Single-layer MoS_2: Devices, Electronics and Mechanics

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EPFL

- Ecole Polytechnique Federale de Lausanne (www.epfl.ch)
- One of two Swiss federal technical universities (institutes of technology)

Dissipated Heat

Processor coolers now and then

today

1993

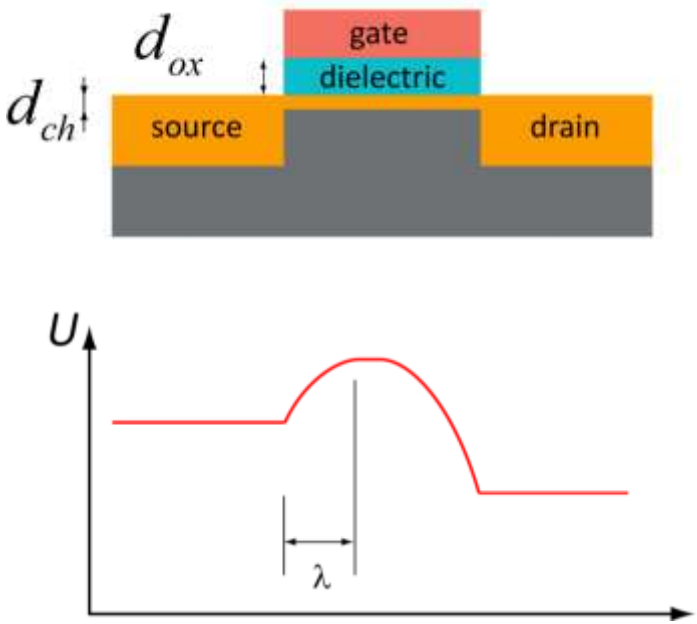
Dissipated Heat

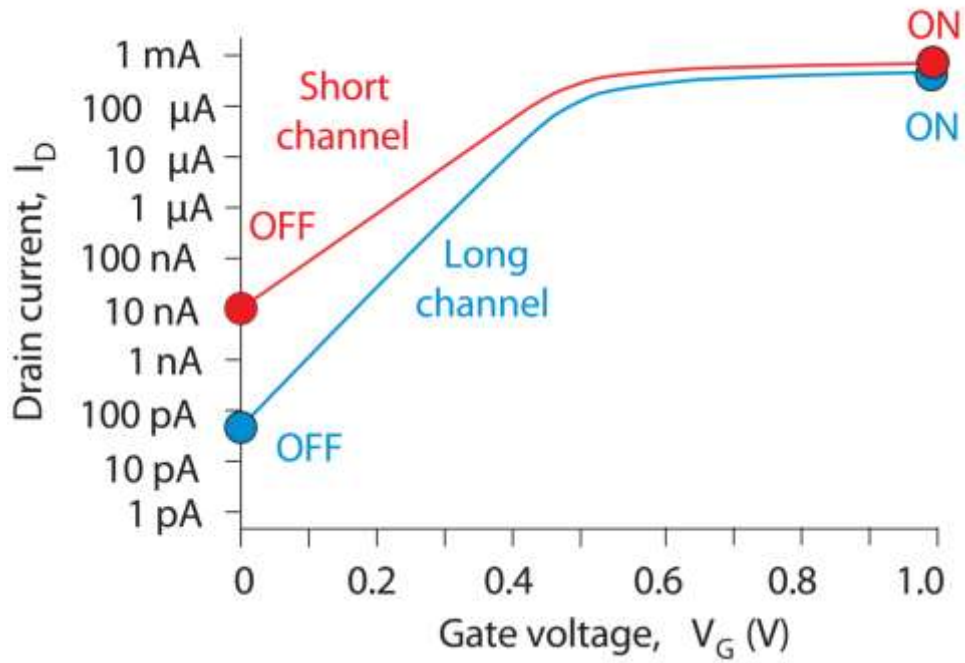
Frying eggs on processors

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

What's Going on with Small Transistors?

Planar MOSFET – short channel effects





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

ε(Si)=11.9

Example:

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

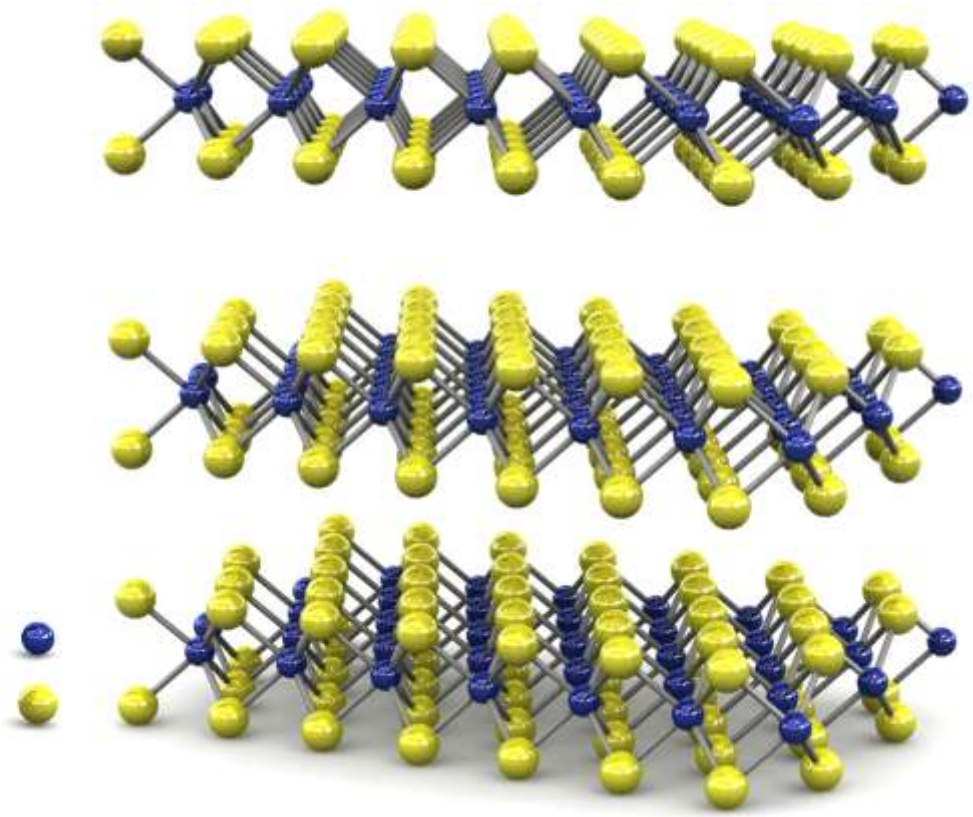
Ferain et al., Nature 479, 310 (2011)

Colinge, Sol. Stat. El. 48, 897 (2004)

Dichalcogenide Nanolayers

- Electronic devices based on dichalcogenide nanolayers

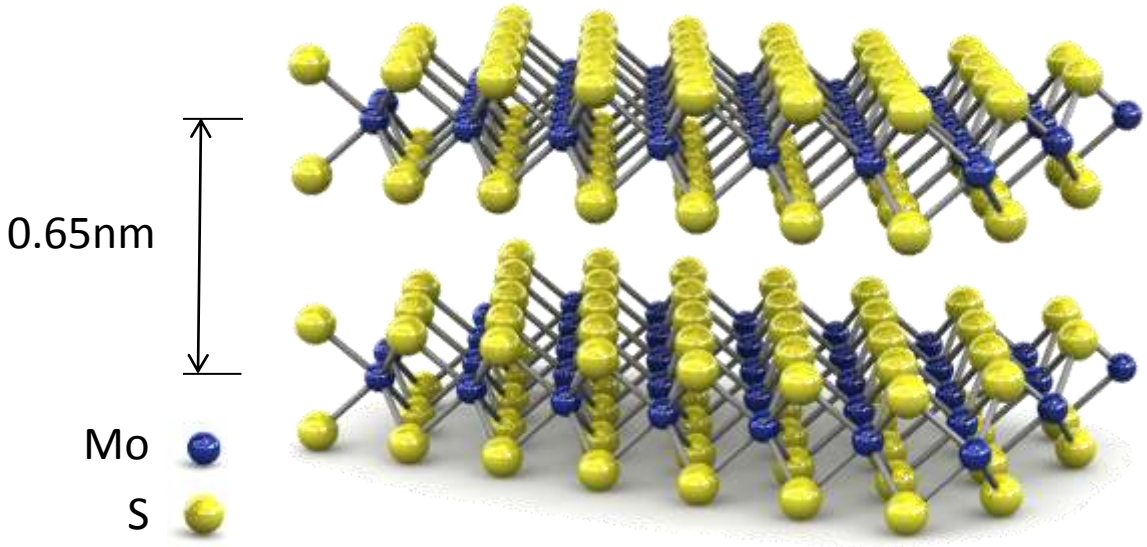
Electrical property	Material
metallic, CDW, superconducting	$NbSe_2$, NbS_2, $NbTe_2$ TaS_2, $TaSe_2$, $TaTe_2$
semimetallic	$TiSe_2$
semiconducting	MoS_2, $MoSe_2$, WS_2, WSe_2, $MoTe_2$, WTe_2

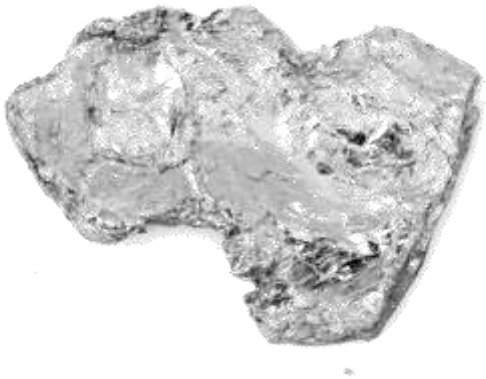


metal M = Ta, Nb, Mo, W, Ti, Re

chalcogenide X = S, Se, Te

MoS_2





MoS_2 crystal

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

Mobility: 200 (monolayer, RT) - 2500 cm^2/Vs (bulk, 70K)

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

Availability: naturally occurring mineral, abundance similar to Ge

Kam et al., J. Phys. Chem. 86, 463 (1982)

Splendiani et al., Nano Let. 10, 1271 (2010)

Mak et al., PRL 105, 136805 (2010)

Fivaz et al., Phys. Rev. 163, 743 (1967)

Radisavljevic et al., Nature Nanotech. 6, 147 (2011)

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.

Proceedings of the Royal Society A 273, 69 (1963)

Mat. Res. Bull., Vol. 21, pp. 457-461, 1986. Printed in the USA.
0025-5408/86 $3.00 + .00 Copyright (c) 1986 Pergamon Press Ltd.

