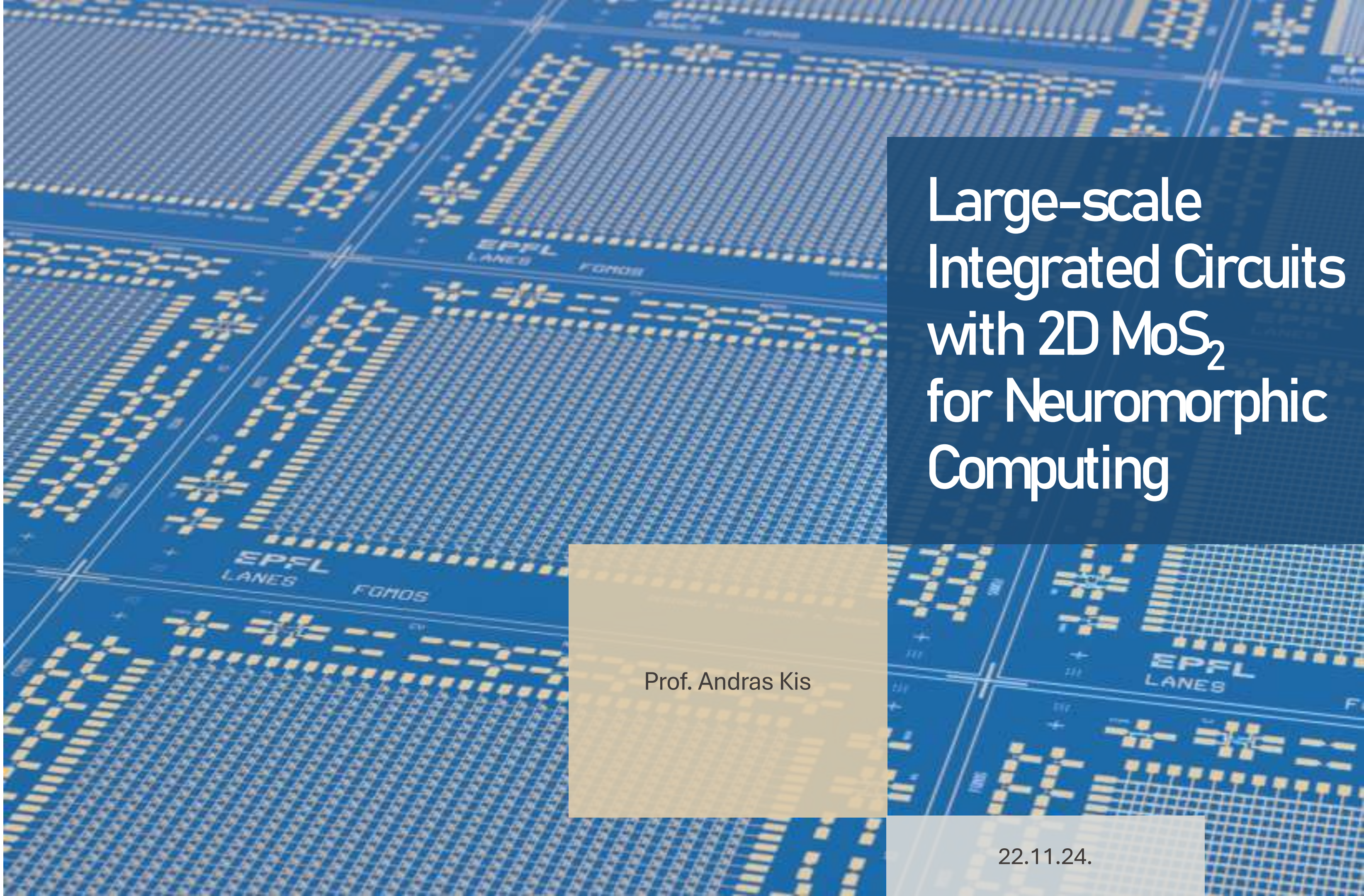
EPFL



Large-scale Integrated Circuits with 2D MoS_2 for Neuromorphic Computing

Prof. Andras Kis

22.11.24.

École Polytechnique Fédérale de Lausanne

Science and Engineering with 2D Semiconductors

“Classical” semiconductor devices

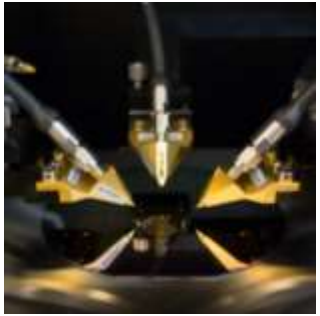
- Mobility, current density, high-frequency performance
- Memory devices, neural networks

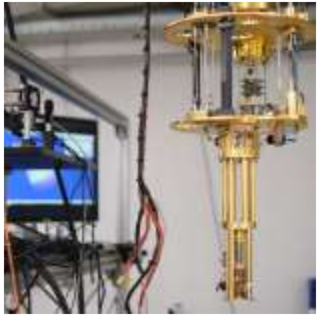
New concepts

- Valley/spin optics and electronics
- Excitonic devices and circuits

Material growth

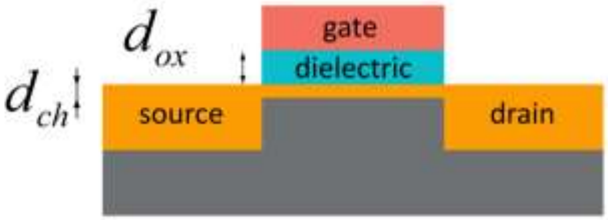
- MOCVD and CVD growth of TMDCs and heterostructures
- MBE growth of TMDCs and heterostructures



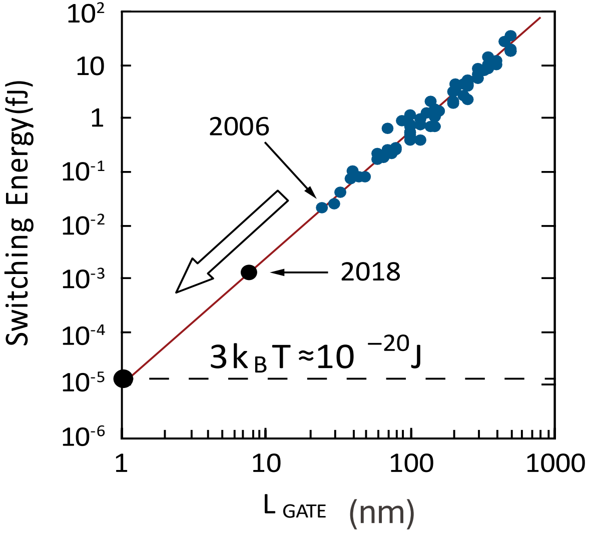


IT Energy Problem

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



Single device:



Landauer limit

Cavin et al. J Nanopart Res (2006)

System level:

Intel Core i7 8700K processor (2017)

$10^9\times$ worse! (2.5 GFLOPS/W)

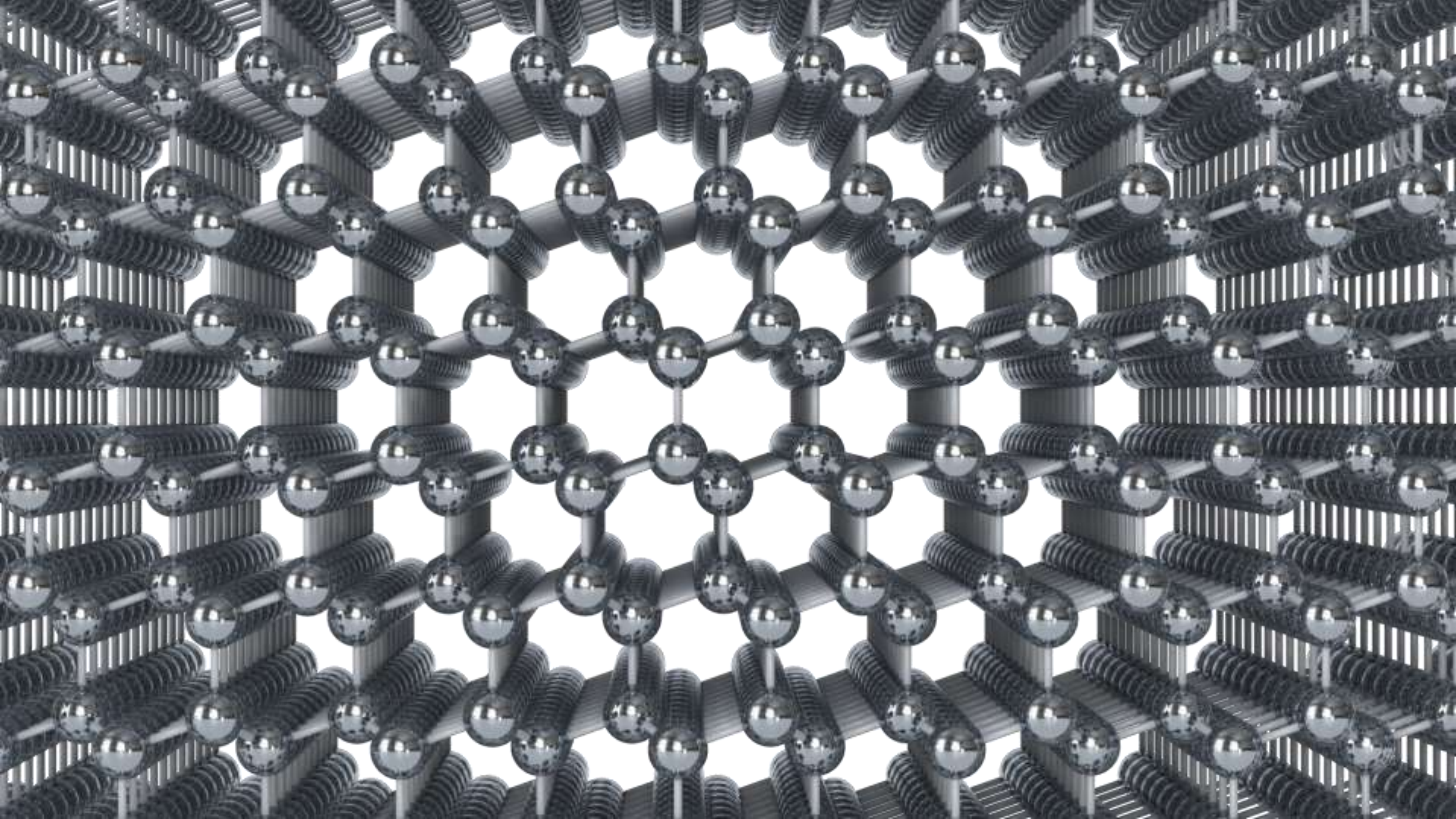
Frontier supercomputer (ORNL, 2022)

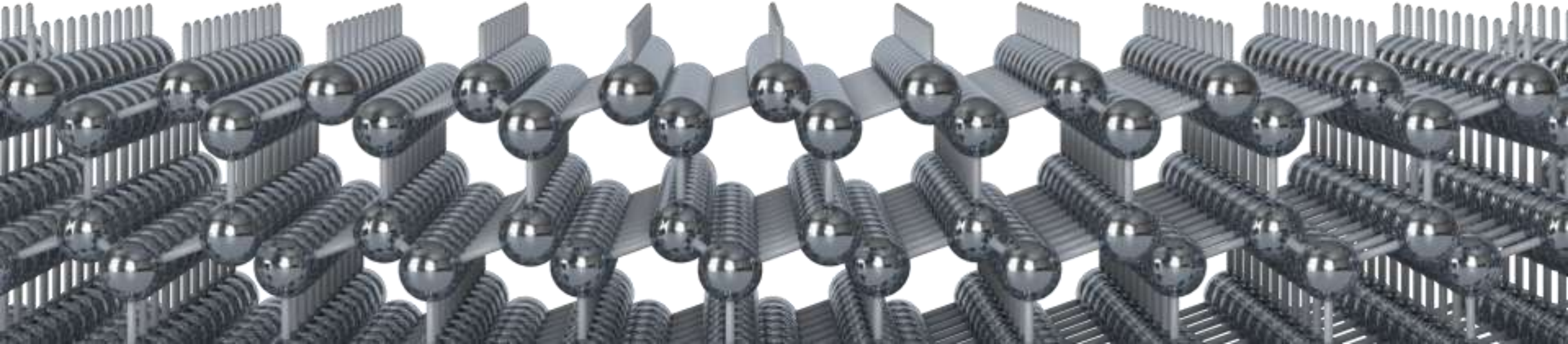
$4{\cdot}10^7\times$ worse (62.68 GFLOPS/W)

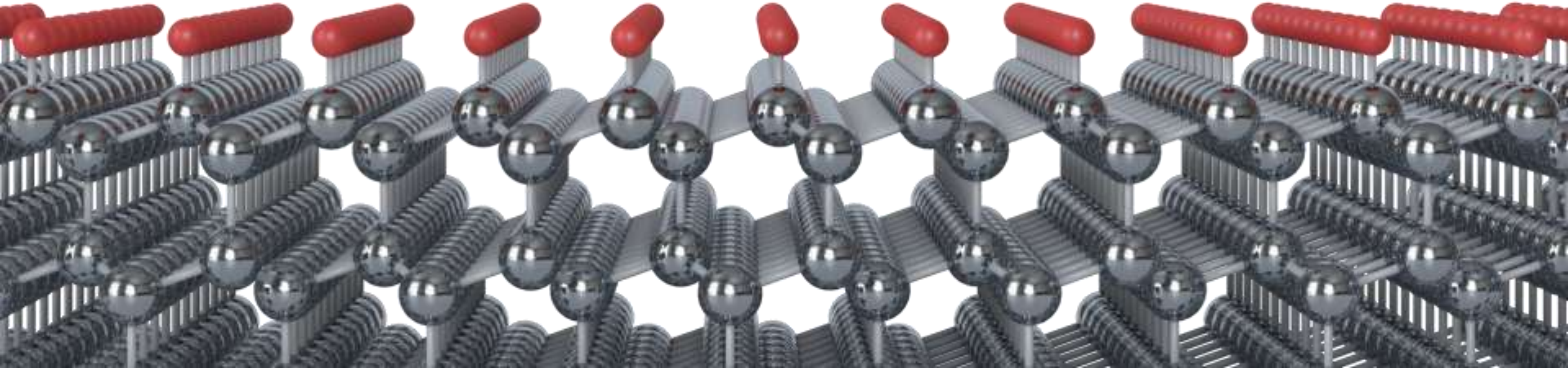
A100 40 GB (NVIDIA, 2023)

$3.7{\cdot}10^7\times$ worse (78 GFLOPS/W)

