2D Materials for Future Heterogeneous Electronics and the 2D-Experimental Pilot Line

Workshop “Promising technologies for ECS”
September 22nd, 2022

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RWTH Aachen University
AMO GmbH

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2D-Materials for Future Heterogeneous Electronics

The (AI) chip makes the product

Chip hardware as a strategic technology

- Technology Sovereignty (Chips Act)
- Energy Efficiency (Green Deal)
- Reliable Supply Chains
- Cyber Security
- Data security and privacy
- Ethics of AI

„Cyber-attacks are moving… from software to hardware, threatening devices in homes, cars, businesses, networks, and cloud.“

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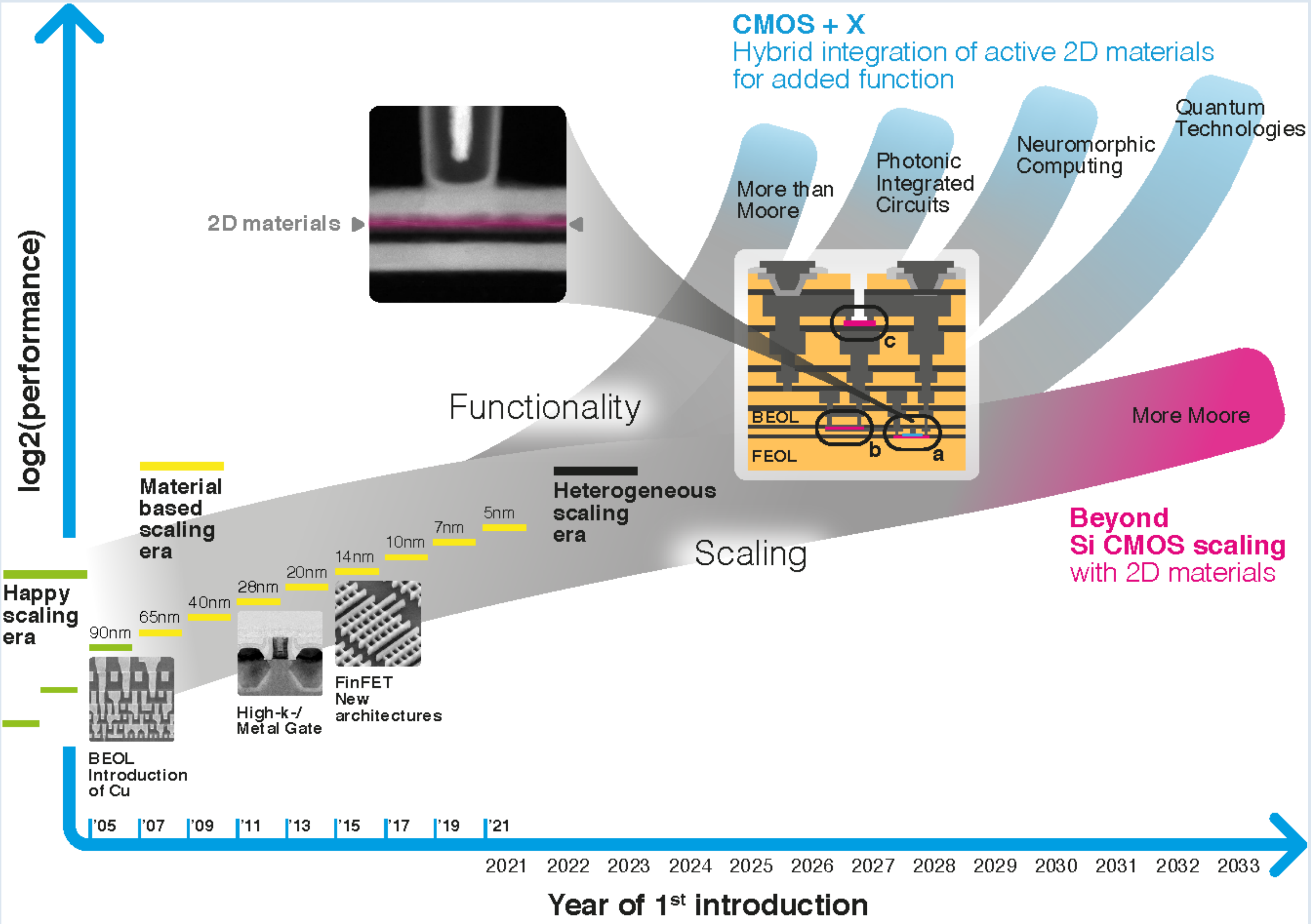

