2D Materials for Energy Harvesting Applications and the Scaling-up Route

Max C. Lemme
AMO GmbH, Aachen
RWTH Aachen University – Chair of Electronic Devices

GreEnergy
Aachen Graphene & 2D Materials Center
AMO
RWTH AACHEN UNIVERSITY

2D Materials for Energy Harvesting

RWTH Aachen University

- Large European Technical Univ.
- 50.000 students
- Triangle:
  Germany / Belgium / Netherlands
- Chair of Electronic Devices

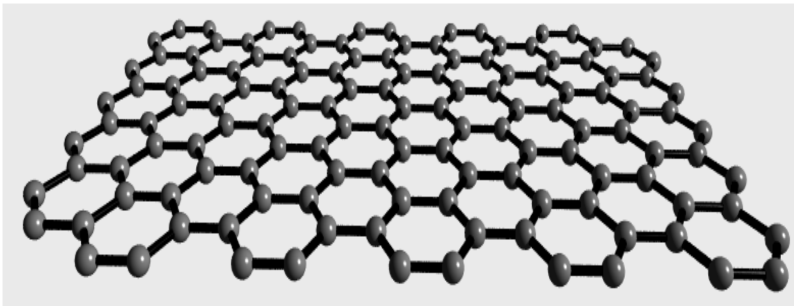
AMO GmbH

- 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)

Aachen Graphene & 2D Materials Center

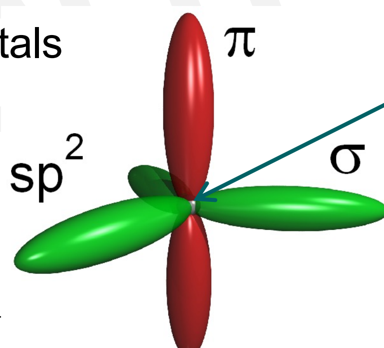
2D Materials for Energy Harvesting

Graphene: Crystal Properties

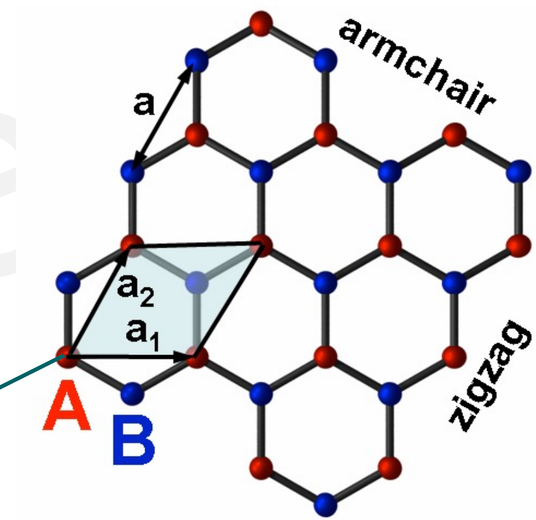


- sp² bonded carbon atoms (~4,3eV)
- Graphite: stacked layers of graphene
- interlayer bond: v.d. Waals

Orbitals



2D-crystal lattice

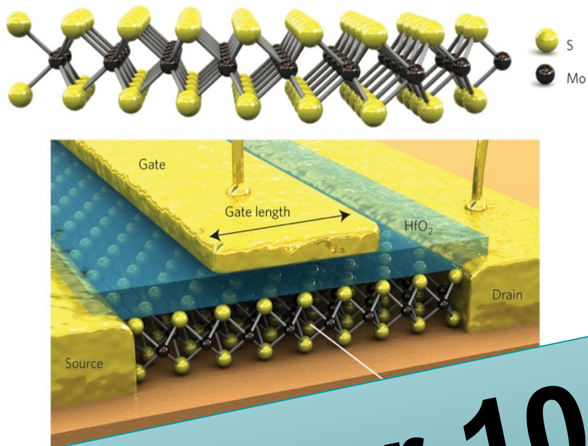


- Lattice constant: a = 0.246 nm
- “Thickness”: d = 0.34 nm

confidential

2D Materials for Energy Harvesting

Semiconductors



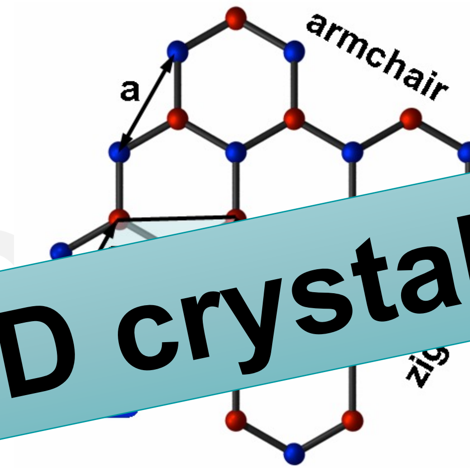
Mol[illegible]ulfide (MoS_2)

Transition Metal Dichalcogenides (TMDs)

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

Radisavljevic, Nat. Nanotech. 2011.

Insulators



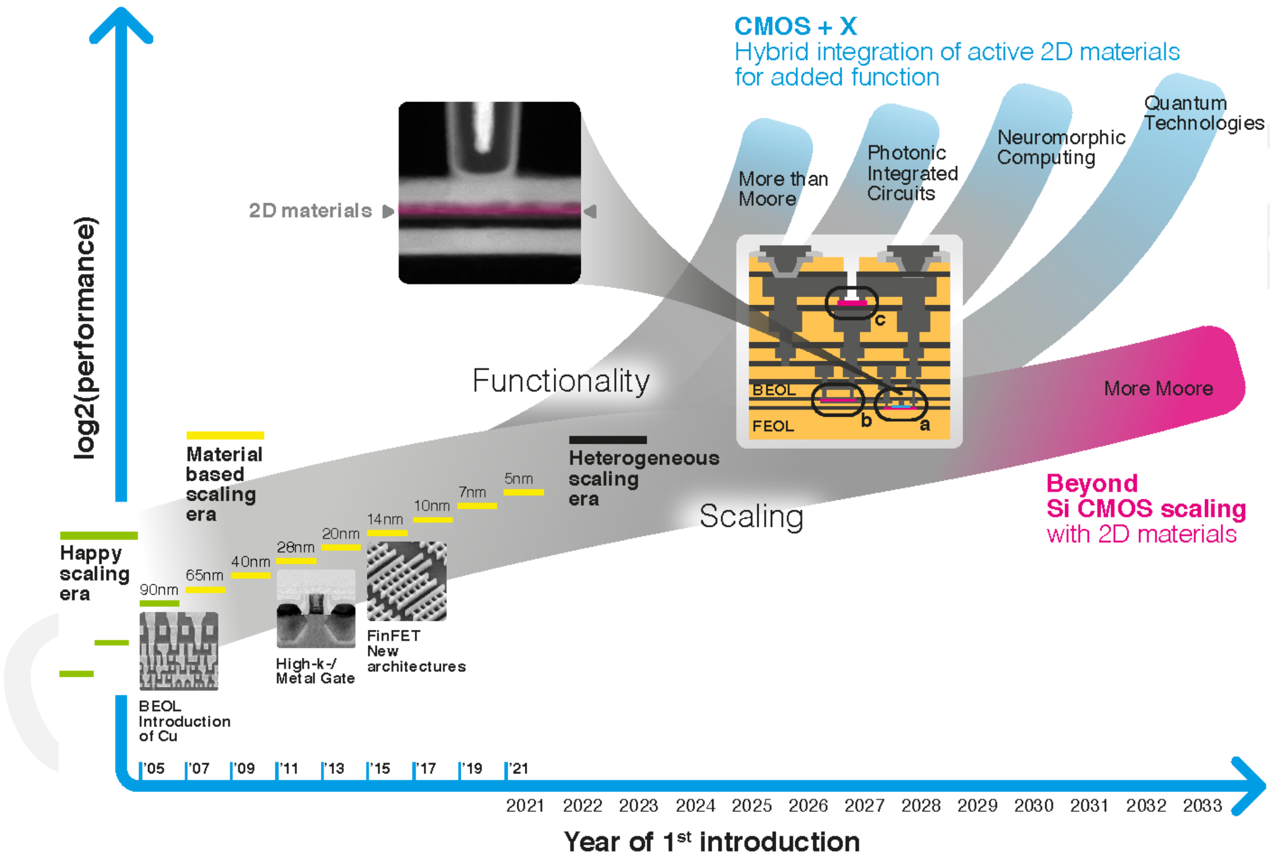
Hexagonal Boron Nitride (h-BN)

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

…over 1000 2D crystals!

