GreEnergy
Power from optical antennas

2D Materials for Energy Harvesting Application

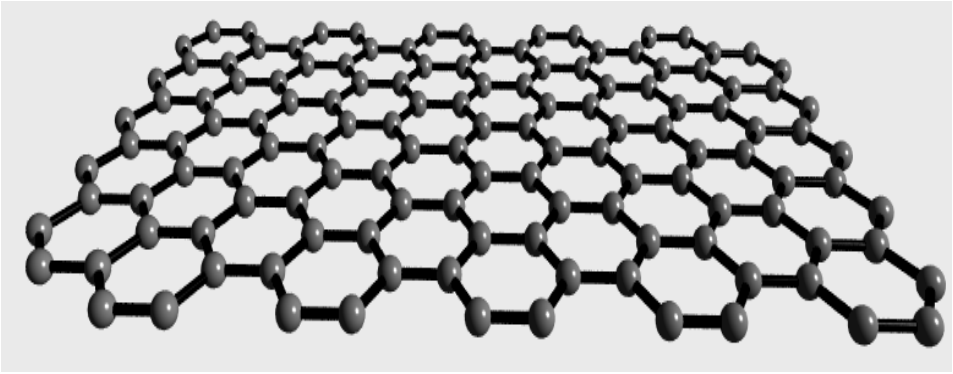
9 September 2024

AMO Intro

AMO GmbH

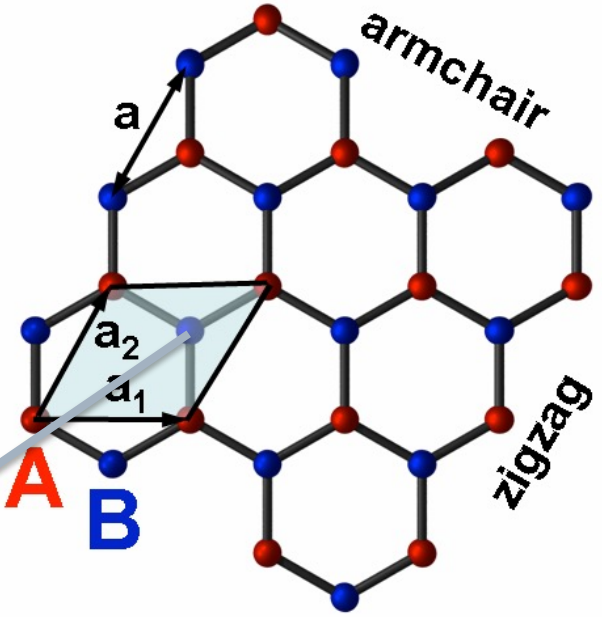
- High-Tech SME / Institute (non-profit) / Research Foundry
- 400 m^2 clean room
- 80 staff members in 35 funded R&D projects
- > 100 R&D partners across Europe and beyond
- Silicon technology, Nanofabrication & New Materials
- Targeted applications
  - Nanoelectronics, Sensors, Flexible Electronics
  - Nanophotonics
  - Quantum Technologies
  - Neuromorphic Computing
  - Environmental Nanotechnology
- Mission: Technology Transfer
  - R&D Partners & Start Ups (Black Semiconductor, Protemics, AMOtronics)

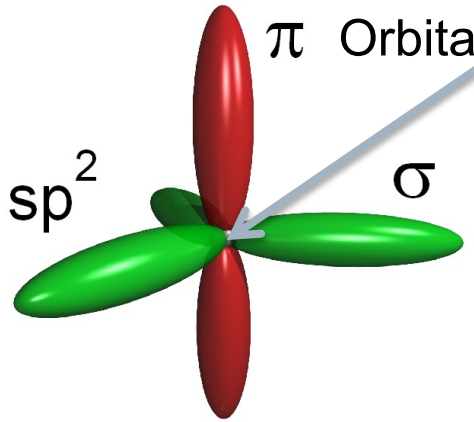
Graphene: Crystal Properties



- sp^2 bonded carbon atoms (~4,3eV)
- Graphite: stacked layers of graphene
- interlayer bond: v.d. Waals

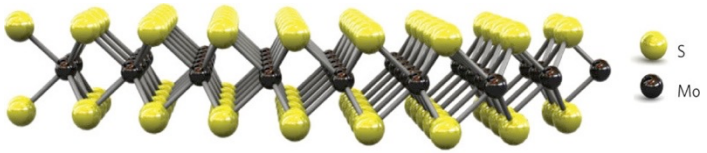
2D-crystal lattice

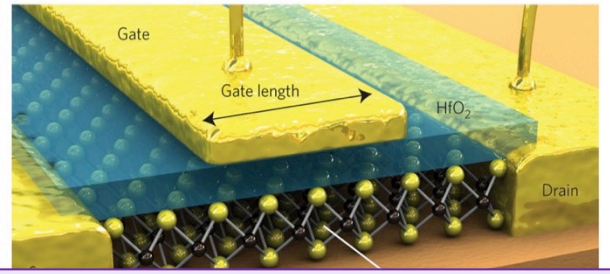


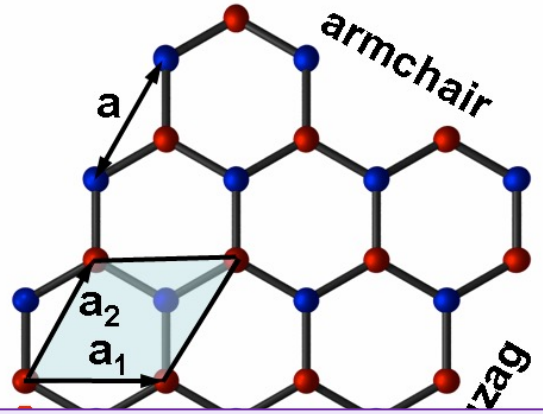


- Lattice constant: a = 0.246 nm
- "Thickness": d = 0.34 nm

Semiconductors & Insulators







...over 1000 2D crystals!

Molybdenum Disulfide (MoS_2)

Transition Metal Dichalcogenides (TMDs)

- E_g = 1.8 eV
- $\mu_{MoS2} \approx 100\ cm^2/Vs$

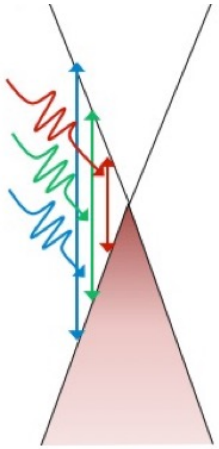
Radisavljevic, Nat. Nanotech. 2011.

