2D Materials for Future Microelectronic Devices

L. LE VAN-JODIN

Outline

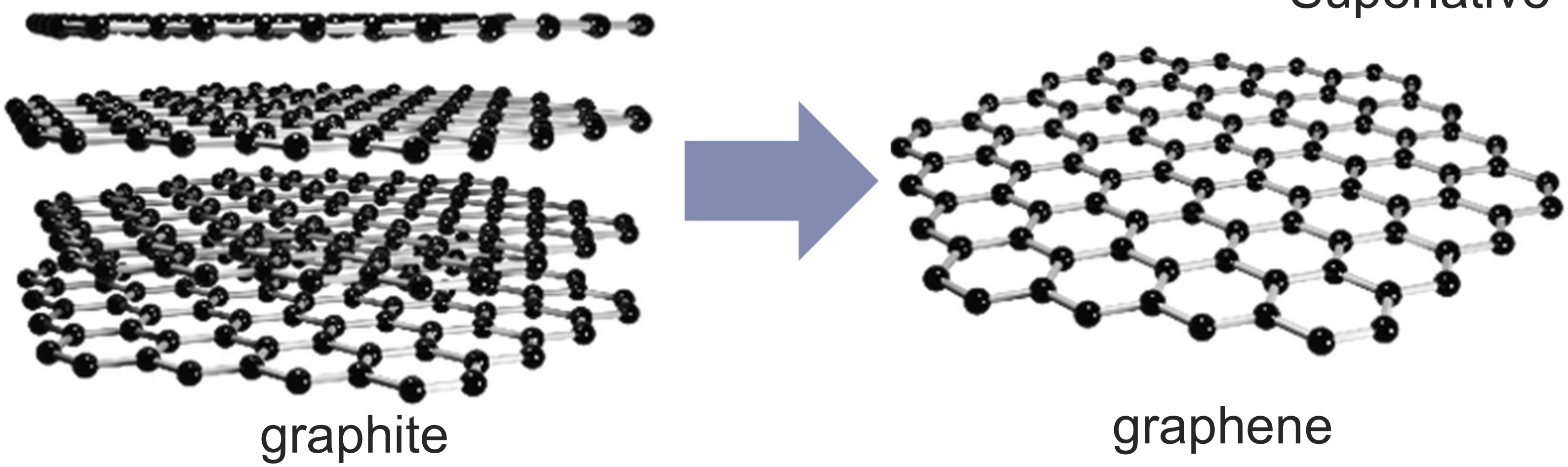
- 2D materials
- Which applications?
- Integration

1. 2D materials

2004 Graphene

K. Novoselov and A. Geim, Nature **438**, 197 (2005)

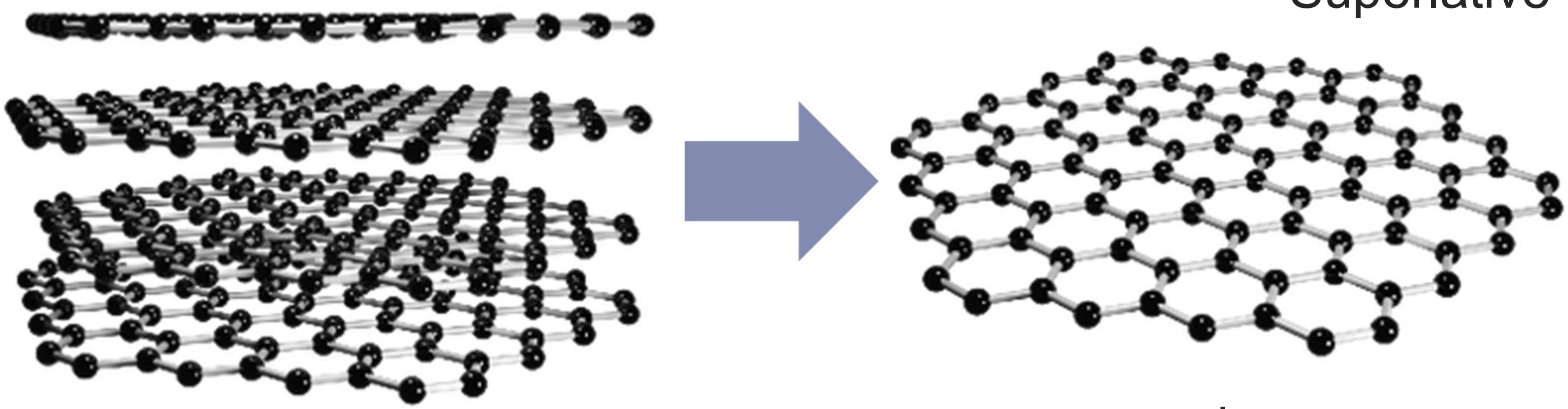
Superlative material



K. Novoselov and A. Geim, Nature **438**, 197 (2005)

2004 Graphene

Superlative material



graphite

graphene

A. Geim
NOBEL PRIZE IN 2010

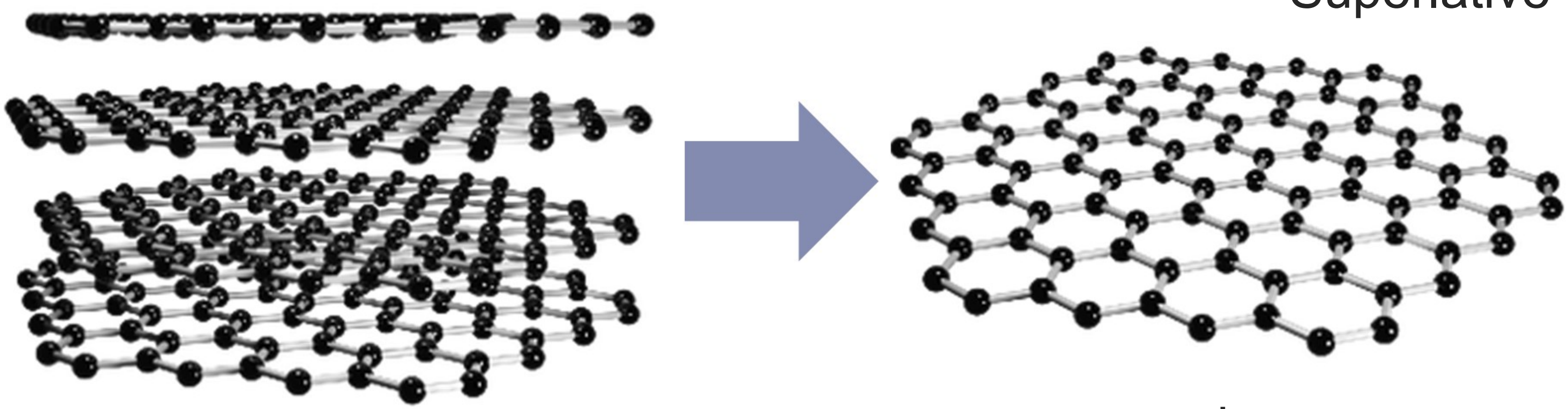
- 200 times stronger than steel
- 1.000.000 times thinner than a single human hair
- The world's lightest material (1 m^2 weighs about 0,77 milligram)
- Flexible
- Transparent
- Impenetrable for molecules
- Excellent electrical and heat conduction

