MoS_2 – based devices and circuits

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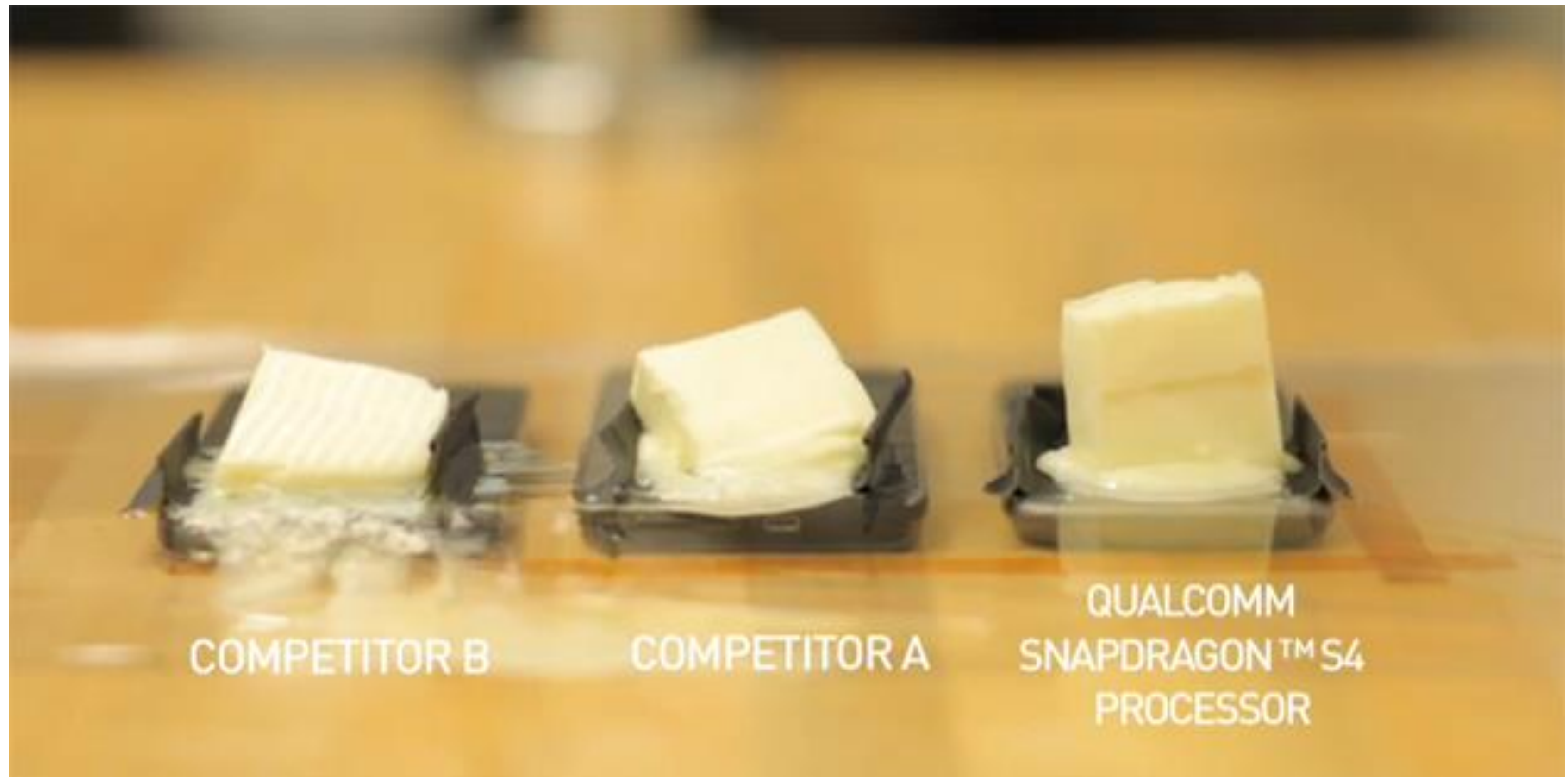
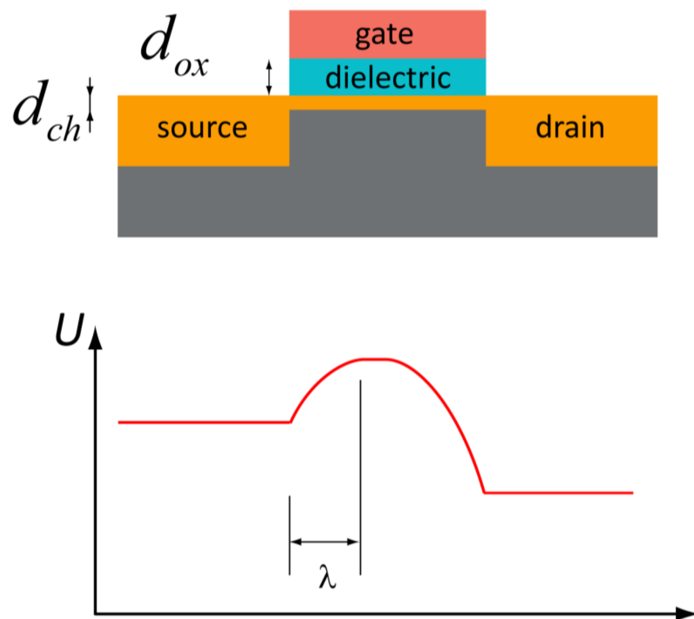
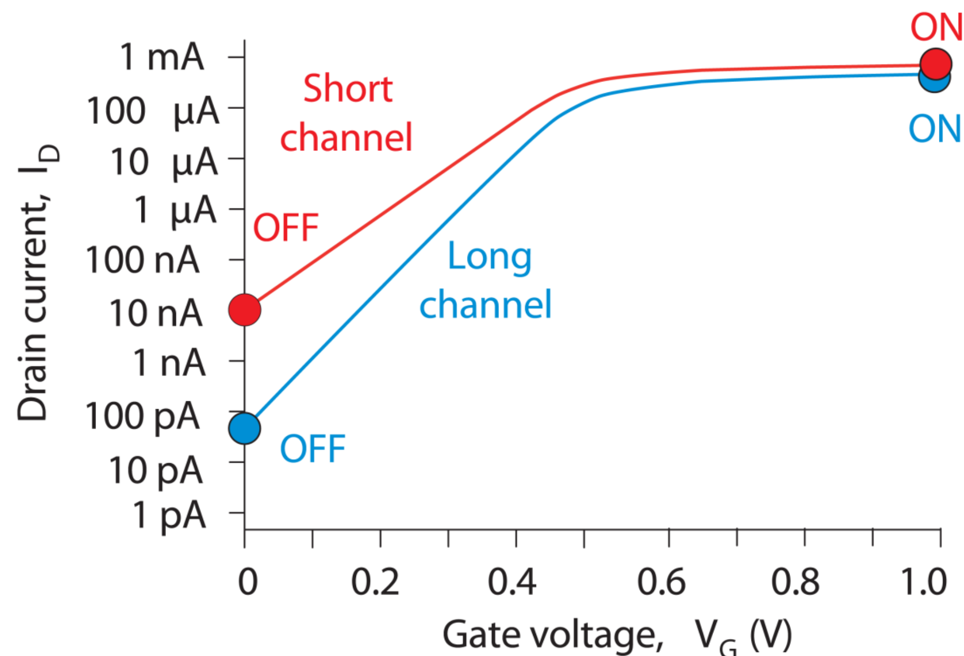
Dissipated Heat



Source: Android and Me.com

Planar MOSFET - Short Channel Effects





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

ε(Si)=11.9

To deplete the channel: min 3-5x λ

Example:

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

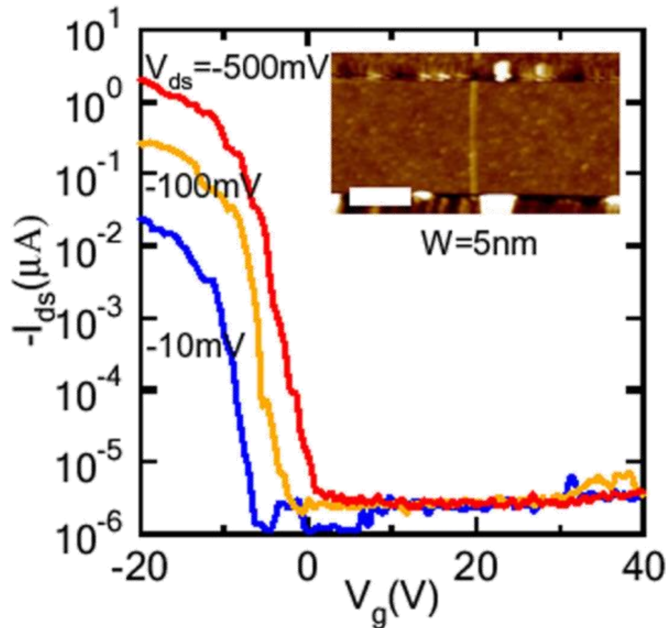
Ferain et al., Nature 479, 310 (2011)