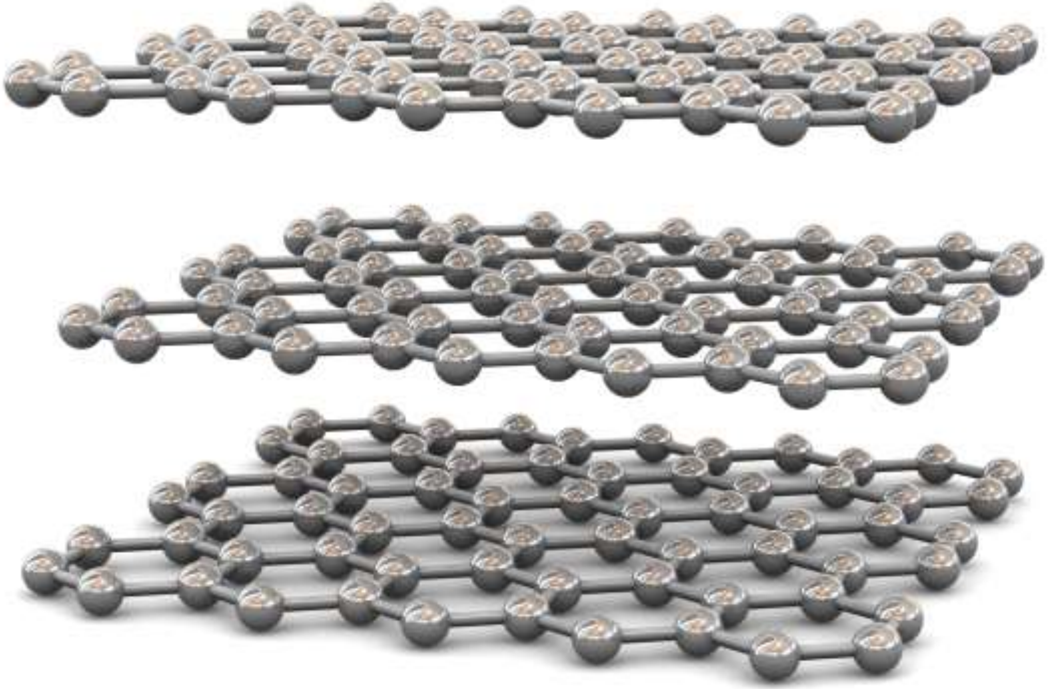
John von Neumann



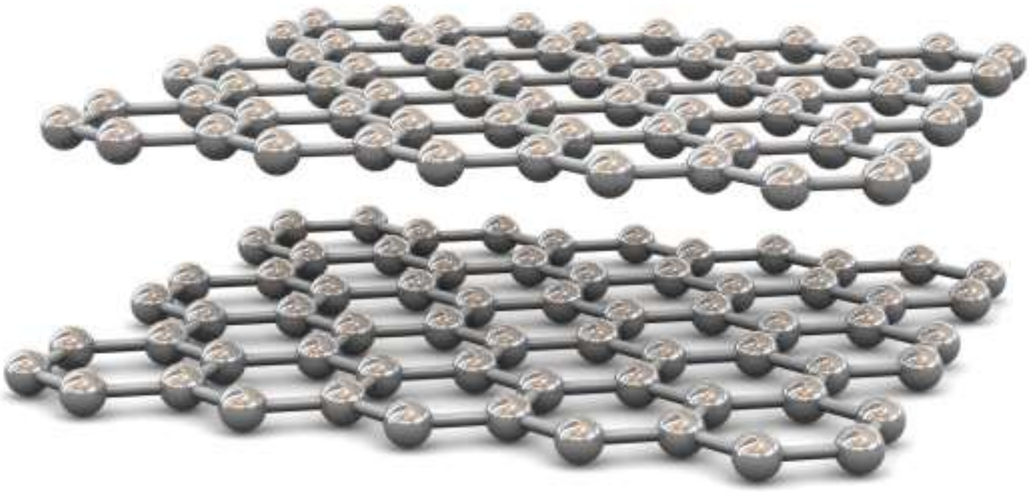




Graphite and Graphene

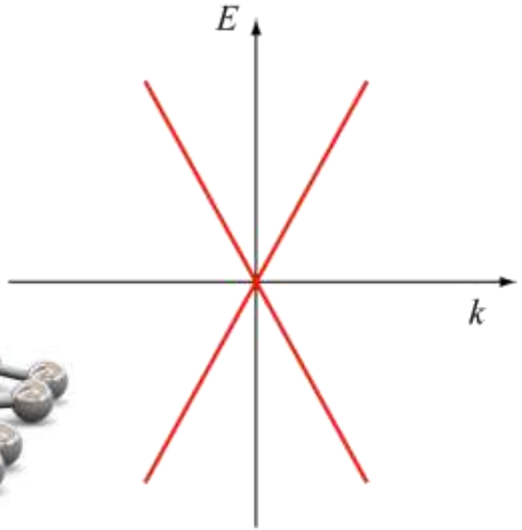


Graphite and Graphene



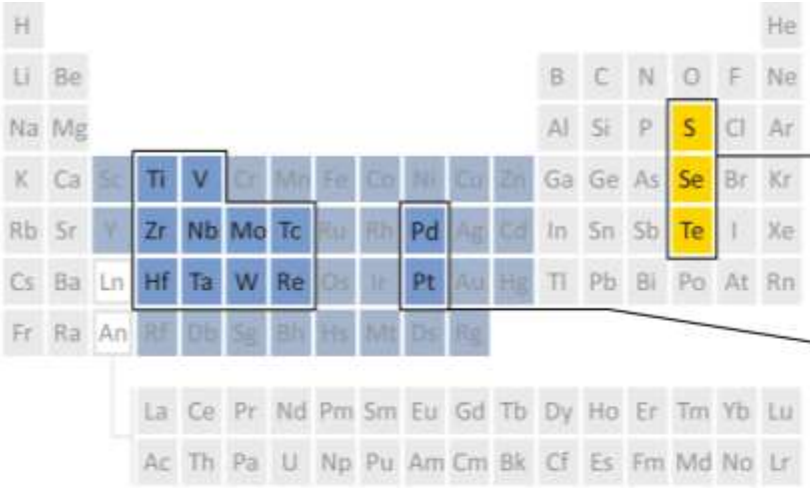
Graphite and Graphene

2010 Physics Nobel Prize (Andre Geim, Konstantin Novoselov)



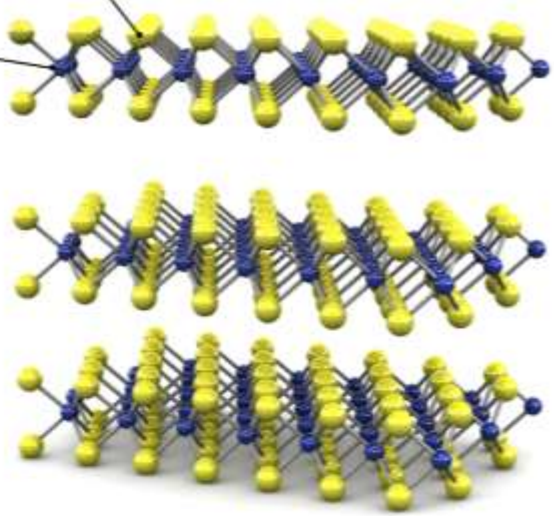
No band gap!

2D Transition Metal Dichalcogenides (TMDCs)



Common formula: MX_2

40 stable materials



Semiconductors: MoS_2 $MoSe_2$ WS_2 WSe_2
$MoTe_2$ WTe_2

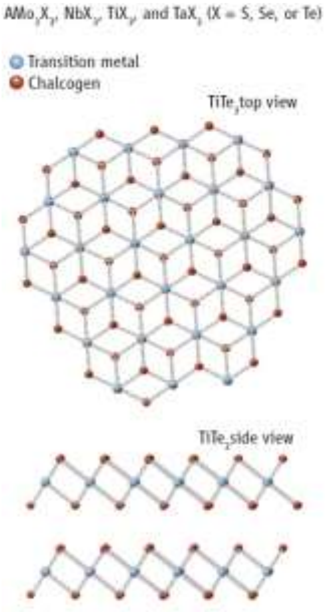
Semimetals: TiS_2 $TiSe_2$

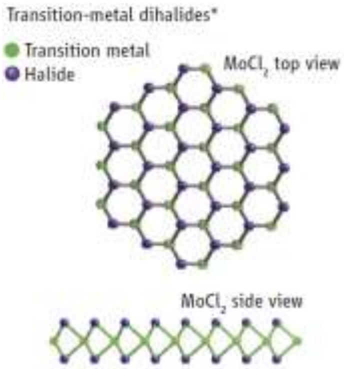
Metals, CDW, superconductors: $NbSe_2$ NbS_2 $NbTe_2$
TaS_2 $TaSe_2$ $TaTe_2$

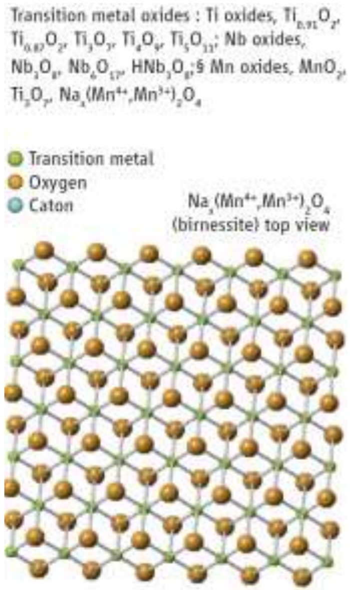
Tip of the Iceberg

>500 potentially interesting 2D materials

Transition metal trichalcogenides	Metal phosphorous trichalcogenides	Transition metal dihalides	Transition metal oxides



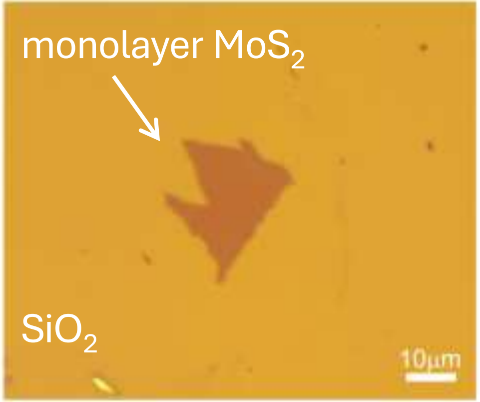


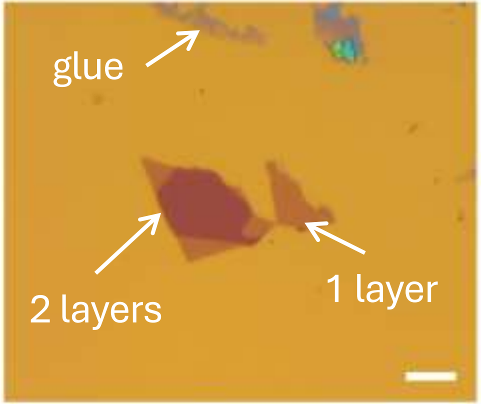


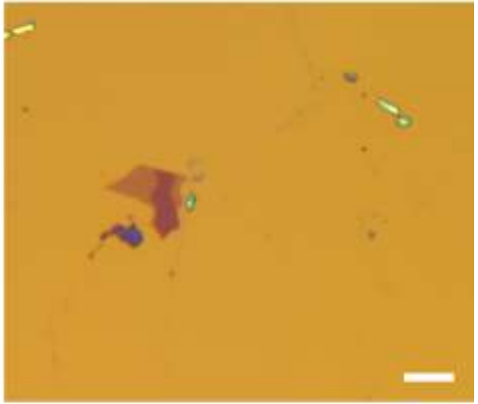
Nicolosi…Coleman; Science (2013)

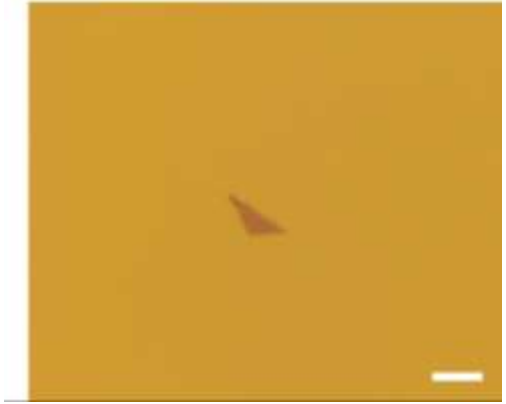
Molybdenite on quartz, Moly Hill mine, La Motte, Québec, Canada
Source: Wikipedia

Scotch Tape Exfoliation



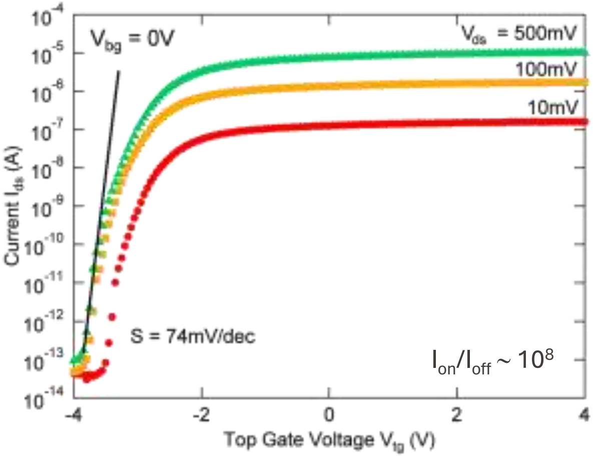


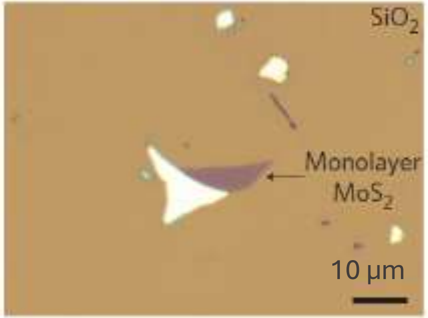


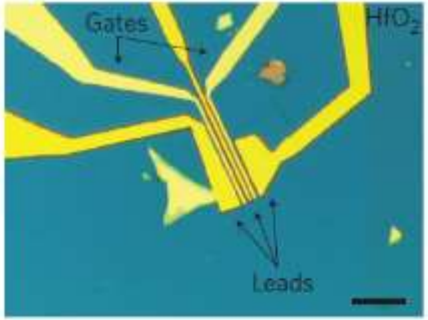


Benameur...Kis, Nanotechnology (2011)

Our First Contribution: Monolayer MoS_2 Transistor







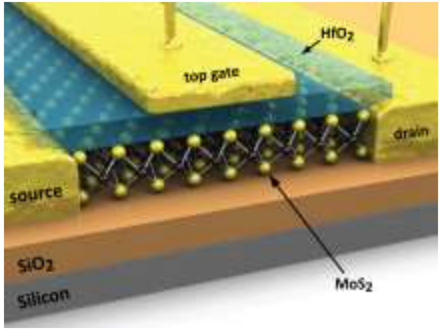
Gate length:	500 nm
Channel width:	4 μm
On/Off:	10^8
ON current:	2.5 μA/μm
OFF current:	25 fA/μm

Radisavljevic...Kis, Nature Nanotechnology (2011)

Patent US9608101B2

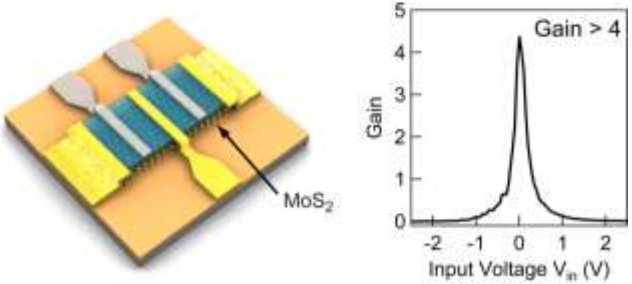
2D Device Breakthroughs

MoS_2 Transistor



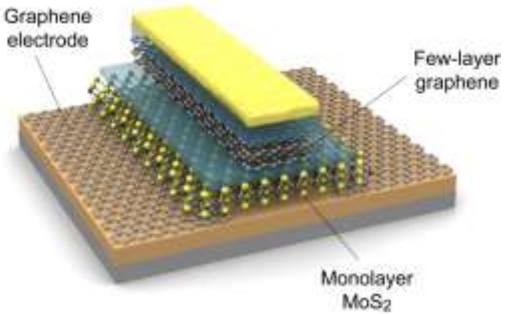
Radisavljevic...Kis; Nature Nanotech. (2011)

MoS_2 Inverter



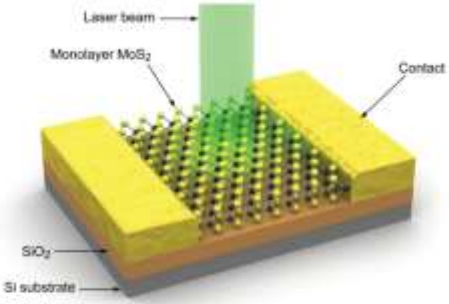
Radisavljevic...Kis; ACS Nano (2011)

MoS_2 Memory Cell



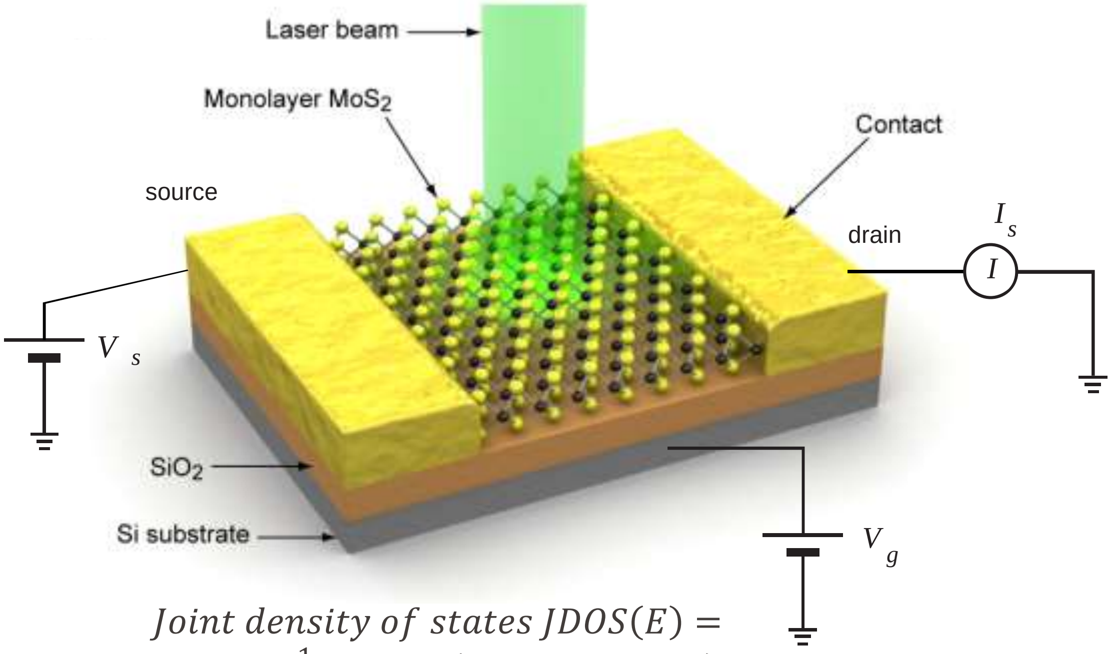
Bertolazzi...Kis; ACS Nano (2013)

