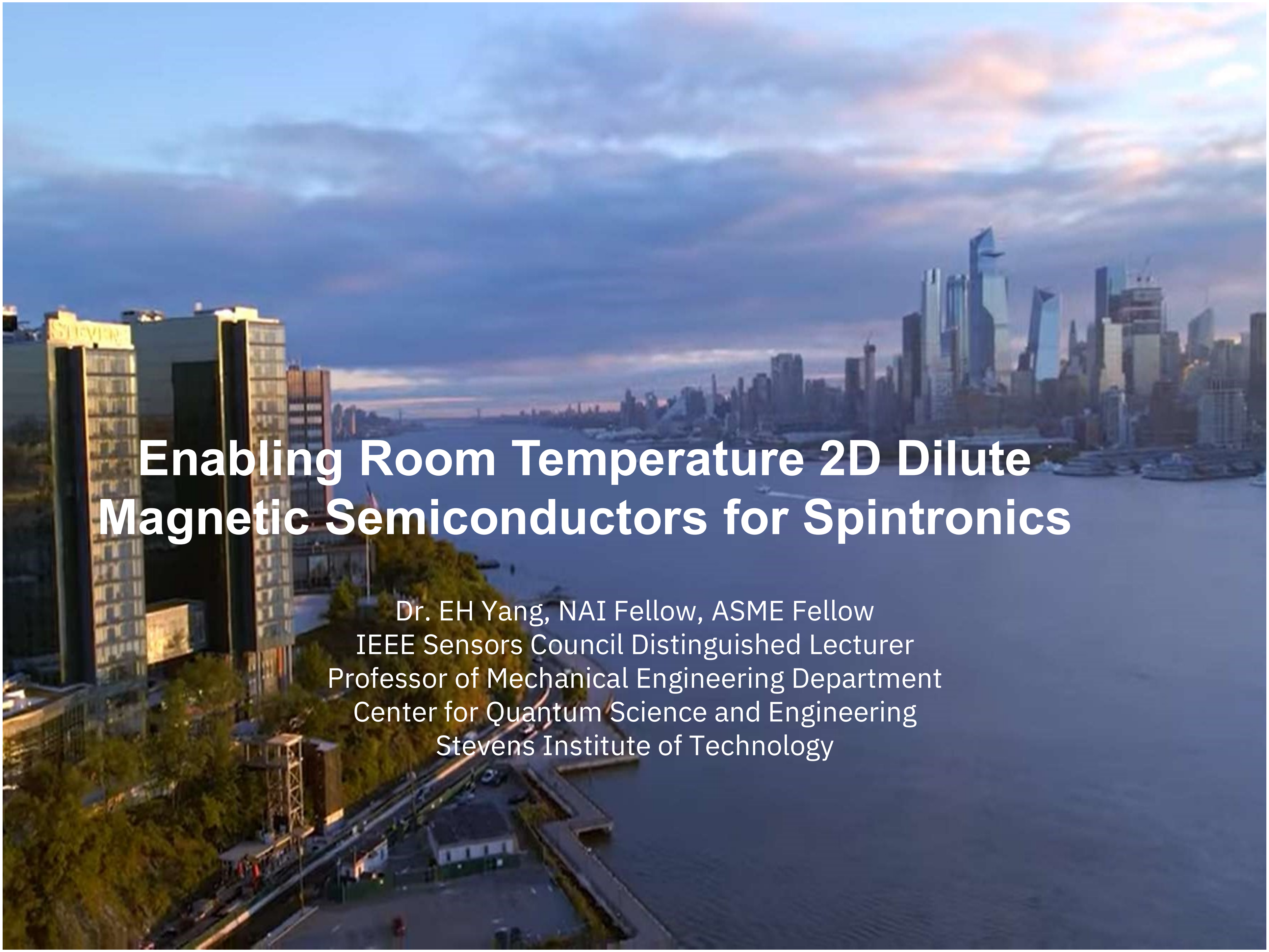
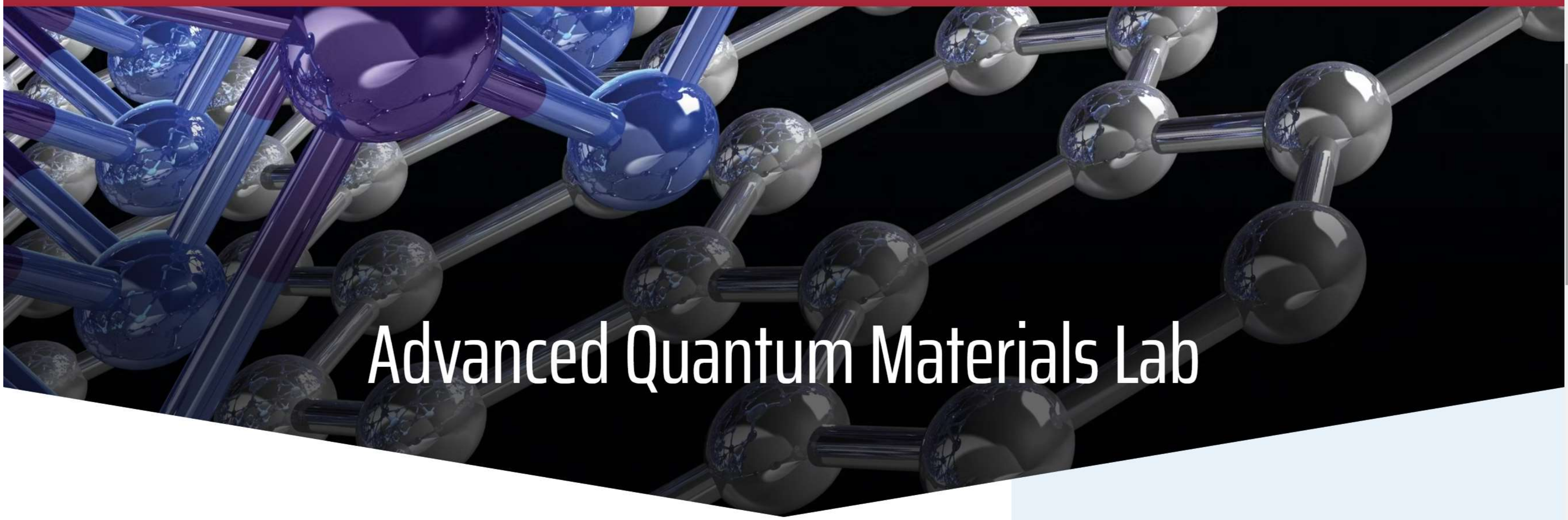


Enabling Room Temperature 2D Dilute Magnetic Semiconductors for Spintronics

Dr. EH Yang, NAI Fellow, ASME Fellow
IEEE Sensors Council Distinguished Lecturer
Professor of Mechanical Engineering Department
Center for Quantum Science and Engineering
Stevens Institute of Technology



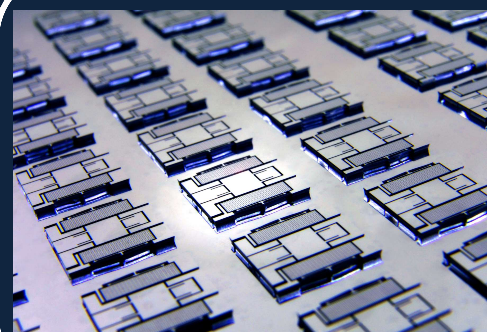
Advanced Quantum Materials Lab

The EH Yang group's research aims to translate discoveries in 2D material synthesis into practical applications. The goal is to develop new strategies that combine fundamental studies with forward-looking engineering efforts that would lead to advanced technologies, with implications in fields ranging from quantum sensing and spintronics to energy, environment and medicine.

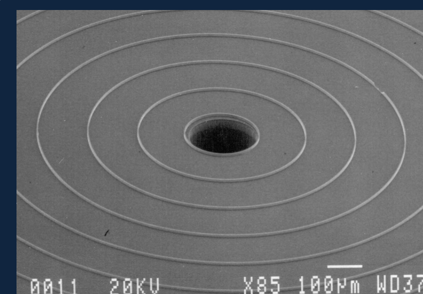
Advanced Quantum Materials Lab

(1999 – 2006)

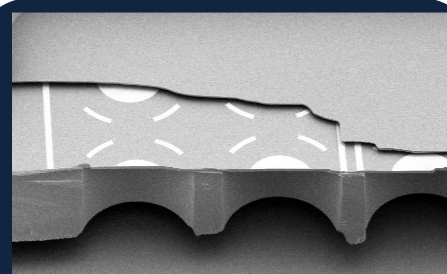
MEMS Technologies for Space Applications



Linear Microactuator



Piezoelectric Microvalve



MEMS Deformable Mirror

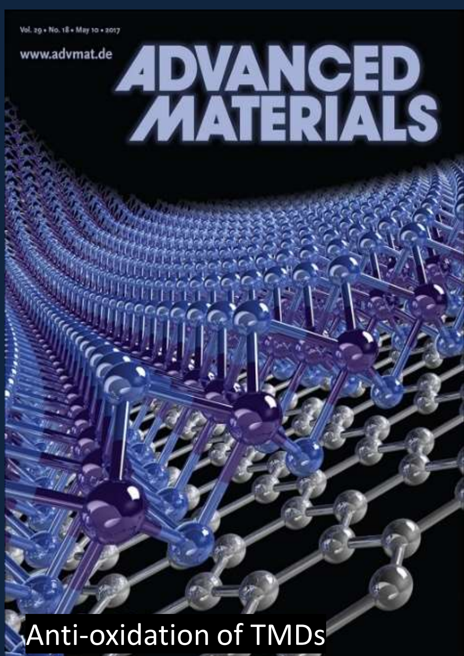
Nano Letters, 3(10), 1339
Nanotechnology, 18
IEEE TNANO, 7, 251
IEEE/ASME J MEMS, 15(5), 1214
IEEE/ASME J MEMS, 15(3), 686
IEEE/ASME J MEMS, 15(2), 370
IEEE/ASME J MEMS, 13(5), 799
IEEE/ASME J MEMS, 12(6), 804

STEVENS
INSTITUTE of TECHNOLOGY
THE INNOVATION UNIVERSITY®

Advanced Quantum Materials Lab

(2006 – current)

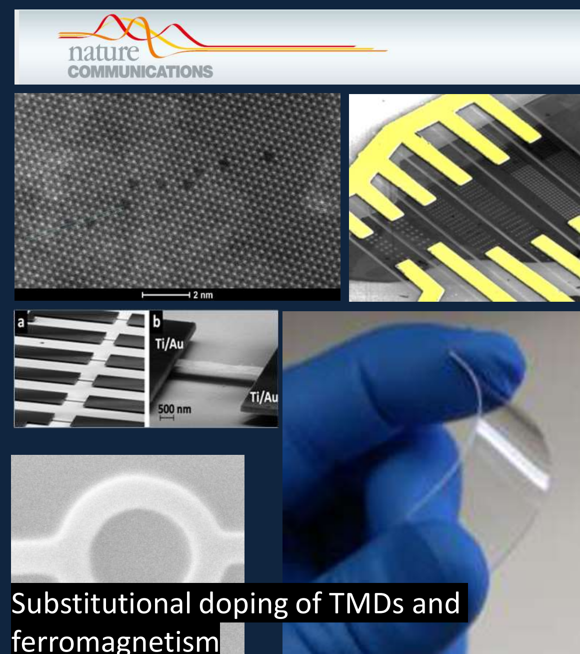
2D Material Synthesis and Nanofabrication



Anti-oxidation of TMDs

Advanced Materials, 18, 1603898
Nano Letters, *11*, 4874
ACS Appl. Mater. Int. ***13***(26), 31271

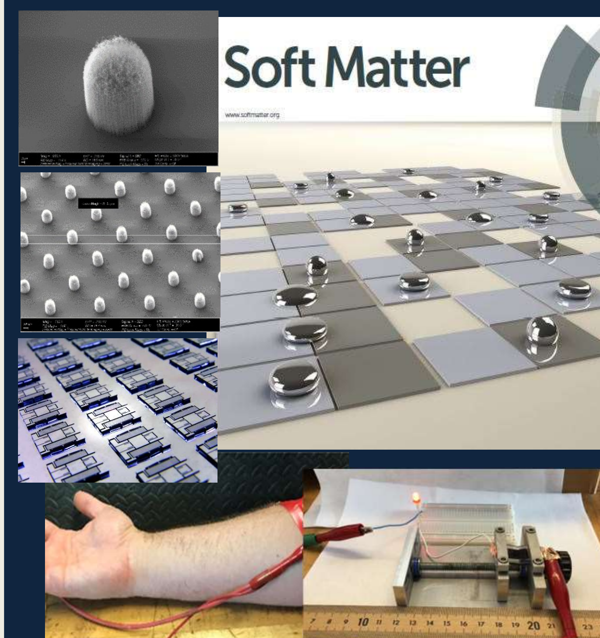
2D Magnets for Quantum Sensing and Memory



Substitutional doping of TMDs and ferromagnetism

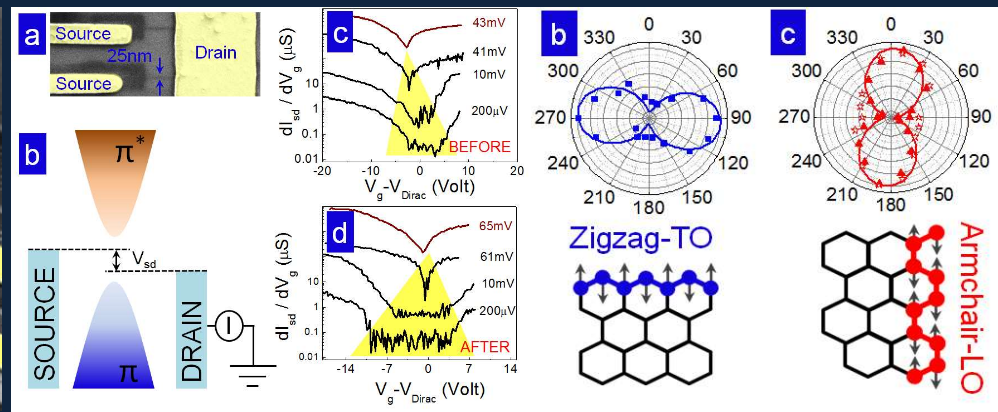
Nature Communications, 11, 2034
Nano Letters, 11(3), 1254
Scientific Reports, (3) 2791

Graphene and CNTs for Energy Storage and Sensing



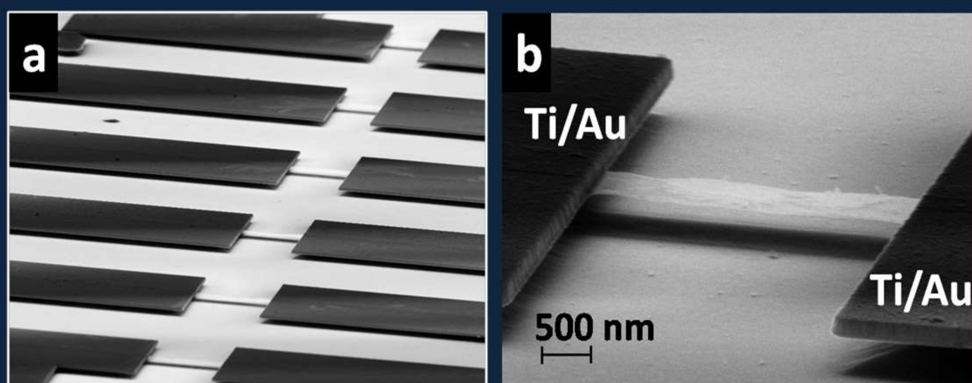
IEEE Sensors Journal, 20(20), 12146
Annalen der Physik., 1800507
Chemistry of Materials, 25(19), 3874

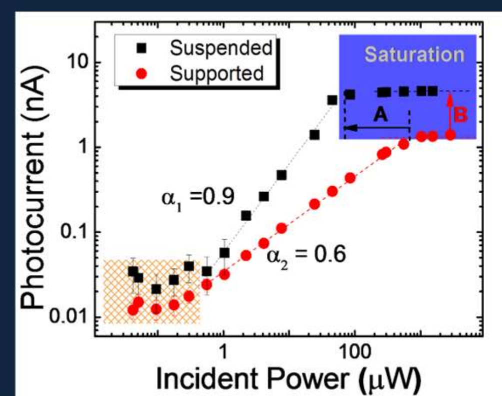
Graphene Optoelectronics and Photodetectors



Nano Letters, 11 (3), 1254

Nano Letters, 11, 4874

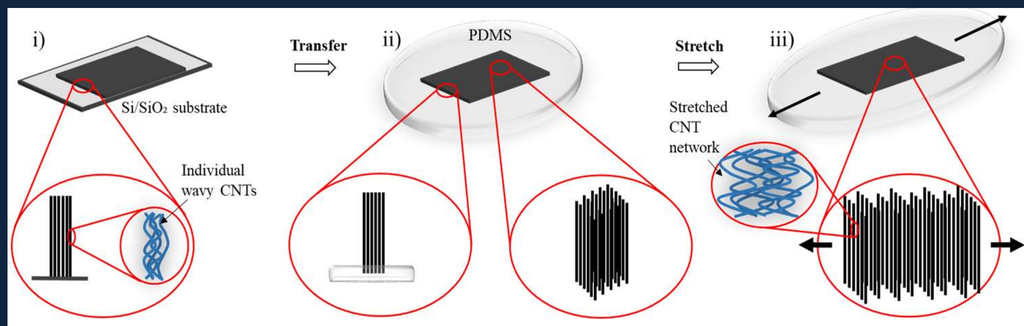


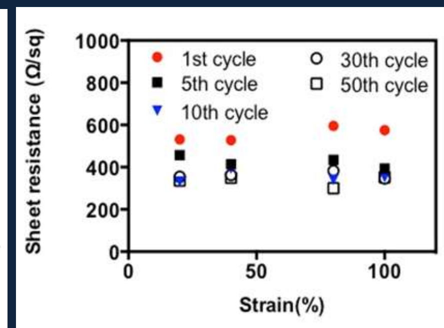


Scientific Reports, (3) 2571

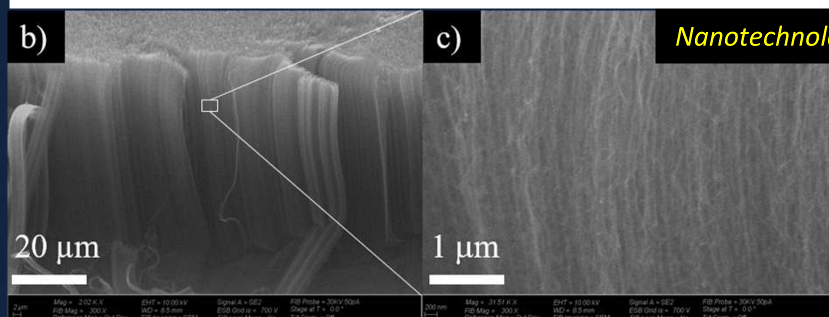
Scientific Reports, (3), 2791

CNTs for Energy Storage and Sensing

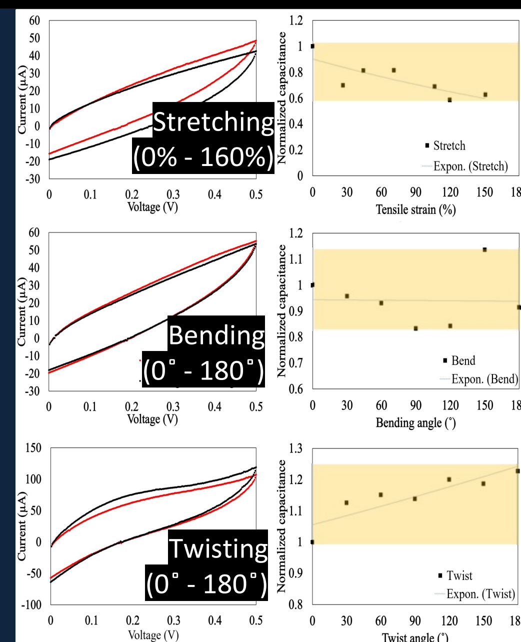


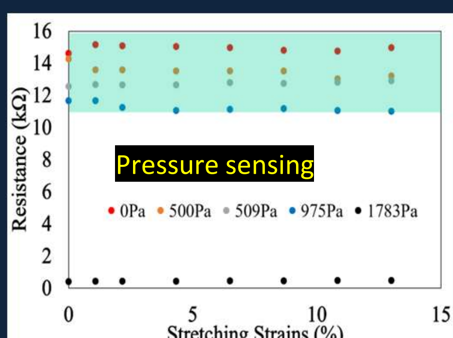


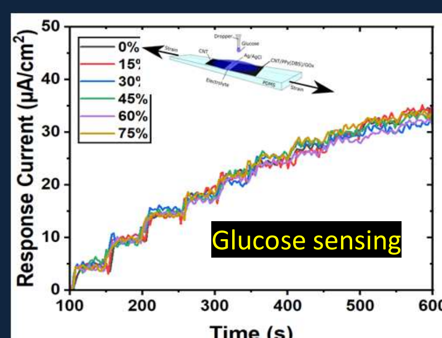
Nanotechnology 28, 465302, *Chemistry of Materials*, 25(19), 3874



ACS Applied Energy Materials, 2048, *1*(5)



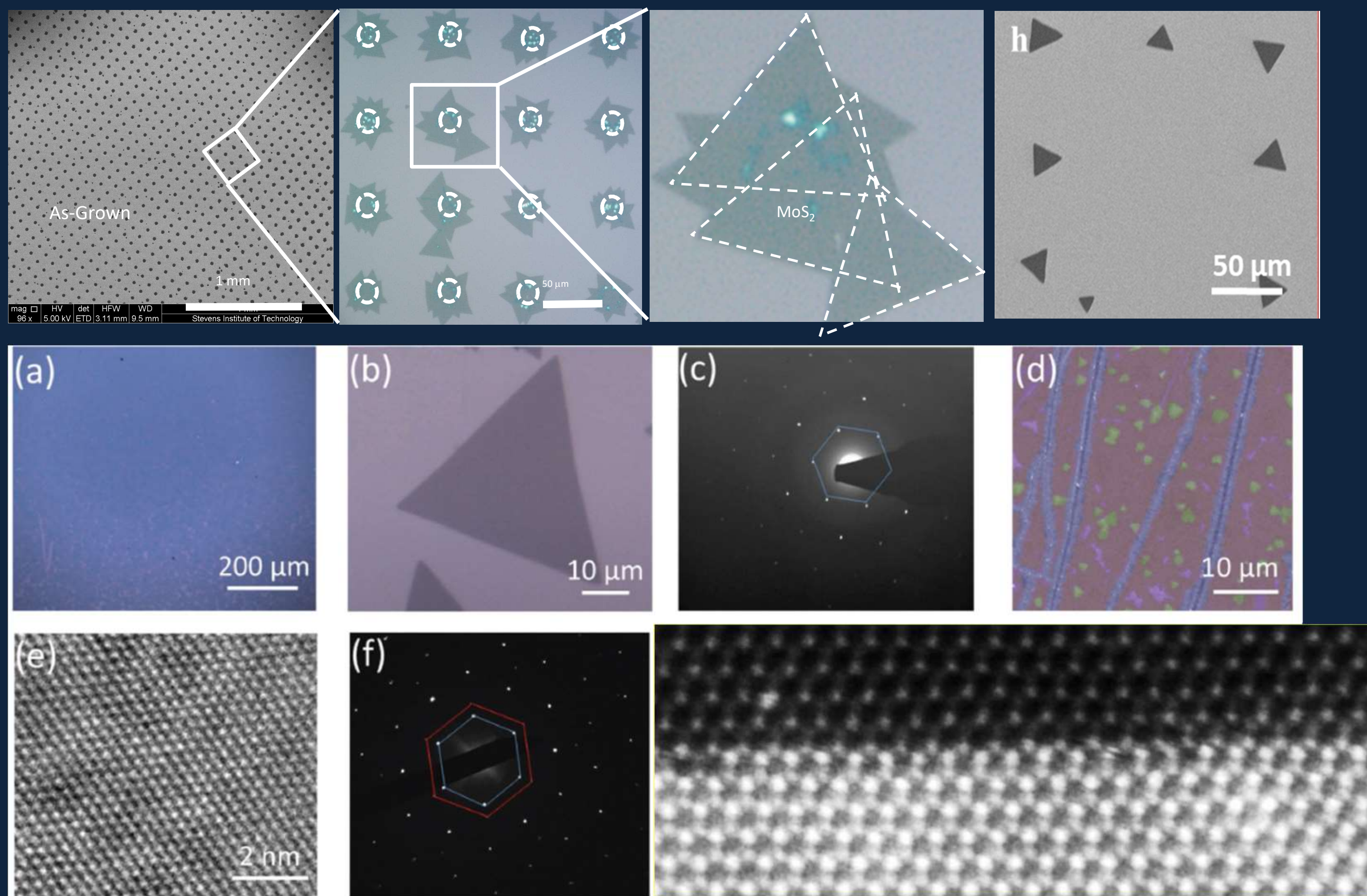




IEEE Sensors Journal, 20(20), 12146 *IEEE J-Flex*, **2**(3), 274

Nanotechnology, ***30***, 095401

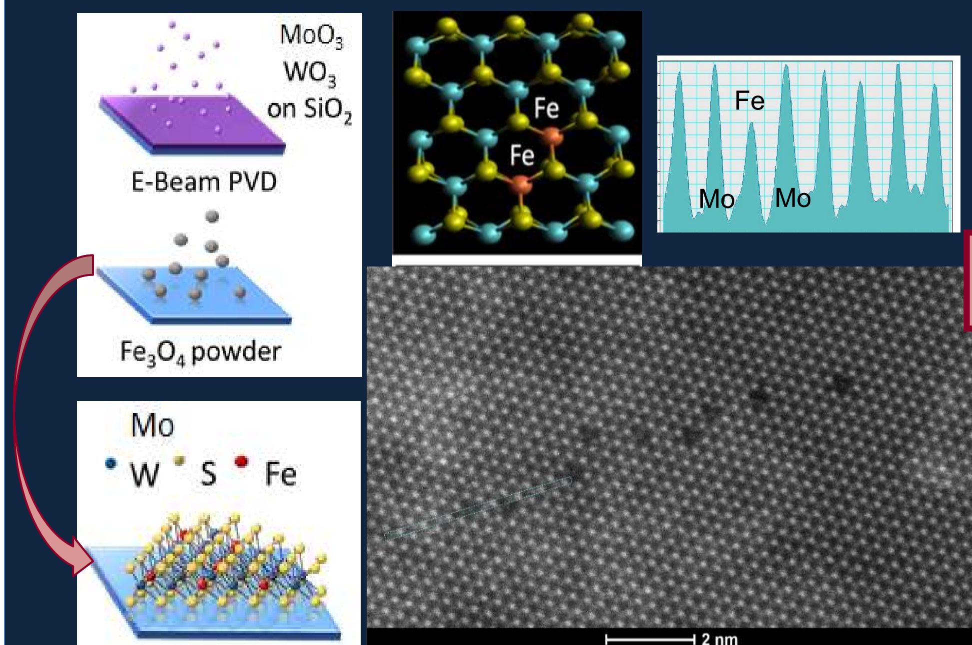
TMD Growth and Characterization



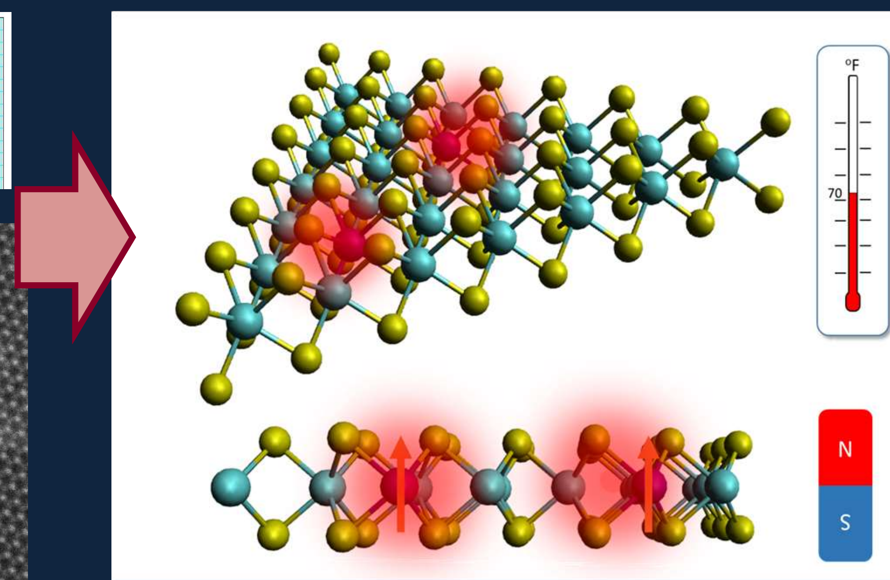
Advanced Materials, 18, 1603898, *2D Materials*, 4, 025093, *Scientific Reports*, 10, 1648, *Annalen der Physik.*, 1800507, *2D Materials*, 4, 025045, *Scientific Reports*, *7*, 17798, *Chemistry of Materials*, *30*, 5148

Atomically Thin Magnetic Crystals

_in situ d_oping of TMD monolayers enabling 2D dilute magnetic semiconductors



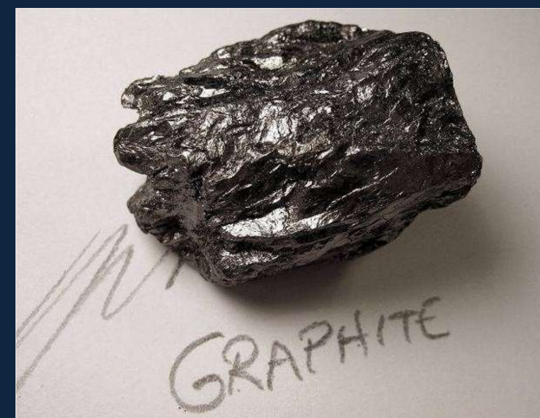
Ferromagnetism with a Curie temperature above room temperature!