Aachen Graphene & 2D Materials Center
AMO
RWTH AACHEN UNIVERSITY

2D Materials for Energy Harvesting



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

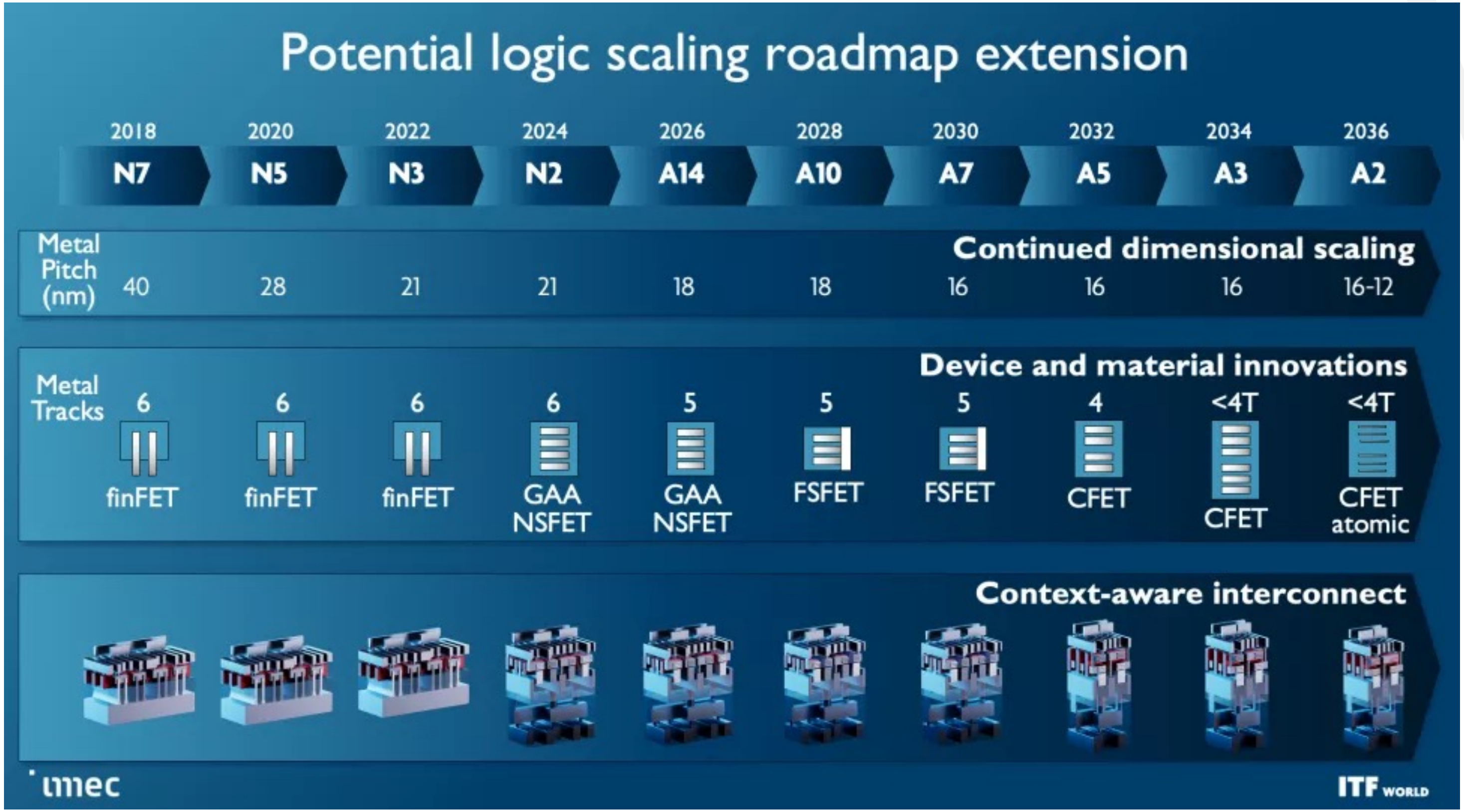
Aachen Graphene & 2D Materials Center

AMO

RWTH AACHEN UNIVERSITY

2D Materials for Energy Harvesting

imec 20-Year Semiconductor Roadmap

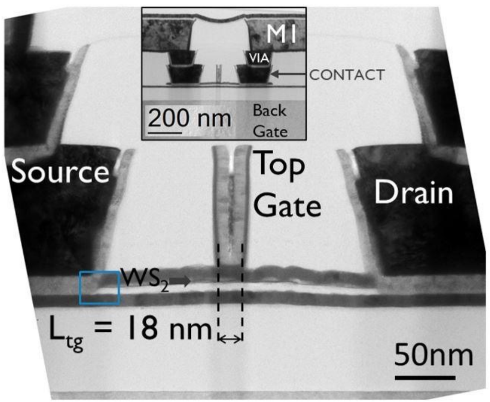


Source: https://www.imec-int.com/en/articles/20-year-roadmap-tearing-down-walls, 2 Aug 2022

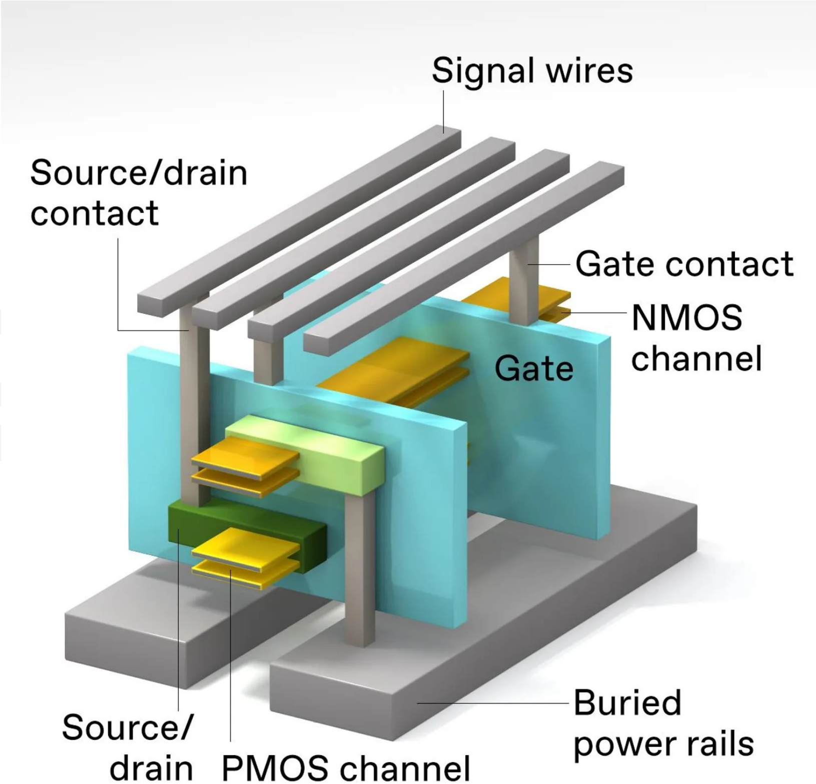
2D Materials for Energy Harvesting

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

Aachen Graphene & 2D Materials Center
AMO
RWTH AACHEN UNIVERSITY

2D Materials for Energy Harvesting

2D-Integration: Opportunities

- **More Moore**
  - Nanosheet FETs
  - Back-End-Of-Line Integration
  - Flexible Electronics
- **More Than Moore**
  - Sensors (Gas, Bio, Chemical,…)
  - RF Electronics
  - Photodetectors & Cameras
  - NEMS
  - Energy Harvesting
- **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

confidential

2D Materials for Energy Harvesting

Graphene and 2D materials:

