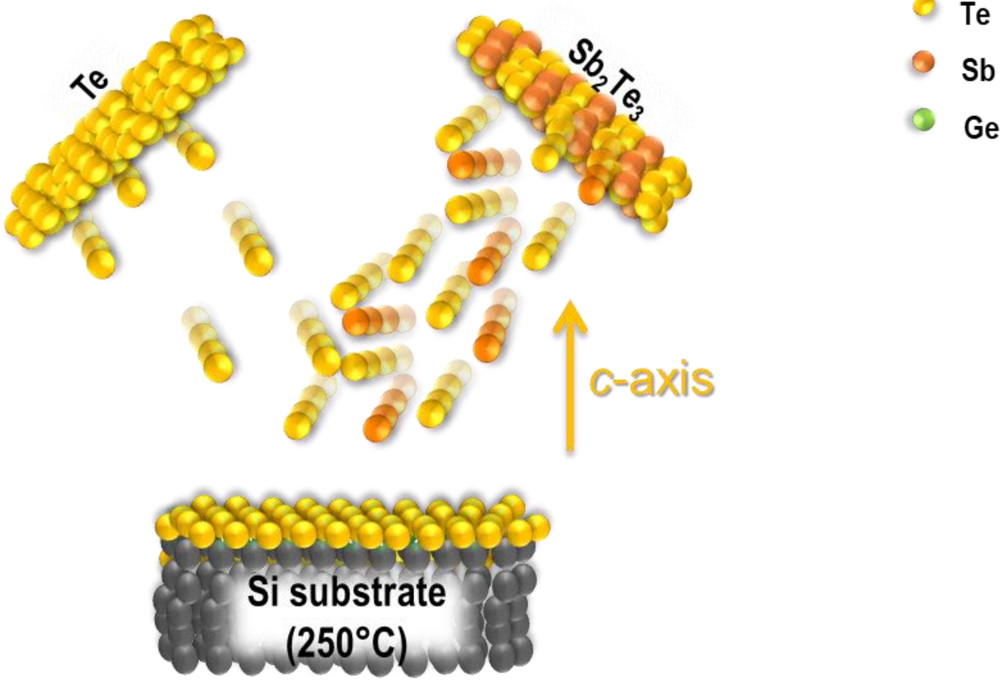

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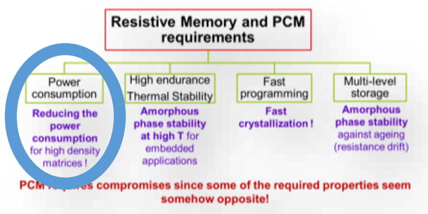

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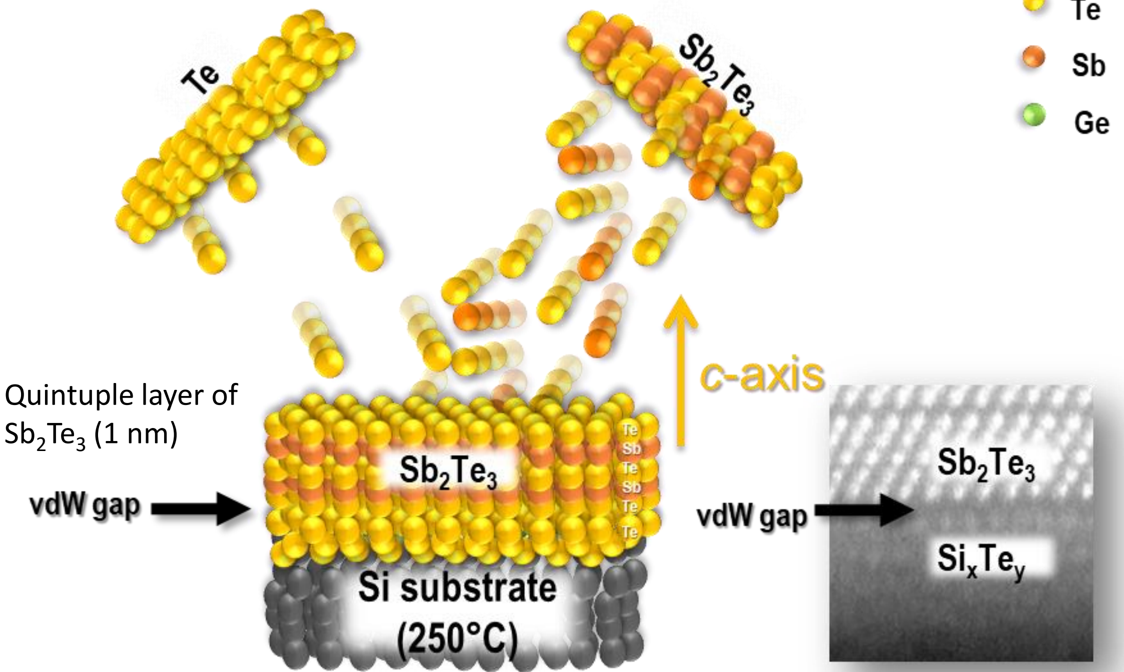

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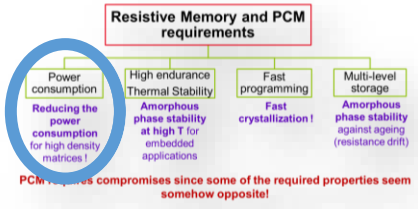

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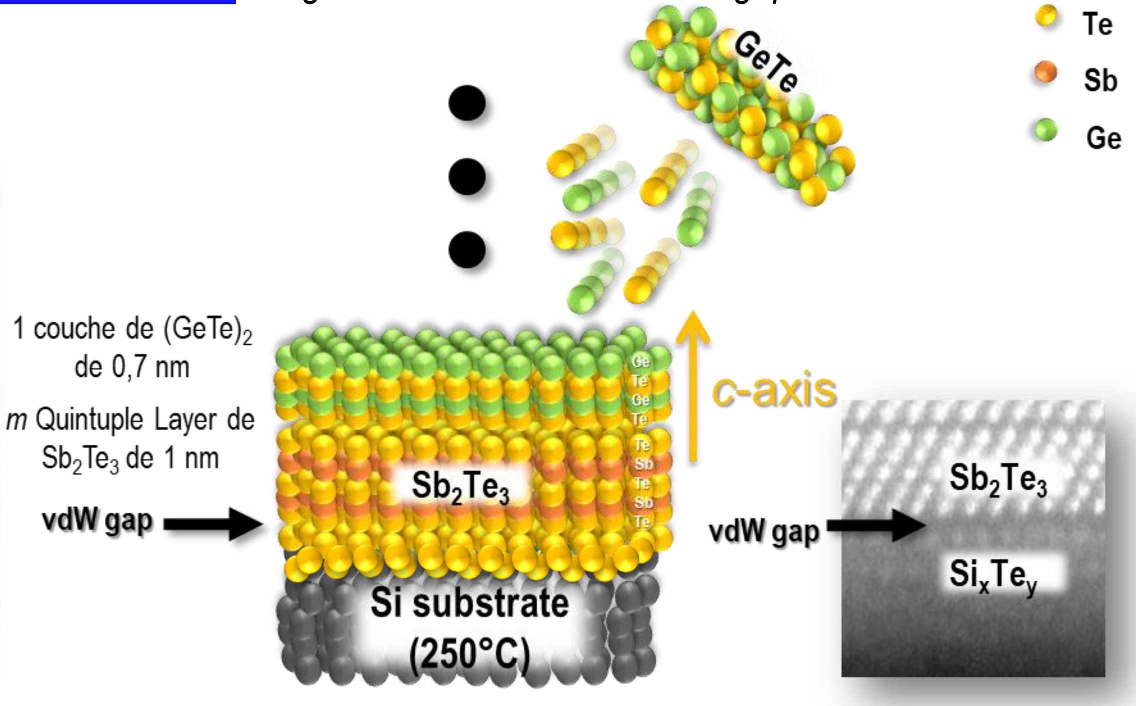

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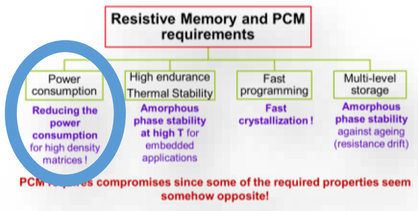

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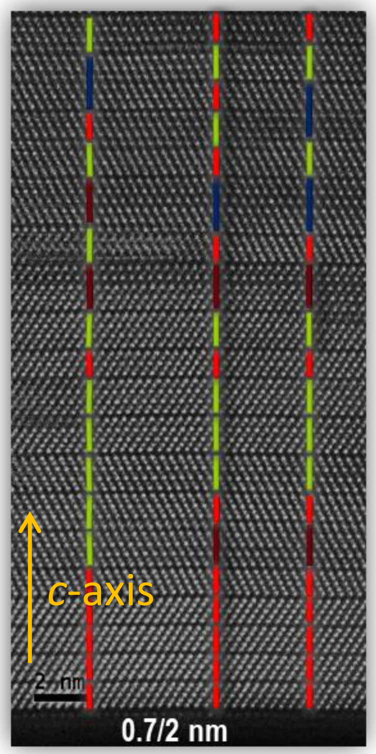
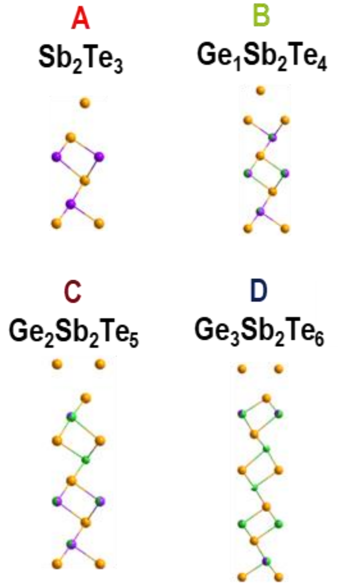
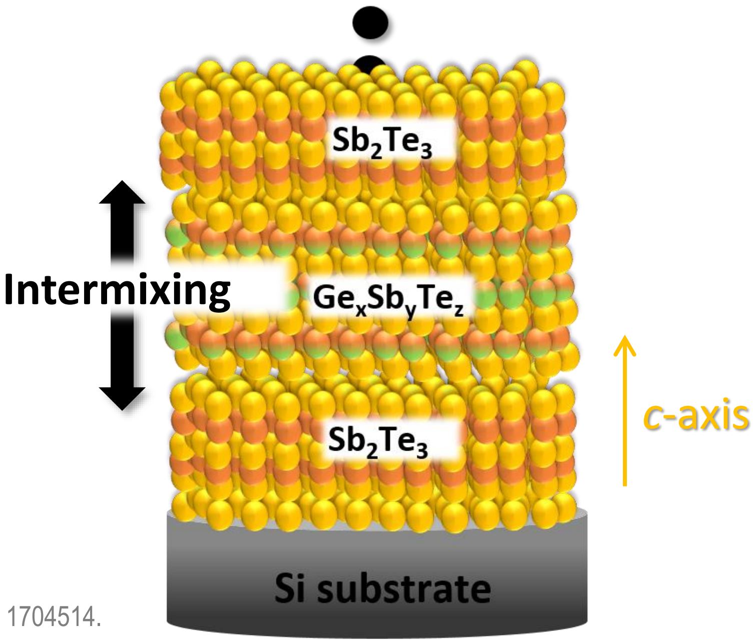




P. Kowalczyk et al., *Small* **2018**, *14*, 1704514.

Super-lattice $[(GeTe)_2/(Sb_2Te_3)_m]_n$



F. Hippert, et al., *J. Phys. D: Appl. Phys.* **2020**, *53*, 154003.

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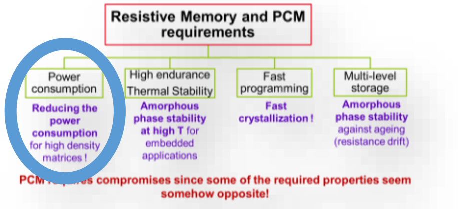

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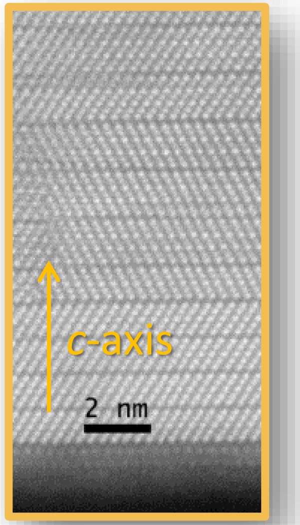
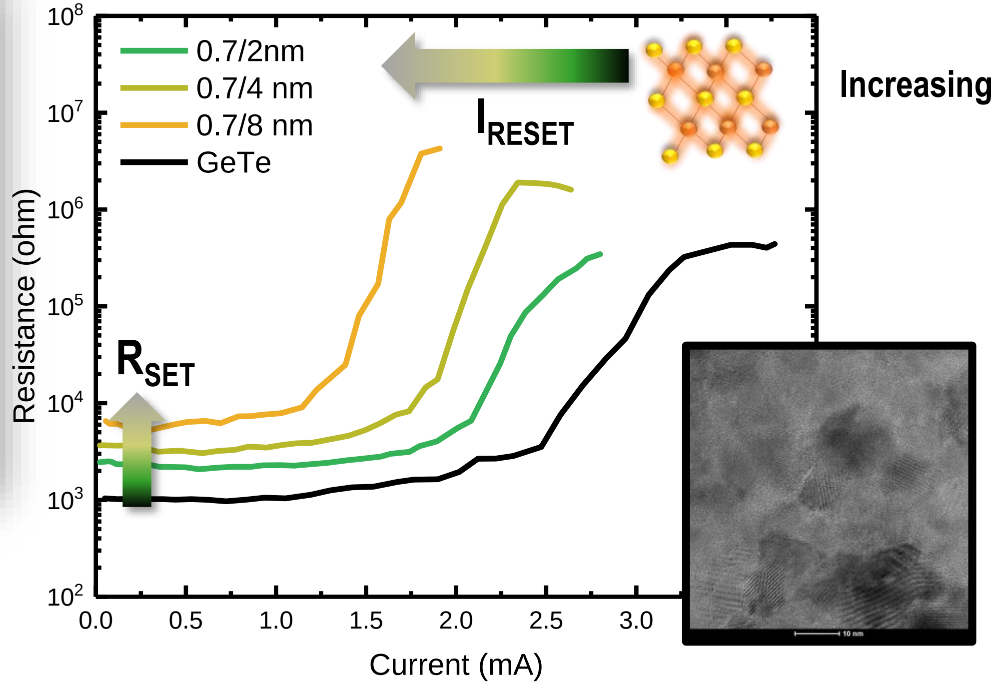


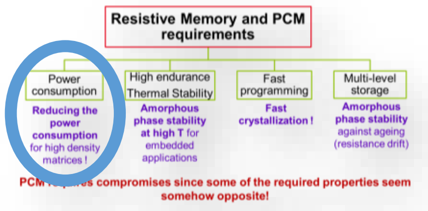


Increasing Sb_2Te_3 thickness

D. Térébénec, et al., Physica Status Solidi (RRL) – Rapid Research Letters **15**, 2000538 (2021).

Courtesy Pierre Noé, CEA LETI, Grenoble

PHASE CHANGE CHALCOGENIDES (PCM) AND PHASE CHANGE MEMORIES



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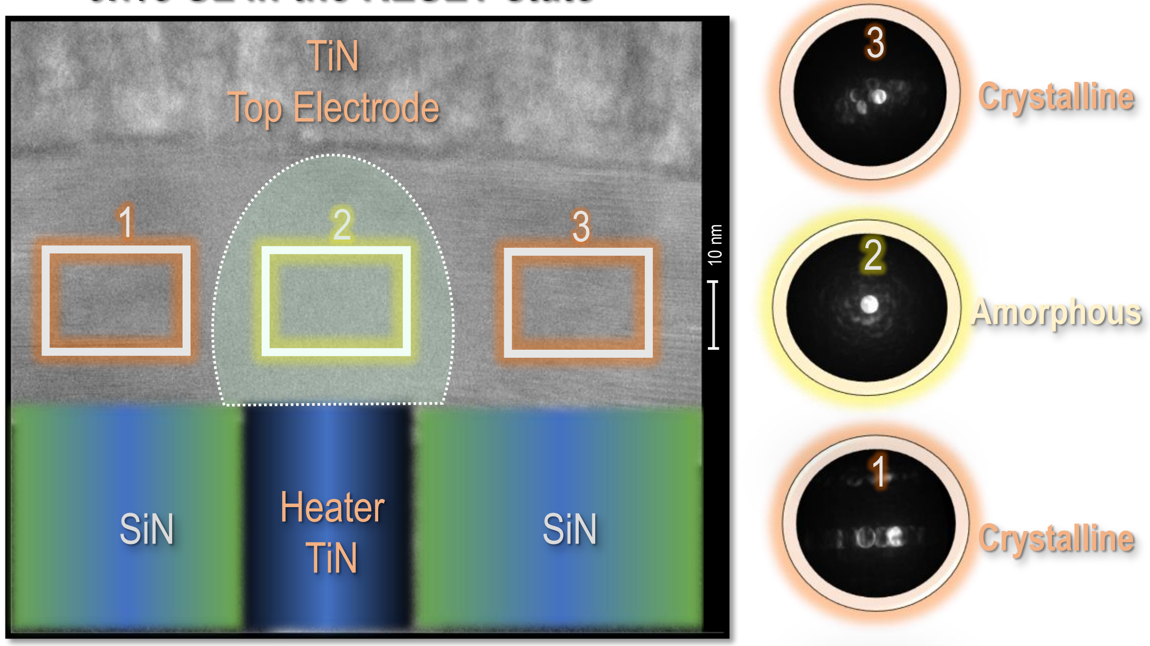
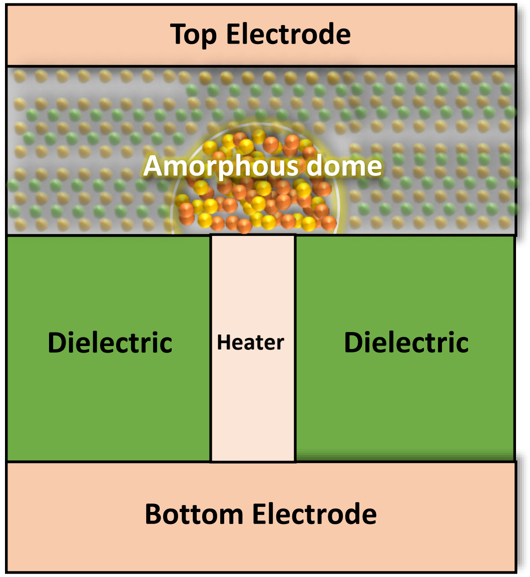
Modify electronic transport along the c-axis with vdW Te-Te gaps

0.7/8 SL in the RESET state





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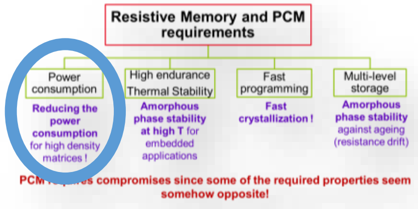

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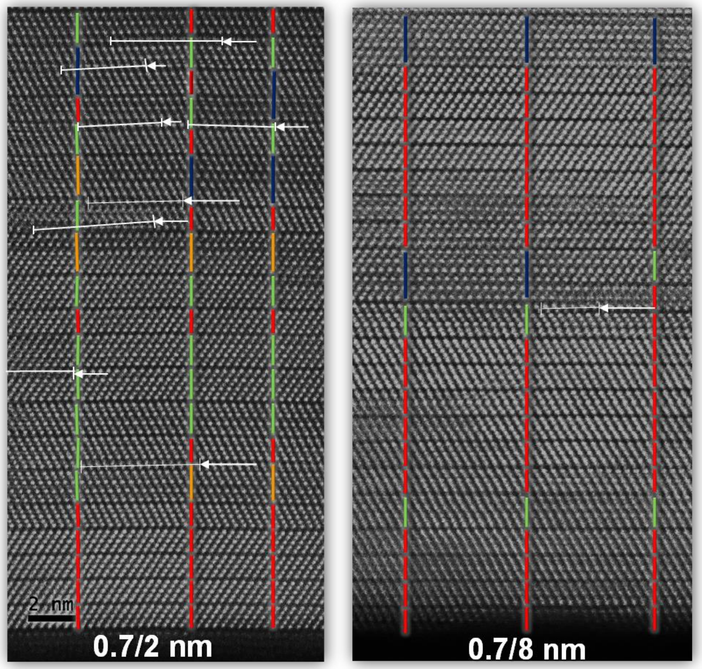
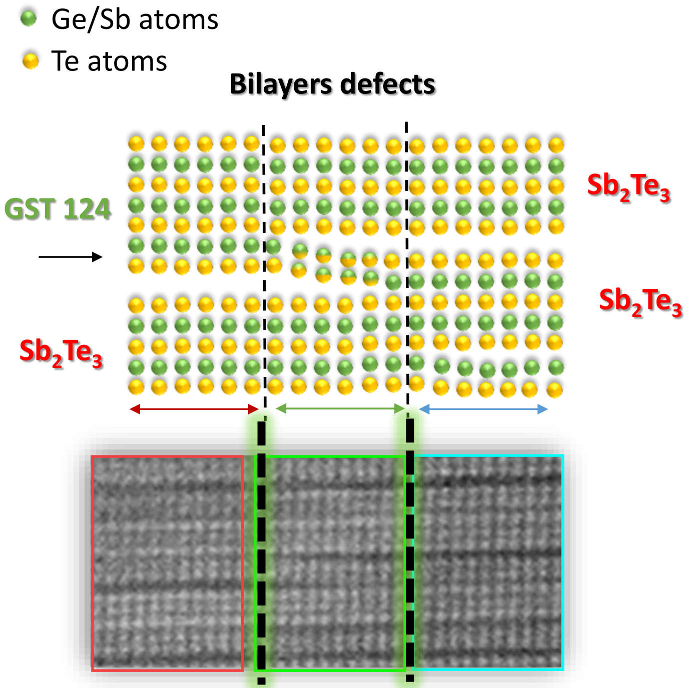
Modify electronic transport *along the c-axis with vdW Te-Te gaps*

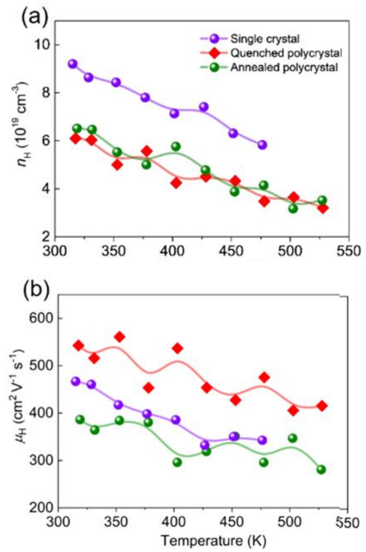
0.7/2 nm **0.7/8 nm**



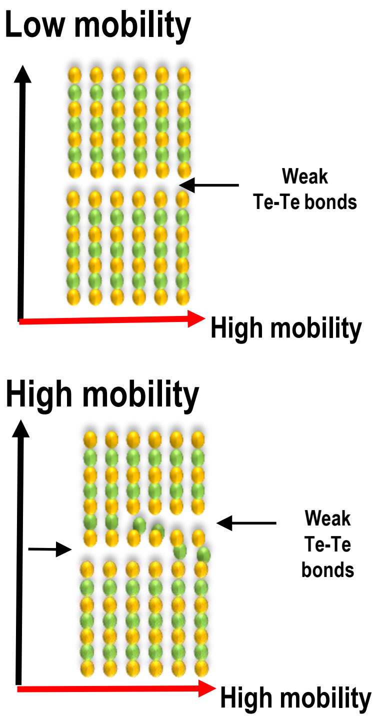


D. Térébénec, et al., Physica Status Solidi (RRL) – Rapid Research Letters **15**, 2000538 (2021).

Impact of Swapped Bilayers on the mobility of charge carriers in polycrystalline Sb_2Te_3