Ultrasensitive Photodetector



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

Phototransistors/photodetectors

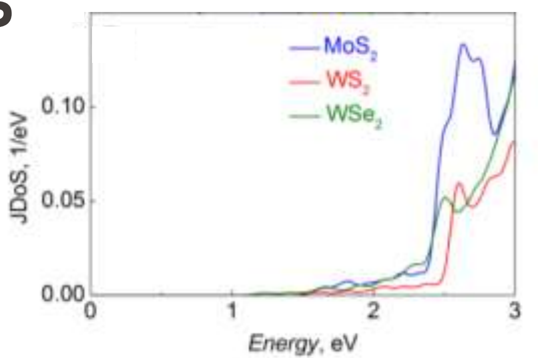


$$Joint\ density\ of\ states\ JDOS(E) = \frac{1}{4\pi^3}\int d^3k\delta\left(E_{V,k} - E_{C,k} - E\right)$$

$$Photocurrent\ I_{ph} = I_{light} - I_{dark}$$

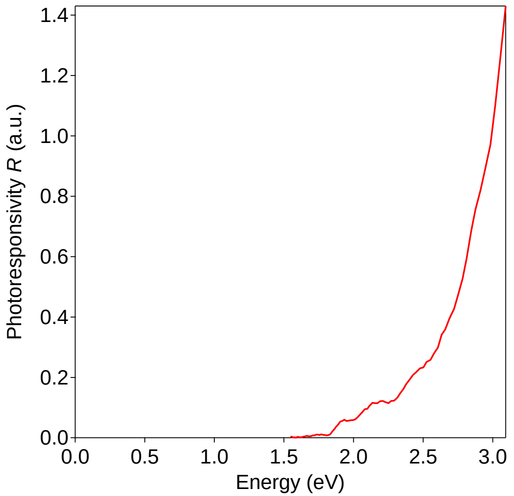
$$Responsivity\ R = \frac{I_{ph}}{P_{inc}}$$

Calculations



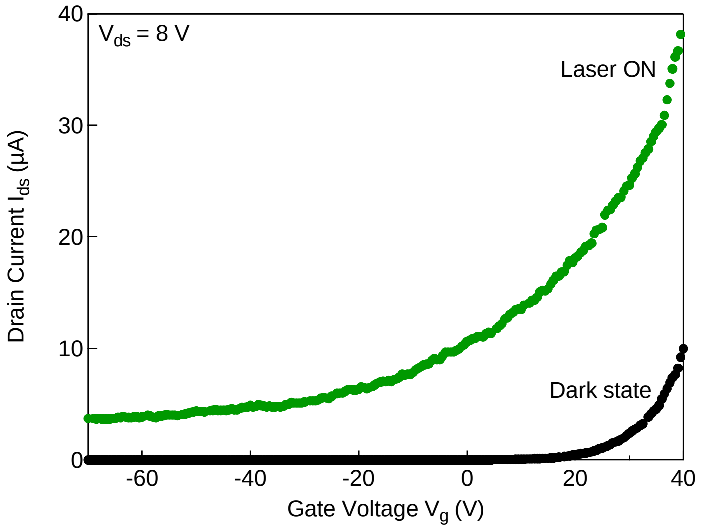
Britnell...Novoselov; Science (2013)

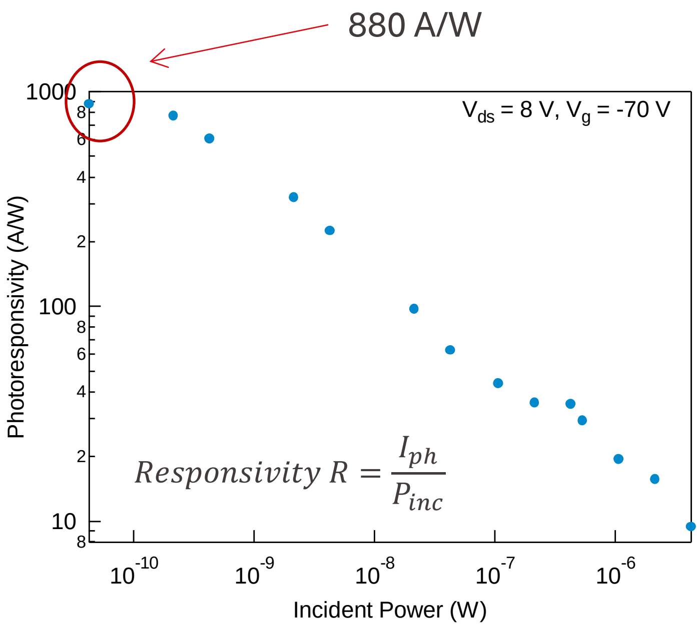
Measurements



Lopez Sanchez...Kis; Nat. Nanotech. (2013)

MoS_2 Photodetectors: Responsivity

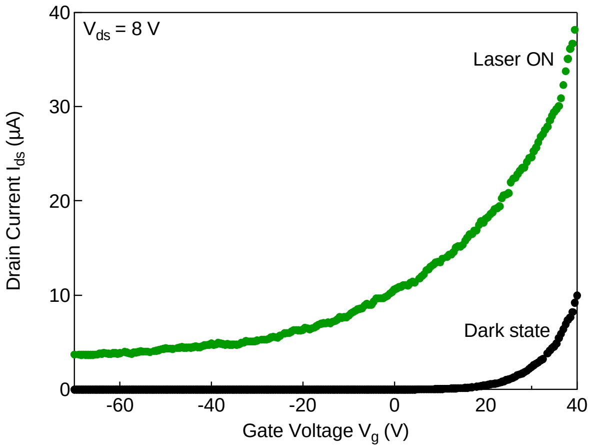


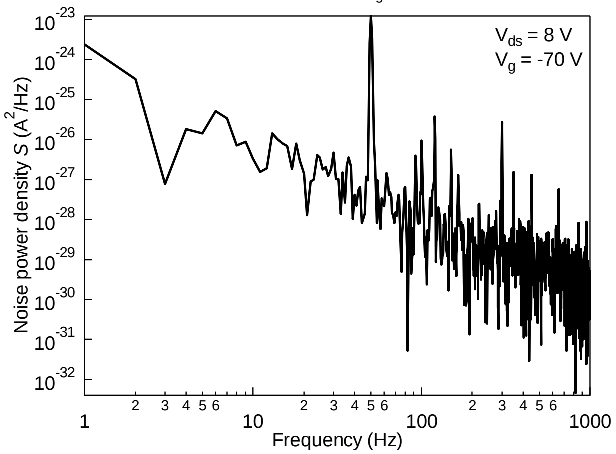


$$Responsivity\ R = \frac{I_{ph}}{P_{inc}}$$

Lopez-Sanchez, Nature Nanotechnology (2013)

MoS_2 Photodetectors: Noise





- **Si diodes**
  Photoresponsivity: 0.5 A/W
  NEP: 1×10^{-14} W/Hz$^{1/2}$

- **MoS_2**
  Photoresponsivity: 880 A/W
  NEP: 1.8×10^{-15} W/Hz$^{1/2}$

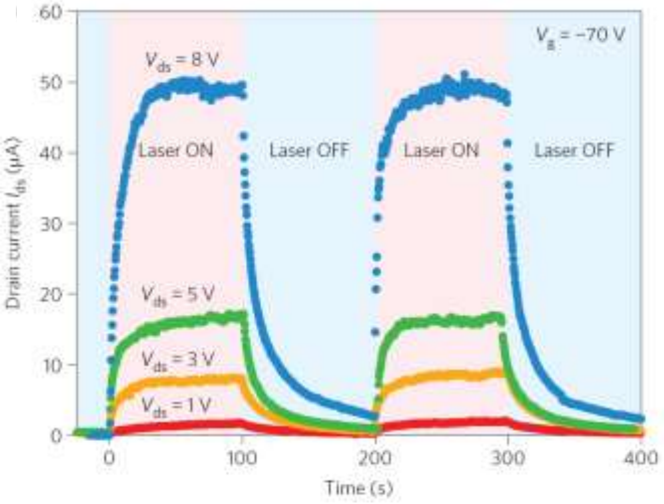
  Equivalent min. photon flux for the MoS_2 photodetector: 1×10^{-17} lux

  Full moon: 0.1-0.3 lux
  Starlight, no airglow, no moon: 0.0001 lux

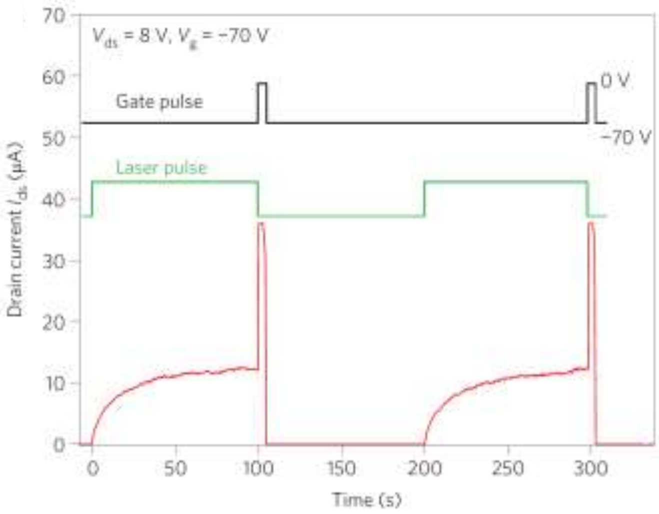
Lopez-Sanchez, Nature Nanotechnology (2013)

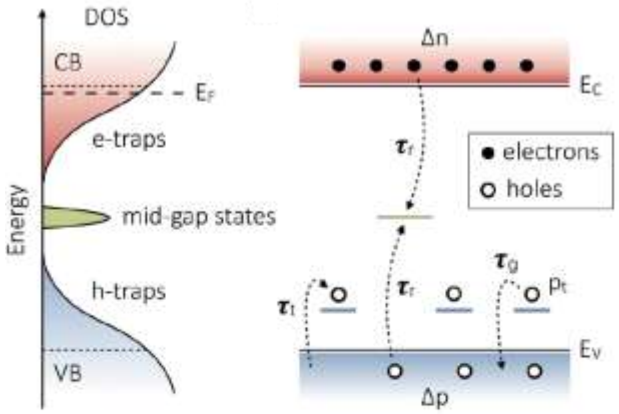
EPFL

Photocurrent Dynamics



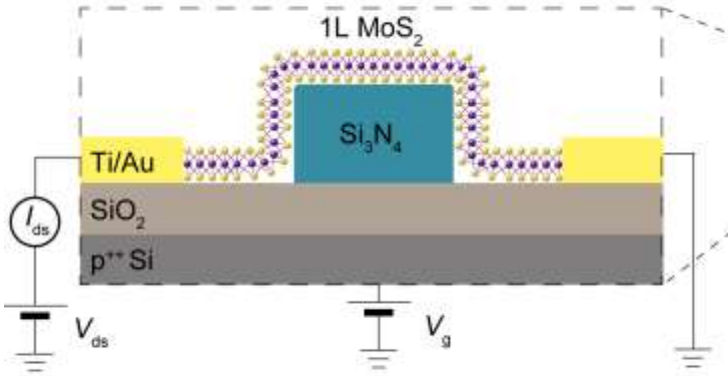
Lopez-Sanchez, Nature Nanotechnology (2013)

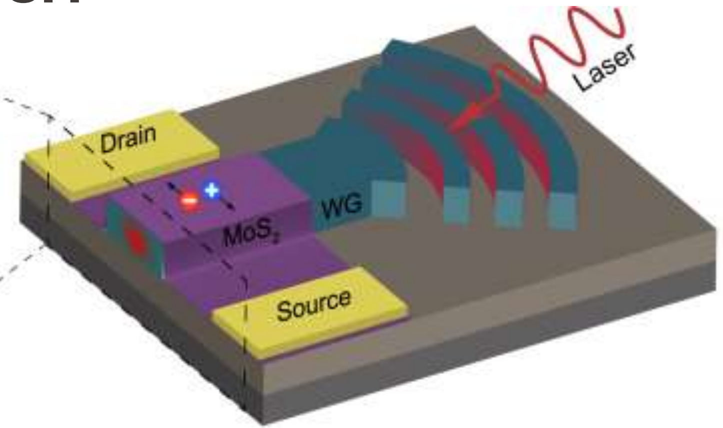


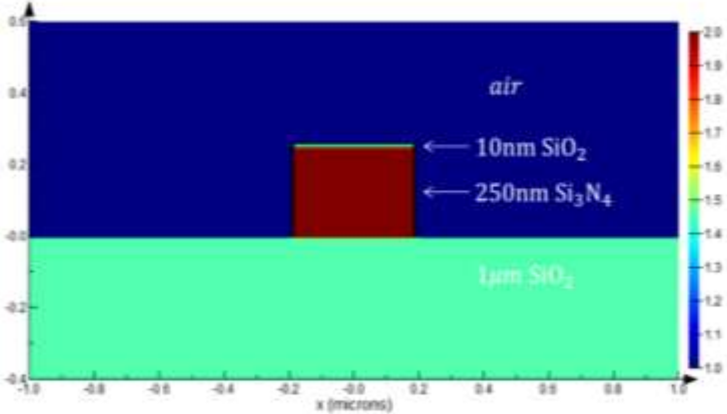


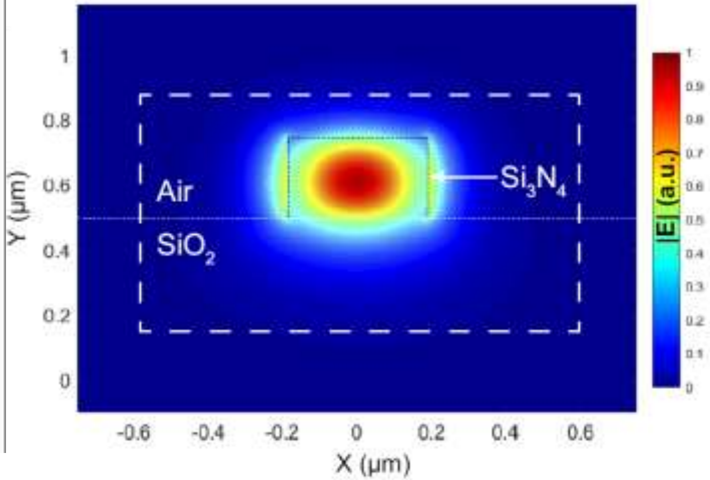
Furchi et al. Nano Lett. (2014)

Photonic Circuit Integration









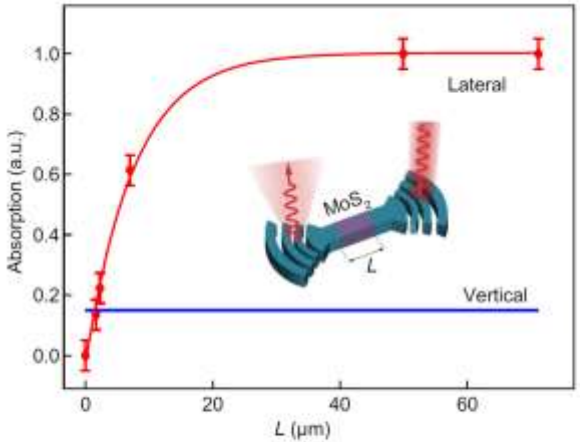
Gonzalez Marin…Kis; npj 2D materials and applications (2019)