+ Ultra broad band spectral response (graphene, $PtSe_2$)

+ Large scale production (CVD)

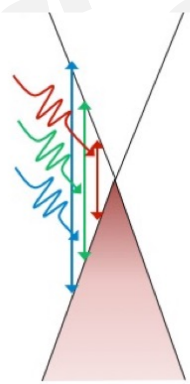
+ High conductivity

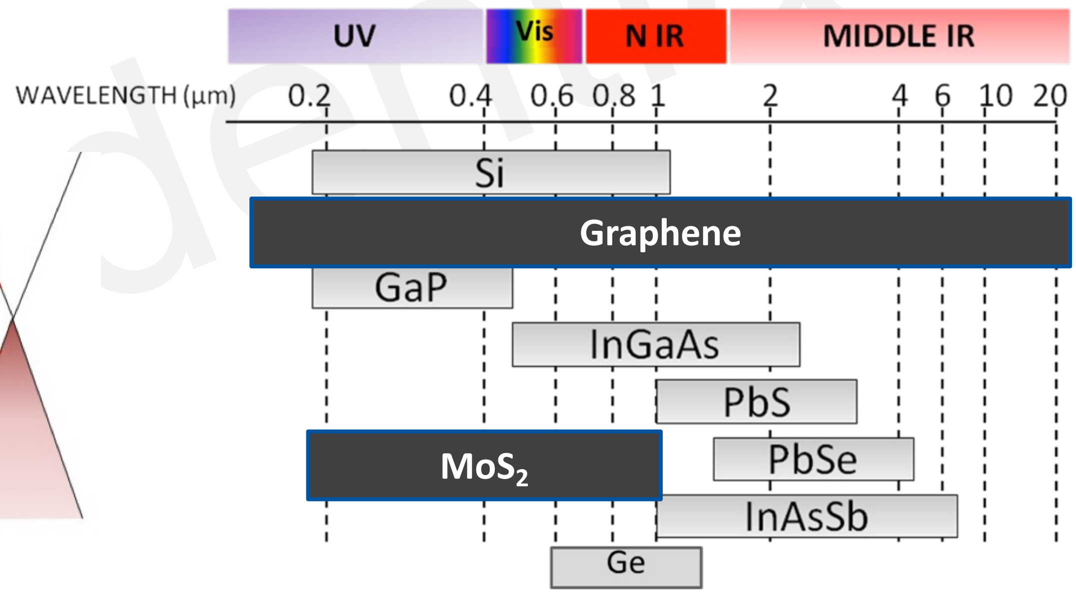
+ mechanical Flexibility

+ Integrability

± Gate tunability

− Low absolute absorption



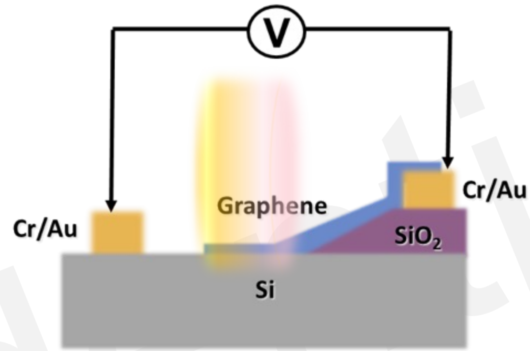


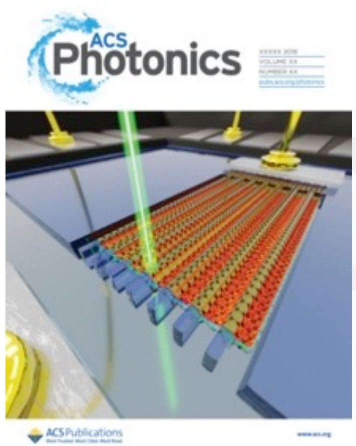
confidential

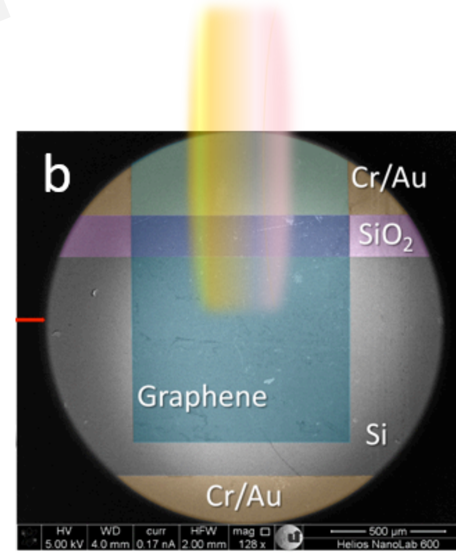
2D Materials for Energy Harvesting

Graphene /silicon Schottky diodes

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







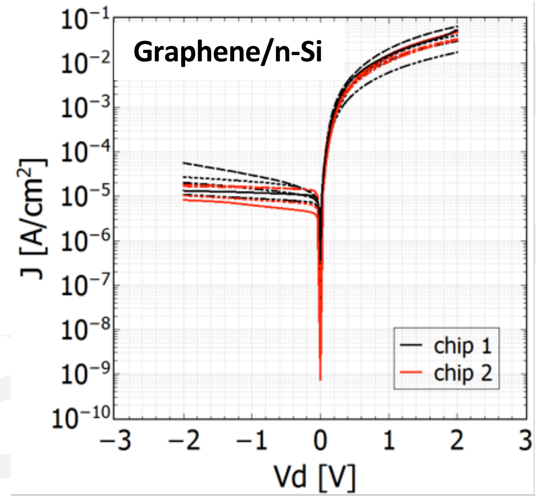
Riazimehr *et al.*, SSE, 2016
Riazimehr *et al.*, ACS Photonics, 2017
Riazimehr *et al.*, ACS Photonics, 2019

Confidential

2D Materials for Energy Harvesting

Graphene / silicon Schottky diodes

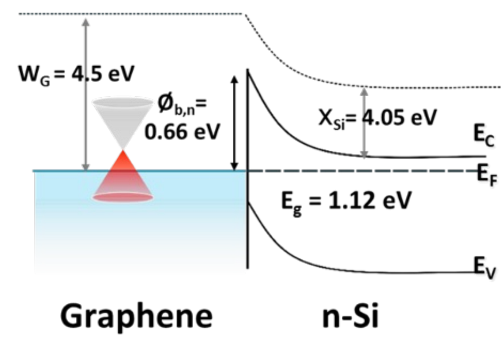
- Vertical device architecture
- High responsivity
- Ease of Integration
- Potential for infrared detection
- Potential for flexible substrates



- 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



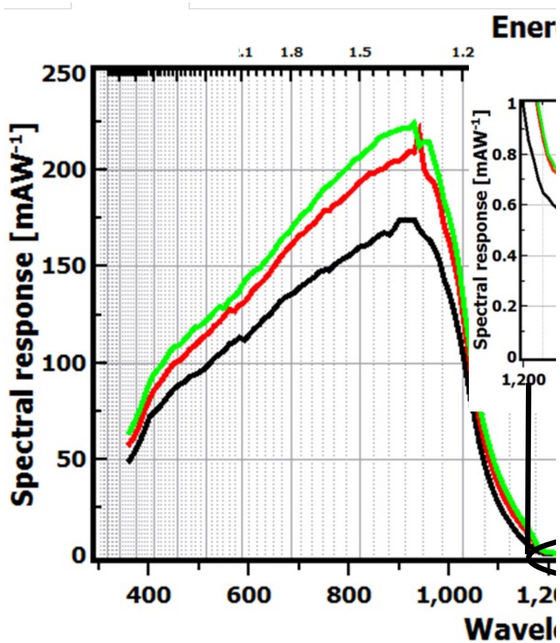
Riazimehr *et al.*, Solid State Electronics, 2016

