5. Production of 2D Materials
Part 2

History of Synthesis in 2D Materials

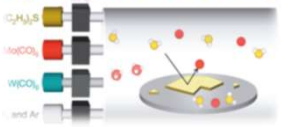
2018, Growth of superlattice

Science (2018)

2017, Vertical stacking

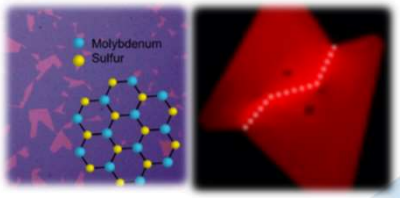
Nature (2017)

2015, MOCVD of TMDCs



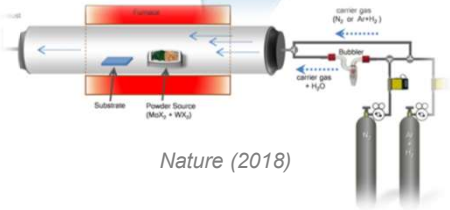
Nature (2015)

2014, CVD of MoS_2



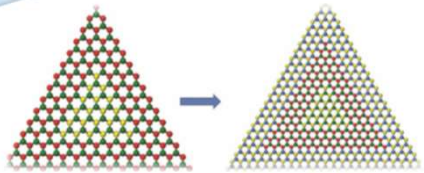
Nature Mater. (2013)

2018, One-pot growth



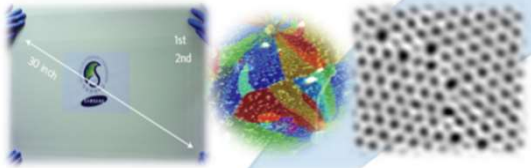
Nature (2018)

2017, Sequential heterostructure



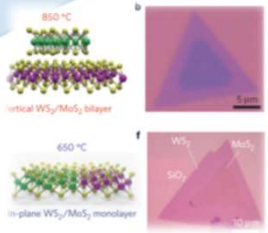
Science (2017)

2009, CVD of graphene



Science (2009)
Nature (2009)
Nature Nanotech. (2010)

2014, Heterostructure



Nature Mater. (2014)

2004, Scotch tape method

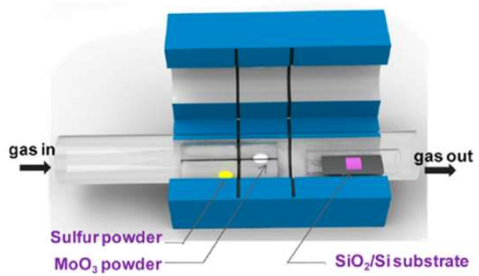
Science (2004)

Issues in synthesis of 2D Materials

- ✓ High quality
- ✓ Large-scale
- ✓ Defect control
- ✓ Heterointerface
- ✓ Epitaxial growth

Source Supply for 2D Material Growth

1. Evaporation of powder

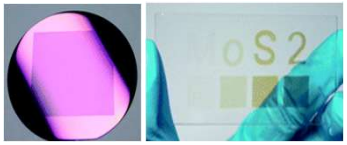


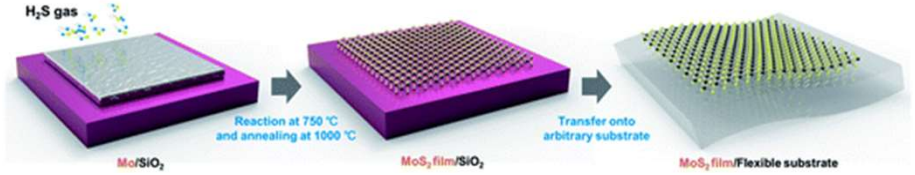
ACS Nano (2014)

Nature Mater. (2013)

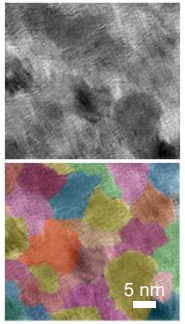
- ✓ High quality crystal
- ✓ Easy process
- ✓ Not continuous
- ✓ Less practical

2. Sulfurization of metal film





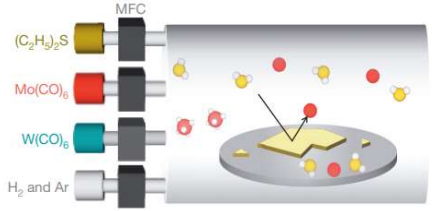
Nanoscale (2014)



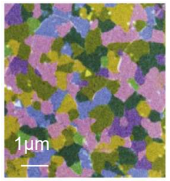
Chem. Mater. (2017)

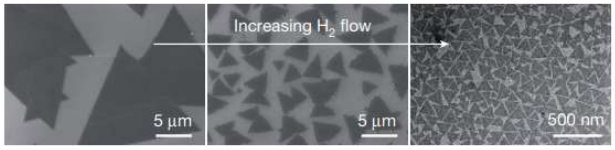
- ✓ Large-scale growth
- ✓ Continuous film
- ✓ Thickness-controllable
- ✓ Nano-size grains
- ✓ Non-stitched grains

3. Metal-organic source



Nature (2015)



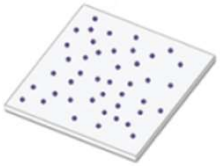


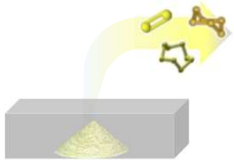
- ✓ Larger grain size
- ✓ Continuous film
- ✓ Long process time (>10h)
- ✓ Grain boundaries

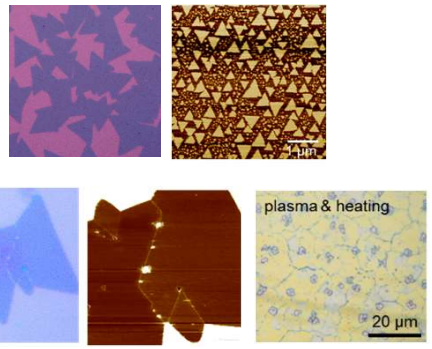
Main Stages for 2D Material Growth

Nucleation

Nucleation sites
Seed
Flatness



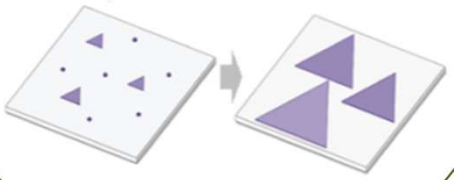


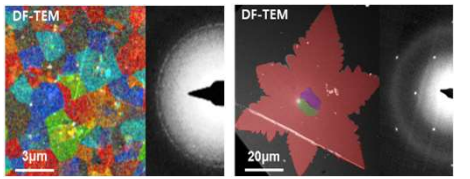


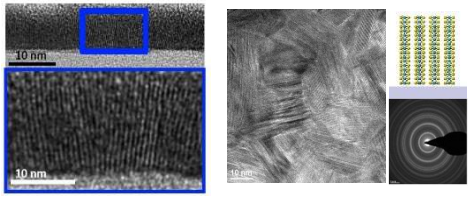
Nature Mater. (2013)

Growth

Coalescence
Abnormal growth
Stitching



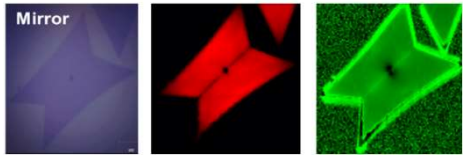


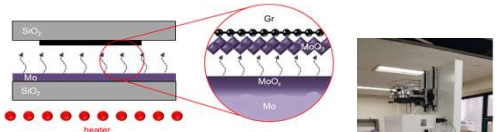


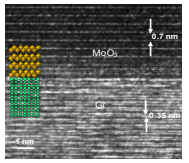
Science (2013)
ACS Appl. Mater. Inter. (2018)

Complete film

Boundary
Epitaxy
Defects

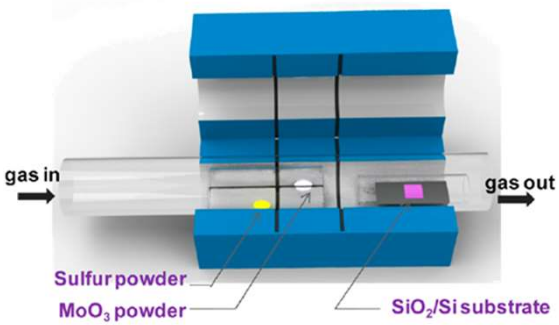


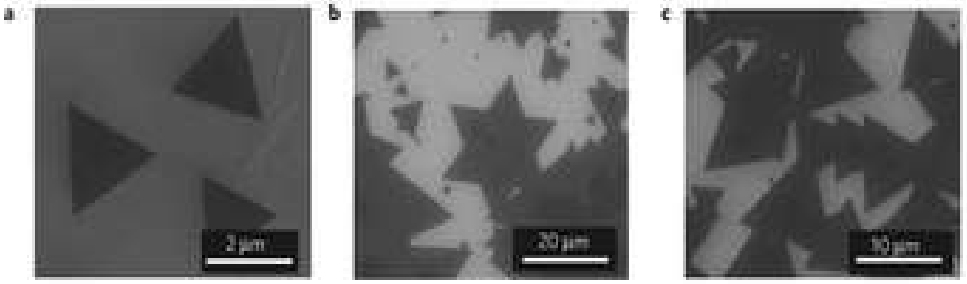


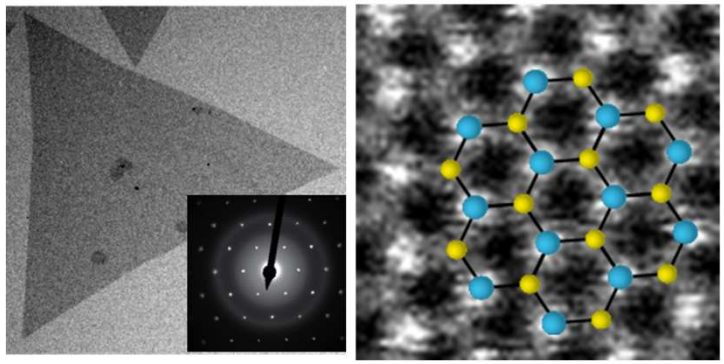


Nature Mater. (2013)
2D Materials (2018)

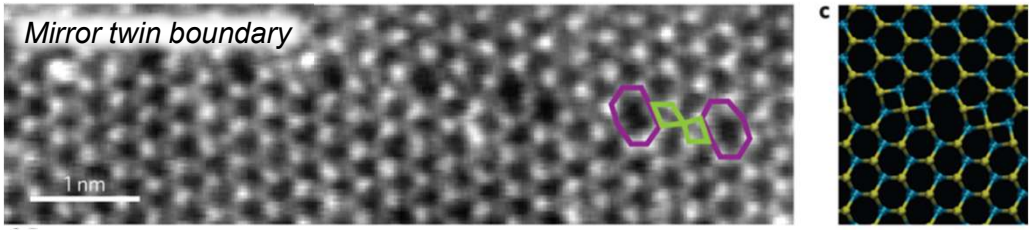
Chemical Vapor Deposition of MoS_2

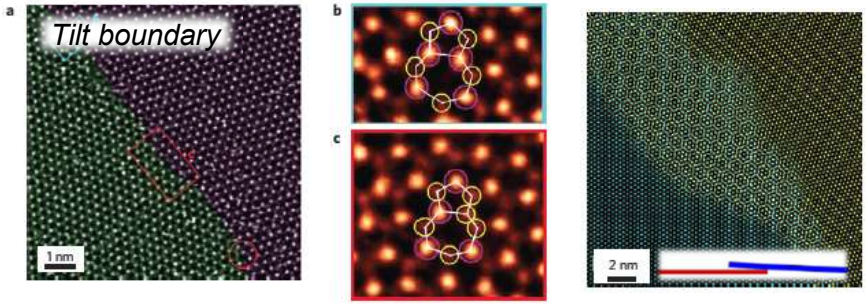






Grain boundaries in CVD-grown MoS_2

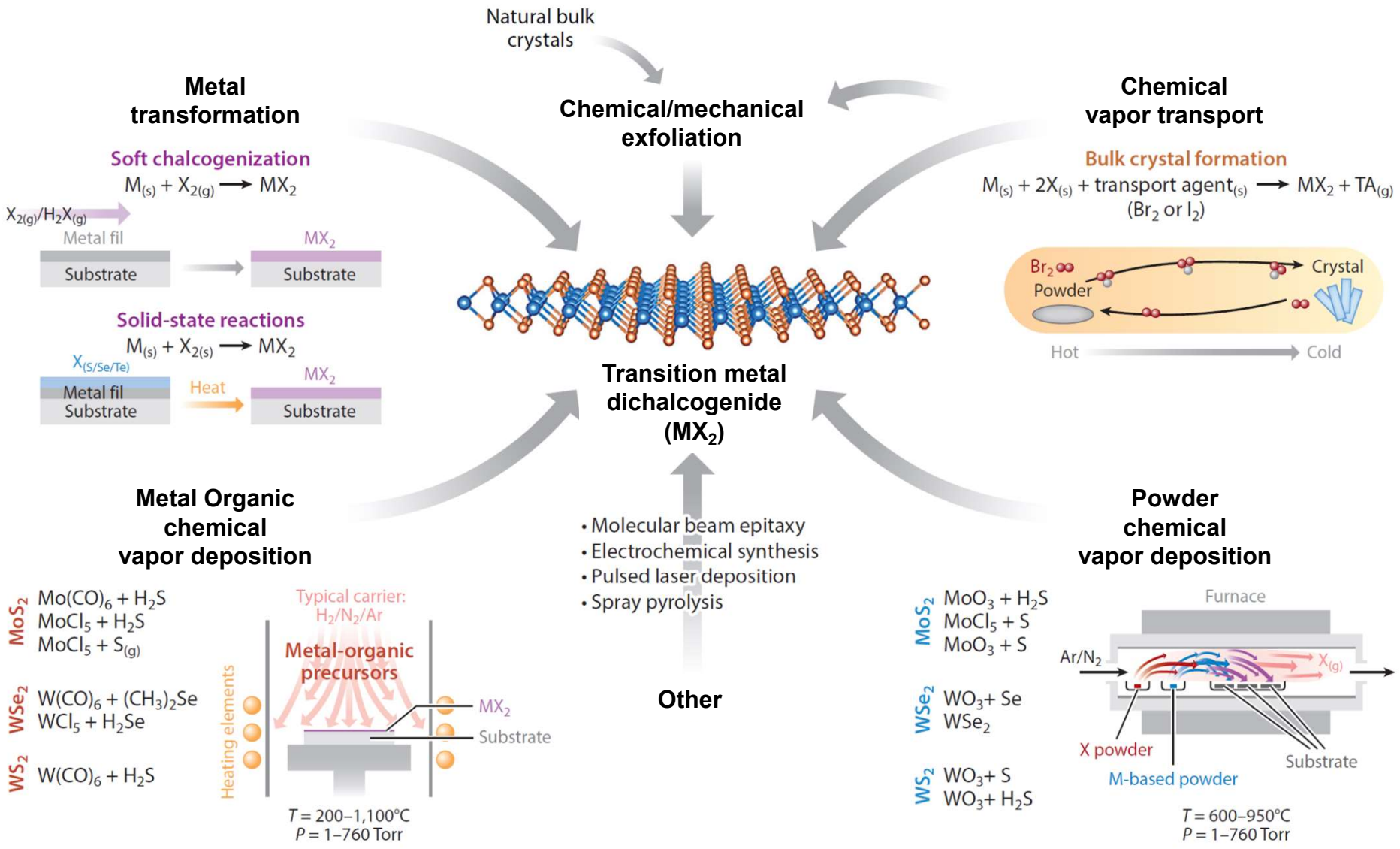




Mirror twin boundary: 8-4-4 defects (n-doped Mo-rich)
Tilt boundary: 5-7 defects (p-doped S-rich)

