MoS$_2$ Field-Effect Transistors: Dielectric, Contacts, and Scaling

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DRC 2D Workshop on 6/23/2013

PURDUE
UNIVERSITY

Outline

(1) Motivation

(2) Fundamental properties of MoS_2 and others

(3) MoS_2 based electronic devices

  a. ALD high-k/MoS_2 integration

  b. Metal contacts to MoS_2

  c. Device scaling factors

  d. Doping in MoS_2 FETs

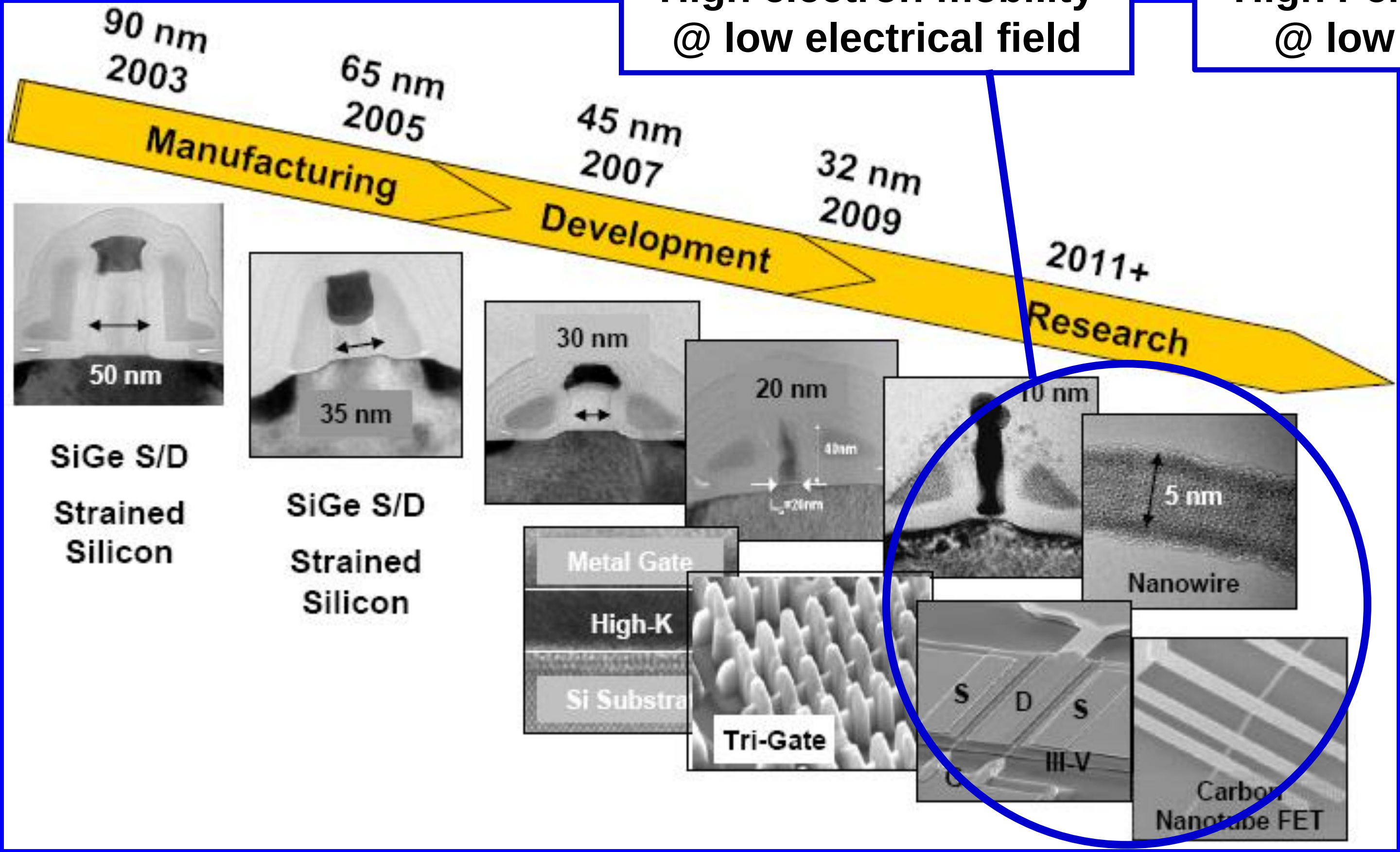
  e. Transport in MoS_2

(4) Summary

Emerging Non-Si CMOS Research

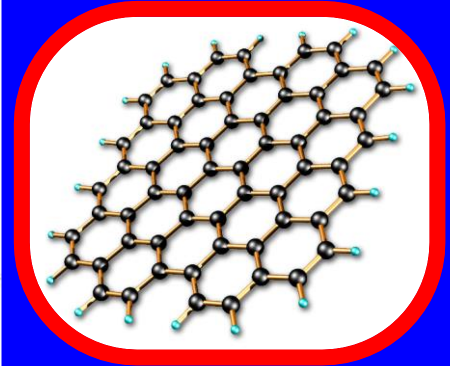
High electron mobility
@ low electrical field

High Performance
@ low voltage

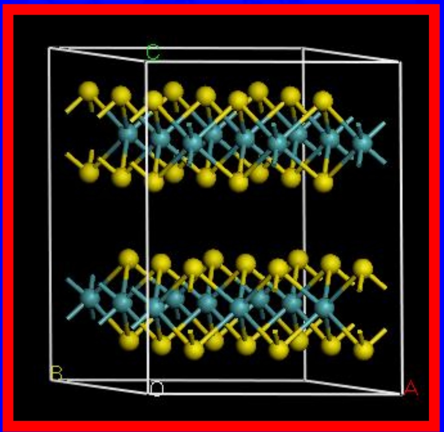


More Non-Si Elements Introduced

Source: R. Chau, DRC 2006



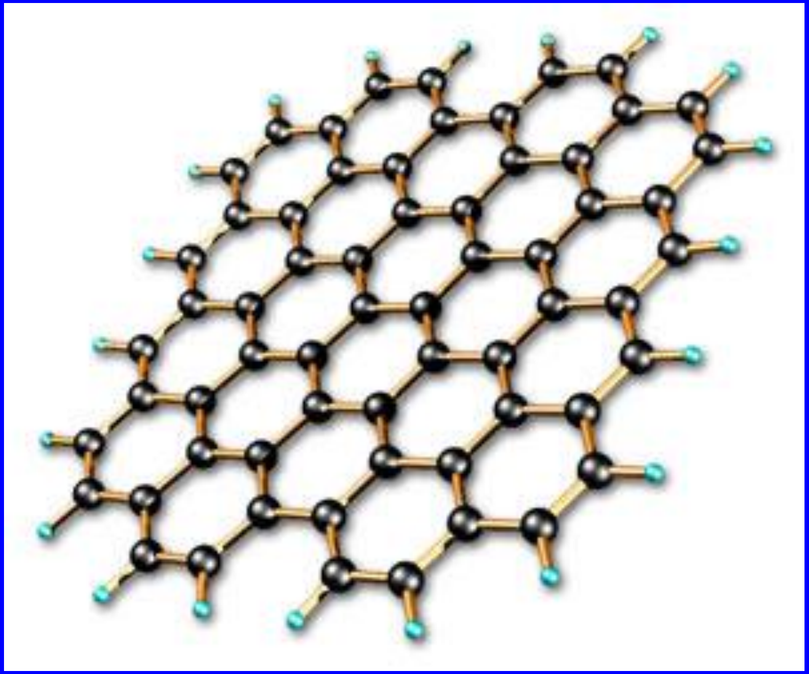
Graphene

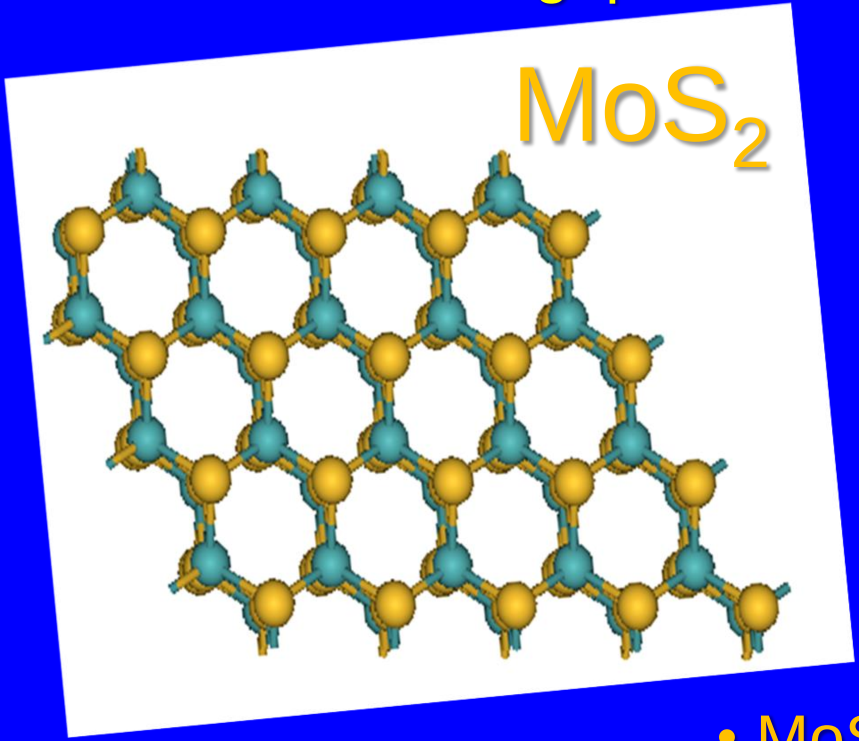


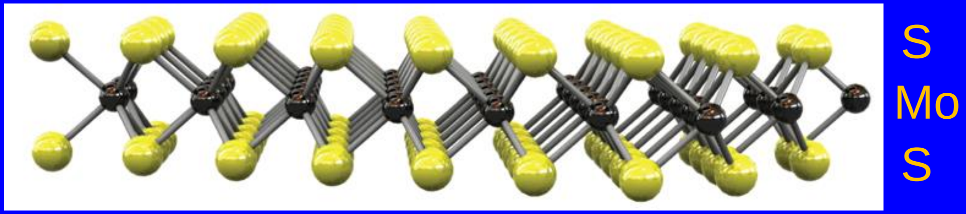
MoS_2

MoS$_2$ - 2D Crystal beyond Graphene

- Graphene has been actively researched for last few years
    - ➢ Zero band gap !



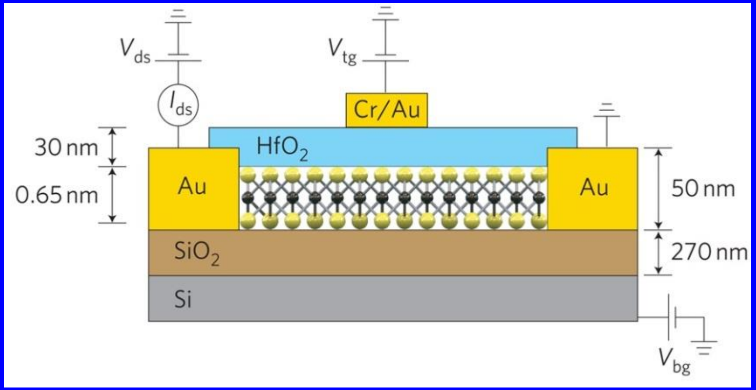


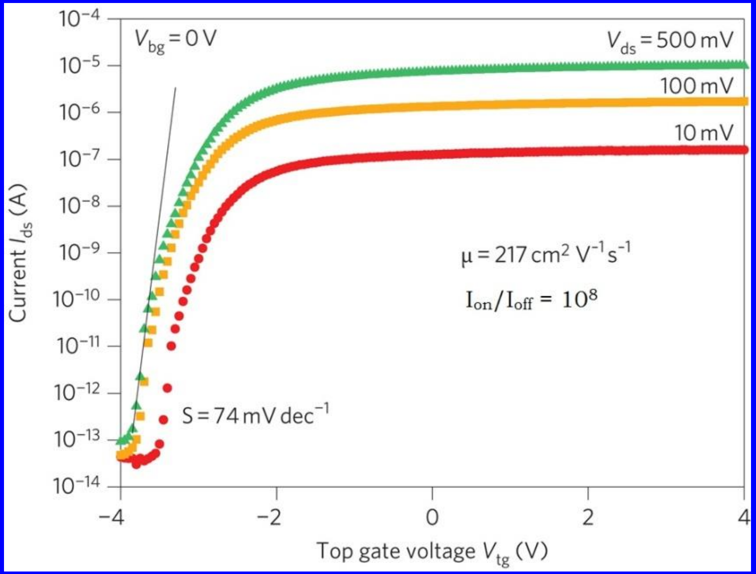


- MoS$_2$ - 2D Crystal beyond Graphene
    - ➢Large band gap ~1.2 eV-1.8 eV
    - ➢First MOSFET Jan 2011

Single layer MoS_2 MOSFET

- Mechanically exfoliated
- Mobility (200 cm^2/Vs)*
- Mobility enhanced by ALD high-k
- Intrinsic direct bandgap for single layer
- Thermal stability up to 1100ºC
- Thin transparent semiconductor





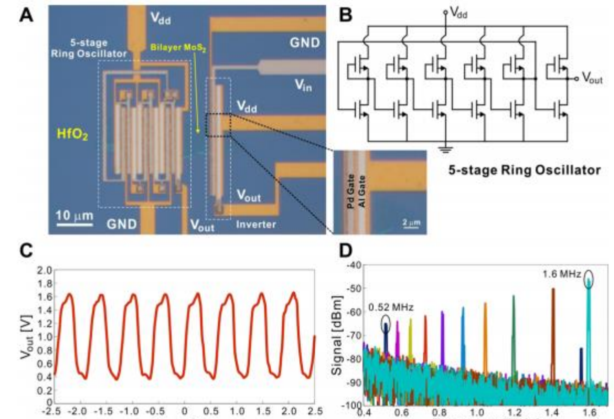
* See also Hone and Fuhrer Nat. Nanotechnol. 2013

nature nanotechnology

B. Radisavljevic, A. Radenovic, J. Brivio, V. Giacometti, and A. Kis, Nature Nanotechnol. 6, 147 (2011).

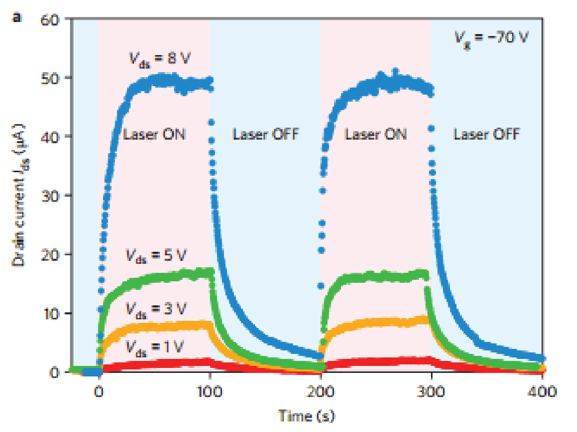
Applications of MoS_2

Integrated Circuits



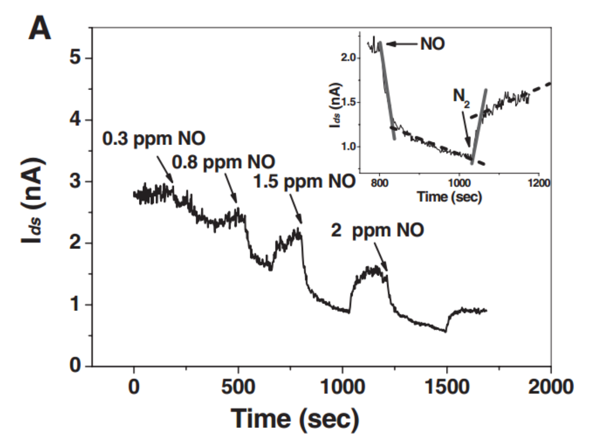
H. Wang et al. Nano Lett 2012

Photodetectors



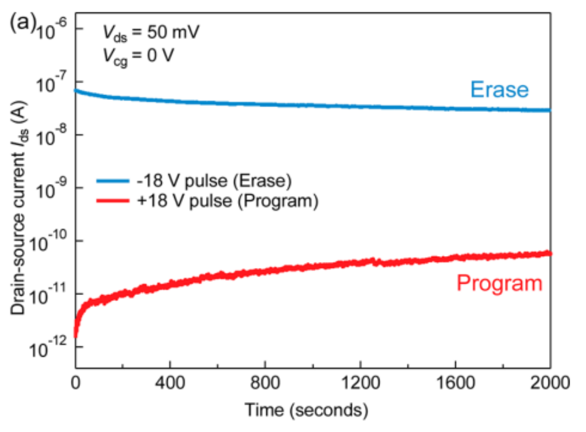
O. Lopez-Sanchez et al, Nat. Nanotechnol. 2013