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)

ABSTRACT

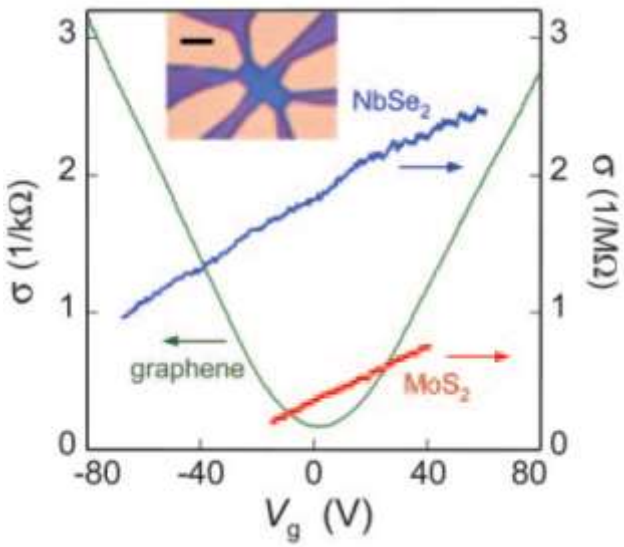
MoS_2 has been exfoliated into monolayers by intercalation with lithium followed by reaction with water. X-ray diffraction analysis has shown that the exfoliated MoS_2 in suspension is in the form of one-molecule-thick sheets. X-ray patterns from dried and re-stacked films of exfoliated MoS_2 indicate 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.

Joensen et al., Materials Research Bulletin 21, 457 (1986)

Previous Work

Two-dimensional atomic crystals

K. S. Novoselov*, D. Jiang*, F. Schedin*, T. J. Booth*, V. V. Khotkevich*, S. V. Morozov†, and A. K. Geim*‡



"For 2D $NbSe_2$ and MoS_2, we measured mobilities between ***0.5 and 3 cm²/Vs*** *for different samples,* ***in agreement with mobilities for*** *the corresponding* ***3D crystals at room temperature****."*

Novoselov et al., PNAS 102, 10451 (2005)

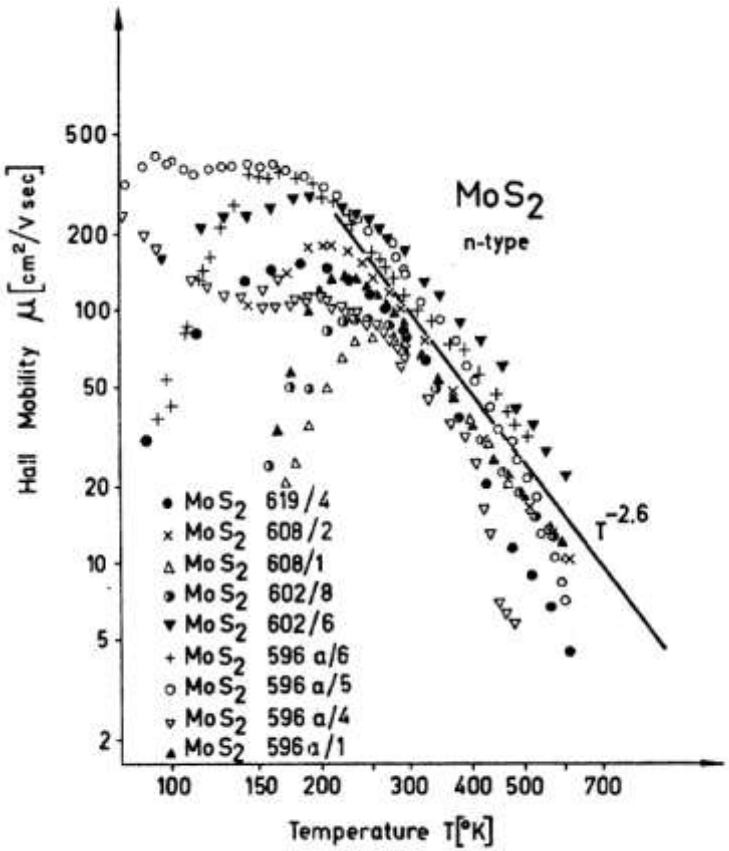


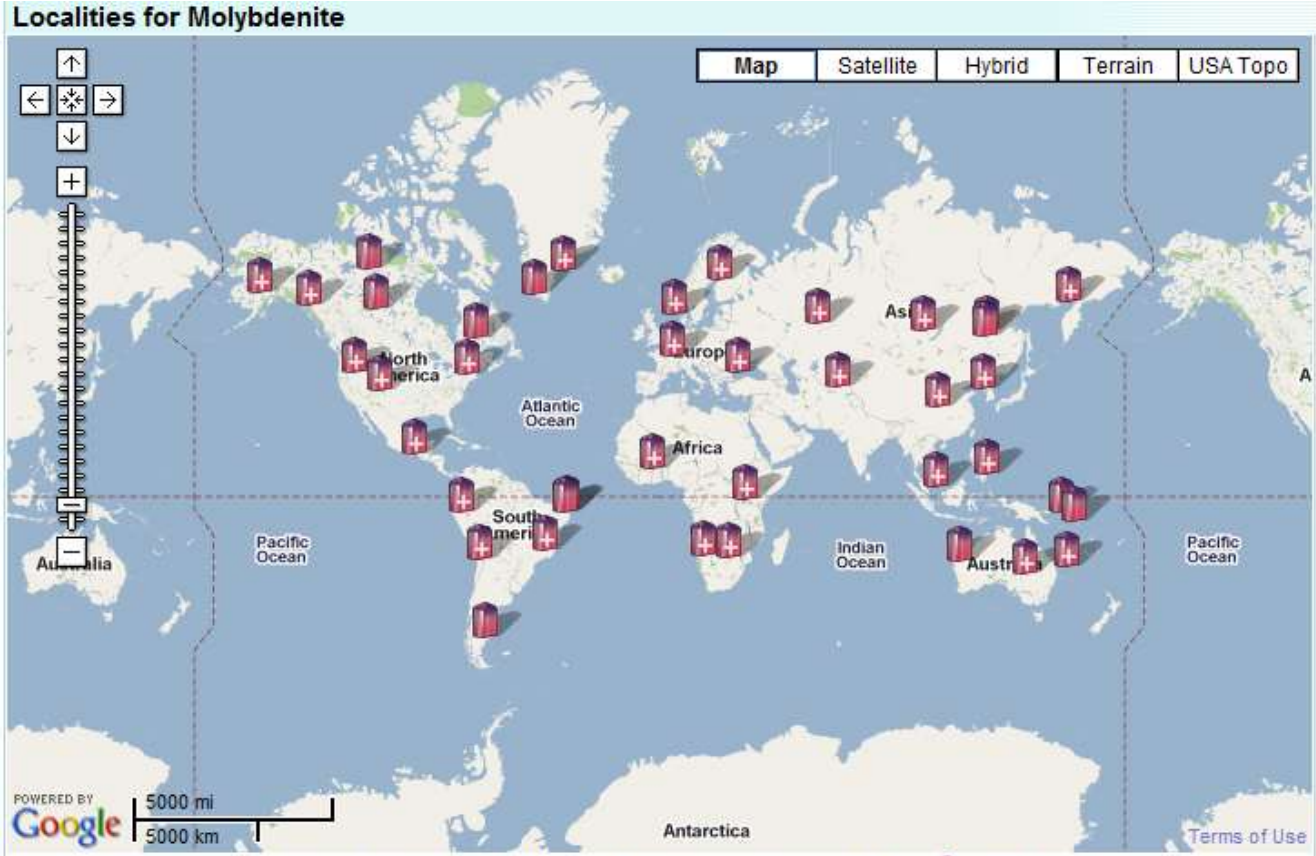
FIG. 7. Mobility of the electrons in MoS_2.

Fivaz et al., Phys. Rev. 163, 743 (1967)

Source: Wikipedia

Localities for Molybdenite

Known reserves: 19M metric tons

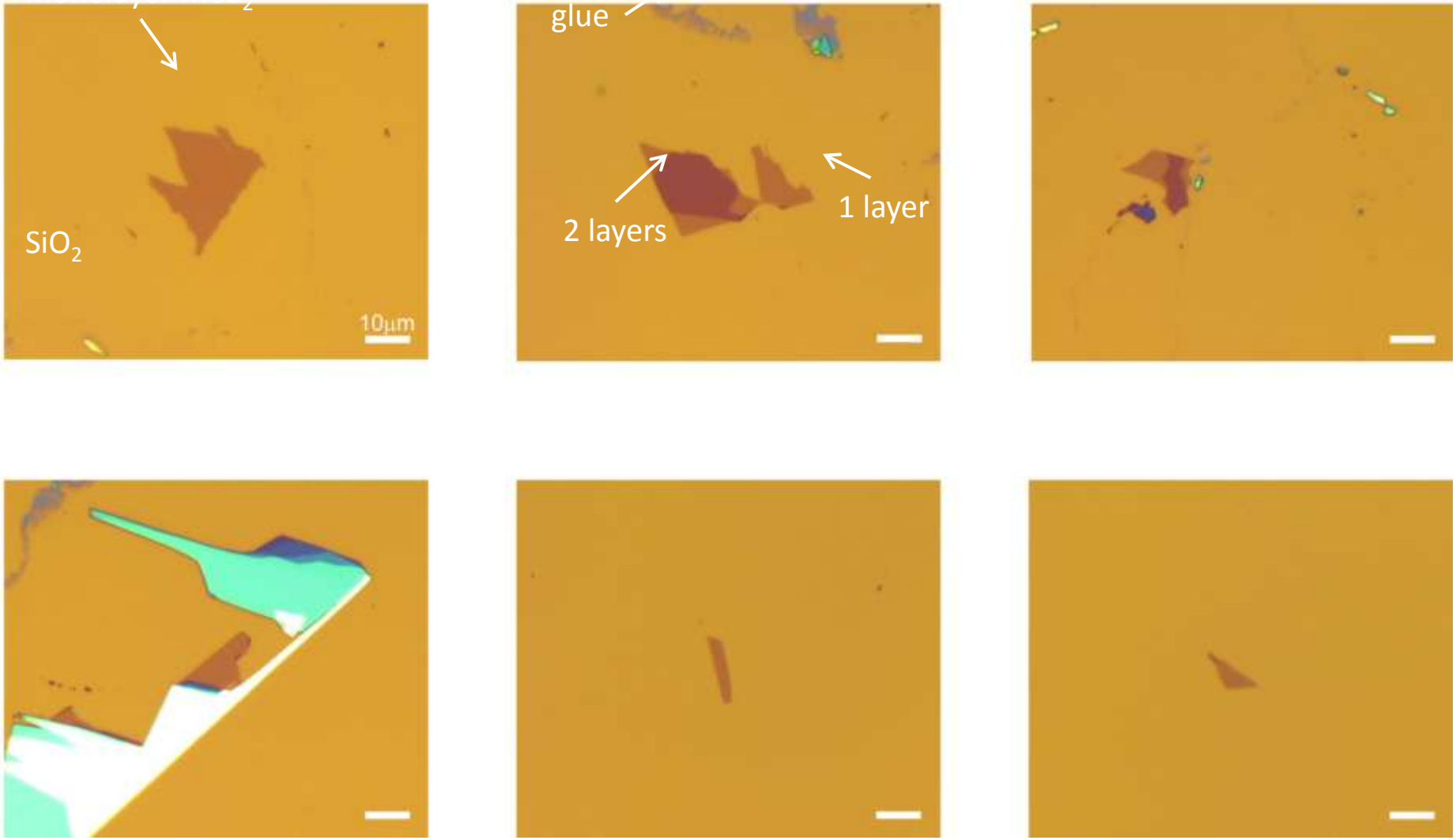


The map shows a selection of localities that have latitude and longitude coordinates recorded. Click on the symbol to view information about a locality. The symbol next to localities in the list can be used to jump to that position on the map.