Nature Communications, **11**, 2034 (2020), *Scientific Reports,* **12**, 6939 (2022), *2D Materials*, **10** 045003 (2023), *Nanotechnology,* **32**. 095708 (2021), *ACS Appl. Mater. Interfaces, **13***, 11 (2021)

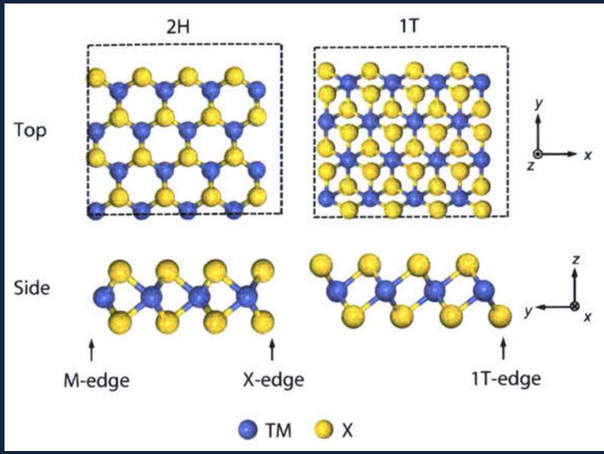
Discovery of Graphene

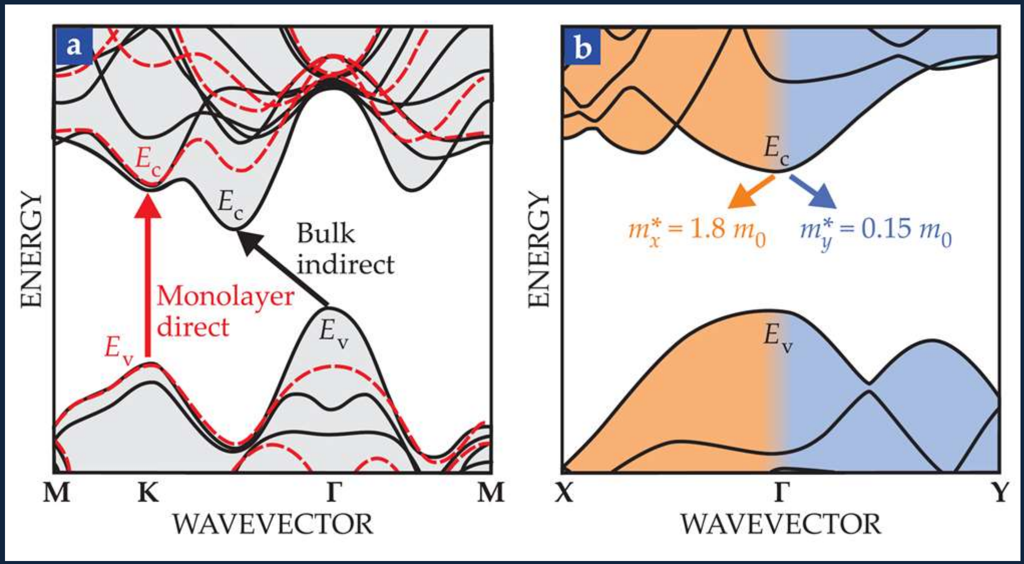
- Although scientists knew graphene existed, no-one had worked out how to extract it from graphite.
- That was until it was isolated in 2004 by Geim and Novoselov who received Nobel Prize (2010)

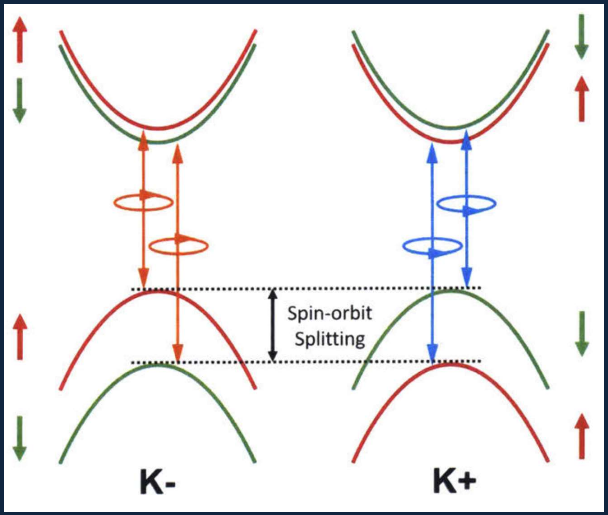


2D Materials beyond Graphene

- Transition metal dichalcogenides (TMDs) can have a *direct bandgap*, complementing graphene.
- TMD monolayers feature strong SOC and inversion symmetry breaking.
- While the conduction band basis is spin degenerate at the K points, the valence band-edge state will split.







Ajayan, Kim, Benerjee, *Phys. Today 69, 38, (2016)*

Single Crystals of MoS_2 Several Molecular Layers Thick

R. F. FRINDT*
Physics and Chemistry of Solids, Cavendish Laboratory, Cambridge, England

(Received 24 March 1965; in final form 18 June 1965)

J. Appl. Phys. **37**, 1928 (1966); doi: 10.1063/1.1708627

Early workers on electron diffraction prepared thin fragments of MoS_2[2,3]; however no direct thickness measurements were made. It is now well known that small MoS_2 crystals thin enough to be transparent in the electron microscope can be prepared by the stripping technique using adhesive tape. Crystals of

The called scotch tape method for exfoliating graphite

SINGLE-LAYER MoS_2

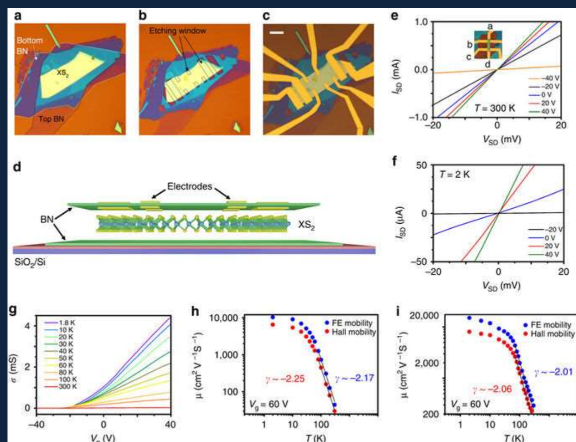
Per Joensen, R.F. Frindt, and S. Roy Morrison
Energy Research Institute
Department of Physics
Simon Fraser University
Burnaby, B.C., Canada V5A 1S6

Mat. Res. Bull., Vol. 21, pp. 457-461, 1986. Printed in the USA.

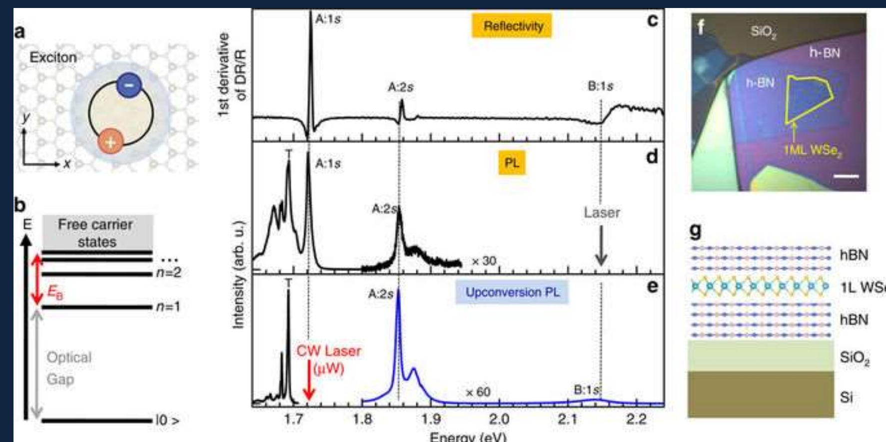
ABSTRACT

MoS_2 has been exfoliated into monolayers by intercalation with lithium followed by reaction with water. X-ray diffraction analysis has shown that the exfoliated MoS_2 in suspension is in the form of one-molecule-thick sheets. X-ray patterns from dried and re-stacked films of exfoliated MoS_2 indicate that the layers are randomly stacked. Exfoliated MoS_2 has been deposited on alumina particles in aqueous suspension, enabling recovery of dry exfoliated MoS_2 supported on alumina.

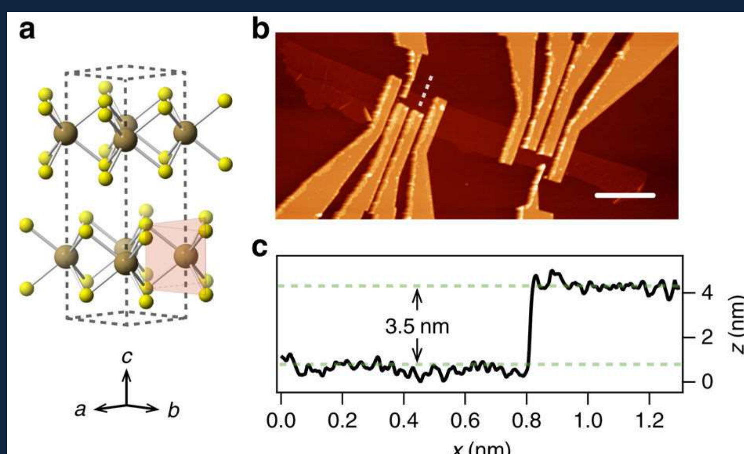
Exploring exotic properties from exfoliated flakes



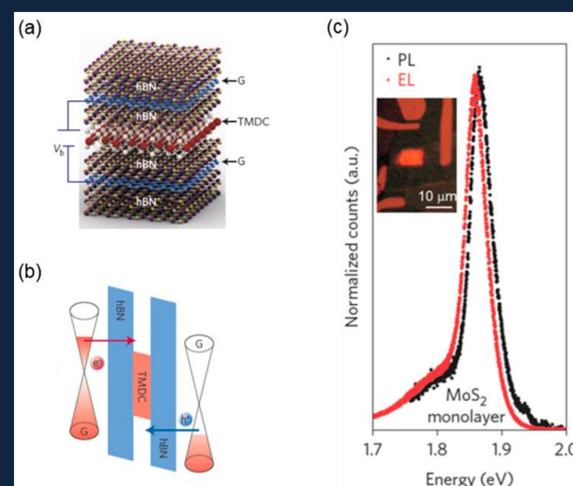
Wu, *et al., Nature Communications* 7, 12955 (2016)



Manca, *et al., Nature Communications* 8, 14927 (2017)

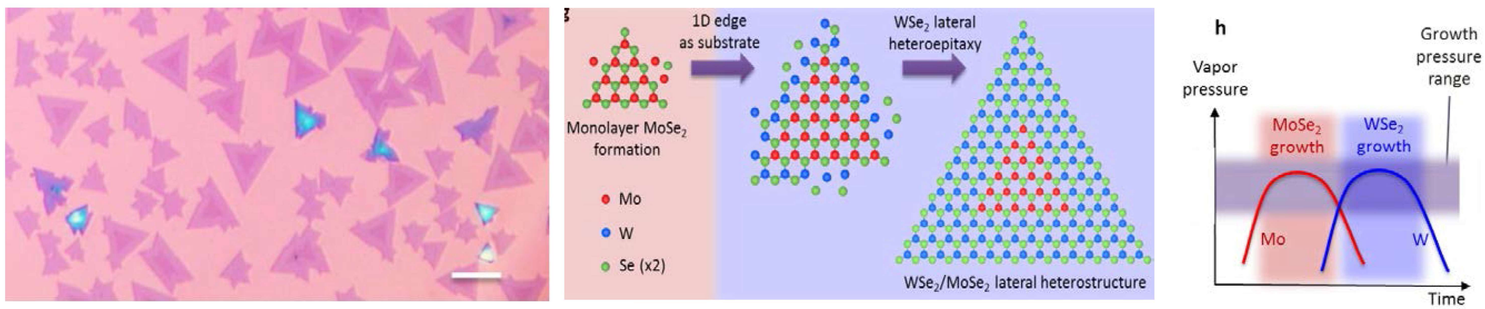


Navarro-Moratalla, *et al., Nature Communications* 7, 11043 (2016)

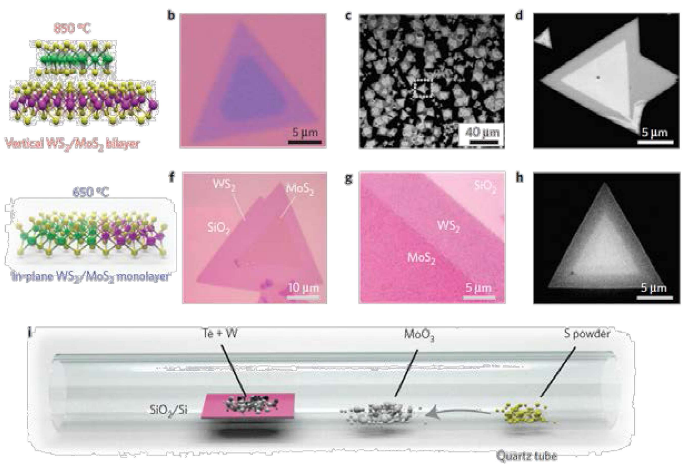


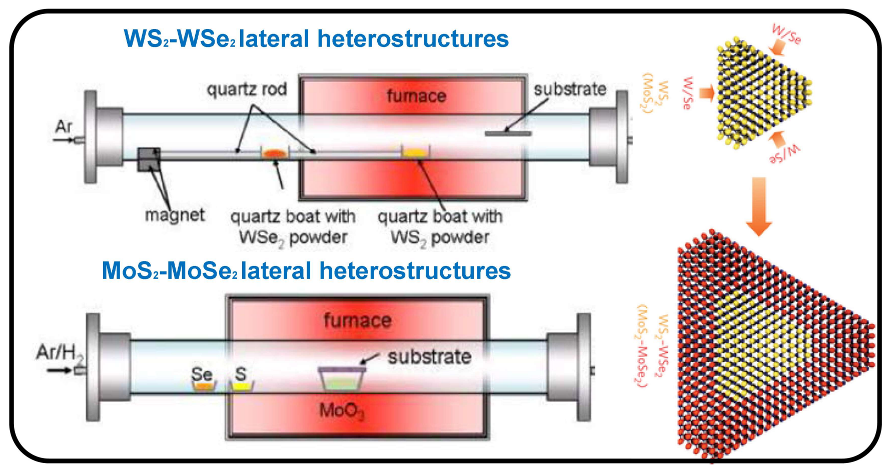
Novoselov *et al., Nature Materials 14*, 301 (2015)

Heterostructures Growth via LPCVD



Xu, *et al., Nature Materials* 13, 1096 (2014)





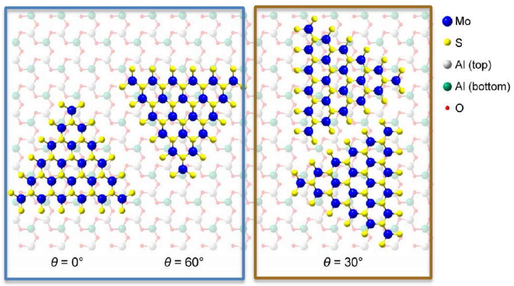
Ajayan, *et al., Nature Materials* 13, 1135 (2014)

Duan, *et al., Nature Nanotechnology* 9, 1024 (2014)

Monolayer Growth via MOCVD and Transfer

MoS_2 on (0001) sapphire

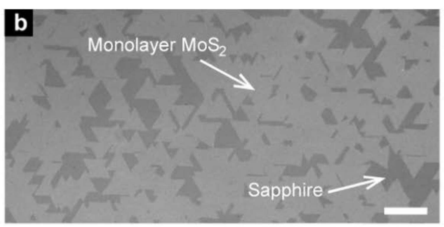
D. Dumcenco, et al. ACS Nano (2015)



Mismatch~-0.4% **Mismatch~13%**

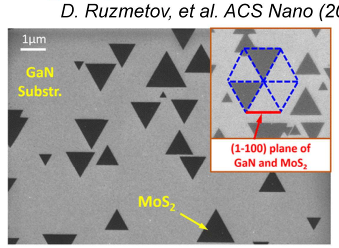
(3x3) MoS_2/(2x2)Al_2O_3

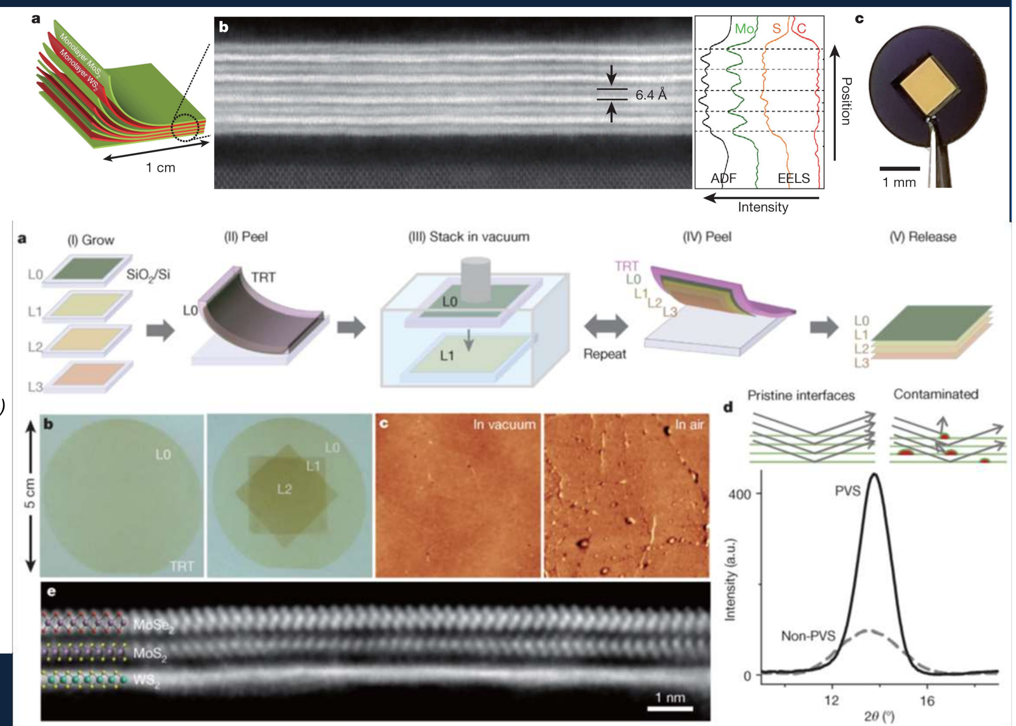
Substrate/Film	a (Å)
(0001)Sapphire	0.476
(0001)SiC	0.307
(0001)GaN	0.319
MoS_2	0.316
WS_2	0.316
WSe_2	0.332



MoS_2 on (0001) GaN

D. Ruzmetov, et al. ACS Nano (2015)

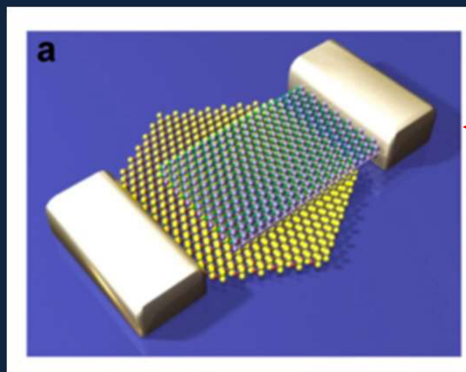




Kis, *et al., ACS Nano, 9* (4), 4611 (2015)

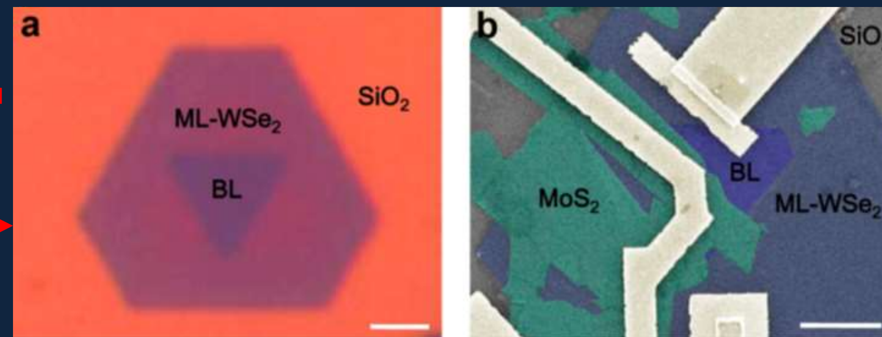
Park, *et al., Nature,* 550, 229 (2017)

How to cheaply produce large, uniform, high-quality layers and heterostructures?

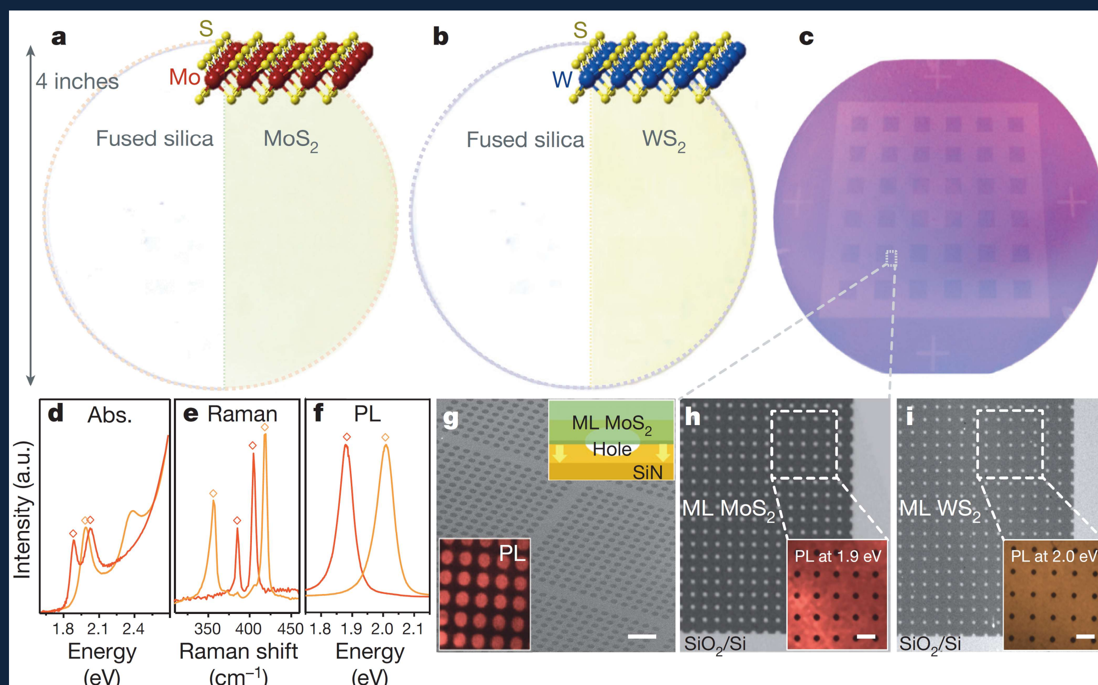


Ideal

Reality



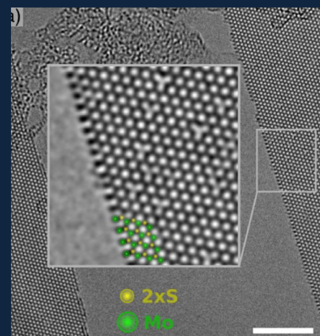
Cheng *et al.*, *Nano Lett.*, 14, 5590 (2014)



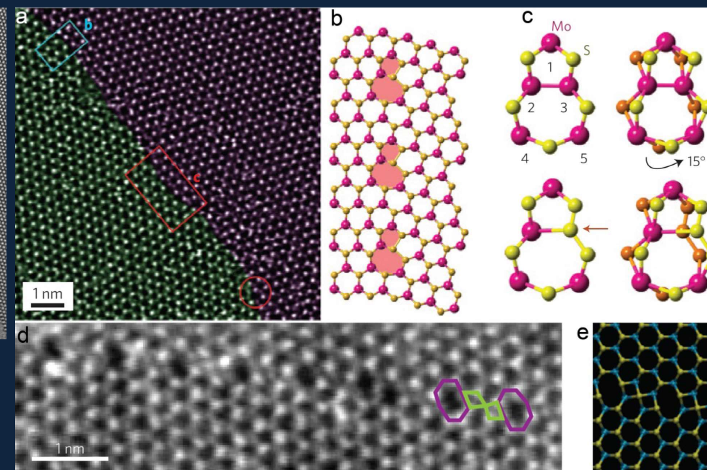
Park, *et al.*,
Nature 520, 656 (2015)

Key Challenges Facing TMD Research

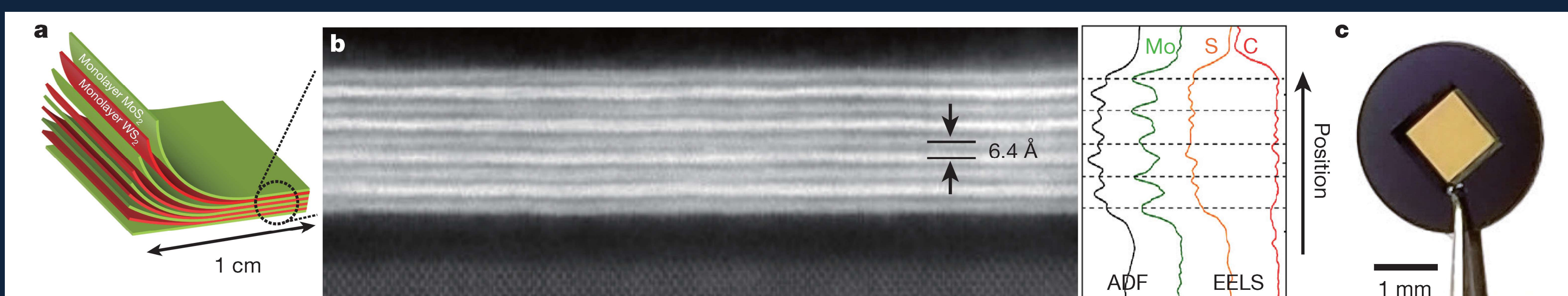
- Scaling up (maybe using MOCVD)
- **Controlled heterostructure growth**
- Control of grain boundaries and defects
- Air stability
- Control of doping (alloys)



Komsa, *et al.*, *PRL*, 109, 035503 (2012)



