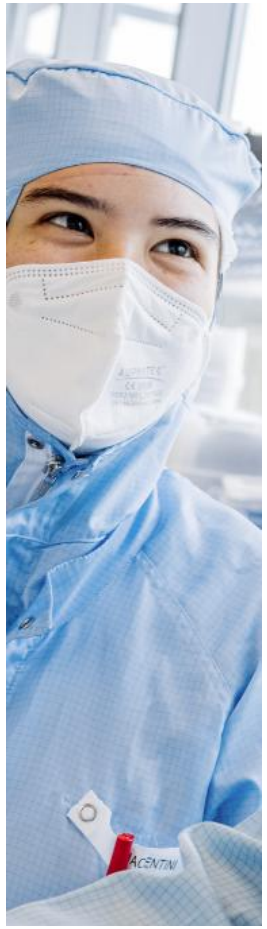
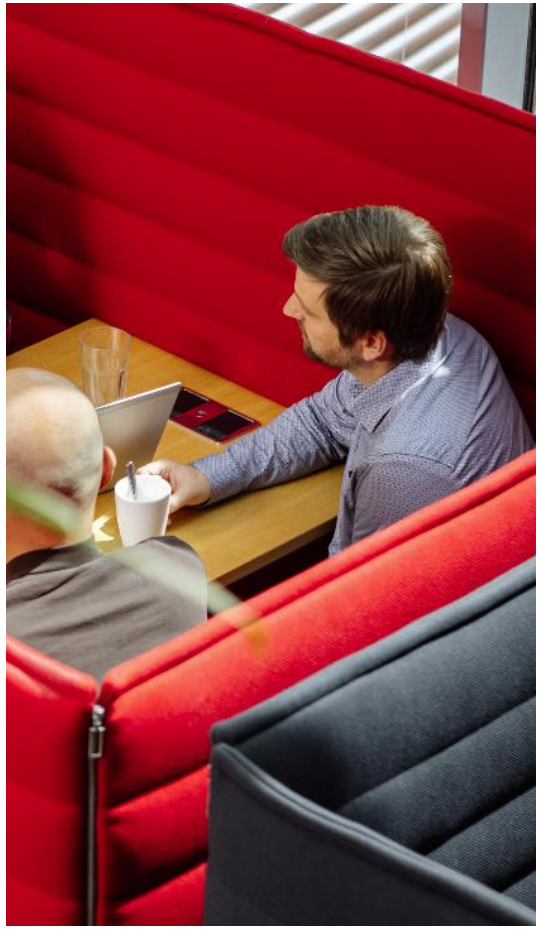
AMO GmbH
Partners of Innovators.









Enabling Research and Innovation in Graphene and 2D Materials Through Integrated Device Fabrication Workflows and Foundry Services

Gordon Rinke
AMO GmbH Aachen

About AMO

Our company profile.

AMO GmbH

- High-Tech SME / Institute (non-profit)
- Johannes Rau Research Institute
- Research Foundry
- 400 m^2 clean room
- > 80 staff members

Managing Director

- Prof. Dr.-Ing Max C. Lemme

RWTH Aachen University

- Large European Technical University
- 45.000 students
- Triangle: Germany / Belgium / Netherlands
- Chair of Electronic Devices (>20 staff members)

Key Technologies

- Silicon Technology Base
- Nanofabrication (NIL, E-Beam, IL,…)
- New Materials Integration (graphene, 2D, perovskites,…)
- Applications for Nanoelectronics, Nanophotonics, Integrated Sensors





Our Infrastructure.

Lithography

Electron beam lithography

- High resolution (~10 nm), highly flexible, 6”/8” wafers

Optical lithography

- Easy and fast fabrication of complex design
- Semi-automatic mask aligner (~5 µm)
- 6’’ I-line stepper (~0.5 µm)
- Automatic resist coater and developer

Interference lithography

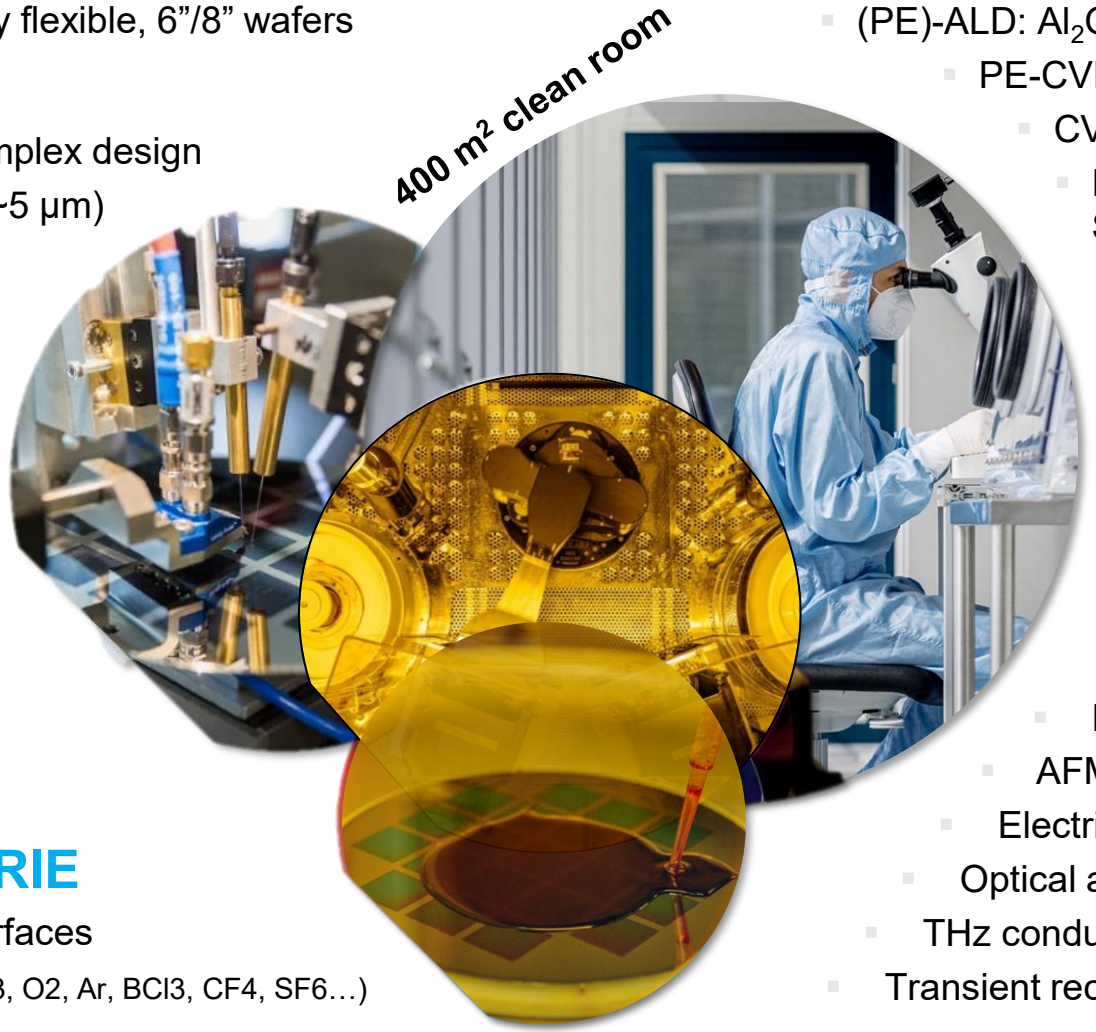
- Large area nano gratings
- 180nm - 2.5 µm Pitch

Laser Writer

- Highly flexible
- 6“ and 8“ wafer
- up to 0.3µm resolution

Pattern transfer by ICP/RIE

- Anisotropic profiles, smooth surfaces
- Flexible chemistry (HBr, Cl2, CHF3, O2, Ar, BCl3, CF4, SF6…)
- Up to 8“ wafer



Deposition

- LPCVD: Si3N4, SiO2
- (PE)-ALD: Al_2O_3, TiO2, AlN, TaN, TiN
  - PE-CVD for 2D-materials (S, Se, Te)
    - CVD for Graphene
      - Evaporation (Au, Al, AlSi, Ti, TiN, Ni, SiO2, Al2O3, etc.)
        - Metal sputtering (Au, Ti, TiN, Al, AlSi, SiO2, Al2O3, Cr…)

Wet processing

Metrology

- Raman spectrometer (vacuum)
- Photoluminescence
- AFM, Ellipsometer, Dektak
- Electrical DC and RF-Measurements
- Optical and Electron Mircoscopy
- THz conductivity (→ Protemics)
- Transient recording (→ AMOtronics)

A broad spectrum of competences

Our groups.

RESEARCH

Graphene & 2DM Electronics



Dr. Zhenxing Wang
Group Leader

Dr. Gordon Rinke
Deputy Group Leader

Nanophotonics



Dr. Stephan Suckow
Group Leader

Dr. Thomas Rijil
Deputy Group Leader

Nanostructuring



Dr.-Ing. Jens Bolten
Group Leader

Dr. Thorsten Wahlbrink
Deputy Group Leader

Perovskite Optoelectronics



Dr.
Maryam Mohammadi

Group Leader

Sensor Technology & Energy Converters



Dr.-Ing.
Ulrich Plachetka

Group Leader

Memristive Devices



Dr.
Jimin Lee

Group Leader

Metrology



Dr.
Satender Kataria

Group Leader

SERVICE

Services, Operations & Communications



Dipl.-Ing.
Herbert Kleinjans

Head of Services, Operations & Communications (COO)

Service & Technology Transfer



Caroline Porschastis

Head of Services



Partners of Innovation

AMO Foundry Services



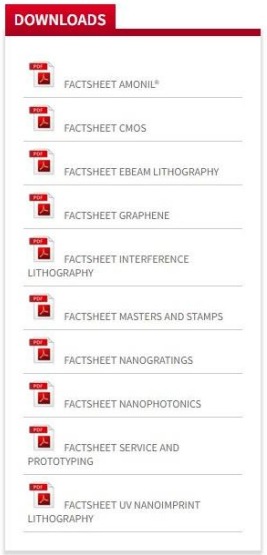


Based on our expertise, we develop tailored solutions for our customers, responding flexibly to their needs.