A. M. van der Zande et al. Nature Mater. (2013) & J. Zhang et al. ACS Nano (2014) & S. Najmael et al. Nature Mater. (2013)

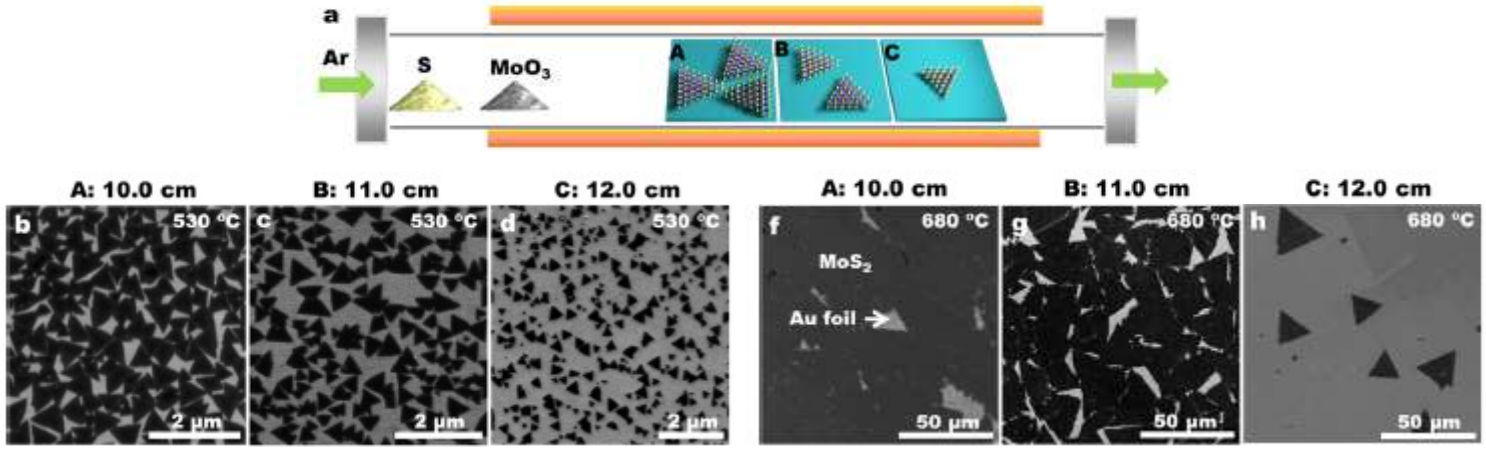
Map of 2D Material Synthesis

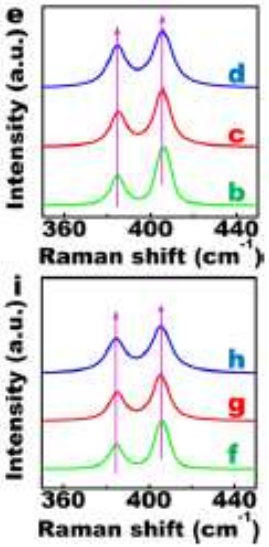


S. Das, J.A. Robinson, M. Terrones, et al..
Annual Review of Materials Research (2015)

Growth Method I

Scalable synthesis of uniform monolayer MoS_2 on Au foils

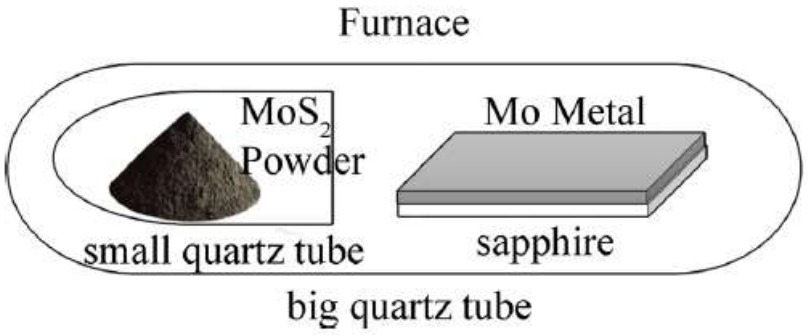




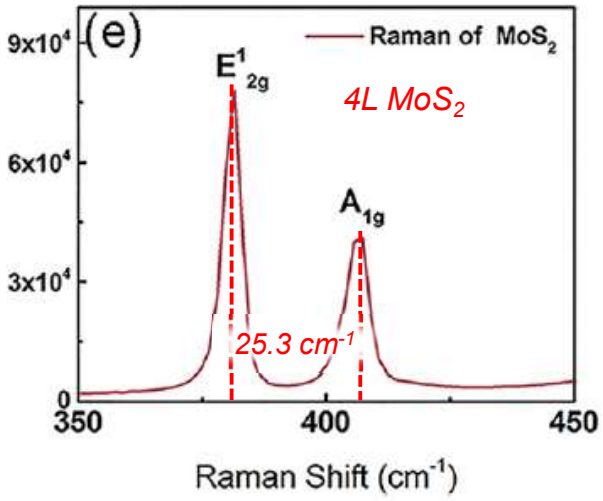
Effect of source-substrate distance and temperature

J. Shi et al. ACS Nano (2014)

Multilayer MoS_2 on sapphire

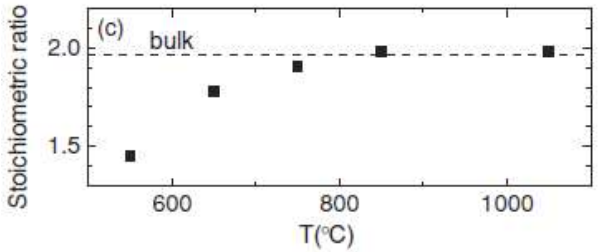


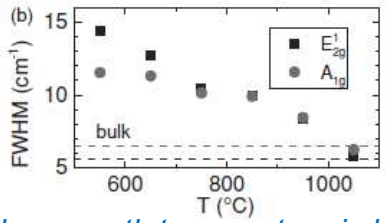
L. Ma et al. Appl. Phys. Lett. (2014)



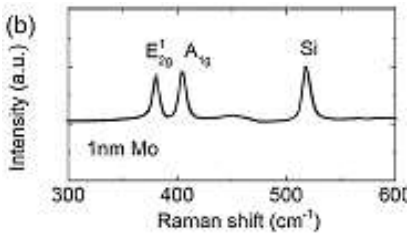
Growth Method II

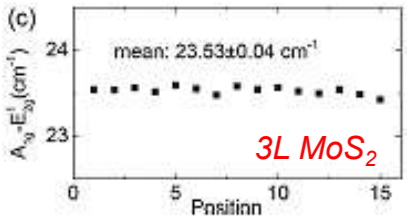
Sulfurization of Mo thin film



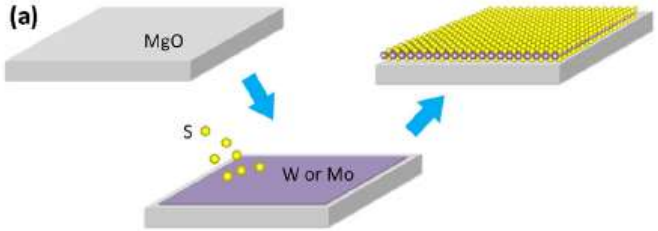


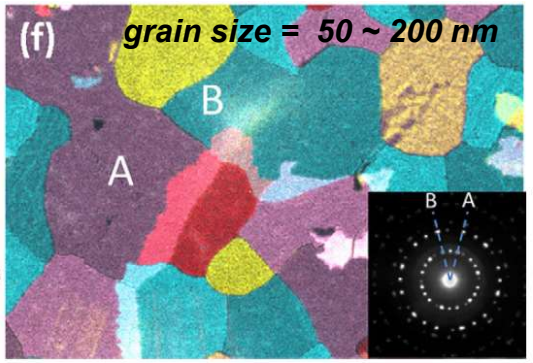
Higher growth temperature is better.





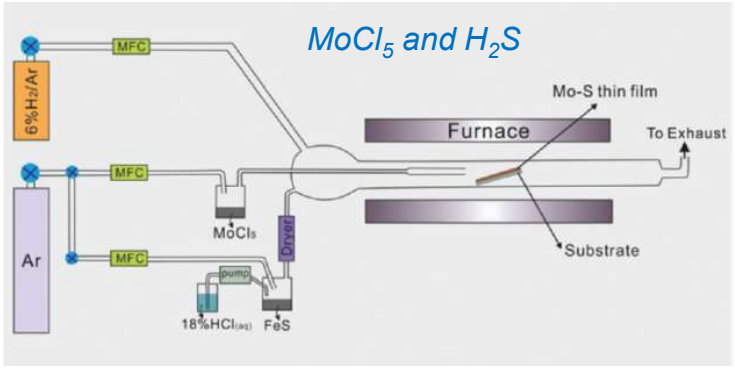
A. Tarasov et al. Adv. Funct. Mater. (2014)