Show Locality List (4313 Items)

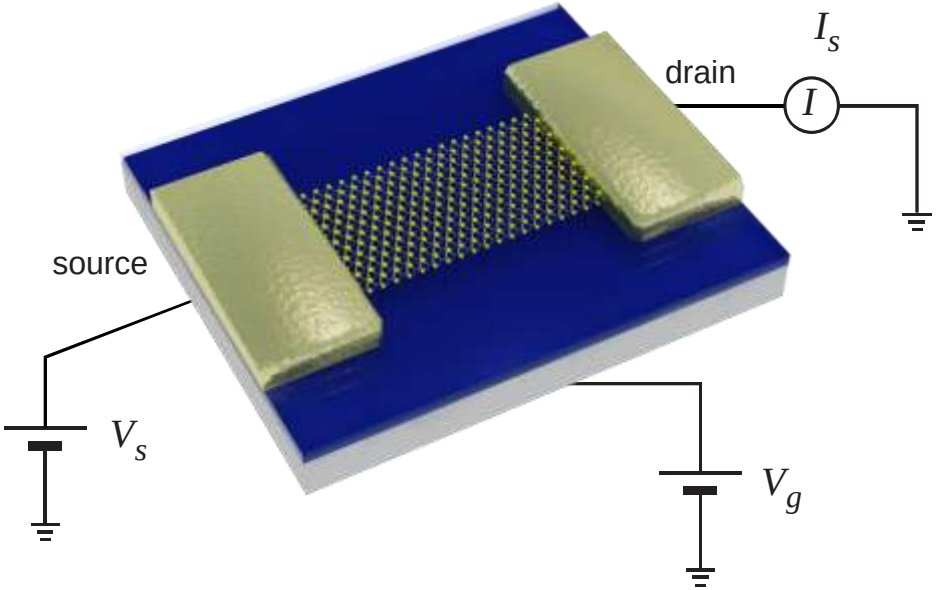
Scotch Tape Exfoliation

270-280 nm SiO_2 gives optimal contrast

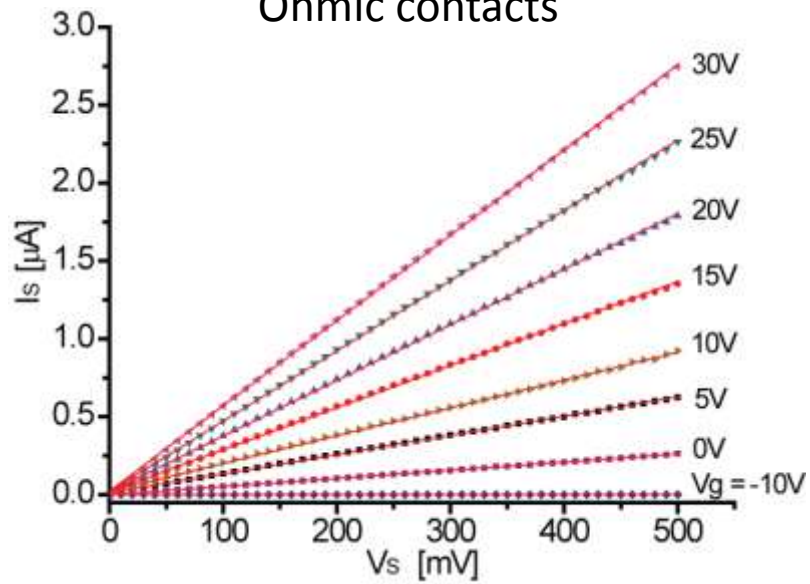


Benameur et al., Nanotechnology 22, 125706 (2011)

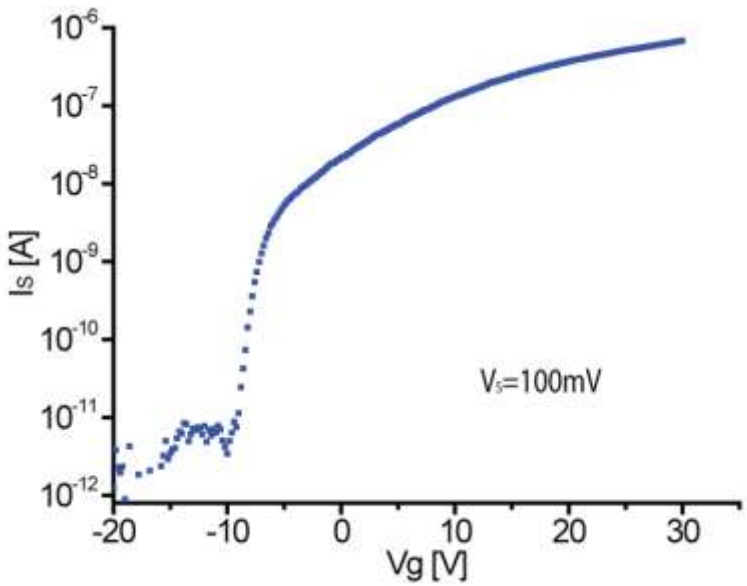
MoS_2 Nanolayer Transistors (2009)



Ohmic contacts



Can be turned off



Good contact materials: Ti, In, Y, Au

Thickness: 4 layers
Mobility: 40 cm^2/Vs
On/Off: 10^5

Dielectric Screening

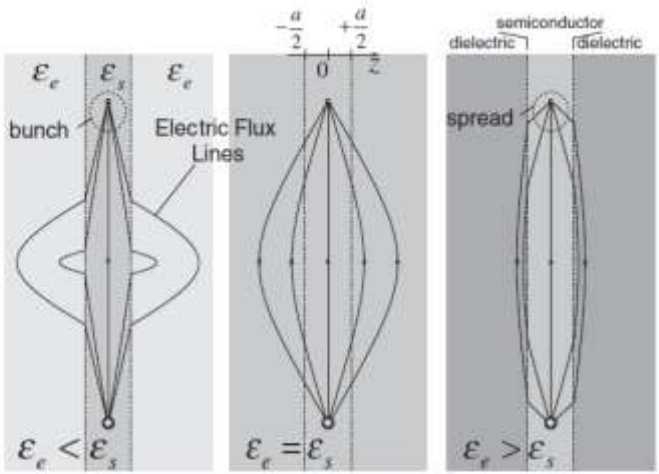


FIG. 1. Electric flux lines originating from a fixed ionized impurity and terminating on a mobile electron, and the effect of the dielectric environment. The flux lines bunch closer inside the semiconductor layer if $\epsilon_e < \epsilon_s$, and spread farther apart if $\epsilon_e < \epsilon_s$, thus enhancing Coulomb interaction in the former case and damping it in the latter.

Jena and Konar, PRL 98, 136805 (2007)

