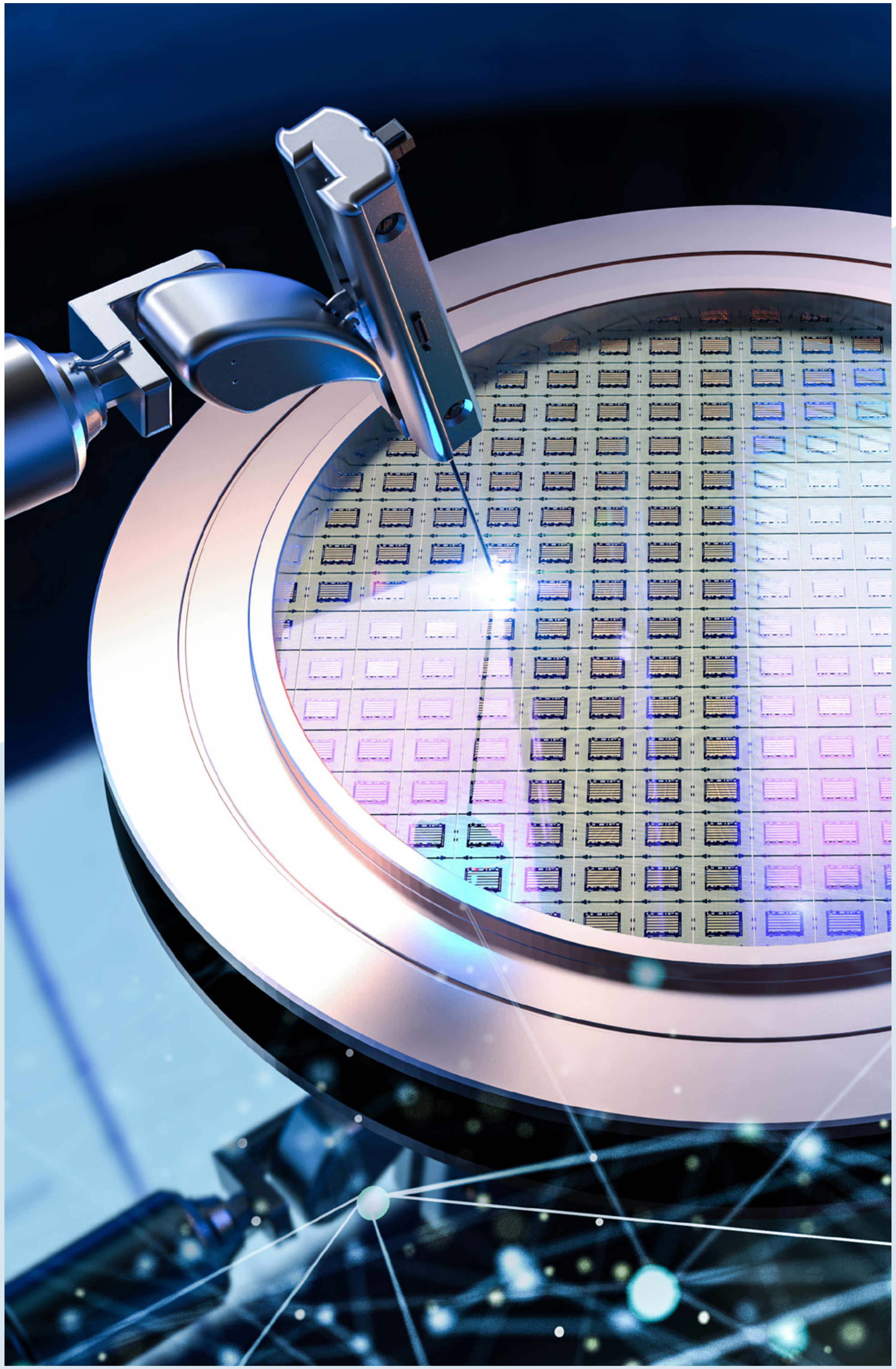
GRAPHENE FLAGSHIP

Annual Report 2023

Funded by
the European Union



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Passing the baton: Former Graphene Director Jari Kinaret (right) congratulates current Graphene Flagship Director Patrik Johansson on a successful Graphene Week 2023 in Gothenburg, Sweden.

From the (new) Director

THE LAST YEAR was nothing like any of the preceeding years for the Graphene Flagship. We celebrated the first ten years of the project as we closed Core 3, and with it the single-project structure of the Flagship. The five-day final review and the broader assessment of the past decade meant a lot of hard work by many. In the end, I think we can proudly say that we have delivered beyond expectations and given European tax-payers extremely good value for their money. It was not a true ending, but nevertheless a feeling of departure for many in the community – the end of the Graphene Flagship as we knew it.

NEW HORIZONS

The past year was also a bright new beginning – the existing 2D-EPL was joined by twelve new research and innovation projects gathered under the GrapheneEU CSA to shape the future of the Graphene Flagship. The transition to this organisation, as all transitions, has meant plenty of challenges but also revitalised the awareness of who we are and why we do what we do in our community. We are not yet finished gathering up all "old" and new elements at full strength for the future endeavours of the Graphene Flagship, so we will continue that work. Combined, we truly are part of the solution to many of the problems Europe is facing at large. We will need to use not only the hard data and scientific and technological advances that we have gathered together, but perhaps even more importantly, the personal interactions that have created trust and a playground for cross-fertilisation of ideas to forge the future of 2D materials innovation. Last but not least, we should not forget that one of our "exports" in 2023 – former Graphene Flagship Director Jari Kinaret – will play a key role in establishing European industrial independence through his leadership of the Chips Joint Undertaking.

COLLABORATIONS

During 2024 we will see our community re-form and gather strength. One particularly important avenue, apart from the Graphene Flagship itself and our Graphene Week conference in Prague in October, will be the Innovative Advanced Materials for Europe partnership. This partnership, drafted with a lot of input and background from our community, is now an official "candidate partnership" in the Second Horizon Europe Strategic Plan. Indeed, looking a bit broader, there are three strategic orientations made therein by the European Commission (EC): the green transition, the digital transition, and a more resilient, competitive, inclusive and democratic Europe. For all of these, the EC stresses that securing Europe's leading role in developing and deploying critical technologies is an overarching principle. I'm sure this is something we all can agree to work towards beyond 2024 and even beyond Horizon Europe.

Patrik Johansson
Graphene Flagship Director

GRAPHENE FLAGSHIP ANNUAL REPORT 2023

The Graphene Flagship sets sail for new horizons

BUILDING ON A DECADE of success, the Graphene Flagship has now continued its journey under the European Commission's Horizon Europe funding programme. In 2023 the single project that had sailed through the EC's FP7 and Horizon 2020 programmes crossed the finish line with a series of celebrations of its remarkable results in terms of research outputs and commercialisation success. In October, the Flagship split into a fleet of separately funded projects.

Bringing together 118 academic and industrial partners in 12 research and innovation projects and 1 coordination and support project, the Graphene Flagship will continue to advance Europe's strategic autonomy in technologies that rely on graphene and other 2D materials with the common goal to commercialise graphene. The GrapheneEU Coordination and Support Action (CSA) ensures that the Graphene Flagship stays the course, providing a link between the past, present and future (see page 22).

The projects work on applications in key areas from composites and energy to biomedical and electronics. Fundamental work on emerging two-dimensional materials is also being addressed in our 2D materials of tomorrow projects. Research into health and safety will continue to be an integral part of the initiative.

TAKING THE HELM

With this new phase of the Graphene Flagship comes new leadership. Patrik Johansson, formerly Vice-Director for the project, has stepped up as the new Graphene Flagship Director. "I'm excited to see the 2D materials community in Europe continue to grow with the launch of the new Horizon Europe projects. It will be interesting to see the new ideas that come from this latest European investment in graphene and other 2D materials," Johansson says.

HORIZON EUROPE

The Graphene Flagship is funded by the European Commission's Horizon Europe research and innovation programme (see page 18), which puts a strong emphasis on tackling climate change and addressing the United Nations' Sustainable Development Goals. Each project within the initiative is committed to creating a more sustainable, more environmentally friendly Europe by creating alternatives to scarce or conflict materials, creating more efficient technologies, strengthening our energy infrastructure and more. Learn about each project's sustainable solutions in their respective sections.

Furthermore, the programme facilitates collaboration, strengthening the impact of research and innovation in developing, supporting and implementing EU policies while tackling global challenges. It supports the creation and dissemination of excellent knowledge and technologies. Collaboration will remain a cornerstone of the Graphene Flagship, largely facilitated by GrapheneEU whose activities will provide opportunities for collaboration, knowledge transfer and community building. Events like the annual Graphene Week conference will continue to draw the broader graphene and 2DM community together.

Finally, Horizon Europe will create jobs, fully engage the EU's talent pool, boost economic growth, promote industrial competitiveness and optimise investment impact within a strengthened European Research Area.

A DECADE OF SUCCESS

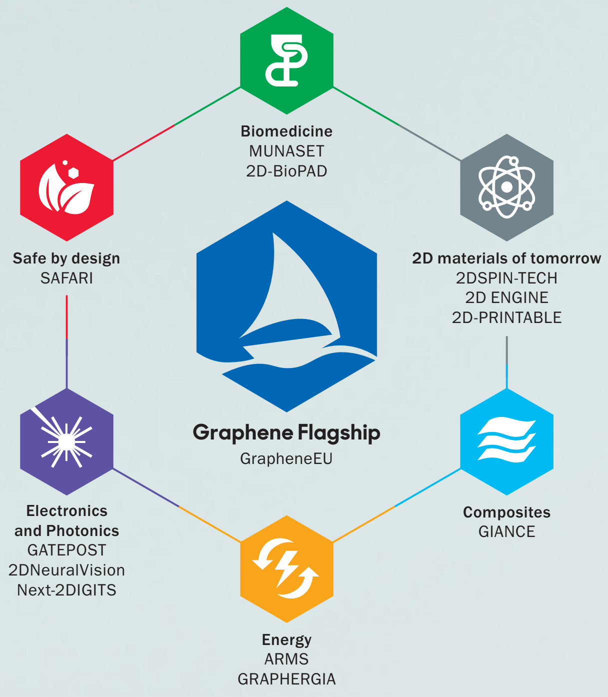
The Graphene Flagship was funded to ensure that Europe would maintain its lead in graphene research and innovation following the scientific breakthrough of graphene's isolation at the University of Manchester. The European Commission launched the unprecedented long-term and large-scale Flagship research initiatives to tackle major challenges in science and technology, bringing positive changes that benefit society and the economy and advance European leadership in technology and industry. A decade on, we are proud to say that the Graphene Flagship has delivered on its promise. The clearly achieved objectives within scientific excellence, as well as societal and economic impact are detailed in the report, Ten years of research, innovation and collaboration: the Graphene Flagship and the 2DM community.

MEETING NEW CHALLENGES

Despite changes in our funding structure and the make up of our community, the Graphene Flagship's core mission to commercialise graphene remains unchanged. From sensors for self-driving cars to Alzheimer's diagnostics systems, power supplies for e-textiles to more effective batteries, 2DM technologies will reshape the future. Moreover, work on novel 2DM will broaden the scope of materials science, creating new opportunities for the future. The CSA industrialisation team provides a link between the past, present and future activities in standardisation, roadmapping, business development and industry outreach. Their experience will accelerate the projects' commercialisation success, helping them to make their mark on European industries.

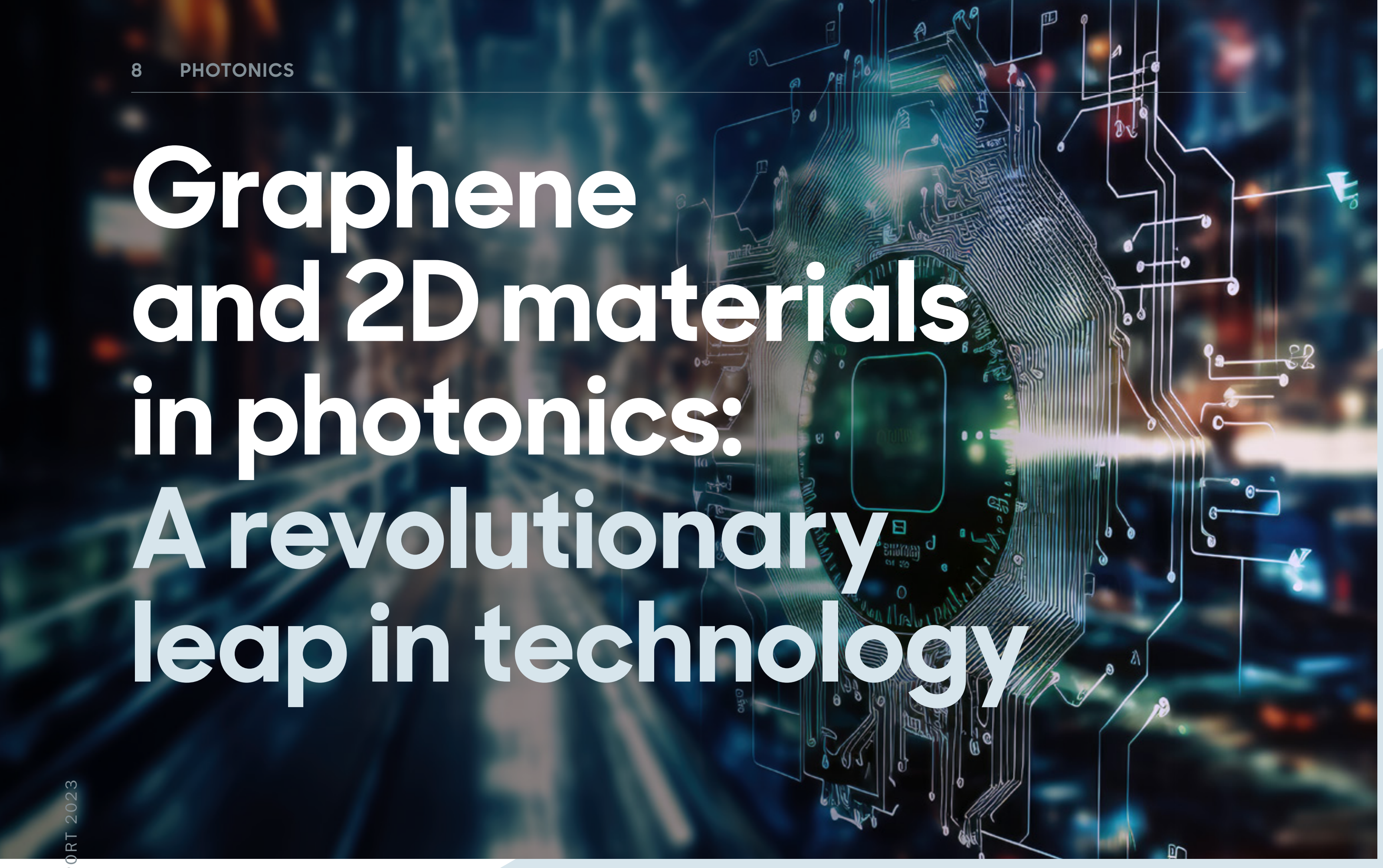
The CSA faces a further challenge to connect the past and present Graphene Flagship partners in a collaborative community. To this end, the association mechanisms that existed in the previous phase will be continued and improved. The Graphene Flagship will not only encourage past partners to associate to the initiative but will also foster collaborations with other EU funded projects, bringing them in as partnering projects in the initiaive. Collaborations with additional agencies, like ISO, REACH-ECHA and others will continue, as will the international workshops that facilitated discourse on 2DM topics with experts around the world.

As the Graphene Flagship sails on to new horizons, we look forward to growing our community and expanding our impact on 2DM research and innovation, European thought leadership and eventually, everyday consumers.



MEET THE NEW FLAGSHIP

Bringing together 118 academic and industrial partners across 13 projects, the Graphene Flagship continues to advance Europe's lead in technologies that rely on graphene and other 2D materials.



Graphene and 2D materials in photonics: A revolutionary leap in technology

IN THE VAST LANDSCAPE of modern science and technology, graphene and two-dimensional materials (2DM) have emerged as game-changers, revolutionising industries with their remarkable properties and diverse applications. Among the myriad fields benefiting from their extraordinary characteristics, photonics stands out as one of the most promising domains. Photonics, the science and technology of generating, detecting and controlling photons, has found new avenues for innovation and advancement through the integration of graphene and 2D materials. In this article, we delve into the captivating realm of photonics and explore how graphene and 2D materials are reshaping its landscape, opening up unprecedented possibilities and paving the way for groundbreaking discoveries.

THE GENESIS OF GRAPHENE AND 2D MATERIALS

Before delving into their applications in photonics, it's imperative to understand the foundational aspects of graphene and 2DM. Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, garnered widespread attention following its isolation in 2004 by Andre Geim and Konstantin Novoselov, earning them the Nobel Prize in Physics in 2010. Since then, graphene has captivated researchers worldwide due to its extraordinary mechanical, electrical and optical properties. Moreover, the family of 2D materials extends beyond graphene, encompassing semiconductors like transition metal dichalcogenides (TMDCs), hexagonal boron nitride (h-BN), and other layered materials, each possessing unique attributes that make them ideal candidates for various applications (see page 40).

HARNESSING GRAPHENE AND 2D MATERIALS IN PHOTONICS

Photonics, with its focus on the manipulation of light, benefits immensely from the remarkable properties offered by graphene and 2DM. These materials have opened up new avenues for the development of photonic devices with enhanced performance, efficiency and versatility. Let's explore some of the compelling uses of graphene and 2D materials in photonics applications:

Photodetectors

Graphene-based photodetectors have garnered significant interest due to their exceptional sensitivity, high-speed response and broadband absorption characteristics. By integrating graphene with other 2DM or heterostructures, researchers have developed photodetectors capable of operating across a wide range of wavelengths, from ultraviolet to infrared. These devices find applications in optical communications, imaging systems and sensing technologies, offering unparalleled performance and reliability.

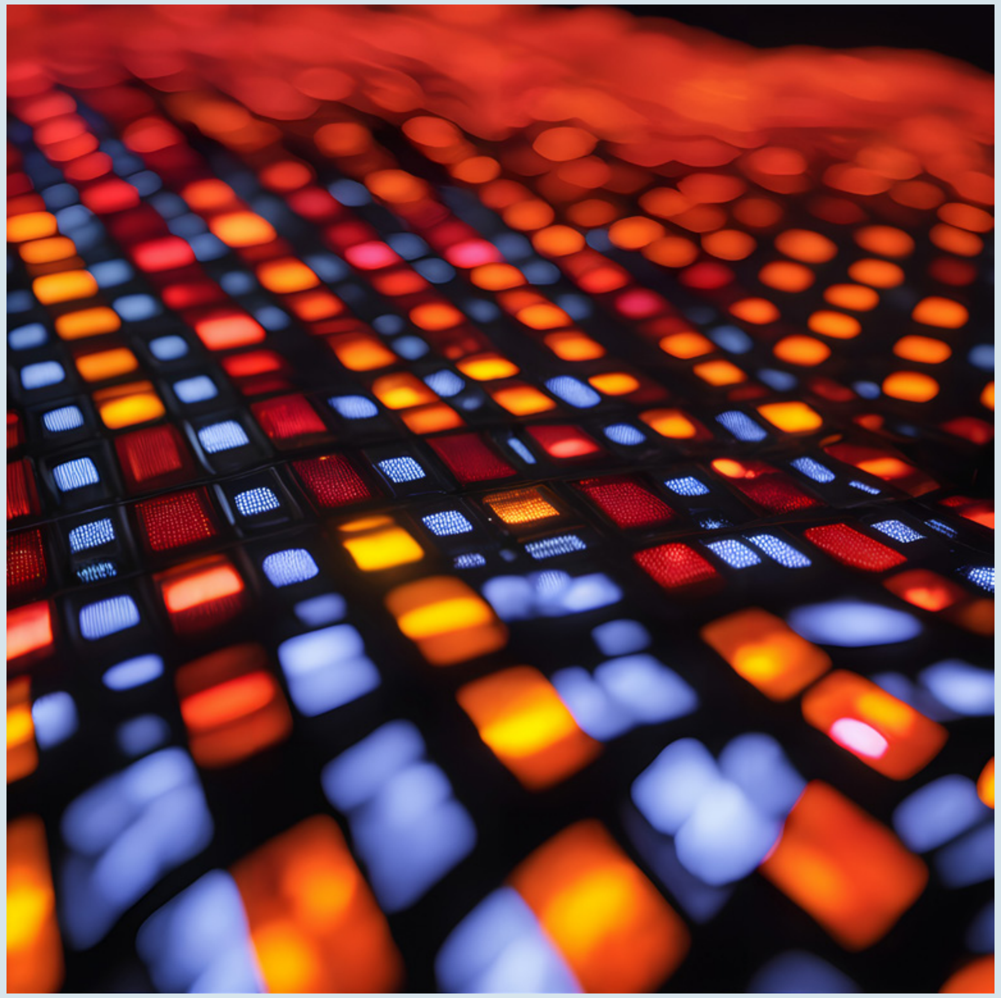
Light Modulators

Graphene's unique ability to control the absorption and transmission of light makes it an excellent candidate for optical modulators. By applying an external electric field, the optical properties of graphene can be dynamically tuned, enabling the modulation of light intensity with ultrafast response times. This capability is instrumental in the development of high-speed optical communication systems, optical switches and integrated photonic circuits, where rapid signal processing is paramount.

