Semiconductor Devices II

Part 2

Chapter 1: Introduction to 2D materials

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Subjects and goals

2D materials – introduction and materials aspects

FETs with 2D materials – switching, contact resistance, trap states, applications in sensing and memories

Optoelectronics with 2D materials

Emerging, post-CMOS concepts: valleytronics, spintronics, excitonic devices

Implementation:

- Lectures
- Exercises
- Lab demonstrations

Introduction

Why semiconducting nanostructures for nanoelectronics

Historic overview

- Graphene
- Transition metal dichalcogenides and 2D materials

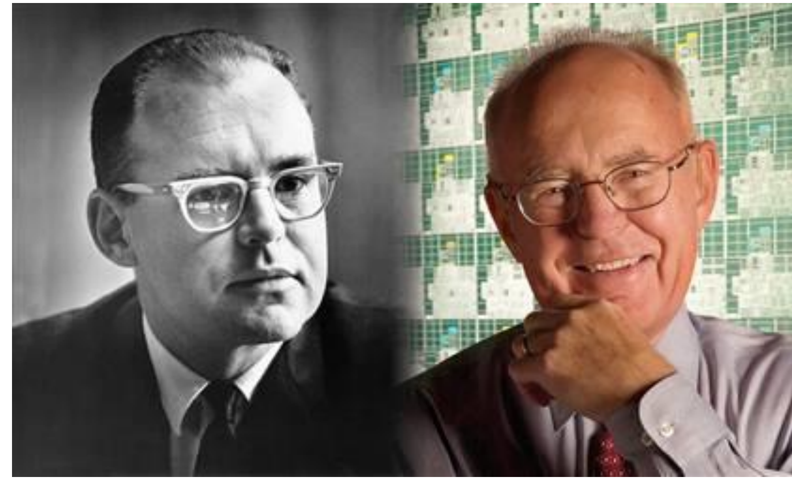
Material growth

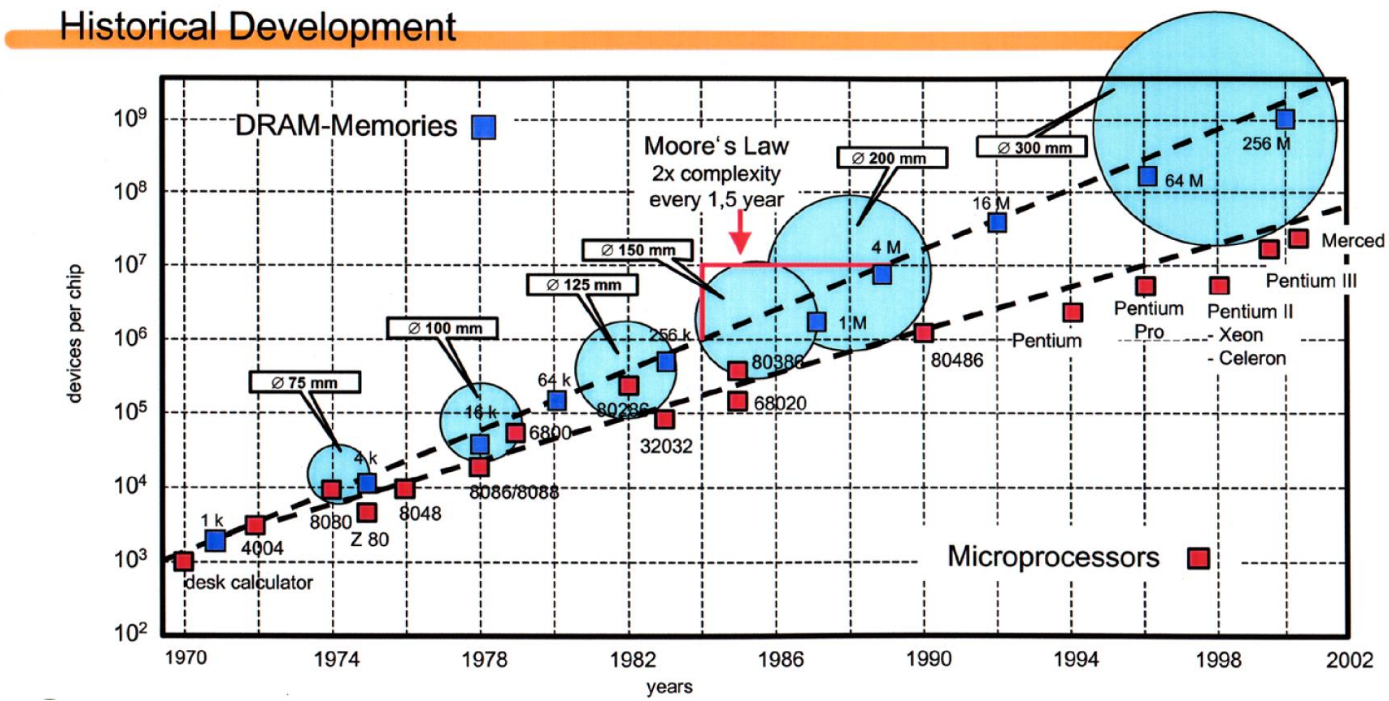
  - CVD

Moore’s Law

Gordon Moore, co-founder of Intel stated in 1965:

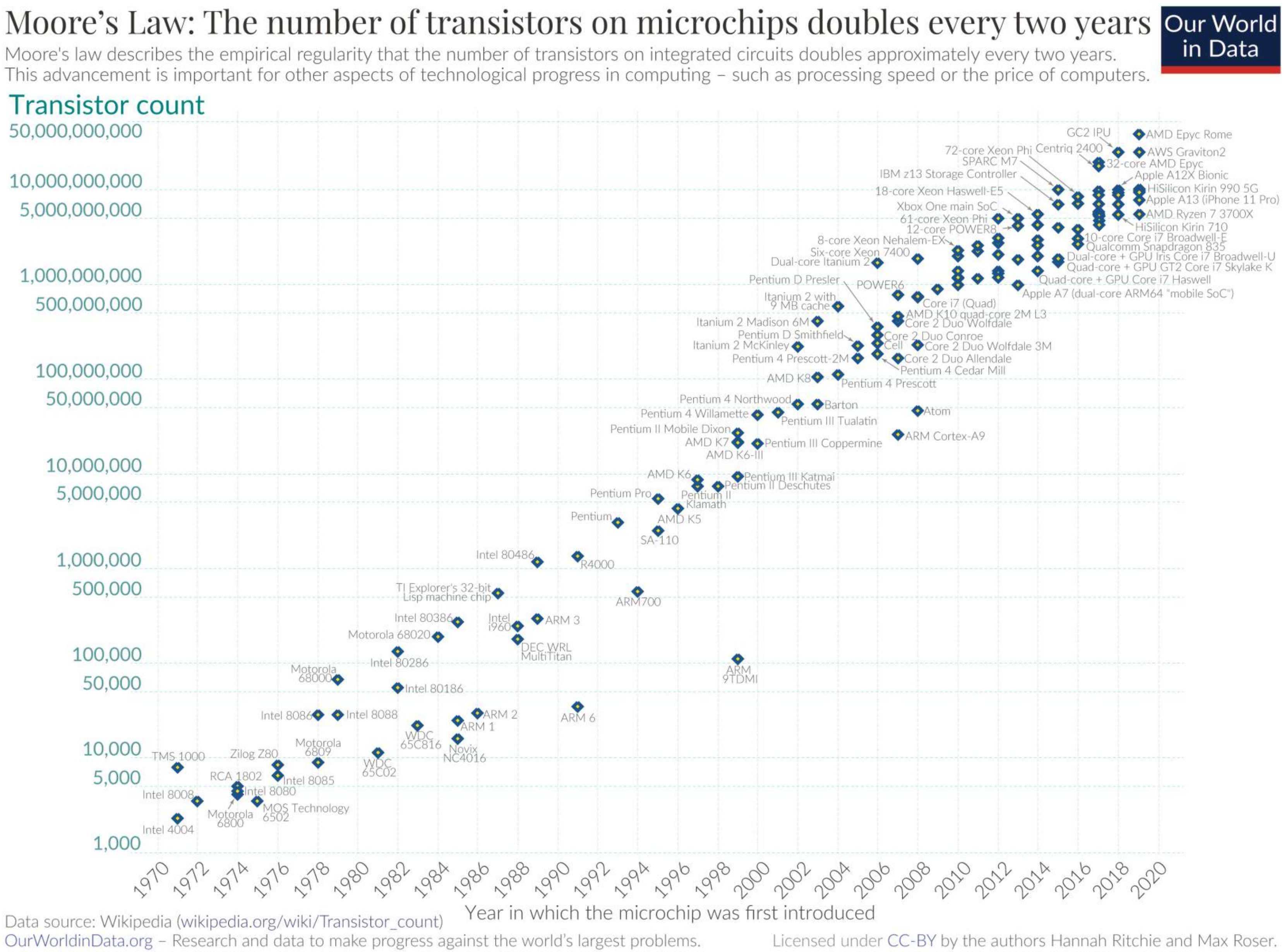
“The number of transistors that can be inexpensively placed on an integrated circuit is increasing exponentially, doubling approximately every two years”





http://nobelprize.org/nobel_prizes/physics/laureates/2000/phyadv.pdf

Moore’s Law



[Source: Wikipedia (Wikipedia.org/wiki/Transistor_count)](https://en.wikipedia.org/wiki/Transistor_count)

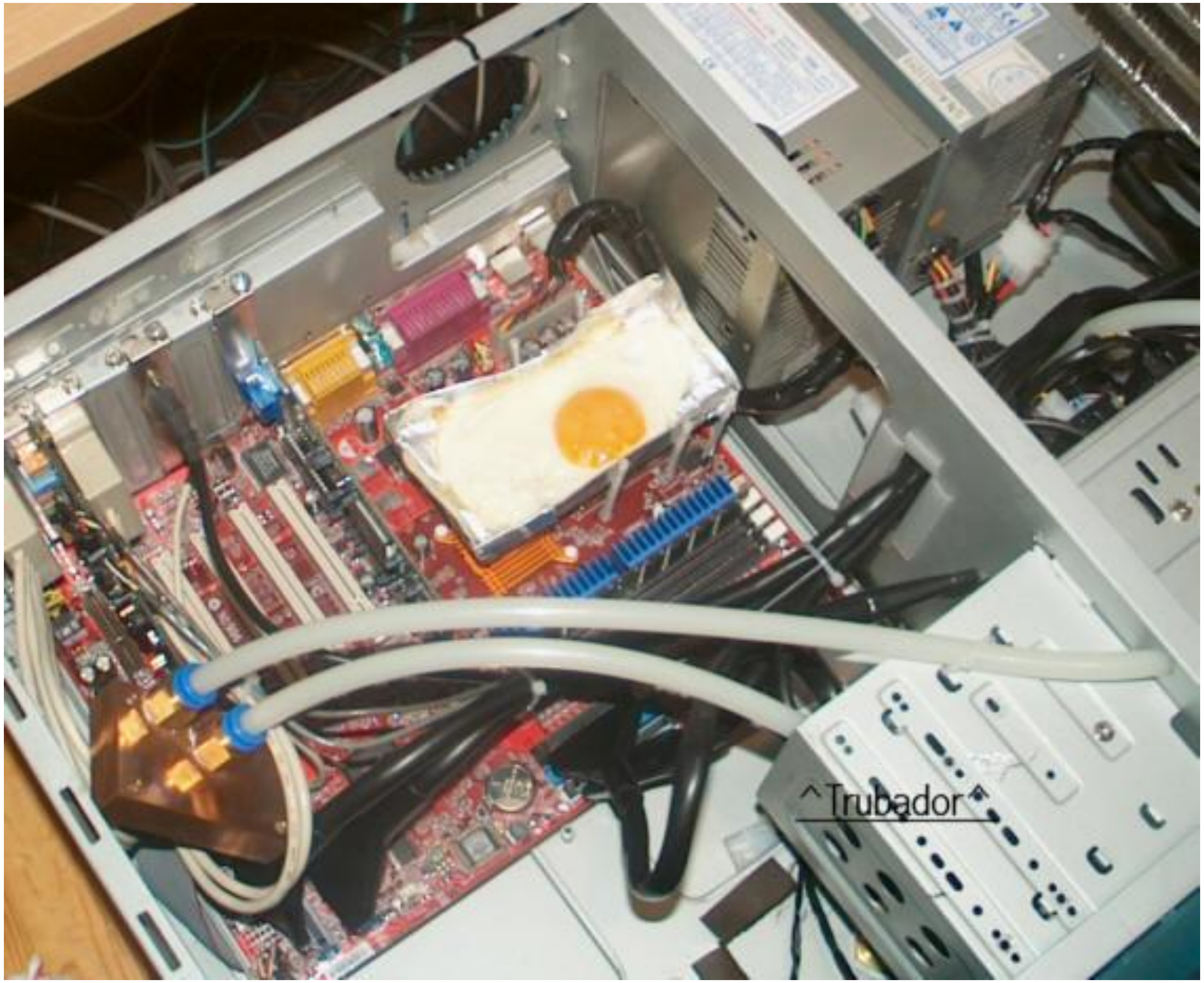
Dissipated Heat

Processor coolers 20 years ago and now

Source: bequiet.com
Dark Rock Elite

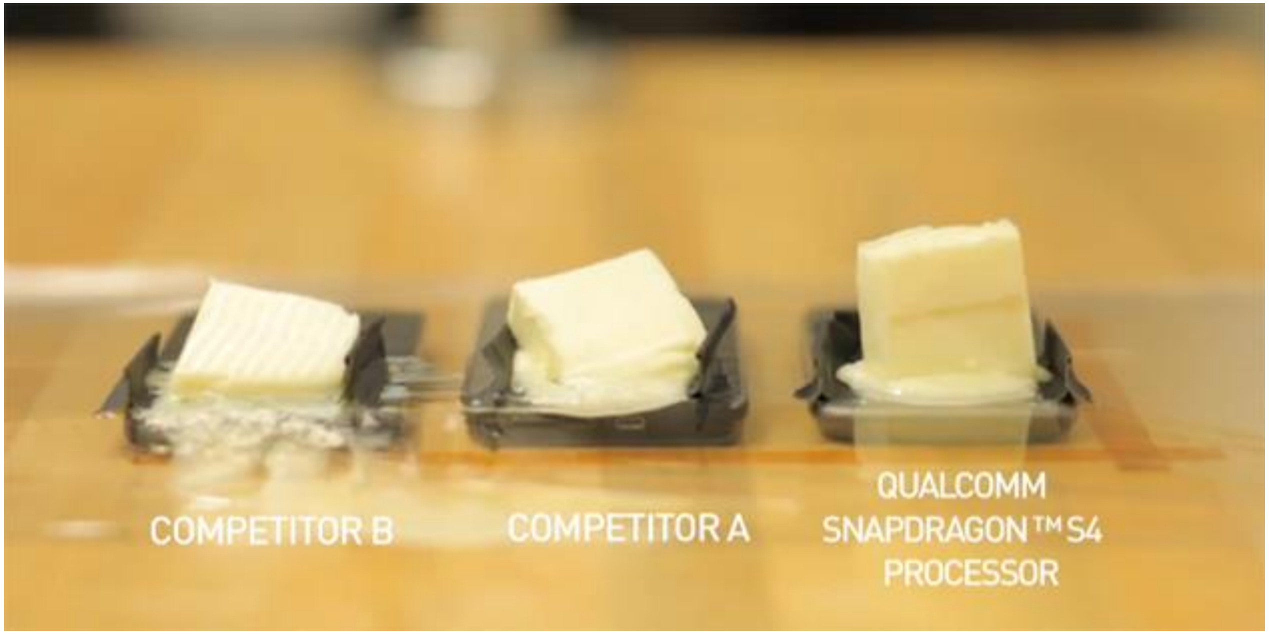
Dissipated Heat

Frying eggs on processors



http://www.phys.ncku.edu.tw/~htsu/humor/fry_egg.html

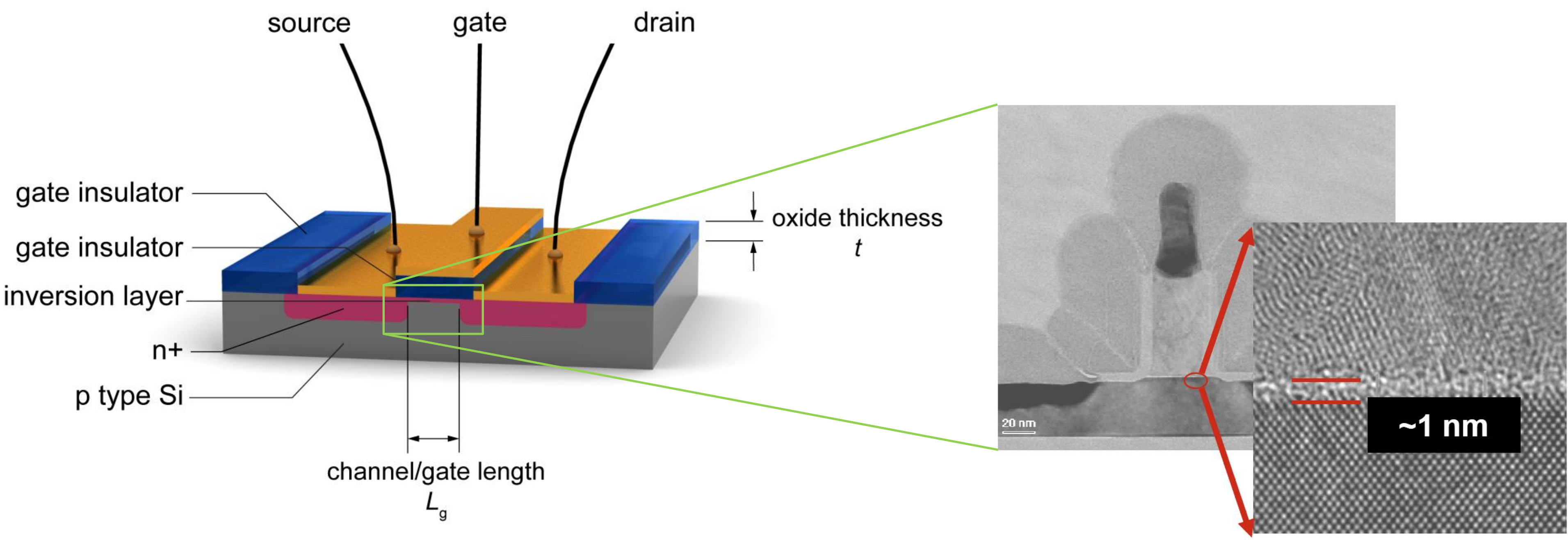
Melting-butter Benchmark



Source: Android andMe.com

MOSFET

Metal–oxide–semiconductor field-effect transistor (MOSFET)



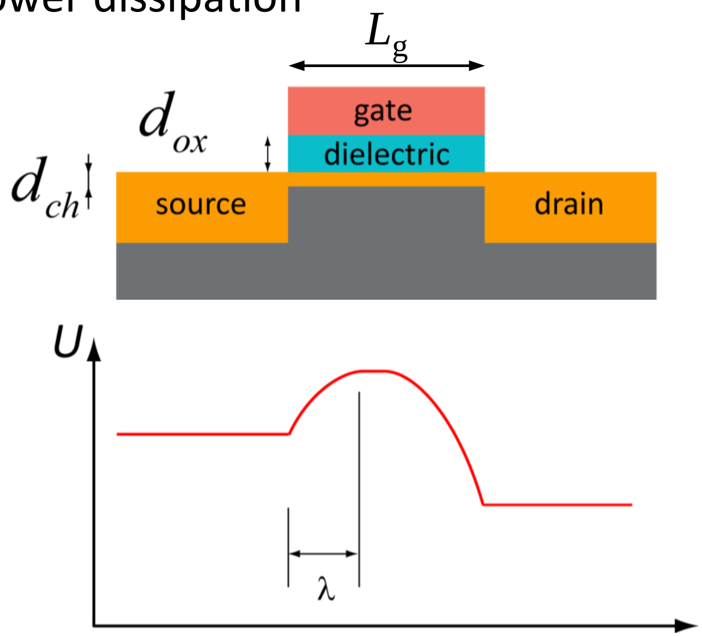
Approaching atomistic limits

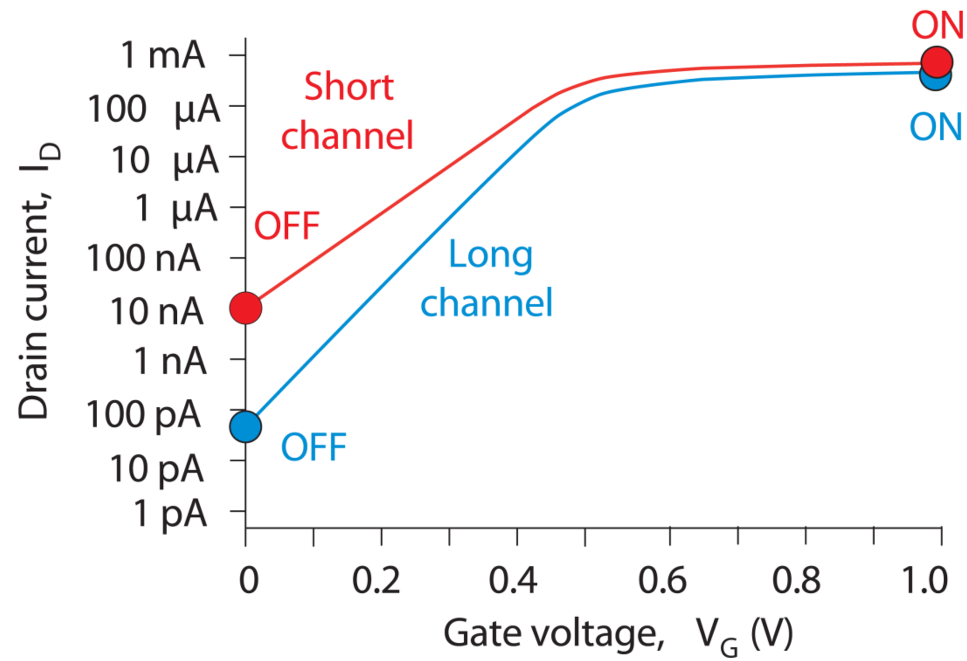
Channel length in Intel processors:

14 nm 2014
10 nm 2017
7 nm 2018? 2022!

Why Heat Dissipation in Small Transistors?