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

One Candidate: Graphene

- Problem: no band gap in its basic form

Nanoribbons



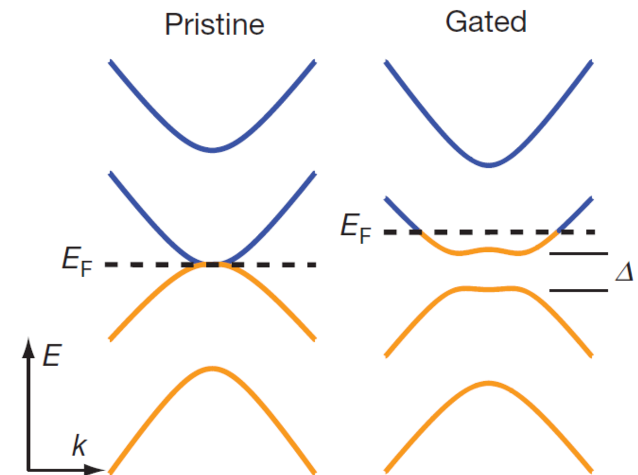
Hongjie Dai group: Science 319 1229 (2008)

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 120V

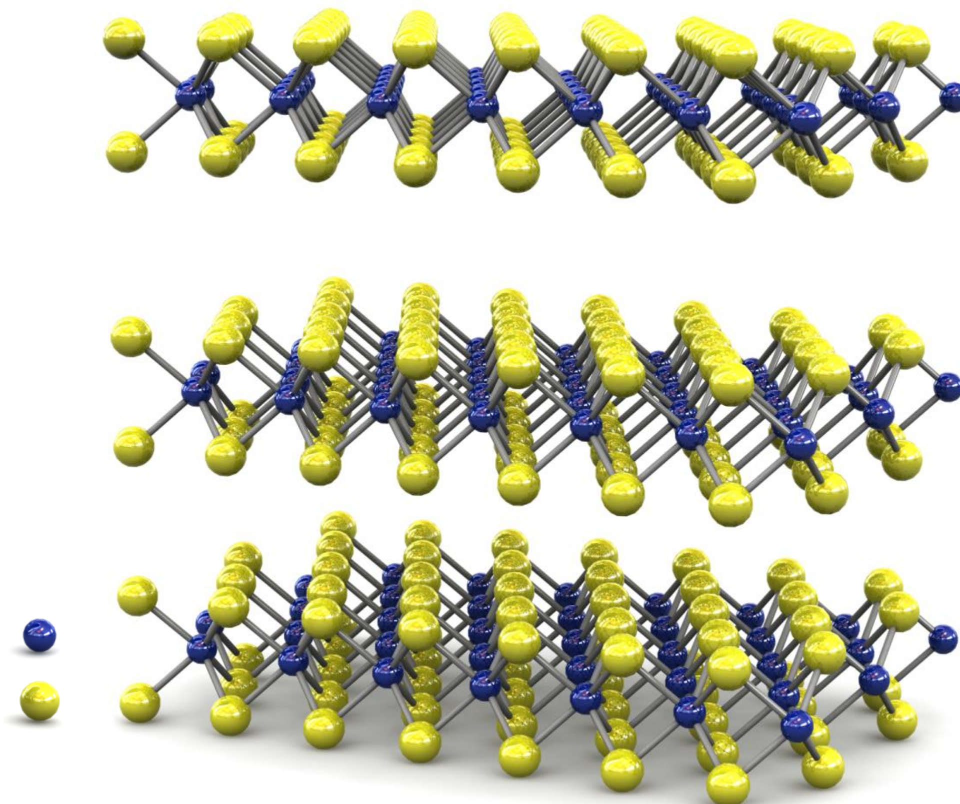
2D Transition Metal Dichalcogenides (TMD)

- Common formula: MX_2

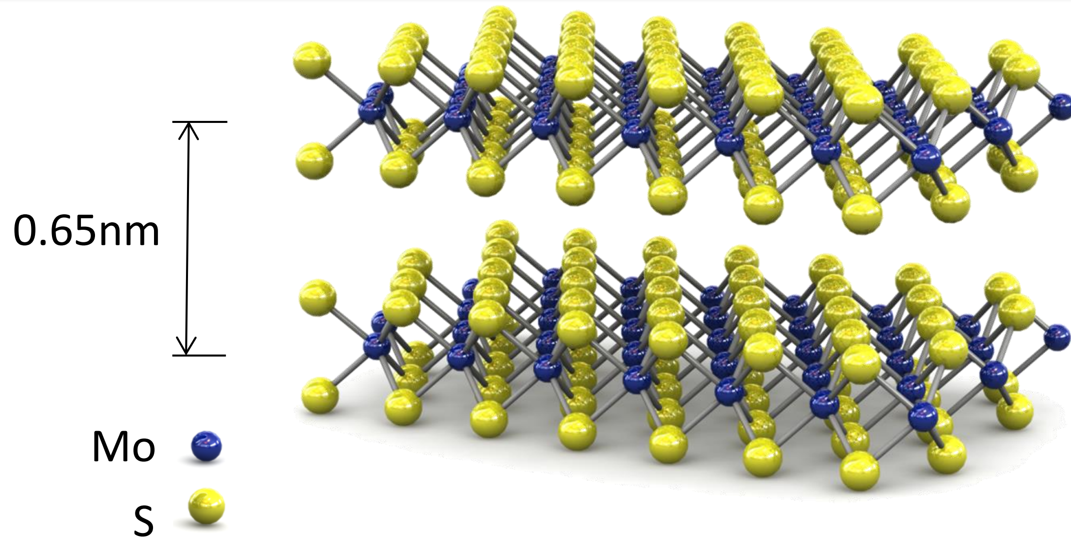
Electrical property	Material
semiconducting	MoS_2 $MoSe_2$ WS_2 WSe_2 $MoTe_2$ WTe_2
semimetallic	TiS_2 $TiSe_2$
metallic, CDW, superconducting	$NbSe_2$ NbS_2 $NbTe_2$ TaS_2 $TaSe_2$ $TaTe_2$

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

Chalcogenide X = S, Se, Te



MoS_2



MoS_2 crystal

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

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

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

Stiffness: 280 GPa (slightly higher than stainless steel)

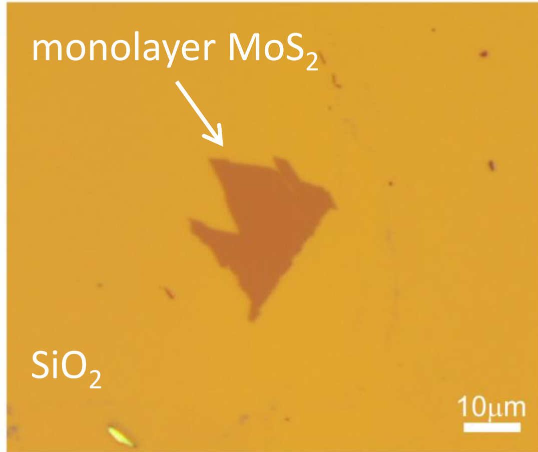
Mech. failure: 6-11% strain (at the theoretical limit of solid materials)

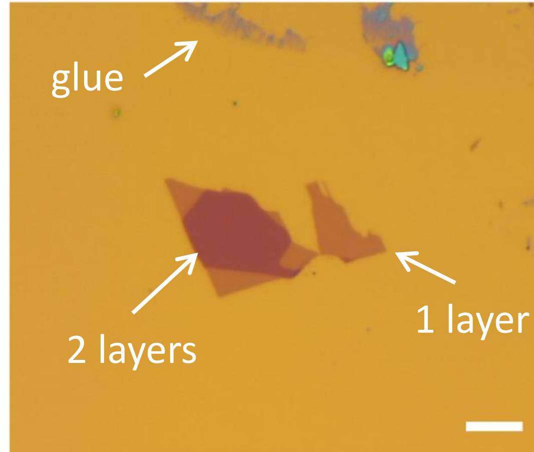
Kam et al., J. Phys. Chem. 86, 463 (1982)
Splendiani et al., Nano Let. 10, 1271 (2010)
Mak et al., PRL 105, 136805 (2010)
Bertolazzi et al., ACS Nano 5, 9703 (2011)
Lembke et al., ACS Nano 6, 10070 (2012)

