GRAPHENE
FLAGSHIP

Annual Report 2024

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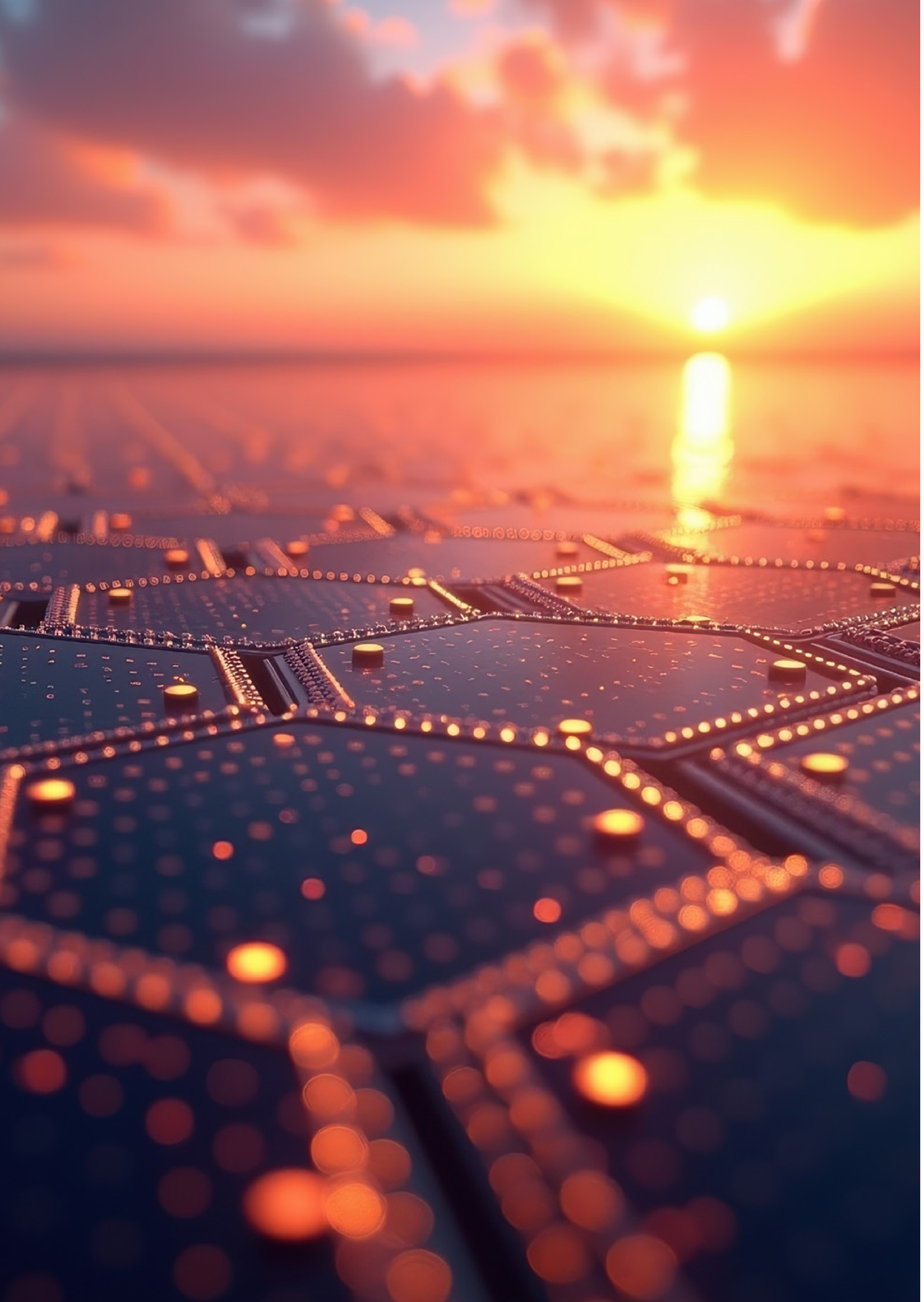

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From the Director

IN 2024 WE CONCLUDED the first full year of the new Graphene Flagship. I am proud that we have taken a group of individual projects and forged them into a community – new and old friends of 2D materials – that collaborates and contributes to a synergetic future. We already see advancements underway in as diverse fields as disease diagnosis, clean and efficient energy, new and more sustainable 2D materials and composites and much more.

Even more important to me personally is that we see past and current Graphene Flagship partners coming together as one community embracing and promoting the future of 2D materials in Europe – as this has been the goal ever since the Graphene Flagship's conception: to promote graphene and 2D materials research and innovation, but more than that, to create a single community striving together toward that goal. Through knowledge sharing, collaboration and cross-topic promotion, we have seen 2D materials mature and become commercially viable and attractive much faster than similar technologies have in the past.

GRAPHENE IN THE SPOTLIGHT

We have, as told many times before, far surpassed the expectations for European funded research and innovation projects. We know that this originates in the power of having a large and dedicated community working long-term on research and development. This year we had the opportunity to share our success story with the European Commission in two exhibitions in Brussels, one at the DG CONNECT building and the other as part of a larger exhibition of European-funded projects at the Berlaymont building (learn more on page 34). While it is important to celebrate our past successes, I am confident that there is much more on the horizon for our projects and community.

BUILDING A COMMUNITY

Our annual conference, Graphene Week, is a hub for collaboration and knowledge exchange, and this year more than ever it was a place for experts to meet, form new connections and initiate new collaborations. In Prague, I got to meet all the experts from Graphene Flagship projects (past and present) that were brought together in one place to network and discuss their work. Connections made there have bloomed into valuable collaborations and deeper discussions on the future of 2D materials. At Graphene Week the new 2D Pilot Line project (the continuation of the previous 2D Experimental Pilot Line project) was also presented, signaling the continued support of the European Commission for 2D material wafer-scale integration.

LOOKING FORWARD

This year has been a foundational year, but that does not mean that we have stopped looking to the future. A great deal of work and planning has gone into preparation for what comes next, which in the case of the Graphene Flagship in many ways will take the shape of funding within the IAM4EU public-private partnership (learn more on page 8). Key players in the Graphene Flagship community have been instrumental in identifying the most important research and innovation areas for 2D materials in the future and ensured a voice and role for our community in the IAM4EU/IAM-I governance.

Summarising this past year's success is a great way to end – and that is a way to tell all of you that I no longer will sail the Graphene Flagship. When you read this, I have already moved on to other professional opportunities but left the Graphene Flagship in the very good hands of my colleague Maria Abrahamsson who steps up as the new Director.

Patrik Johansson
(former) Graphene Flagship Director

GRAPHENE FLAGSHIP ANNUAL REPORT 2024

Graphene Flagship celebrates the past while sailing into the future

TWENTY YEARS AGO, graphene was first isolated in the lab, earning Andre Geim and Konstantin Novoselov the Nobel Prize. The possibilities for this material were immediately apparent, and since then graphene has found itself in hundreds of innovative applications from sensors and electronics to energy storage and healthcare. Research did not stop at graphene but has expanded to a whole family of two-dimensional and layered materials (2DM) opening up a world of possibilities.

In 2013 the Graphene Flagship was launched as a first of its kind, long-term and large-scale research initiative. Over the first ten years, spanning three Core projects, the Graphene Flagship succeeded in developing viable production methods for commercial quantities of graphene, expanded its research beyond the basics to explore new possibilites for 2DM and helped to push the most promissing application areas toward market-ready solutions.

EUROPEAN COMMISSION EVALUATION

In October, the European Commission published a report giving a comprehensive overview of the main scientific, technological and industrial achievements of the Graphene Flagship. The report showcases some of the many achievements of this decade-long initiative.

“The Graphene Flagship has demonstrated the potential of graphene, which consists of a single layer of carbon atoms and has many highly useful properties, as well as of other new 2D materials. It has laid the groundwork, for instance, for graphene-based brain-computer implants that can help to reduce the symptoms of Parkinson’s disease, de-icing systems to help planes fly safely and more efficient batteries and solar panels. The Graphene Flagship has also created a flourishing EU ecosystem, built on in-depth collaborations between over 200 scientific and industrial partners. The project has launched the careers of around 1,000 doctoral and postdoctoral students, created 20 spin-offs and brought more than 100 products to market.”

The report not only describes the project’s key achievements but also evaluates how it contributed to strategic EU goals and the visibility of European research in these fields. They highlight what can be achieved by dedicated teams of researchers from across Europe working together over a ten-year period.

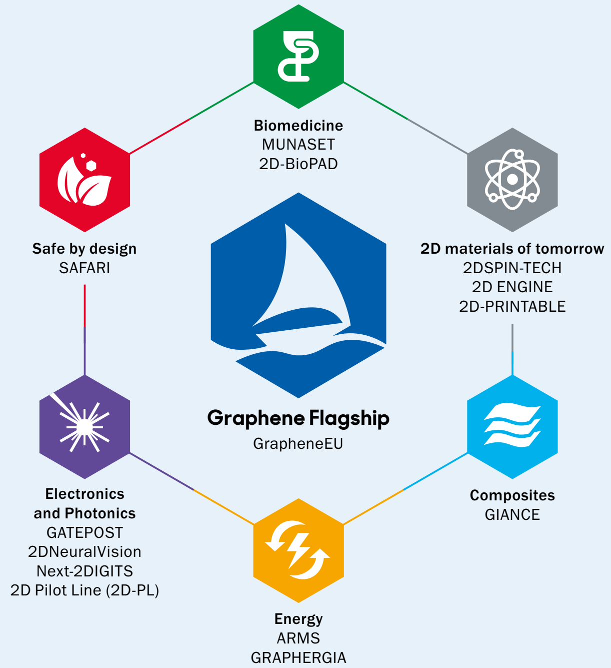
SAILING ON

The Graphene Flagship is now comprised of 13 research and innovation projects and 1 coordination and support project with a total of 126 academic and industrial partners and 32 Associated Members. The initiative continues to advance Europe’s strategic autonomy in technologies that rely on graphene and other 2D materials in six key focus areas:

- Electronics and Photonics
- Energy
- Biomedical
- Composites
- 2D materials of tomorrow
- Safe by design

GRAPHENE FLAGSHIP ANNUAL REPORT 2024

Above: The new Graphene Flagship projects were introduced to the 2DM community at Graphene Week 2024. Credit: Kateřina Antoš
Below: Former Graphene Flagship Director, Jari Kinaret, and Nobel Laureate Konstantin Novoselov recreate the original “sticky-tape experiment” by which graphene was first isolated.
Credit: Graphene Flagship



MEET THE FLAGSHIP
Bringing together 126 academic and industrial partners across 14 projects, the Graphene Flagship continues to advance Europe’s lead in technologies that rely on graphene and other 2D materials.

The overall coherence of the Graphene Flagship is guaranteed by Graphene Europe in the Lead (GrapheneEU) a Coordination and Support Action (CSA) that allows the separate actions to exploit synergies in their scientific and technological activities and work more efficiently by utilising common services and support functions.

Over a year into these projects, we are seeing exciting progress in disease diagnostics, energy solutions from supercapacitors and batteries to solar panels and even toward the developmnet of new materials. This Annual Report details the current progress in the projects and the plans to address future challenges.

BUILDING A COMMUNITY

The key to the Graphene Flagship’s success is its community. Bringing together 2D materials experts from all fields helps to identify collaborations, exchange knowledge and advance research and innovation in a more efficient and productive way. Although the projects work independently, the Graphene Flagship ecosystem encourages cooperation. Over the past year, the RIA/IA projects have begun to find common ground and to benefit from joint activities. The next challenge will be to help connect experts from the Core projects with those from the new. Some of this work has begun through public events like Graphene Week and the revival of past committees for which past experts have been brought in to provide continuity. One such activity is the REACH/ECHA committee which liases with the European Chemical Agency on materials classifications, safety information and more. These challenges will continue to be addressed in the next year.

This year has also been pivotal in building the Association Mechanism that allows projects and institutions outside the Graphene Flagship projects a way to collaborate with the partners in the initiative. In the first year, the Graphene Flagship welcomed 11 Partnering Projects and 32 Associated Members. These associated entities include members that have been collaborating with the Graphene Flagship for the past ten years as well as new organisations, showing the capacity to continue attracting new stakeholders and further grow the 2DM community in Europe.

In the next year, GrapheneEU will create a committee representing the Initial Graphene Flagship Community (IGFC) to help connect the experts from the original Core projects to those in the current projects, to support knowledge exchange and continuity not just in research but in supporting future 2DM actions in Europe.

From the Graphene Flagship to IAM4EU: A journey of Innovative Advanced Materials

From June 2023[1] the Graphene Flagship joined forces with the Advanced Materials 2030 initiative (AMI2030) to prepare the launch of a new public-private partnership with the European Commission: Innovative Advanced Materials for Europe (IAM4EU).

A Partnership Coordination Panel (PCP) was appointed in September 2023 by the Graphene Core 3 Executive Board, chaired by the Core 3 Science and Technology Officer Andrea Ferrari. This panel, representing all areas of interest for the Graphene Flagship, appointed five representatives to the IAM4EU drafting group, a body comprising members of the EC, AMI2030 and the Graphene Flagship meeting on an bi-weekly basis to prepare all the documents needed to launch IAM4EU. The PCP and the drafting group worked tirelessly to define the principles for the Strategic Research and Innovation Agenda (SRIA) indicating the key priority areas for IAM4EU for the rest of Horizon Europe, drafted the memorandum of understanding (MoU), ruling the interactions between the private-side association IAM-I (Innovative Advanced Materials Initiative) and the European Commission, as well as the concept paper, addressing why IAM4EU is being proposed, the current problems and strategic opportunities it aims to tackle and the drivers of the problem and their relative importance.

At the close of 2024, several key milestones were achieved, with the active contribution of the Graphene Flagship PCP and drafting group members.

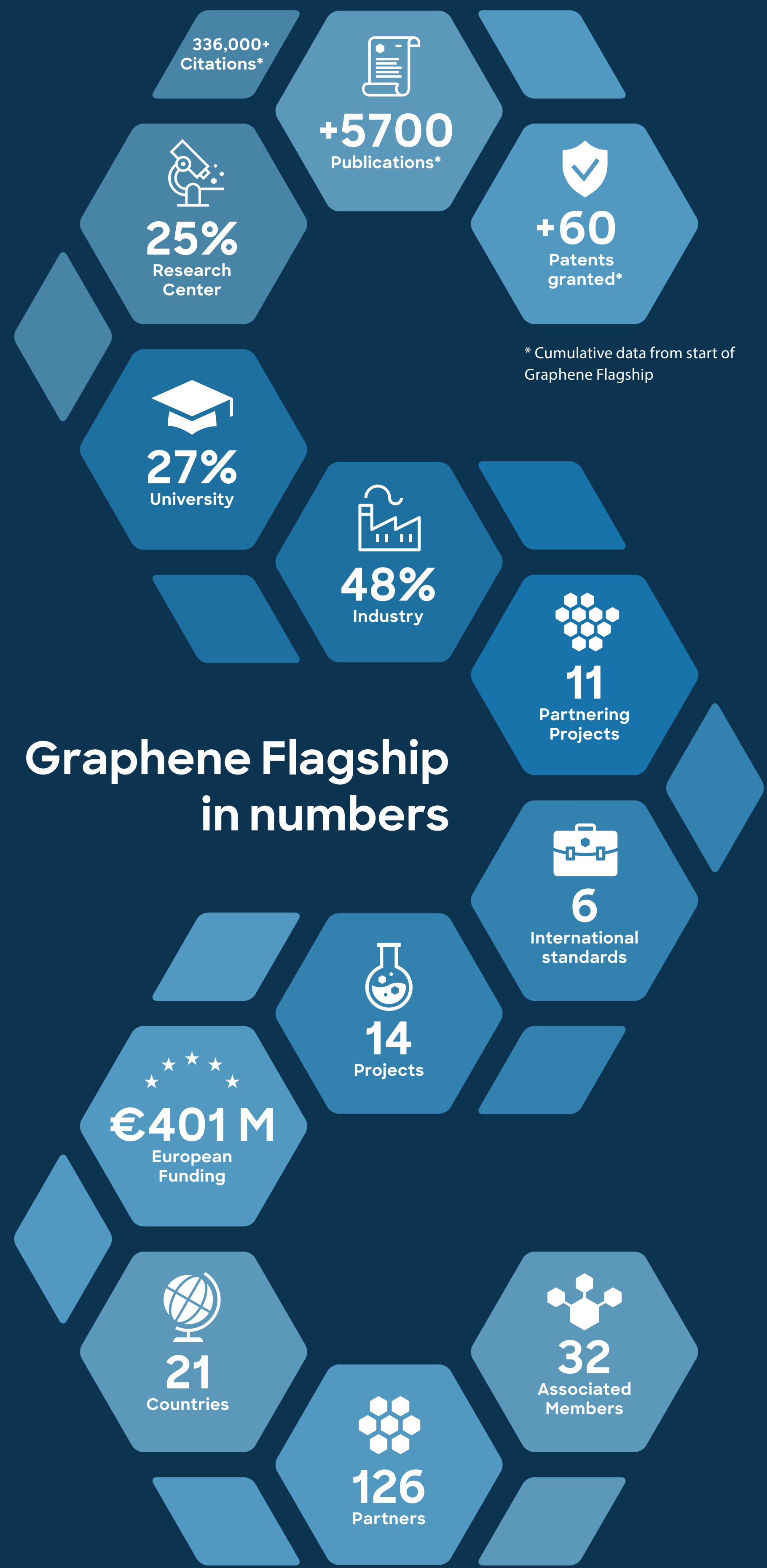
2025 will be the year of innovatiove advanced materials in Brussels and we are all very excited about the opportunities this will bring to the European ecosystem. The scene is set for a very positive outlook for innovatiove advanced materials thanks to the following initiatives/actions: The High-level Technology Council on Advanced Materials met to advance strategic initiatives; progress was made on an IPCEI for Advanced Materials, critical for Europe's future; the Advanced Materials Act was prioritized by President Ursula von der Leyen in her mission letter to EU Commissioner for start-ups, research and innovation.

On 31 January 2025, the inaugural General Assembly and start of IAM-I took place in Brussels with over 250 companies, research organisations and university participants.

The Graphene Flagship community was very well represented. The most important items on the IAM-I inaugural General Assembly agenda were to vote for the Executive Board (EB) and the Association Delegation (AD). Together, these form the Partnership Board (PB) that will work with the European Commission on all the key topics for innovative advanced materials funding. The result of the EB and AD vote is that quite a few candidates with a history and engagement in graphene and 2D materials got a place. Amongst these, Gianluca Fiori, University of Pisa, former Division leader in Core 3 of the Graphene Flagship, was elected as the EB Vice-President for Research. The Graphene Flagship itself has an observer post in the EB.

Altogether, this shows, once again, how important 2D materials are for the European ecosystem of innovation for almost any thinkable sector. The important work of bringing impact of innovative advanced materials to the European citizen has started, and the Graphene Flagship's future is one of close cooperation with IAM-I.

1. https://bit.ly/IAM-I



GrapheneEU

Providing coordination and support to the Graphene Flagship projects

THE GRAPHENE EUROPE in the Lead (GrapheneEU) coordinating and support action (CSA) serves as a hub for the Graphene Flagship projects' cross cutting actions.
It ensures a strong and coherent initiative by providing key support functions in coordination and governance, industrialisation, dissemination, and European and International alignment. The CSA accomplishes this by organising joint actions and managing a series of cross-project working groups to further the core Graphene Flagship objectives.

> GrapheneEU helps bring all the Graphene Flagship projects together to create actions for the mutual benefit of the entire European 2DM community."
>
> **Patrik Johansson**
> Chalmers University of Technology

HIGHLIGHTS FROM 2024

We started 2024 by welcoming the Graphene Flagship community to a common kick-off meeting, where RIA/IA representatives had the opportunity to meet in person and connect with both new and familiar colleagues. During the event, the key GrapheneEU services were presented and the RIA/IAs introduced their projects and outlined their plans for the coming months. This meeting was the foundation for the CSA's actions throughout the year.

Coordination and Governance

The Coordination and Governance work package is responsible for the overall coordination of the Graphene Flagship initiative's activities. The team, from Chalmers University of Technology, manages the decision-making bodies of the Graphene Flagship, is responsible for high-level representation of the initiative and for contacts with key stakeholders, supports monitoring and reporting across the initiative and ensures synergies between the projects. The kick-off meeting launched these efforts, bringing the projects together and presenting the shared goals and collaboration potential between them. In parallel, the Science and Technology Forum was organised to discuss and determine the Graphene Flagship's priorities for 2024 and forward, not the least with respect to the IAM4EU partnership, which will be a key part of future European Commission funding for 2D materials (2DM) research and innovation. The coordination and governance team ensured that the Graphene Flagship's interests were represented in discussions and negotiations related to the IAM4EU partnership throughout the year. These discussions, and other key issues were closely followed by the Coordination Board.

This work package also relaunched the REACH/ECHA committee, which connects the Graphene Flagship to ECHA (the European Chemicals Agency) and EUON (European Observatory for Nanomaterials) and provides guidance on the registration of 2DM under the registration, evaluation, authorisation and restriction of chemicals (REACH) regulations. The committee organised an information session during the Graphene Flagship's annual conference, Graphene Week, which saw strong participation from the Graphene Flagship community. Another action organised by the team was the Annual Meeting, where all the RIA/IA projects presented their developments and successes. This meeting was held immediately after Graphene Week.

The Chalmers team also runs the Project Managers Network. This working group plays an important role in supporting the contribution of RIA/IA projects to the Graphene Flagship's objectives. It has helped define the set of common KPIs to monitor the initiative's progress in terms of project outputs and contributed to discussions on coordinated project reviews.

European and International Alignment

Through the European and International Alignment work package from the European Science Foundation, GrapheneEU actively encourages and supports collaborations and alignment with national and regional initiatives in Europe, as well as international exchange with overseas countries.
To facilitate the establishment of scientific collaborations with the large 2DM research community throughout Europe, an Association Mechanism has been set up. Through this framework, organisations working with graphene and 2DM can join the Graphene Flagship as Associated Members and Partnering Projects, to gain the possibility to interact with the RIA/IA projects to create opportunities for collaborative initiatives. In 2024 our community welcomed 11 Partnering Projects (PPs) and 32 Associated Members (AMs) from 11 European countries. These associated entities include members that have been collaborating with the Graphene Flagship for the past ten years (i.e. former partners and AMs) as well as new organisations, thus showing both the solidity of the established Graphene Flagship network, as well as the capacity to continue attracting new stakeholders and further grow the 2DM community in Europe. AMs and PPs bring complementary expertise that integrates all the different focus areas of the Graphene Flagship projects, often in a transversal way, therefore creating an ecosystem where opportunities for collaborative research are facilitated.

Further support to the alignment with national initiatives is also provided by the newly established network of national and thematic representatives (nNTR). Currently composed of 29 recognised members of the graphene and 2DM community from 24 European countries, this strategic network is expected to facilitate contacts with relevant stakeholders and initiatives at the national and regional level, including national funding agencies and research infrastructures.

GrapheneEU is also promoting exchange and opportunities for international cooperation through the organisation of dedicated workshops. The interaction with global stakeholders has been

Ana-Maria Ciubotaru and Stefania Vitale present the Graphene Flagship at the European Science Foundation's 50th Anniversary. Credit: ESF

2D-PRINTABLE postdoctoral researcher Joyce Matsoso shares her experiences as a researcher during the Diversity in Graphene session at Graphene Week. Credit: Kateřina Antoš

pursued over the past year, with particular effort in ensuring the continuation of well-established international collaborations. This led to the organisation of the third Europe-United Arab Emirates workshop during Graphene Week 2024.

Dissemination

The Dissemination work package, run by Chalmers University of Technology, is responsible for communication activities and events for both GrapheneEU and the Graphene Flagship as a whole. This includes managing the Graphene Flagship website, social media accounts, and promoting the Graphene Flagship in external publications.

In 2024, the largest dissemination action was the organisation of Graphene Week. This being the first year of the conference with the new projects, it was particularly important to bring them visibility. All the projects, were therefore showcased in the exhibition, allowing project representatives to network and connect with attendees during the coffee breaks and lunches. Furthermore, the agenda was reorganised to create opportunities for the Graphene Flagship projects to host workshops (singly or in collaboration with other projects) or facilitate parallel sessions related to their topics. The Project Managers Network helped to coordinate the participation of the RIA/IA projects, where they hosted three workshops and four parallel sessions. All of the projects contributed to the event in some way, and this week-long, in-person event helped to bring the community together. Following the event, the projects began to collaborate and contribute more to the GrapheneEU working groups and activities, marking a key shift in the new Graphene Flagship community.

The Graphene Flagship was also showcased in Brussels in both the lobby of the European Commission's Directorate-General for Communications Networks, Content and Technology (DG CONNECT) offices and as part of a larger exhibition of European funded projects at the Berlaymont building, the EC headquarters. The exhibition at DG CONNECT was celebrated with an inauguration at which Graphene Flagship Director Patrik Johansson and former-Director Jari Kinaret as well as the scientific coordinator for the 2D Experimental Pilot Line Inge Asselberghs presented the project, its results in the first ten years, some products and prototypes developed in a variety of application areas and the new projects that are now forging the future of the Graphene Flagship. The opening was attended by key EC personnel, including Director-General Roberto Viola and Deputy Director-General Thomas Skordas.

The Dissemination Working Group brings together representatives from all the projects to exchange best-practices, plan joint activities including Graphene Week and other events and to align on communications initiatives. Through the working group we have organised quarterly social media campaigns highlighting the projects and their teams as well as collected project news for our quarterly newsletter.

The Diversity in Graphene initiative, managed by GrapheneEU, has been successfully continued in the past year. The Mentoring Programme, which pairs junior researchers with more experienced researchers, provides one-on-one support and guidance. Mentors were matched with mentees outside their own projects to give them the opportunity to meet someone they would not have otherwise connected with. The Diversity session at Graphene Week included a keynote talk from the Royal Society of Chemistry's Inclusion & Diversity group Ilaria Meazzini who presented their latest report on disability in chemical sciences and the need for allyship. This was a new topic for the session and prompted some interesting discussion in and outside the session.

Industrialisation Support

The Industrialisation Support work package seeks to create an innovation ecosystem for 2DM that will enhance and sustain 2DM industrialisation. As in other GrapheneEU work packages, this group builds on the frameworks established in the first ten years of the Graphene Flagship bringing expertise and sharing best practices to help accelerate the RIA/IA industrialisation efforts. The partners involved are Chalmers Industriteknik (Sweden), Bundesanstalt für Materialforschung und prüfung (Germany) and Fraunhofer-Institute for Systems and Innovation Research ISI (Germany).