Planar MOSFET – short channel effects; standby power dissipation





$$\lambda = \sqrt{\frac{\varepsilon_{ch}}{\varepsilon_{ox}} d_{ox} d_{ch}}$$

ε(Si)=11.9

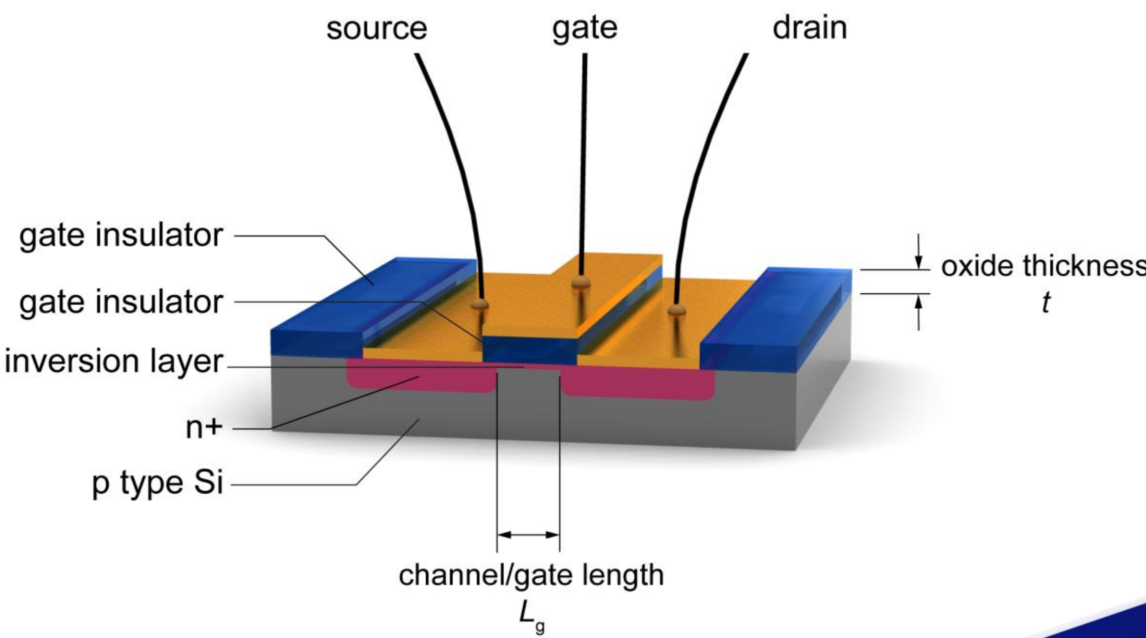
To deplete the channel: L_g at least 3–5× λ

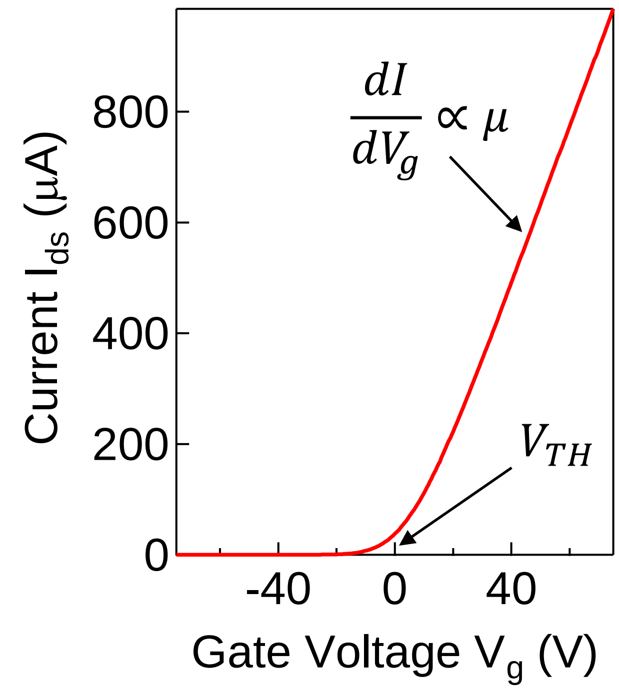
Example:

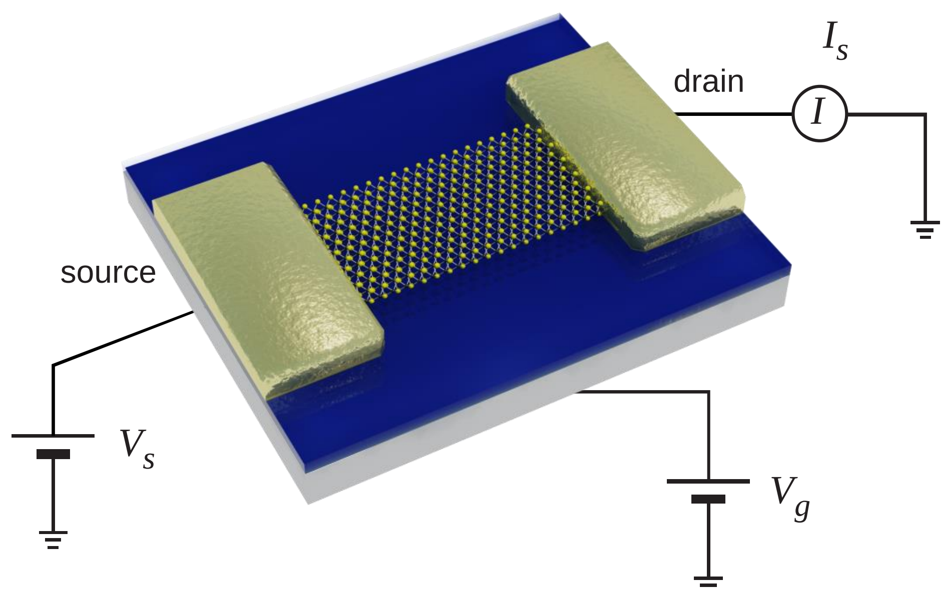
2 nm thin Si, 1 nm SiO_2: L_g > 10 nm

Ferain et al., Nature 479, 310 (2011)
Colinge, Sol. State El. 48, 897 (2004)

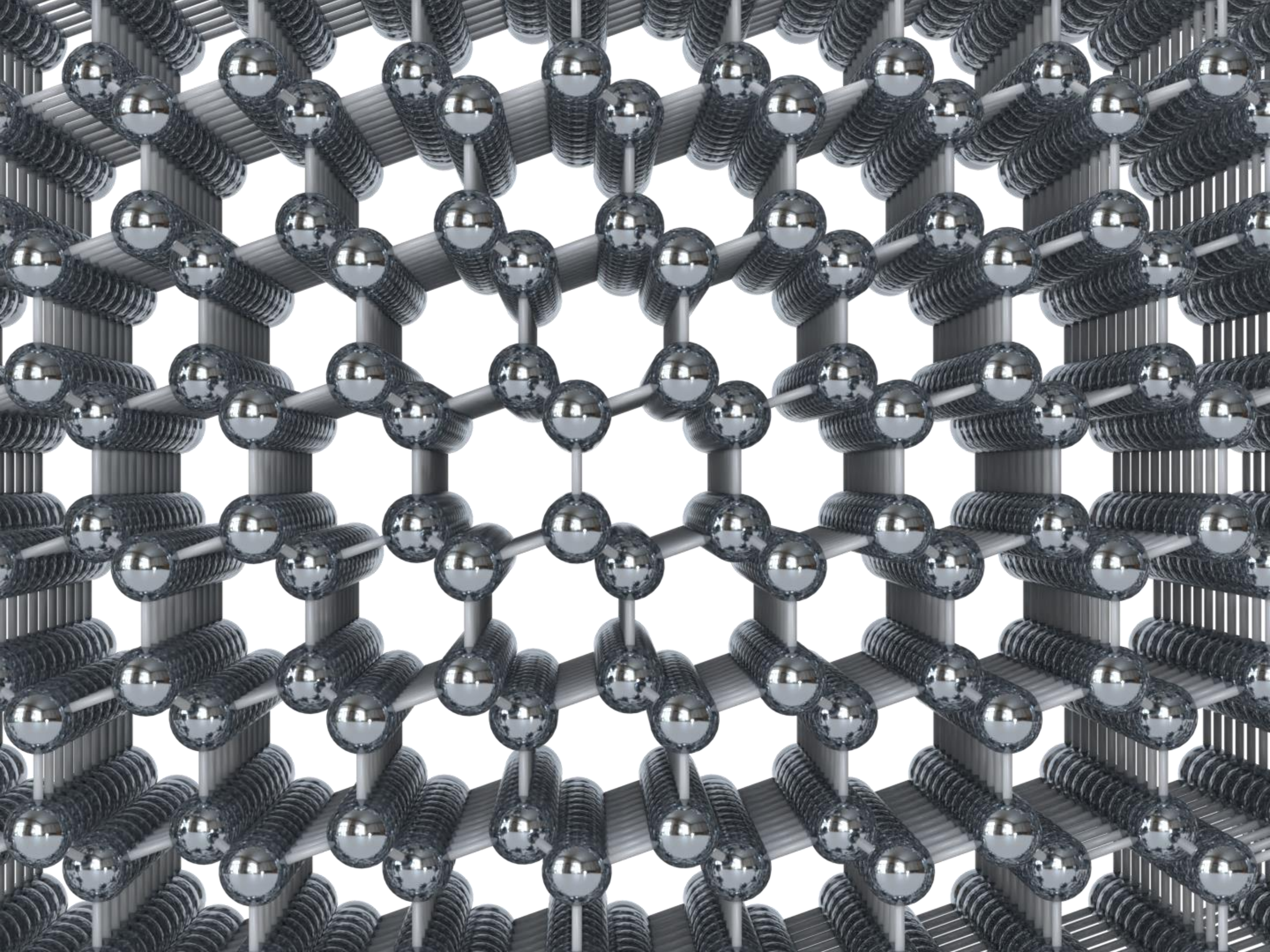
FETs Based on Nanomaterials

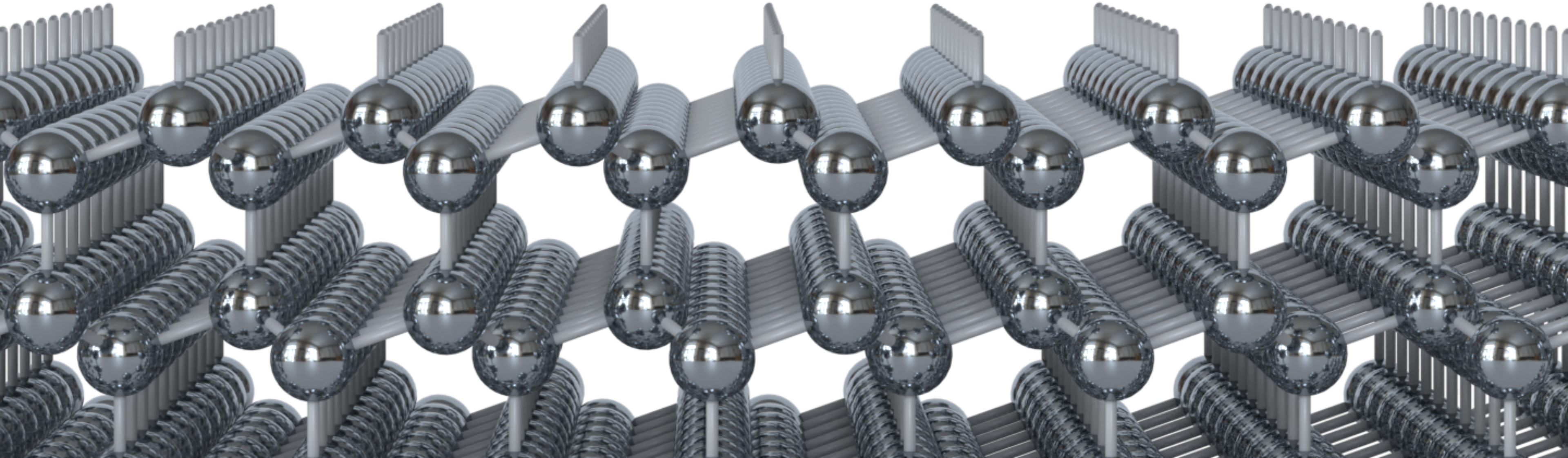


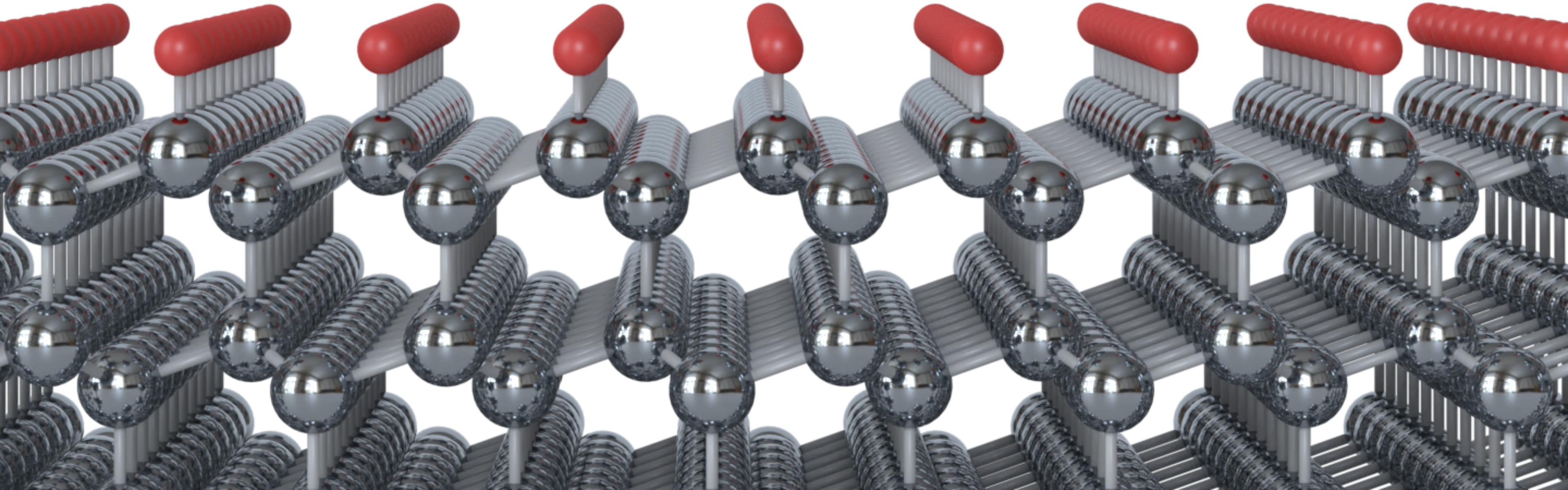




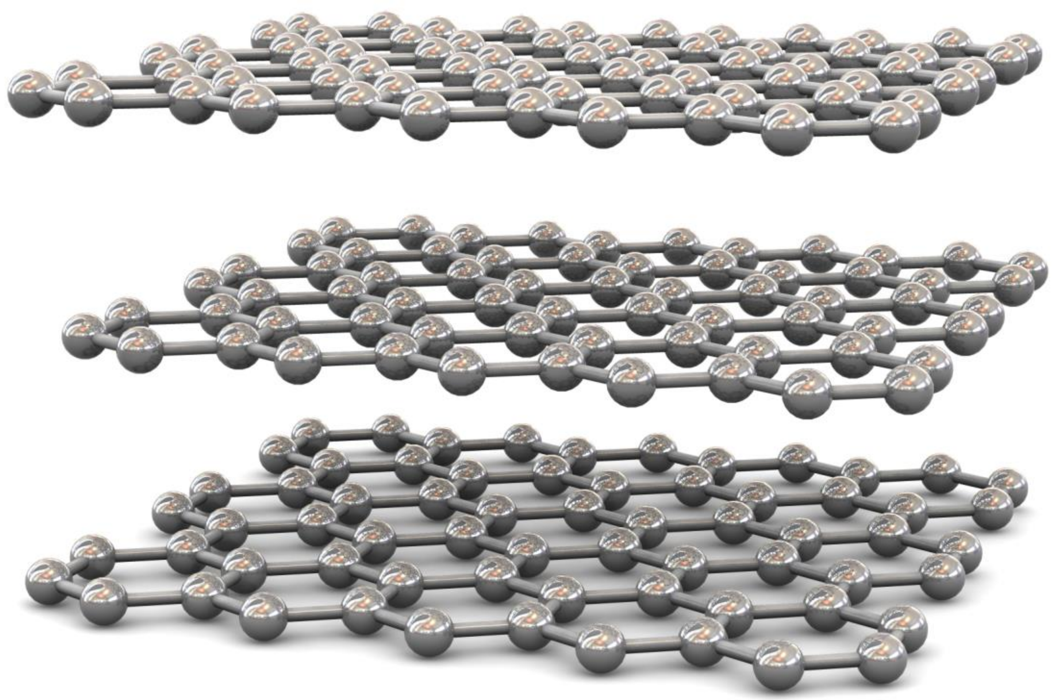
FET with a nanomaterial channel



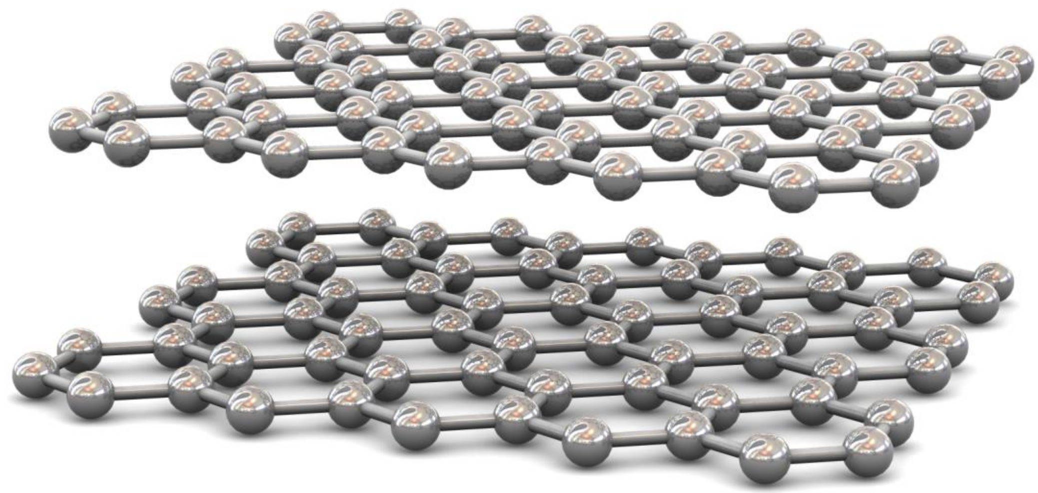




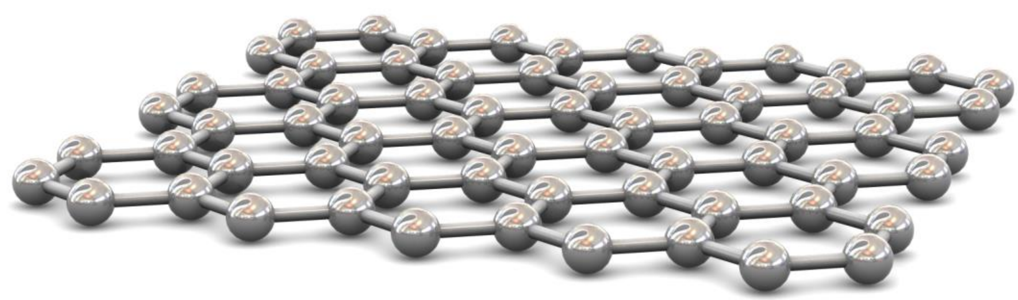
Graphite and Graphene



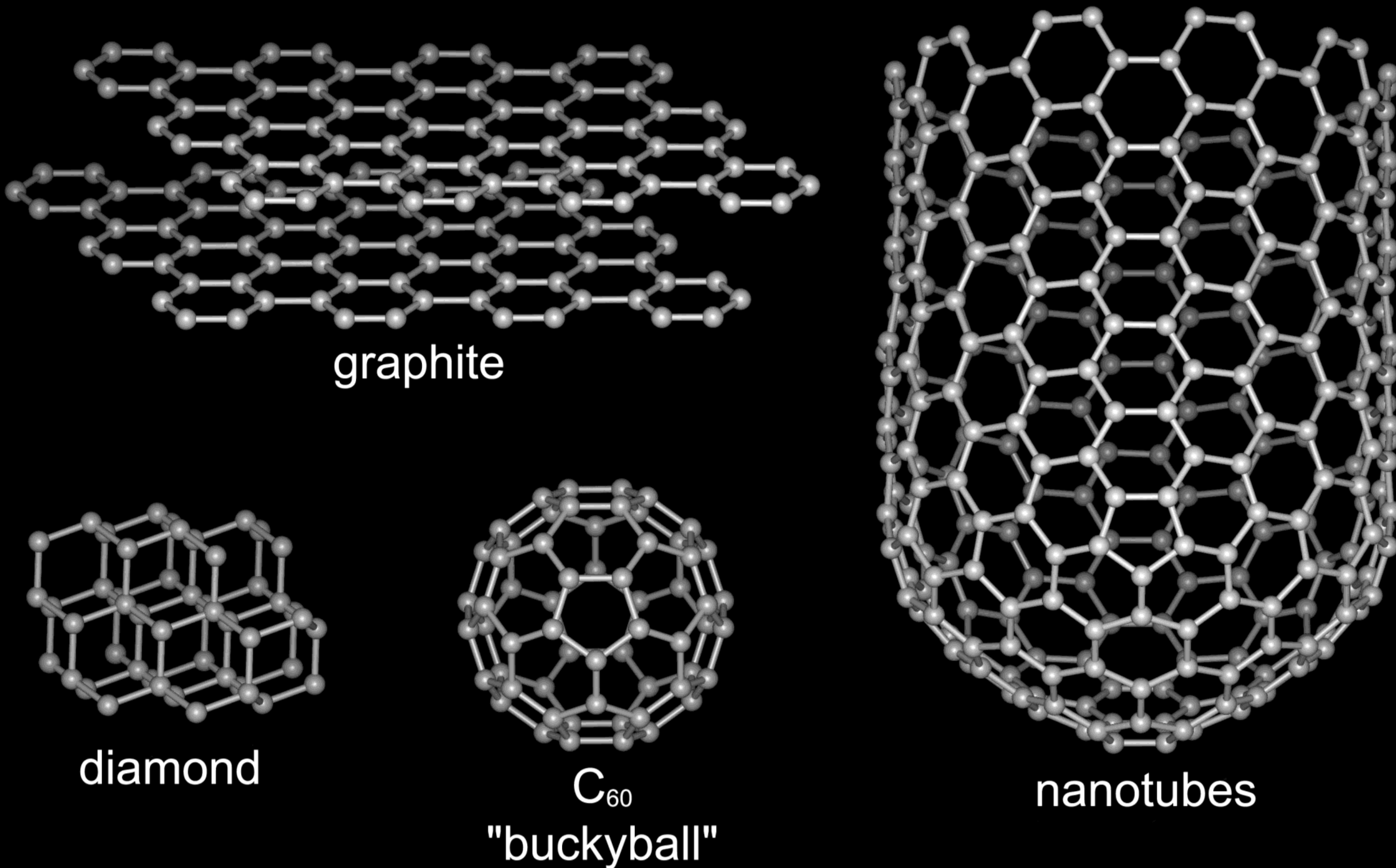
Graphite and Graphene



Graphite and Graphene



(Some) Carbon Nanostructures



Smalley group web site http://smalley.rice.edu/

Dimensions in Geometry and Semiconductor Physics

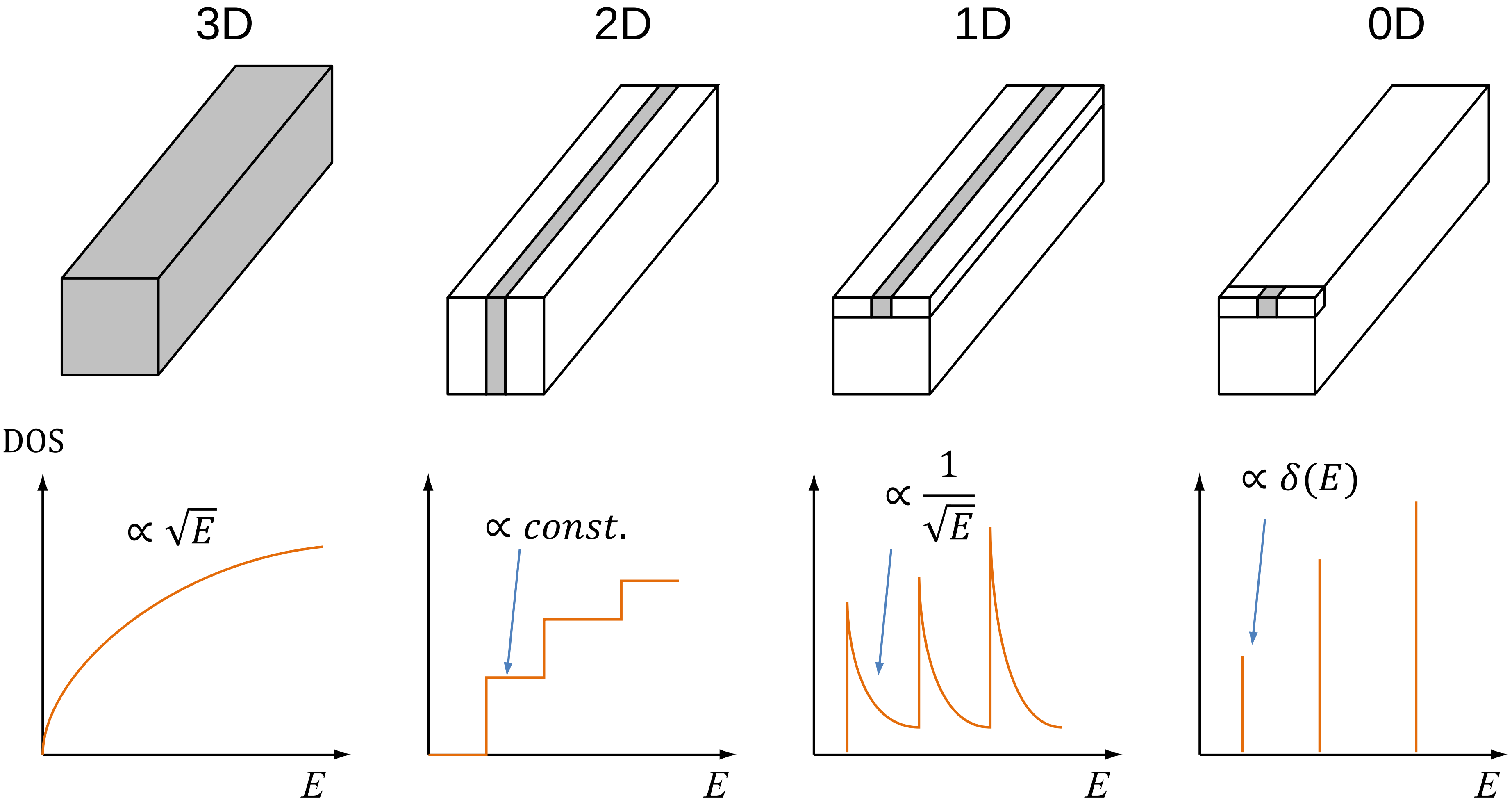
Geometry

- Refers to the system size
- Planes (2D), lines (1D), dots (0D)