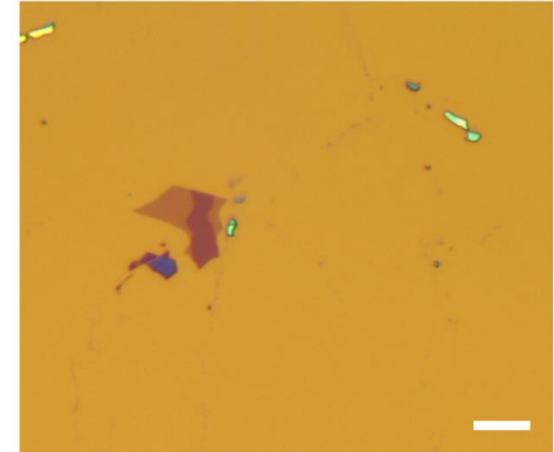
Recent review:
Wang et al., Nature Nanotech. 7, 699 (2012)

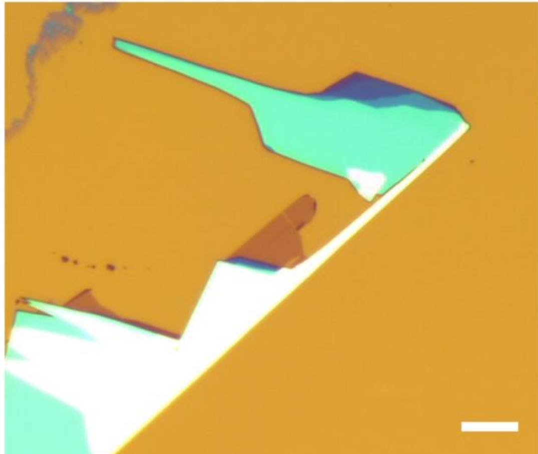
Das Original
Rostlöser
Schmiermittel
Reiniger
Korrosionsschutz
Kontaktspray
Kriechöl
Kunststoffverträglich
Verharzt nicht
Silikonfrei