- **MPW runs**
- **Individual Services for external partners**
- New design concepts **from prototyping up to small series**
- Manufacturing within a **highly flexible technological environment**

Main Fields of Expertise:

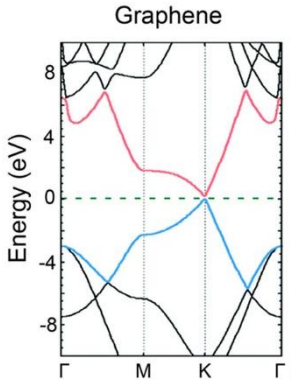
- NANOSTRUCTURING
- NANOPHOTONICS
- GRAPHENE ELECTRONICS & 2D MATERIALS
- SENSOR TECHNOLOGY





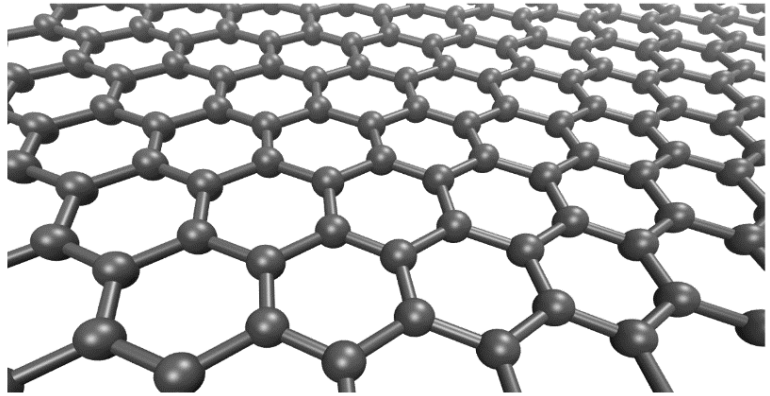
Introduction 2D Materials

Graphene



- single layer of carbon atoms
- very high carrier mobility[1,2]
- low carrier density
- high flexibility and strong
- large tensile strength[3,4]
- Bio compatible
- Optical transparent

● = Carbon



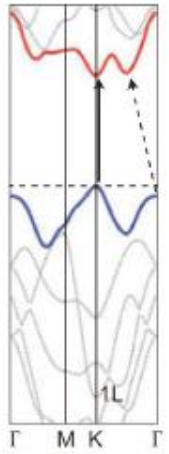
Semiconductors

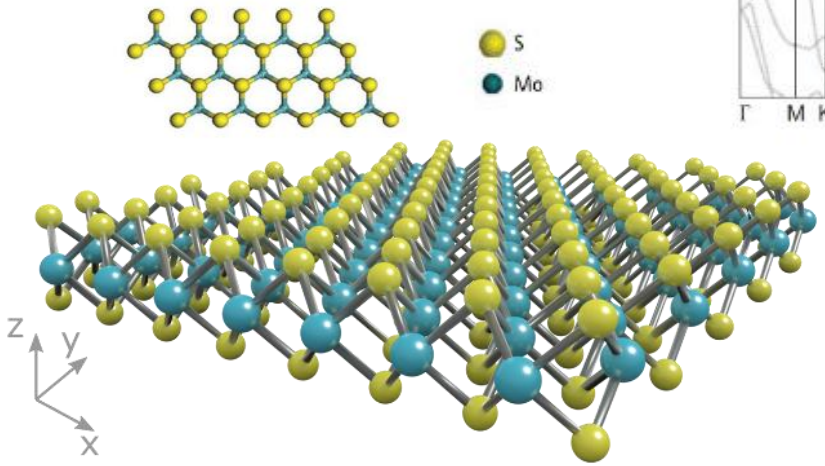
Transition Metal Dichalcogenides

(TMDs) with the composition MX_2
(M = Mo or W; X = S, Se, or Te)

Molybdenum disulfide (MoS_2)

- direct bandgap of 1.8 eV,
- fairly high electron mobility (~200 cm^2/Vs),
- excellent *I* on / *I* off ratio (~10^8),
- low subthreshold swing (~74 mV/dec)



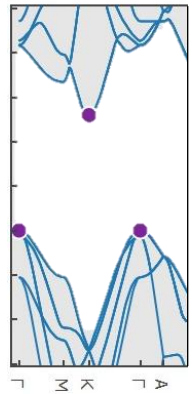


Chem. Rev. 2020, 120, 22, 12563-12591

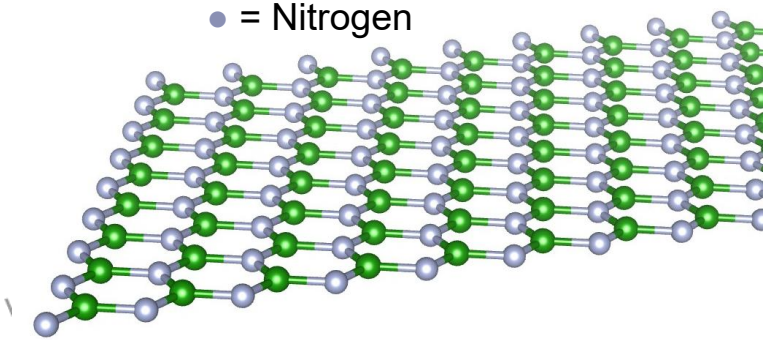
Insulator

Hexagonal Boron Nitride (h-BN)

E_g = 5.9 eV

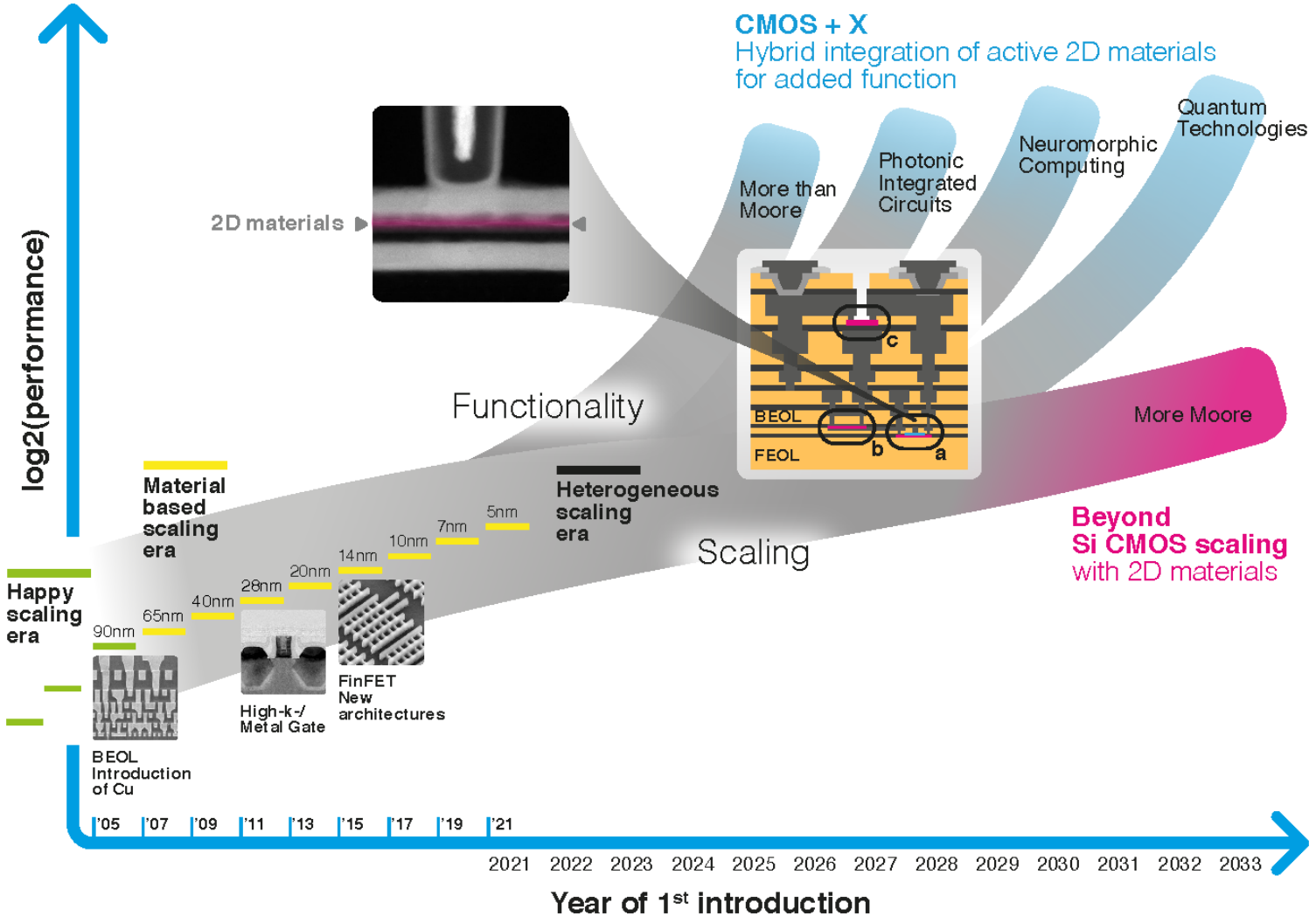


● = Boron
● = Nitrogen



1 Geim et al., 2007, 10.1038/nmat1849
2 Weiss et al., 2012, 10.1002/adma.201201482
3 CHANGGU LEE et al., 2008, 10.1126/science.1157996
4 Haider I. Rasool et al., 2013, 10.1038/ncomms3811
image source: Angelo Armano et al., 2019, 10.3390/c5040067

2D materials for future heterogeneous electronics



Lemme, M.C., Akinwande, D., Huyghebaert, C. *et al. Nat Commun* **13**, 1392 (2022)

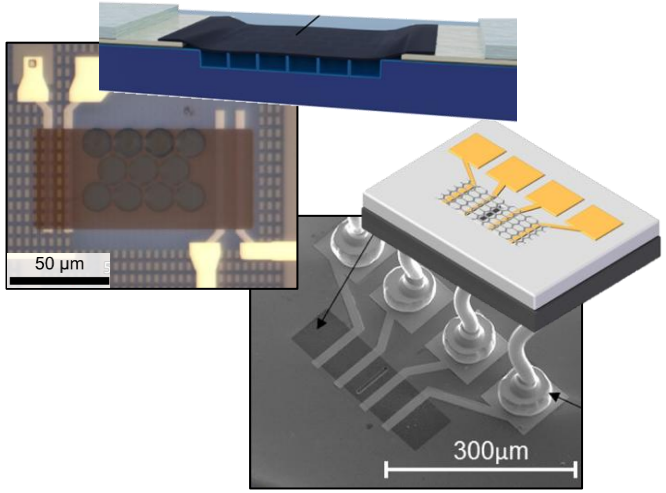
- **More Than Moore**
  - Sensors (Gas, Bio, Chemical,…)
  - RF Electronics
  - Photodetectors & Cameras
  - NEMS
- **Photonic Integrated Circuits**
  - Detectors
  - Modulators (Amplitude & Phase)
  - Attenuators
  - Heaters
- **Neuromorphic Computing**
  - Threshold Memristive Switching
  - Bipolar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

More than Moore

Current Activities & Examples

- Several examples for the integration of 2D materials such as Graphene and Semiconductor TMDCs (MoS_2, WSe_2..) for different applications

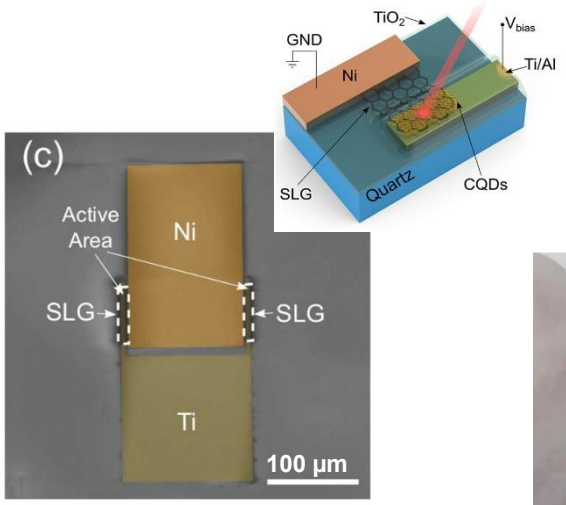
MEMS/NEMS



Pressure sensors

Research, 2020, 8748602, 2020
ACS Nano **18**, 25614–25624 (2024)
ACS Nano, **19**, 7026–7037 (2025)

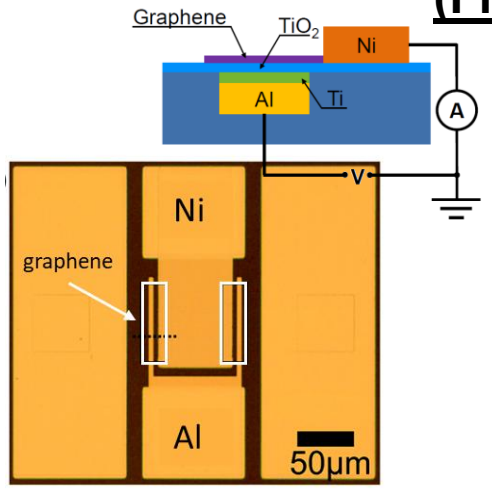
Optoelectronics



Graphene/ QD Photodetector

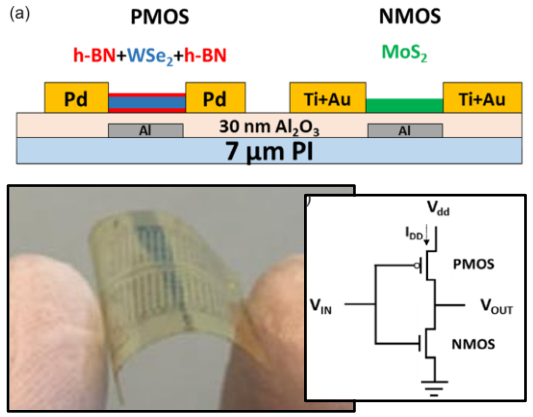
ACS Nano, 14, 11897, 2020.
Sci Rep **15**, 14706 (2025).