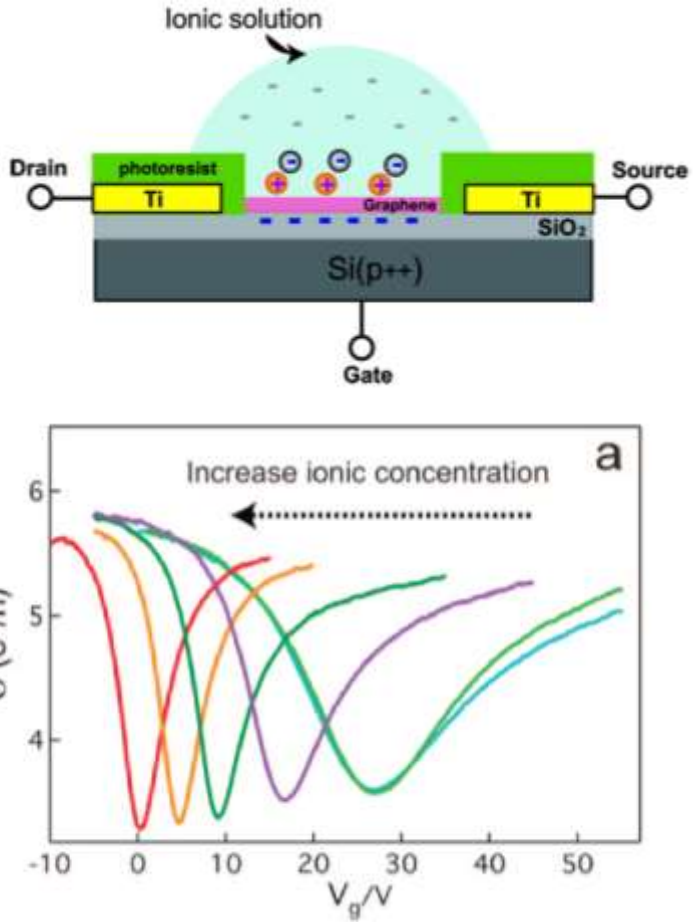
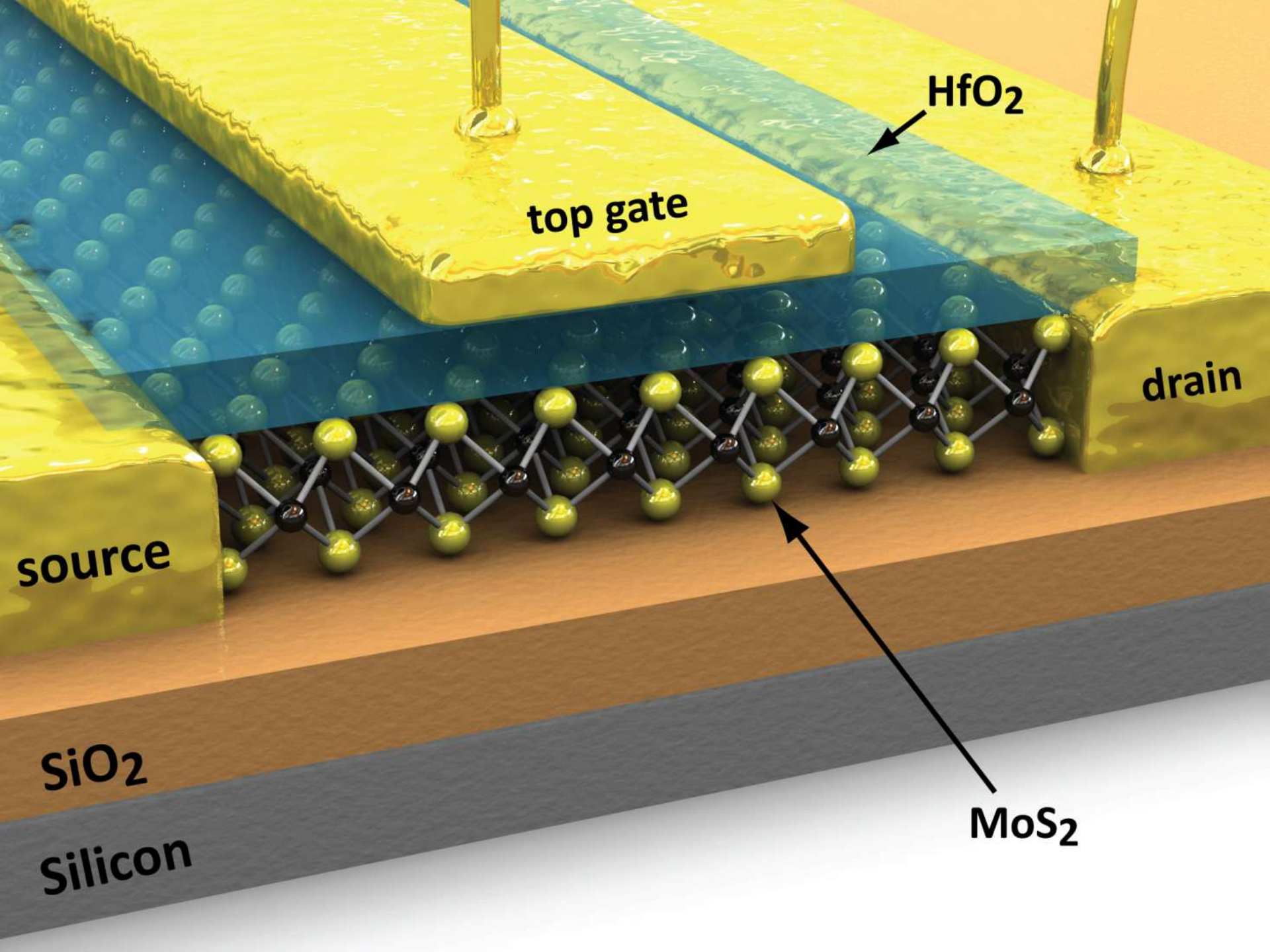
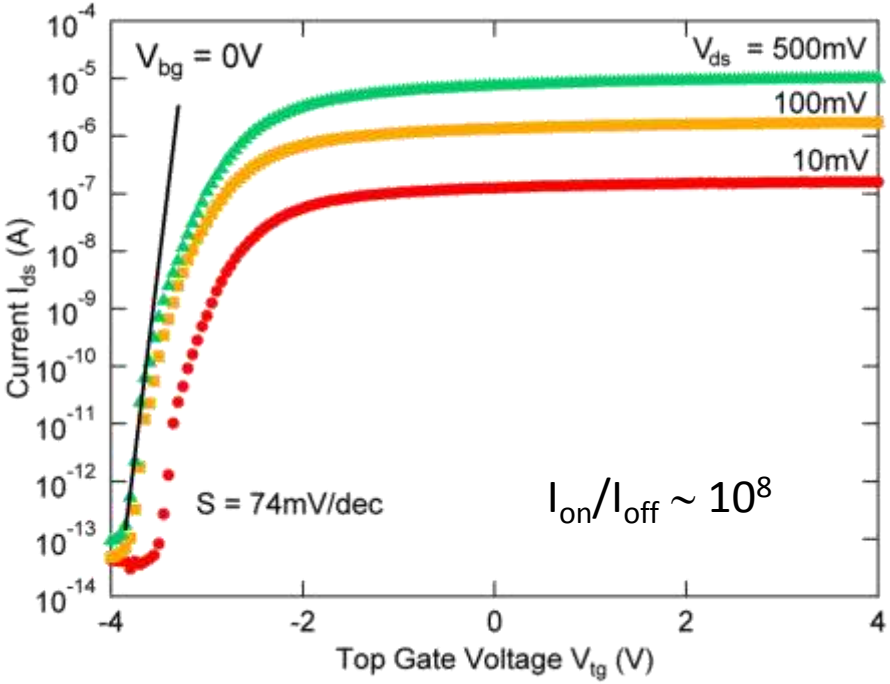


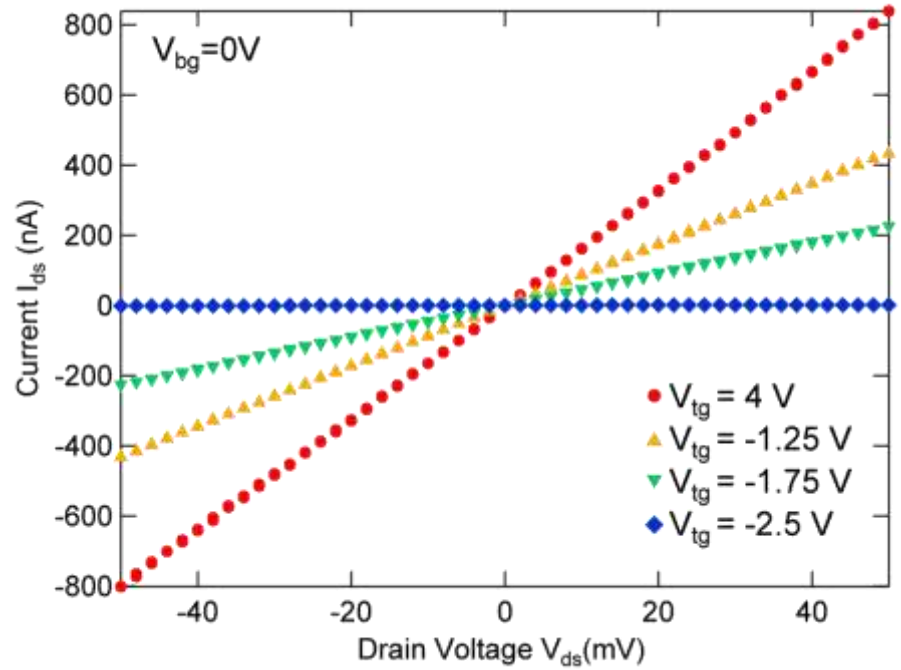
Figure 2. (a) Conductivity comparison in aqueous solution containing different concentrations of NaF (5 mM, 10 mM, 0.05 M, 0.1 M, 0.5 M, 1 M, respectively). (b) Conductivity vs backgate voltage in argon and water.

Chen et al., NanoLet 9, 1621 (2009)


HfO2
top gate
drain
source
SiO2
Silicon
MoS2

Ultralow-power MoS2 Transistor

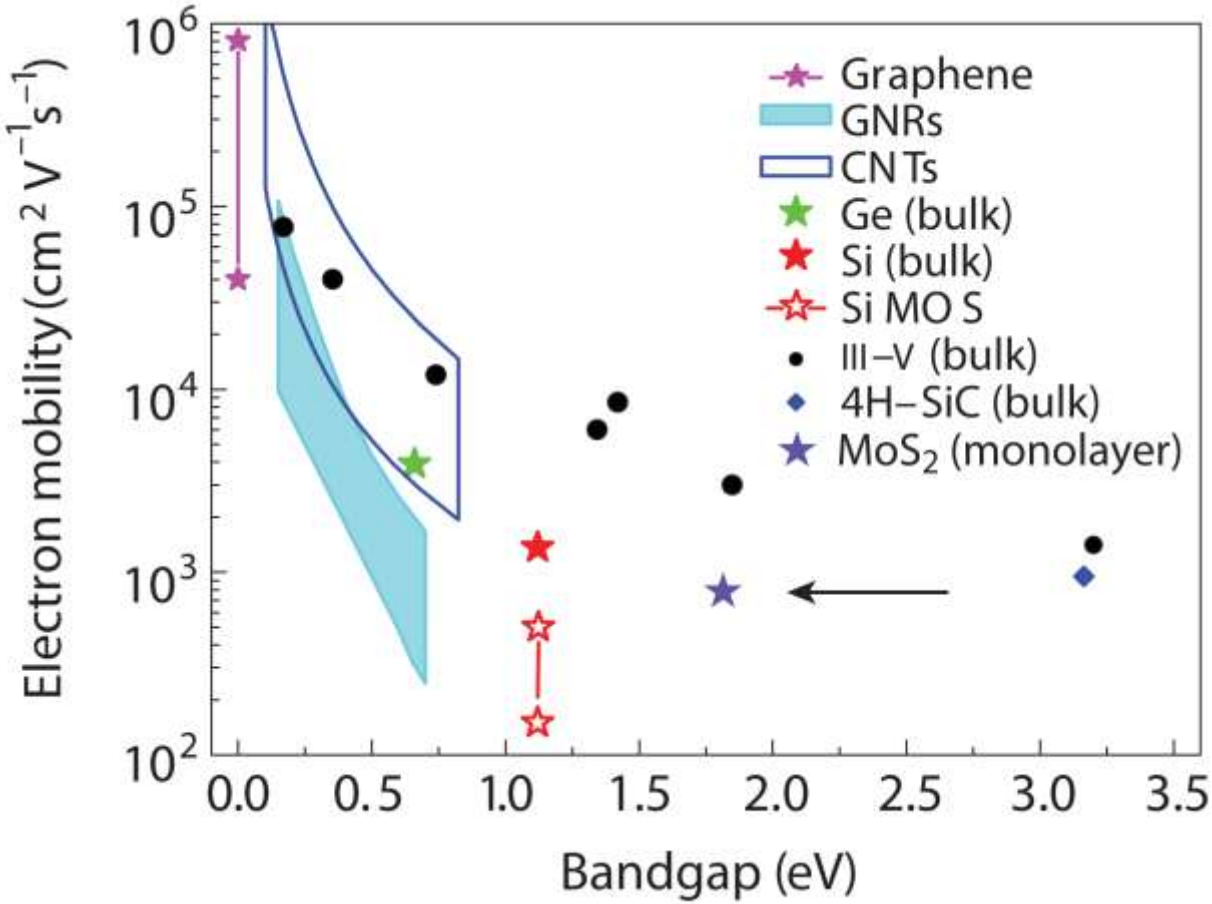




Gate length:	500 nm
Channel width:	4 µm
Mobility:	200-1000 cm^2/Vs
On/Off:	10^8
ON current:	2.5 µA/µm
OFF current:	25 fA/µm
Transconductance:	1 µS/µm