Chemical Sensor



H. Li et al. Small, 2012

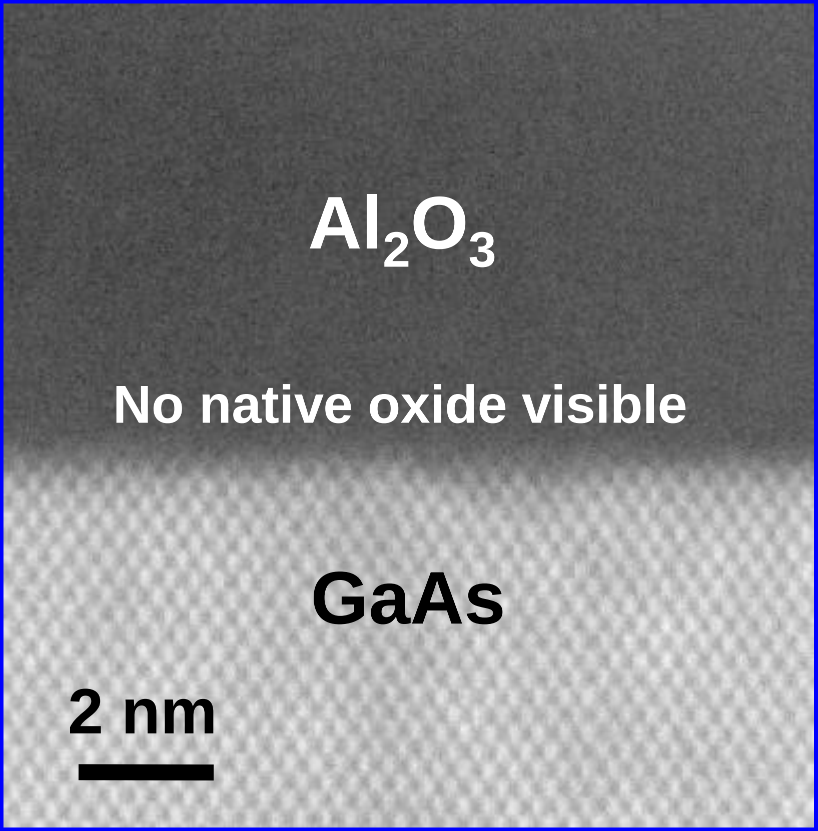
Non-volatile Memory



S. Bertolazzi et al, ACS Nano 2013

(1) Dielectric (2) Contact Resistance (3) Channel Mobility

Ex-situ ALD high-k on 3D substrates vs. 2D



ALD self-cleaning effect

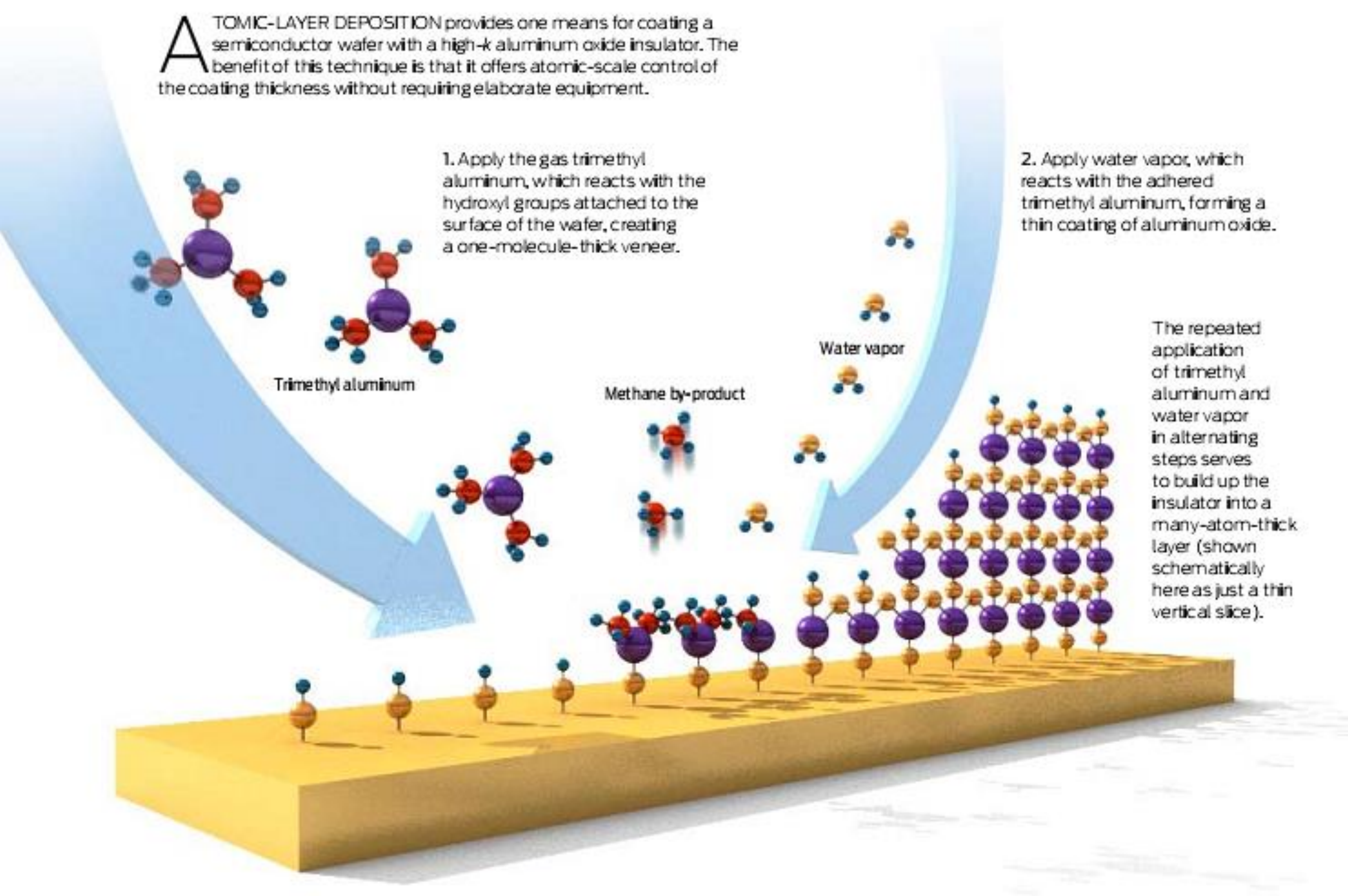
2 ASM ALD Systems at Purdue

3D Semiconductors: Passivation >> Many works at Intel, IBM, SEMATECH, IMEC, AIST, Purdue, U. Tokyo, Stanford, MIT, UCB, UCSB, NUS, UT Austin, UT Dallas, many other universities

2D Semiconductors: No dangling bonds

Yoon et al. Nano Letters 2011

ALD Al_2O_3 Process with TMA and H_2O



ATOMIC-LAYER DEPOSITION provides one means for coating a semiconductor wafer with a high-*k* aluminum oxide insulator. The benefit of this technique is that it offers atomic-scale control of the coating thickness without requiring elaborate equipment.

1. Apply the gas trimethyl aluminum, which reacts with the hydroxyl groups attached to the surface of the wafer, creating a one-molecule-thick veneer.

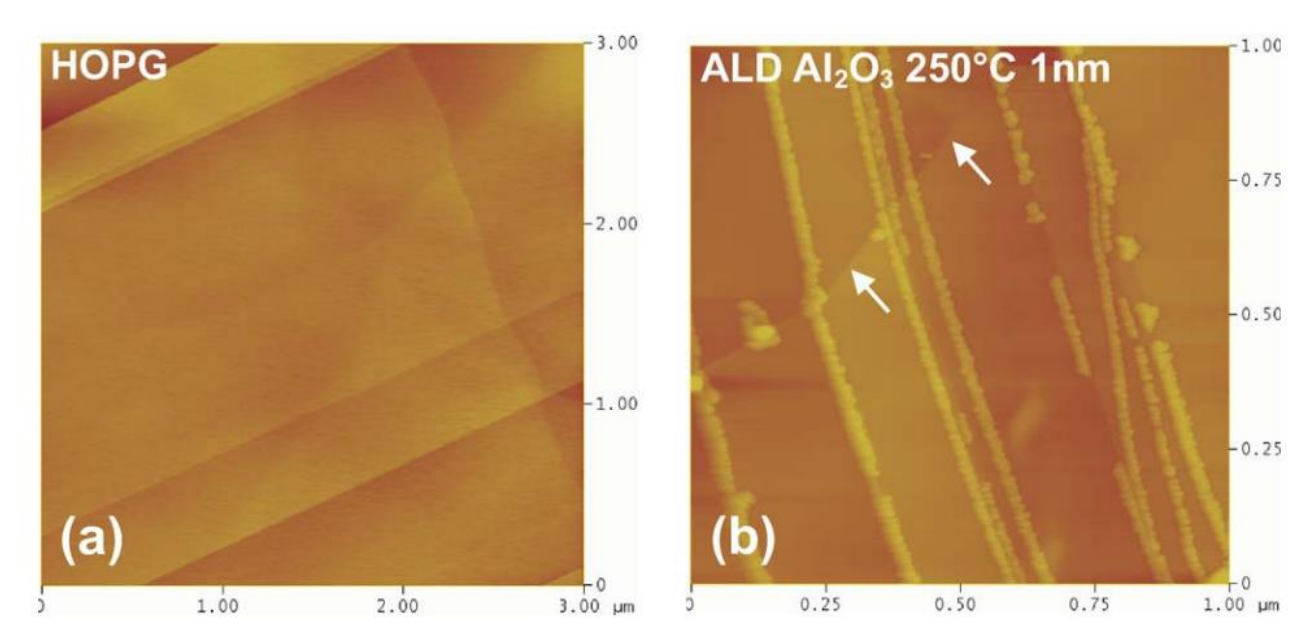
2. Apply water vapor, which reacts with the adhered trimethyl aluminum, forming a thin coating of aluminum oxide.

The repeated application of trimethyl aluminum and water vapor in alternating steps serves to build up the insulator into a many-atom-thick layer (shown schematically here as just a thin vertical slice).

Peide D. Ye, IEEE Spectrum Sept. 2008

ALD Cannot Simply Grow on Graphene

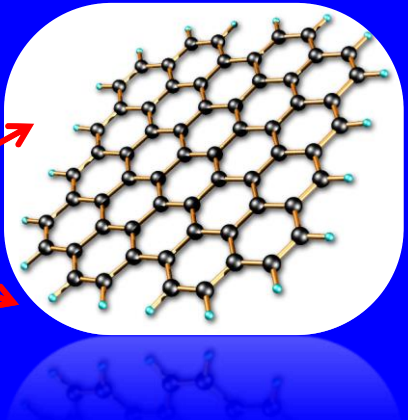
If we do not have dangling bonds….



No Al_2O_3 on basal plane

the graphene case…

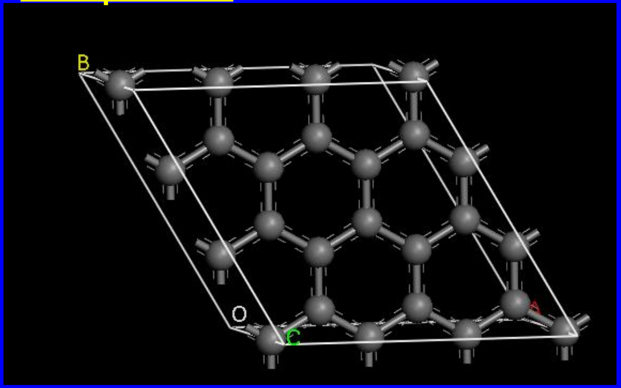
Al_2O_3 on edges

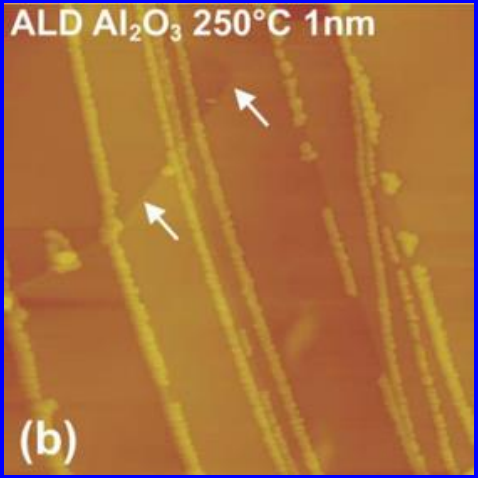


Y. Xuan et al. APL 2008

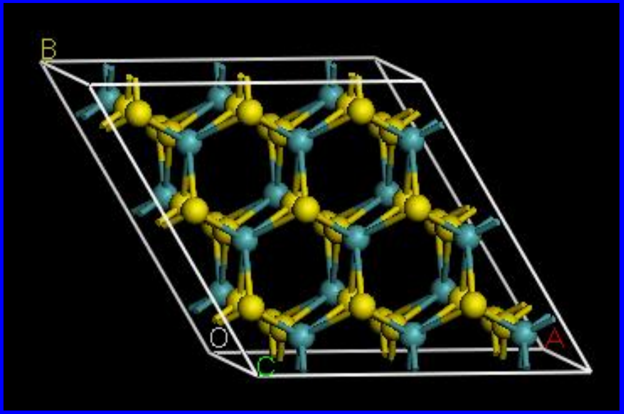
ALD on MoS_2 2D Crystal

Graphene





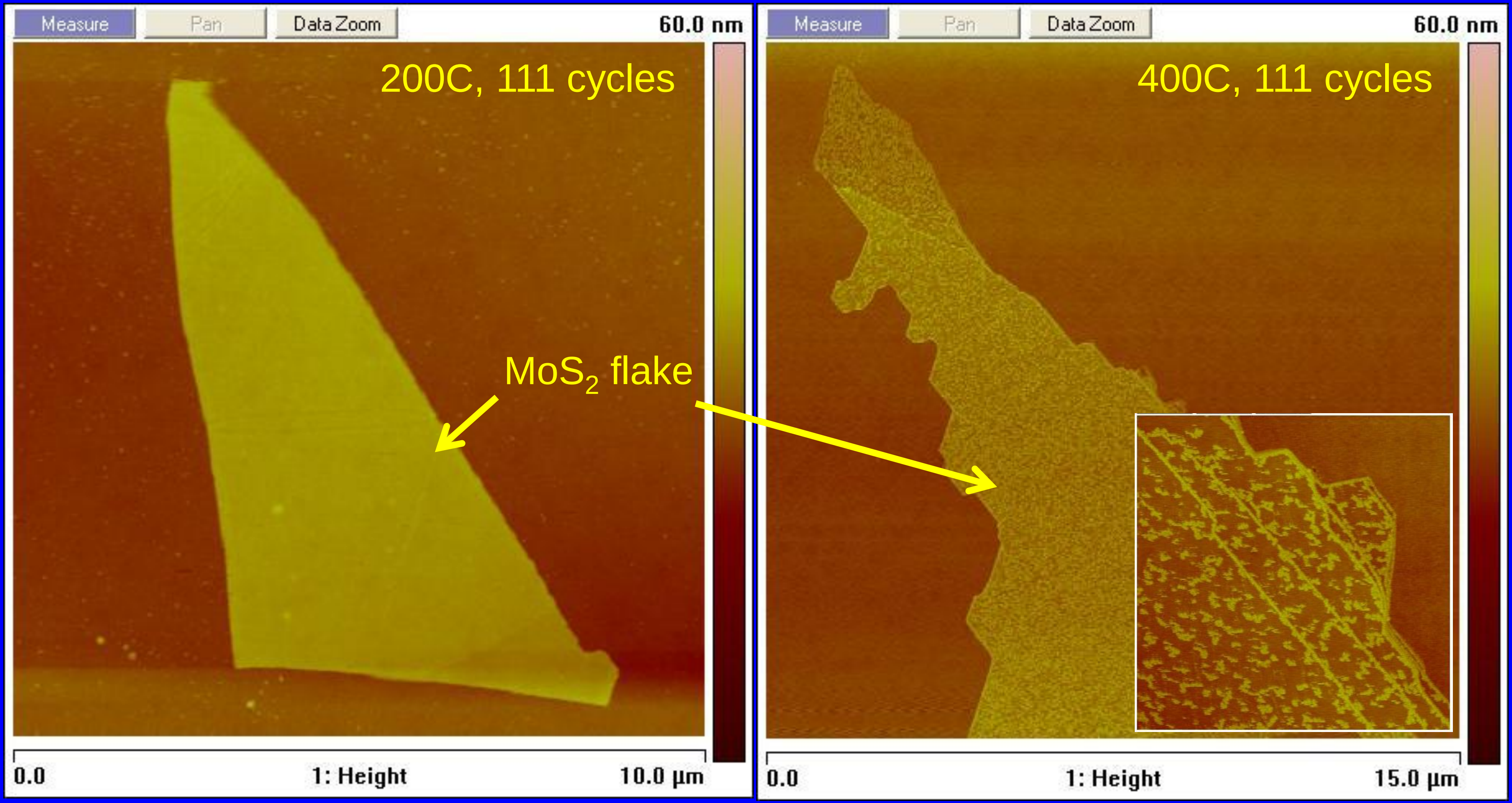
MoS_2



?

Q: Can we realize ALD growth on other 2D crystals?