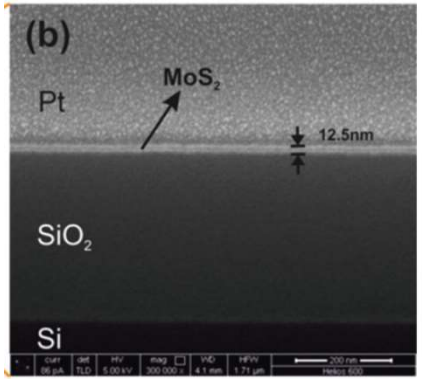


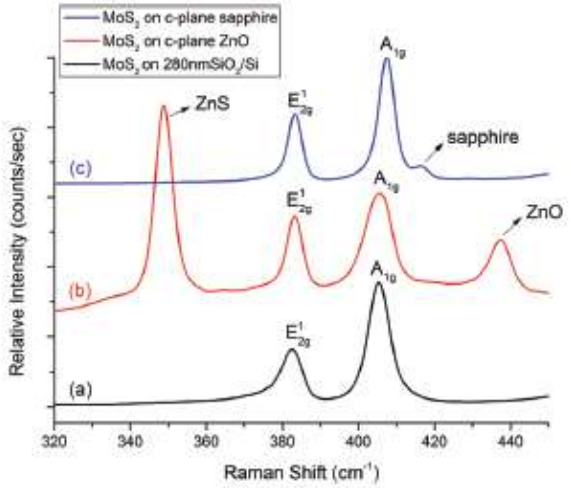


C. M. Orofeo et al. Appl. Phys. Lett. (2014)

Growth Method III

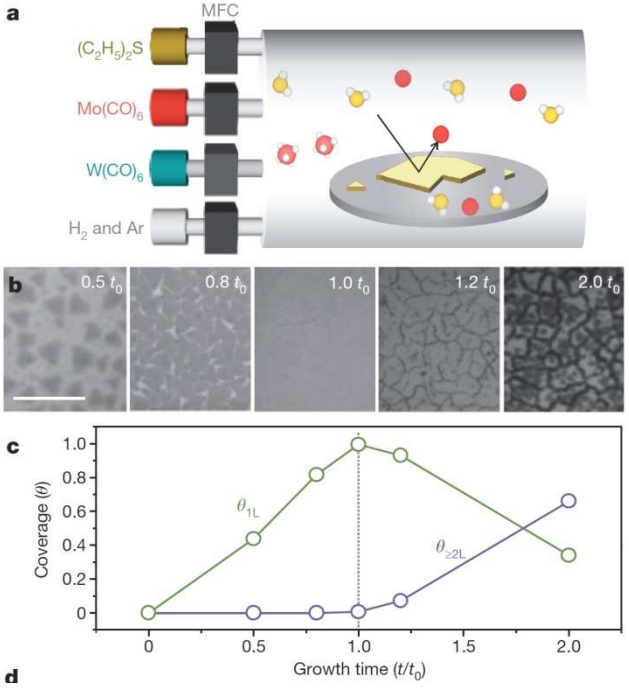


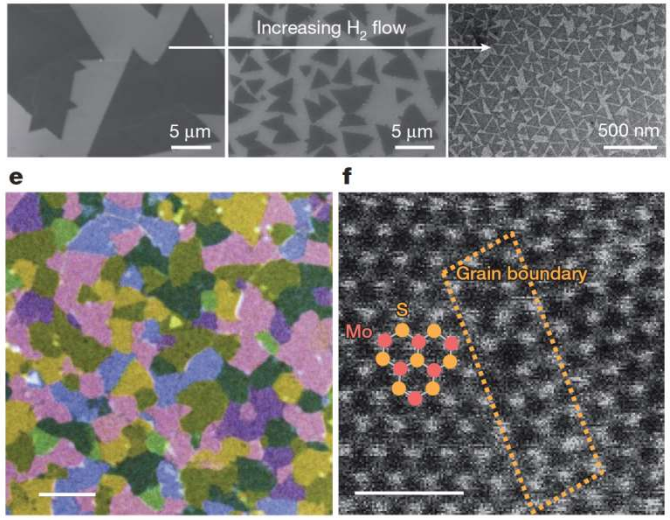


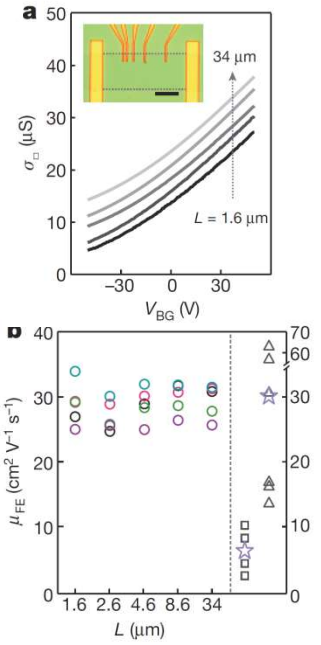


C. C. Huang et al. Nanoscale (2014)

MOCVD (Metal-Organic CVD) growth



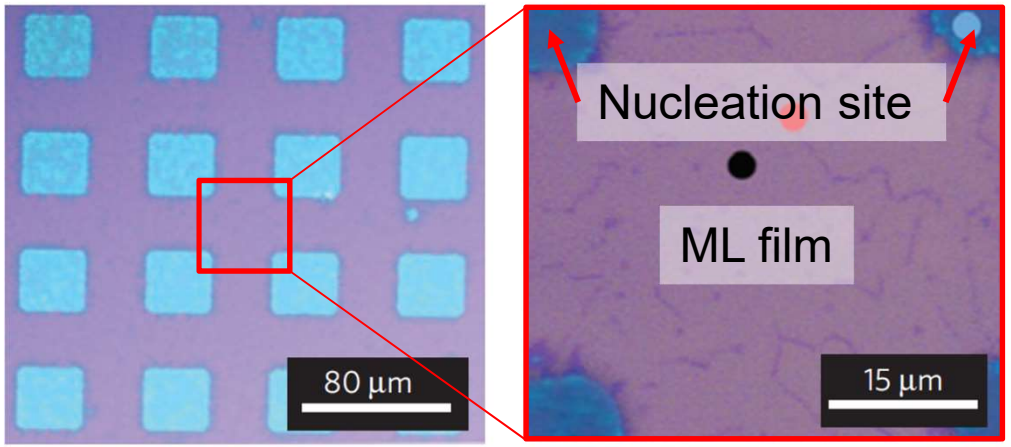




K. Kang et al. Nature (2015)

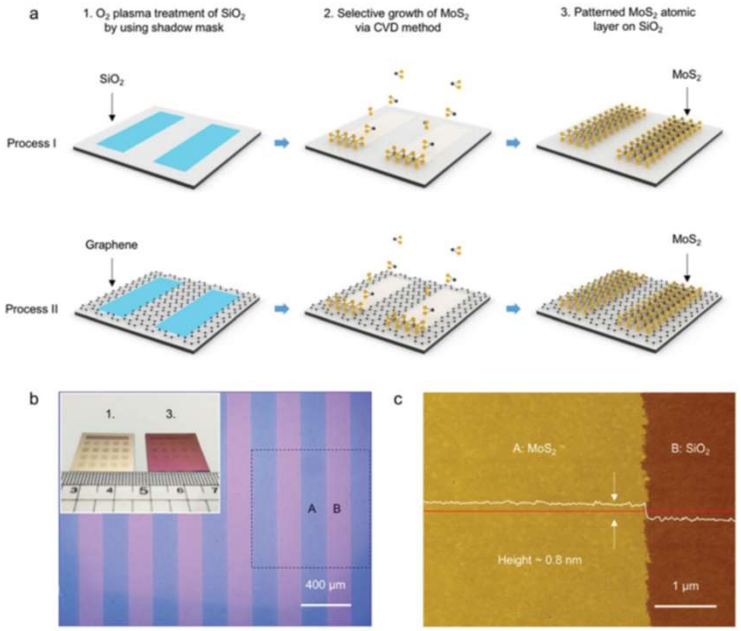
Nucleation and Patterned Growth

Pre-patterned nucleation control (SiO_2 pillars)



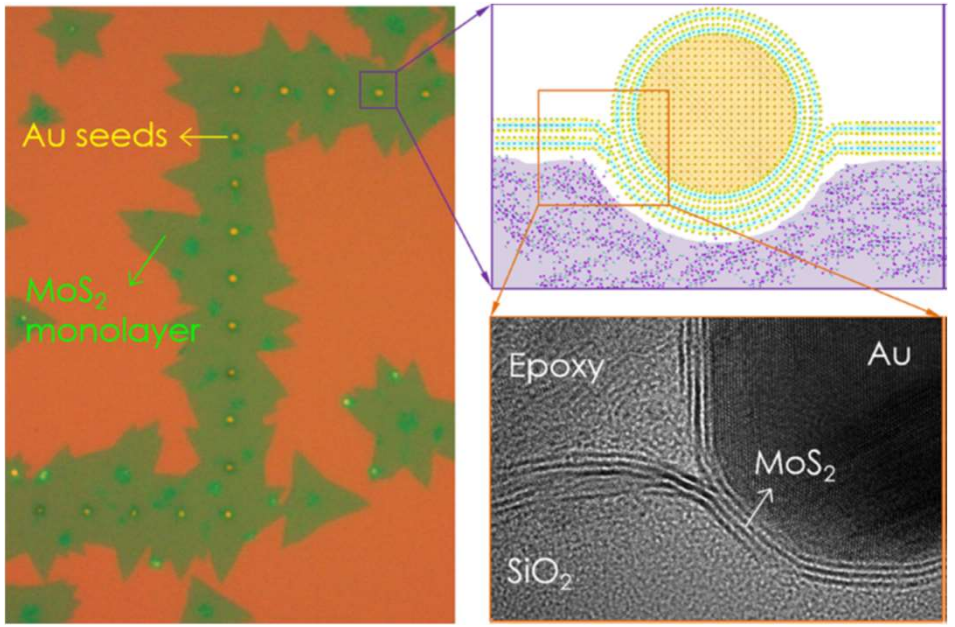
Nazmaei et al. Nat. Mater. (2013)

Plasma patterned nucleation control



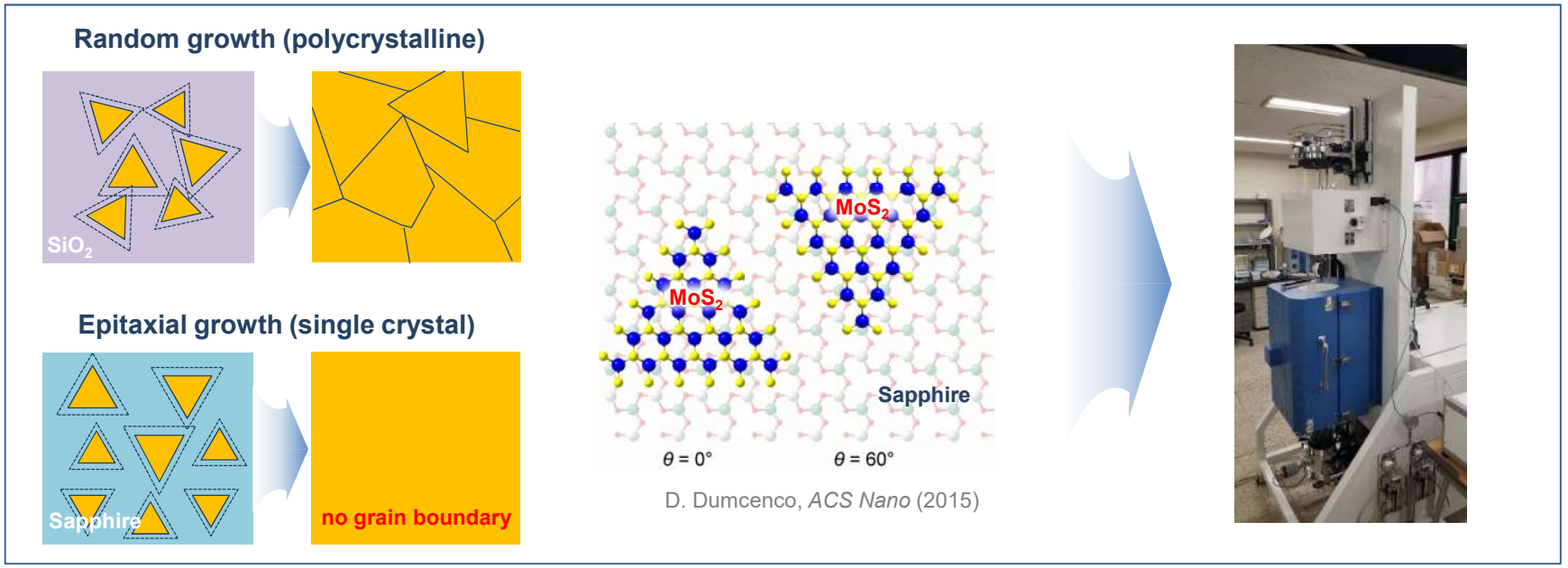
Chen et al. Nanoscale (2016)

Au patterned nucleation control

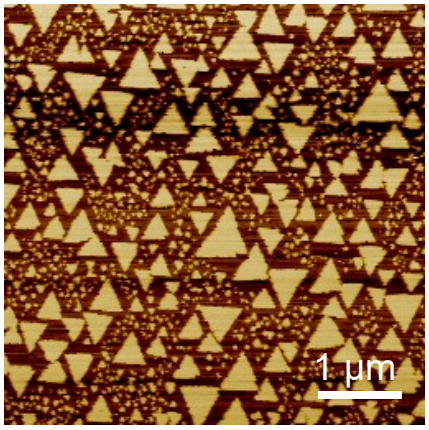


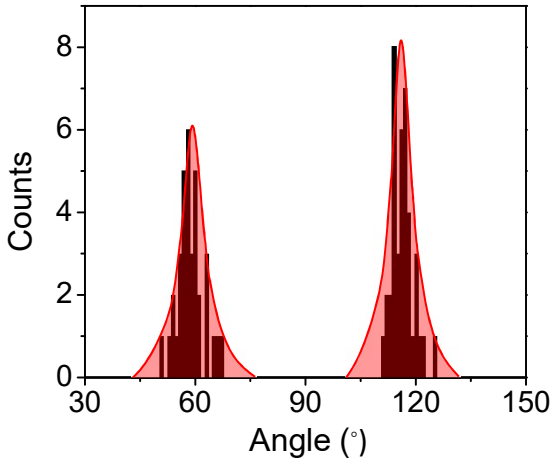
Li et al. ACS Nano (2018)

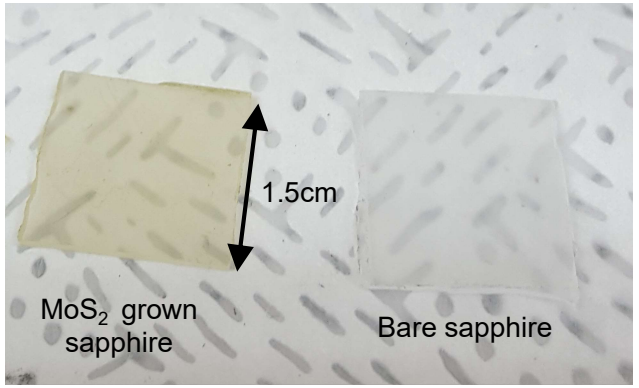
Epitaxial Growth



D. Dumcenco, *ACS Nano* (2015)

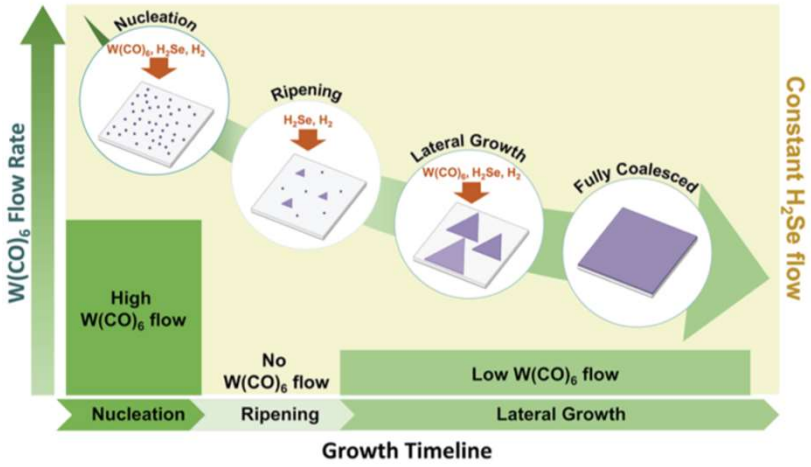


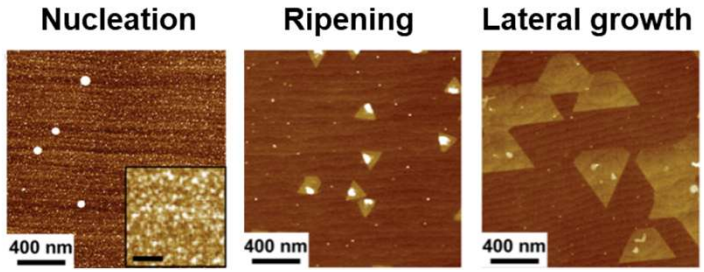




Epitaxial Growth

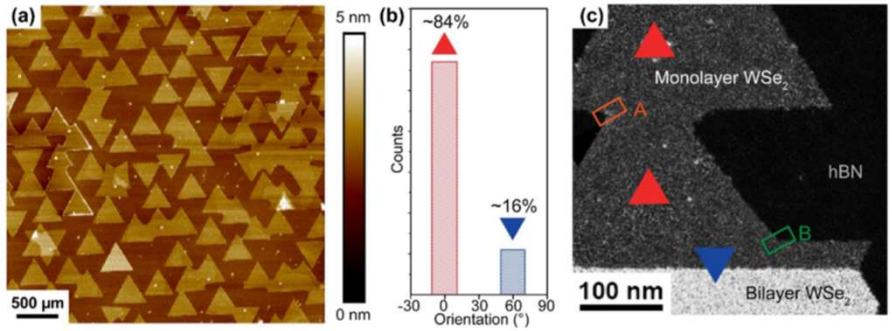
Three step process of WSe_2 growth on c-Sapphire