Standardisation

The creation of common standards for 2DM has long been identified as the first hurdle to industry adoption. The Graphene Flagship, through its standardisation team at Bundesanstalt für Materialforschung und prüfung (BAM), is a strong leader in international bodies working to identify these standards. Last year, the activities in ISO TC 229 (Nanotechnologies) were continued and the cooperation with IEC TC 113 was re-established. From ISO, one standard on "Nanotechnologies – Vocabulary – Part 13: Graphene and other two-dimensional (2D) materials" was published which was revised from a former standard. At the moment, six standards are under development with the participation of members of the Graphene Flagship Standardisation Working Group.

In the pre-normative research under the auspice of the Versailles Project on Advanced Materials and Standards (VAMAS), two projects on the lateral size of graphene oxide

Sofia Öiseth, Jörg Radnik and Grzegorz Kubicki representing the Graphene Flagship at Materials Week 2024 in Limasol, Cyprus. Credit: Sofia Öiseth

flakes and on the chemical composition of functionalised graphene are ongoing. The interlaboratory comparisons were successfully finished and the data analysis is ongoing. It can be expected that the projects will be finished in 2025 with the publication of the results.

The Graphene Flagship Standardisation Working Group was established at the begining of the year and has met four times. The first meeting was in person, the other meetings remotely. In the first two meetings, it was necessary to get to know each other, introduce the standardisation activities and identify the members' expectations. In the other meetings the activities by ISO, IEC and OECD were presented and discussed.

One training session was co-organised at Materials Week 2024 (together with the EU-funded projects Macramé, NanoHarmony, ACCORDs and the national association NanoMeasure France) and one training session was organised at Graphene Week 2024. The foci of the training sessions were the validation of methods, and the standardisation needs for graphene and related 2D materials. Furthermore, a webinar was organised about "Interlaboratory comparisons and reference products for advanced materials" together with the BAM academy.

Roadmapping
The core task of the Fraunhofer Graphene Roadmap Team in GrapheneEU is enabling the technical projects within the Graphene Flagship to carry out their own application specific roadmap processes based on the successful innovation interface investigation (3I) mechanism conceived, implemented and refined in earlier project phases. For that purpose, we established the Graphene Roadmap Working Group to assemble the designated Roadmap Officers of all involved project. This forum is the primary venue for exchange on roadmap methodology, progress and results within the Graphene Flagship and assembles roughly in quarterly fashion for online sessions. Earlier meetings were mainly educational to empower Roadmap Officers to drive roadmap processes within their respective projects. Recently, the Roadmap Working Group meetings started to shift towards multilateral exchange on roadmapping plans, experiences and first results. Eventually, the forum shall enable the alignment of application specific roadmap results and inform the creation of an overarching technology roadmap on the status and prospects of graphene and related materials from the joint viewpoints assembled in the Graphene Flagship.

Following popular demand, the fall session was implemented in person and with a longer timeframe prior to and co-located with Graphene Week in Prague. Here, the Fraunhofer Graphene Roadmap Team switched gears from the usual exchange format to live and interactive roadmap training sessions, where the participating Roadmap Officers assumed carefully crafted hypothetical expert roles for the visionary topic of graphene-based space elevators. The engaging role play enabled the Roadmap Officers to a) place themselves in the role of external industry experts that they might want to engage for their own roadmap work, b) experience the set-up, methodology and moderation of a successful roadmap workshop first-hand and c) gather valuable experience to promote and drive the roadmap processes within their respective projects.

Beyond that, the Fraunhofer Graphene Roadmap Team actively engages in the publication and dissemination of Graphene Roadmap results. A primary venue is the publication of Graphene Roadmap Briefs in the renown IoP peer-review journal of 2D Materials. In the past year, two more manuscripts have been produced: Graphene Roadmap Brief No. 3 engages in meta-market analysis and was published in 2024, while Graphene Roadmap Brief No. 4 has recently been accepted for publication and is scheduled to appear in spring 2025. Meanwhile, the Graphene Roadmap Team also delivered several talks on key roadmap results, for instance during the plenary session at Graphene Week and during specialised workshops on graphene-enhanced water purification in both Dresden and Prague.

Innovation
The Innovation team has actively promoted the Graphene Flagship at external and internal events throughout the year. At Chalmers Industriteknik, the team promoted engineering as a great career path for younger generations at IGE (introduce a girl to engineering) day. Twenty 14-year-old girls spent the day in their office and learnt about graphene.

In April, a two-day workshop on 2D Materials in Water Applications was held in Dresden, organised by 2D-PRINTABLE in collaboration with RIC2D, Khalifa University, Technische Universität Dresden and Max Planck Institute. The workshop explored the challenges where 2D materials could create a positive impact for the planet, for example designing more efficient water purification solutions. It was a great opportunity to discuss issues and solutions with participants from all over the globe (Europe, USA, Canada, UAE, Saudi Arabia, Singapore and Australia).

The GrapheneEU team spread information about the Graphene Flagship to the delegates at Materials Week 2024 in Limassol, Cyprus in June through presentations, an exhibition table and networking sessions. Standardisation expert, Jörg Radnik, inspired the participants of a special standardisation training session. Grzegorz Kubicki from the SAFARI project gave a talk about MXenes and Sofia Öiseth presented the Graphene Flagship and how sustainability can be driven by 2D-materials.

Later in June, Kari Hjelt represented the Graphene Flagship with the talk, "Summary of the ten years of Graphene Flagship and the way ahead," at Graphene 2024 held in Madrid, Spain. Hjelt has been awarded CEO Monthly's Leadership Innovation Award for Global Energy R&D Consultancy Innovator of the Year for 2024! Hjelt was also invited to the UK Parliament for the Lord Kelvin Bicentenary, Commemorating 200 years of innovation, invention and inspiration.

The Innovation Forum at Graphene Week is the innovation team's main event of the year. This year's Innovation Forum was spread over three days and focused on innovation and commercialisation of applications containing 2D materials. The forum provided an opportunity to hear about successful implementations and challenges from both start-ups and larger corporations. A highlight was the Suppliers Forum where four different graphene producers (BeDimensional, Paragraf, Bright

The Dissemination team celebrates a successful Graphene Week. Credit: Kateřina Antoš

Day Graphene and Yerrawa) talked about delivering products at a commercial scale. An interactive panel discussion about industry perspective, with representatives from Graphenea, Euronova, Melexis, Graphmatech and Gerdau Graphene, looked into future opportunities and new applications. The Graphene Flagship's work in both standardisation and roadmapping was also presented. Moreover, the Innovation Forum created plenty of opportunities to network and discuss ideas and future collaborations with the presenters as well as fellow attendees.

The Innovation Working Group meets regularly to discuss the organisation of workshops with a commercialisation focus as well as the annual Innovation Forum at Graphene Week. Planning for Graphene Week 2025 in Vicenza, Italy is already underway.

POWERING THE GRAPHENE FLAGSHIP

With the Graphene Flagship comprising 14 projects, the GrapheneEU CSA has become critical to the continuation of the Graphene Flagship community. The strength of the Graphene Flagship has always been the breadth of graphene and 2DM focus areas it covers and the way it encourages cross-topic collaboration and knowledge exchange. The new projects have helped to grow our community of 2DM researchers and innovators, and GrapheneEU has worked hard to connect this new group to the vibrant community that existed. The Association Mechanism has allowed past project partners a way to continue their collaboration with the Graphene Flagship and committees like the REACH/ECHA committee benefit from the experience of some past members who have joined to provide insights into the work that came before. In this way, the GrapheneEU helps to bridge the new projects to the past Core projects ensuring a spirit of collaboration, community and continuity.

SAILING FORWARD

Over the next year, GrapheneEU aims to facilitate even more interactions and foster collaborations within the Graphene Flagship community. While some members have developed a clear understanding of the initiative's concept and objectives, there is still a need for broader understanding across the community. We have found that around 30% of RIA/IA partners couldn't describe other projects, and 47% don't know anyone in other projects. However, 68% are interested in collaborating. To address this, GrapheneEU and the RIA/IAs have agreed on several action points, including providing clearer, more accessible information about the Graphene Flagship and its community. We expect the results of the first project reviews to offer guidance on further steps.

Additionally, the newly launched committee of representatives of the Initial Graphene Flagship Community (IGFC) will play a key role in connecting members of our community who were active as part of the Core projects but are not part of the ongoing projects.

The project also plans to maintain strong representation and contact with key players such as the IAM-I association, other European Partnerships and important stakeholders like the European Commission and ECHA.

At the 2025 Science and Technology Forum, we aim to focus on defining the Graphene Flagship's common interests and priorities with regards to the new structures scenario and potential funding opportunities.

Dissemination actions will continue to foster collaborations, particularly at Graphene Week and the upcoming digital workshop series. By bringing together Europe's vibrant 2DM community to share their work, form new acquaintances and network, we ensure a successful continuation of the Graphene Flagship and its mission to strengthen the European 2DM ecosystem.

PARTNERS
Chalmers University of Technology, Sweden
Chalmers Industriteknik, Sweden
European Science Foundation, France
University of Cambridge, United Kingdom
Fraunhofer Institute for Systems and Innovation Research ISI, Germany
Bundesanstalt für Materialforschung und – prüfung (BAM), Germany

ASSOCIATED MEMBER
Spanish National Research Council (CSIC), Material Science Institute of Madrid

Graphene: a Nobel story

By: Fernando Gomollón-Bel

GRAPHENE WAS FIRST isolated twenty years ago, launching a new era in materials research. The potential created by this new material was only the tip of the iceberg, researchers are now exploring whole families of 2D materials, each with their own unique properties and possible applications. Graphene Flagship projects are even exploring the creation of made-to purpose and safe by design materials with the potential to bring myriad advantages in sustainability, functionality and more. Read on to discover how it all began.

Graphite is the most stable form of carbon, and it has been known since ancient times. In graphite, the carbon atoms arrange themselves into a series of layers, bound together by weak interactions. This unique structure makes it a great lubricant, a good conductor of heat and electricity and the ideal ingredient for pencils: because the layers easily slide apart, they can be precisely transferred to a piece of paper, allowing us to write, draw, imagine and wonder.

Among these wonderers were scientists, who first dreamt of isolating single layers of graphite in the late 1940s. They predicted that such a material – the thinnest ever conceived – would have very unusual electronic properties, due to both quantum phenomena and relativistic effects, because the laws of physics can be very different at the nanoscale. But could they be really different enough to allow a single layer of graphite to exist? Many of the brightest minds thought it would be unstable, and some believed it to be utterly impossible – a theoretical utopia.

THE JOURNEY BEGINS

More than anything, scientists love to explore the unknown. They chase their dreams, sometimes fighting against all logical odds, in the ceaseless pursuit of knowledge and understanding. So it wasn't long before the hunt began for a single, pristine layer of graphite.

In 1962, they gave it a name: **graphene**. Because the layers of graphite peel off so easily, the keen investigators thought that would be the best way to obtain it. They attempted to 'exfoliate' single layers of graphene using different mechanical techniques, including 'the drawing method' – literally trying to draw the finest lines possible with an incredibly sharp graphite point. But alas, it seemed like an insurmountable quest. Their best results were graphite sheets 10 nanometres thick, 2000 times thinner than a human hair, but still 30 times thicker than a single layer of carbon atoms.

But after decades of intense theorycrafting and research, back in 2004, on an otherwise unremarkable Friday night in Manchester, the dream finally came true.

Andre Geim (right) and Kostya Novoselov (left) received the 2010 Nobel Prize in Physics for their groundbreaking experiments with graphene. Credit: National Graphene Institute, University of Manchester

1962

One-atom-thin graphite is given a name: graphene. The search begins.

PIONEERS MAKE THEIR MARK

Every week, Andre Geim and Konstantin Novoselov would stay in the lab after work to discuss new ideas and try out unconventional experiments – some of which are just as whimsical as the concept of drawing atomically-thin strokes of graphite with a super-sharp pencil. Indeed, in a running theme, one of their experiments also involved playing with office supplies. They grabbed a roll of sticky Scotch tape, tore off a few pieces, and began to attach and detach them from a big chunk of graphite. Some fragments came off that looked extremely thin, almost invisible to the human eye and nearly indistinguishable from the tape itself.

Could this be graphene? Perhaps a microscope could determine the nature of these delicate carbon films.

Novoselov remembered that a few days earlier, he overheard some colleagues boasting about a new tunnelling microscope in their department. This device was capable of rendering sharp images of nanoscale objects and, at the same time, could measure their electrical properties. Right away, Novoselov knew that this device was the key to elucidating their material. And Eureka! The tunneling microscope killed two birds with one stone: it enabled them to observe, for the first time, individual layers of graphene – called **graphene monolayers** – and allowed them to demonstrate that the physical behaviour of graphene matched their theoretical predictions.

Was graphene about to enter the realm of modern electronics? The answer is history.

HISTORY, WRITTEN IN GRAPHENE

It quickly became clear that graphene would be sticking around. It was no longer merely a fantasy – graphene could now be isolated easily from graphite, and it was stable at room temperature and ambient pressure. Even further than this, measurements showed that graphene was a 'zero-gap

A demonstration of the famous "sticky tape experiment". Credit: National Graphene Institute, University of Manchester

semiconductor,' a rare type of material in which electrons can seamlessly jump to the conduction band, resulting in unique and unusual physical properties.

Zero-gap materials are extremely sensitive to small changes in their environment, such as pressure, magnetic field or the presence of molecules. In addition, further experiments showed that graphene conducts heat better than any known material, and that it conducts electricity even better than copper and silver. This rare combination of unusual properties makes graphene an ideal candidate for next-generation sensors, electronic devices, optical instruments and more.

A one-atom-thin layer of carbon may sound fragile, but graphene is flexible and 200 times stronger than steel. Once again, the classical laws of physics break down at the nanoscale – the effects we see in graphene are unthinkable in metals, silicon and plastics. The isolation of graphene kicked off a whole new era in materials science.

Graphene is also the first two-dimensional material: "it expanded our toolbox to a whole new dimension," as Geim often says. And ultimately, it did. Scientists have gone on to discover that other materials can be exfoliated too, just like graphite, leading to a family of two-dimensional and layered materials with extraordinary properties. By combining them like ingredients in a sandwich, we can manufacture devices for all sorts of different applications that would've been unfathomable just a couple of decades ago.

NOBEL RECOGNITION FOR A NOBLE ACHIEVEMENT

Geim and Novoselov didn't expect this at all. They were purely driven by scientific curiosity, in pursuit of unfound knowledge and undiscovered possibilities. They were not looking for fame

Graphene timeline

or fortune, so they decided not to file a patent on the new method to isolate graphene – much like how Marie Curie decided not to patent her discoveries for the greater good. In October 2010, almost exactly six years after their original Science paper was published, the Royal Swedish Academy of Sciences gave them a call. Geim and Novoselov had been selected for the most prestigious award a scientist can get – and like Curie, they were presented with the Nobel Prize just a few years after their ground-breaking discovery.

The Nobel committee highlighted the strength of graphene, famously stating that "an invisible hammock made from graphene could hold a cat without breaking" – as well as shining the spotlight on its superlative versatility, in that "it could give new twists to quantum physics, (...) speed up transistors and computers and be suitable for producing transparent touch screens, light panels and solar cells."

Soon after, the European Commission decided to invest €1 billion in a one-of-a-kind multidisciplinary project, to boost research into graphene and layered materials, and to put the EU at the forefront of this new technological innovation.

They called it the **Graphene Flagship**, and the rest is history.

ARMS

Eco-friendly supercapacitors

THE ARMS PROJECT is distinguished by its innovative approach to developing eco-friendly supercapacitors. These supercapacitors, with energy density comparable to batteries, are crafted from sustainable materials (like plant-based carbon) and innovative manufacturing techniques. This unique approach not only makes them cost-effective and scalable for various applications but also sets a new standard in the field. The project focuses on creating two types of supercapacitors: flexible supercapacitors for use in things like wireless sensors and structural supercapacitors that can be integrated into the structure of products like drones. The goal is to create a more sustainable and efficient energy storage solution.

HIGHLIGHTS FROM 2024

The year 2024 was a period of significant progress for the ARMS project. Building upon previous foundational work, the project demonstrated remarkable growth across several key areas: scientific research, international collaborations, internal consortium cohesion, impactful dissemination of research findings and, ultimately, the publication of its first scientific paper. This expanded account delves deeper into the specifics of each event, offering a more nuanced understanding of the achievements and their significance within the broader context of sustainable energy research.

Navigating the Frontier of Printed Intelligence
In January 2024, the ARMS project was represented at the 8th PrintoCent Industry Seminar, PRINSE'24, in Oulu, Finland, which attracted over 300 participants from around the globe. This biennial event is a hub for industry insights, networking and business opportunities, enabling attendees to connect with peers and industry leaders. The ARMS representatives used this platform to engage with various stakeholders and share valuable information about this EU-funded project.

The seminar provided a lively and inviting setting that fostered meaningful discussions and connections. ARMS representatives highlighted the importance of the event in identifying key individuals and organisations relevant to the project, paving the way for potential collaborations and partnerships. Additionally, the organised training sessions and visits to pilot factories and printed electronics companies enhanced ARMS' understanding of the latest innovations in the field, ensuring that the project stays aligned with current industry trends.

The networking opportunities and insights from PRINSE'24 have significantly bolstered the project's trajectory. The relationships established and knowledge acquired during the seminar have laid a strong foundation for future collaborations, positioning ARMS at the cutting edge of technology within the industrial landscape.

Graphene Flagship Common Kick-Off Meeting and Science and Technology Forum
Five researchers from the ARMS project participated in the Graphene Flagship Common Kick-off Meeting and Science and Technology Forum held 5–6 February 2024, at Chalmers University of Technology in Gothenburg, Sweden. This event brought together collaborators from the 13 EU-funded projects associated with the Graphene Flagship, allowing for face-to-face interactions among the projects. Each project presented its objectives and future initiatives, fostering a collaborative environment aimed at transitioning graphene technologies from research labs to market applications. The meeting included various sessions focused on project management, innovation strategies and coordination, emphasising the importance of collaboration among the research and innovation actions (RIAs) and innovation actions (IAs).

"In our first year, the ARMS project focused on networking with relevant partners. Our active participation in numerous networking events helped to better understand the application requirements. This has been a foundational step in aligning the project with the needs of our stakeholders and ensuring its success."

Matti Mäntysalo
Project ARMS coordinator,
Tampere University

The event marked the official commencement of cooperation among the 13 projects, focusing on shared goals such as innovation roadmapping, standardisation and outreach efforts to accelerate the practical use of graphene. The following day, the Science and Technology Forum explored the advancements in graphene technology and the significance of EU funding, particularly through the Innovative Advanced Materials for the EU (IAM4EU) partnership. The discussions highlighted the critical years ahead for 2D advanced materials, underlining the importance of strategic planning and collaboration in shaping the future of this field. The meeting fostered valuable connections and set the stage for future collaborations among the participating projects.

Project ARMS Co-hosted Workshop at the IEEE FLEPS 2024 Conference
Co-hosting a workshop at the IEEE FLEPS (IEEE International Conference on Flexible and Printable Sensors and Systems) 2024 Conference in Tampere, Finland, provided a high-impact platform for ARMS to showcase its research and engage in meaningful dialogue with a broader scientific community. The workshop centred around the cutting-edge realm of energy-autonomous self-powered wearable electronic devices, spotlighting the dynamic interplay between energy harvesting systems and transformative energy storage solutions, specifically batteries and supercapacitors.

The workshop emphasised the integration of energy storage systems with energy harvesting solutions, particularly showcasing the relevance of the Graphene Flagship to the GRAPHERGIA and ARMS projects, which leverage 2D materials in battery and supercapacitor development. By bringing together experts and enthusiasts in the field, the workshop fostered collaborative discussions and explored the future of wearable electronics, highlighting the vital role of sustainable energy solutions.

ARMS Project at Graphene Week 2024
ARMS' participation in Graphene Week 2024, held in Prague, placed the project at the forefront of the international graphene research community. Throughout Graphene Week 2024, ARMS representatives participated in various Graphene Flagship meetings, including roadmapping, coordination board discussions, the project managers meeting and the annual general meeting. These sessions offered an excellent platform to discuss ARMS' contributions and align with the Graphene Flagship's strategic goals.

The ARMS project was well-represented with its dedicated pod in the Graphene Flagship Hall, where representatives from the project team introduced ARMS to attendees eager to learn more about the research conducted within project consortium. Engaging discussions with researchers and representatives from related Graphene Flagship projects facilitated meaningful connections and opened avenues for potential collaborations.

During Graphene Week 2024, ARMS co-hosted the "Integrating Graphene Innovations: From Smart Textiles to High-Performance Energy Storage" workshop with GRAPHERGIA. In the workshop, project representatives provided insights into ARMS' technical advancements. The workshop also initiated several interesting discussions with international researchers.

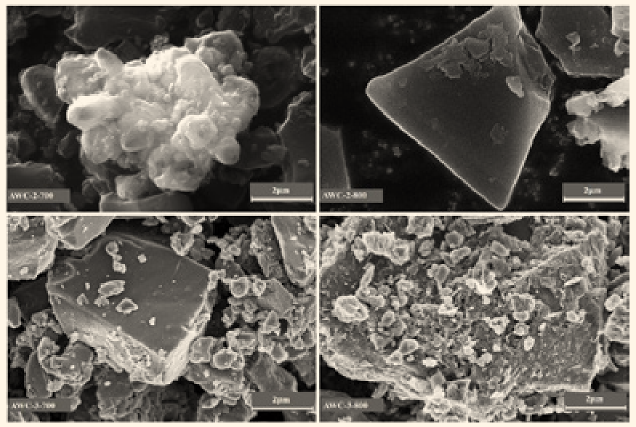
The poster session showcased recent ARMS innovations in detail, sparking interest and conversation among attendees.

The Graphene Week 2024 was an enriching experience, allowing ARMS representatives to exchange knowledge with experts across various fields, discuss breakthroughs, connect with peers from other Graphene Flagship-associated projects, and build their network. The event was a significant opportunity for the project to highlight its advancements on a global stage.

ARMS Consortium Meeting in Riga
The 3rd Consortium Meeting of the project took place on 5–6 November at the Institute of Solid State Physics, University of Latvia (ISSP UL), bringing together consortium partners and members of the External Advisory Board. This meeting was a crucial milestone in the project, which is focused on advancing energy storage technologies by developing eco-friendly supercapacitors. The collaborative efforts of experts aim to enhance the performance and sustainability of energy storage devices, thereby contributing to innovative solutions for global energy challenges.

The ARMS project is structured into eight work packages, each addressing different aspects of supercapacitor technology. These include synthesising raw materials, electrode fabrication and the development of electrolytes to improve device performance. Additionally, the project encompasses sustainability assessments and strategies for effectively disseminating findings to stakeholders. During the meeting, partners reviewed their progress over the first year, particularly discussing the initial four work packages and planning future collaborations based on insights from the External Advisory Board.

First Scientific Publication from the ARMS Project
ARMS has achieved a significant milestone with the publication of its first scientific paper titled "Enhancing Specific Capacitance and Energy Density in Printed Supercapacitors: The Role of Activated Wood Carbon and Electrolyte Dynamics" in the



Above: ARMS and GRAPHERGIA speakers of the joint workshop at Graphene Week 2024. Credit: Hamed Pourkheirollah (Tampere University)
Below: SEM images of AWC samples. Credit: Līga Grīnberga (ISSP UL)

open-access journal Carbon Trends. This publication highlights the innovative use of Activated Wood Carbon (AWC), a sustainable material, in developing printed supercapacitors. The collaborative research involved teams from Tampere University, the Latvian State Institute of Wood Chemistry, InnoCell ApS and the Institute of Solid State Physics, University of Latvia, focusing on how AWC's unique structural properties influence energy storage performance.

The article explores Activated Wood Carbon (AWC) as a sustainable material for making printed supercapacitors, which are devices used to store energy. Traditional activated carbons are often derived from non-renewable resources, but AWC is produced from biomass, offering a greener alternative. The research highlights how the structure of AWC and its compatibility with different electrolytes can significantly improve energy storage performance. In tests, supercapacitors made with AWC showed up to 93% higher specific capacitance and 90% higher energy density compared to conventional activated carbon, largely due to AWC's larger surface area and better pore structure that allows for more efficient ion storage and movement.

The study emphasises the importance of choosing the right materials and electrolytes to optimise supercapacitor performance. By using a potassium phosphate electrolyte instead of the more common sodium chloride, even better results were achieved, indicating the potential for AWC to be used in advanced energy storage systems. Overall, the findings suggest that AWC not only enhances the efficiency of supercapacitors but also aligns with global sustainability goals by utilising renewable resources, paving the way for future environmentally friendly energy solutions.

Full article: https://www.sciencedirect.com/science/article/pii/S2667056924001159

Dr. Hamed Pourkheirollah and Prof. Jinhua Sun at Graphene Week 2024. Credit: Hamed Pourkheirollah (Tampere University)

DISSEMINATION AND EXPLOITATION

Project ARMS has created visibility and built a constantly growing community through several strategic initiatives. The fully functioning website is a central hub featuring monthly contributions from project partners detailing their teams and tasks, fostering transparency and engagement. Active social media accounts on LinkedIn and the X platform further amplify the project's reach. Campaigns such as project partner introductions and the "Did You Know" series explained the project to the broader public, while the "Christmas/New Year campaign" with wishes from all project partners added a personal touch. The new series of ARMS interviews with project Work Package leaders, titled "Faces Behind Science," highlights the people driving the project, making science more relatable and engaging.

ARMS technical project manager Dr. Hamed Pourkheirollah, WP1 leader Dr. Gints Kučinskis, project coordinator Prof. Matti Mäntysalo at the Graphene Flagship Common Kick-Off event. Credit: Hamed Pourkheirollah (Tampere University)

Participation in Graphene Week 2024 also played a crucial role in enhancing visibility. Represented by project team members, ARMS showcased its advancements and engaged in valuable discussions with international researchers and Graphene Flagship sibling projects.

Close collaboration with the Graphene Flagship allows for shared communication and access to a broader audience, enhancing visibility.

POWERED BY THE GRAPHENE FLAGSHIP

Project ARMS benefits significantly from its integration within the Graphene Flagship, which enhances ARMS' objectives for developing graphene-rich, bio-based carbon materials and graphene-decorated carbon fibres to create eco-friendly supercapacitors. Through collaboration with the Graphene Flagship, ARMS participates in common governance structures, standardisation activities and innovation outreach efforts that align closely with its goals of producing scalable and sustainable energy storage solutions. This partnership facilitates sharing knowledge, resources and best practices across European initiatives, enabling ARMS to leverage collective expertise in developing graphene-rich materials and advanced manufacturing processes. By contributing to common reporting on project outputs, ARMS ensures that its advancements in energy storage technologies are recognised and disseminated within the broader Graphene Flagship community, ultimately fostering innovation and market uptake.