(Flexible) Electronics



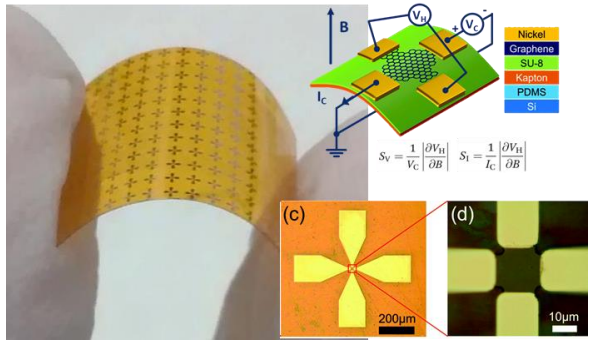
MIG Diode for RF electronics

Nanoscale, 9, 11944, 2017.
Advanced Electronic Materials **7**, 2001210 (2021)



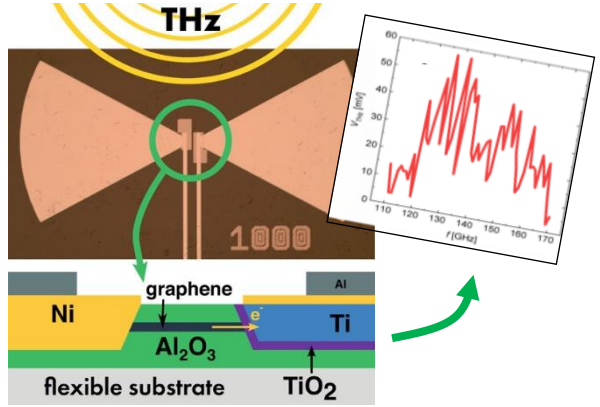
Complementary inverter based on TMDCs

Phys. Status Solidi A ***2024***, *221, 2300913*



Flexible Hall Sensors

Nanoscale, 8, 7683, 2016
Sci Rep **9**, 18059 (2019)



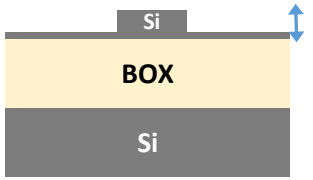
Flexible graphene THz rectennas

ACS Applied Electronic Materials (2021) 3, 3747.

Photonic Integrated Circuit (PIC)

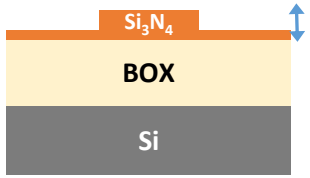
AMO‘s platforms

Top-Si 220 & 400 nm



SOI Si_3N_4

Si_3N_4 up to 500 nm



Passive

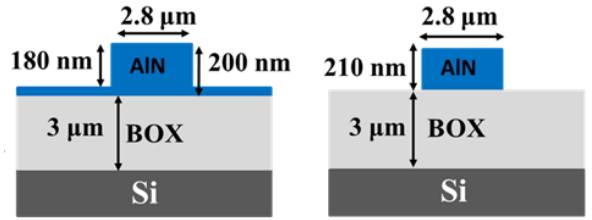
- **Wave-guides** Strip, rib, slot
- **Grating couplers**
- **Microring resonators**
- **Mach-Zehnder interfero-meter**
- **Directional couplers**
- **Spot-size converters**

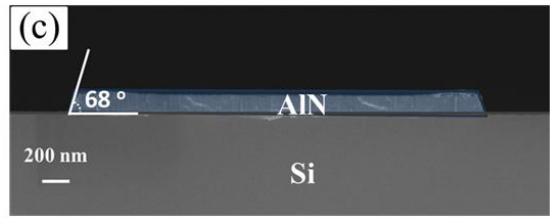
Active

- **Heaters** Ti, TiN, Al-contact Pads
- **EO-Modulators** Microrings
- **EO-Modulators** MZIs
- **2D-Photo-detectors**
- **Thermo-optical switches**

(almost) substrate-independent 2D material integration

Emerging platforms: AlN and Al_2O_3





SEM image

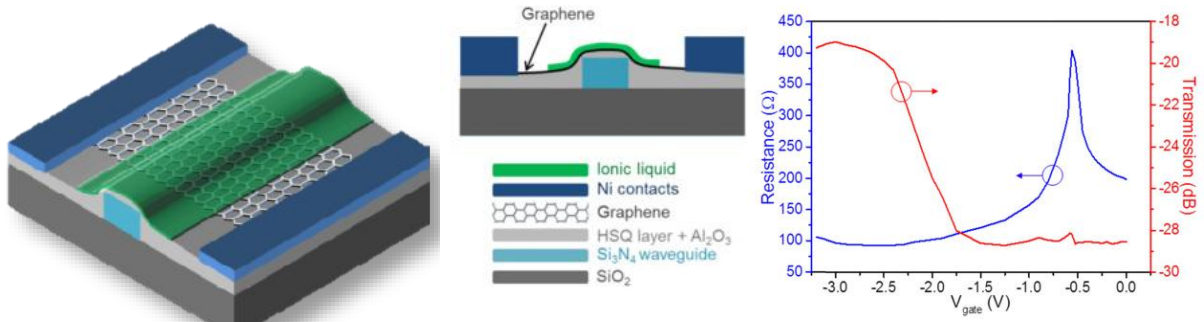
- Lowest loss in the data comm range
- 0.13 dB/cm @ 1310 nm wavelength
- Beating epitaxial MOCVD AlN growth with sputtered layers on oxidized Si

R. Singh et al., “*Sputtered Aluminum Nitride Waveguides for the Telecommunication Spectrum with less than 0.16 dB/cm Propagation Loss*”, Opt. Express **32**(25) (2024)

Photonic Integrated Circuit (PIC)

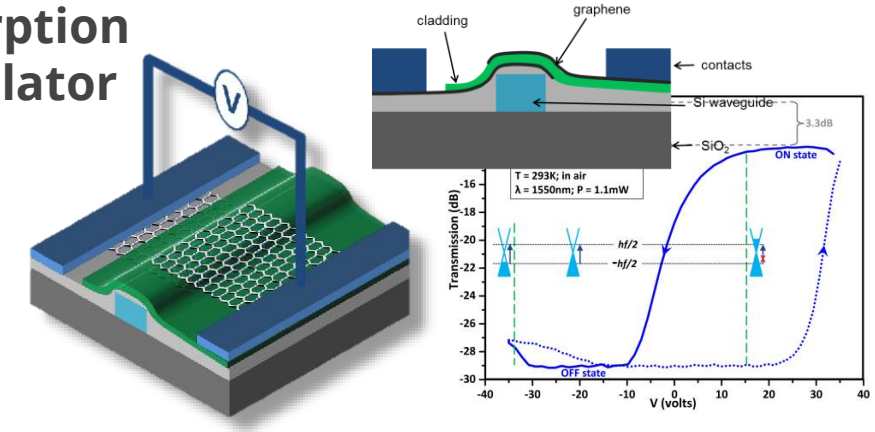
AMO‘s opto-electronic 2DM based Devices

Variable Optical Attenuators



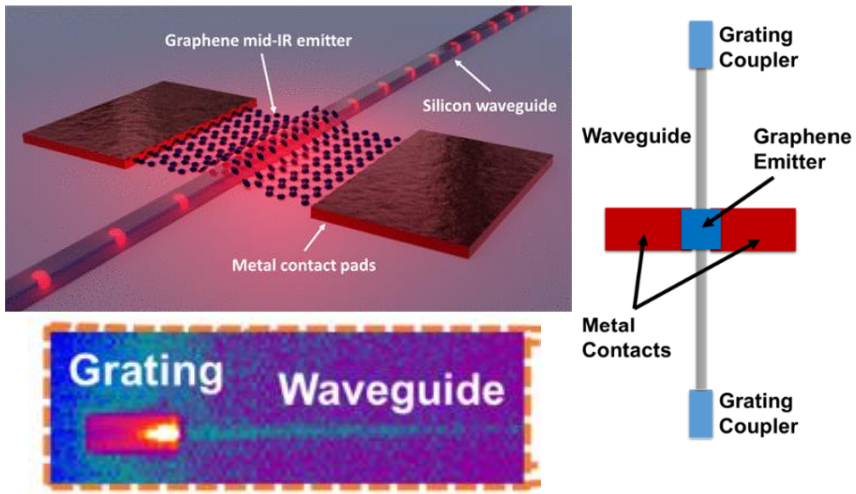
M. Mohsin *et al.*, *Opt. Express*, vol. 25, no. 25, p. 31660, 2017.

Absorption Modulator



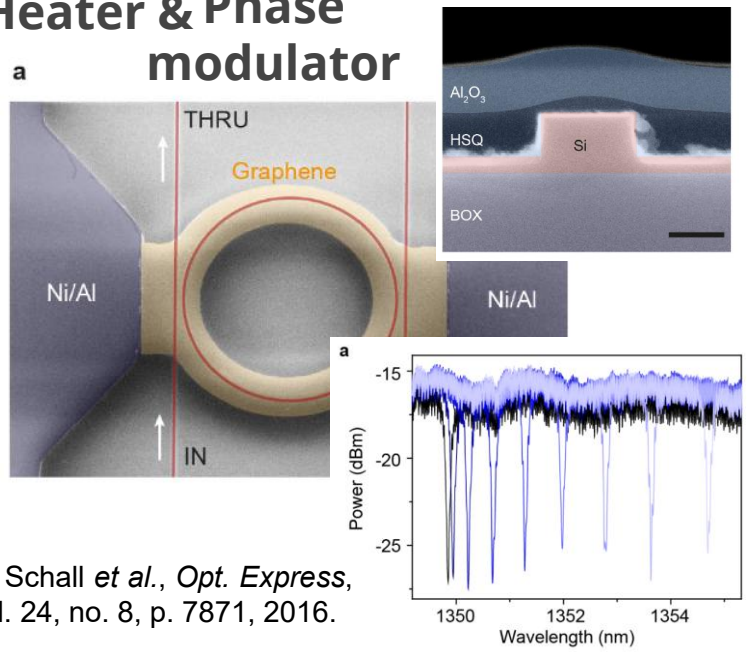
M. Mohsin et al., Opt. Express 22, 15292-15297 (2014).