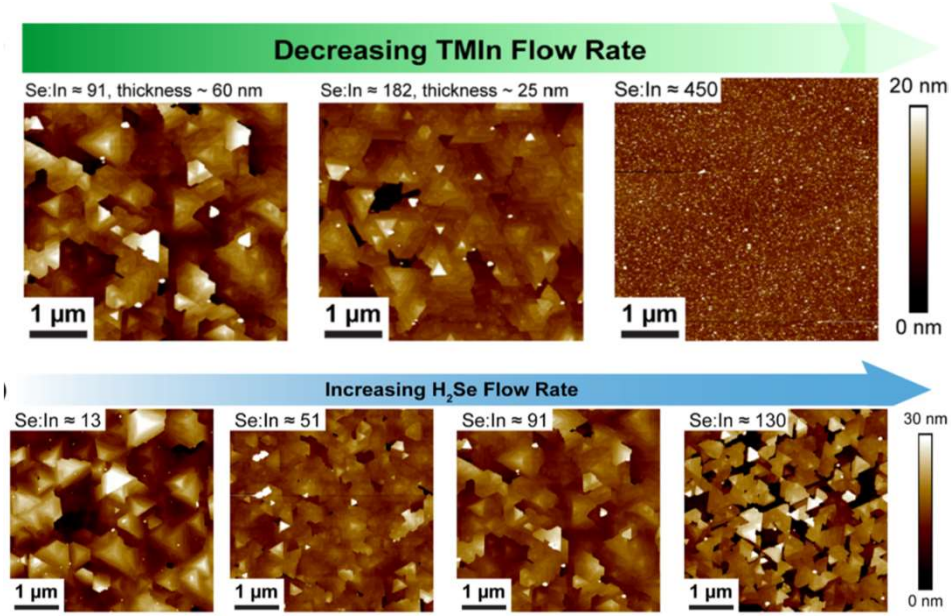
X. Zhang, et al. Nano Lett. (2018)

Epitaxial growth of WSe_2 on h-BN



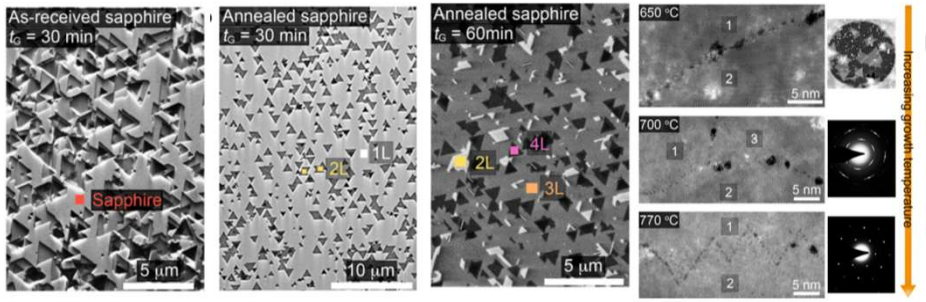
X. Zhang, et al. ACS Nano. (2019)

Epitaxial growth of In_2Se_3 on c-sapphire



Zhang et al. J. Crys. Growth (2020)

Epitaxial growth of WSe_2 on c-sapphire

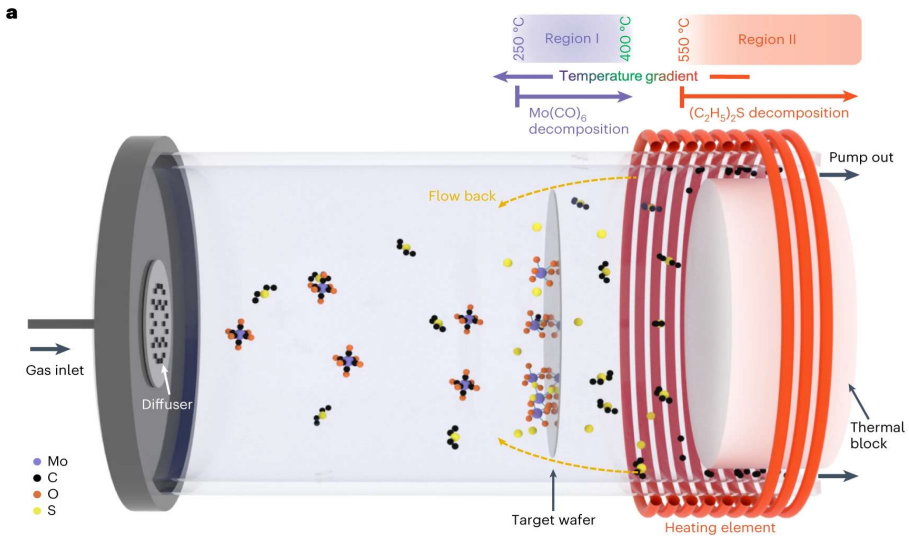


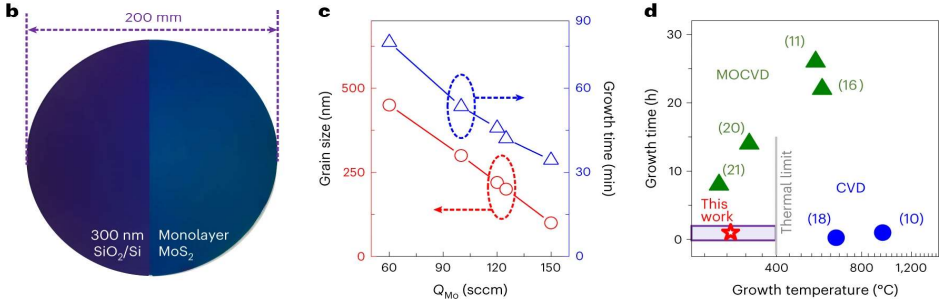
Y. Lin, et al. ACS Nano. (2018)

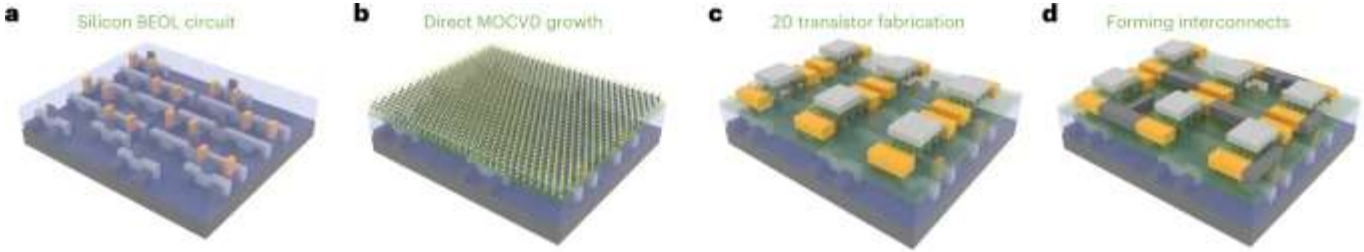
Low Temperature Growth of MoS_2

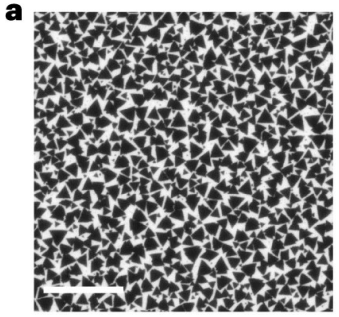
Safe temperature for the silicon process (400°C)

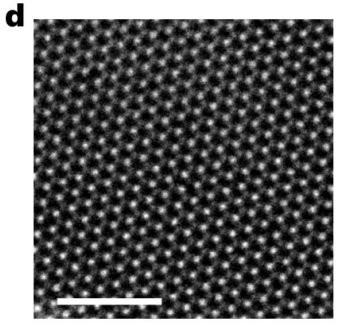
Decomposition temperatures of $Mo(CO)_6$ (~250°C) and $(C_2H_5)_2S$ (550°C)



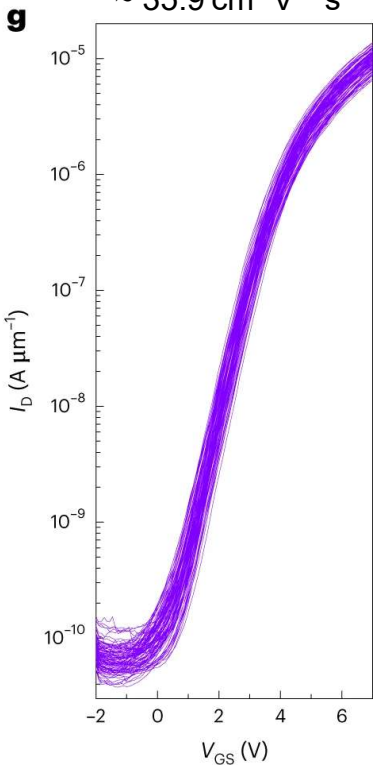


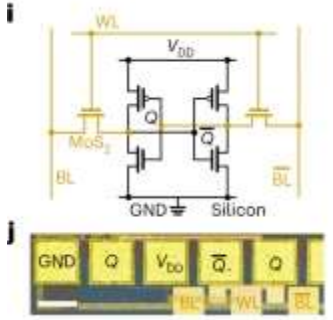






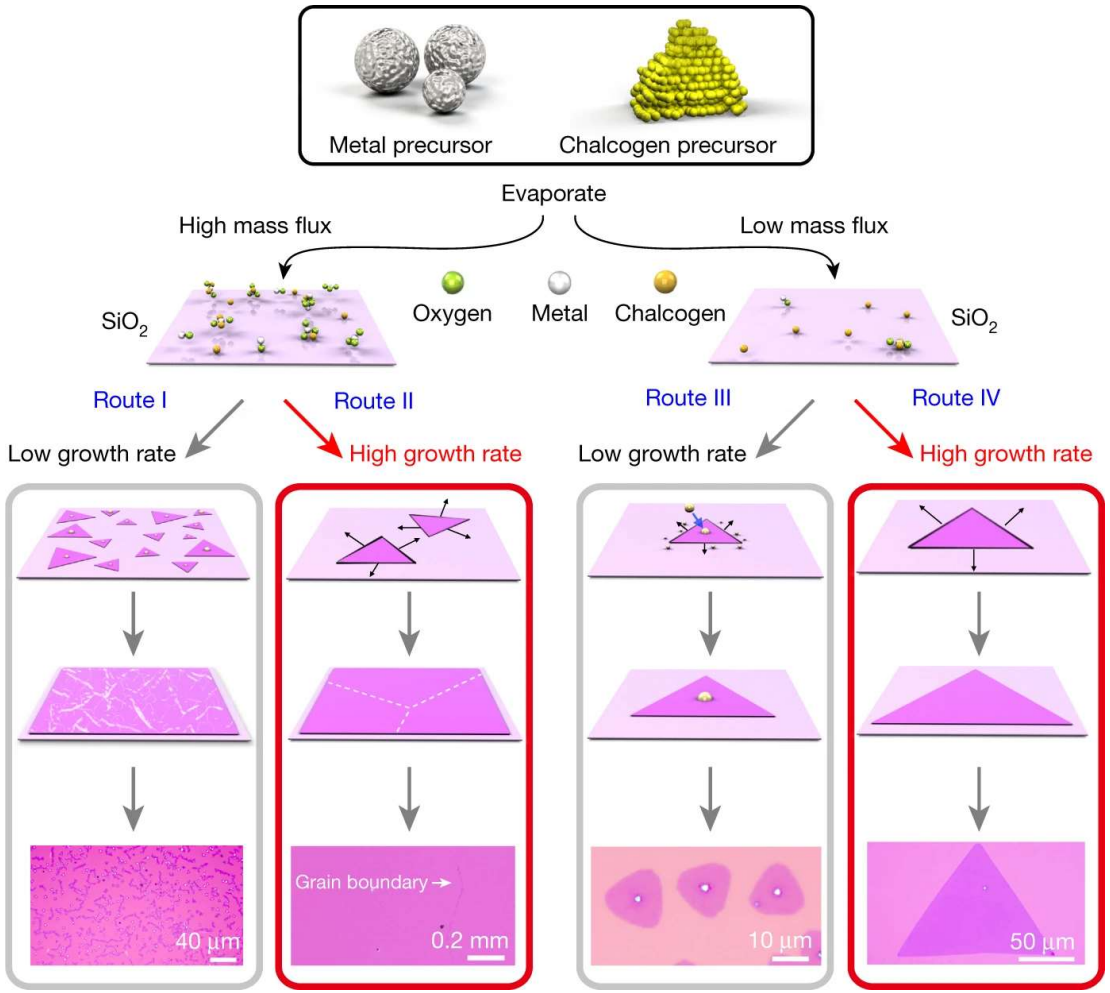
electron mobility
~ 35.9 $cm^2 V^{-1} s^{-1}$