Semiconductor Physics

- Refers to the free motion of charge carriers
- Can be constrained due to quantum confinement
- Quantum wells (2D), quantum wires (1D), quantum dots (0D)

Dimensions in Semiconductor Physics



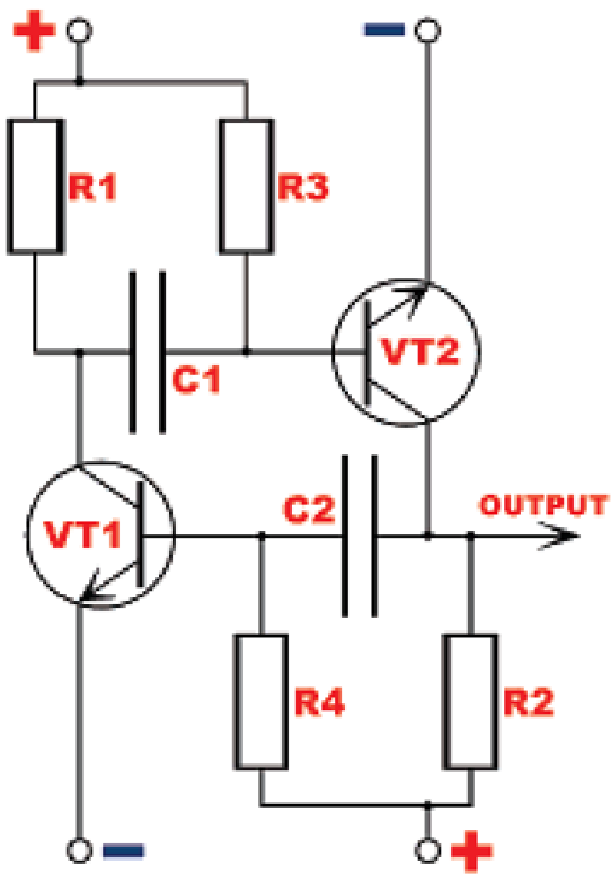
assuming $E = \frac{\hbar^2 k^2}{2m}$

→ Exercise session 1

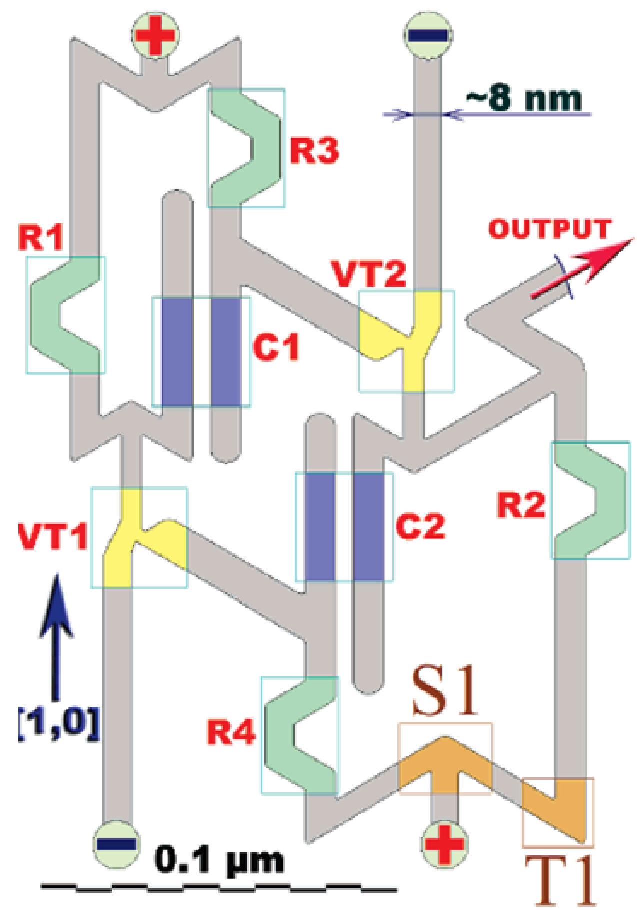
2D Circuits

Example: Flip-flop circuit

Circuit diagram

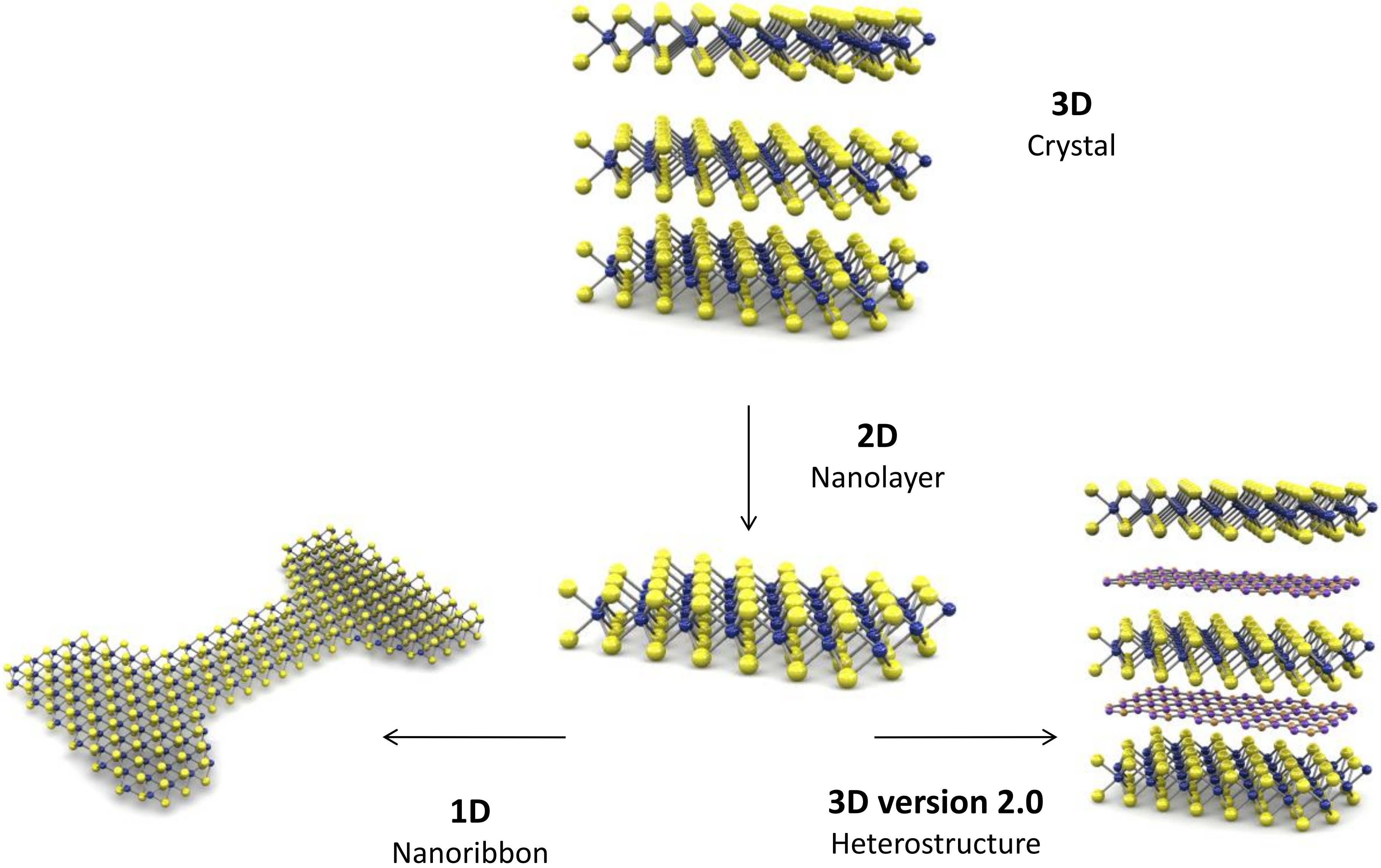


Graphene circuit



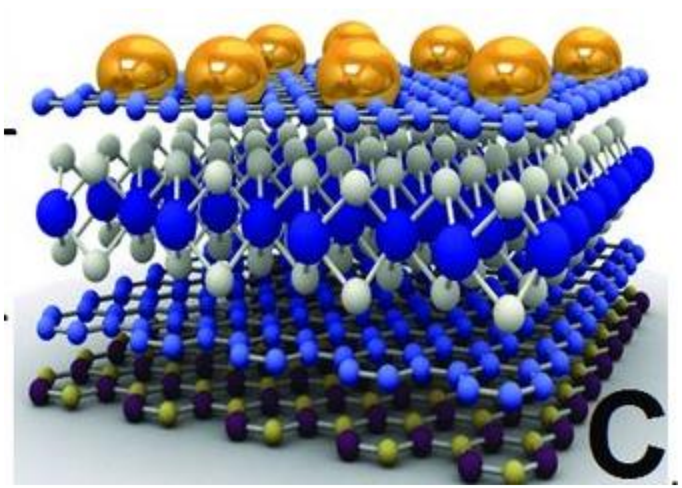
Areshkin et al., Nano Letters 7, 204 (2007)

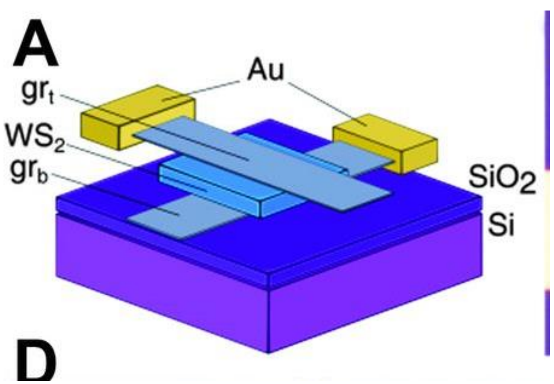
2D Materials: Wide Range of Geometries



Heterostructures Based on 2D Materials

Vertical: FETs, solar cells

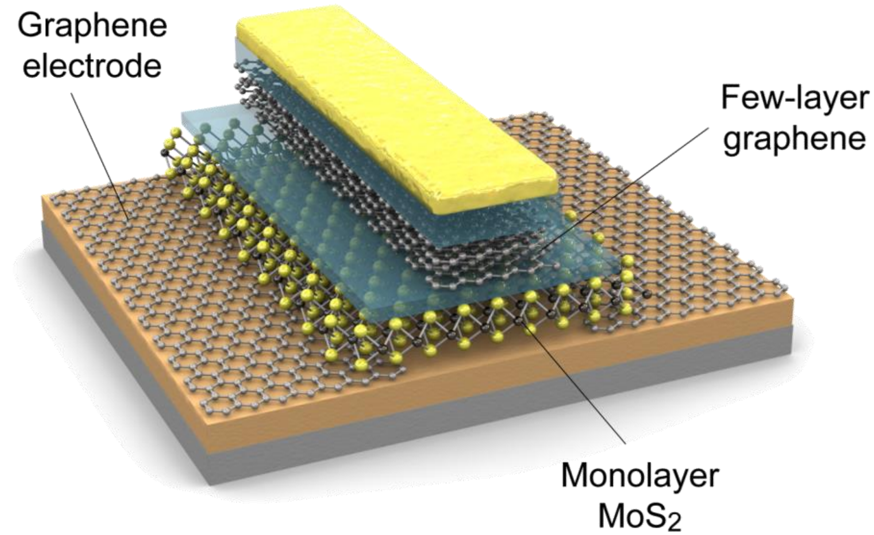


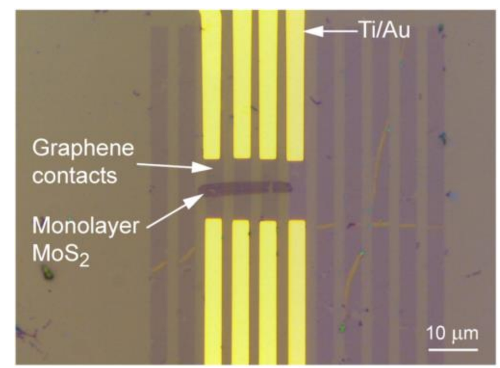


Britnell, Novoselov et al.

Science 340, 1311 (2013)

Lateral/vertical: Flash memory





Bertolazzi, Krasnozhon, Kis

ACS Nano (2013)

Early Attempts

Graphene in 3-Dimensions: Towards Graphite Origami

By Thomas W. Ebbesen* and Hidefumi Hiura

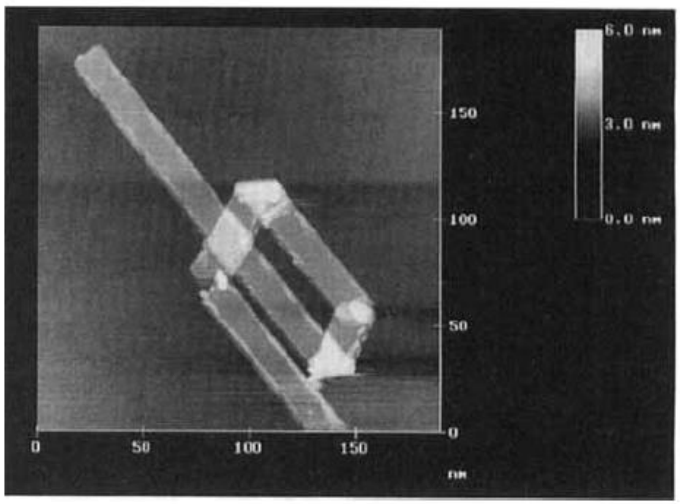


Fig. 1. AFM picture of a graphitic ribbon folded 4 times on the surface of HOPG reminiscent of origami.

AFM image of a folded graphitic ribbon

Ebbesen et al., Adv. Mater. 7, 582 (1995)

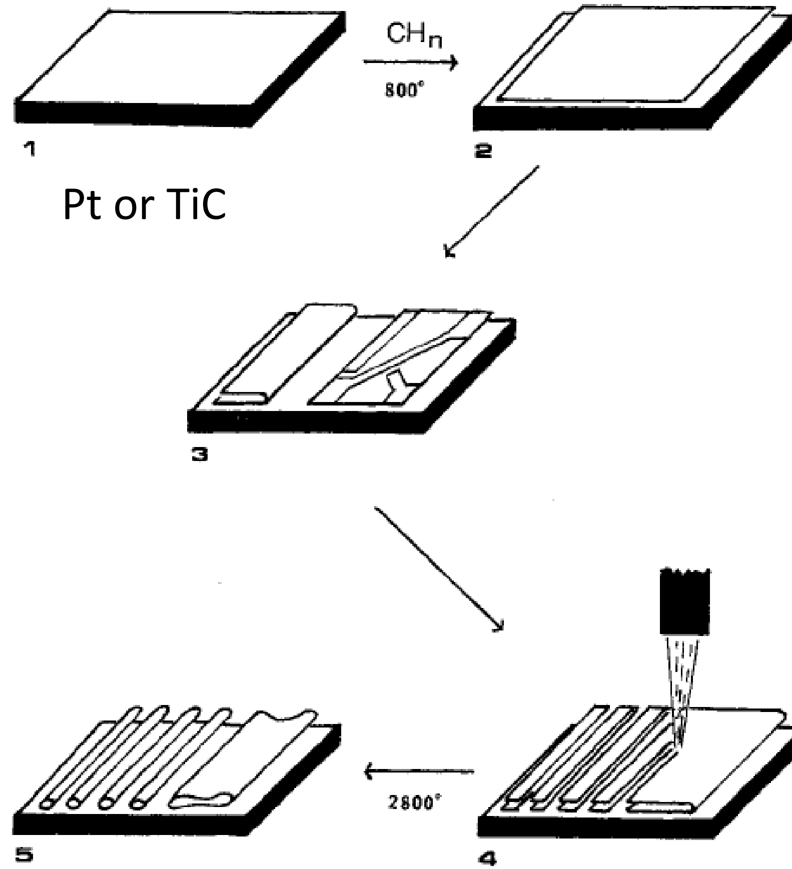


Fig. 6. Schematic diagram of possible approaches for fabricating carbon structures by design (see text).

Proposed device fabrication procedure

Early Attempts

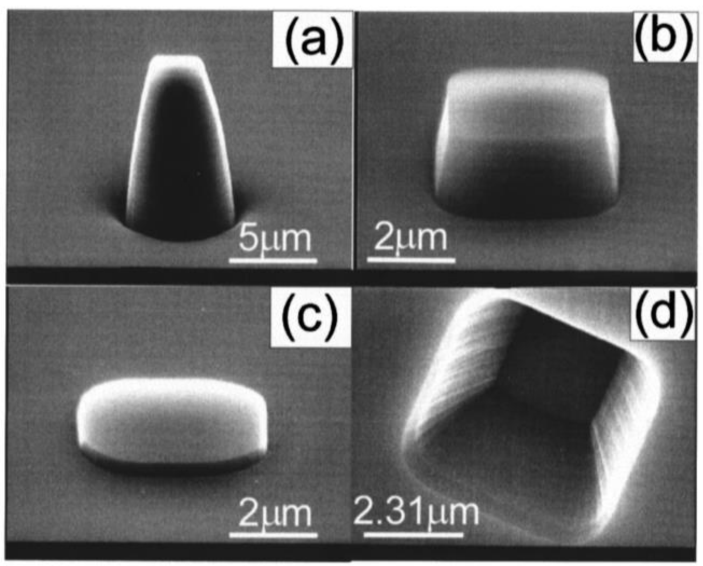
APPLIED PHYSICS LETTERS VOLUME 75, NUMBER 2 12 JULY 1999

Patterning of highly oriented pyrolytic graphite by oxygen plasma etching

Xuekun Lu,[a)] Hui Huang, Nikolay Nemchuk, and Rodney S. Ruoff[b)]
Department of Physics, Washington University, CB1105, St. Louis, Missouri 63130

(Received 18 January 1999; accepted for publication 18 May 1999)

We were motivated to pattern HOPG because of our interest in the mechanical strength of graphite in the basal plane, which has not been determined to date. Mechanical strengths as high as ~300 GPa for defect-free regions are theoretically predicted from local-density approximation cal-



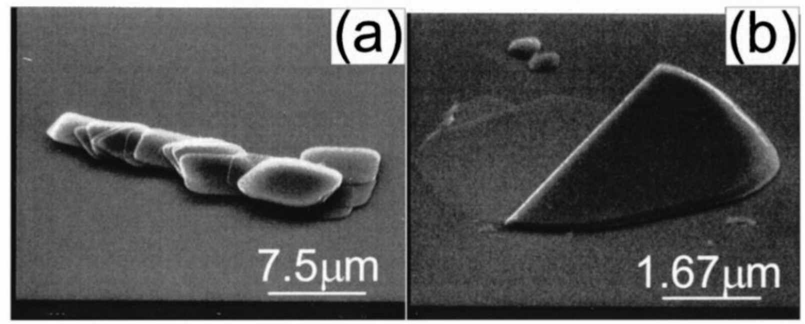
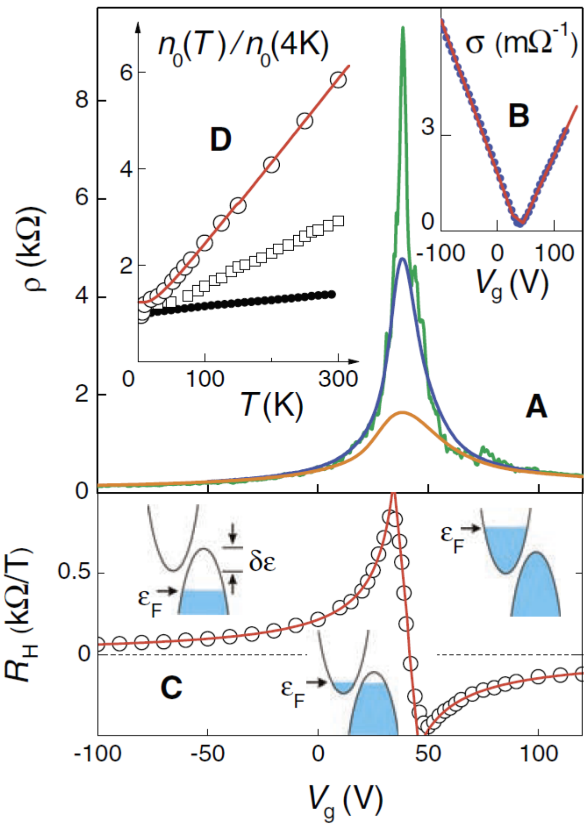


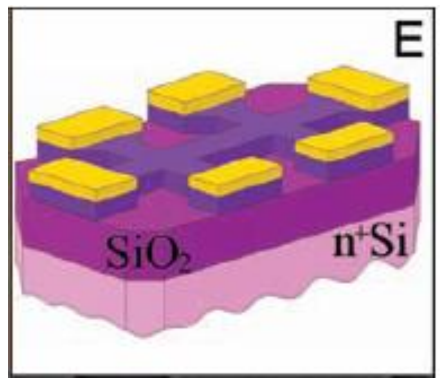
FIG. 5. SEM images of HOPG islands smeared on a Si(001) substrate. (a) Stacked thin platelets. (b) Example of a very thin layer left on the substrate while the platelet folds over.

First Devices: Geim and Novoselov

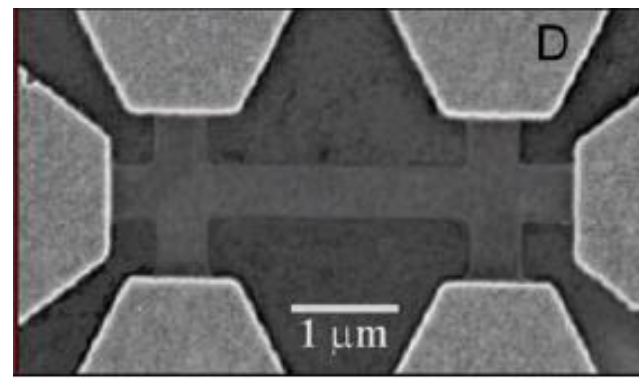
Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov,[1] A. K. Geim,[1*] S. V. Morozov,[2] D. Jiang,[1]
Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]





Schematic of the Hall bar device



SEM image of the graphene Hall bar device

Novoselov et al., Science 306, 666 (2004)

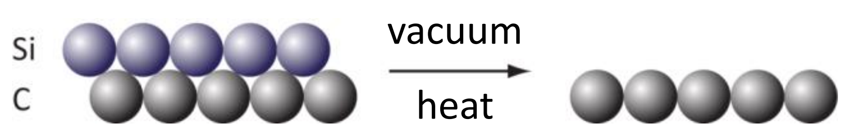
De Heer Group: Epitaxial Graphene

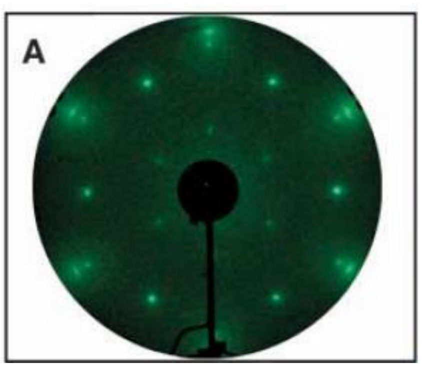
Ultrathin Epitaxial Graphite: 2D Electron Gas Properties and a Route toward Graphene-based Nanoelectronics

Claire Berger,† Zhimin Song, Tianbo Li, Xuebin Li, Asmerom Y. Ogbazghi, Rui Feng, Zhenting Dai, Alexei N. Marchenkov, Edward H. Conrad, Phillip N. First, and Walt A. de Heer*

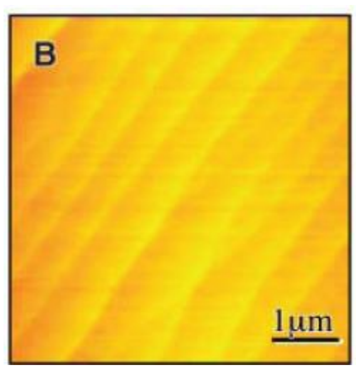
School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430

Received: October 7, 2004

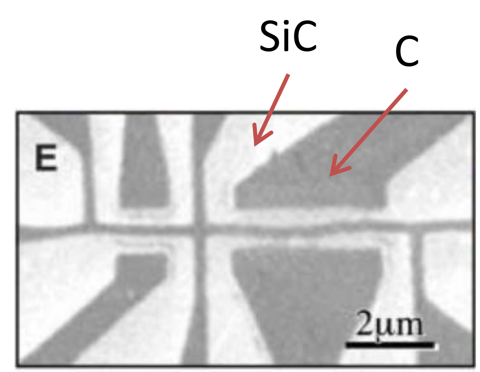




Diffraction pattern



AFM image
of the surface



Device

Berger et al., J. Phys. Chem. B 108, 19912 (2004)
Berger et al., Science 312, 1191 (2006)