Radisavljevic et al., Nature Nanotechnology 6, 147 (2011)

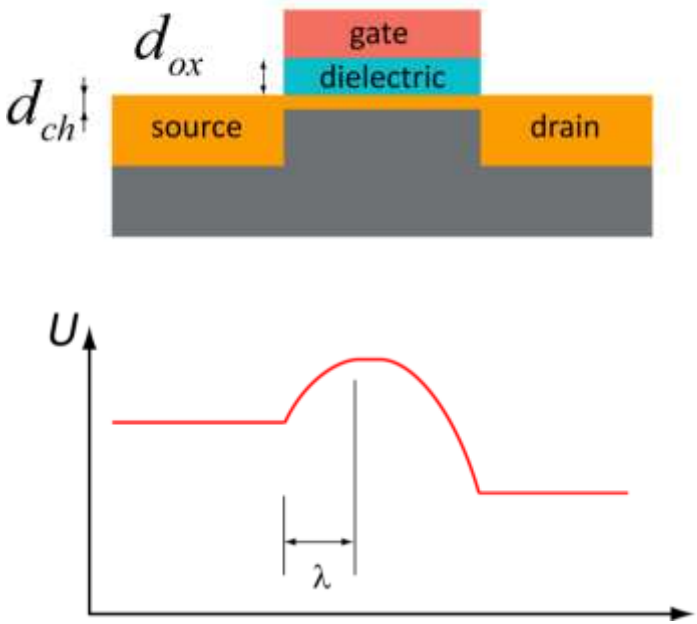
Comparison with Other Semiconductors

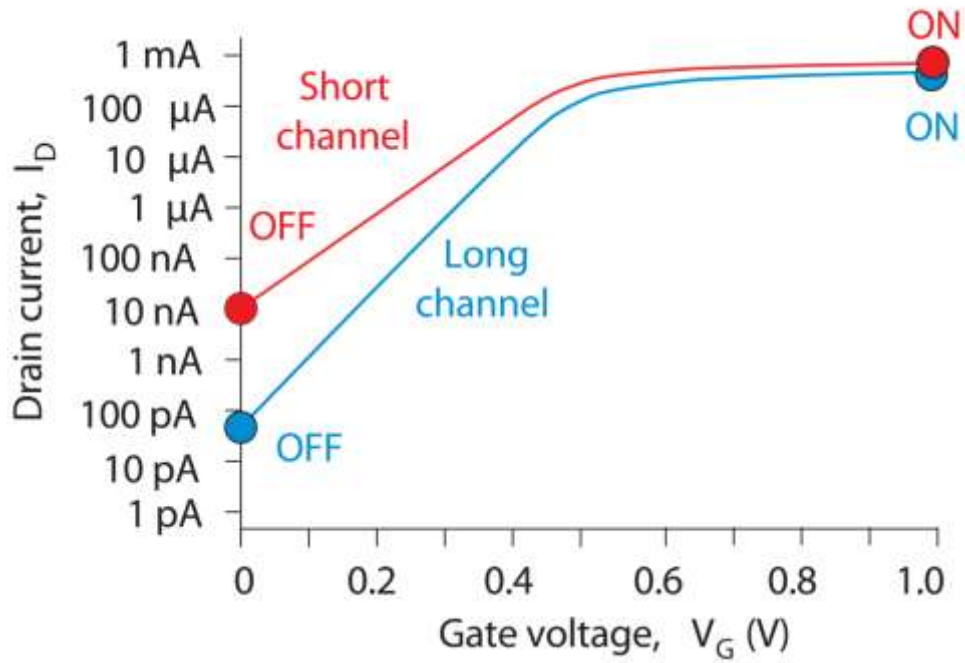


Adapted from F. Schwierz, Nature Nanotechnology 5, 487 (2010)

MoS2 and Short Channel Effects

Planar MOSFET – short channel effects





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

$\varepsilon(Si)=11.9$
$\varepsilon(MoS_2)=3.9$

Example:

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

MoS_2, 1nm SiO_2: L_g >3nm

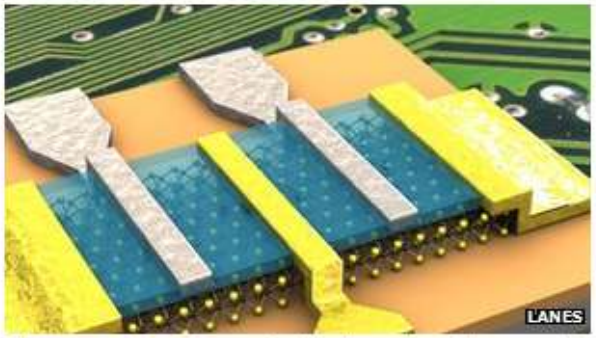
would need 0.27 nm thick Si film for same L_g!

5 December 2011 Last updated at 17:19 GMT

61 Share

Silicon rival MoS2 promises small, low-energy chips

The first computer chip made out of a substance described as a "promising" alternative to silicon has been tested by researchers.



The researchers say molybdenite microchips would need less power than existing silicon-based circuits

The Switzerland-based team used molybdenite disulfide (MoS2) - a dark-coloured, naturally occurring mineral.

The group said the substance could be used in thinner layers than silicon, which is currently the most commonly used component in electronics.

It said MoS2 could make smaller, more flexible chips that used less energy.

The substance is currently used as an ingredient in engine lubricants, ski waxes and as a strengthening agent for plastics.

Prof Andras Kis, the director of the Laboratory of Nanoscale Electronics and Structures (LANES) in Lausanne, published **details of the research** in the latest edition of the ACS Nano journal.

He said the team chose to experiment with this semiconductor, rather than another material, in part because it was easily available.

"There is something like 19 million metric tonnes around," Prof Kis told

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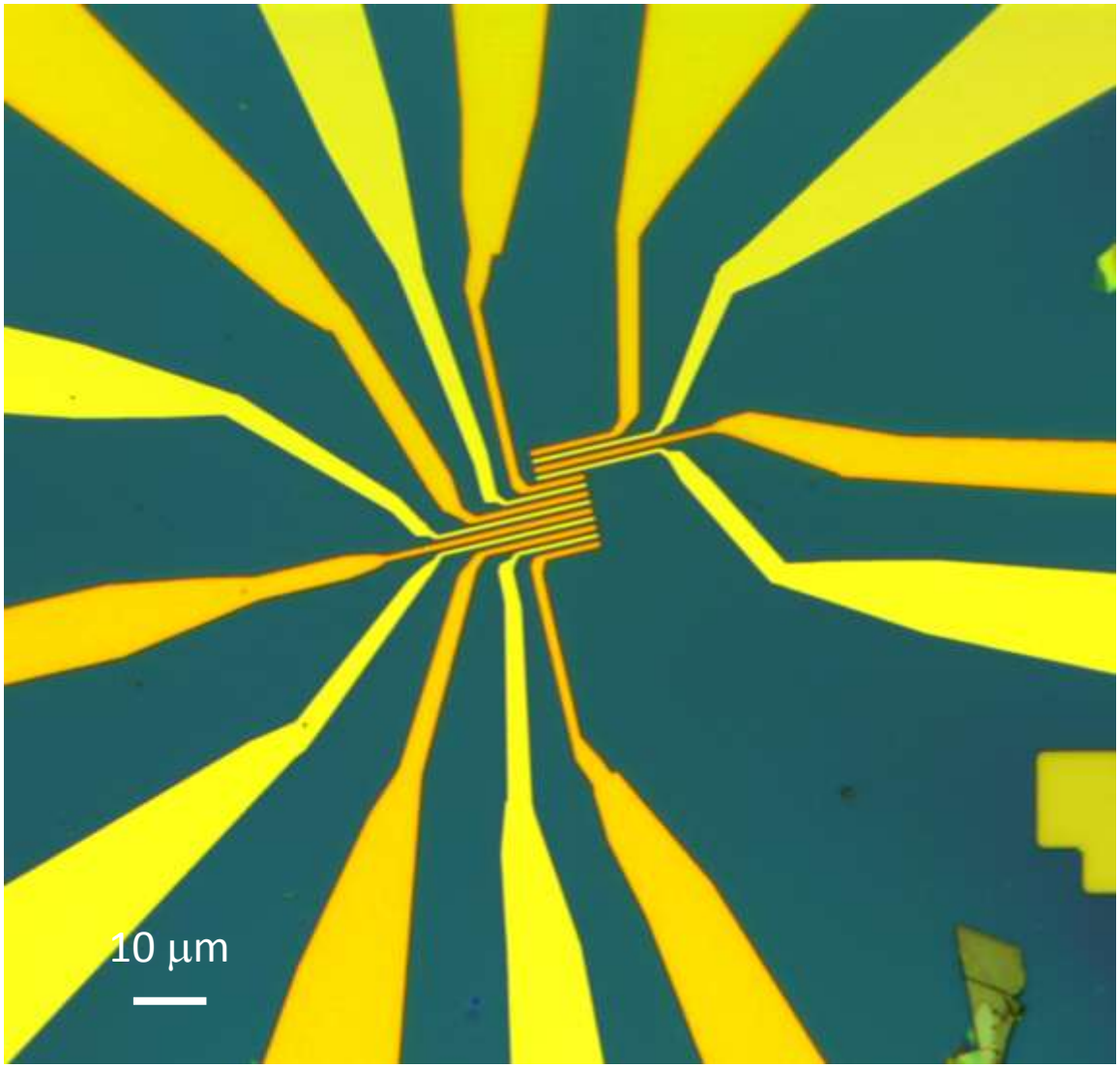
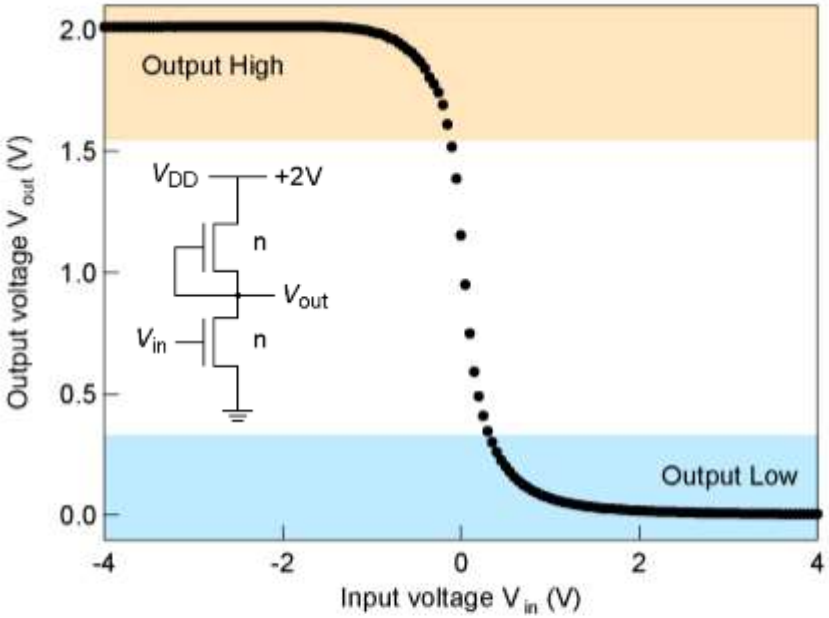
MoS_2 - based Integrated Circuits