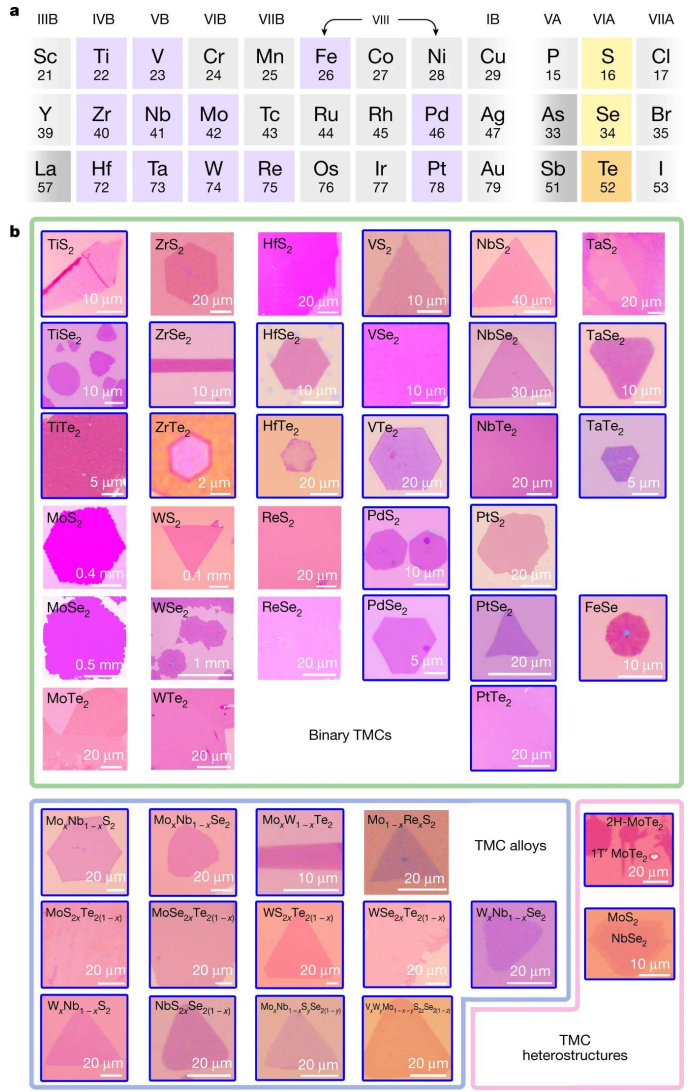




J. Zhu, T. Palacios, *et al.* Nature Nanotechnology (2023)

Promoter-assisted MOCVD

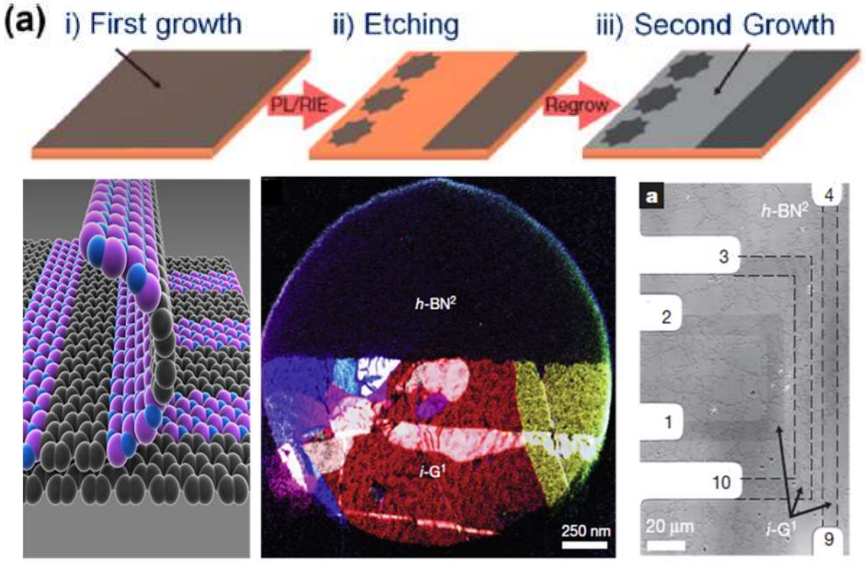




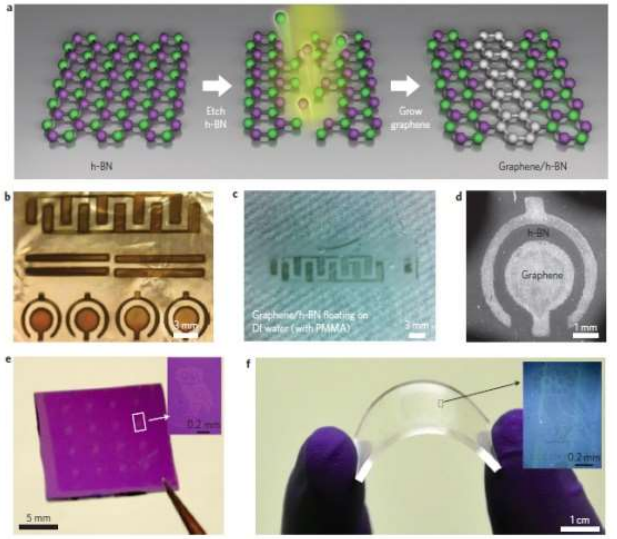
Nature 556, 355–359 (2018)

Growth of Heterostructures

Growth of graphene-hBN heterostructure

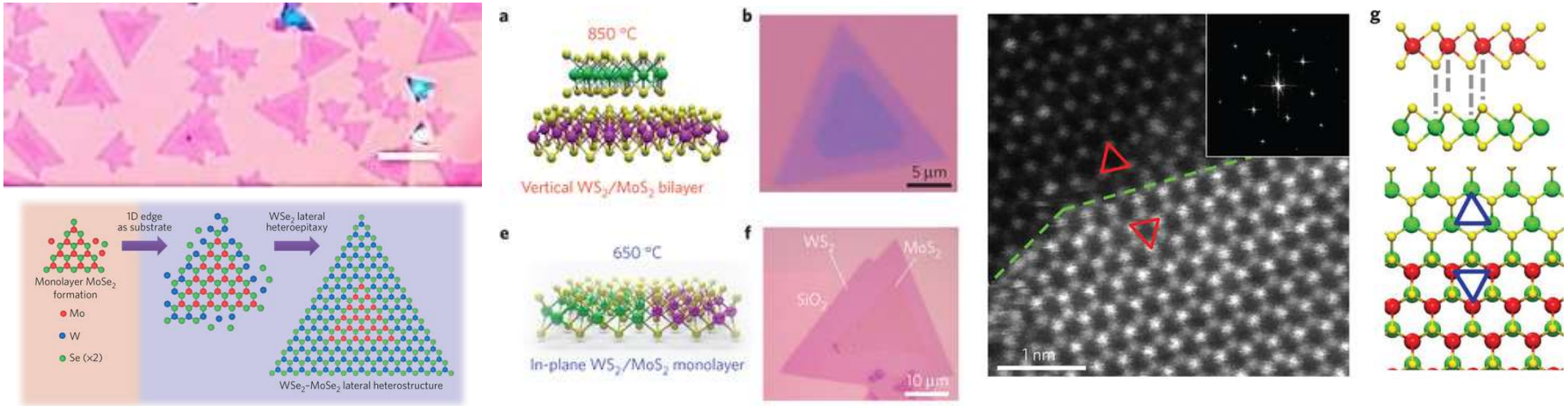


M. P. Levendorf et al. Nature (2012)



Z. Liu et al. Nat. Nanotech. (2013)

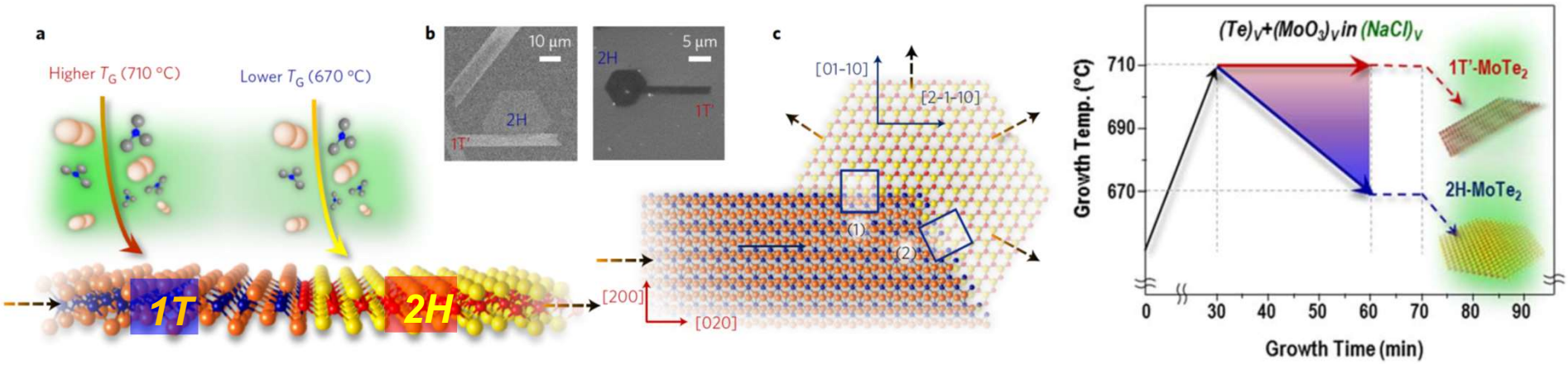
Growth of semiconductor heterostructure

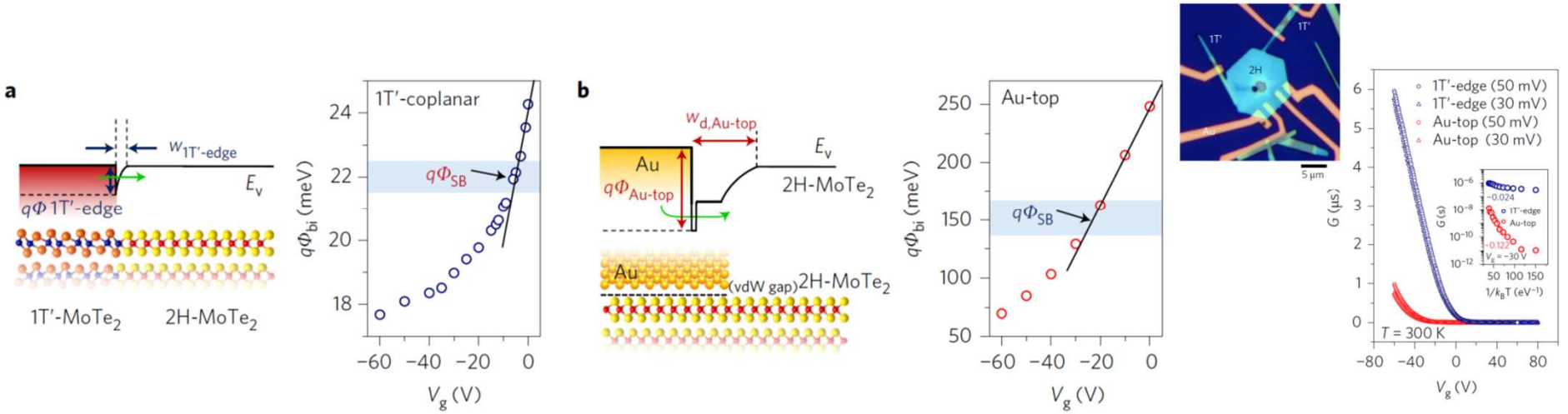


C. Huang et al. Nature Mater. (2014) & Y. Gong et al. Nature Mater. (2014) & G. S. Duesberg et al. Nature Mater. (2014)

Growth of Heterostructures

Sequential growth of coplanar heteroepitaxy (1T′/2H $MoTe_2$)

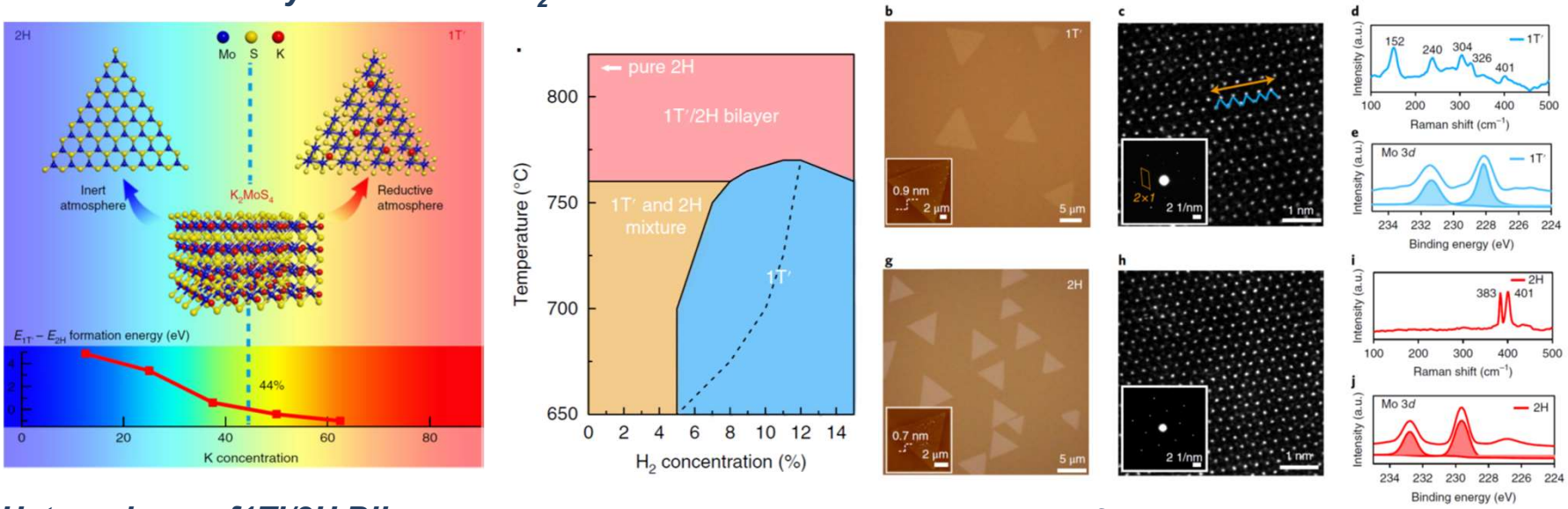




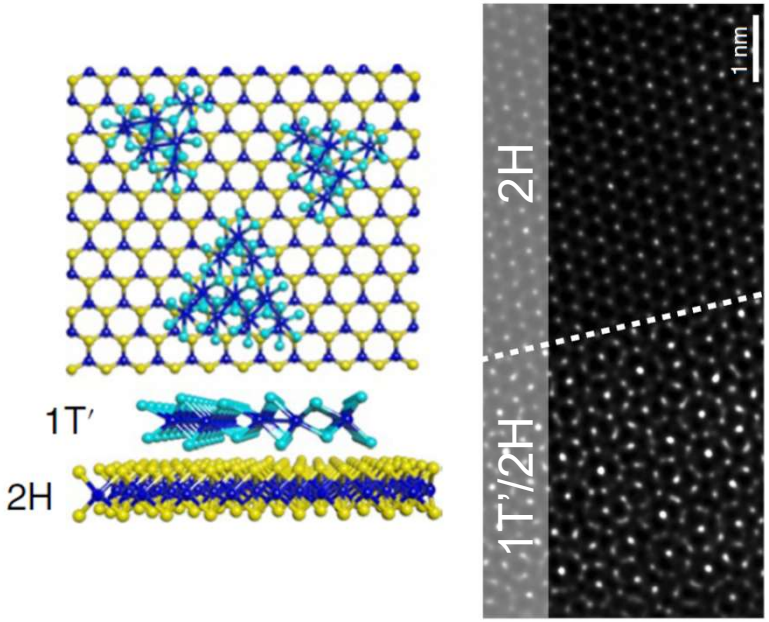
Sung et al. Nat. Nanotech. (2017)