SAILING FORWARD

In 2025, the ARMS project will be in its second year, focusing on key activities to develop and optimise materials and processes for our supercapacitor. The project has a detailed action plan for this year, and our team will navigate the complex technical, logistical and regulatory tasks necessary to meet our objectives.

ARMS Consortium and External Advisory Board (EAB) members. Credit: Laura Ločmele (Institute of Solid State Physics, University of Latvia (ISSP UL)

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ARMS and GRAPHERGIA speakers of the joint workshop at the IEEE FLEPS 2024. Credit: Hamed Pourkheirollah (Tampere University)

The implementation of the project will continue across several work packages. Work Package 1 will focus on synthesising raw graphene-based carbon electrode materials, optimising the production of bio-curved graphene and characterising the synthesised materials. Work Package 2 will concentrate on the fabrication and enhancement of graphene electrodes, while Work Package 3 will work on the electrode booster, using atomic layer deposition (ALD) to improve electrode performance. In Work Package 4, our team will develop and optimise electrolytes for supercapacitors. Finally, Work Package 5 will integrate these advanced materials into functional supercapacitor devices, with prototype demonstrations expected by the end of the year.

The research conducted in 2025 within the active ARMS work packages is expected to yield results that will contribute to several scientific and popular science publications.

ARMS also intends to continue its communication and dissemination activities to foster a deeper understanding of the project's scope and outcomes, thereby enhancing the involvement of external stakeholders. The project results available at this implementation stage will be shared at scientific conferences, seminars and stakeholder events. Previous successful experiences co-hosting workshops with the Graphene Flagship sibling project GRAPHERGIA serve as a promising example and encourage ARMS researchers to co-host additional events. These will not only involve GRAPHERGIA, which is also focused on 2D material-based energy storage solutions in the context of the Graphene Flagship, but will also include collaboration with another Graphene Flagship project—the SAFARI project—which aims to develop new, sustainable and safe 2D materials for a wide range of applications, such as biosensors, conductive ink and EMI shielding.

As the project progresses, we may face some challenges; however, the ARMS team remains very optimistic about successfully implementing the project according to the established plan and expectations.

The project's success relies on a comprehensive approach combining technical expertise, collaboration and flexibility. Consistent communication and feedback with project partners and the External Advisory Board will help ensure our progress aligns with industry standards and regulations.

ARMS technical project manager Dr. Hamed Pourkheirollah at PRINSE'24. Credit: Hamed Pourkheirollah (Tampere University)

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

THE GRAPHERGIA PROJECT seeks to transform energy solutions with sustainable and efficient power technologies. It focuses on developing eco-friendly "dry-electrode" fabrication for energy storage devices, leveraging the potential of lasers in graphene synthesis. Through the development of a novel process for laser-assisted synthesis, functionalisation and integration of graphene materials into electrodes, GRAPHERGIA is paving the way for climate-neutral production of energy storage devices, with applications piloted in two key areas: energy-autonomous smart textiles and Li-ion batteries.

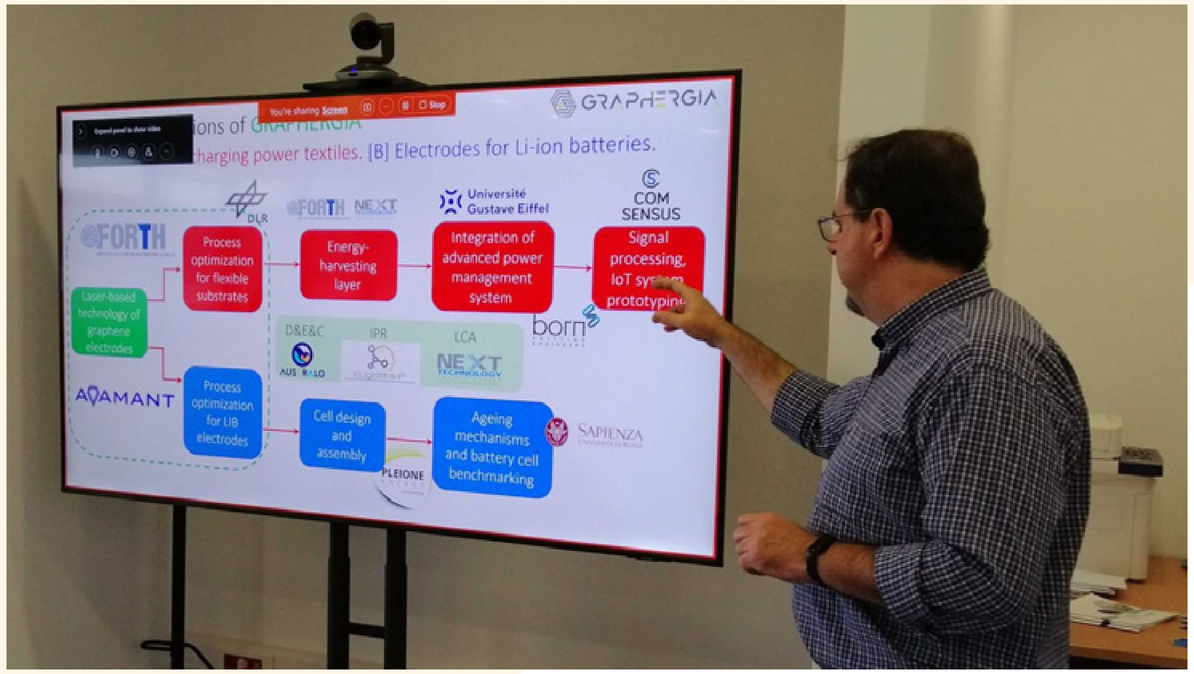
HIGHLIGHTS FROM 2024

The first year of the project focused on the establishment of key strategies for various areas including the research roadmap, the technical work packages (WP2 to WP6), the dissemination, communication and exploitation strategy and planning for scientific coordination and project management. By implementing concrete action plans and holding regular monitoring meetings, the GRAPHERGIA consortium promoted strong collaboration and achieved initial tangible results across the work packages. These efforts are paving the way toward the main goal of creating innovative pilot lines for sustainable graphene-based flexible and structural energy harvesting and storage devices.

> This year, GRAPHERGIA has advanced sustainable, laser-assisted graphene technologies for eco-friendly energy storage and flexible electronics. Looking ahead, we will focus on refining these innovative methods and showcasing their impact in key applications, such as energy-autonomous textiles and Li-ion battery anodes. GRAPHERGIA is not just about technological advancements but also about driving a greener and more energy-efficient future."

Spyros Yannopoulos
Project Coordinator

GRAPHERGIA Overview of all WPs explained by Coordinator Spyros Yannopoulos. Credit: GRAPHERGIA team



GRAPHERGIA Team at Consortium Meeting in Prato. Credit: GRAPHERGIA team

Work Package 1
Work Package 1 is dedicated to Scientific Coordination and Project Management and is led by Spyros Yannopoulos from the Foundation for Research and Technology – Hellas (FORTH). This year, we established robust internal communication and collaboration channels and ensured effective project and data management. The project steering committee, gathering all work package leaders, convened every two months to monitor the progress of all work packages and to ensure synchronisation of the next steps across the various ongoing tasks. Also, the consortium met physically in the general assembly hosted in October 2024, by Next Technology Tecnotessile (NTT), in Prato, Italy.

In parallel, the coordination team facilitated GRAPHERGIA's active involvement in the Graphene Flagship community, starting with participation in a joint kick-off meeting held in February 2024 in Gothenburg, Sweden, where four project partners attended. Additionally, the coordinator ensured that the different partners are involved in the Graphene Flagship dissemination, project management, road mapping and standardisation working groups. A significant achievement in this regard was successfully inviting the energy-related sister project, EMPHASIS[1], to join Graphene Flagship as a partnering project.

Finally, the project delivered two public reports under this work package: Deliverable 1.1 Project Management Plan[2] and Deliverable 1.2 Data Management Plan[3].

Work Package 2
Work Package 2: Design, Development, and Optimisation of Textile-Based TENGs and Micro-Flexible SCs, is led by the coordination team at FORTH.

During the first year of the project, FORTH focused on optimising the laser-assisted in-situ growth of graphene and graphene nanohybrids on various flexible substrates, including textiles. This effort led to the publication of one peer-reviewed paper[4] (closed access), with two additional manuscripts currently under review in high-impact journals. The method is now being further enhanced to accommodate various types of textile substrates relevant to the beneficiaries involved, particularly Born GmbH.

Specifically, during this first phase of the project, graphene oxide (GO) dispersions supplied by Graphenea, a partner of the GIANCE[5] project under the Graphene Flagship, were used as the graphene precursor. FORTH optimised a lab-scale process for the laser-assisted reduction of GO into high-quality graphene (LrGO) directly on textile surfaces. Building on this, the project partner ADAMANT undertook the upscaling of the process to parameters compatible with the roll-to-roll pilot line, which is expected to become operational in the final phase of the project.

Following this optimisation, a systematic evaluation of the laser-reduced GO (LrGO) electrodes will be carried out for applications in triboelectric nanogenerators (TENGs) and various supercapacitor configurations. Additionally, alternative cost-effective precursors for high-quality graphene production were investigated. Polyacrylonitrile (PAN) nanofibers, which can be easily and scalable produced over large areas through electrospinning, were shown to yield high-quality graphene with excellent conductivity after mid-IR laser irradiation. This material is currently under evaluation as an electrode for both TENGs and interdigitated (planar) supercapacitors. FORTH has successfully achieved uniform and conformal deposition of the energy-harvesting layer (various fluoropolymers) on graphene-coated textiles. The process took place using plasma-enhanced chemical vapour deposition (PE-CVD). The resulting materials have been thoroughly characterised in terms of thickness, stability, uniformity, surface energy, degree of cross-linking and breathability. Structural analysis and durability assessments are currently ongoing.

In parallel, inorganic carbide precursors, such as SiC, have been subjected to laser-assisted decomposition using two approaches: direct irradiation of a precoated layer of the SiC powders on current collectors (e.g., Cu foils) and the patented LEST technology developed by FORTH where the SiC materials was adhered to a transparent tape. This process successfully produced high-quality graphene structures decorated with Si and SiOx nanoparticles. These materials are currently under investigation as anode materials for Li-ion batteries.

The partners presented research work primarily related to WP2 to the scientific community at four scientific events, including two workshops. GRAPHERGIA's results were disseminated at the following events:

At the ICOOPMA Conference – 10^{th} International Conference on Optical, Optoelectronic and Photonic Materials and Applications, held in June 2024 in Pardubice (CZ), Prof. Yannopoulos delivered a lecture titled: *"Leveraging Laser-Assisted Techniques for High-Quality Graphene and Graphene-Based Nanohybrids in Energy Storage Applications"*.[6]

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GRAPHERGIA 2024 Events Collage. Credit: GRAPHERGIA team

At the FLEPS Conference – International Conference on Flexible and Printable Sensors and Systems (an IEEE event), held in July 2024 in Tampere (FI), Prof. Yannopoulos and D. Hoxha were invited to present GRAPHERGIA's concepts and recent results at a Workshop co-organised by the ARMS project[7], titled *"Synergising Sustainability: Integrating Advanced Energy Storage with Harvesting for Wearable Electronics."*[8]

At the SSC 2024 Conference – 15th International Conference on Solid State Chemistry, held in September in Ústí nad labem (CZ), members from FORTH and DLR presented the latest advances of the GRAPHERGIA project at a workshop titled *"Electrochemical Energy Storage Materials and Processes"*. This workshop, hosted as a satellite event of SSC 2024 event, was co-organised by GRAPHERGIA and two other H2020 projects focused on electrochemical energy storage[9].

At the XXXVIII Panhellenic Conference on Solid State Physics & Materials Science, an event with international participation held in September 2024 in Ioannina (GR), Mrs. E. Amirali (then an undergraduate student, now a master's student supported by GRAPHERGIA) delivered an oral presentation on the preparation and characterisation of PAN-based laser-derived graphene[10].

The project achieved significant progress in WP2, optimising the laser-assisted production of graphene-based materials on textiles and various flexible substrates. Looking ahead, the focus will be on further optimising these processes and integrating them into functional devices, ensuring their successful implementation in the project's two demonstrators: self-charging, energy autonomous textiles and anodes for Li-ion batteries.

Work Package 3
Work Package 3 focuses on the design and assembly of Li-ion battery (LIB) cells, with an emphasis on preparing laser-scribed graphene-based anodes. This work package is led by Pleione Energy GmbH (PLE).

The primary scientific objectives of WP3 are to design LIB cells incorporating anodes made from laser-synthesised graphene-related materials, investigate the ageing mechanisms of graphene-based LIB cells and establish benchmarks for their performance. These goals are addressed through four tasks, with two of them initiated during the first year of the project. Task 3.1, *"Cell Design of Graphene-Based Anode Materials,"* commenced in March 2024 (M6), while Task 3.2, *"Graphene-Based Battery Assembly and Performance Evaluation,"* started in July 2024.

In the past period, the focus was on designing graphene-based anode cells and conducting preliminary experiments on coating SiC powders of various sizes and film thicknesses onto copper foil. These coatings were decomposed using different types of lasers to prepare anodes based on 3D graphene structures decorated with Si and SiOx nanoparticles. Alternatively, the LEST method was employed to simultaneously synthesise and deposit such 3D graphene films onto Cu current collectors. The primary goal was to initiate the development of the battery manufacturing process and evaluate the performance of the resulting anode materials.

Currently, University Sapienza Rome (URM) and FORTH are defining the next steps to utilise Kerr-gated Raman spectroscopy and Impulsive Transient Reflectivity spectroscopy (developed by URM). These advanced techniques aim to provide critical insights into the state of charge of graphene and graphene/nanohybrid electrodes, as well as to understand the electron/phonon coupling between graphene layers and the nanoparticles decorating them.

Additionally, in this context, URM took a leading role in organising and hosting the 28th International Conference on Raman Spectroscopy (ICORS 2024[11]), where GRAPHERGIA was prominently featured as a Flagship ongoing research initiative, showcasing its advancements and contributions to the field.

Work Package 4
Work Package 4 is focused on advanced electrical modelling and efficient power management of Tribo-Electric Nanogenerators (TENGs) for energy harvesting and self-powered sensing Internet of Things (IoT) applications and is led by Université Gustave Eiffel / ESYCOM lab (UGE).

During the first year, activities focused on the design and development of conditioning circuits for TENG rectification (Task 4.1). Specifically, UGE developed theoretical models to establish a strategy for selecting the optimal unstable charge-pump conditioning circuit for a given TENG, based on specific mechanical excitation parameters and the maximum allowable voltage in the system. This theoretical approach was validated through simulations. In parallel, the automatic test bench for characterising a gap-closing TENG – a modelled as a voltage source in series with a variable capacitor – was successfully finalised.

The leading partner, UGE, presented the ongoing WP4 research at three scientific events, including the symposia/workshops (a) "Self-Powered Sensors Based on Nanogenerators" at the European Materials Research Society (e-MRS) 2024 Spring Meeting[12], (b) Materials Challenges in Alternative and Renewable Energy 2024 (MCARE'24)[13] and (c) PowerMEMS+ 2024: Micro and Miniature Power Systems, Self-Powered Sensors and Energy Autonomous Devices[14].

Work Package 5
Work Package 5 focuses on the design, manufacturing, and testing of representative technology demonstrators and is led by ADAMANT Composites Ltd. (ADA). It started in February 2024. During this period, efforts were concentrated on early eco-design analysis and the optimisation of critical parameters for the technology demonstrators (Task 5.1 led by NTT). This task serves as the foundation for ensuring that the design and development processes align with eco-design principles, supporting the overarching objective of minimising environmental impact across the entire product life cycle.

The key activities have included a literature review and an evaluation of eco-design practices relevant to the demonstrators, as well as an assessment of European legislation on eco-design, circularity and carbon neutrality goals. This research will be continuously updated and refined as the partners developing the demonstrators provide more specific information. Furthermore, the eco-design analysis will be closely integrated with the materials, components and processes associated with each demonstrator, which will be addressed in later stages starting in March 2026. This collaborative approach will facilitate the identification of the most appropriate eco-design strategies and regulatory frameworks to ensure compliance and sustainability.

This work package also ensures alignment with European legislation and monitors the evolving regulatory landscape, including the Eco-design for Sustainable Products Regulation (ESPR). This alignment is essential for defining the eco-design criteria for the demonstrators as the project advances. During the first year, the focus was on establishing a solid foundation for future activities by conducting essential eco-design evaluations and preparing for more detailed work in the later stages of the project.

Work Package 6
Work Package 6 is dedicated to Life Cycle Assessment, Sustainability and Eco-design Approach, and is coordinated by Next Technology Tecnotessile (NTT).Over the past 12 months, efforts have focused on introducing and engaging the GRAPHERGIA team with sustainability and eco-design concepts, which will be implemented as a comprehensive approach throughout the project's research activities.

The applied Life Cycle Assessment (LCA) methodology was outlined in detail during dedicated online meetings, covering the four key steps defined in ISO 14040. This LCA approach was integrated with the Life Cycle Costing (LCC) methodology, which evaluates all costs incurred throughout a product's lifetime, work or service. The LCC methodology was also introduced to GRAPHERGIA partners during webinars, where strategies for assessing both direct and indirect costs of the developed products were discussed.

In parallel, partners initiated a preliminary Social Life Cycle Assessment (S-LCA) survey to gather feedback from involved stakeholders. Additionally, the eco-design methodology, which will guide the development of components and products during the project, was presented in online meetings to ensure its seamless integration into the project's implementation.

Work Package 7
The last work package focuses on the dissemination, exploitation and communication of project results. The leading partner is AUSTRALO Marketing Lab (AUS).

The first year has been highly productive in terms of communication and dissemination activities. The project has evolved from a concept on paper into an active initiative with attractive branding, actively engaging European and international research and innovation communities across different channels and stakeholder events.

The first step was to create GRAPHERGIA's branding, which enabled it to be identified among other related projects, especially the Graphene Flagship Initiative. A solid strategy guiding all communication, dissemination and exploitation activities throughout the project was also established. The communication activities have focused on sharing updates and knowledge from the project; the GRAPHERGIA website and social media channels are essential tools for communication. The dissemination activities aim to enable stakeholders to use GRAPHERGIA's research results effectively. This includes participation in various events, the submission of scientific publications, and the publication of non-sensitive project results, which are essential for dissemination. In parallel, the partners have been engaged in the implementation of the exploitation strategy and especially the first exploitation workshops, to reflect the key exploitable outcomes and the value proposition of GRAPHERGIA. In addition, deliverable 7.1[15], a public report outlining the impact strategy to be implemented throughout the project, was submitted.

Current and future actions aim to promote active stakeholder participation through targeted channels, increasing visibility and establishing a robust network of stakeholders around the GRAPHERGIA project. This approach will enhance sustainability and facilitate the market uptake of the key exploitable results achieved through GRAPHERGIA.

DISSEMINATION AND EXPLOITATION

GRAPHERGIA members have shown a strong commitment to the project, united by shared objectives and a cohesive visual branding identity. This collaboration has resulted in the development of a growing network of stakeholders, the GRAPHERGIA hub, with a keen interest in the project's three key research areas: graphene, smart textiles and Li-ion batteries, along with their novel applications.

In its first year, GRAPHERGIA effectively communicated its main activities and results through targeted channels, including social media platforms, where it has garnered over 1,400 followers (LinkedIn, X and BlueSky), a bi-annual newsletter[16] with almost 500 subscribers and the project website (graphergia.eu), which features over 40 blog articles highlighting project updates and news. Finally, the project launched its first video[17] played for the first time at the Graphene Week 2024.

Regarding dissemination, the team has presented GRAPHERGIA's ongoing research at 11 scientific events across Europe and submitted a few scientific publications to peer reviewed journals.

GRAPHERGIA partners hosted three joint scientific workshops engaging the research community in the Graphene Flagship and beyond, gathering around 190 participants in total.

GRAPHERGIA team at Graphene Week 2024. Credit: Kateřina Antoš

The first workshop was "Synergising Sustainability: Integrating Advanced Energy Storage with Harvesting for Wearable Electronics"[18] and co-organised with the ARMS project in June 2024 in Finland.

The second workshop was "Electrochemical Energy Storage Materials and Processes", and co-hosted with EMPHASIS and INERRANT, during the 5th International Conference on Solid State Chemistry 2024 (SSC 2024)[19] in September in the Czech Republic.

The third workshop, "Integrating Graphene Innovations: From Smart Textiles to High-Performance Energy Storage,"[20] was hosted as a part of Graphene Week 2024 in collaboration with the ARMS-project.

POWERED BY THE GRAPHENE FLAGSHIP

The GRAPHERGIA project has greatly benefited from its integration into the Graphene Flagship ecosystem at multiple levels, enabling us to achieve and expand our project goals effectively.

Enhanced visibility and dissemination opportunities
Being a member of the Graphene Flagship community has significantly enhanced the public visibility of our ongoing research. During the first project year, we recorded 16 external online media articles about GRAPHERGIA, while our participation in Graphene Flagship events and activities has provided numerous opportunities to showcase our work to the global graphene and materials science community. Additionally, we have secured prospects for joint publications with other Graphene Flagship projects, further extending our reach and impact.

Strengthened partnerships and collaboration
Participation in the Graphene Flagship ecosystem has allowed GRAPHERGIA to establish and strengthen partnerships with other related projects. In particular, we partnered with the Graphene Flagship's ARMS project focusing on the energy sector. Together, we co-hosted a joint workshop and participated in dissemination and scientific activities. Additional joint initiatives are currently being organised to further strengthen this partnership. GRAPHERGIA has also joined forces with other Graphene Flagship projects, i.e. 2D-BioPad, MUNASET and SAFARI, collaborating on the biosensing aspects of smart textile demonstrations. Based on this partnership, a joint paper has been scheduled for publication early next year. Collaboration with GIANCE is planned for 2025.

Optimised resource utilisation and management
The Graphene Flagship community has provided strong support in optimising the project's resources, particularly through collaborative dissemination and project management. By working alongside the 13 sister projects within the Graphene Flagship, we have been able to achieve better outcomes while sharing best practices across projects.

Direct engagement with stakeholders
GRAPHERGIA partners actively participated in Graphene Week 2024[21] through poster sessions and a dedicated workshop. This event served as an excellent platform for engaging directly with new stakeholders, sharing our project's vision and building networks that can lead to future collaborations.

Strategic Collaboration and Standardisation
GRAPHERGIA teams have actively contributed to the Graphene Flagship's standardisation and roadmapping committees for graphene-related materials. This participation ensures that our research outputs align with emerging global standards and support the strategic development of the project's demonstrators for rapid market adoption.

SAILING FORWARD

On the R&D front, the GRAPHERGIA partners have outlined a detailed plan for the second year of the project to advance the technology readiness level (TRL) of various activities toward the targeted goals. In summary, GRAPHERGIA aims to:

- Fully optimise laser-based graphene production methods to establish pilot-scale processes for the fully operational production of e-textiles.
- Develop a pioneering method for the fabrication and performance optimisation of graphene-on-textile TENGs, effectively coupled with electrochemical energy storage devices.
- Advance the design of LIB cells utilising laser-assisted graphene-based electrodes.
- Investigate the aging mechanisms of graphene-based LIB cells to improve their performance and longevity.
- Define and refine the input data required to progress robust life cycle assessment (LCA), life costing (LCC), and social life cycle assessment (S-LCA).

In addition, in mid-2025, we have the first interim review of GRAPHERGIA by the European Commission committees. To ensure a robust presentation of the project's progress, the coordination team will oversee the preparation of the interim report. This report will highlight key achievements for all work packages and outline a clear roadmap for the following phases of the project. Early in 2025, we will actively participate in joint activities between the Graphene Flagship and its projects to maximise the collective impact of these initiatives.

Finally, GRAPHERGIA will continue its proactive engagement with its established community of stakeholders and will work on broadening its spectrum. We are planning participation in key events, including Graphene Week 2025 and other high-profile scientific conferences in the fields of energy storage, graphene technologies and smart textiles. GRAPHERGIA also aims to launch a podcast series and special communication campaigns, including features on Women in Science and the contributions of the next generation of researchers involved in the project.

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GRAPHERGIA team visiting facilities at ADAMANT partner. Credit: GRAPHERGIA team

Energy

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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.

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GRAPHENE FLAGSHIP ANNUAL REPORT 2024

MUNASET

Multiparametric nanoelectronic biosensors for therapy response testing

MUNASET IS DEVELOPING a rapid, highly sensitive graphene-based biosensor platform to address therapy response prediction and allow faster and more precise treatment identification, with the goal to improve therapy outcomes and reduce hospitalisation time. MUNASET aims to 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 that 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.

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 and detection principles on the same device.
- Novel sensing mechanism based on specific charge removal by proteases to ensure clear signals and high reproducibility.
- Integrated CMOS readout to enable robust multi-analyte measurements with built-in calibration, averaging and measurement readout.

HIGHLIGHTS FROM 2024

The MUNASET project focuses on the development of a graphene-based biosensor platform for real-time, label-free detection of protease activity of MMP-9 utilising custom-made peptides designed for high sensitivity and selectivity. The system is supposed to be capable of detecting protease activity at low nanomolar concentrations and offers potential applications in both diagnostics and therapeutic monitoring. The cleavage of the custom peptides by the target proteases causes a change in the graphene layer that can be measured as an electrical signal. Below our technology highlights:

1. Graphene-Based Sensing Platform:

- The core of the biosensor is a graphene layer, which provides exceptional conductivity, sensitivity and biocompatibility.
- This platform translates protease activity into measurable electronic signals, enabling precise real-time monitoring.
- The devices are currently provided by Graphenea and are measured in a custom-made measurement chamber.
- At a later stage of the project, graphene devices integrated on CMOS chips will be provided by VTT.

2. Custom Peptides:

- Peptides are synthesised by JGU Mainz.
- MMP-9 specific peptides are immobilised on the graphene surface.

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, Kaiserslautern University of Applied Sciences

- Protease cleavage of these peptides results in a detectable signal change, offering high specificity and selectivity.

3. Label-Free Detection:

- By eliminating the need for complex labelling steps, the platform simplifies the detection process, making it efficient and cost-effective while maintaining high performance.
- Detection in complex media:
- Proteases are detected in patient samples, e.g. blood or serum.

Work carried out in 2024 and key achievements

- **Device Preparation:** A modification assay has been established for the measurement of peptide cleavage with target proteases.
- **Detection Sensitivity:** The biosensor has demonstrated reliable detection of MMP-9 activity at low nanomolar concentrations in buffer, showcasing its capability for sensitive measurements.
- **Sample Complexity:** The sensing platform was able to measure MMP-9 at 10 nM concentrations in human cerebrospinal fluid (CSF).