ALD on MoS_2 2D Crystal

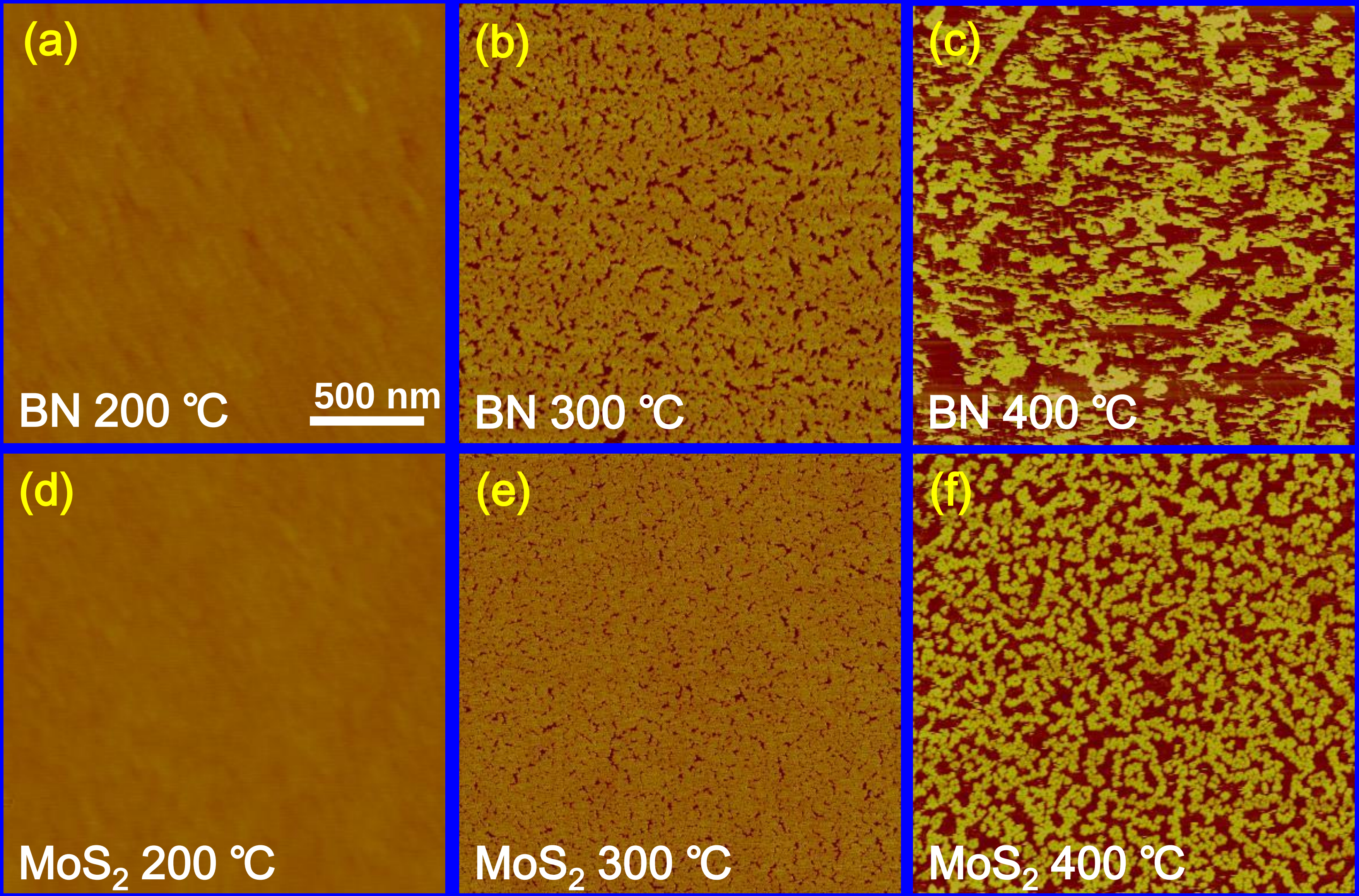


200C, 111 cycles

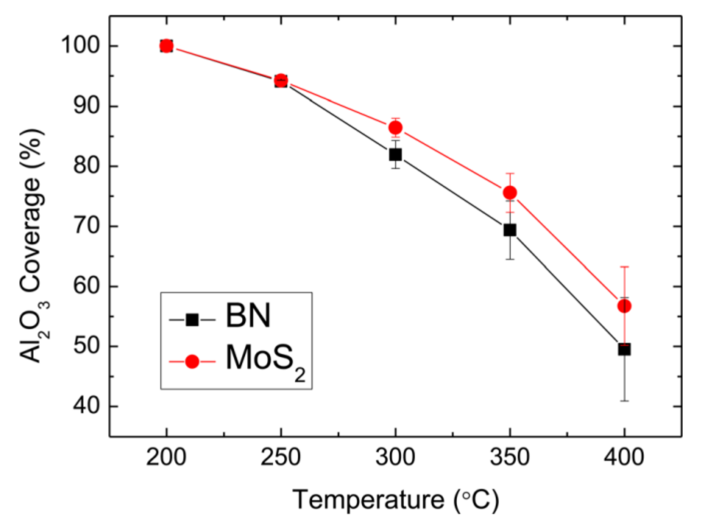
400C, 111 cycles

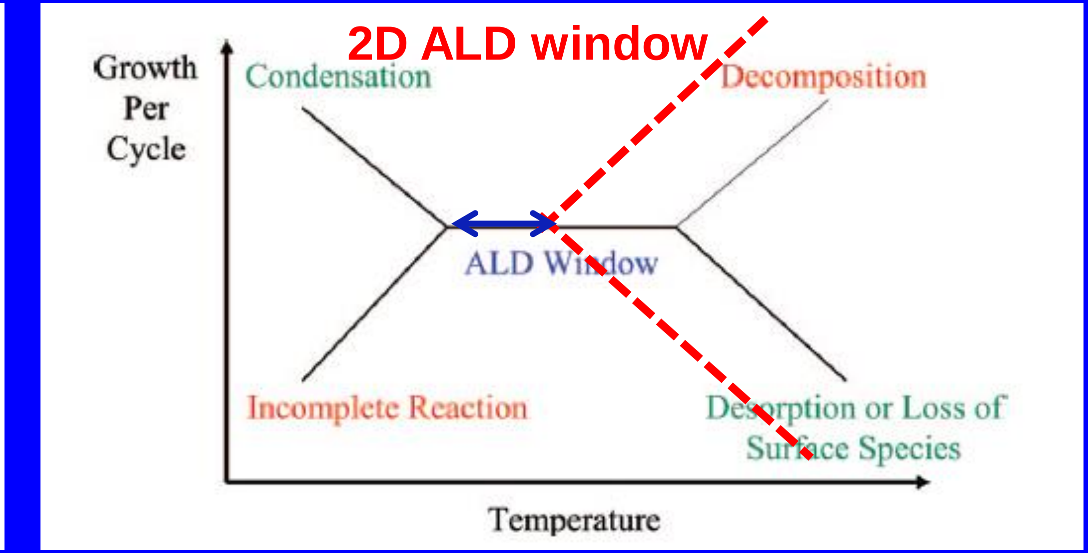
MoS_2 flake

ALD on h-BN and MoS_2 2D Crystal



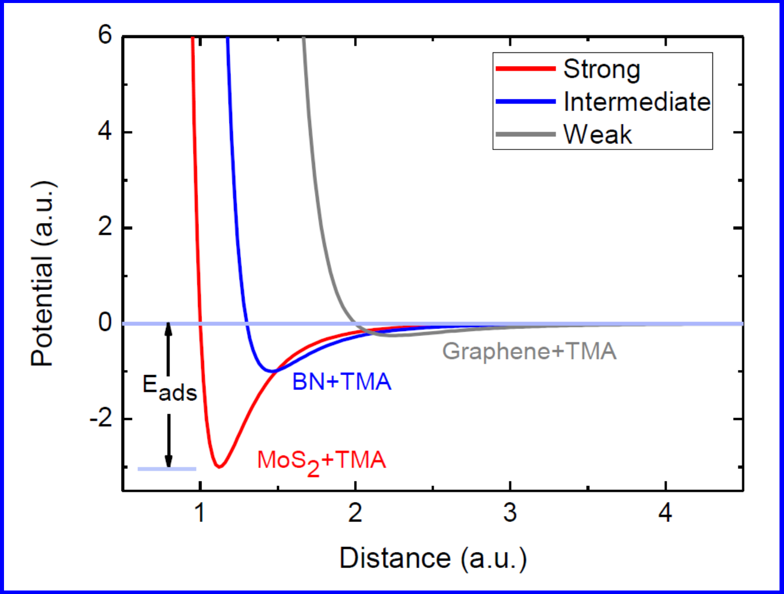
ALD on h-BN and MoS_2 2D Crystal





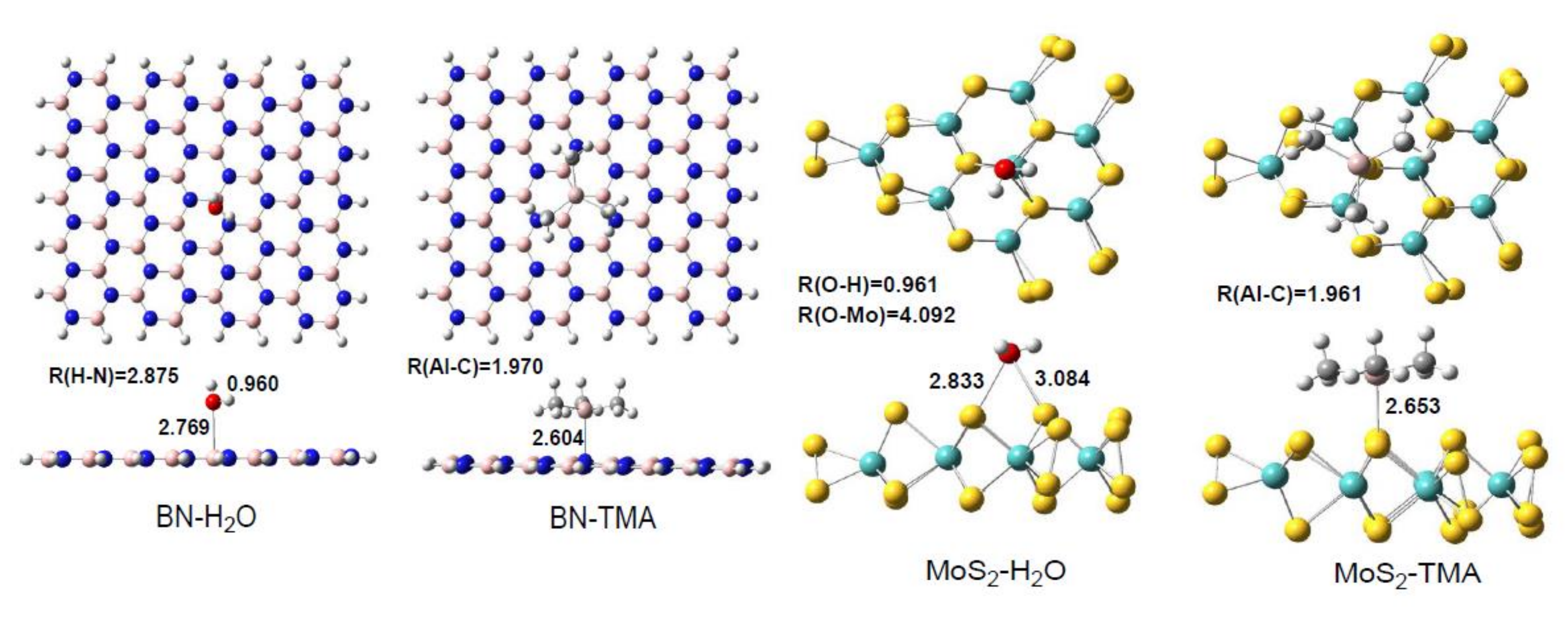
Lennard-Jones Potential Model

$$V_{LJ} = 4\varepsilon \left[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}\right]$$
$$= \varepsilon \left[\left(\frac{r_m}{r}\right)^{12} - 2\left(\frac{r_m}{r}\right)^{6}\right]$$



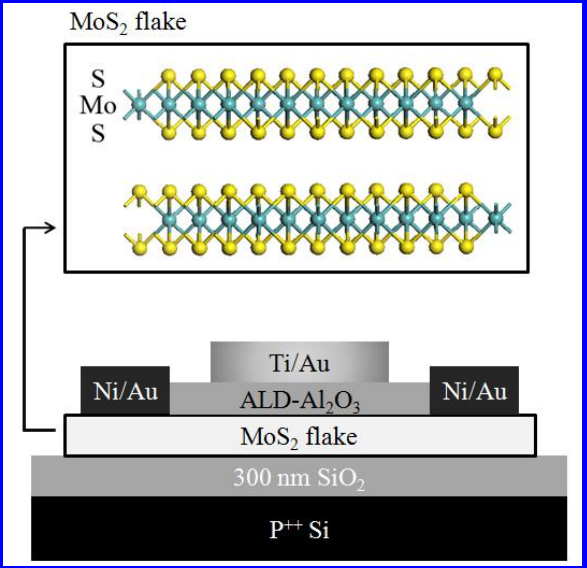
ALD on h-BN and MoS_2 2D Crystal

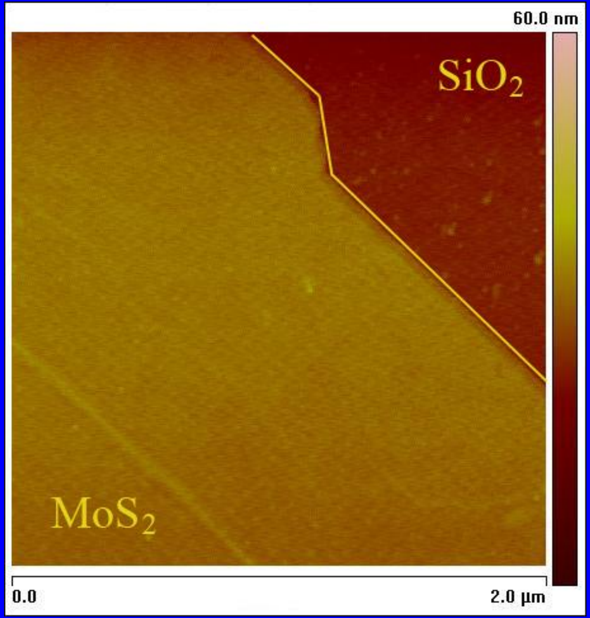
***Ab initio* DFT calculations:**



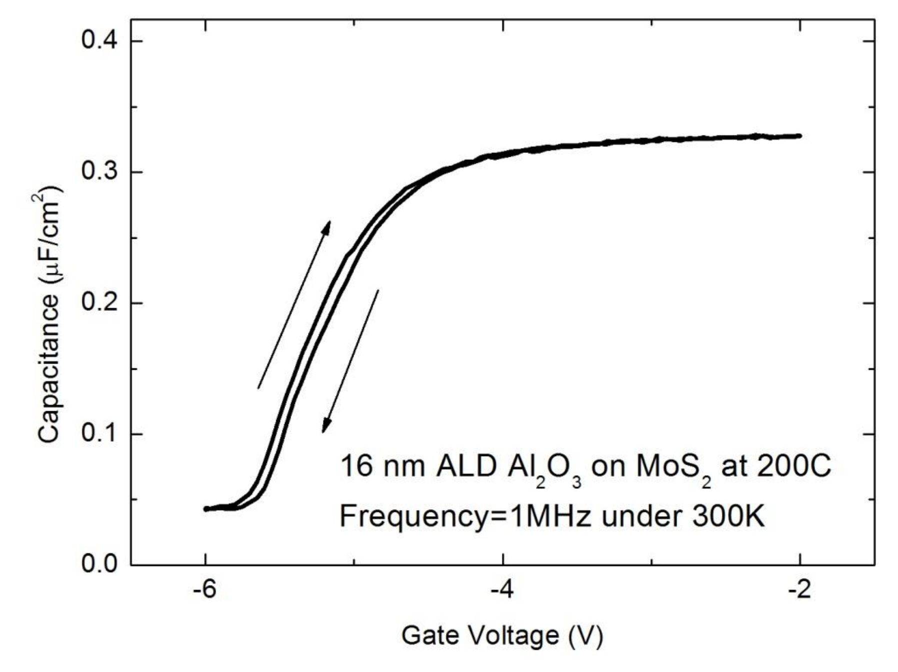
Han Liu et al. APL 100, 152115 (2012)

ALD high-k/MoS_2 dual-gate MOSFET





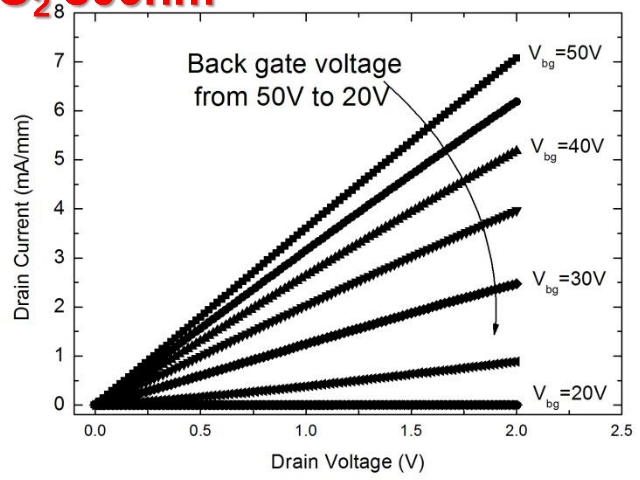
Few-layer MoS_2



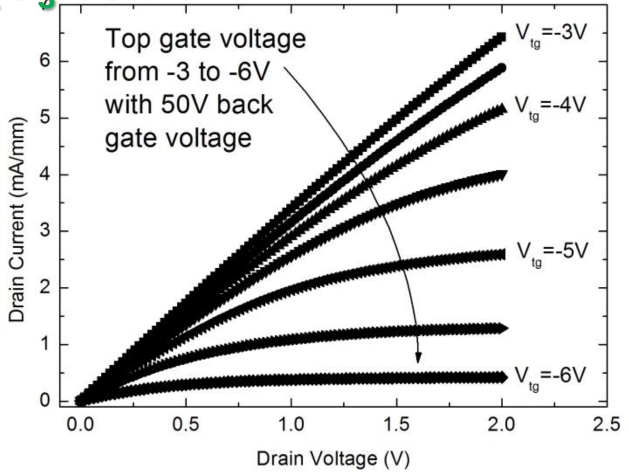
Han Liu et al. IEEE EDL 33, 546 (2012)