AEOLUS Light Emitter



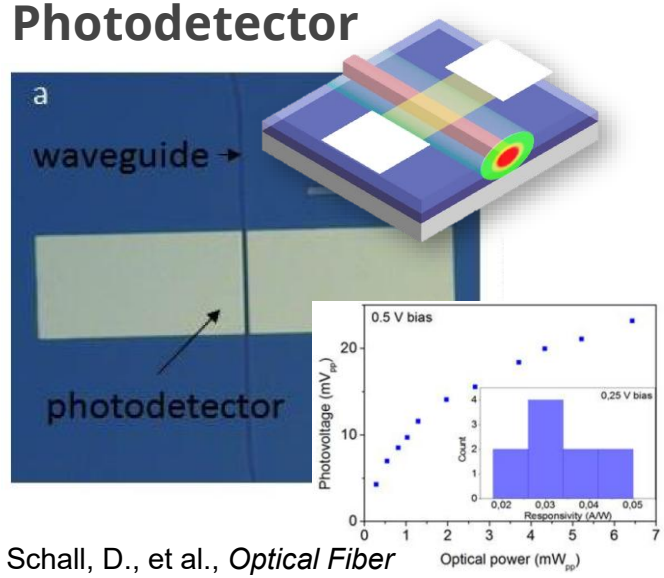
N. Negm et al., *ACS Photonics*, 11, 8, 2961–2969, 2024.

Heater & Phase modulator



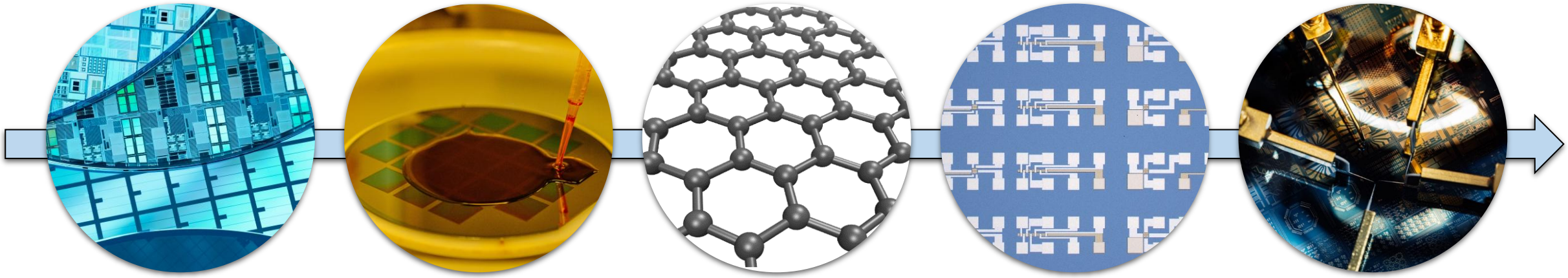
D. Schall *et al.*, *Opt. Express*, vol. 24, no. 8, p. 7871, 2016.

Photodetector



Schall, D., et al., *Optical Fiber Communication Conference*. Optical Society of America, 2018.

Typical Process Flow for 2DM devices and Integration Challenges



Start Wafer
- CMOS
- Si/SiO2

Target wafer Preparation
- Back gate
- Contacts
- Dielectric deposition

2D Material Deposition
- Growth of the 2D material
- Layer Transfer to the target wafer
- Cleaning of the wafer

Post Processing
- Active patterning
- Top contacts
- Top gate

Application specific Processing
- Encapsulation
- Via/Channel opening
- Functionalization

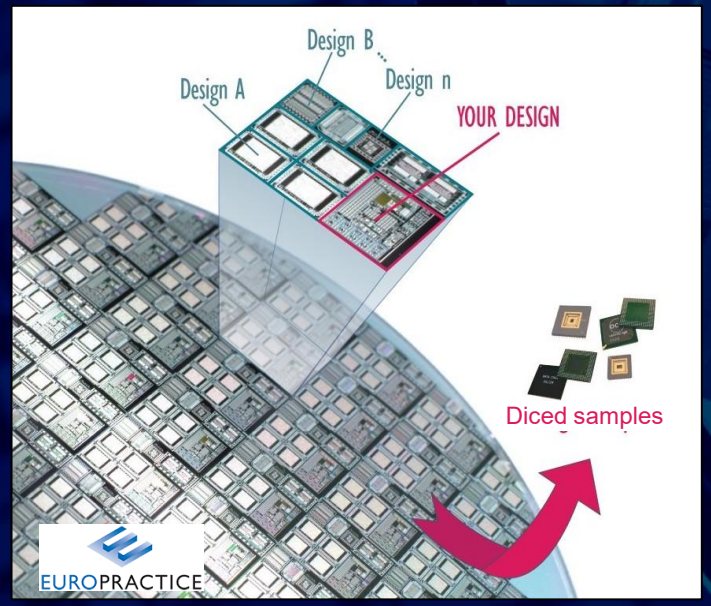
CHALLENGES

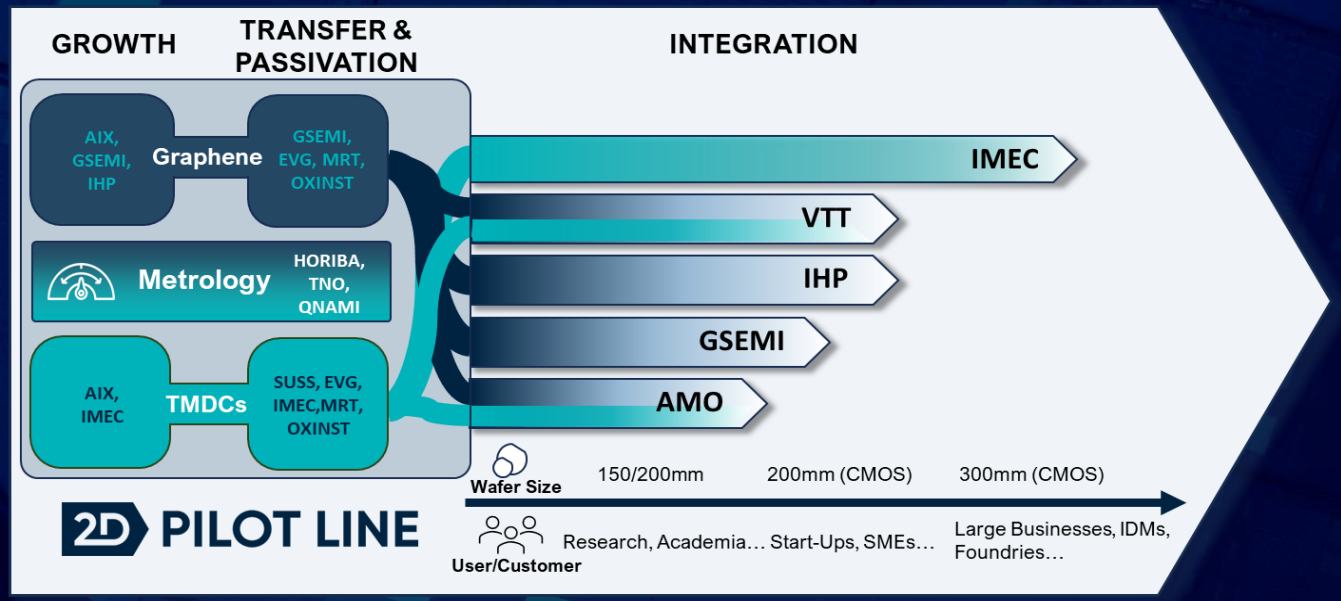
- **2DM Growth:** Catalytic CVD on metals, Temperatures: 400-1000°C, Quality
- **2DM Transfer:** wafer-scale, Automation, Quality
- **Fabrication flows:**
  - must be compatible with 2DM before and after the transfer
  - contacts, Interfacial dielectric layer, etch stop,
  - additional contamination and residue potentials