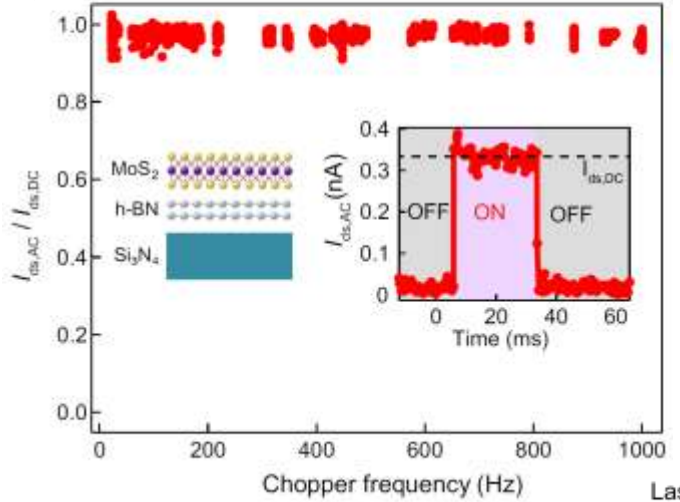
EPFL

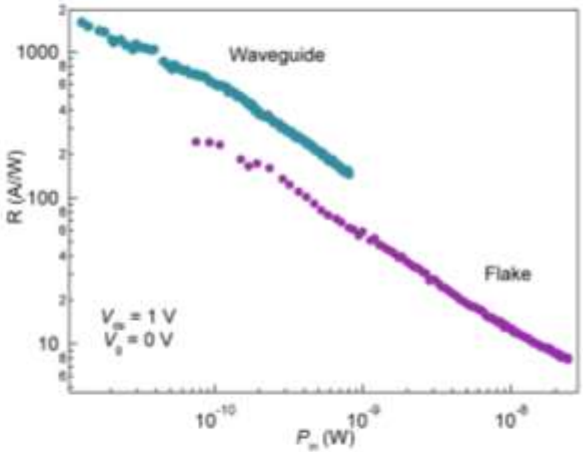
Integrated Photodetectors

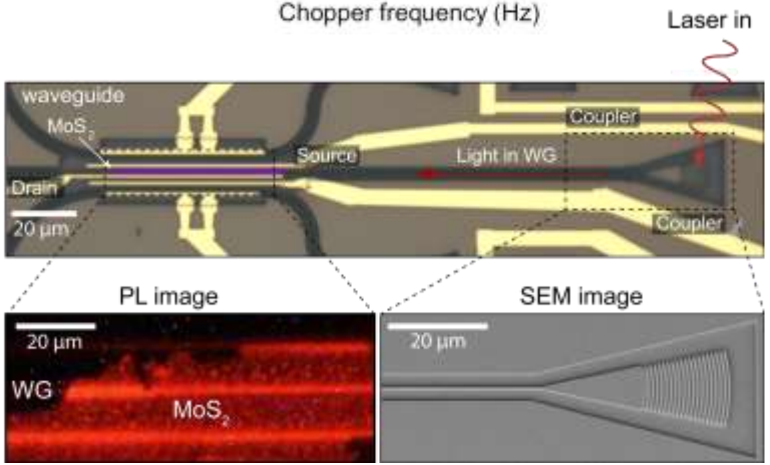
Andras Kis

Light absorption









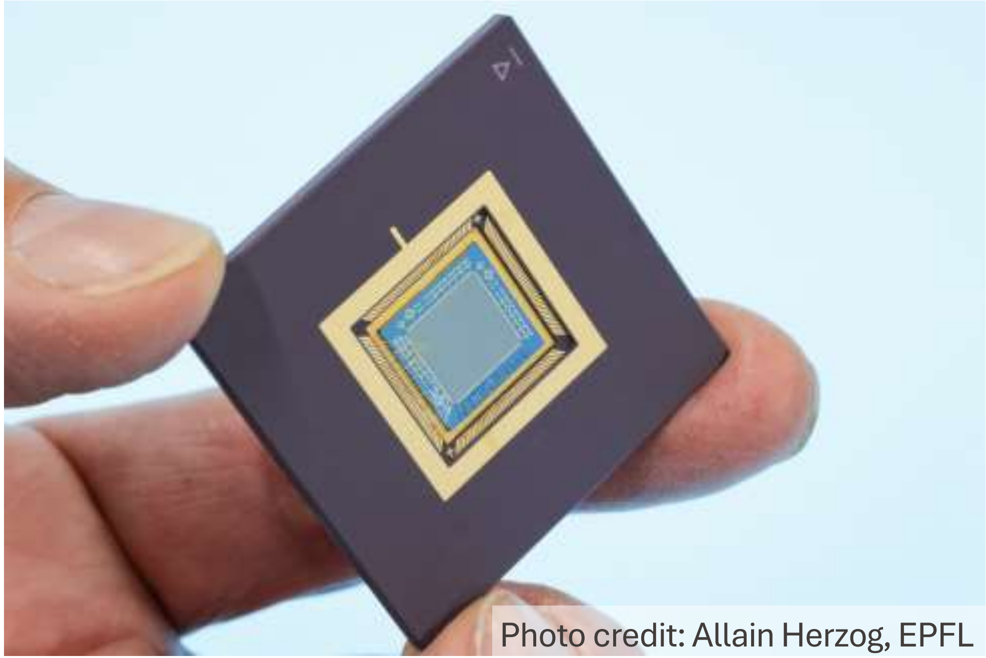
INTRODUCTION

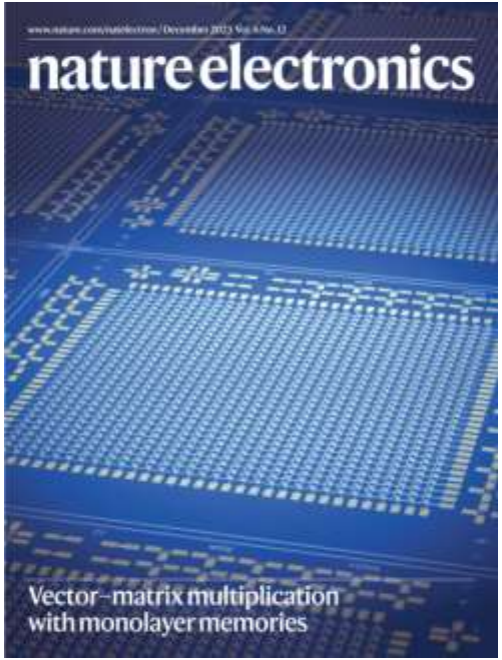
MoS_2 Photodetector Benchmarking

Technology	Material	Band Gap (eV)	Responsivity (A/W)	NEP (W/√Hz)
Silicon PIN Photodiode	Si	1.12	0.5-0.7	10^-14 - 10^-15
InGaAs PIN Photodiode	$In_{0.53}Ga_{0.47}As$	0.75	0.8-1.0	10^-14 - 10^-15
Germanium Photodiode	Ge	0.67	0.5-0.7	10^-13 - 10^-14
Silicon APD	Si	1.12	50-130	10^-15 - 10^-16
MoS_2	MoS_2	1.8	880	10^-15
PMT (Photomultiplier Tube)	Various	N/A	10^5 - 10^7 A/W	10^-17 - 10^-18
Quantum Dot	PbS or PbSe	0.37 or 0.27	0.3-0.5	10^-12 - 10^-13
Graphene	Graphene	0	0.1-0.5	10^-12 - 10^-13
MCT (Mercury Cadmium Telluride)	$Hg_{1-x}Cd_xTe$	0.1-1.5	2-20	10^-11 - 10^-12

Compiled using perplexity.ai

Today: 1024 Transistors on a Chip





Marega...Kis, Nature Electronics (2023)

MOCVD Growth

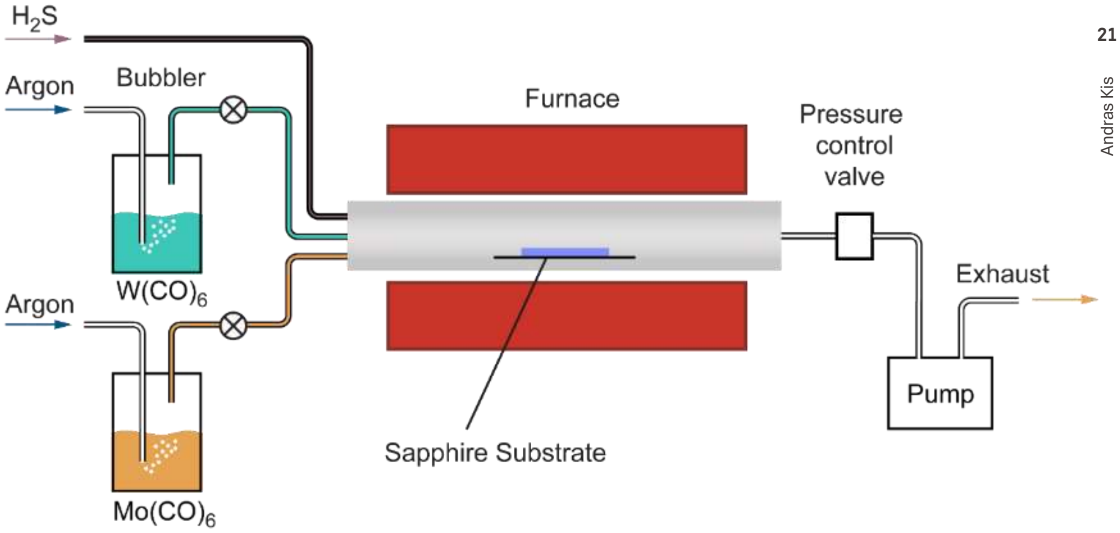
Metalorganic chemical

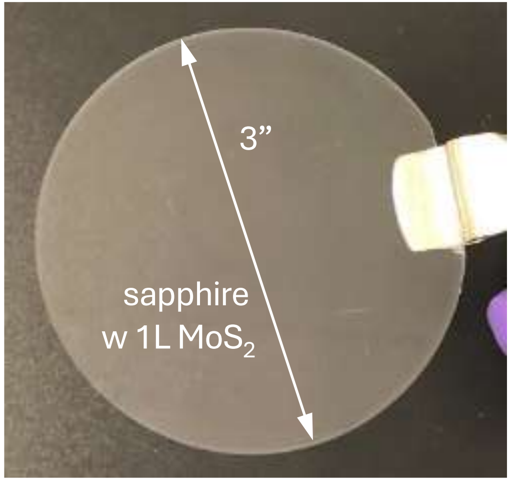
vapour deposition

Cun, Kis, Radenovic et al. (2019)

Large single crystals
EPFL, Kim…Kis, Nano Lett (2017)

$\mu \approx 50\ cm^2 V^{-1} s^{-1}$





IRDS – International Roadmap for Devices and Systems

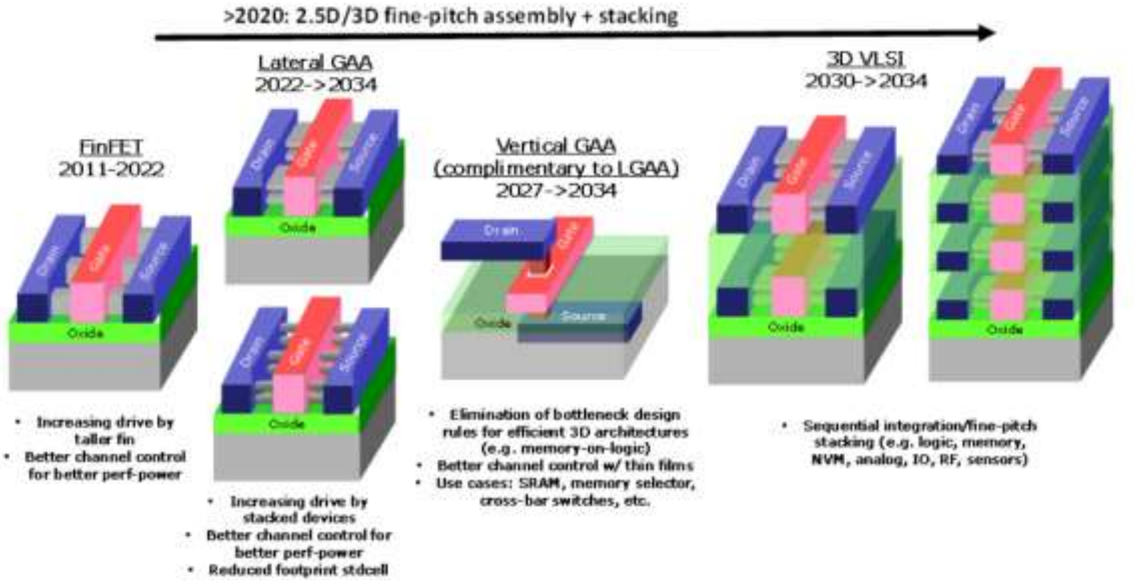


Figure ES48 Change in the MOSFET device architecture from the 2D planar through 2.5D FinFets to 3D monolithic VLSI with GAA

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

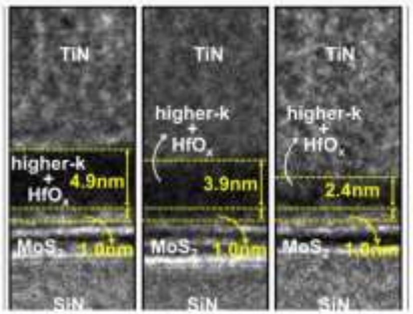
IRDS – International Roadmap for Devices and Systems

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

2D Materials in the Industry



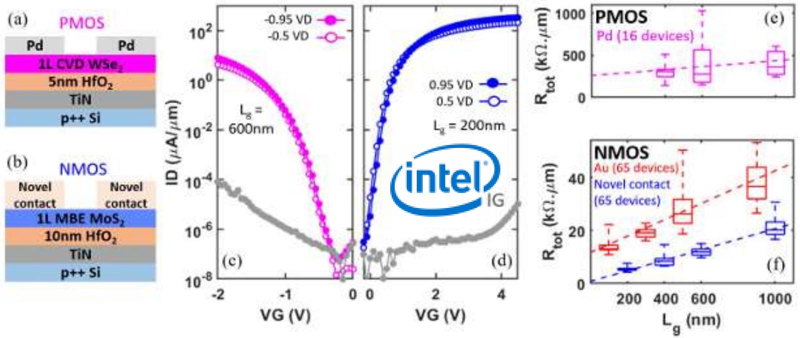
TSMC heads below 1nm with 2D transistors at IEDM

Technology News | October 18, 2022

By Nick Flaherty

MATERIALS & PROCESSES

https://www.eenewseurope.com/en/tsmc-heads-below-1nm-with-2d-transistors-at-iedm/



[INTEL, IEEE TED (2021), doi:10.1109/TED.2021.3118659]

First Demonstration of GAA Monolayer-MoS₂ Nanosheet nFET with 410 μA/μm I$_D$ at 1V V$_D$ at 40nm gate length

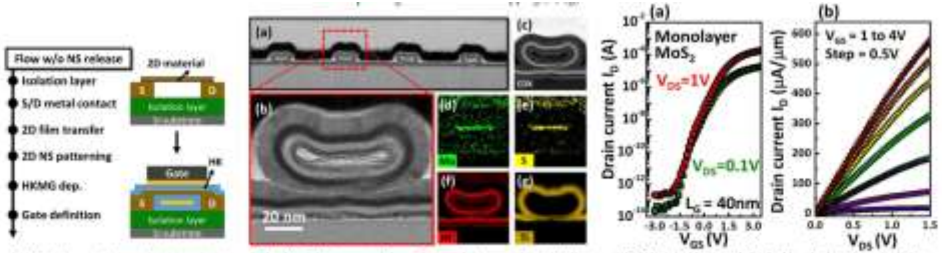


Fig. 19. Process flow and schematic of single 2D NS device without sheet release.

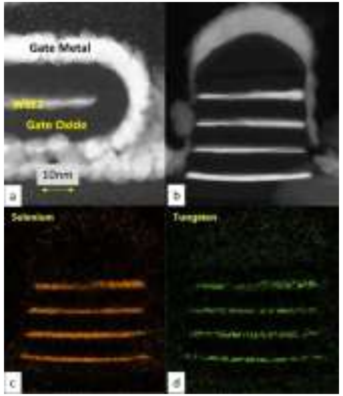
Fig. 20. TEM cross section of (a) and (b) monolayer MoS₂ nanosheet device with gate stack fully wrapped around the channel. Corresponding EDX elemental mapping (d)-(g).

Fig. 21. (a) I$_D$-V$_{GS}$ and (b) I$_D$-V$_{DS}$ device characteristics of monolayer MoS₂ NSFET with Lg=40nm.

[TSMC, IEDM (2022), doi:10.1109/IEDM45625.2022.10019563]

Process integration and future outlook of 2D transistors

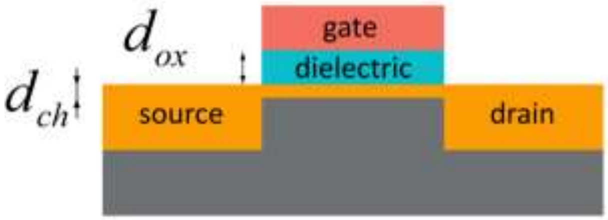
nature communications



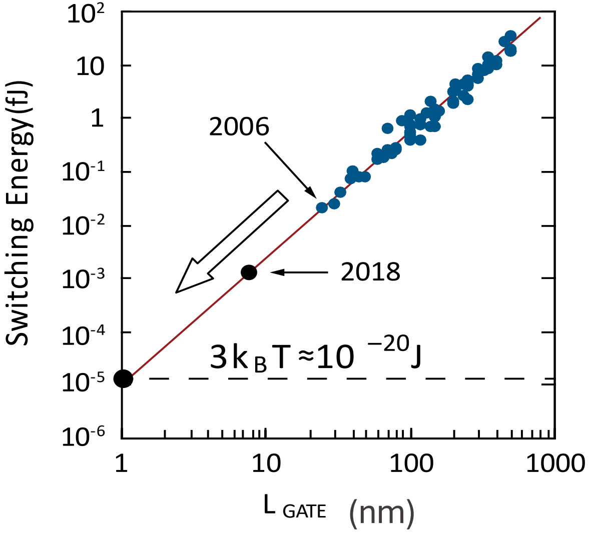
[INTEL, *Nature Comm.* (2023), DOI: 10.1038/s41467-023-41779-5]

IT Energy Problem

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



Single device:



Landauer limit

Cavin et al. J Nanopart Res (2006)

System level:

Intel Core i7 8700K processor (2017)

$10^9\times$ worse! (2.5 GFLOPS/W)

Frontier supercomputer (ORNL, 2022)

$4{\cdot}10^7\times$ worse (62.68 GFLOPS/W)

A100 40 GB (NVIDIA, 2023)