Optical Sensors

The exceptional sensitivity of graphene and 2DM to external stimuli makes them ideal candidates for optical sensing applications. Whether detecting minute changes in environmental conditions, biomolecular interactions or gas molecules, graphene-based sensors offer unparalleled performance in terms of sensitivity, selectivity and response time. These sensors find applications in diverse fields, including healthcare, environmental monitoring and industrial process control, facilitating real-time, label-free detection with high accuracy.

Hybrid graphene/TMD structures can be used to create novel light-emitting devices.



Light-Emitting Devices

While graphene itself is not a direct emitter of light, its integration with other 2DM in heterostructures has enabled the development of novel light-emitting devices. TMDCs such as molybdenum disulfide (MoS_2) and tungsten diselenide (WSe_2) exhibit strong photoluminescence properties, making them suitable for applications in optoelectronics and light-emitting diodes (LEDs). By combining graphene with TMDCs in hybrid structures, researchers have demonstrated efficient light emission with tunable properties, paving the way for next-generation display technologies and optoelectronic devices.

Optical Waveguides and Modulators

Graphene's exceptional optical transparency and high carrier mobility make it an attractive material for integrated photonic circuits. Graphene-based waveguides and modulators offer low insertion losses, high-speed operation and compatibility with existing silicon-based platforms, making them promising candidates for on-chip optical interconnects and data communication systems. Moreover, the flexibility and scalability of graphene-based photonic devices enable the realisation of compact, energy-efficient solutions for diverse applications in telecommunications and computing.

CHALLENGES AND FUTURE DIRECTIONS

While the integration of graphene and 2D materials has unlocked unprecedented opportunities in photonics, several challenges remain to be addressed. Issues such as scalability, device reproducibility and interface engineering pose significant hurdles to the widespread adoption of these materials in commercial applications. Moreover, the development of scalable fabrication techniques, reliable material quality control and efficient device integration strategies are essential for transitioning from laboratory demonstrations to practical implementations.

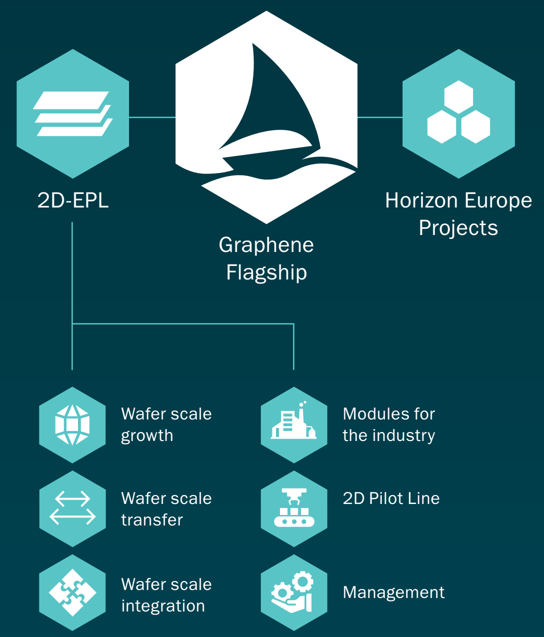
Looking ahead, ongoing research efforts focus on overcoming these challenges and exploring new avenues for innovation in graphene- and 2DM-based photonics. Emerging concepts such as van der Waals heterostructures, quantum confinement effects and hybrid nanophotonic platforms hold immense promise for advancing the frontiers of photonics and unlocking new functionalities. As researchers continue to unravel the mysteries of these fascinating materials, the future of photonics shines brighter than ever, propelled by the transformative potential of graphene and 2DM.

The marriage of graphene and 2DM with photonics represents a paradigm shift in the way we generate, manipulate and harness light. From photodetectors and modulators to sensors and light-emitting devices, the integration of these extraordinary materials has unlocked a plethora of opportunities for innovation and discovery. As researchers continue to push the boundaries of science and engineering, the synergistic interplay between graphene, 2DM and photonics will continue to drive technological advancements, shaping the future of communication, sensing, imaging and beyond. With each breakthrough bringing us closer to realising the full potential of these remarkable materials, the journey towards a brighter, more connected world accelerates.

2D-EPL Creating an ecosystem for 2DM integration

The 2D Experimental Pilot Line (2D-EPL), now in its fourth and final year, is a €20 million project launched to address the challenges of upscaling 2D material production processes for the semiconductor industry. The project helps create a European ecosystem for the integration of 2D materials in applications like sensors, electronics and photonics.

At this stage, the project is mostly on track, having achieved some important checkpoints in creating new processes and modules for the generic integration flow. In parallel, the 2D-EPL has been working to enable new processing tools.



HOW WE WORK

The project is constructed around two pillars. In the first pillar, we started prototyping from day one. The 2D-EPL's multi-project wafer (MPW) runs have been providing academic groups, start-ups and other companies the opportunity to test novel ideas for 2D material devices on a larger scale at relatively low costs. This is a key step toward bringing products to the market.

The second pillar focuses on process enablement. Within that scope, we have built two new tools for the fabrication of 2D materials. The 200/300 mm compatible MOCVD reactor by Aixtron is allowing the 2D-EPL to advance its work on the deposition of transition metal dichalcogenides (TMDCs) on 300 mm sapphire wafers. In parallel we also now have an automated transfer tool for the de-bonding of the 2D layer from the growth substrate to a rigid carrier from SUSS MicroTec.

Both of these tools have been installed in the imec cleanroom. The availability of these unique tools allow us to take the next step forward in the set-up of mature modules for 2D-material growth and layer transfer: both are essential modules in establishing pilot-line process capability.

LOOKING AHEAD

"In this last year of the project, it's really our ambition to go in a full sequence through using the new tooling from growth to transfer and use the lessons we have learned thus far on the integration flow," says Inge Asselberghs, director of the 2D Experimental Pilot Line. "We are also looking forward to seeing the final outcomes of the MPW runs and how we can build on this project's foundation in the future."

1. DEVELOPMENT OF TOOLS AND METARIALS

2. DEVELOPMENT OF MODULE AND PLATFORM

3. MULTI-PURPOSE WAFER RUNS

Coordinator: Chalmers University of Technology
Innovation support: Chalmers Industriteknik

Above: 2D-EPL Director Inge Asselberghs prepares to speak at Graphene Week.

Upper left: The 2D-EPL has worked on prototyping from the beginning through its MPW runs. Credit: AMO

Left: The Aixtron MOCVD reactor installed in the imec cleanroom. Credit: Aixtron

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Wafer Scale Growth

WORK PACKAGE LEADER
Michael Heuken, AIXTRON, Germany

WORK PACKAGE DEPUTY
Amaia Zurutuza, Graphenea Semiconductor, Spain

SCALING UP 2D MATERIAL GROWTH

The goal of the Wafer Scale Growth Work Package is to scale up the growth of high-quality TMDCs and graphene to large wafer sizes in order to provide 200- and 300-mm films to the 2D Experimental Pilot Line (2D-EPL).

THIS YEAR'S PROGRESS

Over the past year, AIXTRON completed the qualification of the new 300 mm MOCVD (metal-organic chemical vapour deposition) reactor for the growth of 2D materials. The reactor was installed in imec's 300 mm cleanroom facilities where the growth of WS_2, MoS_2 and graphene on 200 mm sapphire was demonstrated.

Further research activities were focused optimising the growth and performance of transition metal dichalcogenides (TMDCs like WS_2, MoS_2) on 50–200 mm sapphire in imec's and AIXTRON's R&D MOCVD reactors. Graphenea Semiconductors and AMO grew graphene on catalytic CuNi(111)/sapphire, Cu(111)/sapphire and copper foil-based templates with sizes up to 200 mm, and Graphenea continuously supplied project partners with high quality graphene grown on copper foils.

Of note was the first reported growth of WS_2 on 300 mm sapphire, with excellent spectroscopic uniformity demonstrated by Raman spectroscopy. Demonstrating uniform growth on a large wafer scale is one of the pivotal requirements for the success of the 2D-EPL.

COLLABORATIONS

Close collaboration between Graphene Flagship partner AIXTRON Ltd. and 2D-EPL partner AIXTRON SE has allowed the successful build, testing and qualification of the new 300 mm MOCVD reactor which will be a key tool for the success of the 2D-EPL. The collaboration included an exchange of personnel as well as regular online meetings during the system testing and qualification phases. Discussions and planning for the implementation of optimised hardware is continuously ongoing.

Close collaboration between imec and AIXTRON has allowed for the successful process demonstration of 2D materials growth, with AIXTRON overseeing the transfer of process recipes and tuning from AIXTRON's R&D systems to the new 300 mm reactor, while imec managed the characterisation of the materials produced and the qualification of the reactor in term of particle levels and metal contamination performance.

MEETING NEW CHALLENGES

The coming year will be dedicated to the quality and performance optimisation of the 2D layers grown in the new reactor installed at imec. Though the TMDC layer (WS_2 and MoS_2) grown on sapphire demonstrated reasonable quality and good uniformity, the electrical performance of the TMDC materials, mobility in particular, needs significant improvement. The challenges include the need to further improve the new MOCVD reactor hardware and software stability.

NEW HORIZONS

The continuation of the 2D-EPL project will be key to the success of the implementation and successful functioning of the 2D-Pilot Line called for within Horizon Europe funding mechanism. The interactions would include close collaboration among the ecosystem of partners established within the 2D-EPL project, targeting the production and efficient characterisation of high performance 2D materials (TMDC and graphene) at high volume manufacturing levels. Many of the Graphene Flagship projects have already shown interest in collaborating with the 2D-EPL, which could prove fruitful.

Above: The new 300 mm reactor by AIXTRON installed in the 300 mm cleanroom at imec. Credit: AIXTRON
Below: First reported WS_2 growth on a 300 mm sapphire wafer in the new AIXTRON 2D reactor at imec. Credit: AIXTRON

Wafer Scale Transfer

WORK PACKAGE LEADER
Steven Brems, imec, Belgium

WORK PACKAGE DEPUTY
Thomas Rapps, SUSS MicroTec Solutions GMBH & CO KG, Germany

DEVELOPING RELIABLE WAFER SCALE 2D TRANSFER

2D materials are of interest for several applications including sensors, imagers, photonic devices, future CMOS transistors, BEOL transistors and more, but high quality 2D materials are needed to enable these applications. The Wafer Scale Transfer Work Package is developing a module to reliably transfer high-quality 2D materials from the growth wafer developed in the Wafer Scale Growth Work Package to a target wafer for the 2D Experimental Pilot Line (2D-EPL).

Wafer scale transfer includes the development of a temporary carrier, bonding of the temporary carrier to a 2D material, debonding the 2D material from the growth wafer using the temporary carrier system, bonding the 2D material on the final device wafer, removing the device wafer and cleaning the adhesives from the 2D materials. This whole transfer module development is one of the main goals of the 2D-EPL and enables further integration work in the pilot lines.

THIS YEAR'S PROGRESS

The Wafer Scale Transfer Work Package achieved several milestones this year. One of the main accomplishments was the demonstration of a 300 mm WS_2 transfer, where a notable transfer yield of more than 99 % was achieved after multiple 300 mm size 2D transfers. A high transfer yield is a necessary step to achieving a real 2D pilot line.

Furthermore, Suss MicroTec's system was installed at imec, which should enable large-scale 2D material debonding from sapphire.

COLLABORATIONS

Interactions within the Graphene Flagship, with Partnering Projects and Associated Members as well as supplier discussions and thought exchanges with foundries, fab-less and fab-lite companies outside the project are essential to get a clear view of market trends, challenges, new capabilities, innovative solutions and more. These collaborations were all key to making sufficient relevant progress in the Wafer Scale Transfer Work Package. They help to finetune the current 2D roadmaps, and also provide technical solutions that allow faster progress in the development of a 2D transfer module.

MEETING NEW CHALLENGES

A 200 mm graphene transfer has already been demonstrated on 200 mm and 300 mm device wafers. Furthermore, a 300 mm MX2 transfer from an amorphous growth wafer to a device wafer has also been demonstrated. Currently, a lot of effort is being put into the transfer of epitaxially grown MX_2 materials on sapphire. The debonding process of epitaxial material from sapphire is challenging and developing a debonding process on the installed Suss system will be essential to making this process a success. Further maturing micro resist technology's temporary adhesive will be critical to successfully finalising the work of the 2D Experimental Pilot Line.

NEW HORIZONS

The efforts in the framework of the 2D-EPL will pave the way towards a 2D pilot line in Europe. The establishment of 2D pilot lines will be essential for innovative companies to get access to 2D material-based devices, which will enable the development of new sensor, photonic, imager and even transistor concepts by multiple companies and will keep Europe at the forefront of research and development in these industries.

Suss MicroTec's 200/300 mm automated tool for debonding 2D materials (TMDCs) from a growth wafer. Credit: SUSS MicroTec Solutions GMBH & CO KG

Wafer Scale Integration

WORK PACKAGE LEADER
Miika Soikkeli, VTT Technical Research Centre of Finland, Finland

WORK PACKAGE DEPUTY
Mindaugas Lukosius, IHP – Leibniz Institute for High Performance Microelectronics, Germany

DEVELOPING PROCESSES

The main goal of the 2D Experimental Pilot Line's Wafer Scale Integration Work Package is to develop mature fabrication processes for graphene- and TMDC-based devices including the contacting, patterning, dielectrics, interface optimisation and passivation. The quality of the devices is closely monitored with the established quality control protocols to ensure that the devices meet the expected criteria.

THIS YEAR'S PROGRESS

The processes developed by the Work Package over the past year have been utilised in the 2D-EPL's multi-project wafer (MPW) runs and directly in tailored customer projects. Project partners have already established stable process flows in the pilot line sites that can be utilised in product development for customers.

COLLABORATIONS

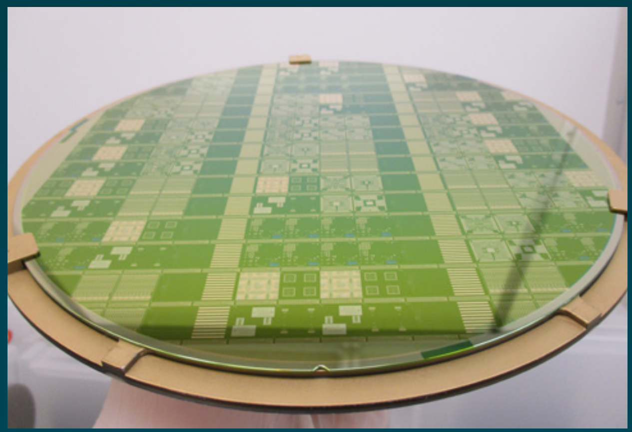
The processes developed in the 2D-EPL have been utilised to fabricate devices for groups in the Graphene Flagship Core 3 project. For example for biosensing and gas sensing devices for the Sensors Work Package and for IR cameras for the GBIRCAM Spearhead project. In addition to supporting those groups, this collaboration between the 2D-EPL and Core 3 partners has also enabled direct feedback on the application specific requirements for device performance. The feedback has further enabled the Wafer Scale Integration Work Package in the 2D-EPL to mature the processes faster by focusing on the most critical device parameters. The processes that were developed have also been made available to everyone through the MPW run service offerings.

MEETING NEW CHALLENGES

The main technological challenges remaining are related to the achievement of stable processes with higher electrical quality for key control characteristics such as mobility, contact resistance, doping and hysteresis. This work includes precise optimisation of the full process flow including interfaces, dielectrics, contacts and passivation. The development of 2D-material specific processing steps is crucial to ensuring the high electrical quality of the devices, because even high-quality material growth and transfer is easily hindered by suboptimal process flows.

NEW HORIZONS

The 2D-EPL project is well connected to several other projects in the new Horizon Europe ecosystem. The processes developed in the 2D-EPL will directly benefit the more application specific development targets in the other projects. This enables faster and easier adaptation of more mature devices in the application development phase and leaves more resources to tackle the specific problems, for example those related to functionalisation in the biosensing application area. The project is also open to collaborations with the projects that are not yet connected to the 2D-EPL.



A graphene-integrated wafer.
Credit: VTT

Modules for the Industry

WORK PACKAGE LEADER
Daniel Neumaier, AMO GmbH, Germany

WORK PACKAGE DEPUTY
Olli-Pekka Kilpi, VTT Technical Research Centre of Finland, Finland

LAUNCHING THE MULTI-PROJECT WAFER RUNS

The main goal of the 2D Experimental Pilot Line's (2D-EPL) Modules for the Industry Work Package is to deliver process modules, which can be adopted by different semiconductor manufacturers with only minimal changes for their specific needs. In addition, by delivering multi-project wafer (MPW) runs, the Work Package provides a cost-efficient solution to smaller companies and universities to perform experiments on state-of-the-art graphene-based sensor devices. This significantly reduces the entry barrier for testing new concepts based on an established technology.

THIS YEAR'S PROGRESS

The Modules for the Industry Work Package is developing fabrication processes for graphene- and MoS_2-based devices having an application focus on electronics, photonics and sensors. Here the specific need to integrate these processes into a conventional semiconductor fabrication line is considered. That means that the fabrication processes are based on processes which are compatible with automated tools and easily transferrable to other production sites.

The main output for the Work Package is the preparation and performance of MPW runs, which are offered to external clients. In these runs, graphene-based devices are fabricated for external clients (companies, research centres and universities) based on their individual designs. This facilitates the testing and validation of the process technology developed in the 2D-EPL. In 2023 two MPW runs were completed: one by VTT and one by AMO with a focus on sensors. Both runs were successful, and the AMO run was even delivered two months ahead of schedule. An additional run, offering graphene-based sensors on silicon-based CMOS electronics, is under preparation by VTT.

COLLABORATIONS

The main collaboration with the Graphene Flagship's Core project over the past year was a continued discussion with the relevant Spearhead projects on how to design the process modules according to their needs. An important aspect of the 2D-EPL in general and the Modules for the Industry Work Package specifically is the interaction with the Industrial Advisory Board, which provides input on the most relevant application areas and venues for advertising the MPW runs.

MEETING NEW CHALLENGES

The key challenge in the future will be to increase the reproducibility for device fabrication. This challenge has been clear for many years, but its importance has significantly increased for the MPW runs. After that, device reliability will be the next big challenge to address.

NEW HORIZONS

In the Horizon Europe funding cycle, several projects on 2D materials related to sensors, electronics and photonics have been funded. For most of these projects there is already an existing link between the partners involved in these projects and the 2D-EPL. These links will be used to identify specific needs for process modules and also for future MPW runs beyond the end of the 2D-EPL project.

Above: The first step in the fabrication process is the wafer coating and development. Credit: AMO
Below: The fabrication process ends with the lift-off performed on a wet-chemistry bench. Credit: AMO

2D Pilot Line

WORK PACKAGE LEADER
Inge Asselberghs, imec, Belgium

WORK PACKAGE DEPUTY
Max Lemme, AMO GmbH, Germany

PAVING THE WAY FOR PILOT LINE DEVELOPMENT

The 2D Pilot Line Work Package supports the 2D Experimental Pilot Line's (2D-EPL) development. From defining the multi-project wafer (MPW) runs and disseminating the results of the project to creating a business model that will shape the future of the Pilot Line, this work package lays the groundwork for success.

THIS YEAR'S PROGRESS

Over the past year the focus has been on maturing the 2D-EPL's offerings. Two multi-project wafer (MPW) runs were organised, building on the experience of the previous year's work. The 2D-EPL's third run, delivered by AMO, was intended for electronics and leveraged the experience from the first run effectively enough to be delivered early. The fourth run, by VTT, took a step further offering a CMOS integrated graphene field-effect transistor. These MPW runs were supported by dissemination activities including workshops, marketing materials and outreach toward relevant industry media.

The 2D-EPL's participation in the Graphene Week conference and in the Graphene Flagship's ten-year anniversary celebration helped the project gain visibility within the graphene community and a wider reach with relevant media covering the milestone.

COLLABORATIONS

The 2D Pilot Line Work Package plays a key role in ensuring collaborations between 2D-EPL work packages in the coordination of the MPW runs as well as in its dissemination efforts. More importantly, however, the Work Package helps to connect the project to the Graphene Flagship and its community. This connection provides mutual benefits where the Graphene Flagship, and its wider community, have access to more mature technologies for graphene integrated devices and the 2D-EPL receives feedback on the specifications that are important to developing a commercial pilot line.

MEETING NEW CHALLENGES

Over the next year, the Work Package will expand its portfolio offering MPW runs from IHP and Graphenea. These runs, not previously included in the project plan, add breadth to the 2D-EPL service offering and help to further gauge the needs of the pilot line customers. These insights will help to form the future sustainability and business plan that will be drafted by the end of the project.