K. Novoselov
NOBEL PRIZE IN 2010

K. Novoselov and A. Geim, Nature **438**, 197 (2005)

2004 Graphene

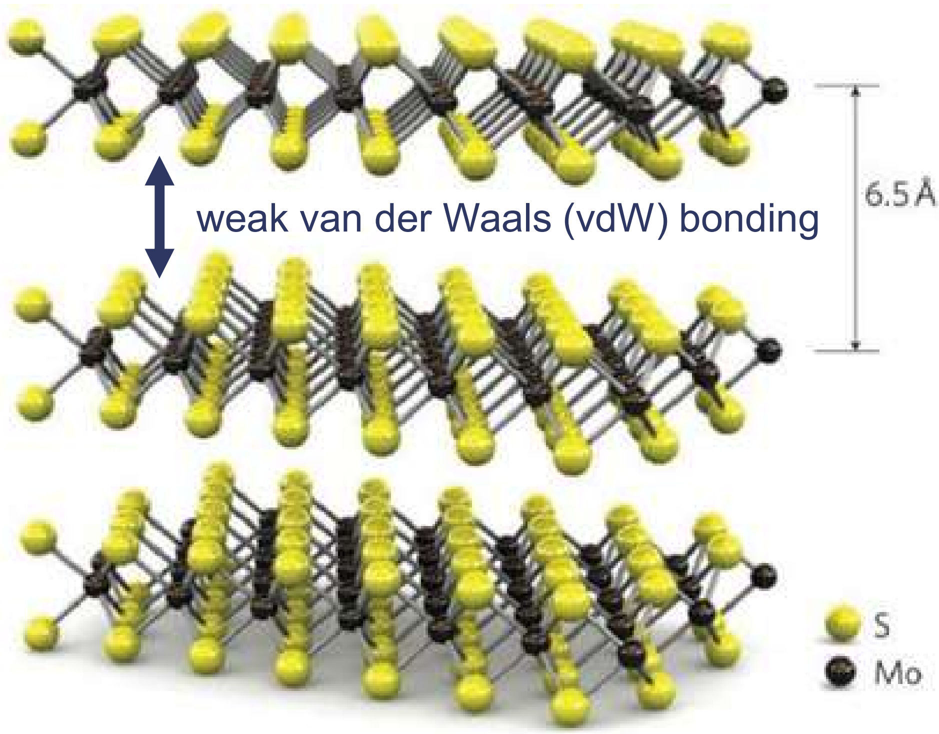
Superlative material



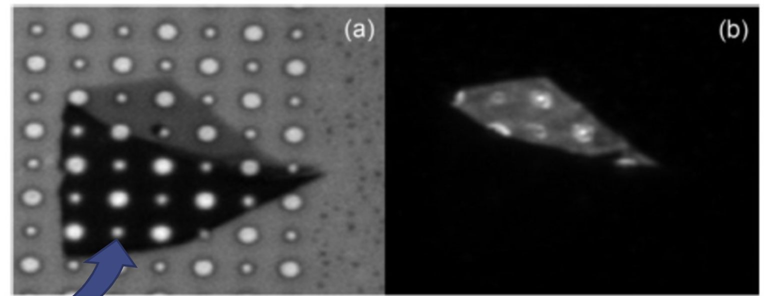
graphite graphene

BUT: graphene IS NOT a semiconductor!