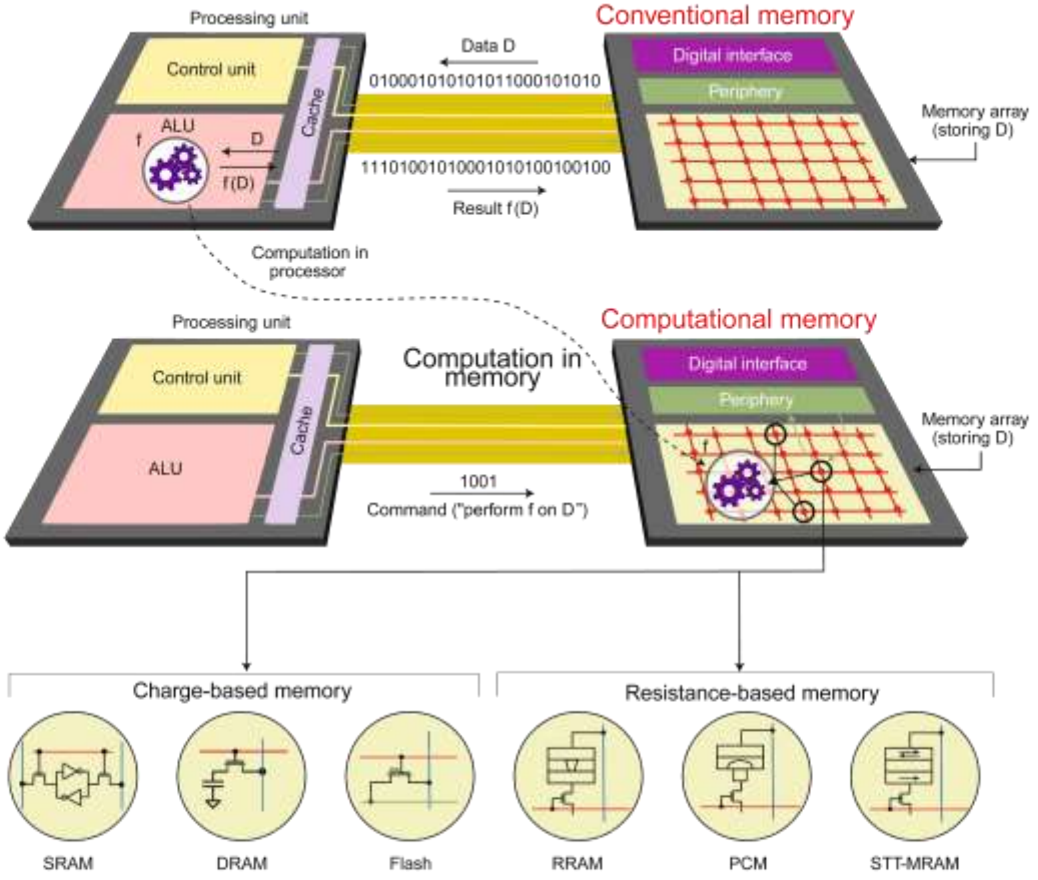
$3.7{\cdot}10^7\times$ worse (78 GFLOPS/W)

John von Neumann

Logic in Memory

Von Neumann

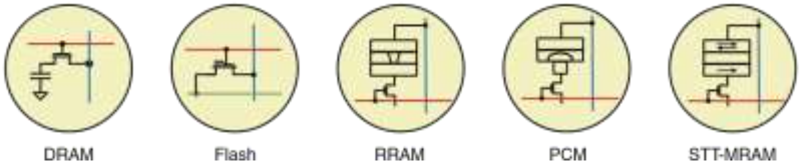
Logic in memory



Sebastian...Eleftheriou, Nat. Nanotech. (2020)

Logic in Memory

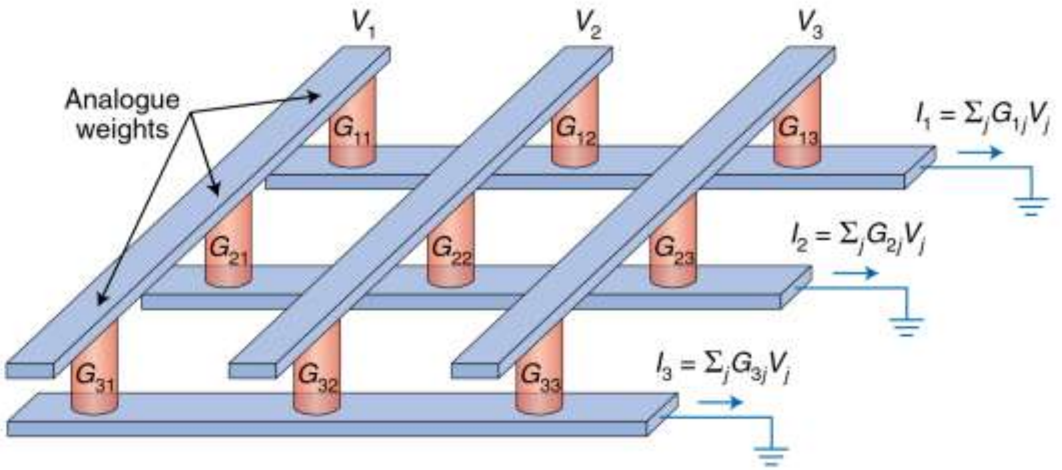
Sebastian...Eleftheriou, Nat. Nanotech. (2020)



Performance metrics	DRAM	Flash	PCM	STT-MRAM	RRAM	HDD
Feature size (nm)	36	22	45	95	9	NA
Cell Area	$6F^2$	$4F^2$	$4F^2$	$4F^2$	$4F^2$	~256*
Write/Erase Time	< 10ns	1/0.1ms	100ns	<10ms	<1ns	5ms
Retention	64ms	>10y	>10y	>10y	>10y	>10y
Endurance	>1E16	1E4	1E9	>1E12	1E12	>1E16
Nonvolatility	N	Y	Y	Y	Y	Y
Multi-level capability	N	Y	Y	N	Y	-
Write Energy (J/bit)	4E-15	> 2E-16	1E-12	2.5E-12	1E-13	-
Standby Power (W/Gb)	1E-1	1E-3	1E-3	1E-3	1E-3	110

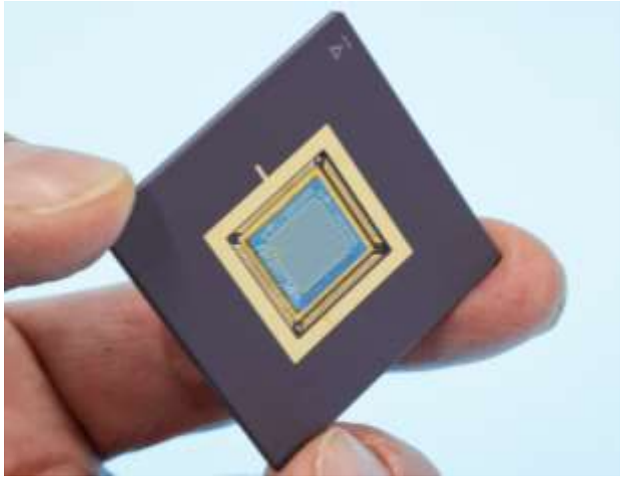
Credit: G. M. Marega

Vector Matrix Multiplication



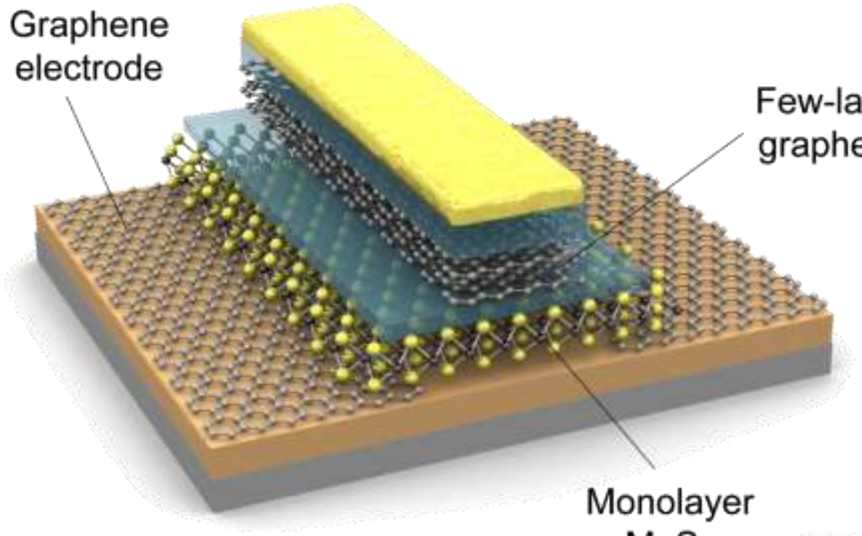
$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

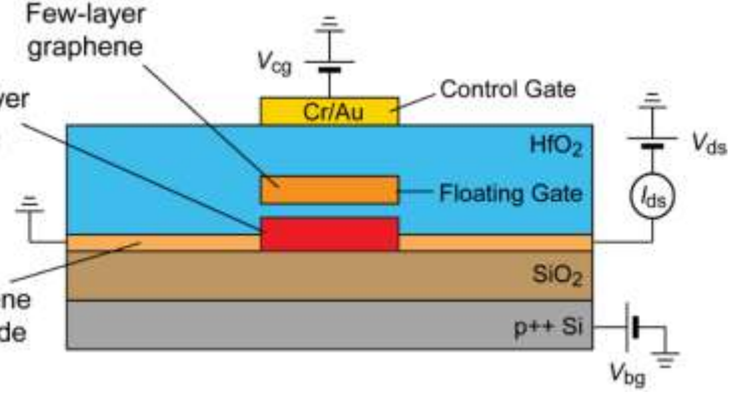
Ielmini and Wong, Nat. Electron. (2018)



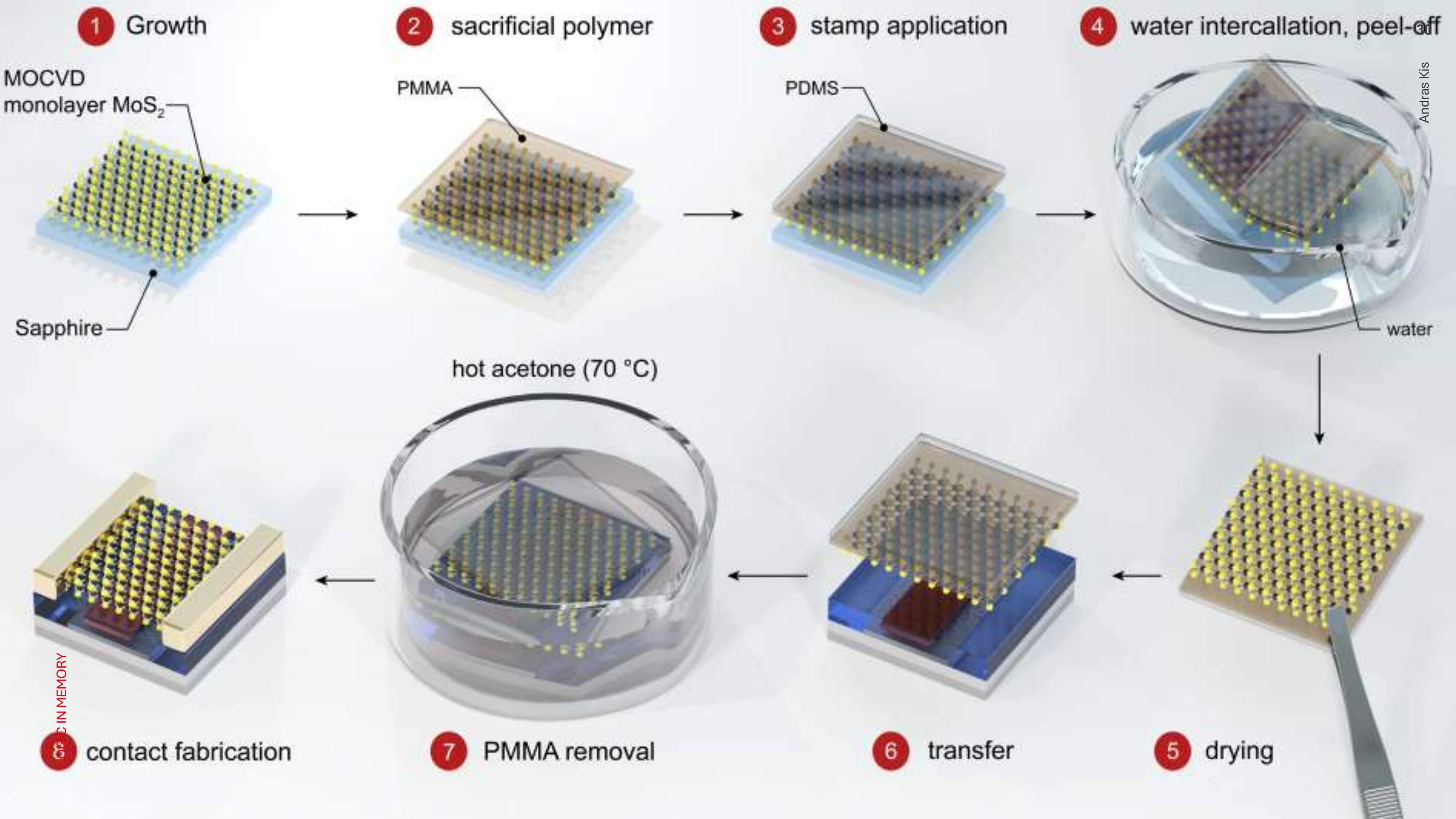
Marega...Kis, Nature Electronics, 2023.

Flash Memory with MoS_2

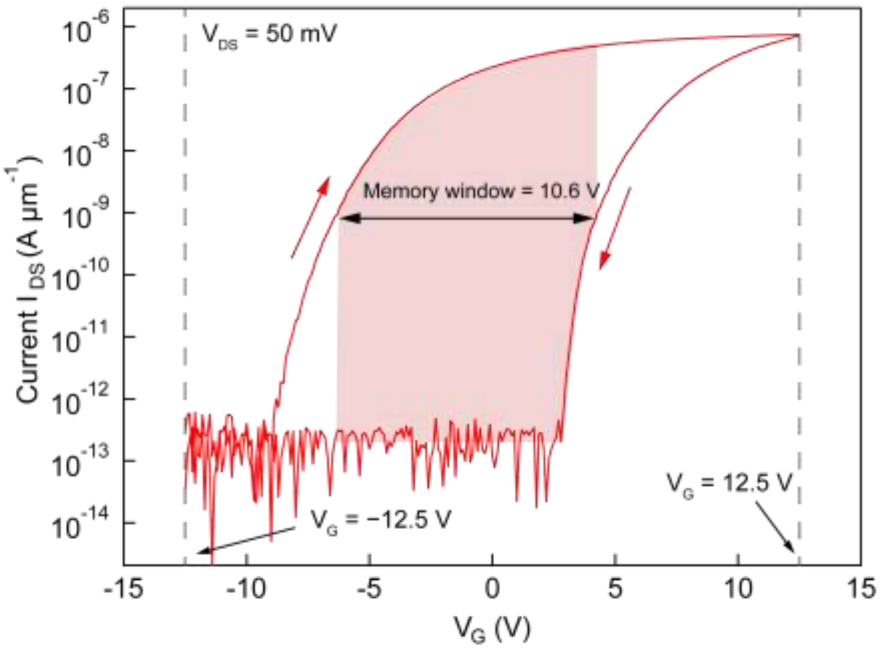


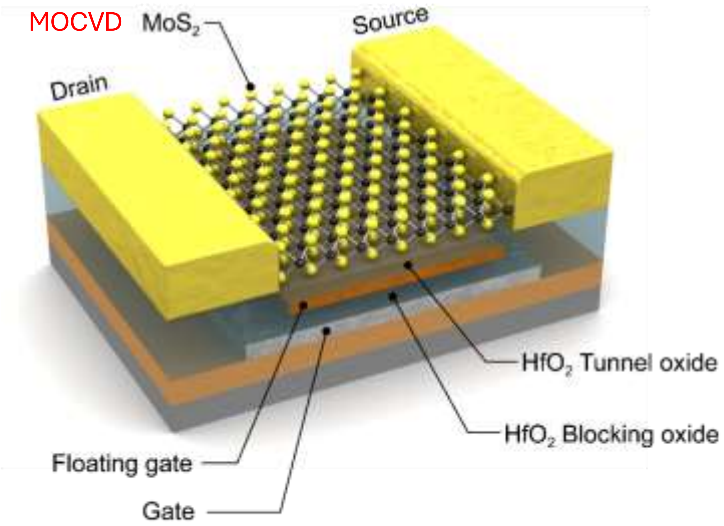


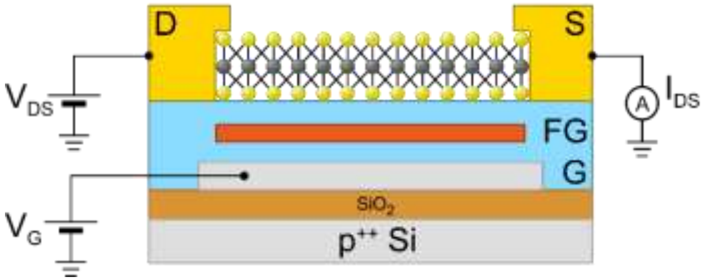
Bertolazzi...Kis; ACS Nano (2013)


1 Growth
MOCVD monolayer MoS_2
Sapphire
2 sacrificial polymer
PMMA
3 stamp application
PDMS
4 water intercallation, peel-off
water
Andras Kis
5 drying
6 transfer
hot acetone (70 °C)
7 PMMA removal
8 contact fabrication