2D Materials for Energy Harvesting

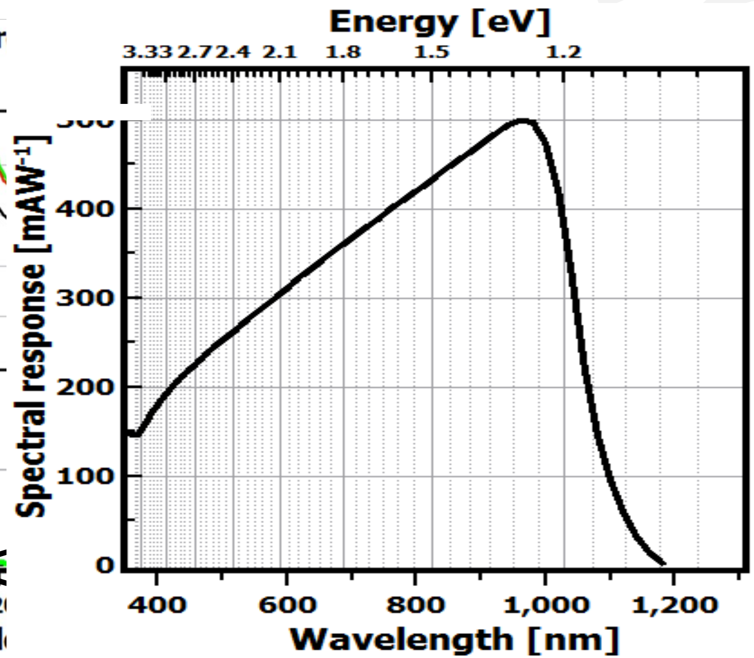
Graphene / silicon Schottky diodes: spectral response

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

Graphene/ n-Si photodiode



Calibrated Si photodiode

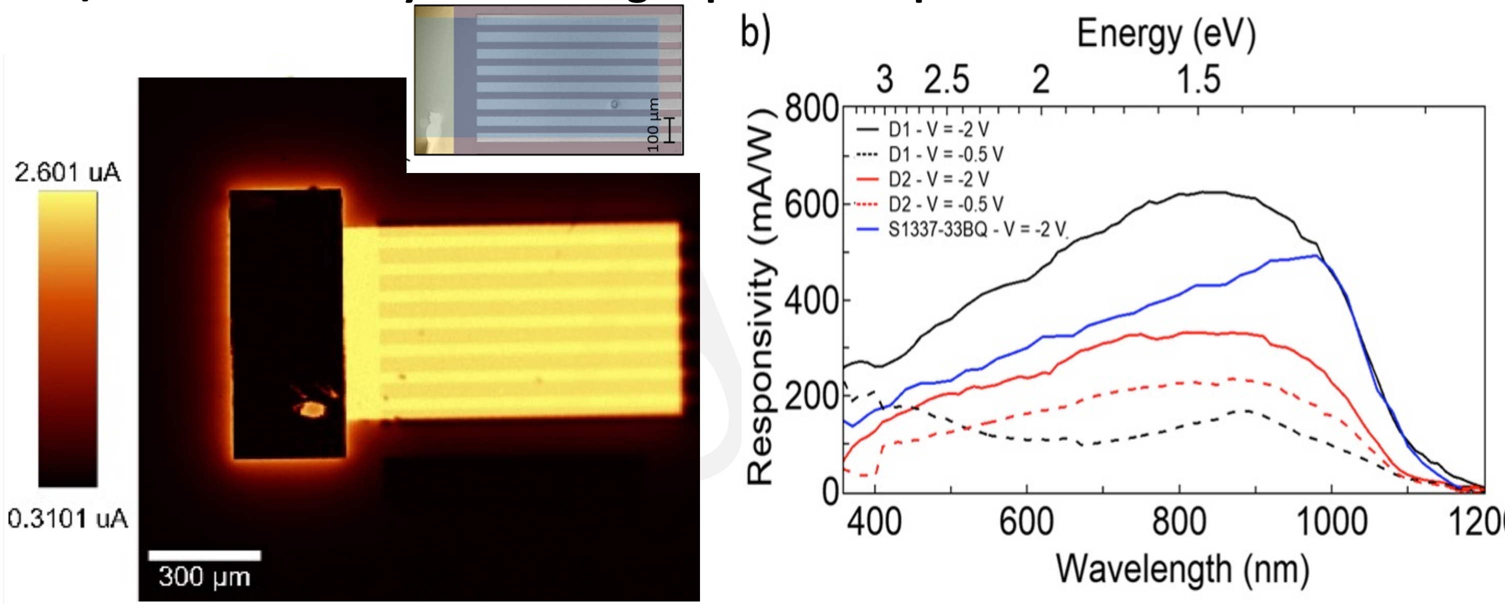


IR : 2.3 % absorption in graphene

Aachen Graphene & 2D Materials Center
AMO
RWTH AACHEN UNIVERSITY

2D Materials for Energy Harvesting

Graphene / silicon Schottky diodes: high spectral response



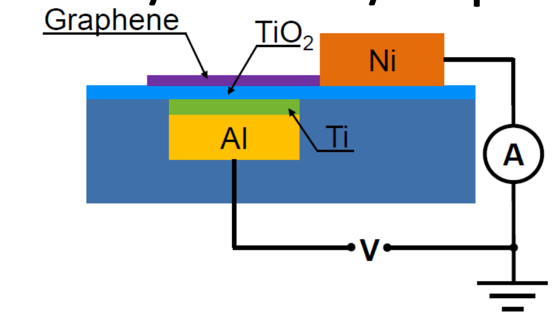
Riazimehr *et al.*, ACS Photonics, 2019

- Interdigitated diode layout
- Very high spectral response / maximum responsivity (635 mA/W) → 1.5x pure Si
- Very high quantum efficiency (>80%)
- Enabled by inversion channel under MOS structure

Aachen Graphene & 2D Materials Center
AMO
RWTH AACHEN UNIVERSITY

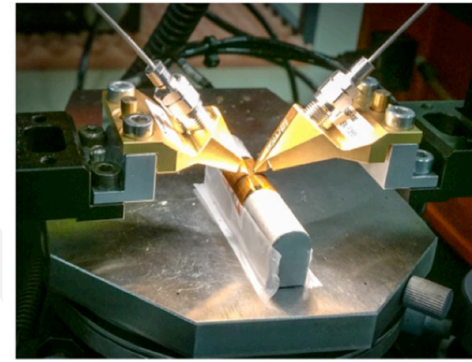
2D Materials for Energy Harvesting

Metal / Insulator / Graphene (MIG) diodes

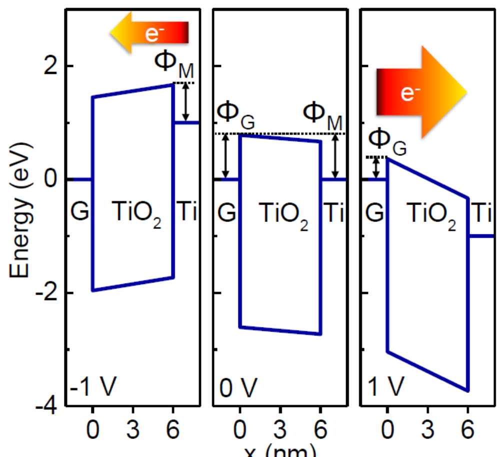


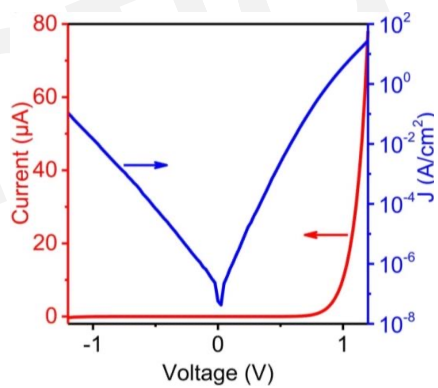
Shaygan *et al*. Nanoscale, 2017
Wang *et al*., ACS Appl. El. Materials, 2019
Wang et al., Adv. El. Mat, 2021