Lemme, Akinwande, Huyghebaert, Stampfer

"2D materials for future heterogeneous Electronics"

Nature Communications, 13:1392, 2022

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2D-Materials for Future Heterogeneous Electronics

Lemme *et al*., Nat. Comm., 2022

2D-Material Integration: Opportunities

- **More Moore**
  - Nanosheet FETs
  - Back-End-Of-Line Integration
  - Flexible Electronics
- **More Than Moore**
  - Sensors (Gas, Bio, Chemical,...)
  - RF Electronics
  - Photodetector & Cameras
  - NEMS
- **Photonic Integrated Circuits**
  - Detectors
  - Modulators (Amplitude & Phase)
  - Attenuators
  - Heaters
- **Neuromorphic Computing**
  - Threshold Memristive Switching
  - Bipolar Memristive Switching
  - Photonic Neuromorphic Circuits
- **Quantum Computing**
  - Qubits
  - Single Photon Emission
  - Single Photon Detection
  - Topological Insulators

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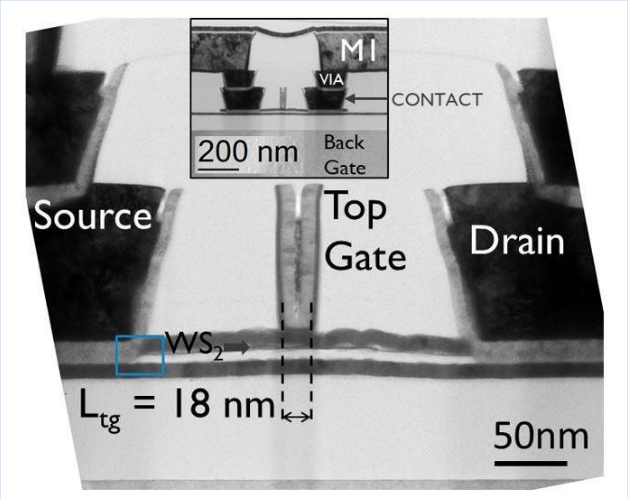
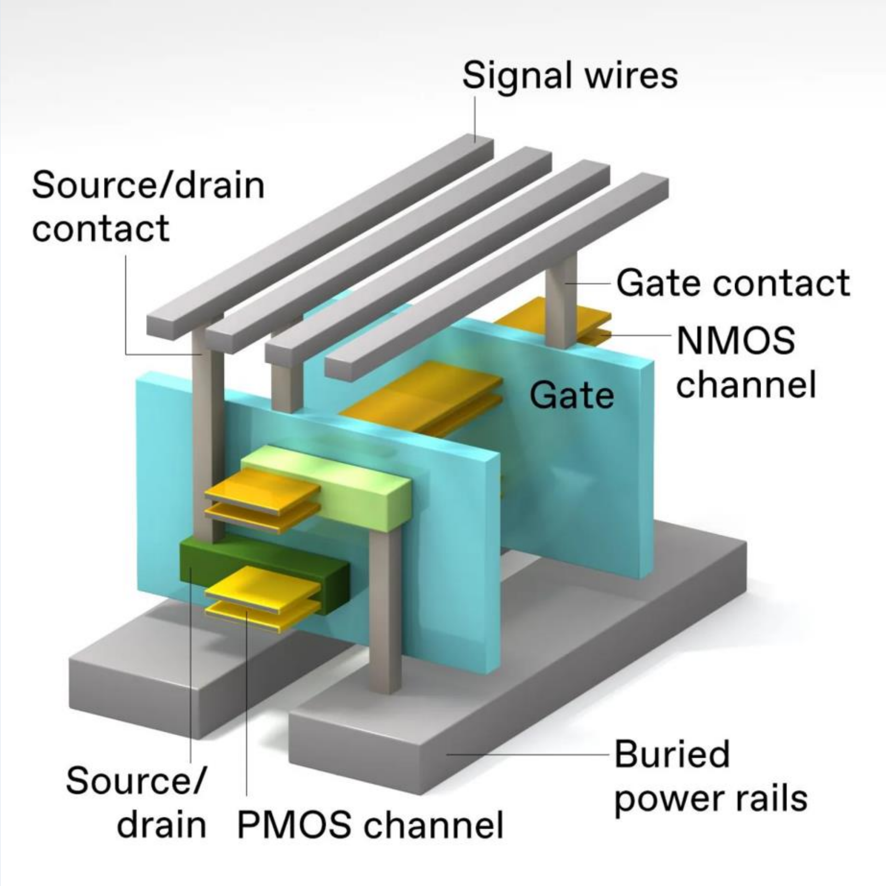
More Moore