Growth of Heterostructures

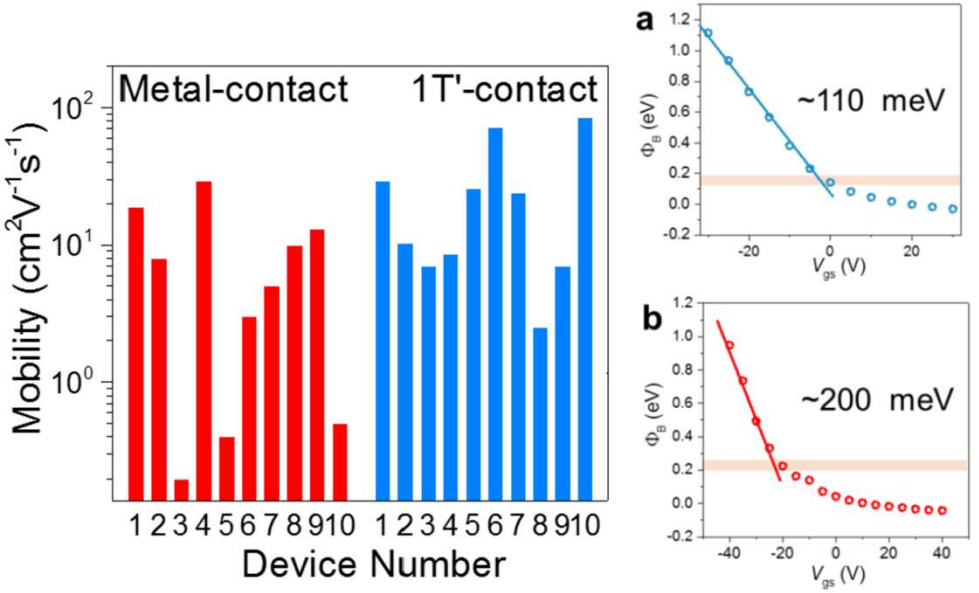
Phase-selective synthesis of MoS_2



Heterophase of1T'/2H Bilayer



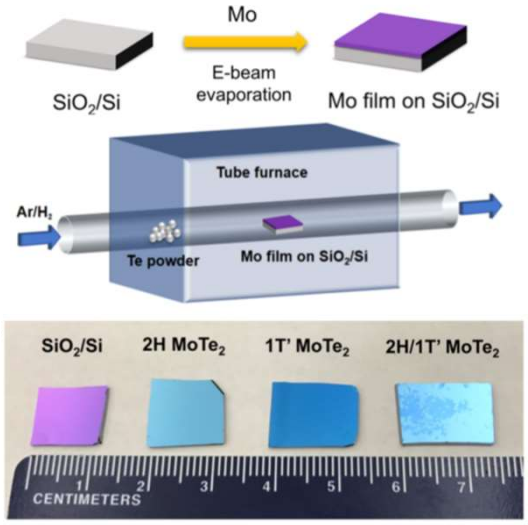
Electrical properties of heterophase contacts



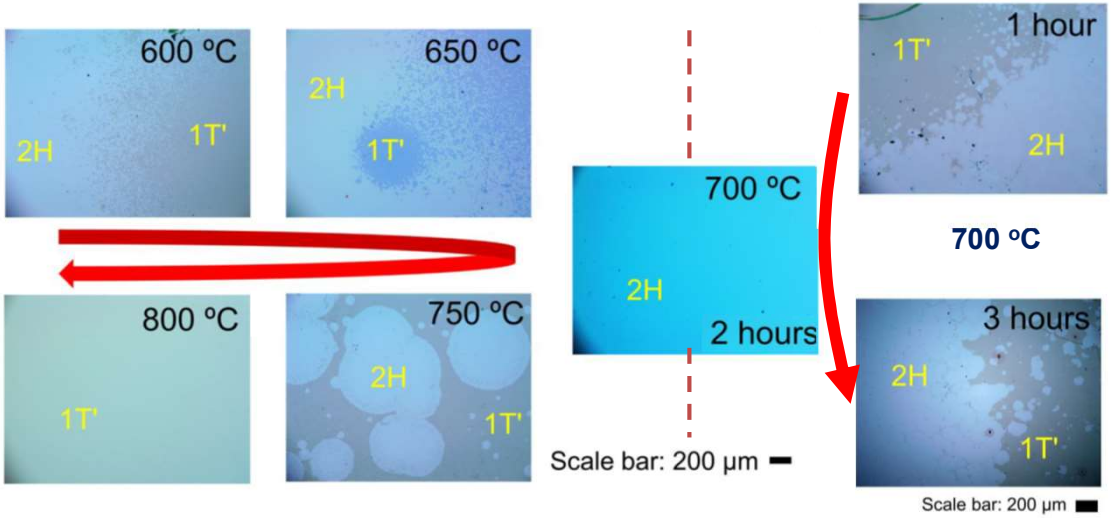
Liu et al. Nat. Mater. (2018)

Growth of Heterostructures

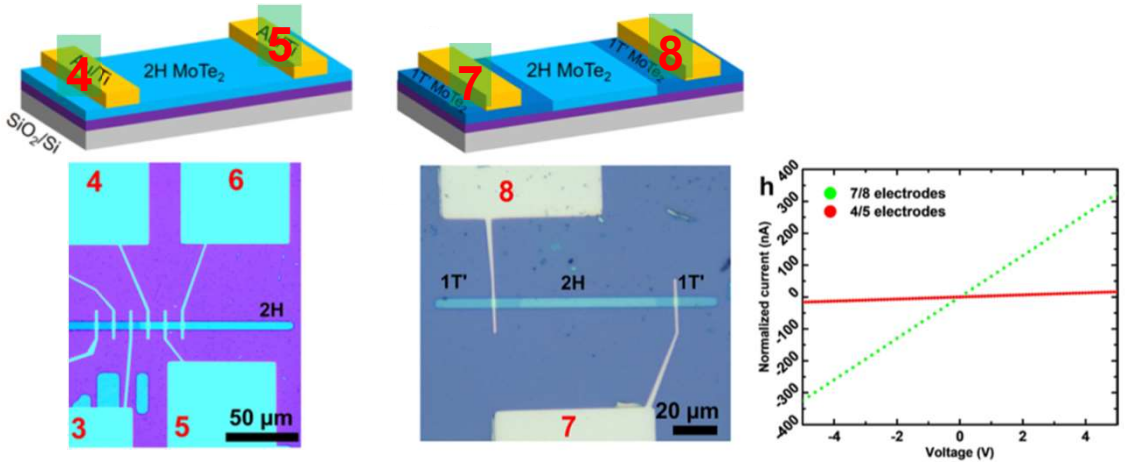
Growth of $MoTe_2$



Effect of temperature and time on the phase



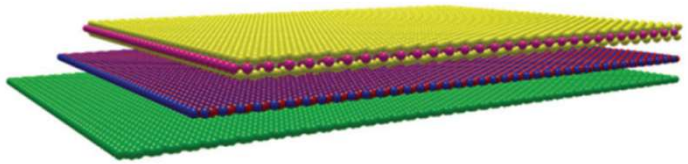
1T' edge contacts to 2H-$MoTe_2$



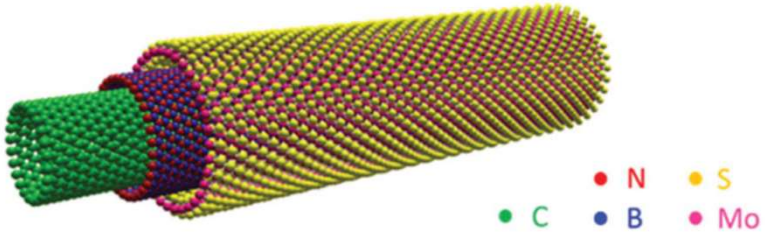
X. Zhang et al. ACS Appl. Mater. Interfaces (2019)

Growth of Heterostructures V

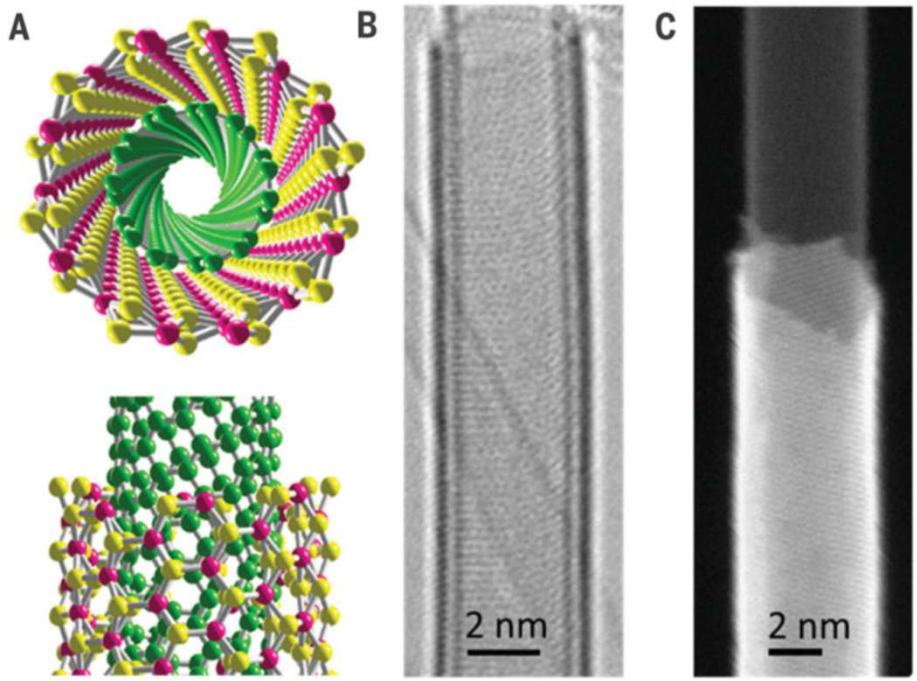
Conventional two-dimensional vdW Heterostructure



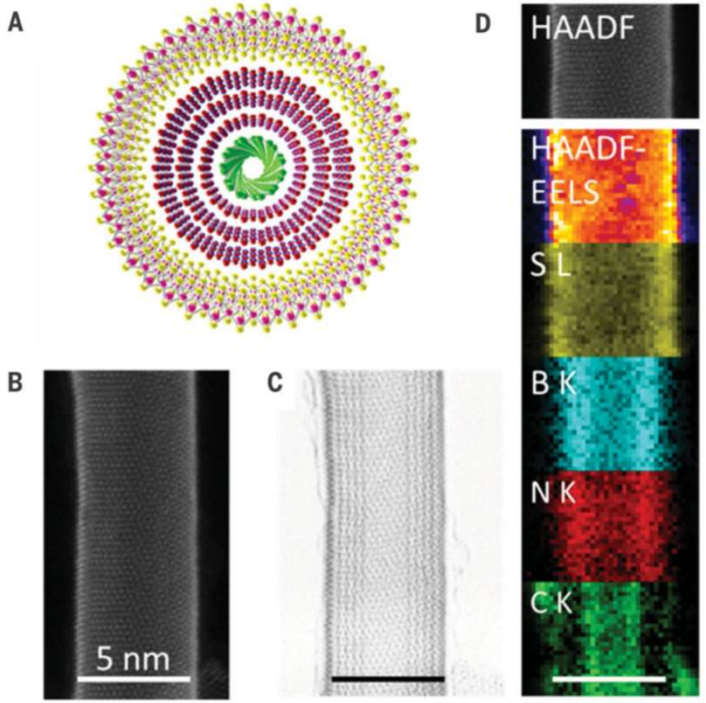
One-dimensional vdW Heterostructure (nanotube)