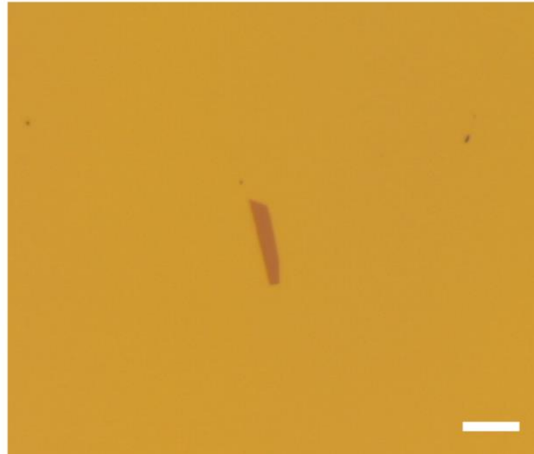
Scotch Tape Exfoliation

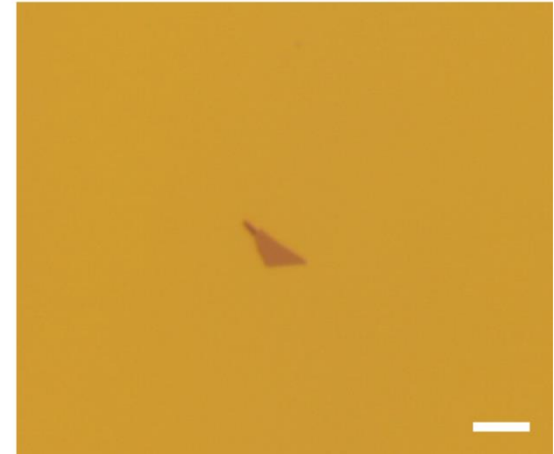




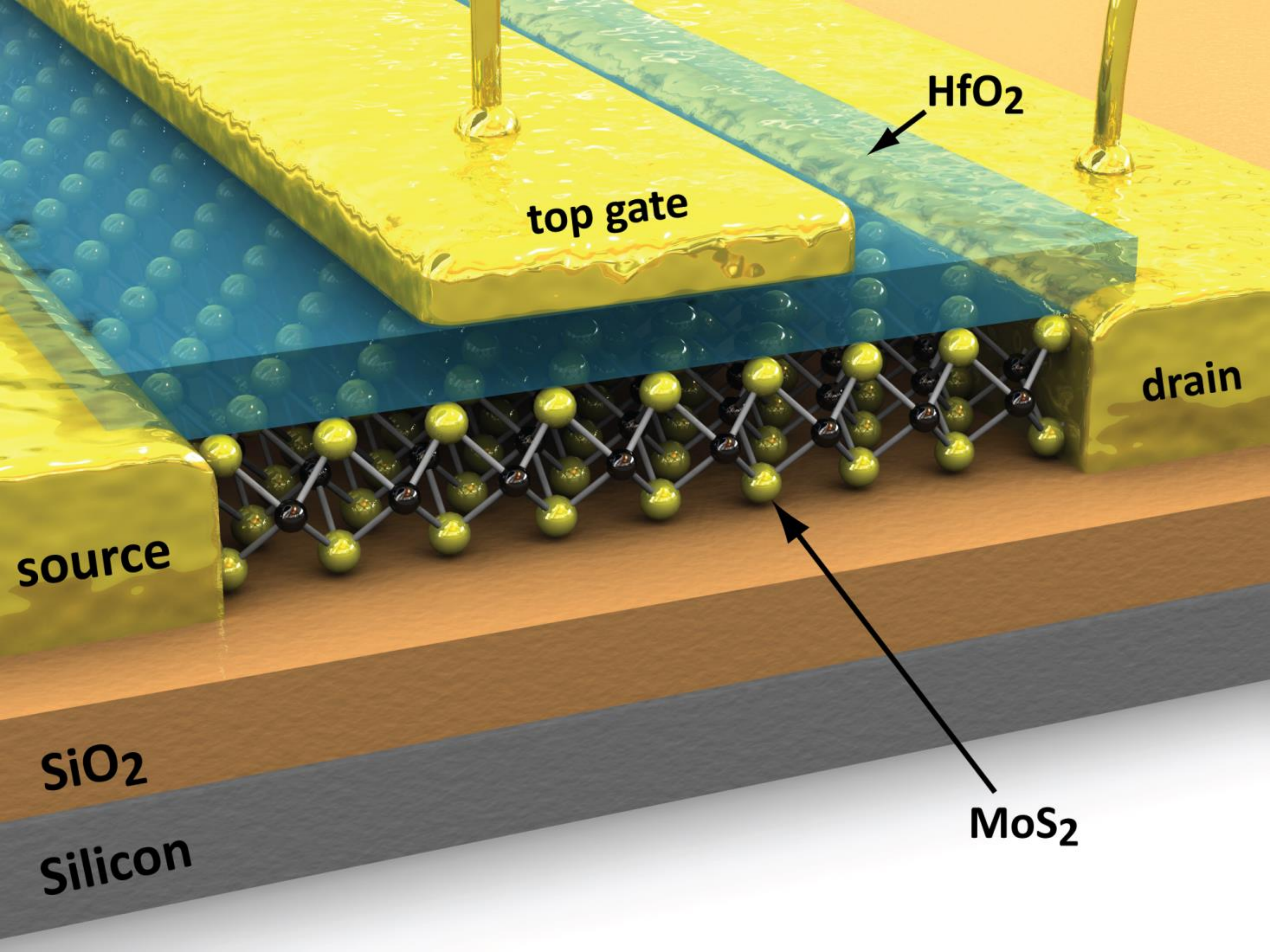




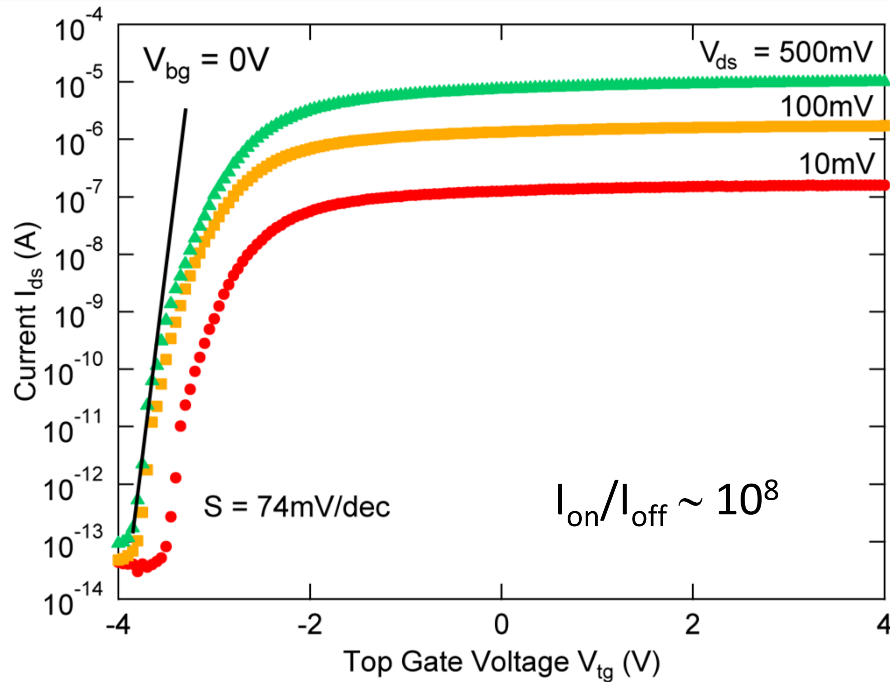


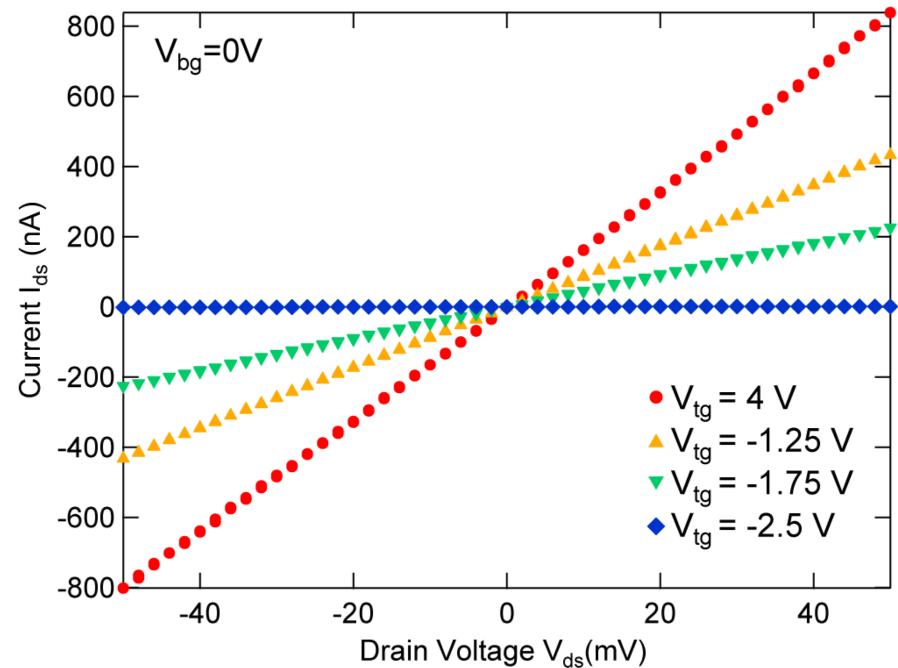


Benameur et al., Nanotechnology 22, 125706 (2011)


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

Ultralow-power MoS_2 Transistor



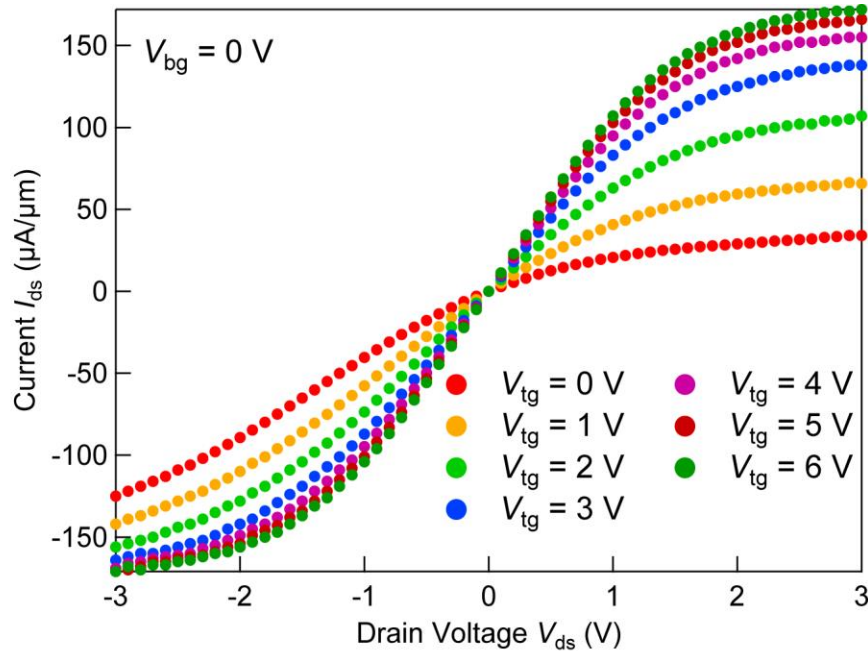


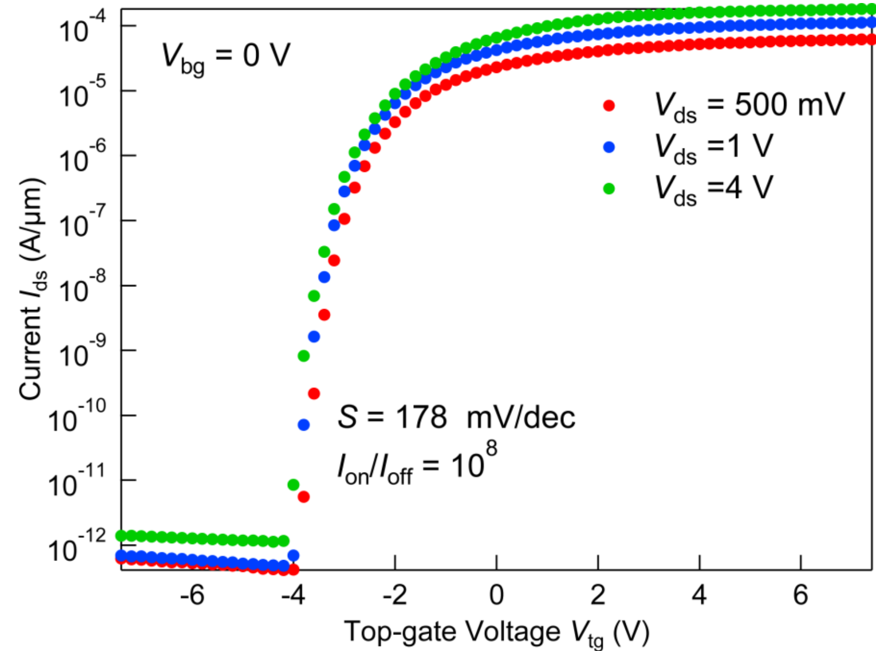
Gate length:	500 nm
Channel width:	4 µm
Mobility:	200 cm^2/Vs (FE)
	60-170 cm^2/Vs (Hall)
On/Off:	10^8
ON current:	2.5 µA/µm
OFF current:	25 fA/µm
Transconductance:	1 µS/µm