- 2D Nanosheet FETs
  - Ultimate electrostatic control
  - No loss of mobility
  - BEOL integration → 3D



Source: IMEC
https://www.imec-int.com/en/articles/imec-introduces-2d-materials-logic-device-scaling-roadmap



Radosavlevic et al., IEEE Spectrum, 2022

2D Materials may be the ultimate channel material for "end of the roadmap" ***CMOS scaling***

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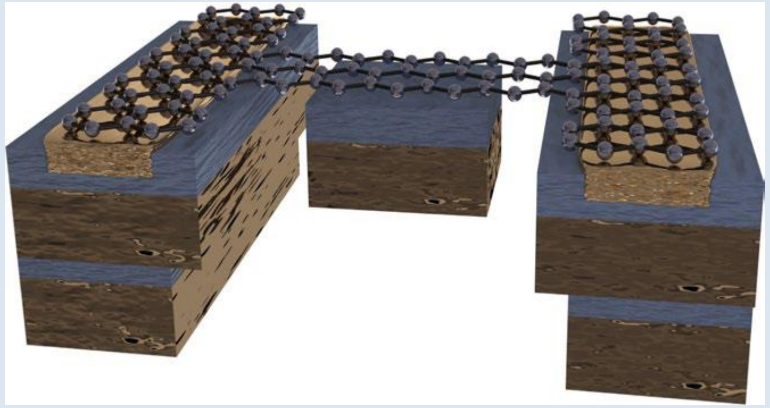
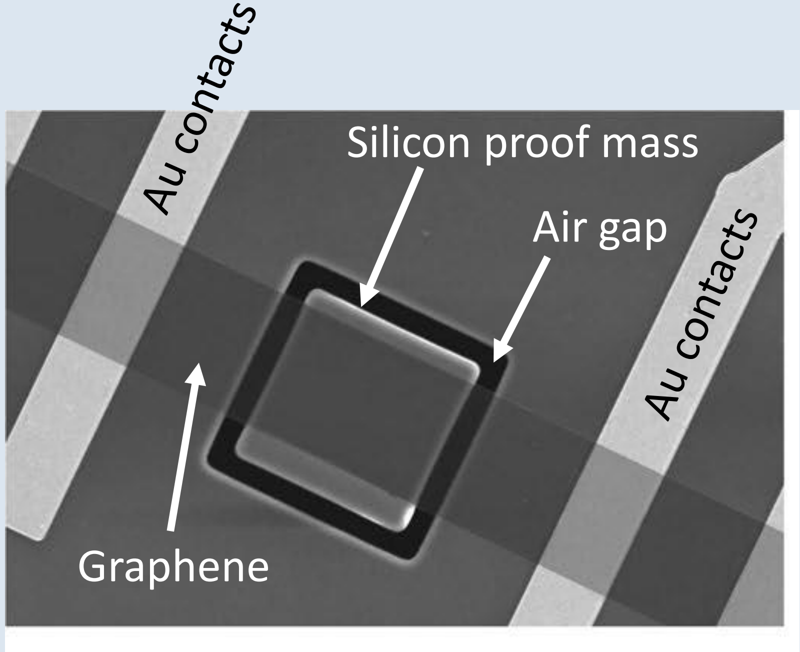
Graphene NEMS Accelerometer

- Graphene acts as membrane and transducer
- Silicon proof mass attached to graphene membranes (1.000 x reduction compared to SoA)
- Reduced footprint compared to SoA (1/100 x)

- Double layer graphene enhances reliability and yield





Fan *et al.* Nature Electronics, 2, 394-404, 2019

Fan et al. Nano Letters, 19, 6788−6799, 2019

Lemme et al., Research, 8748602, 2020 (review)

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2D materials make superior:
- pressure sensors
- microphones
- accelerometers
- mass sensors
- gas sensors