2010 Transition Metal Dichalcogenides (TMD)



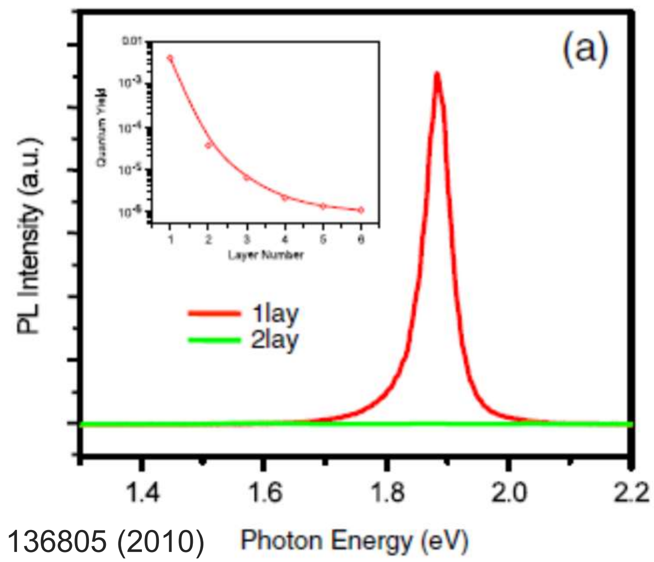
MoS$_2$



from the mine…to a single layer flake

MoS$_2$ becomes direct bandgap semiconductor in 1 monolayer

exceptional
light absorber/emitter

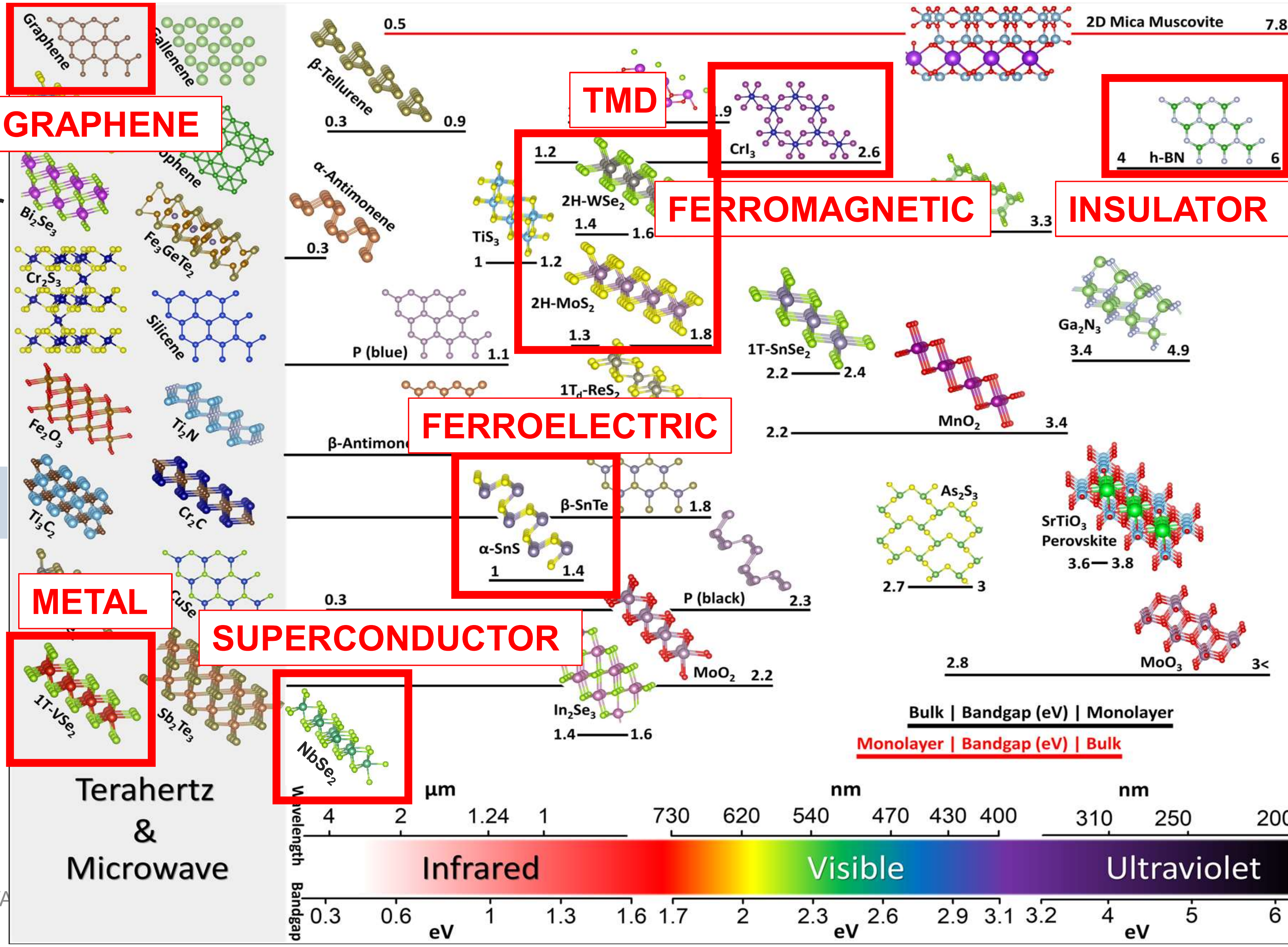


K. F. Mak, T. F. Heinz, Phys. Rev. Lett. **105**, 136805 (2010)

2004-2021

Boom in the number of 2D materials

2D constellation

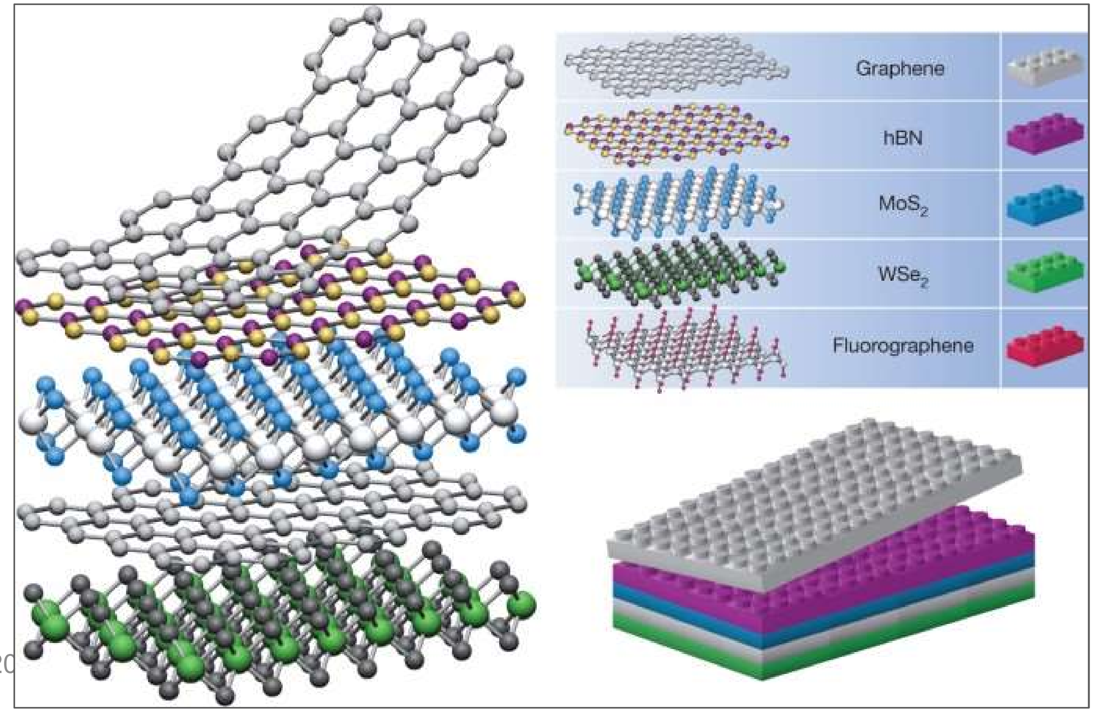


A. Chaves et al., npj 2D Mater. & Appl. **4**, 29 (2020)

Why so much success ?

- <u>vdW interfaces:</u> perfectly clean and sharp interfaces with no chemical reaction or atomic intermixing. Perfect control of interface effects: proximity effects (magnetism, superconductivity…), band engineering with well defined band offsets

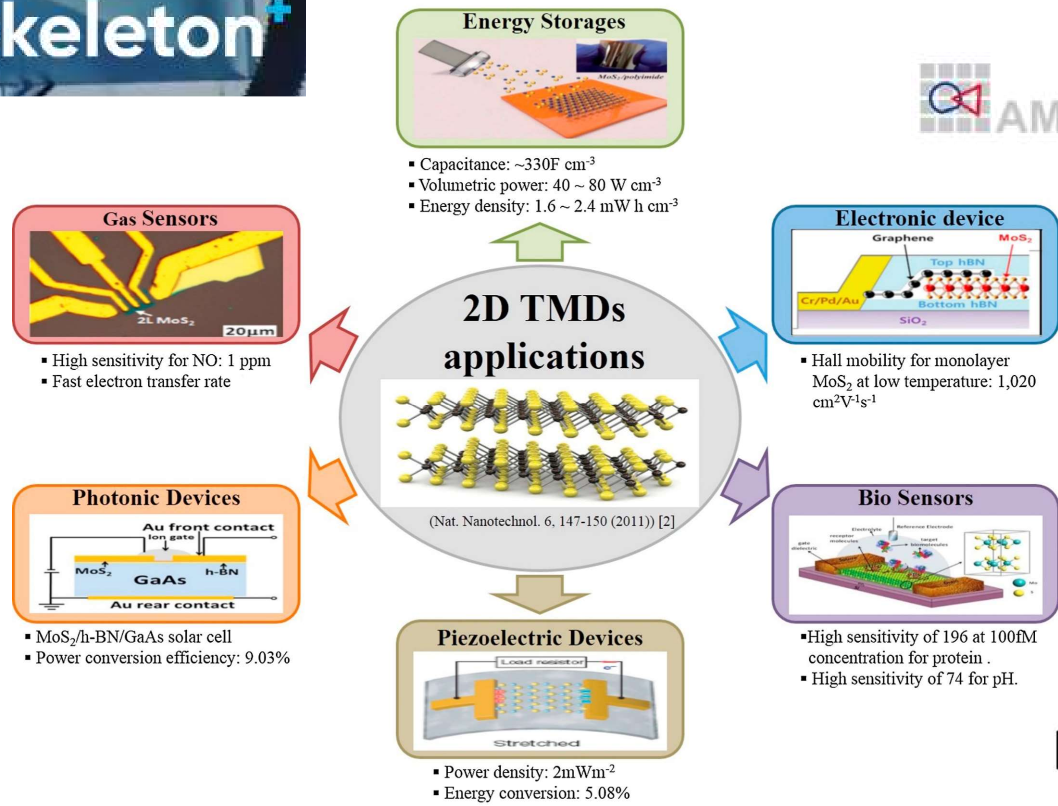
→ NEW PHYSICS AND VERTICAL DEVICES



A. K. Geim et al., Nature **499**, 419 (2013)

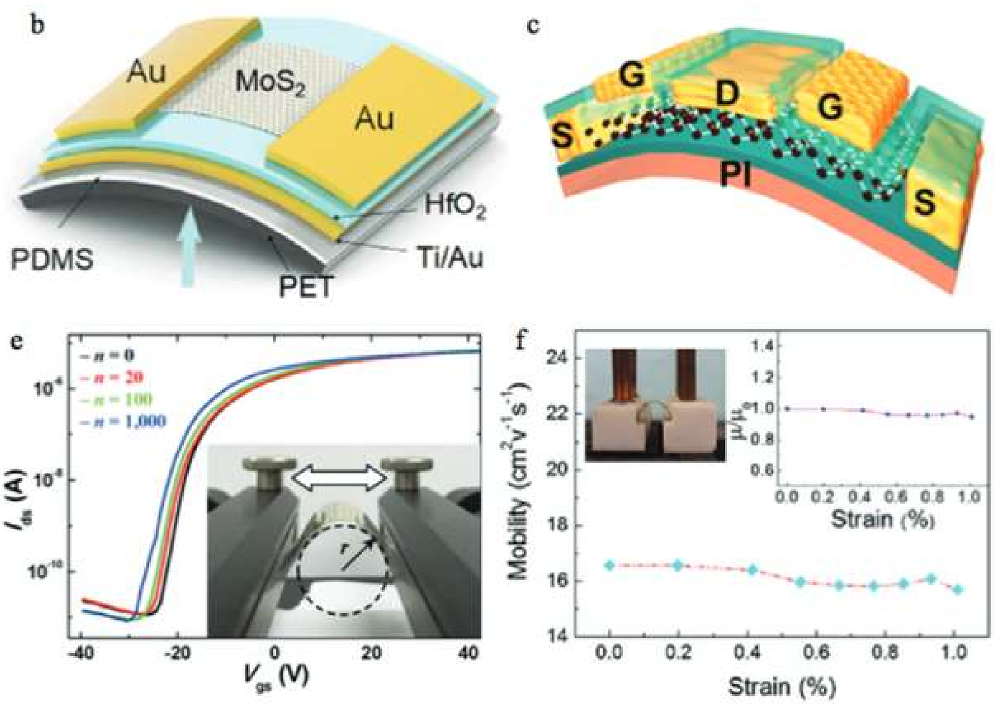
2. Which applications for 2D materials?