DISSEMINATION AND EXPLOITATION

MUNASET and 2D-BioPAD hosted a joint workshop on 17 October 2024, during Graphene Week 2024, aimed at fostering collaboration and exploring synergies in the areas of 2D Materials (2DM) for biomedical applications. The event showcased both projects' commitment to advancing cutting-edge solutions that address pressing biomedical global challenges under the banner of the Graphene Flagship.
The workshop brought together experts, researchers and industry leaders to present and discuss the latest trends and developments in bioengineering, biosensing and antimicrobial resistance, with a focus on creating impactful innovations that can benefit citizens, patients, caregivers, healthcare professionals and health systems. Participants engaged in open dialogue and knowledge-sharing sessions, exploring new avenues for cooperation and identifying potential joint initiatives for future research and innovation projects.

Project Coordinator Alexey Tarasov and project members at Graphene Week. Credit: Kateřina Antoš

Dr. Aristeidis Bakandritsos, Group Leader, Czech Advanced Technology and Research Institute (CATRIN) at Palacký University, coordinator of the 2D-BioPAD project and co-chair of the Graphene Week 2024 commented on the collaboration: *"This workshop provides the groundwork for developing synergies between similar activities, driving innovation and accelerating progress towards application of 2D materials in biomedical and other applications".*

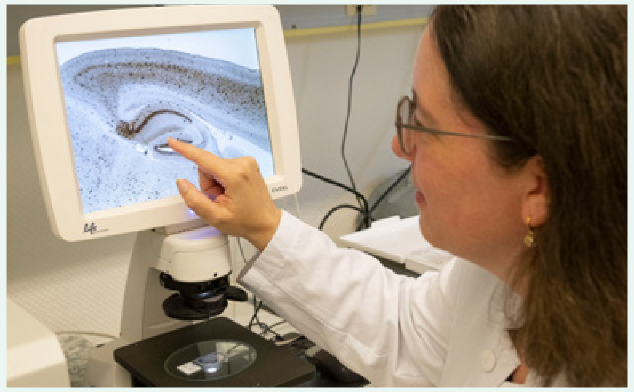
Prof. Dr. Alexey Tarasov, Professor of Biomedical Engineering, Kaiserslautern University of Applied Sciences, coordinator of the MUNASET project and co-chair of the Biomedical parallel session added: *"Our projects have the same vision, we want to bring 2D materials to biomedical applications. Collaboration is key to achieving this and the two projects will work closely together to realise this vision."*

Prof. Dr. Arben Merkoçi, ICREA Research Professor and Group Leader, Institut Català de Nanociència i Nanotecnologia (ICN2), co-chair of the Biomedical parallel session added: *"Indeed this session demonstrated that the potential of graphene and 2D materials is enormous. There have been many impressive applications so far for diagnostics and therapies. We should keep the momentum and try to collaborate to demonstrate more mature technologies with clear benefits for society in the next Graphene Week."*

This joint workshop marks the beginning of an extended partnership between MUNASET and 2D-BioPAD, paving the way for future collaborations and joint results for 2D materials in biomedical applications. Both projects reaffirm their commitment to advancing research and innovation through mutual support and collaboration, welcoming also other projects and initiatives to join forces.

POWERED BY THE GRAPHENE FLAGSHIP

Being part of the Graphene Flagship has significantly supported our project's goals by providing access to cutting-edge research, expertise and a collaborative network dedicated to advancing graphene technology. This partnership has enabled us to leverage state-of-the-art materials, share knowledge with leading scientists and accelerate the development of our graphene-based biosensor platform. The Flagship's infrastructure and resources have been instrumental in overcoming technical challenges and fostering innovation, bringing us closer to realising our vision of a rapid, sensitive diagnostic tool for personalised therapy in major depressive disorders.



Alzheimers Psychiatrist Kristina Endres. Credit: Peter Pulkowski

Project Coordinator Alexey Tarasov networking at Graphene Week. Credit: Kateřina Antoš

MUNASET project M6 Meeting Zweibrüken. Credit: MUNASET

SAILING FORWARD

This graphene-based biosensor platform is poised to advance the field of protease diagnostics, with a particular focus on addressing the unmet needs in mental health and other chronic diseases. By enabling real-time, sensitive detection of biomarkers like MMP-9, this technology offers a transformative approach to understanding and managing complex disorders such as MDD, major depressive disorder. The platform will be further developed to:

- Detect multiple proteases simultaneously, expanding its utility for biomarker profiling in neurological and systemic diseases.
- Adapt the technology for use in more complex biological media, such as serum or blood, to validate its clinical relevance.

Biomedical

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MUNASET
PART OF THE GRAPHENE FLAGSHIP

2D-BIOPAD

Supple Graphene Bio-Platform for point-of-care early detection and monitoring of Alzheimer's Disease

> The 2D-BioPAD project lays the foundation for fostering synergies between complementary research and technological fields, driving innovation, and accelerating progress towards the application of 2D materials in biomedical and other sectors."

Aristeidis Bakandritsos
Czech Advanced Technology and Research Institute (CATRIN) at Palacký University

THE 2D-BIOPAD project will develop an innovative, user-friendly decision support tool/device for the early detection of Alzheimer's Disease (AD). Using advanced graphene materials, the tool will enable a quick, minimally invasive test capable of measuring up to five key AD biomarkers in real time. The tool will undergo clinical testing in Finland, Greece and Germany to demonstrate its effectiveness and safety.

HIGHLIGHTS FROM 2024

Co-designing with key stakeholders
In 2024, 2D-BioPAD made important progress in research, development and collaborations. The project established a Patient and Public Involvement & Engagement Strategy to better support the design and implementation of the 2D-BioPAD system and its clinical pilot studies. This strategy aims to interact with the project's target audience and gather valuable insights through consultations, which will guide its user-centred and clinical-oriented implementation.

As part of this strategy, we actively engaged with our stakeholders via 26 semi-structured interviews and a survey with 90 participants, including healthcare professionals, patients and caregivers, as well as technology providers and biomarker experts. This survey helped define the initial set of target biomarkers (Aβ1-40, Aβ1-42, p-tau217, NfL, GFAP) and user requirements for the 2D-BioPAD decision support tool. The insights from this engagement were refined during a workshop with our Scientific and Industrial Advisory Board and were shared at the 34th Alzheimer Europe Conference in Geneva, Switzerland, held in October 2024. These contributions helped further the conversation on Alzheimer's research and diagnostics.

Advances in biosensing technologies
In the development of our decision support tool, key achievements started with a complete first version of the 2D-BioPAD system architecture, covering technical details about the individual technical components and the integrated system for both the graphene-based electrochemical and field-effect transistor (FET) biosensors. Per component significant steps have been achieved:

- Successful aptamer selection for GFAP, a key biomarker of inflammation, and significant progress for NfL, a biomarker of neurodegeneration. Next in the pipeline is p-tau217, whereas ongoing discussions with leading AD labs have been initiated for the Aβ1-40 and Aβ1-42 peptides.
- To support the selection process, the Apta-MCTS modelling protocol has been selected as a promising computational methodology, delivering high interaction scores and secondary structures, for Aβ and pTau-217.
- Delivery of three distinct Au-Fe3O4 magnetic nanoparticle systems with variable architecture, size and magnetic properties (Au-Fe3O4 MNPs, Fe3O4@Au core-shell MNPs and Janus Au-Fe3O4 NPs) for improving sample handling and signal readings on the biosensors through in-flow preconcentration and flow control. Conjugation with thrombin aptamers was also established, introducing a versatile and reproducible protocol for other bioreceptors.
- Development of densely and selectively single and doubly functionalised graphene derivatives (terminated with -SH, -OH, (SH+NH2), (SH+OH) and -COOH groups) that allow up to 12% functionalisation degree. The selective functionalisation helps in controlling the electrochemical response, the solvation properties which are important for processing, and offers a potent tool for structure-properties optimisation and a pool of derivatives for needs-oriented selection. These derivatives introduce a specific binding with the aptamers (ongoing) through their short linkers, and improve the signal to noise ratio, the selectivity and sensitivity.[1]
- A first electrochemical biosensor prototype was developed with improvements in LFA production and the graphene stamping on LFA.[2] Exploiting a laser-enabled process, graphene oxide reduction, conductivity enhancement and nitrocellulose patterning can be concurrently achieved, creating robust connection sites and bypassing sample leakage. Different strategies leveraging aptamer conformational changes have been developed and successfully demonstrated by using thrombin aptamer as proof of principle. Research with the GFAP aptamer has been initiated, whereas the direct immobilisation of antibodies is also being explored.
- Scale-up activities on GFET production with high quality CVD graphene and on integration of GFET into a miniaturised diagnostic platform are ongoing. This leads towards a manufacturing blueprint that will be the foundation of the device scale-up pilot line. First GFET biosensor prototypes were also developed, achieving up to two channels working simultaneously, supporting the detection of two different target analytes. Integration for aptamers/antibodies for GFAP and NfL has been initiated.
- Electronics for onboard signal analysis and wireless transmission to a mobile app have been integrated, with first functional versions allowing for clear demonstration of current prototypes.

2D-BioPAD's Expert, Patient and Public Involvement & Engagement. Credit: UP

Preparing for clinical (pilot) validation
A uniform clinical pilot study protocol was created for both the retrospective and prospective clinical studies. The protocol was translated into Greek, Finnish and German, and received approval from ethics committees in Greece, Finland and partially in Germany.

Close collaboration with regulatory experts ensures that all steps are aligned with regulatory requirements for clinical trials and future market uptake. To this end, an Ethical Consideration Roadmap has been developed early on, detailing ethical principles and a method for considering and documenting those principles for the 2D-BioPAD project activities. These activities are interconnected with the 2D-BioPAD decision support tool, whereas a first draft of a Regulatory Acceptability Plan has initiated discussions about regulatory considerations for future uptake. Following a stepwise approach, the 2D-BioPAD technical specifications have been regularly updated following implementation progress, whereas partners have emerged in relevant workshops to discuss compliance with the IVDR.

2D-BioPAD's Ethical Principles

As the consortium understands the significance of regulatory compliance by design, an online public webinar on the European Requirements for the CE-Certification of Medical Devices and In Vitro Diagnostics was held on 10th February 2025. The session focused on Medical Device EU Regulations (MDR and IVDR) and aimed to transfer this knowledge to the entire Graphene Flagship community and beyond.

Strengthening collaboration
2D-BioPAD organised and participated in a series of events throughout the year, actively engaging with the international scientific and industrial community.

The highlight was the co-organisation of the Graphene Week 2024. Our coordinator, Dr. Aristeidis Bakandritsos from Palacký University in Olomouc, at CATRIN (Czech Advanced Technology and Research Institute), served as one of the chairs of the conference, several other partners participated with plenary talks, presentations and posters.

On top of that, 2D-BioPAD established a very strong collaboration with its sister project MUNASET, exchanging knowledge through online meetings and workshops, while also co-organising the Biomed parallel session during Graphene Week 2024. The two projects have agreed to jointly pave the way for 2D Material research in the biomedical focus area under the Graphene Flagship. This collaboration brought together experts, researchers and industry leaders to present and discuss the latest trends and developments in bioengineering, biosensing and antimicrobial resistance, with a focus on creating impactful innovations that can benefit citizens, patients, caregivers, healthcare professionals and health systems.

Finally, 2D-BioPAD has engaged with several organisations through the partnering mechanism within the Graphene Flagship introducing and collaborating with Associated Members (AMs) and Partnering Projects (PPs).

Top: The 2D-BioPAD coordinator (left) was one of the chairs of Graphene Week 2024. Credit: Kateřina Antoš. **Bottom:** The 2D-BioPAD and MUNASET joint Biomed Workshop at Graphene Week 2024. Credit: Kateřina Antoš

GRAPHENE FLAGSHIP ANNUAL REPORT 2024

ICNd showcases 2D-BioPAD at SENSE workshop. Credit: UP

Targeting international outreach, 2D-BioPAD was showcased at the SENSE Workshop in San Sebastián, Spain, and in the Know4Nano Workshop in Novi Sad, Serbia, where ICN2 presented research on using 2D materials for Alzheimer's diagnosis. The project was also introduced by AUTH at the XVI International Symposium on Self-Propagating High-Temperature Synthesis, where the focus was on magnetic nanoparticle-based systems for medical use. Additionally, NanoBalkan 2024, the second edition of an international conference, was co-organised by ICN2, bringing experts together to discuss the latest developments in the field. The project has also reached key stakeholders in Asia, introduced by GRAPHEAL at the 2D Materials 2024 conference in Wenzhou, China. Finally, the project's partners showcased 2D-BioPAD not only at the international level but also at the national level. A prime example is the clinical partner from Greece, Alzheimer Hellas, which has actively participated in numerous events, radio and TV shows, as well as national press across Greece.

These achievements in 2024 highlight 2D-BioPAD's continuous progress in advancing Alzheimer's diagnostics and its growing presence in the scientific community through presentations and collaborations.

DISSEMINATION AND EXPLOITATION

Early on the project established a strategic dissemination and communication plan, followed by numerous activities, that aim to capture and share every significant moment and achievement within the context of the project with both current and potential stakeholders.

With a strong presence on social media (LinkedIn, Facebook, Twitter, YouTube), the project has reached over 10,000 international stakeholders. This outreach is complemented by two promotional videos that provide an overview of the project and its key information, as well as interviews highlighting advancements, such as those on graphene-based biosensors within the context of the 2D-BioPAD project. Additionally, two bi-annual newsletters, three press releases and a regularly updated website serve as essential tools to keep stakeholders informed and engaged.

To engage with a wider audience, six informative articles have been drafted to explain key terms and their relevance to the project, along with four scientific publications presented at international conferences and two in journals. The project has also participated in over 20 in-person and virtual events, including workshops, lectures and conferences, with a notable highlight being its role as a co-host/co-chair at Graphene Week 2024. This participation underscores the strong collaboration with the Graphene Flagship community.

In terms of exploitation, 2D-BioPAD has already drafted a clear exploitation strategy, followed by internal workshops and bilateral meetings with partners. These efforts have helped identify potential exploitation pathways that could be realised during and after the duration of the project.

POWERED BY THE GRAPHENE FLAGSHIP

Being a member of the Graphene Flagship has significantly contributed to our progress towards one of the core objectives of the community: collaboration and knowledge transfer. The consortium had the opportunity to meet and exchange knowledge with peers and colleagues around the world and collectively push scientific progress on 2D materials research. The Graphene Flagship also plays a pivotal role in the dissemination and communication of information regarding both biomedical research and critical issues related to Alzheimer's disease, raising awareness on the increasingly important early diagnosis and prevention aspects. The initiative offers a strong network that aids in promoting our actions and organising working groups for coordination, governance, dissemination, roadmapping and standardisation, fostering mutual support among projects.

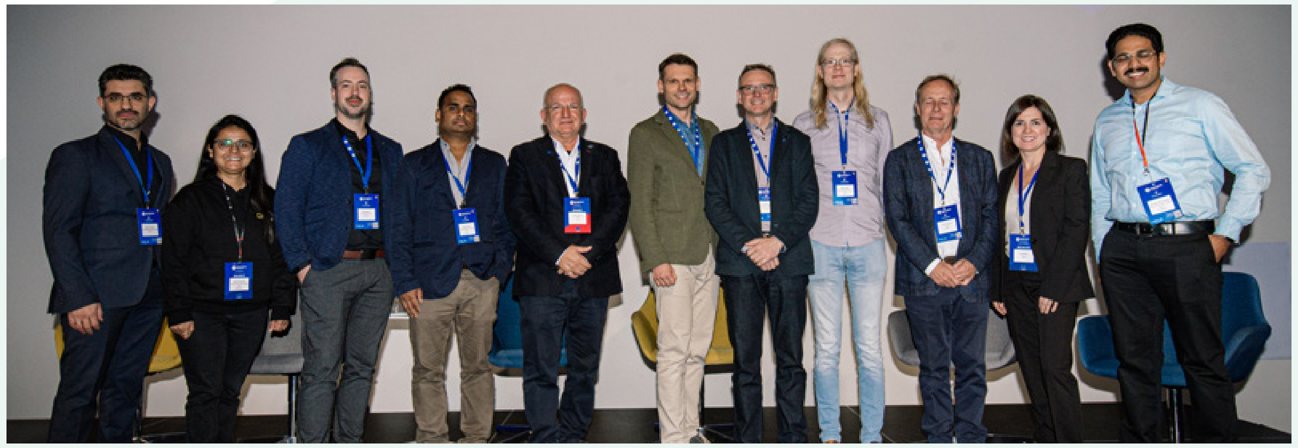
Under the Graphene Flagship, a long-term partnership between 2D-BioPAD and MUNASET has been established. Preliminary ties with GRAPHERGIA and SAFARI have also been created and the potential for future collaborations extend to all other projects within the Graphene Flagship, underscoring our shared commitment to advancing research and innovation in this exciting field.

SAILING FORWARD

2D-BioPAD's plans for 2025 focus on advancing the development and validation of biomarkers, biosensing technologies and clinical protocols. Ongoing efforts include testing and characterising aptamers, progressing with biomarker selection and advancing biosensing capabilities. Partners are closely collaborating to streamline these processes and deliver functional prototypes for use with real fluid samples.
Efforts to address regulatory aspects, including potential protocol updates and ethical approvals, will continue with consultations planned to align approaches across regions. Preparatory work on retrospective and prospective studies is progressing, with discussions on device-specific requirements and timelines planned.

Further focus will be placed on dissemination and outreach activities, including updates to events, conference participation and article promotion. Preparations for upcoming meetings, and workshops are underway, ensuring alignment and progress toward project objectives. All eyes are set for Graphene Week 2025, with the aim to demonstrate our technologies live.

1. Check the relevant publication from UP-CATRIN: https://doi.org/10.1002/adma.202410652
2. Check the relevant publications from ICN2: https://doi.org/10.1016/j.bios.2024.116315



The 2D-BioPAD and MUNASET partners at Graphene Week 2024. Credit: UP

Biomedical

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2D BioPAD

GRAPHENE FLAGSHIP ANNUAL REPORT 2024

Explore the Graphene Flagship Exhibition

The European Commission hosted an exhibition showcasing the Graphene Flagship's accomplishments and key graphene applications in the lobby of the Directorate-General for Communications Networks, Content and Technology (DG CONNECT) building in Brussels, Belgium. The exhibition was launched with a grand opening attended by key EC personnel, including Director-General Roberto Viola and Deputy Director-General Thomas Skordas. Photos courtesy of the European Commission

GATEPOST

Revolutionising IoT security with graphene-based all-optical data processing for high-speed, low-power computing

GATEPOST DEVELOPS INNOVATIVE technologies that enhance the security and performance of the Internet of Things (IoT). By using advanced 2D materials such as graphene, GATEPOST aims to create faster and more efficient computing systems that can handle the growing demands of connected devices. The project focuses on using light to process information, which supports faster, high-throughput computing. Ultimately, GATEPOST works on shaping the future of computing by providing solutions that are not only powerful but also energy-efficient and capable of supporting next-generation networks like 5G/6G and beyond.

In the last year, GATEPOST has taken important steps toward revolutionising data processing and security for the IoT era. With our innovative graphene-based technologies, we're reshaping what's possible in all-optical computing. As we move forward, our mission is to lead the charge toward a more secure, efficient and interconnected future."

Mindaugas Lukošius
IHP GmbH – Leibniz Institute for High Performance Microelectronics

HIGHLIGHTS FROM 2024

First photonic integrated GATEPOST chip unveiled
For GATEPOST, 2024 marked an important milestone in the further development of the project. In April, after months of design and fabrication, the team revealed GATEPOST's first photonic integrated chip at the first bi-annual meeting of the project consortium attended by eight European partners from industry and academia.

Leonardo Del Bino, co-founder of Akhetonics GmbH, explains: "The chip is based on graphene on silicon nitride (SiN) technology and the IHP GmbH – Leibniz Institute for High Performance Microelectronics multi-project wafer run for the 2D Experimental Pilot Line (2D-EPL) . To put it simply, the chip can be imagined as a cake consisting of many layers with different ingredients. Each layer has its own mask that determines exactly where the ingredient is placed in the cake. The design of the GATEPOST chip initially contains nine layers, each of which, with its mask, represents a specific material at a specific point in the cake," Del Bino explains. The GATEPOST's first chip was produced in the project's lead partner, IHP's pilot line.

"The chip contains 46 different devices, many of those are simplified versions of the elements that will go in the final output of GATEPOST, for example all-optical logic gates, optical neurons and neuromorphic neural networks (NNN). For each of these devices we also test the individual sub-components to verify their performance", Del Bino explained.

Presentation of first scientific publications
The publication of the first scientific papers from the WinPhos (Wireless and Photonic Systems and Networks) research group at the Aristotle University of Thessaloniki in Greece, led by Christos Vagionas and his colleagues, constitutes another highlight from last year. The WinPhos team presented the first two GATEPOST-related papers at the Optical Fiber Communications Conference and Exhibition (OFC) 2024, which took place in San Diego, California at the end of March.

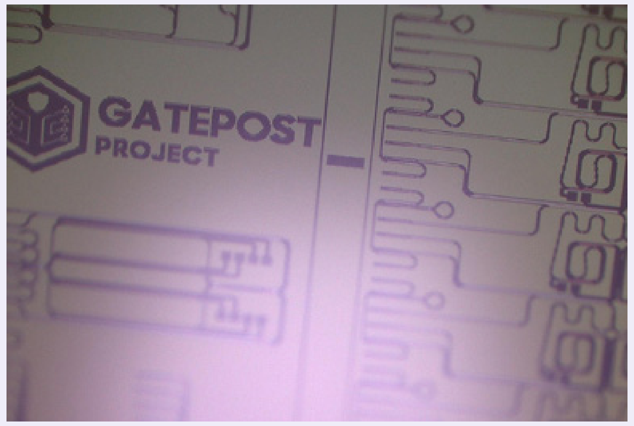
Project progress in all work packages
Overall, GATEPOST can look back on a successful first year, with progress being made in each of the six work packages. The consortium examined the status of the work detail at the second bi-annual meeting, which took place at WinPhos research group's facilities in Thessaloniki, Greece, in October 2024.

Theodoros Moschos of WinPhos presented the development of a 20 GHz silicon-integrated optical ternary content-addressable memory cell (CAM) aimed at fast packet inspection and data operations for content comparison.

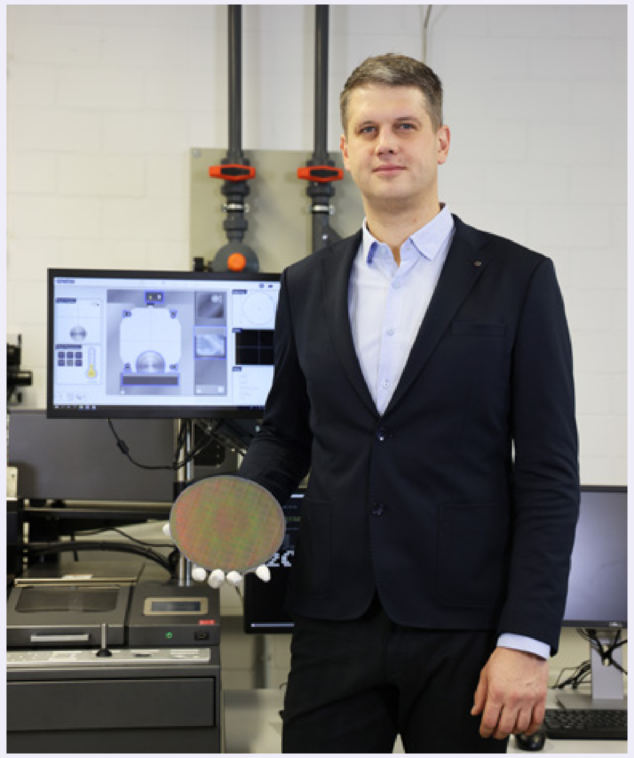
In turn, Matěj Hejda from the Brussels-based team of Hewlett Packard Labs (part of the US-based Hewlett Packard Enterprise) gave the project partners an update on the development of a simulator framework enabling accurate modelling and training of photonic AI accelerator architectures. "This will be used for the detection of various network intrusions and cyberattacks using machine learning (ML), including DDoS attacks - one of the goals of our project, where DDoS stands for Distributed Denial of Services," explained the HPE project team.

These achievements bring GATEPOST closer to its goal of creating ultra-efficient, low-latency solutions for securing IoT devices and networks. The successful integration of graphene-based materials into these circuits also positions GATEPOST at the forefront of future technological advancements in optical computing and network security.

Graphene Week 2024
A highlight for GATEPOST in 2024 was Graphene Week 2024, which took place in October in Prague. GATEPOST was represented by project partners including Mindaugas Lukošius and his team from IHP, Michael Kissner from Akhetonics and Chris Vagionas from the WinPhos research group at the Aristotle University of Thessaloniki. GATEPOST members not only attended as visitors but also as active participants, wherein the team co-organised a joint workshop with 2DNeural-Vision, another Graphene Flagship project.



Project partner Akhetonics presented the first integrated GATEPOST chip. Credit: Akhetonics, Michael Kissner



Dr. Mindaugas Lukošius: "While graphene is often seen as a miracle material, its integration into standard Si pilot lines comes with great challenges. For instance, most of the existing infrastructure and processes in cleanrooms is designed for mainstream Si processing. This makes the "lab-to-fab" transition for graphene very challenging." Credit: IHP, Inesa Posypai

Although the development of the graphene-based, all-optical technology platform is a major part of the project, the team also focuses on activities related to disseminating and exploiting project results.

The workshop focused on 2D materials for photonic applications and discussed topics ranging from theory to integration and devices. Marta Sans, PhD, ICFO, who represented the 2DNeuralVision project, and Mindaugas Lukošius, PhD, IHP, on behalf of GATEPOST, opened the workshop, and afterwards, six renowned experts from different scientific fields gave presentations.

"The workshop proved to be an excellent event, with an exciting line-up of speakers who are experts in the field of graphene-based integrated photonic devices, followed by a panel discussion focusing on the integration processes, electronic-photonic circuit design and applications where graphene-based electronic-photonic devices could be an ideal fit", summarised Chris Vagionas from WinPhos.

The GATEPOST team also presented two scientific posters during Graphene Week. Daniele Capista from IHP presented his poster on 'Effects of contact architecture on the contact resistance of graphene'. He explained to visitors that his work aimed to fill the knowledge gap in the relationship between contact resistivity values obtained from different contact architectures (TOP, EDGE and TOP-EDGE hybrid).