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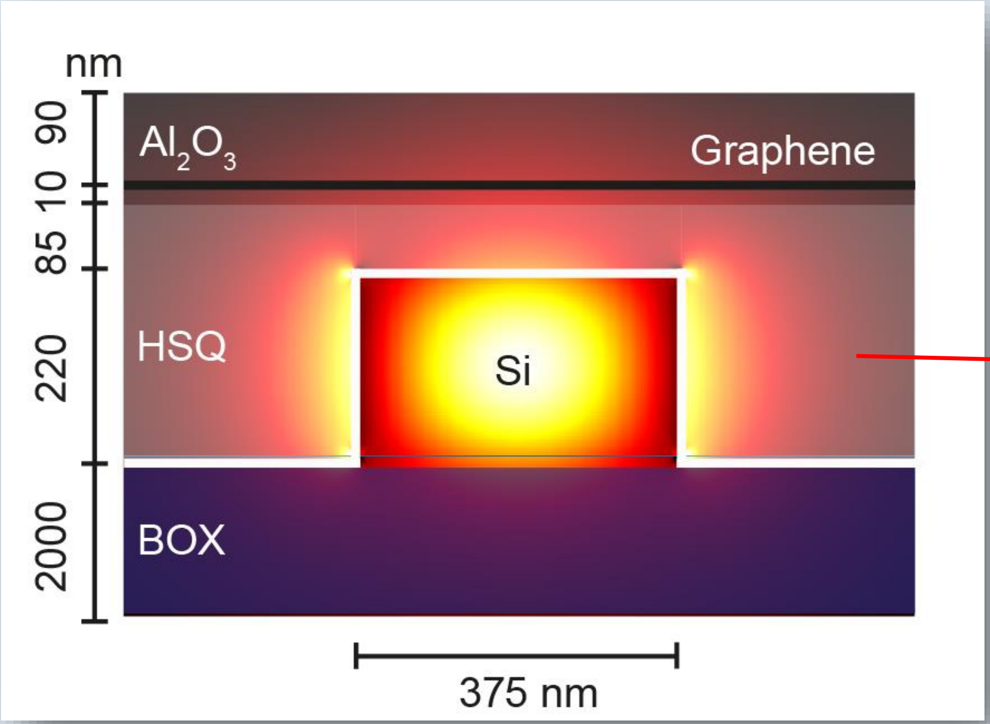
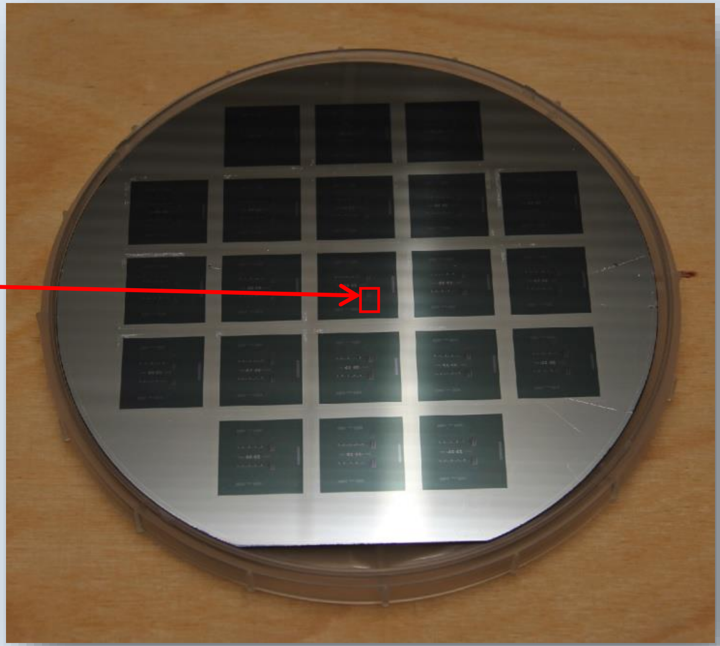
Graphene / Silicon Photonics Integration



Schall *et al.*, ACS Photonics, 2014



Active silicon photonics in the back end of the line (BEOL)

Graphene photodetector key performance indicators:

- Integrable on various substrates, here silicon (SOI) waveguide
- Possible intrinsic bandwidth: few hundred GHz
- **Ultrafast charge carrier dynamics ► ultrafast photonic devices**