ALD high-k/MoS_2 dual-gate MOSFET

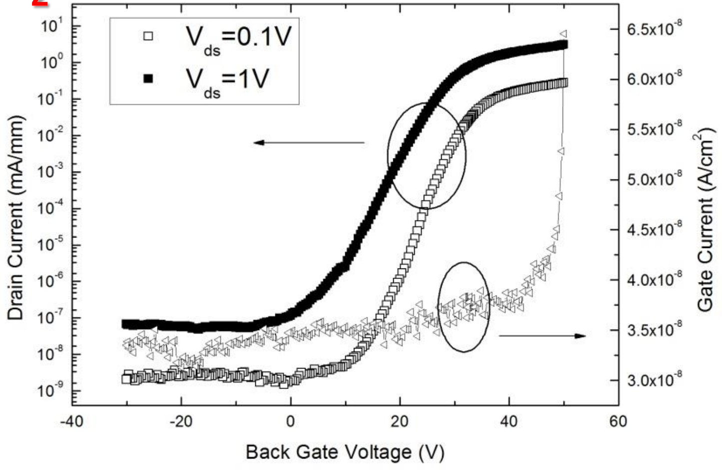
SiO_2 300nm



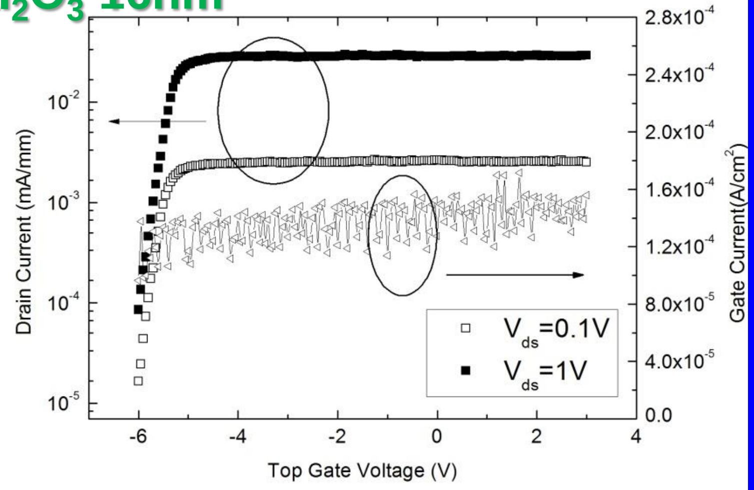
Al_2O_3 16nm



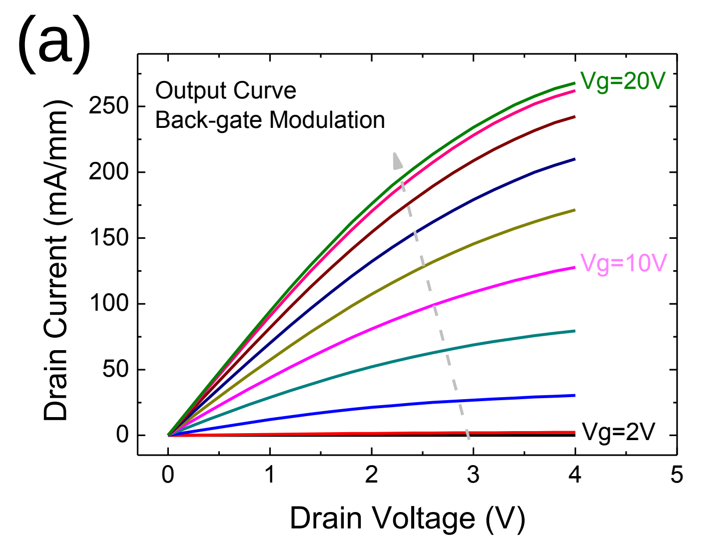
SiO_2 300nm

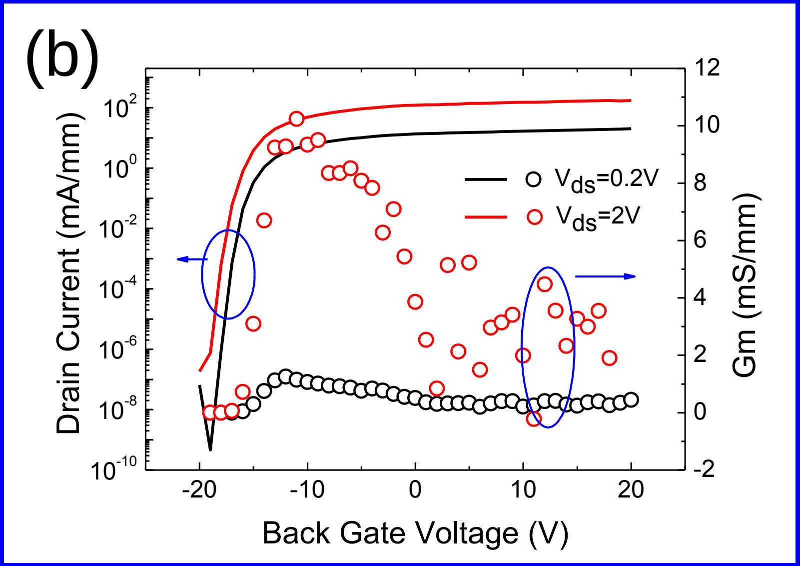


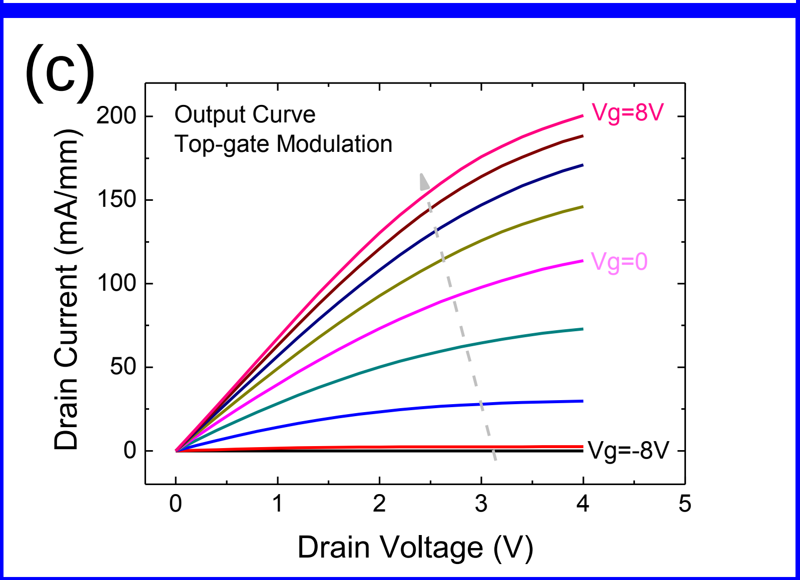
Al_2O_3 16nm

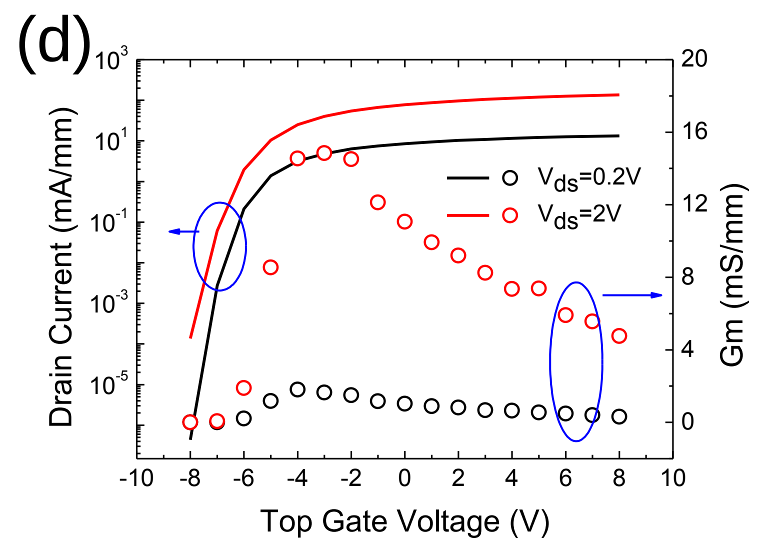


Low Work-function Metal (Ti) for MoS_2 NFET



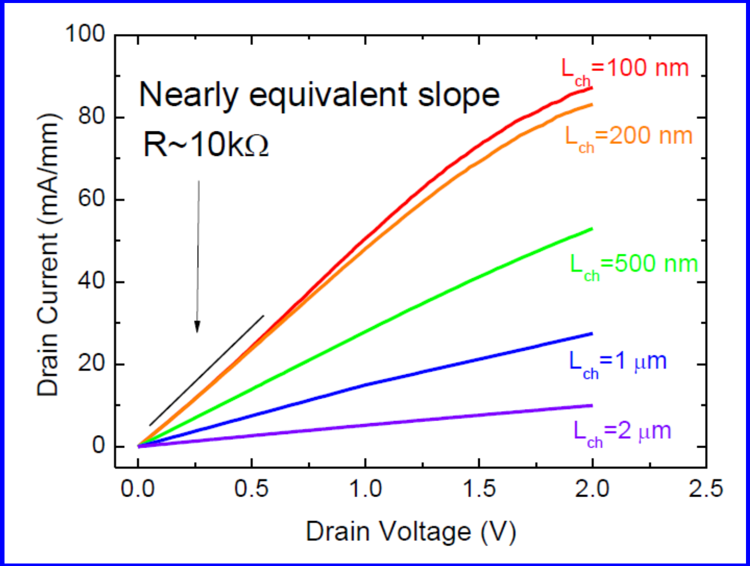


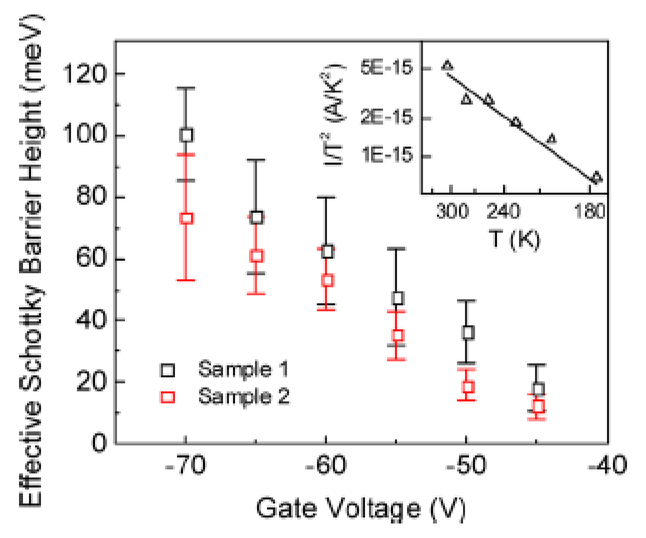


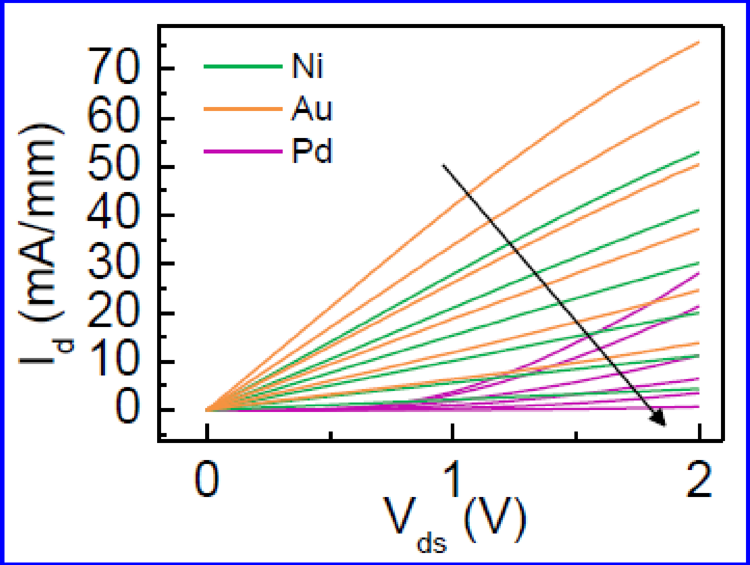


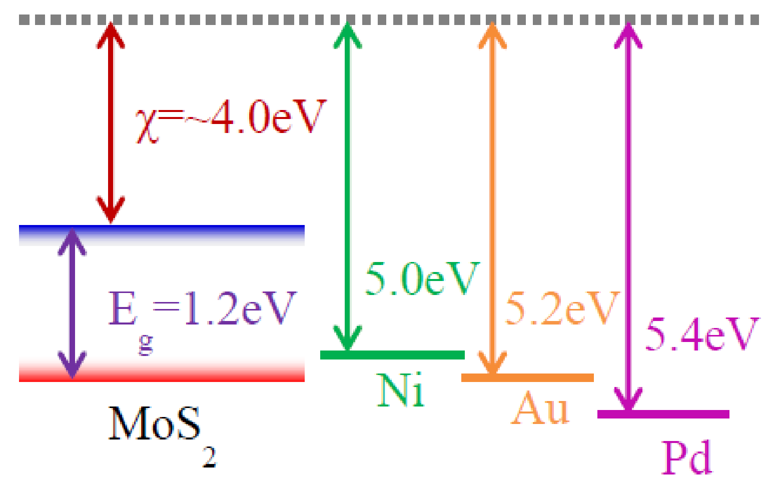
Drain current ~ 300 mA/mm starts encouraging as transistors

MoS_2 MOSFET Contacts



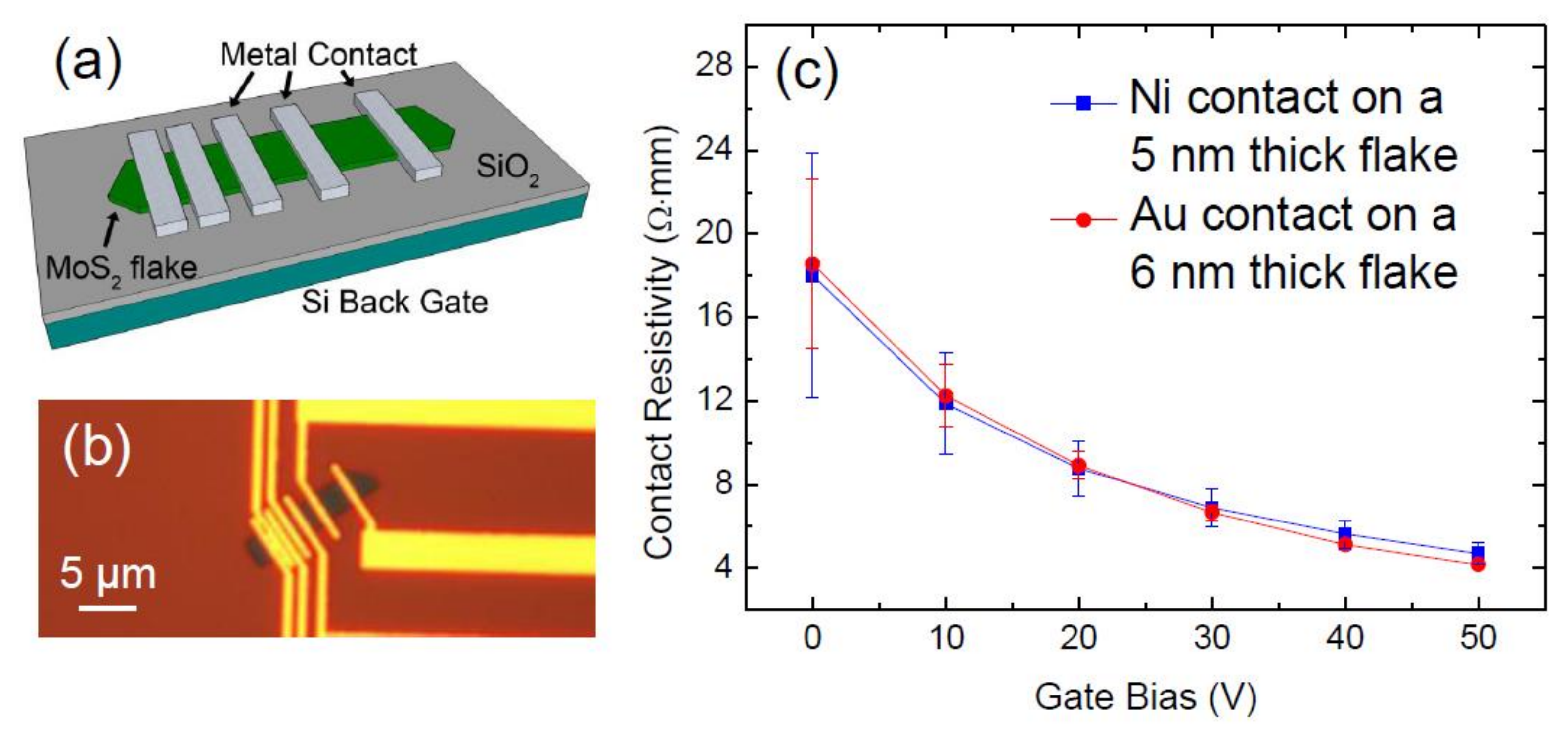






Adam Neal et al. DRC 2012

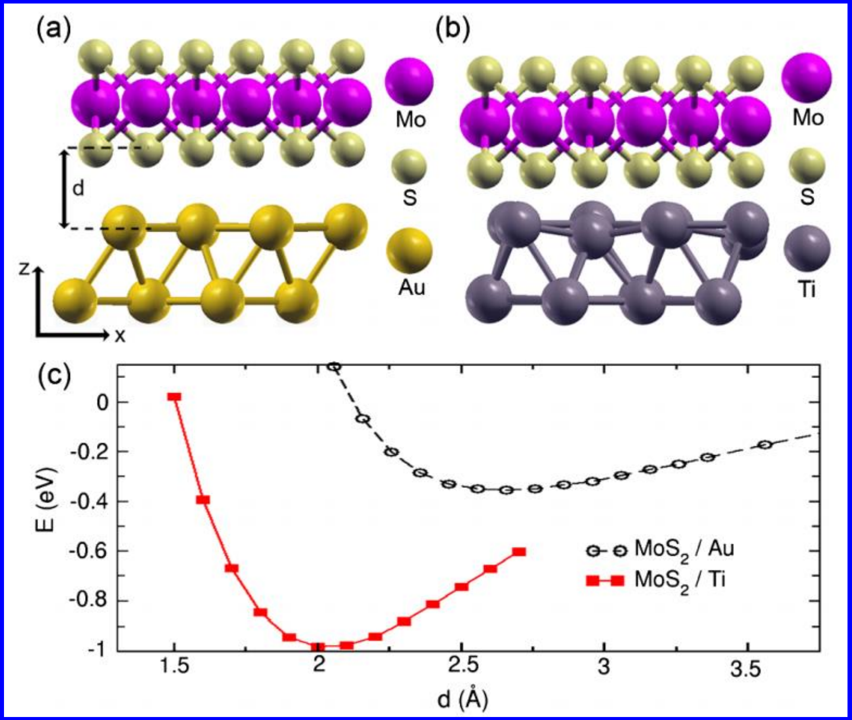
R_c of MoS_2 MOSFETs by TLM

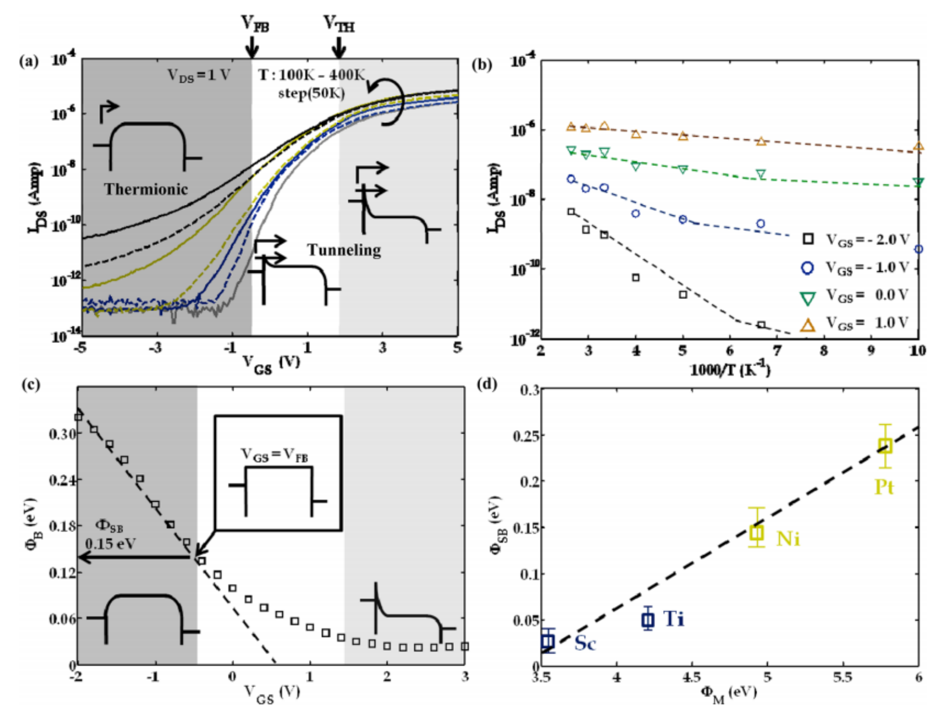


Contact Resistance: 5 Ω·mm (too large!)

Han Liu et al. ACS Nano 6 (10) 8563-8569, 2012

Metal Contacts on MoS$_2$





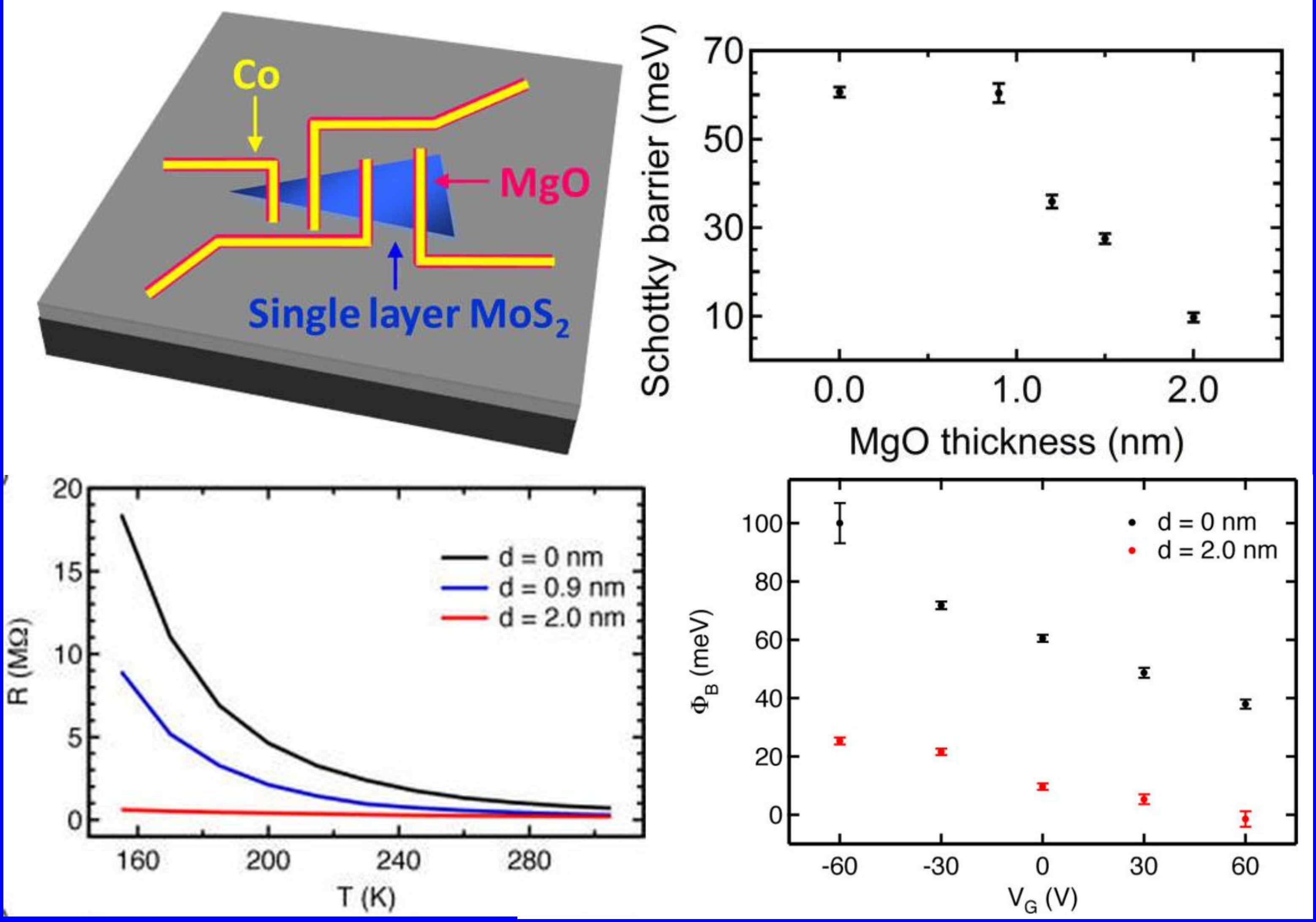
I. Popov et al, PRL 2012

S. Das et al, Nano Lett. 2012

Much more work on contact engineering is needed:

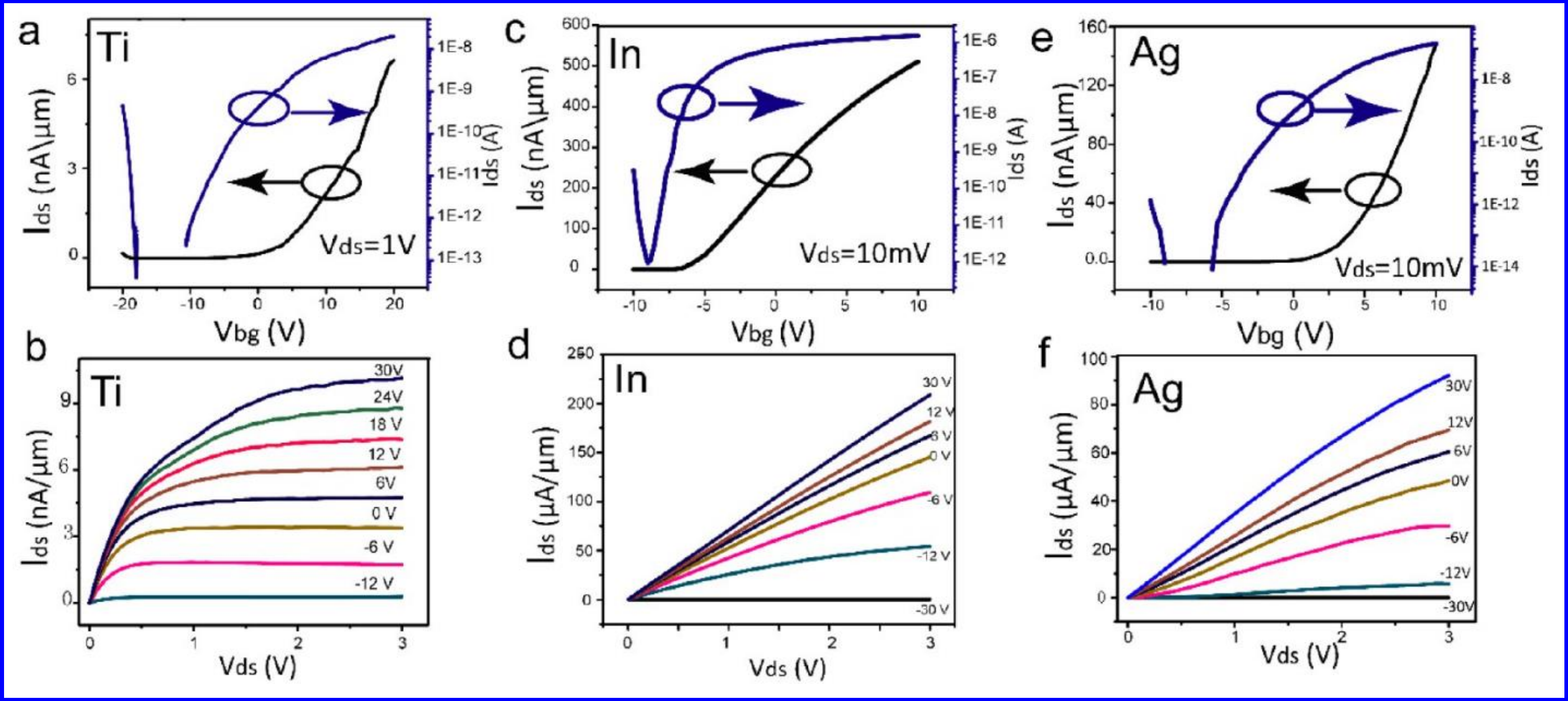
R_c<0.1Ω·mm at least For ITRS 10nm ρ_c=1x10^{-9}Ωcm^2

Tunneling Barrier on MoS_2



J.-R. Chen et al, Nano Lett. 2013

Metal contacts on WSe_2

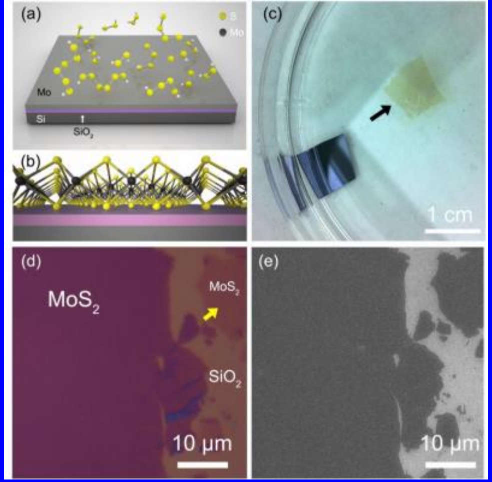


W. Liu et al, Nano Lett. 2013

Different material sources
Different laboratories
Different students
Different time

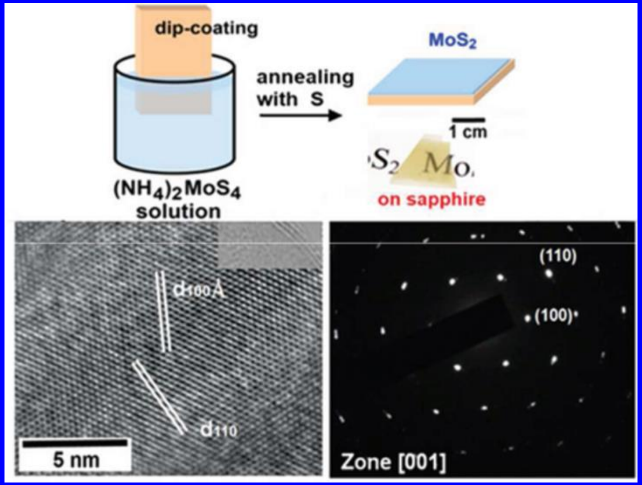
Same starting materials
Hundreds of devices

MoS$_2$: CVD Synthesis



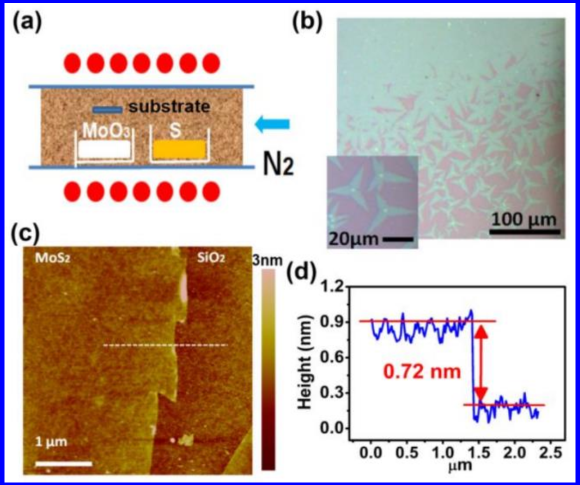
Direct Sulfurization of Mo layer

Y. Zhan et al, Small, 8, 966 (2012)



Sulfurization of Mo Compound (NH$_4$)$_2$MoS$_4$

K.K. Liu et al, Nano Lett. 12, 1538 (2012)

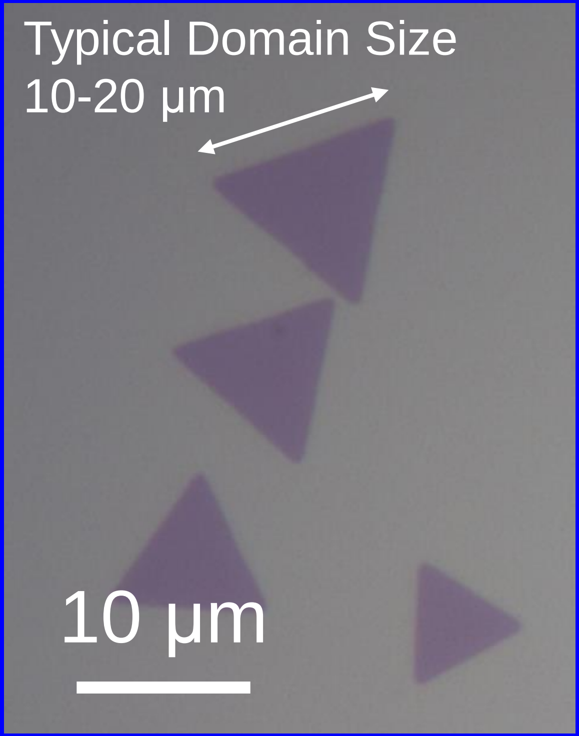


Sulfurization of MoO$_3$

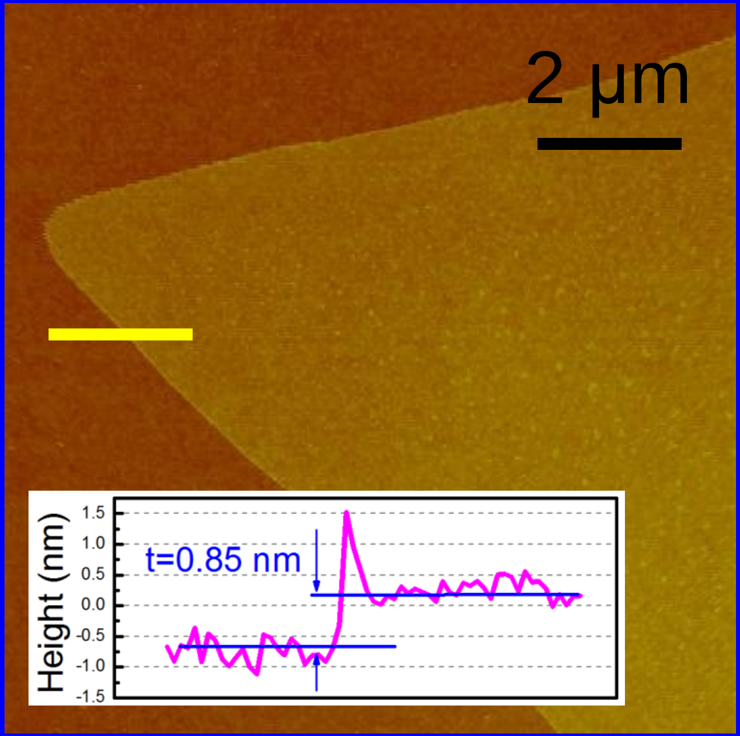
Y.H. Lee et al, Adv. Mater. 24, 2320(2012)

CVD Monolayer MoS_2

Optical Micrograph



Atomic Force Microscope

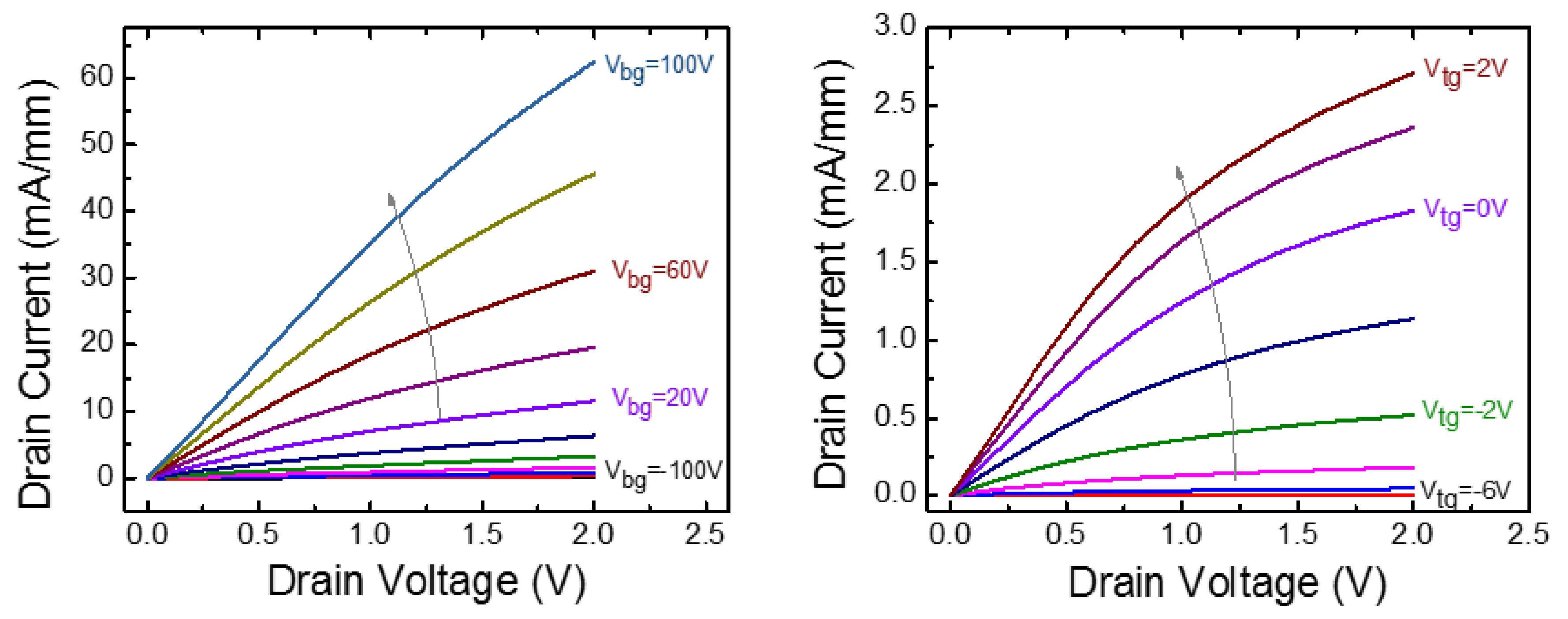


H. Liu et al. Nano Lett., 13, 2640 (2013)

In collaborations with Jun Lou and P.M. Ajayan's groups at Rice University

Transistor: Output Behavior

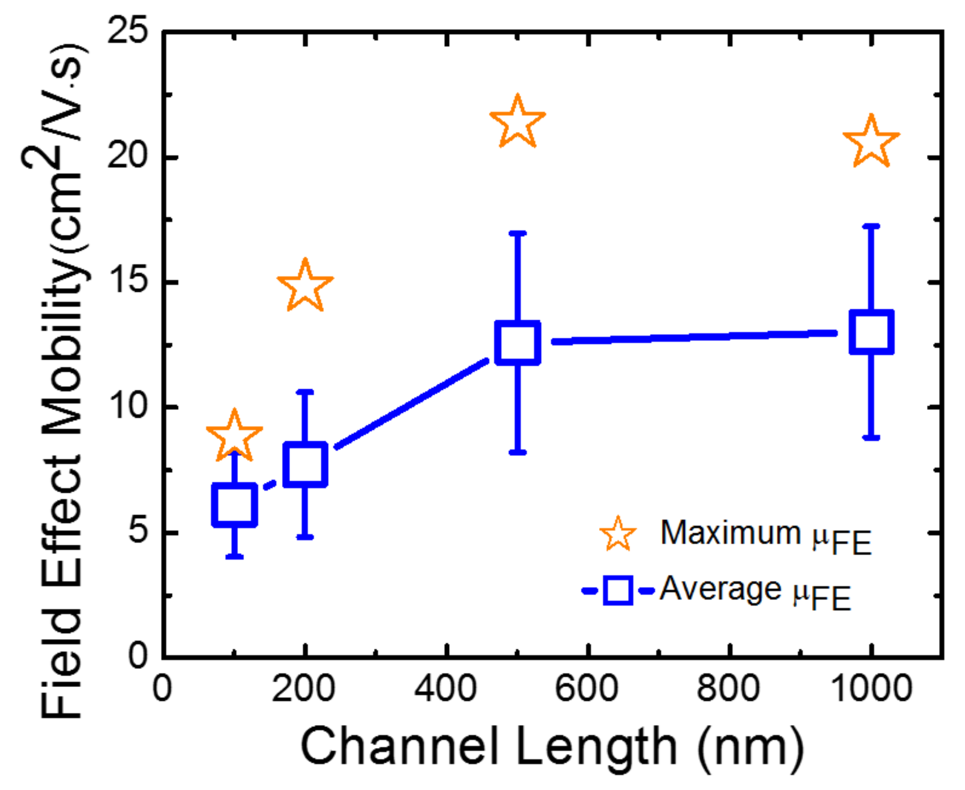
L_{ch}=100 nm



The difference between Top/Back Gate modulation mostly comes from R_c.

H. Liu et al. Nano Lett., 13, 2640 (2013)

Field-Effect Mobility

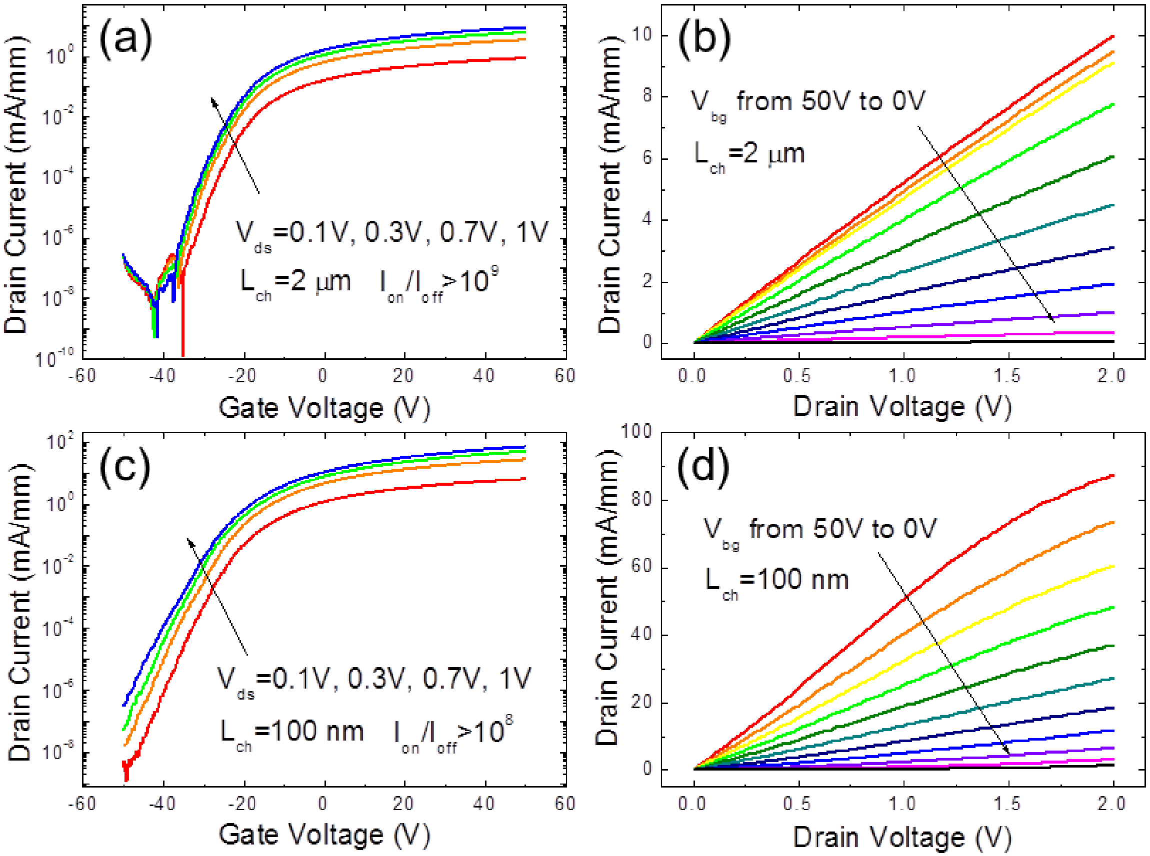


$$g_m = \frac{\partial I_{ds}}{\partial V_{gs}} = \mu_{FE} C_{ox} \frac{W}{L} V_{ds}$$

$$\mu' = \mu \left(\frac{R_{ch}}{R_{tot}} \right)^{-1} = \mu \left(1 - \frac{2R_c}{R_{tot}} \right)^{-1}$$