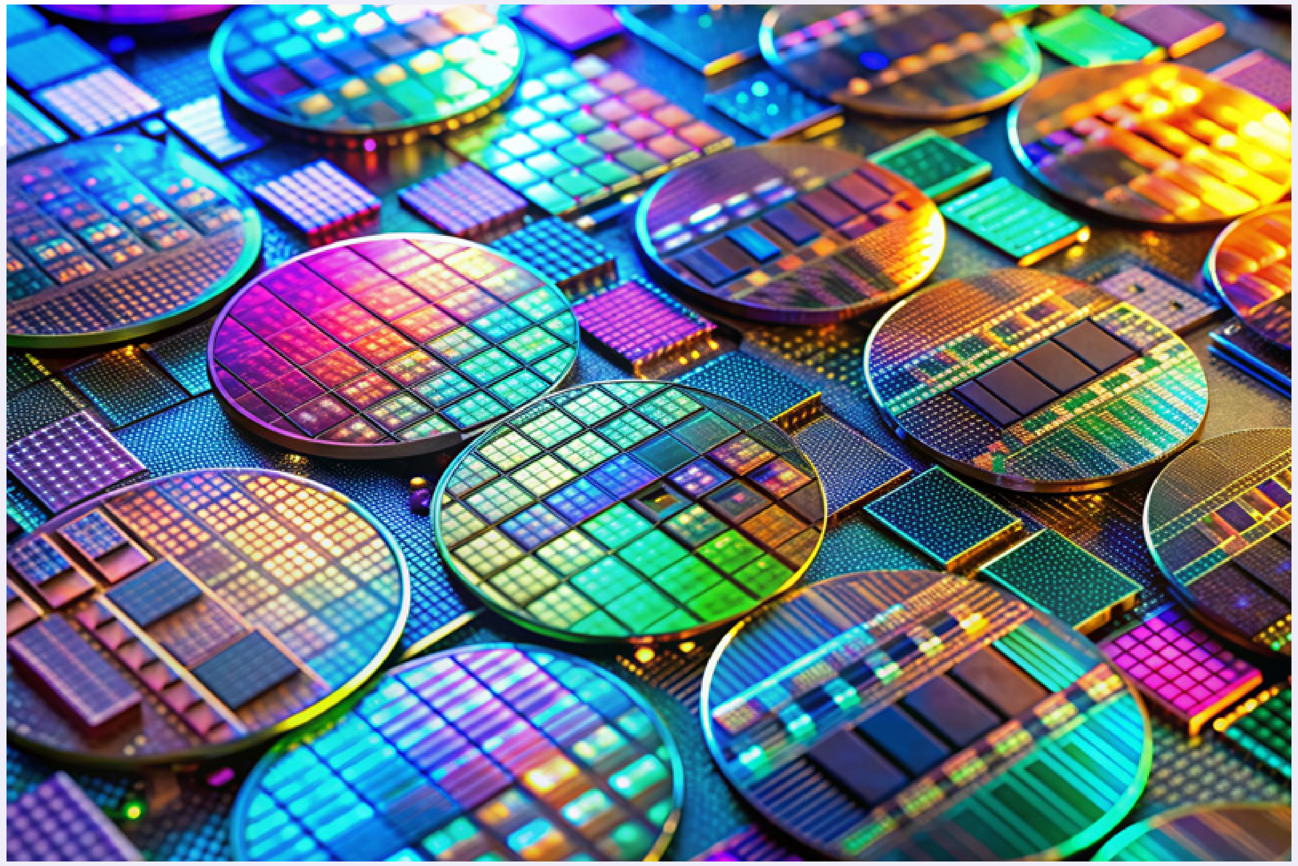
Farnaz Majnoon, a PhD student at IHP, presented a scientific poster and talked about her scientific work. "Graphene, a remarkable two-dimensional material, has emerged as a leading candidate for the next generation of microelectronic devices due to its exceptional electrical, mechanical and thermal properties. At this point, it is critical to maintain these properties during the fabrication of various graphene-based microelectronic devices, and quality control during processing is essential. Our analysis examines the effects of different contacting methods, with the aim of understanding their impact on the graphene structure. Understanding these changes is crucial for identifying the sources, which is essential for improving manufacturing processes and achieving higher quality graphene devices in microelectronic applications," explained Farnaz during her presentation.

DISSEMINATION AND EXPLOITATION

Although the development of the graphene-based, all-optical technology platform is a major part of the project, the team also focuses on activities related to disseminating and exploiting project results.

At the start of the project, a page was set up on the business social network LinkedIn. Posts are regularly published on this page. The series 'Meet the GATEPOST project team' introduced the consortium, gradually presenting and linking all project partners. The series of posts enabled the development of a #GATEPOST community comprised of individuals interested in content related to graphene and photonics. In addition, the GATEPOST project team provides regular project status updates and reports on exciting topics from the Graphene Flagship.

GRAPHENE FLAGSHIP ANNUAL REPORT 2024



The GATEPOST project website has also been added, deliberately hosted on the Graphene Flagship website to emphasise its affiliation with the Graphene Flagship. The website has been populated with content at the start of the project and provides key facts about GATEPOST, an overview of the funding, information about all the project partners and longer press releases on specific highlighted events. In the future, the website will be also regularly updated with exciting content and news.

The GATEPOST project team is particularly strong in presenting the project at events. The project's work has been presented at several conferences around the world, such as the Optical Fiber Communications Conference and Exhibition (OFC) held in San Diego, California, USA last March. The Swiss project partner Enlightra, for example, had its own exhibition stand, presented GATEPOST and distributed marketing material about the project.

GATEPOST also received publicity at the INL – International Iberian Nanotechnology EU Neuromorphic Research Day in Braga, Portugal. There, Matěj Hejda from HPE Labs gave an invited talk where he provided insight into the project and talked about the development of photonic AI accelerators. Hejda also shared his perspective on the field of optical computing. 'An exciting field of research that is maturing into more system-level demonstrations,' he concluded.

In addition, scientific posters were regularly presented at events and conferences. Daniele Capista and Farnaz Majnoon from IHP presented their latest scientific results and research activities at the Graphene Week in Prague. The WinPhos research group was also active in publishing their scientific papers and presenting posters highlighting GATEPOST-related achievements in the first year of the project. For example, Antonios Prapas (WinPhos) presented a poster at the 9th Silicon Photonics Summer School at the University of Southampton in the UK, organised by ePIXfab – the European Silicon Photonics Alliance. During the interactive poster session, participants had the opportunity to talk to each other and learn more about the project.

GATEPOST stands for cooperation and is a clear example of how advanced all-optical technologies based on graphene can be created through interaction between science and industry. The project partners are in active dialogue with the scientific community and industry representatives. Through social media, conferences and publications, the project has successfully built a vibrant network of interest and expertise. Its presence at prestigious global events and platforms underlines the importance of its work in the fields of photonics, AI and optical computing.

POWERED BY THE GRAPHENE FLAGSHIP

GATEPOST is proud to be part of the Graphene Flagship. Being part of this prestigious consortium allows the project team to benefit from cutting-edge research and development in the field of graphene and other two-dimensional materials. The partnership is a key factor in advancing the goal of the GATEPOST project.

By collaborating with Europe's leading experts in graphene technology, GATEPOST can make an important contribution to the development of secure, low-power, high-bandwidth solutions for the Internet of Things and enable future 5G/6G applications. The collaboration not only strengthens the European photonics and electronics ecosystem but also paves the way for advances in computing beyond traditional paradigms.

GATEPOST's membership in the Graphene Flagship enables the project team to drive innovation, foster interdisciplinary collaboration and address critical challenges in next generation computing platforms, thereby strengthening Europe's strategic autonomy in key technology areas.

The first bi-annual meeting took place on 9 April 2024 in Ellwangen, Germany. Credit: EurA AG, Diana Tezlaw

SAILING FORWARD

For the second year together in the GATEPOST project, the team will continue to make progress in each of the six work packages. Specifically, we have in mind our next sub-goals, including the fabrication of 2nd generation integrated photonic structures, and the development and characterisation of InP-based components for the micro-comb-based optical clock and WDM source," said Mindaugas Lukošius of IHP and lead partner in the project.

The entire GATEPOST project team looks forward to further interdisciplinary collaboration. As it evolves, GATEPOST is a beacon of progress in the graphene and photonics landscape, paving the way for breakthrough applications and inspiring the next wave of technological innovation,' the project team agrees.

Electronics and Photonics

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Mindaugas Lukosius, IHP, Germany

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Hewlett Packard Enterprise Belgium, Belgium
Aristotle University of Thessaloniki, WinPhoS Research Group, Greece
Enlightra Sárl, Switzerland
Fraunhofer-Institut für Nachrichtentechnik, Heinrich-Hertz-Institut, Germany
imec, Belgium

ASSOCIATE MEMBER

Paragraf Ltd

GATEPOST PROJECT

2DNEURALVISION

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

THE 2DNEURALVISION PROJECT, funded with 5.5 million euros from the European Commission, brings together seven European research centres, universities and companies from four countries. It aims to develop a low-power computer vision system to be used under adverse weather and low light conditions. This innovation could significantly impact sectors like the automotive industry.

HIGHLIGHTS FROM 2024

After its kick-off at the end of 2023, the year of 2024 proved to be productive, smooth and collaborative. With technical advances, some KPIs achieved that contributed to the awareness of the project and a solid project management, 2DNeuralVision has started taking its first (big) steps.

Starting with scientific achievements, in Work Package 2: Spec definition and validation, led by Volkswagen, all partners are collecting specifications in their field of expertise.
The focus is on the two technical demonstrators:

- A quantum dot based short-wave infrared camera
- Optical neural network elements containing graphene

For validation purposes of different camera types, a test vehicle was set up. First fog tests were done at CEREMA in Clermont-Ferrand, France.

Looking at Work Package 3: Image sensor component development, its leader, Qurv, has acquired new equipment to support its wafer scale colloidal quantum dot (CQD) processing capabilities. In collaboration with ICFO researchers, the team has successfully conducted an initial lead-free quantum dot patterning process during a dummy run, marking a significant milestone in advancing environmentally friendly and scalable short-wave infrared (SWIR) imaging technologies. IMEC is developing a 200 mm 2D integration flow and in 2024 completed the first short-loop integration learning cycle using directly grown MoS_2 material. Insights from this cycle are being applied to the subsequent back end of line (BEOL) short-loop integration flow, as well as the full integration flow on CMOS (complementary metal-oxide-semiconductor) device wafers with transferred MoS_2 material.

Led by BLACK (Black semiconductor) in Work Package 4: Optical neural network component development, a first iteration of a process design kit (PDK) was deployed for the design of optical neural networks (ONN) on BLACK's optical platform. This PDK consisted of specifications of graphene integrated devices like modulators, weights and photodetectors under the parameters defined for an optical multiplication matrix. Additionally, general information about the cross section of the technology, fabrication flow and process variations were included in the document with the aim of providing an easy understanding of the platform

The Graphene Flagship has been instrumental in supporting the 2DNeuralVision project, which aims to achieve major breakthroughs in computer vision technology for machine imaging and automotive applications exploring and leveraging graphene and other 2D materials. This collaboration advances Europe's strategic autonomy in technologies that rely on these materials. In particular, the Graphene Flagship's support has been crucial in bringing together leading experts and resources to drive the project's success."

Gerasimos Konstantanos
Project Coordinator, ICFO, Spain

The first deliverable of the work package was also achieved by the University of Heidelberg, providing the first iteration of an ONN with graphene integrated photonics. This structure consists of a 4x2 multiplication matrix, and it will be fabricated and tested in the following year.

Included in Work Package 5: System integration, the University of Heidelberg has focused on designing ONNs to minimise signal loss and crosstalk for high-performance optical transmission. Key efforts include achieving ultra-low losses of 0.1 dB in waveguide crossings and using directional couplers with a 0.6 µm gap and 65 µm crossover length in a 4x2 testing configuration. Passive component losses are ~20 dB, reduced to ~15 dB with graphene-based devices using on-chip photodetectors. The integration of ONNs has been advanced using field programmable gate array (FPGA) technology to enable 8-bit precision edge detection for images and videos, ensuring efficient and reliable operation.

Last but not least, the coordination team, led by ICFO, ensured effective project management and consortium collaboration. Key highlights include:

- **Collaborative Tools:** Established a SharePoint platform and two mailing lists for efficient communication.
- **Bimonthly Teleconferences:** Regular meetings to monitor progress and address risks.
- **Consortium General Assemblies:** Held two CGAs – online in March and in person at IMEC in November – to review progress, achievements and roadmap plans.
- **Financial & Administrative Support:** Provided consistent support to all partners for compliance and smooth execution.

A discussion during the 2DNeuralVision and GATEPOST co-organised workshop at Graphene Week 2024. Credit: Kateřina Antoš

DISSEMINATION, COMMUNICATION AND EXPLOITATION

2024 was intense and active when we look at Communication and Dissemination of 2DNeuralVision, which can be explained by the fact that this was the first year of the project, a time when there are many things to release for the first time, but also, a testing period, when we start asking ourselves: are we moving in the right direction? Are we reaching our target? Are we engaging?

After the initial brand package creation that includes a visual identity for 2DNeuralVision (including logo, brand book and templates for all documents), the online and offline channels and tools to communicate and disseminate the project were defined in the Plan for Dissemination and Exploitation, including Communication activities in the first quarter of 2024, reported and reviewed at the end of the year. This means that, after the website launch at the end of 2023 – 2dneuralvision.eu – Social Media channels – LinkedIn / 2DNeuralVision and Twitter / X / @2DNeuralVision – were also launched, regularly updated and fed with relevant content. This includes the promotional materials (brochure, rollup, poster, a consortium map, the first infographic, the first video and a general overview presentation), newsletter and press releases, public project deliverables and the first scientific publication available on the resources' webpage – 2dneuralvision.eu/resources. Additionally, the news and events sections were constantly updated and published on social media. This makes the website the central hub of the project where everything about the project is published and integrated – meaning the online and offline communication and scientific materials, information, channels and tools. At the same time, we are contributing to increasing the number of website visits / sessions (which is also one of the project's KPIs), monitored through the Google Analytics tool and improved with SEO (search engine optimisation) techniques.

It is important to mention that communication planning is a live document, to be constantly updated and adjusted when we realise that something is not going as expected and this is how we have been doing it. A good example is the newsletter subscription ongoing campaign. We considered that the number of subscribers is low and under expectations, a campaign to collect more was created and shared not just in the project's social media channels, but also with the Graphene Flagship and internally, with project partners that are

Being a participant in the Graphene Flagship has profoundly benefited our project aims in various aspects. The cooperative environment promoted by the Graphene Flagship has facilitated our access to a wealth of expertise and resources from different working groups.

sharing in their organisations' channels, helping to spread the word about it. So, "never miss a thing about 2DNeuralVision" and subscribe to the newsletter here: 2dneuralvision.eu/#newsletter!

Besides Communication and Dissemination, there's an Exploitation strategy work rolling out. An internal working group has been created and started its meetings in September 2024. Currently, the KERs (key exploitable results) are being re-identified by all partners, and aligned with the IPR Strategy Plan, and a contact form to create a stakeholders database is being developed and of course, to be disseminated in the online channels of the project.

Finally, one of the most important aspects of the Communication, Dissemination and Exploitation work package has been collaborations, especially those powered by Graphene Flagship and increased by its iconic annual event that is Graphene Week.

POWERED BY THE GRAPHENE FLAGSHIP

Being a participant in the Graphene Flagship has profoundly benefited our project aims in various aspects. The cooperative environment promoted by the Graphene Flagship has facilitated our access to a wealth of expertise and resources from different working groups.

The roadmapping group has contributed with essential insights that have helped us define potential products emerging from our project. Additionally, the innovation group has provided perspectives on intriguing projects and has created avenues for

GRAPHENE FLAGSHIP ANNUAL REPORT 2024

potential collaborations. The same applies to the dissemination working group. Here, the collaborations became effective, especially in the co-organisation, together with the GATEPOST project, of the Workshop “2D materials for photonic applications” that was part of the Graphene Week 2024 programme.

It is also important to highlight the permanent support of the Graphene Flagship dissemination working group in helping to increase the awareness of all 2DNeuralVision activities, by sharing our content online as well as during Graphene Week, where the good organisation made everything smoother and possible.

In this sense, we can say that this cross-disciplinary teamwork within the Graphene Flagship structure has accelerated our development, empowering us to confront intricate challenges more adeptly and advance towards realising the complete potential of 2DM-based technologies.

SAILING FORWARD

When our year recap is so intense and positive we can’t help but raise our expectations for the next year.

In our agenda, there’s an interim reporting period approaching, plans to make 2DNeuralVision’s participation in Graphene Week 2025 even more memorable, an exploitation strategy development, bonding collaborations and scientific advancements running to achieve the planned milestones.

So, “knock knock 2025”, the 2DNeuralVision project hopes and expectations are sailing forward to keep contributing to advancing Europe’s strategic autonomy in technologies that rely on 2D materials.

2DNeuralVision and GATEPOST co-organized workshop at Graphene Week 2024.

Electronics and Photonics

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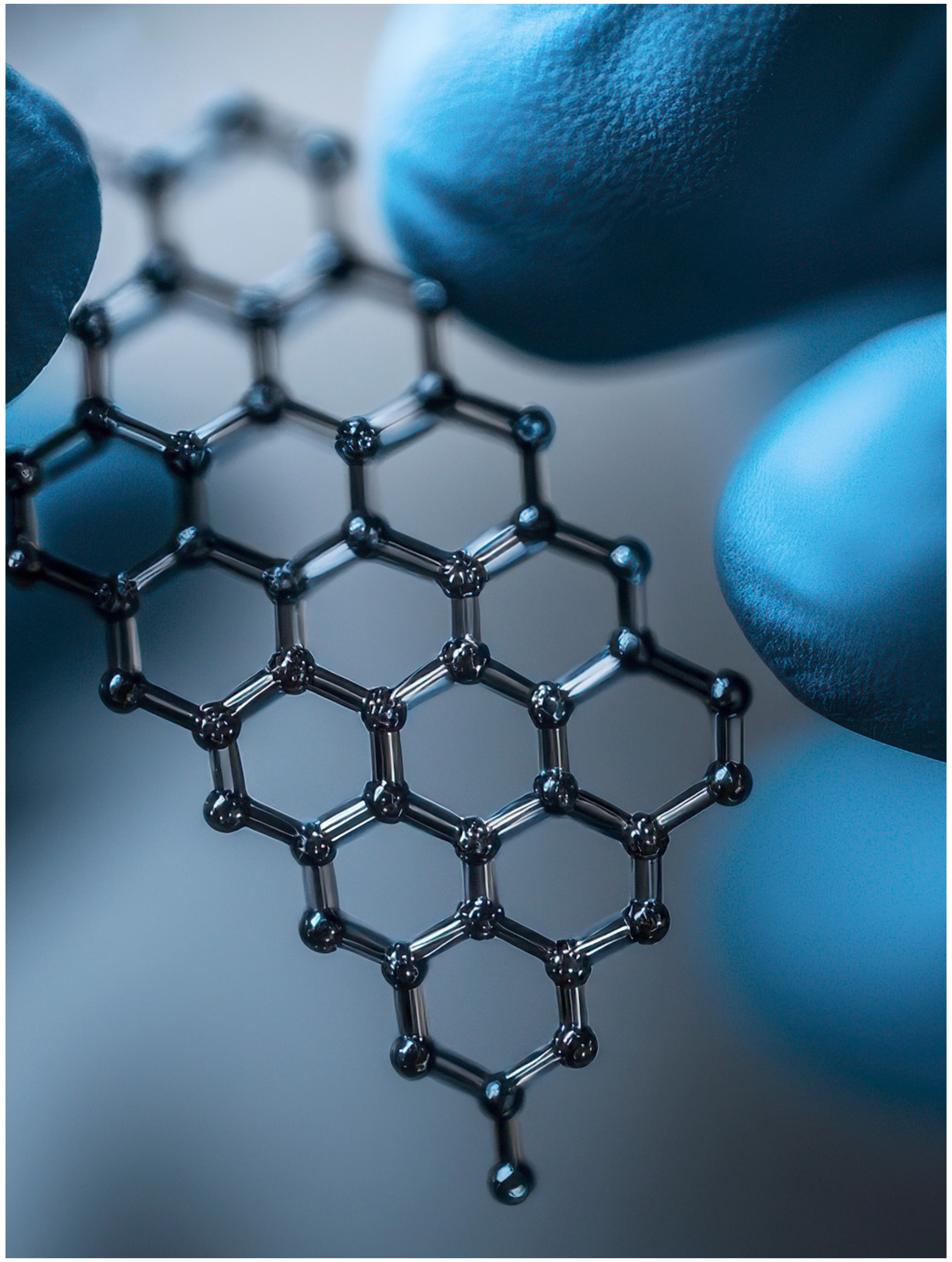
2DNeuralVision



GRAPHENE FLAGSHIP ANNUAL REPORT 2024

NEXT-2DIGITS

The next generation of sensors and imagers enabled by 2D materials digital integration

NEXT-2DIGITS IS ADVANCING the integration of graphene and 2D materials (2DM) into photonic and optoelectronic integrated circuits (PICs and OEICs) to enhance performance, compactness and cost-efficiency. The direct wafer-scale integration of graphene will minimise impurities and defects, leveraging two innovative transfer methods:

1. Semi-dry transfer for wafer-scale and direct die processing.
2. Laser Digital Transfer (LDT) for selective placement and patterning of 2DM pixels in a single step.

These techniques show significant advantages in terms of minimisation of defects and clean interfaces thus improving electronic mobility and bandwidth while reducing costs, materials, energy use and waste.

KEY APPLICATIONS

Graphene integration with Next-2Digits methods will be demonstrated in three applications:

1. LiDAR for drones: Integrating graphene photodetectors enables compact, high-resolution geo-mapping with a miniaturised footprint.
2. Greenhouse gas sensors: A multi-sensing PIC device for biogas plants integrates IoT networks for real-time, cost-effective monitoring and leak detection.
3. Polarisation diversity receivers (PDRs): Used in biomedical imaging, for optical coherence tomography (OCT), this solution employs graphene-integrated PICs to achieve higher resolution and bandwidth compared to bulk optics.

SOLVING CHALLENGES

- LiDAR: Overcomes detector footprint issues with a compact 10x10 mm² array, achieving sub-0.1 mm resolution and high-speed detection (500 GHz) and offering the long distances and component weight required by the application.
- Gas sensors: Uses graphene for mid-IR emission and detection, facilitating nondispersive infrared (NDIR) sensing with a detection limit of ~50 ppm.
- PDRs: Miniaturises architectures with graphene PICs, optimising detection for multiple polarisations without bulky optics. This reduces alignment stages in the assembly, speeding manufacture.

SUSTAINABILITY AND INNOVATION

Aligned with the European Green Deal, Next-2Digits employs LDT, a solvent-free, laser-based process that reduces waste and engineering time while improving device efficiency. This green technology delivers smaller, cost-effective components with up to six times lower power consumption.

"By harnessing the latest advancements in 2D materials, transfer technologies and wafer-scale integration, Next-2Digits paves the way for a new generation of high-performance photodetectors and modulators. Our goal is to push the boundaries of photonic technology, unlocking unprecedented capabilities for future optical communication and sensing applications."

Ioanna Zergioti
National Technical University of Athens

PROJECT PHASES

In its first year of implementation, the project set the key specifications and designs for the PICs manufacturing. During its second year, Next-2Digits' activities have been focusing on PIC platform development and 2DM device fabrication, with first sensor tests to be carried out. Finally, the third year will integrate and validate the demonstrators, in the three application areas, at TRL5.

The key challenge that Next-2Digts aims to overcome is maintaining compatibility between new 2D material transfer methods and existing silicon-on-insulator (SOI) platforms without compromising material integrity.

HIGHLIGHTS FROM 2024

In order to successfully progress towards its goals, Next-2Digits divided its activities into seven work packages (WPs): five relate to technical activities, one concerns Dissemination, Communication and Exploitation and one the Overall Project and Consortium Management.

All of them have been active through 2024, with the exception of WP5, which began in early 2025. Nevertheless, technical progress has been made in all five work packages, with the main outcomes described below.

Work Package 1: *Requirements and Specifications*
The recent progress involved reviewing existing system specifications and proposing advanced ones for the project's success. As each application had different priorities – for instance, size and weight for the LiDAR sensor, response time and stability in different environmental conditions for the greenhouse gas sensor or responsivity and spectral response for OCT – discussions between all the partners have brought the successful definition of the tailored requirements and specifications for the fabrication of the three demonstrators.

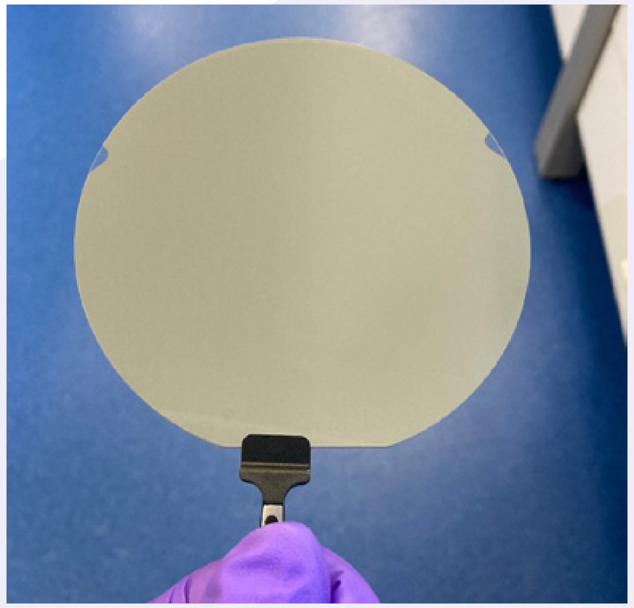


Figure 1: Graphene donor substrate used for LDT.
Credit: Graphenea Semiconductor

In the first phase of WP1, technology providers met regularly to define design choices for PICs, focusing on waveguides and materials for enhanced interaction. The second phase concentrated on detection improvements, exploring solutions with graphene detectors and modulators.

Work Package 2: *2D materials growth and passive platform development.* Graphenea Semiconductor developed and delivered several combinations of graphene donor substrates to the National Technical University of Athens (NTUA) for LDT. In **Figure 1** a graphene donor substrate is shown. NTUA carried out extensive quantum-mechanical calculations based on the density functional theory (DFT) approach to investigating materials and processes which are of central importance to the Next-2Digits project. In particular, studies have focused on the properties of a graphene monolayer on a receiver substrate and on the detachment of two-dimensional materials (e.g. graphene and hexagonal boron nitride sheets) from donor metallic substrates. In parallel, VTT performed simulations of optical modes to optimise the graphene integration into detector systems. The qualification tests for the first generation of 2D materials and SOI platforms have been completed. The very first wafers were successfully processed by Silex Microsystems and VTT for graphene integration on Si platforms.

Work Package 3: *2D Material digital transfer and integration.* This workpackage saw preliminary experimental work by NTUA on LDT station design and development in order to meet the graphene PD requirements of three use cases and the optical profilometer assembly based on phase shifting interferometry. We successfully demonstrated the laser induced forward transfer (LIFT) technique as a fast and cost-effective method for integrating 2D materials onto chips, eliminating the need for complex processing. Graphene's exceptional properties - such as ultra-fast carrier dynamics enabling terahertz-speed modulation and strong light absorption despite its atomic thickness – make it ideal for optoelectronic applications. We successfully transferred arrays of graphene "pixels" with lateral dimensions of 10–50 µm (**Figure 2**) and showcased photodetector configurations integrating such pixels. The resulting devices are under evaluation and characterisation by VTT.