2D PILOT LINE

FROM THE GRAPHENE FLAGSHIP

2024-2028

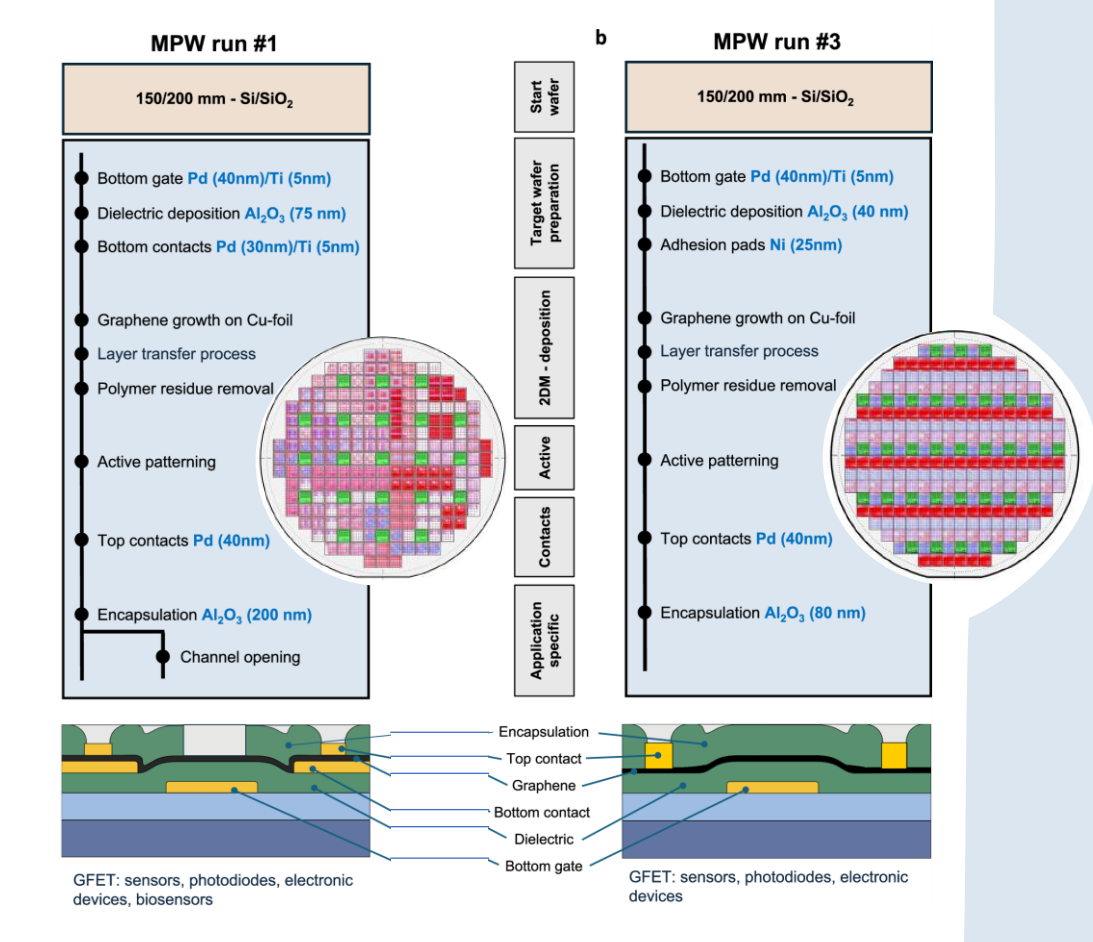




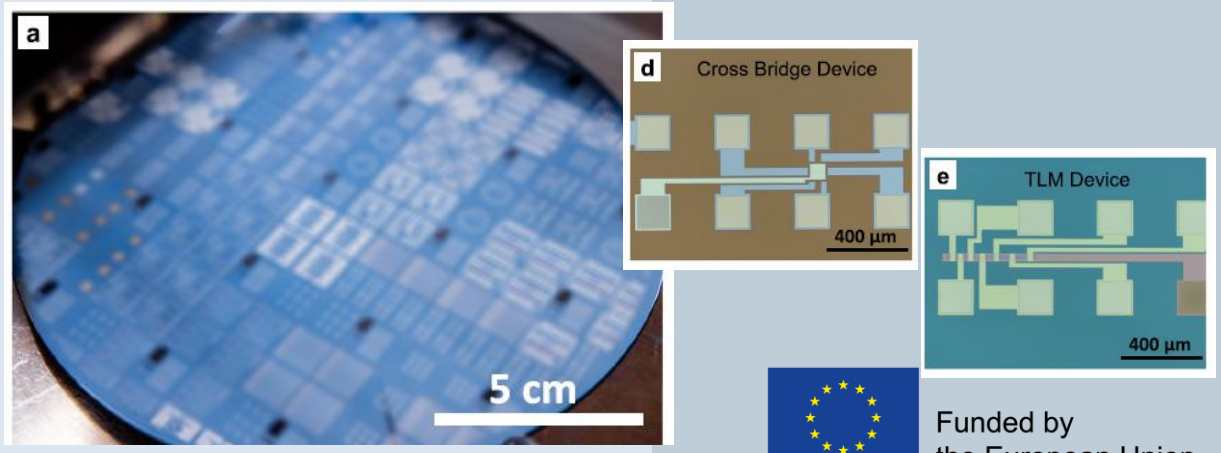
2D-PL connects material growth, transfer, integration and access.

Funded by the European Union

Wafer-scale Graphene MPW Runs @ AMO



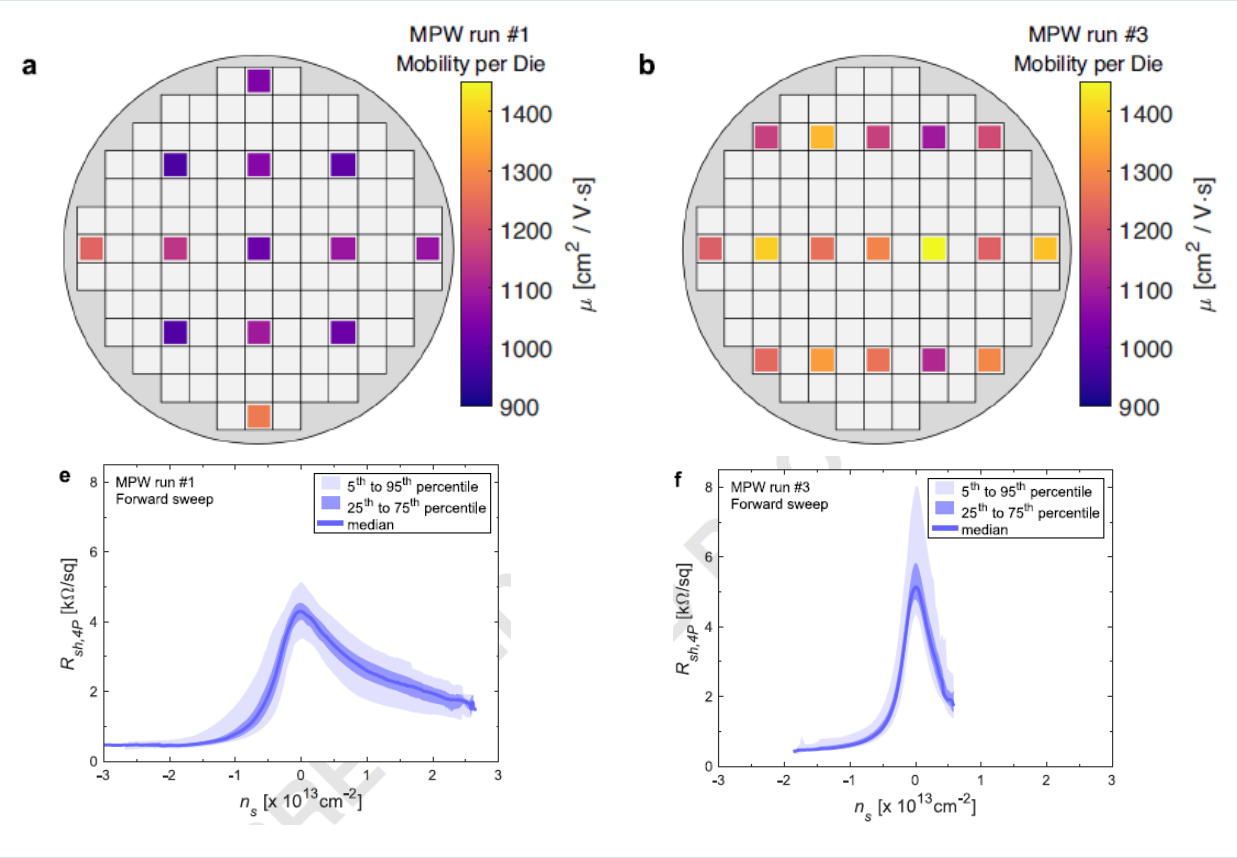
- Two MPW runs attracted **60 applications** and produced orders from **19 entities**.
- **MPW run 1** was intended mainly for graphene-based sensors
  - Sandwich contact
  - Encapsulation: 200 nm evaporated Al2O3
- **MPW run 3** focused on graphene electronics
  - Top contact
  - Encapsulation: 80 nm ALD Al2O3



Funded by the European Union

Canto *et al.* . *Nat Commun* **16**, 1417 (2025).
https://doi.org/10.1038/s41467-025-56357-0

Wafer-scale Graphene MPW Runs @ AMO



- The specified target values were achieved for both runs.
- Room for improvement: Symmetry, hysteresis, doping, etc

Table 1 | Target and achieved values for MPW runs 1 and 3

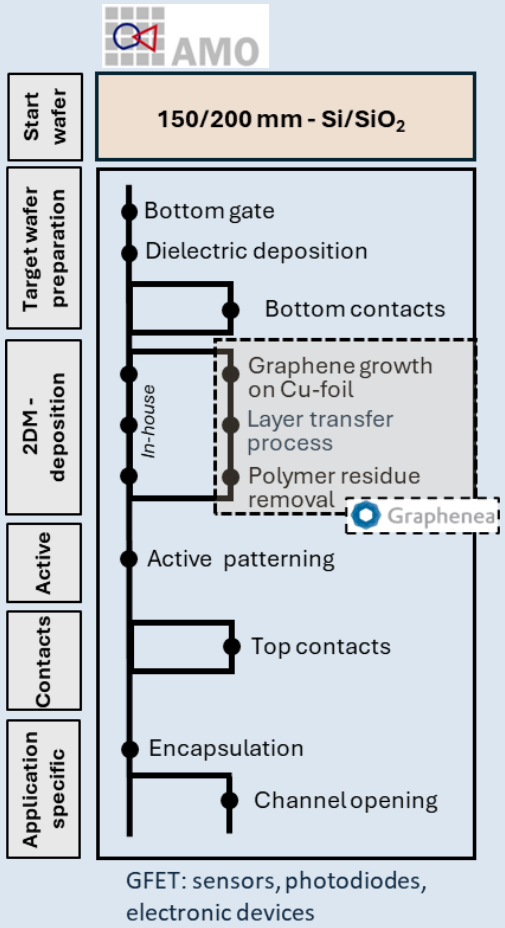
Parameters		Target values MPW run 1 and MPW run 3	Achieved values MPW run 1	Achieved values MPW run 3
Graphene Mobility		>1000 cm²/Vs	1023 cm²/Vs	1185 cm²/Vs
Avg. Sheet Resistance	$n_s = -10 \times 10^{12}$ cm^{-2}:	~1 kΩ /sq	0.72 kΩ/sq	0.6 kΩ/sq
	at CNP:	~4 kΩ /sq	4.3 kΩ/sq	5.2 kΩ/sq
Avg. Contact Resistivity	$n_s = -10 \times 10^{12}$ cm^{-2}:	~1 kΩ·µm	0.8 kΩ·µm	1.5 kΩ·µm
	at CNP:	~4 kΩ µm	3.5 kΩ·µm	5.3 kΩ·µm
Dirac Voltage		<15 V	−2.85 V(forward)/ 37 V(backwards)	6.5 V (forward)/ 7 V(backwards)
Yield:		>80 %	94 %	87 %

Canto *et al.* . *Nat Commun* **16**, 1417 (2025). https://doi.org/10.1038/s41467-025-56357-0

2D PILOT LINE

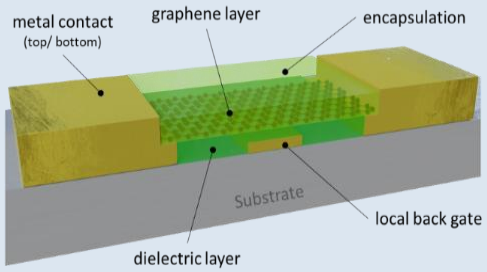
Funded by the European Union

AMO process flows in 2D-EPL…



GFET: sensors, photodiodes, electronic devices

2D-EPL MPW #1

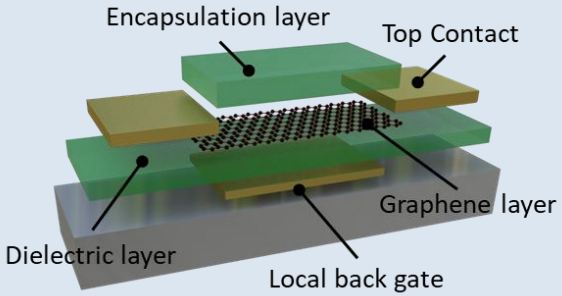


Layer Thicknesses

1	**Back Gate Contact**	Ti/Pd	5nm /40nm
2	**Dielectric Layer**	Al_2O_3	75 nm
3	**Bottom Contact**	Pd	30 nm
4	**Graphene**	Single layer	
5	**Top Contact**	Pd	40 nm
6	**Encapsulation**	Al_2O_3	150 nm
6	**Encapsulation**	SU-8	7 µm

- Sandwich contacts
- Metal: Pd
- **evaporated Al_2O_3**

2D-EPL MPW #3

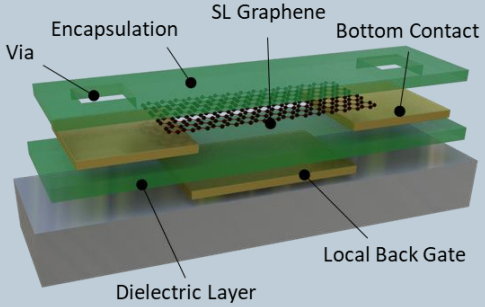


Layer Thicknesses

	Rigid Substrate	Si/SiO_2	90 nm
1	**Back Gate Contact**	Ti/Pd	5nm /40nm
2	**Dielectric Layer**	Al_2O_3	40 nm
3	**Adhesion Layer**	Ni	25 nm
4	**Graphene**	Single layer, CVD on Cu	
5	**Top Contact**	Pd	40 nm
6	**Encapsulation**	Al_2O_3	80 nm