J. Wang, & al, *Nano Energy* **2021**, *79*, 105484.



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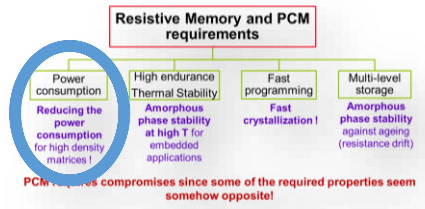

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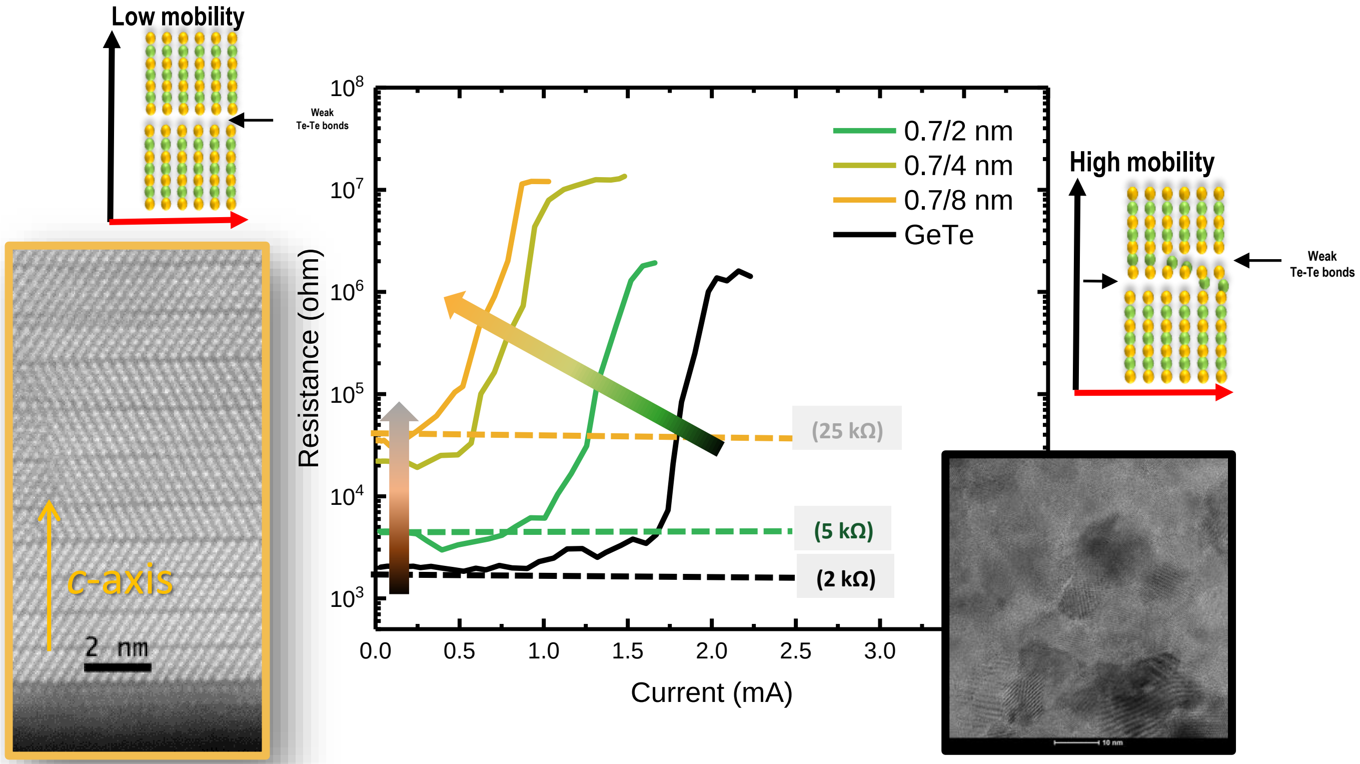


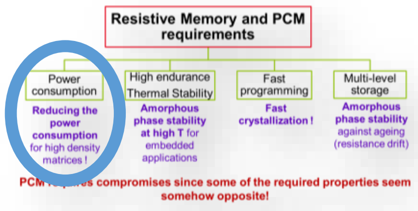
D. Térébénec, et al., Physica Status Solidi (RRL) – Rapid Research Letters **15**, 2000538 (2021).

The main difference between SLs is the degree/density of disorder/defects in the crystalline structure at the vdW gaps

The difference of R_{SET} between SLs can be attributed to the number of swapped bilayers in the crystalline structure.

Courtesy Pierre Noé, CEA LETI, Grenoble

PHASE CHANGE CHALCOGENIDES (PCM) AND PHASE CHANGE MEMORIES



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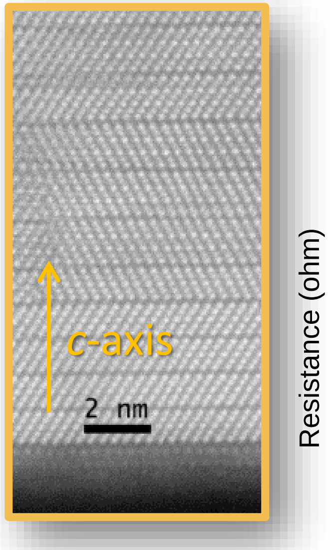
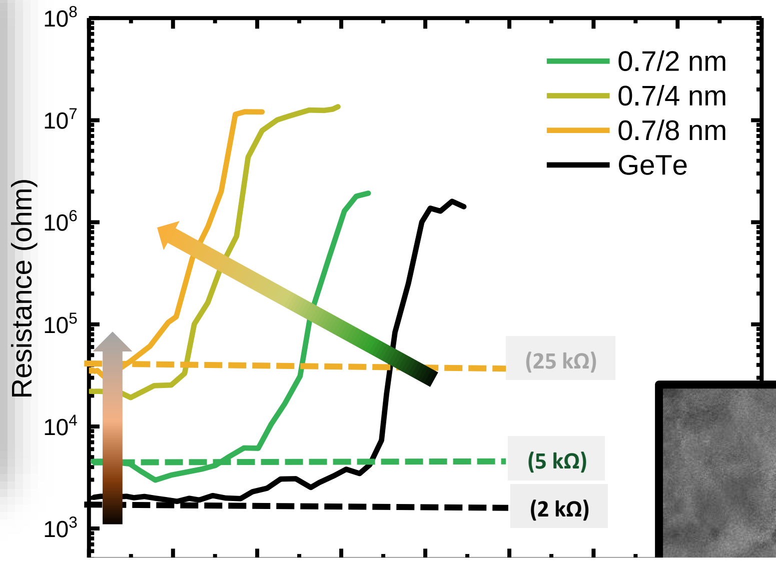
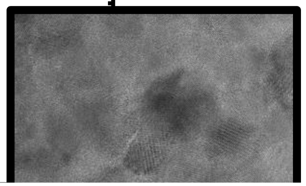




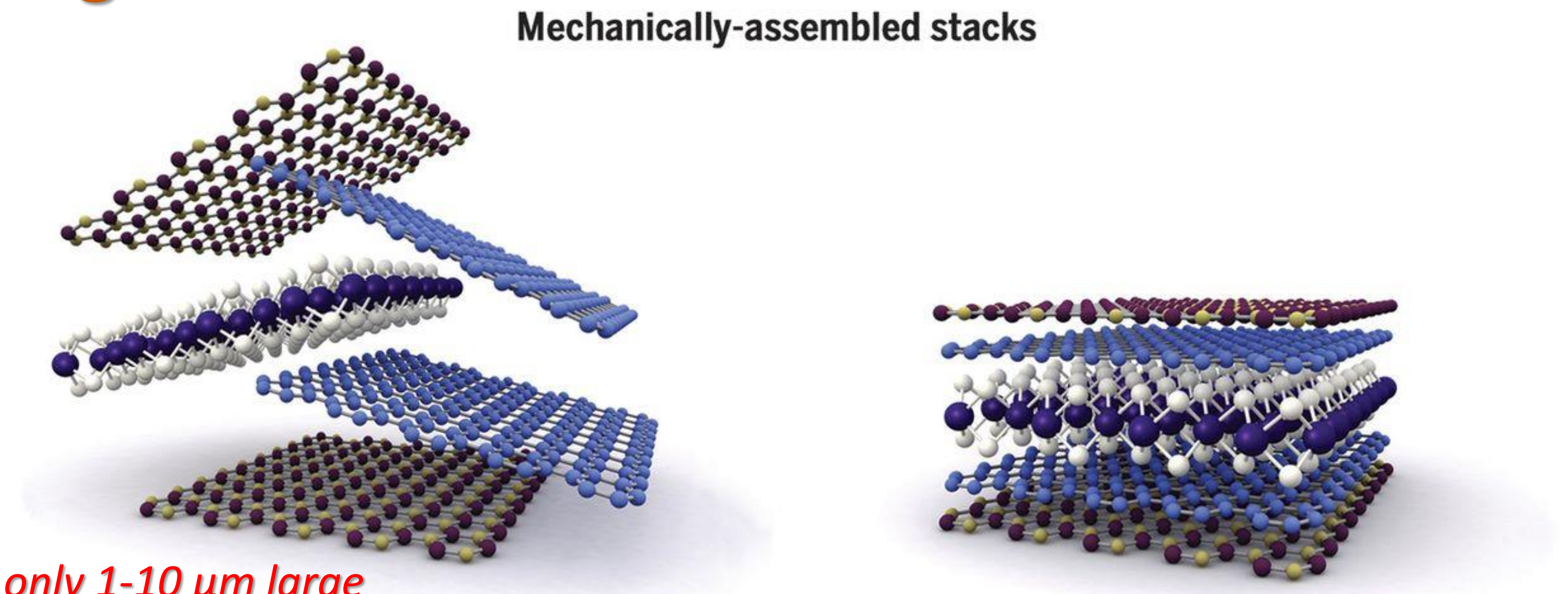


Challenge: understand experimentally and theoretically the anisotropy of thermal and electronic properties in these systems !

The different growth methods: MBE

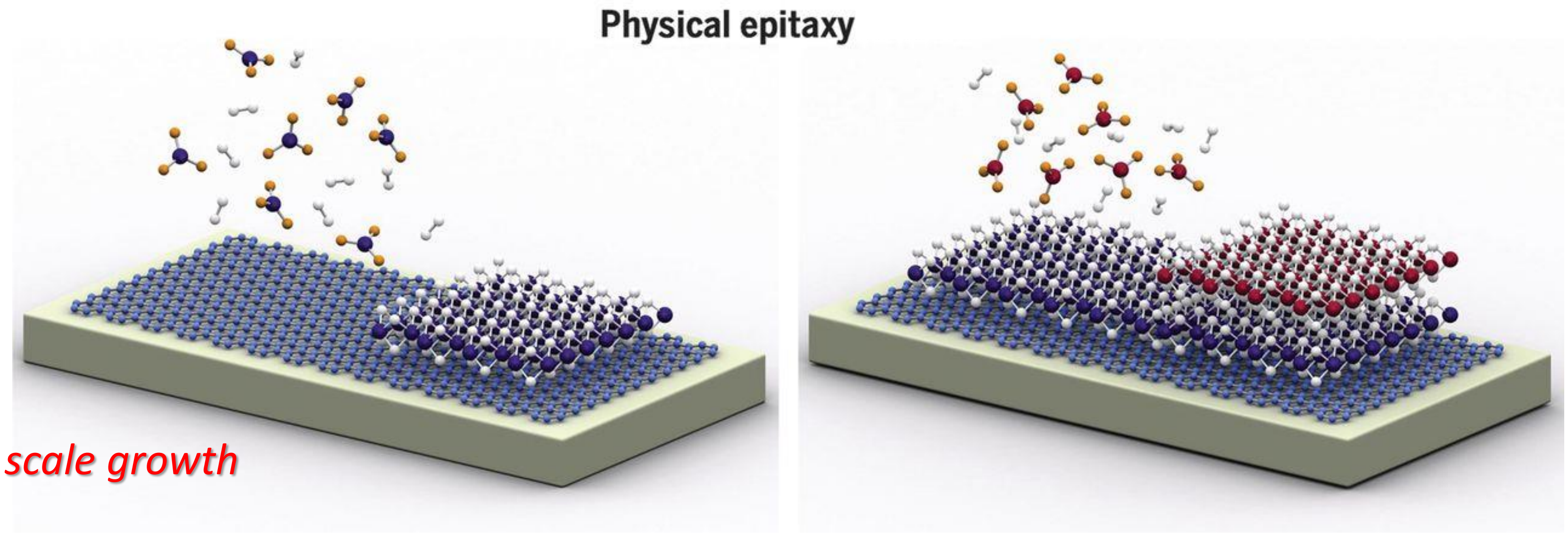
TODAY

FUTURE



Flakes are only 1-10 µm large

transistor, photodetectors…with flakes



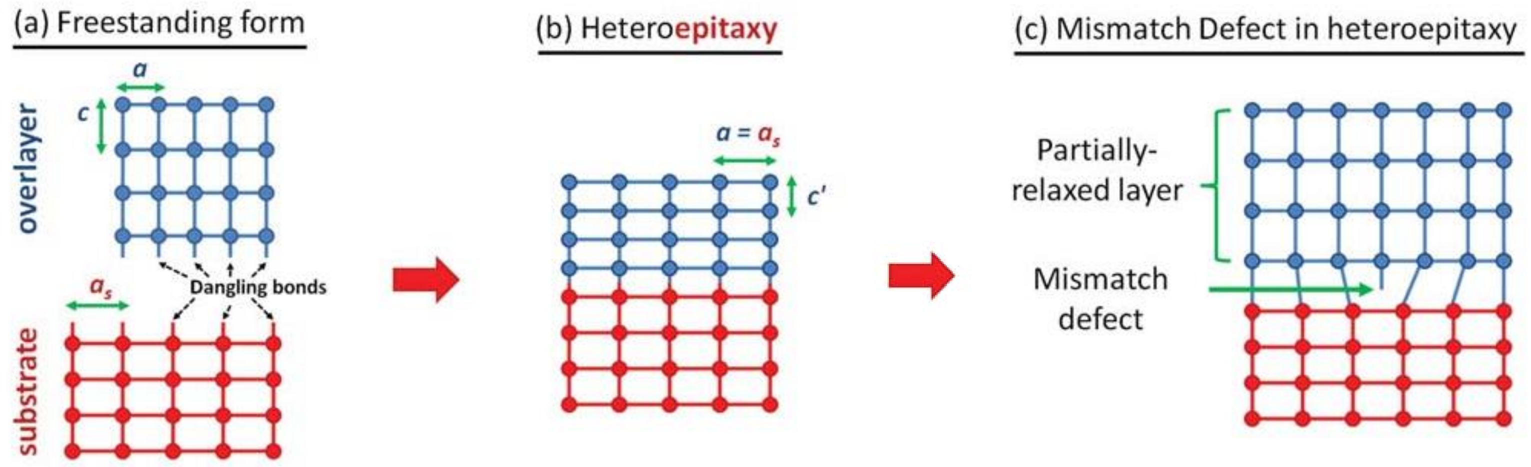
Wafer scale growth

K. Novoselov et al., Science **353**, 6298 (2016)

FUTURE

Develop the growth on large scales of single crystalline 2D materials by using epitaxial growth like for Si, Ge, GaAs or GaN technologies after almost 60 years of effort

Principle of epitaxial growth:



Low lattice mismatch (<5 %) → Strained layer

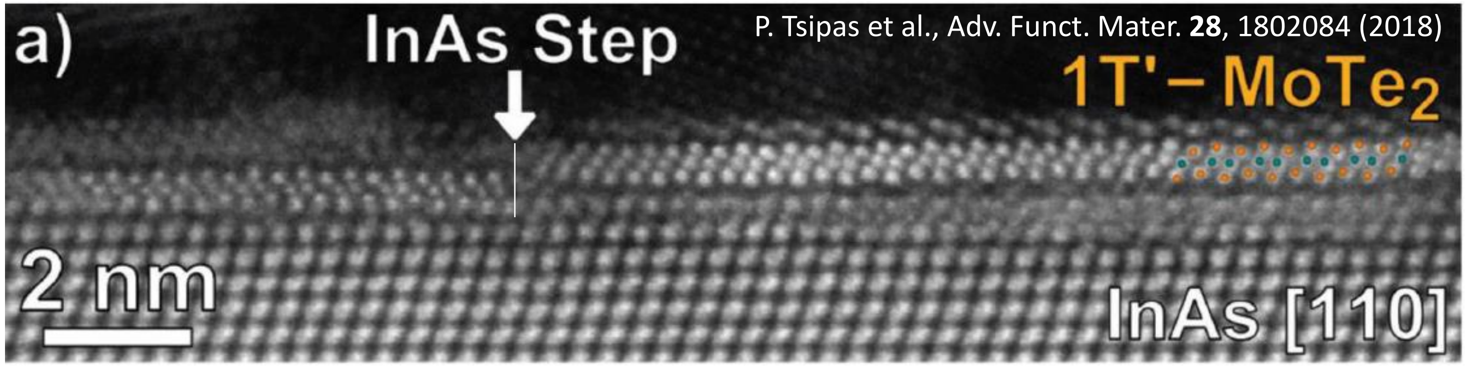
Large lattice mismatch (>5 %) → Interface dislocations

NO substrate with hexagonal symmetry and low lattice mismatch for the epitaxial growth of 2D Materials!

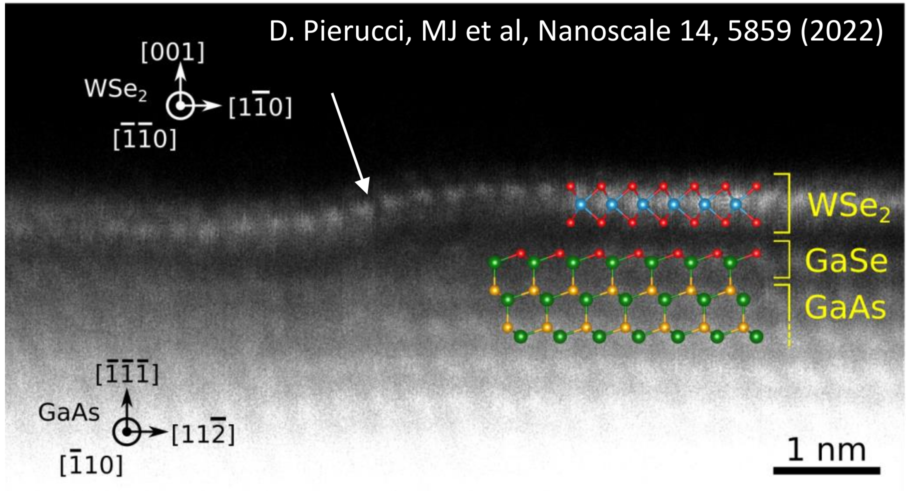
Extra constraints for 2D materials:

- Substrate topography important: should be perfectly flat

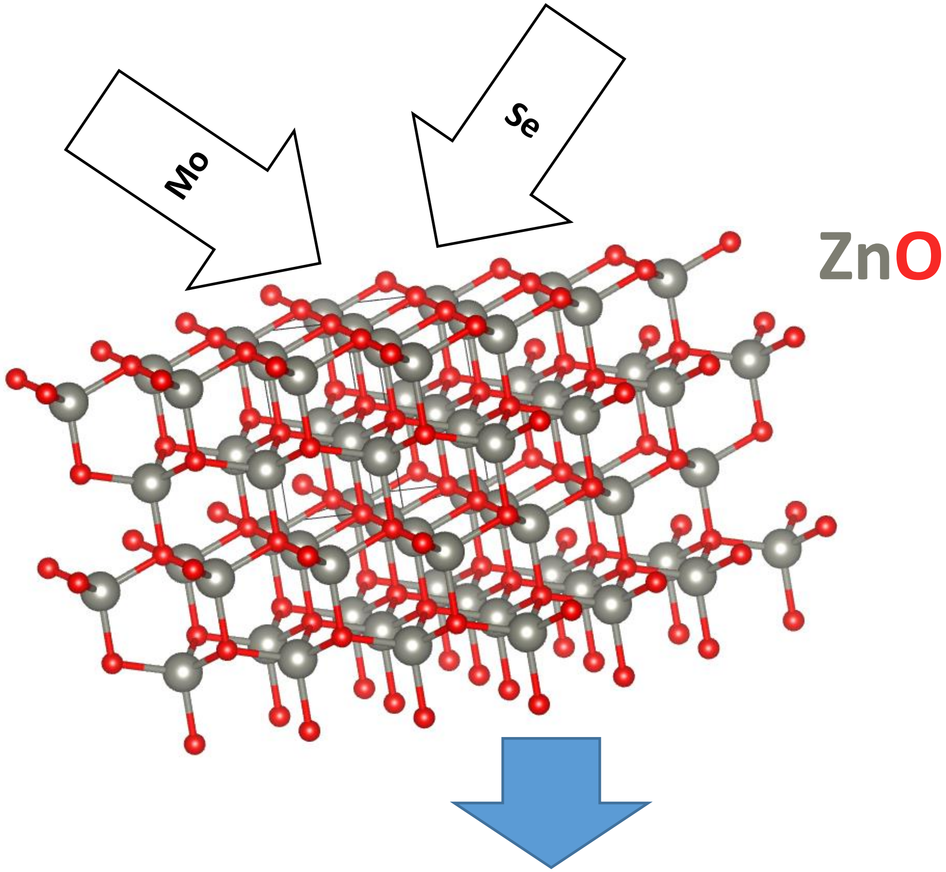
- Chemical reaction with chalcogen atoms (depends on the formation enthalpy of the different compounds and T)