2D materials applications



Choi et al. Material Today 20 (2017), 116-130

Flexible devices



Gao et al. Small (2017),13, 1603994

E-Biosensing

Digital test strips
TestNpass

Wearables
WoundLAB

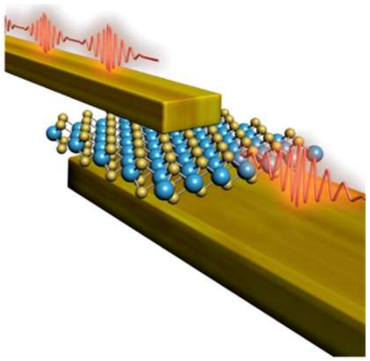
Antigen tests

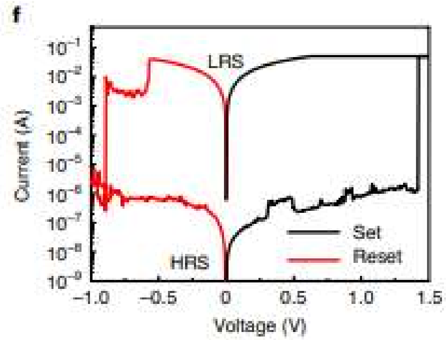
Water sensors

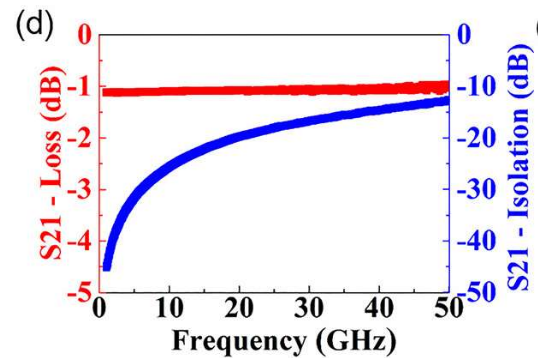
Grapheal

- **Properties preserved**
- **Health application**

RF switch







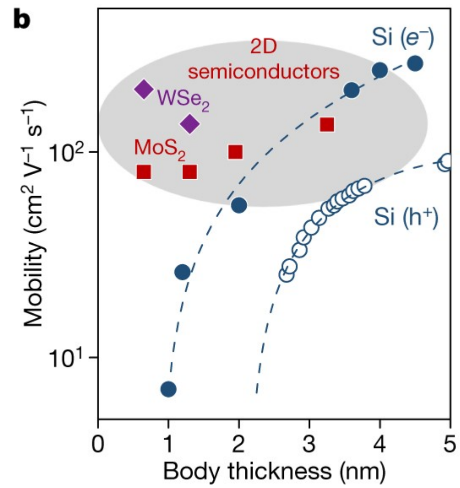
	RF MEMS	FET	Ge et al MoS2 - CVD	Kim et al. MoS2 - CVD
voltage	20-80V	1-5V	0.5-1.5V	0.5-1.5V
Switching time	1-300µs	1-100ns	<15ns	0.5ns
Figure of merite	20-50THz	0.5-2THz	70 THz	22 THz
Nonvolatility	No	No	Yes	Yes
Switching energy	50pJ-10µJ	50fJ-10pJ		50pJ
Area (μm^2)	10^2-10^4	10-10^3	0.02	0.04

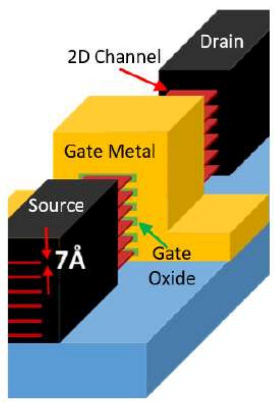
- **Promising first results for speed, miniaturization and new frequencies range**

Ge et al. Nano Lett. 2018, 18, 1, 434–441, Kim et al. Nature electronics 2022 5, 367-373, Wainstein et al IEEE (2021) 109, 77

Transistor more Moore

- **Moore's law limit ➔ « short channel effect »**
  - Si mobility is strongly decreased for thickness < 3 nm
  - 2D materials: a « more Moore » solution?
- **Transistors: GAA-FET**
  - 2D materials to replace silicon





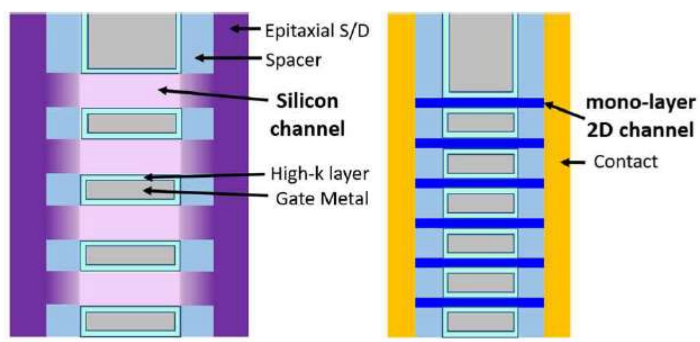


Fig. 1. 2D mono-layer nanosheet channels allow for ultra-scaled gate lengths and increased number of channels per stack height.

Liu et al. Nature 591, 43–53 (2021), Dorrow et al. IEEE IEDM 2022 DOI: 10.1109/IEDM45625.2022.10019524