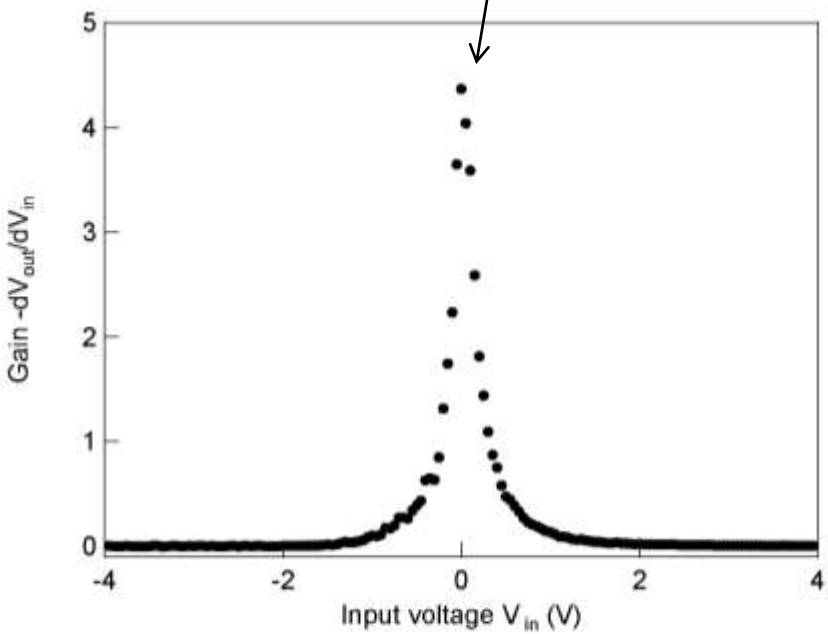


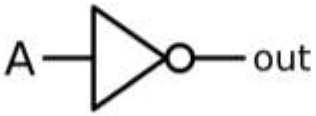
Example with 6 transistors integrated on the same piece of MoS_2

MoS_2 Digital Inverter



Max. Gain: 4.5





A	out
0	1
1	0

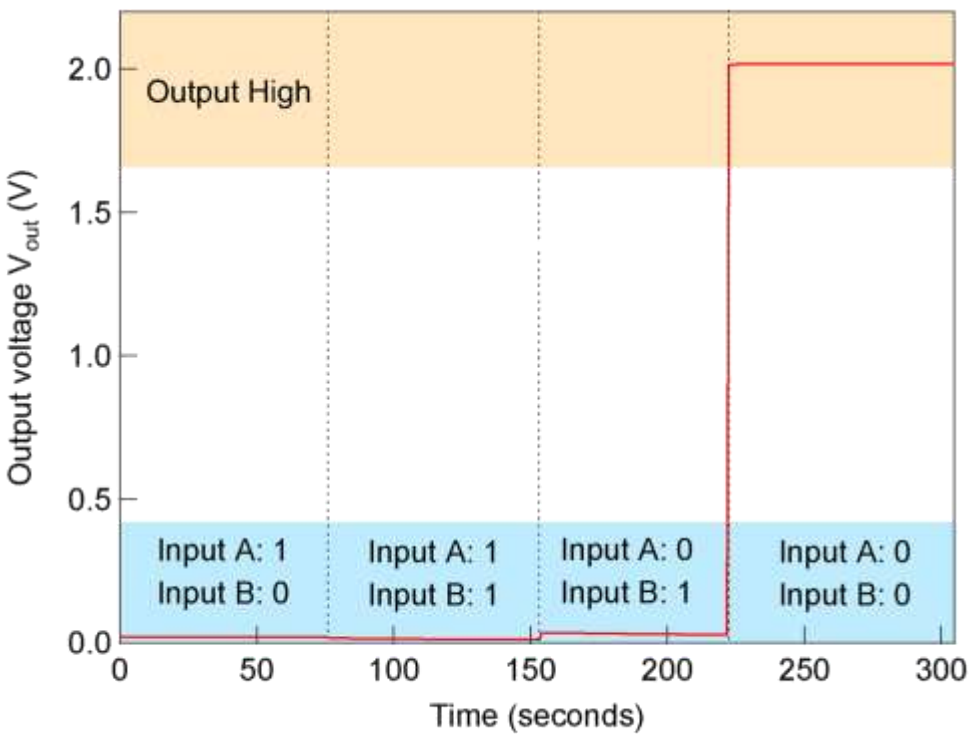
Best for graphene: 2.5 gain at 70K

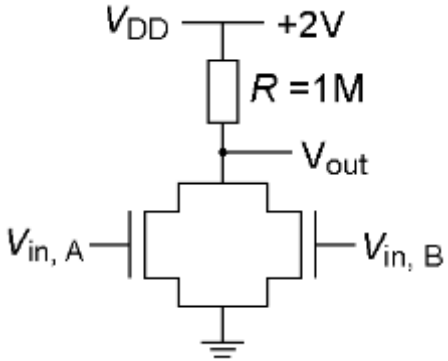
Li et al., Small (2011)

Radisavljevic, Whitwick, Kis; ACS Nano 5, 9934 (2011)

MoS_2 NOR Gate

- All logic operations can be expressed using a combination of NOR operations

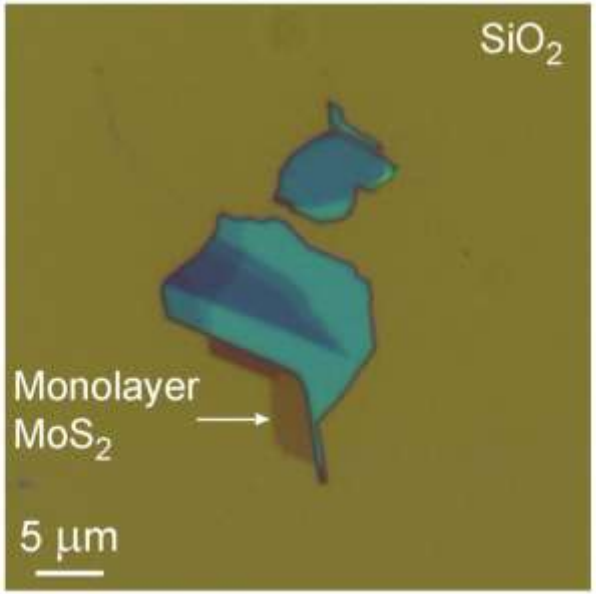




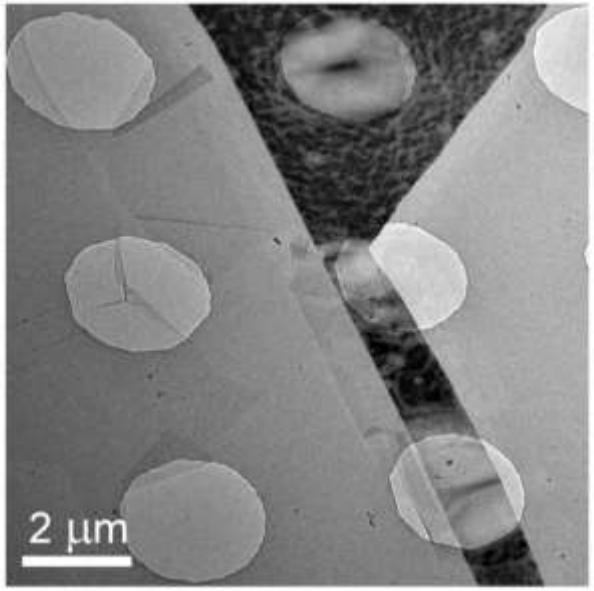
A	B	out
0	0	1
0	1	0
1	0	0
1	1	0

Radisavljevic, Whitwick, Kis; ACS Nano 5, 9934 (2011)

TEM Imaging



Optical



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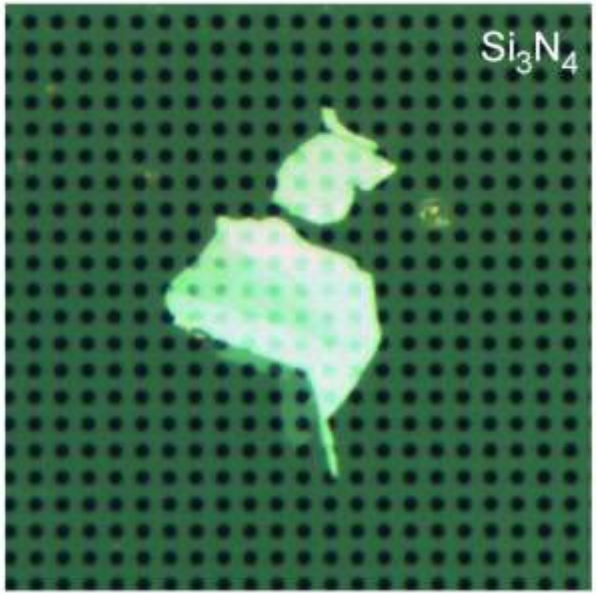