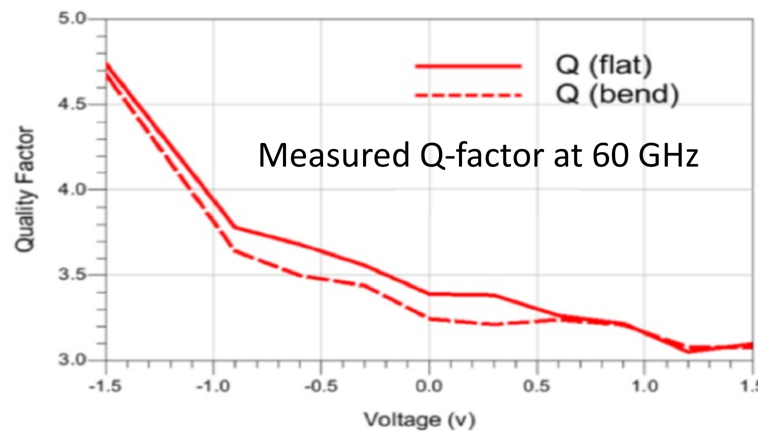
RF measurements of flexible diodes



Bias induced barrier lowering



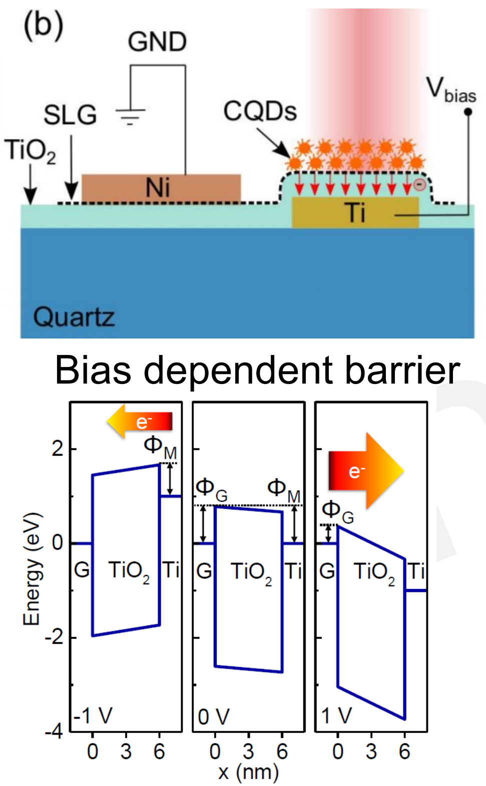


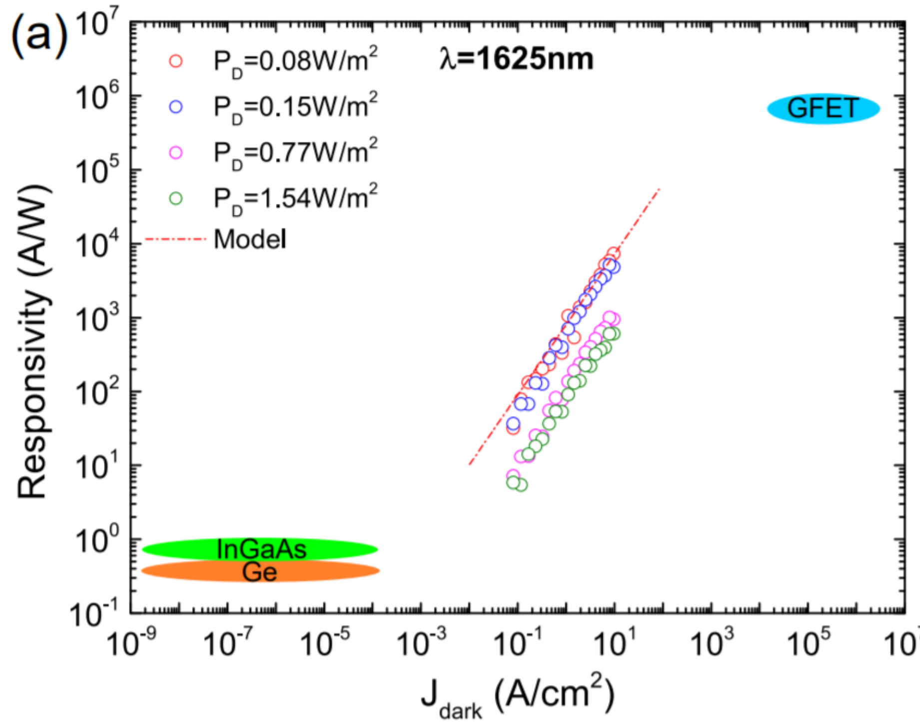


Aachen Graphene & 2D Materials Center
AMO
RWTH AACHEN UNIVERSITY

2D Materials for Energy Harvesting

Graphene / Quantum Dot Integration for IR Photodetection



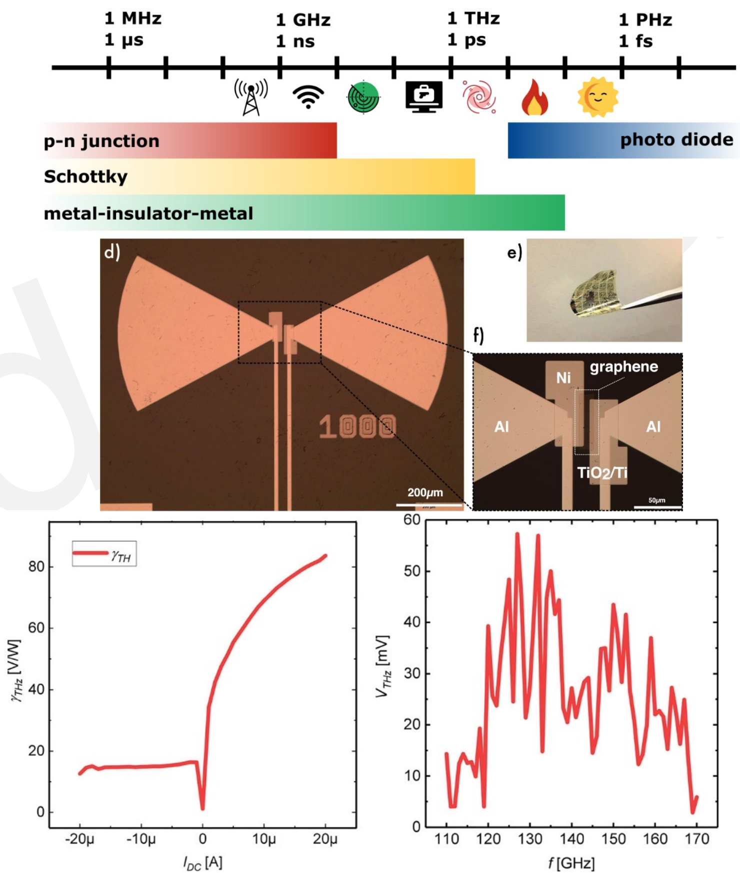


De Fazio *et al*. ACS Nano 2020

2D Materials for Energy Harvesting

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

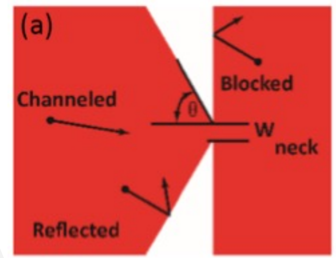


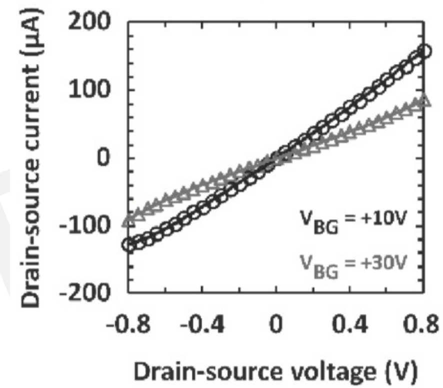
Sinohara, *River Publishers* **2017**
Hemmetter *et al., ACS Applied Electronic Materials* **2021**