Transistor more Moore

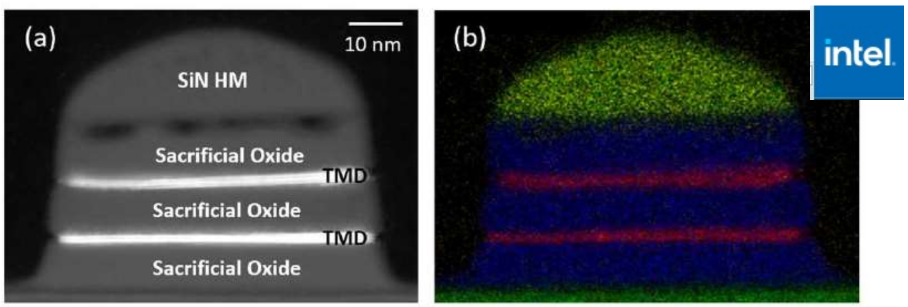
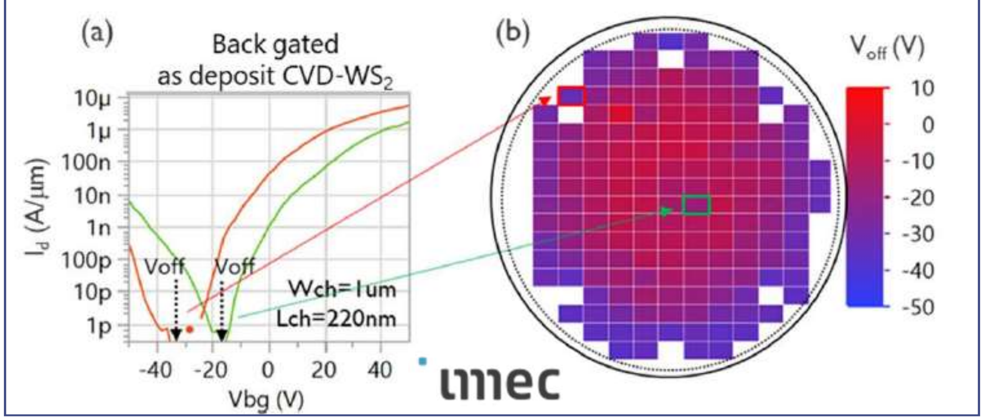
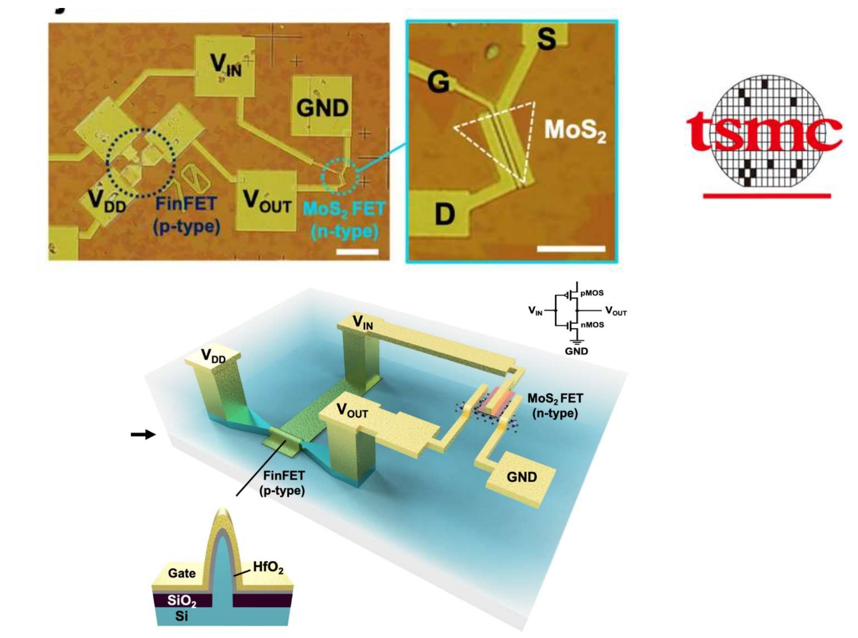


Fig. 2. TEM cross section of a two-layer TMD stacked nanoribbon structure showing 2 – 3 ML per nanoribbon. (b) TEM elemental mapping of stacked 2D nanoribbons.



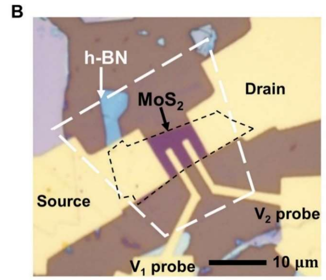


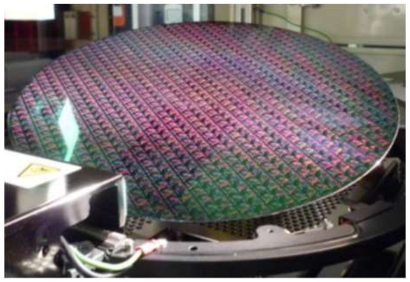
- Intel: stack with 2D materials
- IMEC: Integration at wafer scale (300 mm)
- TSMC: co-integration of Si n-FinFET and MoS_2 p-FET

Guan et al. npj 2D Mat. & App. (2023) 7:9, Dorrow et al. IEEE IEDM 2022, Asselberghs et al. 2020 IEEE International Electron Devices Meeting (IEDM)

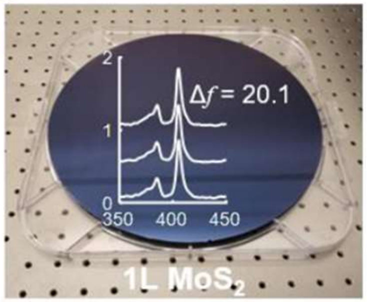
3. Integration

Integration challenges

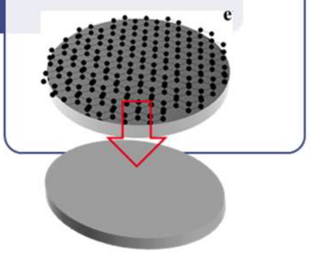




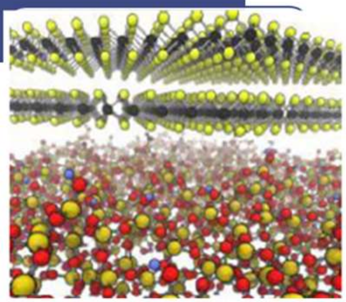
Wafer scale growth



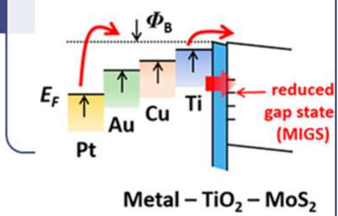
Wafer scale transfer



Van der Waals interfaces



Electrical contact



O'Brien et al. IEEE | IEDM 2021 , Das et al. Nat. Elec. 4 (2021), Kim et al. ACS Nano (2018) 12 (6) 6292

Large scale growth: historical way

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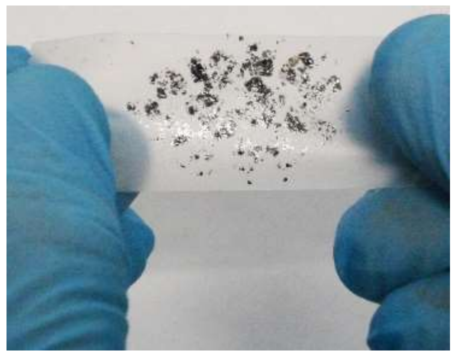

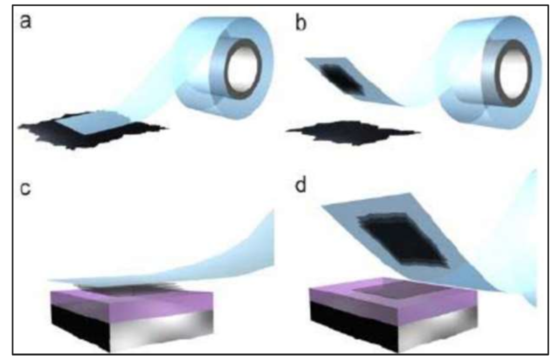

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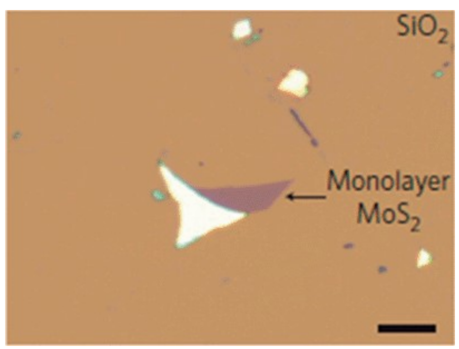


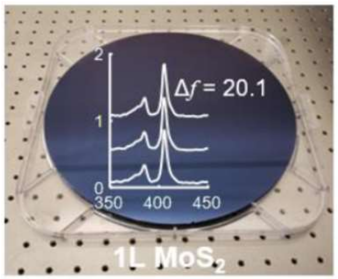
?