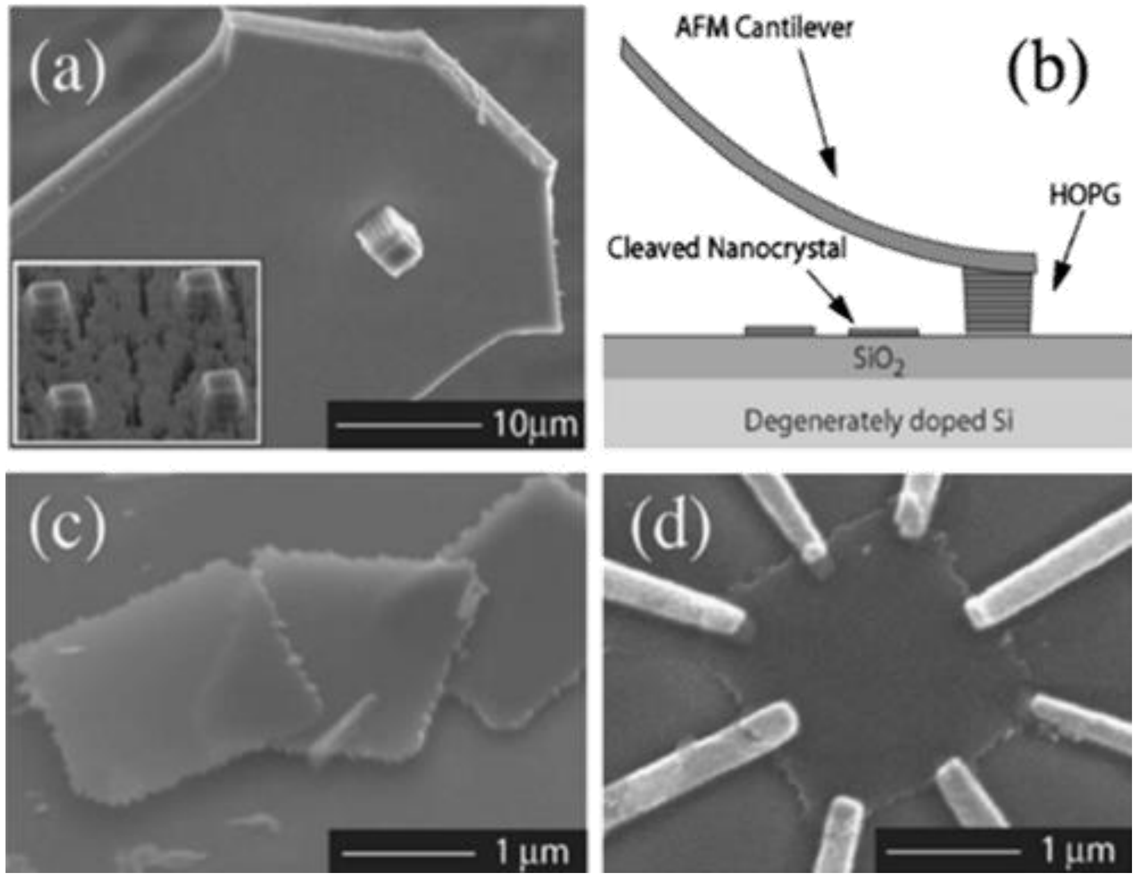
Berger et al., J. Phys. Chem. B 108, 19912 (2004)
Berger et al., Science 312, 1191 (2006)

Kim Group: Mechanical Exfoliation

Fabrication and electric-field-dependent transport measurements of mesoscopic graphite devices

Yuanbo Zhang, Joshua P. Small, William V. Pontius, and Philip Kim[a)]
Department of Physics and the Columbia Nanoscale Science and Engineering Center, Columbia University, New York, New York 10027

(Received 31 August 2004; accepted 11 December 2004; published online 7 February 2005)



Zhang et al., Phys. Rev. Lett. 94, 176803 (2005)

Zhang et al., App. Phys. Lett. 86, 073104 (2005)

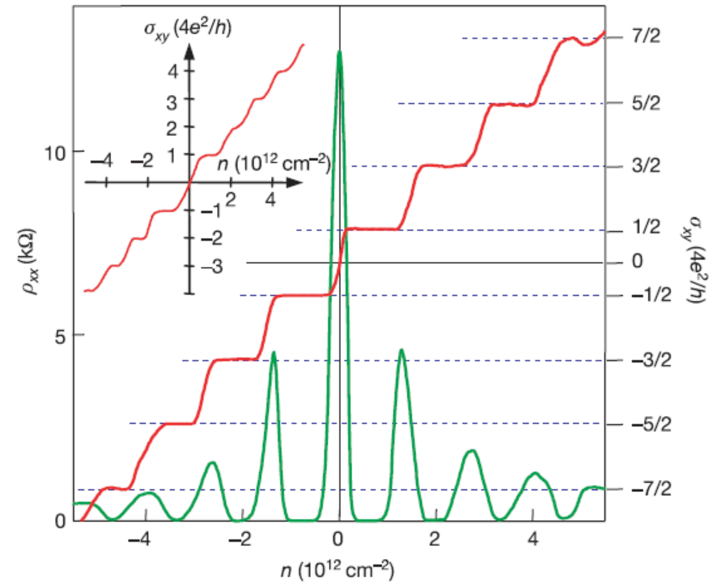
First Actual Measurements on Graphene

Vol 438|10 November 2005|doi:10.1038/nature04233 nature

LETTERS

Two-dimensional gas of massless Dirac fermions in graphene

K. S. Novoselov[1], A. K. Geim[1], S. V. Morozov[2], D. Jiang[1], M. I. Katsnelson[3], I. V. Grigorieva[1], S. V. Dubonos[2] & A. A. Firsov[2]



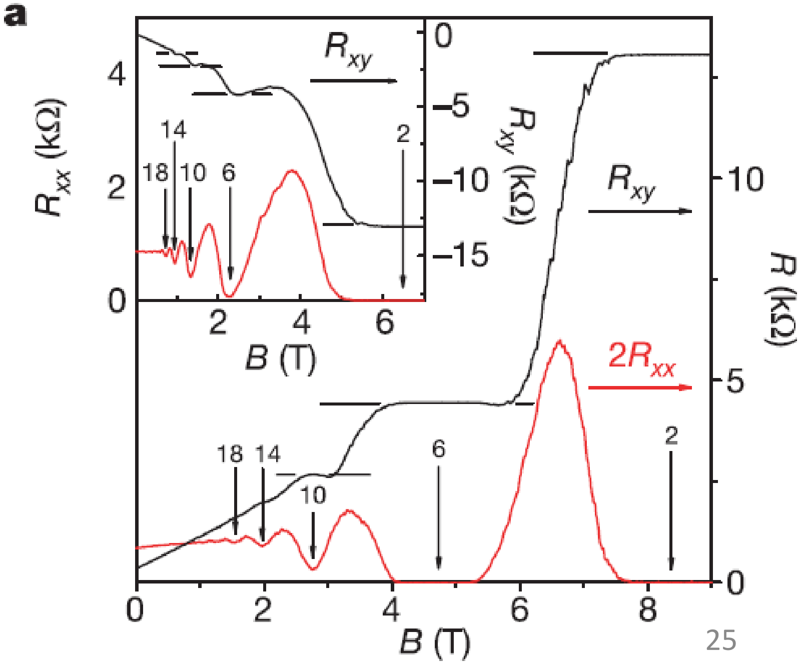
Vol 438|10 November 2005|doi:10.1038/nature04235 natu

LETTER

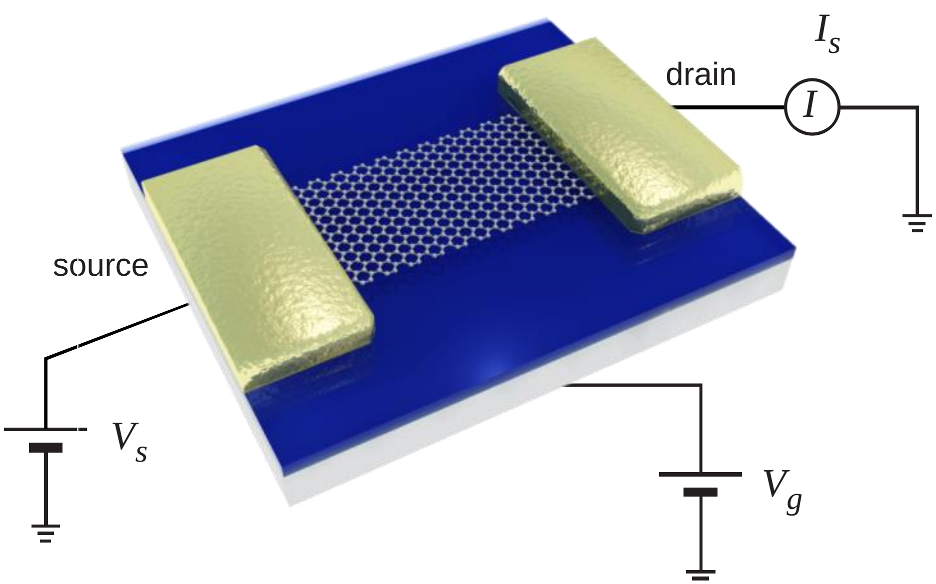
Experimental observation of the quantum Hall effe and Berry's phase in graphene

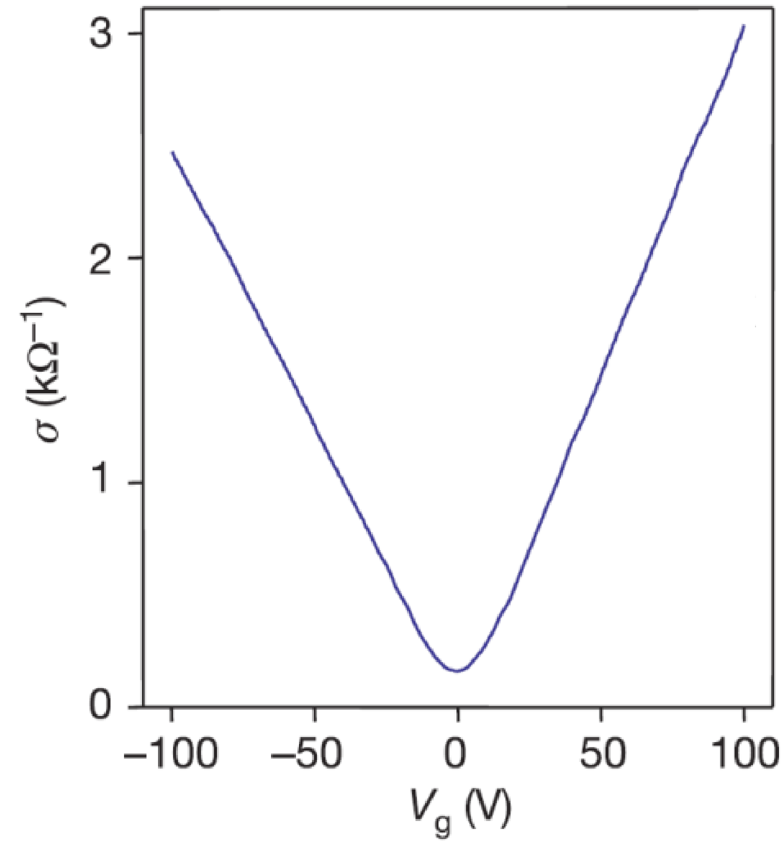
Yuanbo Zhang[1], Yan-Wen Tan[1], Horst L. Stormer[1,2] & Philip Kim[1]

a



Graphene FET Characteristics





Novoselov et al., Nature 438, 197 (2005)

Ambipolar behavior

Large current density – 10^8 A/cm^2

- Moser et al.; APL 91, 163513 (2007)

High mobility – 200 000 cm^2/Vs

- Bolotin et al.; Sol. St. Comm. 146, 351 (2008)

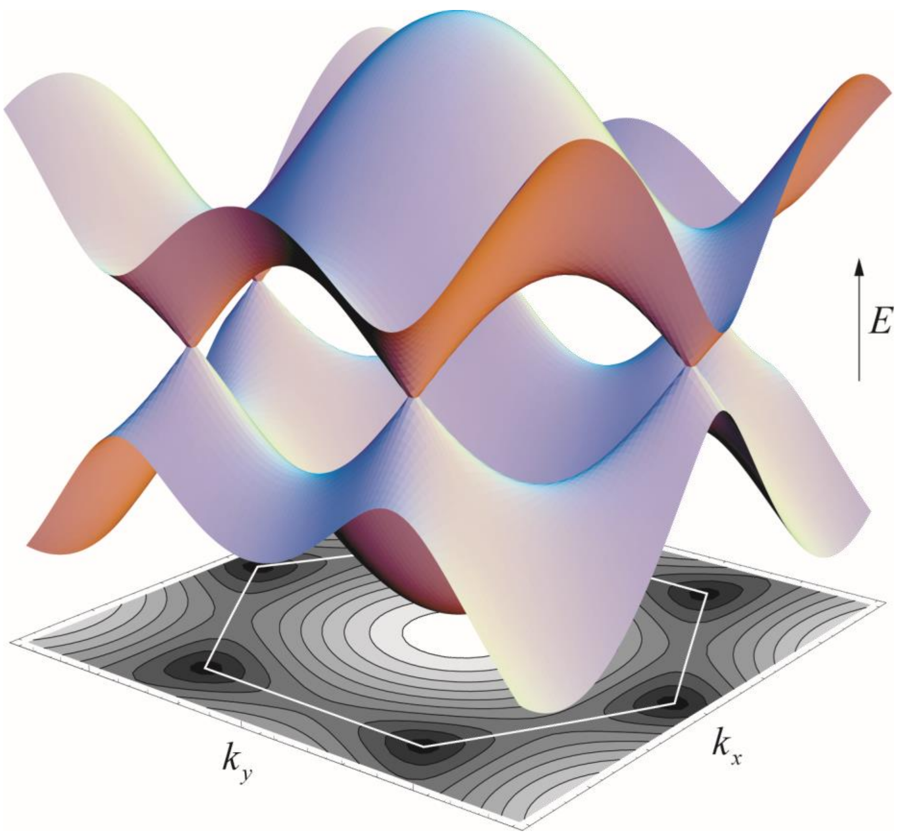
Suppression of noise in double layers

- Lin and Avouris; Nano Letters 8, 2119 (2008)

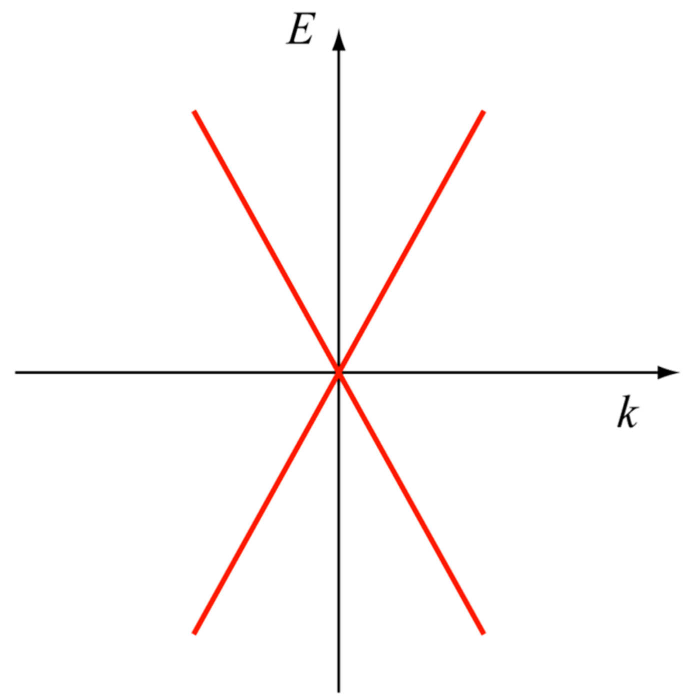
Graphene Band Structure

Dispersion relation:

$$E(k) = \pm t\left[1 + 4\cos\left(\frac{\sqrt{3}k_x a}{2}\right)\cos\left(\frac{k_y a}{2}\right) + 4\cos^2\left(\frac{k_y a}{2}\right)\right]^{1/2}$$



No band gap!

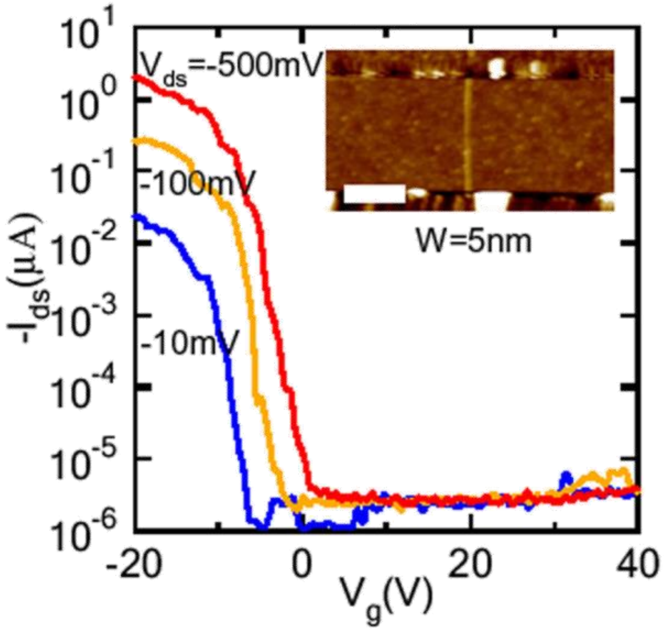


$$\cancel{E = \frac{\hbar^2 k^2}{2m}} \qquad E = \hbar k v_F, \quad v_F = c/300$$

Graphene Has No Band Gap

Possible solutions

Nanoribbons



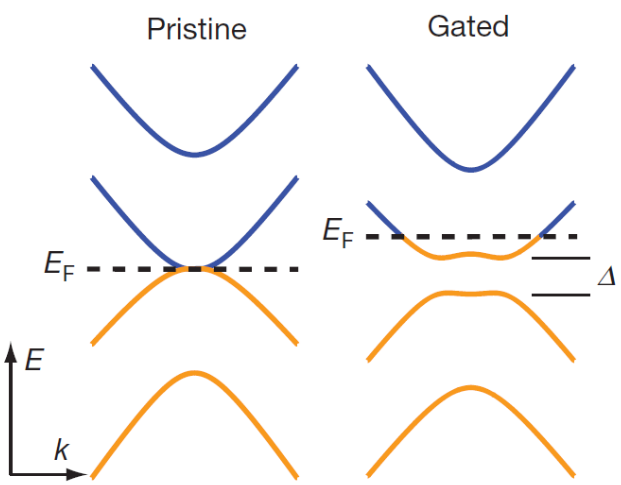
Hongjie Dai group: Science 319 1229 (2008)

Kim group: PRL 98, 206805 (2007)

Avouris group: Physica E 40, 228 (2007)

Max band gap: 400 meV for 5 nm

Bilayer Graphene



Zettl, Crommie, Wang: Nature 459, 820 (2009)

Avouris group: NanoLet 10, 715 (2010)

Max band gap: 250 meV for 120 V

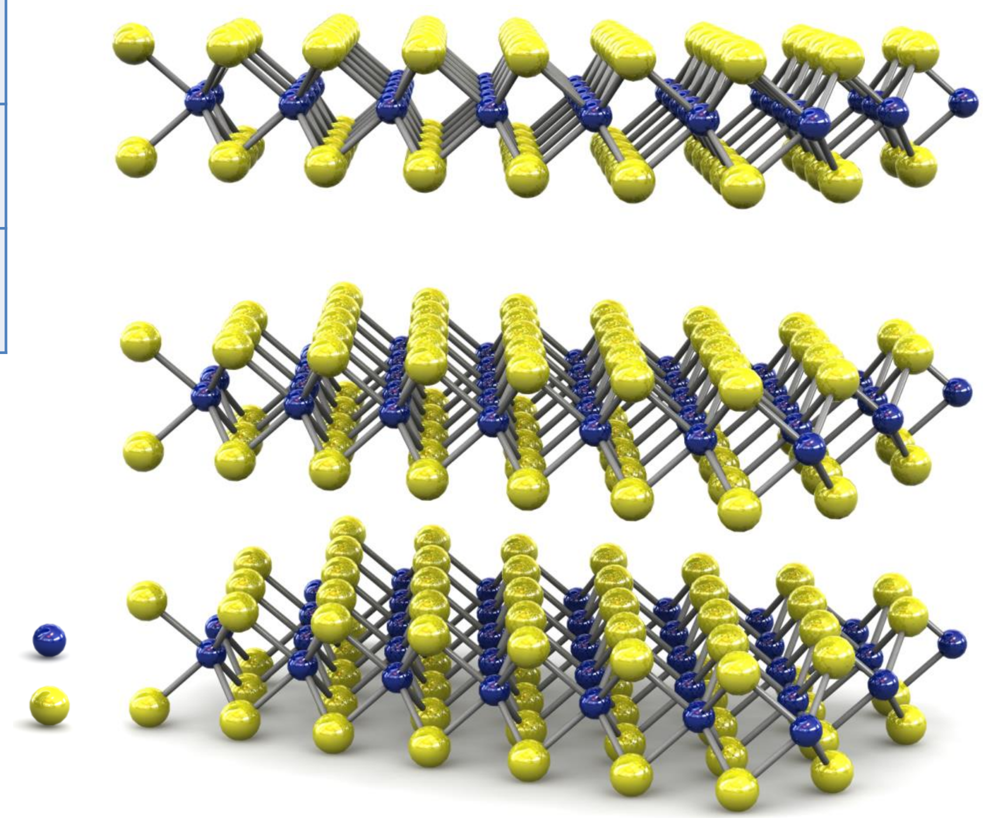
2D Transition Metal Dichalcogenides (TMDCs)

Common formula: MX_2

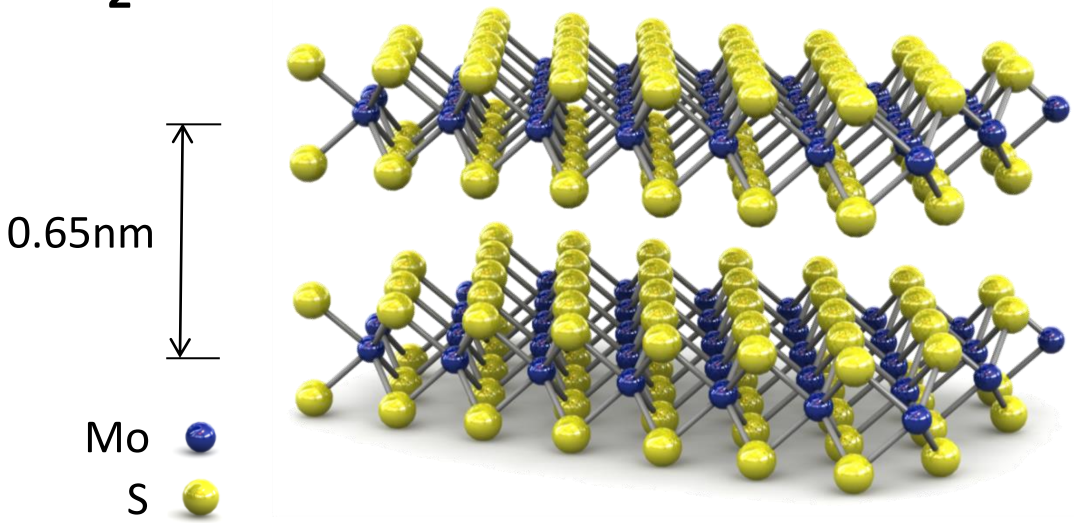
Electrical property	**Material**
semiconducting	MoS_2 $MoSe_2$ WS_2 WSe_2 $MoTe_2$ WTe_2
semimetallic	TiS_2 $TiSe_2$
metallic, CDW, superconducting	$NbSe_2$ NbS_2 $NbTe_2$ TaS_2 $TaSe_2$ $TaTe_2$

Metal M = Ta, Nb, Mo, W, Ti, Re

Chalcogenide X = S, Se, Te



MoS_2



MoS_2 crystal

Band gap: 1.2 eV (bulk); 1.8 eV direct (optical) gap (single layer)

Stability: > 1000 °C in inert atmosphere
no dangling bonds

Max J: 5×10^{7} A/cm^2 (copper: 10^5, graphene: 10^8)

Stiffness: 280 GPa (slightly higher than stainless steel)

Mech. failure: 6-11% strain (30x stronger than steel)

Kam et al., J. Phys. Chem. 86, 463 (1982)
Splendiani et al., Nano Let. 10, 1271 (2010)
Mak et al., PRL 105, 136805 (2010)
Bertolazzi et al., ACS Nano 5, 9703 (2011)
Lembke et al., ACS Nano 6, 10070 (2012)

Review papers:
Wang et al., Nature Nanotech. (2012)
Allain…Kis; Nature Mater. (2015)


SONAX
Das Original
MoS2Oil
Rostlöser
Schmiermittel
Reiniger
Korrosionsschutz
Kontaktspray
Kriechöl
Kunststoffverträglich
Verharzt nicht
Silikonfrei

Physical properties of layer structures: optical properties and photoconductivity of thin crystals of molybdenum disulphide

By R. F. Frindt and A. D. Yoffe
Physics and Chemistry of Solids, Cavendish Laboratory, University of Cambridge

(*Communicated by F. P. Bowden, F.R.S.—Received* 16 *August* 1962—*Revised* 23 *November* 1962)

[Plates 1 and 2]

Very thin crystals of molybdenum disulphide, less than 100 Å thick, have been prepared by cleavage. The optical absorption spectra in the thickness range several micrometres to less than 100 Å are similar. Absorption coefficients have been measured to values close to 10^6 cm^{-1}. The absorption bands observed with thin crystals are associated with bulk rather than surface properties.