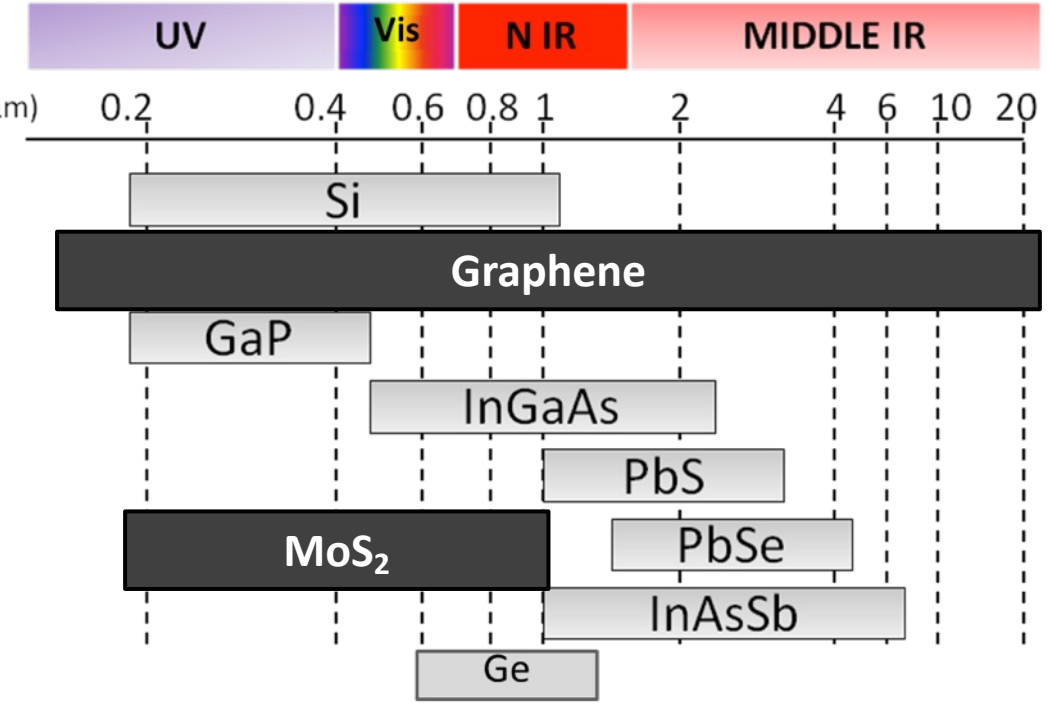
Hexagonal Boron Nitride (h-BN)

- E_g = 5.9 eV
- **A** = Boron
- **B** = Nitrogen

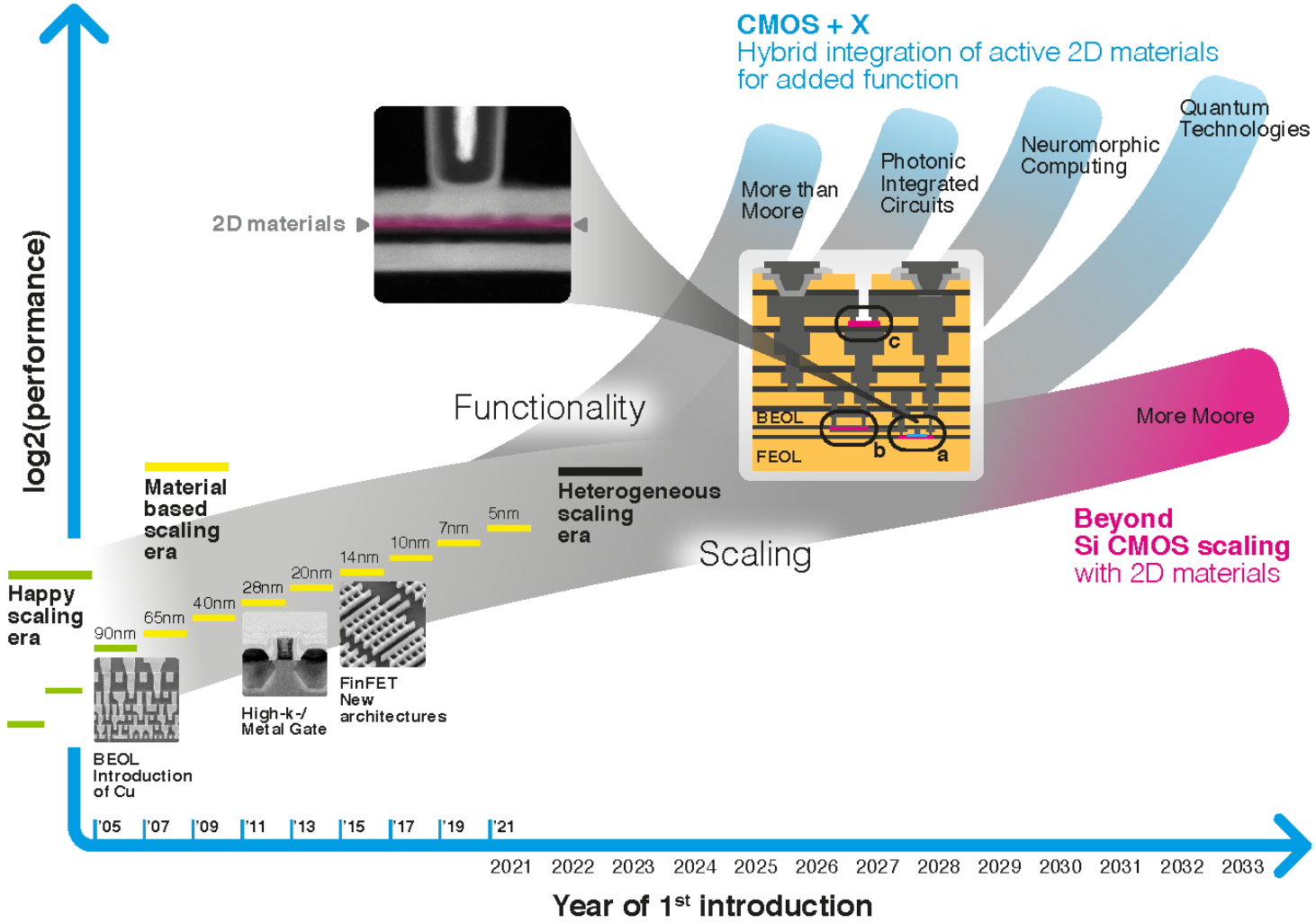
Graphene and 2D materials:

+ Ultra broad band spectral response (graphene, $PtSe_2$)
+ Large scale production (CVD)
+ High conductivity
+ mechanical Flexibility
+ Integrability
± Gate tunability
− Low absolute absorption