Layer breaking at atomic steps

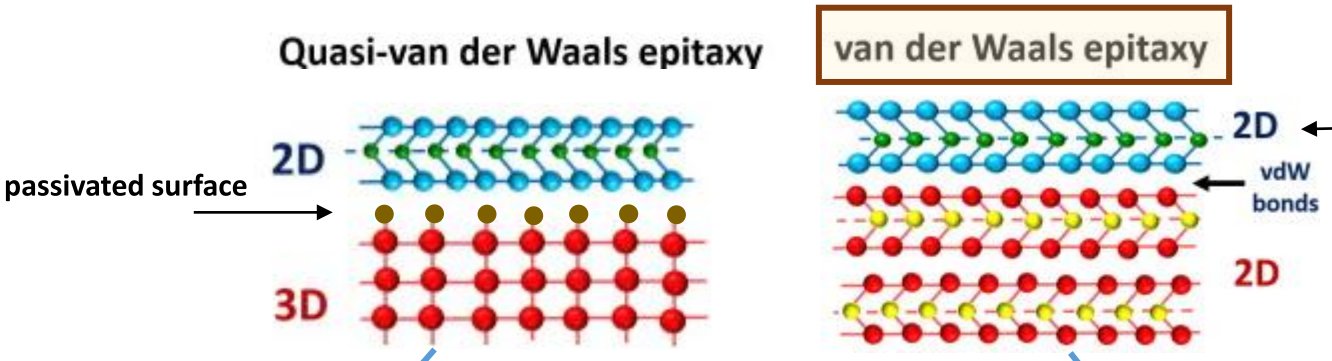


Local strain



Formation of MoO_3 and ZnSe

Solution: reduce substrate-2D material interaction from dangling bonds (0.1-1 eV/at) to vdW bonds (~10 meV/at)

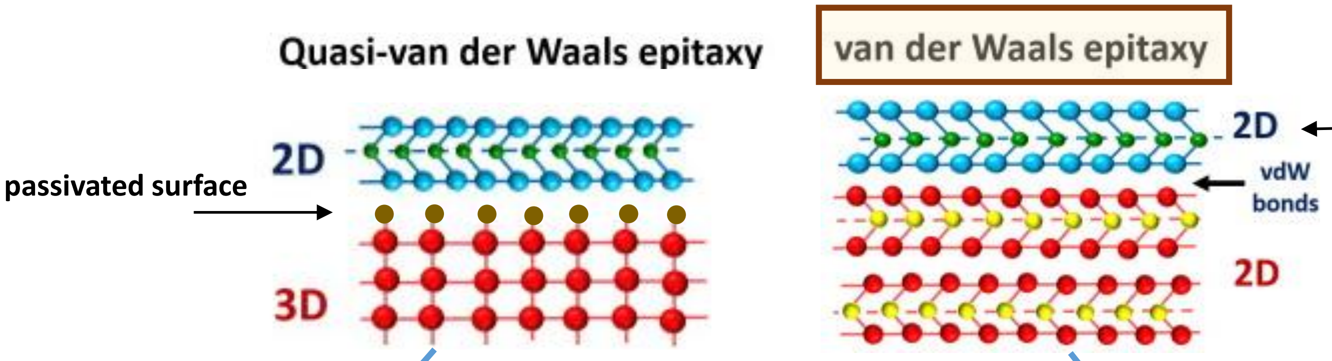


fully relaxed monolayer

$MoSe_2$, $NbSe_2$ / passivated GaAs(111) surface
K. Ueno, A. Koma, Appl. Phys. Lett. **55**, 327 (1990)

$MoSe_2$, $NbSe_2$ / mica
K. Ueno, A. Koma, J. Vac. Sci. Technol. A **8**, 68 (1990)

Solution: reduce substrate-2D material interaction from dangling bonds (0.1-1 eV/at) to vdW bonds (~10 meV/at)

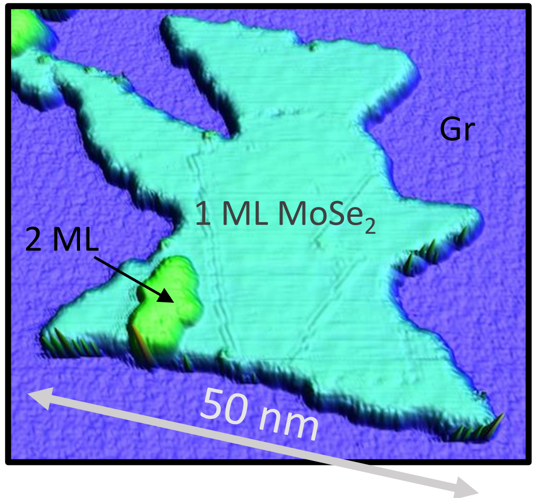


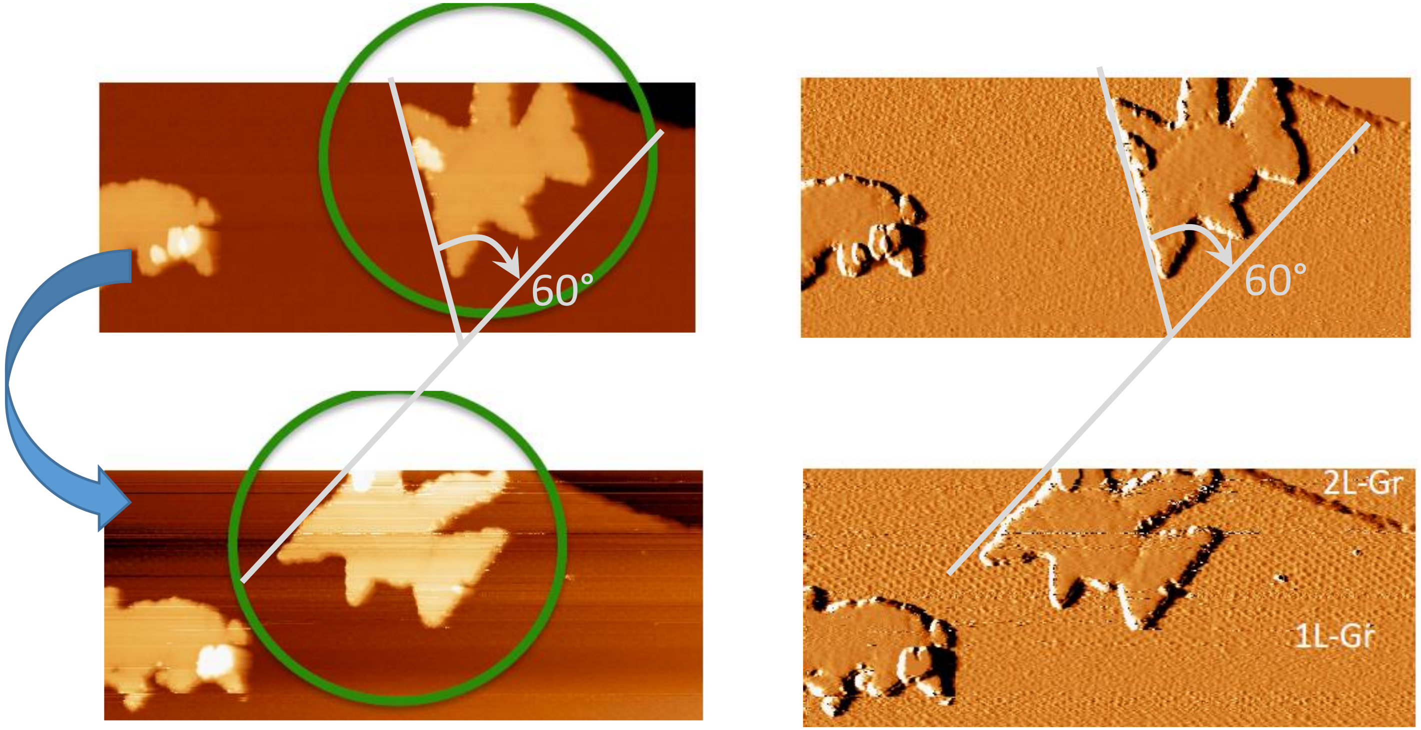
fully relaxed monolayer

$MoSe_2$, $NbSe_2$ / passivated GaAs(111) surface
K. Ueno, A. Koma, Appl. Phys. Lett. **55**, 327 (1990)

$MoSe_2$, $NbSe_2$ / mica
K. Ueno, A. Koma, J. Vac. Sci. Technol. A **8**, 68 (1990)

vdW epitaxy of $MoSe_2$ on graphene/SiC





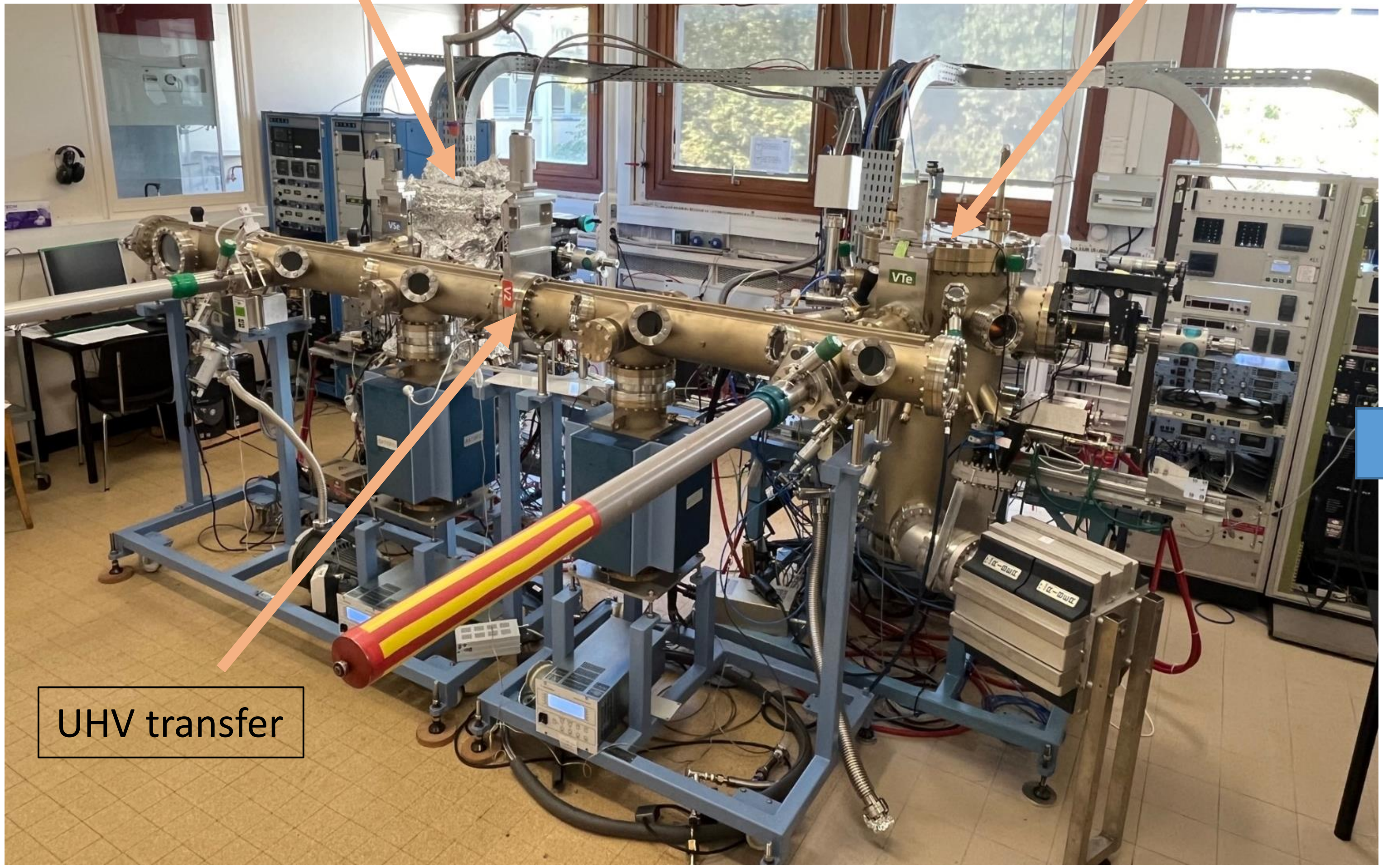
Dau et al., ACS Nano **12**, 2319 (2018)

Molecular beam epitaxy (MBE)

@ Spintec

selenides

tellurides

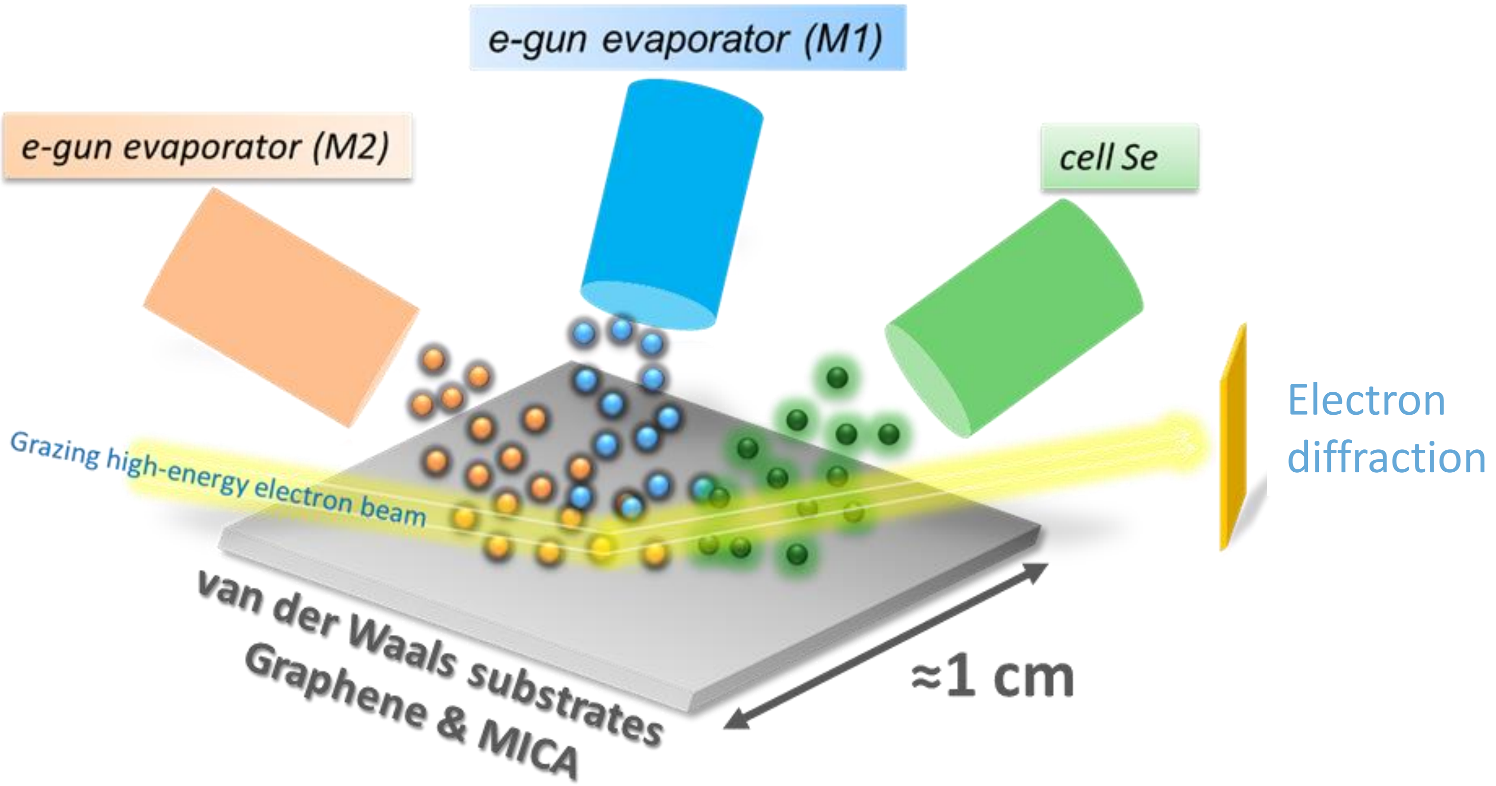


UHV transfer

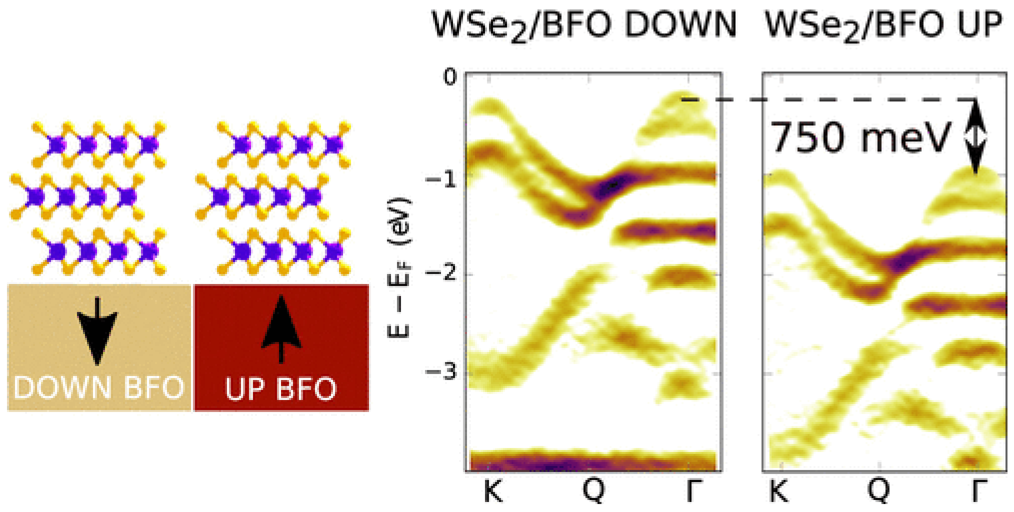
Ultrahigh vacuum (UHV)
10^{-10} mbar

15 metals available in each reactor

Molecular beam epitaxy (MBE)



vdW: easy to detach the film



R. Salazar et al., Nano Lett. 22, 9260 (2022)

- High crystalline quality, UHV conditions: low density of impurities
- Accurate control of number of layers by using quartz microbalance
- Stacking of different MSe_2 or MTe_2 monolayers for complex vertical heterostructures
- Flexible choice of metals : Mo, W, Nb, Pt, Pd, V, Fe, Mn + doping and alloys