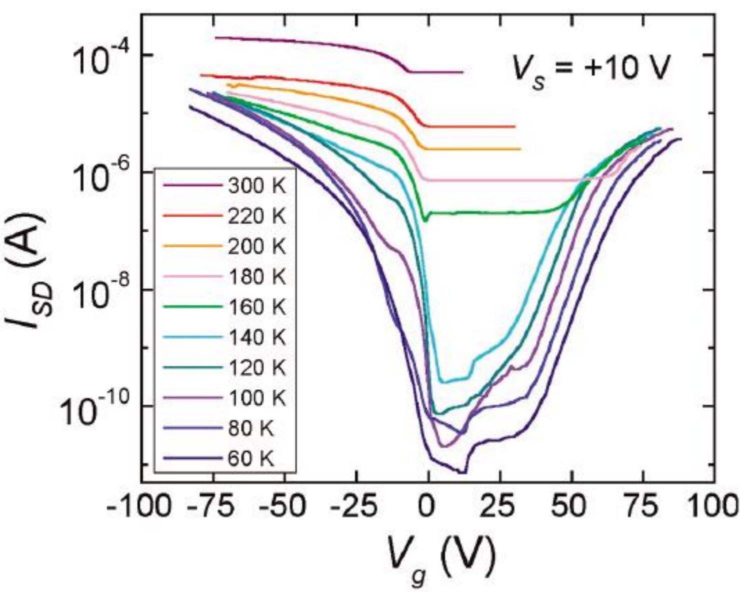
Frindt and Yoffe, Proc. Roy. Soc. A (1963)

SINGLE-LAYER MoS_2

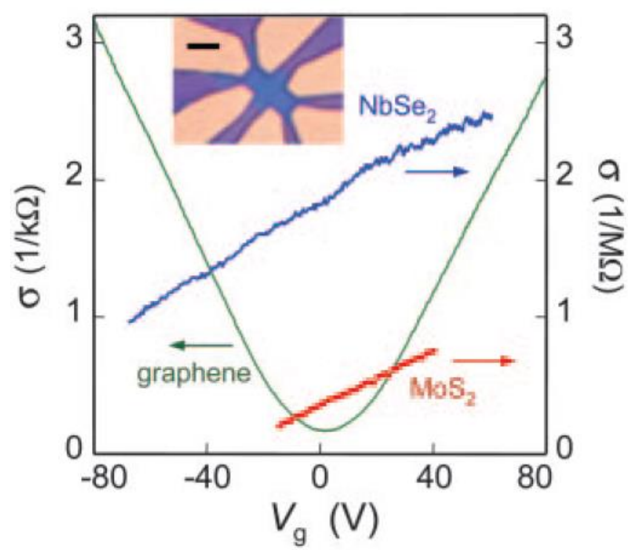
Per Joensen, R.F. Frindt, and S. Roy Morrison
Energy Research Institute
Department of Physics
Simon Fraser University
Burnaby, B.C., Canada V5A 1S6

(Received January 27, 1986; Communicated by A. Wold)

Joensen et al., Mat. Res. Bull. 21, 457 (1986)



Podzorov et al. APL (2004)



Novoselov et al., PNAS (2005)

Prevailing Opinion at the Time

Perspectives on the 2010 Nobel Prize in Physics for Graphene

Mildred S. Dresselhaus* and Paulo T. Araujo

ACS Nano 4, 6297 (2010)

In 2005, Novoselov and Geim performed comparative studies in other atomically layered 2D systems like boron nitride (BN), MoS_2, $NbSe_2$, and $Bi_2Sr_2CaCu_2O_x$.[31] All of the materials were exfoliated in the same way as had been done for graphene and were shown to be morphologically stable, although with electrical and mechanical properties much inferior to those of 2D graphene. Later, the production of monolayer graphene suspended over microfabricated trenches exhibited striking stability and opened a new channel for technological devices.[32,33]

Was the Mobility Really Supposed to Be low?

PHYSICAL REVIEW VOLUME 163, NUMBER 3 15 NOVEMBER 1967

Mobility of Charge Carriers in Semiconducting Layer Structures

R. Fivaz* and E. Mooser
Cyanamid European Research Institute, Cologny, Geneva, Switzerland

(Received 26 May 1967)

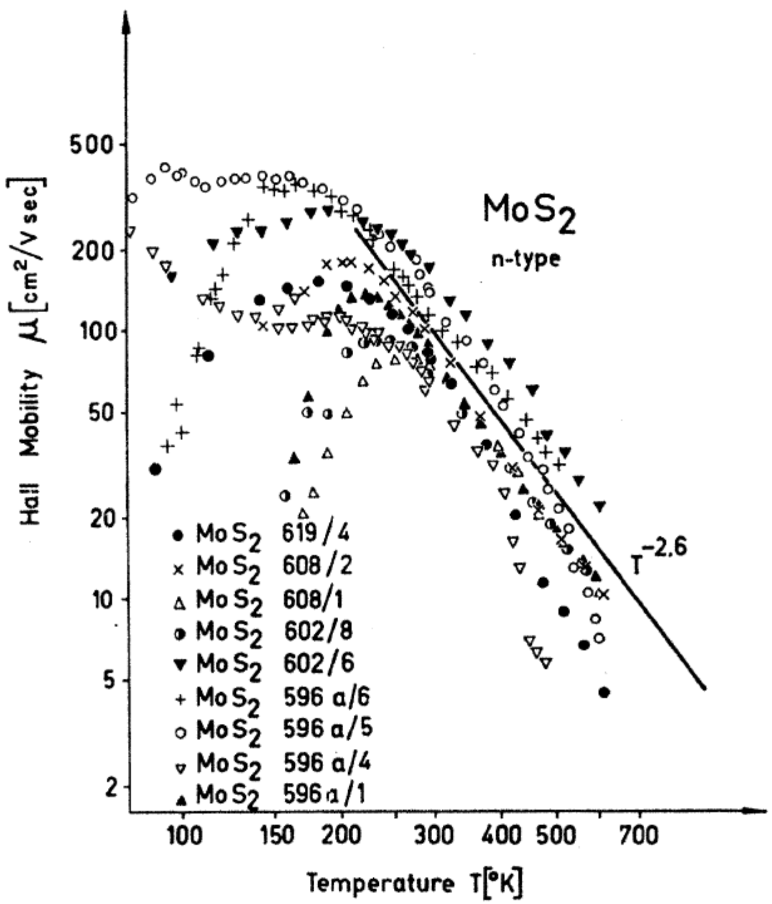
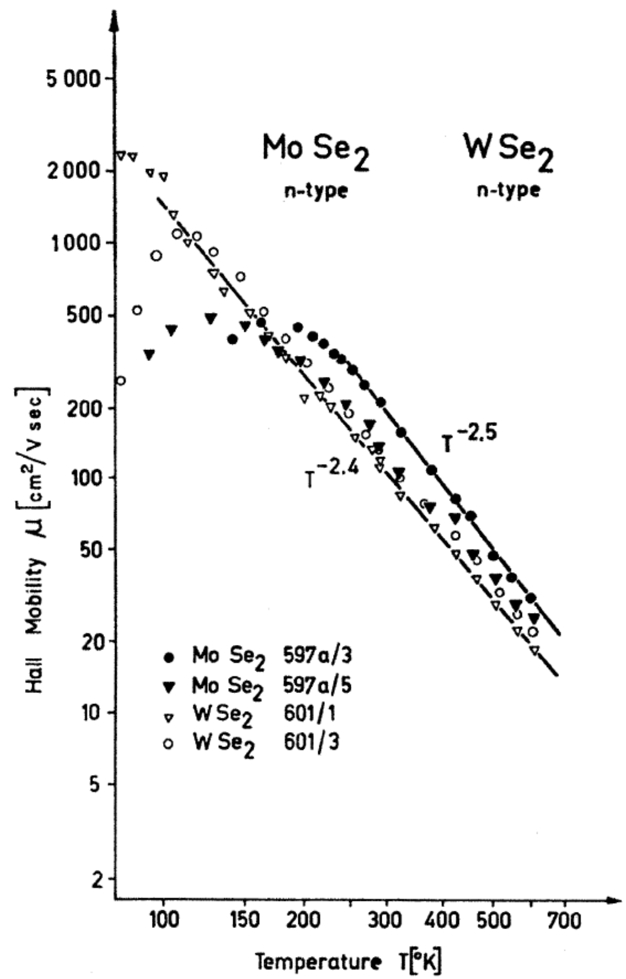
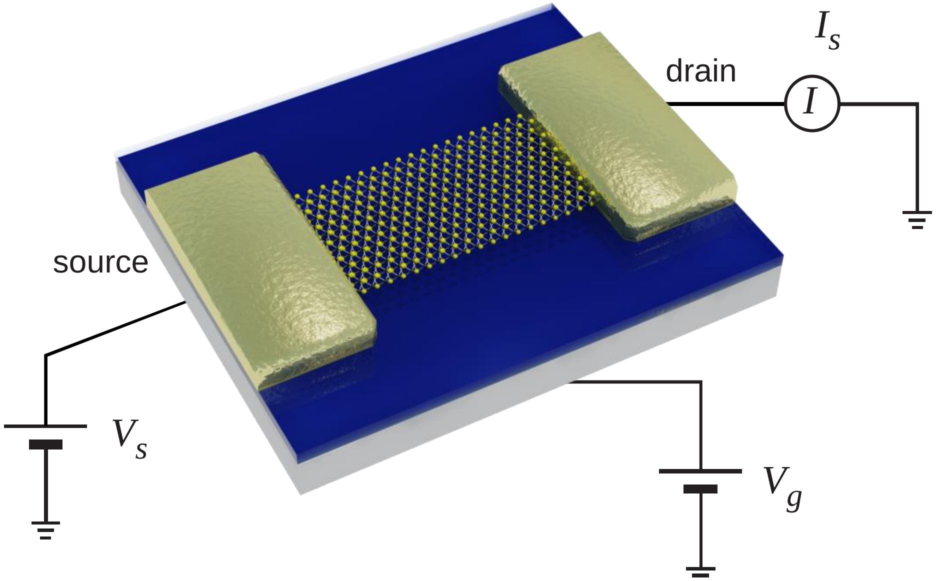
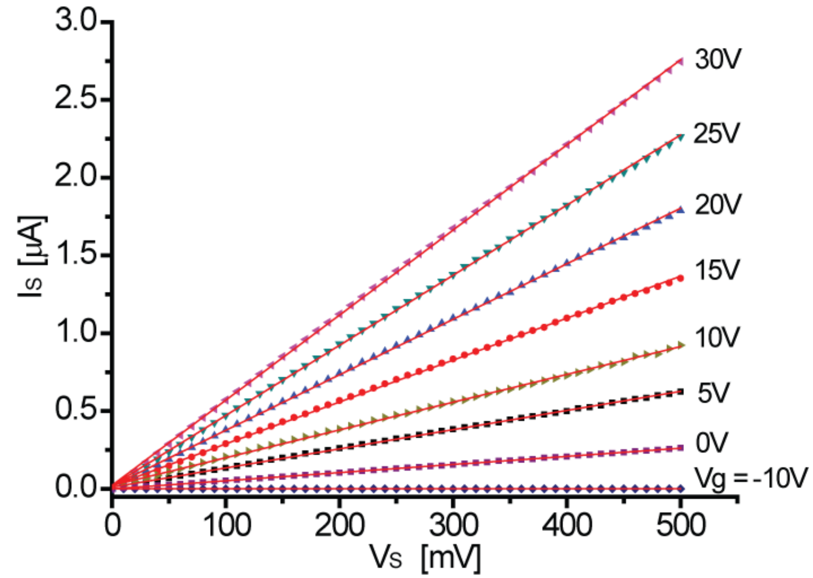


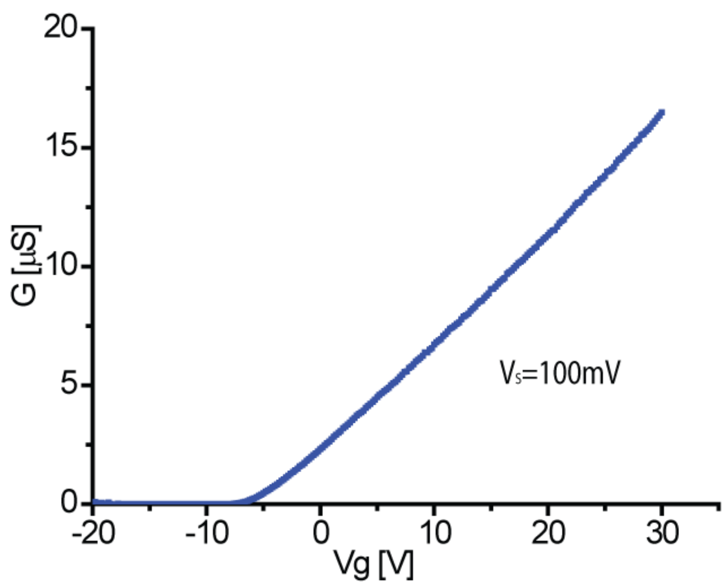
FIG. 7. Mobility of the electrons in MoS_2.

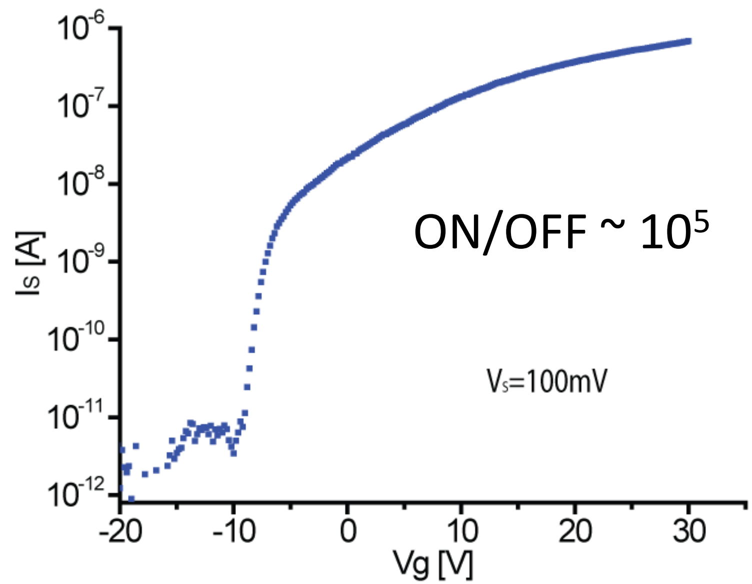


Our First MoS_2 Transistor (5 layers, 2009)

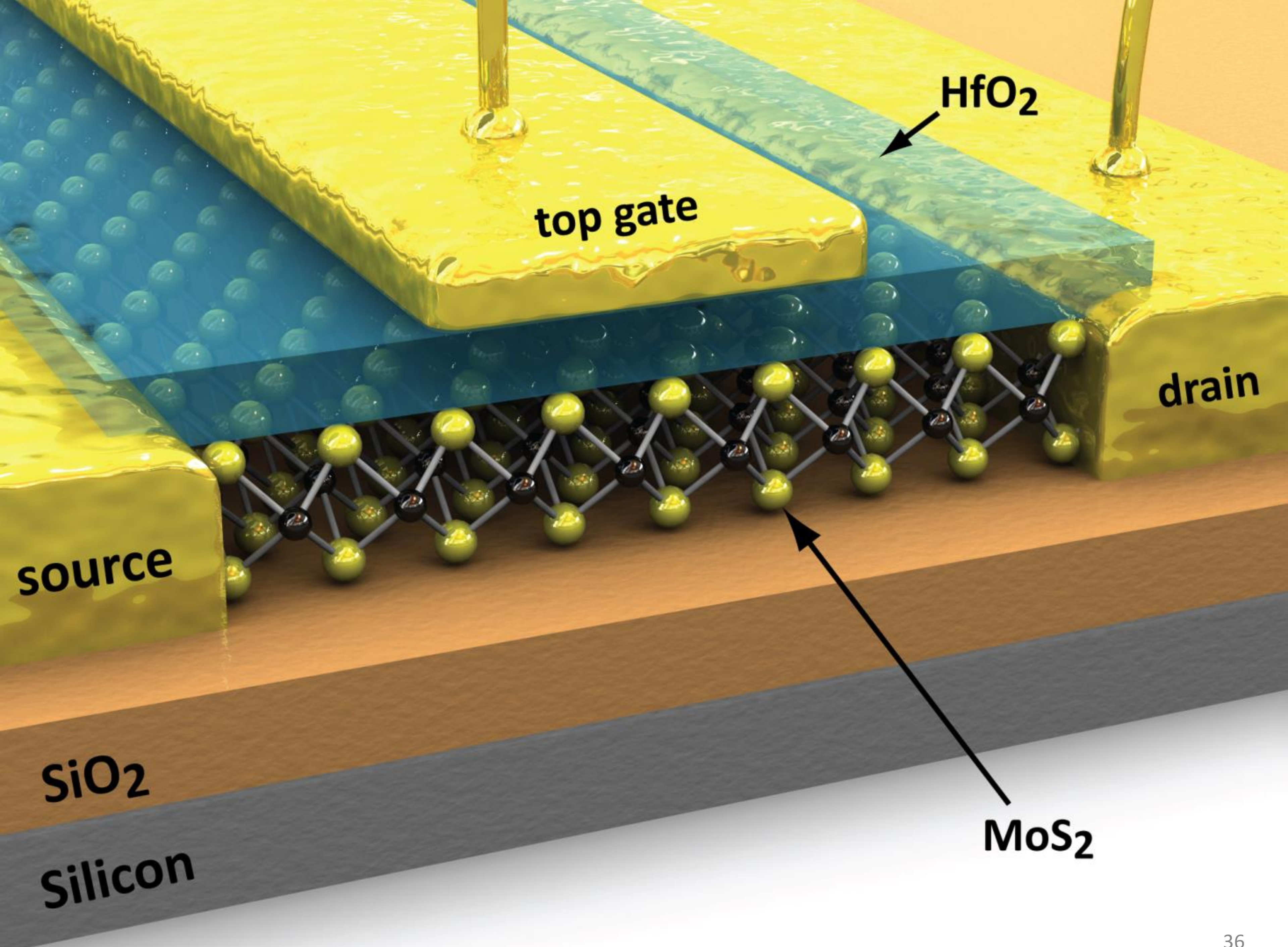




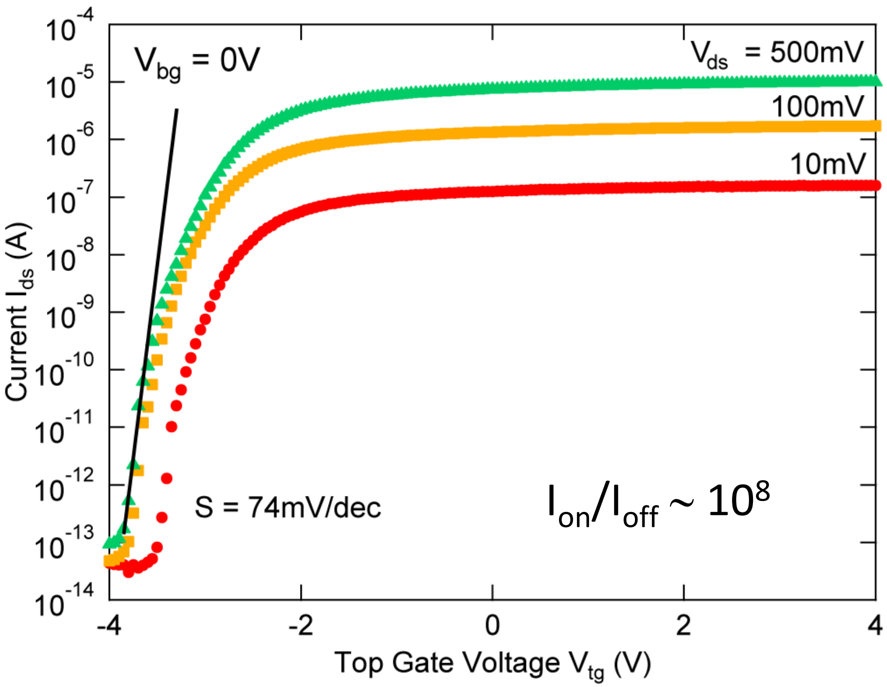


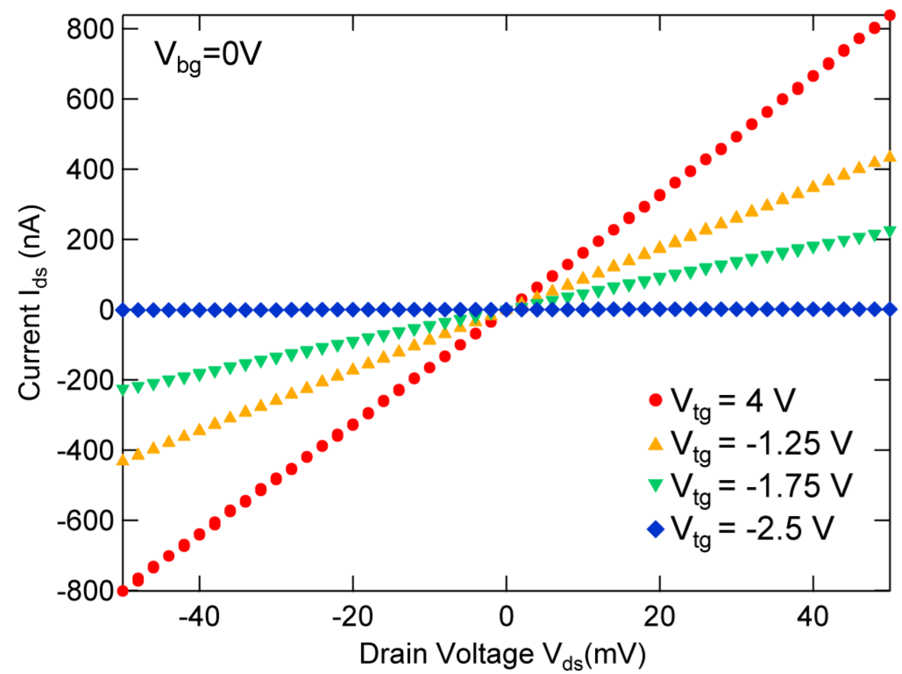


TMCN 2010, Rehovot, Israel


HfO$_2$
top gate
drain
source
SiO$_2$
MoS$_2$
Silicon

Monolayer MoS_2 Transistor





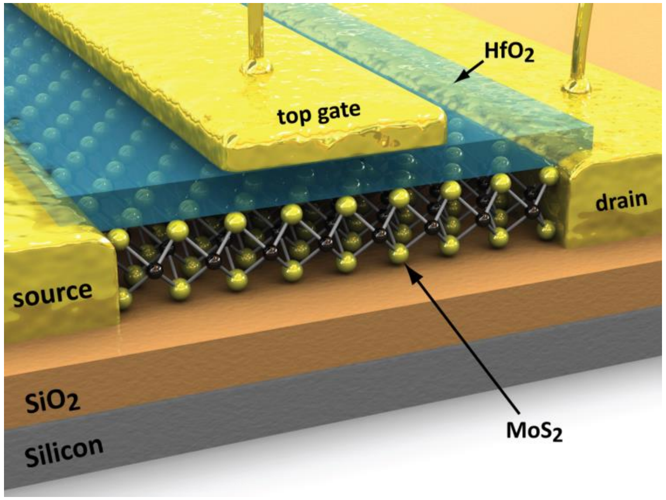
Radisavljevic…Kis,

Nature Nanotechnology (2011)

Gate length:	500 nm
Channel width:	4 µm
On/Off:	10^8
ON current:	2.5 µA/µm
OFF current:	25 fA/µm
Transconductance:	1 µS/µm