Novoselov, Phys. Scr. T146 (2012) 014006,
Joe et al. Electronics 2023 12, 45

Large scale growth: MOCVD and ALD

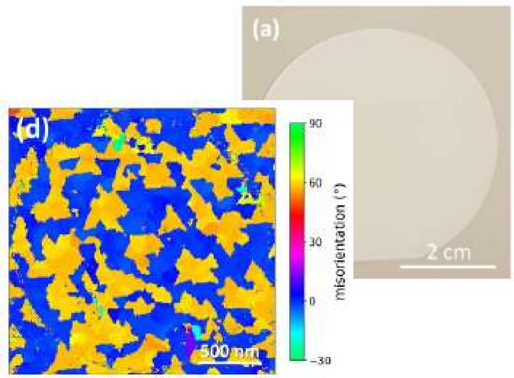
Metal Organic Chemical Vapor Deposition

300 mm growth on Si-wafer/SiO_2



MoS_2 by Intel

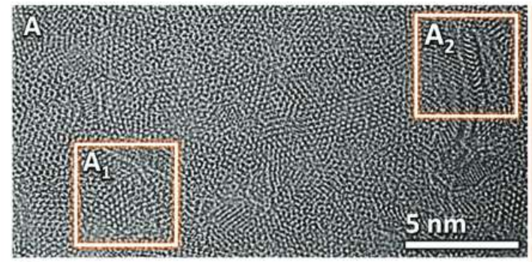
Epitaxial growth on sapphire

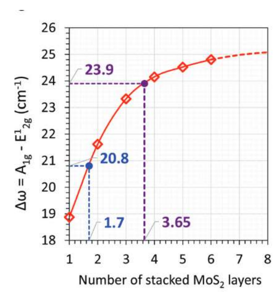


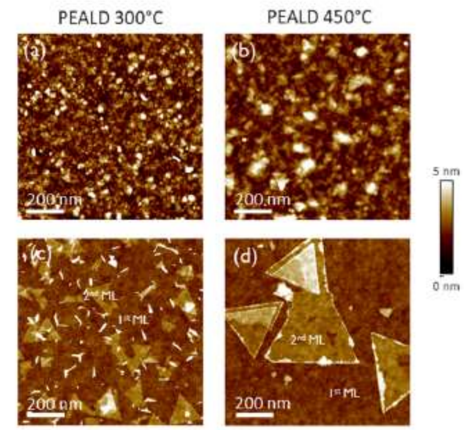
WS_2 by Aixtron

- **Large grain size**
- **Growth at high temperature**

Atomic Layer Deposition







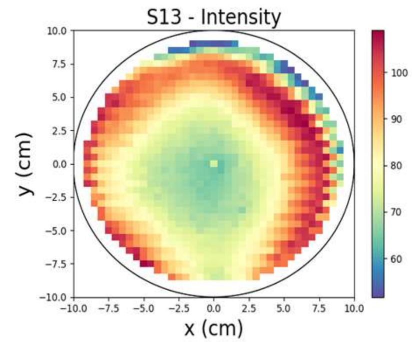
- **Small grain size**
- **Good control of number of layers**

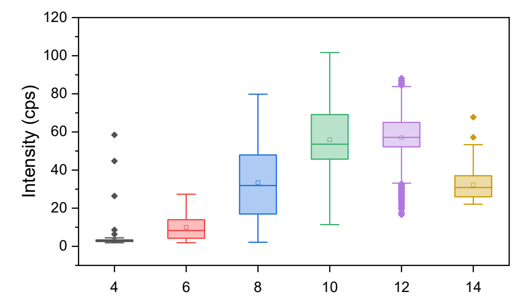
Dorrow et al. IEEE IEDM (2022), Dosenovic et al. *2D Mater.* (2023) Cadot et al. Nanoscale (2017),9,538–546, Asselberghs 2020 IEEE IEDM | 978-1-7281-8888-1

Large scale growth: characterization

- **Development of large scale growth**
  ➔ large scale characterization of 2D materials
  - Measurement automation
    - Automatic treatment
      - Graph design
- **Photoluminescence, Raman, AFM, SEM, WDXRF**