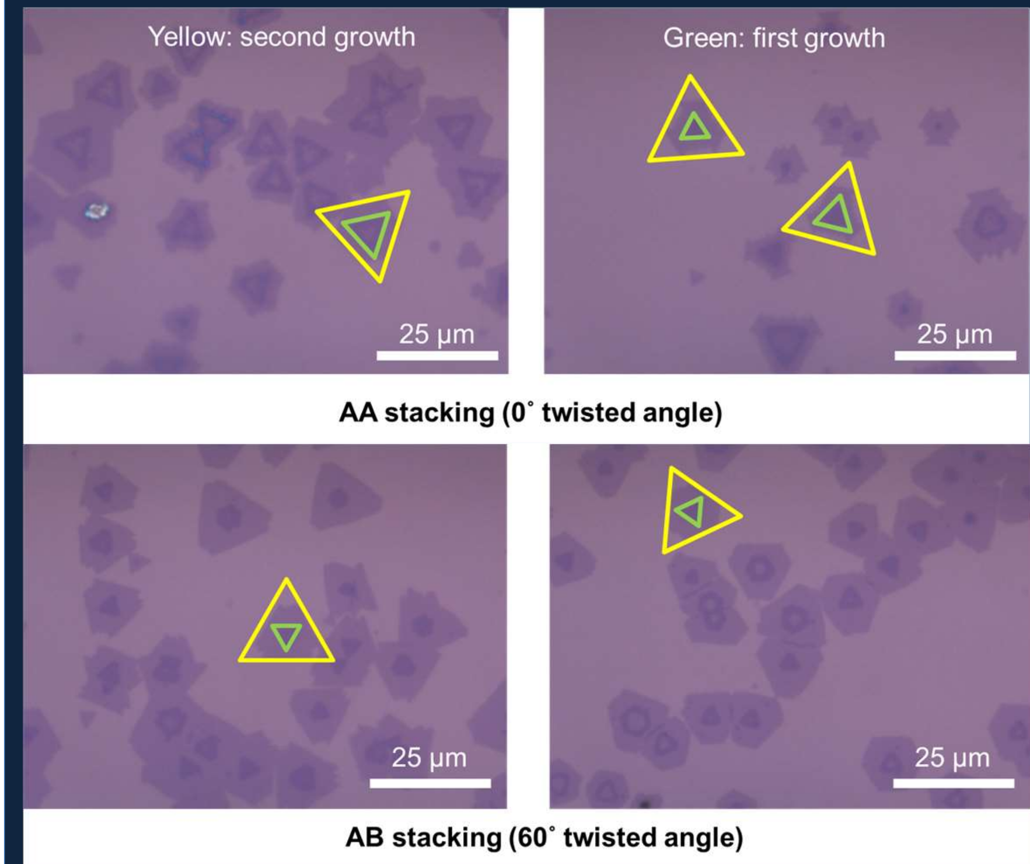
Najmaei, *et al.*, *Nature Materials*, 12, 754 (2013)

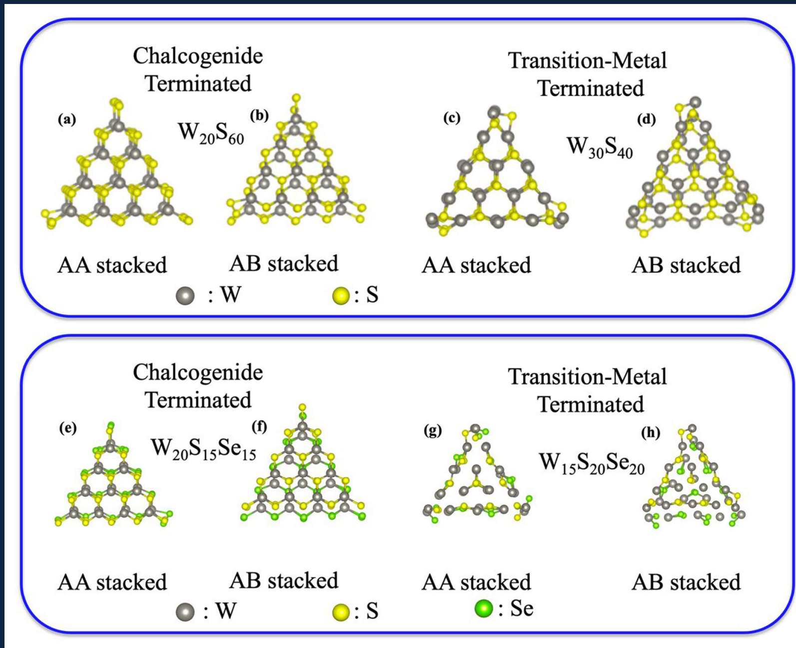


Park, *et al.*, *Nature*, 550, 229 (2017)

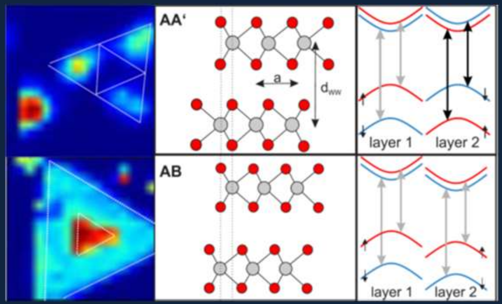
Control of Stacking Angles

WS_2 on WS_2 (homobilayers)



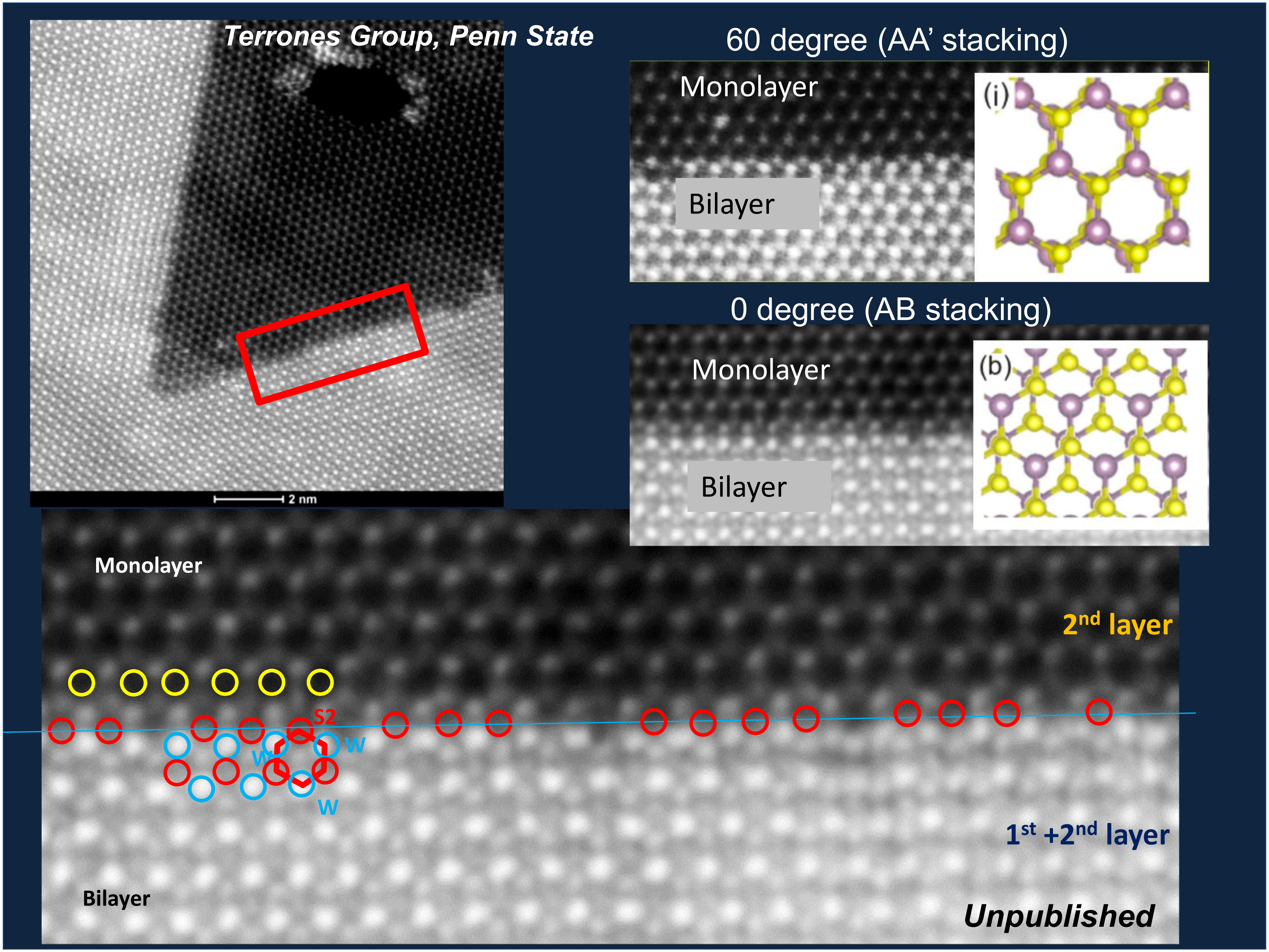


Led by Datta (*NJIT)*



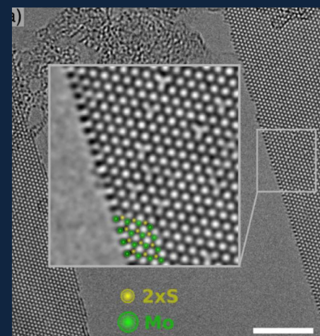
Led by Rahimi-Iman *(Philipps-Universität Marburg)*

Scientific Reports, 10, 1648 (2020)
Journal of Physical Chemistry C, 123(35), 21813 (2019)

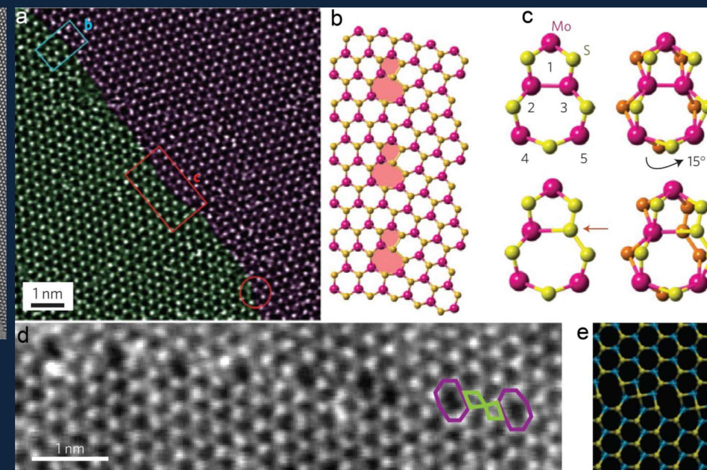

Terrones Group, Penn State
2 nm
60 degree (AA' stacking)
Monolayer
Bilayer
(i)
0 degree (AB stacking)
Monolayer
Bilayer
(b)
Monolayer
2nd layer
S2
W
W
W
1st +2nd layer
Bilayer
Unpublished

Key Challenges Facing TMD Research

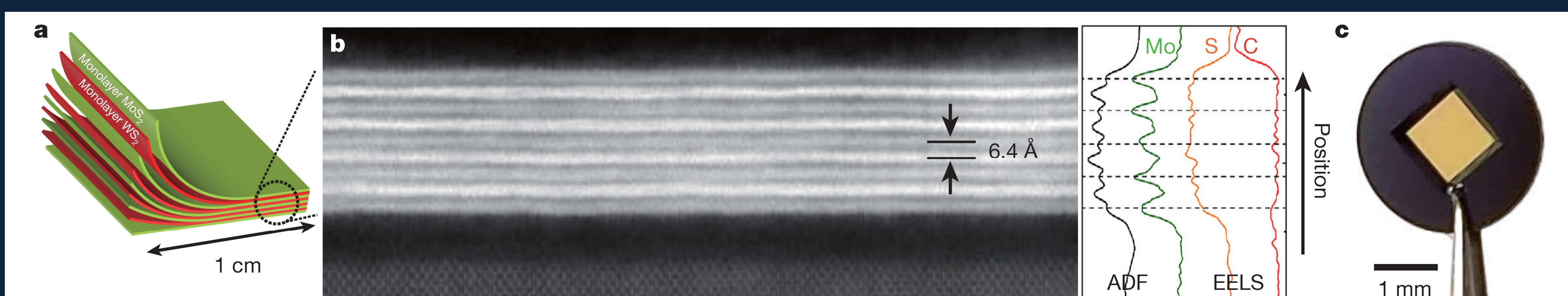
- Scaling up (maybe using MOCVD)
- Controlled heterostructure growth
- Control of grain boundaries and **defects**
- **Air stability**
- Control of doping (alloys)



Komsa, *et al., PRL*, 109, 035503 (2012)



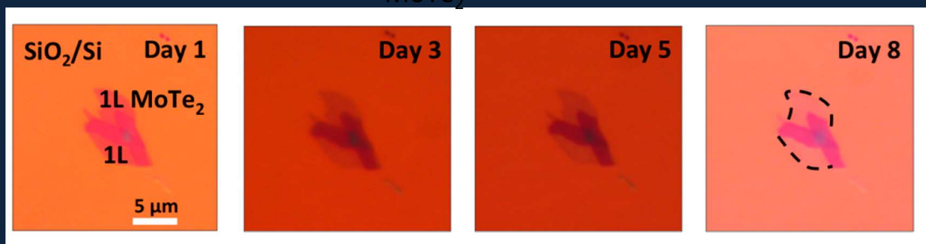
Najmaei, *et al., Nature Materials*, 12, 754 (2013)



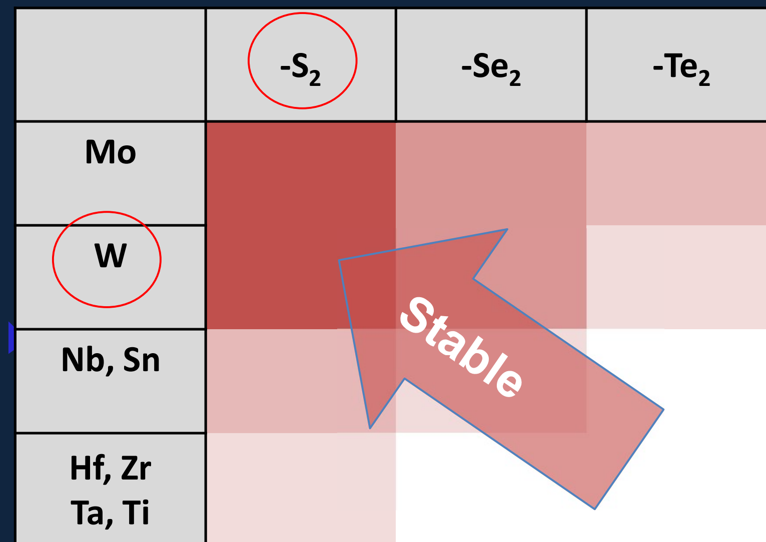
Park, *et al., Nature,* 550, 229 (2017)

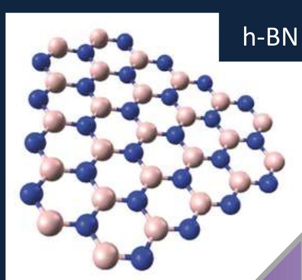
Air Stability of 2D Materials

MoTe$_2$



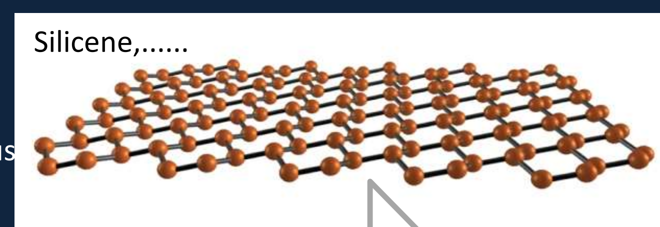
B. Chen et al. *ACS nano* 9.5326 (2015)