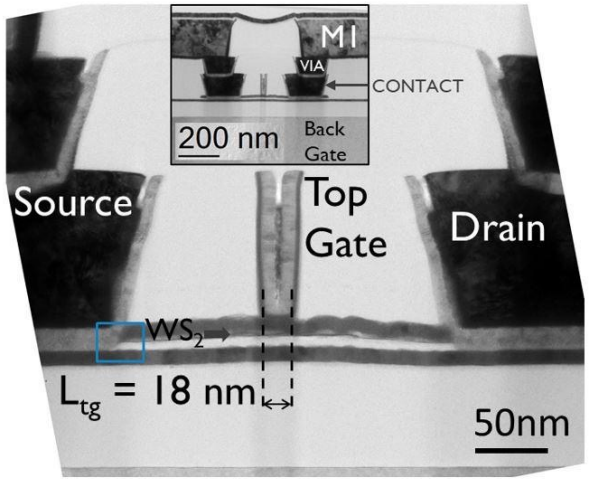
CMOS+X



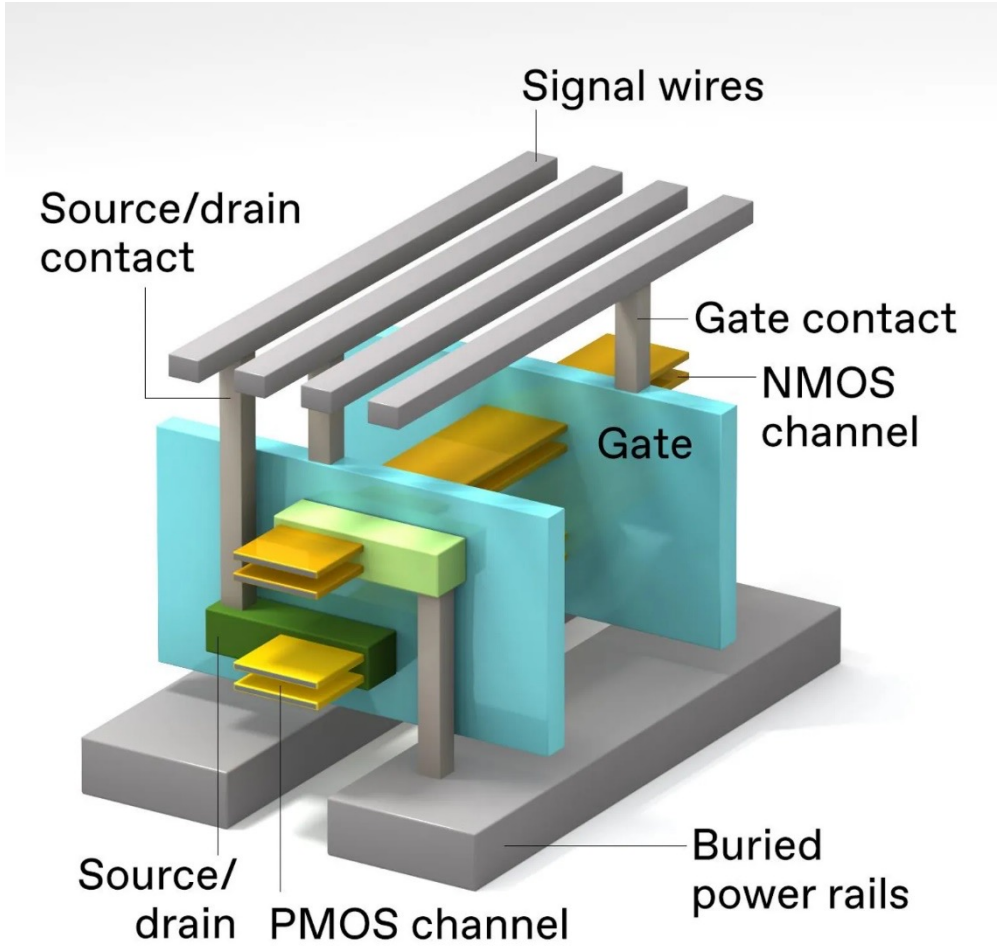
Lemme *et al.*, Nat. Comm., 2022

More Moore

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



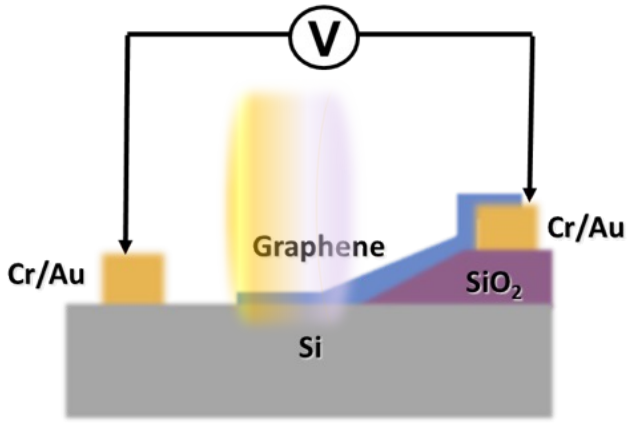
Source: IMEC
https://www.imec-int.com/en/articles/imec-introduces-2d-materials-logic-device-scaling-roadmap

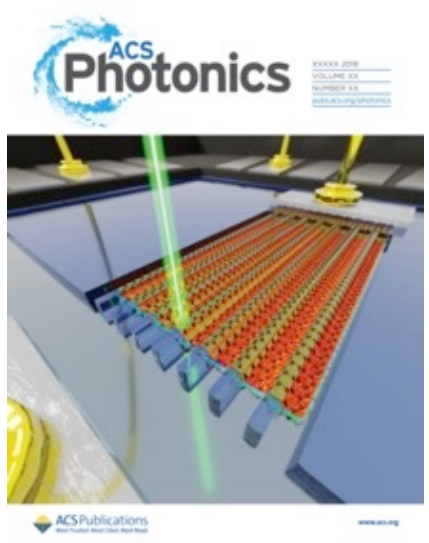


Radosavlevic et al., IEEE Spectrum, 2022

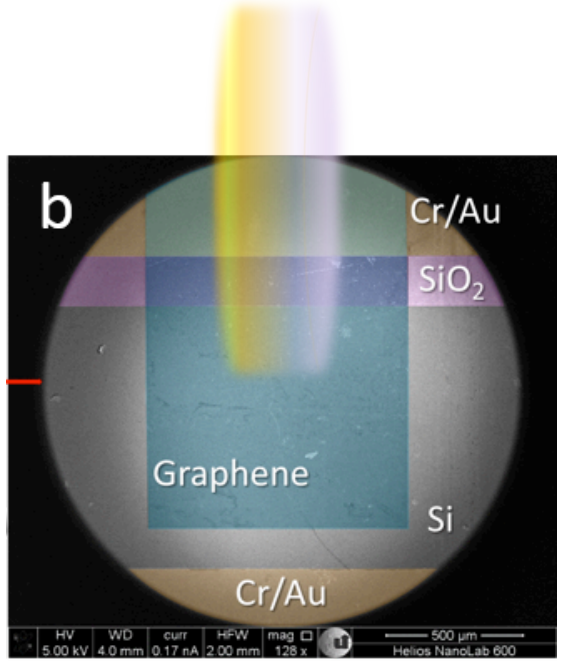
Graphene-Silicon Schottky Diodes

- Vertical Schottky diode architecture
- High responsivity
- Ease of Integration
- Potential for infrared detection
- Potential for flexible substrates





Riazimehr *et al.*, SSE, 2016
Riazimehr *et al.*, ACS Photonics, 2017
Riazimehr *et al.*, ACS Photonics, 2019