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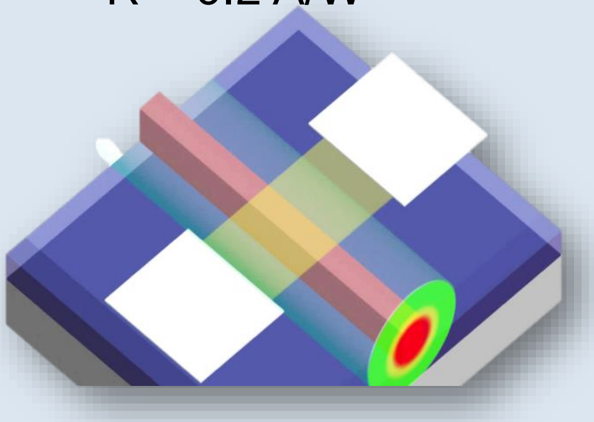
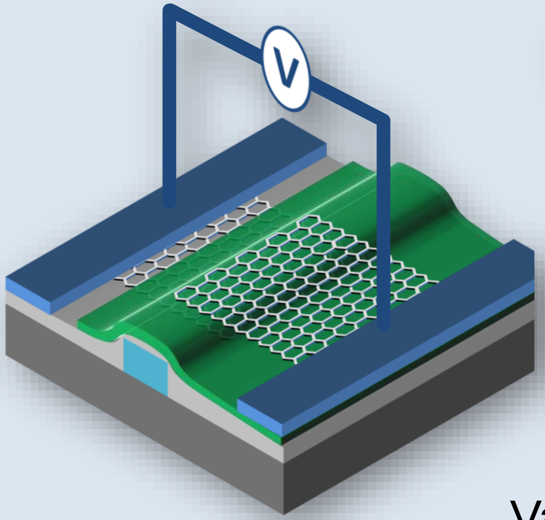
Graphene / Silicon Photonics Integration

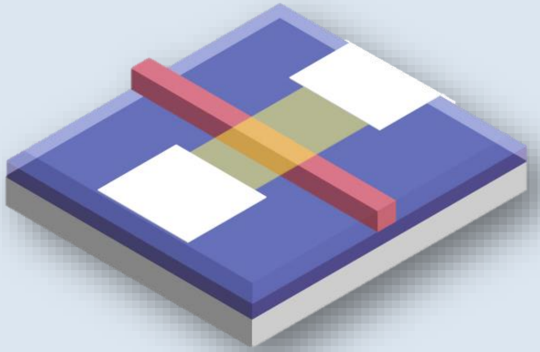
Photodetector: 130 GHz
R = 0.2 A/W



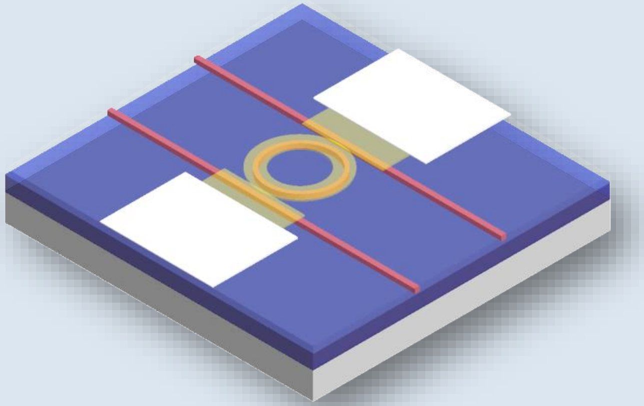
Absorption modulator:
Extinction 16 dB, IL 3 dB