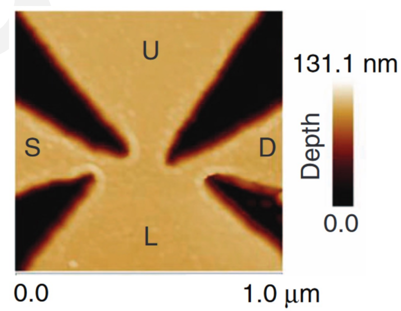
2D Materials for Energy Harvesting

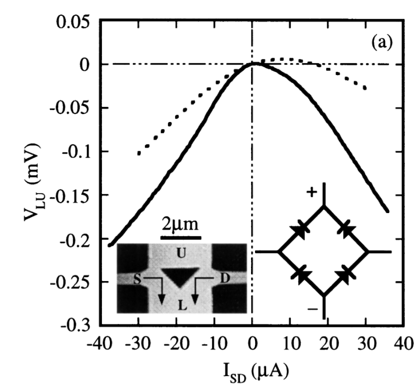
Ballistic Rectification

- 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









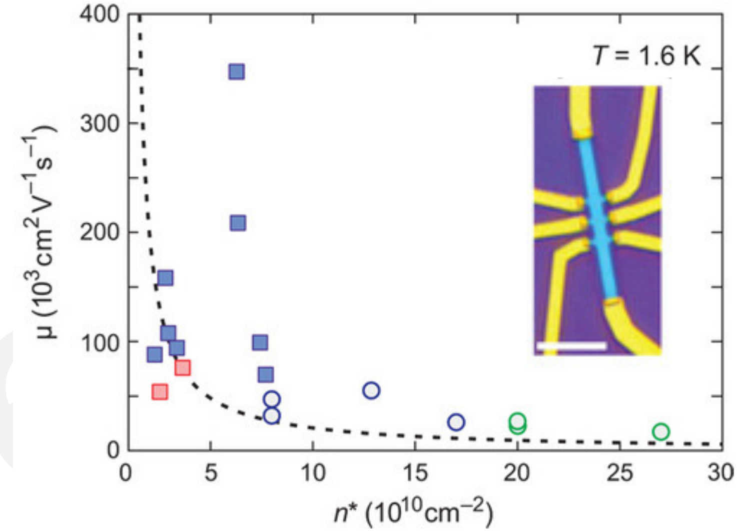
Passi *et al., 2017 Silicon Nanoelectronics Workshop*, 2017
Song *et al., Phys. Rev. Lett.* 1998
White *et al., ACS Applied Nano Materials* 2023
Auton *et al., Nat Communications* 2016

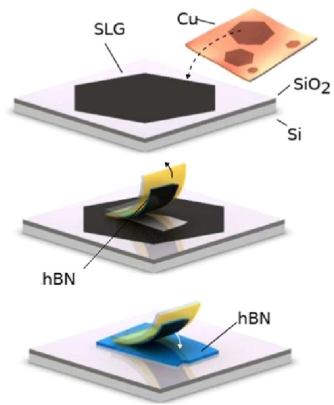
confidential

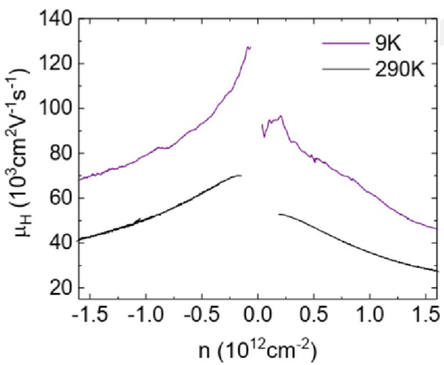
2D Materials for Energy Harvesting

Ballistic Transport in Graphene

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



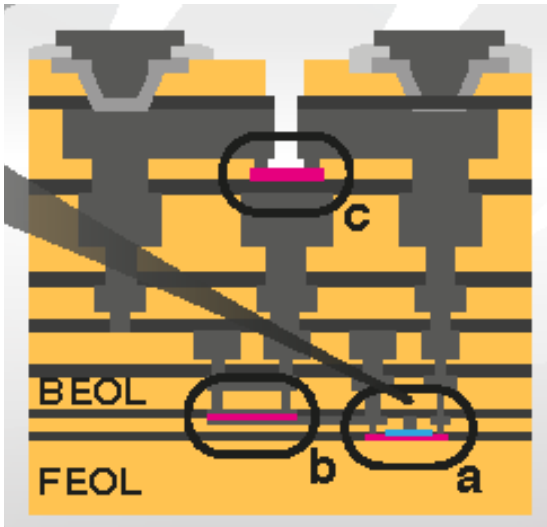




Banszerus *et al., Nano Letters* 2016
Banszerus *et al., Sci. Adv.* 2015
De Fazio *et al., ACS Nano*, 2019

2D Materials for Energy Harvesting

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

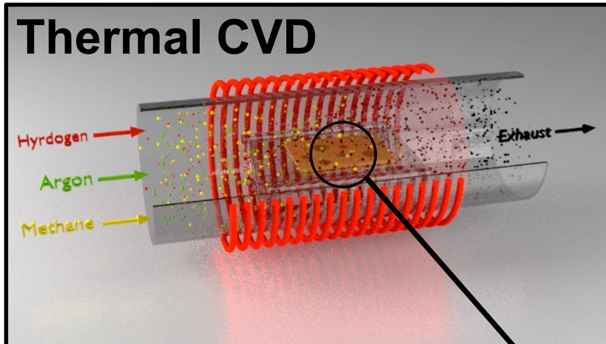
A number of ***Engineering Challenges*** remain before we see 2D Materials-based electronics / optoelectronics

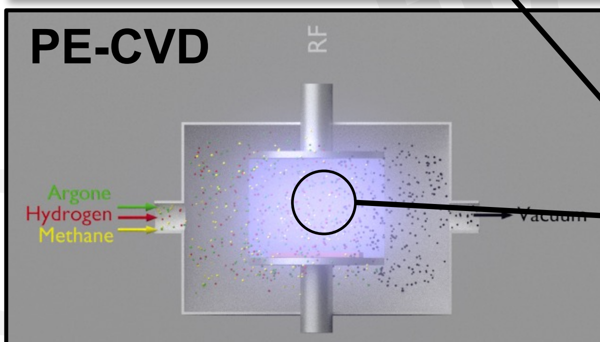
Addressed by the ***2D-Experimental Pilot Line***

confidential

2D Materials for Energy Harvesting

Chemical vapor deposition (CVD)