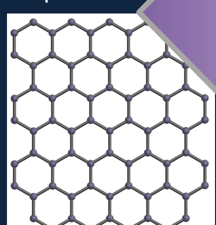


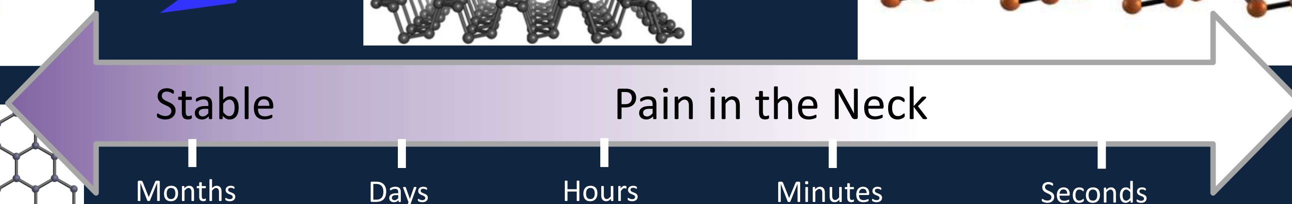
h-BN

Black Phosphorus



Graphene

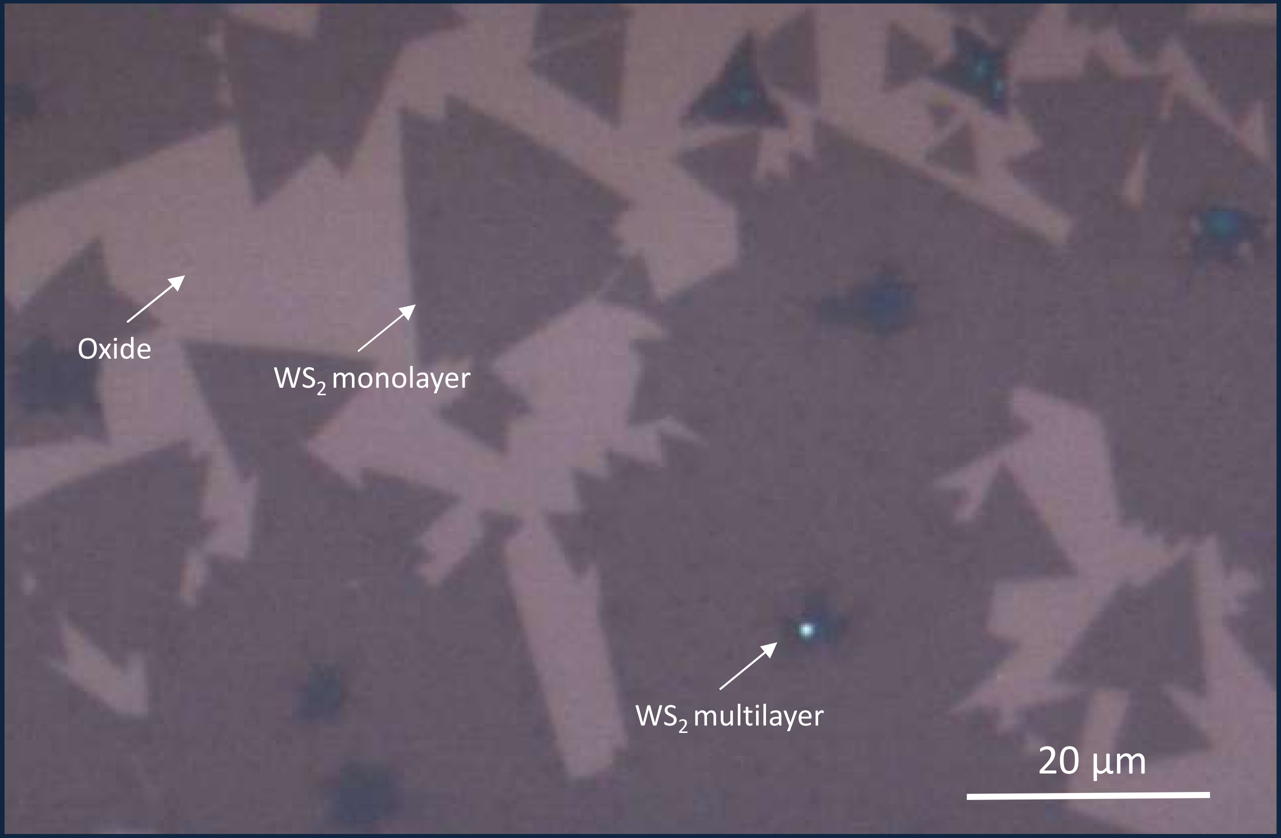




Time scale of degradation

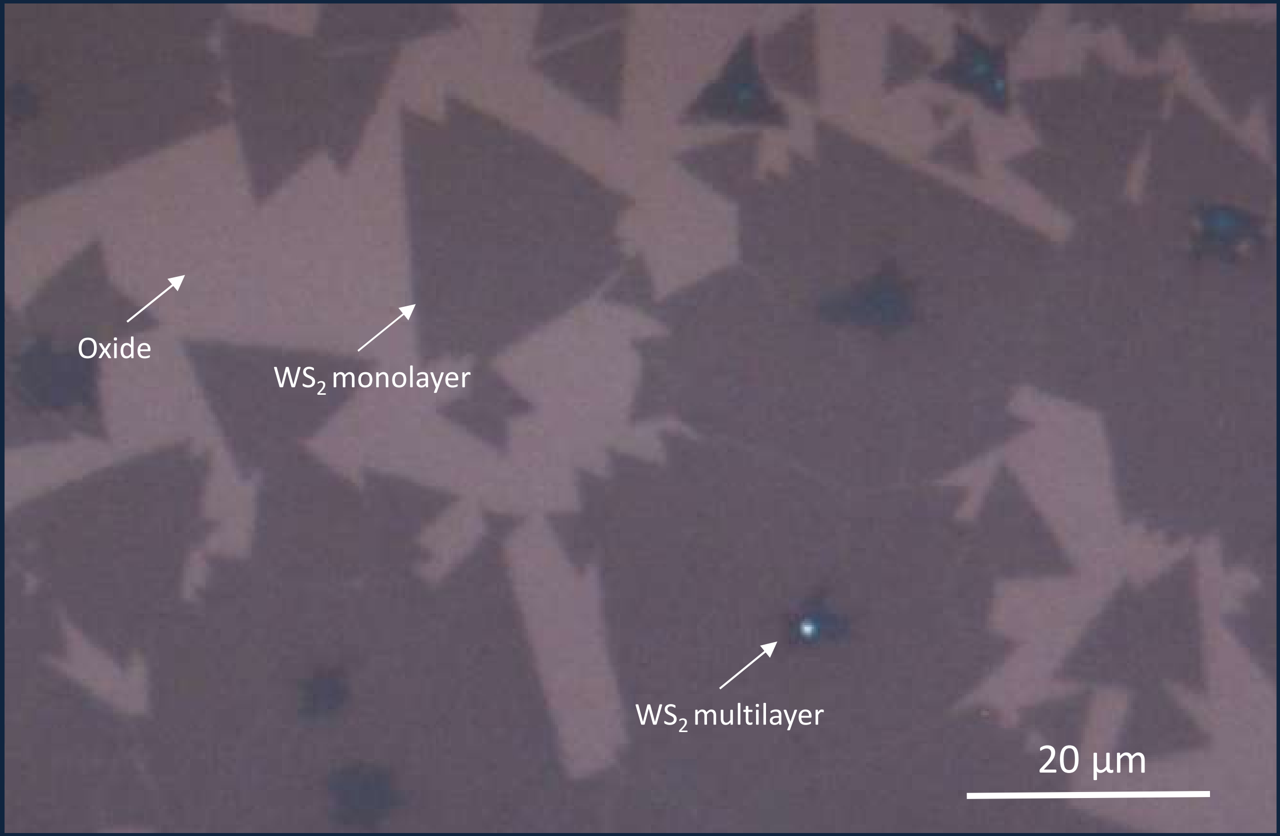
Temporal Degradation of WS_2

Day 1



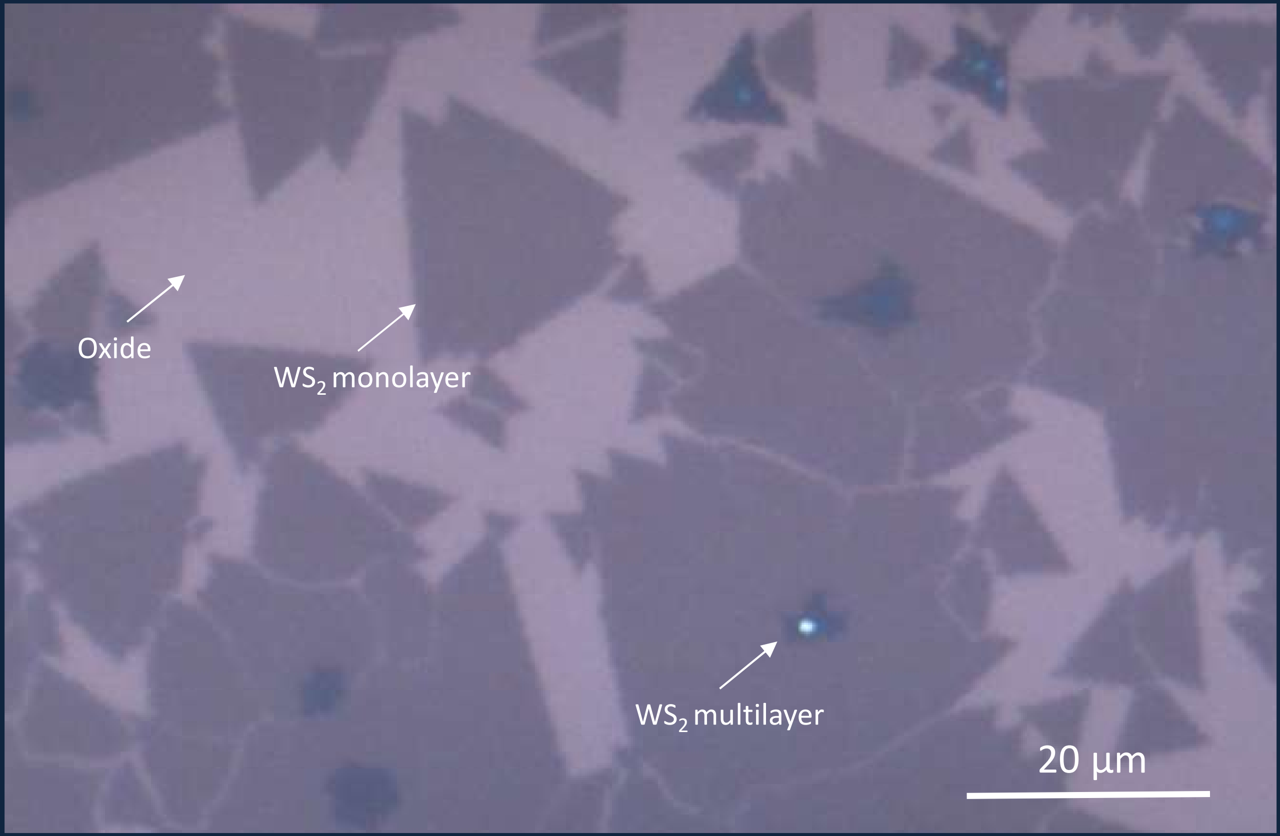
Temporal Degradation of WS_2

Day 5



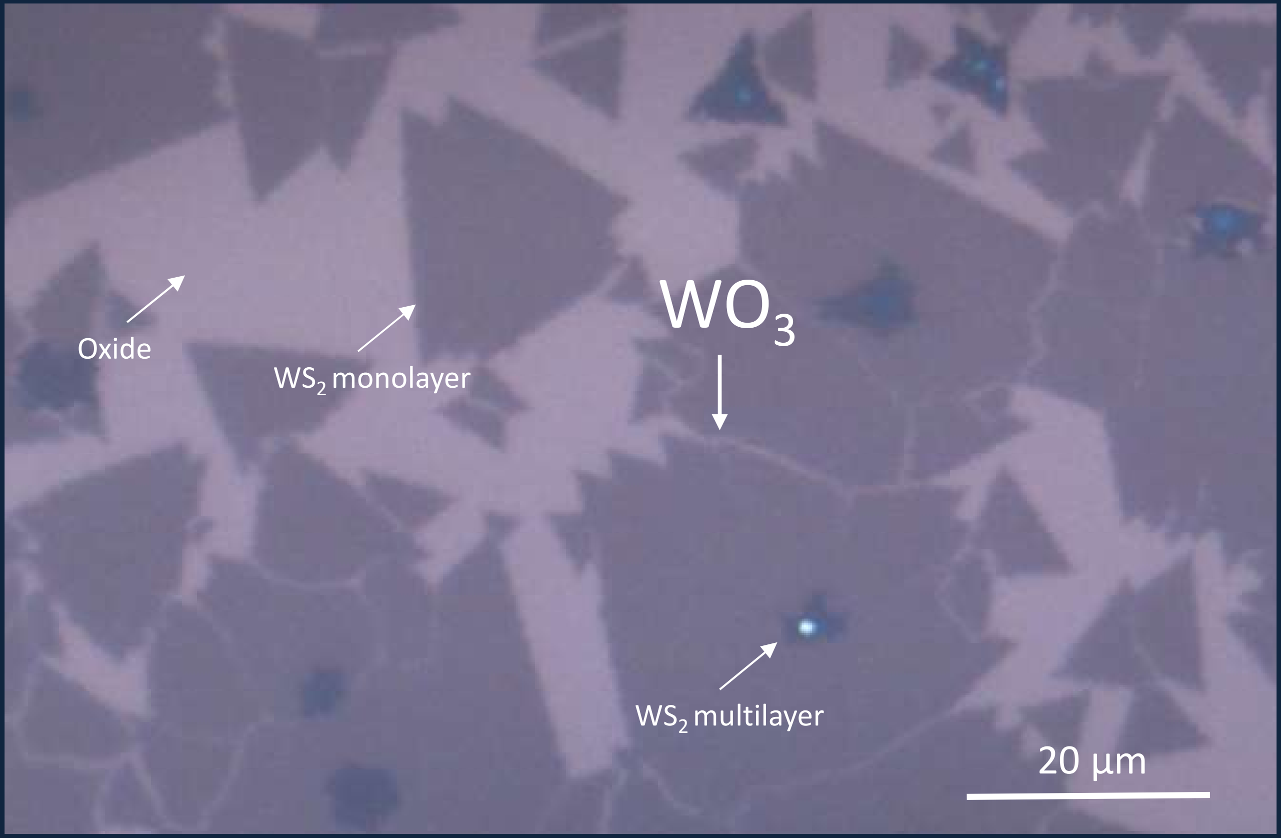
Temporal Degradation of WS_2

Day 13

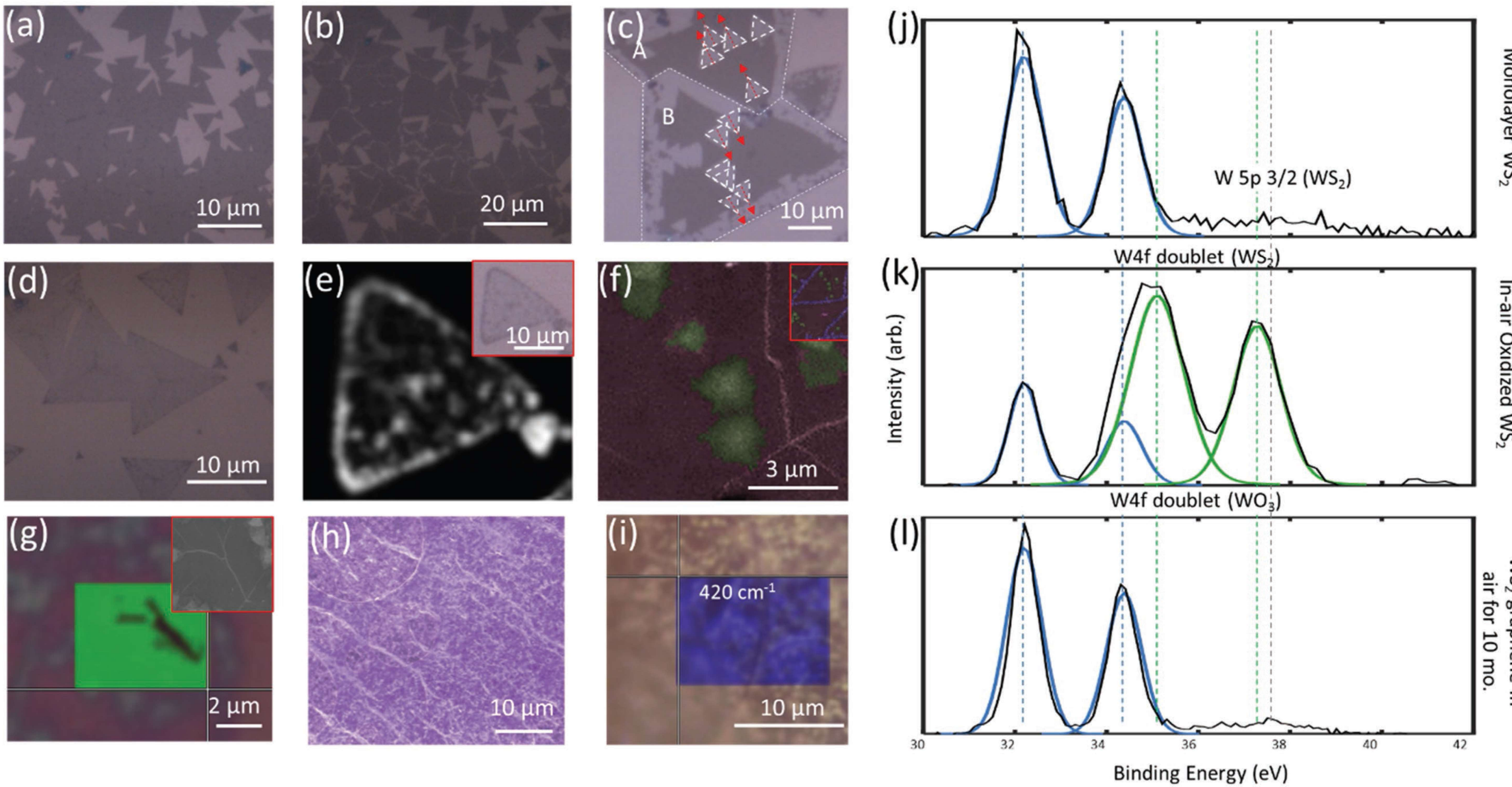


Temporal Degradation of WS_2

Day 13

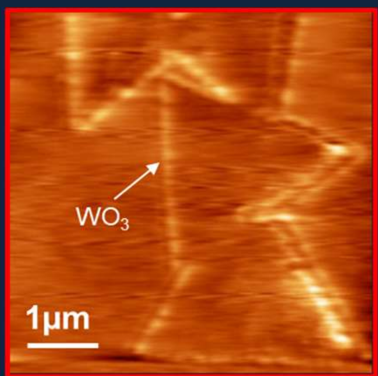


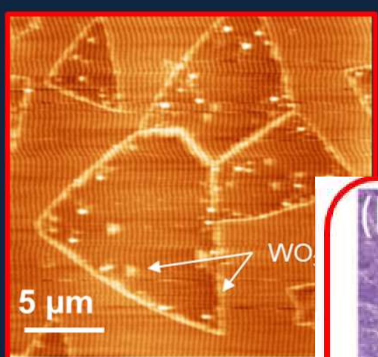
Enhanced Air Stability: WS_2 Grown on Graphene

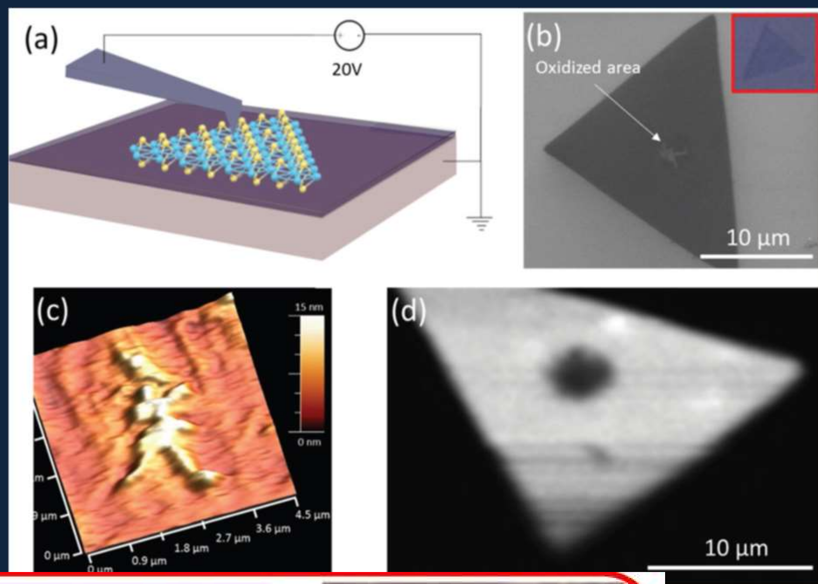


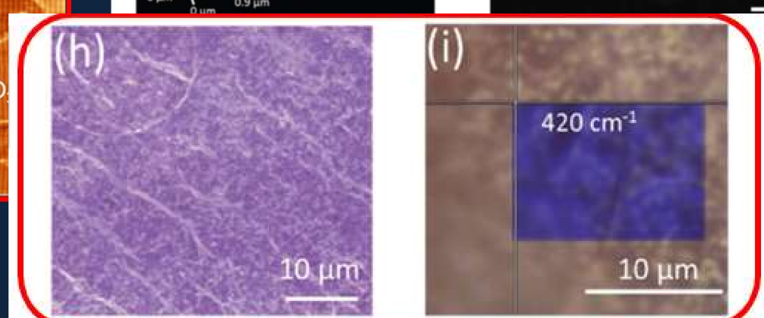
Advanced Materials, 18, 1603898 (2017)

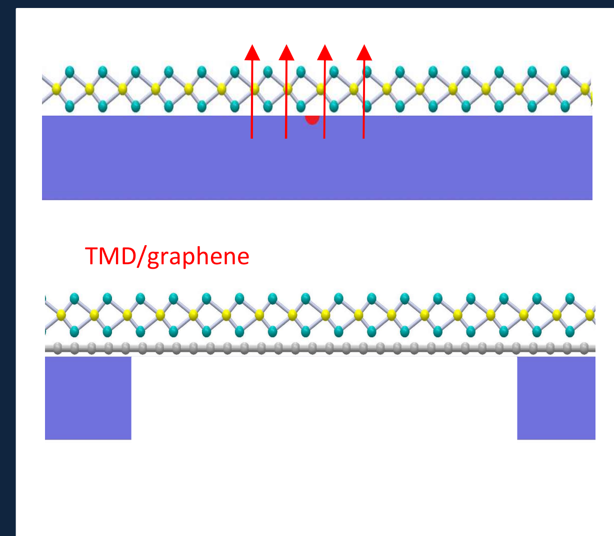
Surface Electric Field and Oxidation









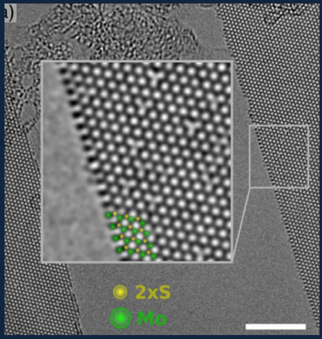


The surface electric fields, affecting the rate of WS_2 oxidation.

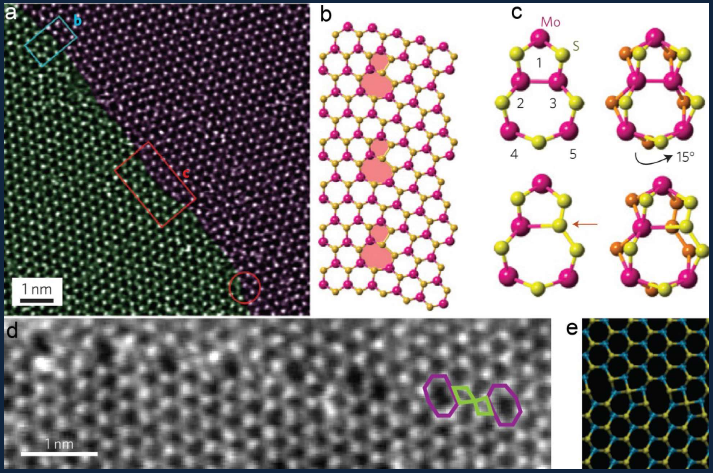
Advanced Materials, 18, 1603898 (2017)

Key Challenges Facing TMD Research

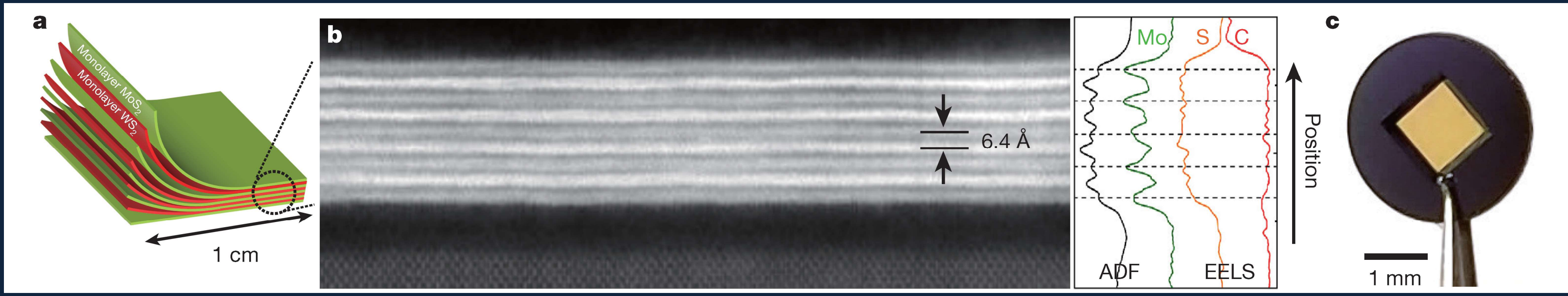
- Scaling up (maybe using MOCVD)
- Controlled heterostructure growth
- Control of grain boundaries and defects
- Air stability
- **Control of doping (alloys)**



Komsa, *et al.*, *PRL*, 109, 035503 (2012)



Najmaei, *et al., Nature Materials*, 12, 754 (2013)



Park, *et al., Nature,* 550, 229 (2017)

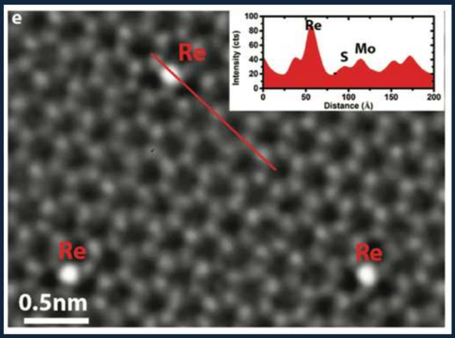
Doping of Transition Metal Atoms in TMDs via Chemical Vapor Deposition

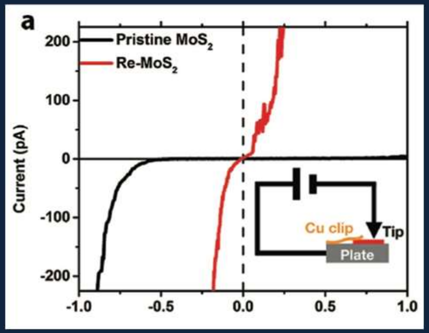
- Doping ➔ at the heart of modern semiconductor technologies

- Substitutional doping of 2D TMDs may effectively tune their electrical, optical, magnetic, and catalytic properties.

Ferromagnetism in 2D materials

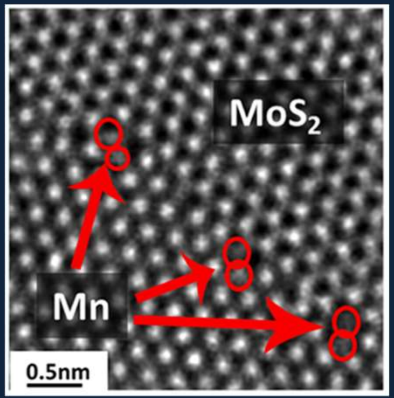
$Re:MoS_2$





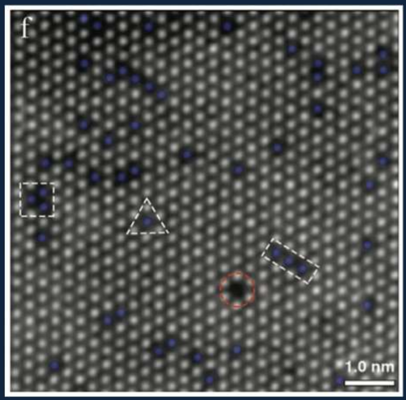
Zhang *et al.*, *Adv. Funct. Mater.*, 2018, **28**, 1706950

$Mn:MoS_2$



Zhang *et al.*, *Nano Lett.*, 2015, **15**, 6586

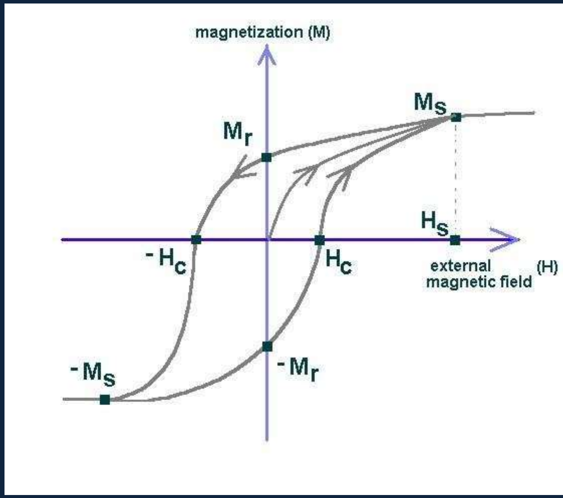
$Nb:WS_2$

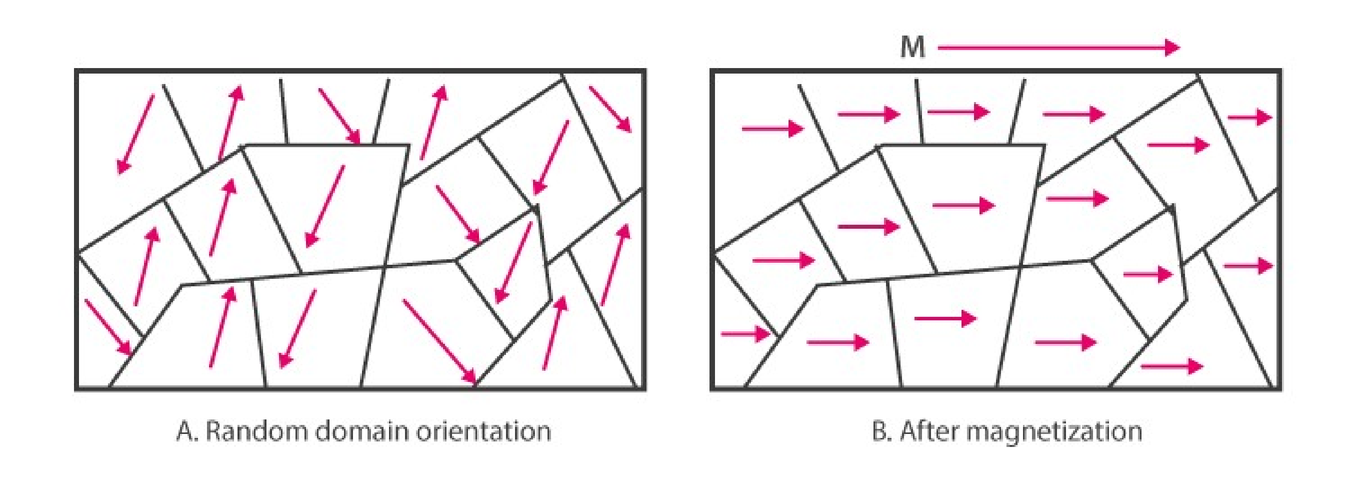


Gao *et al.*, *Adv. Mat.*, 2016, **28**, 9735

What is Ferromagnetism?

- Intrinsic magnetic dipole moment (on each crystal lattice) align in the same direction.
- Hysteresis
- Curie temperature





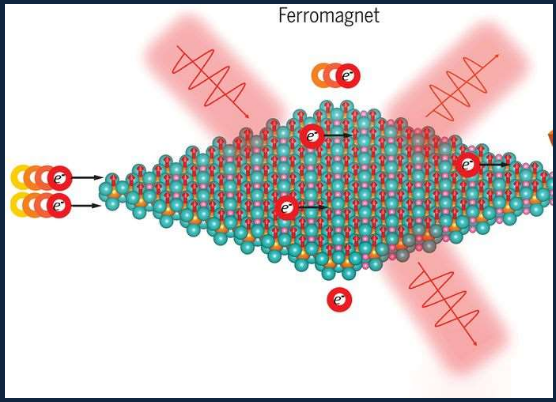
A. Random domain orientation

B. After magnetization

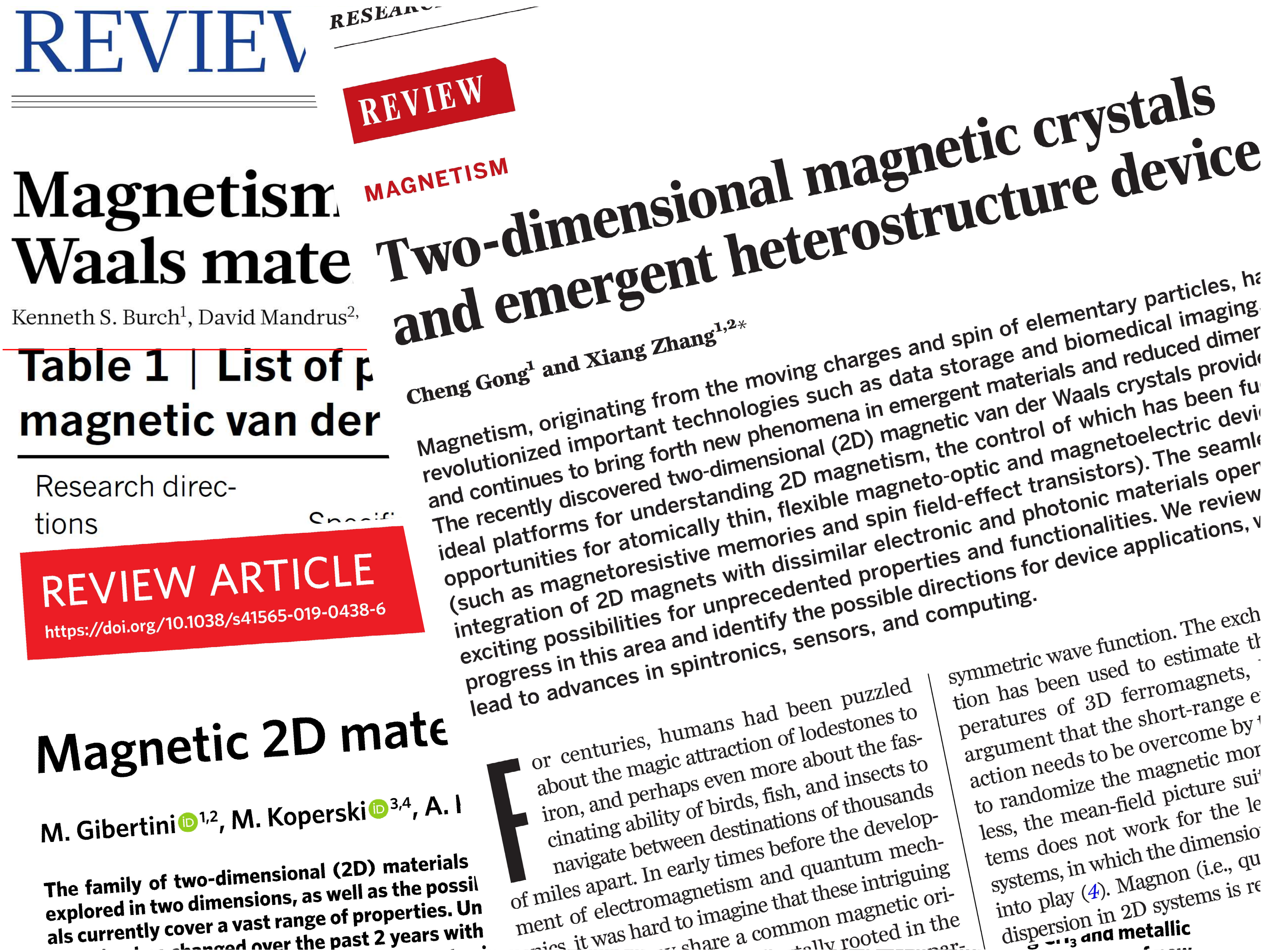
Ferromagnetism in 2D Limits

- Access the fundamentals of magnetism in reduced dimensions.
- Decouple from the substrates, electrical control, flexible, and functionalized
- Integrate into emergent heterostructures: interplay of distinct physical properties
- Spintronics, quantum information science

- **Extrinsic magnetism:** defect engineering, surface functionalization, doping
- **Intrinsic magnetism:** CrX_3 (X = Cl, Br and I), $CrGeTe_3$, Fe_3GeTe_2, MnX_2 (X = S, Se), VX_2 (X = S, Se, Te), and 2D oxides, halides, nitrides, carbides…



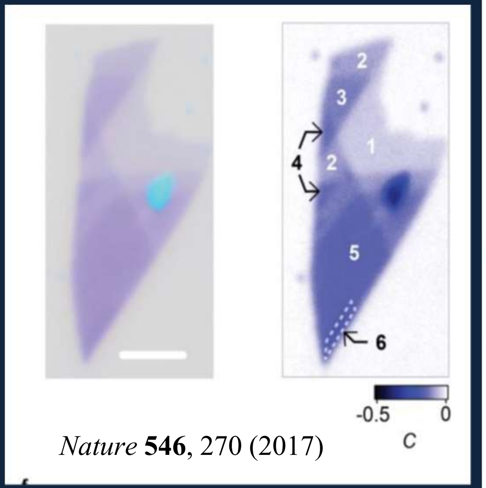
Gong and Zhang, Science, 363(6428), 4450 (2019)

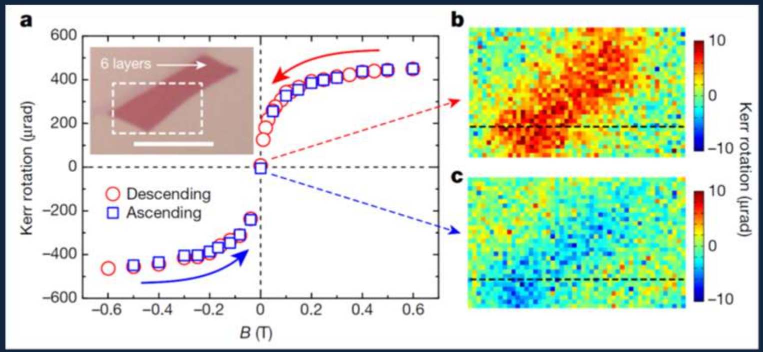

REVIEW
RESEARCH
REVIEW
MAGNETISM
Magnetism
Waals mate
Two-dimensional magnetic crystals
and emergent heterostructure device
Kenneth S. Burch1, David Mandrus2,
Cheng Gong1 and Xiang Zhang1,2*
Table 1 | List of
magnetic van der
Research directions
Magnetism, originating from the moving charges and spin of elementary particles, has
revolutionized important technologies such as data storage and biomedical imaging,
and continues to bring forth new phenomena in emergent materials and reduced dimen
The recently discovered two-dimensional (2D) magnetic van der Waals crystals provide
ideal platforms for understanding 2D magnetism, the control of which has been fu
opportunities for atomically thin, flexible magneto-optic and magnetoelectric devi
(such as magnetoresistive memories and spin field-effect transistors). The seaml
integration of 2D magnets with dissimilar electronic and photonic materials oper
exciting possibilities for unprecedented properties and functionalities. We review
progress in this area and identify the possible directions for device applications, v
lead to advances in spintronics, sensors, and computing.
REVIEW ARTICLE
https://doi.org/10.1038/s41565-019-0438-6
For centuries, humans had been puzzled about the magic attraction of lodestones to iron, and perhaps even more about the fascinating ability of birds, fish, and insects to navigate between destinations of thousands of miles apart. In early times before the development of electromagnetism and quantum mechanics, it was hard to imagine that these intriguing
symmetric wave function. The exch
tion has been used to estimate th
peratures of 3D ferromagnets,
argument that the short-range e
action needs to be overcome by
to randomize the magnetic mor
less, the mean-field picture sui
tems does not work for the le
systems, in which the dimensio
into play (4). Magnon (i.e., qu
dispersion in 2D systems is re
Magnetic 2D mate
M. Gibertini1,2, M. Koperski3,4, A. I
The family of two-dimensional (2D) materials
explored in two dimensions, as well as the possil
als currently cover a vast range of properties. Un
als currently changed over the past 2 years with

Discovery of Ferromagnetism in 2D Crystals

- In early 2017, the first observations of ferromagnetism at cryogenic temps were reported.
- CrI_3 on EuS, WSe_2 monolayers on EuS, WSe_2 monolayers on 10 nm CrI_3.

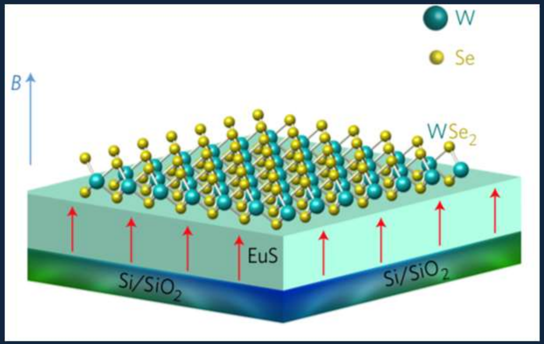
exfoliated, insulator or conductor, unstable in air





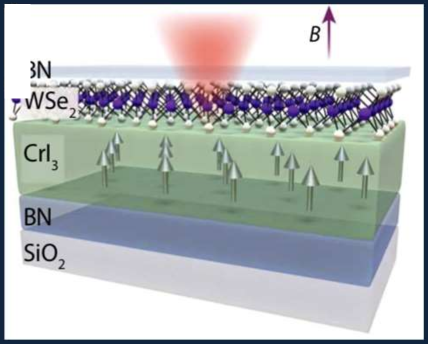
CrI_3 on EuS ➔ T_c ~ 45K

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



WSe_2 on EuS ➔ T_c ~ 16.5K

Zhao *et al., Nat. Nano.*, **12**, 757 (2017)



WSe_2/CrI_3 ➔ T_c ~ 61K

Zhong *et al., Sci. Adv.*, **3**, 6586 (2017)

1 JULY 2005 VOL 309 SCIENCE

At *Science*, we tend to get excited about new discoveries that lift the veil a little on how things work, from cells to the universe. That puts our focus firmly on what has been added to our stock of knowledge. For this anniversary issue, we decided to shift our frame of reference, to look instead at what we *don't* know: the scientific puzzles that are driving basic scientific research.