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

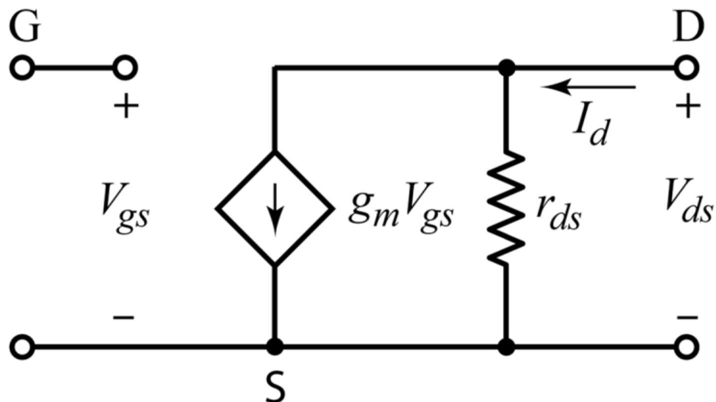
Recent Monolayer FET w Saturation

Saturation





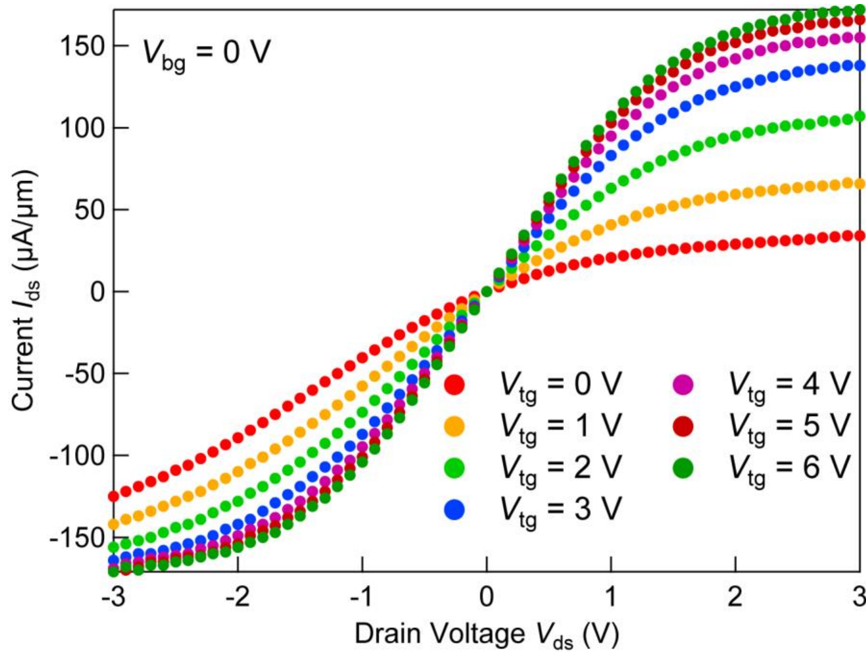
Conductance $g_{ds} = \frac{dI_{ds}}{dV_{ds}} = \frac{1}{r_{ds}}$



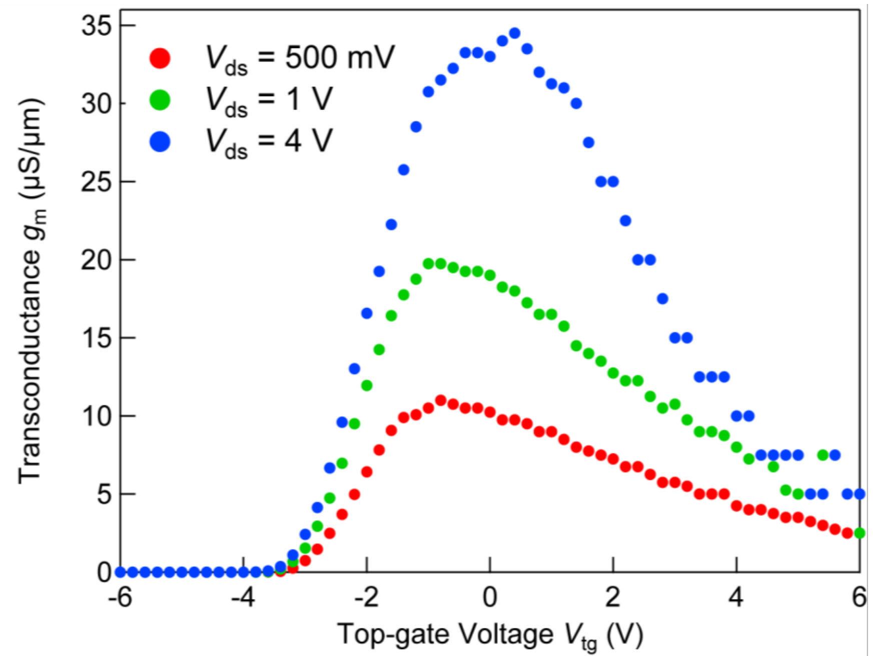
Lembke and Kis; ACS Nano 6, 10070 (2012)

Recent Monolayer FET w Saturation

Saturation

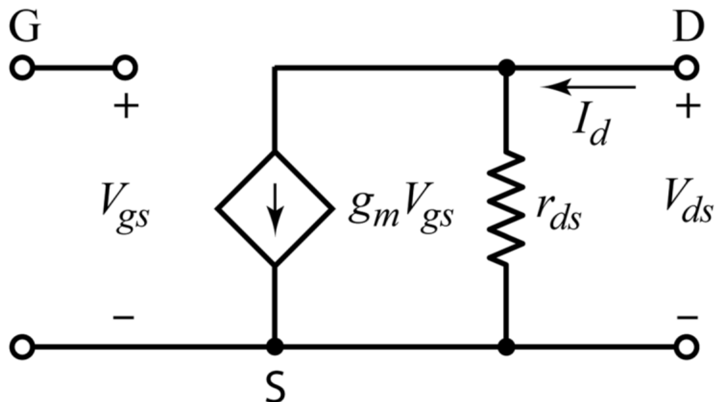


Transconductance



Conductance $g_{ds} = \frac{dI_{ds}}{dV_{ds}} = \frac{1}{r_{ds}}$

Transconductance $g_m = \frac{dI_{ds}}{dV_{tg}}$

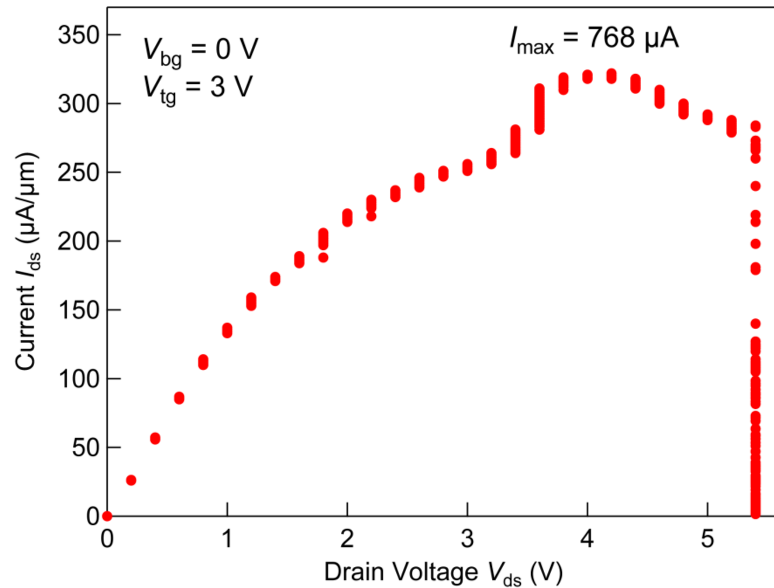


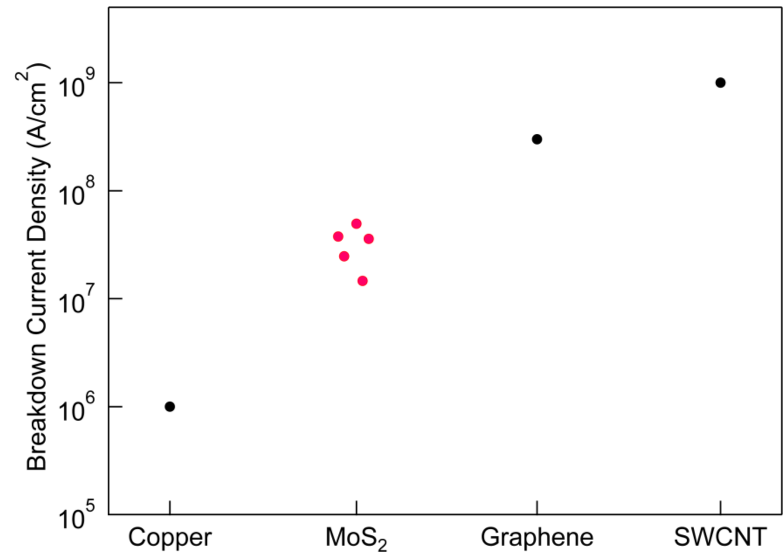
Gain $= \frac{g_m}{g_{ds}} \sim 10$

On/Off: 10^8
ON current: 170 μA/μm
Transconductance: 34 μS/μm

Lembke and Kis; ACS Nano 6, 10070 (2012)