Growth strategy

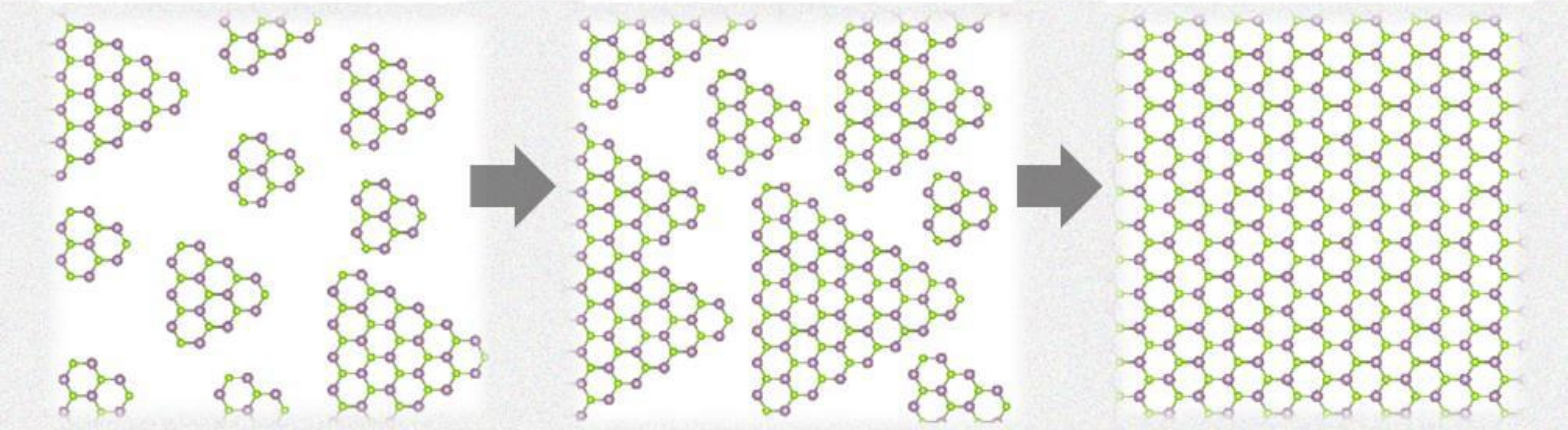
By MBE…

low growth T, high nucleation rate

ORIENTED NUCLEI

GROWTH

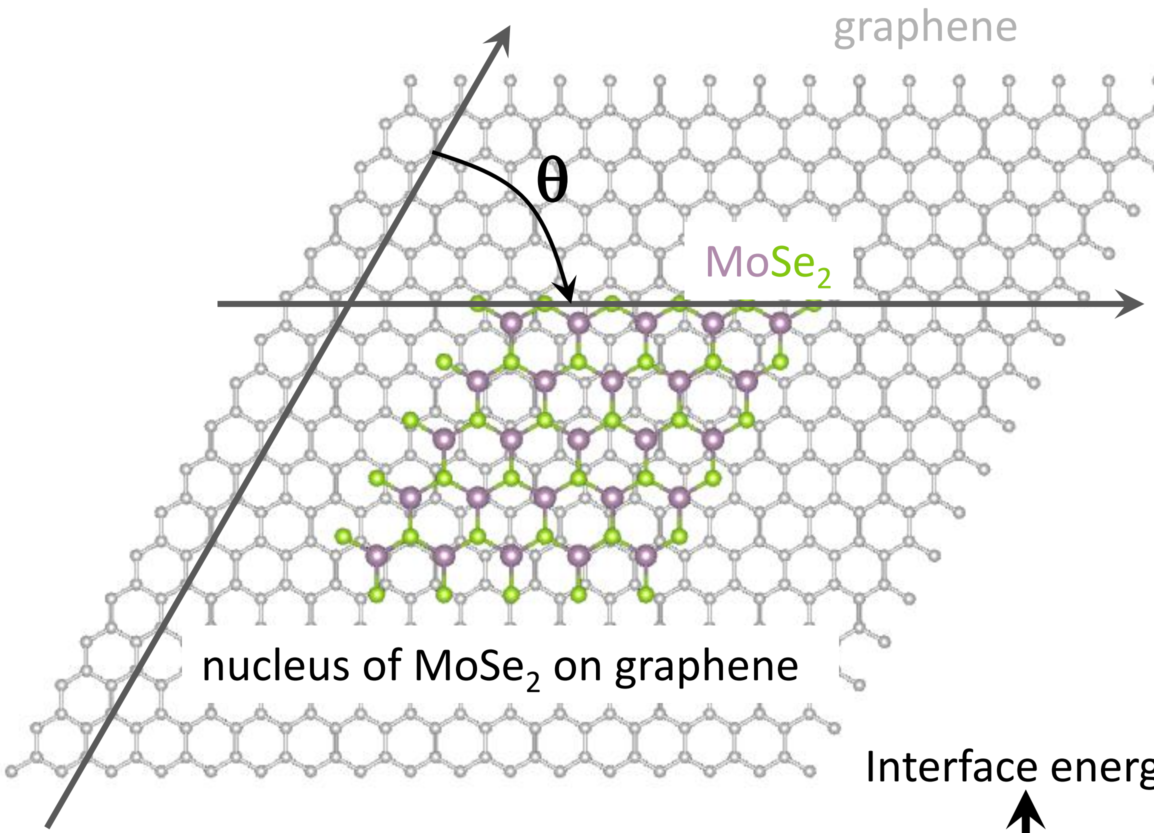
COALESCENCE

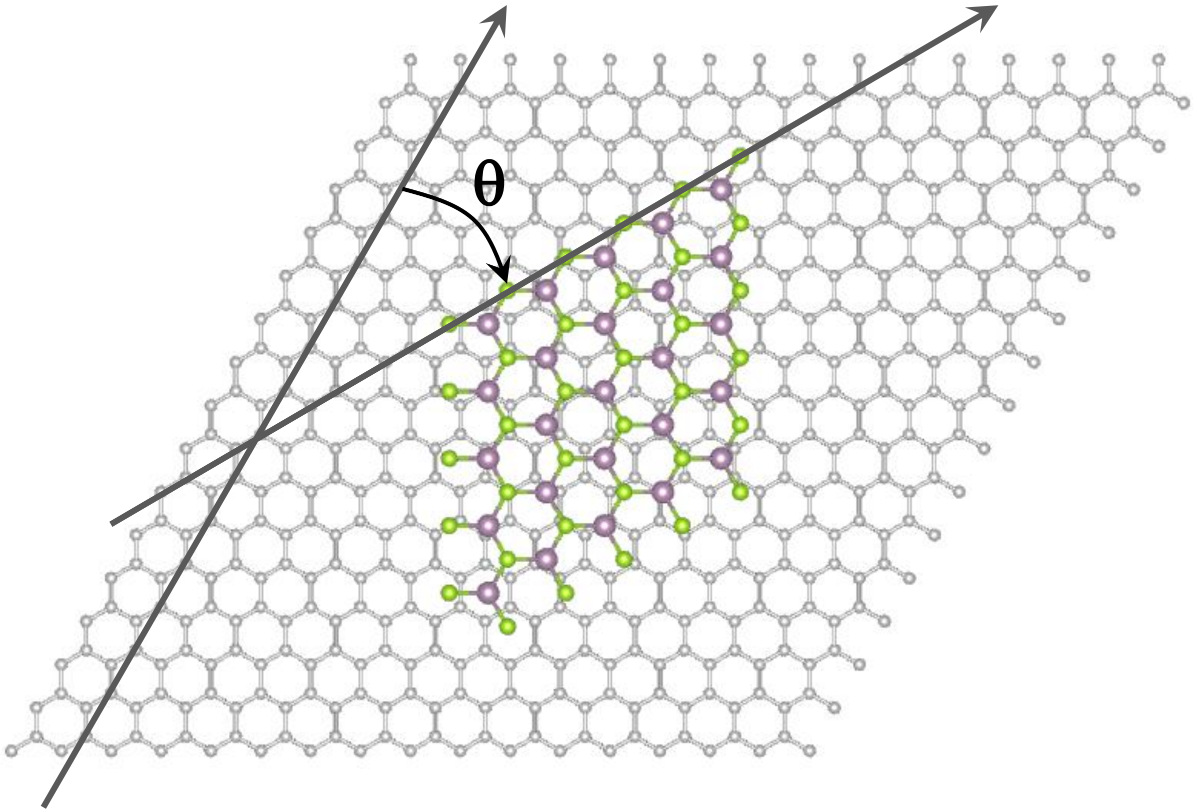


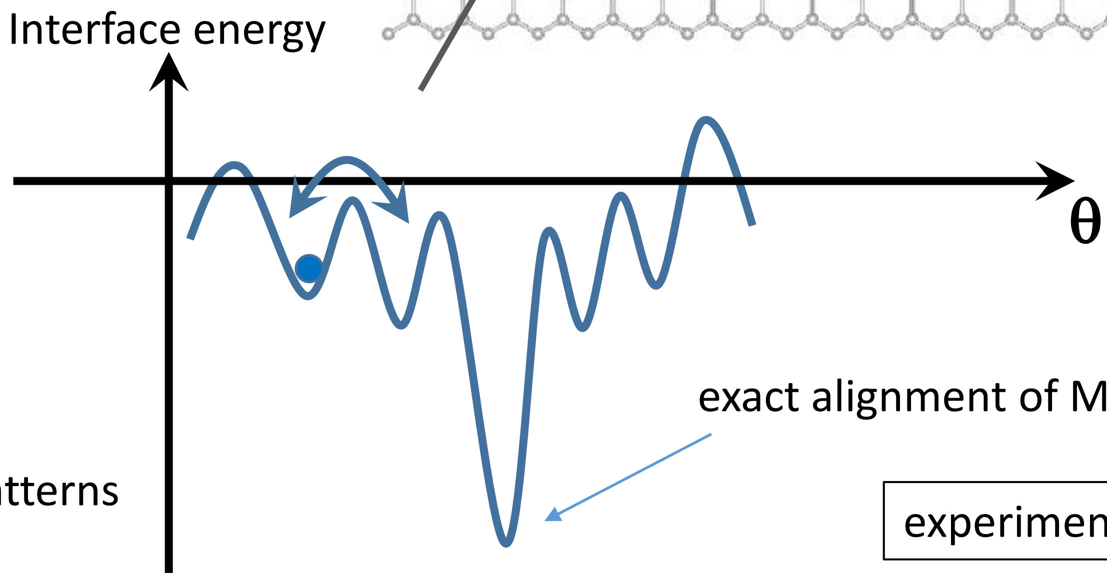
C. Vergnaud, PhD 2020

1st issue: mosaic spread

a consequence of low interaction between substrate and 2D layer





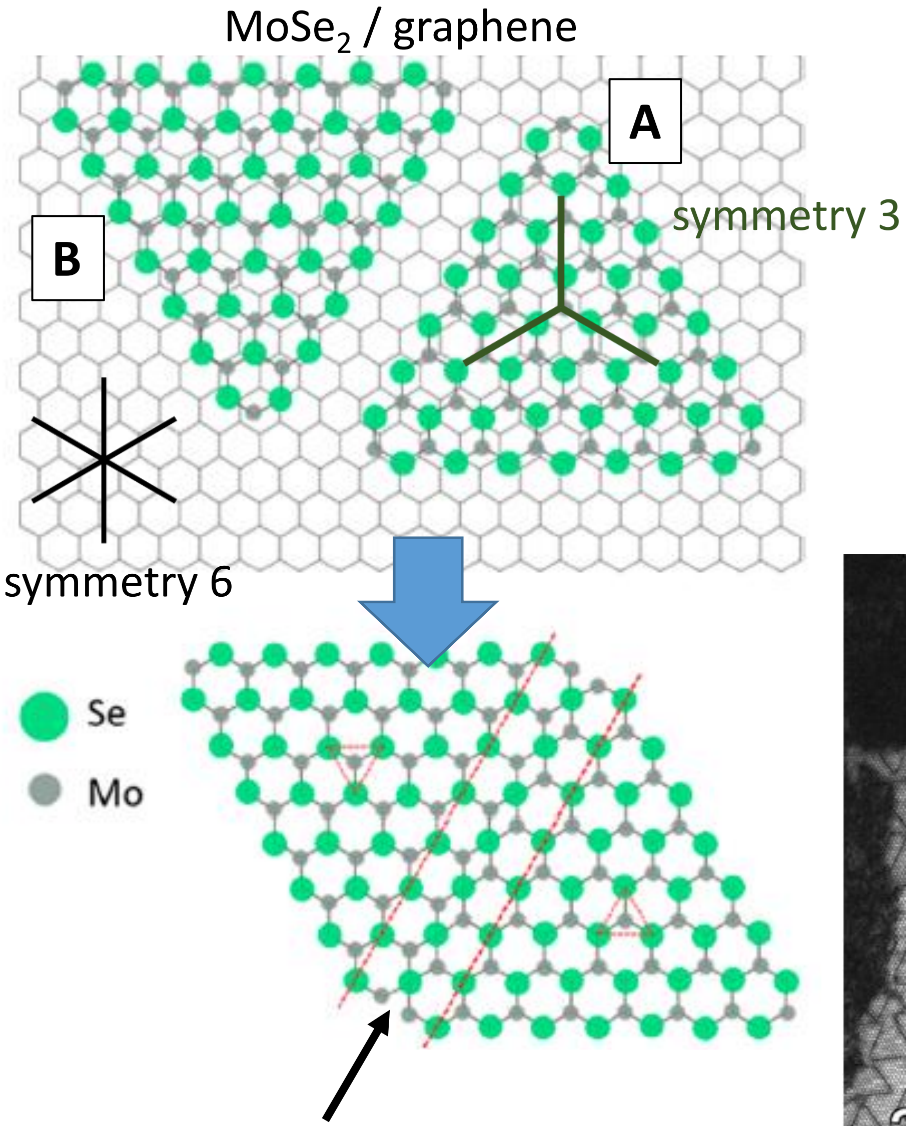


exact alignment of $MoSe_2$ & graphene lattices

Atomic coincidences lead to Moiré patterns

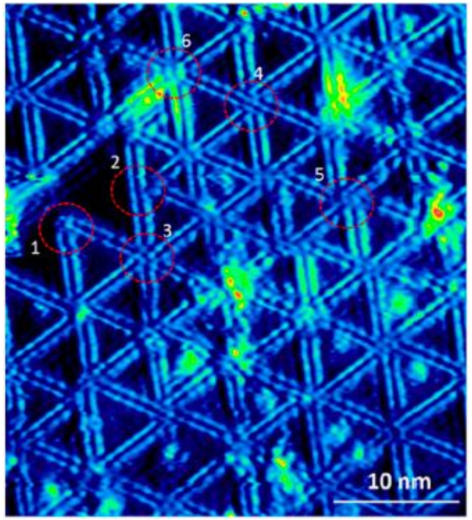
experimentally $MoSe_2$/Gr: ±3°

2nd issue: symmetry 3 versus symmetry 6

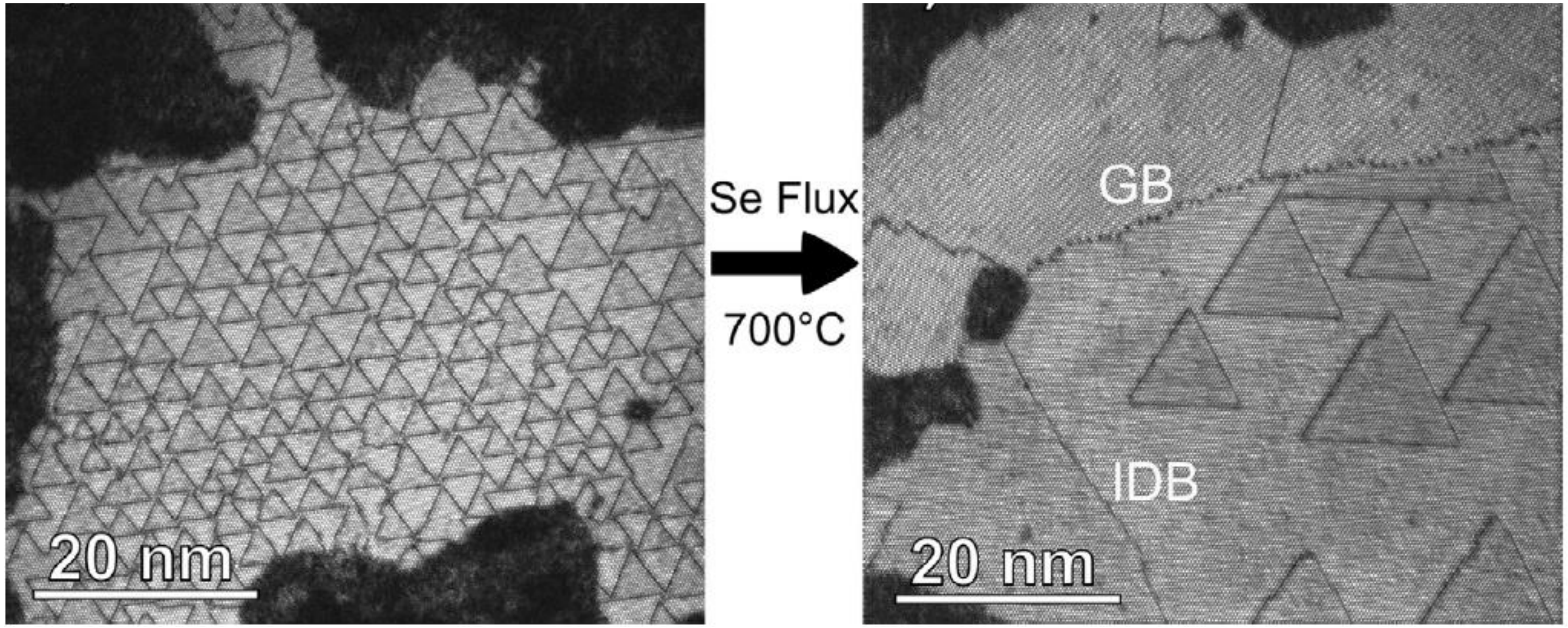


defect: mirror twin boundary (MTB)

Y. Ma et al., ACS Nano **11**, 5130 (2017)

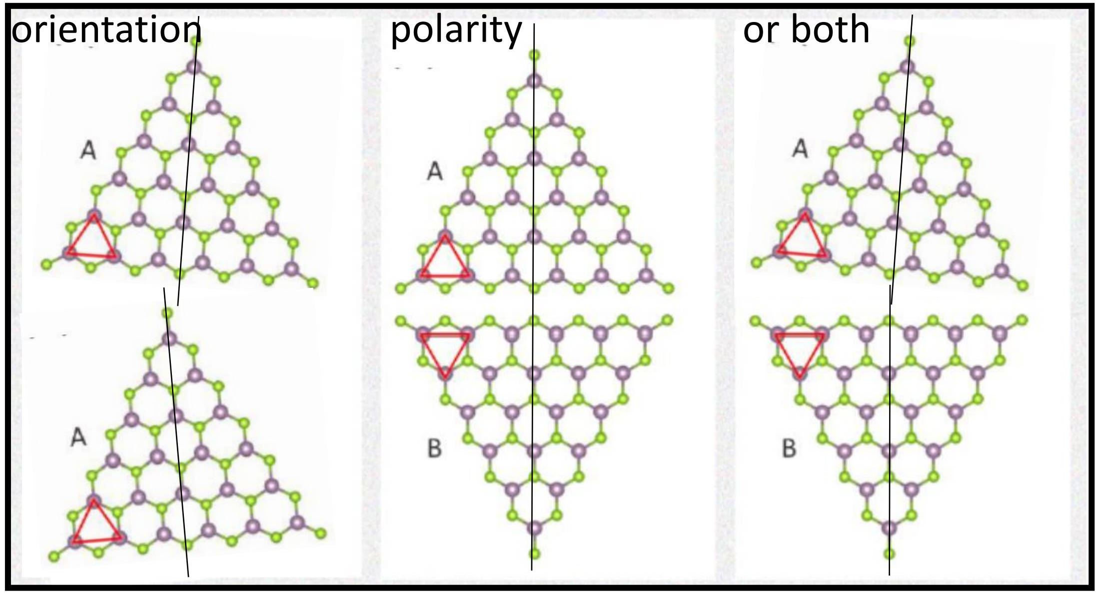


MTBs can form a wagon-wheel regular pattern

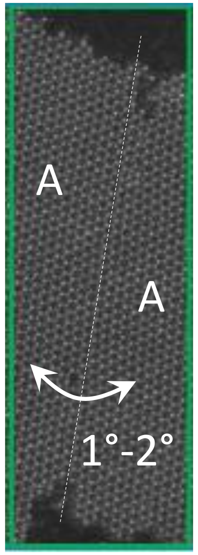


Alvarez et al., Nanotechnology **29**, 425706 (2018)

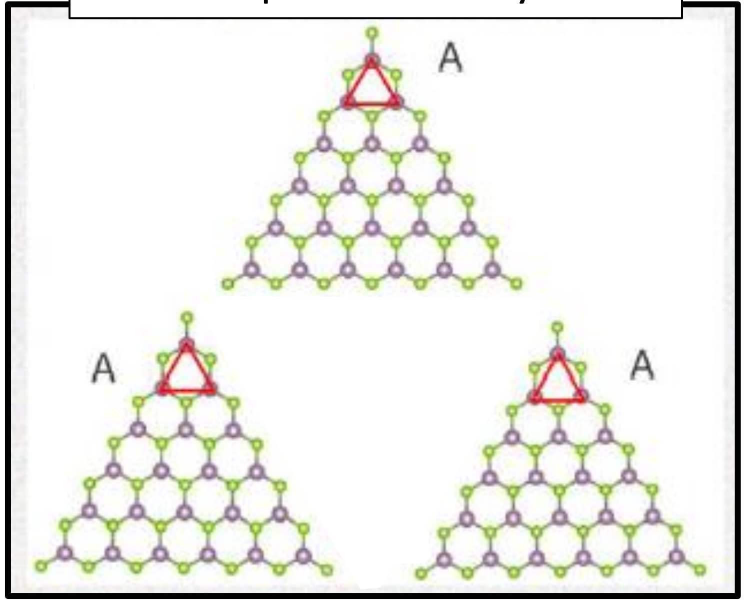
Controlling grain orientation AND polarity



low defective boundary



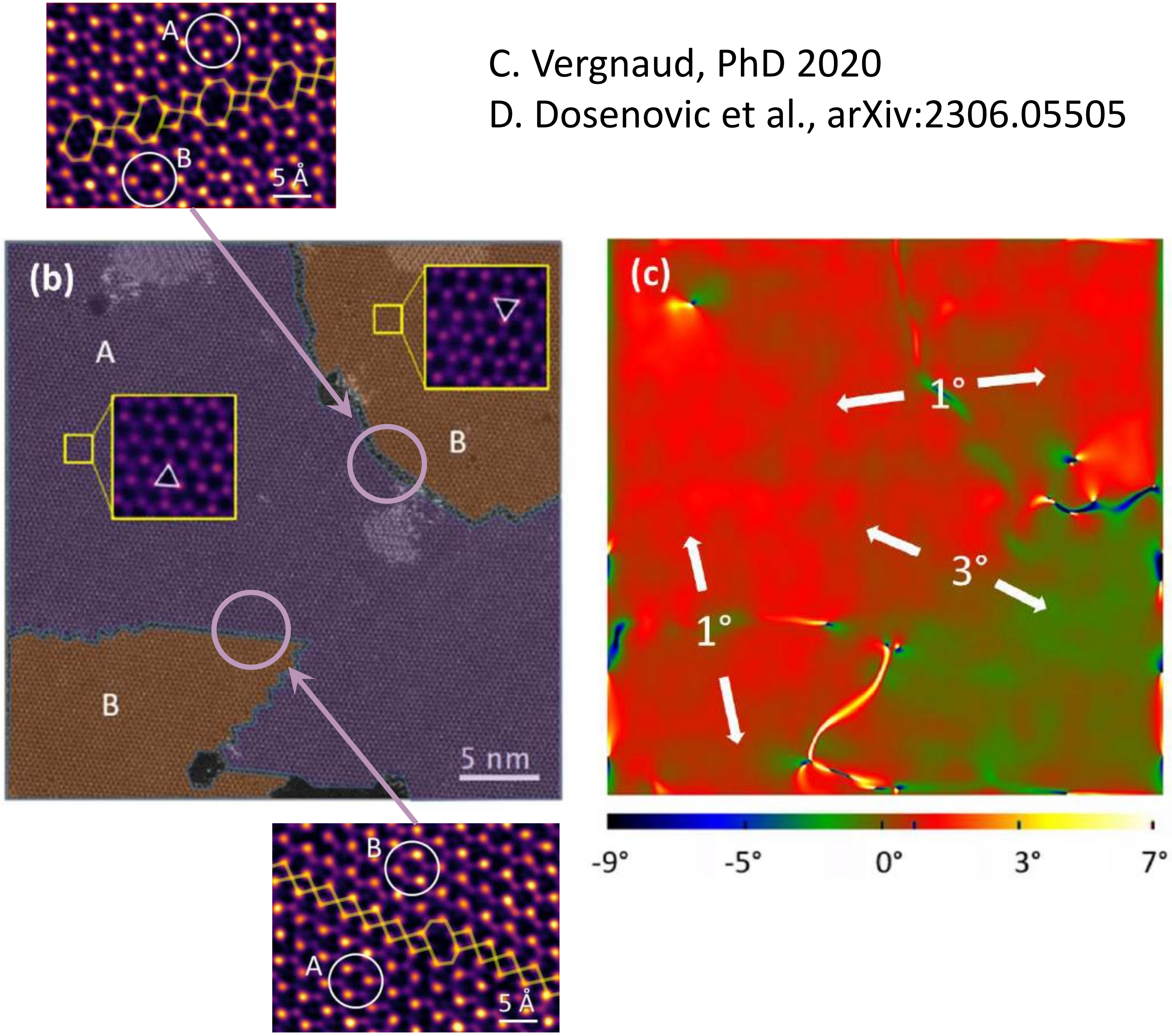
to reach perfect 2D crystals…



4/4/8 defect between misaligned A & B grains

C. Vergnaud, PhD 2020

D. Dosenovic et al., arXiv:2306.05505

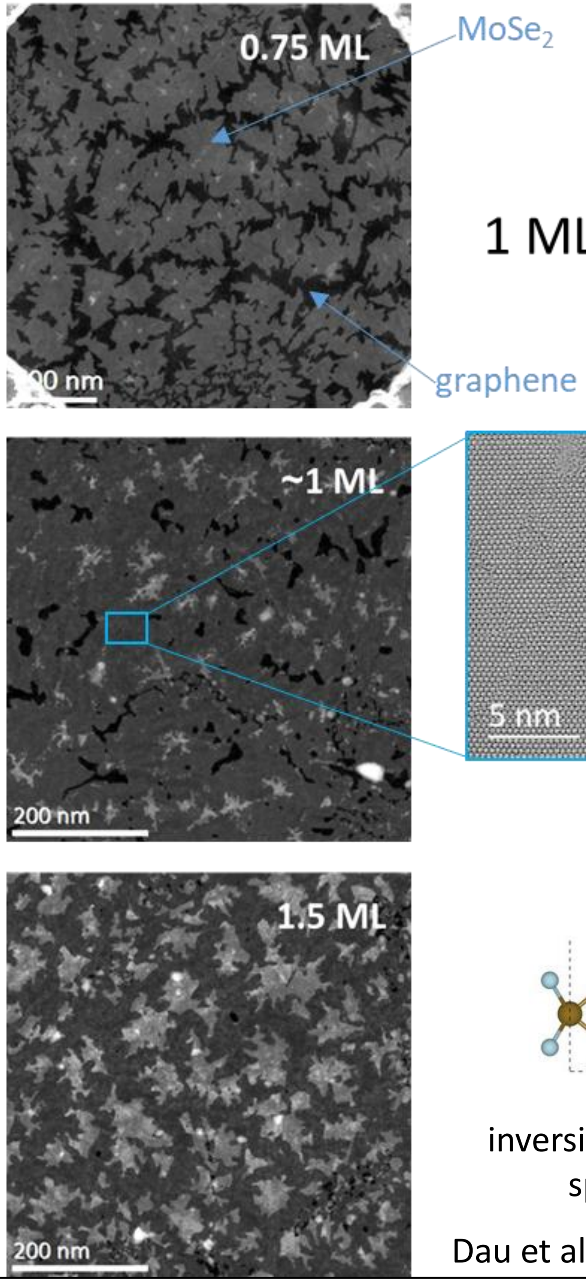


4/4P defect between aligned A & B grains= MTB

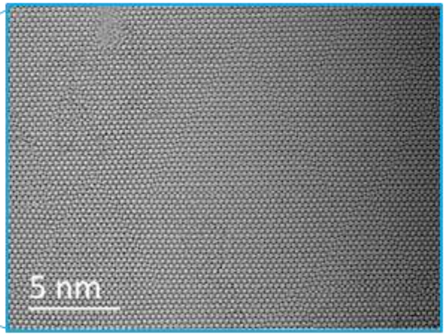
OUTLINE

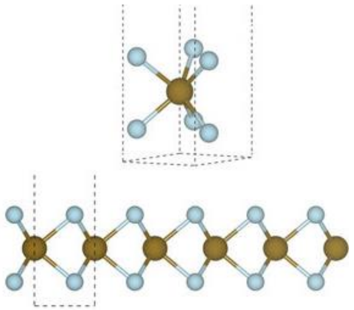
1. Introduction to 2D and van der Waals materials
2. Growth of 2D materials and chalcogenides: from exfoliation to molecular beam epitaxy
3. **Recent achievements in MBE-grown 2D materials: narrow excitonic lines, doping, alloys, superconductivity, ferroelectricity, ferromagnetism**
4. 2D magnets for spintronics: $Cr_{1+\delta}Te_2$, $Fe_{3\text{-}5}GeTe_2$
5. Conclusion and perspectives