- Top contacts
- Metal: Pd
- **ALD Al_2O_3 for Encap**
- Thinner dielectric

…and 2D-PL



Layer Thicknesses

	Rigid Substrate	Si/SiO_2	90 nm
1	**Back Gate Contact**	Ti/Pd or Ti/Au	5nm/40nm
2	**Dielectric Layer**	Al_2O_3	40 nm
3	**Bottom Contact**	as layer 1	5nm /40 nm
4	**Graphene**	Single layer, CVD on Cu	
5	**Encapsulation**	Al_2O_3	40 nm
6	**Bondpads**	Au	300 nm

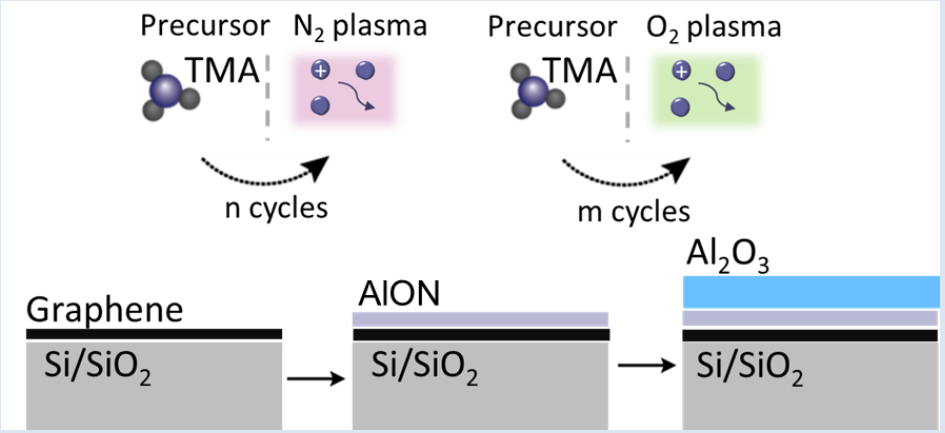
- Bottom contacts
- Metal: Pd or Au
- **PE-ALD Al_2O_3[1,2] for Encap & Dielelectric**
- Optional bondpads

2D PILOT LINE

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[1] Riazimehr, S. *et al.* Plasma-enhanced atomic layer deposition of Al2O3 on graphene via an *in situ*-deposited interlayer. *Materials Science in Semiconductor Processing* **199**, 109829 (2025).
[2] Esteki, A. *et al.* Tunable Doping and Mobility Enhancement in 2D Channel Field-Effect Transistors via Damage-Free Atomic Layer Deposition of AlOX Dielectrics. Preprint at https://doi.org/10.48550/arXiv.2408.07183 (2024).

In-situ protective layer for 2D materials before dielectric deposition



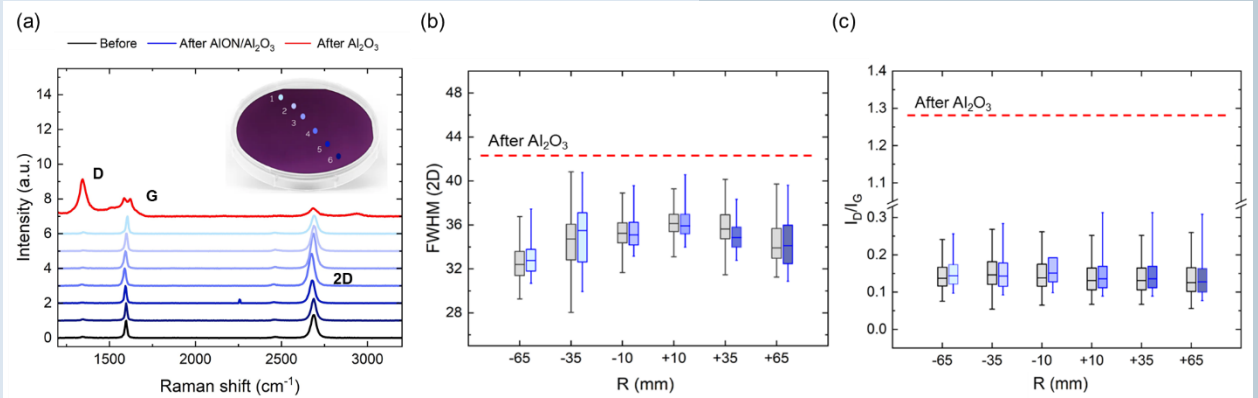


Figure 1: (a) Raman spectra across the wafer radius (R) (inset) for Gr/SiO_2/Si wafers before and after Al_2O_3 deposition, with (blue) and without (red) AlON protective layer. (b) FWHM (2D) across the wafer radius (R) (c) I_D/I_G across the wafer R.

- Graphene etching prevented by low-dose remote nitrogen plasma
- Effective protection through thin AlON layer
- The dielectric constant of AlON is very close to that of Al_2O_3
- Thickness uniformity < ± 0.8 %

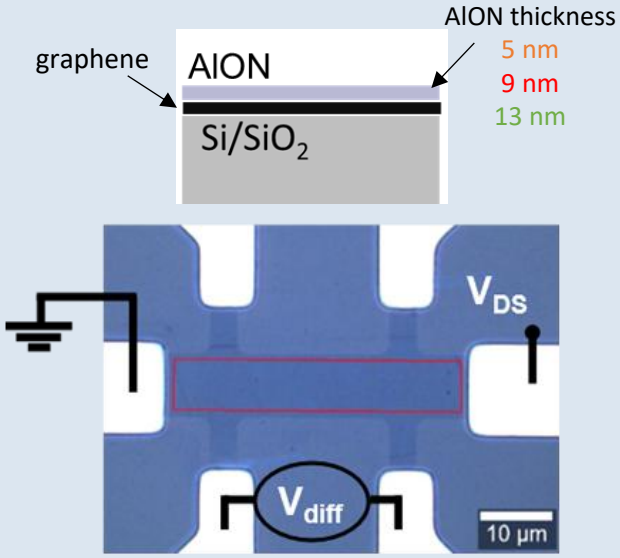


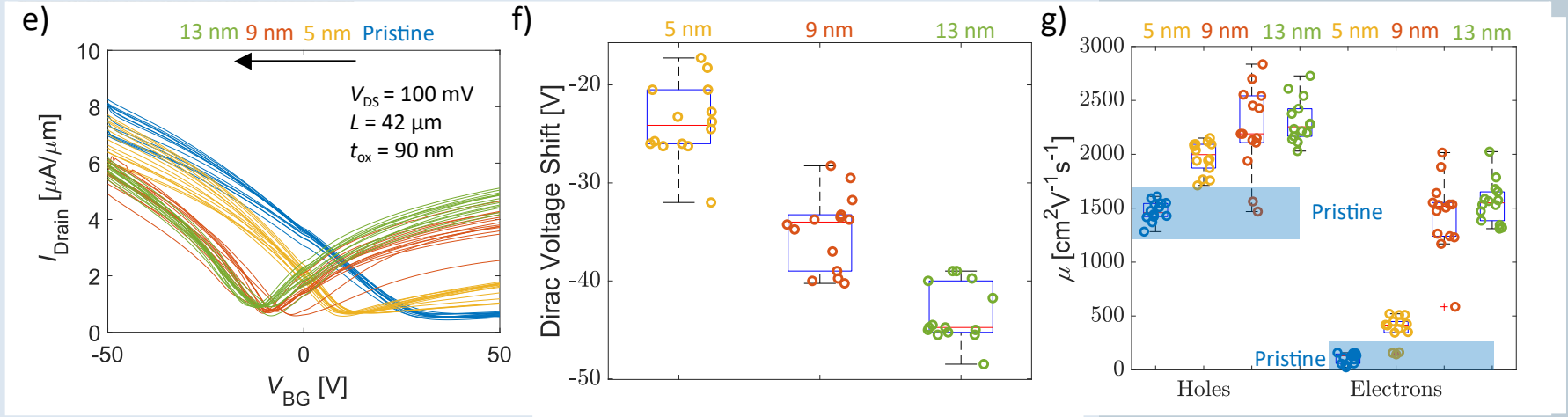
Atomfab

Production plasma ALD system for GaN HEMT devices

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Encapsulating and Tuning Graphene





- Comparison of graphene encapsulated with AlON layers at t_d values of 5 nm, 9 nm, and 13 nm.
- Measured shift in the Dirac voltage due to deposition of the AlOX layer towards negative values
- Hole and electron mobilities increase with thickness

⇒ **Nice example of how the process workflow affects performance**

2D PILOT LINE

Esteki, A. *et al.*. Preprint at https://doi.org/10.48550/arXiv.2408.07183 (2024).

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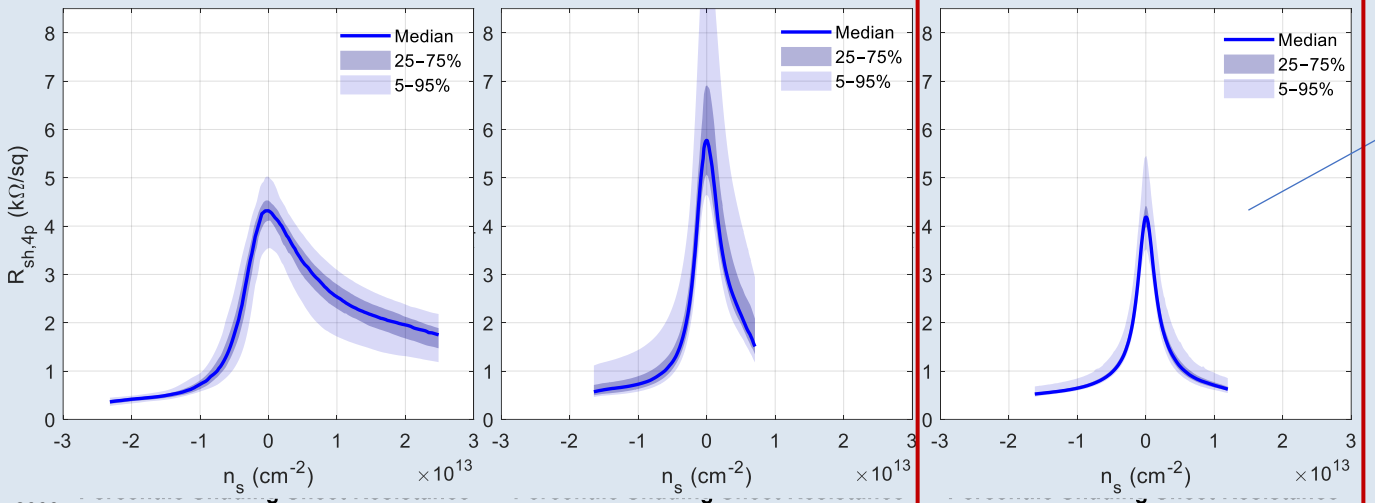
Ongoing Process Improvement