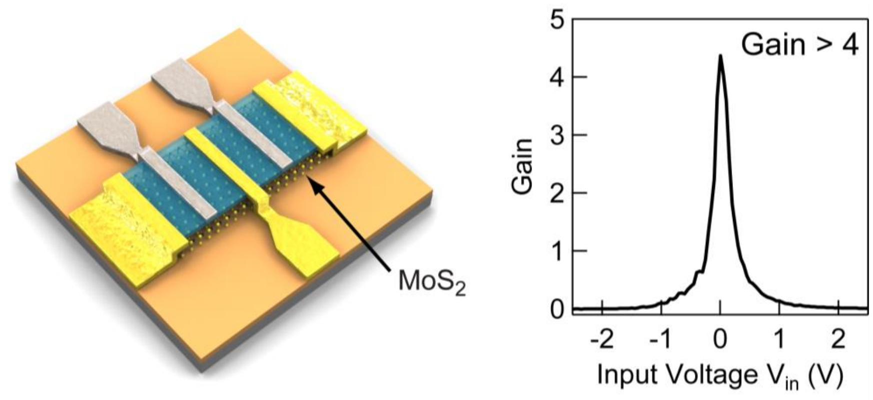
Devices Based on Monolayer MoS_2

MoS_2 Transistor



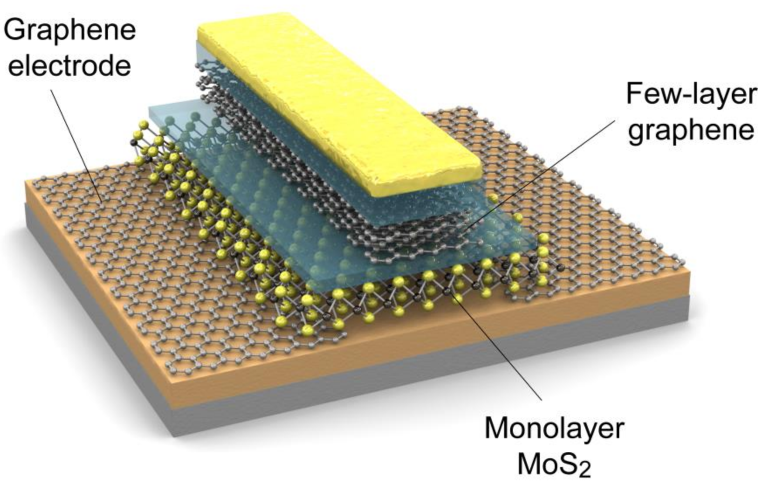
Radisavljevic…Kis; Nature Nanotech. (2011)

MoS_2 Inverter



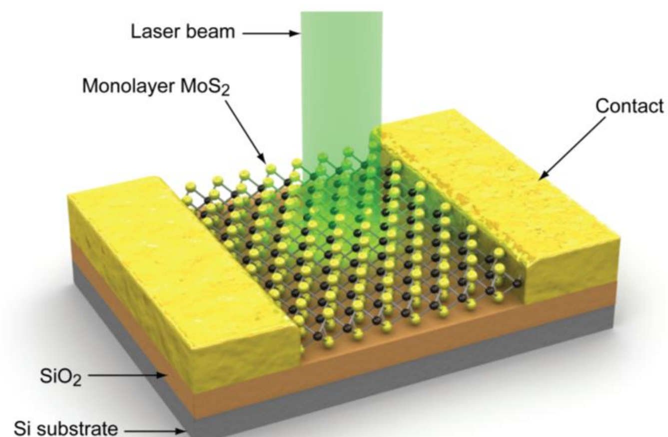
Radisavljevic…Kis; ACS Nano (2011)

MoS_2/graphene Memory Cell



Bertolazzi…Kis; ACS Nano (2013)

Ultrasensitive Photodetector



Lopez-Sanchez…Kis; Nature Nanotech. (2013)

IRDS - International Roadmap for Devices and Systems

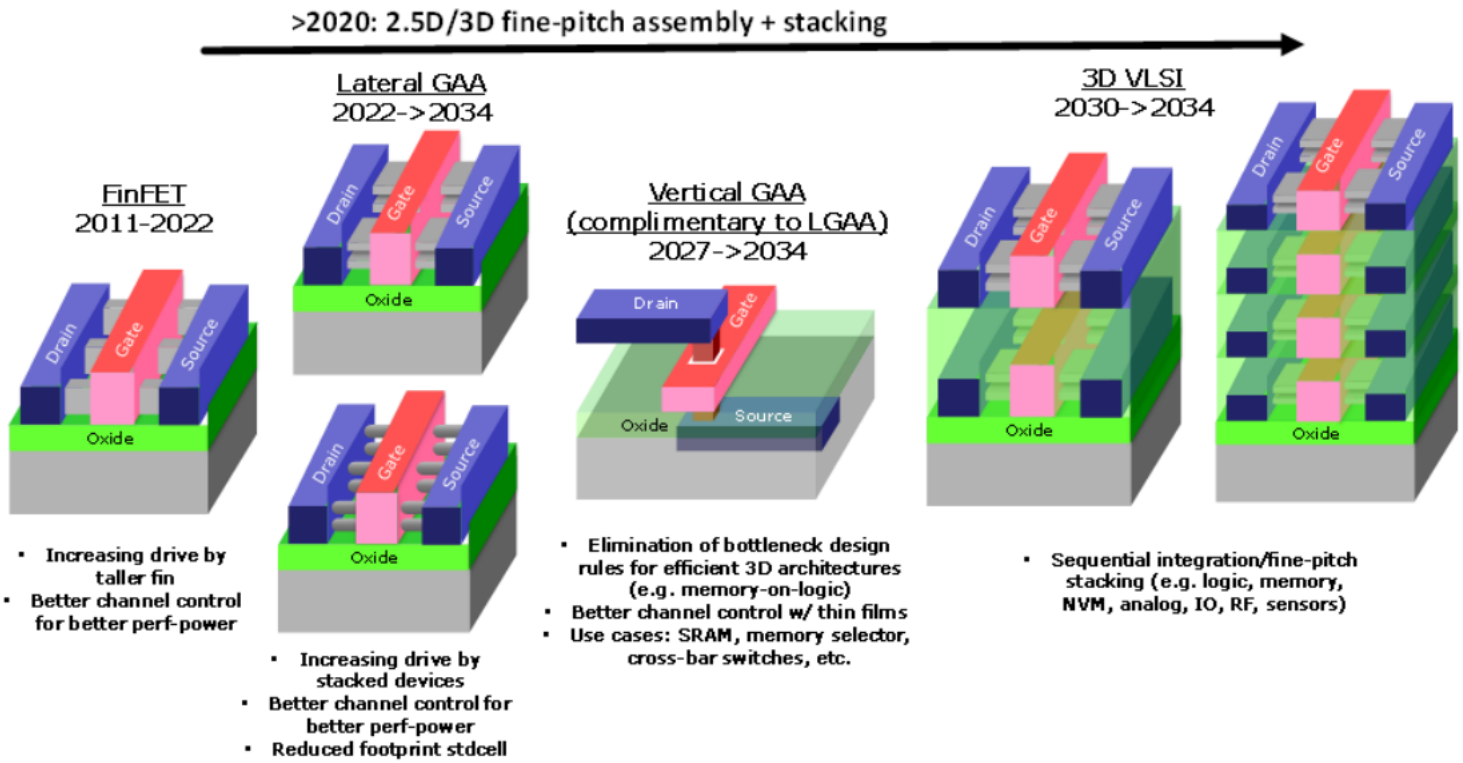


Figure ES48 Change in the MOSFET device architecture from the 2D planar through 2.5D FinFets to 3D monolithic VLSI with GAA

https://irds.ieee.org/editions/2021/executive-summary

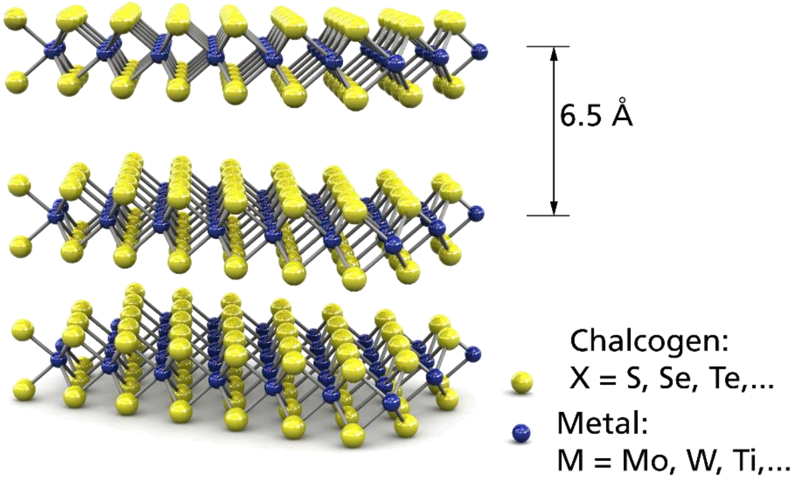
IRDS - International Roadmap for Devices and Systems

YEAR OF PRODUCTION	2021	2022	2025	2028	2031	2034
	G51M30	G48M24	G45M20	G42M16	G40M16/T2	G38M16/T4
Logic industry "Node Range" Labeling (nm)	"5"	"3"	"2.1"	"1.5"	"1.0 eq"	"0.7 eq"
IDM-Foundry node labeling	i7-f5	i5-f3	i3-f2.1	i2.1-f1.5	i1.5e-f1.0e	i1.0e-f0.7e
Logic device structure options	FinFET	finFET LGAA	LGAA	LGAA	LGAA-3D	LGAA-3D
Platform device for logic	finFET	finFET	LGAA	LGAA	LGAA-3D	LGAA-3D
Frequency scaling - node-to-node	-	0.02	0.16	0.09	-0.08	-0.01
CPU frequency at constant power density (GHz)	3.13	2.83	3.53	2.50	1.48	0.86
Power at iso frequency - node-to-node	-	-0.16	-0.27	-0.05	-0.06	-0.08
Power density - relative	1.00	1.12	1.04	1.59	2.51	4.27
LOGIC TECHNOLOGY ANCHORS						
Patterning technology inflection for Mx interconnect	193i, EUV DP	193i, EUV DP	193i, EUV DP	193i, High-NA EUV	193i, High-NA EUV	193i, High-NA EUV
Beyond-CMOS as complimentary to platform CMOS	-	-	-	2D Device, FeFET	2D Device, FeFET	2D Device, FeFET
Channel material technology inflection	SiGe25%	SiGe50%	SiGe50%	Ge, 2D Mat	Ge, 2D Mat	Ge, 2D Mat
Process technology inflection	Conformal Doping, Contact	Channel, RMG	Lateral/AtomicEtch	Non-Cu Mx	3DVLSI	3DVLSI
Stacking generation inflection	2D	3D-stacking: W2W, D2W Mem-on-Logic	3D-stacking: W2W, D2W Mem-on-Logic	3D-stacking, Fine-pitch stacking, P-over-N, Mem-on-Logic	3D-stacking, 3DVLSI: Mem-on-Logic with Interconnect	3D-stacking, 3DVLSI: Logic-on-Logic

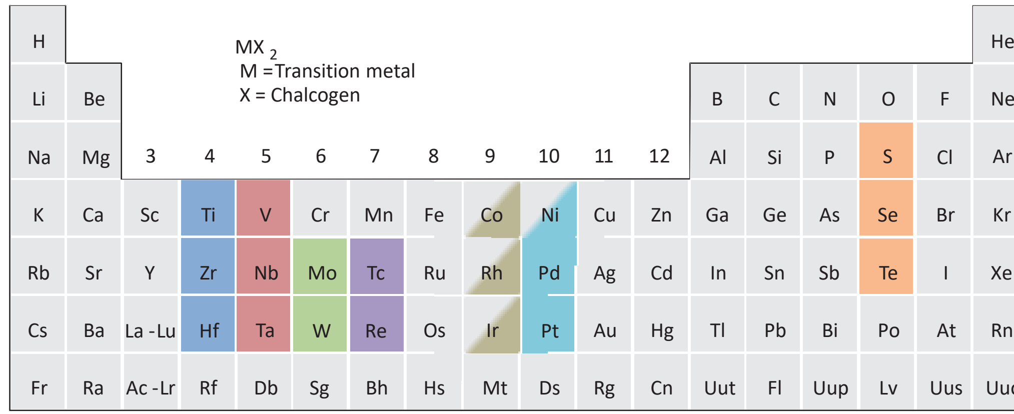
Figure ES9 Devices will continue to aggressively scale in the next 5 years

https://irds.ieee.org/editions/2021/executive-summary

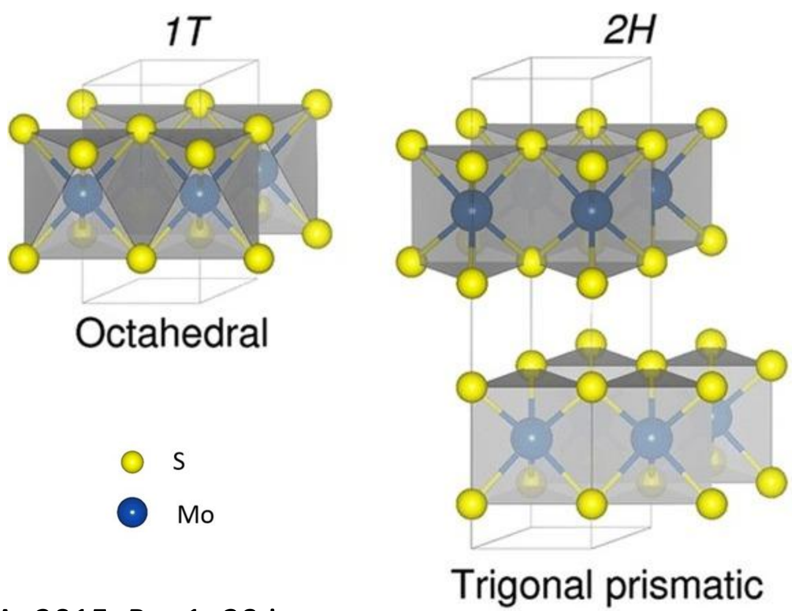
Structure

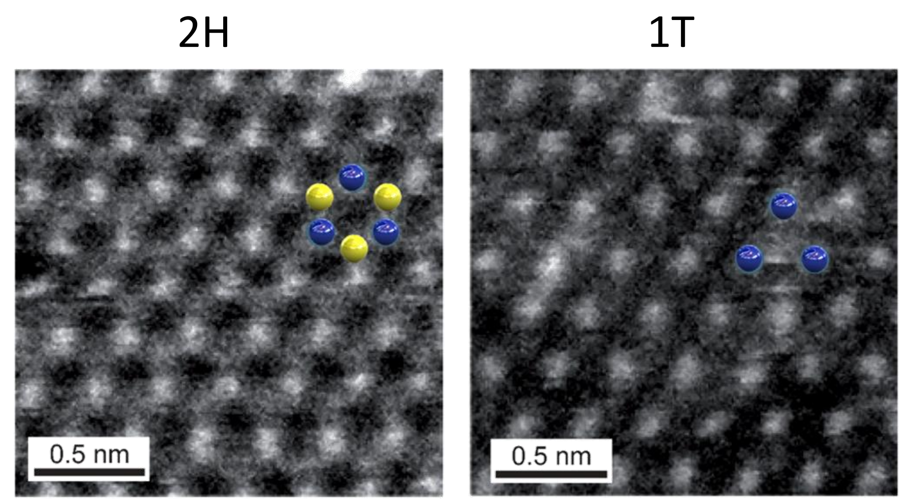


Radisavljevic…Kis; Nature Nanotech. (2011)



Chhowalla…Zhang; Nature Chemistry (2013)





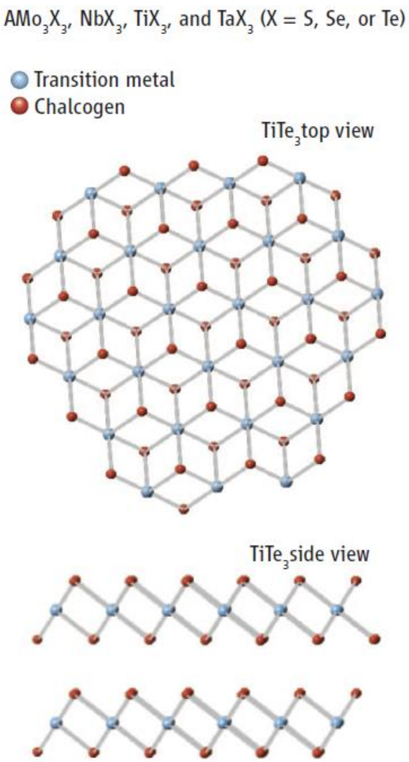
Kuc, A. 2015. Pp. 1–29 in
M. Springborg, and J. Joswig, ed. Chemical modelling: volume 11

Eda…Chhowalla; ACS Nano (2012)

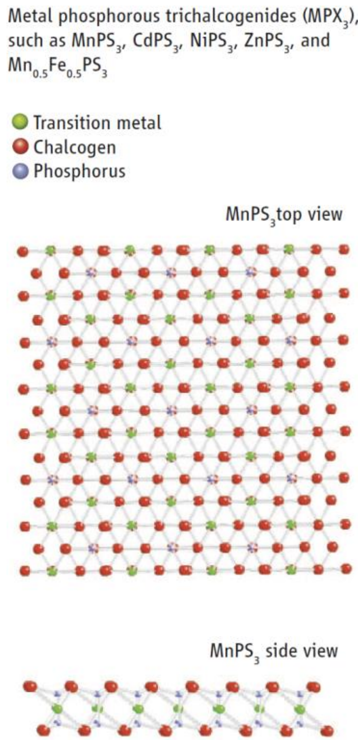
Tip of the Iceberg

>500 potentially interesting 2D materials

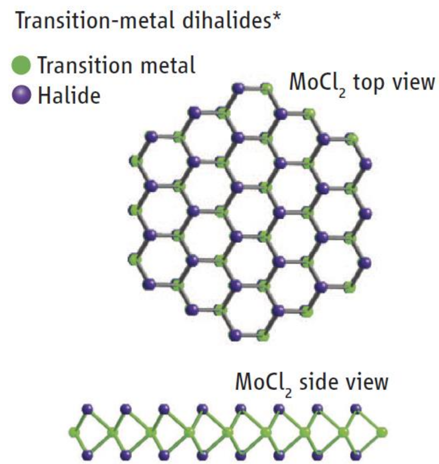
Transition metal trichalcogenides



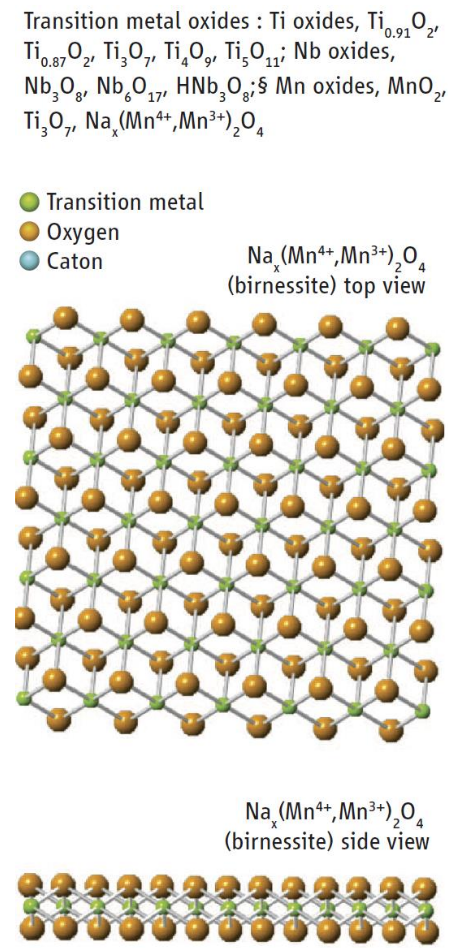
Metal phosphorous trichalcogenides (MPX_3)



Transition metal dihalides

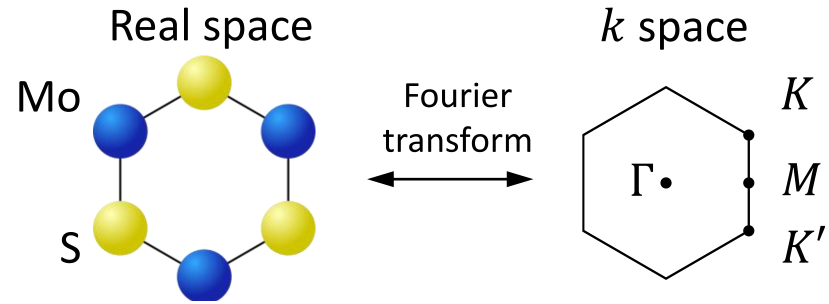


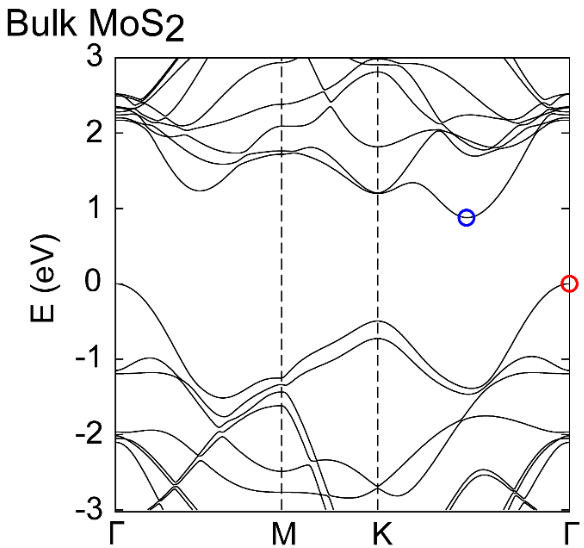
Transition metal oxides

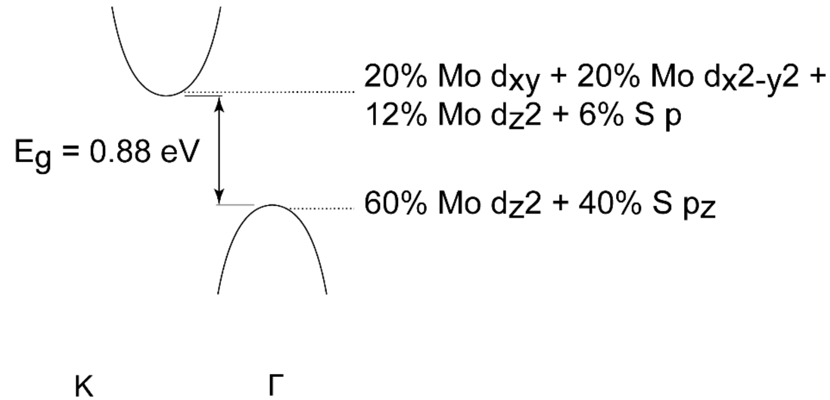


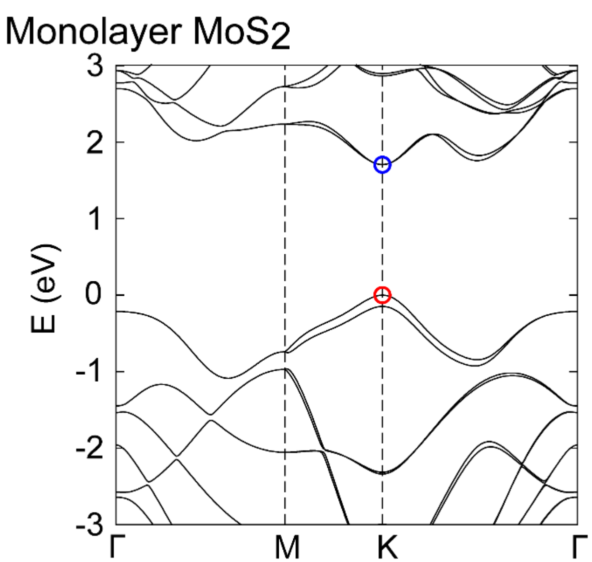
Nicolosi…Coleman; Science (2013)