Graphene-Silicon Schottky Diodes

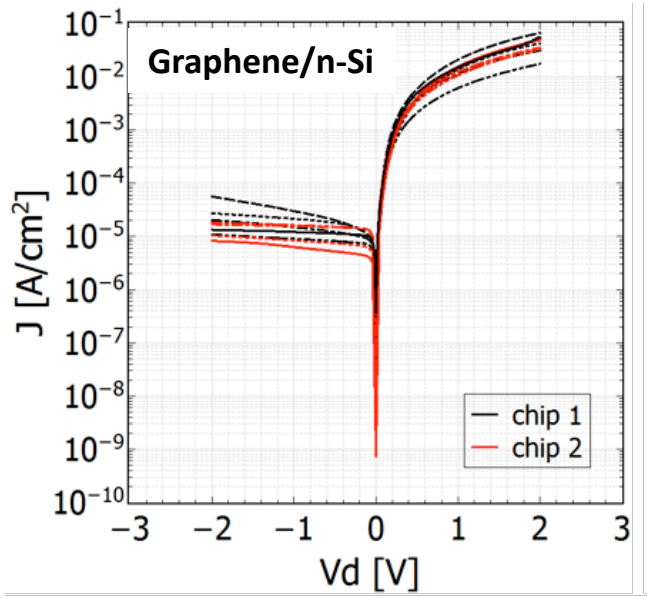
- Vertical device architecture
- High responsivity
- Ease of Integration
- Potential for infrared detection
- Potential for flexible substrates

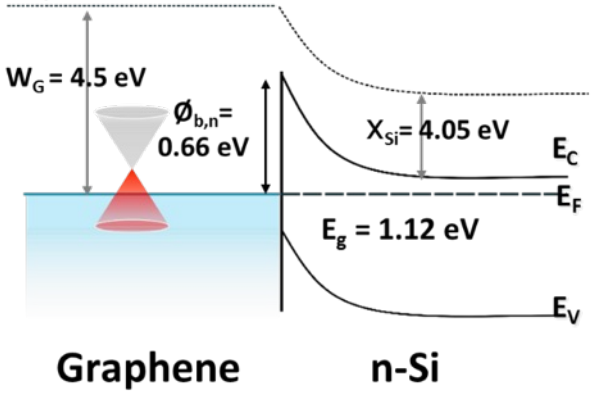
- Shockley equation:

$$I = I_S[\exp\left(\frac{qV_d}{nk_BT}\right) - 1]$$

  - Ideality factor n =1.52
  - Barrier height $\emptyset_b$ =0.66 eV

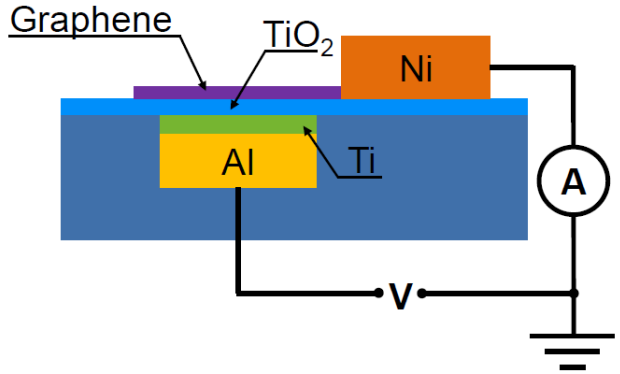
- p doping due to exposure to ambient atmosphere





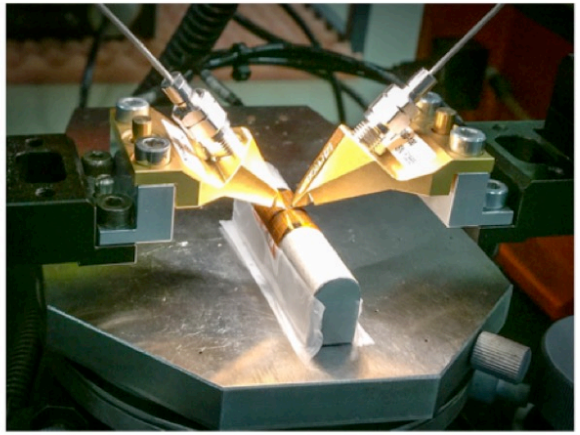
Riazimehr *et al.*, Solid State Electronics, 2016

Metal-Insulator-Graphene Diodes

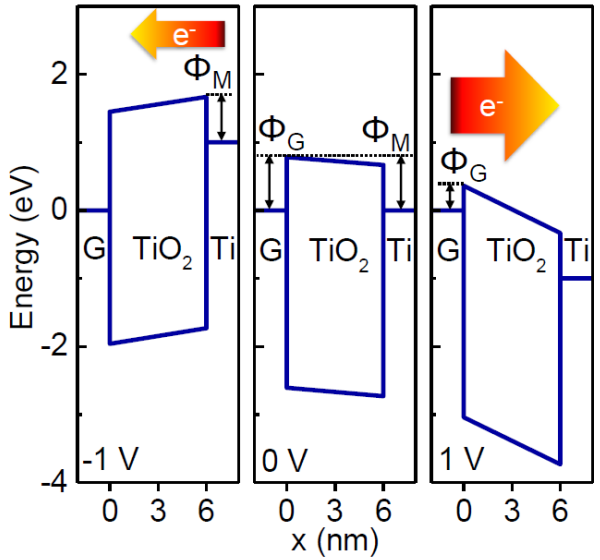


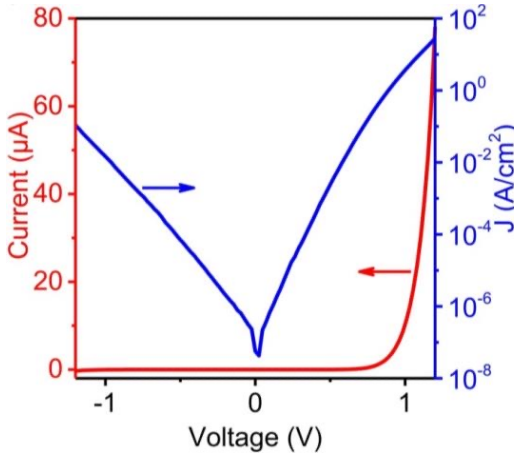
Shaygan *et al*. Nanoscale, 2017
Wang *et al*., ACS Appl. El. Materials, 2019
Wang et al., Adv. El. Mat, 2021