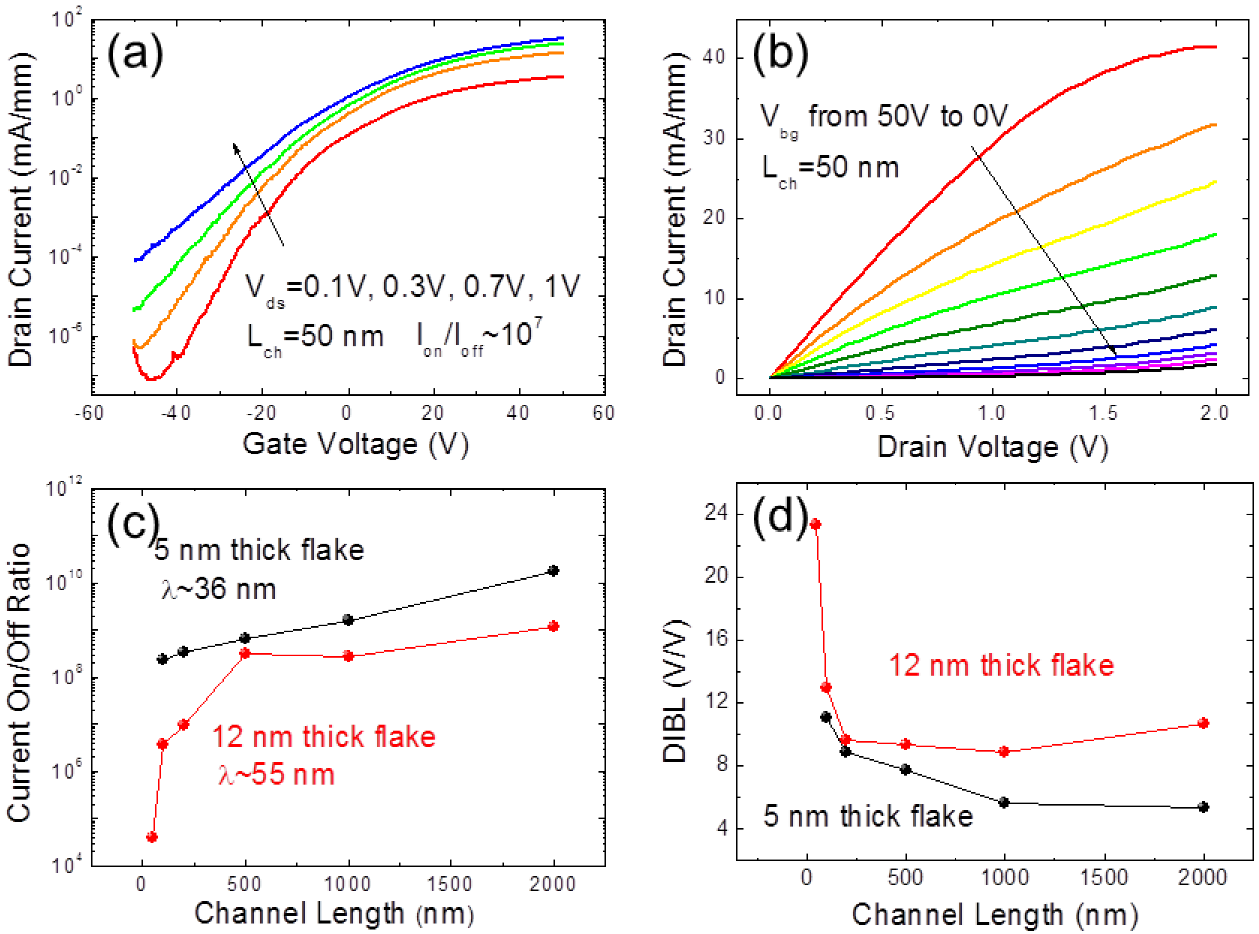
L_{ch}	$\mu_{FE,mean}$ (cm²/V·s)	$\mu_{FE,max}$ (cm²/V·s)
100 nm	6.10	8.82
200 nm	7.71	14.8
500 nm	12.6	21.6
1 μm	13.0	20.6

MoS_2 MOSFET Length Scaling



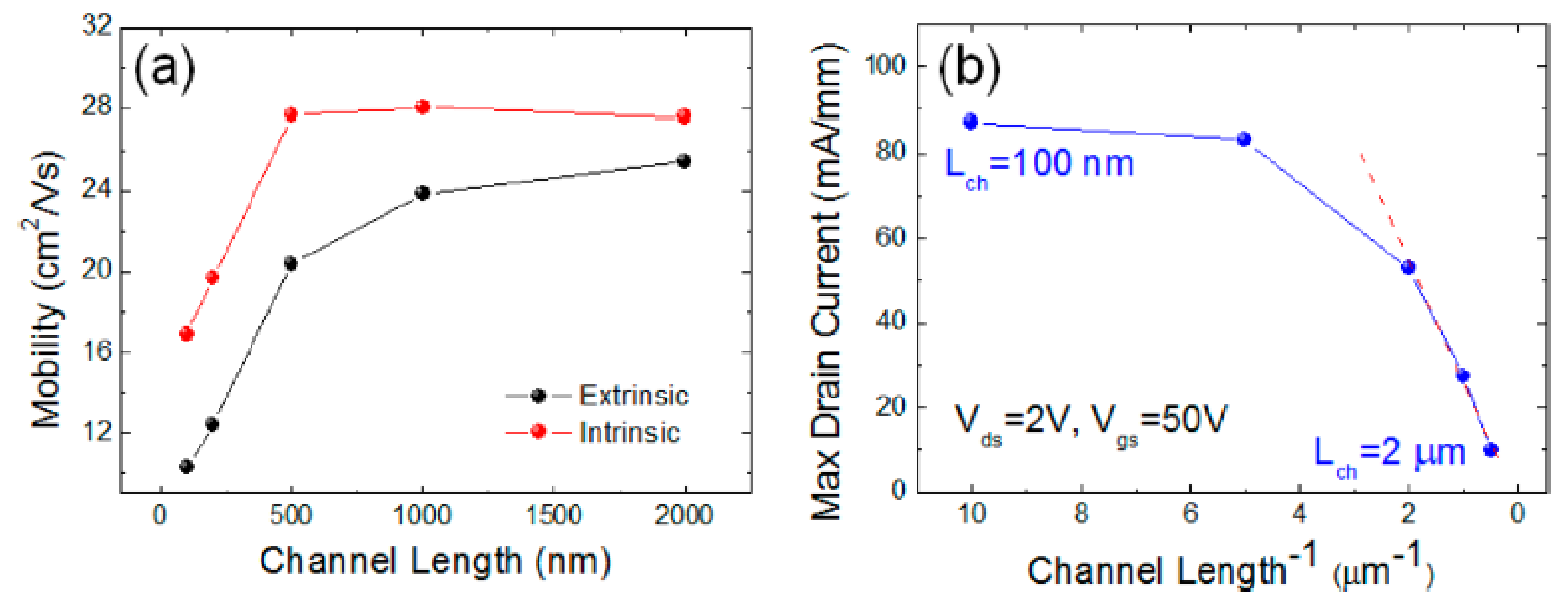
H. Liu et al. ACS Nano, 6, 8563 (2012)

MoS_2 MOSFET Length Scaling

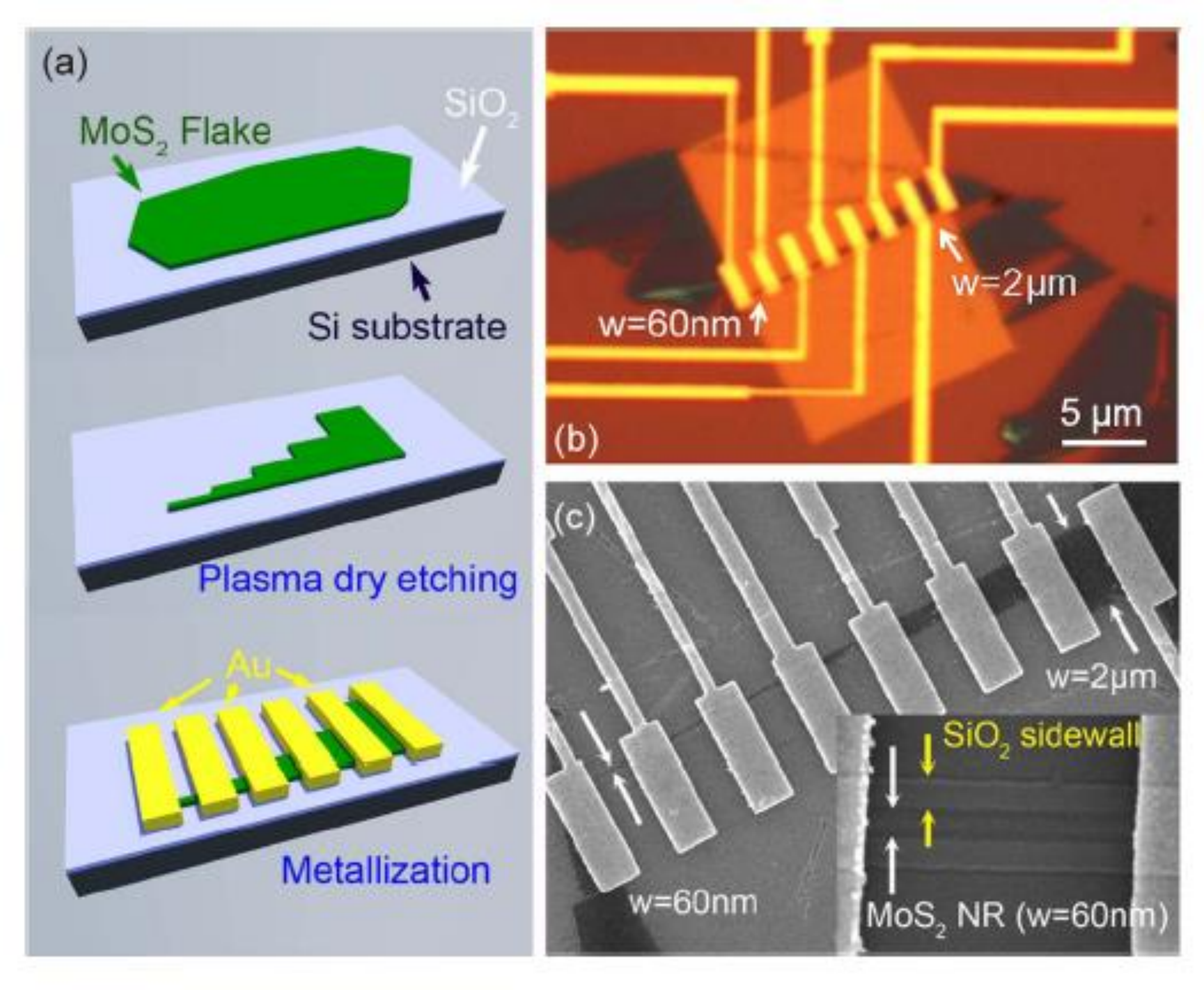


Evident short-channel effects at 12nm thick MoS_2 and L_{ch}=50nm

MoS_2 MOSFET Length Scaling

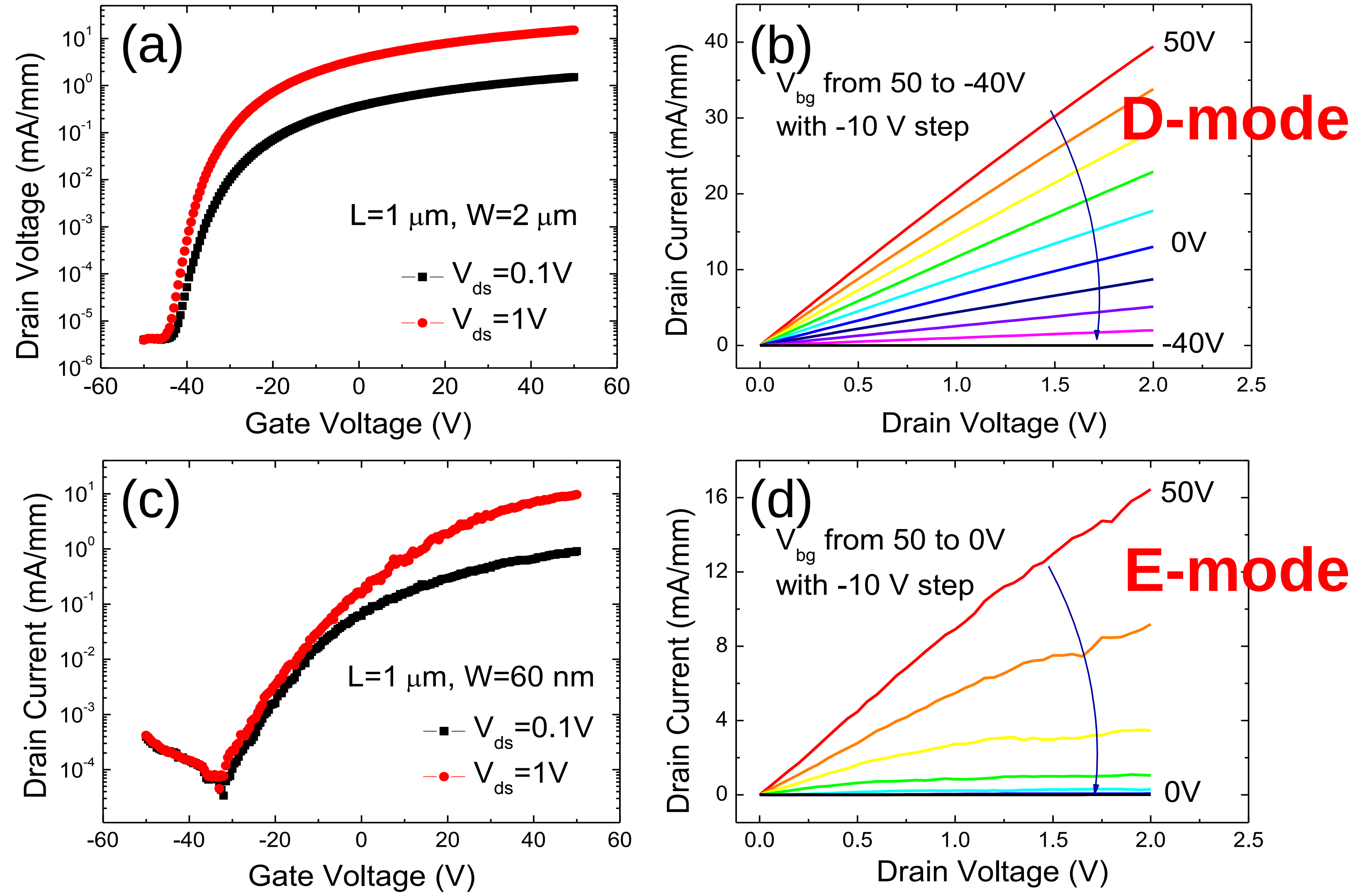


MoS_2 MOSFET Width Scaling



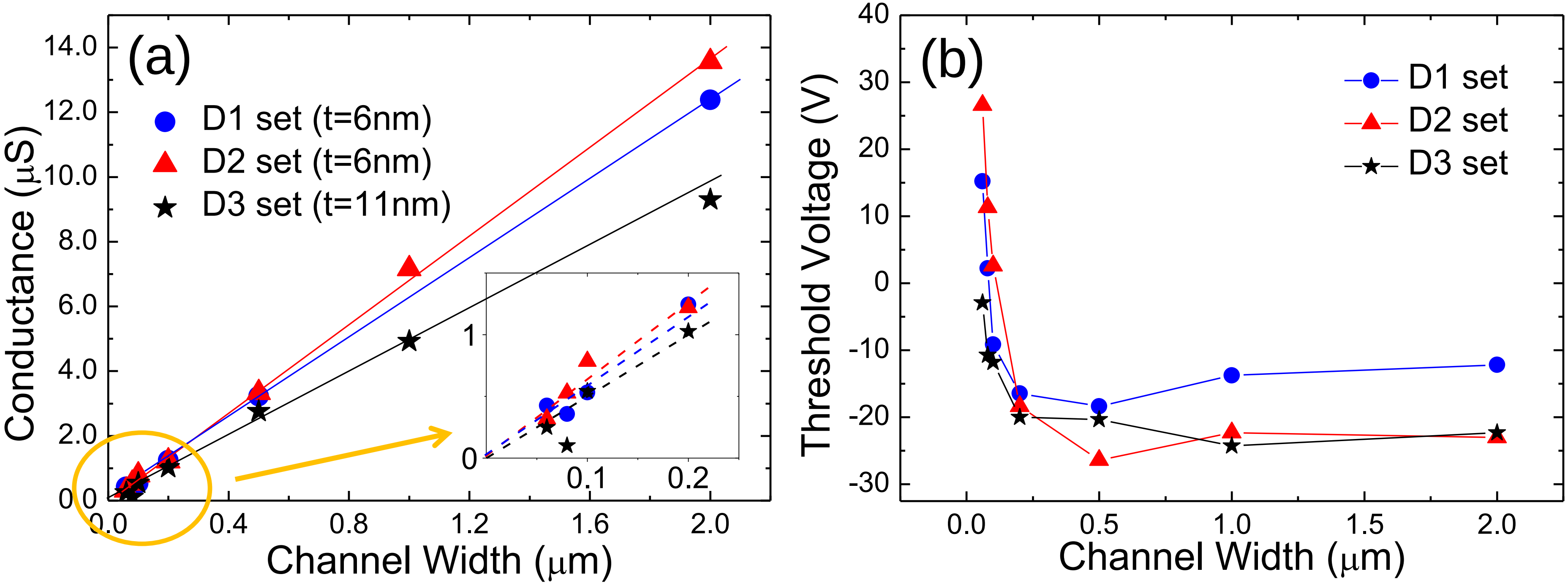
Han Liu et al. IEEE EDL 33 (9) 1273 (2012)

MoS_2 MOSFET Width Scaling



MoS_2 MOSFET Width Scaling

D-mode to E-mode transition by simple width trimming

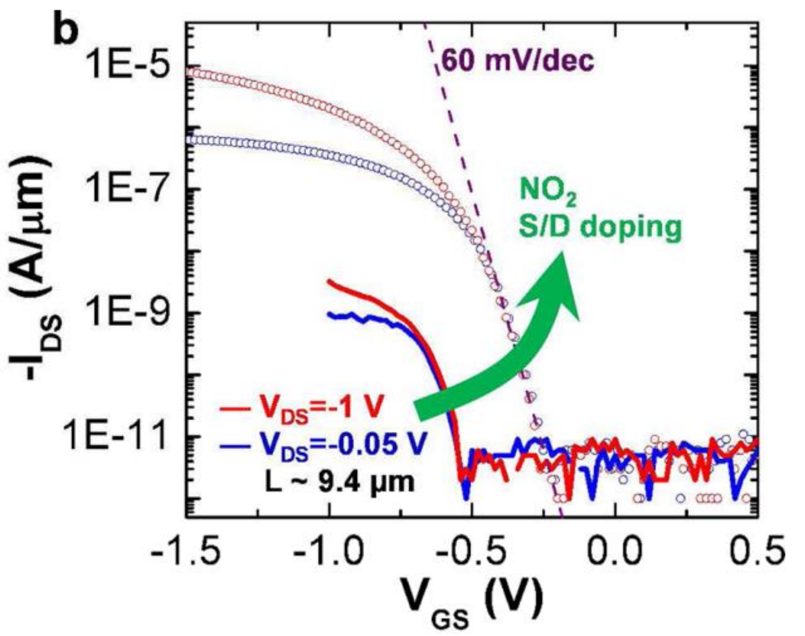


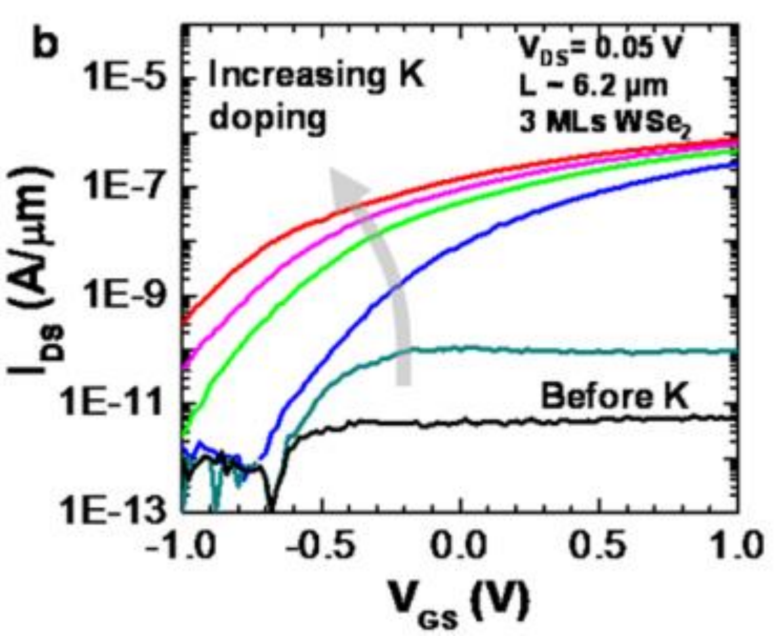
Han Liu et al. IEEE EDL 33 (9) 1273 (2012)