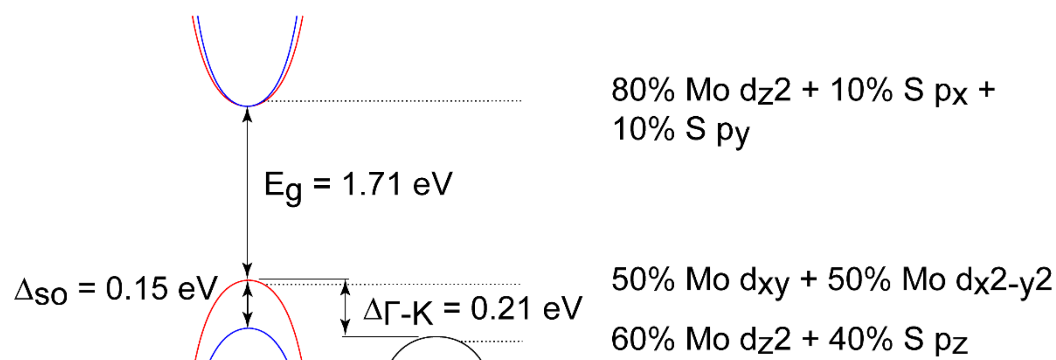
Band Structure of 2H MoS_2







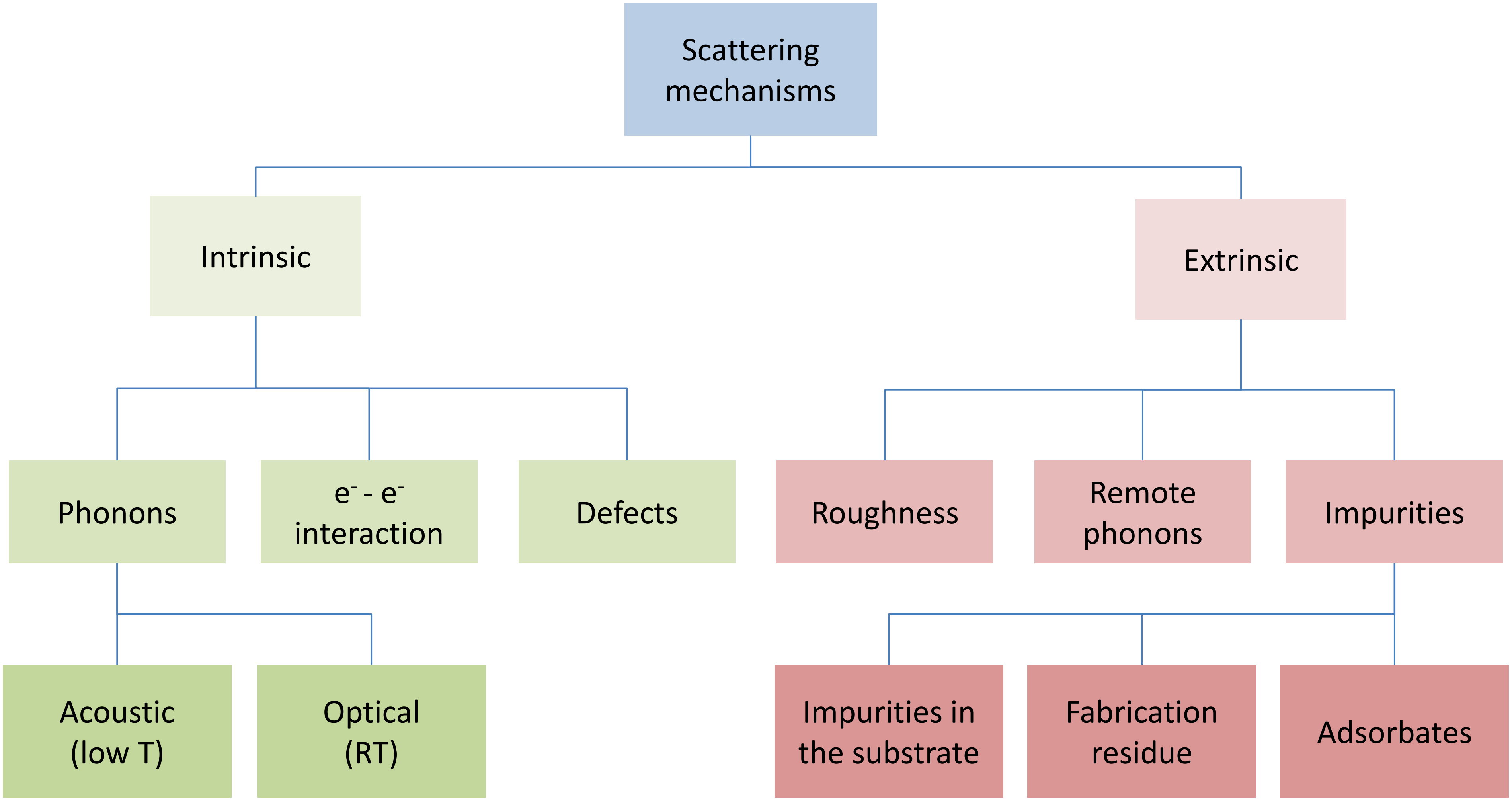




Kuc…Heine; Physical Review B (2011)

Yazyev and Kis; Materials Today (2014)

Charge Scattering Mechanisms



Mobility follows Mathiessen's rule: $$\frac{1}{\mu} = \frac{1}{\mu_{defects}} + \frac{1}{\mu_{phonons}} + \frac{1}{\mu_{remote\ phonons}} + \cdots$$

Material Preparation


Quartz (SiO_2)
MoS_2

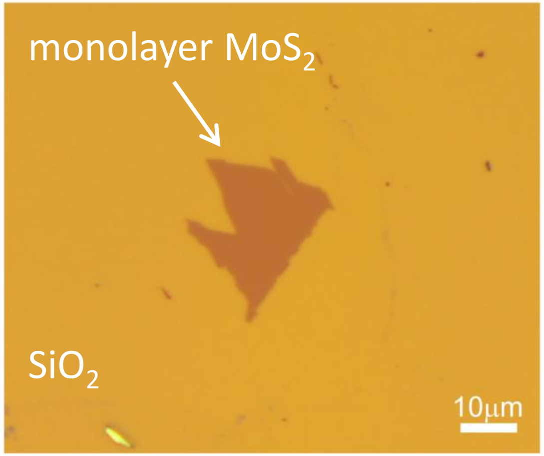
Molybdenite Mining

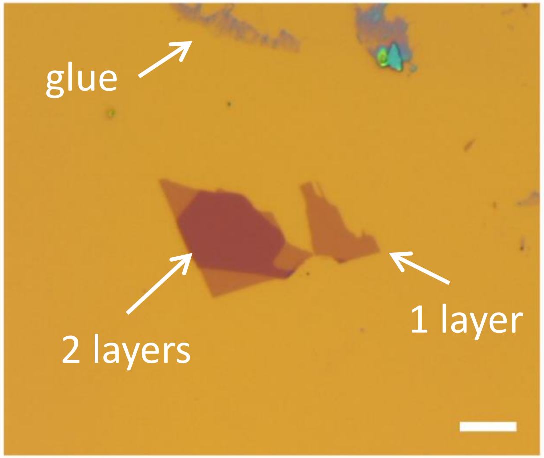
Los Bronces, Chile

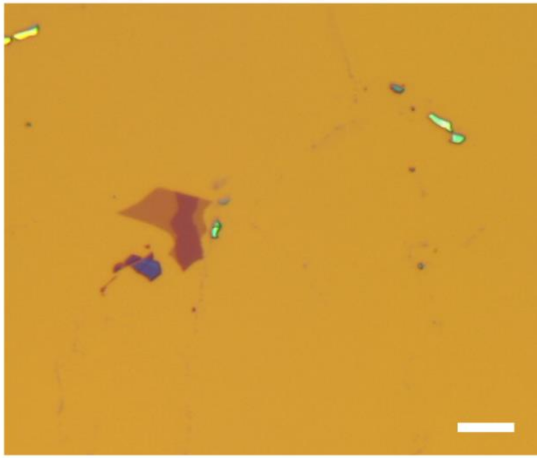
Pinto Valley, Arizona, USA

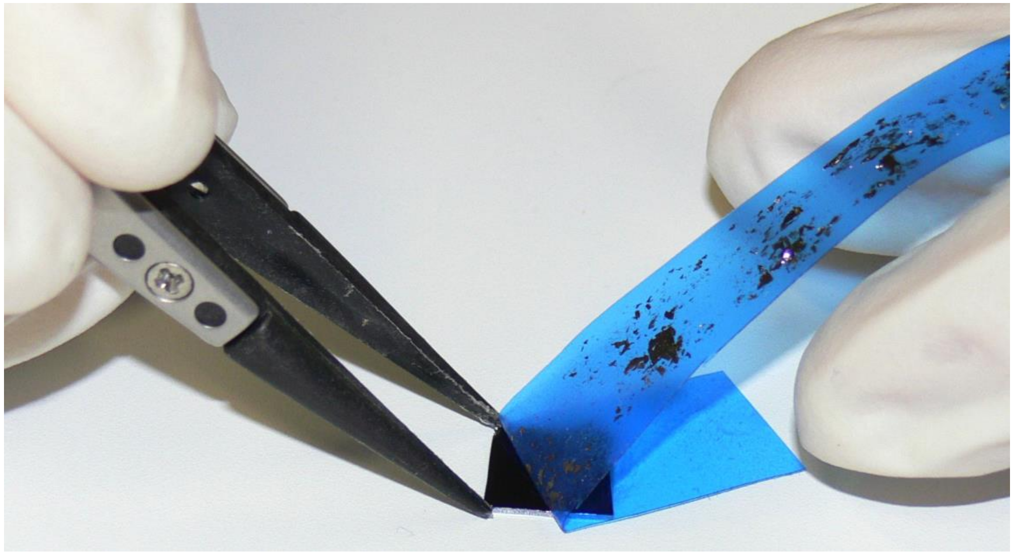
Climax mine, Colorado, USA

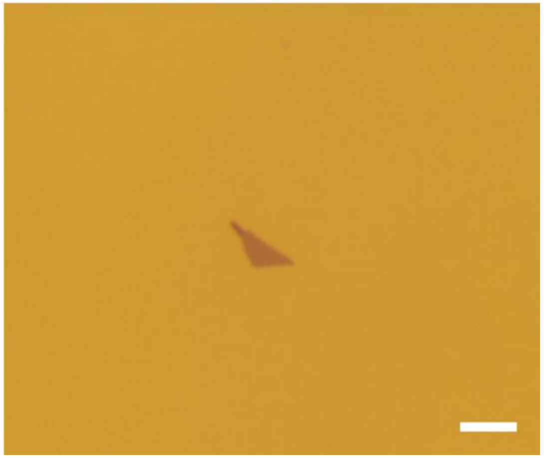
Scotch Tape Exfoliation





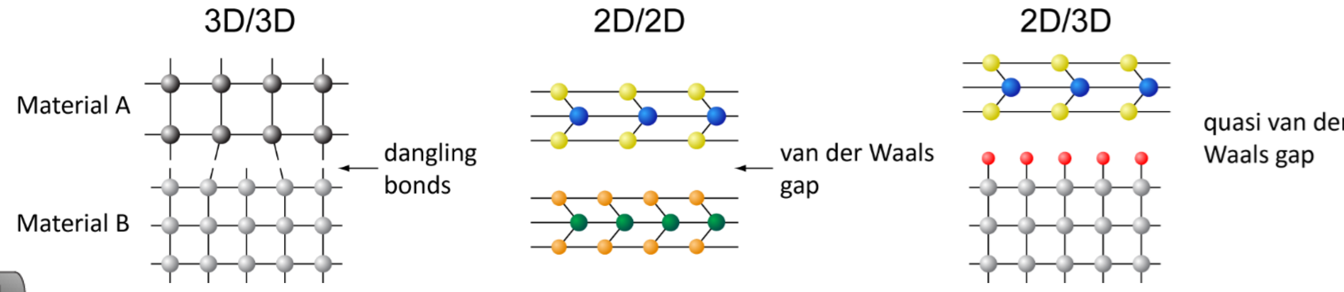






Benameur et al., Nanotechnology (2011)

Van der Waals Epitaxy Using an MBE



Ohuchi…Koma; J. Crystal Growth (1991)

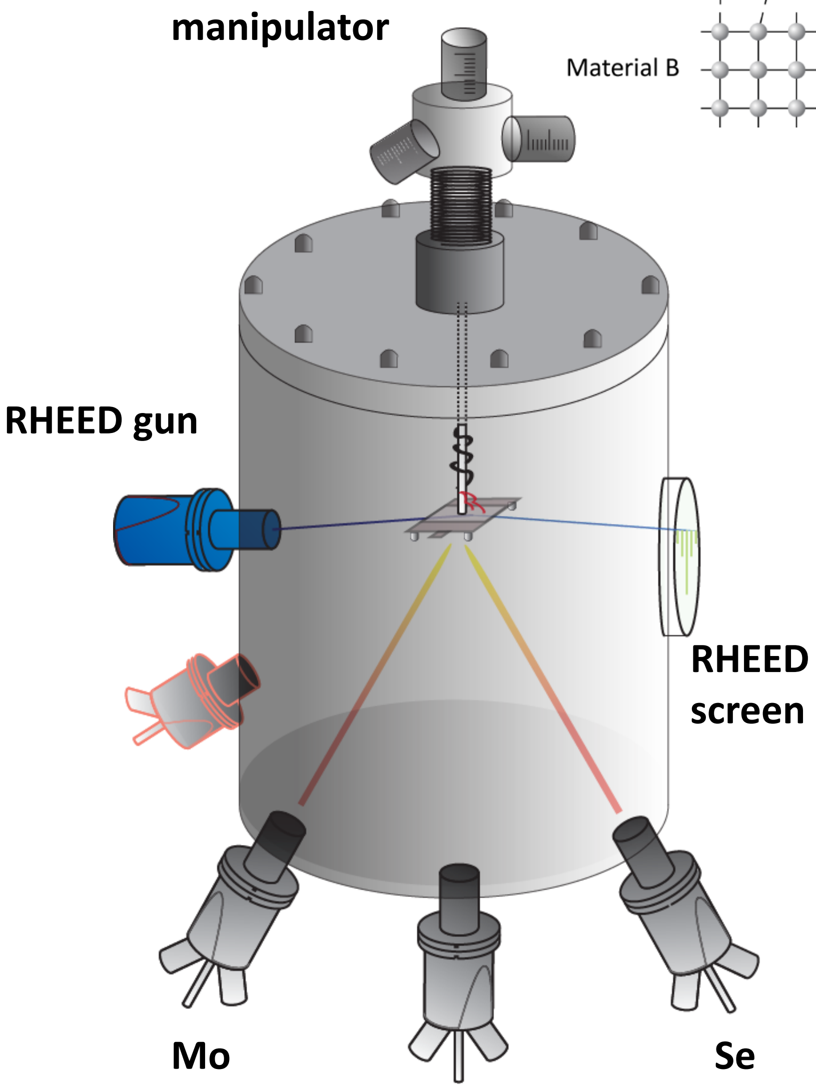


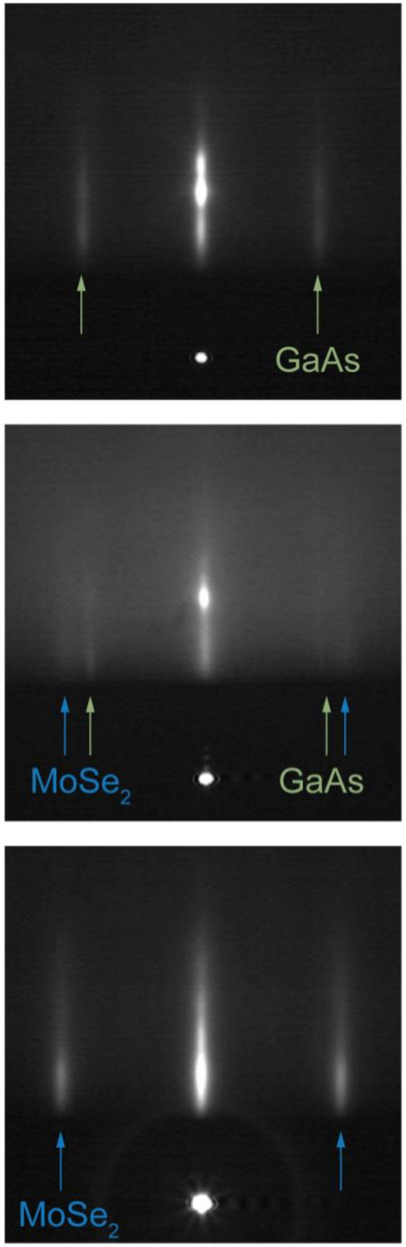
TABLE 1. Materials grown with van der Waals epitaxy (here TX_2 denotes transition metal dichalcogenide)

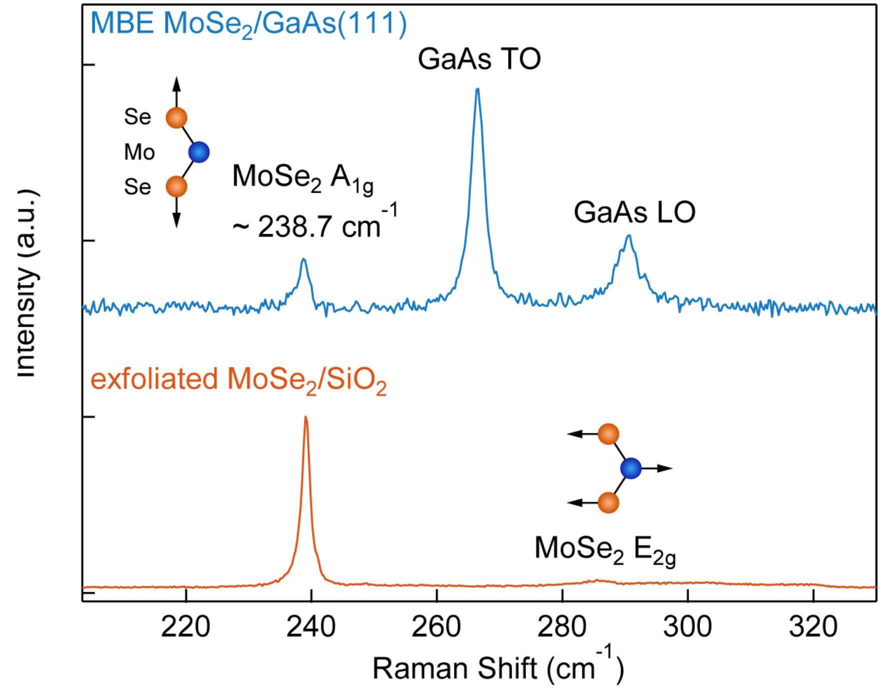
Material group	Materials grown with van der Waals epitaxy	References
Quasi-one dimensional	Se/Te	8
	Te/Se/Te	
Quasi-two dimensional	TX'_2/TX_2	3–5
	TX_2/SnS_2	10
	TX_2/mica	12, 13
Quasi-two dimensional on three-dimensional	TX_2/S–GaAs(111)	15
	$TX_2/CaF_2(111)$	20
	GaSe/Se–GaAs(111)	16, 17
	GaSe/H–Si(111)	
Organic	Phthalocyanines/TX_2	
	Coronene/TX_2	
	C_{60}/MoS_2	21

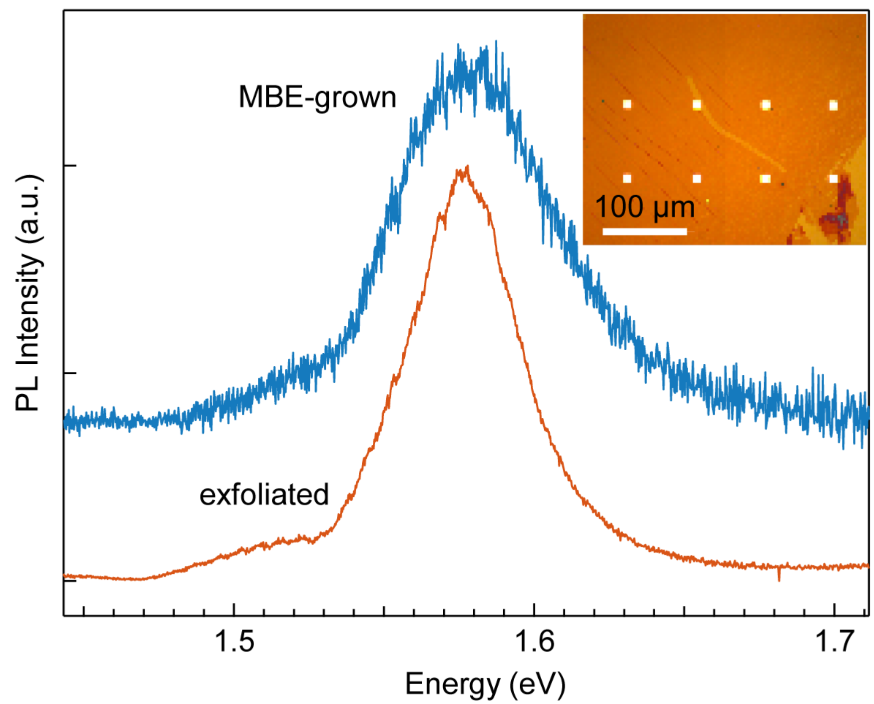
Koma; Thin Solid Films (1992)

MBE $MoSe_2$ on GaAs(111)B

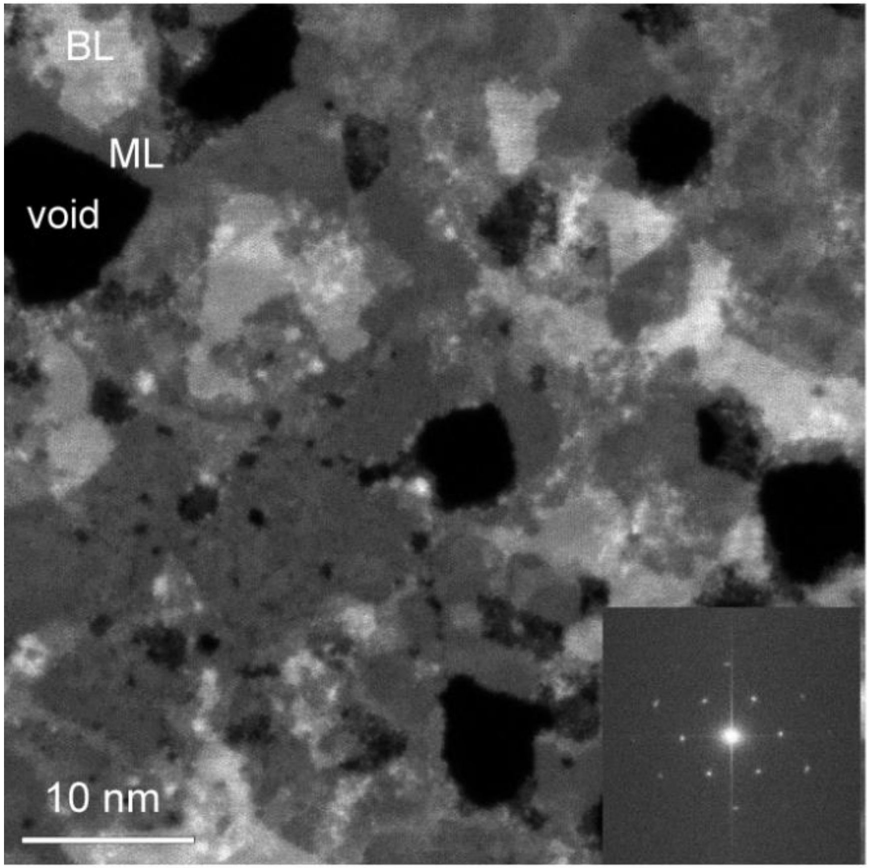
time

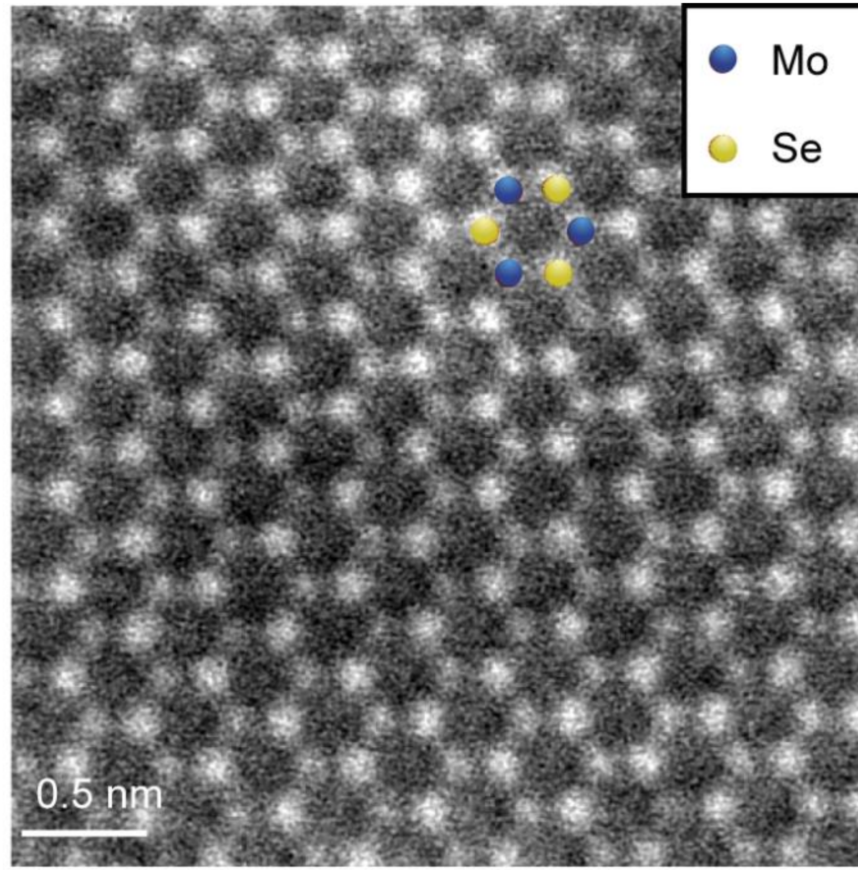






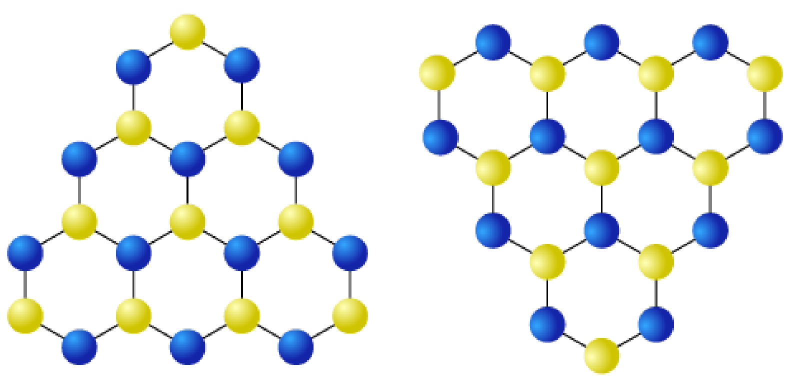
Highly Aligned $MoSe_2$ on GaAs by MBE



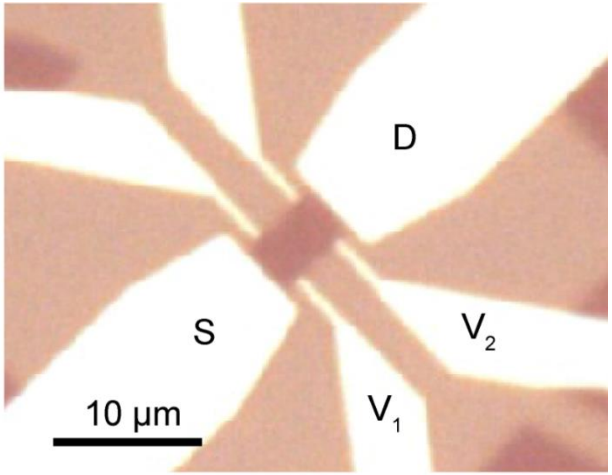


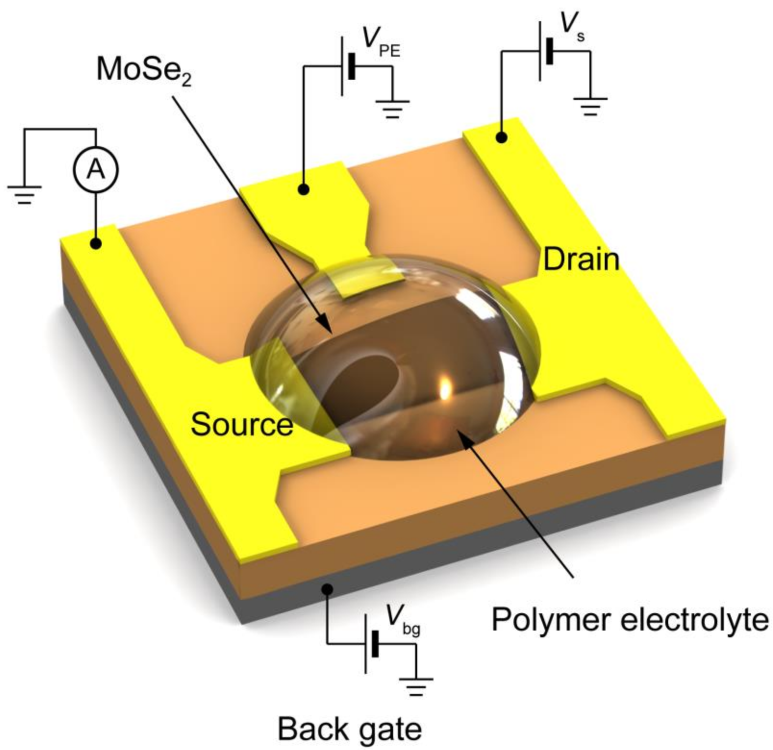
Chen…Kis; ACS Nano (2017)