Flash Memory with MoS_2





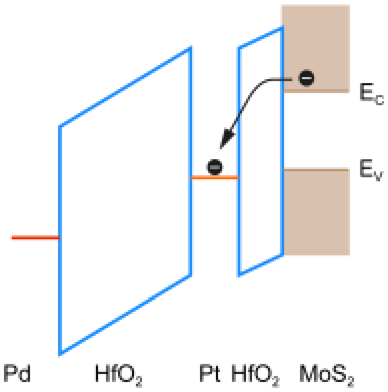


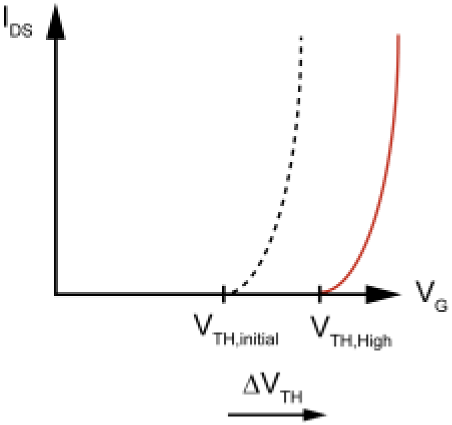
Marega...Kis; Nature (2020)

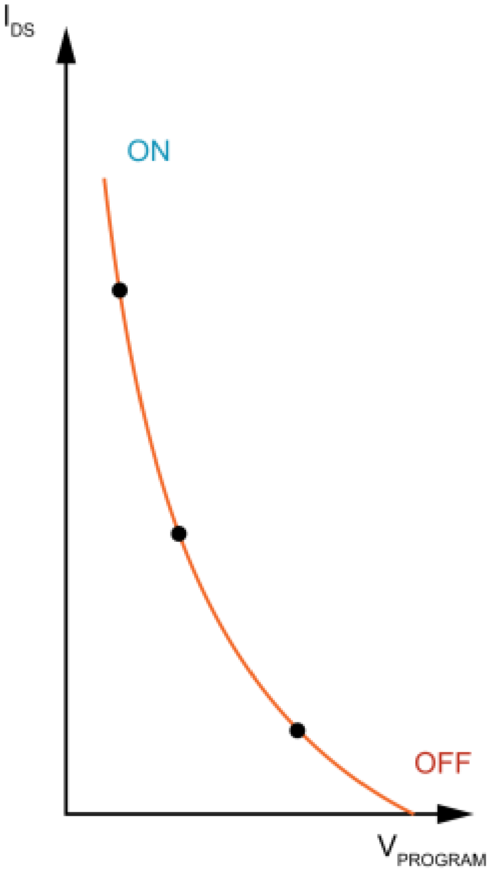
Memory Effect

Program

$V_G > 0$



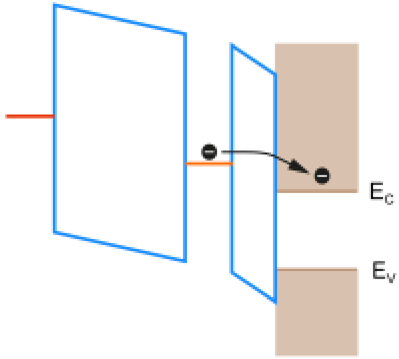


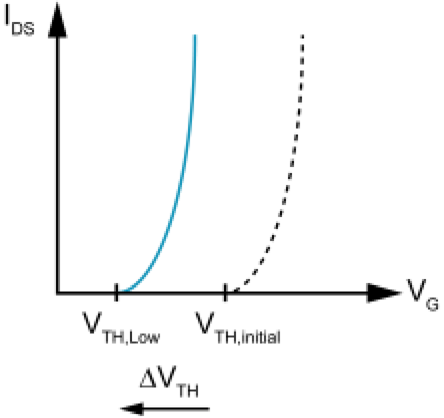


Intermediate states

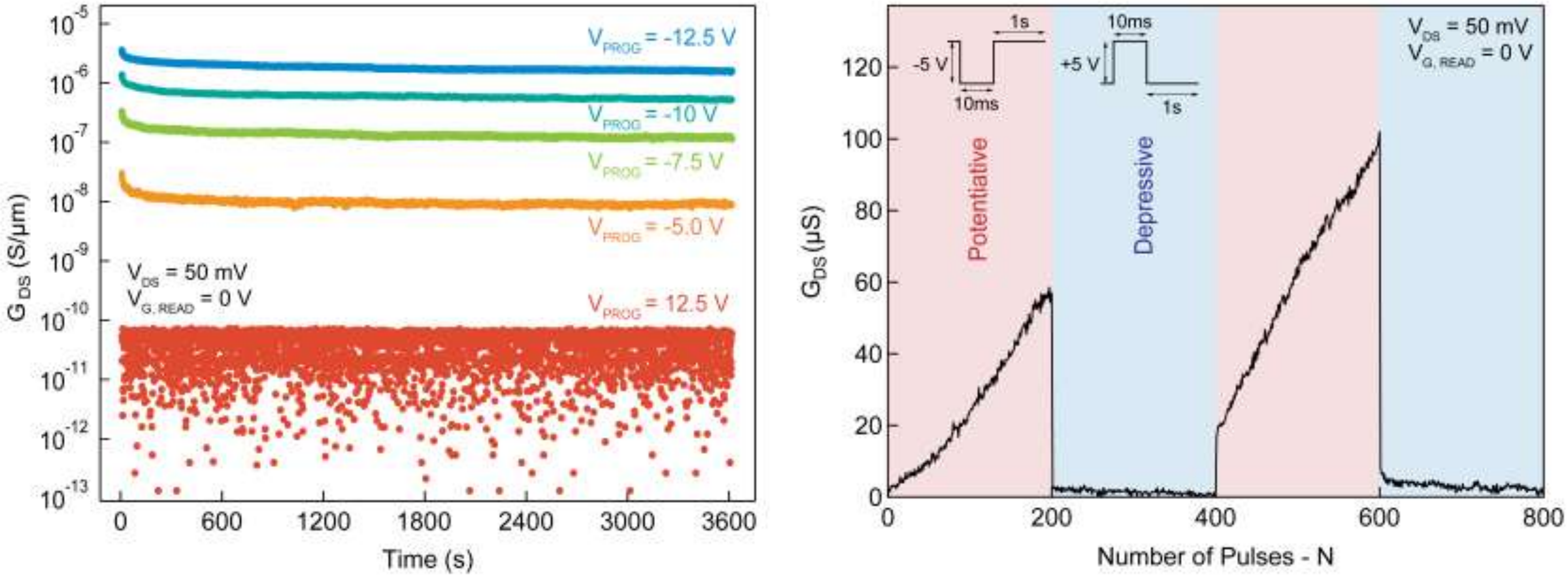
Erase

$V_G < 0$





2D Logic in Memory

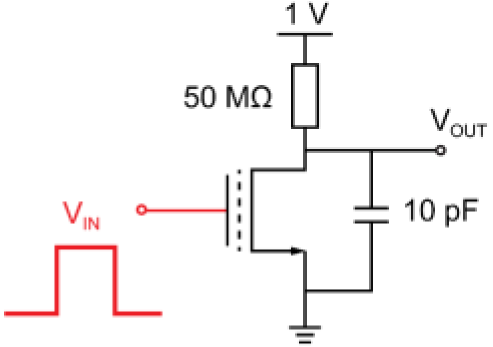


2-state retention >10 years
Endurance: 60,000 program/erase cycles

Marega...Kis; Nature (2020)

Andras Kis

Programmable Inverter

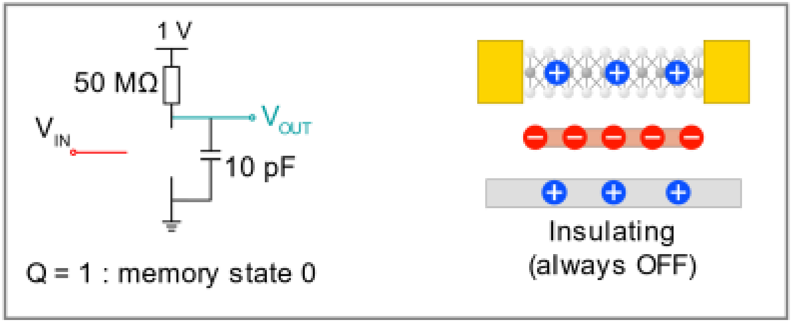


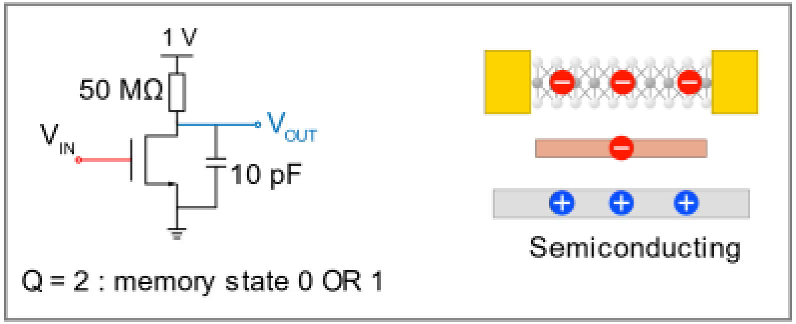
Q	IN		$X^{(Q)}$	
1	0	1	0	0
2	0	1	0	1
3	0	1	1	1

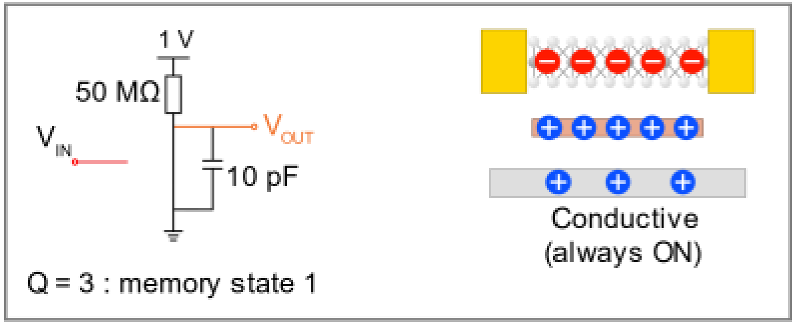
Logic input and memory states

$X^{(Q)}$	OUT
0	1
1	0

Memory states and logic output

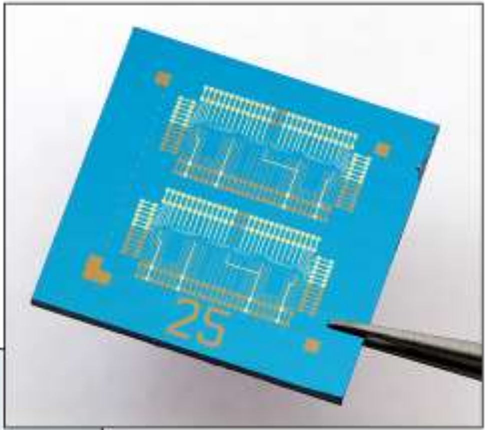


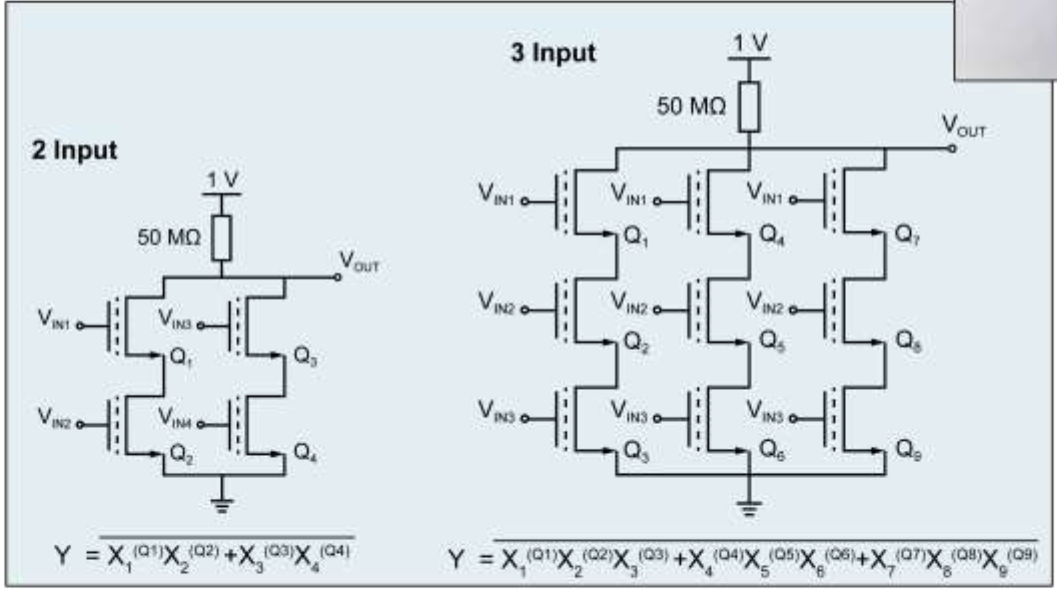




Universal Logic Gate

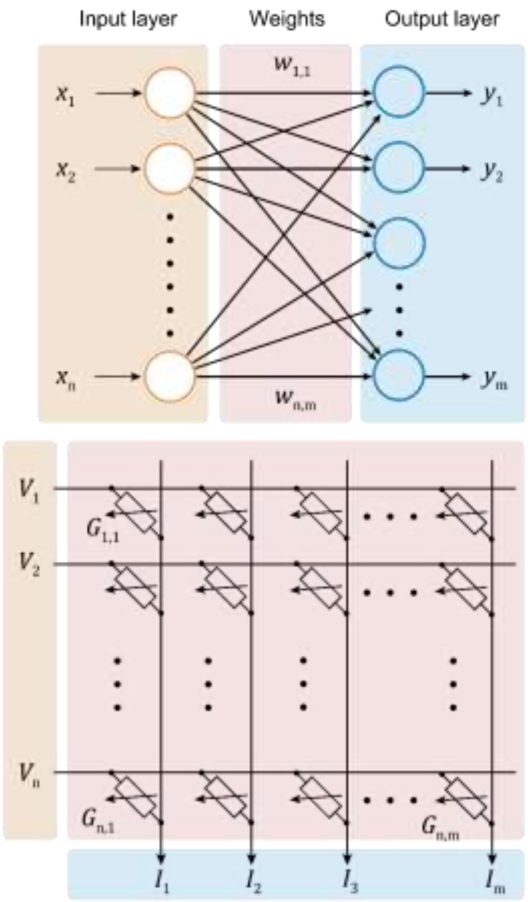
12 mm × 12 mm die
80 memory devices

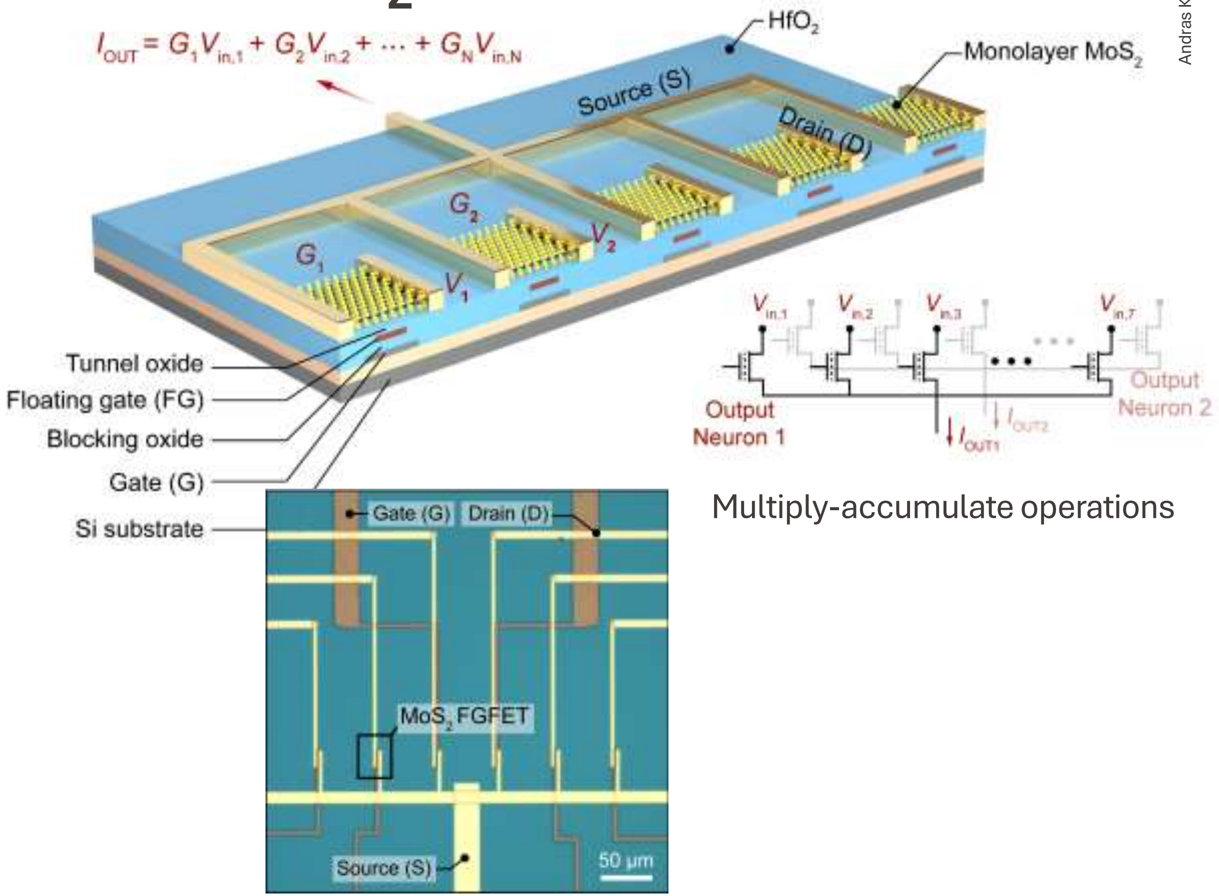




Marega...Kis; Nature (2020)