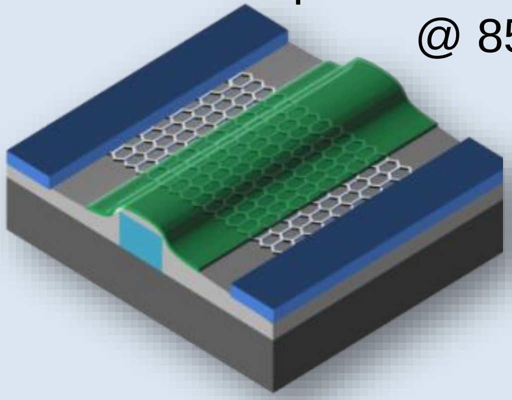
Heater: 0.3 nm/mW
rise/fall 3 µs



Phase modulator: $V_{\pi}L\alpha$ = 14 dBV



Variable Optical Attenuator
@ 855 nm



Active ***ANY***
photonics,
anywhere

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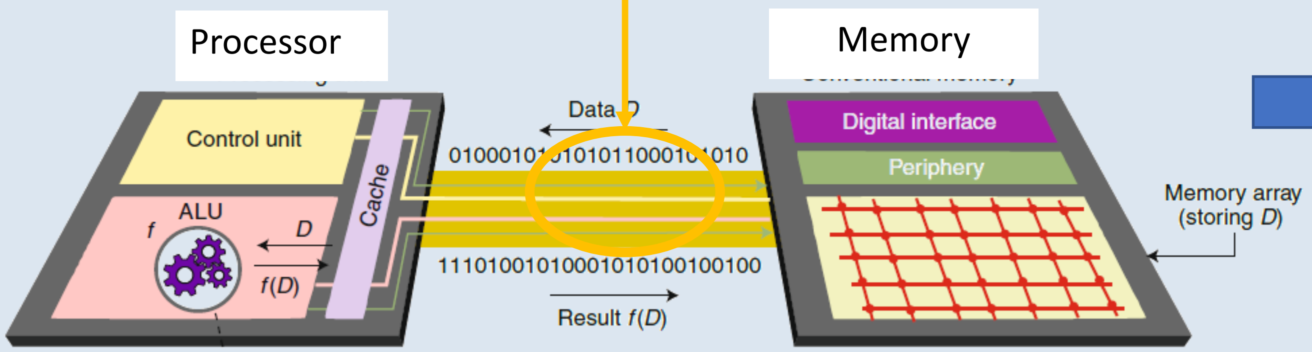
Machine Learning and Artificial Intelligence: Why new hardware?

Von-Neumann bottleneck



(2) A. Sebastian et al., Nat. Nanotechnol., 1–16 (2020).

Neuromorphic Computing

Consumption	CO_2e (t)
Human life, avg, 1 year	5
US American life, avg, 1 year	16.4
Car, avg incl. fuel, 1 lifetime	57.152
Training one model (GPU)	
NLP pipeline, full tuning	35.592
Transformer (big), full tuning	284.019

Estimated CO_2 emissions from training common natural language processing (NLP) models and familiar consumption [(1)]

(1) E. Strubell et al., in Proceedings of the 57th Annual Meeting of the Association for Computational Linguistics Italy, 2019 pp. 3645–3650.

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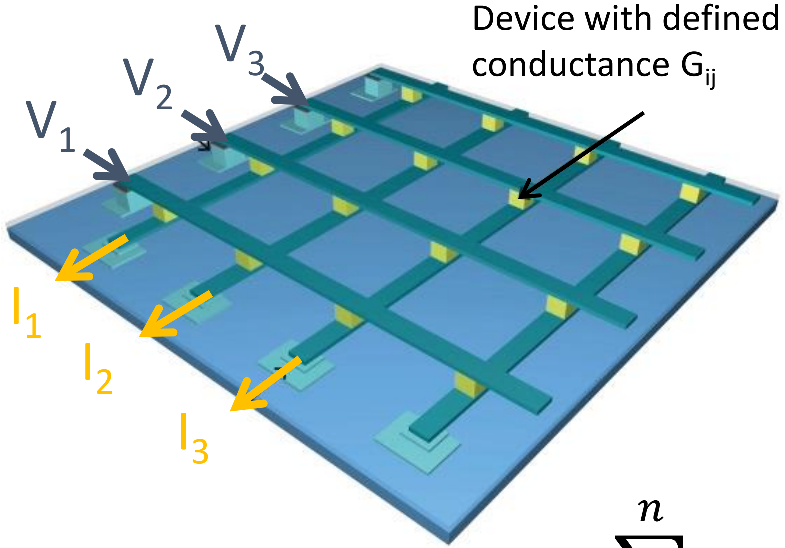
Neuromorphic computing: „Beyond-von-Neumann“-Concepts

Computing in memory



$$\vec{I} = G\vec{V} \Leftrightarrow I_i = \sum_{j=1}^{n} G_{ij} V_i$$

Adapted from: (3) A. Mehonic et al., Advanced Intelligent Systems. 2, 2000085 (2020).

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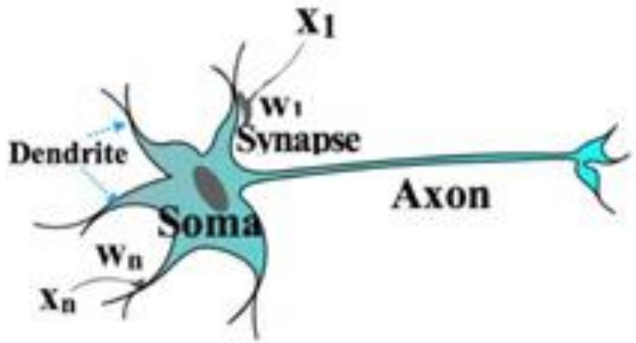
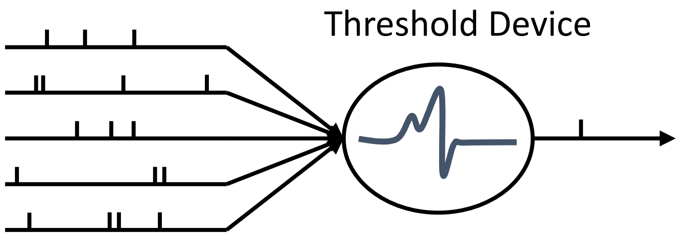
Biological Neural Network



Spiking Neural Network



Adapted from: (4) X. Zhang et al., physica status solidi (a). 215, 1700875 (2018).