NEW HORIZONS

The launch of the new Graphene, Europe in the Lead projects in Horizon Europe has presented an opportunity for the 2D-EPL to connect with the next generation of collaborators. There are existing connections with the photonics and electronics projects which all have some partners in common with the 2D-EPL, but interest in collaborations among the other projects has been high. These collaborations will form a framework for the future of the project.

The 2D-EPL workshop at Graphene Week helped to engage the graphene and 2D materials community in the project's work. Credit: Graphene Flagship

2D-EPL Management

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Maria Recaman Payo, imec, Belgium

COORDINATING

The Management Work Package ensures that the 2D Experimental Pilot Line (2D-EPL) project runs efficiently. It coordinates the project and facilitates the 2D-EPL's interactions and collaborations with the Graphene Flagship's Core project, with Horizon Europe projects, and with the European Commission.

THIS YEAR'S PROGRESS

With the end of the Graphene Flagship's Core 3 project in September 2023, the Management Work Package worked to create a smaller, more streamlined governance structure which is more appropriate to a 12-partner project. The Graphene Flagship's Management Panel and Strategic Advisory Board were dissolved, and the roles of the Executive Board and General Assembly were redefined. The new Executive Board is made up of the six work package leaders, while the General Assembly has a representative from each partner. In addition, 2D-EPL partners also voted to approve the addition of Chalmers Industriteknik (CIT) to the consortium.

The Management Work Package also organised an interim project review in 2023 to help the Work Packages to assess what needs to be improved ahead of the project's final review. The review successfully highlighted several areas that will require attention in 2024.

Synergies between the Core 3 and 2D-EPL Management teams ensured integration between the projects in key internal activities. This included the Graphene Flagship Annual Meeting where the 2D-EPL was able to share its results with the rest of the consortium, and a Roadmapping and Vision Workshop where industrial priorities through 2050 were identified.

COLLABORATIONS

The Management Work Package has been integral to the smooth operation of the 2D-EPL, helping to ensure collaborations between partners and Work Packages through Division Meetings, like the one held in-person at Graphene Week 2023, and its leadership role in the Pilot Line Coordination Team. Collaborations between Management Work Package partners, Chalmers University of Technology and imec, helped to ensure a smooth governance transition at the close of Core 3.

Furthermore, due to synergies with the Core 3 project, the Management Work Package helped to monitor collaborations across the entire Graphene Flagship and suggested avenues for further collaborations. In fact, the incorporation of the 2D-EPL in the Graphene Flagship governance until the end of Core 3 was key to ensuring opportunities for knowledge transfer and further collaborations.

MEETING NEW CHALLENGES

Over the next year, the Management Work Package will work to ensure a successful final review and close of the project. Guidance on technical and financial reporting and a critical review of deliverables will ensure that the project's success is evident in the final review.

NEW HORIZONS

The continuity between the Graphene Flagship Management in Core 3 and the new GrapheneEU Coordination and Support Action (CSA) has ensured a smooth transition between Horizon 2020 and Horizon Europe. This continuity has also made possible to create a natural and strong connection between the 2D-EPL and the new projects handled by the CSA. The opportunity now presented by the call for "Pilot line(s) for 2D materials-based devices" enables the possibility for further collaborations beyond 2D-PL, providing an avenue in the European ecosystem for wafer-scale integration of 2D materials to grow at large. A future pilot line project on 2D materials will then be fully integrated in the Graphene Flagship, and the relationships forged now will thus be key to growth in the future.

The 2D-EPL team met at Graphene Week 2023 for a Division Meeting. Credit: Graphene Flagship

GRAPHENE FLAGSHIP ANNUAL REPORT 2023

Europe in the Lead

IN 2013, the European Commission (EC) started its largest research and innovation project to date: the Graphene Flagship, with a budget of €1 billion. This project ran for ten years and provided funding to a consortium of approximately 170 academic and industrial partners spanning 22 countries and collaborating on the development of marketable products containing graphene and related 2D materials. The project and investment have been largely successful, with collaboration and longevity pinpointed as being the biggest benefits of the project, which generated €5.9 billion in economic impact and helped to create 81,622 jobs.[1] Considering the success of the Graphene Flagship and the European Union's aim to strengthen science and technology within its borders, the initiative will continue under the Horizon Europe programme.

HORIZON EUROPE

Horizon Europe is a continuation of what was previously called Horizon 2020 and is Europe's leading research and innovation (R&I) initiative, also focusing on the United Nation's Sustainable Development Goals. It is set to run from 2021–2027 with a budget of €95.5 billion.[2] With the intention of keeping Europe at the forefront of global research and innovation, Horizon Europe plans to: maximise its impact and deliver on EU's strategic priorities (i.e. digital and green transition); strengthen science and technology through increased investment; foster industrial competitiveness; and enhance access for researchers to participate and collaborate in a broader global dialogue.[3]

"With Horizon Europe, the European research community, research organisations and our citizens can count on one of the world's largest research and innovation Programmes. It is our main tool to strengthen our scientific and technological base, develop solutions for healthier living, drive digital transformation and fight climate change, for our collective resilience." Mariya Gabriel, Commissioner for Innovation, Research, Culture, Education and Youth[3]

> With Horizon Europe, the European research community, research organisations and our citizens can count on one of the world's largest research and innovation Programmes.
>
> **Mariya Gabriel**
> Commissionaer for Innoavtion, Research, Culture, Education and Youth

The Programme boosts the EU's competitiveness and growth by fostering collaboration and the dispersion of knowledge and technologies to address global challenges. Simultaneously by investing in European R&I the initiative bolsters the economy by creating jobs and promoting industrial competitiveness. New elements include, a European Innovation Council, a set of five measures to reach goals within a set timeframe, an open science policy and objective driven partnerships with industry.

LEADERSHIP FOR ADVANCED MATERIALS

However, to maintain and further advance Europe as a leader in both the green and digital transition, the EC has proposed an encompassing strategy for the further development of advanced materials. The Communication about leadership for advanced materials, reached through dialogue with member states and stakeholders, "addresses not only R&I needs, but also efforts towards strengthening the production, use and uptake of advanced materials"[4] and stands on five main pillars:

1. Develop research and innovation of advanced materials.
2. Fast-track these materials to market.
3. Increase capital investment and access to financing (Horizon Europe).
4. Support production and use of advanced materials.
5. Create a Technology Council.

The Communication addresses the advanced materials ecosystem within the EU and proposes actions that "address the entire value creation, spanning from early-stage research to deployment and market uptake."[4] The intention is that together these actions will pave the way for a more "coordinated and responsive" ecosystem, one with "new economic opportunities" and larger "more rapid deployment" thus "reinforcing EU resilience and open strategic autonomy."[4]

Although the Graphene Flagship project was successful in taking investment and translating it into a wealth of knowledge, including thousands of peer-reviewed articles and hundreds of marketable products, the "graphene gold-rush" and the impact of the project's investment will be hard to assess until approximately 15-years after its completion. Kari Hjelt, the Graphene Flagship's head of innovation, says that is how long the path is from research to commercialisation.[5] It has been noted that while the EU has funded R&I heavily, the commercial conversion has fallen behind, with shortcomings when it comes to venture capital and infrastructure support; some of which can be attributed to production challenges, funding gaps and competition from China and the United States.[6]

PARTNERSHIPS FOR THE FUTURE

Fortunately building partnerships and bridging gaps is an area that the Graphene Flagship and Horizon Europe initiatives excel in and have taken great strides in developing. International collaboration and information exchange between a broader community has been addressed through international workshops and partnerships forged under the Flagship umbrella and have the potential to lead to greater success in commercialisation in the future.

The Graphene Flagship international outreach activities act as a support mechanism to bring the broader 2D material (2DM) community together for knowledge exchange and collaboration toward a joint vision. With the launch of the rearranged Graphene Flagship initiative, there are now 12 projects each with partners spread across Europe, working under the umbrella of the Coordination and Support Action (CSA) group/project.

Although the focus is on EU member states, with the Horizon Europe grants call titled "Europe in the Lead", the European Commission is eager to promote international collaborations, including with "associated" countries that stretch beyond EU borders. There are also opportunities for other interested public and private research organisations from around the world to partner with Horizon Europe members, but often at their own cost.[7]

Taken together, the Graphene Flagship collaborations and contribution to the realm of advanced materials R&I and the revised European commitment and support for the production and use of advanced materials sets a course for a future where Europe continues to lead us towards the green and digital transition that we have all set our compasses for.

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Boost Europe's innovation uptake, competitiveness and jobs

GRAPHENE FLAGSHIP ANNUAL REPORT 2023

GrapheneEU

Ensuring coordination, collaboration and cooperation in the Graphene Flagship

THE GRAPHENE EUROPE in the Lead (GrapheneEU) Coordination and Support Action (CSA) ensures the overall coherence of the Graphene Flagship. Building on ten years of experience providing central support and coordination to the Graphene Flagship, the GrapheneEU project partners will help to unite the new Horizon Europe Research and Innovation Actions (RIAs) and Innovation Action (IA) and provide services to help increase the initiative's visibility, effectiveness and voice.

The CSA's primary function is to encourage collaborations and knowledge transfer between the RIA/IA projects and with the broader 2D materials (2DM) community. GrapheneEU ensures a strong and coherent initiative by providing key support functions in coordination and governance, industrialisation, dissemination and alignment, enabling the participating projects to identify and utilise synergies in their work, share best practices and promote interactions with relevant national and regional initiatives. GrapheneEU will help secure a sustained European leadership in 2DM by capitalising on the investments in the Graphene Flagship from the FP7 and Horizon 2020 European funding programmes and fostering and facilitating the work to be continued during Horizon Europe.

> GrapheneEU will help secure a sustained European leadership in 2DM by capitalising on the past decade's investments in the Graphene Flagship.

COORDINATION AND GOVERNANCE

GrapheneEU's management in conjunction with the Graphene Flagship Director help coordinate the initiative, bring the projects together to make strategic decisions and influence the European research and innovation landscape for 2DM. The CSA monitors specific aspects of the RIAs/IA's progress, increases internal cohesion of the initiative by organising strategic meetings, supports the RIA/IA coordinators regarding EC regulations and requests and handles contacts with other key stakeholders.

The Graphene Flagship governance structure relies on one common decision-making body, the Coordination Board, which includes the coordinators of the RIAs/IA as well as representatives of GrapheneEU. In this way the projects are kept appraised of the work being done inside the initiative and are encouraged to collaborate and contribute to broader activities.

INDUSTRIALISATION

Industrialisation support is a key element in maximising the impact of the Graphene Flagship in terms of new products, companies and jobs in Europe. On this matter, GrapheneEU partners collaborate with the RIAs/IA through three interlinked tasks: roadmapping, standardisation and innovation support. The continuity of the Graphene Flagship partners working on industrialisation will facilitate early adoption and growth.

Roadmapping

Technology and Innovation Roadmaps identify the areas where new 2DM technologies can make the most significant impact on society, the economy and the environment using a highly successful combination of workshops, interviews and literature studies. The CSA will build on the past roadmapping success, working jointly with the RIAs/IA to create field-specific roadmaps based on their technical and scientific input.

Standardisation

The aim of the standardisation work is to address regulatory compliance as one crucial factor in a successful innovation process of 2DMs. GrapheneEU promotes international standards through the ISO and IEC organisations, supporting the RIAs/IA in creating regulatory-ready products. Standardised and regulatory compliant characterisation methods will be made available to be applied during product development.

Innovation

To maximize their utilisation potential the RIAs/IA will be guided by the CSA's innovation support to extend beyond European industries and the Graphene Flagship. Past experience in industrial outreach, business development for 2DM technologies and hosting innovation events will help to strengthen the impact of these activities.

DISSEMINATION

GrapheneEU ensures that the work of the Graphene Flagship is communicated to all stakeholders from the research and innovation community to decision-makers and the public. Sharing a common message and combined voice ensures greater visibility and impact for all the Graphene Flagship projects. Coordination of individual messages will help ensure collaboration rather than competition in reaching the various communication channels. This begins with a common website and events calendar, helping the Graphene Flagship to remain the single-entry point for news and information about graphene and 2DM.

The continuation of the popular Graphene Week conference which allows for networking and knowledge transfer in all areas of 2DM as well as digital workshops on more targeted topics will be key to the collaborative dissemination efforts of the Graphene Flagship. The RIAs/IA will contribute with speakers, strategic leadership and expertise to the conference, while the event will provide an avenue for collaboration and cooperation. The Graphene Flagship's established educational programmes and workshops and the Diversity in Graphene networking and coaching events continue to support the next generation, with a particular focus on underrepresented groups within the 2DM community.

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Sofia Öiseth will continue to coordinate the Innovation Forum at Graphene Week, forwarding GrapheneEU's Industrialisation and Dissemination goals.
Credit: Graphene Flagship

ALIGNMENT AND INTERNATIONAL COLLABORATIONS

Collaboration and knowledge transfer are key to the Graphene Flagship's success. GrapheneEU will continue the past work on international collaborations and alignment with national and regional initiatives in Europe. The 2DM research community in Europe is comprised of over 1500 institutions actively working in the field, with over 150 European companies involved in various segments of the market (materials production, product development, equipment manufacturing, etc.). While part of the research activities will be covered by the RIA/IA projects, a larger number of research activities will be supported at the national level or through other EU funding programmes. The CSA provides an interface for these activities, so that they can all contribute to the Graphene Flagship and its objectives. This will be achieved by offering the possibility for organisations or projects to join the initiative as Associated Members or Partnering Projects.

GrapheneEU is also establishing a strategic network of national and thematic representatives to facilitate the interactions and exchange of information between the Graphene Flagship and other national, regional and thematic initiatives. Moreover, as a result of the Graphene Flagship's excellent research activities and demonstrated scientific impact over the last ten years, Europe is recognised as a 2DM leader. This position has made the initiative an attractive global collaboration partner, a position that the CSA will continue to strengthen through a series of international workshops that will address topics of interest to individual actors as well as international partners.

Flash Graphene: Trash to Treasure

THE APPLICATIONS for graphene use are broad, having altered the composition of electronics, energy storage and biomedical devices, sensors and composites and coatings over the past two decades. This is all due to its exceptional mechanical, electrical and thermal properties. However, what are the environmental impacts of its use and how does the cost limit its application?

Graphene was first isolated in 2004, and since then the cost has come down significantly. However, this is still dependent on the quality of the graphene desired, and the production methods used to isolate it. Commercial-grade, high-quality graphene can still be extremely expensive, with retail prices ranging from $60,000 to $200,000 per ton.[1] In some instances, the cost is high (both economically and environmentally) due to the resources needed to produce it.

A promising discovery made by scientists at Rice University in the lab of chemist James Tour, in January 2020, may upend our graphene production processes and our concept of trash altogether. Their findings were first published in Nature (2020) and describe the use of Flash Joule Heating (FJH) to create flash graphene or flake graphene (FG). The process uses inexpensive carbon sources, such as coal, discarded food, rubber tires, plastic waste, etc. to make FG which is suitable for use in bulk composites of plastic, metals, plywood, concrete and other building materials.[2] The electrical cost is about 7.2 kilojoules per gram, which is just "a fraction of the cost used by other bulk-graphene producing methods," says Tour.[3]

This inexpensive process of turning trash into treasure is a simple flash of super-hot electricity focused on the source of carbon, which reorders the atoms and creates graphene. Since its discovery there have been many promising plans and proposals for its use.

CONSTRUCTION

As populations and urbanisation thrive, the construction industry faces tremendous challenges when it comes to reducing its carbon footprint, especially the footprint linked to cement-based products.

According to an article in Forbes (2020), concrete is only second to water, as the most consumed product in the world, with the production of cement producing 8% of the world's carbon emissions.[4]

This is where graphene can enter the equation. As a strong, but light material it can be added to concrete, and in small increments of 0.03% which then increases its compressive strength by 25%.[4] Graphene-enhanced concrete is 2.5 times stronger and four times less water permeable than standard concrete. It uses much less cement to deliver the desired strength. As a result, it is expected to reduce CO_2 emissions by 30%.[5]

> Most conventional production methods include high energy use and chemical leakage. As the production of graphene-related materials (GRM) continues to scale, they will inevitably leak into our soil and waterways, therefore we must form an informed understanding of what this means for the environment and health of the impacted ecosystems".

END-OF-LIFE VEHICLES

Another top carbon emissions contributor is the automotive/transportation industry. These emissions are not only from vehicles in use, but also from the end-of-life vehicle (ELV), in the form of non-recyclable waste of plastics (ELV-WP).

According to a Nature (2022) article, "the automotive sector produces an estimated 5% of the global industrial waste in the form of ELV" which is only estimated to increase as global standards of living increase, and the cost of entry decreases. Although global processing standards vary from country to country, in the United States as of 2020, an estimated 10–30% of total vehicle weight is saved from shredding. "EVL waste plastic (EVL-WP) is the largest non-recycled material in vehicles, and the increased use of next-generation polymer composites exacerbates recycling of ELV-WP through traditional methods which generally focus on singular plastic sources."[1] For instance, the Graphene Flagship partner Nanografen, based in Turkey, transforms old tyres into graphene-based nanoplatelets through a process of pyrolysis, chemical and thermal treatments.[6] This offers not only a solution to the issue of toxic tyre waste, but a low-cost graphene source for thermoplastic applications in automotive components.[7]

The difficulty and cost of upcycling depolluted, dismantled and shredded end-of-life plastics still remains, and has made EVL-WP a pressing environmental concern, however, with the introduction of FJH and FG the possibility of processing the waste into useable graphene is hopeful.

Additionally, the Graphene Flagship spearhead project, G+Board features conductive patterns, sensors and devices based on multi-functional graphene or reduced graphene oxide to replace copper that is currently used in car dashboards.[8] This substitution reduces the number of production steps and lowers vehicle weight, while also improving aesthetics and recyclability.

PLASTICS

The problem of plastic is familiar to anyone visiting the grocery store or an open beach. It is everywhere and inescapable.

Plastics are made of polymetric materials and are used in many indispensable applications throughout our daily lives, but their long-decomposition time has left the unsolved problem of trash in its wake. Although some plastics can be recycled, most end up in landfills or floating in our seas, taking hundreds (if not thousands) of years to decompose.

Since the Rice University discovery of FG, some have begun to ponder and test whether the conversion of plastic waste (PW) to graphene could be an answer to overcoming this immense problem.

One approach to upcycling PW relies on FJH to convert PW to FG. According to findings in an ACS (2020) article, "to make high-quality graphene, a sequential alternating current (AC) and direct current (DC) flash is used. The FJH process requires no catalyst and works for PW mixtures, which makes the process suitable for handling landfill PW." The authors also suggest that not only could FJH manage PW from landfill, but that the energy required "is ≈23 kJ/g or ≈$125 in electricity per ton of PW, potentially making this process economically attractive."[9]

Another promising use for PW could be to produce not only graphene, but hydrogen, an alternative to fossil fuel. Researchers from Rice University found that when using FJH they can transform PW into hydrogen gas, producing FG as a byproduct.[10] By using FJH and PW they can produce clean hydrogen for free, by selling the graphene at a fraction of its current market value.[9] "Hydrogen could be the green fuel of the future."[11]

MUNICIPAL WASTE

With over 2 billion tons of municipal solid waste (MSW) generated globally every year, equating to "around 70% of waste ending up in landfills or open dumps... technologies that can minimise waste volume or convert waste into valuable products are required."[12] In an ACS publication, the use of FJH to make FG as a waste management strategy is assessed as a form of "waste valorisation" one which could "help achieve near-zero waste and an economy-boosting MSW management system."[12]

The paper also points to this method as less polluting than its conventional counterparts, used to produce bulk-graphene, which can be resource intensive and polluting.

CRUDE OIL BYPRODUCT (ASPHALTENE) INTO GRAPHENE COMPOSITE

Rice University researchers have also uncovered a potential use for asphaltene a byproduct of crude oil production, that when flashed turns into useful turbostatic graphene that can be used in composites for thermal, anti-corrosion and 3D-printing applications.[13] These applications tie into the Graphene Flagship project GIANCE which works to support, develop and advance innovative solutions to environmental challenges thus establishing a holistic, integrated and industrial-driven platform for the design and scalable fabrication of the next generation of recyclable graphene.[14]

CONCLUSION

The Flash Joule Heating (FJH) process has been shown to produce high-quality flash (flake) graphene (FG) that can lessen the carbon and water footprint by more than 90%, compared to other bulk-graphene production methods; not to mentioned that it's more cost effective than other retrieval methods.[15]

Graphene Flagship Associated Member Nanografen is producing graphene from waste tyres with the goal of improving recycling systems and making cars more eco-friendly. Credit: Nanografen

However, according to a One Earth (2022) article "the sustainability credentials of the FJH approach remain unclear, and it is far from certain whether FJH can use biomass waste to produce industry-quality graphene." Overall, their study revealed "that the FJH technology can contribute greatly to the environmental and economic sustainability of graphene production, with the potential to facilitate the transition of circular bioeconomy by valorising biomass waste.[16]

While there is still much research to be done, the resounding message is clear; we need new ways to minimise carbon emissions and to deal with waste, and the process and production of FG could be one way to turn our trash into treasure.