Quality assessments using optical and electron microscopy, Raman spectroscopy, and molecular dynamics simulations

Figure 2: Graphene square flakes laser transferred directly on test substrates without any post-processing or patterning.
Credit: National Technical University of Athens –Silex Microsystems

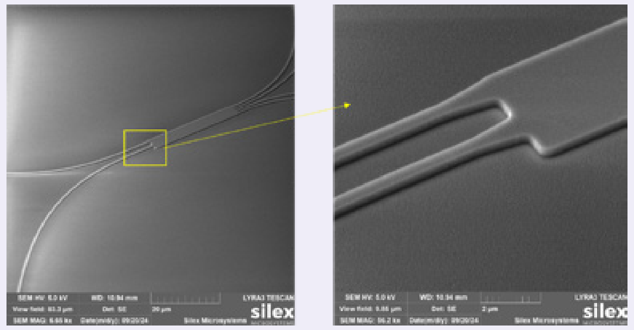


Figure 3: Next-2Digits LiDAR waveguide design.
Credit: Silex Microsystems

confirmed the successful transfer and integrity of the materials. These findings open new possibilities for efficient, high-quality graphene-based optoelectronic device fabrication.

Additionally, high-quality monolayer graphene semi-dry transfers have been achieved by Graphenea on 25 eight-inch wafers from SILEX, along with promising preliminary semi-dry transfer results on a six-inch planarised wafer from VTT. These advancements aim to enhance digital fabrication processes for graphene-based photodetectors.

Work Package 4: *2DM component and PIC fabrication*
Preliminary work in this work package was dedicated to defining the short-loops and designing and testing masks for all three use case applications. Next, the mask layouts and fabrication short loops resulting in test patterns for all three use cases have been developed and manufactured. Specifically, to each use case:

For the LiDAR sensor, Silex and Ommatidia Lidar are collaborating to further optimise the waveguide platform, in order to enhance the LiDAR sensor's performance (**Figure 3**, **Figure 7**).

For the greenhouse gas sensor, simulations have been made by Senseair, to identify suitable dimensions for waveguides and other optical components, such as MMI-splitters and gratings for input and output. Different versions of these components, optimised for each of the two target gases (CH_4 and CO_2), are combined into different structures to enable testing of all component functionalities. CAD layouts of these structures were prepared, and the structures are currently being produced. On the electronics side, the design of the emitter driver and amplification stages has been completed and the design of the PIC board for hosting the devices has been started (**Figure 4**).

For the polarisation diversity receiver (PDR), partners VTT and Gooch & HouseGo have been actively collaborating to establish the design specifications for the PDR and its sub-devices. As part of this effort, VTT developed building blocks, an Si escalator integration, for graphene detector integration with thick SOI. This component enables the project to bring

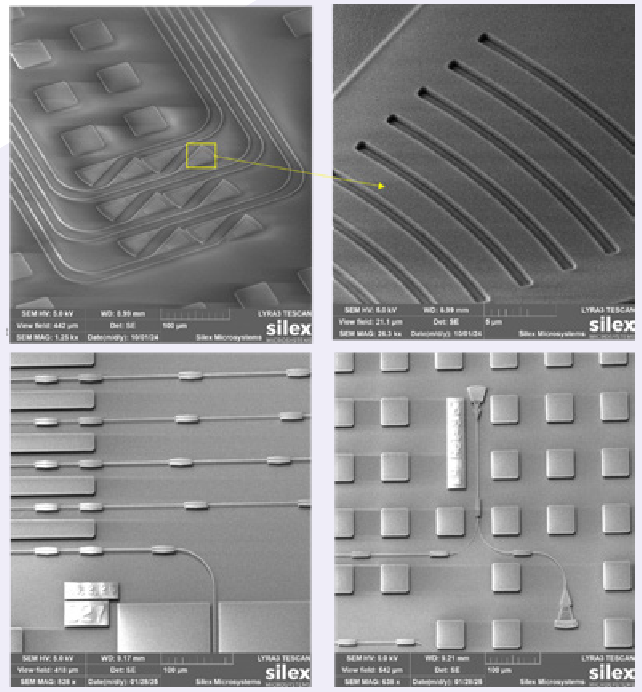


Figure 4: Next-2Digits Greenhouse Gas sensor waveguide design. Credit: Silex Microsystems

maximum intensity of the light mode to the graphene detector. Based on the specifications, VTT has completed the design for the integrated photonics PDR chip (**Figure 5**), which is currently manufactured in VTT's internal MPW run. For the graphene detector, VTT has completed the first escalator graphene detector integration (**Figure 6**). These detectors were integrated on straight waveguides, and they are currently under characterisation.

Work Package 5: *Use Cases Integration & Validation*
The main focus of this WP has been to develop specific integration strategies per use case.

In Use Case 1, ground-based testing has been conducted using an existing YellowScan system, using hand-held LiDAR and mobile mapping. The tests have shown that the trajectory can be accurately reconstructed through a combination of SLAM and GNSS-Inertial data fusion. Further development awaits a Doppler-ready scanner. Overall, a LiDAR system model has been developed with the collaboration of Ommatidia Lidar and YellowScan to facilitate the development of LiDAR on drone.

For Use Case 2, preparatory steps have been put in place. Experimental plan coordination between Senseair, Linköping University and Bert Energy and purchasing of necessary equipment and analysis materials (i.e., gases) has been initiated, to prepare and implement the planned experiments.

In Use Case 3, Gooch & HouseGo has carried out preparatory work for the testing and validation of the PDR devices (**Figure 8**). In addition to the design, basic test and optimisation of test setups for fibre-chip coupling, fibre optic arrays have been specified and purchased to enable simultaneous coupling to multiple device outputs. This will allow device testing to be undertaken to determine device performance, in addition to basic characteristics such as total insertion loss. Comparing these passive tests to the evaluation of similar devices with integrated graphene photodiodes, the use-case suitability of the graphene PDs can be determined.

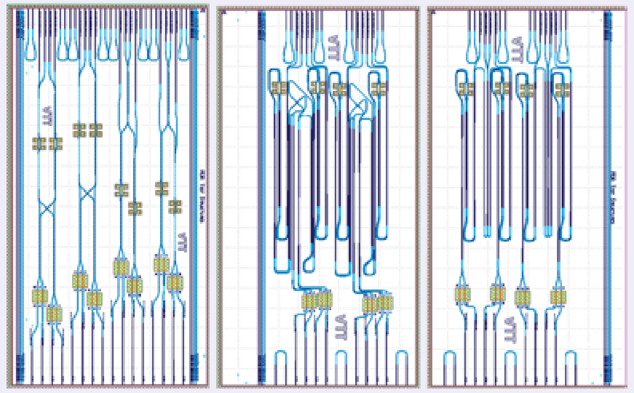


Figure 5: Next-2Digits PDR chip design. Credit: VTT

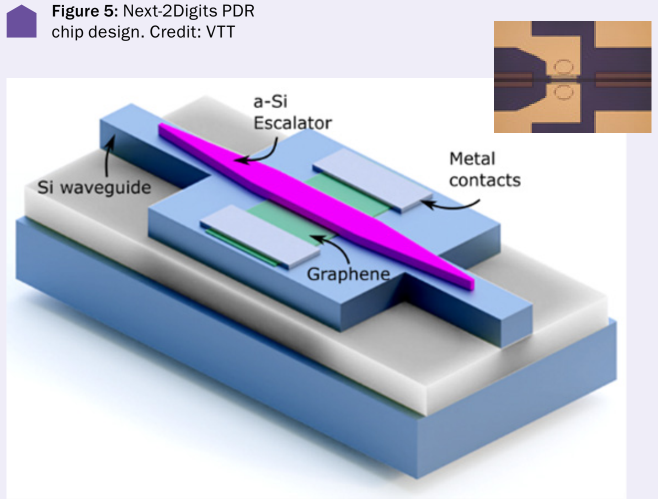


Figure 6: Microscopic photo of the graphene photodiode integrated on thick-SOI waveguide by escalator and a schematic illustration of escalator concept. A-Si escalator lifts the mode maximum to graphene. Credit: VTT

DISSEMINATION AND EXPLOITATION

To ensure that gained knowledge or exploitable foreground from Next-2Digits can benefit the European 2D materials community and, eventually, society as a whole, the project has carried out several dissemination and communication activities, enhanced by its communication channels (website, LinkedIn, YouTube and the Graphene Flagship community).

First and foremost, the Next-2Digits website (www.next-2digits.eu) and social media (www.linkedin.com/company/next-2digits) presence have been established, sharing the project's information and its main goals and impact.

Along with this, several informative materials have been prepared. Factsheets, flyers, a banner and a press release are all available for download on the Next-2Digits website. Additionally, a project video was created to present the Next-2Digits partners and the processes and technologies that will be developed within the project. This can be found on the AMIRES' YouTube channel (www.youtube.com/@amires-video3301) and the project website.

Furthermore, the project consortium has participated in eight international conferences, showcasing the Next-2Digits goals and most recent results, giving oral presentations or submitting scientific articles and posters.

The project has contributed to the Graphene Flagship and its main event, Graphene Week. In the most recent edition of the conference, chaired by Next-2Digits coordinator, Ioanna Zergioti, several partners have showcased, through presentations or posters, Next-2Digits' main results. In particular, the consortium presented its work on graphene integration in MEMS production lines, laser-induced transfer methods for 2D materials, development of lab to fab processes and simulations of graphene photodetectors for enhanced optoelectronic applications.

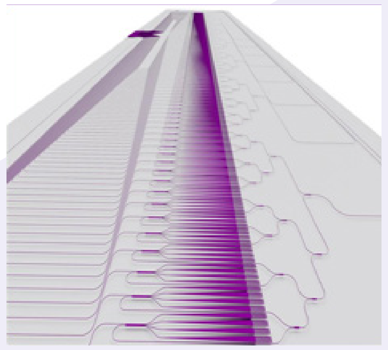


Figure 7: LiDAR PIC 3D design. Credit: Ommatidia Lidar

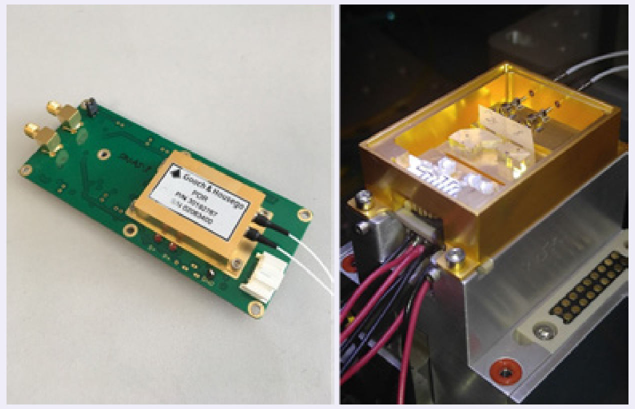


Figure 8: G&H PDR based on micro-optics. Next-2Digits project aims to reduce the size and simplify the alignment of this device. Credit: Gooch & HouseGo

POWERED BY THE GRAPHENE FLAGSHIP

Next-2Digits is collaborating with the Graphene Flagship, alongside several other European projects dedicated to bringing graphene and related materials from the laboratory to the market. The end goal of this collaboration is to contribute to increasing the expertise in the graphene field and to spread knowledge among various stakeholders.

Being part of the Graphene Flagship ecosystem offers the Next-2Digits consortium significant opportunities to enhance its innovation capabilities and establish collaborations with global experts in the design, synthesis and application of 2D materials. This ecosystem provides access to an extensive network of researchers, organisations and specialists in graphene and 2D materials, creating an environment that promotes knowledge exchange, the sharing of best practices and engagement in synergistic initiatives.

This partnership enables the Graphene Flagship community to leverage the vast expertise and experience of the Next-2Digits consortium, contributing to a unified and robust initiative. Such collaboration amplifies the impact of individual projects while reinforcing Europe's leadership in the field of 2D materials.

Notably, Next-2Digits has been actively involved in the Graphene Europe in the Lead CSA even before its official launch and is dedicated to making substantial contributions, with a highlight being the co-organisation of the latest Graphene Week conference, which was conducted successfully in Prague.

SAILING FORWARD

Next-2Digits has successfully completed its first 18 months of implementation. Now that the devices' specifications and designs have been identified and the fabrication processes have already been initiated, the plan is to test and evaluate the first chips within the second half of the project.

For all three use cases, the plan of activities entails further optimising and carrying out graphene transfers on wafers and completing the first fabrication runs. For the LiDAR and the greenhouse gas sensors, work will focus on finalising the shortloops and full flows. Partners involved in the LiDAR use case will perform an integration critical design review (mechanical interface/synchronisation/LiDAR data), while for the Gooch & HouseGo use case partners will perform functionality testing of the chips in a lab environment, sending them on for field tests. For the PDR, the full PICs will be manufactured, demonstrating the graphene detector integration on a thick SOI (silicon-on-insulator) waveguide platform using the escalator concept. Gooch & HouseGo will compare systems with and without graphene detectors to evaluate detector performance in application-like conditions.

Electronics and Photonics

PROJECT COORDINATOR
Ioanna Zergioti, National Technical University of Athens, Greece

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2D PILOT LINE

Creating an ecosystem for 2D material integration

THE 2D PILOT LINE (2D-PL) project aims to further strengthen the European ecosystem by working on the development of integration modules for photonics and electronics. It is working to mature semiconductor technologies while providing information to aid industrial uptake. This four-year project builds on the foundation of the 2D Experimental Pilot Line project (2D-EPL) which first began the work toward integrated 2D materials in the semiconductor industry. The 2D-PL will offer comprehensive prototyping services for the integration of graphene and TMDCs (Transition-metal dichalcogenides) on established semiconductor platforms that use silicon technologies.

> The further development of integration flows builds on the 2D-EPL's pathfinding work and will continue with the 2D-PL's process maturation efforts and the set-up of systematic characterisation routes."
>
> **Inge Asselberghs**
> IMEC

HIGHLIGHTS FROM 2024

The past year marked the transition between the 2D-EPL and 2D-PL projects. The 2D-PL launched in October welcoming five new partners, and the 2D-EPL, which ended in September, held its final review in December. Since the transition, the project has worked to set up the foundations for its continued work.

2D-EPL

Wafer Scale Growth
Good progress was achieved in the last year by the Wafer Scale Growth work package. The AIXTRON 300 mm MOCVD reactor, previously installed at IMEC as part of the 2D-EPL project, has demonstrated uniform growth of 2D transition metal dichalcogenides on 200 mm and 300 mm sapphire and SiO_2/Si substrates, supported by various *in situ* techniques. This tool aims for high-quality production of 2D layers once fully optimised and integrated into the fab management system in the 2D-PL project.

In collaboration with IMEC, AIXTRON has developed capabilities for 300 mm scale Raman spectroscopy mapping and automated image analysis techniques for in-line 300 mm scale SEM images, enabling the assessment of growth uniformity and quality of 2D layers.

Throughout the project, Graphenea has optimised and supplied partners with high-quality, uniform graphene grown on up to 200 mm Cu foils. The quality of graphene has been further enhanced by developing high-smoothness Cu foil templates with RMS roughness <5 nm.

Wafer Scale Transfer
The Wafer Scale Transfer work package achieved important milestones in advancing scalable transfer techniques for graphene and other 2D materials this year. These innovations enable integration of high-quality 2D materials into CMOS-compatible processes. Key achievements included the development of automated 200 mm and 300 mm transfer processes, establishing a foundation for next-generation 2D-based electronic, sensing and photonic device applications.
A particularly noteworthy accomplishment was the creation of a novel graphene transfer strategy, which overcomes long-standing challenges in debonding graphene from its growth template, enhancing reliability and scalability for industrial applications. Building on this knowledge, the recently launched 2D Pilot Line project aims to further refine and mature these scalable, CMOS-compatible 2D transfer technologies.

Wafer Scale Integration
The wafer scale integration work package ensures the exploration of the essential building steps to provide for the set-up of relevant integration routes to fabricate the test structures. Process, test structure and data analysis optimisation result in a monitor for quality control. Furthermore, each of the essential building steps like dielectric deposition, contacting schemes and patterning options are further explored and assessed in their relevant integration flows. Analysis is done both by imaging and spectroscopic methods as well as electrical device read-out.

Modules for the Industry
The Modules for the Industry of work package developed fabrication processes for graphene- and MoS2-based devices in electronics, photonics and sensors, ensuring compatibility with conventional semiconductor manufacturing. It delivered adaptable process modules for semiconductor manufacturers while providing a cost-efficient testing solution for smaller companies and universities. The key output for the work package was six multi-project wafer (MPW) runs, allowing external clients to fabricate graphene-based devices from their designs. These runs were offered by the 2D-EPL partners AMO, Graphenea, IHP and VTT over the past four years.

2D Pilot Line Development
Turning R&D developments into customer projects is an important milestone. The set-up of the experimental process definition kits (PDKs) provided first pilot line customers access to the pilot line. In total, six multi-project wafer runs were launched from which five went into fabrication. The webinar series, Pioneering 2D Materials for the Semiconductor Industry provided an avenue for staying in touch with the project's R&D progress and the MPW service offerings. Innovation workshops are essential tools for the support of roadmap activities and conducting market analysis. We received great support and guidance from the industrial advisory board (IAB) made up of industry experts inside and outside the Graphene Flagship community.

Management
During the final year of the 2D-EPL, the Management work package focused on creating the smooth transition needed following the end of the Graphene Flagship Core 3 project, which left the 2D-EPL as a stand-alone project within the new structure of the Graphene Flagship in Horizon Europe. This included changes to the project governance and the legal contracts, but also updating routines and ways of working. An in-person final meeting, connected to the 2D-EPL Symposium held in Brussels, Belgium, gave partners the chance to share results and plan for the final activities. Much of the year was spent preparing for the final reporting and review, which was completed successfully in December. Overall, the close of the 2D-EPL represents the end of the Horizon 2020 era of the Graphene Flagship.

Project coordinator Inge Asselberghs presents the 2D-PL project at Graphene Week 2024. Credit: Kateřina Antoš

A SWOT analysis workshop was held at the end of the 2D-EPL to help define the future 2D-PL project goals. Credit: Jackie Brown-Bauer

2D-PL

Process Modules for Graphene Integration
The Process Modules for Graphene Integration work package will address the growth, transfer and encapsulation module for graphene integration. The main objective is to further mature the development of process modules for graphene integration using conventional semiconductor tools and utilising the wafer carrier transfer method developed in the 2D-EPL. Particular attention will be given to addressing the following specific challenges: 1) Maturation of industrially compatible graphene carriers; 2) Further development of bonding and debonding processes; 3) Achievement of clean interfaces. The 2D-PL is targeting graphene with the high charge carrier mobility needed for graphene commercialisation. Additionally, this work package will secure the graphene material supply to the other work packages for photonics, sensor applications, characterisation and metrology development and external MPW run offerings.

Process Modules for TMDC Integration
In the Process Modules for TMDC Integration work package, we develop the main process modules for the integration of 2D TMDC, i.e., the growth on sapphire, the transfer to the final substrate, and the encapsulation with a dielectric. The first goal is to mature the different processes, transitioning from proof of concepts demonstrated in the 2D EPL project to in-line stable production, with a special interest in inter-module optimisation. The second goal is to supply 2D TMDC to the other work packages and the consortium partners to enable TMDC pilot line development. Our primary challenges in 2025 will be to ensure the production of sufficient good-quality 200 mm 2D TMDC wafers and to scale up the development of the transfer process on large wafers.

2D for Photonics Applications
The overall goals of the 2D for Photonics Applications work package are to develop and mature photonic platforms to leverage the unique properties of graphene and TMDC materials in standard 200 mm Si pilot lines at IHP and VTT and to build the foundation for MPW runs within the 2D-PL project. This includes the modelling and simulations of graphene and TMDC devices on the component and device level, design and parameter specification definition and the fabrication of the proof-of-concept photonic devices. Moreover, process design kits for graphene and TMDC technology will be created. The main challenges in 2025 include integrating graphene and TMDC materials into standard 200 mm Si pilot lines while ensuring process compatibility.

GRAPHENE FLAGSHIP ANNUAL REPORT 2024

Innovation Forum panel discussion at the 2D-EPL Symposium in Brussels. Credit: Rebecca Waters

2D for Electronic and Sensing Applications
The primary focus of the 2D for Electronic and Sensing Applications work package is the wafer-scale fabrication of electronic and sensing devices based on graphene and TMDCs. The objective is to develop robust and improved fabrication processes that can be applied across entire wafers to create TMDC-based and graphene-based device modules. This process includes the crucial steps of characterising and benchmarking both the processes and the resulting components. The developed processes form the foundation of the MPW runs and the individual services offered by the 2D-PL project.

In the next year, one challenge the work package needs to address is the initiation of processes for manufacturing TMDC devices on wafers up to 200 mm at VTT and AMO, with the support of the *Process Modules for TMDC Integration* work package. Additionally, preparations for the first graphene MPW runs at Graphenea, VTT, IHP and AMO must be initiated.

Characterisation and Metrology
The Characterisation and Metrology work package aims to define and verify the protocols for chemical, electrical and structural characterisation of graphene and TMDCs produced for the 2D-PL. This will require the development of an automated Raman/PL tool for up to 300 mm wafer in-line metrology. The work package will also utilise scanning nitrogen-vacancy microscopy (SNVM) to detect low-dimensional defects in 2D materials.

Pilot Line Operation and Access
Smooth operation of the pilot line entails the coordination of the 2D-PL service offerings. Successful MPW runs also imply efficient interactions with the applicants and build upon their feedback regarding future specific demonstrator requirements for 2D technology. Dissemination, communication, training and exploitation activities are developed to promote the 2D-PL. In the first year the work package will announce the first schedule of the service offerings and the first hands-on training sessions using the PDKs.

Project Management and Coordination
The goal of the Project Management and Coordination work package is to coordinate the activities of the 2D-PL via efficient project management shared by the Coordinator, IMEC, and the project manager, Chalmers University of Technology. During the first six months of the project, the main objectives have been to set up the important steps and routines needed to manage the project for the next four years. The work package successfully organized a Kick-off Meeting and is now looking ahead to the reporting and monitoring activities necessary to ensure a strong start of the project. In addition, we are keen to establish and increase our collaborations with the other Graphene Flagship projects and the GrapheneEU CSA, as well as external stakeholders such as the Chips JU.

The main challenge during the first year of the 2D-PL is to ensure a good transition from the previous project, 2D-EPL. We have new partners and new activities in the project, as well as new ways to monitor our progress, which we hope will contribute to a more flexible, resilient and mature 2D-Pilot Line. As always, managing a project comes with its surprises and unexpected events, and we look forward to taking them on!

DISSEMINATION AND EXPLOITATION

With the transition from the 2D-EPL to 2D-PL projects, it has been an active year for dissemination and exploitation activities. To celebrate the 2D-EPL's accomplishments, the project held a two-day, lunch-to-lunch Symposium in Brussels to highlight the project's progress, the biomedical and photonics applications for our technologies and their commercialisation potential in the future. This event was paired with a press conference and an Annual Meeting, bringing together not just outside parties but also the majority of the consortium to celebrate results and plan for the future. A highlight of the event was the Innovation Forum panel discussion, in which experts from Infineon, X-FAB, Oxford Instruments, Paragraf and Black Semiconductor discussed the potential for graphene to revolutionise wafer-scale technologies. The need for a "killer application" was highlighted as the main challenge toward industry adoption.

The Symposium press conference, as well at the press releases and other communications celebrating the success of the 2D-EPL garnered a fair amount of media attention, with articles in key business-to-business publications like *Electronica Weekly, Engineering Update* and *evertiq*. The European Commission's Horizon Magazine also covered the project, helping news of the project reach decisionmakers in Brussels.

The 2D-PL project met at Graphene Week to present the new project and to get to know the newest project members. Credit: Kateřina Antoš

The 2D-EPL also held two digital workshops over the past year, as well as an in person 2D Materials: Challenges and Opportunities workshop at ESSERC 2024. The 2D-PL was announced at an in-person workshop held at Graphene Week 2024 in Prague, Czech Republic. These workshops provide an opportunity to update the project's key audiences about the project and to discuss topics relevant to our community and future work.

Finally, the 2D-EPL was featured prominently in the Graphene Flagship exhibitions in both the lobby of the European Commission's Directorate-General for Communications Networks, Content and Technology (DG CONNECT) building and as part of a larger exhibition of European funded projects at the Berlaymont building, the EC headquarters. 2D-PL Coordinator Inge Asselberghs presented the project during the opening events for each exhibition.

POWERED BY THE GRAPHENE FLAGSHIP

The 2D-EPL has always been closely integrated with the Graphene Flagship, having been spun out of the Core project and benefitting from synergies in dissemination, coordination and management. These ties remain now with the GrapheneEU CSA which coordinates and supports the new Graphene Flagship community and RIA/IA projects. The Graphene Flagship helps to bring greater visibility to the 2D-PL and by building on the initiative's foundation, the project was able to get up and running with ease streamlining many of the difficulties of establishing governance and ways of working and creating a website and other infrastructure. Beyond this, the Graphene Flagship community provides a valuable platform for collaboration, knowledge exchange and support.

SAILING FORWARD

Now that the 2D-PL has established its foundations, the project is ready to focus on its main tasks, developing the materials and technologies needed to launch its first MPW runs and further mature the processes developed in the 2D-EPL.

Electronics and Photonics

PROJECT COORDINATOR
Inge Asselberghs, IMEC

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IHP - Leibniz Institute for High Performance Microelectronics
VTT
Graphenea Semiconductor SL
Oxford Instruments Nanotechnology Tools Limited
Akhetonics GmbH
EVG

ASSOCIATED MEMBERS
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Technical University of Denmark

2D PILOT LINE
FROM THE GRAPHENE FLAGSHIP

Graphene Week at a Glance

Graphene Week 2024 was held in Prague, Czech Republic, in October. The Graphene Flagship's yearly conference brings together experts to discuss graphene and other 2D materials, find new collaboration opportunities and network. Photos by Kateřina Antoš

GIANCE

Shaping the future of multifunctional composites and transforming industries with sustainable graphene-enhanced materials

> GIANCE is redefining the future of sustainable materials by integrating graphene technologies into real-world applications. Our achievements this year reflect a strong foundation for long-term industrial impact and environmental stewardship."