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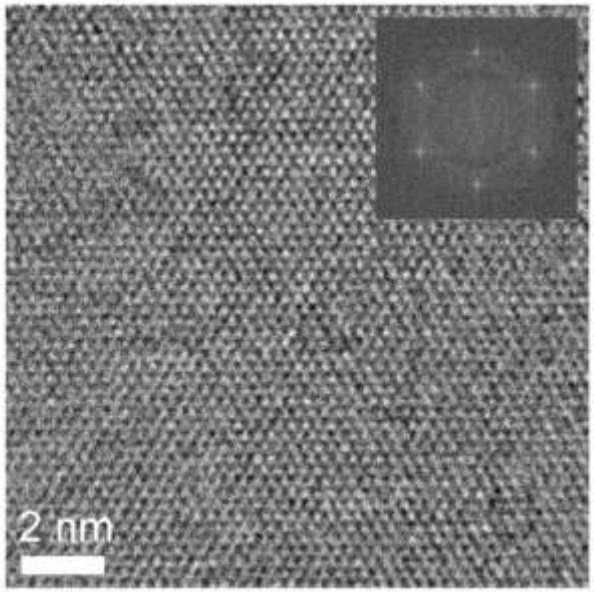
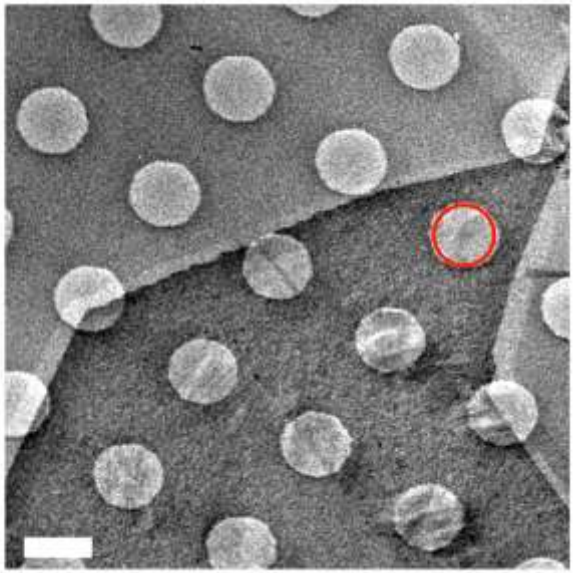
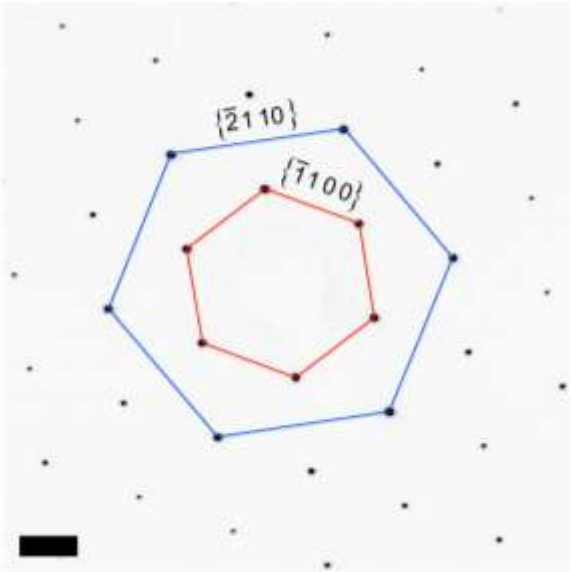


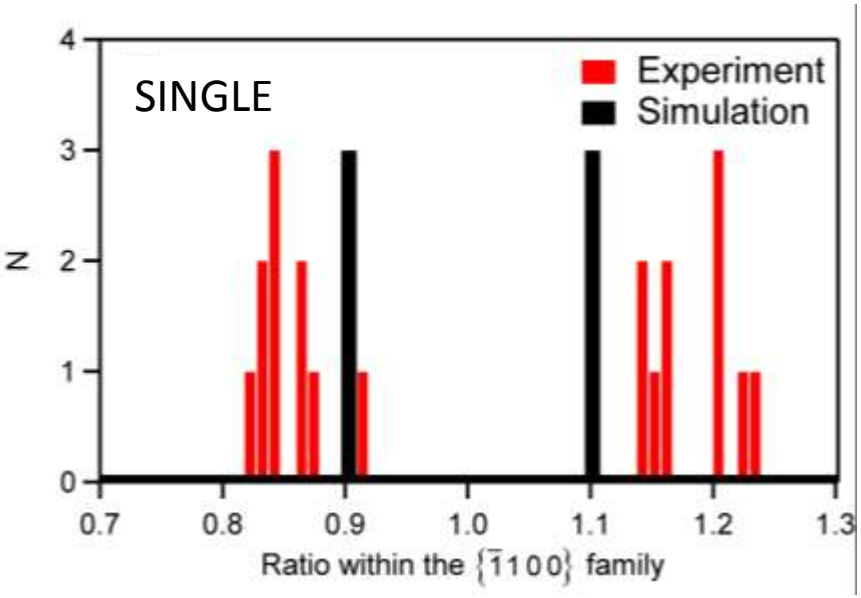
HRTEM

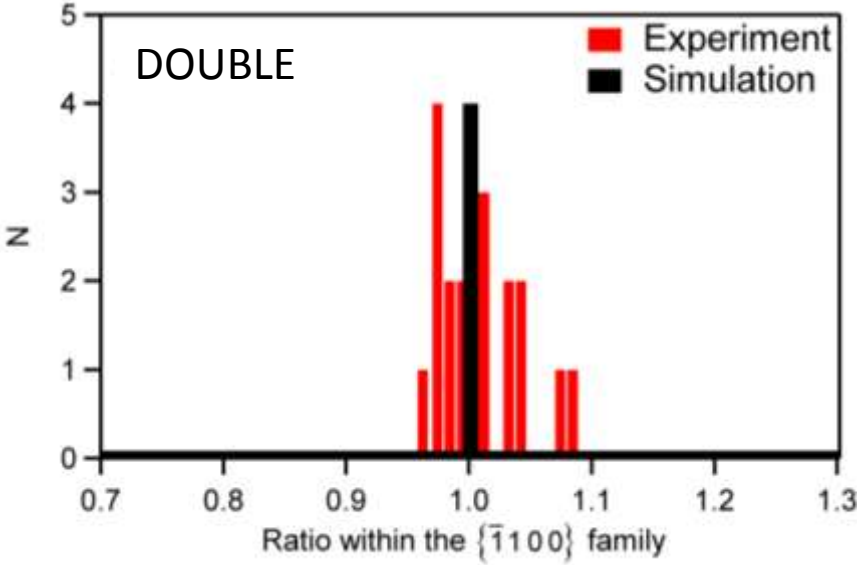
Brivio, Alexander, Kis; Nano Letters 11, 5148 (2011)

How to Recognize Single Layers





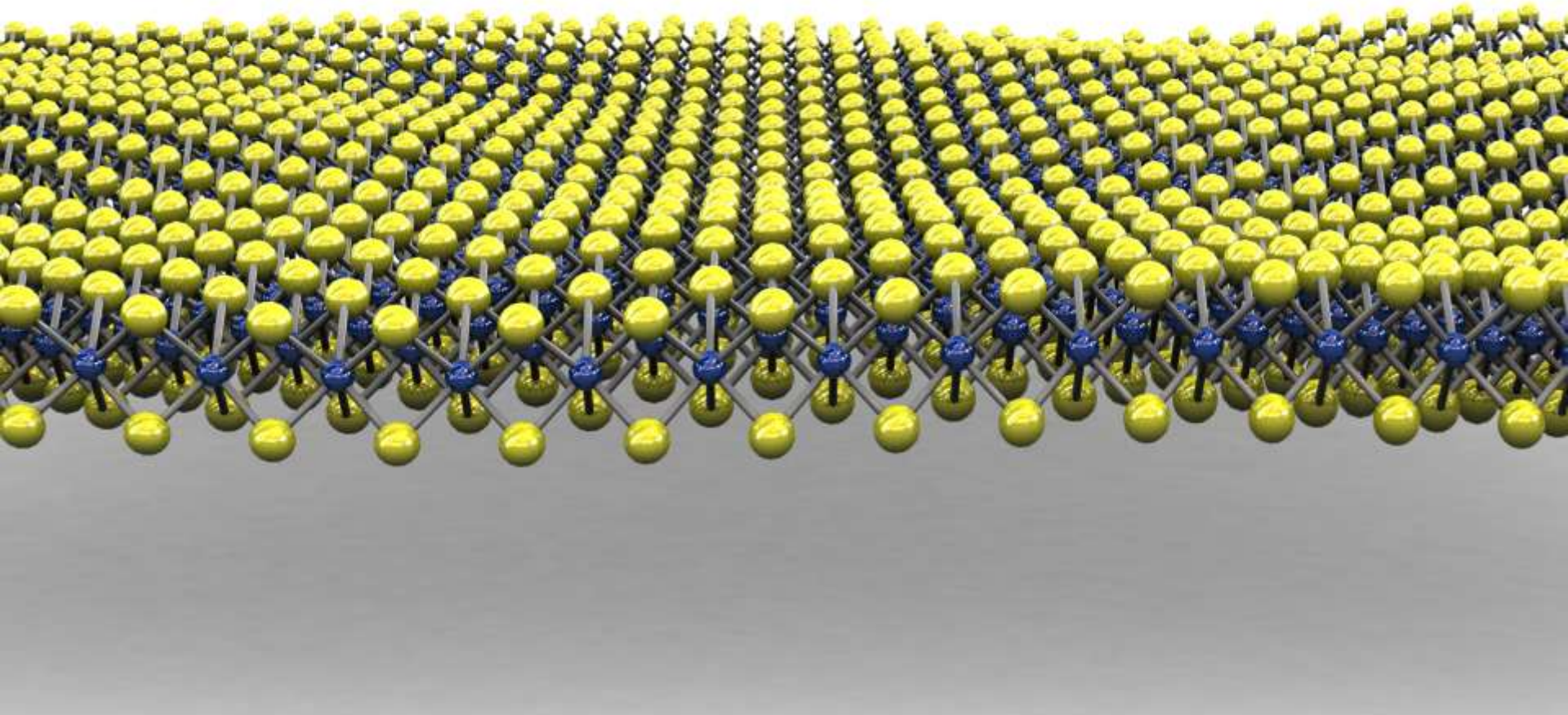




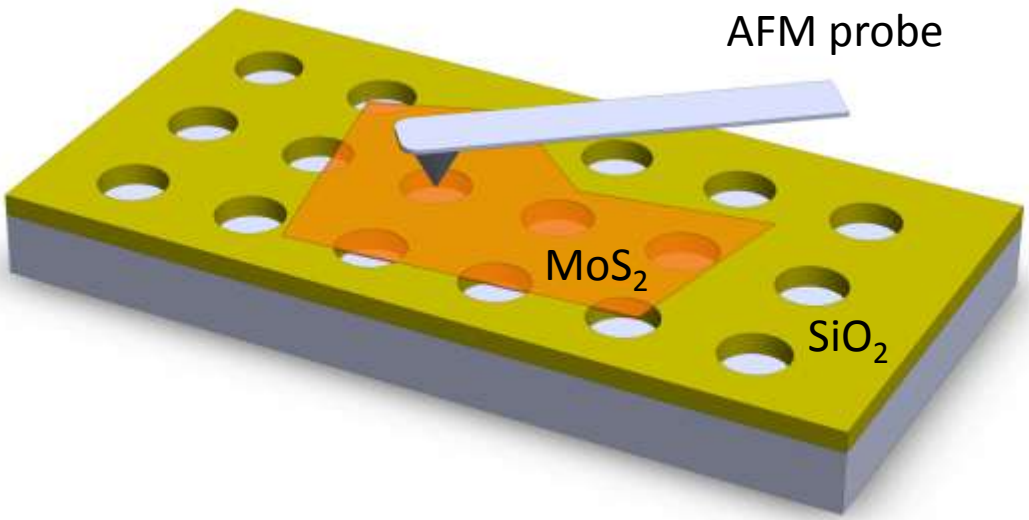
Brivio, Alexander, Kis; Nano Letters 11, 5148 (2011)