CNT-MoS_2 nanotube heterostructure

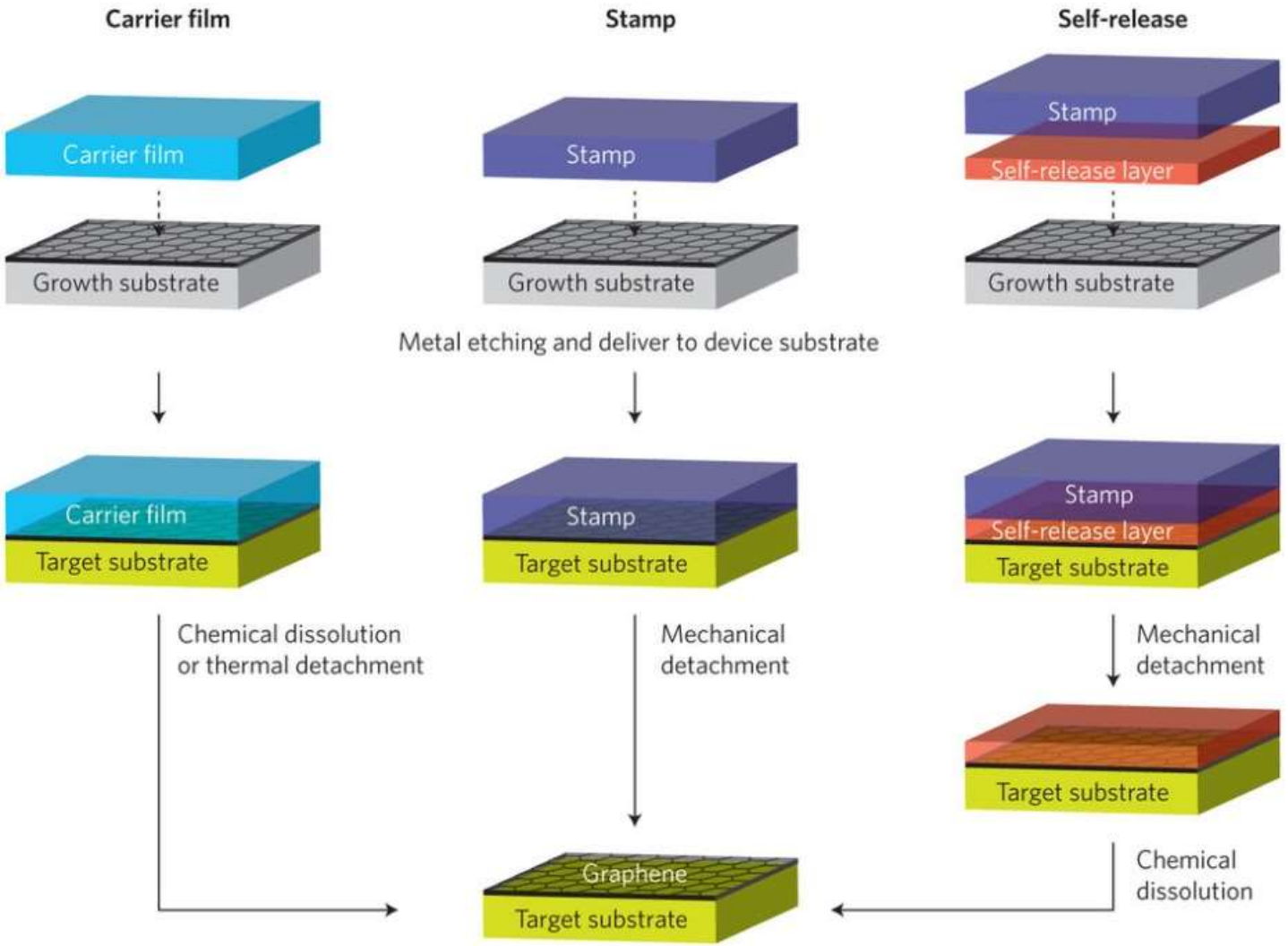


CNT-BNNT-MoS_2 heterostructure



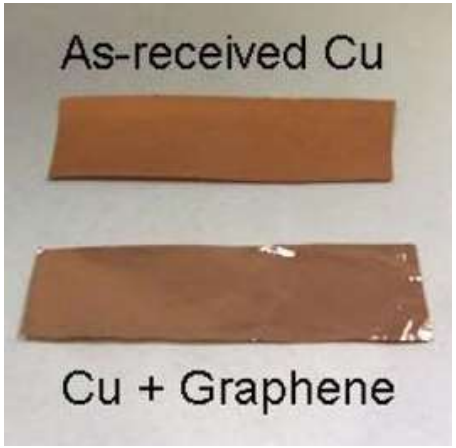
R. Xiang, Science (2020)

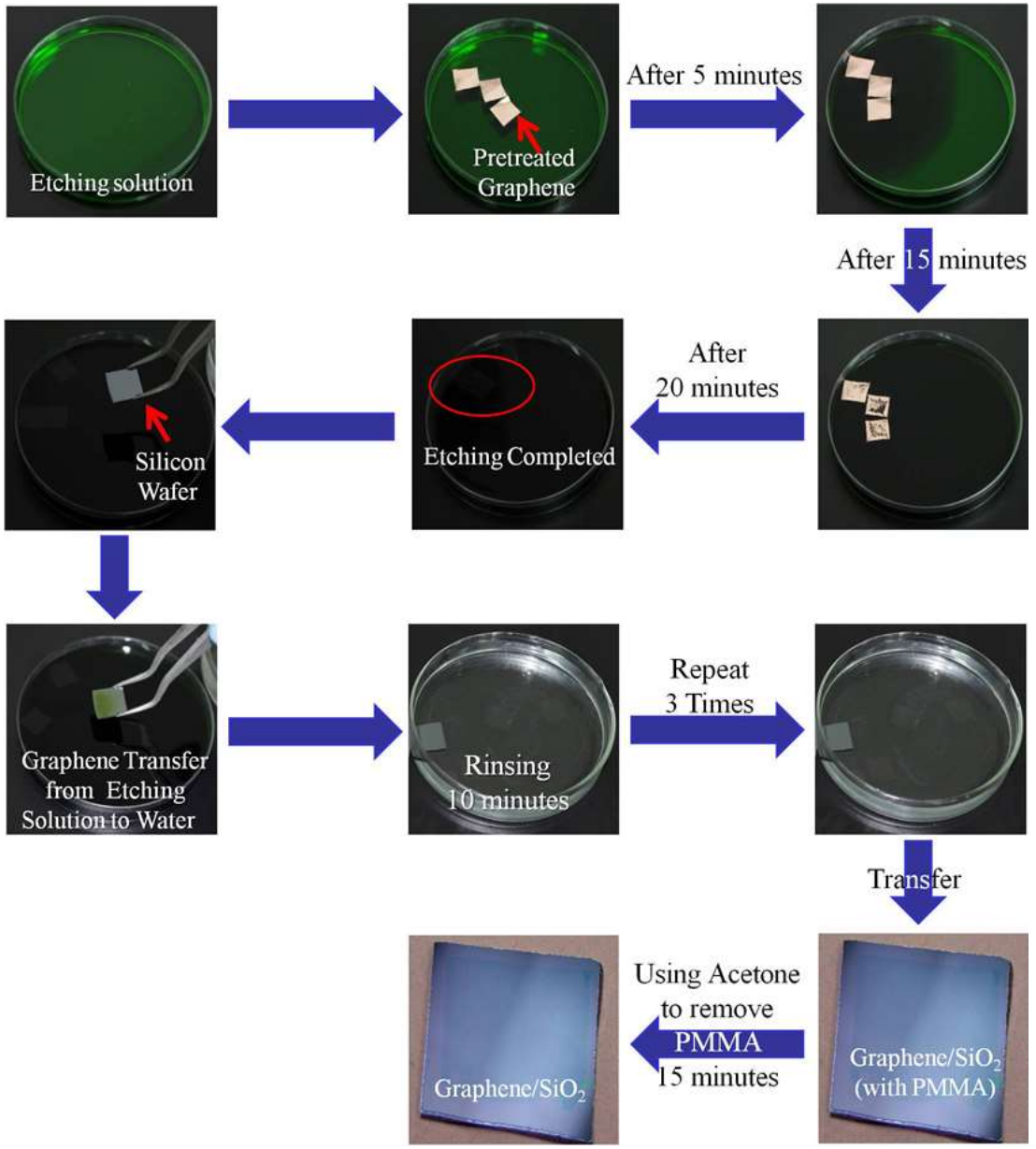
Graphene Transfer Techniques



J. Y. Choi, Nature Nanotechnol. (2013)

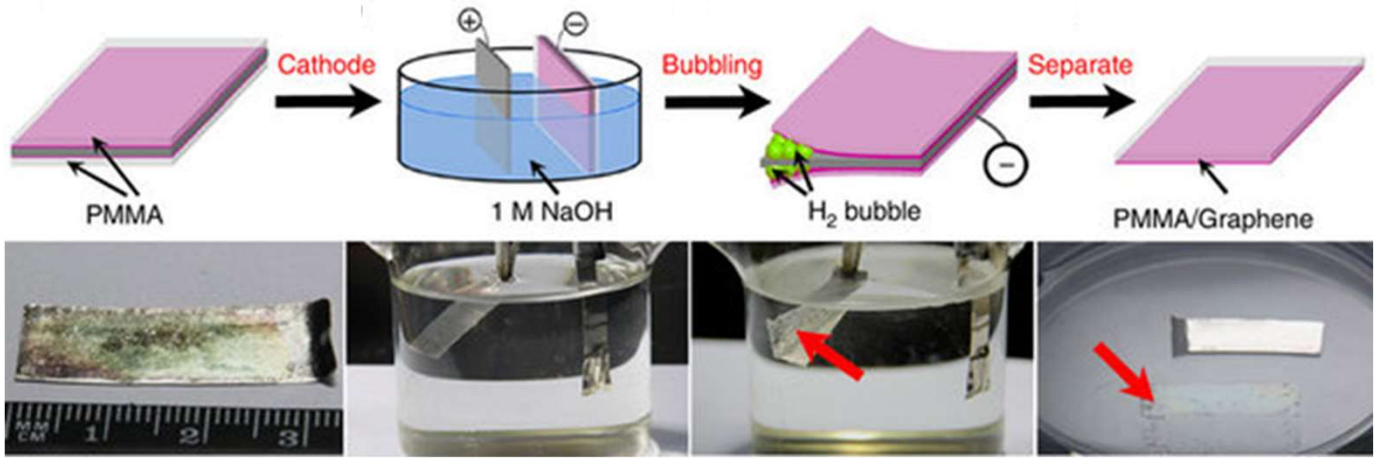
General PMMA Transfer Technique





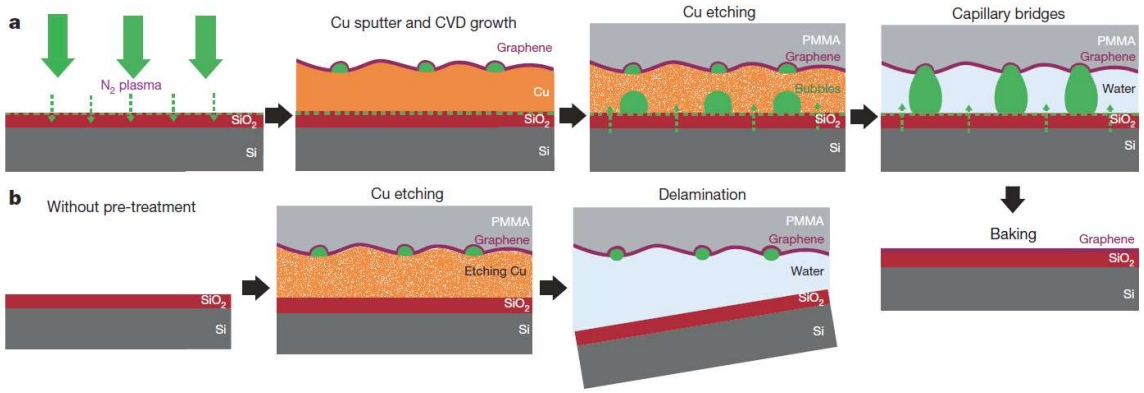
Other Transfer Techniques

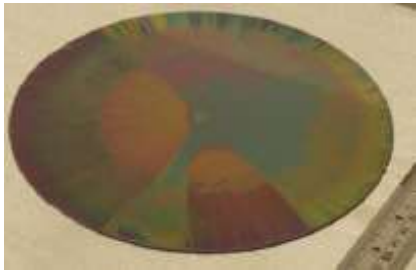
Bubble Transfer Technique



L. Gao et al. Nature Commun. (2012) & C. J. Lockhart de la Rosa et al. Appl. Phys. Lett. (2013)

Face-to-Face Transfer Technique

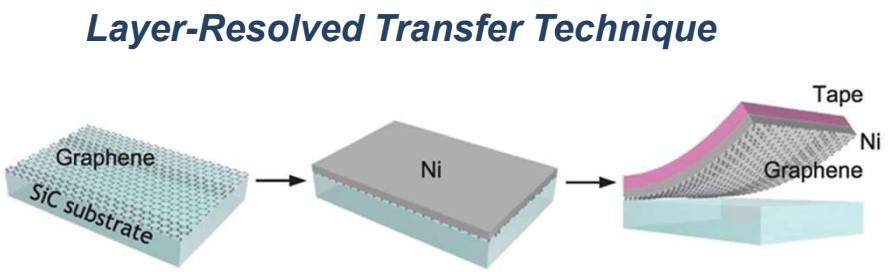


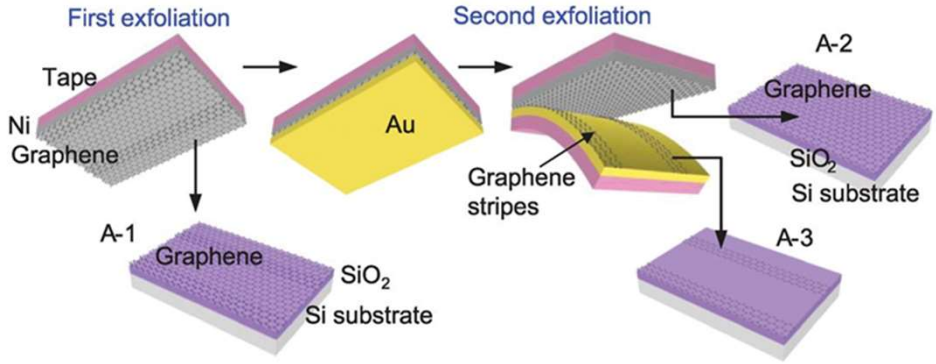


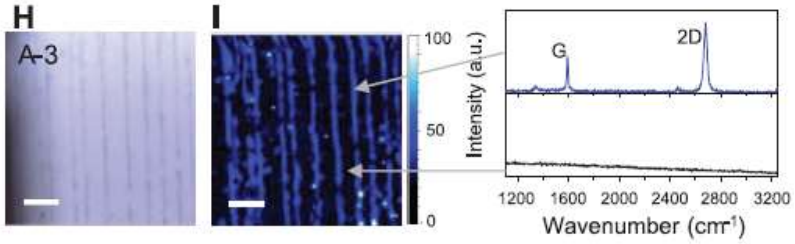
L. Gao et al. Nature (2014)