Neural Networks with MoS_2

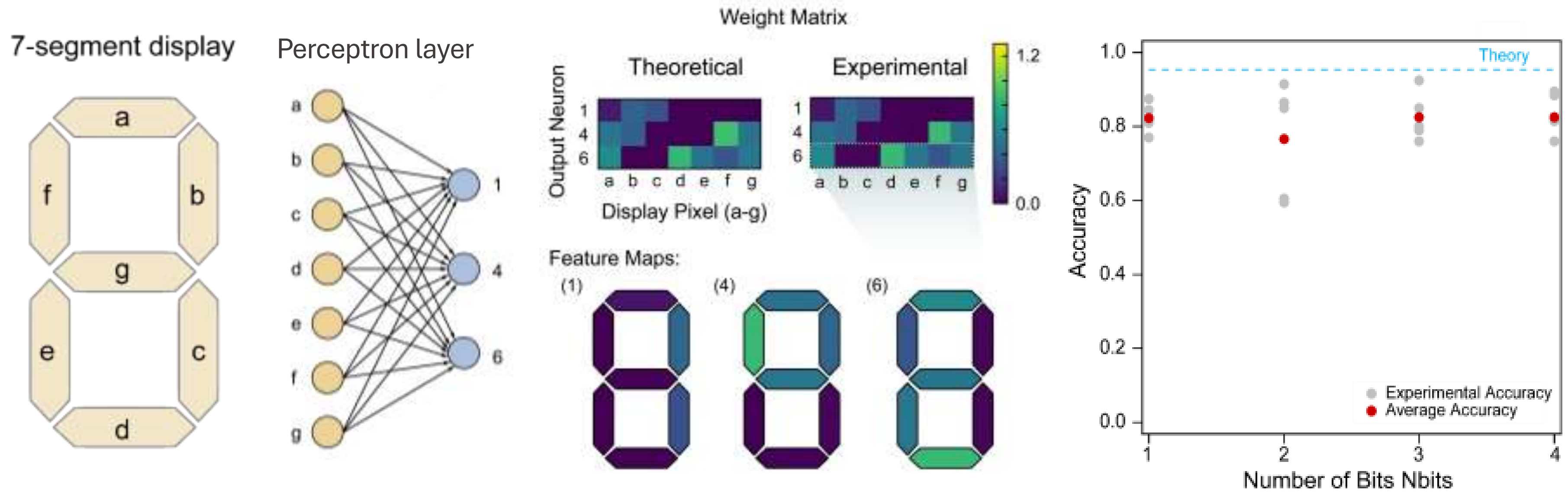




Multiply-accumulate operations

Marega...Kis; ACS Nano (2022)

Digit Classification



Simulations: 38× energy advantage over CMOS - Giuseppe Iannaccone (U. of Pisa)

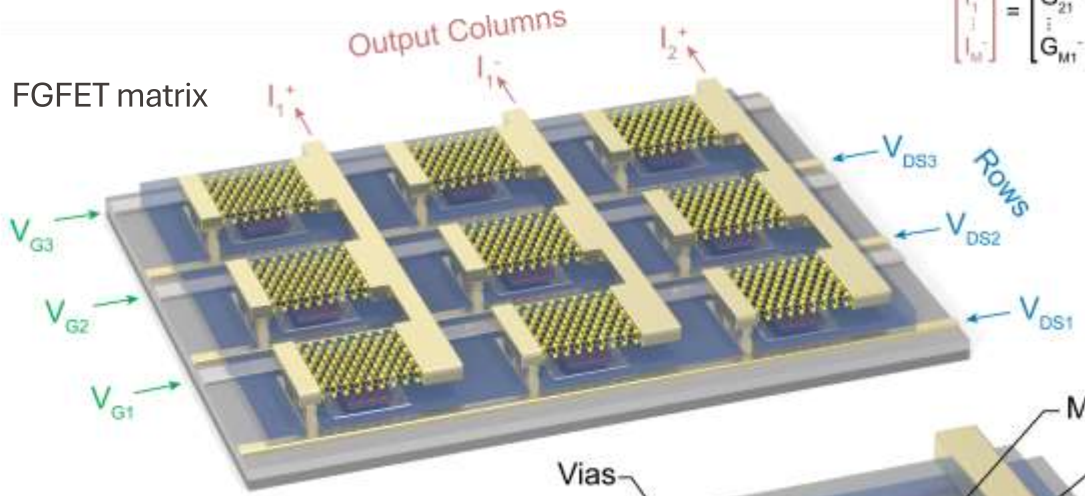
Marega...Kis; ACS Nano (2022)

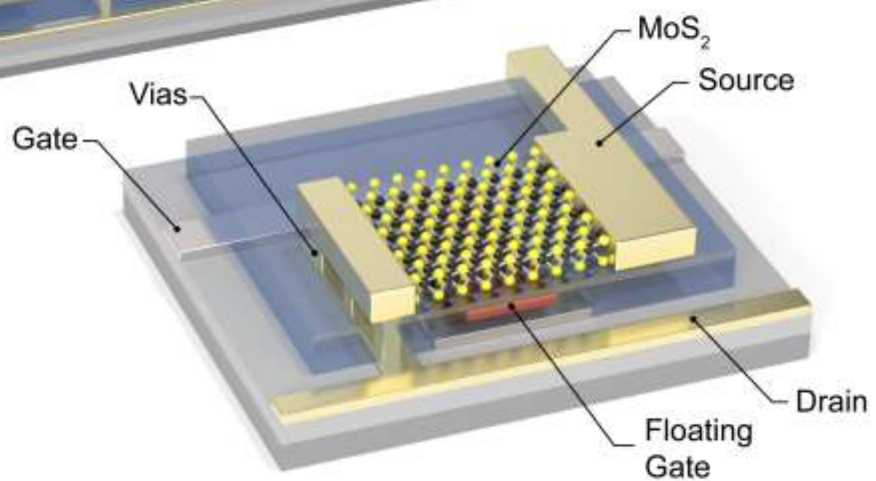
Large-scale Integration

Vector-Matrix Multiplication

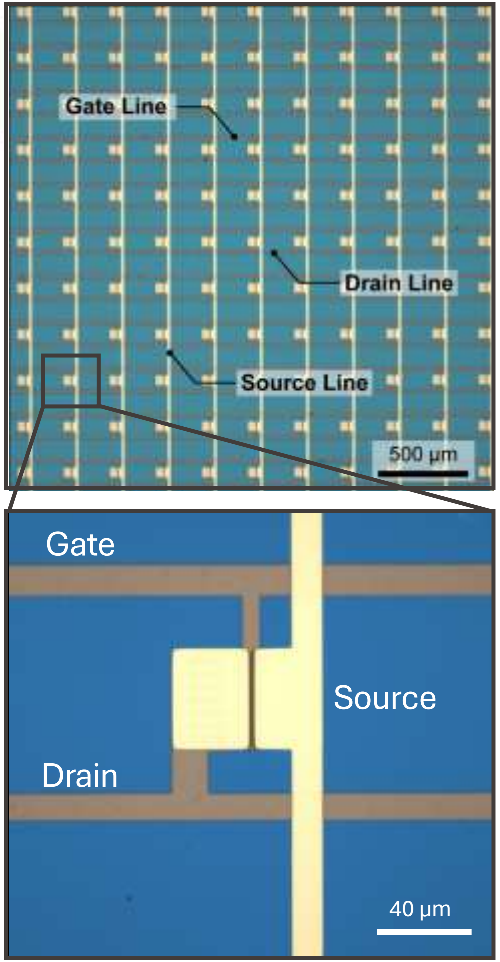
$$\begin{bmatrix} I_1^+ \\ I_1^- \\ \vdots \\ I_M^- \end{bmatrix} = \begin{bmatrix} G_{11}^+ & G_{12}^+ & \cdots & G_{1N}^+ \\ G_{21}^- & G_{22}^- & \cdots & G_{2N}^- \\ \vdots & \vdots & \ddots & \vdots \\ G_{M1}^- & G_{M2}^- & \cdots & G_{MN}^- \end{bmatrix} \cdot \begin{bmatrix} V_{DS1} \\ V_{DS2} \\ \vdots \\ V_{DS(N)} \end{bmatrix}$$

FGFET matrix





Floating-gate Field-effect Transistor

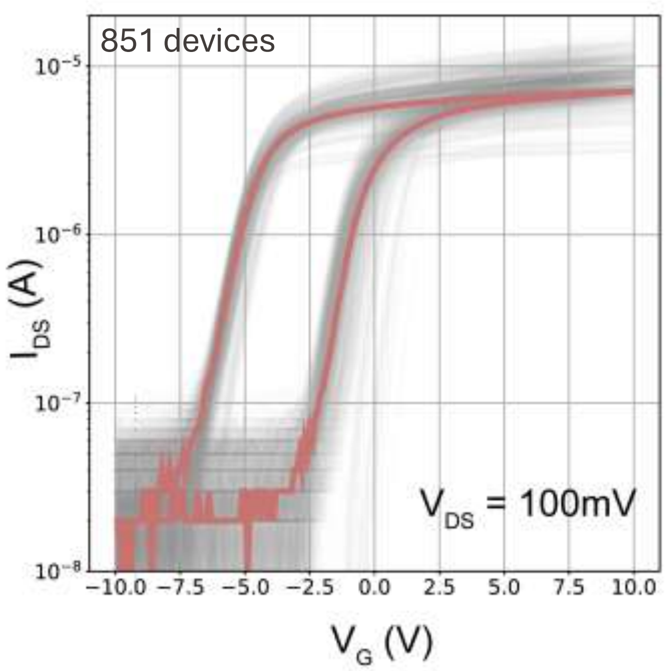


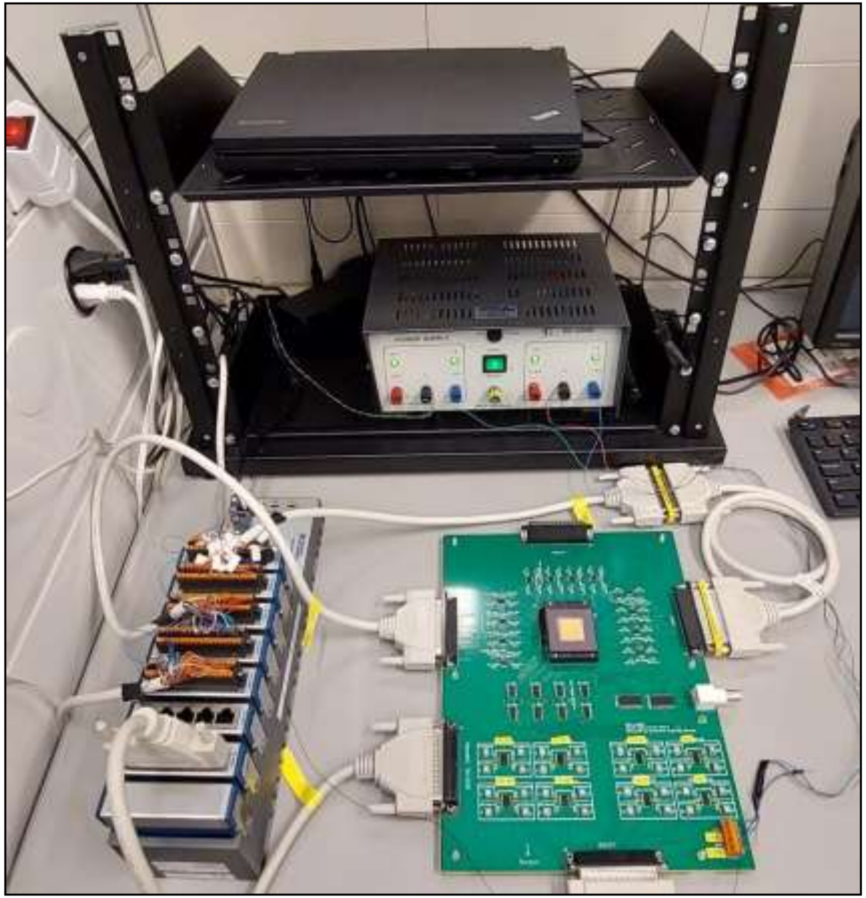
32×32 FGFET array
1024 devices

Marega...Kis; Nat. El. (2023)

Large-scale Integration

32×32 FGFET array
1024 devices
83% yield

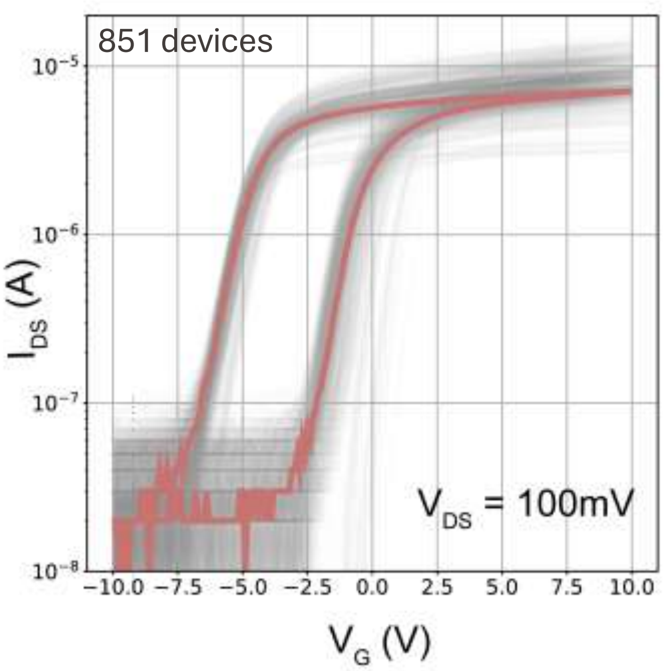


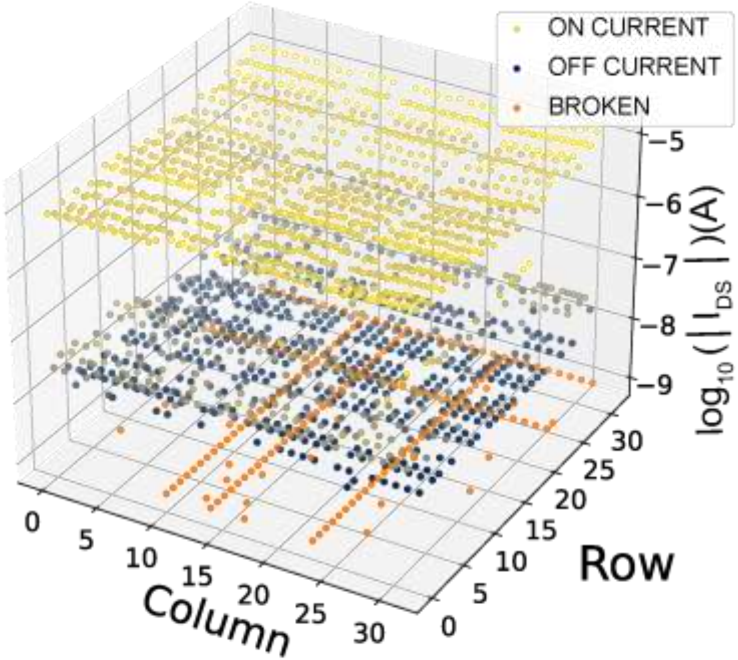


Marega...Kis; Nature Electronics (2023)