Chemical Doping on 2D Crystals

Gaseous Doping (NO_2)

Solid Doping (K)

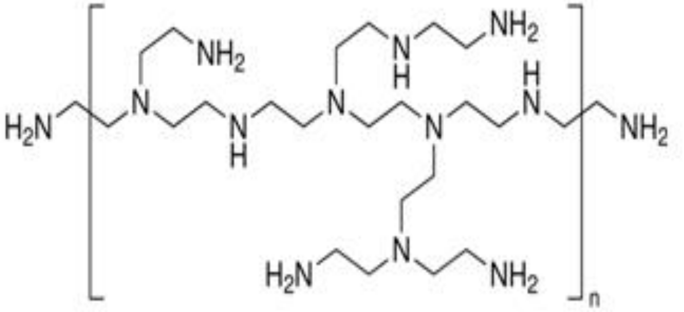


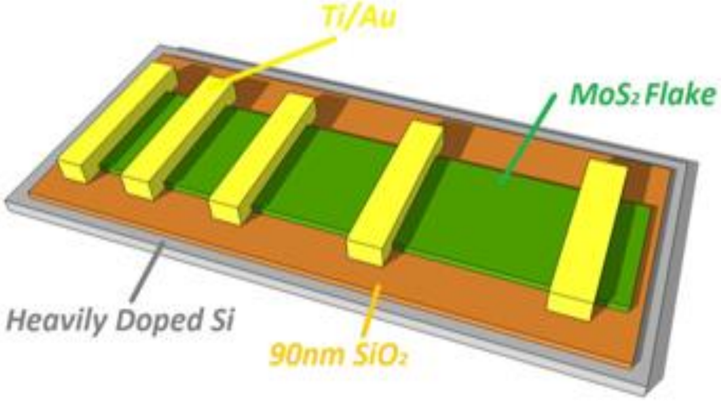


WSe_2

H. Fang et al. Nano Lett 2012
H. Fang et al. Nano Lett 2013

MoS_2 Molecular Doping

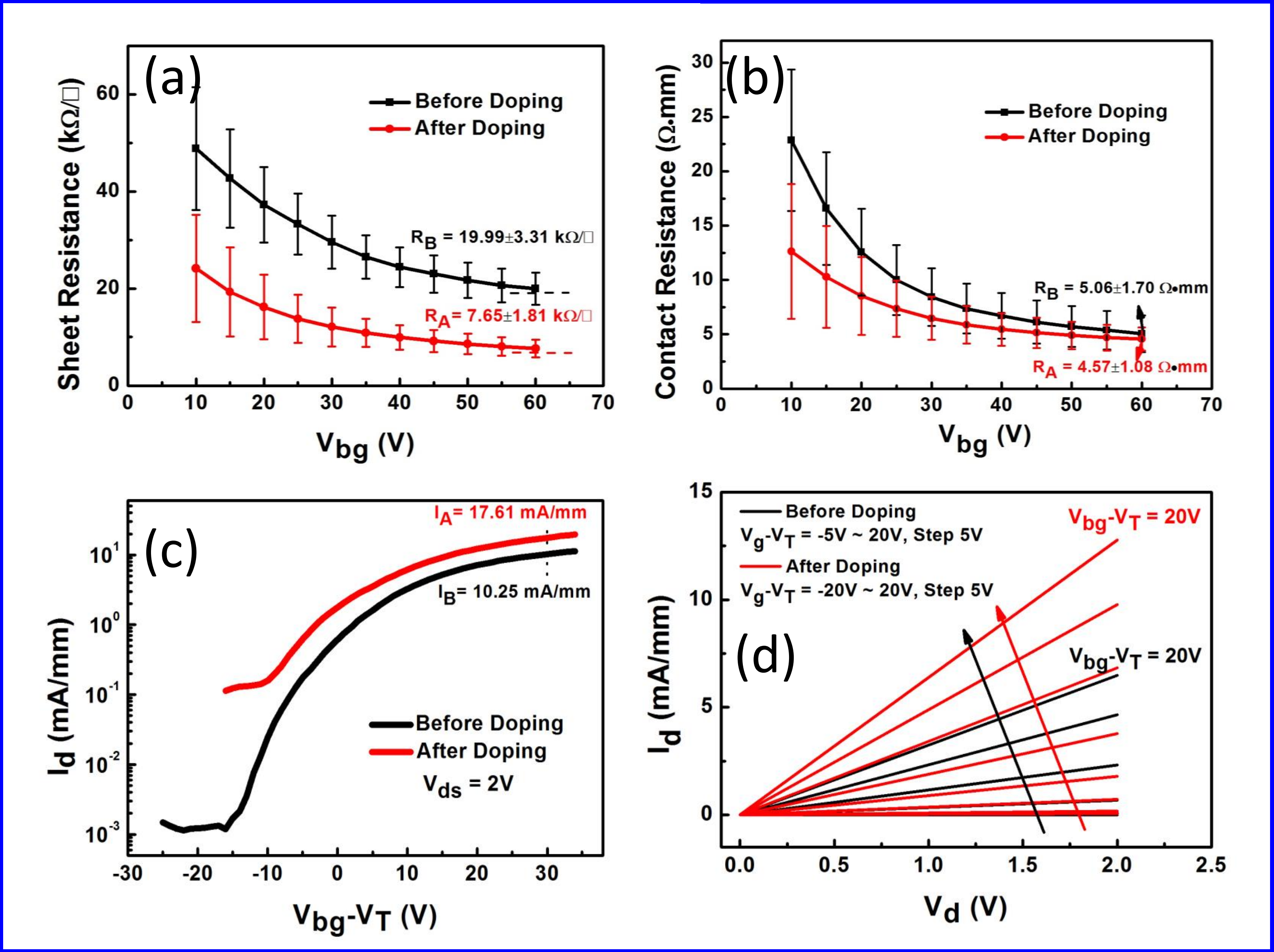




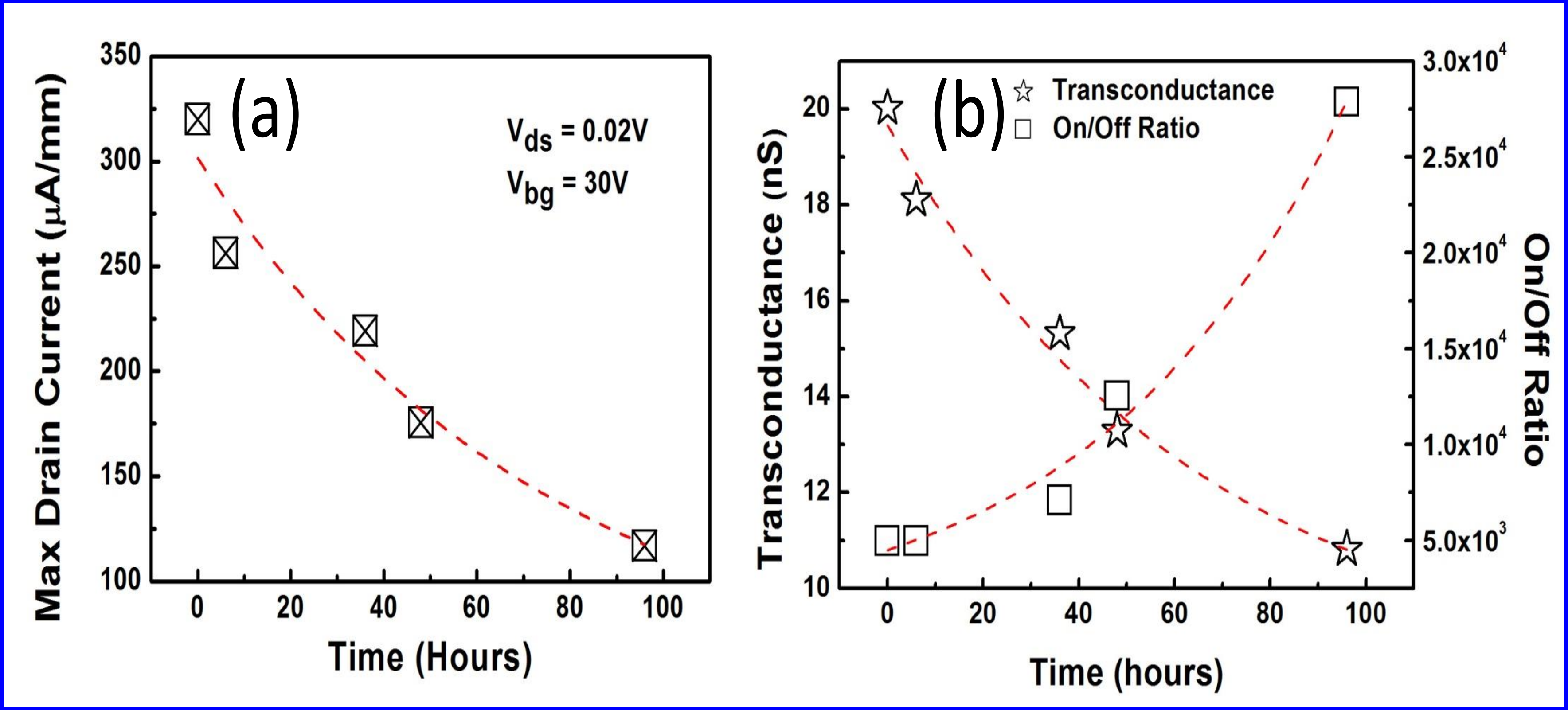
Strong n-type dopant:
Polyethyleneimine (PEI)

Submitted to IEEE EDL

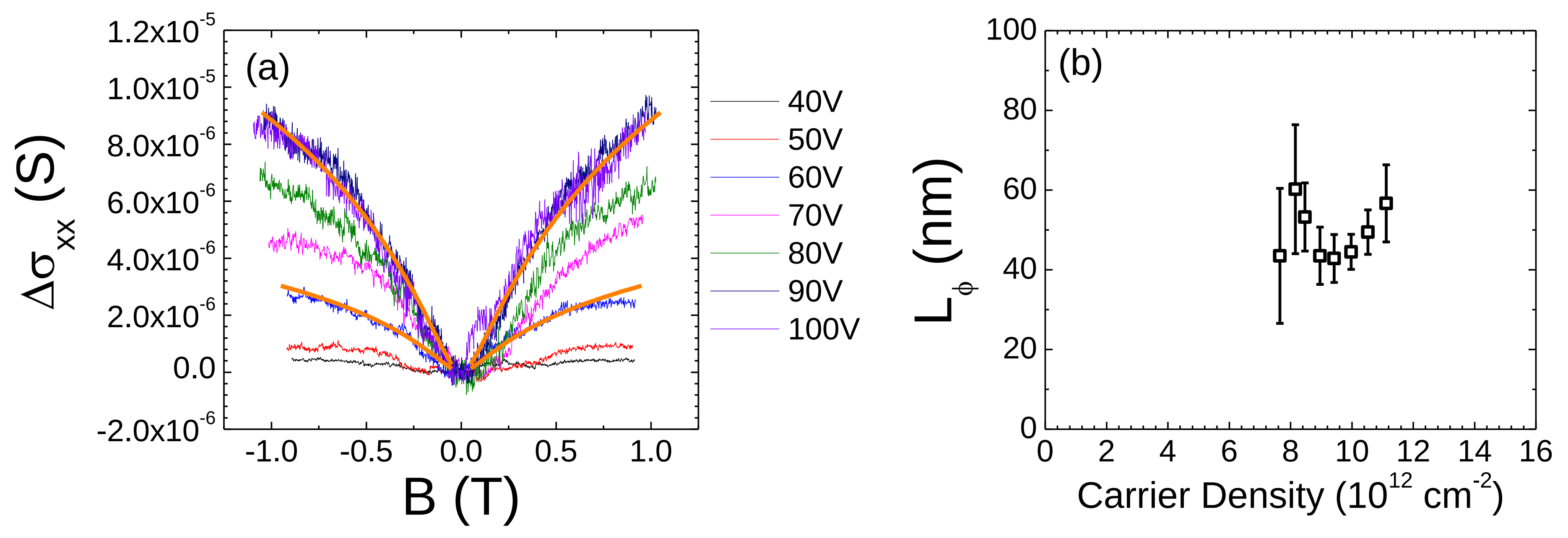
MoS$_2$ Molecular Doping



MoS_2 Molecular Doping



Electron Phase Coherence in MoS_2



$$\Delta\sigma = \sigma(B) - \sigma(B=0) = \alpha \frac{e^2}{4\pi^2\hbar} F\left(\frac{B}{B_\phi}\right)$$

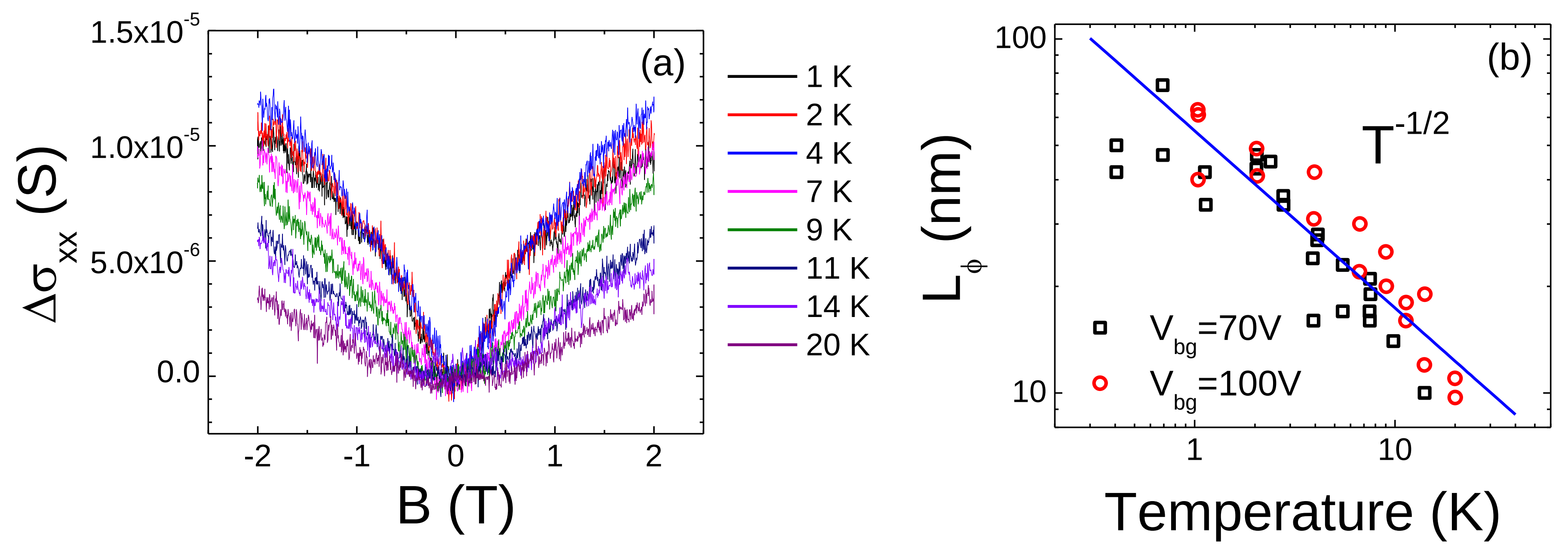
$$F(z) = \psi\left(\frac{1}{2} + \frac{1}{z}\right) - \ln(z)\,, \qquad B_\phi = \frac{\hbar}{4eL_\phi{}^2}$$

L_ϕ~50nm

T=400mK

Hikami et al. PTP 63 707 (1980), Kawaguchi et al. JPSJ 48 699 (1980)
Ye, J.T. et al. Science 338 1193–1196 (2012)

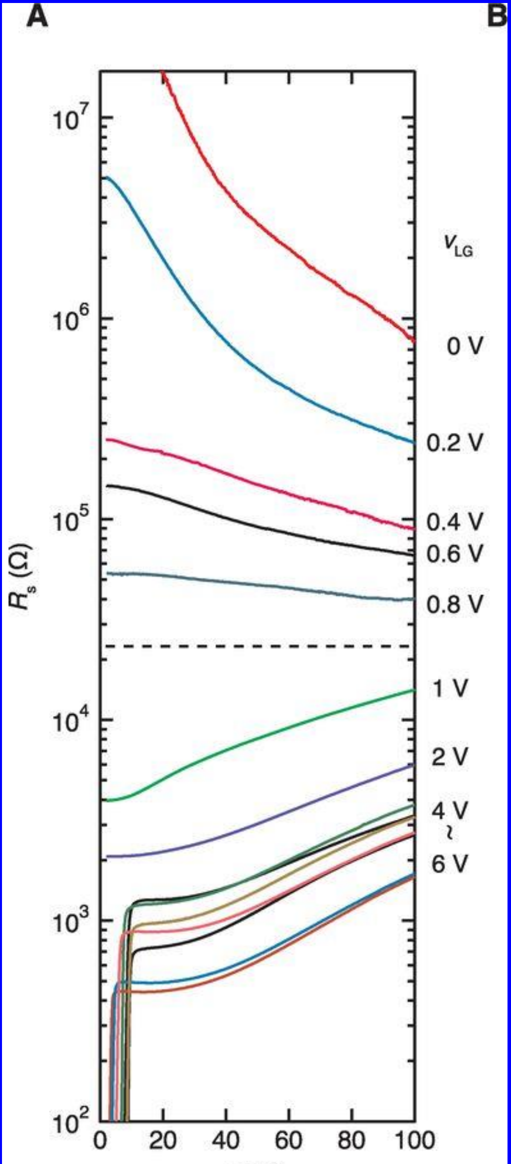
L_ϕ vs. Temperature



L_ϕ decreases as $T^{-1/2}$

Indicates electron-electron scattering responsible for dephasing

MoS_2 Superconductivity



J.T. Ye et al.