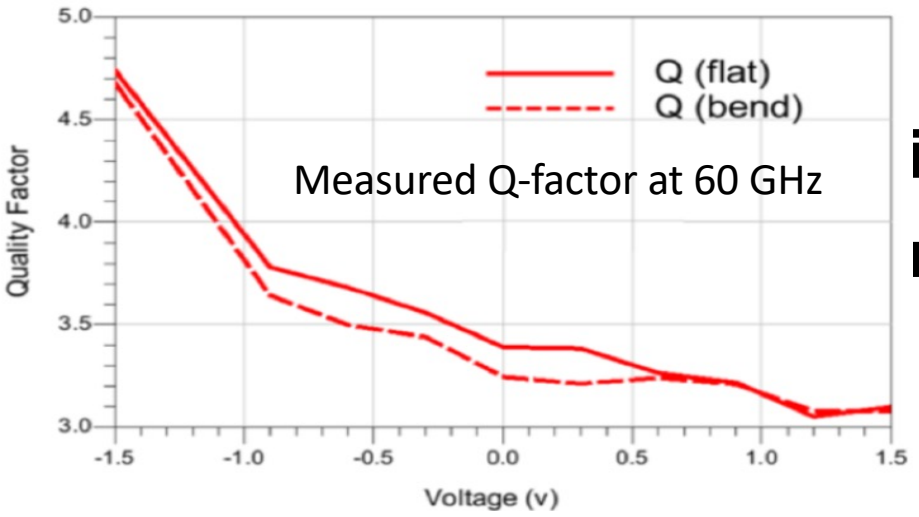
RF measurements of flexible diodes



Bias induced barrier lowering







ion

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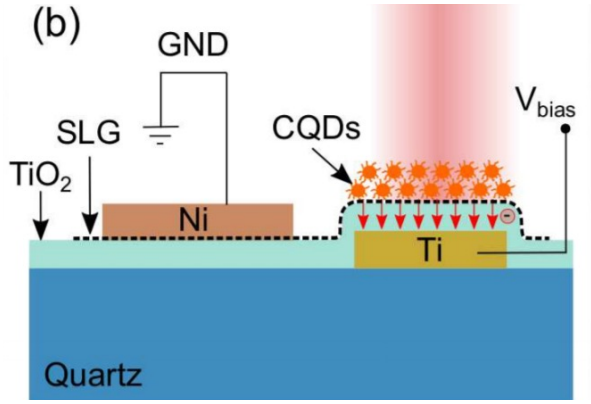
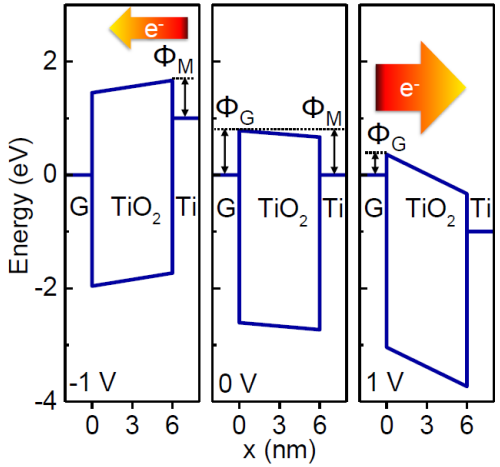
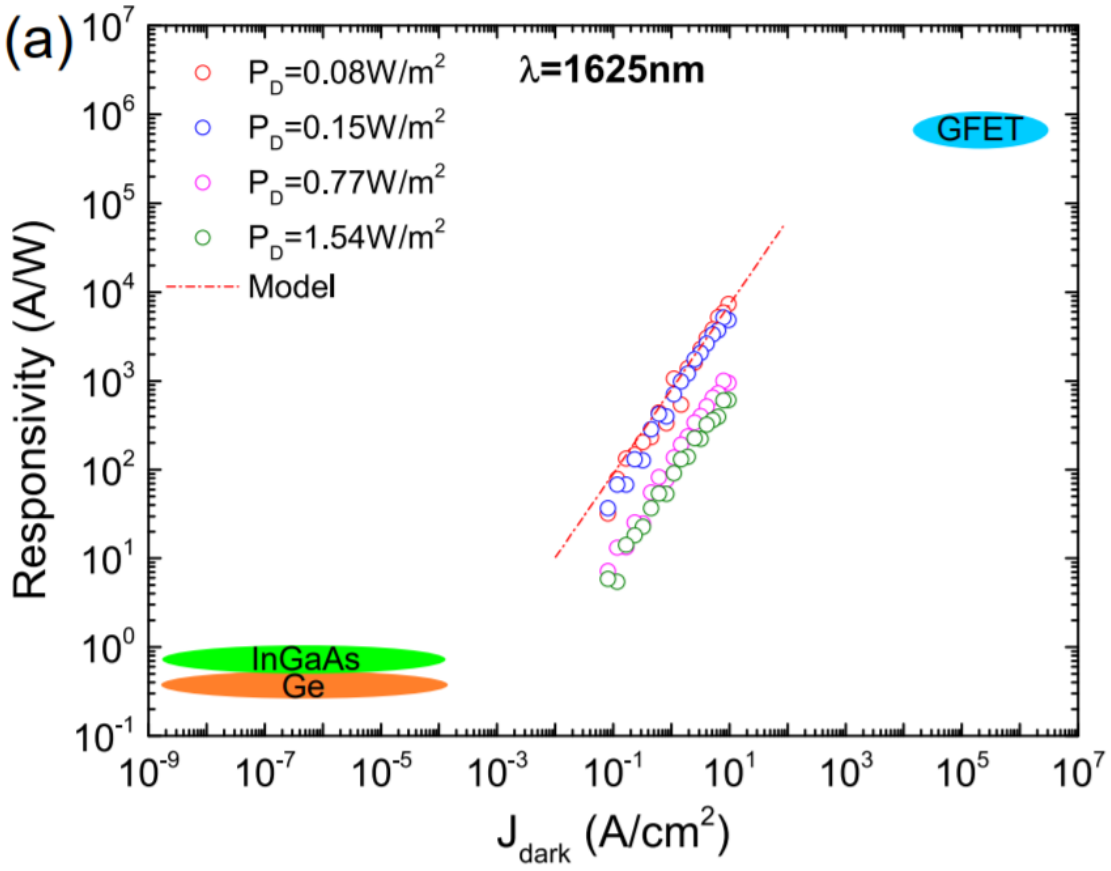
Graphene / Quantum Dot Integration for IR Photodetection