Large-scale Integration

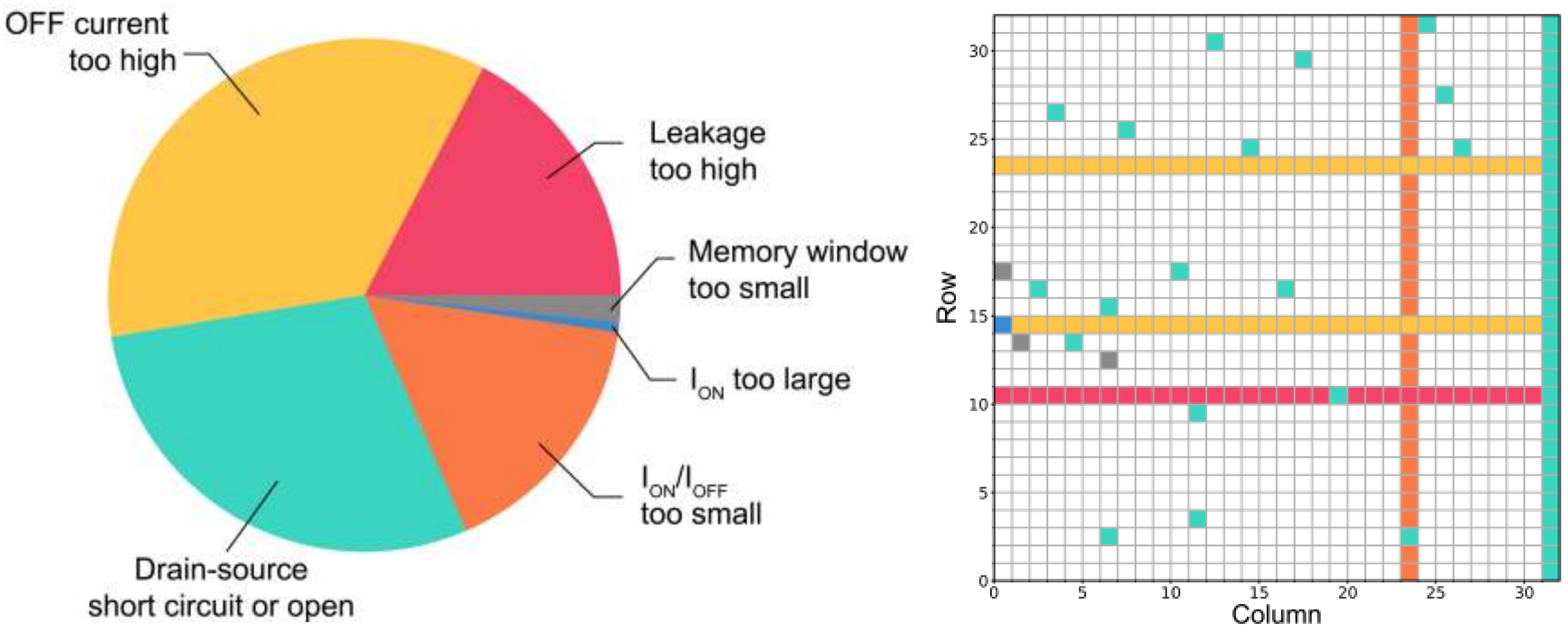
32×32 FGFET array
1024 devices
83% yield





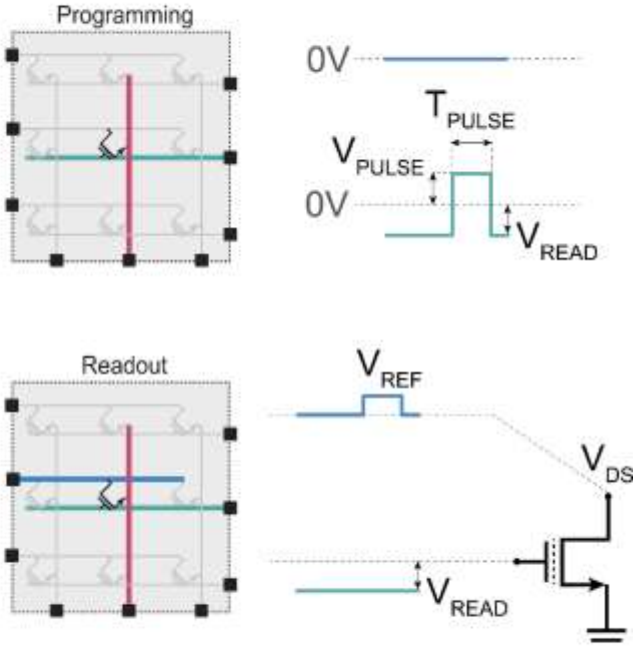
Marega…Kis; Nature Electronics (2023)

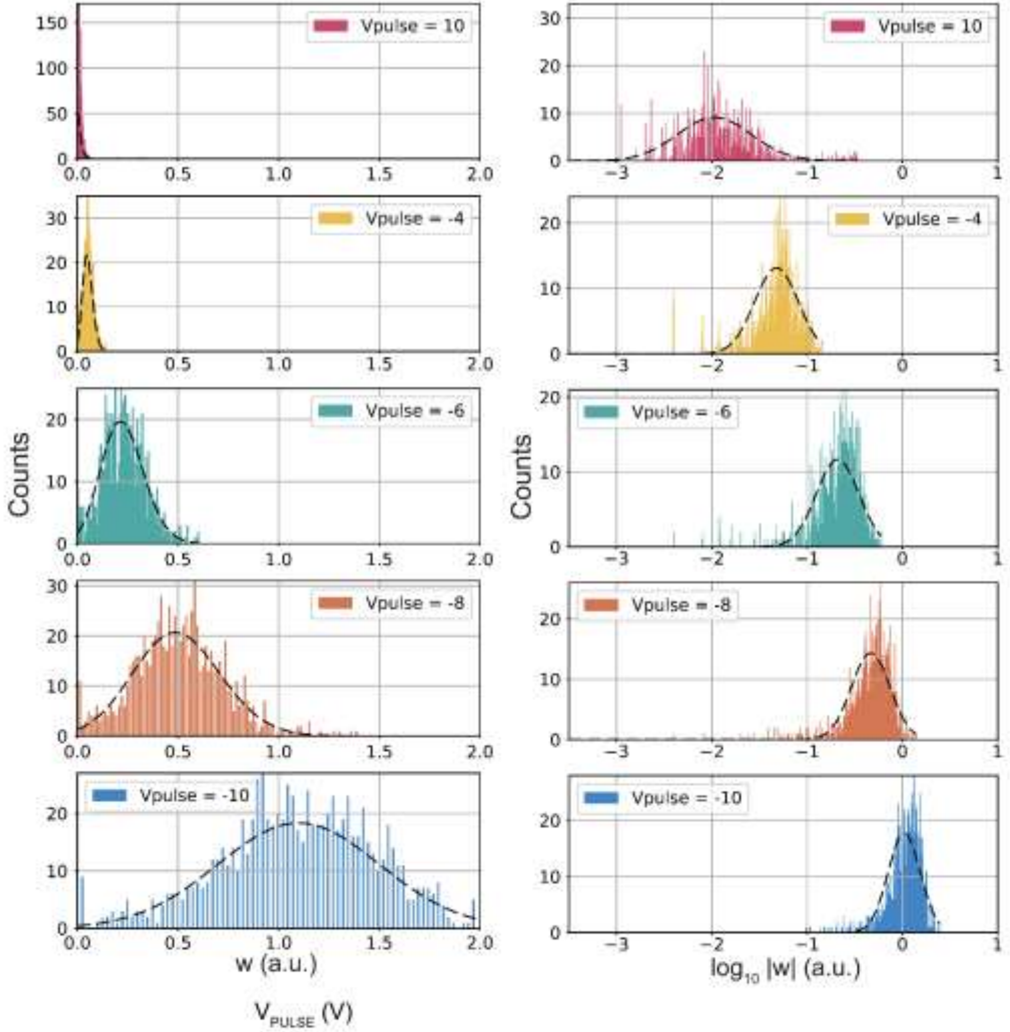
Device Failure Modes



Marega…Kis, Nature Electronics (2023)

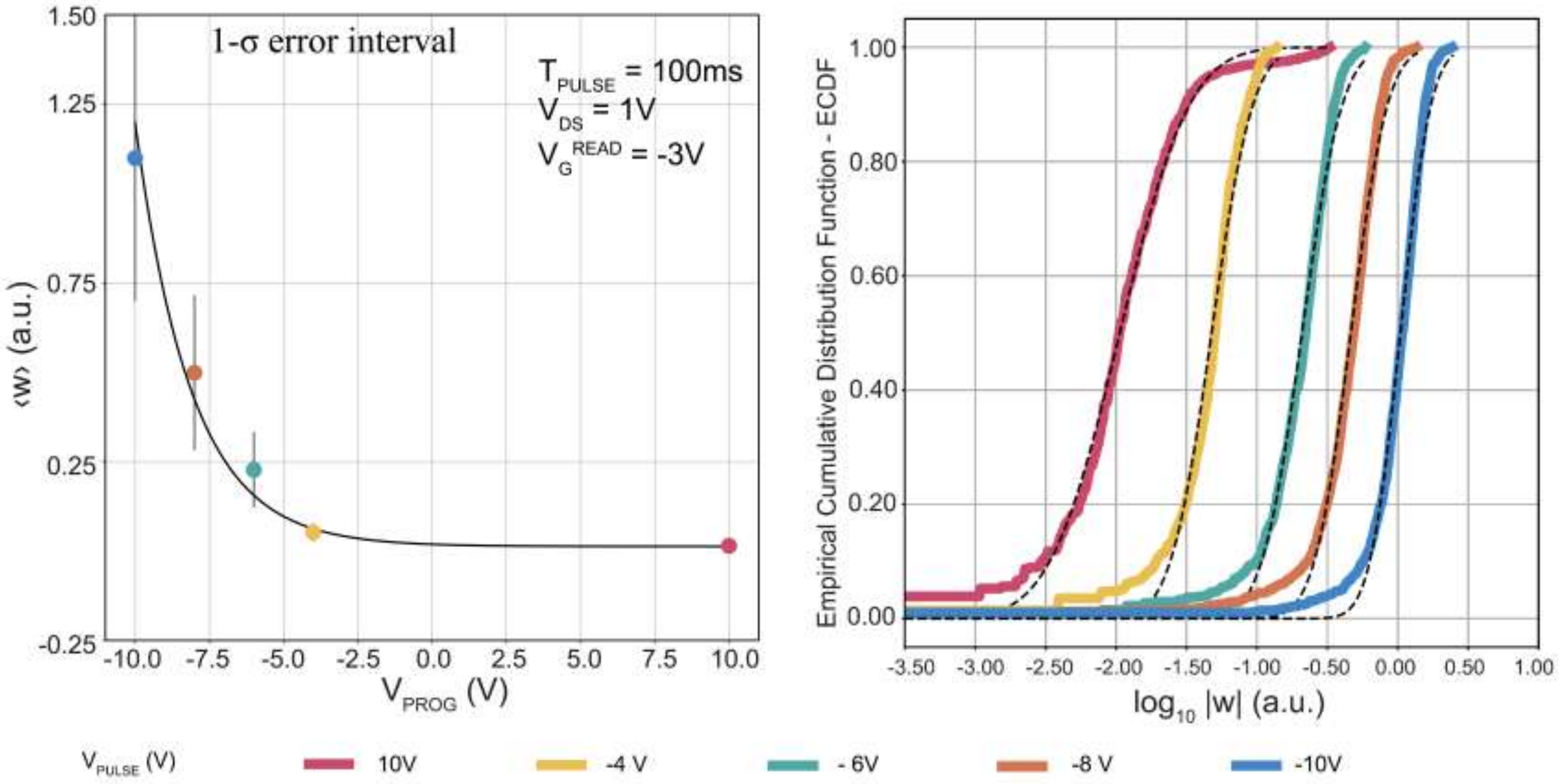
Open-loop Programming





Marega...Kis, Nature Electronics (2023)

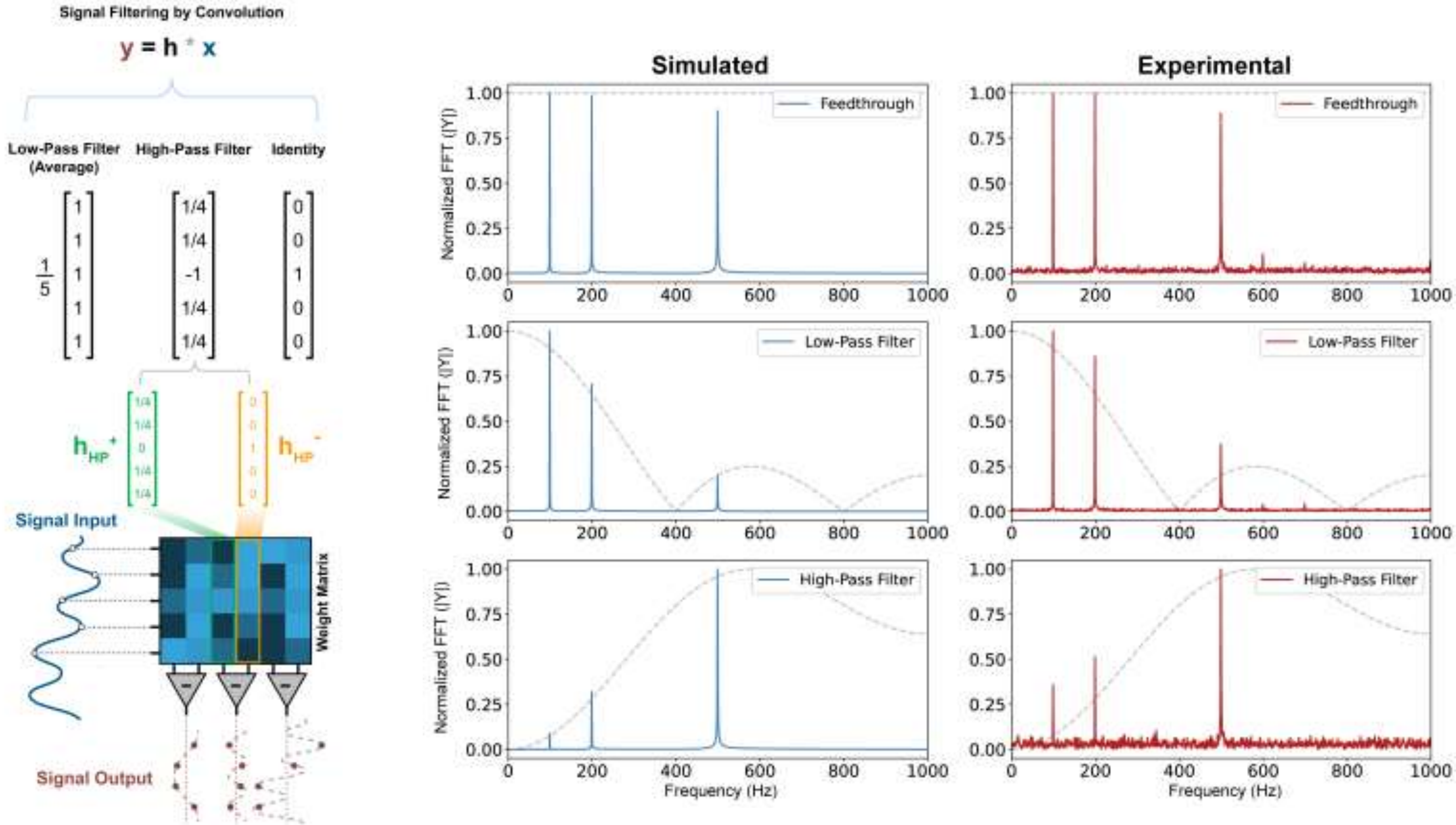
Open-loop Programming



Marega…Kis, Nature Electronics (2023)

In-Memory Signal Processing

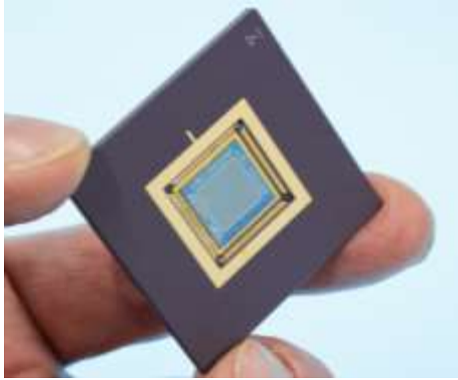
Andras Kis

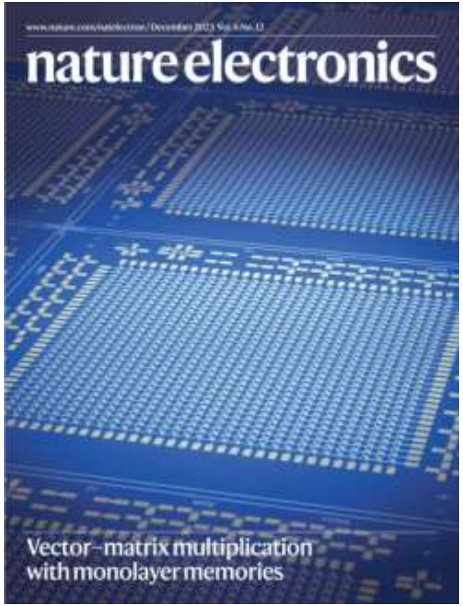


Marega…Kis; Nature Electronics (2023)

Summary

- MoS_2 photodetectors
  - Lopez-Sanchez...Kis, Nature Nanotechnology (2013)
    doi: 10.1038/nnano.2013.100
  - Gonzalez Marin...Kis, npj 2D Mat. (2019)
    doi: 10.1038/s41699-019-0096-4
- Logic-in-memory based on an atomically thin semiconductor
  - Marega...Kis, Nature 587, 72 (2020)
    doi:10.1038/s41586-020-2861-0
- Artificial neural networks based on MoS_2
  - Marega...Kis, ACS Nano 16, 3684 (2022)
    doi:10.1021/acsnano.1c07065
- Large-scale integration and in-memory data processing
  - Marega...Kis, Nature Electronics (2023)
    doi:10.1038/s41928-023-01064-1





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Kis group

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- Dr. Feng Shun
- Fedele Tagarelli

Former members

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- Dr. Gabriele Pasquale
- Zhenyu Wang

Collaborations

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- Prof. Gianluca Fiori
- Prof. Gino Giusi
- Prof. Aleksandra Radenovic

erc

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European Commission

Horizon 2020
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for Research & Innovation

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