We began by asking *Science*'s Senior Editorial Board, our Board of Reviewing Editors, and our own editors and writers to suggest questions that point to critical knowledge gaps. The ground rules: Scientists should have a good shot at answering the questions over the next 25 years, or they should at least know how to go about answering them. We intended simply to choose 25 of these suggestions and turn them into a survey of the big questions facing science. But when a group of editors and writers sat down to select those big questions, we quickly realized that 25 simply wouldn't convey the grand sweep of cutting-edge research that lies behind the responses we received. So we have ended up with 125 questions, a fitting number for *Science*'s 125th anniversary.

First, a note on what this special issue is not: It is not a survey of the big societal challenges that science can help solve, nor is it a forecast of what science might achieve. Think of it instead as a survey of our scientific ignorance, a broad swath of questions that scientists themselves are asking. As Tom Siegfried puts it in his introductory essay, they are "opportunities to be exploited."

We selected 25 of the 125 questions to highlight based on several criteria: how fundamental they are, how … r scientific disciplines. Some have few … verse, for example. Others we

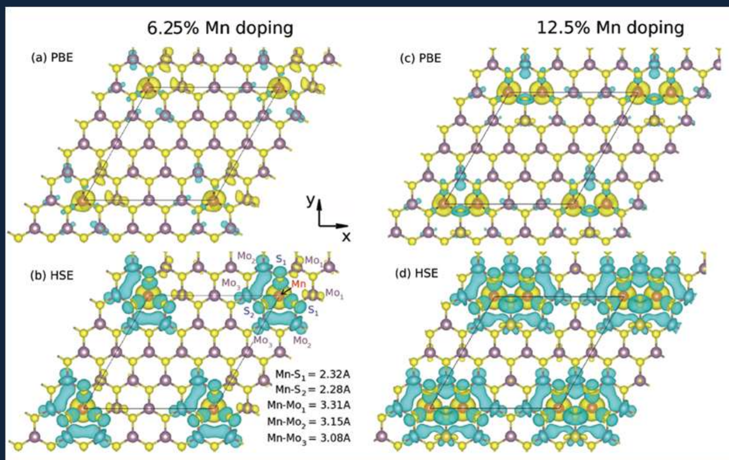
Is it possible to create magnetic semiconductors that work at room temperature?

Such devices have been demonstrated at low temperatures but not yet in a range warm enough for spintronics applications.

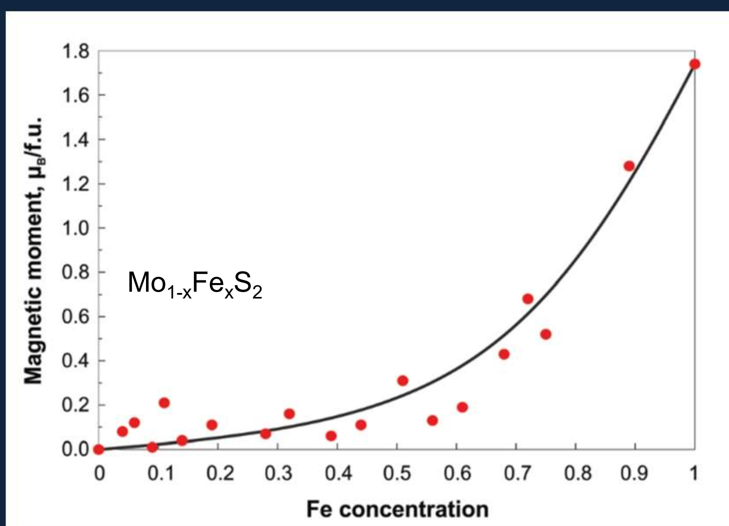
Critical Factors for Practical Applications

- Air Stability
- Curie Temperature above RT…..
- Scalability (uniformity)………
- 2D Dilute Magnetic Semiconductors…

2D DMS with High Curie Temperatures?



Ramasubramaniam, Phys Rev. B. ***87***, 195201 (2013)



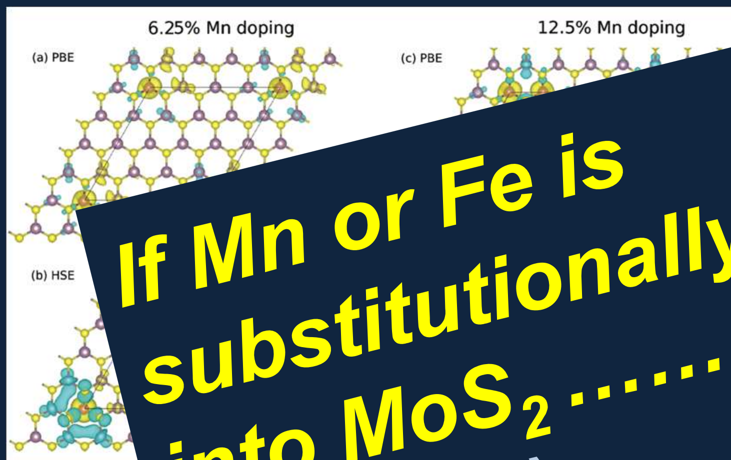
Antipina *et al.*, *Phys. Chem. Chem. Phys.*, **18**, 26956 (2016)

5	6	7	8
23 V	24 Cr	25 Mn	26 Fe
41 Nb	42 Mo	43 Tc	
73 Ta	74 W	75 Re	

Material	Ti	V	Cr	Mn	Fe	Co	Ni
MoS_2	NM	28 K (Z)	AFM	190 K (Z)	271 K (Z)	AFM	NM
WS_2	NM	109 K (Z)	AFM	271 K (X-Y)	375 K (X-Y)	AFM	NM
$MoSe_2$	NM	224 K (Z)	AFM	131 K (X-Y)	201 K (X-Y)	0 K (Z)	NM
WSe_2	NM	179 K (Z)	AFM	310 K (X-Y)	331 K (X-Y)	190 K (Z)	NM
$MoTe_2$	NM	AFM	AFM	AFM	94 K (Z)	21 K (Z)	NM

Tiwari et al., npj 2D Materials and Applications, 54 (2021)

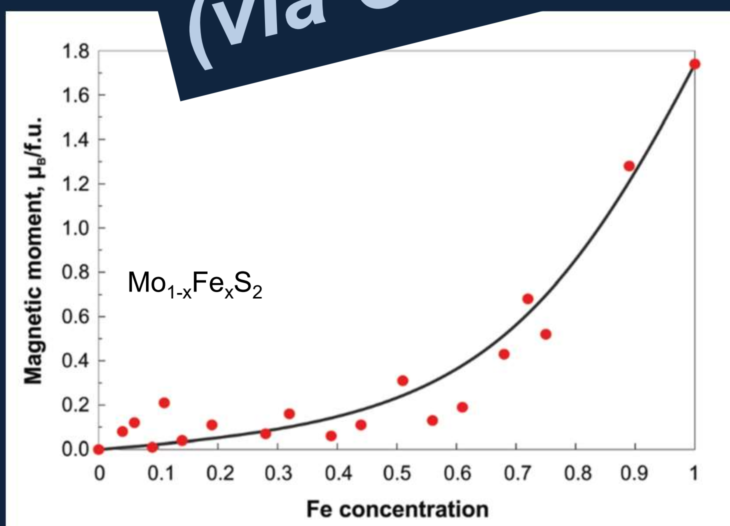
2D DMS with High Curie Temperatures?



Ramasubra

If Mn or Fe is substitutionally doped into MoS_2 ……. (via CVD)

5	6	7	8
23 V	24 Cr	25 Mn	26 Fe
41 Nb	42 Mo	43 Tc	
73 Ta	74 W	75 Re	



Antipina *et al.*, *Phys. Chem. Chem. Phys.*, **18**, 26956 (2016)

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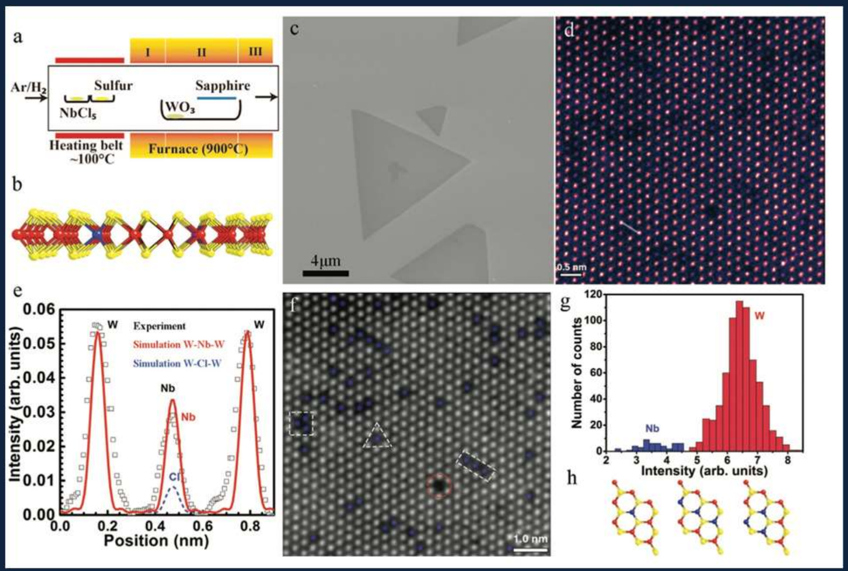
WSe_2	NM	179 K (Z)	AFM	310 K (X-Y)	331 K (X-Y)	190 K (Z)	NM
$MoTe_2$	NM	AFM	AFM	AFM	94 K (Z)	21 K (Z)	NM

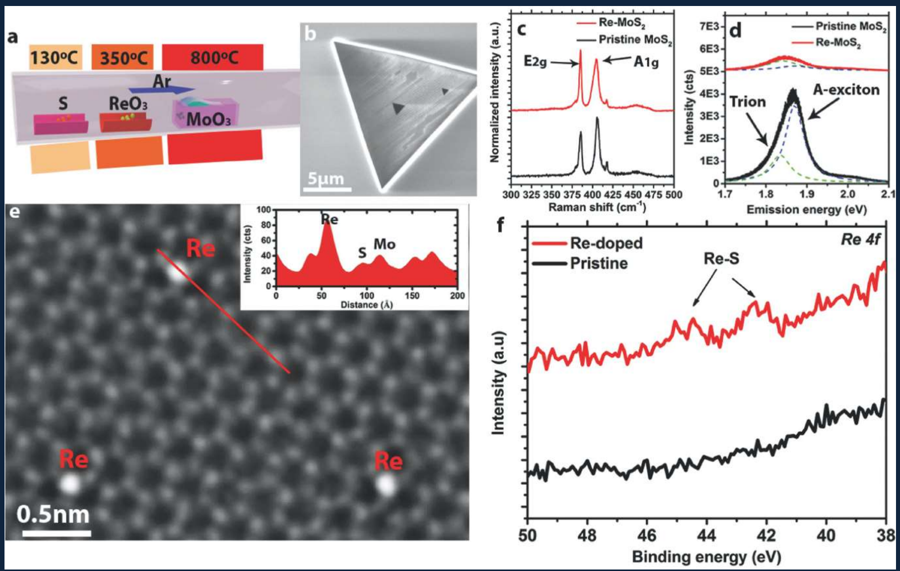
Tiwari et al., npj 2D Materials and Applications, 54 (2021)

*in situ D*oping of TMDs via CVD Growth



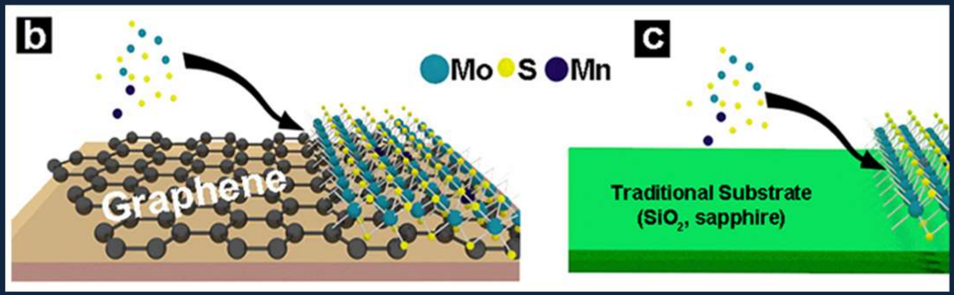
Gao *et al.*, *Adv. Mat.*, 2016, **28**, 9735-9743

6.7 at% Nb doping of WS_2 monolayer



Zhang *et al.*, *Adv. Funct. Mater.*, 2018, **28**, 1706950

1 at% Re doping of MoS_2 monolayer



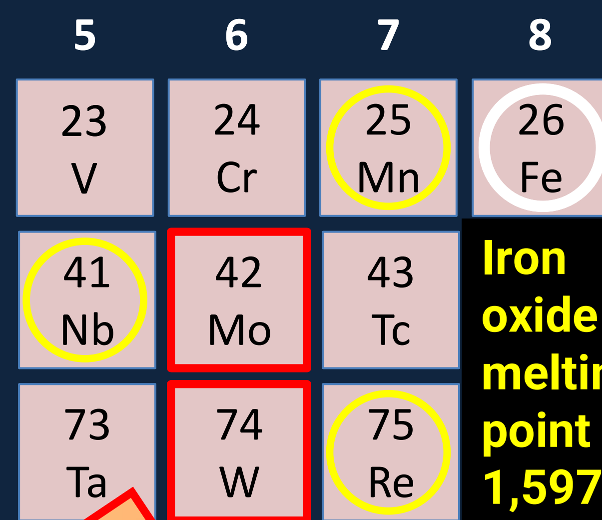
Zhang *et al.*, *Nano Lett.*, 2015, **15**, 6586-6591

Enhanced 2 at% Mn doping of MoS_2 monolayer via Graphene as a substrate

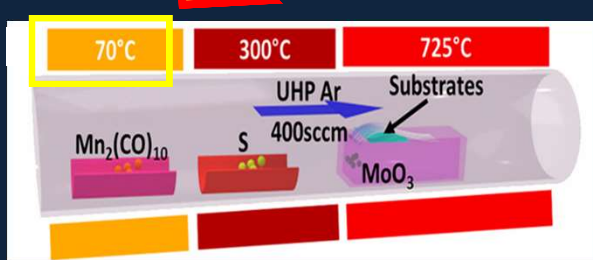
Ferromagnetism NOT observed

Fe-doping via CVD Growth?

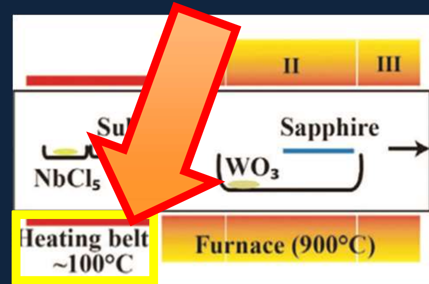
Dopant	Mn	Nb	Re
Source	$Mn_2(CO)_{10}$	$NbCl_5$	ReO_3
Melting point	154 °C	204.7°C	400 °C
Heating Temp.	70 °C	100 °C	350 °C 500 °C



Iron oxide melting point 1,597°C



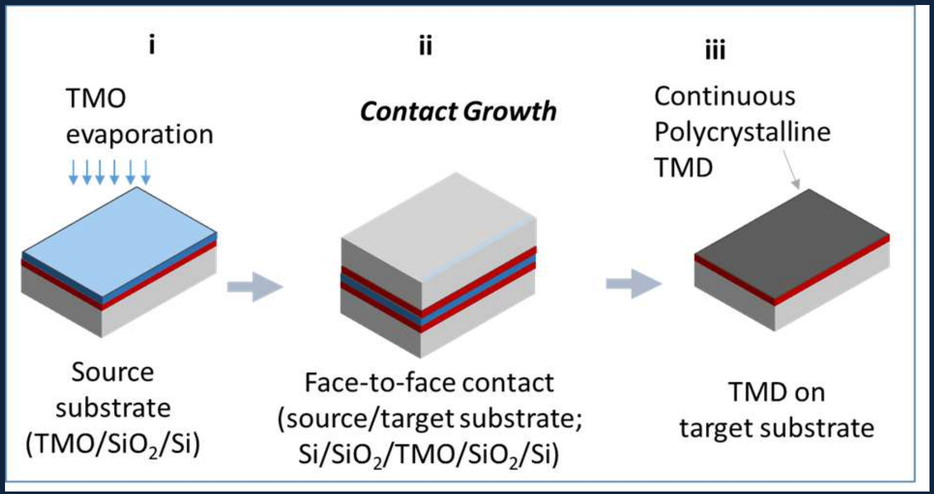
Zhang *et al., Nano Lett.*, 2015, **15**, 6586-6591

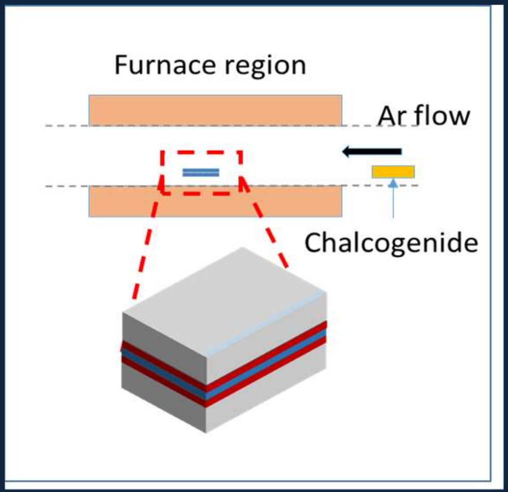


Gao *et al., Adv. Mat.*, 2016, **28**, 9735-9743

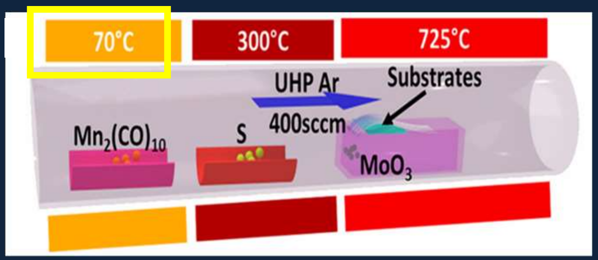
Zhang *et al., Adv. Funct. Mater.*, 2018, **28**, 1706950

Contact-Growth of TMDs

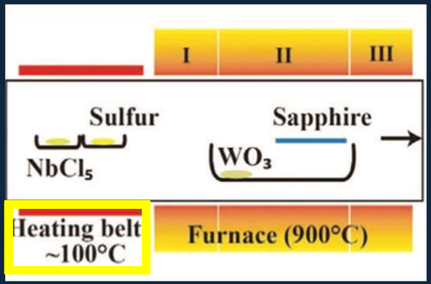




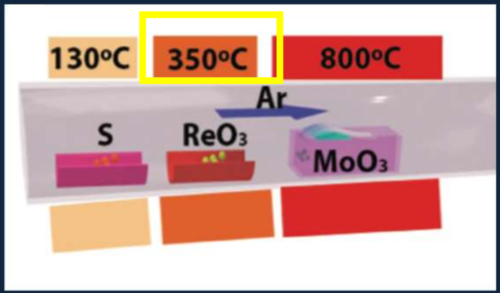
US Patent US 9,640,391 (2017)



Zhang *et al., Nano Lett.*, 2015, **15**, 6586-6591



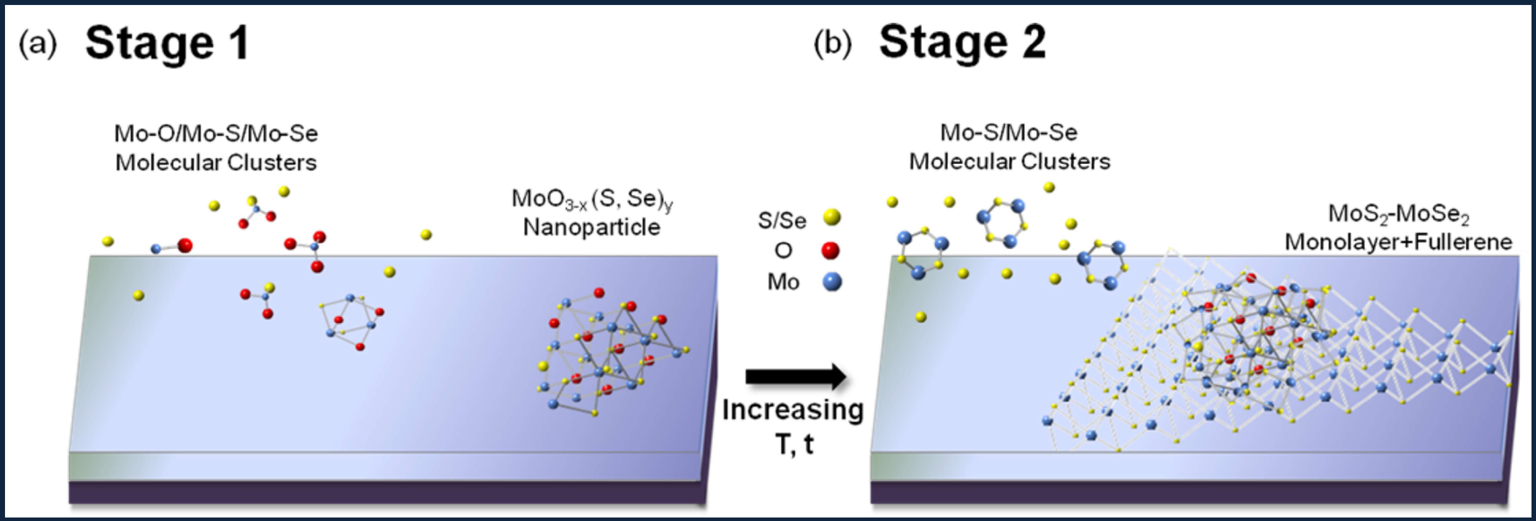
Gao *et al., Adv. Mat.*, 2016, **28**, 9735-9743



Zhang *et al., Adv. Funct. Mater.*, 2018, **28**, 1706950

MoS_2 Growth Mechanism

- Initial reaction between MoO_3 and S → intermediate volatile $MoO_{3-x}S_y$, (for MoS_2) and further sulfurization of $MoO_{3-x}S_y$ → conversion into MoS_2 grains



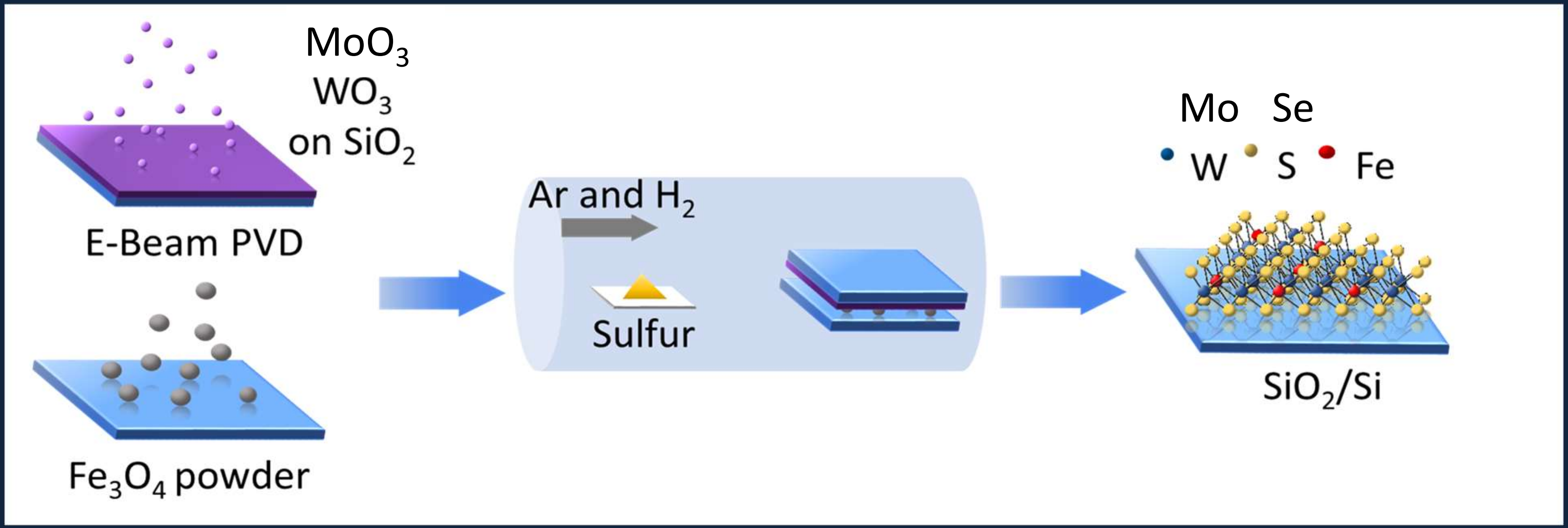
Cain *et al., ACS Nano* 2016, 10, 5440−5445

Braunecker *et al., Cryst. Growth Des*. 2018, 18, 1012−1019

In situ Fe Doping Process

Shichen Fu

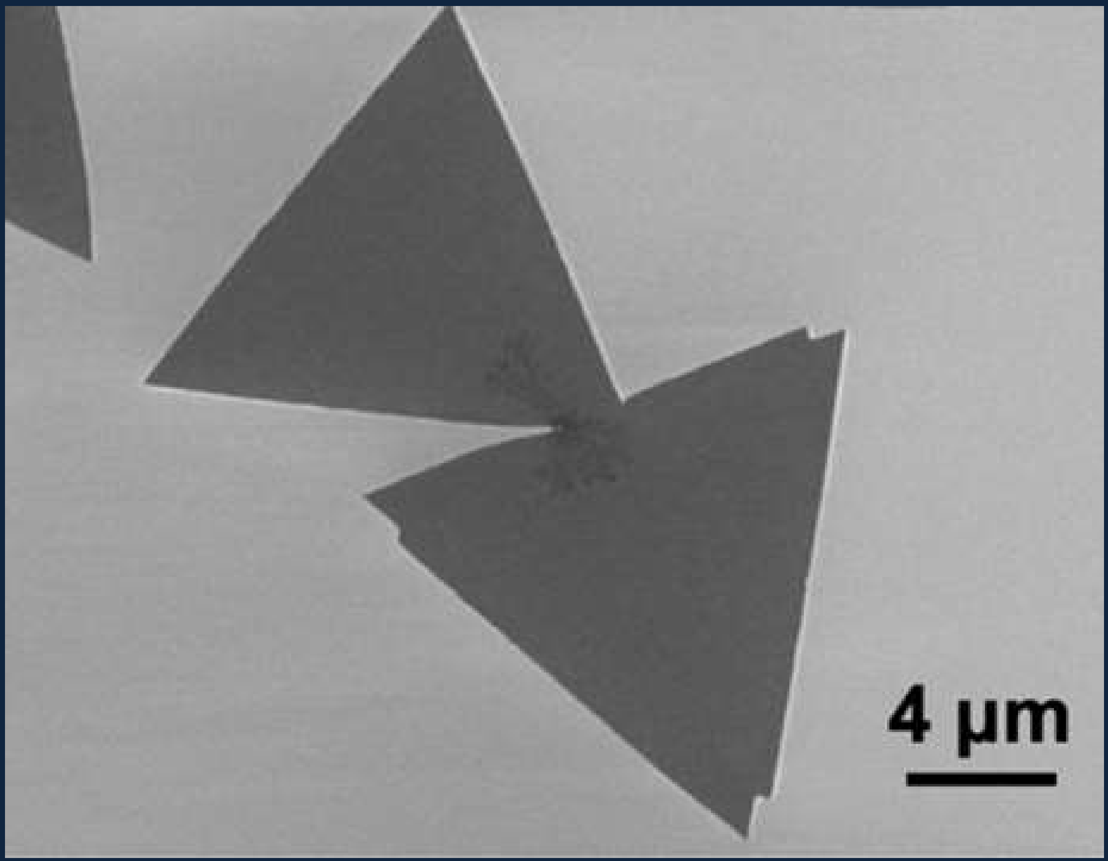
Kyungnam Kang

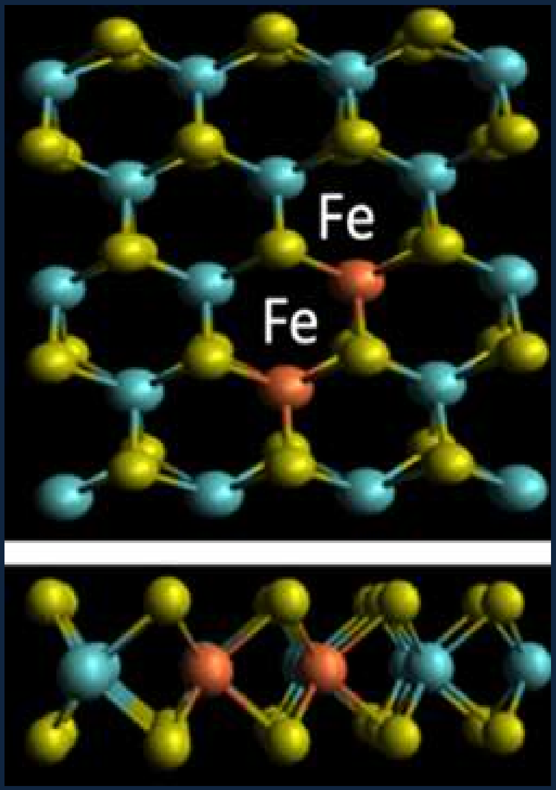


US Patent pending 18/008,126

Nanotechnology, 32. 095708 (2021)