Bias dependent barrier

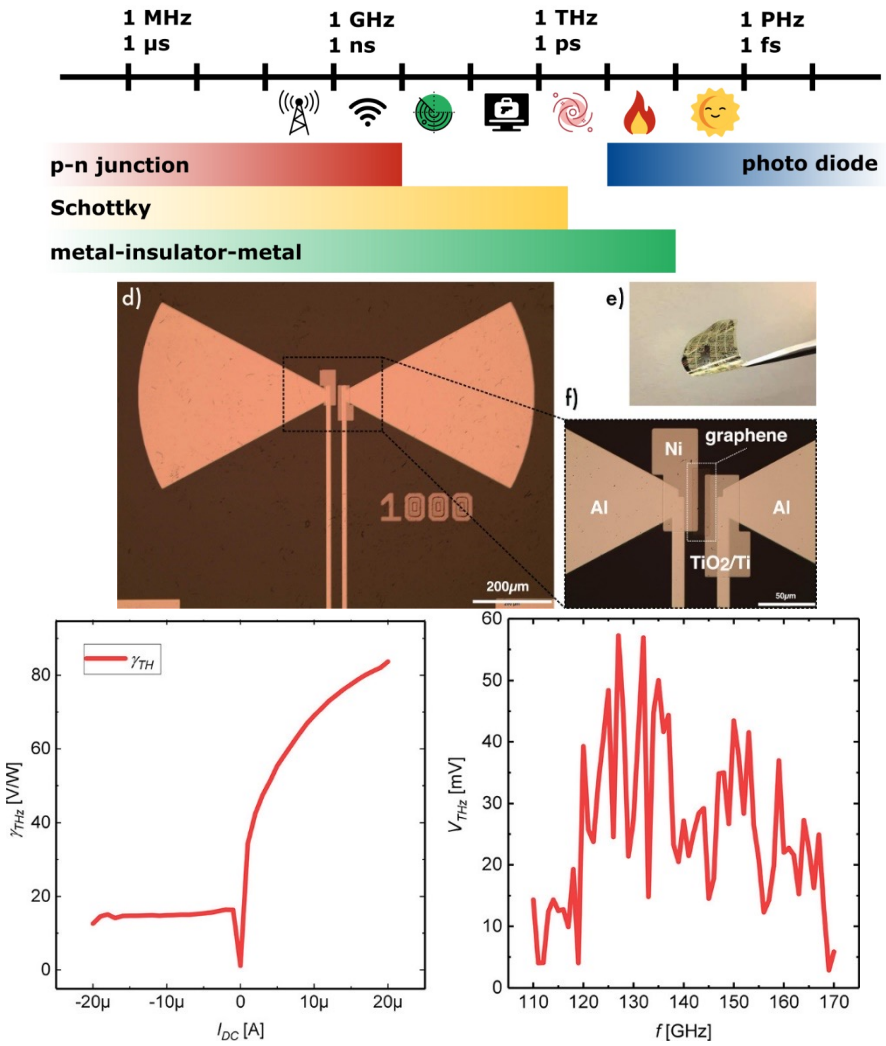




De Fazio *et al*. ACS Nano 2020

Rectennas

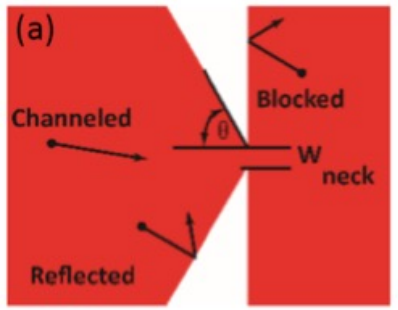
- High RF-to-DC conversion efficiency demonstrated with monochromatic MHz-GHz sources (>90% at 2.45 GHz)
- Bottleneck in adapting to higher frequencies: response time of the rectifier
- Metal-insulator-metal diodes
  - Fast response time due to majority charge carrier transport
  - Usually low responsivity, low rectification efficiency
- Metal-insulator-graphene diodes
  - Enhanced responsivity
  - Reduced junction capacitance increases frequency response

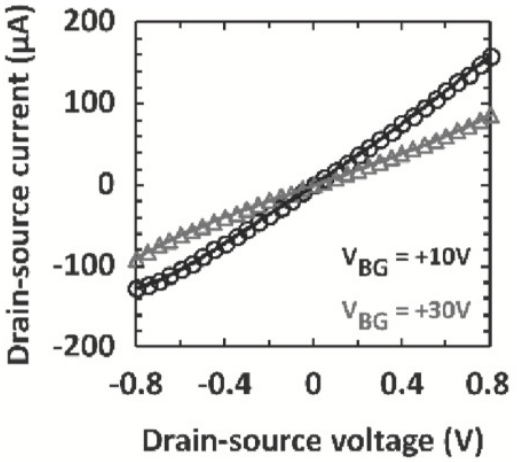


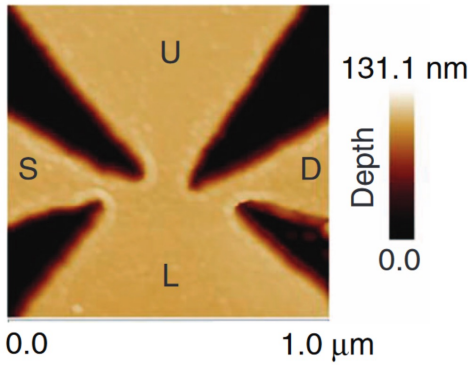
Sinohara, *River Publishers* **2017**
Hemmetter *et al., ACS Applied Electronic Materials* **2021**

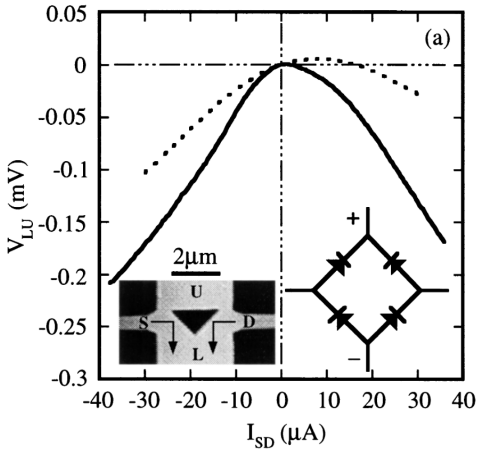
Ballistic Rectification

- Ballistic rectifier
  - Charge carrier scattering occurs primarily at the device edges
  - No potential barrier inhibits current → zero-bias operation
- Two-terminal and four-terminal devices have been demonstrated
  - GaAs-AlGaAs and InAs/AlGaSb heterostructures
  - Si nanowires
  - graphene
- Long mean free path requires high charge carrier mobility