MPW Run #1
Evaporated Al2O3 200nm

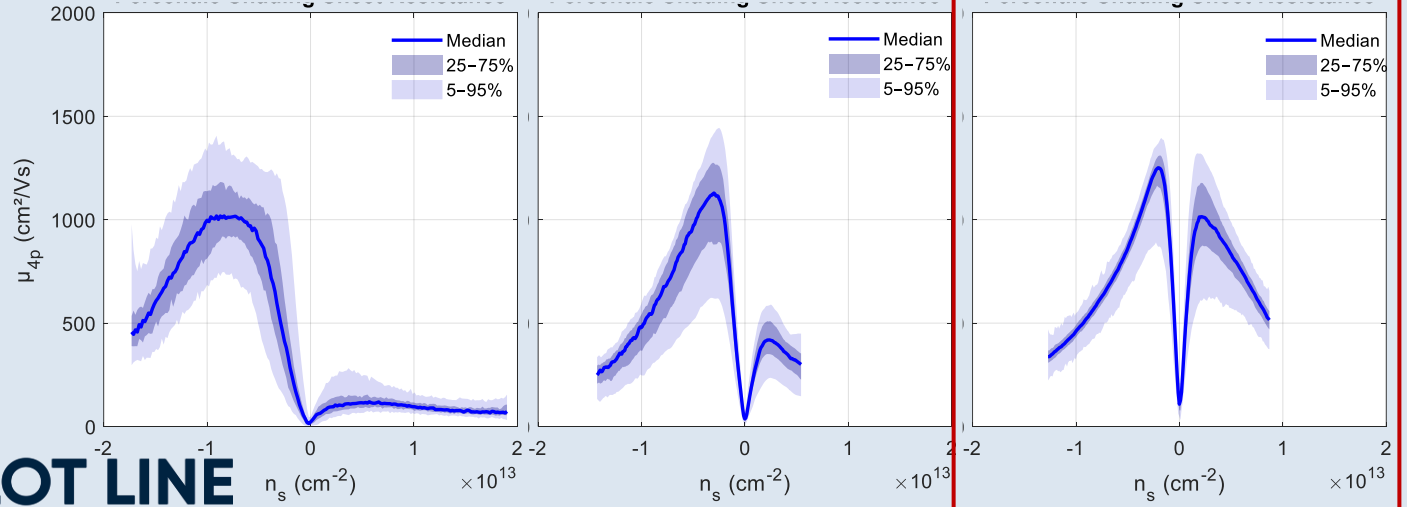
MPW Run #3
Thermal ALD Al2O3 80nm

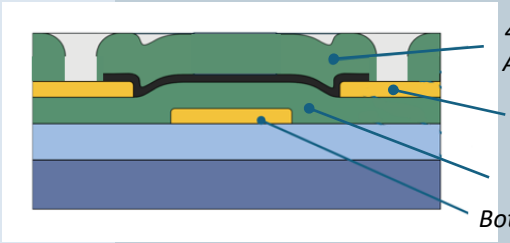
Current process
Atomfab ALD Al2O3 40nm

Sheet Resistance



Mobility





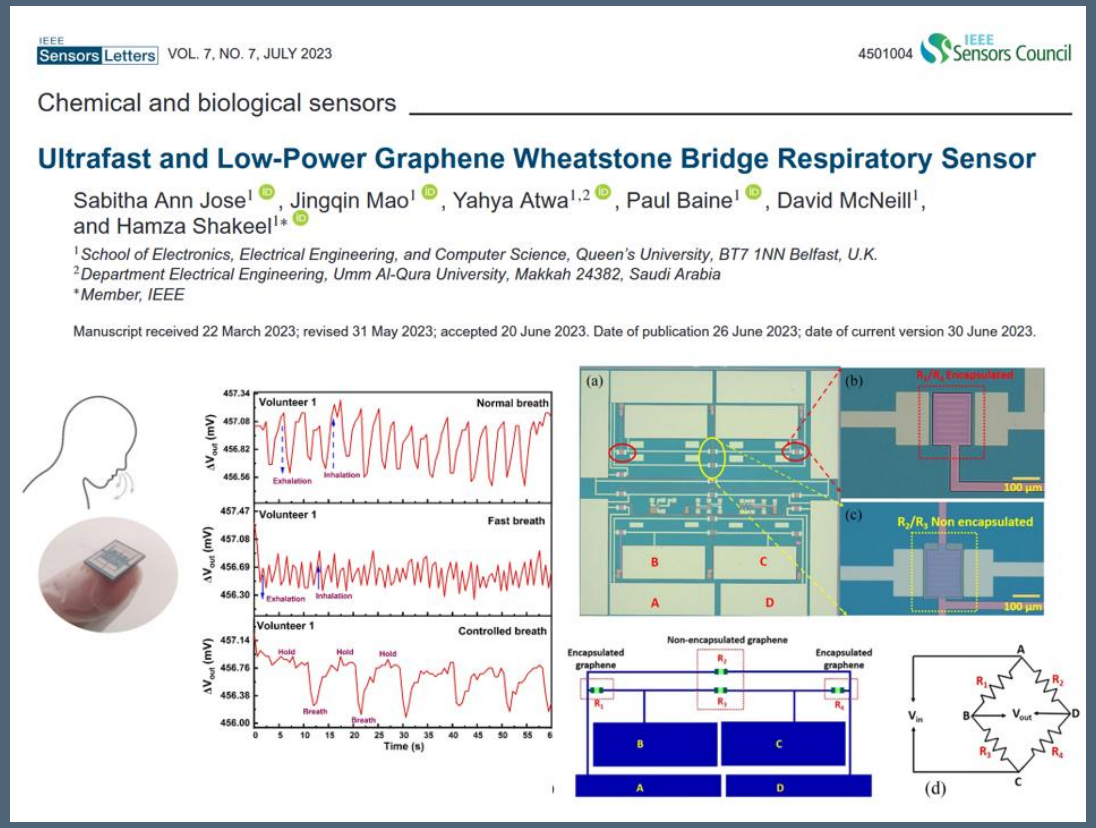
- Curve is symmetric
- Sheet resistance improved
- Mobility & Hysteresis improved

	MPW1	MPW3	Current
Graphene Mobility	1023 cm2/Vs	1185 cm2/Vs	1275 cm2/Vs
Dirac Voltage	− 2.85 V	6.5 V	1.8 V
Hysteresis	~40V	~0.5V	~0.3V

2D PILOT LINE

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Customer Application Example
Graphene Wheatstone Bridge Respiratory Sensor



IEEE Sensors Letters VOL. 7, NO. 7, JULY 2023 4501004 IEEE Sensors Council

Chemical and biological sensors

Ultrafast and Low-Power Graphene Wheatstone Bridge Respiratory Sensor

Sabitha Ann Jose[1], Jingqin Mao[1], Yahya Atwa[1,2], Paul Baine[1], David McNeill[1], and Hamza Shakeel[1]*

[1]School of Electronics, Electrical Engineering, and Computer Science, Queen's University, BT7 1NN Belfast, U.K.
[2]Department Electrical Engineering, Umm Al-Qura University, Makkah 24382, Saudi Arabia
*Member, IEEE

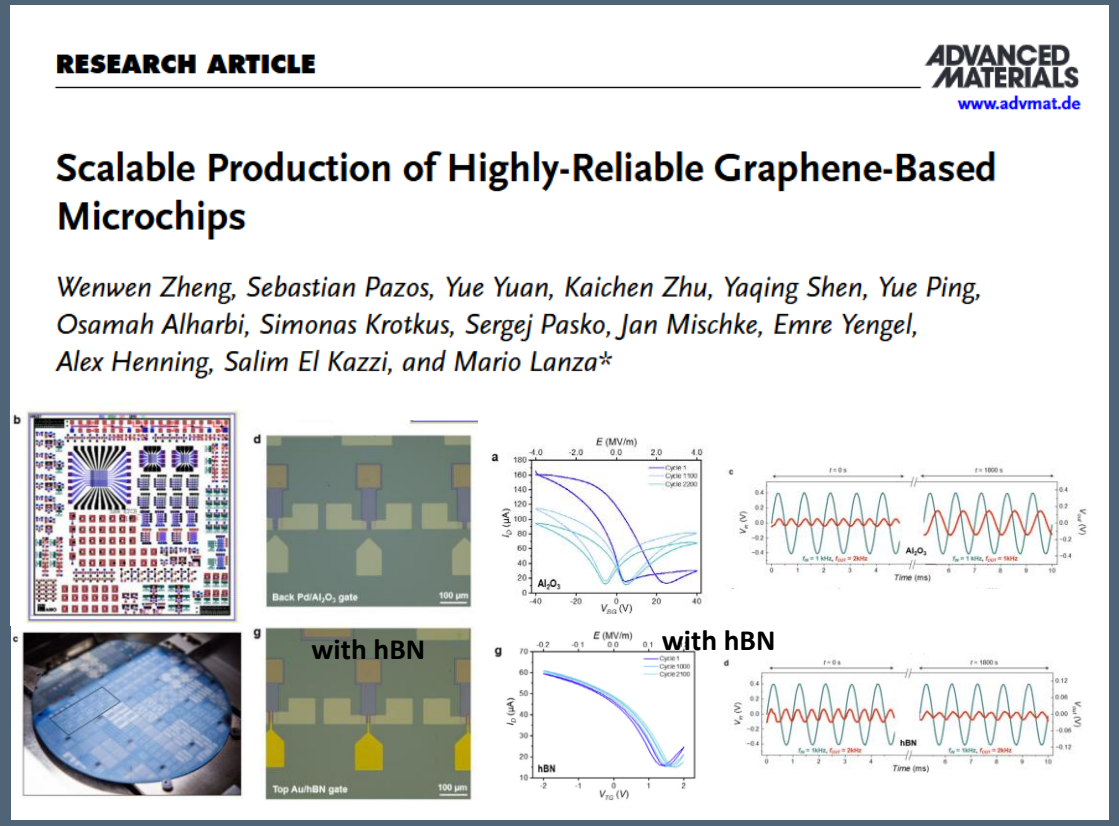
Manuscript received 22 March 2023; revised 31 May 2023; accepted 20 June 2023. Date of publication 26 June 2023; date of current version 30 June 2023.

- Graphene respiratory sensor chips fabricated in the **2D-EPL MPW run #1 at AMO**
- Demonstrated **real-time monitoring of breathing patterns**.
- Detected changes in breath composition, showing potential for breath analysis.
- Achieved sub-second response times with only **0.3 mW** power consumption.
- Showed **stable and reproducible performance** over long-term operation.
- **AMO graphene platform** suitable for wearable health-monitoring applications.

Jose, S. A. *et al.* Ultrafast and Low-Power Graphene Wheatstone Bridge Respiratory Sensor. *IEEE Sensors Letters* **7**, 1–4 (2023).