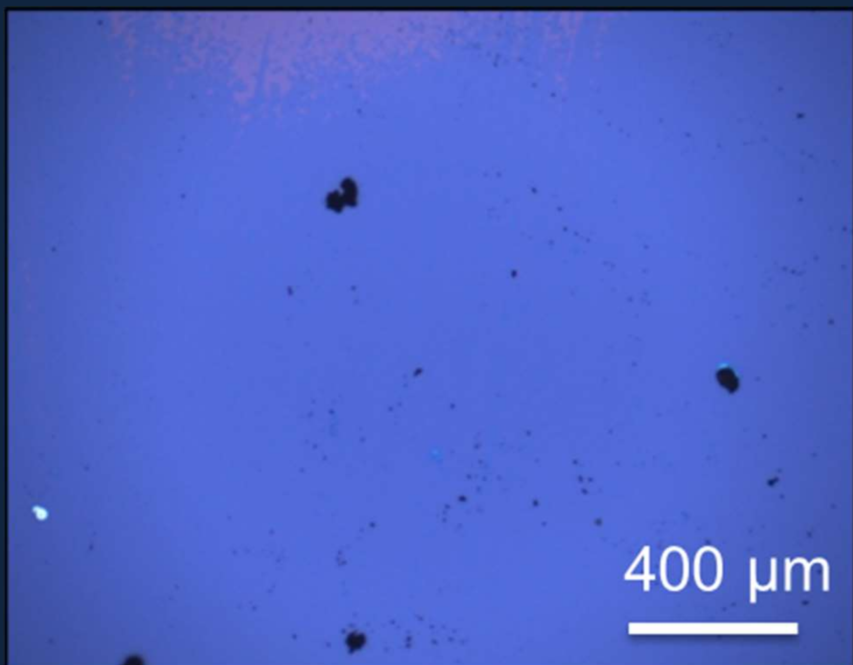
CVD-grown Fe:MoS_2 Monolayers

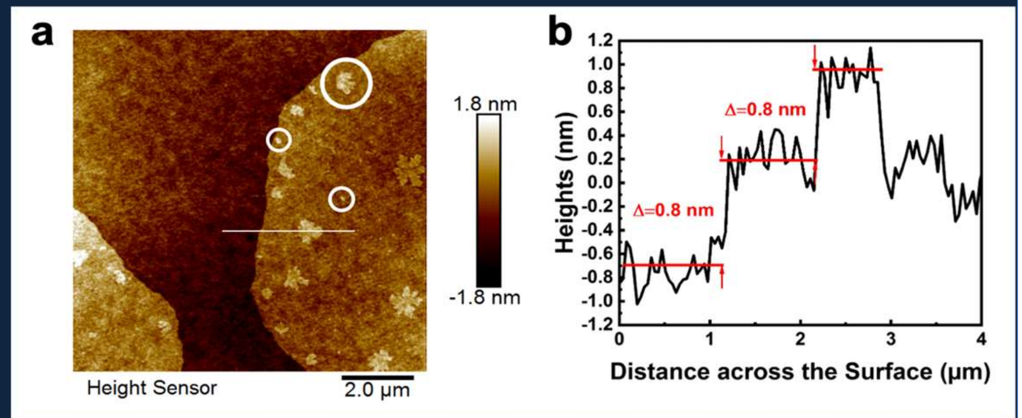


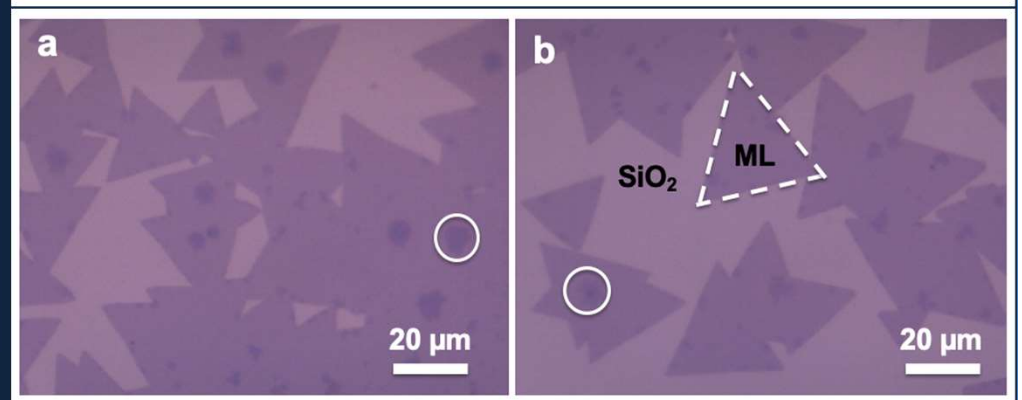


Nature Communications, 11, 2034 (2020)

CVD-grown Fe:MoS_2 Monolayers

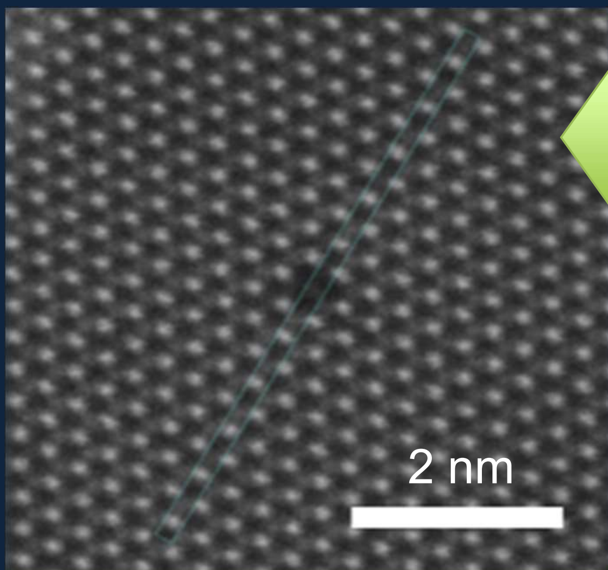


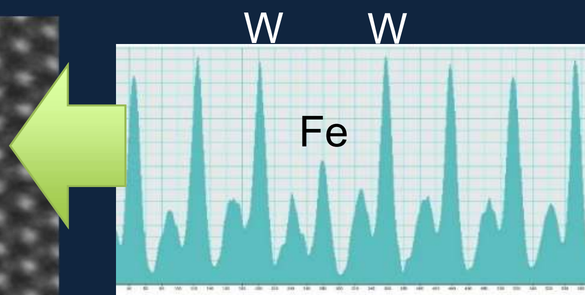


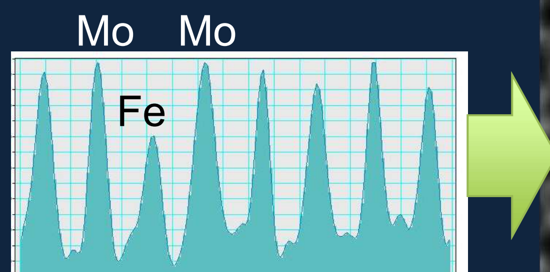


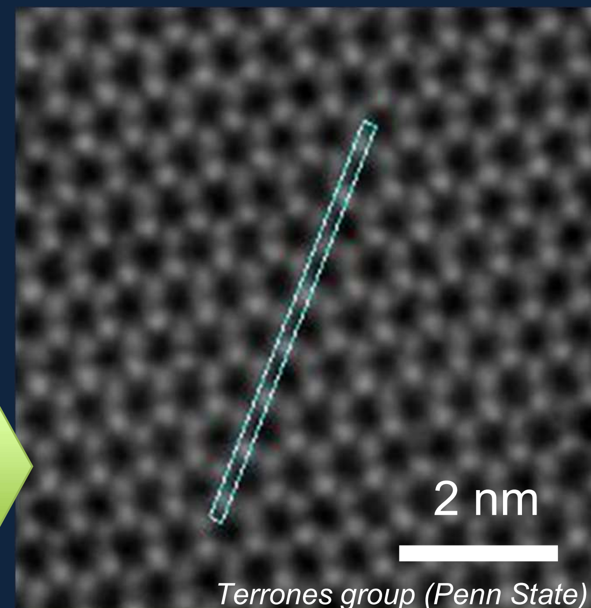
Nature Communications, 11, 2034 (2020)

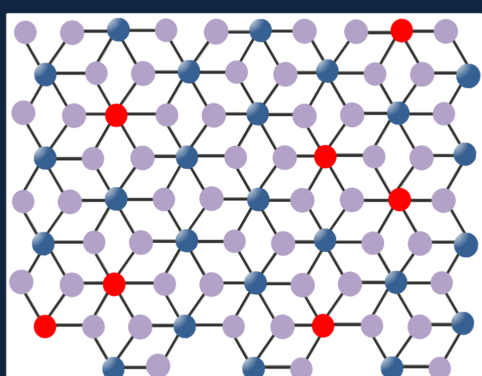
Substitutional Doping of Irons







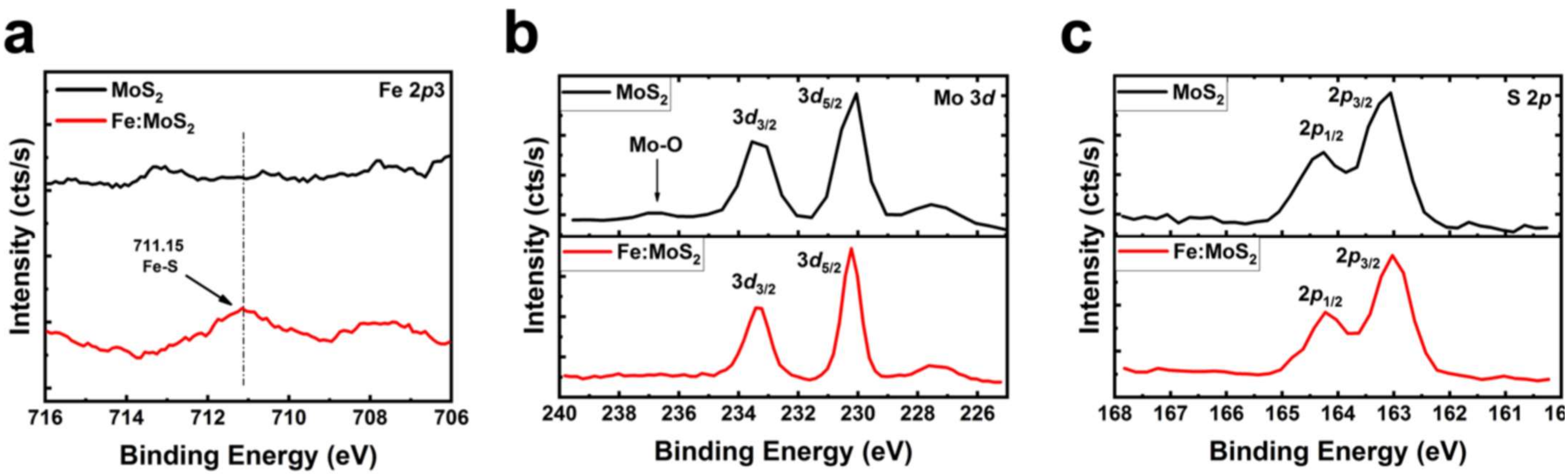




(left, right) Contrast-corrected STEM images of $Fe:WS_2$ and $Fe:MoS_2$ monolayers.
(center) STEM intensity spectra of the selected areas, where Fe atoms exhibit approximately 40% lower intensity than Mo atoms.

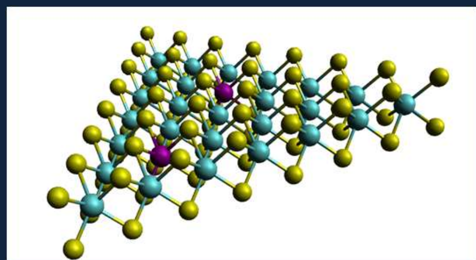
Nanotechnology, 32. 095708 (2021)

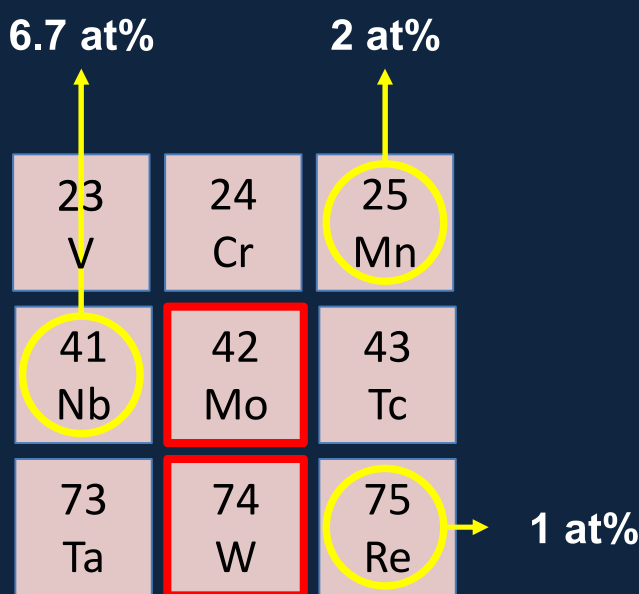
X-ray Photoelectron Spectroscopy (XPS)



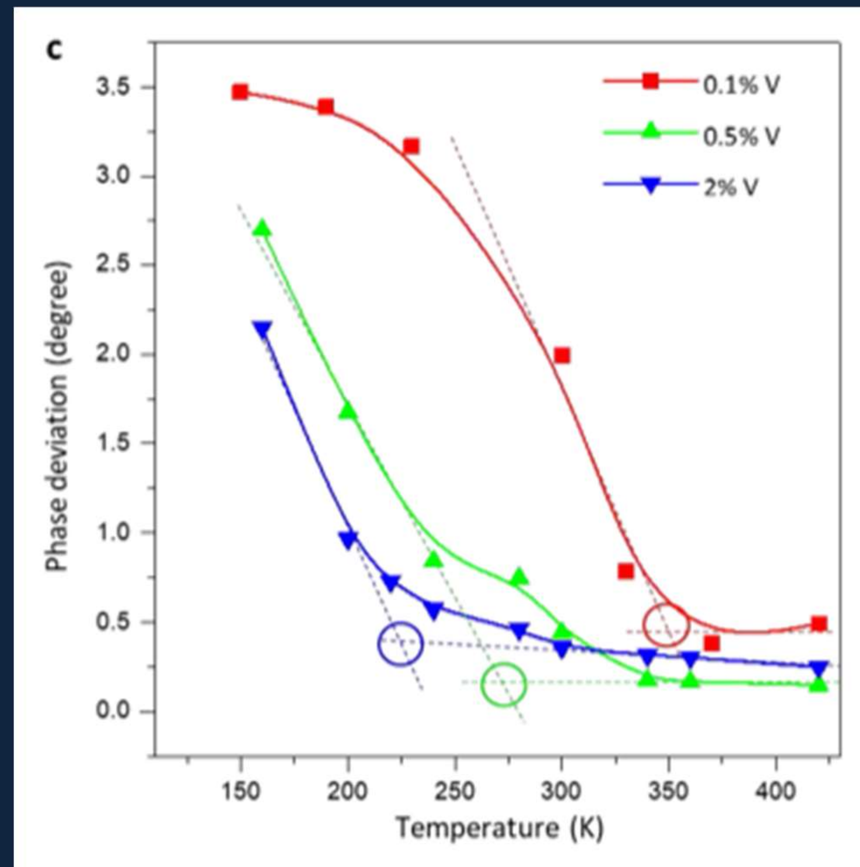
(a) Fe 2*p*3 peaks; (b) Mo 3*d* peaks. The reduced intensity of the Mo-O bond in Fe:MoS_2 (237 eV) as compared to MoS_2 is indicative of an underlying reduction of the sulfur vacancy concentration upon doping; (c) S 2*p* peaks.

Low-Doping Concentration in 2D Materials





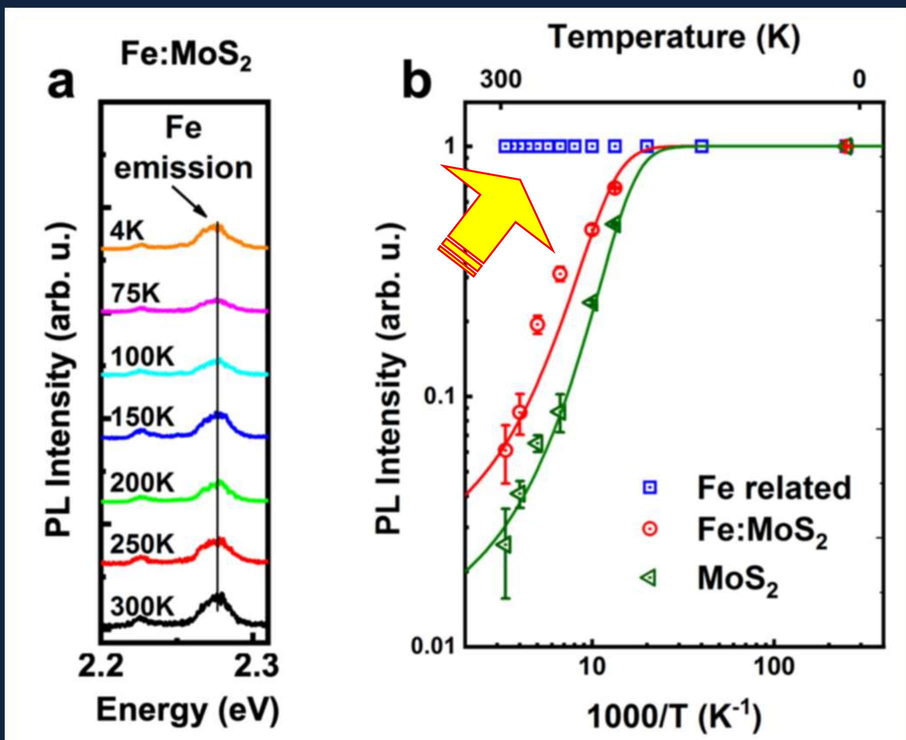
Zhang *et al., Nano Lett.* **15**, 6586-6591 (2015)
Gao *et al., Adv. Mater.* **28**, 9735-9743 (2016)
Zhang *et al., Adv. Funct. Mater.* **28**, 1706950 (2018)

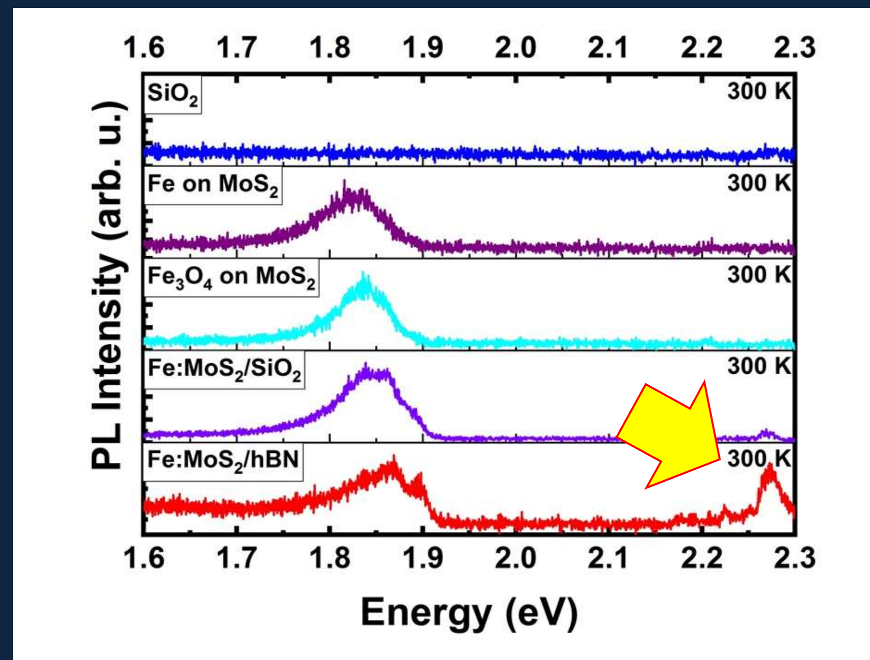


V-doped WSe_2

Yun, *et al., Adv. Sci.* 1903076 (2020)
Duong, *et al., Appl. Phys. Lett.* **115**, 242406 (2019)

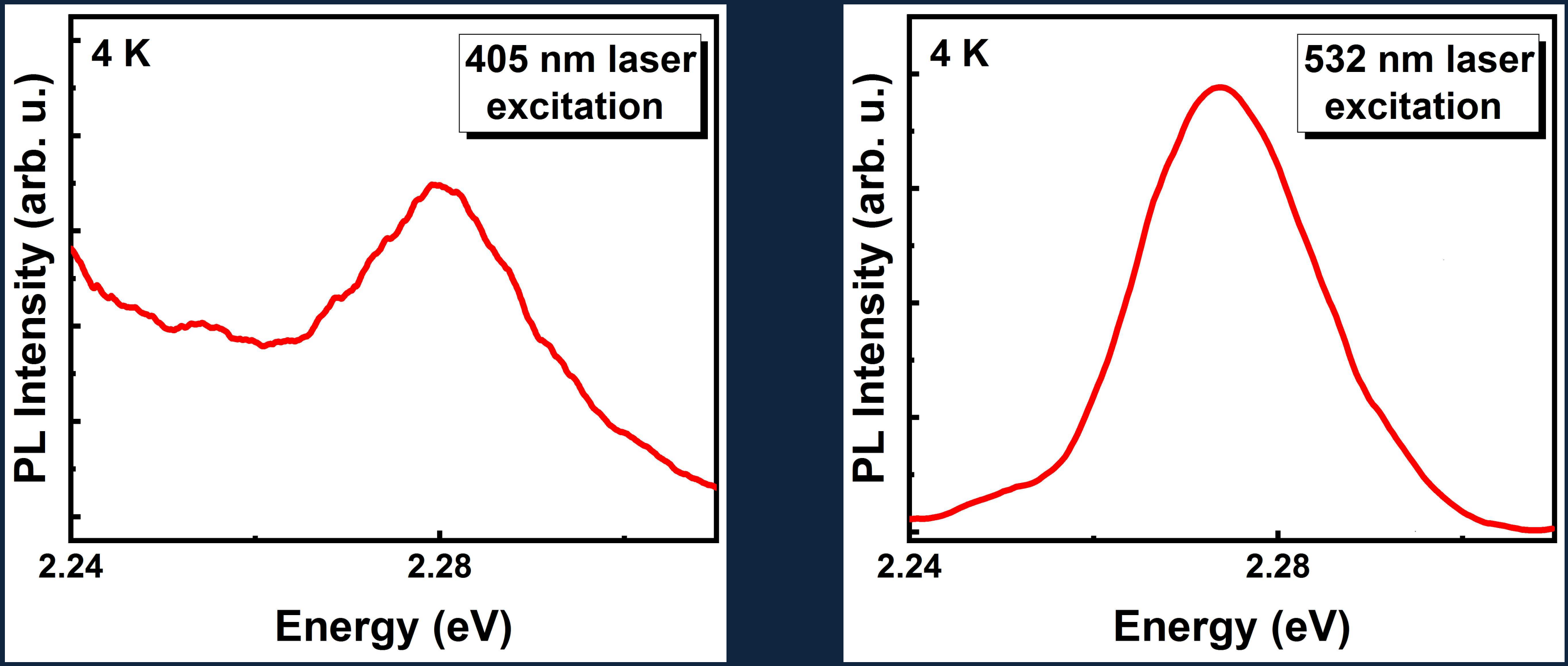
Fe-related PL Emission





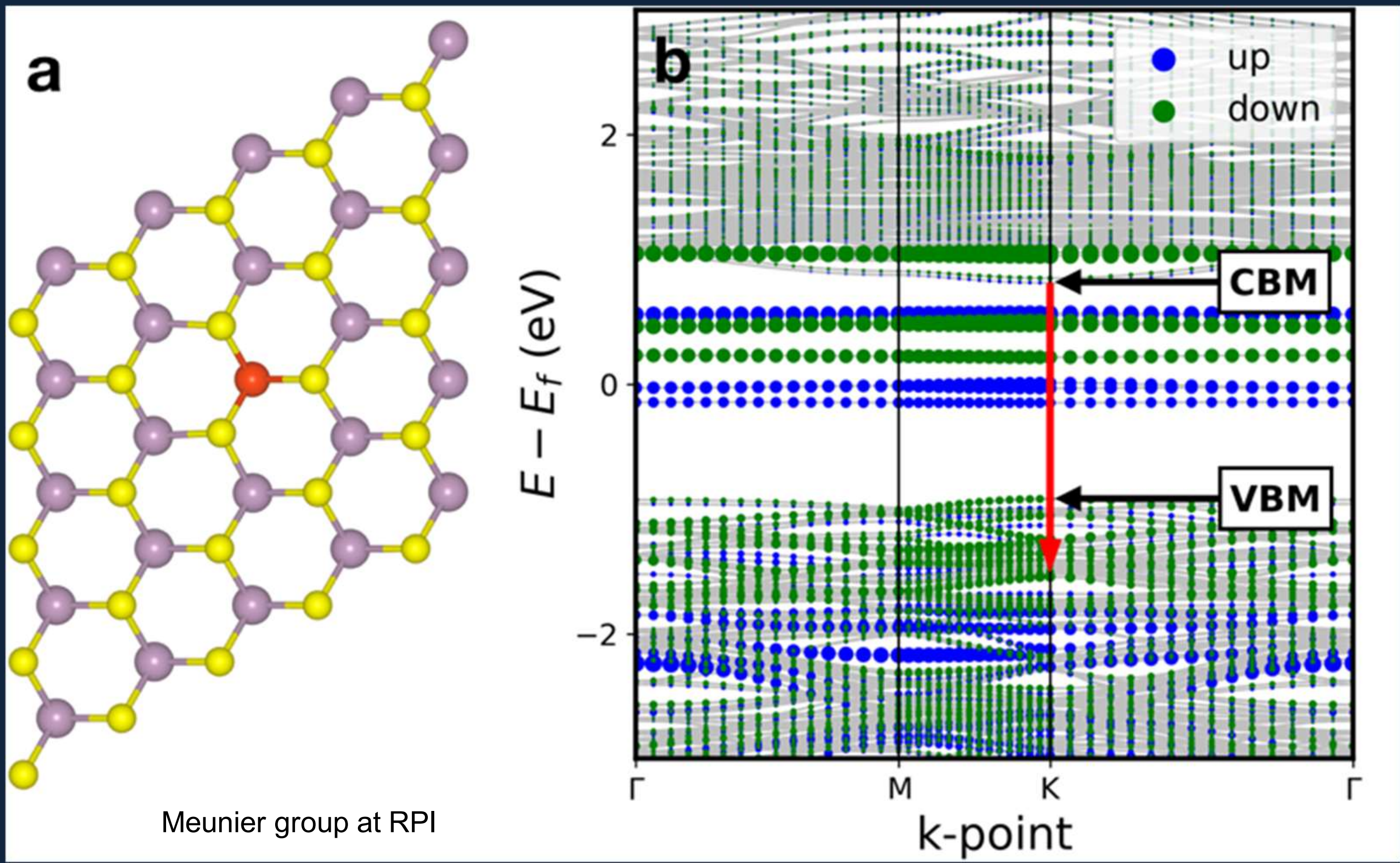
Nature Communications, 11, 2034 (2020)

Fe-related Emission from Fe:MoS_2



This Fe-related emission peak is consistent at different excitation wavelengths, showing that this emission is not related to a Raman peak.