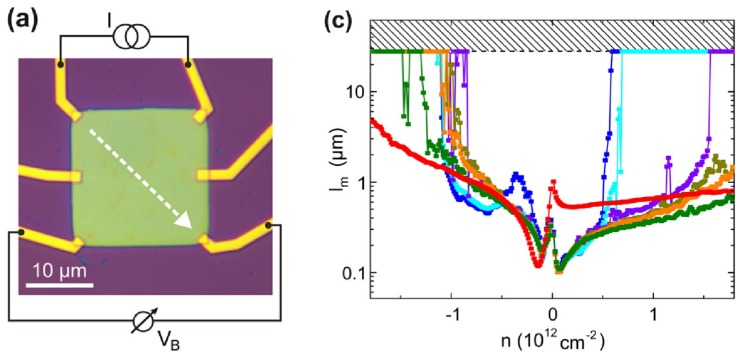


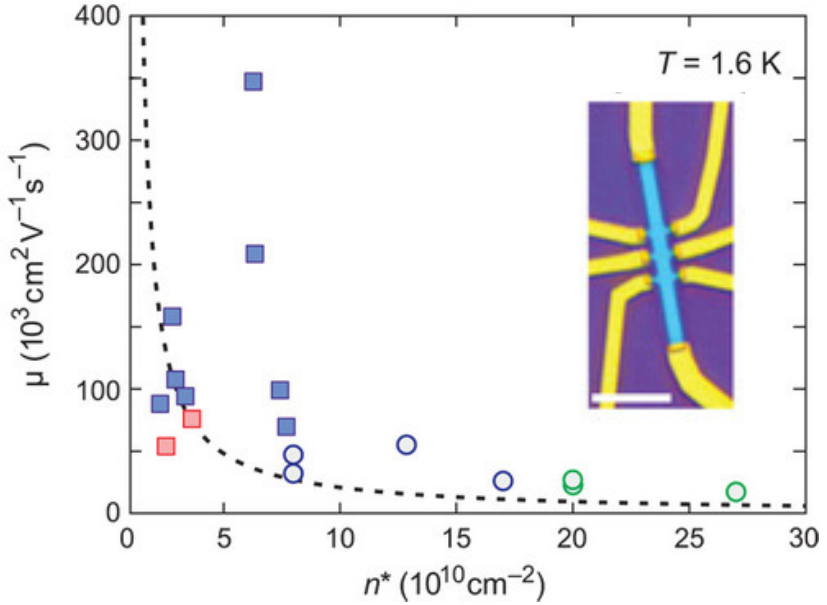


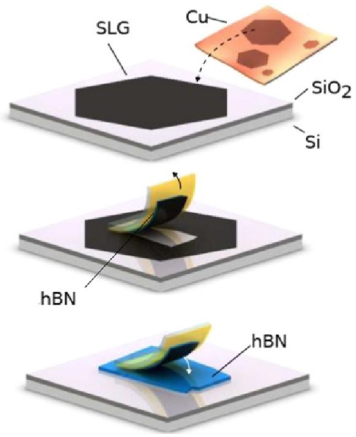
Passi *et al., 2017 Silicon Nanoelectronics Workshop*, 2017
Song *et al., Phys. Rev. Lett.* 1998
White *et al., ACS Applied Nano Materials* 2023
Auton *et al., Nat Communications* 2016

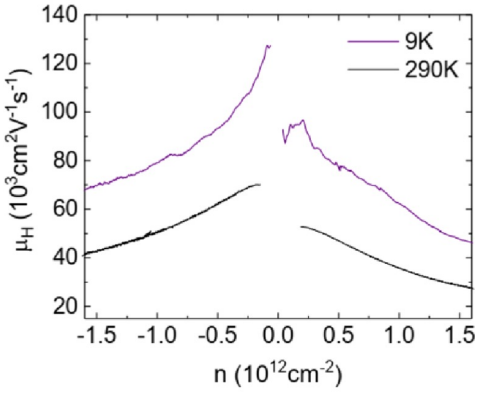
Ballistic Transport in Graphene

- Graphene: >350,000 cm^2/Vs
- Exceptional mobility largely retained
  - On insulating substrates
  - At room temperature
  - With scalable material growth techniques (CVD)
- Mean free path >28um demonstrated in CVD-grown graphene
- Ballistic reflection especially important at the graphene edge



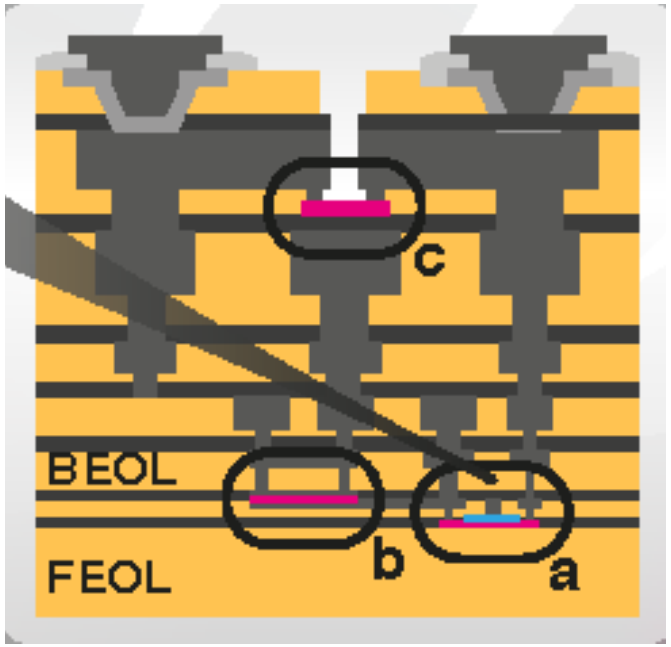






L. Banszerus, *et al. Nano Letters* **2016** *16* (2), 1387-1391
L. Banszerus, *et al. Sci. Adv.* **2015** *1*, e1500222
D. De Fazio, *et al. ACS Nano*, **2019** *13* (8), 8926–8935

2D-CMOS Integration: Challenges



Neumaier, Pindl, Lemme, Nature Materials, 2019
Akinwande *et al.,* Nature, 2019
Illarionov *et al*., Nature Communications, 2020
Quellmaltz *et al*., Nature Communications, 2021
Lemme *et al.,* Nature Communications, 2022

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-Experimental Pilot Line***

2D Experimental Pilot Line

1. **Development of tools & materials**
   - 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

European Commission

2. **Development of module & platform**

SÜSS MicroTec · AIXTRON · micro resist technology · OXFORD INSTRUMENTS · Graphenea