2D Materials can be integrated into “memristive devices” that excel at key specifications for ***Neuromorphic Computing***

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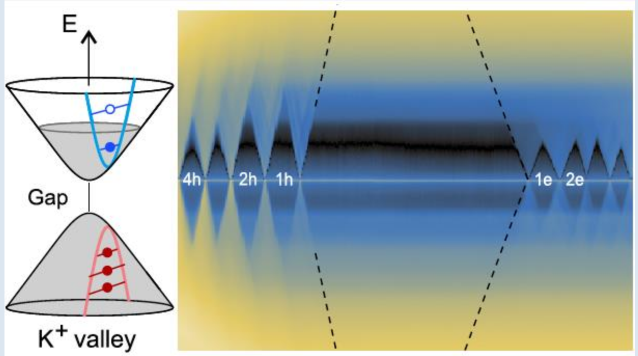
Quantum Computing

Liu and Hersam, Nat. Rev. Mat., 2019

Qubits

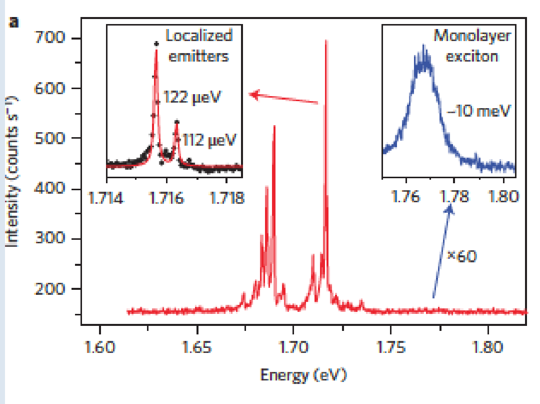
- Valley and spinvalley qubits
- „Valleytronics“



Banszerus, *et al*., Nano. Lett, 2020

Single photon emitters

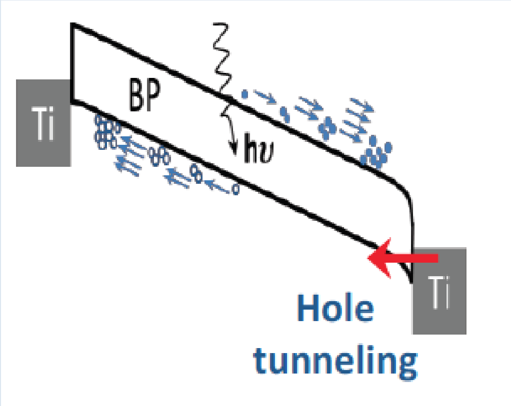
- Si-Photonics integrable



He, *et al*., Nat. Nano., 2015

Single photon detectors

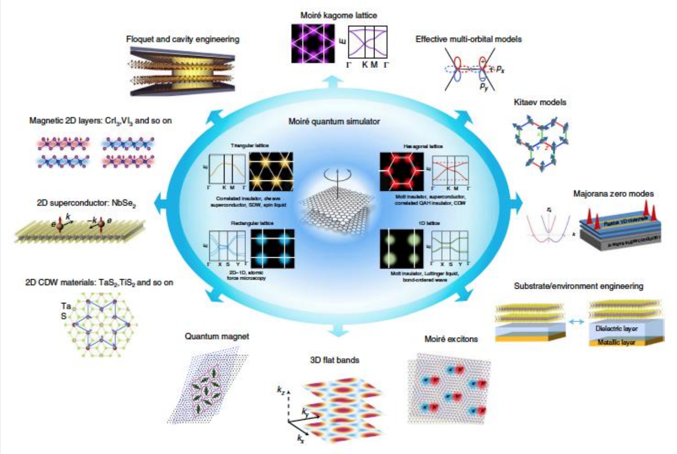
- Avalanche photodetector



Atalla and Koester, DRC, 2017

Topological Insulators

- Moire Heterostructure
- „Twistronics“



Kennes *et al*., Nat. Phys, 2021

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2D Materials may provide key components for ***Quantum Computing***