- Catalytic growth on Ni, Cu, Ru, Ir, TiC, Ta…

+ Process Temperatures: 850-1000°C

+ Transfer to random substrates

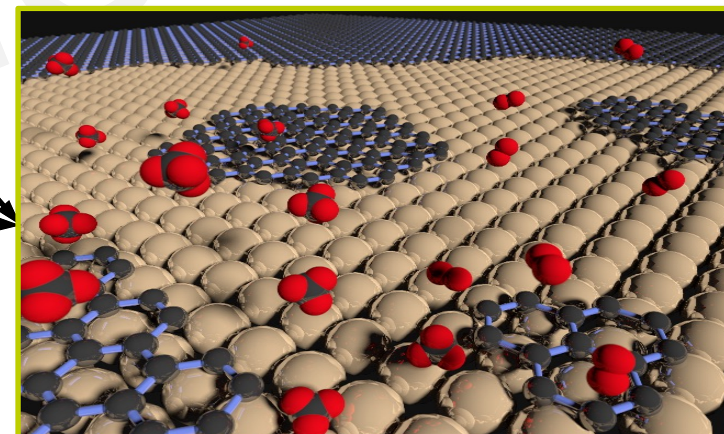
- Transfer process

+ High potential for large areas (R2R)

- Monolayer vs. multilayer control (solubility)

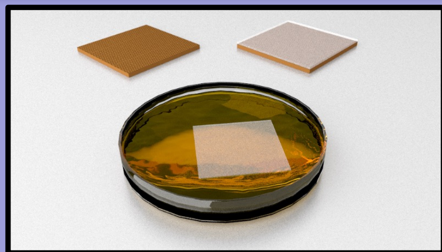
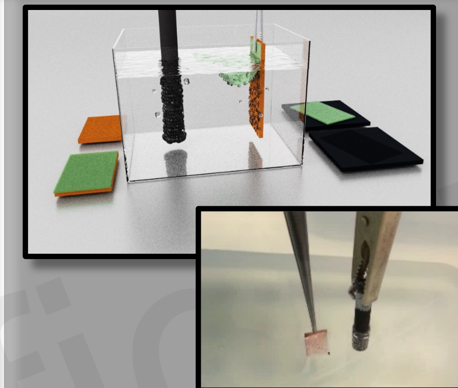
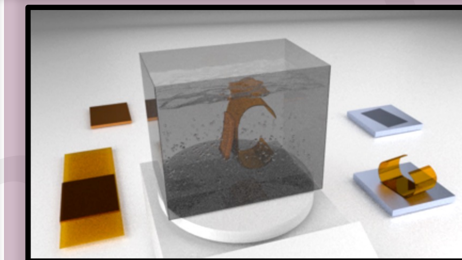
- Quality (grain boundaries, defects etc.)

S. Kataria et al., physica status solidi (a), 2014., 2014



confidential

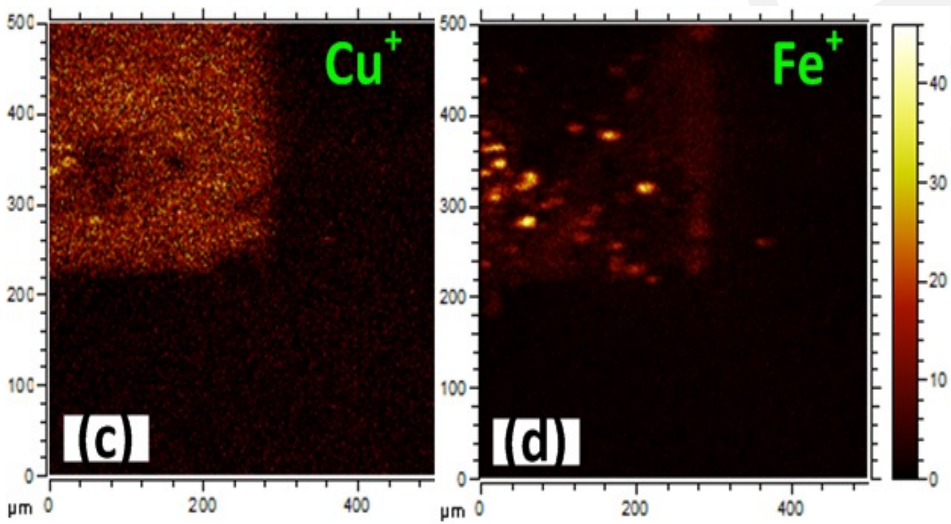
2D Materials for Energy Harvesting

Etching method	Bubble method	Capillary method
		
Chemical process	Electrochemical process	Physical process (Capillary effec
Copper is etched away	Copper is removed by bubbles created at the interface	Copper is removed by water between copper and graphene
Etchant: $FeCl_3$, Sodiumpersulfate	Electrolyte: NaOH	Reactant: DI-Water
Duration: 1h 30min	Duration: 30s	Duration: 8h

2D Materials for Energy Harvesting

Integration challenge: contamination

- Time-of-flight secondary ion mass spectrometry (ToF-SIMS) and
- Total reflection x-ray fluorescence (TXRF) →
  - Elemental fingerprints of residual contamination with a sensitivity better than 10^9 atoms/cm^2.

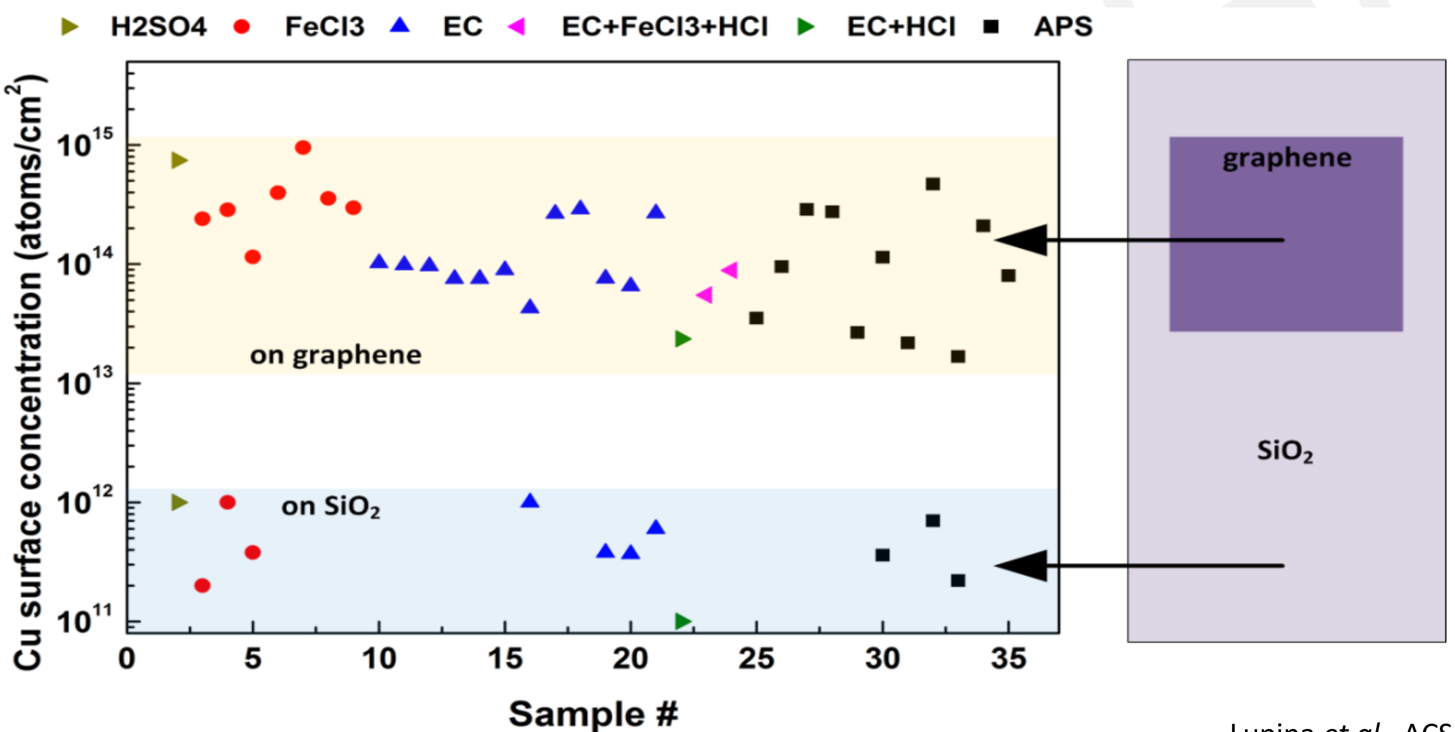


ToF SIMS $^{63}Cu^+$ and $^{56}Fe^+$ maps on the corner of a graphene layer on SiO_2