3. **Multi-purpose wafer runs**

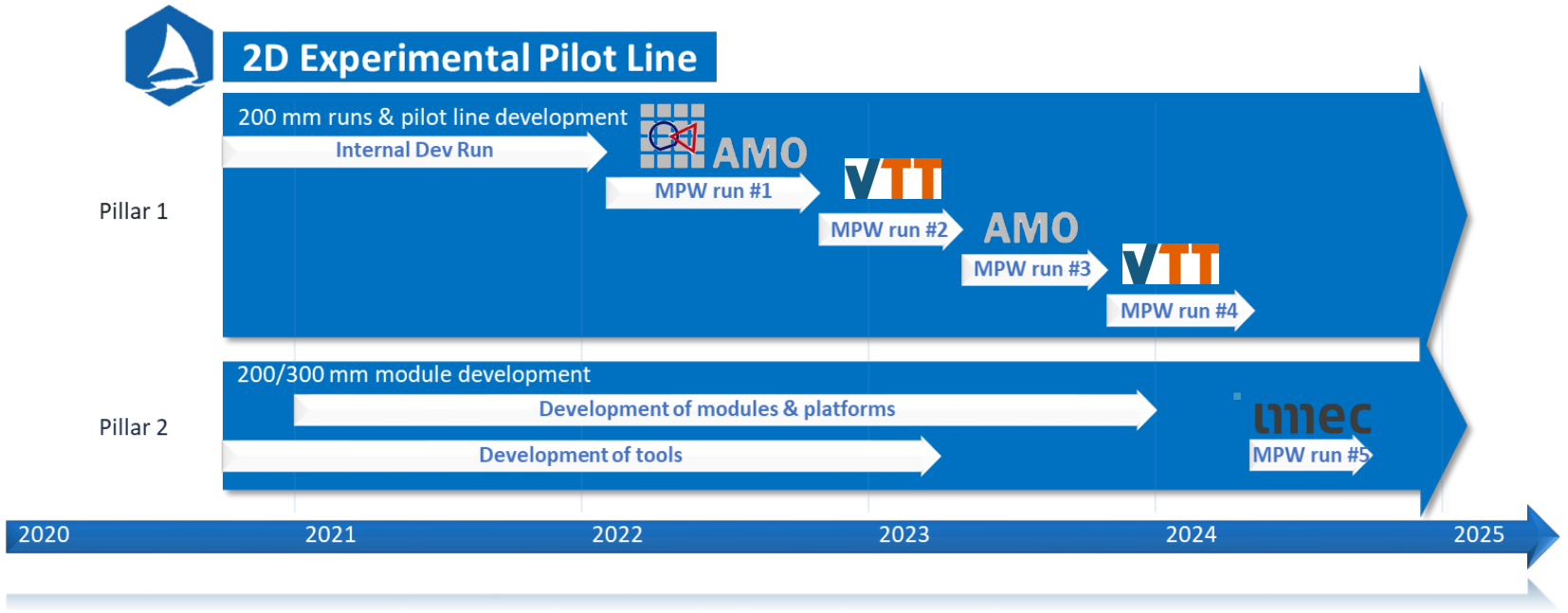
VTT · imec · AMO · ihp solutions

VTT · imec · AMO

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

2D Experimental Pilot Line

2D EPL Project Timeline (MPW runs)



Run 1 — AMO — Graphene Sensors — DELIVERED Dec 2023

Run 2 — VTT — Graphene Sensors — DELIVERED June 2023

Run 3 — AMO — Electronic Devices incl. Graphene Sensors — DELIVERED Oct 2023

Run 4 — VTT — Graphene Sensors devices on CMOS wafers — June 2024

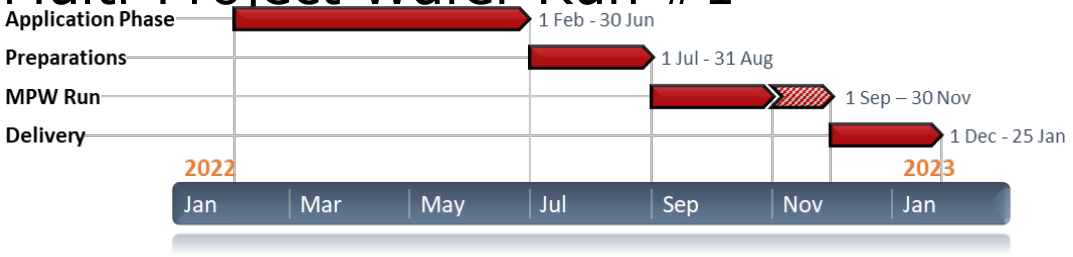
Run 5 — imec — TMDC based transistors — Oct 2024

+ additional runs

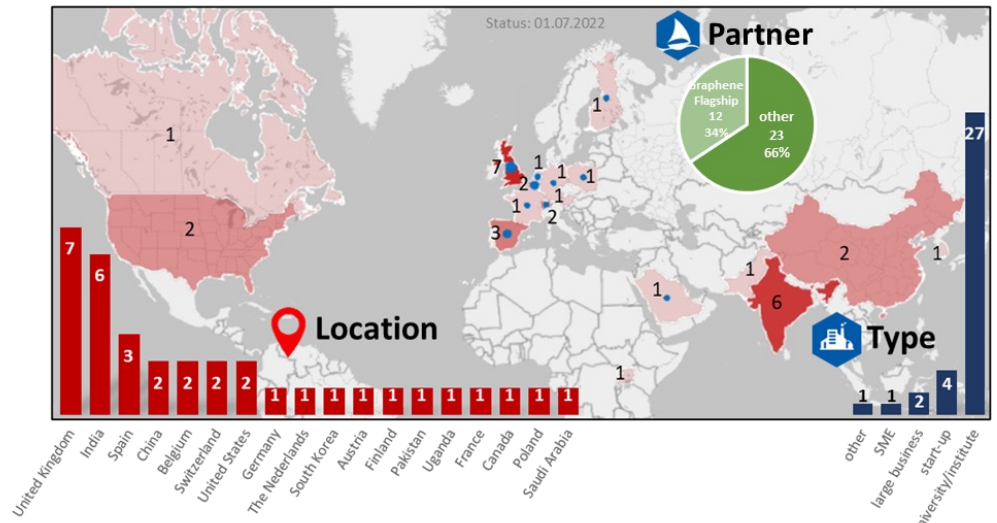
Development of tools, modules and platforms in parallel with the offer of MPW runs.

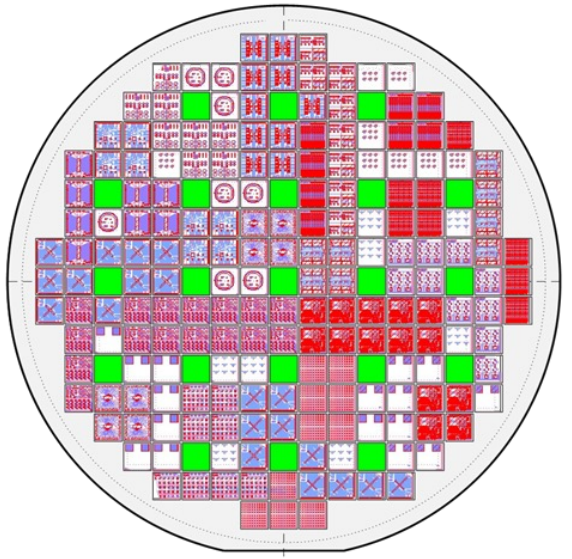
2D Experimental Pilot Line

Multi-Project Wafer Run #1

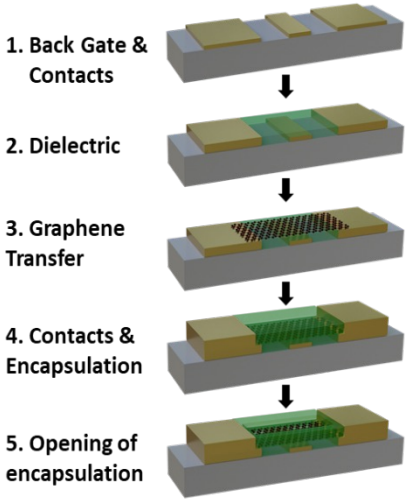


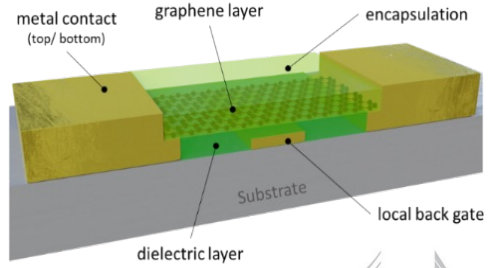
Overall applications





Mask with costumer dies distributed over 8" wafer; 21 different designs, 108 order dies





35 applications => 14 participating customers

Thank you!

GreEnergy
Power from optical antennas

www.greenergy-project.eu
www.linkedin.com/company/greenergy-project

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006963 (GreEnergy).