Recent achievements on epitaxial growth of 2D materials



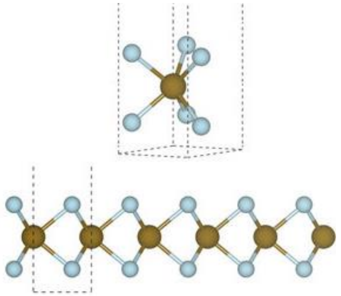
1 cm^2
1 ML $MoSe_2$/graphene
single crystal





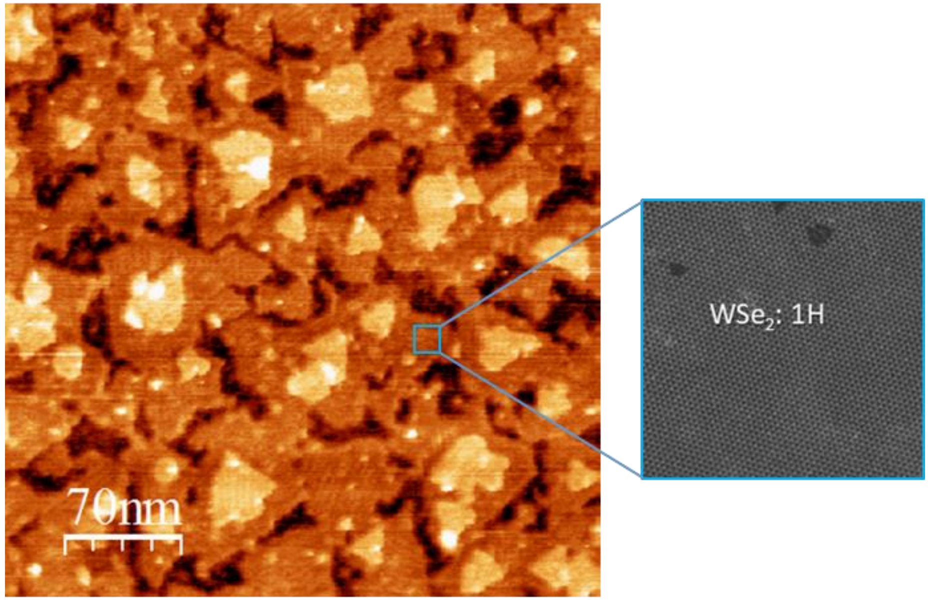
1H-phase
inversion symmetry breaking
spins out-of-plane

Dau et al., ACS Nano **12**, 2319 (2018)

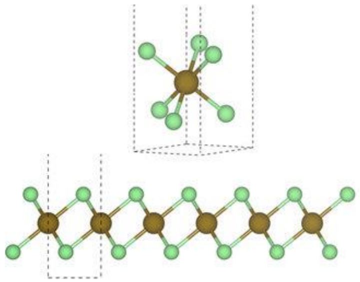


1H-phase

1 cm^2
1 ML WSe_2/mica
single crystal

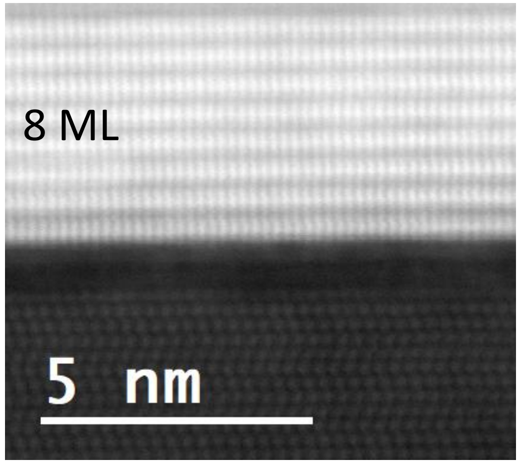


C. Vergnaud, PhD 2020

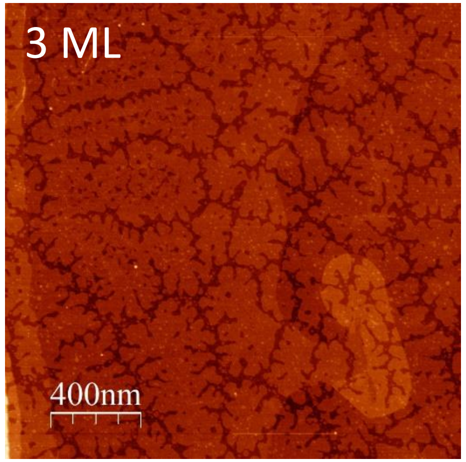


1T-phase
inversion symmetry
Rashba SOC

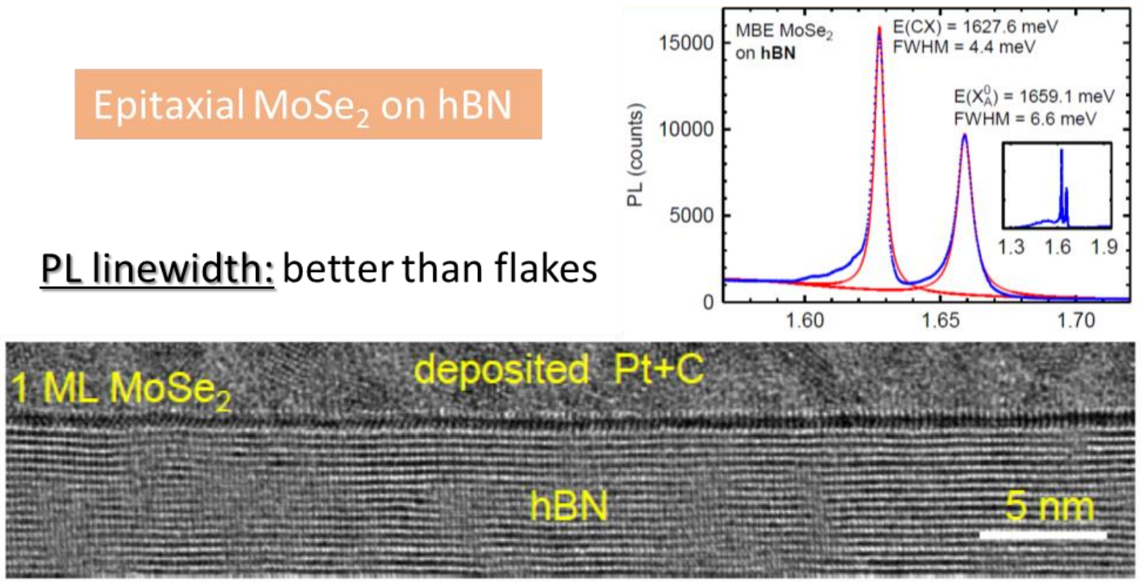
1 cm^2, $PtSe_2$/graphene



K. Abdukayumov, PhD 2022

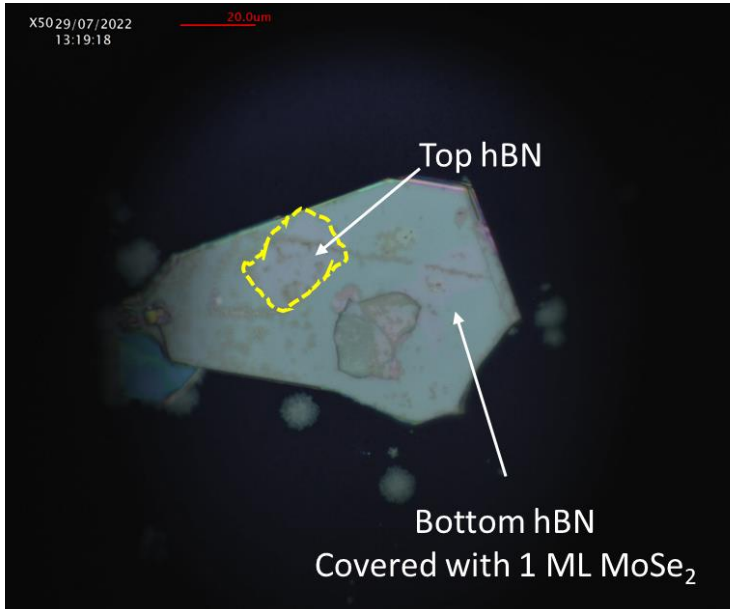


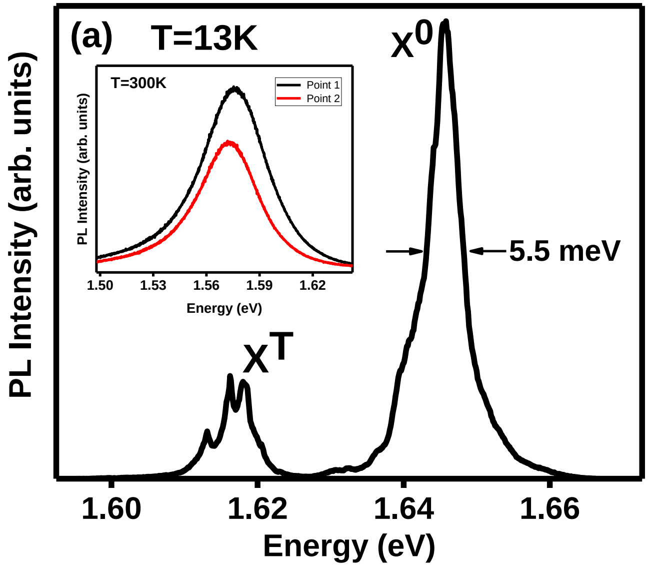
MBE growth of $MoSe_2$ on exfoliated hBN flakes



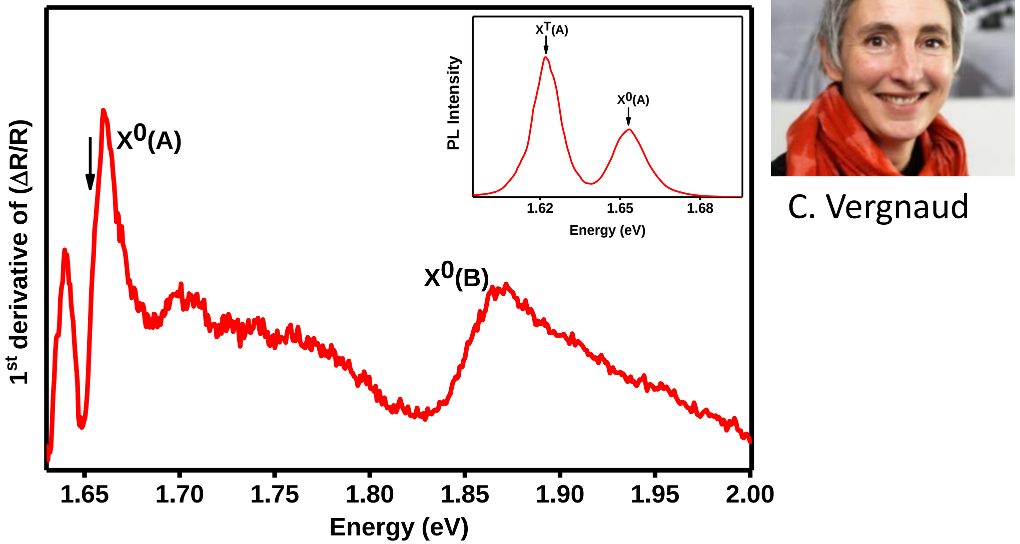
W. Pacuski et al., Nano Lett. **20**, 3058 (2020)

@ Spintec in collaboration with LPCNO (Toulouse, X. Marie, C. Robert)





C. Vergnaud et al., in preparation

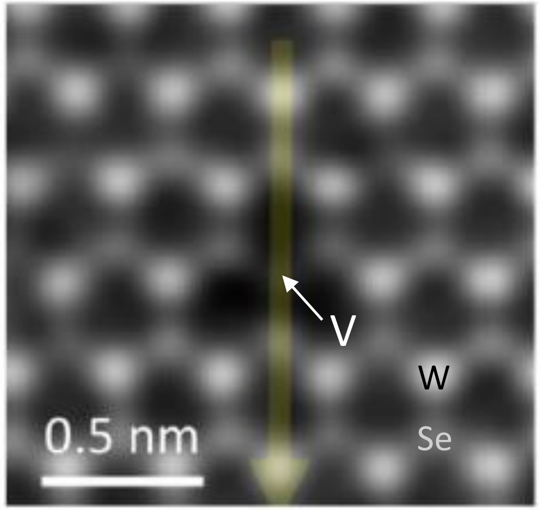


C. Vergnaud

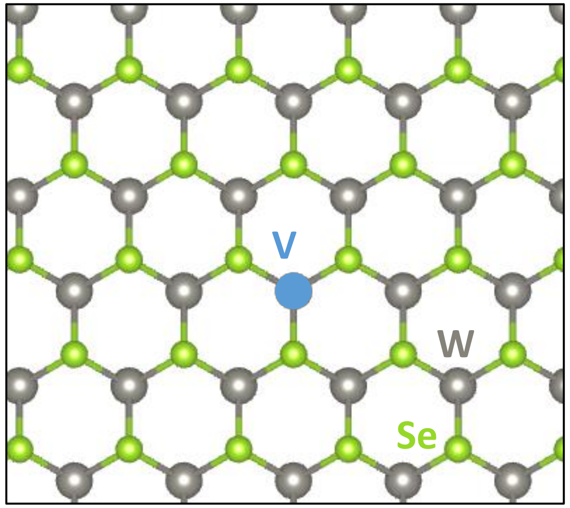
CVD MoS_2: 5 meV at 4 K (S. Shree et al., 2D Mater. 7, 015011 (2020))

Recent achievements on epitaxial growth of 2D materials

p-type doping of WSe_2 with vanadium atoms

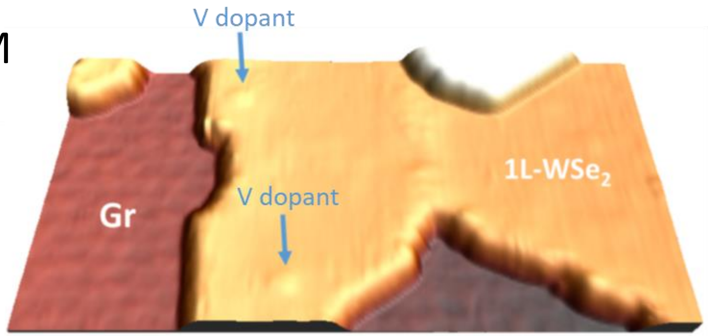


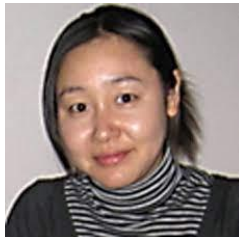
V atoms substitute W atoms



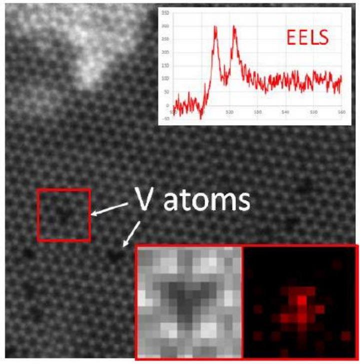
Atomic model

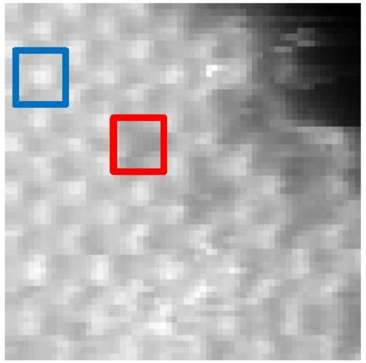
STM

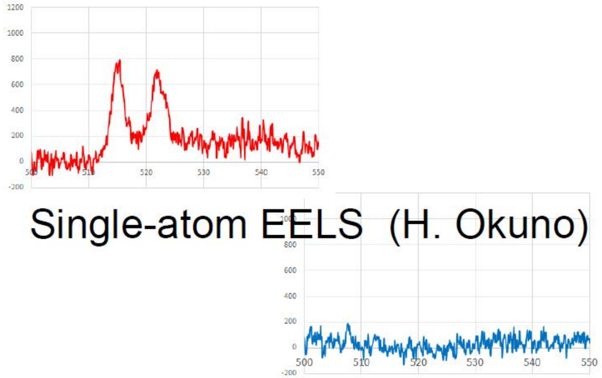




H. Okuno





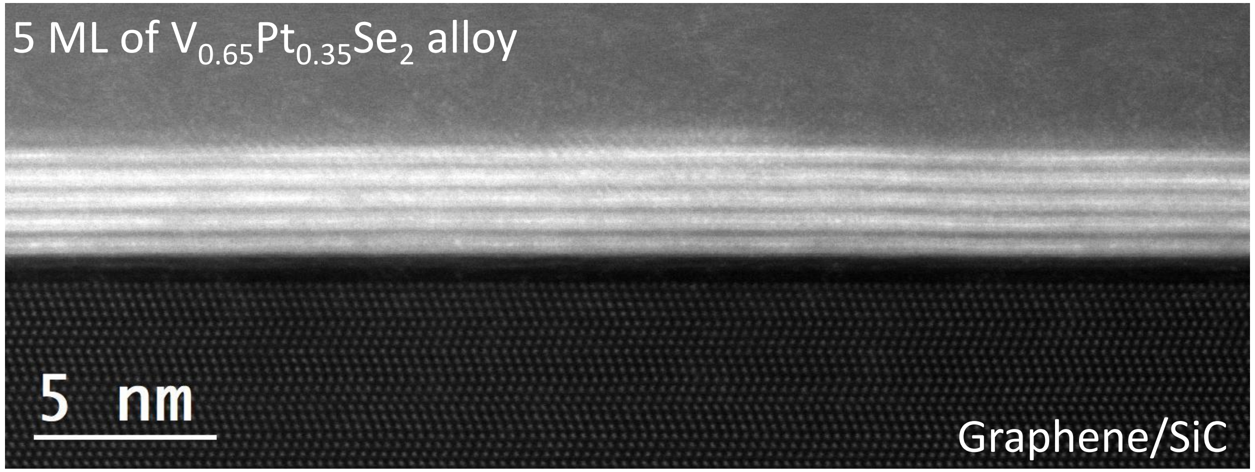


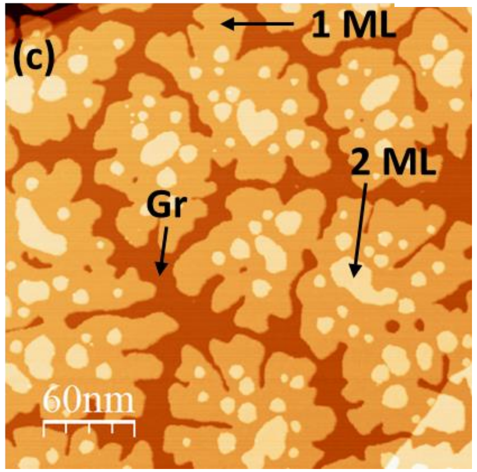
Single-atom EELS (H. Okuno)