MoS_2 Transistor Breakdown





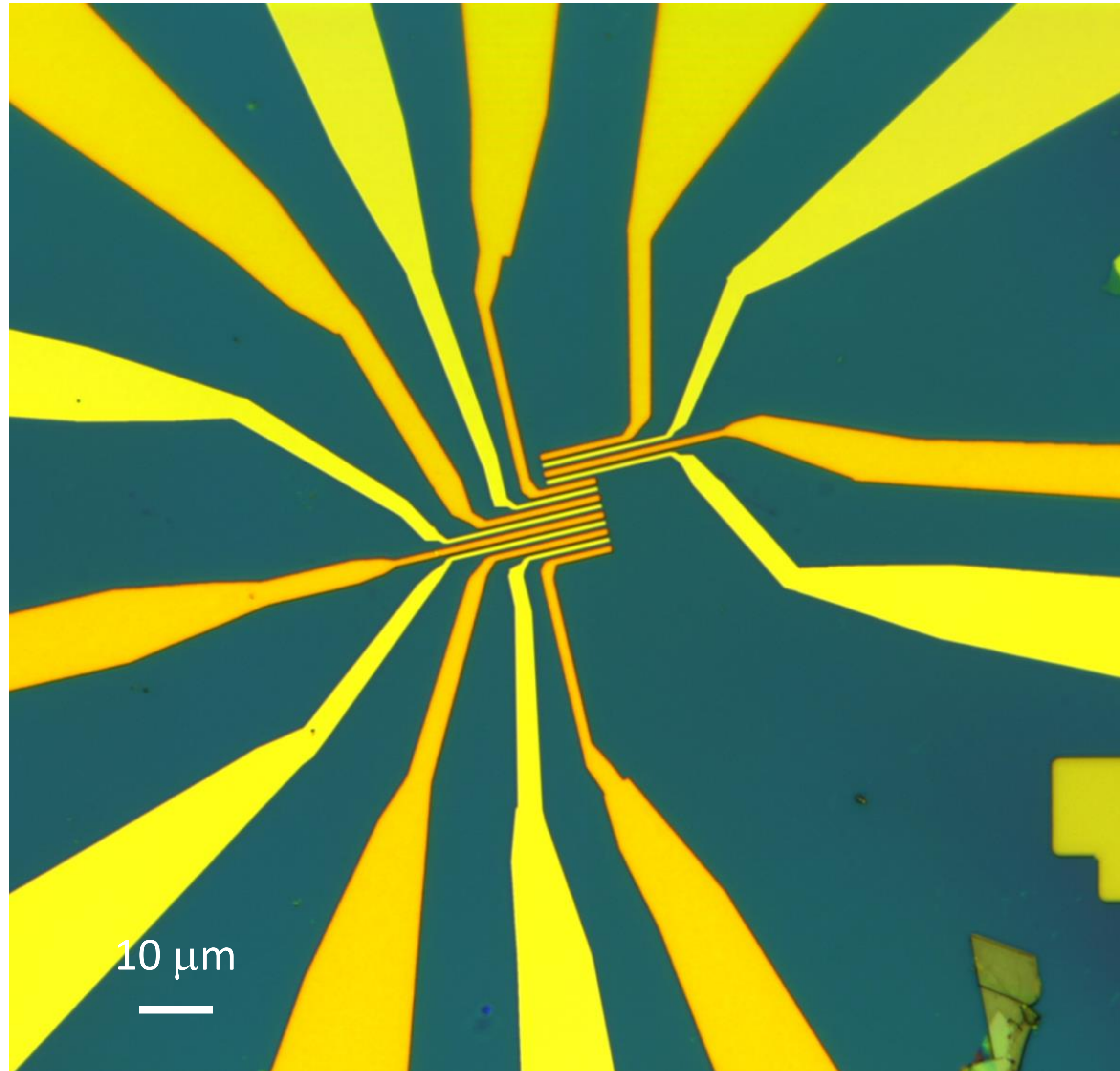
Max ON current: 320 μA/μm

Max current density: 5×10^{7}A/cm^{2} (50× higher than Cu)

Lembke and Kis; ACS Nano 6, 10070 (2012)

MoS_2 - based Integrated Circuits

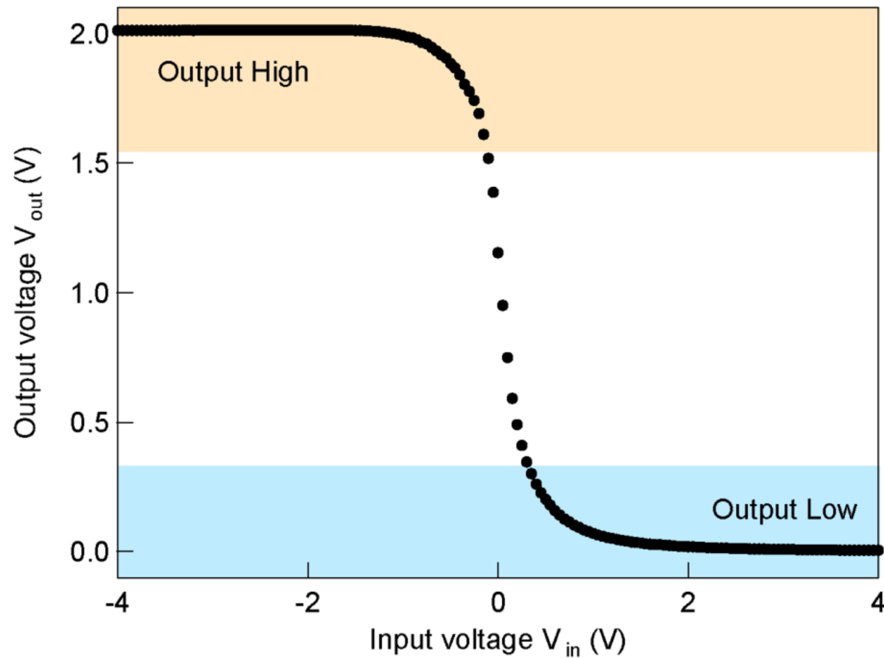
EPFL



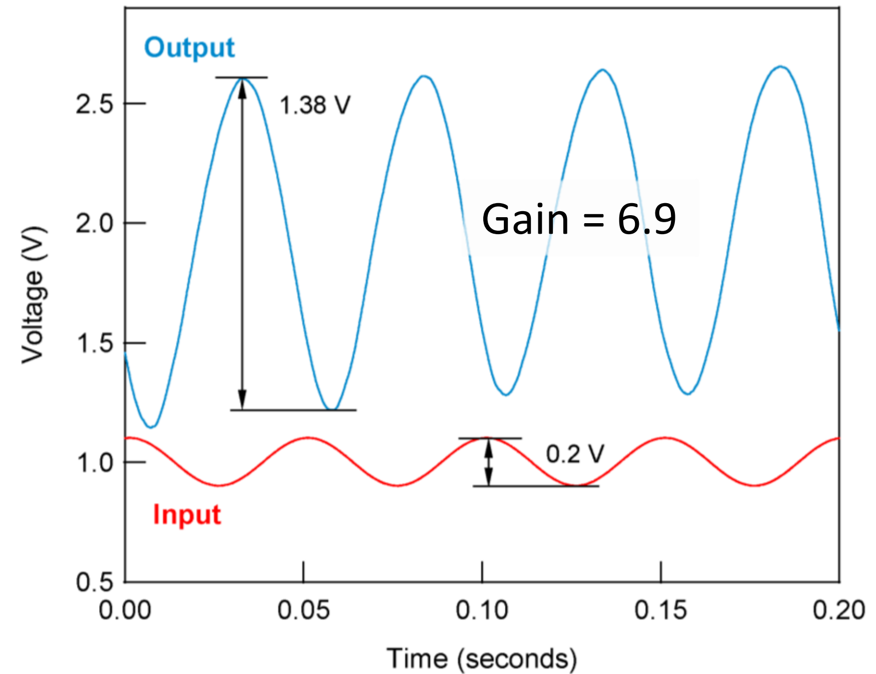
Example with 6 transistors integrated on the same piece of MoS_2