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GRAPHENE WEEK
Patrik Johansson


This is the
Graphene Flagship
What is graphene?

ARMS

Eco-friendly supercapacitors

THE ARMS PROJECT, short for **A**tomic layer-coated g**R**aphene electrode-based **M**icro-flexible and **S**tructural supercapacitors, aims to create environmentally-friendly supercapacitors with high energy density (>50 Wh/kg), similar to batteries. By incorporating graphene-rich bio-based carbon materials and graphene-decorated carbon fibres and utilising scalable and cost-effective atomic layer deposition (ALD) manufacturing technology, the project seeks to maintain power density, cycle life and eco-friendliness. The ultimate goal is to establish a new value chain for supercapacitor manufacturing, with European small and medium-sized enterprises (SMEs) playing a key role in this innovative initiative.

> One key innovation within ARMS is the use of scalable atomic layer deposition (ALD) processes to modify graphene-rich activated carbon electrodes by applying ultrathin conformal coatings of metal oxides at the nanoscale, promising a major increase in energy density. These electrodes are designed to offer high power density and long cycle life, addressing the limitations of conventional supercapacitors."

Matti Mäntysalo
Project Coordinator

MEETING NEW CHALLENGES

The outputs of the ARMS project, focusing on developing supercapacitors with enhanced energy density and cycle life, have diverse real-world applications. These advanced supercapacitors offer a sustainable and cost-effective alternative to conventional batteries, featuring large amounts of graphene on the surface of electrode materials but formulated so that macroscopically useful quantities of the material can be used. The sustainability, scalability and enhanced functionalities of the developed supercapacitors make them versatile solutions for a range of industrial processes and consumer products. The applications include consumer electronics (remote controls, Internet of Things (IoT) devices, fire alarms and other small wireless devices), toys and drones, and electric grid applications.

Although currently outside the project's scope, the enhanced functionalities of ARMS materials suggest a potential future application in electromobility. The supercapacitors developed within the ARMS project could contribute to advancing electric vehicle technology, providing an eco-friendly and cost-effective alternative to traditional batteries.

The project addresses the performance gap between batteries and supercapacitors using 2D materials, aiming to enhance energy storage technologies. This effort could lead to improved energy density, environmental sustainability and technological innovation within the European ecosystem of 2D materials. Successful outcomes may foster research collaboration, economic growth and increased competitiveness in the global market for energy storage solutions.

The ARMS project aims to tackle several critical challenges faced by Europe, including the aftermath of the COVID-19 pandemic, the impact of climate change leading to extreme weather events and the geopolitical shift with the disruption in the supply of Russian fossil fuels due to the war in Ukraine. By focusing on developing graphene-enhanced, eco-friendly, bio-based carbon supercapacitors, ARMS seeks to provide a vital solution for renewable green energy in Europe. These supercapacitors are anticipated to offer energy densities comparable to batteries while maintaining power density and cycle life comparable to conventional supercapacitors. The project attends to the urgent need for sustainable energy storage solutions, especially in the context of achieving the goals outlined in the Green Deal.

SUSTAINABLE SOLUTIONS

The ARMS project plays a vital role in helping Europe meet its sustainability goals by contributing to the Green Deal and aligning with the continent's objectives for a circular, climate-neutral and sustainable economy. By developing new technology solutions for portable energy sources, the project aims to outperform alternative technologies in terms of energy and power density, safety, stability, flexibility, lightweight, thinness and cost-effectiveness. The supercapacitors developed by ARMS will be designed to be entirely made of eco-friendly materials. They will be applicable to various sectors, from consumer goods and IoT objects to electrification of transport. The project's emphasis on sustainable materials and processes, such as bio-based carbon and environmentally friendly electrolytes, supports Europe's transition to a digitally led circular and climate-neutral economy.

The outputs of the ARMS project are expected to lead to a more environmentally friendly future through the development of supercapacitors with energy densities comparable to batteries. The use of eco-friendly bio-based carbon and metal oxides in the electrodes, along with sustainable fabrication processes, ensures that the materials are sourced and produced in an environmentally responsible manner. The project contributes to creating a sustainable and autonomous materials value chain for EU industrial ecosystems, promoting the use of naturally abundant and non-toxic materials. Additionally, the focus on sustainable-by-design materials in the production of supercapacitors enhances their functionalities while minimising the impact on worker health and safety. Overall, ARMS aims to establish a circular and sustainable economy by addressing environmental concerns throughout the entire lifecycle of the developed energy storage solutions.

NEW HORIZONS

Over the next few years, the ARMS project has an ambitious roadmap encompassing various crucial activities. In the first year, the baseline synthesis parameters for both bio-graphene and wood-derived carbon nanomaterials will be established, laying the groundwork for subsequent research. Concurrently, benchmark and test procedures will be developed to evaluate electrode performance in hybrid electrolyte systems. Later, the focus will shift towards providing feedback on electrolyte interactions and presenting a Systems Safety by Design (SSbD) framework report outlining criteria for safety, sustainability and circularity assessments.

Executing the ARMS project's roadmap faces challenges in bio-graphene and wood-derived carbon nanomaterial synthesis, demanding rigorous experimentation and collaboration. Coordinating interdisciplinary activities requires effective communication and resource management while adapting to evolving industry standards. Benchmarking electrode performance in hybrid electrolyte systems entails iterative testing and collaboration with electrochemistry specialists.

Ensuring regulatory compliance and safety criteria within the SSbD framework requires engagement with regulatory experts and ongoing updates. The project's success relies on a holistic approach, combining technical expertise, collaboration and adaptability to ensure smooth progress aligned with industry standards and regulations.

COLLABORATIONS

Being part of the broader Graphene Flagship ecosystem presents a myriad of anticipated benefits. Firstly, the collaborative nature of the Graphene Flagship allows for unparalleled networking opportunities with leading researchers, experts and industry players in the field of graphene and 2D materials. This network fosters knowledge exchange and opens avenues for potential collaborations and partnerships.

Secondly, being part of the Graphene Flagship ecosystem enhances visibility and credibility within the scientific and industrial communities. The association with a renowned and collaborative initiative strengthens our position as a noteworthy player in the graphene domain. This enhanced visibility can attract funding opportunities, partnerships and collaborations that may not have been possible without the support of the Graphene Flagship.

Moreover, participation in Graphene Flagship events adds a dynamic dimension to these benefits. The project organises various events tailored for researchers, industry professionals and early career researchers. These events serve as invaluable platforms for inspiration, encouraging us to engage in better research, innovation and collaboration. The exchange of ideas and experiences in these events is expected to enrich our perspective and fuel our commitment to excellence.

The ARMS project team.
Credit: ARMS

The ARMS project will contribute to the Graphene Flagship community by actively engaging in cutting-edge research, sharing insights at community events and fostering collaborative partnerships. Through these efforts, we aim to enhance the collective knowledge base, contribute to the community's goals and increase visibility and credibility, ultimately working towards advancing graphene-related technologies and fostering innovation within the Graphene Flagship ecosystem.

Energy

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ARMS
Supercapacitors: Energize your world

GRAPHERGIA

Innovative pilot lines for sustainable graphene-based flexible and structural energy harvesting and storage devices

> We expect that GRAPHERGIA's dual focus on represents a paradigm shift in the graphene industry, promising scalable and sustainable advancements that will shape the future of energy storage and smart textiles."

Spyros Yannopoulos
Project Coordinator

THE GRAPHERGIA project seeks to transform energy solutions with sustainable, efficient power technologies. It focuses on developing eco-friendly dry electrode fabrication for energy storage devices, leveraging the potential of lasers in graphene synthesis. The project's ambition is two-fold: it will create self-charging e-textiles for biomechanical energy harvesting, making the charge-as-you-go lifestyle a reality for everyone. In parallel, it aims to develop cost-effective lithium-ion batteries (LIBs) for space applications, marking a significant step towards a more sustainable energy future.

MEETING NEW CHALLENGES

GRAPHERGIA will establish scalable, eco-friendly pilot-scale methods for crucial real-world applications. It focuses on breakthrough developments in materials, processes, and integration, aiming to provide sustainable, long-term solutions in the rapidly advancing fields of energy harvesting and storage, meeting the growing market demands for cutting-edge energy applications.

Smart e-textiles: Envision clothing that not only connects you wirelessly to the IoT but also powers itself. GRAPHERGIA will develop multifunctional, self-charging smart textiles that integrate advanced wearable electronic systems seamlessly into fabrics. It will revolutionise the fabrication of graphene-based triboelectric nanogenerator (TENG) electrodes on textiles and develop a ground-breaking power management system, designed to significantly enhance the efficiency of TENG output.

Li-ion batteries: GRAPHERGIA will redefine LIB technology with advanced graphene-based electrodes, employing a novel "dry-electrode" fabrication approach integrating 2D materials and process-oriented methodologies, utilising cost-effective raw materials and scalable fabrication techniques to ensure economically viable and environmentally sustainable solutions. It will create highly efficient graphene-based electrodes for LIBs using scalable, green, laser-assisted processes.

SUSTAINABLE SOLUTIONS

GRAPHERGIA embodies a commitment to pioneering advancements in graphene technology, underscored by several fundamental principles:

Eco-friendly manufacturing: Our process is waste-free and excludes the use of hazardous substances, aligning with environmental protection goals.

Cost-effective production: We implement a single-step method at room temperature, eliminating the need for specialised equipment or further treatment of graphene.

Scalable technology: The process is designed for rapid, large-scale production, leveraging industrial-type laser technology for immediate graphene synthesis and integration.

High-quality standards: Our method produces graphene quality in harmony with the "Good Practice Guides" and ISO graphene standards.

Adaptability: Direct graphene growth on various substrates negates the need for transfer processes.

Integrated modularity: The ambient condition synthesis facilitates an integrated system with real-time quality monitoring capabilities.

Versatile precursor usage: Capable of converting a range of precursors, including polymers, biomass, and carbides, into premium graphene and graphene-nanohybrids through tailored laser treatment.

Resourcefulness: Reducing dependence on traditional wet-chemistry methods, thereby streamlining production processes, and enhancing efficiency.

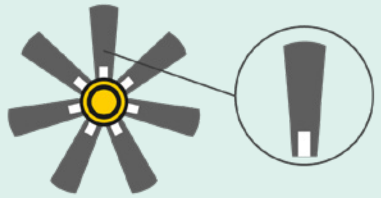
Promoting material independence: By reducing reliance on imported Critical Raw Materials (CRMs), it enhances the EU's energy autonomy while simultaneously strengthening environmental sustainability and conserving resources.

NEW HORIZONS

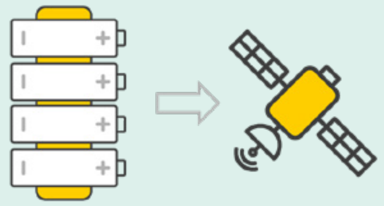
During 3.5 years, GRAPHERGIA is dedicated to enhancing the scalable, economic and environmentally friendly production of graphene-based materials, targeting high-impact products in the energy sector for significant societal, economic and environmental benefits. Our three demo cases include:

Self-charging textile development: Manufacturing an all-in-one textile capable of energy harvesting and storage. It will integrate single electrode TENGs into, e.g., T-shirts and belts for energy storage and gait monitoring, and embedding these technologies into upholstery fabrics for transport interiors to boost comfort and safety.

Self-charging textile development.



Self-powered structurally integrated sensors for aerospace structures.



Advanced graphene-based LIB module for space applications.

Self-powered structurally integrated sensors for aerospace structures: Demonstrating a miniaturised TENG-based sensor in a scaled aerospace composite structure. This demo case aims to integrate a self-powered wireless temperature/strain sensor into a composite fan blade, enhancing data accuracy for better and quicker design decisions in aerospace.

Advanced graphene-based LIB module for space applications: Designing, manufacturing and testing a graphene-based LIB module prototype for space applications. This demo will validate the efficacy of our laser-assisted fabrication technology at TRL 5, focusing on optimal laser-scribed graphene electrodes and LIB cells.

Challenges in these areas will be addressed through rigorous research and development, leveraging our beneficiaries' expertise in graphene technology and our commitment to innovative solutions.

COLLABORATIONS

By joining the Graphene Flagship community, GRAPHERGIA stands to gain substantial benefits. Participation in this dynamic network offers unparalleled opportunities for collaboration, knowledge sharing, and visibility. Our project will gain access to cutting-edge research, key stakeholders, and potential partners across Europe. This involvement will not only accelerate our own graphene innovations but also help in disseminating our breakthroughs to both the scientific community and the public at large, enhancing our project's impact and recognition.

In parallel, our project will bring fresh perspectives, innovative approaches to graphene-related material development, and a commitment to advancing the collective goals of the community. Through active participation and sharing of our research advancements, GRAPHERGIA aims to be a key contributor to the continuation of the GFi's mission, fostering advancements in graphene technology and applications.

The GRAPHERGIA team.
Credit: GRAPHERGIA

Energy

PROJECT COORDINATOR
Spyros Yannopoulos, Foundation for Research and Technology Hellas (FORTH), Greece

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Started in October 2023 and running until March 2027, the GRAPHERGIA project unites 11 partners from six European Union countries. It is supported by a budget of € 4.5 million, funded through the European Commission Horizon Europe programme.

GRAPHERGIA

MUNASET

Multiparametric nanoelectronic biosensors for therapy response testing

MUNASET will develop a highly sensitive graphene-based biosensor platform to diagnose neurological and psychiatric diseases.

MEETING NEW CHALLENGES

Proteases recently emerged as a promising new class of biomarker with a broad diagnostic, prognostic and therapeutic potential for different human diseases including neurological and psychiatric diseases, several types of cancer and immune system disorders. However, there is a lack of tools for real-time activity analysis of disease-related protease biomarkers.

As a specific business case, we plan to address therapy response prediction along treatment of major depressive disorder (MDD). MDD is one of the most common and burdensome mental disorders worldwide. MDD is also among the most expensive brain diseases in Europe. While effective treatments exist, there is a high variability in treatment response. There are no serum-based tests to predict personalised therapy for MDD patients. The effective treatment is identified through trial and error, a great burden for patients and the health care system.

MUNASET will develop a rapid, highly sensitive and easy-to-use graphene-based biosensor platform to address therapy response prediction and allow faster and more precise treatment identification, improve therapy outcomes and reduce hospitalisation time. MUNASET will also help secure Europe's industrial leadership over the entire value chain of novel graphene-based bio-analytical tools.

Our goal is a next-generation biosensor platform technology that combines several existing technologies into a unique biosensor device that can potentially revolutionise the way biochemical reactions and physiological interactions are studied. If successful, we expect that the resulting platform technology will significantly advance biomedical research and permit the development of novel point-of-care diagnostic and drug screening tools that can provide a competitive advantage for the healthcare and wellbeing sector in the European Union (EU).

By using 2D graphene, we plan to demonstrate the following advantages compared to conventional tools:

- Improved biosensing performance; including low detection limits, low drift, high chemical stability and biocompatibility to allow sensitive and selective biomarker detection in real time.
- Versatile surface chemistry via pi stacking of linker molecules on graphene to attach capture peptides for different analytes.
- A novel field-effect sensing mechanism based on specific charge removal by proteases to ensure high and homogeneous signals.
- An integrated complementary metal-oxide semiconductor (CMOS) readout to enable robust multi-analyte measurements with built-in calibration, averaging, etc.

> The aim of the MUNASET project is to develop graphene-based devices to help doctors monitor the therapy of patients with depression and other psychiatric disorders. The envisioned test is fast, easy-to-use, only requires blood samples and can be used at the point-of-care to develop personalised therapies. It can greatly improve the treatment outcomes for psychiatric diseases."

Alexey Tarasov
Project Coordinator

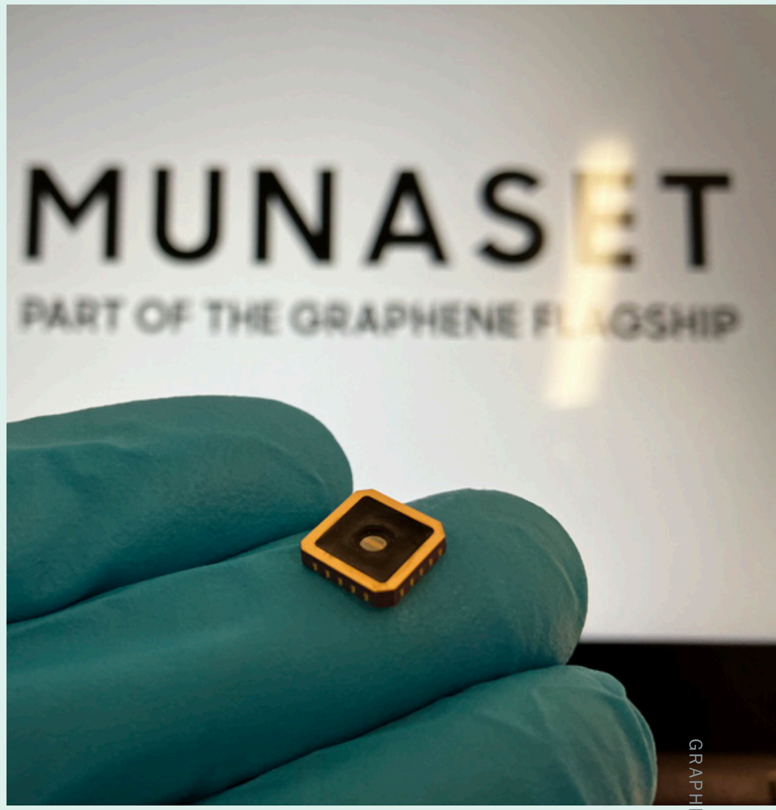
SUSTAINABLE SOLUTIONS

MUNASET will contribute to a more sustainable industry because the same underlying technology could be used in different industries and application scenarios. The platform will also be miniaturised and have multi-analyte detection capability on a single small chip, which will save materials and resources needed to perform the tests.

The project aims to further the United Nation's Sustainable Development Goal (SDG) for health and well-being. Not only will the developed platform be used for MDD patients to improve the therapy and monitor its effectiveness, but the platform will also give valuable insight into the development of point-of-care devices for multiple other diseases such as cancer.

The MUNASET project is working to simplify the therapy process associated with MDD. This approach will reduce the number of resources used in classical therapies. Not only will the use of the MUNASET devices reduce the time spent at clinics, but it will also reduce the amount of medication that is being used and streamline the tests that must be performed in a laborious way in standard laboratories.

The project's month six meeting took place in Zweibruecken on 29 February 2024. Credit: MUNASET



MUNASET Graphenea chip.
Credit: MUNASET

NEW HORIZONS

The project starts at technology readiness level (TRL) 3. In previous work by MUNASET partners and other researchers, experimental proof-of-concept was demonstrated for two key components:

- Analytical performance of graphene-based biosensors was characterised for clinically relevant analyte in different media, including buffer and serum.
- A CMOS readout was already fabricated, and its function demonstrated in liquid without chemical functionalisation. In the next two years, MUNASET will reach TRL 4. Detection of purified protease in buffer using peptide-coated graphene biosensors will be validated in a lab environment.

Point-of-care devices testing blood or serum samples often suffer from the complexity of the analyte solution. In the MUNASET project a novel approach for the detection of proteases in serum is being investigated, offering a highly sensitive and selective method to detect active proteases in complex samples. The integration of highly sensitive devices with integrated electrical readout, as well as a microfluidic integration ensures that the previous limitations in the field can be overcome.

COLLABORATIONS

Through interactions within the Graphene Flagship ecosystem, we anticipate a higher impact for our research, enabled by discussions leading to new scientific insights, new project ideas and collaboration opportunities; in addition to, access to various tools and knowledge from the GrapheneEU Coordination and Support Action.

Contribution to the Graphene Flagship initiative will be an essential goal of MUNASET, with four tasks articulating our commitment and involvement. As such MUNASET will be able to participate in the activities, contribute technical expertise, provide key exploitation results and report overall indicators assessment to the new GrapheneEU CSA.

Having initiated synergies with both the Graphene Flagship and other biomedical-oriented projects and initiatives, such as the sister project 2D-BioPAD, MUNASET expects to contribute via tangible actions and activities for promoting graphene biomedical research and innovation within and beyond the Graphene Flagship ecosystem.

Biomedical

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Alexey Tarasov, Kaiserslautern University of Applied Sciences, Germany

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MUNASET
PART OF THE GRAPHENE FLAGSHIP

GRAPHENE FLAGSHIP ANNUAL REPORT 2023

2D-BioPAD

A supple graphene bio-platform for point-of-care early detection and monitoring of Alzheimer's disease

THE PROJECT 2D-BioPAD aims to introduce a fast and cost-effective, non-invasive, reliable, digitally and graphene-enabled point-of-care (PoC) *in-vitro* diagnostics (IVD) system for supporting the early diagnosis and progression monitoring of Alzheimer's Disease directly at primary healthcare settings.