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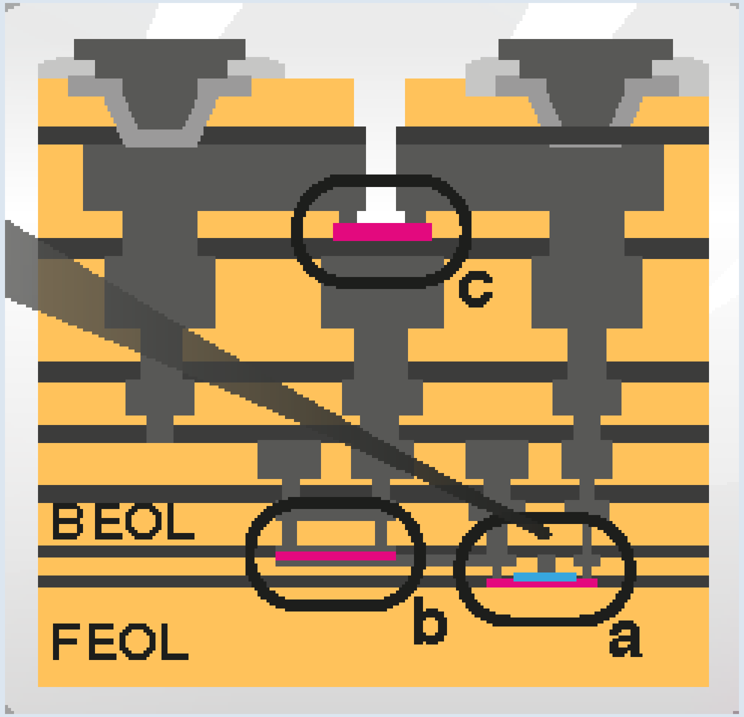
2D-CMOS Integration: Challenges



Neumaier, et al., Nature Materials, 2019
Akinwande *et al.,* Nature, 2019
Illarionov *et al*., Nature Communications, 2020
Quellmaltz *et al*., Nature Communications, 2021

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Growth

- Catalytic CVD on metals
- Temperatures: 400-1000°C
- Quality

Transfer process

- Quality
- Automation

Etching

- Etch stop → ALE

Encapsulation

- ALD vs. 2D

Electrical contacts

- Graphene
- Semiconducting 2D

A number of ***Engineering Challenges*** remain before we see 2D Materials-based electronics / optoelectronics

Addressed by the ***2D-EPL***

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2D-Materials for Future Heterogeneous Electronics

European 2D Experimental Pilot Line

- H2020 project to develop technology (not a specific application)
- Start in 10/2020, 4 years, 20 M€ funding
- Goal: technology transfer to Europractice and European Industry

1. **Development of tools & materials**
2. **Development of module & platform**
3. **Multi-purpose wafer runs**

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Industrial Advisory Board
X-FAB
AMS
NXP
Infineon
STMicroelectronics
Emberion
Nokia
ELMOS
QERV

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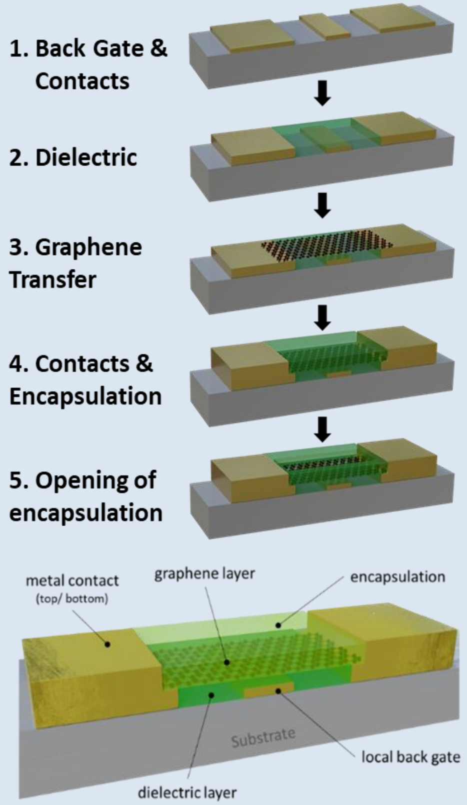
2D-Materials for Future Heterogeneous Electronics

- **MPW run #1 - In the fabrication line**
- **MPW run #2 - Open for Application**

Graphene FETs for sensor application



Submit form → **Confirmation email** → **AMO response, NDA send** → **Meeting for details**

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Important Dates

1 Feb. 2022:
Call opens for applications

30 June 2022:
Call closes

1 Sept.– 31 Oct. 2022:
MPW run

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