MoS_2 - based Integrated Circuits

Digital Inverter



Analog amplifier



Radisavljevic, Whitwick, Kis; ACS Nano (2011)

Radisavljevic, Whitwick, Kis; APL (2012)

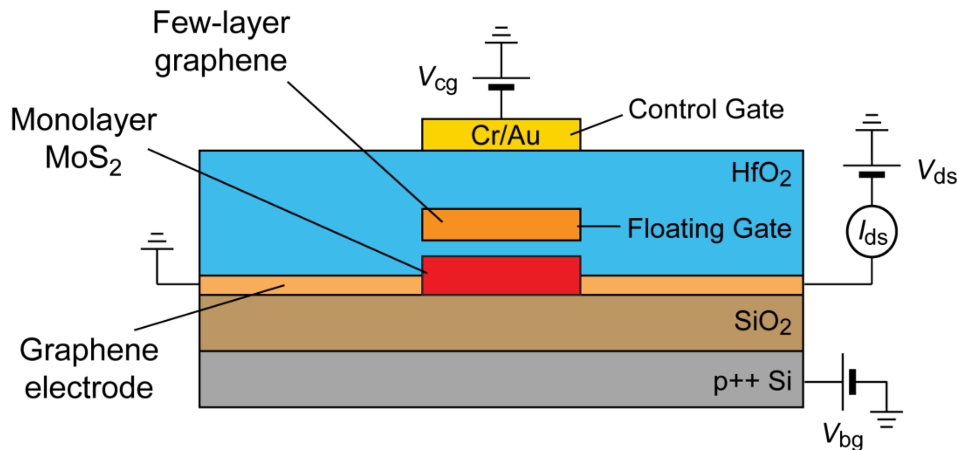
For bilayer MoS_2 see Wang, Palacios et al., Nano Lett. (2012)