MEETING NEW CHALLENGES

Alzheimer's disease (AD) is the most prevalent form of dementia,[1] affecting more than one in nine people aged 65 and older. The disease is one of the most severe factors driving brain dysfunction in elderly people and is expected to affect roughly 18.8 million people by 2050 in Europe alone[2].With an enormous phycological, social and financial burden for healthcare, long-term care and hospice (over $355b just in the US in 2021, without including an additional ~$257B in unpaid caregiving) at a global scale. Perhaps most important of all, the incidence and mortality due to AD keep rising, with an increase of 145.2% from 2000 to 2019, while heart diseases have decreased by 14%. This situation will worsen due to population ageing; life expectancy in Europe is expected to increase by ~10% in 2065 reaching 92.8 years for women and 90.5 years for men[3]. Absent of a cure, and with current practices targeting the symptoms rather than the cause[4], the need for a preventive approach to diagnose as early as possible and get a better insight into the progression of AD is of utmost importance, especially at earlier stages such as mild cognitive impairment (MCI).

An early and accurate Alzheimer's diagnosis would offer significant benefits such as (i) a better chance of benefiting from treatment, (ii) lessening emotional and social burden, (iii) allowing more time and better quality of life, and (iv) saving trillions of Euros in terms of overall costs[5]. On top of that, emerging promising treatment through novel drugs requires extensive screening to identify the people who are at risk for AD, while aiming to limit adverse effects[6]. As we speak, such screening processes are too expensive and inaccessible to the public.

2D-BioPAD leverages the unique properties of 2D materials (2DM), such as graphene and its derivatives, and goes beyond the 2DM state-of-the-art to deliver a graphene-based PoC IVD system that will (i) introduce a versatile surface chemistry that combines nano and DNA technologies towards improved biocompatibility, stability, as well as high sensitivity and specificity for enhanced biosensing; (ii) be able to reliably identify and quantify in real-time and simultaneously up to five AD biomarkers in blood samples effectively supporting healthcare professionals in early diagnosis and progression monitoring; (iii) offer an easy to use and understand digital interface with key metrics and insights regarding the measured results; and (iv) employ artificial intelligence (AI) to improve the overall system implementation and drive the next generation of graphene design and implementation.

> 2D-BioPAD will leverage the rich physical and chemical properties of graphene, as well as the expertise of the consortium partners to develop hand-held sensors for Alzheimer disease and validate them in a clinical setting from patients' blood samples."

Aristeidis Bakandritsos
Project Coordinator

SUSTAINABLE SOLUTIONS

According to research findings,[7] the current healthcare sector contributes negatively to society, in the form of environmental degradation and costs that affect patients and those close to them. Considering that by 2050, almost 20 million individuals will be affected by Alzheimer's in Europe, there is much work that needs to be done to reshape the healthcare sector and its negative impact on the environment and society. To tackle these challenges, the transition from curative medicine towards prevention, pre-care and health promotion,[8] is considered one of the most effective approaches. Such strategy also aligns with AD clinical research findings that support early diagnosis and prevention as the only effective countermeasures for delaying progression, providing access to new medication and eventually improving quality of life.

Towards that direction, 2D-BioPAD contributes to a greener healthcare digital supply chain by introducing a low-power, advanced, digitalised PoC IVD system, able to cost-effectively support widely accessible early diagnosis and progression monitoring of AD in primary healthcare settings. Through this, we anticipate significant reductions in the burden for patients and the environment compared to current required treatments, by enabling the related healthcare sector to achieve improved outcomes with fewer examinations, less hospitalisation time, delayed disease progression and hence the mitigation of intense clinical support.

Moreover, 2D-BioPAD introduces two additional and important merits towards a greener digital supply chain, that will further improve the European industrial and technology landscape. First, the graphene design envisioned is expected to be CRM-free taking advantage of state-of-the-art developments on graphene and aptamer technologies. Secondly, through its digitalised implementation, it will be able to generate a significant volume of (paperless) data on several biomarkers, enabling a patient-oriented and clinically robust device, catalysing the transformation of the contemporary complex and energy-demanding methods for Alzheimer's Disease diagnosis and monitoring, to a sustainable, POC, minimally invasive and effective hand-held sensor.

NEW HORIZONS

2D-BioPAD kicked-off its activities in October 2023, and since then has successfully implemented key elements to establish a strong and coherent presence. The project designed a well-defined graphic identity that extends across various promotional materials (i.e., leaflet, poster, banner). The online sphere is also effectively covered with the creation of a website and active social media accounts on platforms such as LinkedIn, Facebook and X (formerly Twitter), whereas a YouTube channel will be launched in March 2024 along with the project's promotional video.

From a scientific perspective, 2D-BioPAD has geared up with numerous activities starting in January 2024, extending from field research to capture end-users' needs via interviews and surveys, to preliminary (co-)design activities for its technical components and the clinical pilot studies. These are also the core challenges that the project will be addressing over the next nine months, aiming to finalise preliminary designs and delve deeper into the implementation of the 2D-BioPAD system.

COLLABORATIONS

The 2D-BioPAD project has established a strong collaboration with the Graphene Flagship community through active participation in joint meetings and undertaking the role of co-organiser of Graphene Week 2024 in Prague.

Wider promotion, visibility and outreach are key benefits that are already showing results, with the online social media interaction between 2D-BioPAD and the Graphene Flagship being frequent and productive. As the project progresses, other aspects such as industrialisation and standardisation will also be explored, to maximise the outcomes of the project.

Having initiated synergies with both the Graphene Flagship and other biomedical-oriented projects and initiatives, such as the sister project MUNASET, 2D-BioPAD expects to contribute via tangible actions and activities for promoting graphene biomedical research and innovation within and beyond the Graphene Flagship ecosystem.

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2D-BioPAD leverages the unique properties of graphene and its derivatives to deliver a graphene-based point-of-care diagnostics system.

Biomedical

PROJECT COORDINATOR

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GATEPOST

Introducing the first Graphene-based All-Optical Technology Platform for a Secure Internet of Things and exciting 5G/6G applications

“If we succeed in combining graphene with standard CMOS processes, we will be on the verge of a breakthrough in data processing and memory.”

Mindaugas Lukosius
Project Coordinator

TODAY, THE INTERNET of Things (IoT) is an integral part of our everyday lives and is no longer a dream of the future. Devices connected locally or over IoT not only make our daily lives easier and more convenient, but also more efficient. The same is true of 5G/6G technologies, which will enable new applications by transmitting data without delay.

Experts will be able to support medical interventions by transmitting camera images from remote locations in real time, complex simulations can be easily sent to customers, and entire cities can become smart cities. Not to mention autonomous driving, where intelligent cars can exchange telemetry data with each other to prevent accidents.

All of these new applications and developments require high-performance computing with the lowest possible power consumption. Add to this the increase in cyber-attacks, which pose a growing threat to the productivity and agility of companies and public institutions. In this context, reliable security solutions are becoming increasingly important – but until now they have mostly lagged in terms of performance, latency and operating costs, or have been unable to defend against a wide range of attacks.

The EU-funded GATEPOST project is the answer. The aim of the project is to revolutionise data processing and the security of the IoT through a ground-breaking approach based on graphene. Graphene and 2D materials (2DM) offer great potential and unprecedented opportunities for efficient non-linear light interactions with ultra-fast response times. The GATEPOST project aims to integrate these innovative materials into complementary metal-oxide semiconductors (CMOS) made of silicon nitride. The project focuses on the combination of graphene with standard CMOS processes, which if successful will lead to a breakthrough in data processing and storage.

GATEPOST stands for Graphene-based All-Optical Technology Platform for Secure Internet of Things. Experts from all over Europe have joined forces to achieve the project’s ambitious goal of developing and manufacturing a robust and massive gateway that will make the IoT safer and take data processing to a new level.

MEETING NEW CHALLENGES

We all know that IT performance has grown enormously over the past decade and is expected to continue to grow through 2025. As a result, the demand for electricity for data centres has also increased in recent years and will continue to do so. The power consumption of data centres is mainly dependent on the efficiency efforts of the operators and the growth in capacity.

Cybercrime continues to be one of the biggest challenges facing data centres, with an estimated value of €294 billion in 2021.

One of the use cases for the technology developed as part of the GATEPOST project is a network security device to detect Distributed Denial of Service (DDoS) attacks and inspect network packets. Despite an average of 170 cyber-attacks per IoT device per day, there is still a huge lack of security. This is often due to additional performance requirements, latency, operational costs and bandwidth limitations.

GATEPOST, the graphene-based computing platform, will enable network security with low power consumption, low latency and high bandwidth. The vision of the GATEPOST project is a secure IoT and 5G/6G future.

The realisation of this solution will serve as first industrial use-case and thus not only prove the viability of 2DM as a non-linear photonics platform for graphene-based photonics technologies and devices, but also demonstrate a significant increase in performance at lower power consumption. The development and integration of the GATEPOST technology allows us to fully integrate the European graphene value chain while creating a sustainable, innovative and competitive solution for the EU.

SUSTAINABLE SOLUTIONS

The GATEPOST technology is helping Europe achieve its sustainability goals. The technology is expected to consume 100 times less power than current data centre equipment. While state-of-the-art electronic devices generally increase power consumption with increasing data rates, the GATEPOST devices can manage data rates up to Terabit per second (TBps) with constant low power consumption. Furthermore, graphene-based optical computing allows the fabrication and production of high-end logic devices using processes that are less wasteful than modern high-end electronics.

The GATEPOST technology therefore makes a valuable contribution to achieving the United Nations’ Sustainable Development Goal (SDG) 9, to develop sustainable and resilient industries and infrastructure. Similarly, the designed devices contribute to SDG 11, to develop sustainable and smart cities and communities. GATEPOST also supports SDG 13, to combat climate change and its effects. The GATEPOST technology enables 56/6G applications of the future, which will reduce greenhouse gas emissions and enable new climate mitigation and adaptation measures.

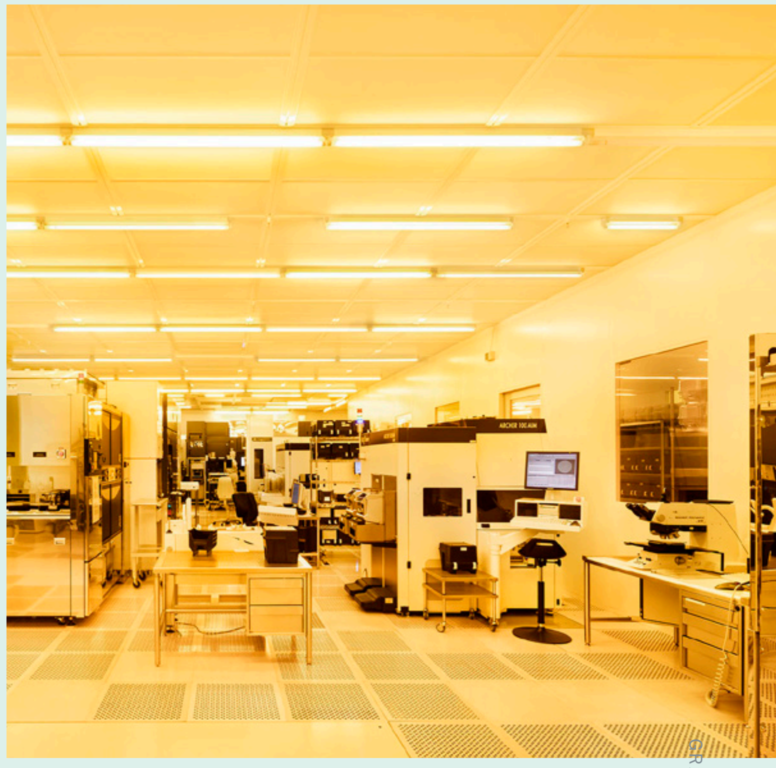
NEW HORIZONS

In the first two years of the project, the focus will be on the conception and design of the system and devices. The GATEPOST project team will achieve the first milestone in the development and integration of the graphene process by the end of 2024. The large-scale integration of graphene into silicon nitride complementary metal-oxide semiconductors (CMOS) has been challenging. Progress has been slow, mainly due to a lack of infrastructure.

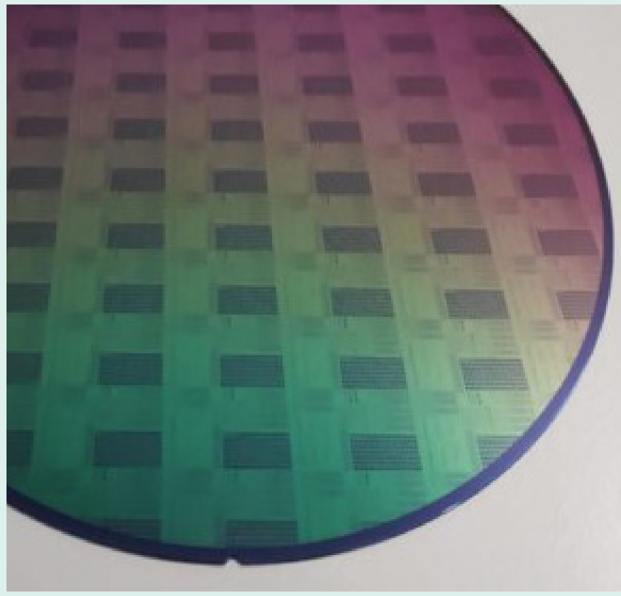
As the main challenge lies in the maturity of graphene processes within standard CMOS environments, the main objective of GATEPOST is to fabricate and demonstrate a radically new graphene-based all-optical processing platform, integrated and tested in a real CMOS pilot line. The unique expertise of each consortium member in all-optical digital logic, neuromorphic computing, memory and ultra-fast clock generation enables the GATEPOST project team to tackle the challenges together.

COLLABORATIONS

From the beginning of the project, the GATEPOST team has worked closely with the Graphene Flagship and its 2D-Experimental Pilot Line (2D-EPL). The project outcomes will be shared to allow for a continuous exchange of knowledge generated, competencies and ideas. With IHP and imec as partners of the 2D-EPL project, and Fraunhofer as well as Akhetonics (associated) as partners of the Graphene Flagship, a great basis for future collaborations has already been established and will be intensified over the course of the GATEPOST project.



From Lab to Fab: The Leibniz Institute for High Performance Microelectronics (IHP) is responsible for process development for the integration of components on a large scale and for compatibility with silicon technology. Credit: Leibniz Institute for High Performance Microelectronics (IHP)



The large-scale integration of graphene and layered materials has been challenging. GATEPOST, in collaboration with the Graphene Flagship Initiative and the 2D-EPL project, is addressing this challenge. Credit: Leibniz Institute for High Performance Microelectronics (IHP)

Electronics and Photonics

PROJECT COORDINATOR
Mindaugas Lukosius, IHP, Germany

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imec, Belgium

GATEPOST PROJECT

GRAPHENE FLAGSHIP ANNUAL REPORT 2023

2DNeuralVision

Developing a novel low-power consumption vision system that could be used for adverse weather and low-light conditions

> 2DNeuralVision envisions the realisation of advanced imaging and vision systems that enable perception for ADAS at scale, featuring low-cost image sensors with extended spectral coverage and low-power consumption optical neural networks. Such breakthroughs will be enabled by the use of 2D materials and quantum dots.”

Gerasimos Konstantanos
Project Coordinator

THE HORIZON EUROPE project 2DNeuralVision brings together seven European research centres, leading universities, and innovative companies from four different countries to develop the enabling components for a low-power consumption, computer vision system that could be used for adverse weather and low-light conditions.

Funded with €5.5 million from the European Commission, this initiative seeks to develop the enabling photonic and electronic integrated circuit components to achieve a novel computer vision system that could be used under any weather and light conditions, while also keeping low power consumption. Its results can lead to disruptive innovations in sectors like the automotive industry.

The project celebrated its kick-off meeting on 9–10 October 2023, hosted at ICFO in Barcelona, Spain. The event propelled the first contact between all partners, who shared their technical backgrounds and presented their expected contributions to 2DNeuralVision. Following a lab tour, the meeting ended with planning for the upcoming activities and deliverables.

So far, during the first three months of the project, a management plan has been developed to guarantee smooth operation, efficiency in the allocation of resources, adequate time planning, quality outcomes and compliance with the European Commission guidelines, as well as fruitful collaboration among partners and with the Graphene Flagship. For that, the coordinator has put in place a common platform for sharing documents, a plan for project meetings, mailing lists for internal communication within the consortium, a governance structure to direct discussions and decision-making, internal quality controls and a risk management strategy, among other tools.

Progress has also been made in the project’s communication. A specific visual identity has been designed for 2DNeuralVision, including the project’s logo, brand book and templates for different types of documents. The website is also developed and available at 2dneuralvision.eu, including a homepage to present the project’s scope, work packages and consortium, and additional pages to access different news and articles related to 2DNeuralVision, events that the project organises or participates in, and resources such as promotional materials, public deliverables, newsletters, press releases, as well as scientific and professional publications.

Meanwhile, the other 2DNeuralVision partners have been planning and kicking off the work for their tasks in the different work packages of the project, including the specification definition and validation, the development of envisioned materials and components for the image sensor and for the optical neural network, and their integration in the computer vision system. ICFO has already initiated research on III-V quantum dot materials and developed processes for their integration on the image sensor.

MEETING NEW CHALLENGES

2DNeuralVision aims to develop the enabling components for a low-power consumption, computer vision system that could be used for adverse weather and low-light conditions. These components involve a two-dimensional (2D) enhanced wide spectrum image sensor and optical neural network with enabling 2D passive and active elements.

Moreover, the hybridisation of 2D materials (2DM) with quantum dots and silicon technologies will enable smaller and more power efficient devices, manufacturable at scale, with greater functionality when compared to the silicon technologies of today. Therefore, the project results will enable disruptive improvements in areas such as the automotive industry, augmented reality (AR), virtual reality (VR), service robotic and mobile device sectors.

In that sense, 2DNeuralVision will make significant progress towards the integration of 2DM technology by developing European competence in semiconductor process technologies, and it will have a wider impact on Europe’s strategic autonomy by sustaining first-mover advantages in strategic areas, including artificial intelligence (AI), data, robotics, quantum computing and graphene, which can be key to sectors like the automotive industry.

SUSTAINABLE SOLUTIONS

By investigating emerging technologies early on, 2DNeuralVision seeks to strengthen European industry leadership across the digital supply chain and establish a robust presence in key aspects of a greener digital supply chain, from low-power components to advanced systems and future networks, new data technologies and platforms.

2DNeuralVision will contribute to Europe’s sustainability goals by developing and implementing advanced technologies in neural vision, leveraging two-dimensional materials (2DM). This initiative likely enhances energy efficiency, reduces the environmental impact through a reduction in the power consumption of 2DM pixels and the use of non-toxic colloidal materials, hence making the solutions environmentally friendly and aligning with the European Green Deal and the Paris Agreement. By aligning with these goals, 2DNeuralVision helps Europe move towards a more sustainable and environmentally conscious technological landscape.

NEW HORIZONS

Over the next years, 2DNeuralVision will make progress in the development of integrated photonic and electronic components, including a 2DM-enhanced wide-spectrum image sensor and optical neural network (ONN). The project also expects to provide significant advances in the development of wafer-scale BEOL (black end-of-line) processes for graphene and transition-metal dichalcogenide (TMDCs). Challenges in this process may include technical hurdles, resource constraints or unforeseen issues. Overcoming them could involve collaborative problem-solving, securing additional resources and staying adaptable to evolving circumstances.

Complementing the work development framework, 2DNeuralVision’s dissemination and communication activities will take place at all relevant points during the project and will be considered at the achievement of each of the project milestones. The strategies on data management, intellectual property rights and exploitation will also be of paramount importance to ensure the project’s sustainability. Possible issues regarding the outreach of these measures could need a readjustment of strategies as the project evolves.

COLLABORATIONS

2DNeuralVision envisions fostering the Graphene Flagship initiative, enhancing graphene- and 2D materials-based developments and providing positive recommendations in terms of modifications or updates in the existing policies.

The project will contribute to the Graphene Flagship governance via its participation in the Coordination Board and the regular Science and Technology Forum, and it will report on its outputs to be presented to the European Commission.

Envisioning the contribution to industrialisation, 2DNeuralVision will promote the coordinated standardisation of its activities, thereby contributing to the ongoing standardisation projects initiated during the H2020 Graphene Flagship phase. 2DNeuralVision can further benefit from synergies with the 2D Experimental Pilot Line (2D-EPL) in prototyping, standardisation and towards pilot manufacturability.

To support innovation work within the project, 2DNeuralVision will also contribute to the overall Graphene Flagship innovation activities, such as participating in industrial outreach activities like workshops and conferences.

2DNeuralVision also takes part in the Graphene Flagship Dissemination Working Group, making the most of its bigger outreach and contributing to its joint communication and dissemination activities. The project will be represented in the initiative’s events, especially in the annual Graphene Week, but also in other workshops, exhibitions, exchanges with international initiatives, etc. Moreover, 2DNeuralVision will provide content for the Graphene Flagship’s communication channels and materials, such as their website, social media, newsletters, press releases and annual reports.