P. Mallet et al., Phys. Rev. Lett. **125**, 036802 (2020)

Alloying VSe_2 and $PtSe_2$

E. Velez et al., ACS Appl. Electron. Mater. **4**, 259 (2022)
E. Velez et al., Phys. Rev. B 106, 075432 (2022)

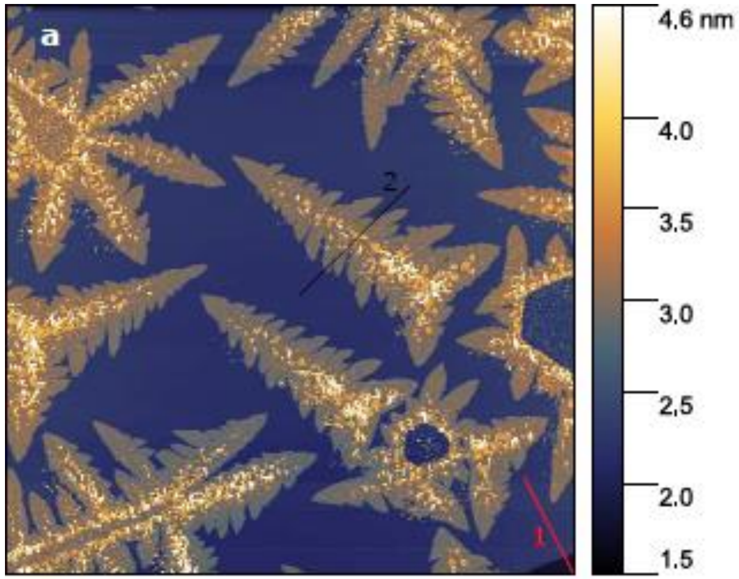




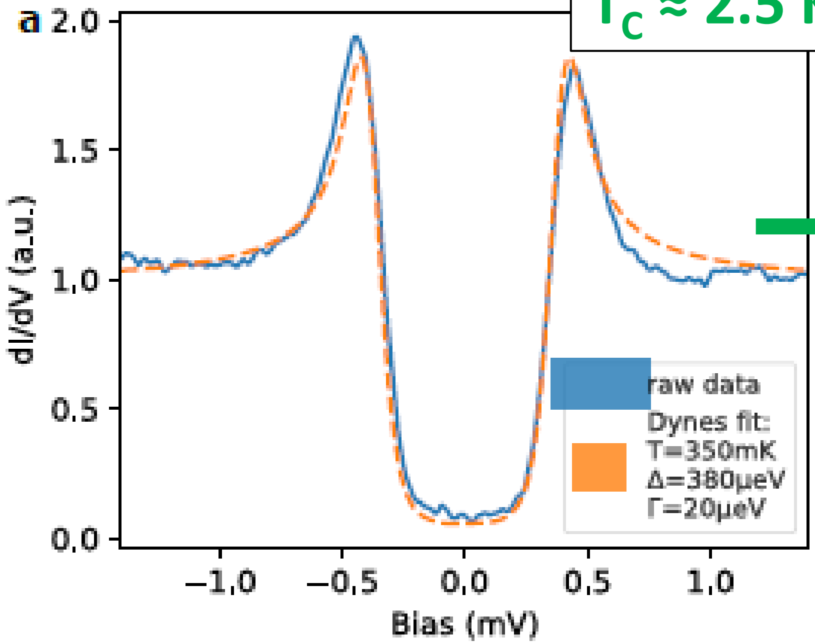
large scale homogeneous alloy

2D superconductivity

1 ML $NbSe_2$ / graphene / SiC

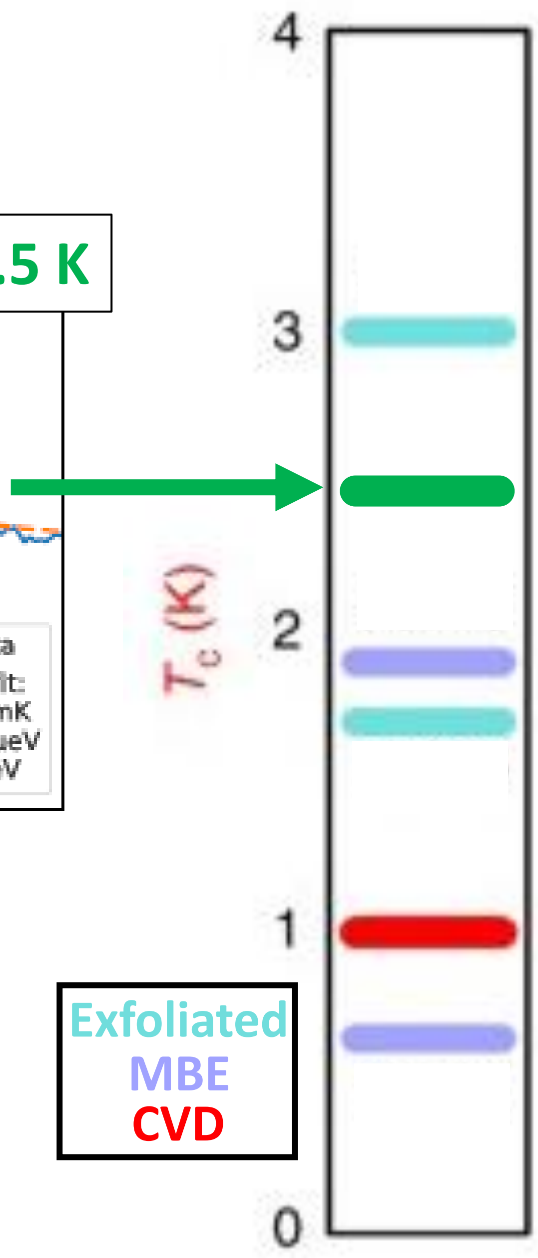


STM image, first growth stage



STS on ML flake

$T_C \approx 2.5$ K



Coll. C. Winkelmann, PhD thesis David Wander, Institut Néel, 2022

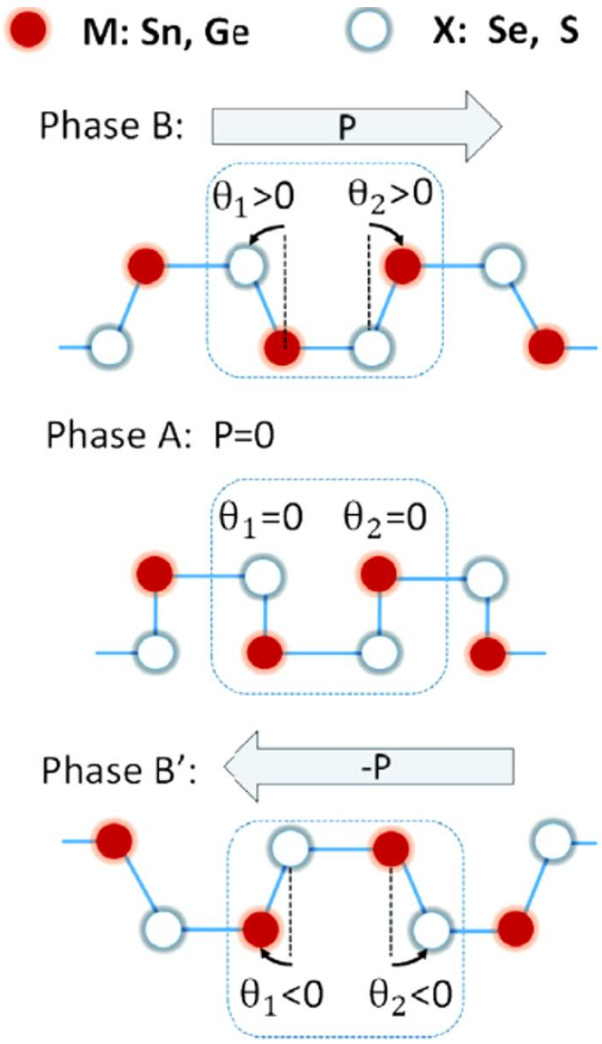
From X. Xiaoxiang et al., Nat. Commun. 8, 394 (2017)

2D ferroelectricity

C. Wang et al., Nat. Mater. 22, 542 (2023)

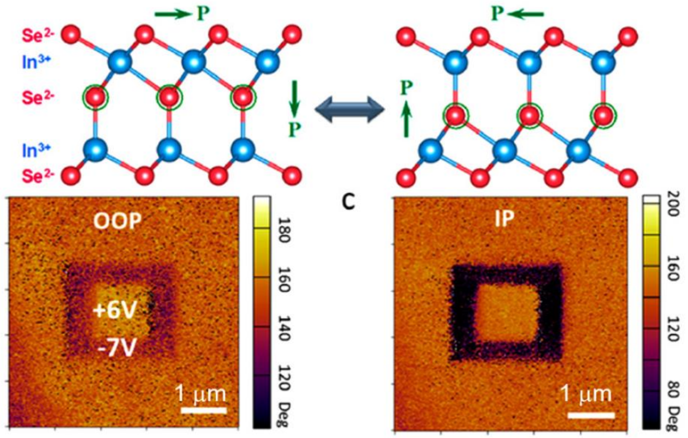
Material (ref.)	Space/point group	P (μC cm^{-2})	E_c (kV cm^{-1})	T_c (K)	Bandgap (eV)
Experimentally confirmed materials					
$CuInP_2S_6$ (refs. [7,27])	*Cc*	2.55	77	5 ML, >320	Bulk, 2.7
$CuCrP_2S_6$ (ref. [22])	*Pc*	10^{-5}	—	Bulk, 32	—
SnTe (refs. [8,15])	*Pnm*2$_1$	1 ML, 22^{T}	—	1 ML, 270; bulk, 100	1 ML, 1.6; bulk: 0.3
SnSe (ref. [15])	*Pnm*2$_1$	—	1 ML, 140	1 ML, >380	1 ML, 2.1; bulk: 0.9
SnS (ref. [15])	*Pnm*2$_1$	—	9 ML, 25; bulk, 10.7	1 ML, >300	1 ML, 1.6; bulk: 1.2
GeTe (ref. [19])	*R*3*m*	1 ML, 32.8	~0.2 V nm^{-1}	1 ML, 570^{T}	Bulk, 0.6
α-In_2Se_3 (refs. [9,10])	*R*3*m*	Bulk, 11.34^{T}; 1 ML, 2.14^{T}	5 nm: 200	4 ML, 700	1 ML, 2.8; bulk, 1.45
d1T-$MoTe_2$ (refs. [14,28])	d-$P\bar{3}m$	—	—	1 ML, 330	2–3 ML, 0; bulk, 0
T_d-WTe_2 (refs. [12,13])	*Pnm*2$_1$	0.2 pC m^{-1}	0.05 V nm^{-1}	2–3 ML, 350	2–3 ML, 0; bulk, 0
WSe_2, $MoSe_2$, WS_2, MoS_2 (refs. [20,21])	—	~2.0 pC m^{-1}	~0.2 V nm^{-1}	2 ML, >300	—
Heterobilayer MoS_2/WS_2 (ref. [32])	3*m*	1.45 pC m^{-1}	2.4 V nm^{-1}	2 ML, >300	2 ML, 0
Twisted bilayer h-BN (refs. [17,18])	—	~1.88 pC m^{-1}	~0.1 V nm^{-1}	2 ML, >300	Bulk, >5
Twisted bilayer graphene/h-BN (ref. [16])	—	~0.09	~0.2 V nm^{-1}	2 ML, >300	—
BA_2PbCl_4 (ref. [11])	*Cmc*2$_1$	13	50 nm, 350	2 ML, >300	Bulk, 3.65
NiI_2 (refs. [23,24])	d-$R\bar{3}m$	0.0125	—	Bulk, 59.5; 1 ML, 21	Bulk, 1.2

1 monolayer MX



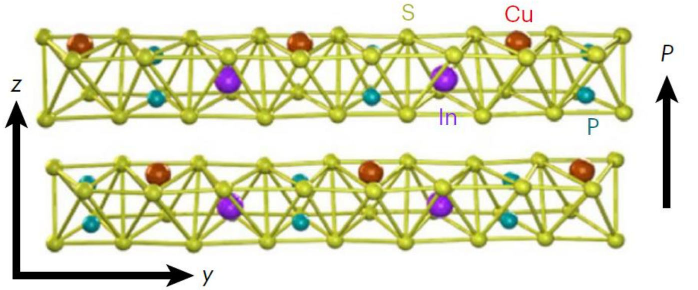
1 monolayer In_2Se_3

PFM @ RT

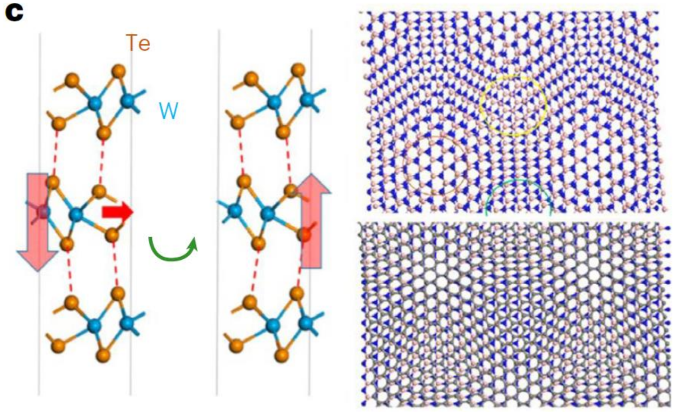


multilayers

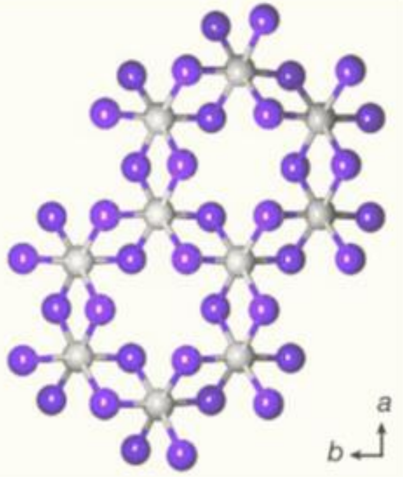
$CuInP_2S_6$



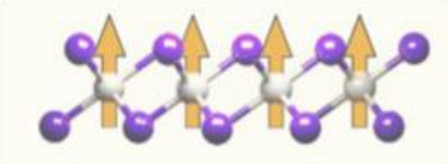
WTe_2



2D ferromagnetism

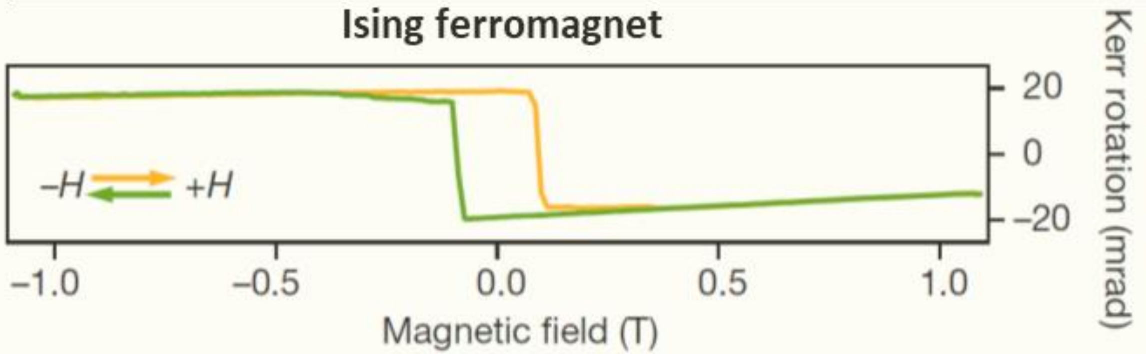


CrI_3

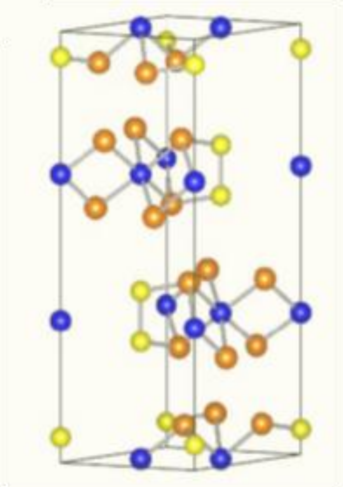


B. Huang et al., Nature **546**, 270 (2017)

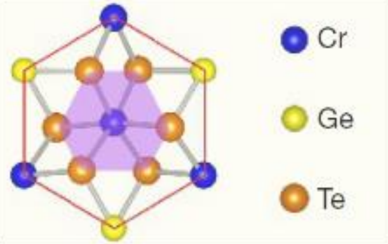
Ising ferromagnet



T_c≈45 K

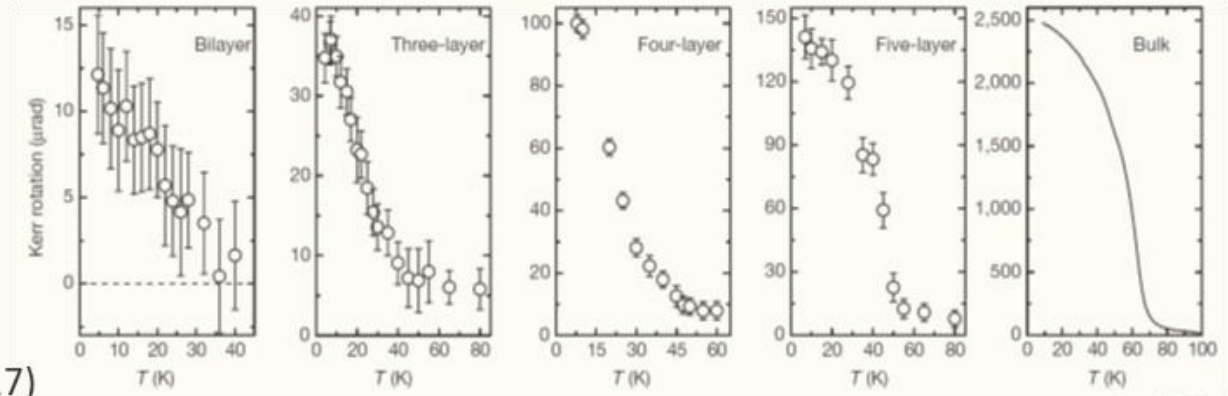


$Cr_2Ge_2Te_6$



C. Gong et al., Nature **546**, 265 (2017)

Heisenberg ferromagnet



T_c≈40 K

and more recently: $Fe_{3\text{-}5}GeTe_2$, $Cr_{1+\delta}Te_2$ with T_c close to RT

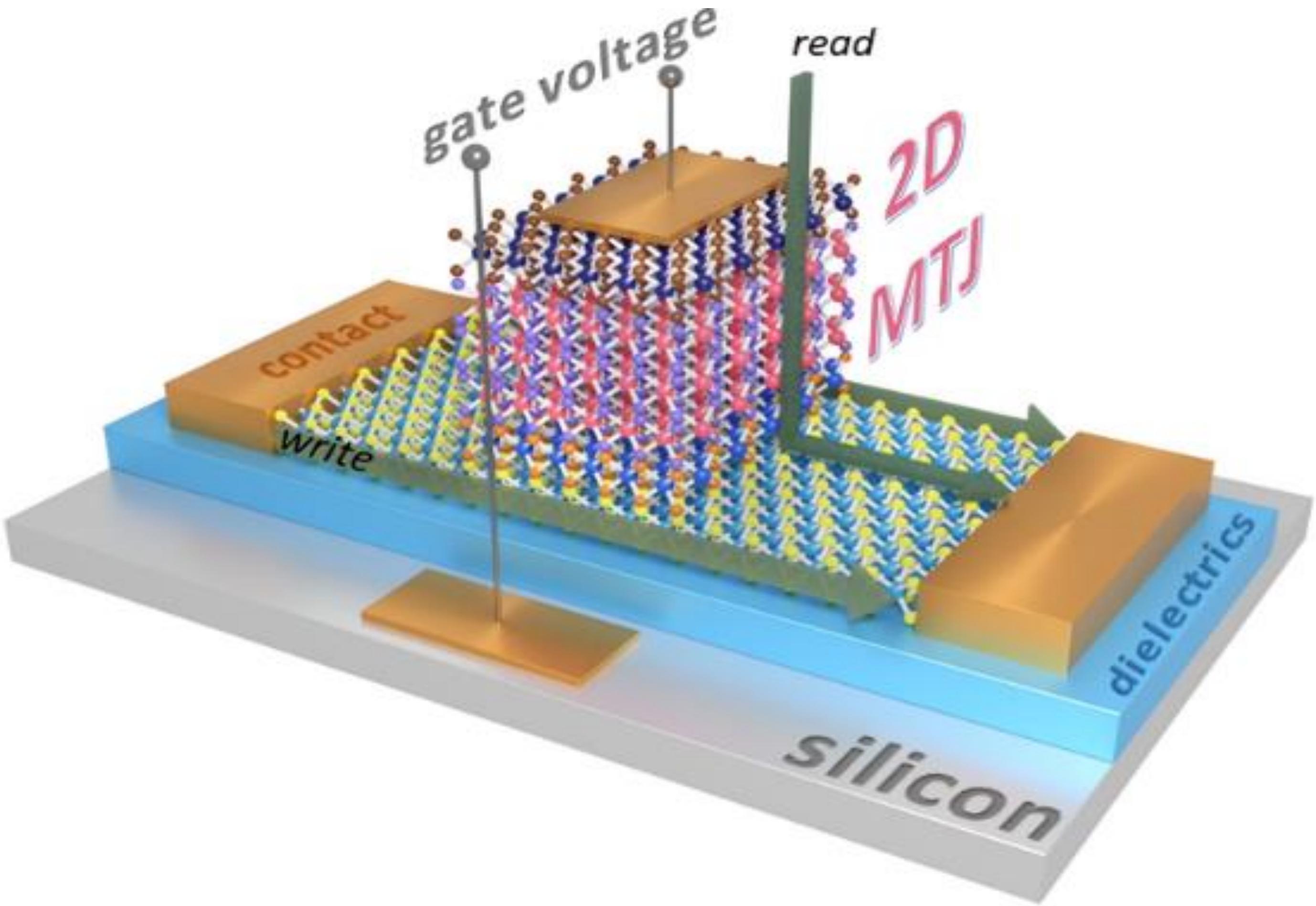
May et al., *ACS Nano.* **13**,4436 (2019)

X. Zhang et al. *Nature Comm.***12**, 2492 (2021)

OUTLINE

1. Introduction to 2D and van der Waals materials
2. Growth of 2D materials and chalcogenides: from exfoliation to molecular beam epitaxy
3. Recent achievements in MBE-grown 2D materials: narrow excitonic lines, doping, alloys, superconductivity, ferroelectricity, ferromagnetism
4. **2D magnets for spintronics: $Cr_{1+\delta}Te_2$, $Fe_{3\text{-}5}GeTe_2$**
5. Conclusion and perspectives

Building « all 2D » magnetic memory (SOT-MRAM)



- Clean and sharp vdW interfaces
- Electric field manipulation of magnetization
- Perpendicular magnetic anisotropy
- Low symmetries for spin-orbit torques
- Large magnetoresistances

H. Yang et al, Nature **606**, 663 (2022)

Cr$_{1+\delta}$Te$_2$ van der Waals ferromagnet

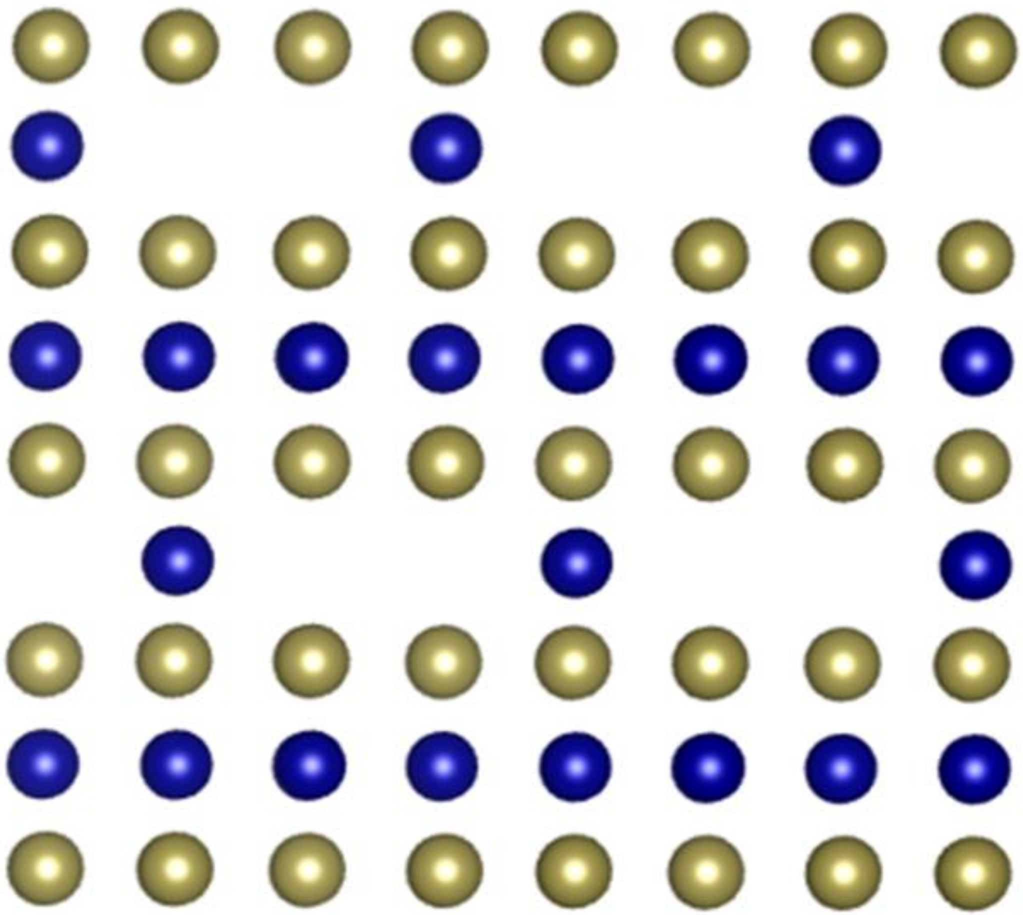
Crystal structure of Cr$_{1+\delta}$Te$_2$