Ana Villacampa
Project Coordinator

THE GIANCE project is at the forefront of developing next-generation solutions to tackle pressing environmental challenges through advanced graphene and related materials (GRMs). Focusing on sustainable, lightweight and multifunctional composites, GIANCE merges cutting-edge scientific innovation with industrial applications to transform industries such as automotive, aerospace, energy and water treatment. Its distinctive approach combines enhanced properties – like thermal and chemical resistance, wear prevention and structural health monitoring – with scalable, environmentally friendly manufacturing processes.

A VISIONARY CONSORTIUM

GIANCE comprises 23 partners from ten countries, the consortium brings together leading OEMs, global research institutions and dynamic SMEs. This broad expertise ensures robust, market-ready innovations that translate breakthrough technologies from research prototypes (TRL4-5) to industrial demonstration and production readiness (TRL6-7). The shared goal is to establish a resilient European value chain for graphene materials, strengthening the EU's global competitive position.

2024 HIGHLIGHTS

Work Package 1: *Technical and performance requirements*
Establishing performance benchmarks was key to the project's initial success. GIANCE identified environmental, technical and end-of-life (EOL) design strategies for multiple use cases. This comprehensive approach incorporated safety assessments and sustainable design principles, setting the stage for eco-friendly, high-performance products.

Work Package 2: *Innovations in material development and upscaling*
Significant progress has been made in developing multifunctional materials using GRMs. The project focused on optimising production methods for graphene nanoplatelets, few-layer graphene, laser-induced graphene and reduced graphene oxide, aiming for cost-effective and scalable manufacturing. A key achievement was the development of lightweight composites and coatings that offer superior strength, low friction and improved thermal conductivity.

Work Package 3: *Sustainable manufacturing technologies and processes*
GIANCE refined industrial processes to align with sustainability goals, including recycling and circular design principles. Novel surface treatments using laser technologies eliminated chemical-intensive steps, reducing environmental impact while improving material properties.

Work Package 4: *Industrial feasibility and demonstration*
Prototypes integrating graphene-enhanced components were produced for automotive and aerospace applications. These included corrosion-resistant coatings, structural components with embedded sensors for real-time monitoring and hydrogen storage solutions for cleaner energy systems.

Work Package 5: *Testing, validation and assessment*
Both physical and virtual testing confirmed the superior performance of GRMs and their enabled products. Reliability assessments showed enhanced durability, while real-world trials validated their structural integrity and environmental resilience. Notably, hydrogen storage tanks and smart composite structures with embedded sensors excelled under a range of operational conditions.

Work Package 6: *Life cycle analysis and life cycle costing*
Life cycle assessments (LCA) evaluated the environmental footprint of the technologies developed. Early results highlighted significant reductions in material waste and energy consumption compared to traditional composites, reinforcing GIANCE's commitment to sustainability.

The GIANCE project's Third General Assembly in Karlsruhe, Fraunhofer ICT. Credit: GIANCE

DISSEMINATION AND COMMUNICATION

To create visibility and foster collaboration, GIANCE launched a comprehensive outreach campaign. Key actions included:

- **Publications:** Scientific papers detailing technical advancements.
- **Events:** Participation in industry forums and international conferences.
- **Digital Presence:** A dedicated website (https://www.giance-project.eu/) and active social media platforms to engage stakeholders.
- **Newsletter:** a specialised newsletter has been sent to an interested target audience (https://www.giance-project.eu/newsletter/).

Training programs also equipped industry professionals and researchers with skills to adopt graphene technologies, enhancing workforce readiness for emerging markets.

POWERED BY THE GRAPHENE FLAGSHIP

Being part of the Graphene Flagship has provided unparalleled opportunities for GIANCE. Access to the Graphene Flagship's vast research network and innovation support mechanisms accelerated technological development, bridging the gap between scientific discovery and commercial viability.

SAILING FORWARD

Looking ahead, GIANCE aims to scale its innovations for broader industrial adoption. Key priorities include:

- Expanding pilot-scale demonstrations to validate market readiness.
- Enhancing recycling technologies to close material loops.
- Strengthening partnerships for commercialisation.

GIANCE's journey exemplifies how innovation, sustainability and collaboration can drive impactful change, transforming challenges into solutions that benefit industry, society and the planet.

Composites

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Ana Villacampa, Fundació EURECAT, Spain

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Crossfire Srl, Italy
Stichting Koninklijk Nederlands Lucht – en Ruimtevaartcentrum, Netherlands
Fundacion Para La Promocion De La Innovacion, Investigacion Y Desarrollo Tecnologico En La Industria De Automocion De Galicia, Spain
Nederlandse Organisatie Voor Toegepast Natuurwetenschappelijk Onderzoek, Netherlands
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Applied Graphene Materials UK Limited, UK
Lenntech BV, Netherlands
V.E. Lashkaryov Institute of Semiconductor Physics of the NationalAcademy of Science of Ukraine, Ukraine
Nanoprom Chemicals S.r.l., Italy
BAX Innovation Consulting SL, Spain
Innovation Engineering SRL, Italy

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.

ASSOCIATED MEMBER
Sixonia Tech GmbH

GIANCE
Fused with Sustainability

GRAPHENE FLAGSHIP ANNUAL REPORT 2024

2D-PRINTABLE

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

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
Trinity College Dublin

TWO-DIMENSIONAL (2D) MATERIALS have transformed materials science and nanotechnology, offering remarkable physical and chemical properties that enable innovative applications across diverse fields such as optoelectronics, energy storage, sensing and composite materials. However, realising their full technological potential depends on developing scalable, cost-efficient methods to exploit these properties at the macroscale, bridging the gap between the exceptional performance of individual nanosheets and large-scale implementations. The 2D-PRINTABLE project addresses this challenge by utilising sustainable and affordable liquid exfoliation techniques.

The project integrates advanced theoretical modelling, materials synthesis and sustainable liquid exfoliation processes to facilitate the efficient production of 2D materials, including conductive, semiconductive and insulating nanosheets. It also focuses on advancing printing and liquid-phase deposition techniques to assemble layer-by-layer heterostructures and ordered multilayers of 2D materials. These printed networks and heterostructures will be optimised for digital applications, enabling novel properties and functionalities. A key highlight of the project is the development of all-printed, all-nanosheet heterostack light-emitting diodes (LEDs) as proof-of-concept devices. Ultimately, 2D-PRINTABLE aims to establish 2D materials as a cornerstone of printed electronics, paving the way for next-generation digital technologies.

HIGHLIGHTS FROM 2024

The most important highlights and achievements of 2D-PRINTABLE in the first year of the project cover the following aspects:

Material design and synthesis
Material design leverages computational screening and literature analysis to identify and synthesise novel 2D materials, including substitutionally doped variants. An open-access database shared via Zenodo provides comprehensive information on exfoliable three-dimensional (3D) layered materials and their corresponding 2D derivatives produced through various liquid-phase exfoliation methods, such as liquid-phase exfoliation (LPE), electrochemical exfoliation (EE), and chemical exfoliation (CE). This database includes key specifications for each material, such as its physical form (e.g., powder or crystal and dimensions), stoichiometry, doping details and the quantities available within the consortium.

In addition, a curated database of over 3,000 potential 2D materials (2DMs) exfoliable from known inorganic compounds is available via the Materials Cloud Two-Dimensional Crystals Database. This resource was developed using high-throughput van der Waals density functional theory (DFT) calculations to identify layered 3D materials that can be efficiently exfoliated into 2DMs. The source data comes from leading repositories, including the Inorganic Crystal Structure Database (ICSD), the Crystallography Open Database (COD) and the Pauling File (MPDS). The curation process initially evaluated 9,306 layered candidates through geometric screening, followed by rigorous first-principles calculations to refine the selection.

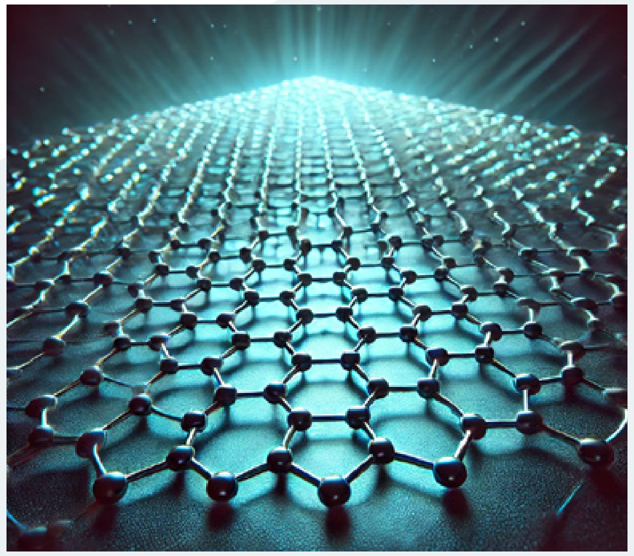
This extensive data infrastructure serves as a critical foundation for advancing the discovery and synthesis of novel 2D materials, facilitating innovative applications across a range of scientific and technological domains.

Based on our computational screening as well as applications considerations, we have synthesised >30 layered crystals of materials ranging from workhorses such as MoS_2 and WSe2 to more novel materials such as TISe and Bi_2O_2Se. It is these homegrown materials, as well as a smaller cohort of commercially sourced layered materials that are the source materials for production of 2D materials by liquid exfoliation.

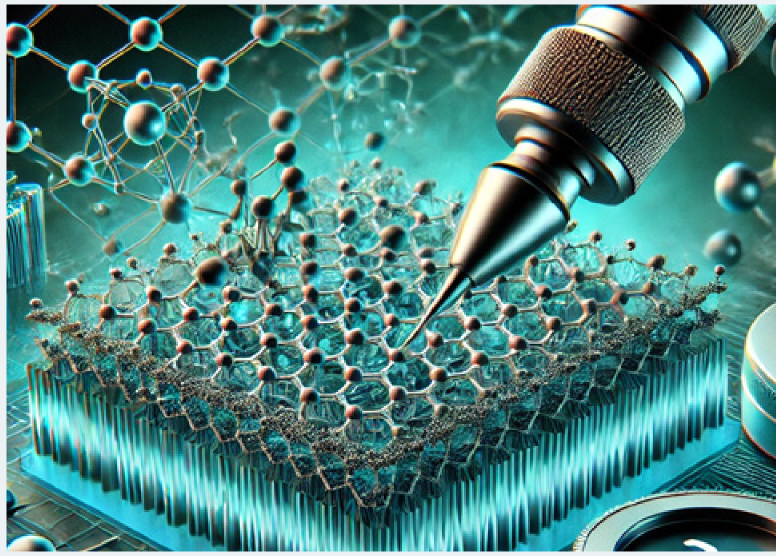
Exfoliation, ink production and printing
Much of our work in the first year has involved liquid exfoliation of 2D materials, their formulation into inks and the printing of these inks to give functional films. Much work has focused on improving the quality and performance of materials by refining their preparation. The keystone has been production of novel 2D materials through liquid exfoliation techniques. We have exfoliated dozens of 2D materials, including conductive electrochemically exfoliated graphene, various semiconducting transition metal chalcogenides, as well as dielectric oxyhalides, giving us access to all the building blocks of electronics. A key part of this work has been developing methods to achieve very high aspect ratio nanosheets suspended in liquids.

The resultant nanosheet suspensions have been formulated into novel 2D material inks. By adjusting properties such as viscosity and solvent composition, we ensured that these inks are optimised for various printing and coating techniques.

We have demonstrated, benchmarked and optimised several printing / solution deposition methods, including spray casting, aerosol jet printing and Langmuir-Schaeffer (LS) liquid-liquid interfacial deposition. In particular, we have developed LS deposition to yield high quality, uniform films.



Artistic visualisation of a graphene layer (AI-generated).



Artistic representation of the production process of 2D materials (AI generated).

These methods are essential for creating uniform and high-performance films from our 2D material inks, as needed for solution-processed digital electronics and such progress is a crucial step toward creating more efficient, flexible and cost-effective digital electronic devices. By enhancing the performance of printed electronics, these advancements could lead to new applications in various fields, including wearable technology, smart packaging and next-generation sensors.

Functionalisation of transition metal dichalcogenides
Despite the numerous functionalisation strategies for transition metal dichalcogenides (TMDs) described in the literature, the underlying mechanisms remain poorly understood. This knowledge gap arises from the complex interplay between functional groups and the TMD surface, coupled with the variety of defects these materials can exhibit. To fully exploit chemical functionalisation for next-generation printed electronics – such as enabling precise and stable doping, cross-linking nanosheets in networks, or tuning properties like photoluminescence quantum yields – a deeper understanding of these interactions is essential. Such insights are not only key to developing chemical intuition but also critical for enabling the rational design of functionalisation strategies. In the first few months of 2D-PRINTABLE, the focus was on the two most widely used functionalisation strategies: i) Filling chalcogen vacancies with thiols, and ii) Electrophilic radical addition using diazonium salts.

For thiol-based functionalisation, the methodology was expanded to include telluride-based TMDs and disulfides in place of thiols. Disulfides were chosen because they reduce unwanted side reactions and dimerisation, an issue previously noted in the functionalisation of gold surfaces. Diazonium functionalisation aimed to shed light on the chemical binding process and the role of defects. By comparing MoS_2 nanosheets produced through different exfoliation methods, researchers used diffuse reflectance infrared Fourier transform (DRIFT) spectroscopy to identify distinct vibrational signatures associated with surface grafting. These findings confirmed the formation of covalent S-C bonds and interactions with oxygen-containing defects such as sulfonyl and sulfoxide groups. The degree of functionalisation varied significantly depending on the exfoliation technique. Chemically exfoliated MoS_2 nanosheets achieved functionalisation levels as high as 40% sulphur, compared to just 2% for liquid-phase exfoliated materials. However, electrochemically exfoliated MoS_2 posed additional challenges. Stabilising agents introduced during exfoliation left organic residues that hindered reagent binding and altered the nanosheets' intrinsic properties, potentially affecting their performance in networks.

To address these issues, DRIFT spectroscopy was used to refine washing protocols, effectively removing the residual organics. This improvement not only enhanced the accuracy of material characterisation but also laid the groundwork for more reliable and efficient functionalisation of TMD nanosheets, bringing them closer to real-world applications in advanced electronic devices.

Material characterisation
A significant number of layered materials have been theoretically predicted, yet only a fraction has been successfully exfoliated and characterised. Following exfoliation, it is crucial to verify that the predicted physicochemical properties of the nanosheets are preserved and remain stable in solution for further processing. Additionally, the development of advanced characterisation techniques to quantify the morphological properties of solution-processed networks is essential for enabling their use in device applications.

Characterisation results have been performed for liquid phase exfoliated (LPE) and electrochemically exfoliated (EE) nanosheets, including materials such as MoS_2, $AsSbS_3$, As_2S_3, SnGe, InSe, $Mo_{0.5}W_{0.5}Se_2$ and $HfSe_3$. Atomic force microscopy (AFM) measurements indicate that the aspect ratio (AR) of EE nanosheets can exceed 10^3, which is nearly 30 times greater than the AR values typically observed for LPE nanosheets (AR ~ 10–30). Further characterisation using UV-Vis and Raman spectroscopy provided insights into the intrinsic properties of the nanosheets. For EE MoS_2, initial investigations suggest that extinction spectroscopy may offer valuable information regarding dimensions and doping.

The Langmuir-Schaefer (LS) method has been identified as a promising technique for fabricating ultra-thin and uniform nanosheet networks. However, quantifying the morphology of these networks remains challenging due to the complex length scales involved, and existing information on technique optimisation is limited. AFM has been employed to characterise such networks, leading to the development of a layer-by-layer fabrication protocol with precise control over layer thickness. Thin-film morphology has been further tailored by tuning

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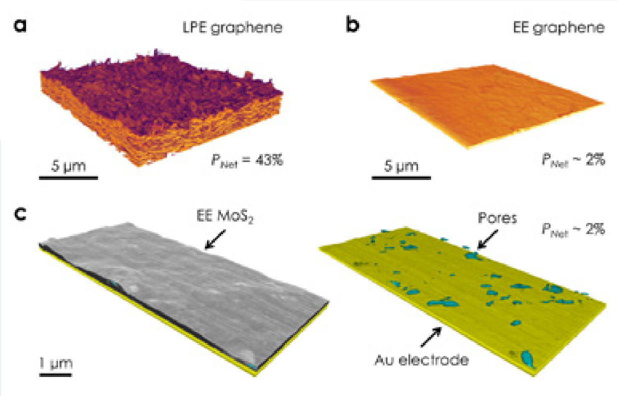

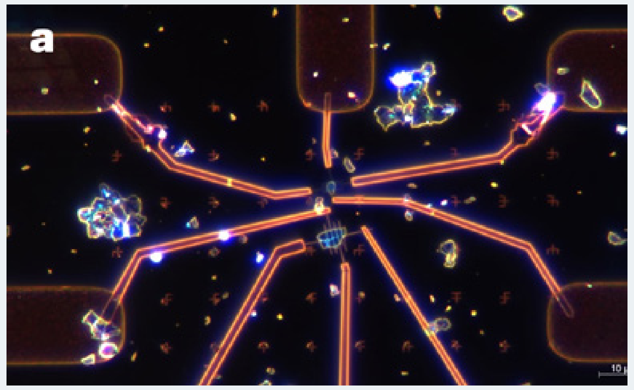

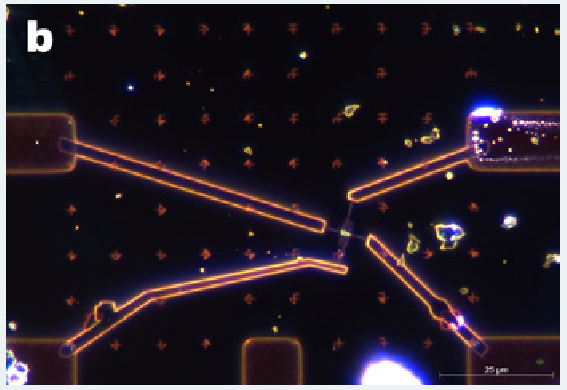

3D reconstructions of printed 2D networks generated using FIB-SEM nanotomography.

Representative structured individual (a) MoS_2 and (b) $PtSe_2$ nanosheets in dark-field microscopy.

deposition parameters, with spatial variations in network morphology assessed using optical transmission scanning measurements.

Focused ion beam–scanning electron microscopy nanotomography has been utilised to reconstruct 2D networks and heterostacks in three dimensions with exceptional resolution. This approach enables detailed analysis of the internal structures of nanosheet films produced under different fabrication conditions and using various nanosheet types.

Electrical characterisation and device measurements
Before evaluating the exceptional electronic properties of macroscale printed devices, individual nanosheets must first be assessed. To address this, precise electrical measurements are essential for fundamental characterisation. Individual nanosheet field-effect transistors were fabricated using a five-terminal electrode configuration enabling four-point probe measurements, allowing accurate determination of nanosheet conductance while minimising or eliminating parasitic contributions at contact interfaces. For EE-$PtSe_2$ nanosheets, such measurements were conducted for the first time, marking a significant advancement. The results are benchmarked against theoretical predictions and compared with findings from terahertz (THz) time-domain spectroscopy.

We have also begun the electrical characterisation of printed networks of nanosheets. After solution depositing various nanosheet types using multiple printing methods, we have performed a range of electrical measurements. We have characterised the DC conductivity of a range of materials, measuring mobility for a subset. In addition, for a smaller cohort we have performed both impedance-based measurements of nanosheet and junction resistance as well as temperature dependent studies to allow us to understand conduction mechanisms. As time goes on, we will build on these learnings and extend them across our range of materials and deposition techniques.

We have started performing basic and preliminary tests on devices fabricated from printed networks and heterostructures. We have fabricated transistors from a range of 2D materials, characterising mobility and on / off ratios. Preliminary results indicate that printed capacitors based in 2D niobates have extremely high permittivity. Printed diodes show reasonable rectification while our first LEDs clearly show light emission.

Dissemination and exploitation
The Communication, Dissemination, and Exploitation activities of the 2D-PRINTABLE project are designed to maximise the impact of its results and effectively engage with a diverse audience. These efforts target experts in nanomaterials, government bodies, industry leaders, suppliers, end-users and the general public, ensuring the broadest possible dissemination and utility of the project's outcomes. The central hub for project information is the 2D-PRINTABLE website (available at https://2d-printable.eu/), which provides updates on key results, publications, partner events and interviews with project members. Additionally, updates are shared through the Graphene Flagship platform under the cluster *"2D Materials of Tomorrow"*, accessible at this link: 2D Materials of Tomorrow.

As part of its outreach, 2D-PRINTABLE publishes a bi-annual newsletter, highlighting recent achievements, partner activities and upcoming events, ensuring stakeholders stay informed. 2D-PRINTABLE also maintains an active presence on LinkedIn, where regular updates and announcements are shared to engage with the professional community.

In its first year, the project has made impressive strides, with 22 papers published on 2D-PRINTABLE, highlighting our dedication to pushing the boundaries of the field. A full list of the publications is available on the project website here.

The 2D-PRINTABLE team has gained global recognition, with our research being featured at prominent events around the world. In 2024, we were proud to be co-organisers of Graphene Week 2024 and to present our work at other prestigious gatherings such as Graphene 2024, MRS Spring and Fall Meetings, the International Conference on Carbon Science and Innovation, Flatlands Beyond Graphene, Wonton 2024, NanoSpain 2024 and many others.

Through these coordinated efforts, 2D-PRINTABLE continues to establish itself as a key contributor to the development and application of nanomaterials, fostering collaboration and innovation across sectors.

Prof. Zdenek Sofer and Prof. Jonathan Coleman from 2D PRINTABLE pose with Prof. Valeria Nicolosi at Graphene Week 2024. Credit: Kateřina Antoš

2D-PRINTABLE represented by Prof. Zdenek Sofer and his team from University of Chemistry and Technology Prague. Credit: Kateřina Antoš

POWERED BY THE GRAPHENE FLAGSHIP
The collaboration within the Graphene Flagship ecosystem has played a key role in advancing the 2D-PRINTABLE project, offering access to a broad network of academic and industrial partners. This creates invaluable opportunities for collaborative research, knowledge exchange, and innovation. By bringing together top experts in graphene and 2D materials, the ecosystem provides 2D-PRINTABLE with unparalleled expertise, insights and potential synergies to accelerate its research.

The Graphene Flagship also plays a crucial role in supporting 2D-PRINTABLE's visibility and impact, facilitating connections with researchers, SMEs and industry leaders through platforms like Graphene Week. Through its website, newsletter, LinkedIn and high-profile events, the Flagship has significantly raised the profile of our work. These efforts are essential in translating cutting-edge research into real-world applications, driving progress across fields such as electronics, energy and healthcare.

SAILING FORWARD
2D-PRINTABLE plans to continue its research in three phases. The first phase involves designing and synthesising novel 2D materials through computational screening and literature analysis. In the second phase, the project aims to develop methods for printing or solution-depositing high-mobility networks of nanosheets while focusing on characterising the printed structures. The third phase is dedicated to fully characterising the electrical properties of individual flakes, networks, films and heterostructures. During this period, the project will also concentrate on optimising the performance of printed structures and devices. Efforts will prioritise optimising exfoliation techniques, particularly sonication-assisted exfoliation of dielectric oxyhalides like LaOBr, to address issues such as flake polydispersity while achieving thinner and more uniform nanosheets. The incorporation of additives to enhance the mechanical stability and durability of deposited films will also be a critical area of exploration, especially for demanding applications. Expanding the range of solvent systems, with an emphasis on environmentally friendly options, will be essential for improving exfoliation efficiency and tailoring film properties for novel materials like oxyhalides. Scaling up deposition techniques, particularly Langmuir-Schaefer deposition, to industrial levels is a key step toward commercialisation, ensuring compatibility with large-scale production processes. Additionally, application-specific testing will be expanded to evaluate the performance of these materials in printed electronics, sensors and energy devices. By updating the database of exfoliable materials and further refining the understanding of their optoelectronic and mechanical properties, 2D-PRINTABLE aims to strengthen the link between fundamental research and industrial application. In the demonstration phase, we will showcase the potential of 2D materials in traditional printed electronic devices such as thin-film transistors, solar cells and LEDs.

These efforts position the project to contribute significantly to the future of scalable 2D materials, paving the way for next-generation printed electronics and innovative technologies.

2D Materials of Tomorrow

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ASSOCIATED MEMBER
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2D ENGINE

Engineering of ultimately thin, inherently 2D semiconductors and insulators for the scaling of integrated digital (opto) electronic devices

THE 2D ENGINE project looks for 2D semiconductor and dielectric materials which cannot be exfoliated from bulk but rather need to be engineered as atomically thin films using chemical vapor deposition on metal catalyst substrates. The semiconducting materials are envisaged to have the outstanding stability of graphene and offer excellent electrostatic control in digital electronic devices, which allows their miniaturisation and their operation with superb energy efficiency. The project mobilises diverse expertise in materials science and engineering, materials growth, condensed matter physics, atomistic simulation, *in-situ* surface characterisation techniques, equipment development, semiconductor processing and electrical engineering to face the challenges.

> During the first year there has been an unprecedented cross-fertilisation between the partners with the aim to obtain the first compelling evidence of the targeted 2D phases. The result was a great success and the consortium very soon will be in a position to test the optoelectronic properties of the grown materials and fabricate functional devices in the second project year."

Athanasios Dimoulas
NCSR DEMOKRITOS, Greece

HIGHLIGHTS FROM 2024

The main objective for the first year was to develop ultrathin 2D semiconductor and dielectric/insulating layers of sufficient quality to be used for the fabrication of thin channel field-effect transistors (FETs) and thin active layer light-emitting diodes (LEDs) in the following project periods.

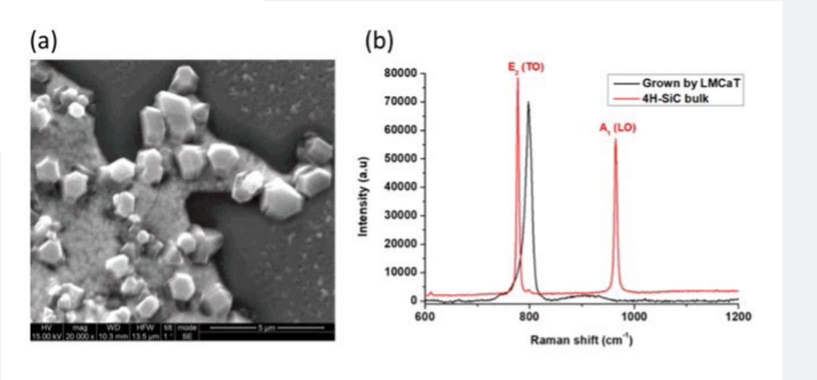
The consortium distributes the work on different materials among different partners for best efficiency. The National Centre for Scientific Research Demokritos (NCSRD) worked on graphitic h-SiC; the University of Patras in collaboration with Leiden Probe Microscopy, Leiden University and the European Synchrotron Radiation Facility (ESRF) on h-BN; and ESRF in collaboration with Leiden University on h-GaN. For all materials, the partners used liquid metal catalysis (LMCat)-based methodology with the necessary adaptations specific to the material under investigation. AMO GmbH worked with all partners preparing appropriate test substrates for the evaluation of their electrical properties. In addition, the Max-Plank Society for the Advancement of Science collaborated with growers and materials process developers to structurally characterise grown materials using both atomistic simulations to produce reference data and AI-guided computer vision to establish an automated analysis of recorded images and spectra.