Funded by the European Union

Customer Application Example
GFET-based frequency doublers

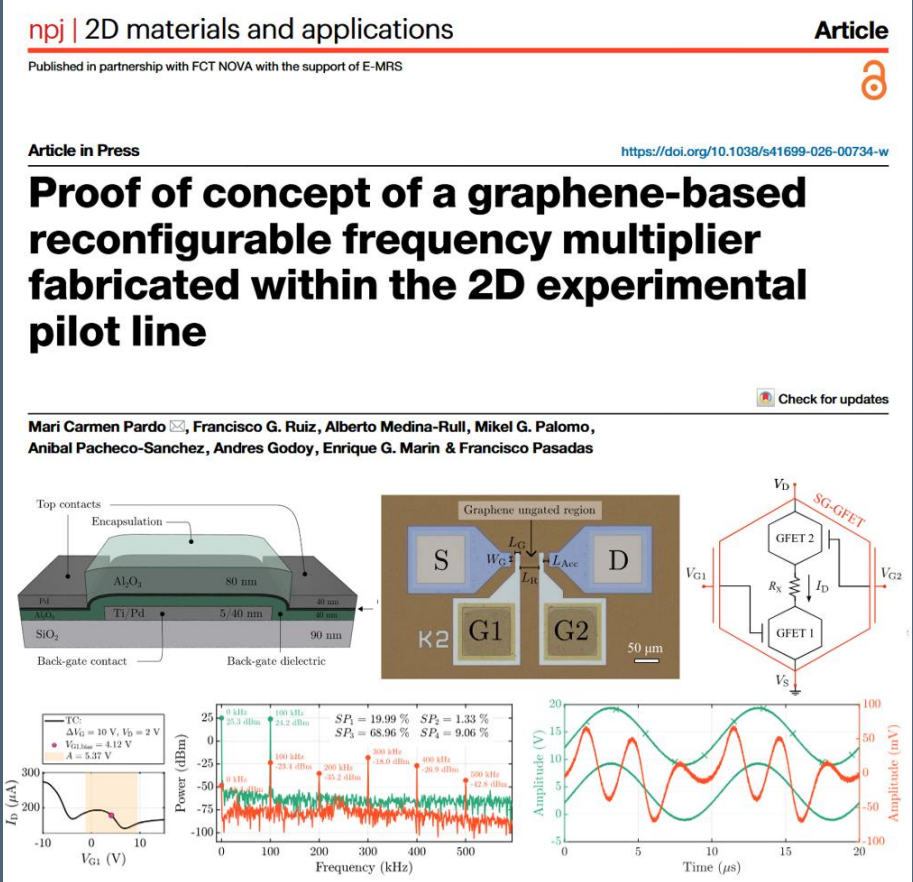


- Graphene microchips fabricated in the **2D-EPL MPW run #1 at AMO.**
- Included **graphene transistor-based frequency-doubler** circuits for high-frequency electronic applications.
- Used structures to **process them further**
  ⇒ Encapsulation with hBN
- Maintained stable frequency-doubling operation, validating the robustness of graphene circuits fabricated on the platform.
- Demonstrated the scalability of the **AMO graphene platform** for reliable graphene-based integrated circuits and future RF and sensing applications.

Zheng, W. , Lanza, M. *et al.* Scalable Production of Highly-Reliable Graphene-Based Microchips. *Advanced Materials* **37**, e10501 (2025)

Funded by the European Union

Customer Application Example
Split-gate graphene FET (SG-GFET) devices



npj | 2D materials and applications **Article**

Published in partnership with FCT NOVA with the support of E-MRS

Article in Press https://doi.org/10.1038/s41699-026-00734-w

Proof of concept of a graphene-based reconfigurable frequency multiplier fabricated within the 2D experimental pilot line

Check for updates

Mari Carmen Pardo ✉, Francisco G. Ruiz, Alberto Medina-Rull, Mikel G. Palomo, Anibal Pacheco-Sanchez, Andres Godoy, Enrique G. Marin & Francisco Pasadas

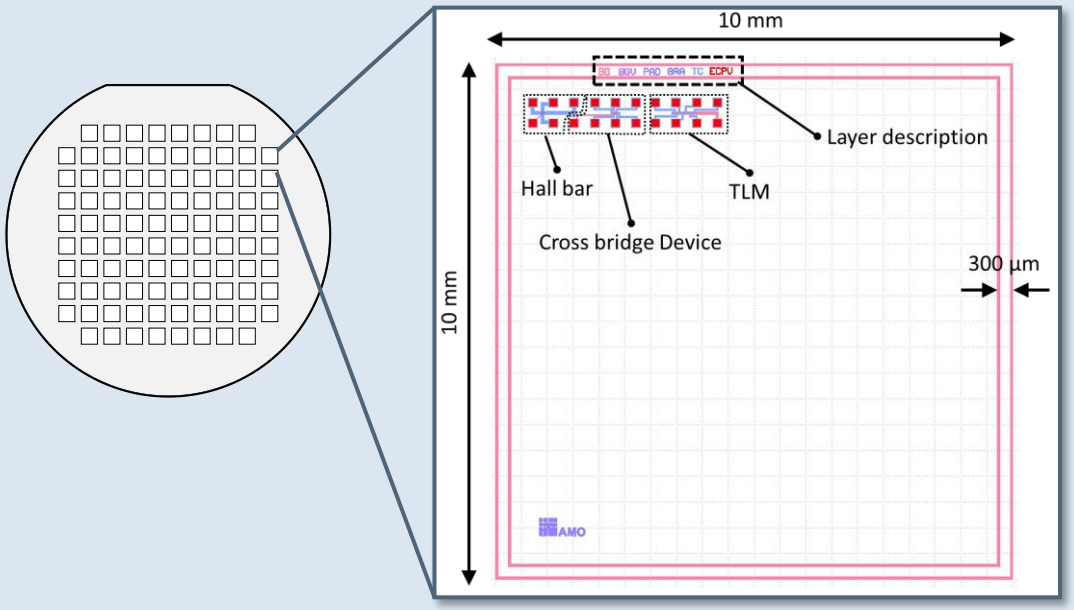
- Split-gate graphene FET (SG-GFET) devices fabricated through **AMO's 2D-EPL MPW Run #3** were used to demonstrate a reconfigurable frequency multiplier.
- Demonstrated a reconfigurable circuit capable of **×2, ×3, and ×4 frequency multiplication** using a single graphene transistor.
- Achieved spectral purities up to **69%** with power consumption below **400 μW**. Provided the **first reconfigurable-circuit demonstration on the 2D-EPL MPW platform**.
- Validated the potential of the **AMO graphene platform** for future high-frequency and RF applications.

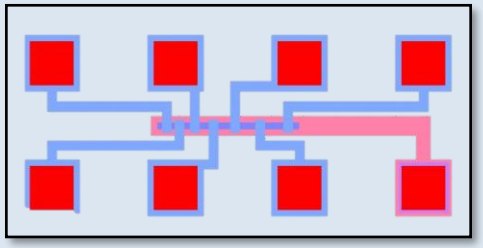
2D PILOT LINE

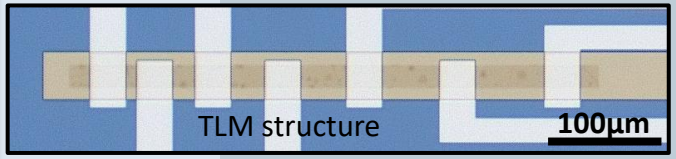
Pardo, M. C. *et al.* Proof of concept of a graphene-based reconfigurable frequency multiplier fabricated within the 2D Experimental Pilot Line. *npj 2D Mater Appl* (2026)

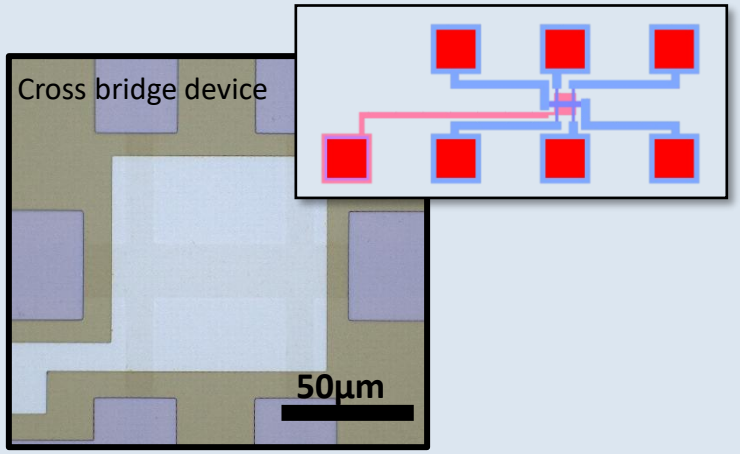
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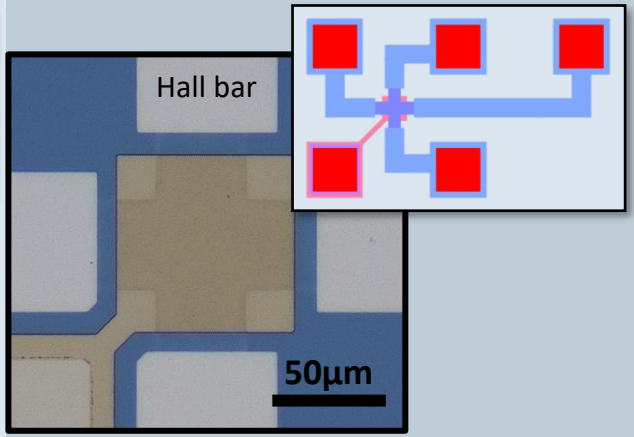
KLayout GDS Template











- The design of the dies with the size of 10 mm x 10 mm can be done individually within the design rules.
- Device Library available for reference devices available as a basis for further modifications
- Details in PDK and GDS template file

Drawing a Design in KLayout and checking design rules
=> Part of the afternoon training

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Conclusion

- **Graphene and 2D materials** offer unique properties for next-generation technologies
- **Integration workflows matter**
- **MPW access and services lower barriers** and enable further research and innovation
- **AMO supports the route from design to devices**
  - MPW runs
  - Individual services



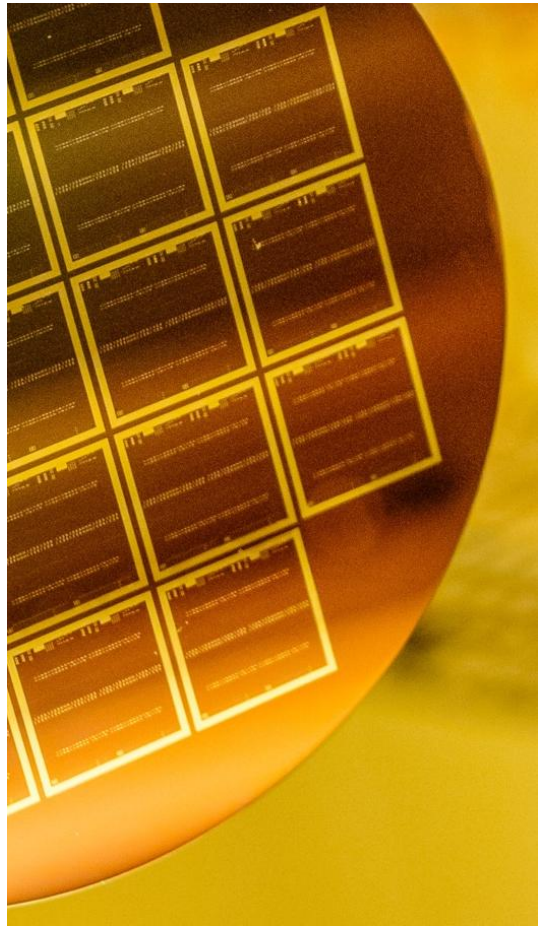
2D PILOT LINE

GRAPHENE FLAGSHIP

AMO

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Herzlichen Dank!
Thank you!







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