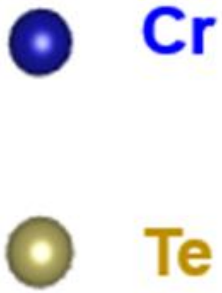
PhD Quentin Guillet

Hervé Boukari

Filled Cr plane →

Partially occupied $0 < \delta < 1$ →





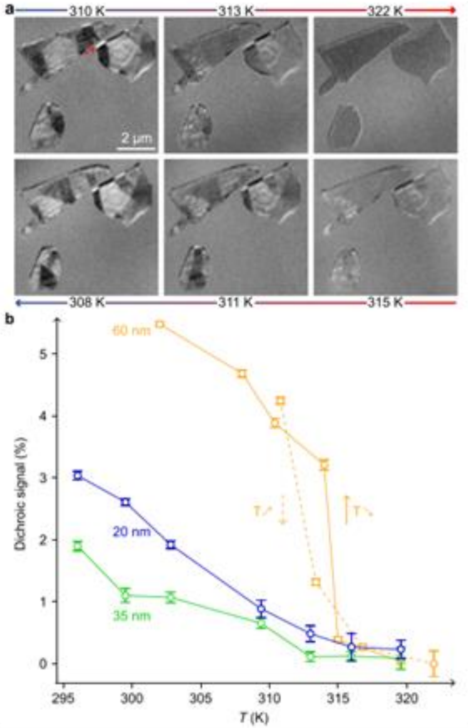
$\delta = 0 \rightarrow CrTe_2$

$\delta = 0{,}33 \rightarrow Cr_2Te_3$

$\delta = 0{,}5 \rightarrow Cr_3Te_4$

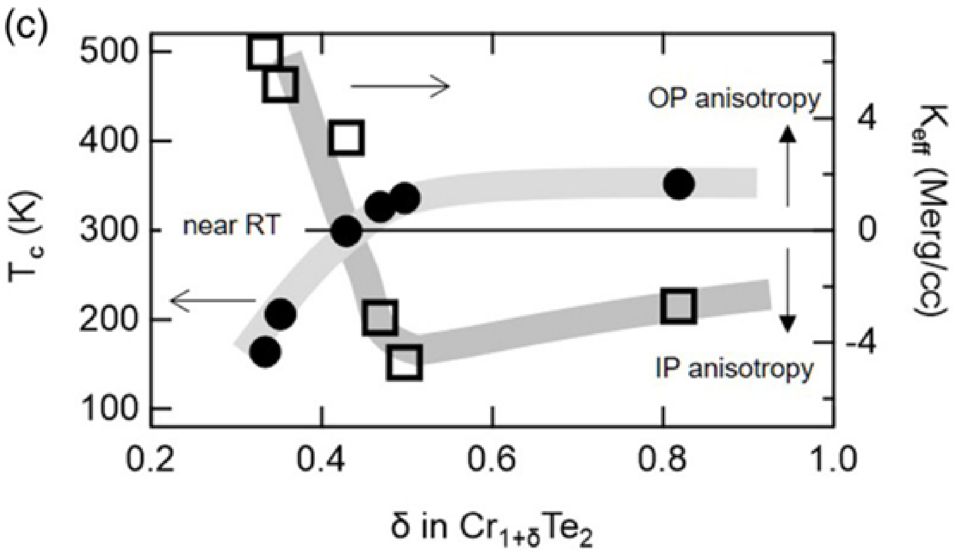
Motivations for the study of $Cr_{1+\delta}Te_2$

In-Plane Magnetic Domains and Néel-like Domain Walls in Thin Flakes of the Room Temperature $CrTe_2$ Van der Waals Ferromagnet



A. Purbawati et al. *ACS Appl. Mater. Interfaces* **12** (2020)

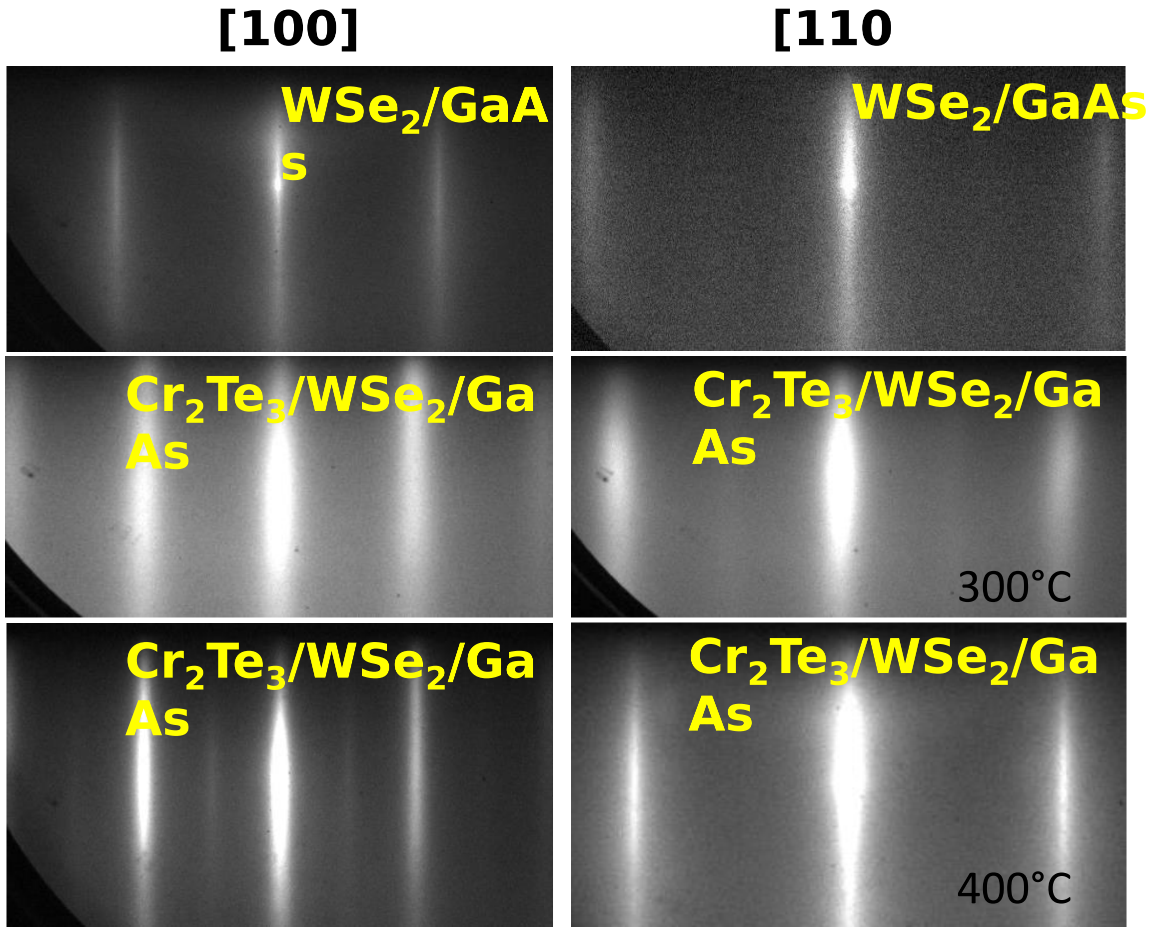
Tailoring magnetism by self-intercalation in $Cr_{1+\delta}Te_2$

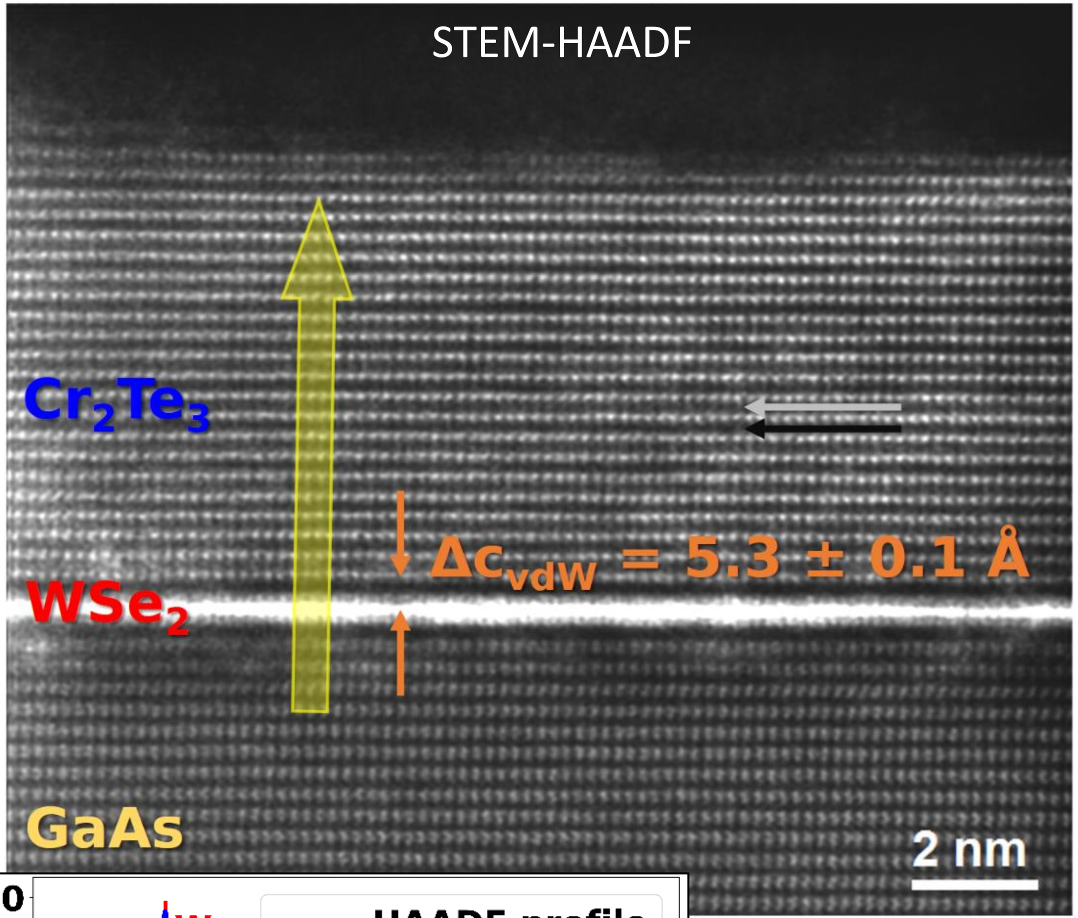


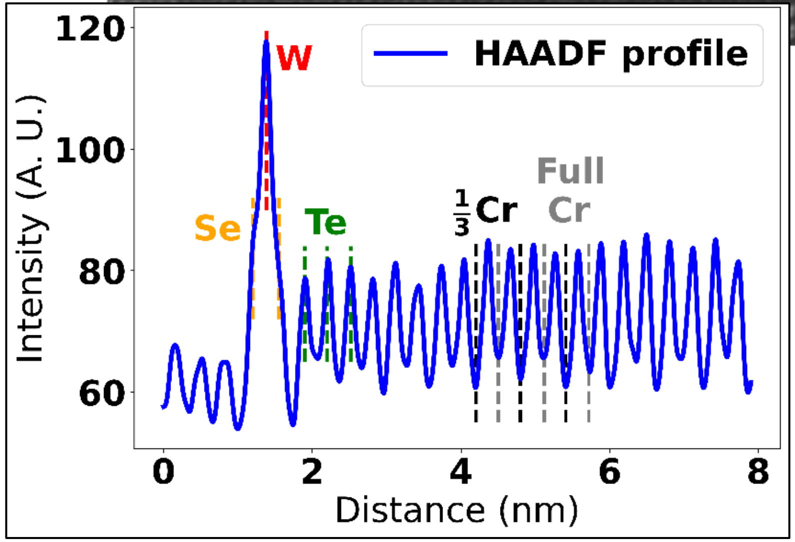
Y. Fujisawa et al. *Physical Review Materials* **4** (2020)

$Cr_{1+\delta}Te_2$ van der Waals ferromagnet

RHEED patterns







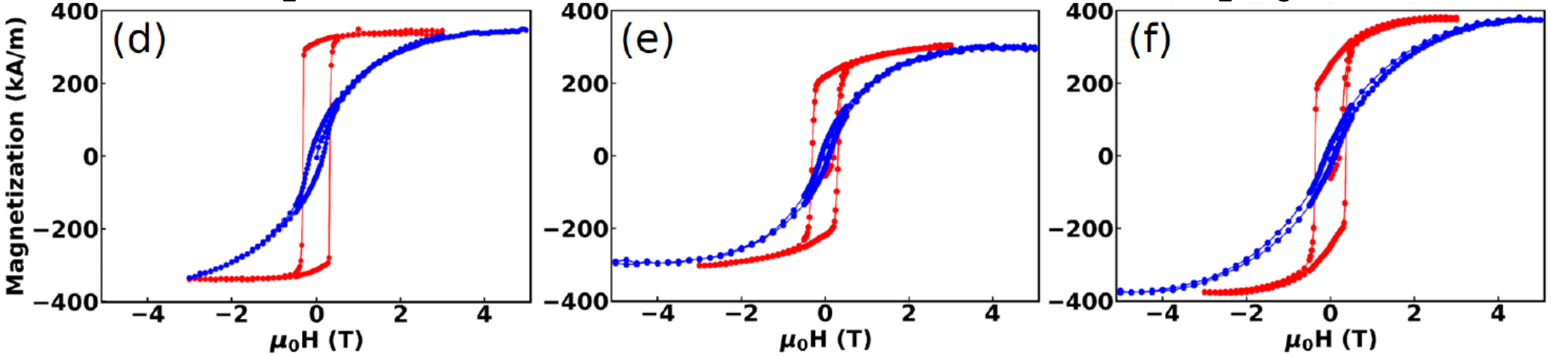
Same growth on **graphene** and **Bi_2Te_3**

Q. Guillet et al., Phys. Rev. Mater. 7, 054005 (2023)

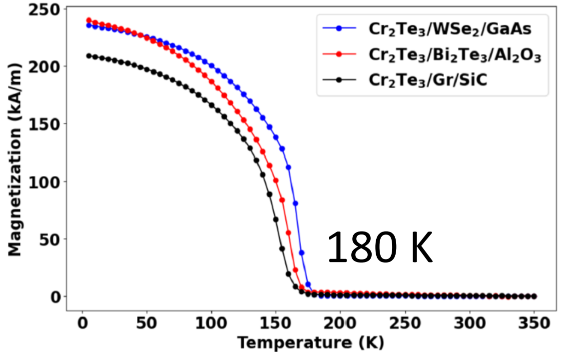
$Cr_{1+\delta}Te_2$ van der Waals ferromagnet

SQUID

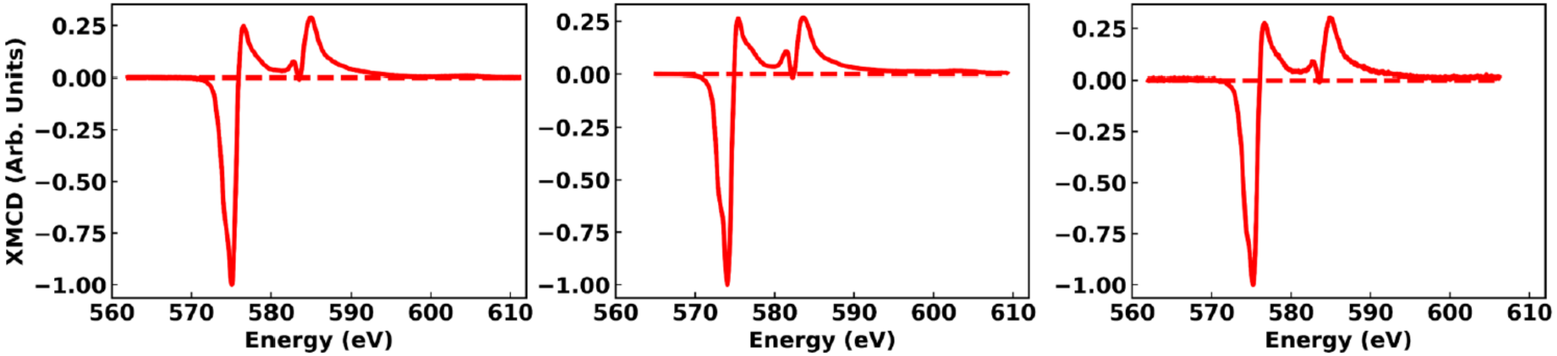
WSe_2/GaAs   Graphene/SiC Bi_2Te_3/sapphire



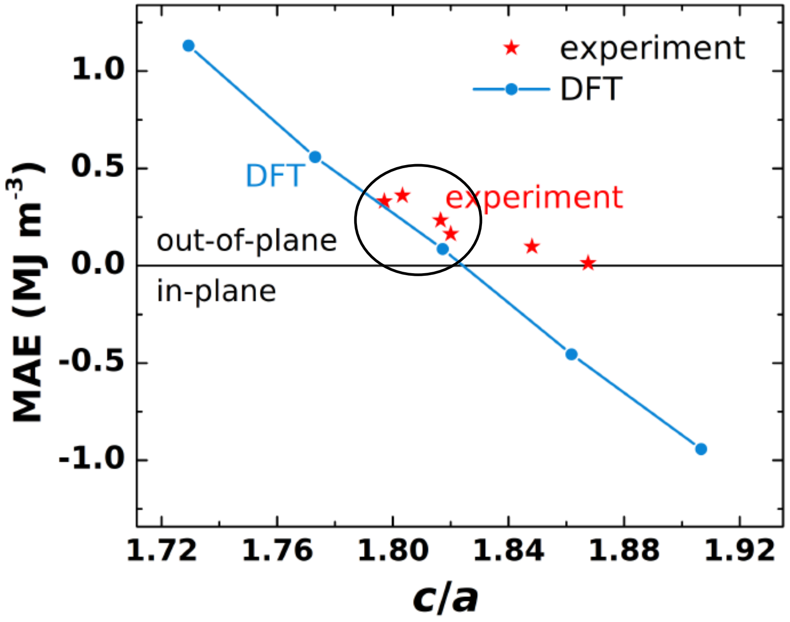
All same T_c



XMCD



(coll. SOLEIL/DEIMOS, P. Ohresser, F. Choueikani)

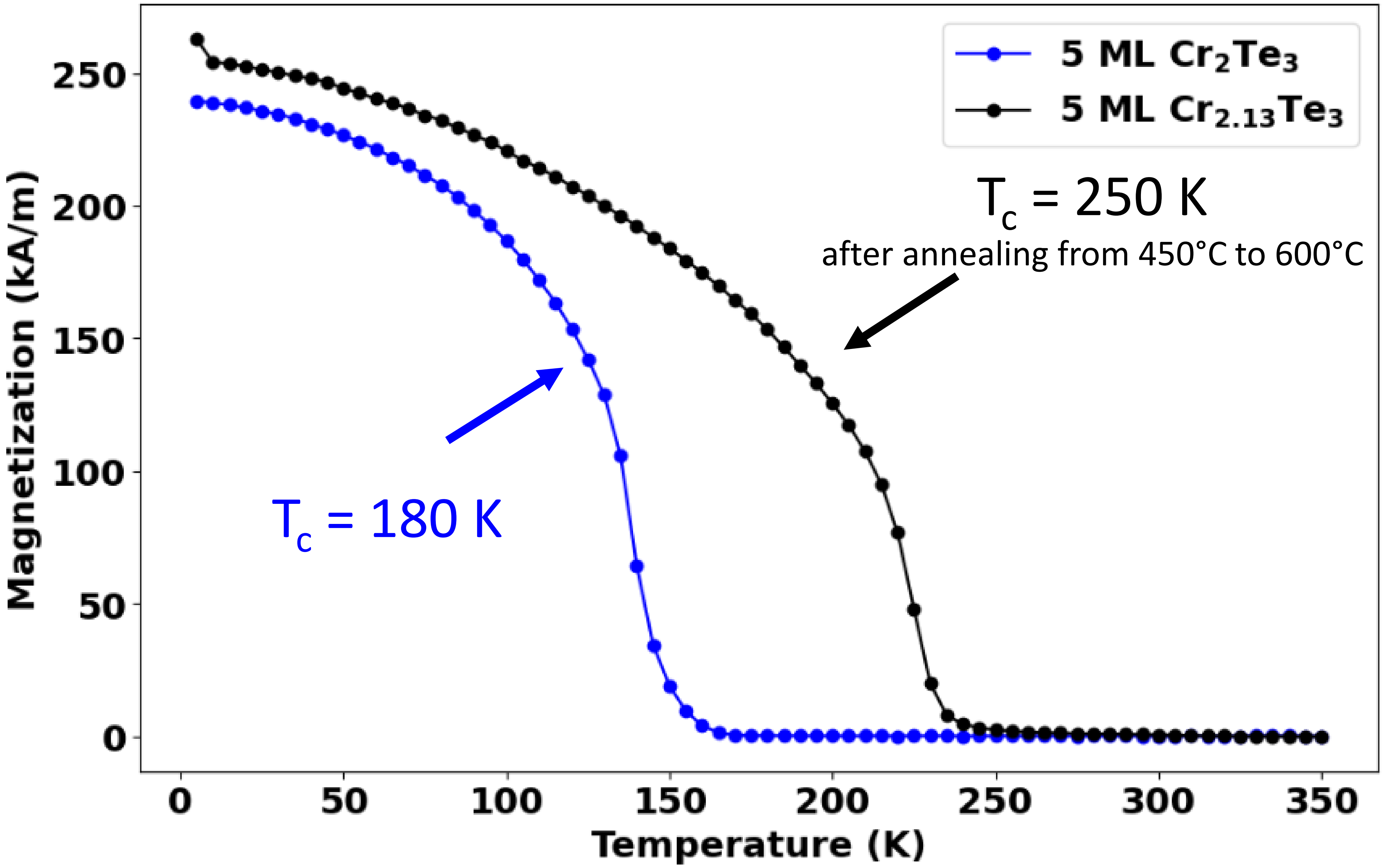


Q. Guillet et al., Phys. Rev. Mater. 7, 054005 (2023)

L. Vojacek, M. Chshiev

$Cr_{1+\delta}Te_2$ van der Waals ferromagnet

$Cr_{1+\delta}Te_2$ / graphene / SiC



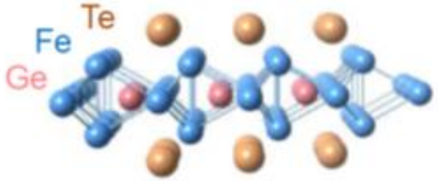
$Fe_{3-5}GeTe_2$ van der Waals ferromagnet

LETTERS
nature materials
https://doi.org/10.1038/s41563-018-0149-7

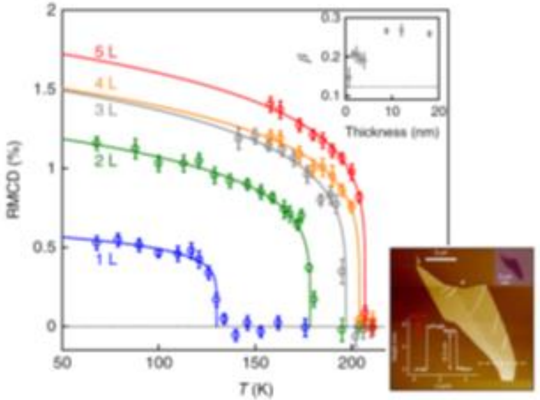
Two-dimensional itinerant ferromagnetism in atomically thin Fe_3GeTe_2