Other Transfer Techniques

Layer-Resolved Transfer Technique

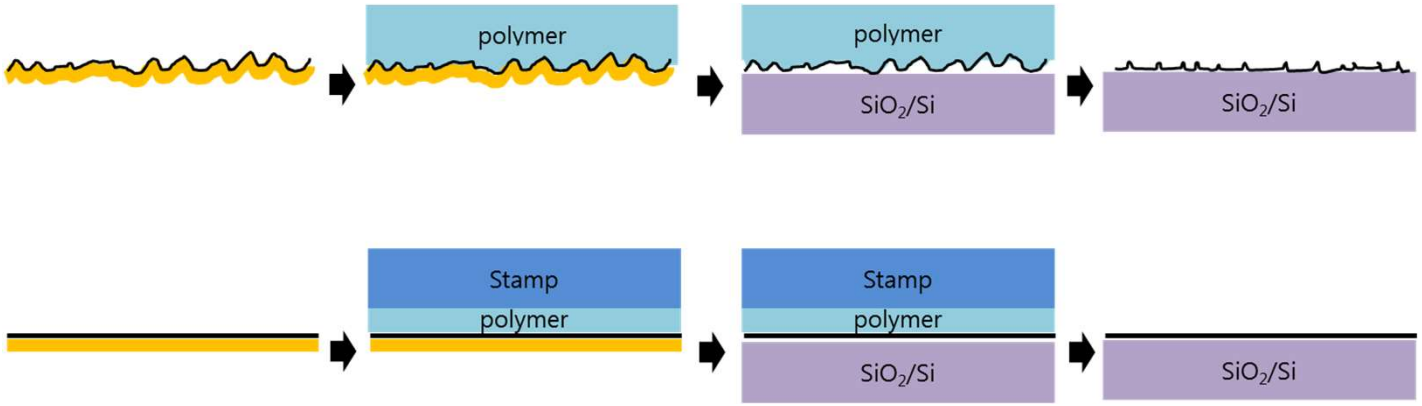






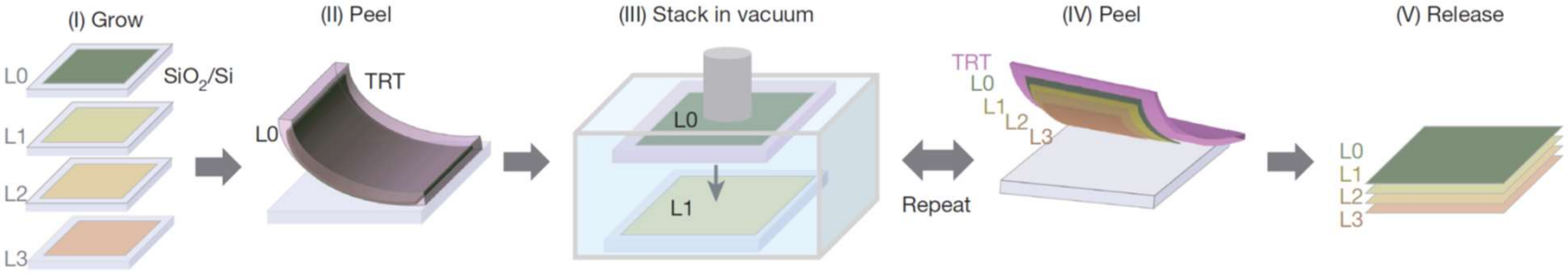
J. Kim et al. Science (2013)

Critical issues in transfer and stacking processes

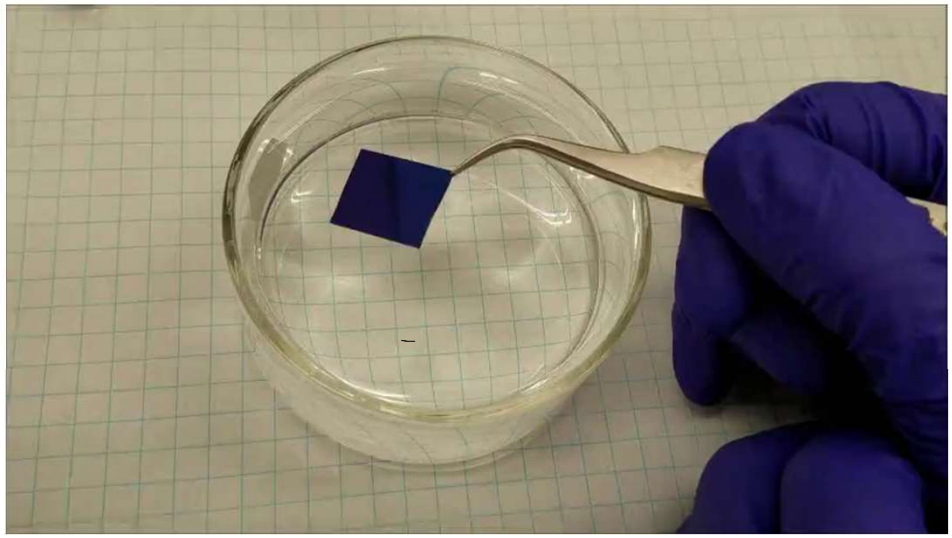


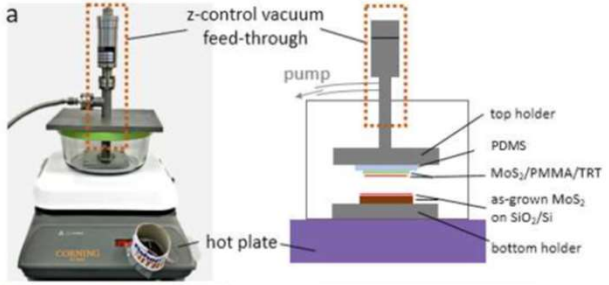
Other Transfer Techniques

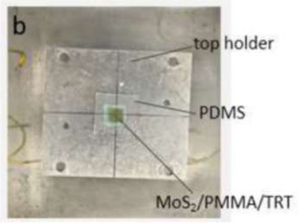
Layer-by-layer assembly of TMDs

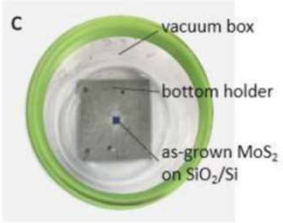


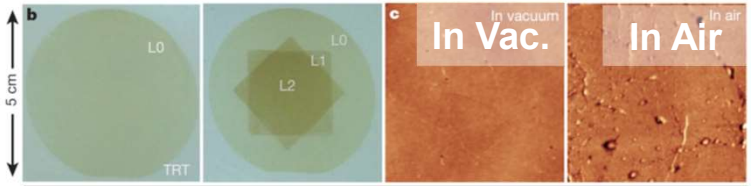
Delamination process of a ML MoS_2 film

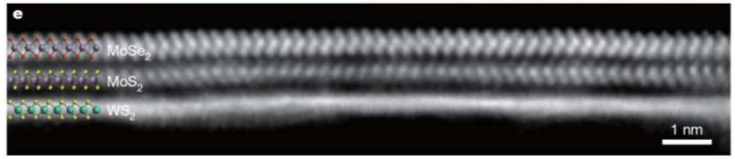








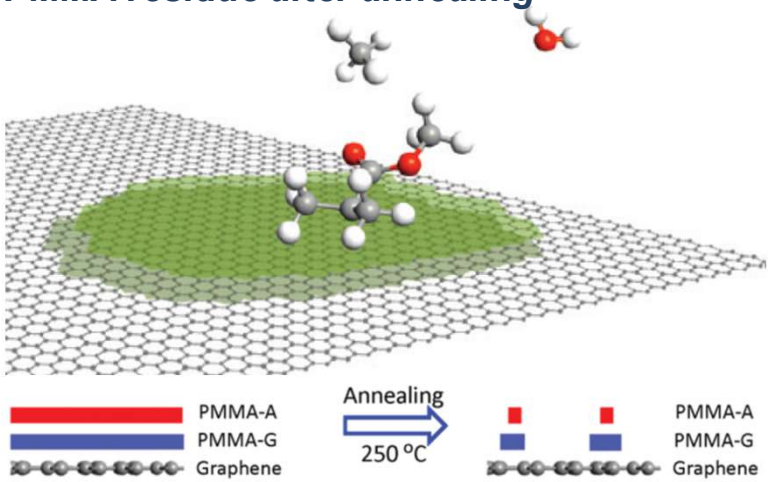


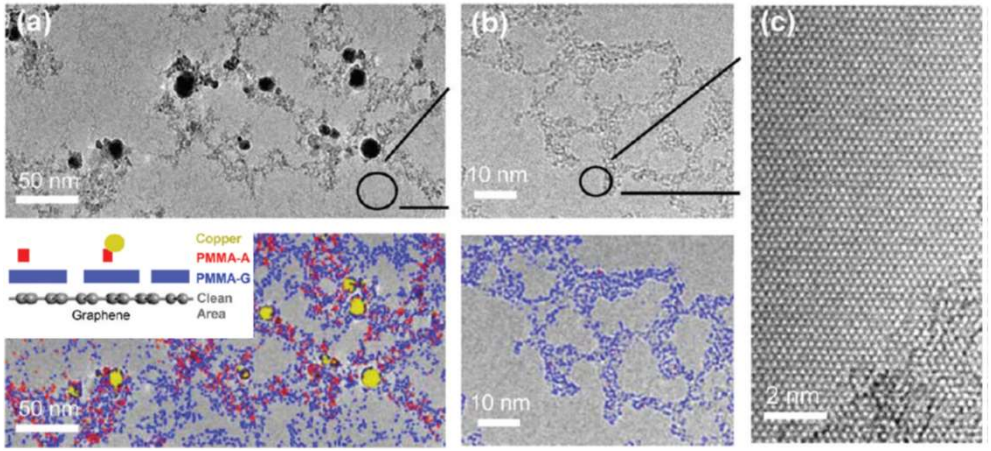


K. Kang et al. Nature (2017)

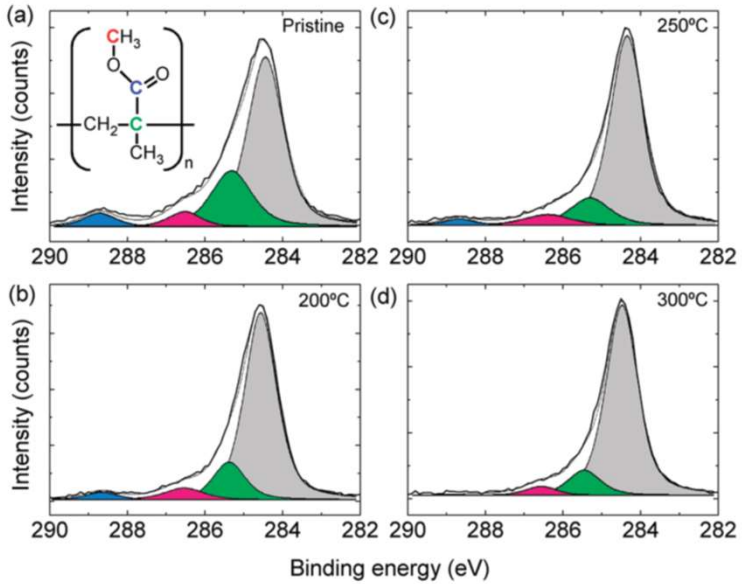
Residue Issue in Transfer

PMMA residue after annealing

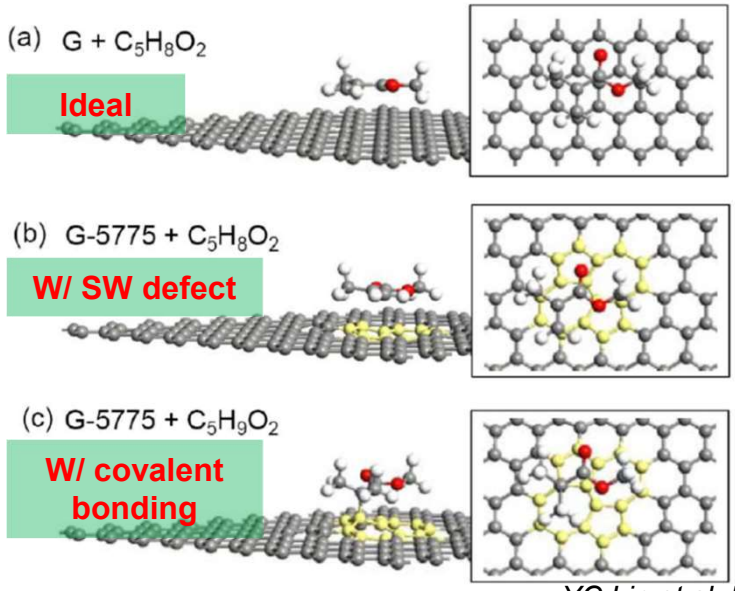




XPS spectra of PMMA-transferred CVD graphene



Side and top view of the optimized adsorption of MMA



YC Lin et al. Nano Lett. (2011)