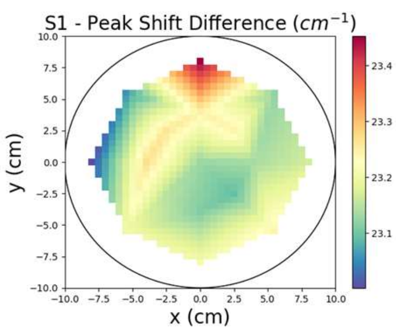
Photoluminescence



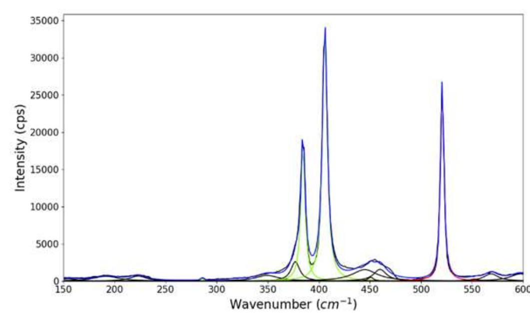


Measurement of 1100 points

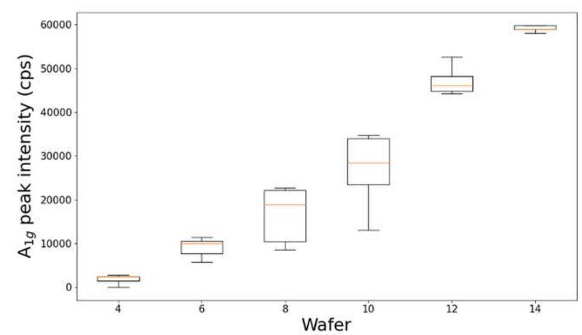
Raman spectroscopy



Measurement of 25 points



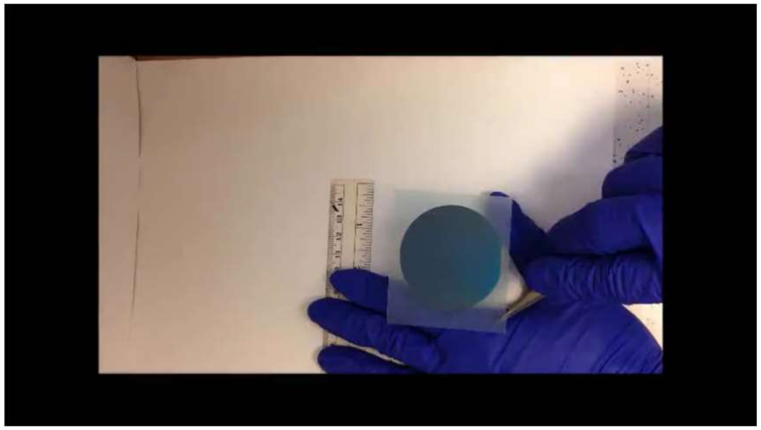
Decomposition with 17 peaks

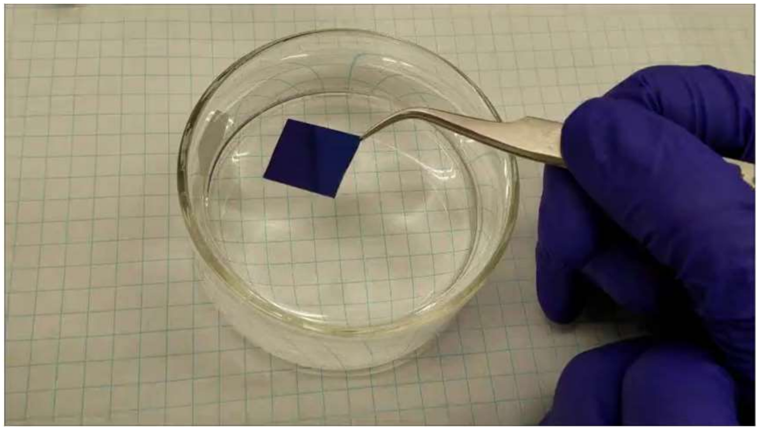


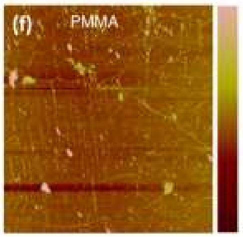
Comparison wafer to wafer

Integration challenges: 2D transfer

- **Lab scale**



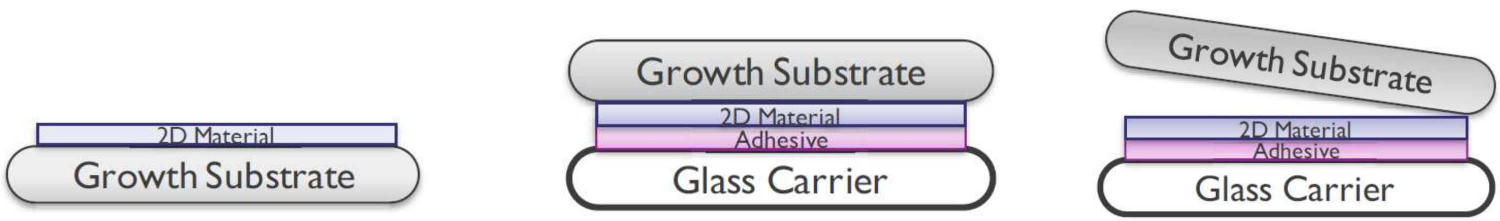


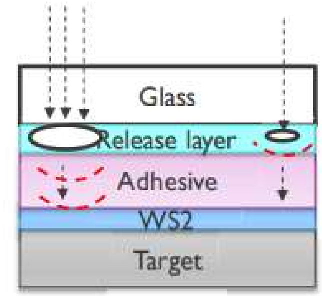


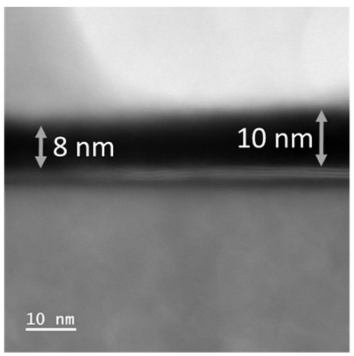
Easy-going
Defects: polymer residues, mechanical defects as wrinkles, holes…

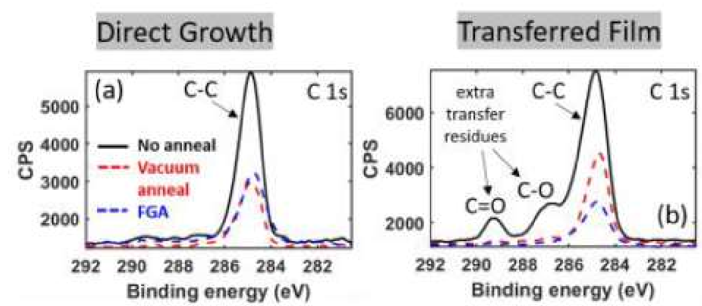
Kang et al., Nature **520**, 656 (2015) J. Cryst. Growth **464**, 100 (2017) ACS Nano **9**, 2080 (2015)

Integration challenges: 2D transfer





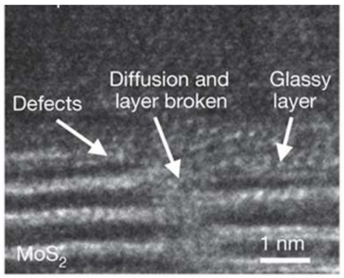


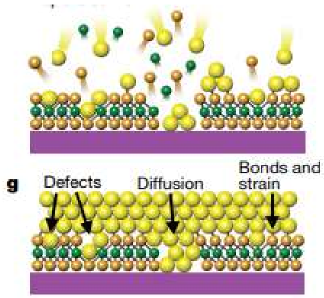


- **Development of a transfer method in 300 mm without polymer → R2D2 project with Intel and CEA-Leti**

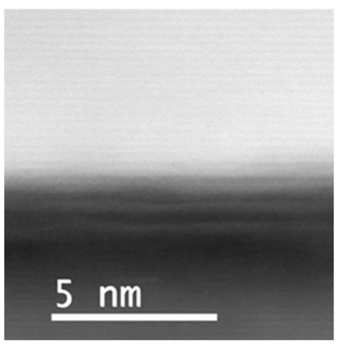
A. Phommahaxay *et al.*,," *2019 IWLPC*, San Jose, CA, USA, 2019, 1-8, Ligaud, Okuno et al. Thesis, TBP, O'Brien et al. 2021 IEEE |

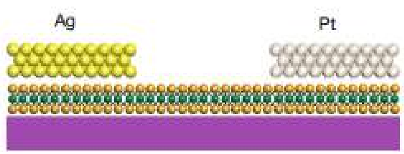
Van der Waals interfaces: deposition



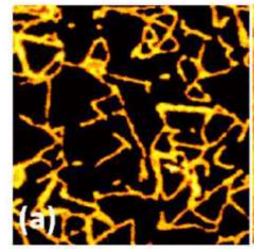


Deposition method



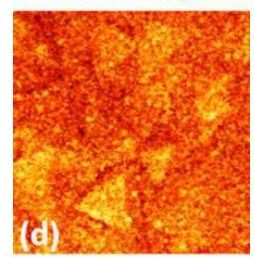


Standard ALD
2.2 nm Al_2O_3
28 % coverage



Deposition process

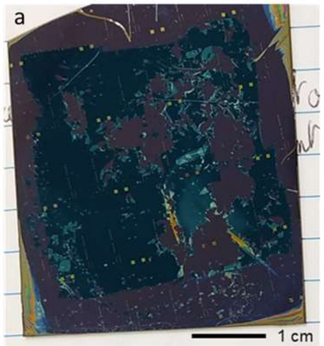
Thick Bilayer Process
2.2 nm Al_2O_3/3.1 nm HfO_2
99 % coverage



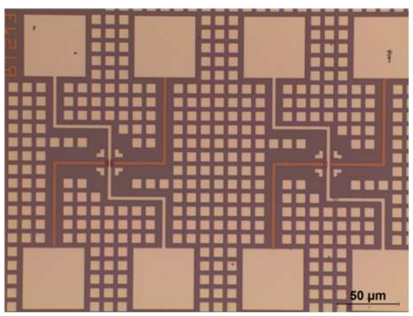
Liu et al. Nature 2018 557:696-700., Dorrow et al 2022 IEEE |, Ligaud, Okuno, Thesis, TBP

Interfaces de van der Waals : lithographie

Standard process



Optimized process



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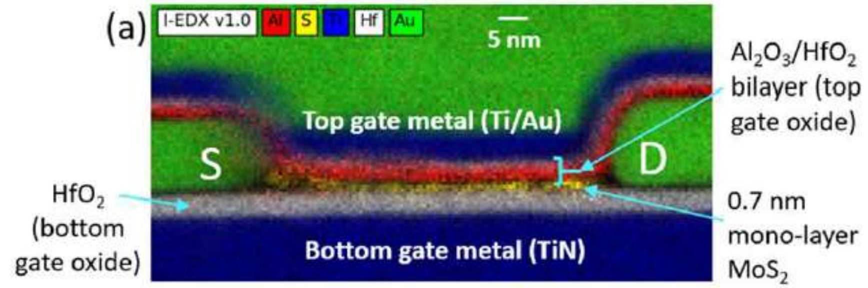
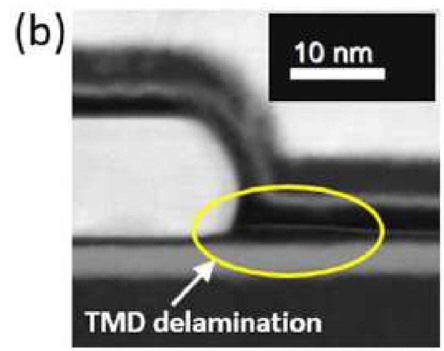
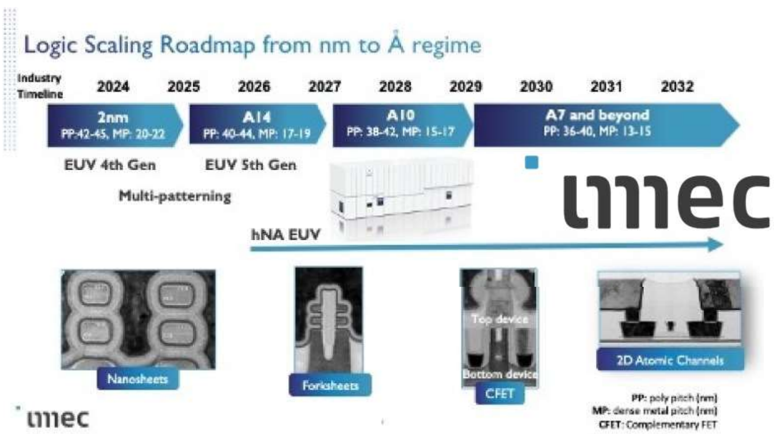