Microscopic Origin of the Fe-Related Emission

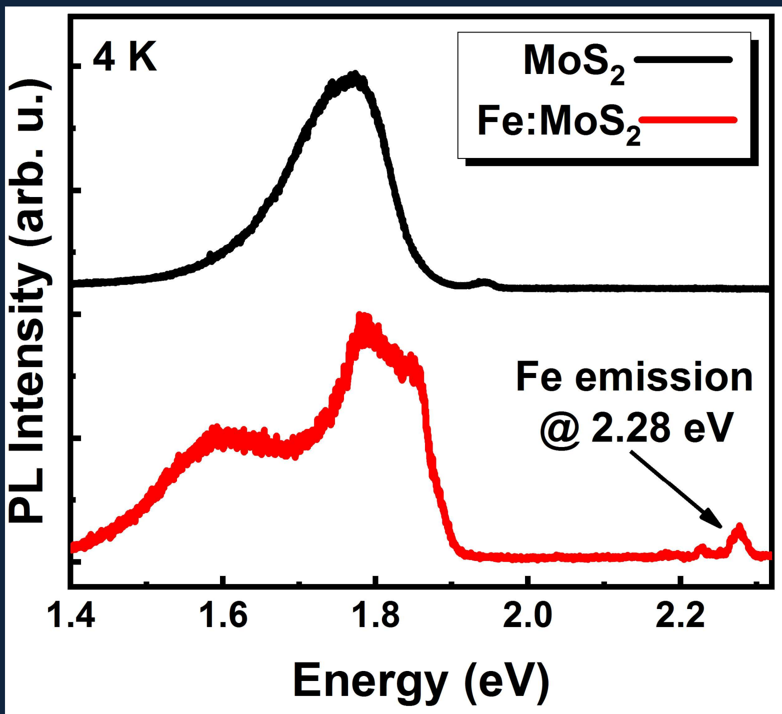


DFT Calculation of Dipole-Allowed Transitions in $Fe{:}MoS_2$ Monolayers

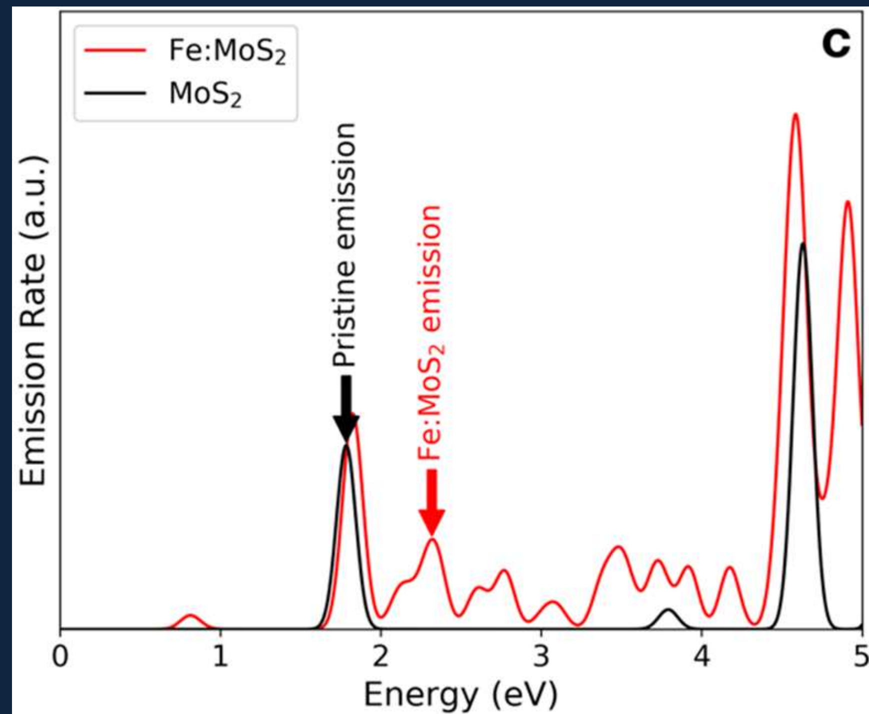
$$A(\omega_{fi}) = \frac{4\alpha}{3c^2}\omega_{fi}^3|\langle f|\hat{\mathbf{r}}|i\rangle|^2$$

Unambiguous Fe-related Emission

Meunier group (RPI)



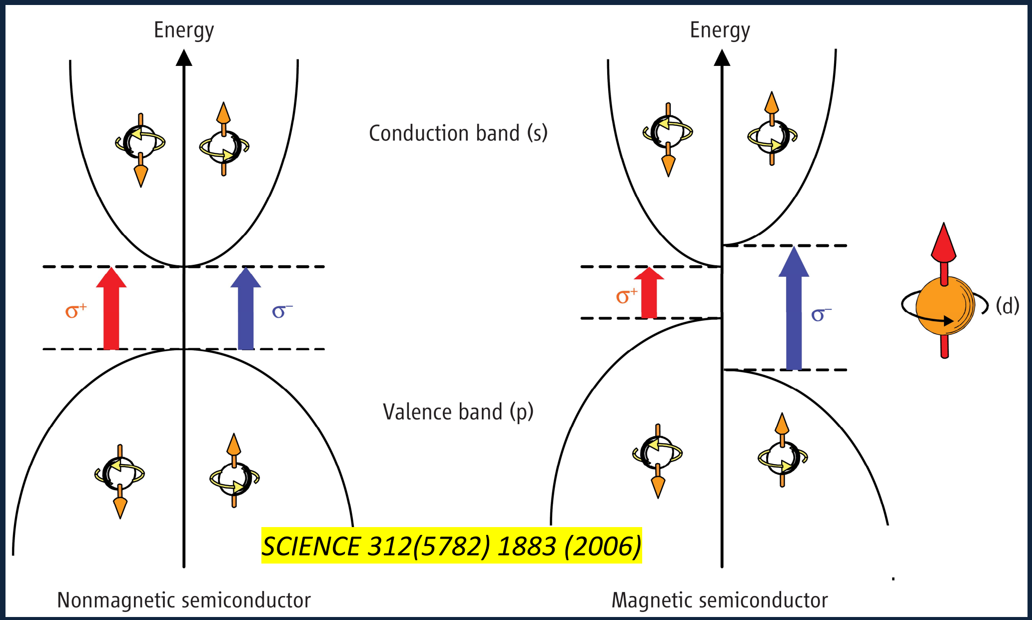
PL spectra of MoS_2 and $Fe:MoS_2$

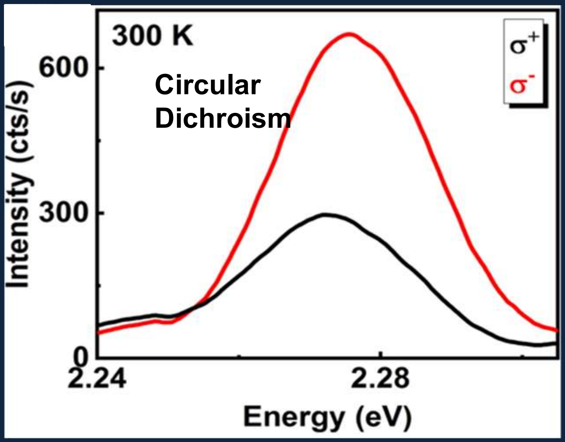


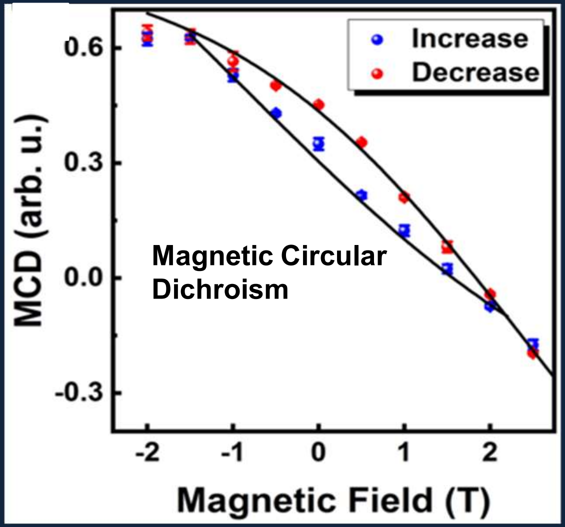
DFT calculations of dipole-allowed transitions

Nature Communications, 11, 2034 (2020)

Zeeman Splitting and MCD Effects

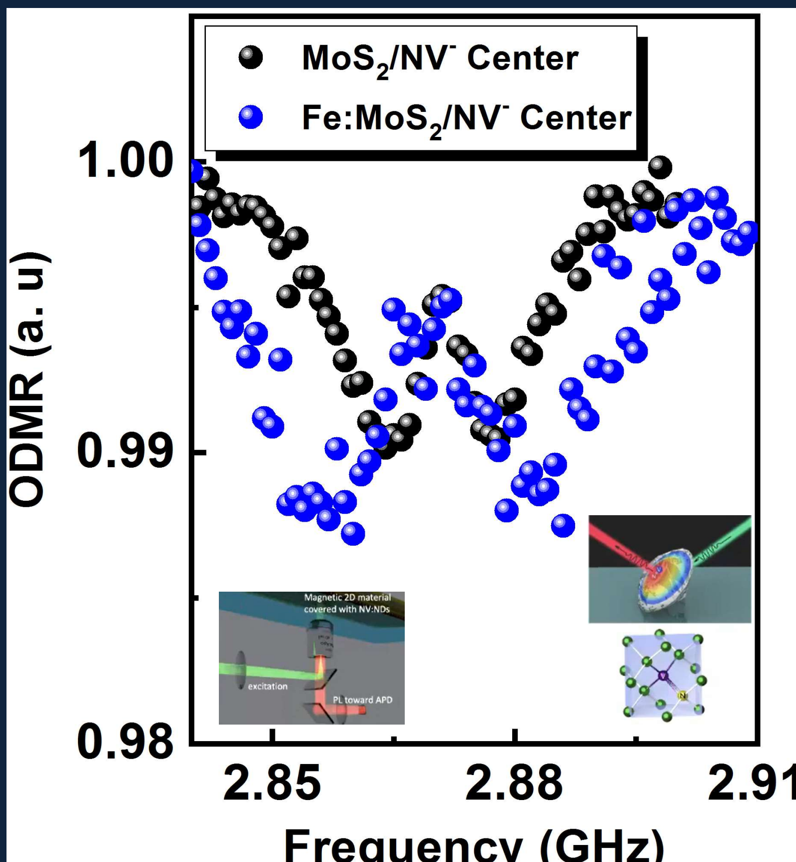




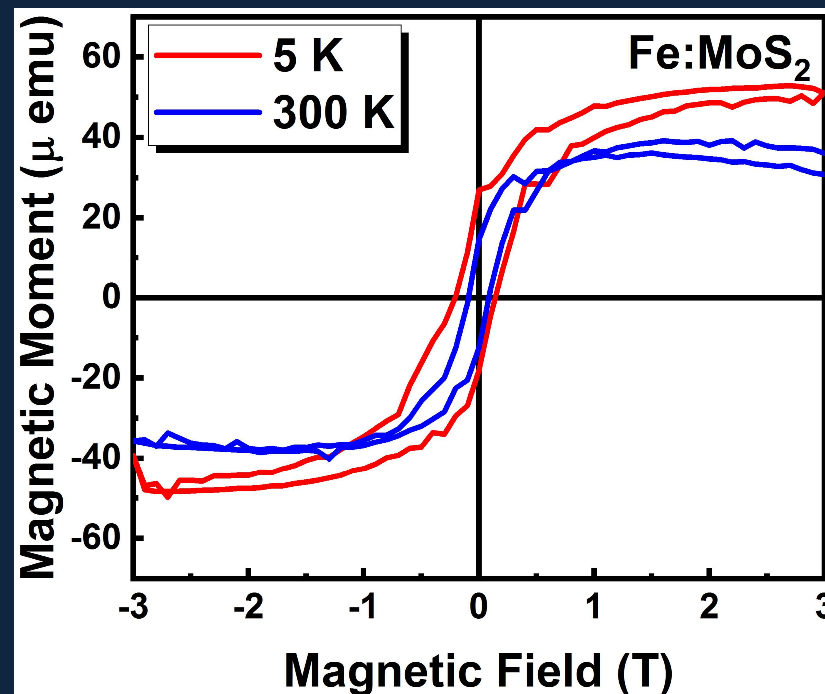


- (Right) the conduction band and valence band are split depending on the spin direction (Zeeman splitting).
- This spin-polarized semiconductor band structure alters the absorption of clockwise and counterclockwise-polarized light (MCD effect).

ODMR Spectra of NV⁻ Centers and Superconducting Quantum Interference Device Measurements



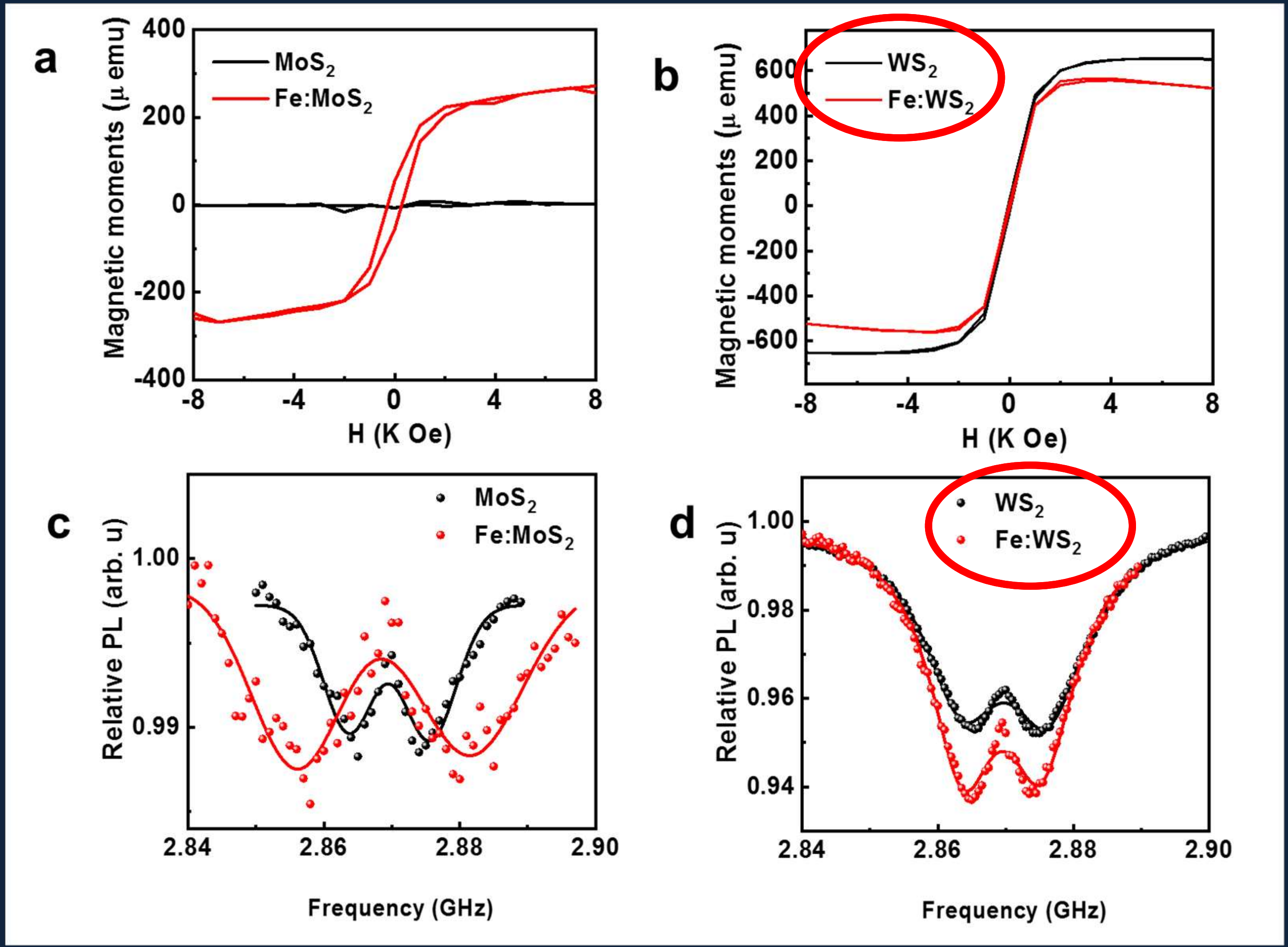
Vamivakas group (U. Rochester)



Pasupathy group (Columbia)

Nature Communications, 11, 2034 (2020)

Fe:MoS_2 vs. Fe:WS_2



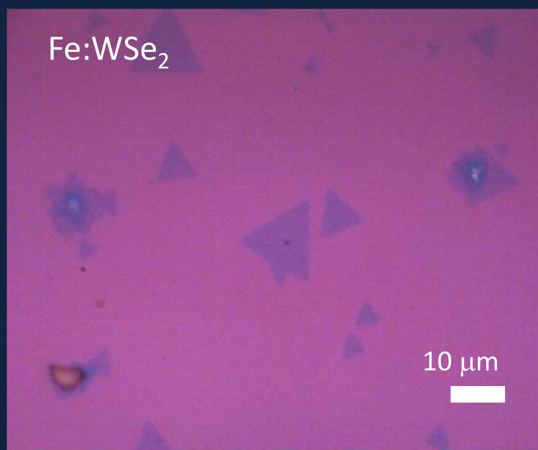
Argonne National Lab (Oakland University)

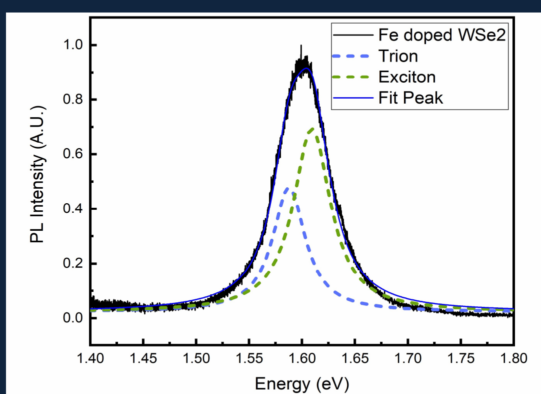
Vamivakas group (U. Rochester)

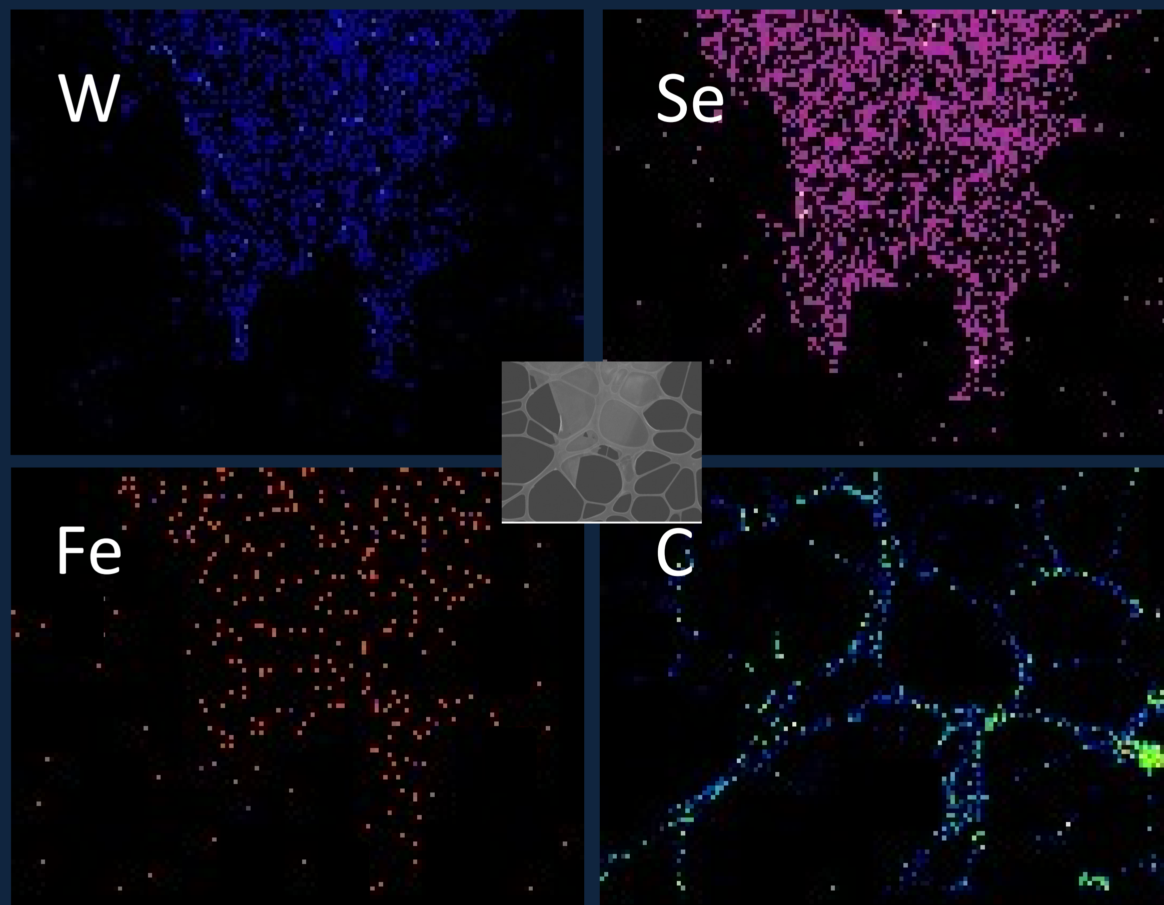
Nanotechnology, 32. 095708 (2021)

Fe:WSe$_2$: Optical, PL & EDS Mapping

Mengqi Fang

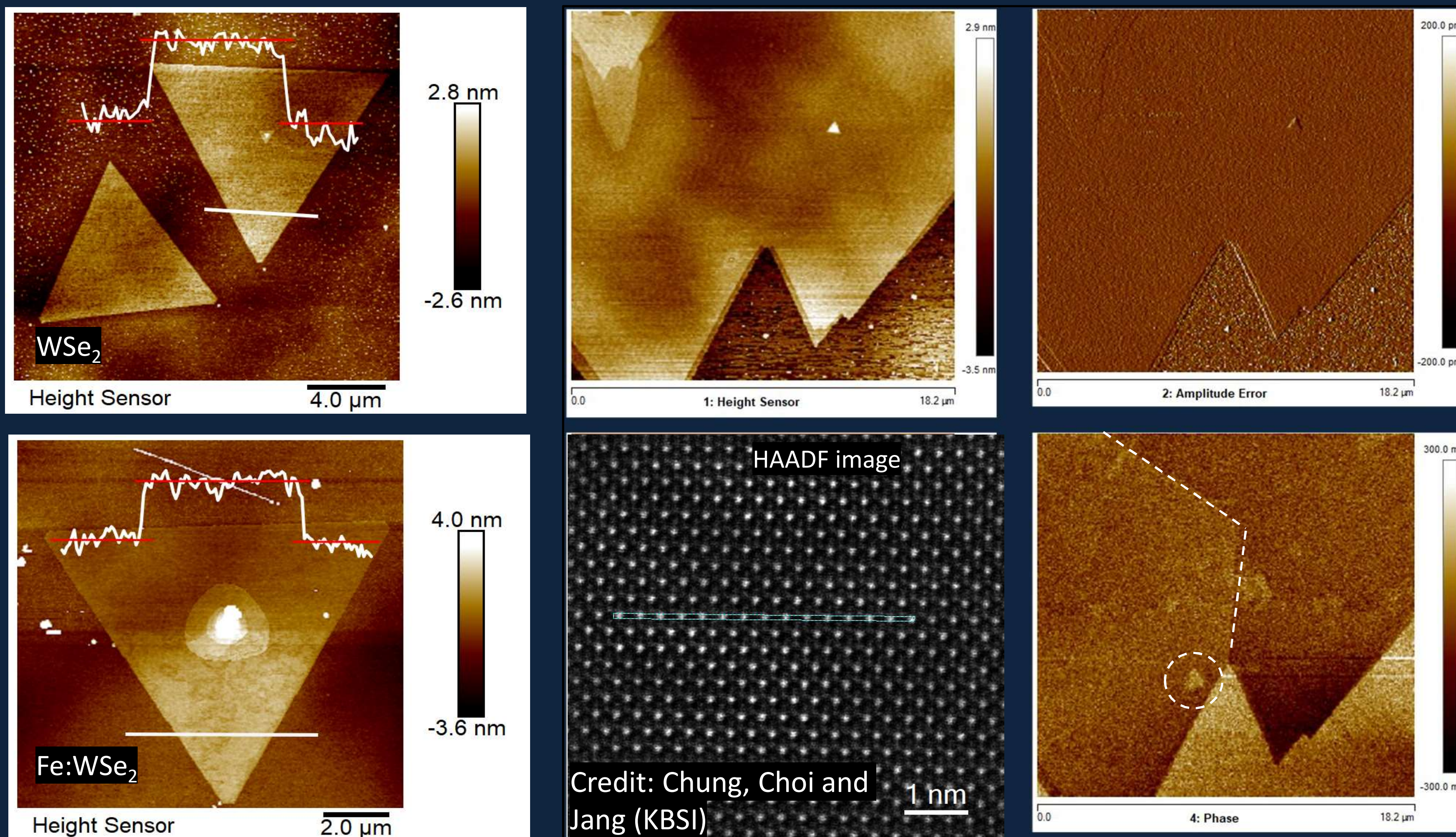






unpublished

AFM, STEM, and MFM Measurements

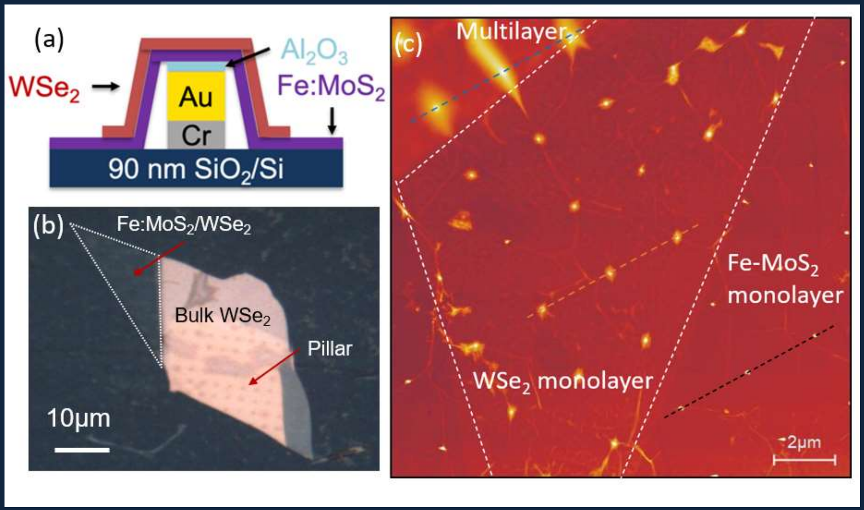


AFM STEM MFM

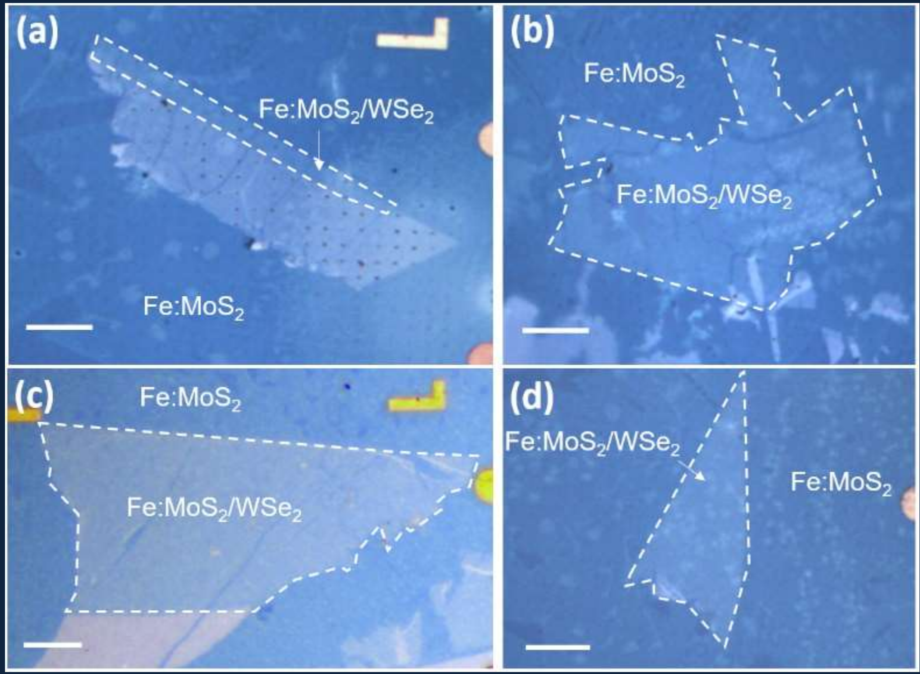
Manuscript in prep.