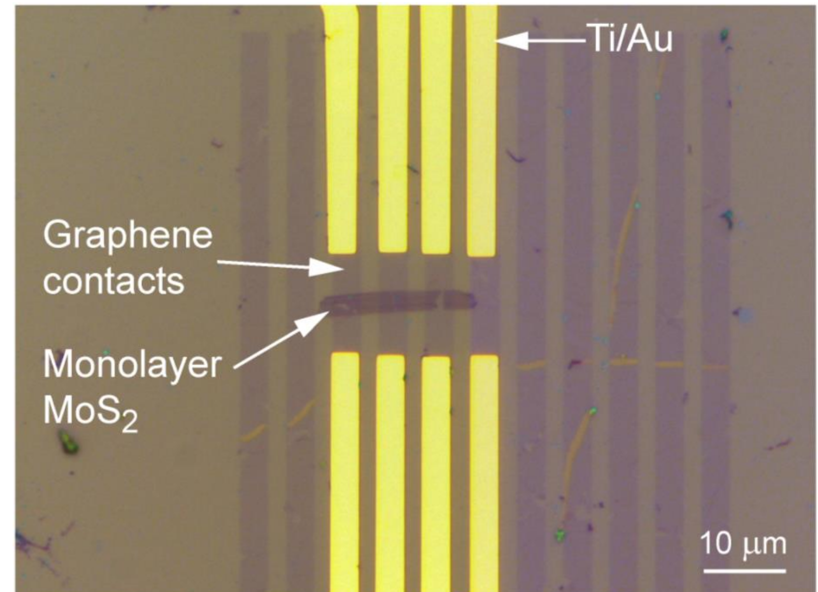
MoS_2 - graphene Flash Memory

Graphene electrode

Few-layer graphene

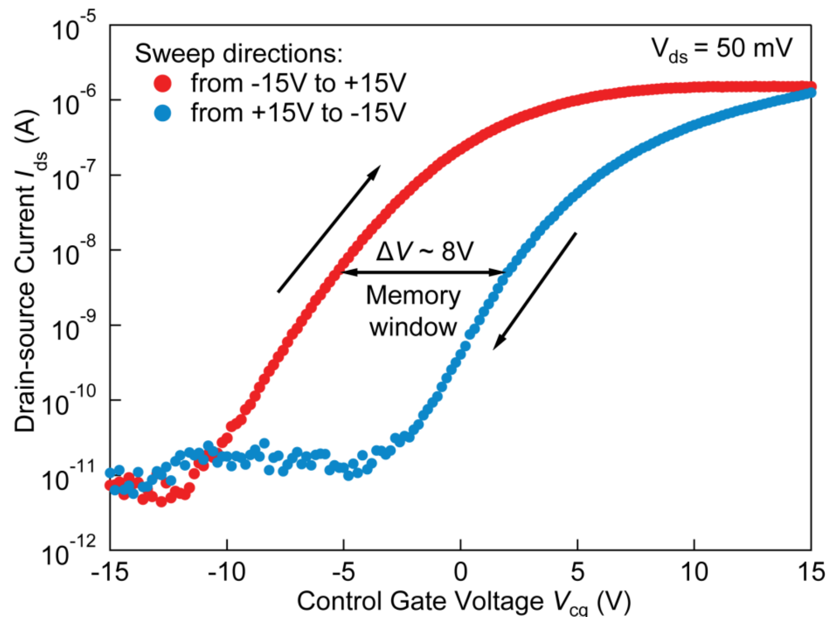
Monolayer MoS_2

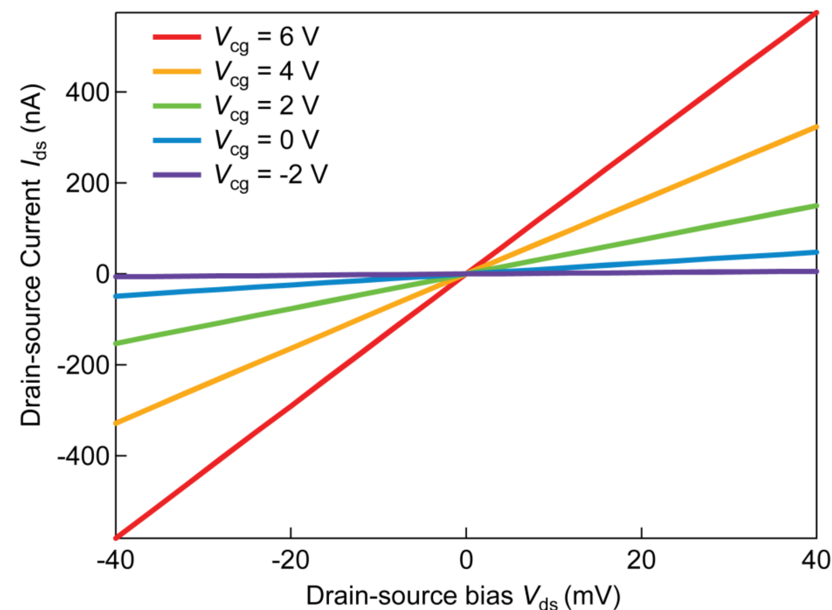


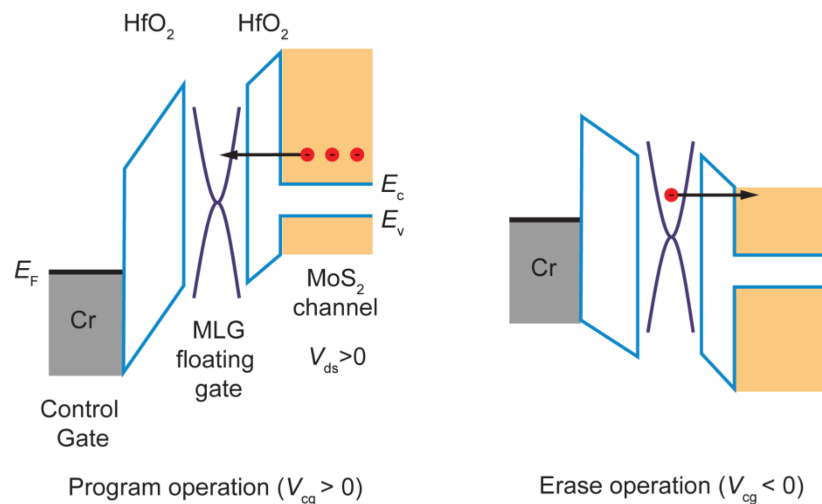


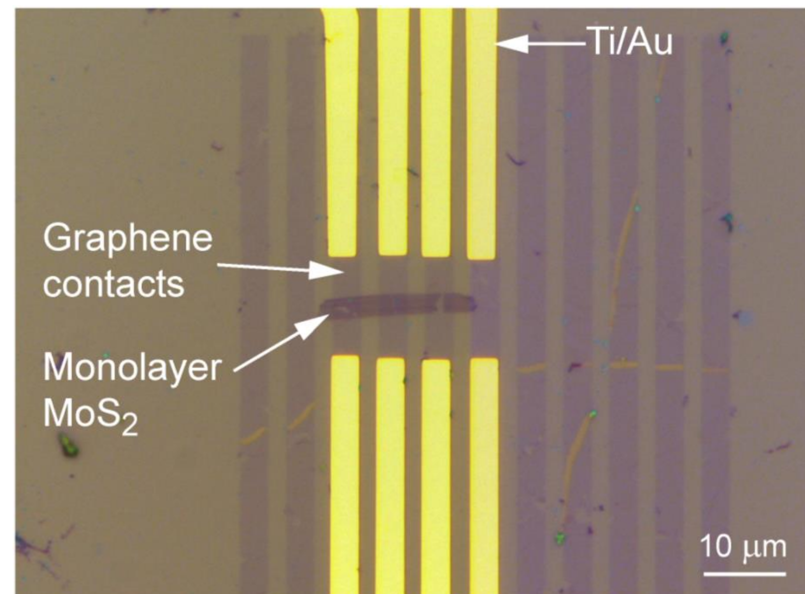
Bertolazzi, Krasnozhon, Kis; ACS Nano (2013)

MoS_2 - graphene Flash Memory



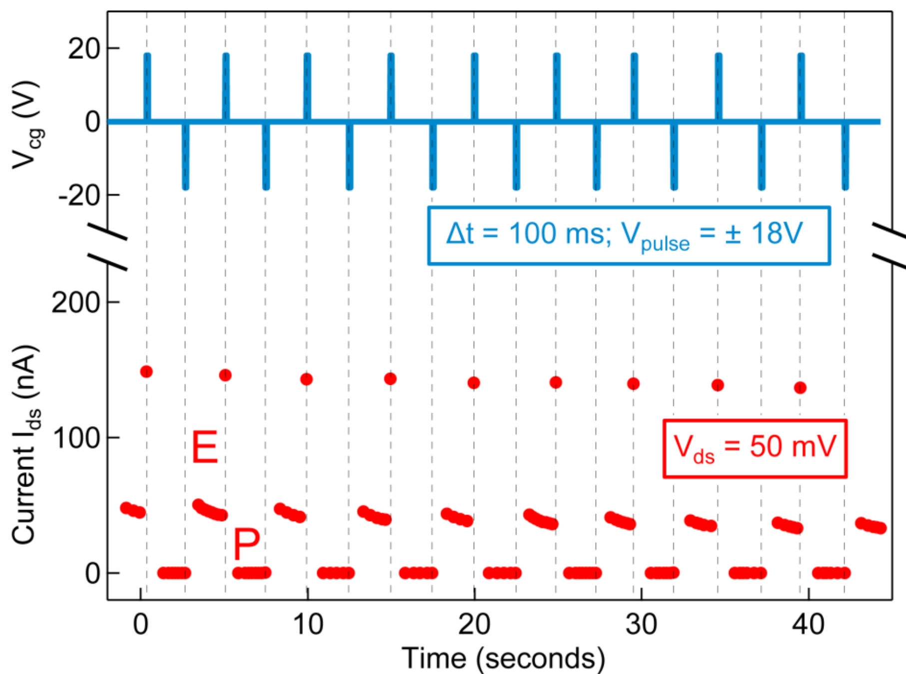


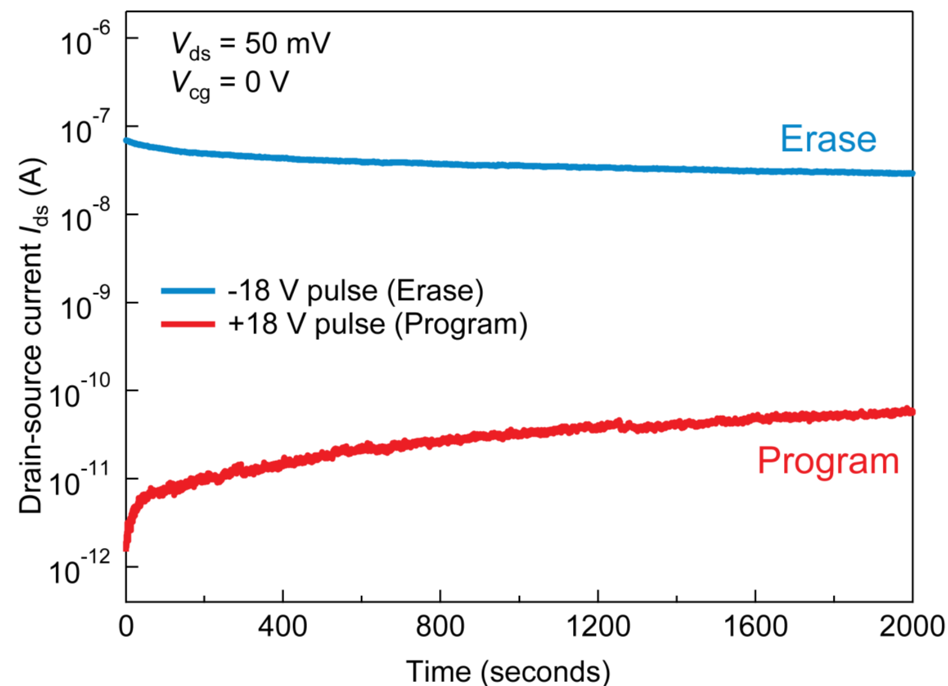




Bertolazzi, Krasnozhon, Kis; ACS Nano (2013)

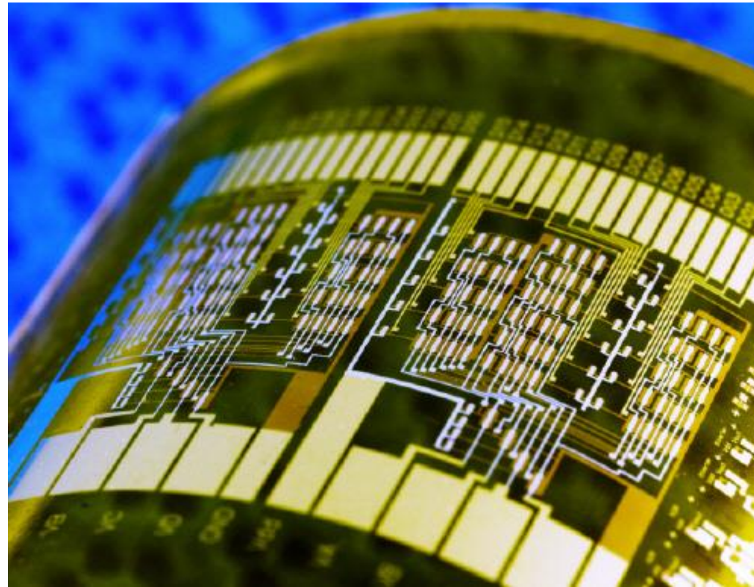
MoS_2 - graphene Flash Memory





Bertolazzi, Krasnozhon, Kis; ACS Nano (2013)

Flexibility of Electronic Materials



Material	Fracture Strain	Material	Fracture Strain
Silicon	0.7%	Polyimide	9%
ITO	0.58-1.15%	**1L MoS_2**	**6-11%**
Au	0.46%	Graphene	13%
ZnO	0.01%		

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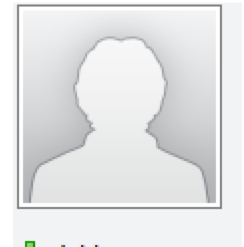
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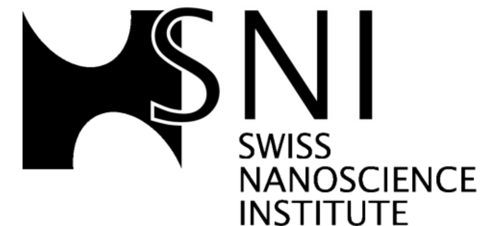

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