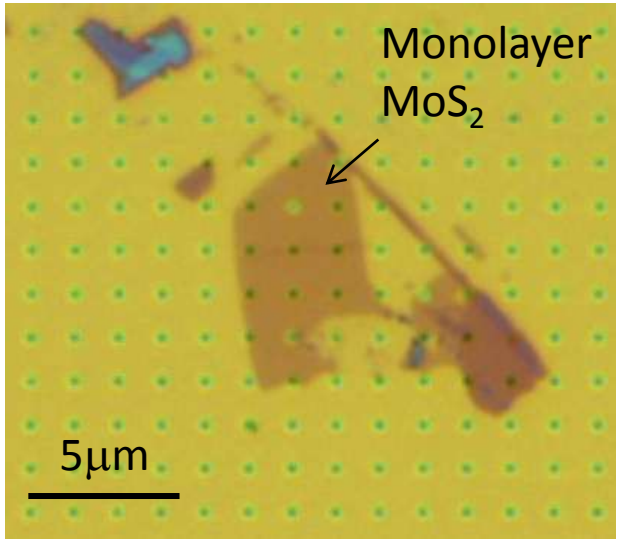
Ripples in MoS_2

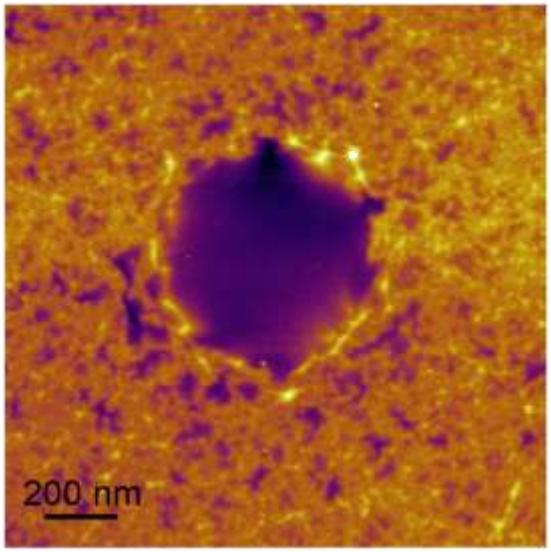
	Lateral size	Amplitude	Surface deviation	
MoS_2 monolayer	≈ 6-10 nm	≈ 0.6 - 1 nm	± 5°	Brivio et al. Nano Letters (2011)
MoS_2 bilayer			± 0.5°	
Graphene	≈ 10 nm	≈ 1 nm	± 5°	Meyer et al., Nature 446, 60 (2007)
Bilayer Graphene			± 2°	



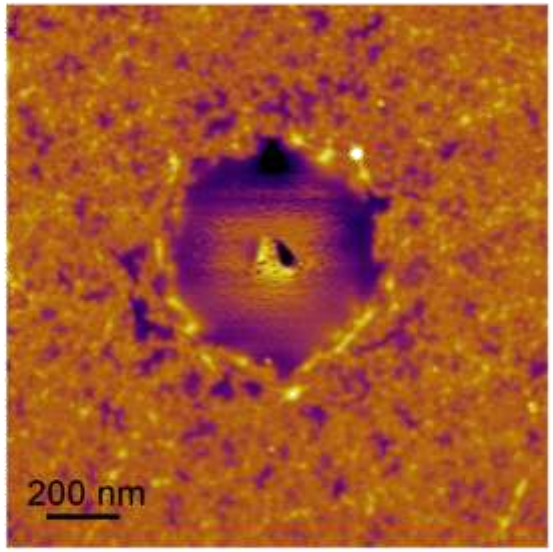
Mechanical Properties of Monolayer MoS_2







AFM image before straining

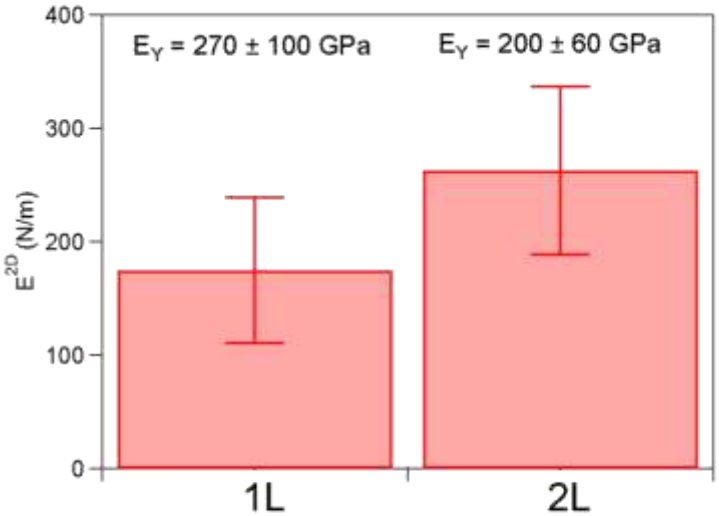


AFM image after failure

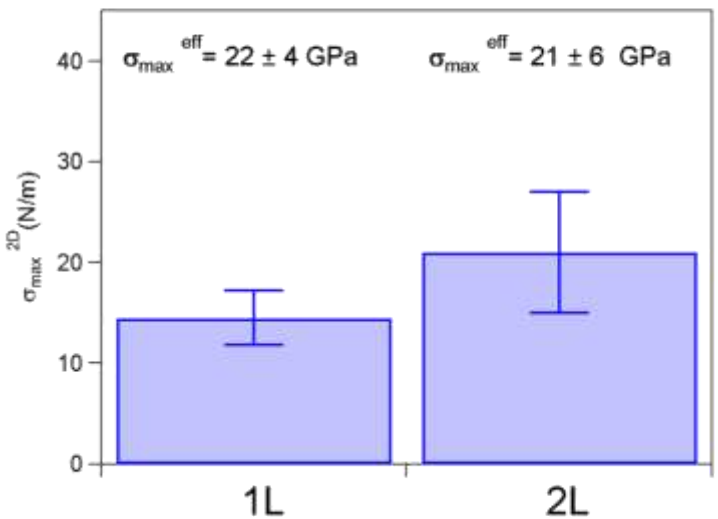
Bertolazzi, Brivio, Kis; ACS Nano 5, 9703 (2011)

Mechanical Properties of Monolayer MoS_2

Elastic modulus



Breaking strength



Material	Young's Modulus GPa	Breaking strength GPa	Strength /Modulus (%)
Stainless steel	205	0.9	0.4
Polyimide	2.5	0.231	9
PDMS	0.3-0.87	2.24	2.5
Monolayer MoS_2	**270**	**16-30**	**6-11%**
Bulk MoS_2	238	-	-
WS_2 nanotubes	152	3.7-16.3	2.4-10
Carbon nanotubes	1000	11-63	1.1-6.3
Graphene	1000	130	13

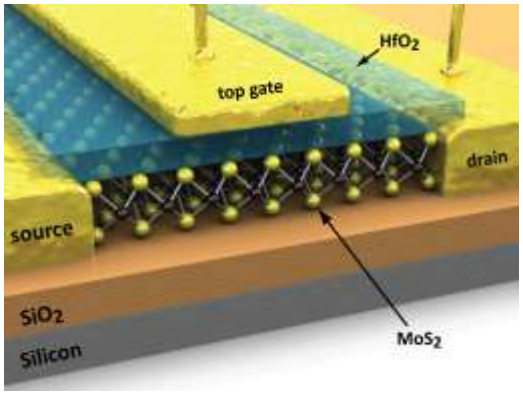
E_{Young}=(270 ± 100) GPa

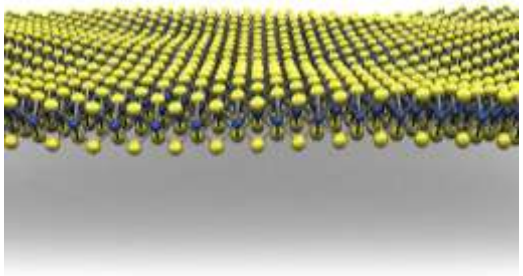
σ_{max}=(22 ± 4) GPa

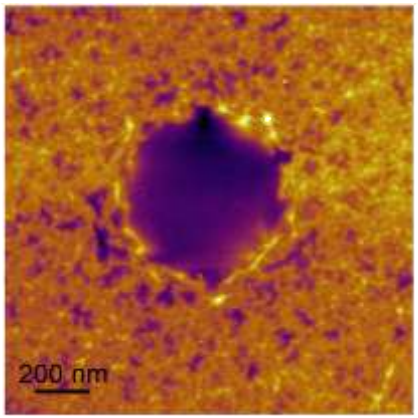
Bertolazzi, Brivio, Kis; ACS Nano 5, 9703 (2011)

Summary

- We have MoS_2 – based transistors with Ohmic contacts
- Our transistors have high ON/OFF ratios, high mobility and low leakage currents
- We have demonstrated basic electronic circuits
- Ripples are there, might be limiting the mobility
- High stiffness, strength and flexibility







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MARIE CURIE ACTIONS

FNSNF SWISS NATIONAL SCIENCE FOUNDATION