The 2DNeuralVision team.
Credit: 2DNeuralVision

Electronics and Photonics

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2DNeuralVision

Next-2Digits

Integrating graphene in photonic integrated circuits

> Graphene empowers photonic integrated circuits with laser precision transfer.”

Ioanna Zergioti
Project Coordinator

THE NEXT-2DIGITS' integration of graphene and other 2D materials (2DM) into photonic integrated circuits (PICs) and optoelectronic integrated circuits (OEICs) will overcome the main challenges associated with performance, compactness and cost-effectiveness of the PIC- and OEIC-based devices.

Impurities and defects in circuits, especially when polymers and solvents are involved, drastically impact devices' performance. Next-2Digits will introduce direct wafer-scale integration of graphene in PICs, a technique that enhances the unique properties of graphene when integrated into optical devices, employing two innovative technologies:

i. Semi-dry transfer of graphene layers for full wafer-scale integration and direct die processing, and
ii. Laser digital transfer (LDT) of intact 2DM pixels selectively on the designated site of the die, without the need for any post-processing.

These two technologies will make the interfaces largely defect-free with high electronic mobility and large bandwidths, therefore improving performance, enabling the advent of the next generation of integrated PDs and MDs. In addition, the proposed technology will have significant advantages in terms of cost, material and energy savings and reductions of resulting waste.

MEETING NEW CHALLENGES

In Next-2Digits, graphene will be the driving force behind the development of three applications:

1. A miniaturised light detection and ranging (LiDAR) with an integrated graphene photodetector (PD) for an unmanned aerial vehicle (UAV). This will offer the drone high resolution and high speed in a compact form factor, while also fulfilling the requirements of long flight times and minimal energy consumption in advanced geo-mapping.
2. A PIC greenhouse gas sensor offering multi-sensing capability. The PIC-based sensor device will be validated in two types of biogas plants and comprise an Internet of Things (IoT) sensor network offering novel cost-effective and real-time monitoring for process optimisation and gas leakage detection.
3. An on-chip polarisation diversity receiver (PDR) with extended bandwidth and high resolution. This will be validated for biomedical optical coherence tomography (OCT) imaging in a cardiovascular application and compared against currently available receivers.

Next-2Digits' innovative work will contribute to the fields of sustainable and efficient environmental monitoring and medical diagnostics.

Graphene and other 2DM have superior optoelectronic properties compared with conventional materials, making them ideal for a wide range of applications. Yet, the integration and processing challenges associated with these 2DM hinder the industrial uptake. With the novel additive and digital manufacturing technologies developed within the project, thanks to the remarkable expertise of its consortium, Next-2Digits will pave the way for large-scale graphene production for photonic devices. This sets the stage for the first market-ready photodetector products, establishing accessible fabrication processes for European industry.

The project aims to solve application-specific challenges that hamper the wide adoption of graphene and 2D materials in optoelectronics and sensors. In addressing LiDAR challenges on Si waveguide platforms, where density is the key, Next-2Digits aims to overcome limitations in detector footprints by ensuring a pitch as large as the waveguide width, around 5 µm, regardless of the platform (SiN or Si). The LiDAR array within the project will cover a 10x10 mm2 area and consist of 20,000 PDs, achieving a resolution of less than 0.1 mm at the maximum distance. The system features fast detection (500 GHz), compactness (less than 250 cm^3), lightweight design (under 300 g) and power efficiency (below 5 W), enabling the demonstration of a LiDAR-based drone for geo-mapping.

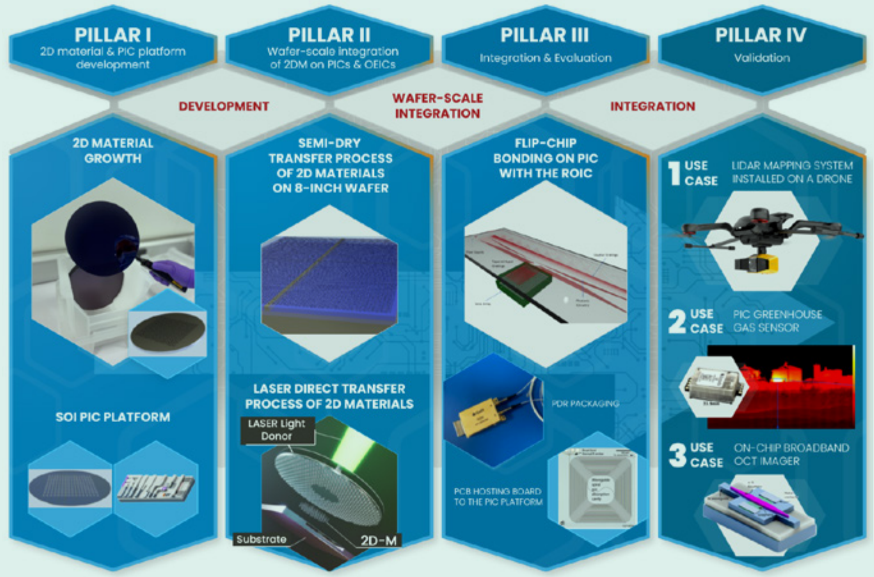
The challenges in PIC gas sensors, which involve integrating cost-effective mid-infrared (mid-IR) LEDs and PDs, include addressing dimensional mismatches with additional photonic coupling structures. The solution proposed by Next-2Digits involves using 2DM as mid-IR emitters and detectors, enabling seamless integration into silicon photonics. The key enabling technology, LDT, will be employed to realise integrated 2D-based modulators (MDs) and PDs on silicon photonics, facilitating non-dispersive infrared (NDIR) gas sensing solutions. The project aims to develop first-generation sensors with a limit of approximately 50 ppm, offering a cost-effective and compact solution for detecting various gas leakages, including those from biogas plants.

The current challenge in polarisation diverse receiver (PDR) applications lies in their reliance on bulk or fibre optics. Being more sensitive to transverse electric (TE) polarisation than transverse magnetic (TM) polarisation, it requires a polarisation rotator for optimal performance, to convert all TM polarised signals to TE before detecting them. Next-2Digits proposes a solution using PIC waveguides and integrated graphene detectors. This approach aims to miniaturise the receiver architecture, reducing the costs, and involves careful simulation of graphene PDs to optimise their lengths for separately detecting TE and TM polarisations, ensuring a well-balanced measurement of signals for both polarisations.

SUSTAINABLE SOLUTIONS

Next-2Digits introduces sustainable solutions in alignment with the European Green Deal and Europe fit for the digital age. The project features a laser-based process for the selective transfer of graphene/2DM, offering a digital and solvent-free additive manufacturing process based on laser pulses. This approach eliminates the use of chemicals, minimises material waste and reduces non-recurring engineering time. The single-step transfer method, free-form processing and absence of masks contribute to a sustainable and efficient process, with minimal waste production.

These sustainable practices offer significant benefits, including the LDT method as a green semiconductor processing example, replacing chemicals with laser light. The intrinsic cleanliness of the transfer method minimises undesired recombination processes and stray doping that typically degrade device performance. As a result, PIC-based components developed through Next-2Digits exhibit up to six times lower power consumption, significantly reduced size and over 50% cost reduction, contributing to a more sustainable and cost-effective technology landscape.



Validation of Next-2Digits use cases: (1) LiDAR-based aerial mapping system; (2) waveguide-based NDIR gas sensor; (3) OCT imager.

NEW HORIZONS

The project is currently in its first year, implementing the specification and design phase. The next year will be dedicated to the development of the PIC platforms and the fabrication of the 2DM-based devices employing laser digital transfer and semi-dry transfer technologies. The third year of the project will focus on the integration of the 2DM-based devices into the TRL5 demonstrator prototypes and the testing and validation of their performance.

The main challenge foreseen at this phase is to ensure the compatibility of the newly introduced 2D material transfer technologies with the SOI platforms and the processes involved in both the fabrication of the waveguides and the integration of the chips, while keeping the 2D material layers intact and defect-free.

COLLABORATIONS

Being part of the Graphene Flagship ecosystem provides the Next-2Digits consortium with excellent opportunities in terms of improving their innovation capacity and forging new collaborations with worldwide experts in 2DMdesign, synthesis and applications. As it provides access to a vast network of researchers, organisations and experts in the field of graphene and 2DM, this collaborative environment facilitates knowledge exchange, sharing of best practices and the opportunity to engage in synergistic activities.

Overall, this partnership allows the Graphene Flagship community to capitalise on the extensive experience and expertise of the Next-2Digits consortium, fostering a strong and coherent initiative. Next-2Digits has been involved with the Graphene Europe CSA even before its official Kick-off and is committed to supporting and contributing to the maximum, starting by co-organising the next Graphene Week (2024).

This collaboration enhances the impact of individual projects and contributes to sustaining European leadership in the field of 2D materials.

The Next-2Digits concept consists of four pillars of R&I activities encompassing: 2D material and Si waveguide development, integration of 2D materials using additive transfer processes on SOI PIC platforms, integration of active components on the PIC platforms and evaluation and validation of Next-2Digits use cases (LiDAR-based aerial mapping system, waveguide-based NDIR gas sensor and OCT imager).

Electronics and Photonics

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Exploring the Marvels of 2D Materials

Properties and applications of TMDCs, MXenes, h-BN and h-AlN

IN THE REALM of materials science, the discovery of graphene heralded a new era of exploration into two-dimensional materials (2DM). Since then, a plethora of novel 2D materials have emerged, each with unique properties and promising applications. Among these, transition metal dichalcogenides (TMDCs), MXenes, hexagonal boron nitride (h-BN), and hexagonal aluminum nitride (h-AlN) have garnered significant attention for their diverse range of properties and potential applications. In this article we delve into the properties and explore the exciting applications of these remarkable materials.

TRANSITION METAL DICHALCOGENIDES

Transition Metal Dichalcogenides (TMDCs) represent a class of 2D materials composed of transition metal atoms sandwiched between layers of chalcogen atoms, typically sulfur, selenium or tellurium. Unlike graphene, which is a zero-bandgap material, TMDCs possess a finite bandgap, rendering them suitable for electronic and optoelectronic applications. One of the most notable properties of TMDCs is their thickness-dependent bandgap, enabling tunable electronic properties by simply varying the number of layers.

TMDCs exhibit exceptional electronic, optical and mechanical properties. They possess high carrier mobility, making them promising candidates for high-speed transistors and flexible electronics. Additionally, TMDCs demonstrate strong light-matter interactions, paving the way for applications in photodetectors, photovoltaics and light-emitting diodes (LEDs). Moreover, their mechanical flexibility and strength make them suitable for applications in flexible and wearable electronics.

TMDCs exhibit exceptional electronic, optical and mechanical properties.”

MXENES

MXenes are a family of 2D transition metal carbides, nitrides and carbonitrides, first synthesised in 2011. Unlike many other 2D materials, MXenes are derived from their bulk counterparts through selective etching of the ‘A’ layer, typically aluminum or silicon, from MAX phases. MXenes exhibit a unique combination of metallic conductivity and hydrophilicity, making them attractive for a wide range of applications.

The versatile properties of MXenes render them suitable for energy storage, catalysis, sensing and electromagnetic interference shielding. They have been extensively studied for their use in supercapacitors and batteries due to their high specific capacitance and excellent rate capability. MXenes also show promise in catalytic applications, where their high surface area and metallic conductivity enhance reaction kinetics.

HEXAGONAL BORON NITRIDE

Hexagonal boron nitride (h-BN), also known as white graphene, shares a similar hexagonal lattice structure with graphene but consists of alternating boron and nitrogen atoms. Unlike graphene, h-BN is an insulator with a wide bandgap, making it an excellent dielectric material. Its exceptional thermal and chemical stability, combined with high thermal conductivity, make it an ideal candidate for high-temperature applications and thermal management.

h-BN finds applications in a variety of fields, including electronics, photonics and aerospace. It is utilised as a dielectric material in field-effect transistors (FETs), where its high breakdown voltage and low leakage current improve device performance. Additionally, h-BN serves as a substrate for graphene and other 2D materials, providing a stable and atomically flat surface for growth and device integration.

HEXAGONAL ALUMINUM NITRIDE

Hexagonal aluminum nitride (h-AlN) is a wide-bandgap semiconductor with properties similar to those of h-BN. It exhibits excellent thermal conductivity, high electrical resistivity and chemical inertness, making it suitable for various electronic and optoelectronic applications. h-AlN is often employed as a substrate material for gallium nitride (GaN) devices due to its lattice matching and thermal expansion coefficient compatibility with GaN.

h-AlN has found applications in high-power electronics, UV optoelectronics and surface acoustic wave (SAW) devices. Its wide bandgap allows for the fabrication of UV photodetectors and light-emitting diodes (LEDs) with superior performance and efficiency. Moreover, h-AlN’s piezoelectric properties make it suitable for SAW devices used in wireless communication systems and sensors.

LIMITLESS POSSIBILITIES

The exploration of 2D materials has unlocked a treasure trove of unique properties and promising applications. TMDCs, MXenes, h-BN and h-AlN exemplify the diverse range of materials available in the realm of 2D materials. Their unique properties are being explored in various high-impact applications. In electronics, these materials could be used in the next generation of transistors, memory devices and flexible electronics, offering potential solutions to the limitations of silicon-based technologies. Their optical and electronic properties are also exploited in the development of novel optoelectronic devices, including LEDs, lasers and photovoltaic cells.

The breadth of 2D materials and their properties present limitless possibilites for future research and advancements in high-impact applications.”

In the energy sector, these 2D materials show great promise in improving the efficiency and performance of energy storage devices, such as batteries and supercapacitors, and in the development of efficient catalytic systems for energy conversion processes. Additionally, their high surface area and tunable surface properties make them excellent candidates for sensing applications, including environmental monitoring and biomedical sensors. As research continues to unravel their mysteries and refine fabrication techniques, the potential for transformative applications of 2D materials remains limitless.

CHALLENGES AND FUTURE PERSPECTIVES

Despite the significant advancements in the field of 2D materials, challenges remain in terms of scalable synthesis, integration into devices and stability. The development of cost-effective and scalable production methods is crucial for the commercialisation of these materials. More work is ongoing to understand the potential of 2DMs and how they can be used for specific applications. The next step is engineering materials with specific properties and for specific applications.

GRAPHENE FLAGSHIP ANNUAL REPORT 2023

GIANCE

Pioneering sustainable solutions for industrial advancement

THE GIANCE project is a pioneering initiative aimed at revolutionising the landscape of graphene and other 2D materials (2DM) by establishing a holistic, integrated and industry-driven platform. Our mission is clear: to design, develop and scale-up the next generation of cost-effective, sustainable and high-performance 2DM-based multifunctional composites, coatings, foams and membranes, all with a keen focus on real-world applications and sustainability.

MEETING NEW CHALLENGES

Our project addresses a myriad of challenges faced by industries worldwide. By engineering advanced materials with enhanced thermal, mechanical and chemical attributes, we aim to provide functionalities ranging from wear resistance to structural health monitoring. These materials hold immense potential for applications in diverse sectors, including automotive, aerospace, energy and water treatment, thus paving the way for ground-breaking innovations and societal benefits.

The applications for our project outputs are vast and impactful. From revolutionising transportation through lightweight and durable components to enhancing energy efficiency in the hydrogen economy, our materials offer solutions to pressing societal and environmental challenges. By incorporating 2DM-based technologies into major civilian sectors, we aim to drive economic growth, promote sustainability and improve quality of life for individuals worldwide.

Within the European ecosystem for 2DM, GIANCE serves as a robust catalyst for innovation and industrial advancement. By fostering collaborations between leading original equipment manufacturers (OEMs), industries, research organisations and small and medium-sized enterprises (SMEs), we create synergies that propel 2DM technologies to new heights. Our project not only strengthens the competitiveness of European industries but also positions the region as a global leader in 2DM research, development and commercialisation.

GIANCE is dedicated to overcoming key challenges in 2DM synthesis, stability, manufacturing and environmental impact. Through advanced research and development efforts, we aim to streamline production processes (increasing 25% productivity), improve a huge range of material properties such as impact strength, fire resistance, weight reduction and different functionalities in a range of up to 30% and minimise ecological footprint (30% improvement in environmental performance). By addressing these challenges head on, we pave the way for the widespread adoption of GRM-based technologies in various industrial applications, thereby driving sustainable growth and innovation.

SUSTAINABLE SOLUTIONS

Our project aligns closely with Europe's sustainability goals by prioritising the development of eco-friendly materials and manufacturing processes. GIANCE will offer a robust modular and integrated conceptual eco-design for products using innovative 2DM-based multifunctional composites, coatings, foams and membranes solutions supported by life cycle assessment, including the optimisation of multifunctional designs. By leveraging 2DM-based technologies, we aim to reduce resource consumption, minimise waste generation and mitigate environmental impact across the entire value chain. Through our sustainable solutions, we strive to promote responsible innovation and contribute to a greener, more sustainable future for generations to come.

The project GIANCE is revolutionising the graphene and related 2D materials landscape, driving sustainable solutions and impactful innovations across various sectors, including automotive, aerospace, energy (hydrogen economy) and water treatment. With our collaborative efforts, we're shaping a greener, more sustainable future for industries worldwide."

Ana Villacampa
Project Coordinator

GIANCE plays a pivotal role in advancing Europe's sustainability agenda by developing sustainable materials and technologies that address critical socio-economic and environmental challenges. By fostering collaborations between industry stakeholders, research institutions and policymakers, we facilitate the adoption of sustainable working, educational and consumption practices and promote the transition towards a circular economy. Through our collective efforts, we aim to drive positive change and create lasting impact on both regional and global scales. Therefore, GIANCE implements the following SDGs: 4,5,8,9,12, 13 and 17.

NEW HORIZONS

Looking ahead, GIANCE has ambitious plans for the next few years. Our focus will be on advancing manufacturing processes, optimising material properties and scaling up production capabilities. However, we anticipate facing challenges such as technical hurdles, regulatory constraints and market uncertainties. Nevertheless, we remain committed to overcoming these obstacles through collaboration, innovation and strategic partnerships.

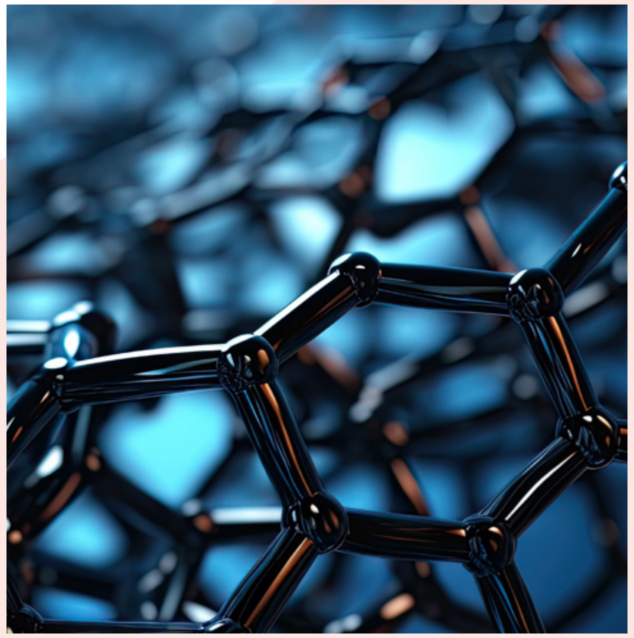
Over the next one to two years, our project will focus on enhancing material properties, optimising manufacturing processes and validating commercial propositions. Within a year the project is expected to have selected all validation strategies and circular designs for its products, and in two years all optimised materials will be implemented. Through experimental investigations and pilot-scale demonstrations, we aim to accelerate the transition of 2DM technologies from research to market. Despite the challenges ahead, we are confident in our ability to deliver impactful results and drive positive change in the industry.

Funding limitations, technical complexities and market uncertainties pose difficulties as the adoption of innovative materials in several markets besides their potential in effective manufacturing and reusability is uncertain due to the established products coming from Asia. To overcome these obstacles, we plan to leverage strategic partnerships, seek additional funding opportunities and engage with industry stakeholders to validate and commercialise our technologies. By adopting a proactive approach and staying adaptable to changing market dynamics, we aim to navigate challenges effectively and achieve our objectives.

COLLABORATIONS

As part of the broader Graphene Flagship ecosystem, GIANCE stands to benefit from enhanced visibility, networking opportunities and access to cutting-edge research facilities. Through collaborations with other research teams and industry partners, we aim to accelerate the translation of research findings into commercial products and services. We anticipate benefiting from access to valuable expertise, resources and infrastructure. By collaborating with other research teams and industry partners, we aim to accelerate the development and commercialisation of 2DM-based technologies. Additionally, our participation in collaborative initiatives and knowledge-sharing activities will enable us to stay at the forefront of materials innovation and drive positive change in the industry.