Lupina *et al.*, ACS Nano, 2015

Aachen Graphene & 2D Materials Center

2D Materials for Energy Harvesting



Lupina *et al.*, ACS Nano, 2015

2D Materials for Energy Harvesting

European 2D Experimental Pilot Line

European Commission

- 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

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

2. Development of module & platform

VTT · imec · AMO · ihp solutions

3. Multi-purpose wafer runs

VTT · imec · AMO

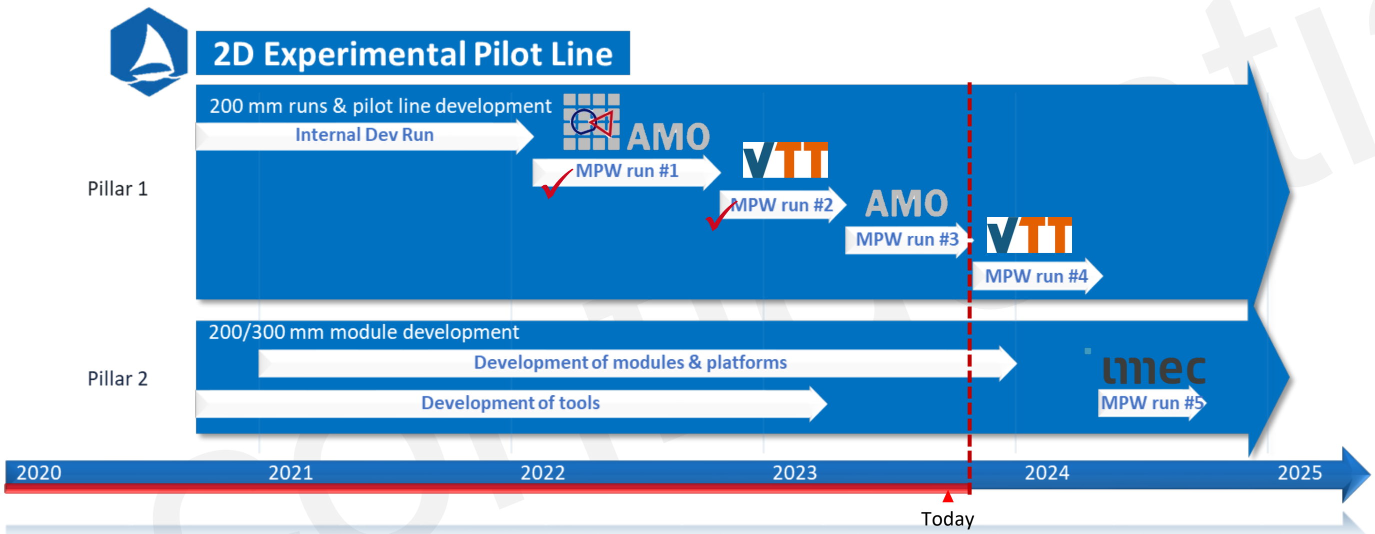
Industrial Advisory Board
X-FAB
AMS
NXP
Infineon
STMicroelectronics
Emberion
Nokia
ELMOS

Confidential

2D Materials for Energy Harvesting

European 2D Experimental Pilot Line

2D EPL Project Timeline (MPW runs)



AMO — Run 1 — DELIVERED
Graphene Sensors — Dec 2023

VTT — Run 2 — DELIVERED
Graphene Sensors — June 2023

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

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

imec — Run 5
TMDC based transistors — Oct 2024

+ additional runs

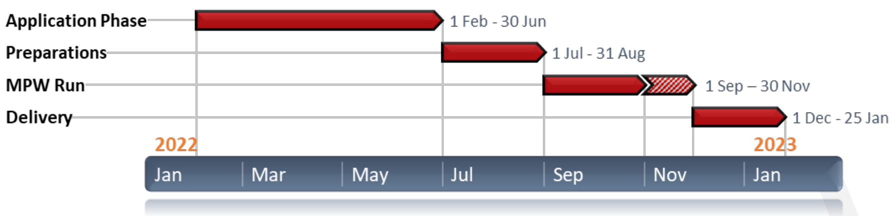
Development of tools, modules and platforms in parallel with the offer of MPW runs.

confidential

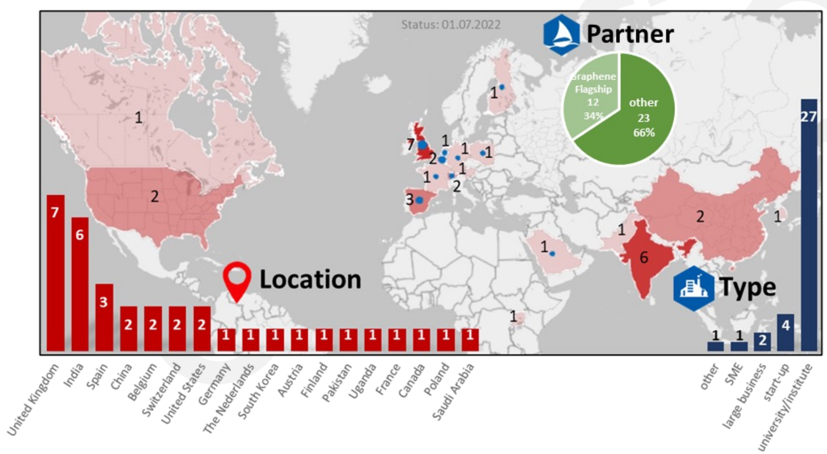
2D Materials for Energy Harvesting

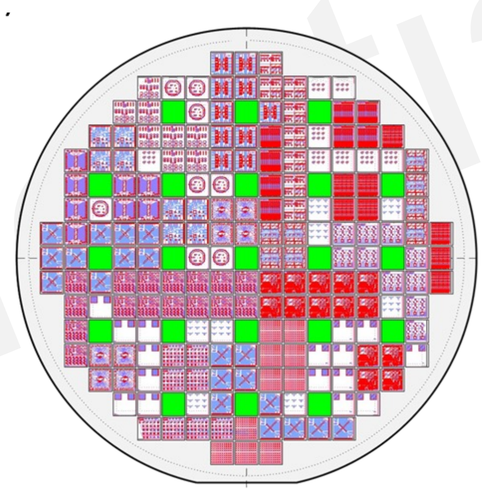
The 2D Experimental Pilot Line

Multi-Project Wafer Run #1

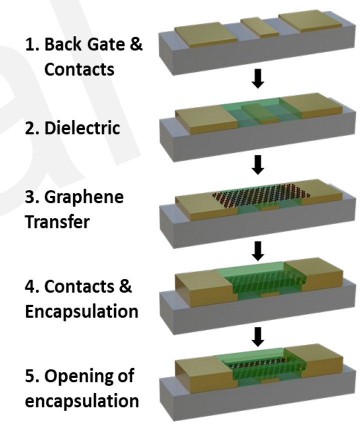


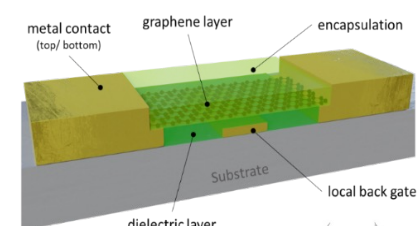
Overall applications





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





European Commission

35 applications => 14 participating customers

Max Lemme

Aachen Graphene & 2D Materials Center

AMO

RWTH AACHEN UNIVERSITY

2D Materials for Energy Harvesting

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

More information is available at **www.greenergy-project.eu**