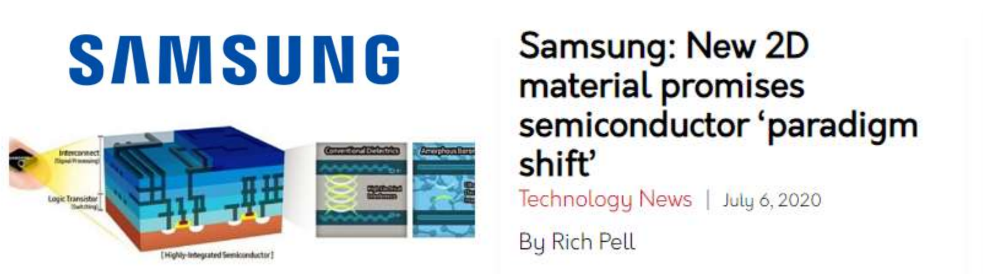


- **Classical lithography technics have to be adapted**

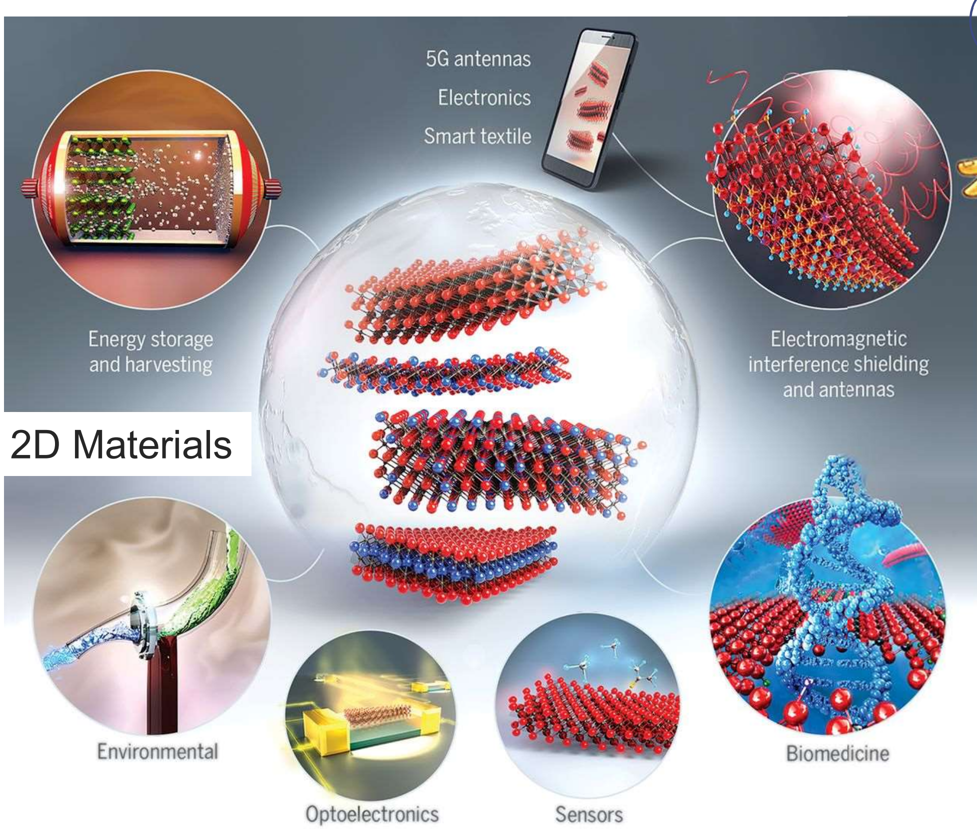
Ligaud Thesis, TBP, Dorrow et al 2022 IEEE

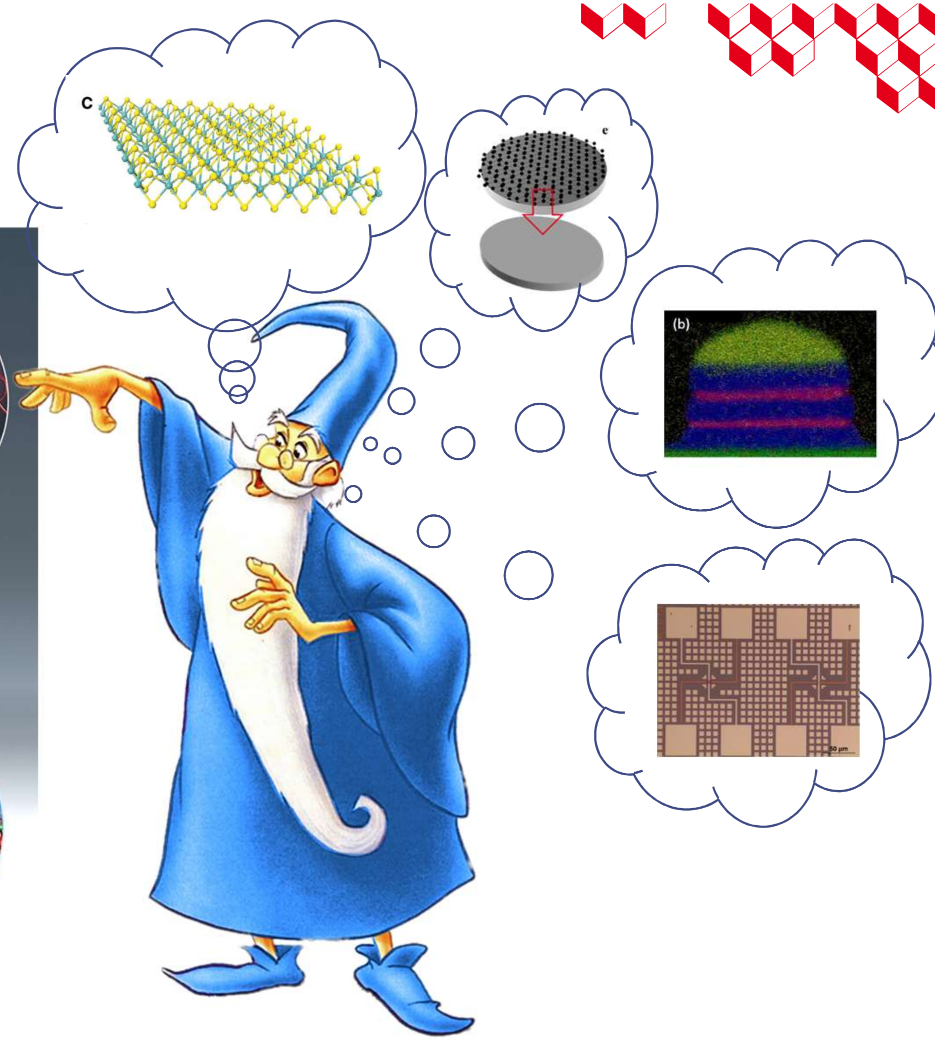
What about manufacturers?





Conclusions





Aknowlegments

- Paul BRUNET
- Emmanuel ROLLAND
- Thibaut MEYER
- Clotilde LIGAUD
- Pierre TROUSSET
- Matthieu JAMET
- Van-Hoan LE
- Stéphane CADOT
- Bruno REIG
- Nicolas GAUTHIER
- Hanako OKUNO
- Jorge DOSENOVIC

Thank you

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