Our project contributes to the Graphene Flagship community by advancing the state-of-the-art in 2DM research, development and commercialisation. Through our collaborative efforts, we aim to generate new insights, develop practical solutions and drive innovation in the field of graphene and 2DM. By sharing knowledge, resources and best practices, we seek to enrich the Graphene Flagship ecosystem and contribute to its mission of fostering materials innovation for societal benefit.



Graphene hexagonal lattice structure, 3D model.

Composites

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With a consortium comprising 23 partners from 10 countries, representing the entire value chain, GIANCE is strategically positioned to maximise its impact on industries and society at large. Through collaborative efforts and innovative solutions, we aim to usher in a new era of sustainable materials and technologies that drive economic growth, promote environmental stewardship and improve quality of life for individuals worldwide.

GIANCE
Fused with Sustainability

GRAPHENE FLAGSHIP ANNUAL REPORT 2023

2D-PRINTABLE

Developing new 2D materials and heterostructures for printed digital devices using sustainable liquid exfoliation and deposition methods.

THE WORLD OF MATERIALS SCIENCE and nanoscience has been revolutionised by 2D materials (2DM).Thanks to their exceptional physical and chemical properties they have enabled ground-breaking applications in various fields, such as optoelectronics, energy, sensing technology and composite materials. However, the key to unlocking their full technological potential lies in finding cost-effective methods to harness these properties on a larger scale, to transfer the superlative electronic properties of individual nanosheets on macroscale samples. The 2D-PRINTABLE project is dedicated to achieving this goal by employing sustainable and affordable liquid exfoliation methods.

The 2D-PRINTABLE project aims to integrate sustainable large-scale liquid exfoliation techniques with theoretical modelling to produce a wide range of new 2DM, including conducting, semiconducting and insulating nanosheets. The focus includes developing the printing and liquid phase deposition methods required to fabricate networks and multicomponent heterostructures, featuring a layer-by-layer assembly of nanometre-thick 2DM into ordered multilayers. The goal is to optimise these printed networks and hetero-structures for digital systems, unlocking new properties and functionalities. The project also seeks to demonstrate various printed digital devices, including proof-of-principle, first-time demonstration of all-printed, all-nanosheet, heterostack light-emitting diodes (LEDs).

The project workplan is divided into the following phases:

Phase 1 – Involves computationally screening and analysing literature for novel 2DM, focusing on doped variants. These materials are exfoliated in liquid media for use in digital devices. Chemical modification follows to study optical and physical properties, ultimately forming heterostructures with well-defined interfaces.

Phase 2 – Focuses on developing methods for printing or solution-depositing high-mobility networks of nanosheets. Subsequently, the characterisation process comes into play, involving the comprehensive assessment of exfoliated and functionalised nanosheets, as well as the printed nanosheet networks and heterostructures.

Phase 3 – The electrical properties of individual flakes, networks, films and heterostructures are then characterised for performance optimisation. This step establishes an understanding of charge transport, charge injection mechanisms and structure-property relationships in printed structures.

In the Demo stage, novel 2DM are showcased in traditional electronic devices like thin-film transistors, solar cells, and LEDs, demonstrating their potential.

"2D-PRINTABLE will be pivotal in allowing us to use liquid exfoliation methods to develop a palette of new 2D materials perfectly designed for use in high performance printed electronic applications."

Jonathan Coleman
Project Coordinator

Through the 2D-PRINTABLE project, we will demonstrate that 2DM are an indispensable asset in the field of printed electronics and have the potential to contribute significantly to addressing some of the world's most pressing global challenges. The knowledge and innovations developed in this project will be instrumental for future emerging technologies in areas such as energy storage, water purification, environmental monitoring and healthcare.

MEETING NEW CHALLENGES

The project aims to produce over 45 new 2DM with properties ideal for electronics and photonic applications. 2D-PRINTABLE will develop all-printed, all-nanosheet devices – a platform technology that could be used in various specific applications. For example, such super-high-performance printed transistors will likely be used as low-cost/high-performance driver circuitry in active matrix displays (e.g., in smartphones), wearable health monitoring devices (e.g., blood pressure or heart rate monitors), and other IoE (Internet of Everything) devices. Ultimately, it will broaden and underpin the supply and value chains of graphene and 2DM in Europe.

Challenges addressed – Case study 1:
Wearable Health Monitoring
Wearable health monitors are vital for tracking various indicators like blood pressure and heart rate. Polymer-graphene pressure sensors can potentially detect symptoms of e.g.: diabetic neuropathy and multiple sclerosis Yet, integrating compact, lightweight, flexible, and affordable driver circuitry into insoles poses a challenge with conventional electronics. Our printed 2D driver circuitry addresses this challenge, enabling the implementation of sensors for early disease detection, particularly in affordable insole-based gait analysis. This breakthrough not only boosts healthcare monitoring but also has the potential to cut down the overall cost of disease treatment.

Challenges addressed – Case study 2:
Electronic Device Displays
Consumer displays, including smartphone screens, predominantly employ active matrix displays utilising thin-film transistors (TFTs) to control LED-based pixels. While many displays feature organic light-emitting diodes (OLEDs) as pixels, the TFTs responsible for switching are typically silicon-based and not printable. In the paradigm proposed by 2D-PRINTABLE, silicon-based TFTs can be replaced with printed nanosheet-based TFTs, to reduce both the cost and energy consumption of mobile devices, thereby ushering in a new era of sustainable and cost-effective electronic displays.

In summary, 2D-PRINTABLE aims to accelerate the outputs of the Graphene Flagship to develop new materials and processing technologies allowing the production of high-performance printed electronic devices, reinforcing European leadership within the printed electronics industry.

SUSTAINABLE SOLUTIONS

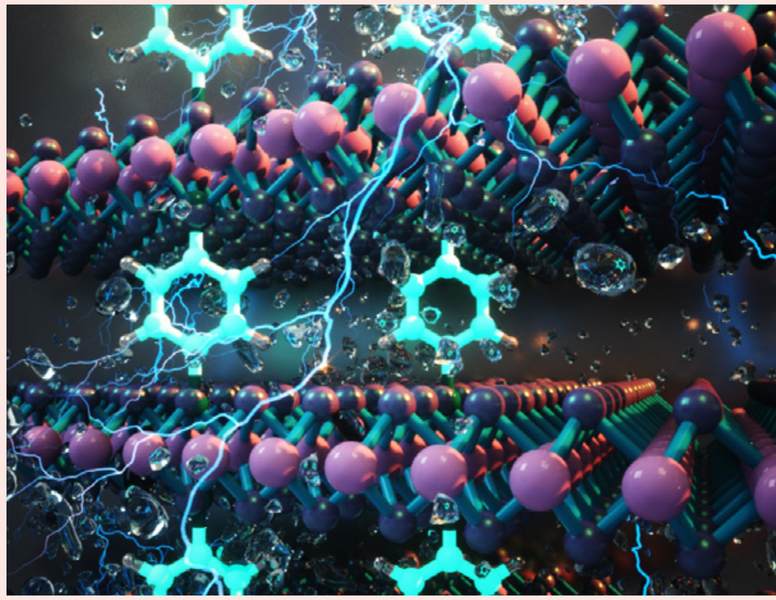
The 2D-PRINTABLE project contributes to Europe's sustainability goals by embracing environmentally friendly practices throughout its entire supply chain. The newly developed materials' potential (nano)toxicity will be evaluated to guarantee maximum safety in the entire supply chain. Such measures will ultimately enable the development of greener, more sustainable, and circular materials and processes. A pivotal aspect of the project's commitment to sustainability is the rigorous identification and application of green solutions. The shift toward greener synthesis methods adheres to Responsible Research and Innovation and Safe and Sustainable by Design criteria, contributing to a more sustainable and environmentally friendly supply chain. The project strongly emphasises utilising inorganic, earth-abundant materials and non-toxic solvents for printing, with a preference for aqueous inks and the use of benign solvents. To further enhance sustainability, any toxic solvents used will be recycled and reused, aligning with circular economy principles. Additionally, demonstrating the potential of all-printed, all-nanosheet devices like LEDs, solar cells and transistors could pave the way for flexible and wearable electronics, reducing electronic waste and contributing to a more sustainable electronics lifecycle.

NEW HORIZONS

There are several challenges related to the successful exploitation of the full potential of 2DM in printed electronics: i) One significant challenge is the limited exploration of materials in printed nanosheet devices. Therefore, the project will expand the materials palette to include a broader range of 2DM, considering their unique characteristics for enhancing device performance. ii) One of the most serious problems for producing high-performance nanosheet-based printed devices is the effect of inter-nanosheet junctions. The junction resistance is often much larger than the nanosheet resistance, limiting mobility and hindering major progress in 2D-printed electronics. The project will develop novel strategies to eliminate or mitigate junction resistance in nanosheet networks. Additionally, scaling up the production of 2D materials will be a focus, with an emphasis on exploring scalable and cost-effective production methods and collaborating with industry partners.

COLLABORATIONS

The broader collaboration within the Graphene Flagship provides valuable access to a diverse network of partners within the initiative, fostering opportunities for collaborative research and knowledge exchange and provide 2D-PRINTABLE with access to expertise, insights and synergies for advancing its research objectives. With its contribution to addressing challenges related to scalable production processes and achieving breakthroughs in the applications of 2DM, the project can contribute valuable knowledge, methodologies, and potentially novel materials to the broader Graphene Flagship community.



Artistic visualization of two dimensional heterostructures.

2D-PRINTABLE actively seeks collaboration with other EU projects addressing 2DM technologies. This collaborative effort aims to establish Europe's long-term technological leadership and industrial competitiveness. The project will engage in joint dissemination activities, including participation in Graphene Week conferences, workshops and webinars. This collaborative and proactive approach underscores the project's commitment not only to advancing its specific objectives but also to contributing to the collective progress and regulatory frameworks within the Graphene Flagship community.

2D Materials of Tomorrow

PROJECT COORDINATOR
Jonathan Coleman, Trinity College Dublin, Ireland

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2D PRINT ABLE

GRAPHENE FLAGSHIP ANNUAL REPORT 2023

2D ENGINE

Engineering new 2D materials
phases not existing in nature

> This project is pushing the boundaries of engineering by synthesising new 2D materials."

Thanasis Dimoulas
Project Coordinator

IMAGINE MATERIALS as thin as a single atom, yet possessing incredible strength, flexibility and electrical properties. These are not the stuff of science fiction, but the result of cutting-edge engineering. Two-dimensional materials (2DM), best exemplified by graphene – a single layer of carbon atoms arranged in a honeycomb lattice – have opened the door to a universe of possibilities that were previously unimaginable.

In this project we are pushing the boundaries even further by engineering new phases of 2DM which cannot be produced in bulk form by equilibrium growth methods, so they cannot be exfoliated but they can only be engineered as atomically thin 2D films by synthetic methods. Essentially, we will be creating materials with tailored properties for specific applications. These materials could revolutionise industries, such as electronics, where they could lead to the development of ultra-fast, ultra-thin and energy-efficient devices.

We target a class of materials that are semiconductors (GaN, SiC) and insulators (AlN) adopting the wurtzite 3D structure in their bulk form. These materials are polar, accumulating charge and building electrostatic energy on their surface. Under a critical thickness of a few monolayers, the materials transition to a flat, non-polar 2D hexagonal phase resembling that of hexagonal boron nitride (hBN) in order to minimise or eliminate the electrostatic energy. The main objective is to engineer these materials in the targeted 2D hexagonal phase and incorporate them into proof-of-concept transistors, memory and light emitting diode devices, to show that they can have an impact on electronic and photonic technologies.

Key enablers are the liquid metal catalyst technology for the seamless growth of large-area single-crystal 2D layers and radiation-mode optical microscopy for real-time monitoring of growth. Our methodology will be further supported by atomistic simulations, molecular beam epitaxy growth and several in situ and ex situ surface analytical techniques to validate the new 2D hexagonal phases. We will leverage previous results published by consortium members on the liquid metal catalyst growth of graphene and the molecular beam epitaxy growth of hexagonal AlN on silver, to extend these methodologies to the new materials phases targeted in this project.

MEETING NEW CHALLENGES

2D ENGINE is expected to impact electronics and photonics and primarily aims to provide solutions for the miniaturisation of mainstream transistors beyond the 2nm technology node. Our materials could help bringing Moore's law to the angstrom regime. Moreover, 2D light-emitting diodes efficiently coupled to planar waveguides could be ideal for the realisation of photonic integrated circuits for on-chip optical communication. It proposes a totally new materials class beyond graphene and 2D transition metal dichalcogenides which have been intensely investigated. The 2D ENGINE materials are 2D semiconductors and insulators with sp2 hybridisation offering stability that rivals that of graphene but additionally possess an electronic band gap that makes them better suited to efficient transistors for digital logic and for light emission and optical information processing.

The proposed new 2DM phases are expected to inherit some of the desired properties of their well-known parent 3D materials (SiC, GaN, AlN), including their processability and compatibility with Si processing. One of the biggest challenges is finding suitable atomically thin and stable 2D semiconductors which will allow the ultimate scaling of the active channel thickness to the angstrom regime. Thin channels allow for better electrostatic control so devices could be laterally scaled to the nanometre range without suffering from short channel effects. In the end, this will allow the miniaturisation of devices for the benefit of reduced cost, combined with higher performance and lower static and dynamic power dissipation. While 2D semiconductors from the transition metal dichalcogenides family do exist, these are not so stable, especially after transferring to target substrates, while optimum contacts and doping have not been identified. The 2D ENGINE semiconductors could help overcome the shortcomings of present 2D semiconductors, providing more stable materials with better processability.

SUSTAINABLE SOLUTIONS

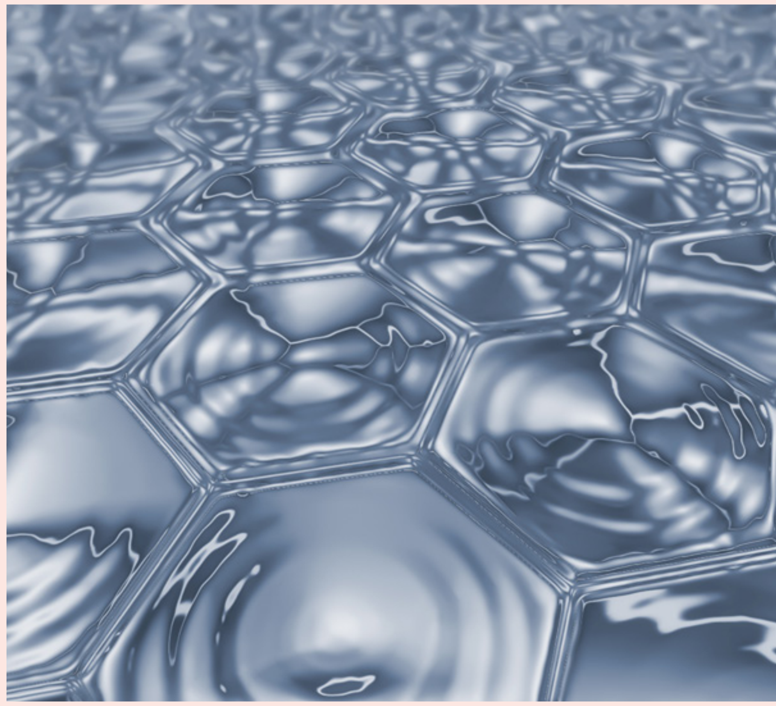
2D ENGINE, through the miniaturisation of mainstream digital electronic and photonic devices, will ensure low cost, high density and low power consumption to face the challenges of handling a large amount of inhomogeneous and unstructured information in the Cloud and at the edge, leading to a sustainable Industry 4.0 evolution. Moreover, device miniaturisation and optical on-chip communications could lead to energy-efficient integrated circuits with an immediate impact on energy savings and the environment.

NEW HORIZONS

In the first year, 2D ENGINE will focus on the growth and validation of 2D phases to make sure that the hexagonal 2D phase is obtained, as targeted. Then, the consortium will evaluate the stability of the materials in order to prepare for the device fabrication planned within the first 36 months of the project. To achieve our most urgent objectives in the first 18 months, the main challenges faced are associated with the growth of ultrathin layers below the critical thickness to induce the transition to the 2D hexagonal phase. An important, related issue is to obtain large-area crystals in the mm scale, to facilitate device fabrication. To face these challenges, two different growth methodologies, namely liquid metal catalysis and molecular beam epitaxy will be employed to maximise our chances of success. An equally important challenge is to confirm the 2D hexagonal phase of the grown thin films. To achieve this, several in situ and ex situ surface analytical techniques will be employed, including high-resolution and high-sensitivity synchrotron X-ray scattering, complemented by atomistic modelling.

COLLABORATIONS

Collaboration with other projects in the electronics and photonic clusters of the Graphene Flagship ecosystem is expected to benefit 2D ENGINE, although these projects have higher technology readiness level (TRL). Interaction with the active 2D-EPL and the possible successor project is expected to promote our goals. We envisage valorising our liquid metal catalyst technology by investigating the compatibility with established 2DM processing practices in a 2D pilot line. Integration of inspection tools developed in 2D ENGINE with the pilot line and investigation of cross-contamination issues will be a priority in our interaction with the 2D-EPL. Depending on the 2D ENGINE results, an MPW run at the 2D pilot line of a photonic integrated circuit based on a 2D light emitting diode integrated with a waveguide is planned at the end of the four-year project. Our long-term vision is that 2D ENGINE catalyses the interaction between the Graphene Flagship community and the broader Chips Act initiative in Europe and the Chips Joint Undertaking in specific. The 2D ENGINE goals match well with the Chips JU pilot lines and competence centre plans. More specifically, the plans of 2D ENGINE regarding a photonic integrated circuit based on 2D SiC or GaN could take advantage of optically addressable spin defects (known in bulk SiC as colour centres/single photon emitters) to create a spin-photon interface for qubit and quantum entanglement targeting quantum communications. Such an activity could contribute to the effort for quantum chips within the Chips JU initiative making the 2DM community a key player in the Chips Act European endeavour.



The possibilities posed by 2D materials and their properties are not the stuff of science fiction, but rather the result of cutting edge engineering.

2D Materials of Tomorrow

PROJECT COORDINATOR
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2DSPIN-TECH

Applying spintronics to provide a break-through for next generation computer memory technologies

> The aim of the project is to demonstrate efficient 2D spin-orbit torque memory devices."

Saroj Dash
Project Coordinator

THE FLOW OF charged electrons can generate electrical current, and in addition to this charge it also carries a spin. In the same way traditional electronics uses charge current to represent information as zeros and ones, the spin current can be used to represent the same binary data in spintronics. Such devices should have quicker switching times and lower power consumption than conventional devices because spin can be manipulated faster and at lower energy costs than charge can.

2DSPIN-TECH envisions a new paradigm in materials science by utilising novel, atomically thin two-dimensional (2D) quantum materials and their heterostructures to develop an experimental prototype memory device based on the spin-orbit torque (SOT) mechanism, advancing the research from technology readiness level (TRL) two to four.

MEETING NEW CHALLENGES

In the conventional 'volatile' memory used for fast random-access memory (RAM), data is only maintained when the memory chip is powered. NAND flash memory achieves non-volatile storage but is orders of magnitude slower than that needed for processor-adjacent memory. A key advantage of spintronics is that electron spin is not energy-dependent, spin is non-volatile – preserving stored data even after loss of power.

The first application of spintronics to computers was based on the work of Professors Albert Fert and Peter Grünberg awarded the 2007 Nobel Prize in Physics for their discovery of giant magnetoresistance (GMR). They realised they could use electron spin to increase the reading rate from a hard disk drive. Ever since, spintronics researchers have been working on introducing the same technology to computer memory, aiming to replace electrical current-based dynamic random-access memory (DRAM) with magnetic RAM (MRAM).

MRAM technologies are built on magnetic tunnel junctions (MTJ) comprised of two ferromagnetic (FM) layers separated by a thin insulator. The structure appears to be simple but practical devices are far more complex. Improving the MTJ stacks and their versatility using conventional materials and integration processes is a difficult challenge. The actual stacks consist of dozens of ultra-thin layers in which each material and interface plays an important role in determining the device performance. However, to date, only a very limited number of optimal material combinations have been identified, in particular CoFeB/MgO has played a prominent role for nearly two decades since no alternative has been found yet. As the MTJ size is downscaled, charge accumulation near the interface reduces the energy dissipation and memory cell area. Consequently, MRAM technology faces severe constraints, threatening its future evolution and broad deployment.

2DSPIN-TECH proposes new concepts for MRAMs and shows that graphene and other 2D materials (2DM) can potentially be the solution to all the current technology roadblocks. For example, graphene has high electron mobility needed for high-speed electronics, while transition metal dichalcogenides (TMDCs) exhibit a wide range of properties: semiconducting, metallic, superconducting, magnetic or topological. The use of 2DM offers several advantages, such as an atomically thin body, ultra-flat interface, with minimal element intermixing between layers, stacked in any preferred combination and order and extreme sensitivity to external stimuli. This allows for large gate tunability and strong interface proximity interactions, which can tune and optimise desirable properties and improve device performance.