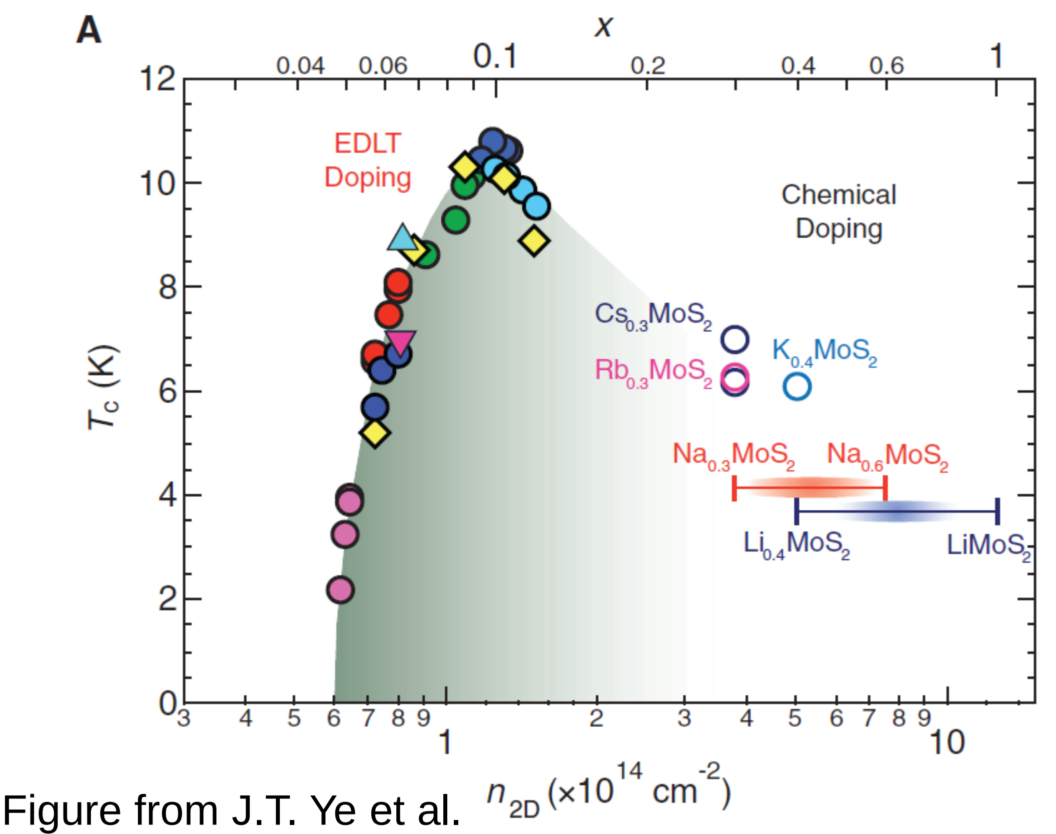


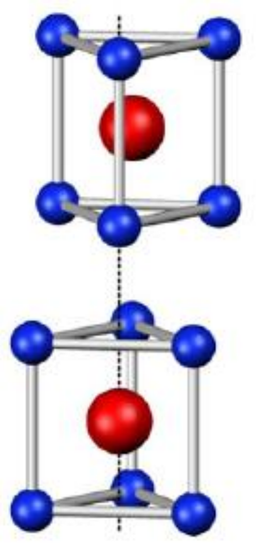
Figure from J.T. Ye et al.

Maximum T_c~11K n~1.3 × 10^{14} cm^{-2}
via ionic liquid gating

Taniguchi et al. APL 101, 042603, (2012).
Ye, J.T. et al. Science 338 1193–1196 (2012)

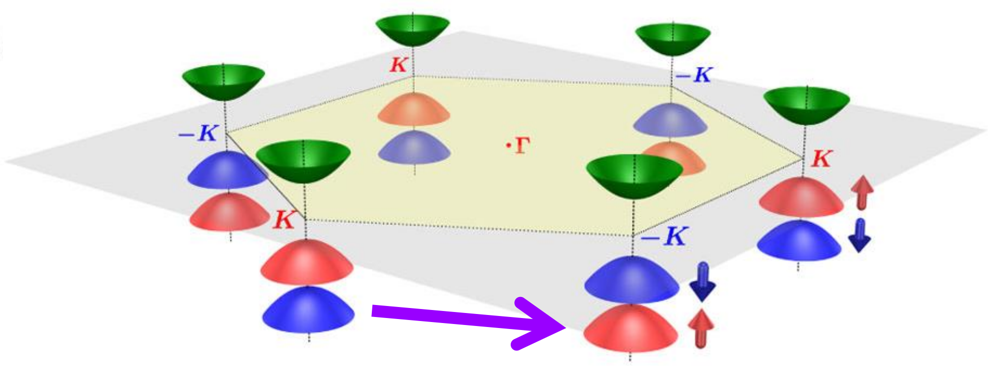
Spin-Valley coupling in MoS_2

Bulk TMD unit cell



spin orbit coupling
+
broken inversion symmetry for odd layer number

Monolayer TMD
low-energy band structure
large valence band spin splitting



graphics from Xiao et al.

	MoS_2	$MoSe_2$	WS_2	WSe_2	III-V's
Predicted monolayer spin splitting from [1]	148 meV	183 meV	426 meV	456 meV	Typically <30 meV

Spin scattering requires intervalley scattering

Enhanced spin lifetime predicted [2]

[1] Zhu et al. Phys. Rev. B **84**, 153402 (2011)
[2] Xiao et al. Phys. Rev. Letters **108**, 196802 (2012)

Optically induced valley polarization in MoS_2

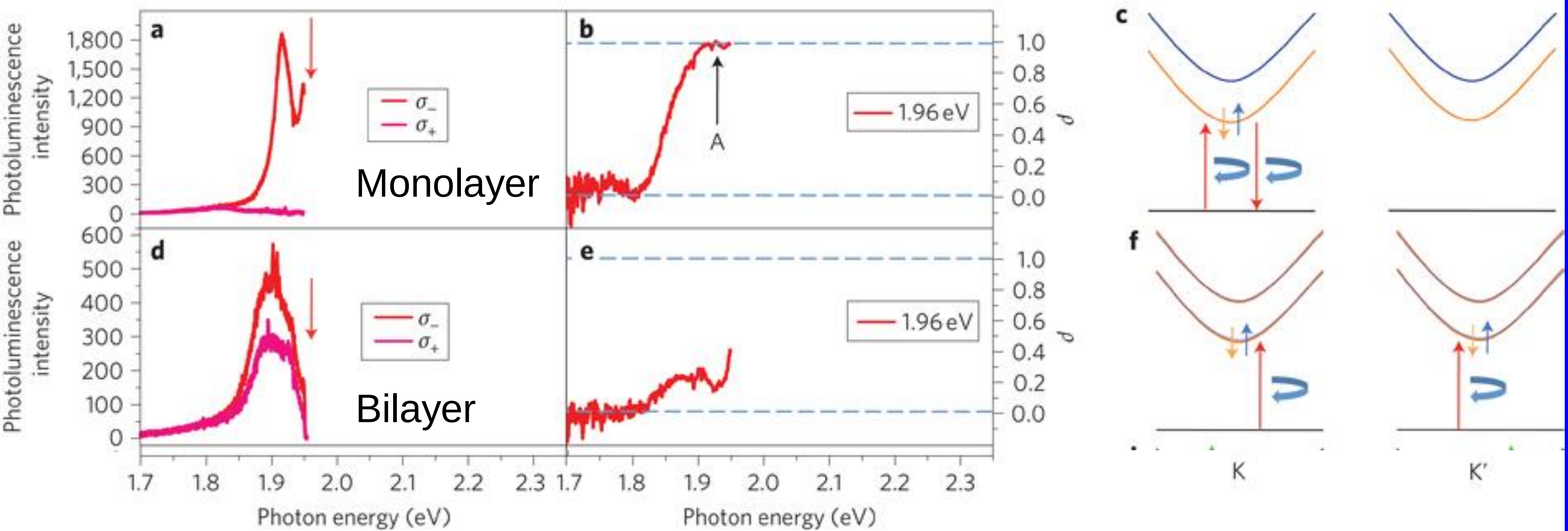


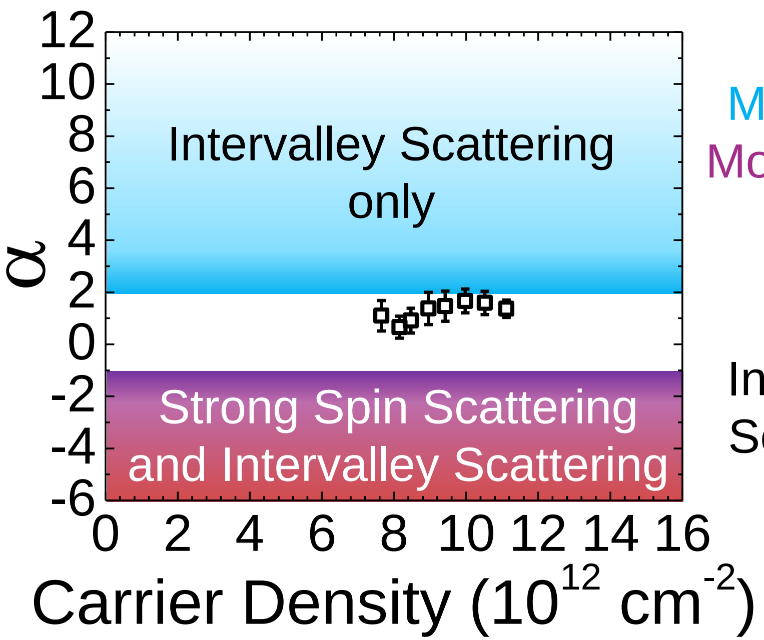
Figure from Mak et al.

Valley polarization induced by optical pumping with circularly polarized light in monolayer MoS_2

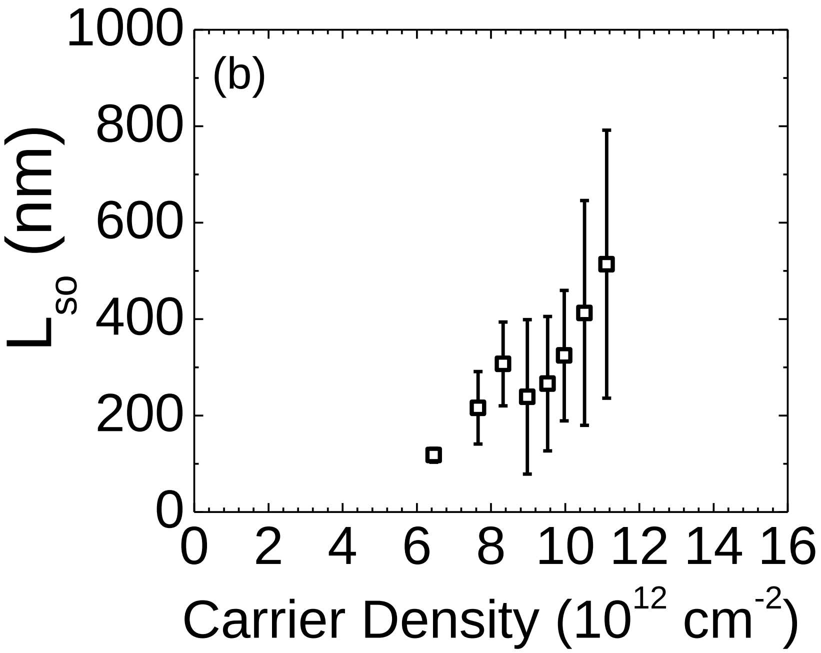
Hole spin-valley lifetime >1ns observed

Mak et al. *Nat. Nanotechnol. 7*, 494–498 (2012)
Zeng et al. *Nat. Nanotechnol. 7*, 490–493 (2012)
Cao et al. *Nat. Commun. 3*, 887 (2012)

Spin-orbit and Intervalley scattering in MoS$_2$



More Blue
More Purple
↓
More Intervalley Scattering



$$0 < \alpha < 2$$

$$\Downarrow \quad \Longrightarrow$$

Strong Intervalley Scattering
Weak Spin Scattering

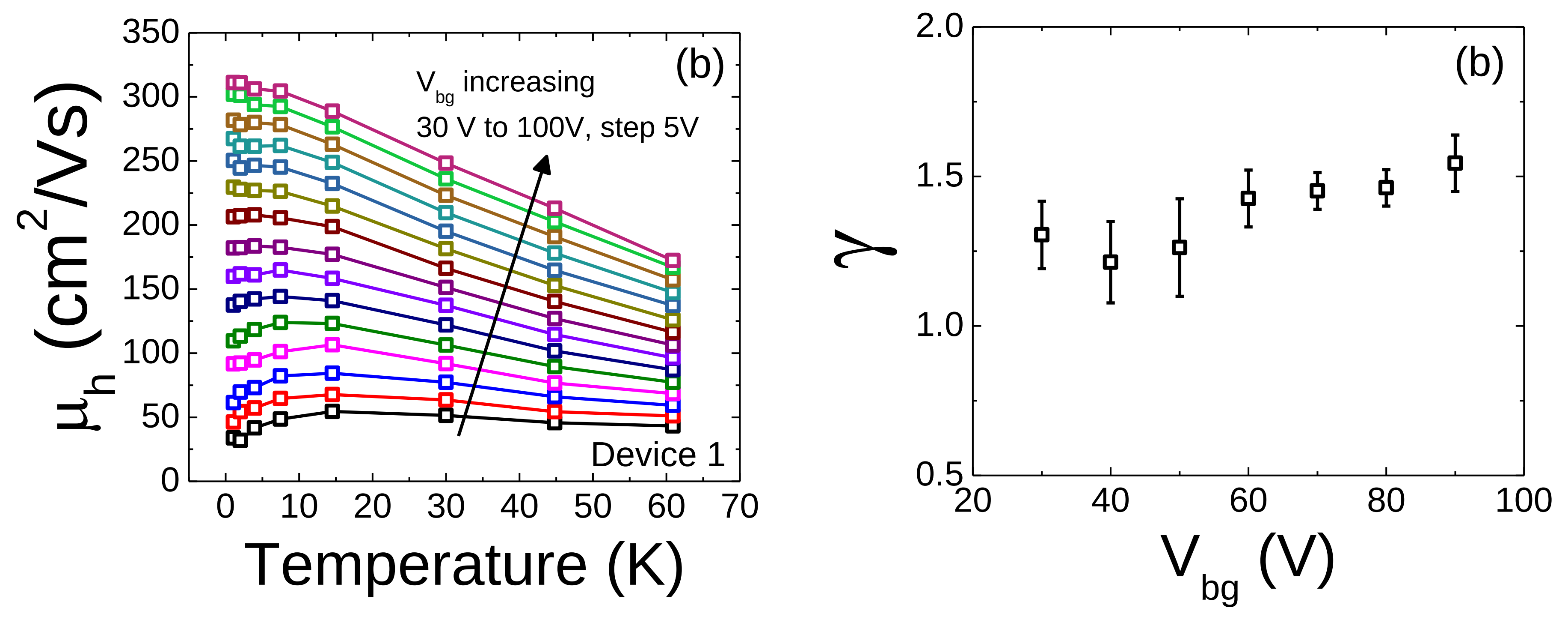
L_{so} as high as 500nm, T=400mK

$$\Delta\sigma = n_s \frac{e^2}{4\pi^2\hbar}\left(F\left(\frac{B}{B_\phi + B_{so}}\right) + \frac{-1}{n_s}\left(F\left(\frac{B}{B_\phi}\right) - F\left(\frac{B}{B_\phi + 2B_{so}}\right)\right)\right)$$

$$B_* = \frac{\hbar}{4eL_*^{\,2}}, \qquad * = \phi, so$$

Fukuyama PTPS 69 220 (1980), Lu et al. PRL 110, 016806 (2013)

Low temperature MoS_2 Mobility

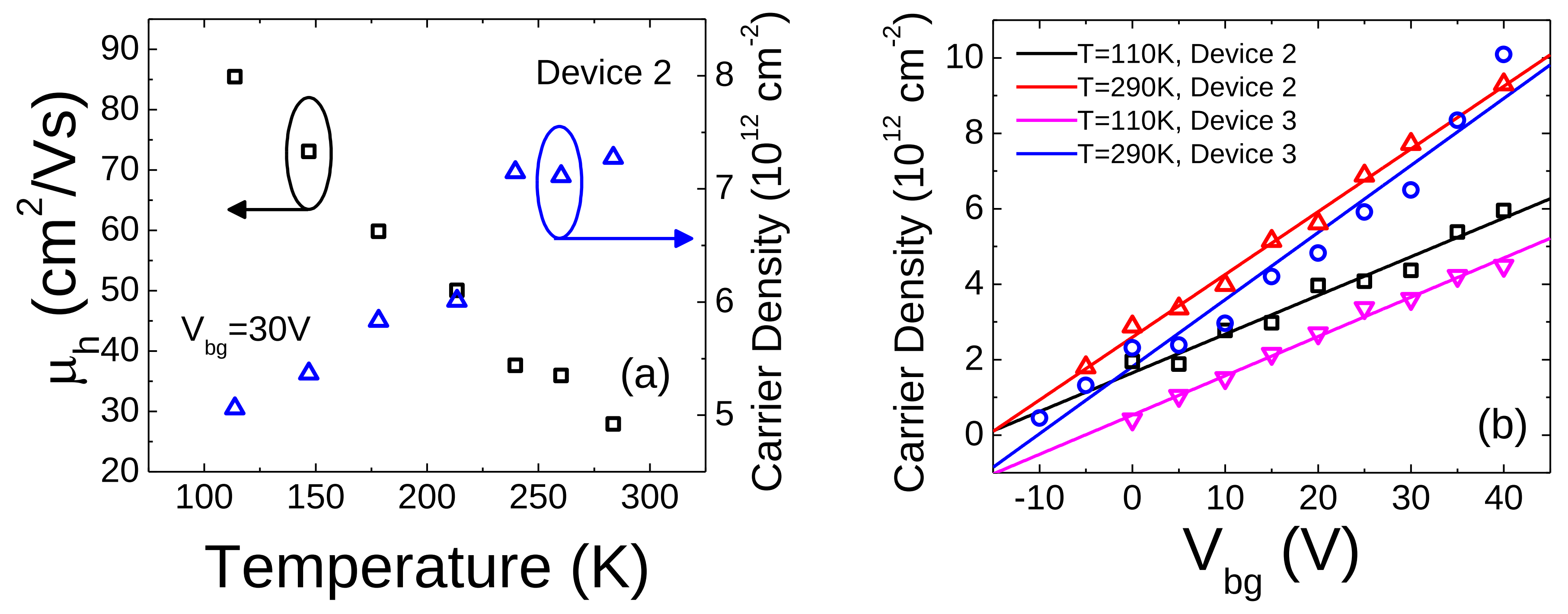


μ_h decreases as $T^{-\gamma}$ γ~1.5, T=10K to 60K

μ_H>300 cm^2/Vs at LT

Adam T. Neal et al. submitted to ACS Nano
Kaasbjerg et al. *PRB*, *85*, 115317 (2012).
Kaasbjerg et al. *arXiv:1206.2003v1* (2012).

Hall Factor of MoS_2



$\frac{dn_h}{dV_g} = \frac{r_h C_{gate}}{q}$, accumulation $\Longrightarrow C_{gate} = C_{ox}$

r_h=1.35, T=1K r_h=2.4, T=290K

$\mu_{drift} = r_h \mu_h$=420 cm^2/Vs @T=1K, 56 cm^2/Vs @T=290K

Summary

1) We demonstrated direct ALD high-k integration on MoS_2 and other 2D crystals.
2) Low work-function metals, i.e. Ti, lead to high-performance MoS_2 MOSFETs.
3) We studied vertical layers (CVD monolayer), channel length and channel width scaling (down to 50-60nm). We observe a D-mode to E-mode transition by scaling width, meanwhile length scaling shows dominate contact resistance.
4) Hall Factor ~2.4, T=290K, multilayer MoS_2. Needed for accurate determination of drift mobility from Hall effect
5) Electron spin orbit scattering length L_{so} as high as 500nm in few layer MoS_2, indicating potential for spintronics applications.

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