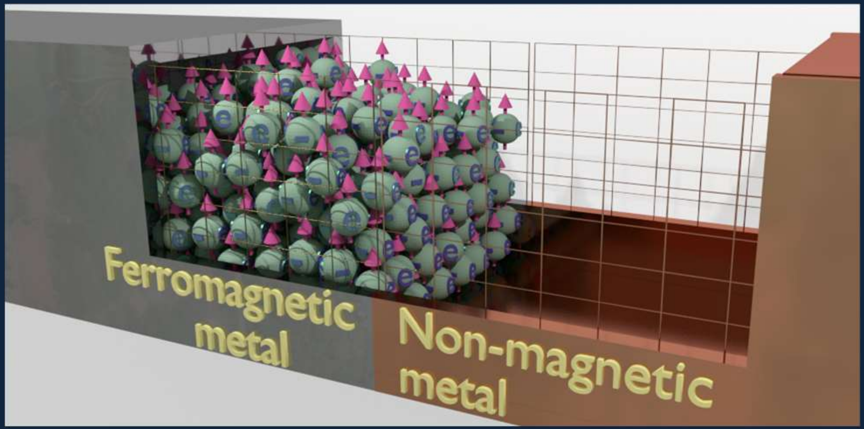
I. Magnetic Proximity Coupling with $Fe{:}MoS_2$

Shichen Fu



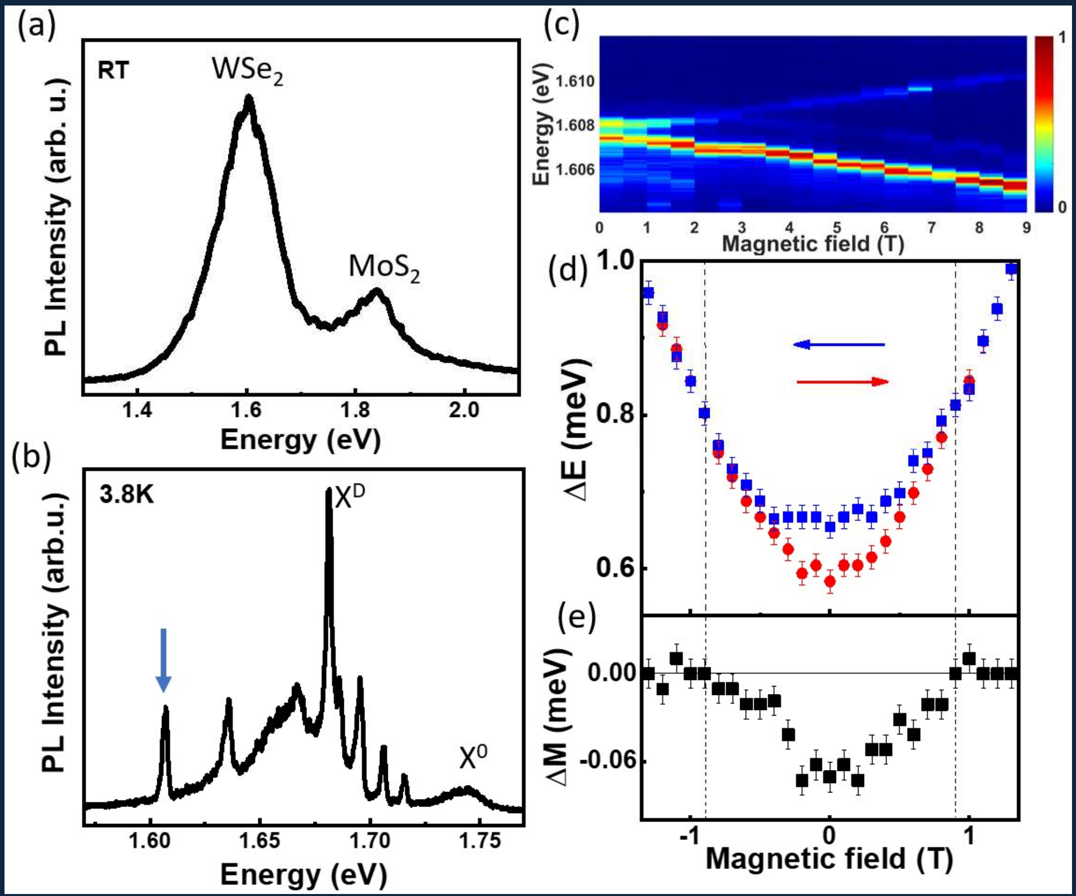
Strauf (lead) and Yang collaboration

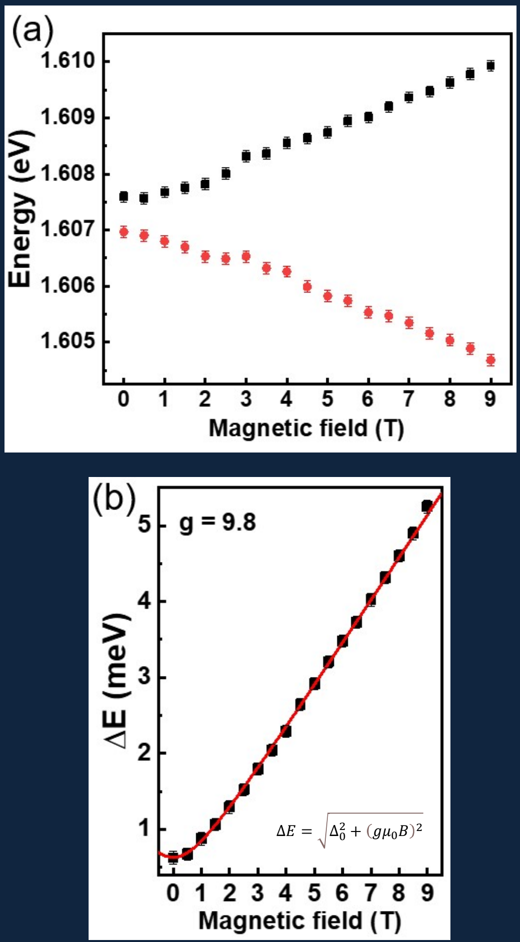




2D Materials, **10** 045003 (2023)

Magneto-optical Characterization of Proximity-coupled Quantum Emitters



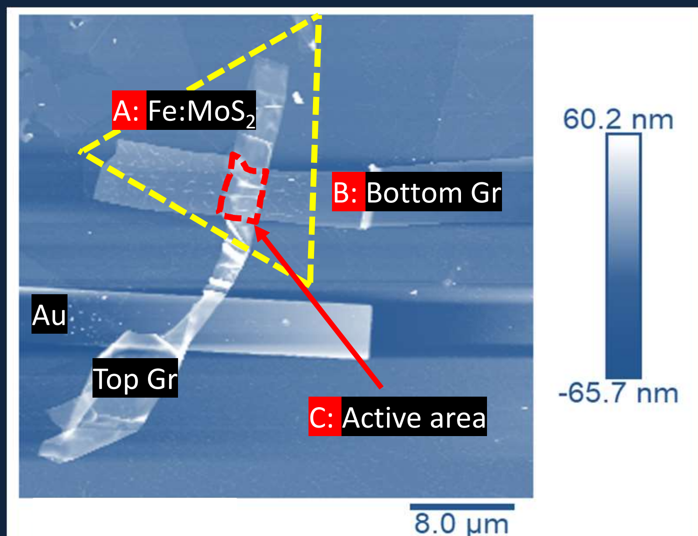


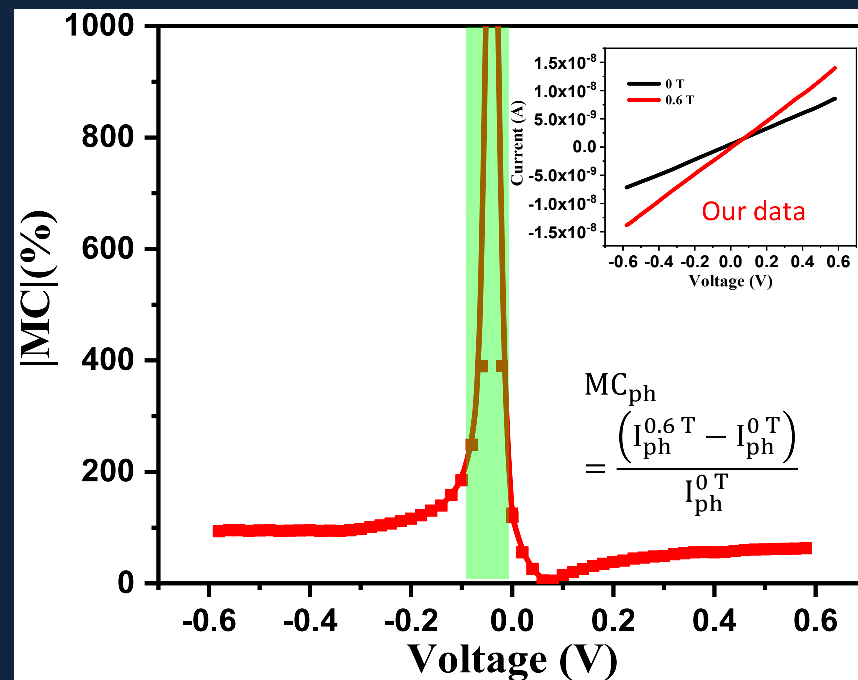
X^0: neutral 2D exciton, X^D: dark 2D exciton transition

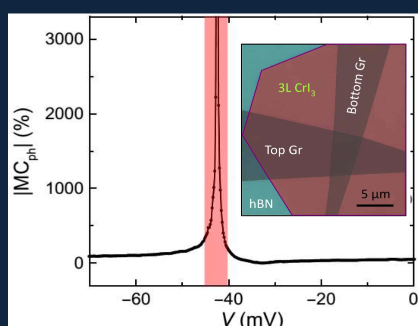
2D Materials, **10** 045003 (2023)

II. Spin Photovoltaics with $Fe:MoS_2$

Abdus Sarkar







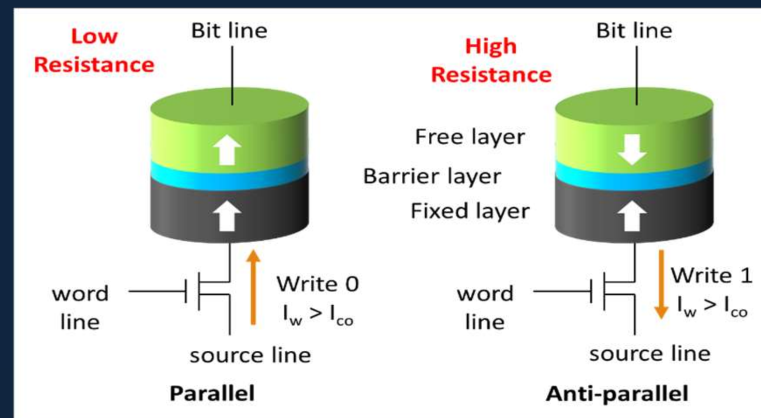
Song et al., Sci. Adv. 7, (2021)

unpublished

III. Magnetic Tunnel Junction

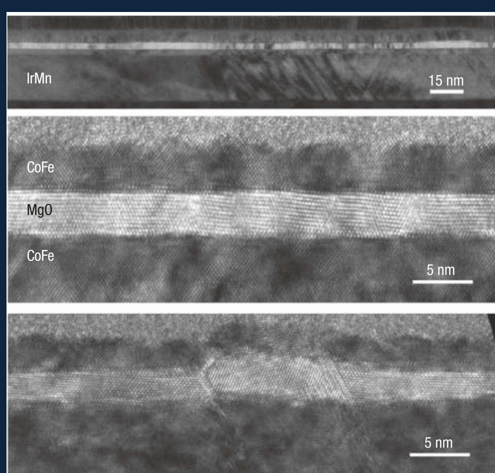
- Electrons flow through the MTJ to transfer spin angular momentum between the magnetic layers.

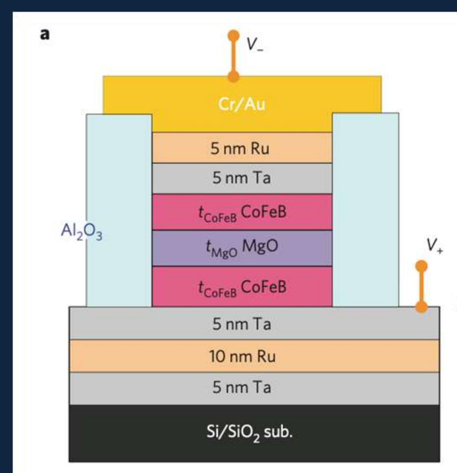
  → Changing the magnetic state of the free layer, and thus writing information.

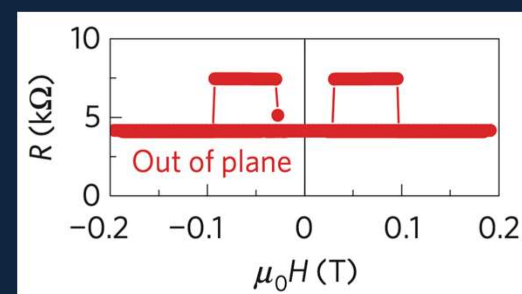


Giant tunnelling magnetoresistance at room temperature with MgO (100) tunnel barriers

STUART S. P. PARKIN[1*], CHRISTIAN KAISER[1], ALEX PANCHULA[1], PHILIP M. RICE[1], BRIAN HUGHES[2], MAHESH SAMANT[1] AND SEE-HUN YANG[1]



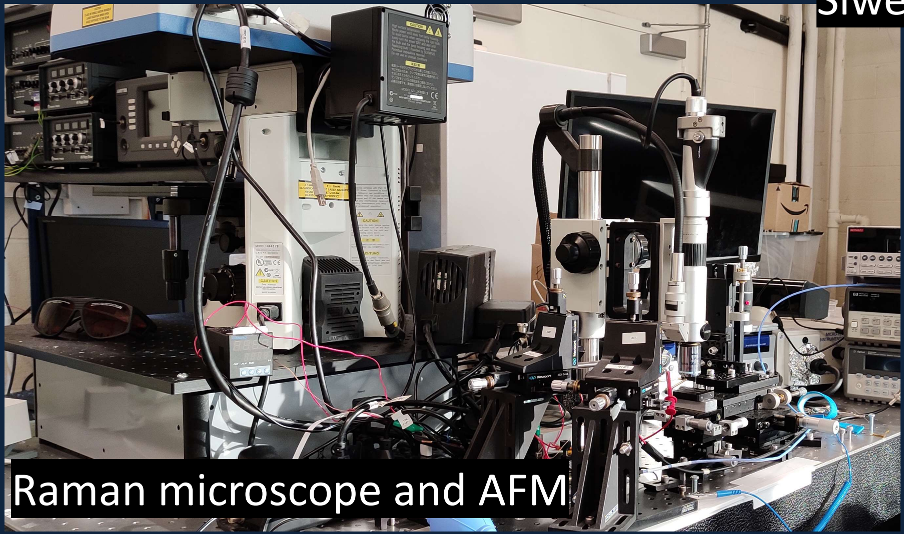


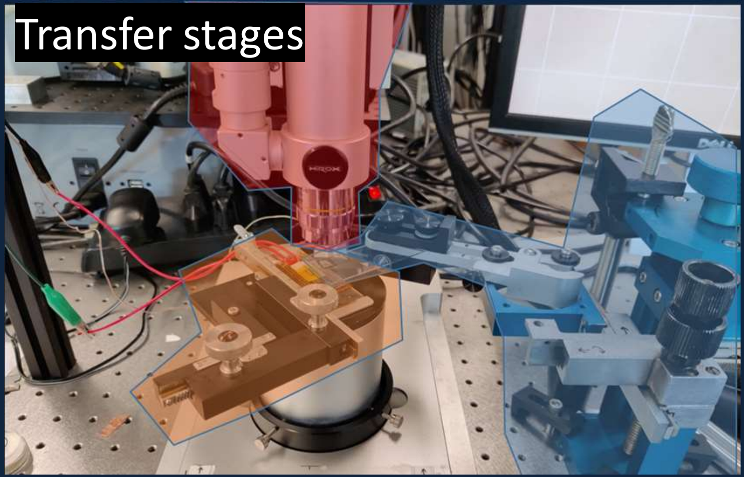


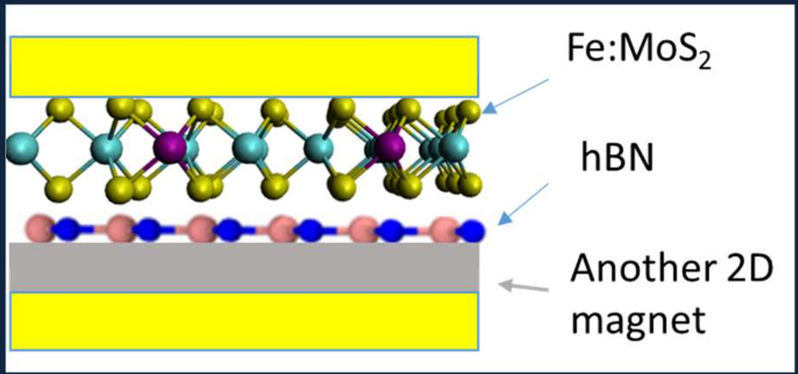
Ikeda, *Nature Materials,* 9.9, 721 (2010)

All 2D Magnetic Tunnel Junction

Siwei Chen

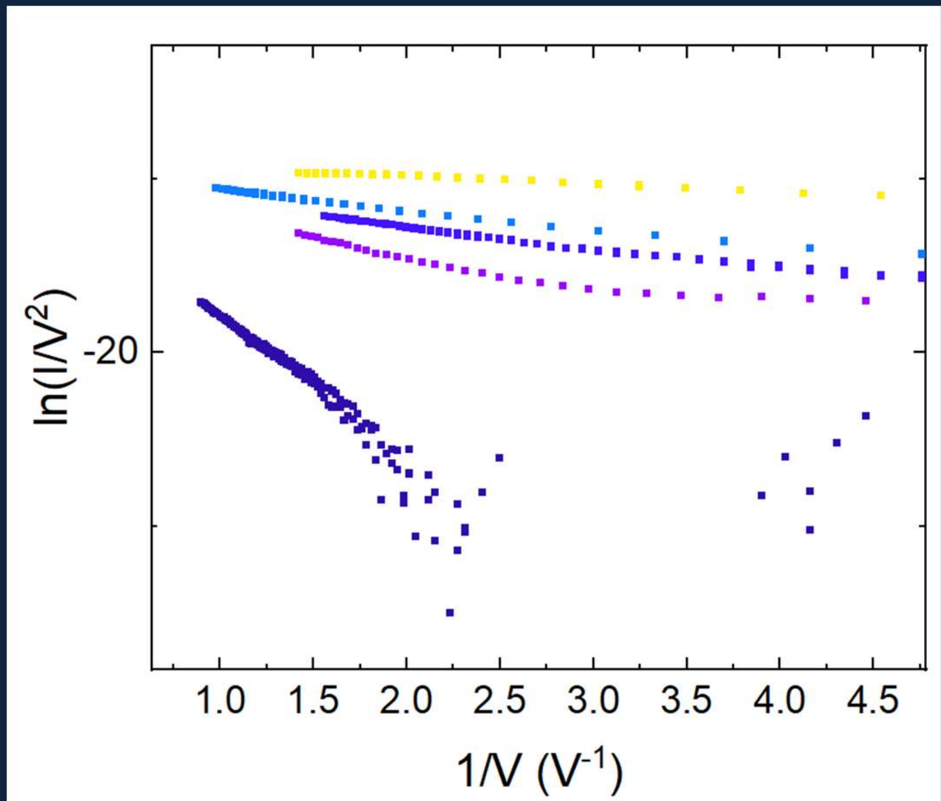






US Patent pending 18/008,126

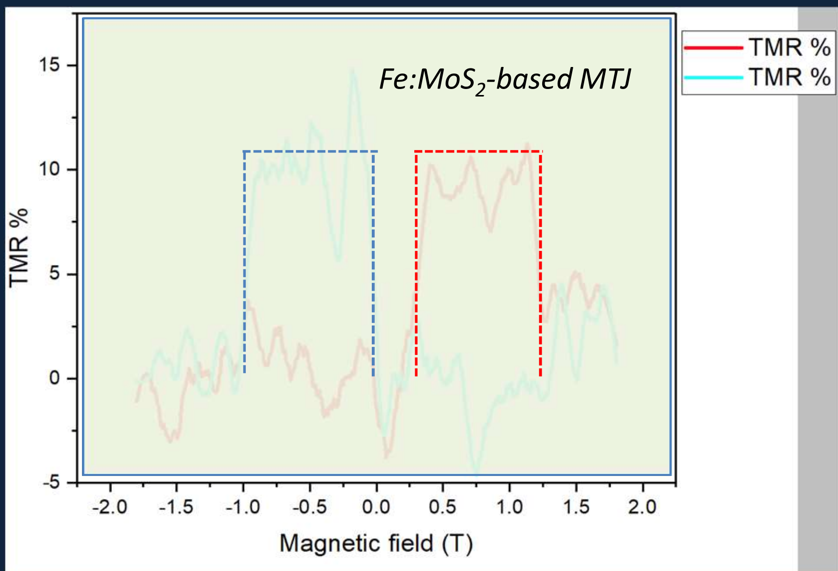
Tunneling Characteristics via Fe:MoS_2

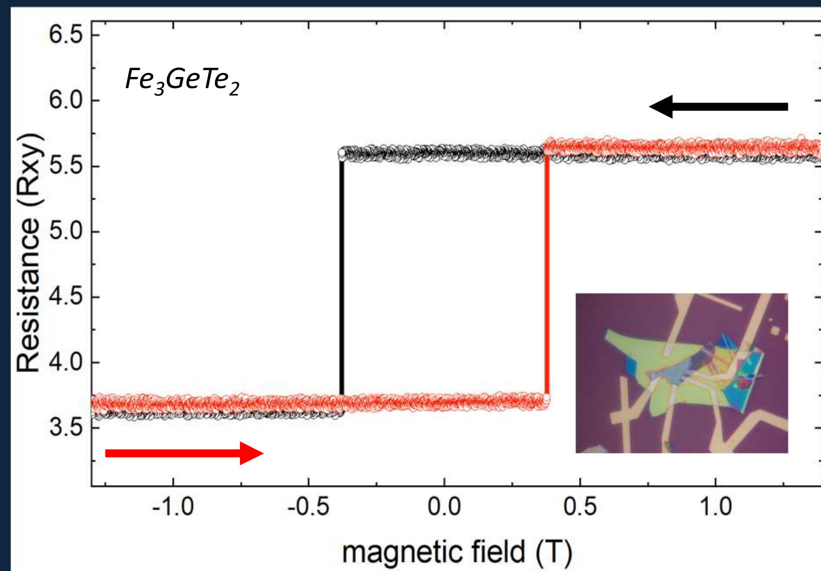


Fowler-Nordheim (FN) tunneling

unpublished

TMR of Fe:MoS$_2$-based MTJ & Anomalous Hall Effect in Fe$_3$GeTe$_2$





Coercivity ~ 0.38T at 30 μA I_{SD}.

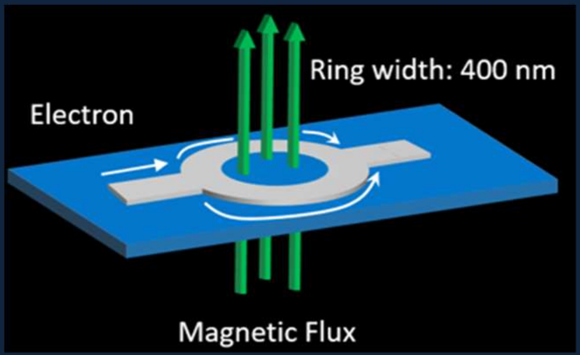
unpublished

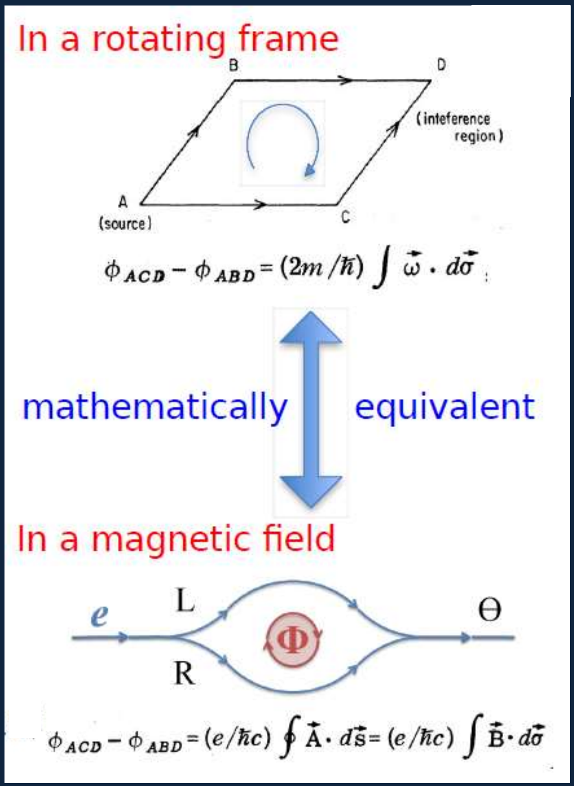
Aharonov-Bohm Effects in CVD-Graphene Rings

Zitao Tang

Siwei Chen

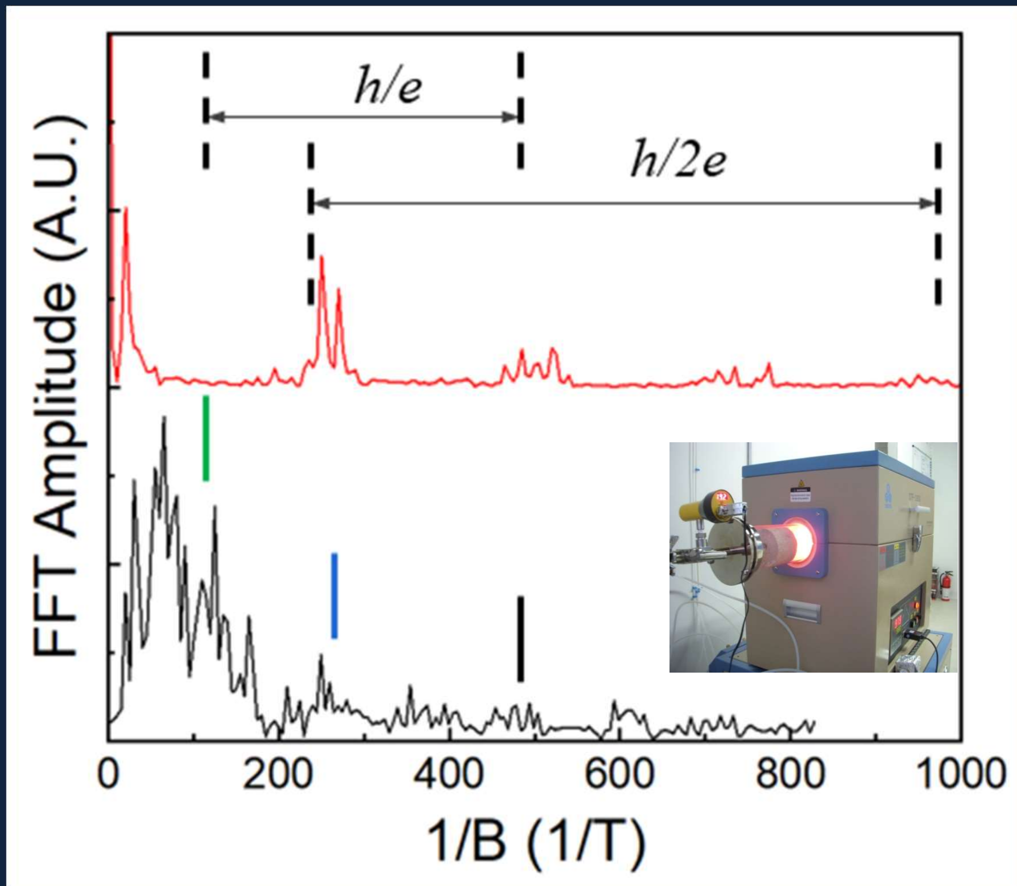
- **Aharonov-Bohm (AB) effect**: the oscillations in the resistance of a conducting ring as a function of an external magnetic flux piercing the ring.
- An interferometer based on AB oscillations is, in principle, equivalent to a rotation sensor.
- Magnetoconductance show fringes as a function of the applied magnetic field.





J. Sakurai, PRD (1980)

Characterization of Aharonov-Bohm Oscillations



FFT of the AB oscillations from a graphene ring

Graphene acts as a 2D ballistic, phase coherent electron system with long phase coherence length - 765 nm to 1.25 μm at 4K. (Science, 317(5844), 1530 (2007))

Manuscript in prep.

Summary

- We investigate chemical vapor deposition (CVD)-grown TMDs, including Fe doping of MoS_2, WS_2, WSe_2 and $MoSe_2$, as well as their heterostructures.
- We demonstrate ferromagnetism in monolayer Fe:MoS_2, demonstrating the magnetic field strength of 0.5 mT at room temperature.
- We currently explore the magnetic proximity coupling of quantum emitters, magnetic tunnel junctions, electron interferometers, and spin photovoltaic devices, which can be readily combined with flexible substrates.
- This research unlocks many new opportunities towards atomically thin magneto-optical and magnetoelectric devices for ultracompact spintronics, on-chip optical communications, and quantum sensing and energy conversion.

STEVENS
INSTITUTE OF TECHNOLOGY
1870

Scan me to request 2D magnets for collaboration.