Zaiyao Fei[1,8], Bevin Huang[1,8], Paul Malinowski[1], Wenbo Wang[2], Tiancheng Song[1], Joshua Sanchez[1], Wang Yao[3], Di Xiao[4], Xiaoyang Zhu[5], Andrew F. May[6], Weida Wu[2], David H. Cobden[1], Jiun-Haw Chu[1*] and Xiaodong Xu[1,7*]

Fe_3GeTe_2



Fei et al.
Nature Mater. 17, 778 (2018)



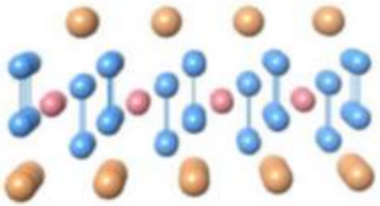
$T_c \sim 230K$
Strong PMA
Bulk/flakes/MBE

SCIENCE ADVANCES | RESEARCH ARTICLE

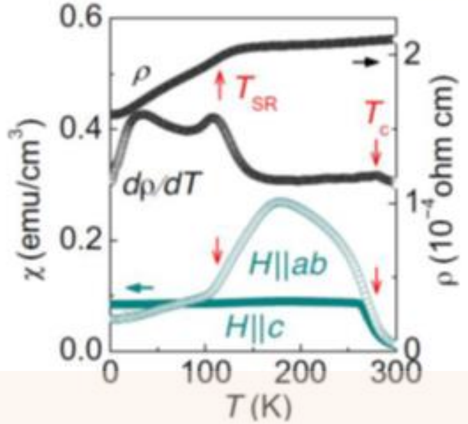
Nearly room temperature ferromagnetism in a magnetic metal-rich van der Waals metal

Junho Seo[1,2*], Duck Young Kim[3*], Eun Su An[1,2*], Kyoo Kim[4], Gi-Yeop Kim[5], Soo-Yoon Hwang[5], Dong Wook Kim[6], Bo Gyu Jang[6], Heejung Kim[4], Gyeongsik Eom[7], Seung Young Seo[1,5], Roland Stania[1], Matthias Muntwiler[8], Jinwon Lee[1,2], Kenji Watanabe[9], Takashi Taniguchi[9], Youn Jung Jo[10], Jieun Lee[7], Byung Il Min[2], Moon Ho Jo[1,5], Han Woong Yeom[1,2], Si-Young Choi[5†], Ji Hoon Shim[6†], Jun Sung Kim[1,2†]

Fe_4GeTe_2



Seo et al.
Sci. Adv. 6, eaay8912 (2020)



$T_c \sim 270K$
Weak PMA
Bulk/flakes only

ACS NANO
Cite This: ACS Nano 2019, 13, 4436−4442
www.acsnano.org

Ferromagnetism Near Room Temperature in the Cleavable van der Waals Crystal Fe_5GeTe_2

Andrew F. May,[*,†] Dmitry Ovchinnikov,[‡] Qiang Zheng,[†] Raphael Hermann,[†] Stuart Calder,[§] Bevin Huang,[‡] Zaiyao Fei,[‡] Yaohua Liu,[§] Xiaodong Xu,[‡,∥] and Michael A. McGuire[†]
[†]Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, United States
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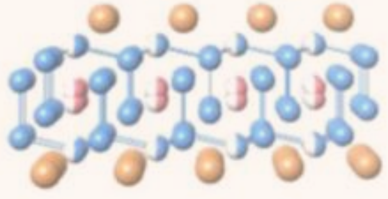
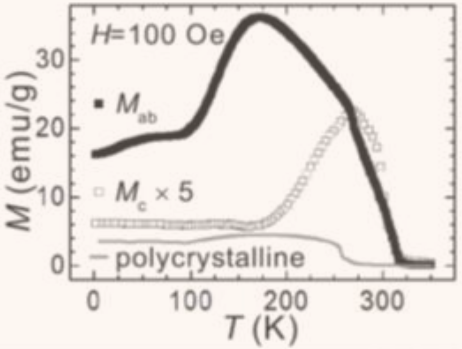
[§]Neutron Scattering Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, United States
[∥]Department of Materials Science and Engineering, University of Washington, Seattle, Washington 98195, United States

Fe_5GeTe_2



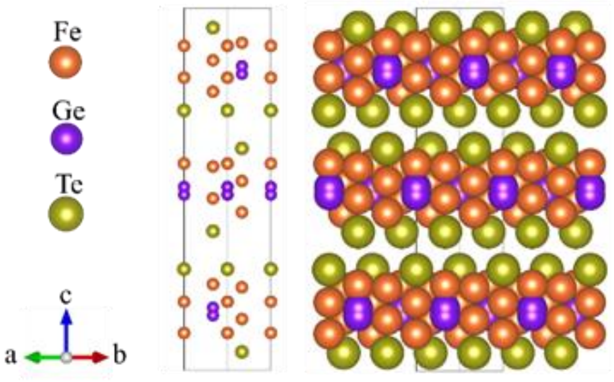
May et al.
ACS Nano. 13, 4436 (2019)

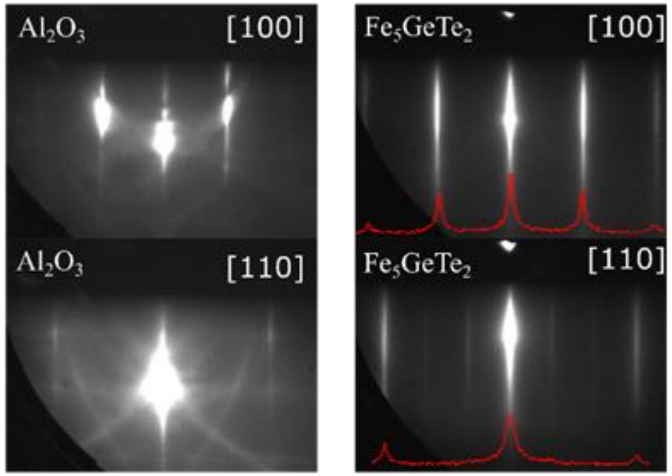


$T_c \sim 300K$
Small/no PMA
Bulk/flakes only

$Fe_{3\text{-}5}GeTe_2$ van der Waals ferromagnet

Uniform, high crystallinity (mosaicity ~3°)

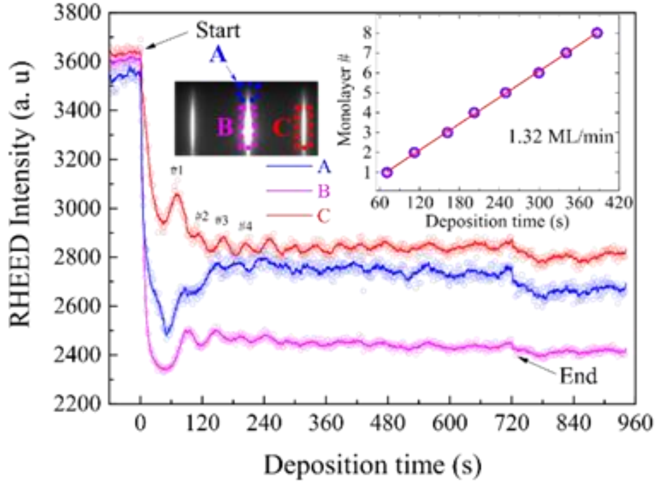




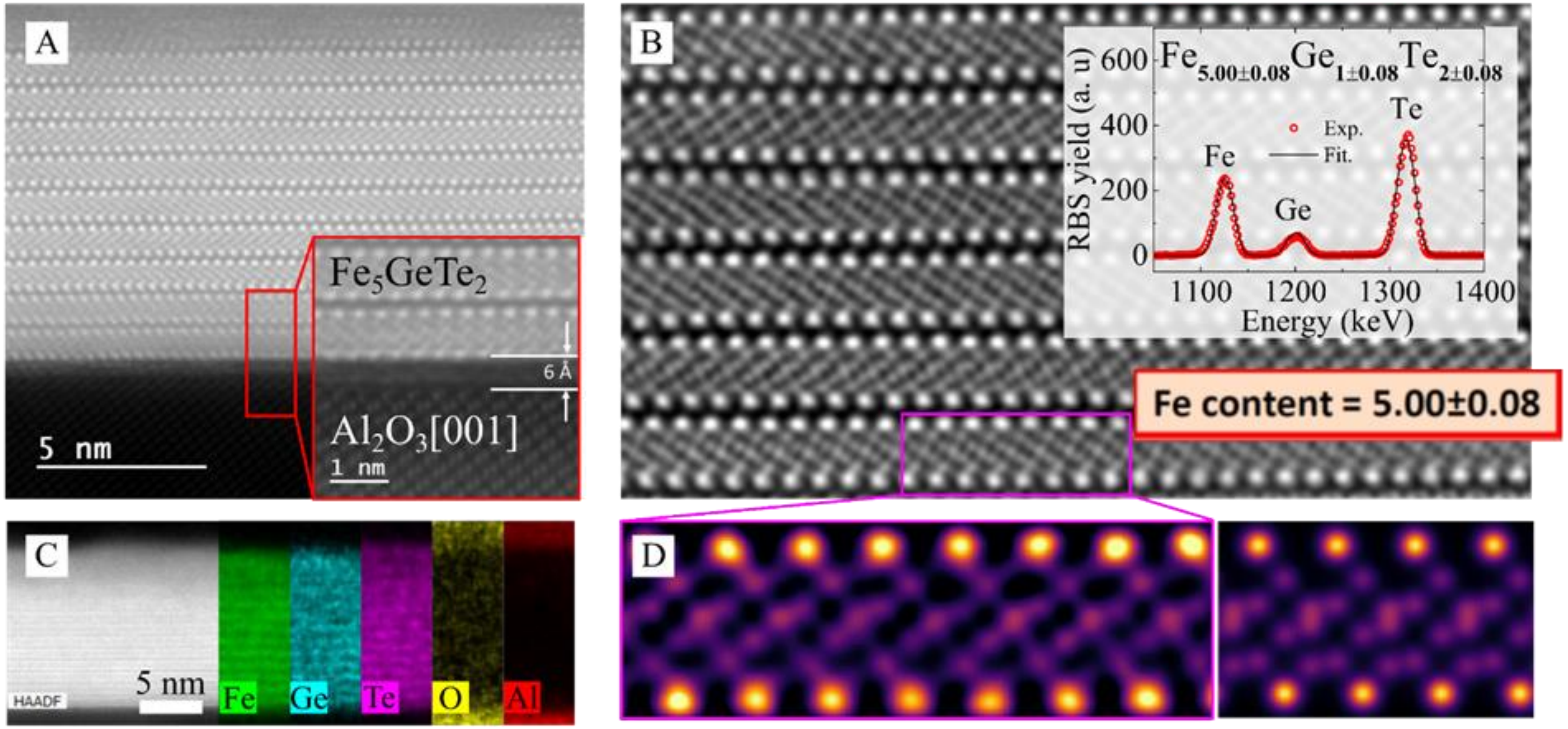
Layer-by-layer growt


M. Ribeiro

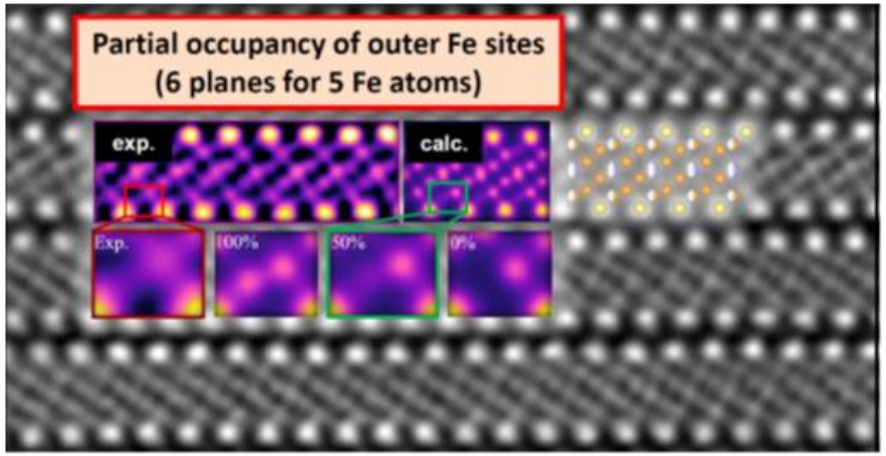

F. Bonell



Ribeiro, MJ et al, npj 2D Mater. & Appl. 6, 1 (2022)



Fe content = 5.00±0.08



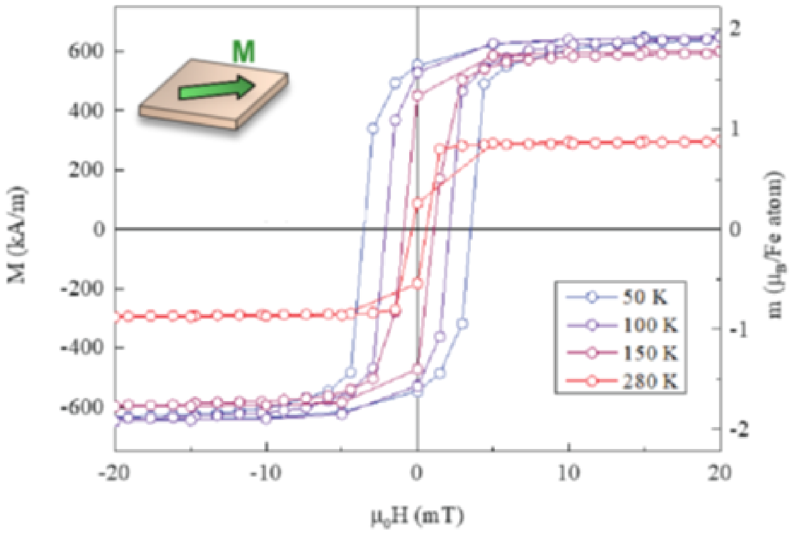
Partial occupancy of outer Fe sites (6 planes for 5 Fe atoms)

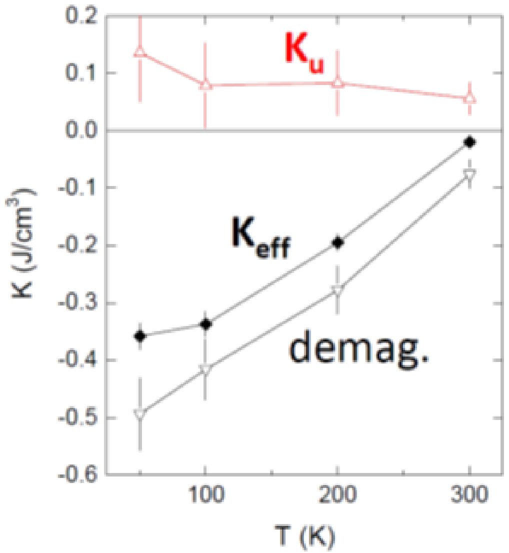
$Fe_{3-5}GeTe_2$ van der Waals ferromagnet

SQUID

in-plane anisotropy, weak out-of-plane one

Ribeiro, MJ et al, npj 2D Mater. & Appl. 6, 1 (2022)





Easy-plane FM

Monotonous M(T)

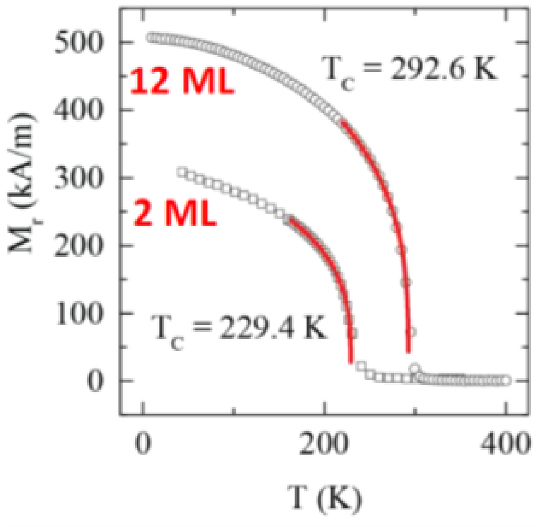
Quasi-3D critical behavior

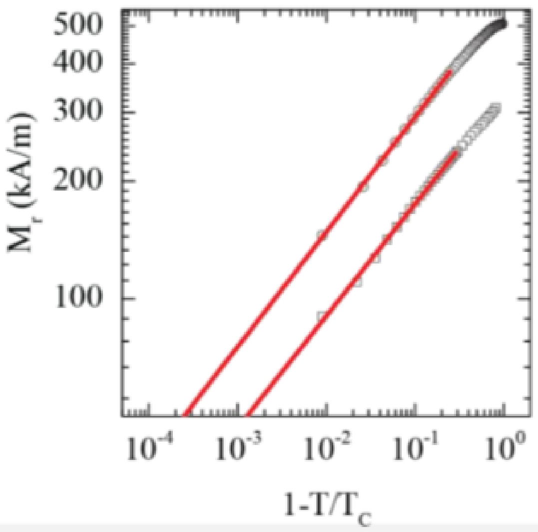
β thickness-independent

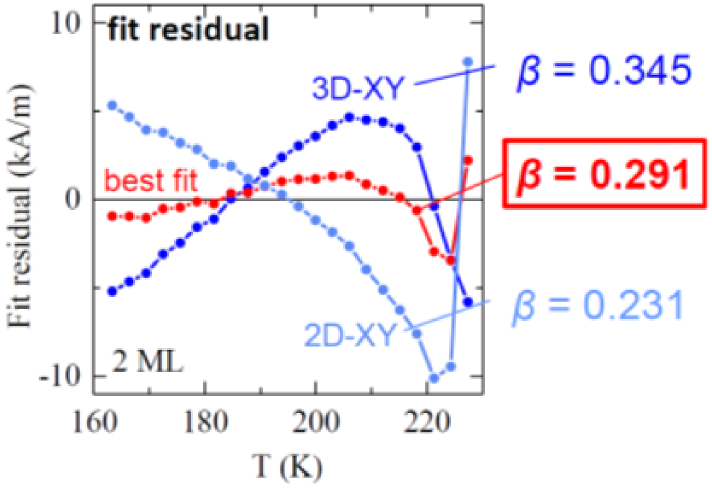
High T_C = 230 K in bilayer

Plot of remanent magnetization

$$M_r \propto \left(\frac{T_C - T}{T_C}\right)^{\beta}$$







OUTLINE

1. Introduction to 2D and van der Waals materials

2. Growth of 2D materials and chalcogenides: from exfoliation to molecular beam epitaxy

3. Recent achievements in MBE-grown 2D materials: narrow excitonic lines, doping, alloys, superconductivity, ferroelectricity, ferromagnetism

4. 2D magnets for spintronics: $Cr_{1+\delta}Te_2$, $Fe_{3-5}GeTe_2$

5. **Conclusion and perspectives**

Conclusion

Van der Waals epitaxy by MBE opens new perspectives as compared to flakes:

- Growth of 2D materials on large areas with superior properties
- Growth of 2D ferromagnets in the limit of one monolayer
- Growth of vdW heterostructures with ultraclean interfaces

Conclusion

Van der Waals epitaxy by MBE opens new perspectives as compared to flakes:

- Growth of 2D materials on large areas with superior properties
- Growth of 2D ferromagnets in the limit of one monolayer
- Growth of vdW heterostructures with ultraclean interfaces

- **Great effort should be dedicated to the development of large scale epitaxial 2D materials**
- **Selection of the best substrate : hBN (ultraflat, inert, 3-fold symmetry)**
- **Growth models for vdW epitaxy are missing**

Acknowledgements

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Postdoc


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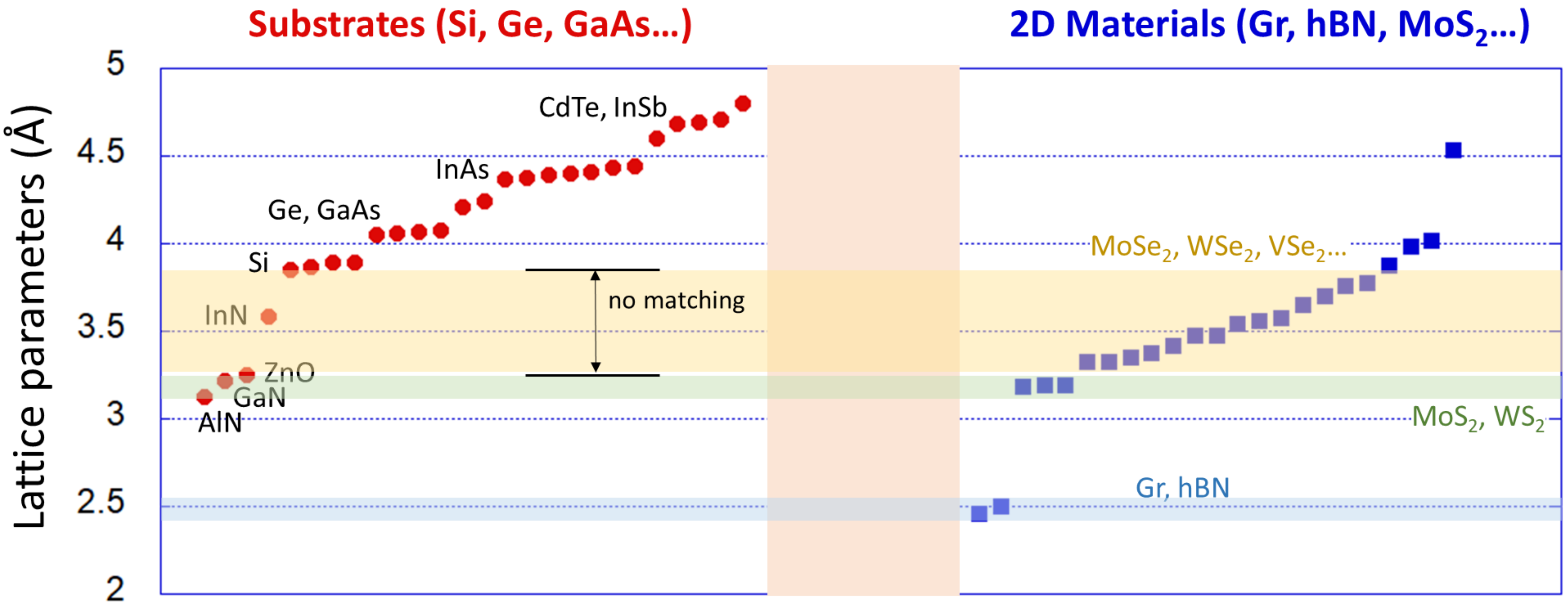
INVESTIR L'AVENIR — ESR/EquipEx+ 2DMAG

lanef Laboratoire d'Alliances Nanosciences-Energies du Futur — 2DMAT project

2D materials: hexagonal symmetry & atomically thin

need for hexagonal bulk crystals or (111) facets of cubic bulk crystals with very good lattice matching



without considering commensurability, crystal rotations or metallic surfaces:

NO substrate with low lattice mismatch for the epitaxial growth of 2D Materials!