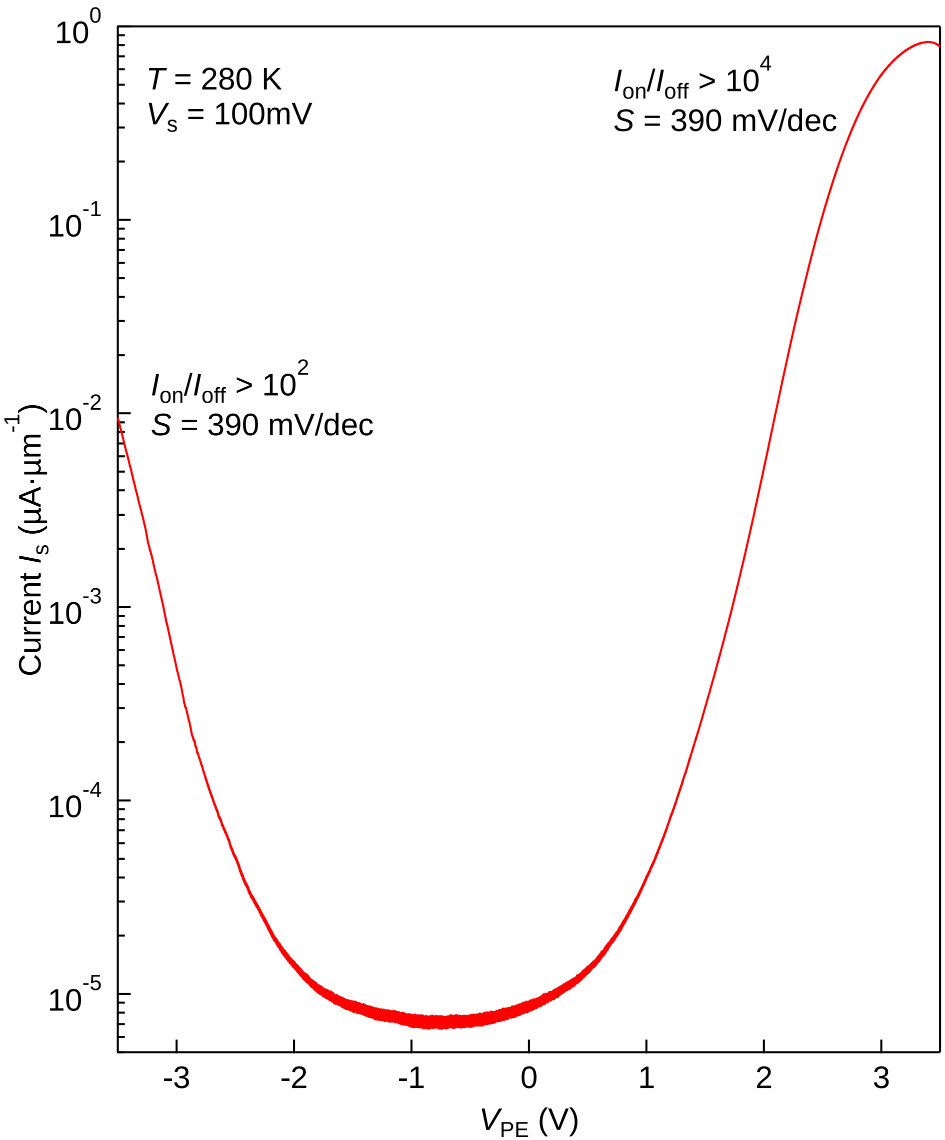
Possible orientations:



Ambipolar Transport in MBE-grown $MoSe_2$ EDLTs

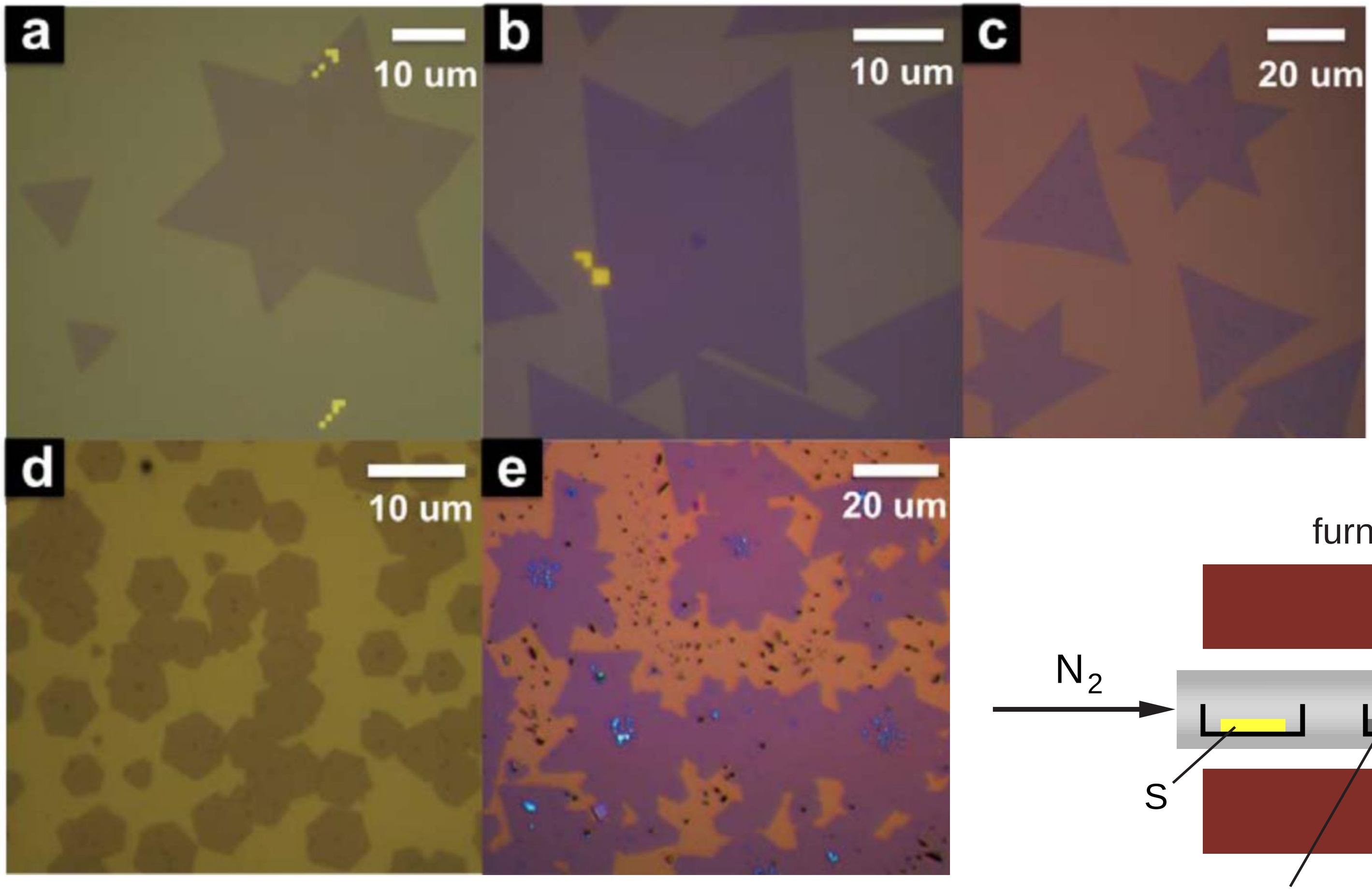


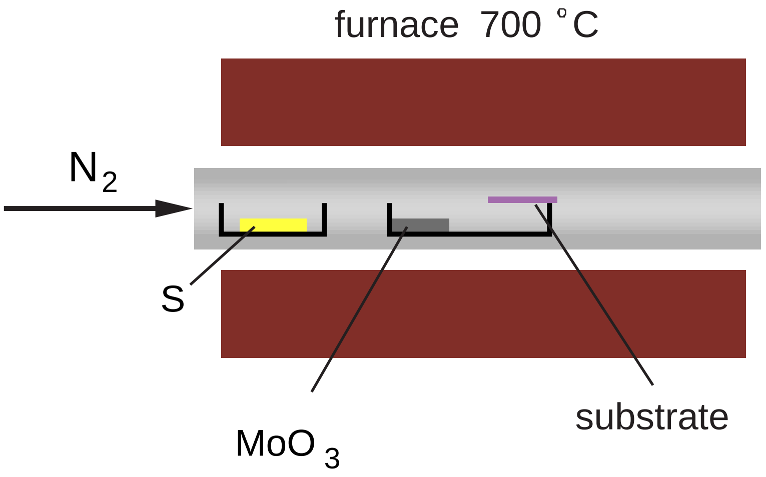




Chen…Kis; ACS Nano (2017)

MoS_2: CVD Growth





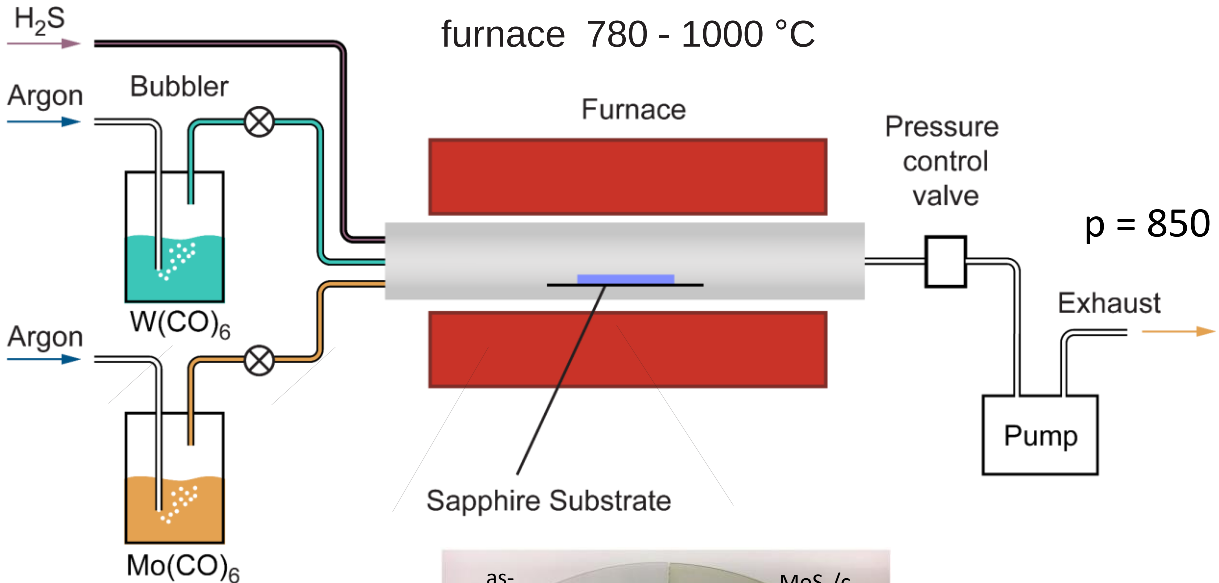
Van der Zande et al. Nature Materials (2013)
Najmaei et al. Nature Materials (2013)

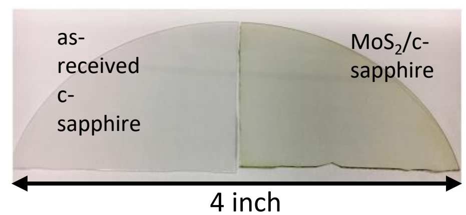
MOCVD Growth

Metalorganic chemical vapour deposition

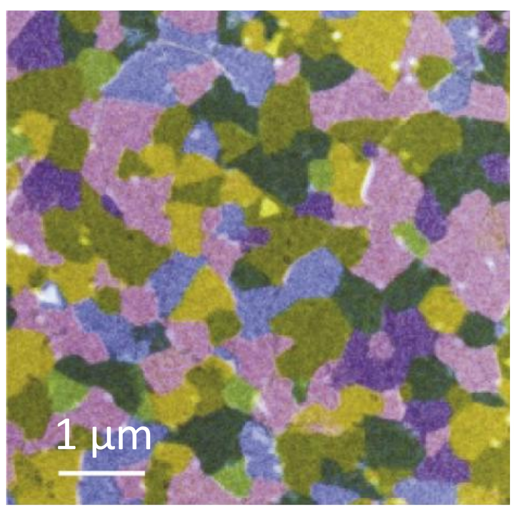
furnace 780 - 1000 °C

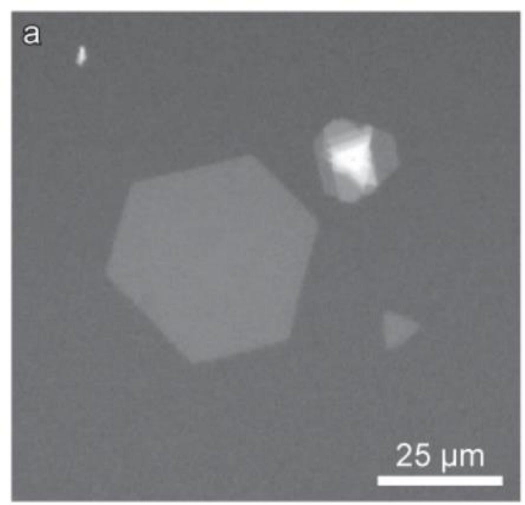
p = 850 mbar





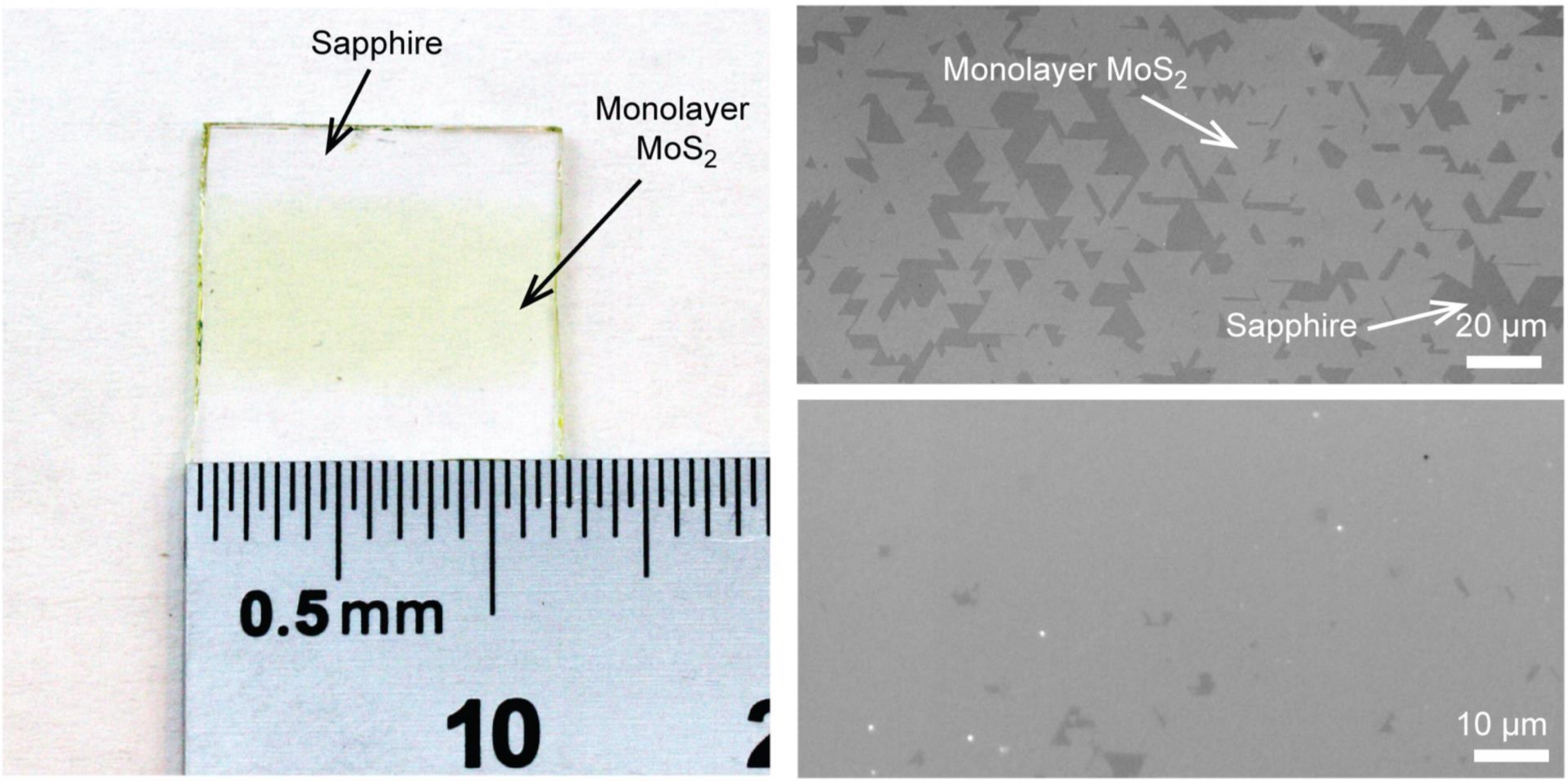
Polycristalline MoS_2
Sub-1µm grain size
Cornell, Nature (2015)





Large single crystals
EPFL, Kim et al,
Nano Lett (2017)

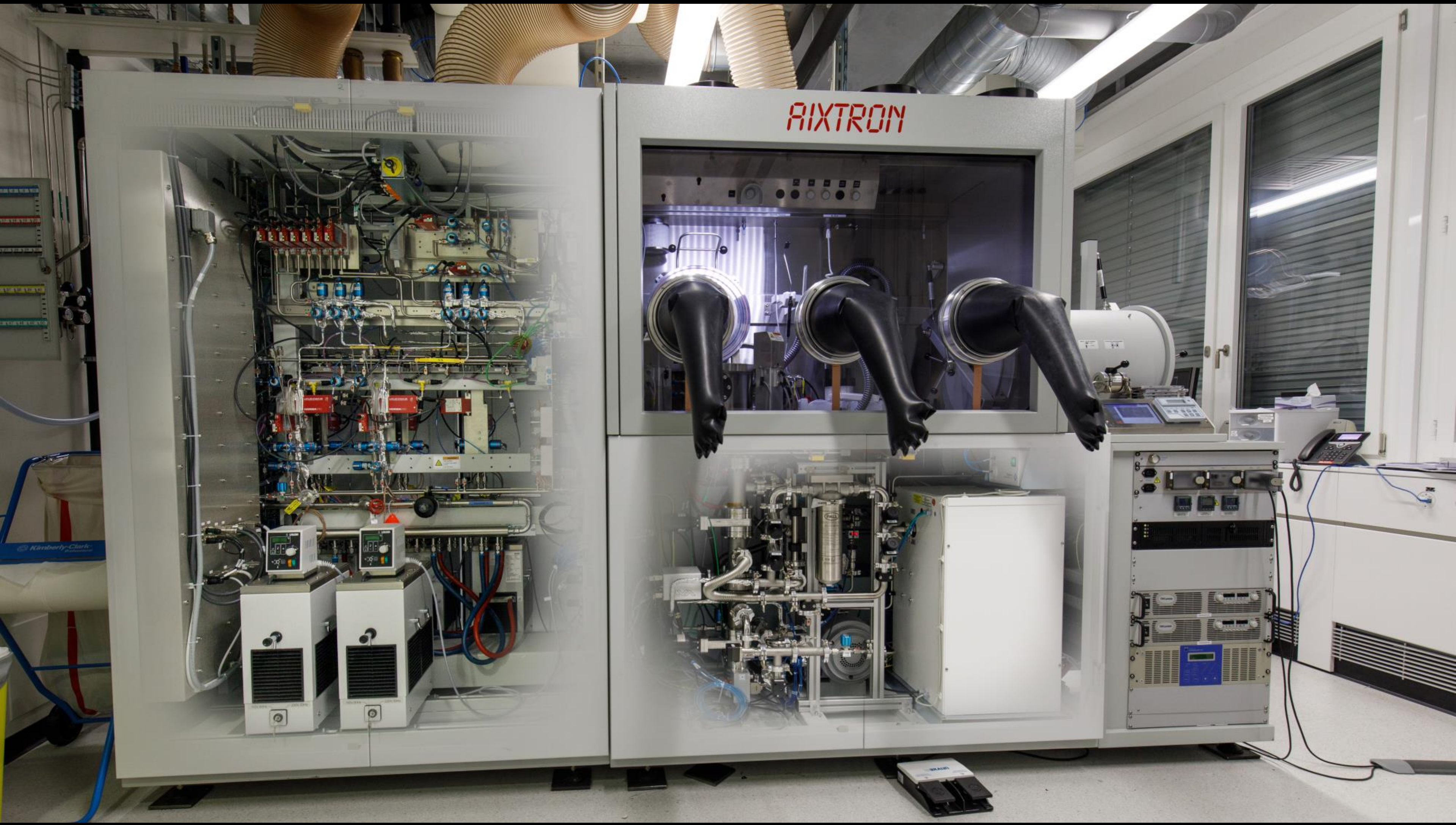
CVD MoS_2



Dumcenco…Kis; ACS Nano (2015)

New at EPFL: MOCVD – BM 2D NOVO

New at EPFL: MOCVD – BM 2D NOVO



Recapitulation

Why semiconducting nanostructures for nanoelectronics

Historic overview

- Graphene
- Transition metal dichalcogenides and 2D materials

Material Growth

- Exfoliation, MBE, CVD, MOCVD