SUSTAINABLE SOLUTIONS

Spintronics has the potential to realise high performance with ultralow power consumption and fast speeds. It offers a way to advance technologies in various areas, such as quantum computing and energy harvesting, which are key to realising a low-carbon society.

Low-Power Electronics: Spintronic devices can operate with significantly lower power consumption compared to conventional semiconductor devices based on charge transport. This is because spintronics utilises the spin of electrons, a quantum property, to manipulate the flow of information, reducing the amount of energy required for switching and processing.

Non-Volatile Memories: Spintronic memory technologies eliminate the need for constant power consumption to maintain memory, leading to significant energy savings, especially in battery-powered devices.

High-Speed Data Processing: Spintronic devices can achieve faster switching speeds compared to conventional semiconductor devices, enabling faster data processing and communication. This can reduce the time required for computations and data transfer, leading to energy savings in data centres and other high-performance computing environments.

Reduced Joule Heating: Spintronic devices generate less heat during operation compared to conventional semiconductor devices. This reduces the need for cooling systems, which consume energy and contribute to greenhouse gas emissions.

Sustainable Materials: Spintronic devices often require less material to manufacture compared to conventional semiconductor devices. Additionally, the use of 2DM in spintronics can further reduce the amount of material required, leading to a smaller environmental footprint.

NEW HORIZONS

The discovery of novel materials and nanoscience has been a driving force behind the modern information technology (IT) revolution. The rapid IT expansion generates a vast amount of digital data that needs to be stored, processed and communicated. However, traditional materials offer limited performance and energy efficiency, hindering their ability to meet future computing demands. 2DSPIN-TECH envisions a new paradigm in IT, one in which, novel atomically thin two-dimensional (2D) quantum materials and their heterostructures are utilised. 2DM will have a significant impact on IT due to their unique electronic properties. 2DSPIN-TECH has the ambition to exploit novel 2DM heterostructures to develop an experimental prototype non-volatile magnetic memory device based on a basic spin-orbit torque mechanism.

The main challenges are the fabrication of high quality 2D heterostructure devices and their interface engineering for utilisation in non-volatile memory applications, which can be faster, energy efficient and multi-functional. To achieve this, we plan to carefully engineer the properties of the 2D heterostructures by controlling the interfacial effects and gain a deeper understanding of the fundamental interactions at play.

COLLABORATIONS

The Graphene Flagship's Coordination and Support Action (CSA) will coordinate 12 graphene and 2DM Research and Innovation Actions (RIAs) and Innovation Actions (IAs) projects. This allows the separate actions to exploit synergies in their scientific and technological activities and work more efficiently by utilising common services and support functions provided by the project.

We hope the 2DSPIN-TECH results can be integrated in the CSA's communication platform to a large extent. 2DSPIN-TECH will provide technical content that can feed into the CSA activities related to road-mapping for industrialisation, especially in the area of 2DM for spintronics and electronics applications. We can make a solid contribution to standardisation on terminology and characterisation of graphene and other 2DM by involving the discussion of new standards and applying existing standards to characterise the materials.

Researchers working in the cleanroom.
Credit: Chalmers University of Technology

2D Materials of Tomorrow

PROJECT COORDINATOR
Saroj Dash, Chalmers University of Technology, Sweden

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University of Manchester, UK
Hq Graphene, Netherlands
Chalmers Industriteknik, Sweden

2DSPIN-TECH

SAFARI

Safe and sustainable by design graphene/MXenes hybrids

MXenes will be applied in energy storage, shielding of electromagnetic field, water purification, construction of sensors and biosensors as well as lubrication and catalysis."

Dariusz Garbiec
Project Coordinator

THE SAFARI PROJECT is developing a new kind of super-thin material called MXenes in a way that's safe for people and the environment. MXenes are remarkable for their properties, which can enhance products we use every day, like electronics and energy devices.

The main goal of the SAFARI project is to find better and safer ways to make MXenes, as the current process is far from perfect. It uses some chemicals that are harmful, and the materials produced aren't always as pure or predictable as they need to be.

In this frame, SAFARI aims to improve the process from scratch. This means finding better ways to prepare the materials we need to make MXenes, making the MXenes themselves in a safer and more efficient way and figuring out how to use them in ways that are good for people and the environment.

Ultimately, SAFARI is working to make MXenes cleaner, more reliable and easier to produce. This will help scientists and companies use them to create new technologies that could make our lives better, without causing harm to the planet or ourselves.

MEETING NEW CHALLENGES

SAFARI addresses several key challenges in the production and utilisation of MXenes, a class of 2D materials (2DM) with exceptional properties. One significant challenge to solve is the development of sustainable and efficient production methods for MXenes. Current production processes often involve the use of hazardous chemicals, leading to environmental concerns and safety risks. SAFARI aims to overcome this challenge by implementing a safe and sustainable-by-design (SSbD) strategy, integrating REACH-compliant chemicals and evaluating processes for safety and sustainability.

By tackling these challenges, SAFARI opens opportunities for a wide range of real-world applications. For instance, we are demonstrating MXene-graphene hybrids in biosensors for glucose and lactate where we target a biosensing sensitivity reaching a detection limit of 10 nM for glucose and 100 nM for lactate. We are also producing conductive inks with a conductivity up to 4.000 S/cm for MXenes and 400 S/cm for Mxene-based inks after curing. Finally, we are developing electromagnetic shielding coatings with MXene paints ranging from 48 to 70 dB over a thickness range of 1.5–45 µm.

Moreover, SAFARI brings significant benefits to the European ecosystem for 2DM, by developing advanced production methods for MXenes. SAFARI enhances the competitiveness of European industries in the global market and with its focus on safety, sustainability and regulatory compliance ensures that European companies adhere to high standards while remaining innovative and efficient. Overall, SAFARI plays a crucial role in unlocking the full potential of MXenes and driving sustainable economic growth and technological advancement in Europe.

SUSTAINABLE SOLUTIONS

SAFARI contributes to Europe's sustainability goals in several ways, aligning with the objectives outlined in initiatives such as the European Green Deal and Horizon Europe. Firstly, SAFARI focuses on developing sustainable production methods for MXenes, reducing energy consumption and minimising the use of hazardous chemicals. By implementing a safe and sustainable-by-design (SSbD) strategy, SAFARI ensures that the entire lifecycle of MXene production, from raw materials to end-of-life scenarios, complies with environmental standards and regulations.

Moreover, SAFARI's emphasis on improving material quality and purity enhances the efficiency and reliability of MXene-based products. Higher-quality MXenes require fewer resources for manufacturing and maintenance, leading to reduced waste and environmental impact over the product lifecycle. SAFARI's outputs, including advanced production methods, standardised characterisation techniques and safety assessment methodologies, contribute to a more environmentally friendly future by promoting responsible innovation and technology development.

NEW HORIZONS

SAFARI just launched and we are in the process of aligning our work across all the work packages and partners involved. The project has established a communication and dissemination plan which includes a visual identity, printed materials and representation in social media and our website. Furthermore, technical meetings have resulted in a detailed workplan for the first year of the project starting with the definition of specifications and requirements for the development and production of MXenes, assessing their toxicological profiles as well as their sustainability through a decision-support tool.

The Safari team.
Credit: SAFARI

A glimpse of graphene, the thinnest and strongest material known, capable of shaping the future of electronics, energy storage and beyond.

COLLABORATIONS

Being a part of the broader Graphene Flagship ecosystem offers several benefits for SAFARI and its stakeholders. Firstly, collaboration within the Graphene Flagship provides access to a vast network of academic and industrial partners across Europe, fostering knowledge exchange, collaboration and synergies. This network enables SAFARI to leverage expertise, resources and infrastructure from diverse disciplines, enhancing the development and implementation of innovative technologies based on graphene and other 2DM.

Our participation in the Graphene Flagship ecosystem enhances our visibility and credibility facilitating opportunities for collaboration and commercialisation. Being part of the initiative supports SAFARI's commitment to excellence and leadership in the field of 2DM research and innovation, strengthening its position within the scientific community and industry.

Moreover, SAFARI's collaboration with the Graphene Flagship offers opportunities for cross-fertilisation of ideas and technologies. By sharing insights, methodologies and best practices with other projects and initiatives within the Graphene Flagship, SAFARI can accelerate progress, address common challenges and maximise impact.

In return, SAFARI contributes to the Graphene Flagship community by bringing its expertise, capabilities and perspectives to the table. SAFARI's focus on safe and sustainable production methods for MXenes complements the Graphene Flagship's efforts to advance the development and commercialisation of graphene and other 2DM. By sharing its research findings, insights and technological advancements with the broader Graphene Flagship community, SAFARI enriches the collective knowledge base and progress towards shared goals.

Safe by Design

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AXIA Innovation GmbH, Germany
Metrohm DropSens SL, Spain

SAFARI

Empowering innovation through Standardisation

Illuminating the world of 2D materials

IN A REALM where innovation thrives on the cutting edge, the quest for new materials with tailored properties propels industries forward at an unprecedented pace. Yet, amidst this surge of ingenuity, a critical challenge emerges: How do we ensure consistency, reliability and trust in these novel materials?

Dr. Jörg Radnik, a distinguished expert at the Bundesanstalt für Materialforschung und – prüfung (BAM), provides invaluable insights into the pivotal role of standardisation, particularly within the realm of 2D materials. In his role as standardisation leader for the GrapheneEU Coordination and Support Action, Radnik will guide the Graphene Flagship projects in standardisation matters and help them to take part in the standardisation decisions being made today which will impact the field for decades to come.

Radnik, with a profound background steeped in decades of research in X-ray spectroscopy, catalysis and analytical methods, brings a wealth of experience to his current role at BAM's Division 6.1: Surface Analysis and Interfacial Chemistry. Since joining BAM in 2016, he has been a driving force behind advancements in analytical techniques, notably X-ray photoelectron spectroscopy (XPS) and has actively contributed to standardisation efforts, both domestically and on a global stage.

THE SIGNIFICANCE OF STANDARDS IN MATERIAL DEVELOPMENT

In a candid dialogue with Radnik, the paramount importance of standards in material development becomes abundantly clear. He articulates how uncertainties often shroud the characterisation of new materials, impeding their widespread adoption and commercialisation. Standards serve as beacons of clarity, providing a common language and framework for precisely defining materials, their properties and measurement protocols. This clarity not only fosters trust among stakeholders but also facilitates reproducibility and comparability, thereby laying the foundation for innovation and industrialisation.

> Standards serve as beacons of clarity, providing a common language and framework for precisely defining materials, their properties and measurement protocols."

THE INFLUENTIAL REACH OF THE GRAPHENE FLAGSHIP

Within the landscape of standardisation, Europe, spearheaded by initiatives like the Graphene Flagship, assumes a central role in shaping international standards for 2D materials. Radnik underscores the significant influence exerted by collaborative efforts within the Graphene Flagship in propelling standardisation forward. Through the initiation of standardisation projects and the proposal of consensus-based protocols, Europe endeavours to lead the charge in defining accepted standards, thereby solidifying its position as a nexus of innovation in the field.

NAVIGATING THE PATH FORWARD

Despite notable strides, Radnik notes that substantial work remains to be done in comprehensively standardising 2D materials. While consensus on terminology and measurement protocols is beginning to emerge, the delineation of standards across the entire product chain remains a priority. Over the next two years, concerted effort will be directed towards establishing standards for chemical composition, defect characterisation, contamination control, morphology assessment and other crucial parameters.

> By establishing robust standards, stakeholders are empowered with confidence in material quality and performance, while societal trust in the safety and reliability of emerging technologies is bolstered."

A CONTEMPLATION ON NANOMATERIALS VS 2D MATERIALS

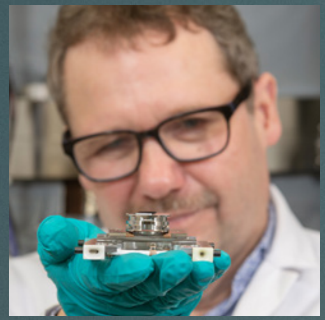
A pertinent question arises regarding the classification of 2D materials within the broader realm of nanomaterials. Radnik acknowledges the prevailing classification but anticipates future deliberations on whether distinct standards for 2D materials are warranted. As the field evolves, collaborative discussions will be imperative to ensure a nuanced approach to standardisation, one that fosters innovation while upholding regulatory rigor and safety standards.

FOSTERING TRUST THROUGH STANDARDISATION

In his closing remarks, Radnik emphasises that standardisation transcends mere technical specifications; it is about instilling trust. By establishing robust standards, stakeholders are empowered with confidence in material quality and performance, while societal trust in the safety and reliability of emerging technologies is bolstered. This trust forms the bedrock for widespread acceptance and adoption of 2D materials in commercial products, thereby propelling innovation and economic growth.

IN CONCLUSION

As we navigate the frontier of materials science, standardisation emerges as a linchpin for progress. Jörg Radnik's insights serve as a guiding light, illuminating the critical role of standards in unlocking the full potential of 2D materials. Through collaborative endeavours, such as those championed by the Graphene Flagship, we can chart a course towards a future where clarity, reliability and trust reign supreme in the realm of materials development. As we embark on this journey, let us recognise the power of standardisation in the commercialisation of graphene, fostering collaboration, and promoting the use of graphene in new exciting products.



Jörg Radnik
Dr. Jörg Radnik is Senior Scientist at the Federal Institute for Material Research and Testing, Berlin in the Division 6.1 "Surface analysis and Interfacial Chemistry" and working in the competence centre nano@BAM.

GRAPHENE FLAGSHIP ANNUAL REPORT 2023

Forging ahead

The 2D-EPL's technical leader Inge Asselberghs reflects on the successes of the project and future of 2DM integration, and the close of the Horizon 2020 phase of the Graphene Flagship.

"It has become apparent that graphene and other 2D materials not only have different unique characteristics, but also require dedicated handling in a fabrication environment."

TEN YEARS HAVE now passed since the kick-off of the Graphene Flagship with European researchers joining forces in developing 2D materials-based processes, material and device models, devices and circuits exploration paving the way towards uptake of this material in various application fields. The 2D Experimental Pilot Line project offers the unique setting for research institutes and industry to jointly develop the essential building blocks for 2D material (2DM) deposition, post-processing and integration evaluation focusing on the domain of sensors, photonics and electronics.

Intrinsically challenging is the project's ambition to create an ecosystem for 2DM integration and contribute to the enablement of the uptake of 2D materials by the semiconductor industry.

The development goals for maturing the wafer scale integration of 2D-materials and delivering reliable deposition modules has resulted in the achievement of important project milestones. The spotlight is on establishing stable deposition modules by the manufacturing and installation of specialised equipment. An MOCVD reactor, uniquely equipped to handle both 200 and 300 mm sapphire wafers, is installed by Aixtron. Layer transfer takes the next step to automation with the installation of an automated be-bonder by SUSS Micro Tec. With this novel dedicated equipment installed in the imec cleanroom facilities, the project's next step lies in demonstrating a reliable layer deposition process from growth to transfer.

Gradually, process integration is moving in the direction of down selecting the more industry-relevant processes with the collection of relevant datasets on repeatability, uniformity and variability.

Essential in a phase one pilot line project is finding the balance between investing in process maturation and serving customers. Today's 2D-EPL customers have both university and company backgrounds. The incentive to join the multi-project wafer (MPW) runs can be research enablement, benchmarking purposes or first prototype testing. Therefore, different stage MPW runs have been offered by AMO and VTT. Having been successful, additional MPW offerings have been added for photonics applications by IHP and sensors by Graphenea.

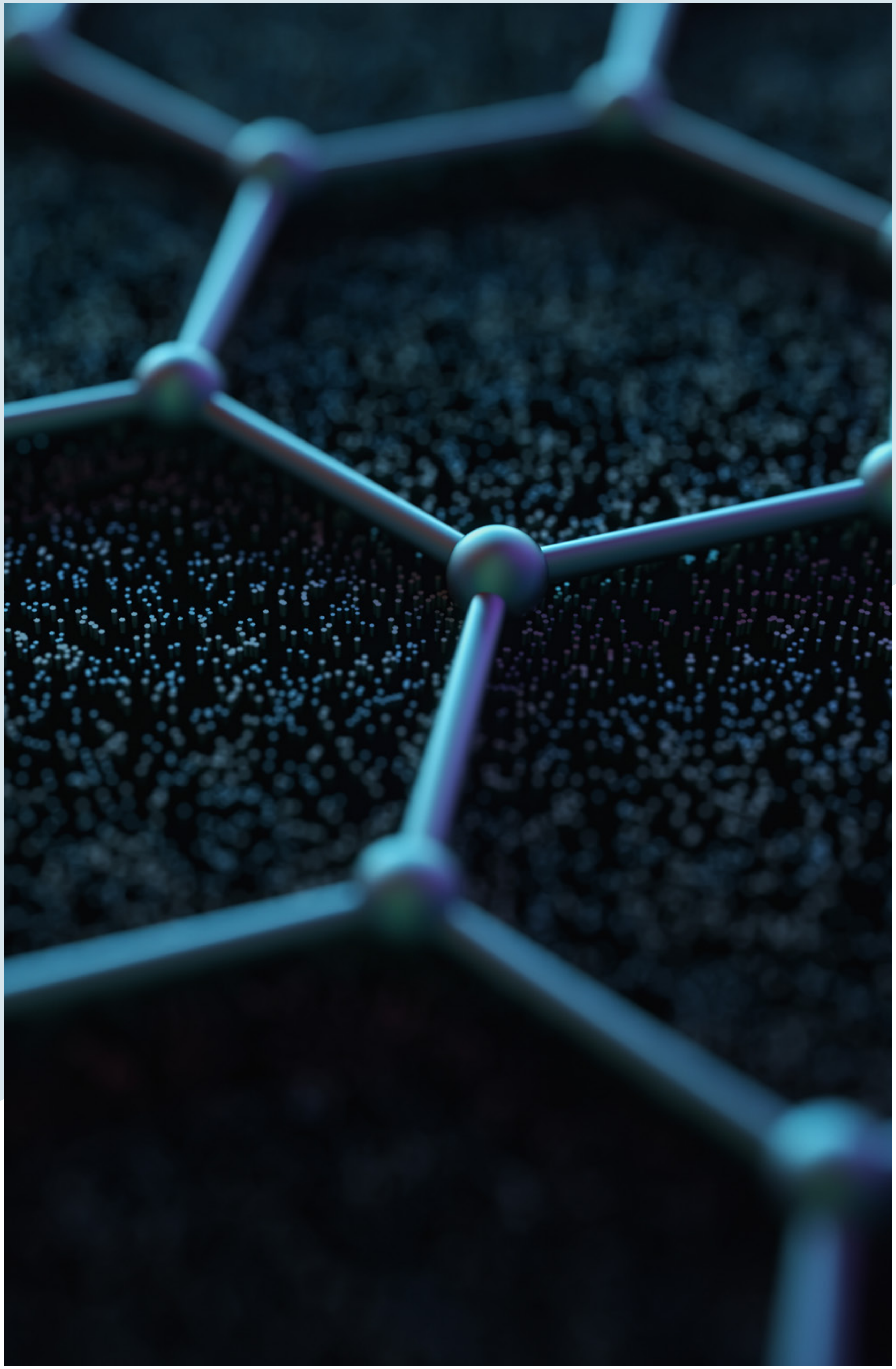
The international research community continues its endeavours to use, implement and explore a multitude of approaches. While it has become apparent that graphene and other 2D materials, like transition metal dichalcogenides, have different unique characteristics, they also require dedicated handling in a fabrication environment due to deviating chemical or thermal stability requirements.

Beyond the scope of this project, more development efforts will be required to further bridge the gap with state-of-the-art performance demonstrated in literature reports. Interestingly, the contribution of this project by exploring various integration routes also shed light on further challenges to tackle. Process translation to industry relevant process conditions, reducing variability, increasing stability and reliability.

Now, the 2D-EPL project has entered its fourth and final year. Relevant milestones are successfully achieved, while other important milestones in process demonstration are on the verge of being reached. Innovation outreach events and business development inquiries are further driving the information collection and guiding the understanding of the requirements for industrial uptake.

The 2D-EPL team is ready to jointly take the final steps for successful project completion, and move towards the next phase of the pilot line.

Inge Asselberghs
2D-EPL Technical Leader
Graphene Flagship Science and Technology Officer



GRAPHENE FLAGSHIP ANNUAL REPORT 2023

What is the Graphene Flagship?

Bringing together 118 academic and industrial partners in 12 research and innovation projects and 1 coordination and support project, the Graphene Flagship will continue to advance Europe's strategic autonomy in technologies that rely on graphene and other 2D materials. The initiative, which builds on the previous 10-years of the Graphene Flagship, is funded by the European Commission's Horizon Europe research and innovation programme.

The 2D-Experimental Pilot Line, addressing the challenges of upscaling 2D material production processes for the semiconductor industry, is another key component of the Graphene Flagship ecosystem.

Visit graphene-flagship.eu

CONTENT AND CONCEPT BY WORK PACKAGE DISSEMINATION

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