2D ENGINE made significant progress in all materials classes mentioned above and a brief account is given below.

Towards graphitic SiC
NCSRD in collaboration with ESRF and the Associated Member Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA) have developed SiC crystal growth and characterisation on liquid copper-silicon catalysts. NCSRD has developed the growth supported by in-house structural characterisation by scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM/EDX) and Raman spectroscopy. ESRF and AM CEA performed high resolution synchrotron XRD on selected growths. The main methodology based on LMCat can be described briefly as: the starting substrate was copper (Cu) foil properly cleaned and placed on silicon or SOI wafers. Subsequently, the composite substrate was annealed at optimal temperature to form a homogeneous Cu silicide layer and then heated above the melting point with simultaneous insertion of carbon precursor to form the silicide. The main results are that well defined SiC crystals imaged by SEM and verified by RAMAN (Fig. 1) are formed mainly at the edge of the melted surface. The crystals have lateral dimensions ~ 1 µm and height ~ a few 100 nm, featuring an unfavourably small aspect ratio (lateral width/height) <10. The main target is to increase the aspect ratio to 100 and 1000 both by increasing lateral size to more than 10 µm and reducing height to 10 nm or below, preferably down to a few monolayers. Based on the existing evidence, it is not possible to unambiguously identify the crystal structure of the observed SiC crystals. Although 4H and 6H polytypes could be excluded, it hasn't been possible so far to distinguish between the 3C (cubic) and 2H (hexagonal) phases of the grown crystals. Morphopological (MPG) analysis of images and spectra is in favour of 3C as the dominant phase. Producing SiC is a very good accomplishment as this material is produced for the first time by LMCat using record low crystal growth temperatures. However, the final target of the project to obtain a few monolayer graphitic SiC has not been accomplished yet and is a matter of intense investigation for the second year of the project.

Ultrathin h-BN achieved
University of Patras in collaboration with Leiden Probe Microscopy developed the growth and in-situ monitoring of ultrathin h-BN 2D dielectrics.

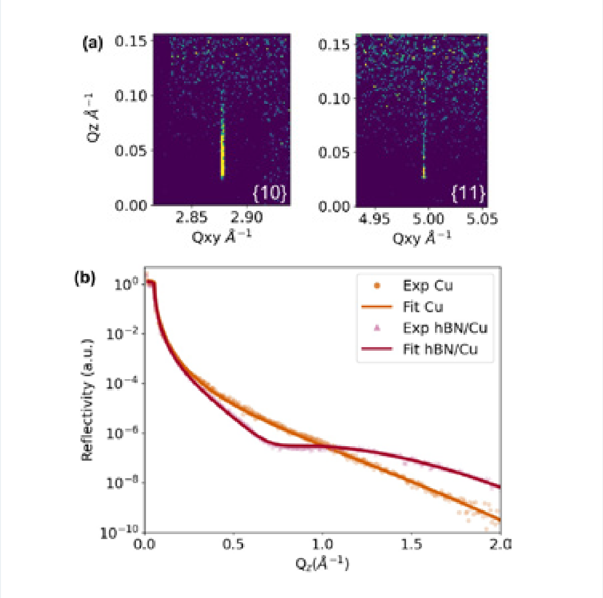
X-ray characterisation performed by ESRF: The initial configuration of the gas distribution system of the LMCat reactor at ESRF was tailored specifically for the growth of graphene; therefore, some modifications have been made to adapt it for h-BN. As such, a cell equipped with a controlled heating element was designed and fabricated to hold the ammonia borane (AB) powder, which served as the precursor. The formation of multilayer structures, as well as ultra-thin h-BN layers, were successfully observed through RMOM. Additionally, *ex situ* X-ray photoelectron spectroscopy (XPS), Raman and SEM analyses confirm the successful synthesis of h-BN, with findings that align with pre-existing literature on solid substrates. We have carried out a beamtime experiment where we performed a first-time *in situ* X-ray characterisation of h-BN growth on an LMCat. This includes measurements of h-BN 2D rods, from which we validated the 2D phase and extracted information regarding our sample's crystallinity and unit cell parameters. X-ray reflectivity (XRR) measurements, which offer insights into the number of layers in a 2D material (2DM), confirmed the existence of single-layer h-BN structures (at least for the early growth stages). Furthermore, these experimentally derived parameters provide a valuable reference point for both experimental and theoretical studies in the ongoing exploration of 2DM systems.



SiC crystals by LMCat. (a) SEM image (b) Raman spectra.

Towards ultrathin h-GaN
ESRF in collaboration with Leiden University have developed the LMCat growth of GaN and the *in-situ* monitoring of growth in a dedicated chamber at ESRF. The technology was successfully transferred to Leiden University and the first results were obtained in a specially designed reactor.

Work performed at ESRF: The existing gas distribution system had to be modified to enable the use of ammonia gas as a precursor for GaN growth. Thus, the fourth gas line was incorporated to ensure the independent delivery of NH_3 gas.



X-ray data on h-BN layer measured in situ: (a) GID, (b) XRR.

During the first round of experiments in 2024, we achieved the growth of GaN crystals in our setup for the first time. As this process was monitored *operando* by RMOM, growth conditions yielding ultrathin and large-area GaN synthesis were identified. Our findings have led us to explore an alternative growth method, alloying Ga with another metal, such as Cu (Au and Ag are planned in the future), for a more controlled Ga intake, similar to what is done for the growth. Grazing incidence diffraction (GID) measurements validated the crystallinity and crystal lattice parameters of the grown GaN phases: 3D cubic, 3D hexagonal and 2D hexagonal. Moreover, the exact thickness of the grown ultrathin GaN layer was measured through XRR measurements.

Work performed at Leiden University: Employing the LMCat reactor previously developed at Leiden Probe Microscopy and upgrading it with a device to evaporate solid-state precursors, Leiden University could successfully transfer the procedure developed at ESRF for the growth of GaN crystals. In the reactor located at Leiden Probe Microscopy, the evaporator device allows to employ urea as the nitrogen source. Employing SEM/EDX and Raman spectroscopy, further structural information can be extracted from the samples produced. The main results are that well defined triangular and hexagonal GaN crystals imaged by SEM and verified by EDX and Raman spectroscopy are formed across the melted surface. Although large coverage such as that obtained at ESRF was not obtained, crystals of similar dimensions, i.e. geometrically-defined crystals with a lateral size of 1 and up to 10 µm, could be grown. At the current state, the extracted information does not yet allow conclusions about the thickness of the crystals. However, it enables the development of a systematic study of GaN ultra-thin film growth on LMCats. Diverse alloy substrates, such as Ga-Au and Ga-Ag, are left to be explored.

Optimisation of the fabrication steps for the field effect transistors using 2D materials
AMO is preparing designs and test devices with graphene for testing and optimising the process that will be used when the new materials will be available and transferred to a substrate. The design of the devices for initial testing of 2D channel materials so far is simply a channel consisting of a 2D material with two metal top contacts and a global back gate. The devices were prepared by e-beam lithography using an e-Line Raith tool and with the design being adapted depending on the sample, a small channel length is the goal (around 10 nm). The process was optimised and tested with graphite and graphene global gate field effect transistors using 90 nm SiO_2 as a dielectric. Different contacts geometries were tested. The top contacts consist of Al/Ti (20 nm/5 nm) deposited by e-beam evaporation and followed by lift-off. The next step for the device optimisation is to transfer and fabricate a smaller channel with graphene or h-GaN, materials that were successfully used as a channel and grown by the 2D ENGINE partners.

Atomistic simulation and image/spectra analysis
As the Fritz Haber Institute of the Max Planck Society's (FHI-MPG)protocols for *ab initio* simulations based on density functional theory (DFT) have been elaborated, and are continuously refined to automatically and accurately explore the thermodynamic stability, the structural and dynamic properties of the 2D materials of interest are made clear. These protocols involve automatic convergence tests on DFT parameters and model sizes, the computation of relaxed hexagonal and wurtzite bulk, single- and multilayer phases, as well as phonon spectra (including common corrections) that allow stability estimates at finite temperatures and serve as a

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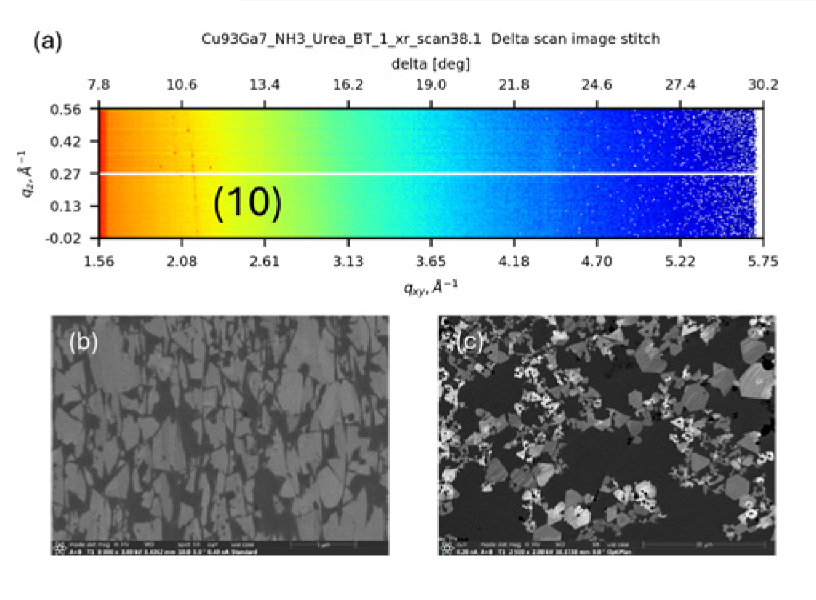

(a) X-ray diffraction data of h-GaN crystals grown on a Cu-Ga alloy and (b) SEM picture of the same sample. (c) SEM image of h-GaN crystals grown on a Cu-Ga alloy in the LMCat reactor available at Leiden Probe Microscopy.

reference for Raman spectra. Specifically, these protocols are now tested on h-BN, GaN, AlN, SiC, as well as ZnO as a further reference. Based on this evaluation, the critical thickness, until which a hexagonal phase is stable, has been evaluated and characteristic Raman signals to discern single-, multi-layer and bulk phases are now identified.

A first machine learning interatomic potential (MLIP) has been trained for h-BN on liquid Cu and simulations have been conducted to compare the interface of the as-synthesised 2D-material. The resulting interfacial profile agrees well with XRR measurements performed by ESRF (compare Fig. 2) confirming the successful synthesis of the 2D-material.

Further, first steps for automated analysis of experimental RMOM and Raman spectra via computer vision have been made at FHI-MPG. For RMOM analysis, using the example of graphene on liquid Cu, an automatic segmentation of pre-processed RMOM videos has been established. Further, the feasibility of real time analysis during RMOM experiments has been demonstrated via a neural network that has been trained to evaluate as-recorded images. This procedure circumvents complex and laborious image pre-processing and is based on training the neural network to synthetic data for which protocols have been developed. For automatic Raman spectra analysis, first attempts with Multivariate Curve Resolution algorithms have been successfully demonstrated for 2D-Raman maps. In an initial analysis of Raman spectra of synthesised SiC by NCSRD, the algorithm could indicate a high likelihood of cubic SiC in the spectrum.

DISSEMINATION AND EXPLOITATION

Although 2D ENGINE is still at an early stage, activities to enhance the project visibility and build a community have already started. A few of these actions are:

- A website was recently constructed and is managed by the coordinator.
- A LinkedIn account is hosted at AMO's LinkedIn platform.
- 2D ENGINE supported technically and financially a Graphene Week 2024 session dedicated to 2D materials of tomorrow.
- A four-minute video has also been produced by the consortium members and montaged by ESRF employees. The video was first projected during the Graphene Week 2024 conference and then was uploaded to the Graphene Flagship YouTube account and redistributed to the LinkedIn account and the website.
- A workshop *"Novel (2D) materials and their applications"* is organised by 2D ENGINE partner AMO and will be held in Aachen, Germany, 17–19 February 2025. 2D ENGINE and two relevant projects on 2D materials are featured in this workshop.
- As part of the activities to build a community around the project, 2D ENGINE supported the application of two Associated Members: CEA and Water2kW. CEA already actively participates to the 2D ENGINE research activities.
- In a different framework, Leiden University organised a workshop on 2D materials where partners of the 2D Engine consortium were well represented. Invited talks were given by AMO and Leiden Probe Microscopy.

POWERED BY THE GRAPHENE FLAGSHIP

Beyond any doubt, the Graphene Flagship is the driving force and the key enabler of all networking and outreach activities for the 2D ENGINE project. The Graphene Flagship provided great assistance to realise the dissemination plans as described above. They provided a fertile environment for networking and the results will soon become visible within the next project periods. While 2D ENGINE is complementary to most of the projects in the Flagship, synergies are emerging at least at the bilateral partner collaborations level. For example, NCSRD from 2D ENGINE and Chalmers University of Technology from 2DSPIN-TECH have found common interests in a class of topological materials, known as altermagnets. Although not directly related to 2D materials, the collaborative work that has already started between these projects can have an impact in the upcoming IAM4EU partnership through collaborative projects.

SAILING FORWARD

Important progress has been made regarding the growth of the targeted materials SiC, BN and GaN using the LMCat methodology as initially planned. In the cases of h-BN and GaN strong evidence has already been obtained that the films are very thin as required but not fully confirmed yet. Therefore, in brief, the action plan for the next year is;

- Verify that atomically thin SiC, h-BN and GaN films can be obtained by LMCat, as required. *Recent results for SiC are very optimistic!*
- Verify that GaN and SiC have the required graphitic form with hexagonal honeycomb lattice structures. Three beam times at ESRF have been secured after competitive proposals have been submitted, to implement this plan.
- Ensure that the grown ultrathin layers can be transferred on suitable target (preferably pre-patterned) substrates for electrical and optical evaluation and device fabrication. *This is a major challenge for next year!*
- Develop suitable atomistic simulation and predictive tools to assist the aforementioned tasks.
- File patents and publish the results in high impact journals.
- Strengthen networking with the organisation of several events. One such event (workshop) has already been decided and will be organised by ESRF in Grenoble, France, December 2025.

First internal 2D ENGINE project meeting in Athens.

2D Materials of Tomorrow

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2DSPIN-TECH

2D materials based non-volatile spintronic memory

PROJECT 2DSPIN-TECH is working to combine 2D materials and innovate beyond-CMOS device concepts – spintronics – to create 2D heterostructure-based devices for spintronics-based memory devices. The team will create novel spin-orbit materials and ferromagnets that remain stable above room temperatures for real-world applications. By stacking these materials in carefully designed heterostructures, researchers focus on controlling how charge, spin and magnetism interact at the atomic level, enhancing memory performance. The project aims to enable fast and energy-efficient switching of magnetic states without needing external magnetic fields – an innovation that could lead to groundbreaking improvements in spintronic memory.

> Memory is a fundamental component of computers, crucial for data storage, caching, buffering and in-memory computing. Due to varying sizes, speeds and storage capacities, different memory devices are in use today, and the search for a universal memory solution continues."

Saroj Dash
Project Coordinator

HIGHLIGHTS FROM 2024

During the first year of development, 2DSPIN-TECH focused on new 2D materials providing out-of-plane spin-polarised current, 2D ferromagnets with beyond room temperature and all-2D spin-orbit material, and ferromagnet heterostructures. All the work packages created a dedicated task force to develop these new combinations of 2D spin-orbit and magnetic materials.

2D topological quantum materials with out-of-plane spin-orbit torque
One important challenge for spin-orbit torque memory technology is to discover 2D spin-orbit materials with out-of-plane spin polarisation. Spin polarisation refers to the alignment of electron spins in a particular direction due to spin textures or broken crystal symmetries in materials. Our aim is to understand the physics of 2D spin-orbit materials with large spin-orbit coupling and novel spin textures of electronic bands to bring out their potential for use in spintronic memory technology.

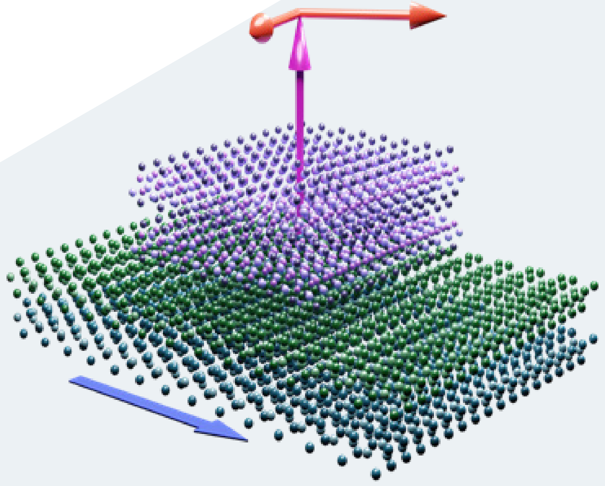
Graphene Flagship scientists discovered that a special class of 2D materials – such as topological quantum materials and materials with broken crystal symmetries – can generate a unique type of spin-polarised electrical current. Traditional materials used in spin-orbit torque memory applications produce only an in-plane spin current, which limits their efficiency. Even recent materials with lower crystal symmetry have not produced enough out-of-plane spin current to be useful in practical devices.

Researchers have now generated a large current-induced out-of-plane spin polarisation using a topological Weyl semimetal candidate $TaIrTe_4$. In addition to their low crystal symmetry, novel spin textures in the electronic bands and strong spin-momentum locking lead to strong spin polarisation. By testing devices made of such topological semimetals combined with a magnetic layer, they observed a much stronger out-of-plane spin current than ever recorded. Spin–torque ferromagnetic resonance and second harmonic Hall measurements are utilised to estimate a large out-of-plane spin-orbit torque efficiency. The out-of-plane spin Hall conductivity is estimated to be an order of magnitude higher than the reported values in other materials. These observations could significantly enhance the performance of spin-orbit torque devices, paving the way for compact, faster, more efficient and lower-power magnetic memory technologies.[1]

EXPLORING MULTIFUNCTIONAL 2D SPIN-ORBIT MATERIALS

A key challenge for field-free deterministic spin-orbit torque is the limited availability of 2D spin-orbit materials capable of generating out-of-plane spin-orbit fields, which require broken mirror symmetry imposed by crystal fields. 2DSPIN-TECH has started to investigate unconventional materials to overcome this challenge, building heterostructures based on mixed lattice symmetries. One striking example is a twisted heterostructure of graphene – which is honeycomb – and SnTe – which has a rectangular lattice. At a very low twist angle between the layers, realistic first-principle calculations predict a giant induced spin-orbit coupling in graphene, on the order of 10 meV, which is highly asymmetric in the momentum space and oriented primarily out of plane. Given that SnTe is a ferroelectric, with an in-plane built-in dipole moment, this induced spin-orbit coupling could be manipulated electrically.[2] While transition metal dichalcogenides are still excellent choices as supporting spin-orbit materials for spintronics applications such as spin-orbit torque, this recent calculation from the 2DSPIN-TECH consortium showed that ferroelectrics should also be viewed as potentially useful platform materials.[2]

Furthermore, 2DSPIN-TECH researchers have developed chemical vapour deposition (CVD) growth of 2D Janus semiconductors SeMoS, which can be useful for the generation of unconventional spin polarisation. Such 2D Janus materials have broken crystal symmetries, with the asymmetric top (Se) and bottom (S) chalcogen atomic planes with respect to the central transition metal (Mo) atoms. The formation of these 2D Janus layers takes place upon the exchange of the bottom Se atoms of the initially grown $MoSe_2$ single crystals on gold foils with S atoms.[3] Moreover, 2DSPIN-TECH researchers investigated the magneto transport properties of van der Waals material $ZrTe_5$, which is known as a candidate topological insulator. However, its topological phase and its relationship with other properties, such as an apparent Dirac semi metallic state, is still a subject of debate. We employ a semiclassical multicarrier transport model to analyse the magneto transport data of $ZrTe_5$ nanodevices at different hydrostatic pressures. The temperature dependence of the transport results is assessed in the context of thermal activation, and we obtain the positions of conduction and valence band edges in the vicinity of the chemical potential. We find evidence of the closing and re-opening of the band gap with increasing pressure, which is consistent with a phase transition from a weak to a strong topological phase.



Schematic diagram of a van der Waals heterostructure of Weyl semimetal $TaIrTe_4$ (bottom) and out-of-plane ferromagnet Fe_3GaTe_2 (top) for spin-orbit torque memory device.

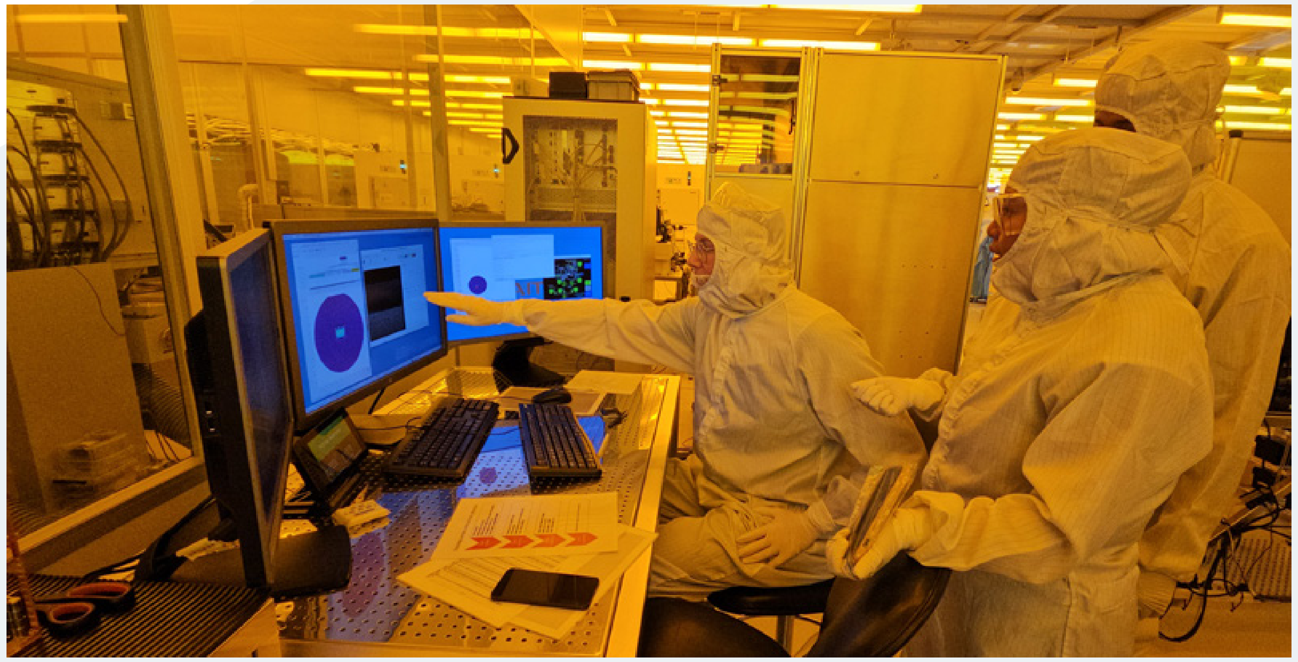
Hyunsoo Yang held a talk at the Graphene Week 2DSPIN-TECH workshop.

New 2D magnetic materials beyond room temperature
2D magnetic materials are crucial for energy-efficient spintronics, enabling low-power, field-free magnetisation control for next-generation memory and computing devices. Their unique magnetic properties and tunability make them ideal for advanced applications in data storage and memory technologies. 2DSPIN-TECH researchers synthesised and investigated beyond room temperature 2D ferromagnets and understood their static and dynamic magnetic properties for use in efficient spin-orbit torque memory technologies. Graphene Flagship scientists developed new van der Waals magnetic materials, Fe_5GeTe_2, with Co and Ni alloys. Magnetic characterisations have confirmed their magnetic ordering to be much above room temperature with a Curie temperature of more than 400 Kelvin. Interestingly, some compositions of these van der Waals materials exhibit a rare combination of ferromagnetism and antiferromagnetism in one material, which is not readily attainable with conventional materials. These new 2D materials demonstrate intrinsic exchange bias and canted magnetism – a highly desirable property for spintronic devices.[4] Traditionally, bilayers of ferromagnet and antiferromagnet thin films are utilised to achieve interfacial exchange bias, which is widely used in research and industry. However, there are challenges in fabricating high-quality multilayer interfaces with traditional thin films, and the discovery of a single material with coexisting magnetic orders is necessary. The discovery of non-trivial spin ordering with the coexistence of ferromagnetic and antiferromagnetic magnetic ordering in a single van der Waals magnet above room temperature can be useful for energy-efficient and non-volatile spintronic devices. The ability to control magnetism at the atomic level opens new possibilities for materials and device design.

Spin-valve devices with graphene and Van der Waals ferromagnets
Graphene spintronics offers a promising route to achieve low-power 2D electronics for next-generation computation. 2DSPIN-TECH researchers developed lateral spin-valve devices with van der Waals ferromagnetic contacts with Curie temperature beyond room temperature for spin injection and detection. Spintronic properties of van der Waals magnets are measured at the interface with graphene with a negative spin polarisation.[5,6] Similarly, the graphene spin-valve devices are also utilised to probe the charge-spin conversion and spin polarisation of topological materials at room temperature using a van der Waals heterostructure with a graphene spin-valve device.[7] The spin-valve and spin-precession measurements in such hybrid devices provide unique insights by probing the spintronic properties of the materials via spin-dynamics measurements, revealing the direction of created spin polarisation.

To enhance the device performance, graphene spin transport properties are optimised to enhance channel mobility with fully encapsulated devices with hexagonal boron nitride and one-dimensional ferromagnetic edge contacts for spin injection and detection. With the reduction of graphene channel length scales reduced to the limit of the electron mean free path, the transport mechanism crosses over to the ballistic regime. 2DSPIN-TECH researchers reported ballistic injection of spin-polarised carriers via one-dimensional contacts from ferromagnetic contacts and a high-mobility graphene channel.[8] The ferromagnet-graphene interface defines an effective constriction that confines charge carriers over a length scale smaller than that of their mean free path. This is evidenced by the observation of quantised conductance through the contacts with no applied magnetic field and a transition into the quantum Hall regime with increasing field strength. These demonstrations of ballistic spin injections present a step towards the development of low-power ballistic spintronic devices.

GRAPHENE FLAGSHIP ANNUAL REPORT 2024



Research inside the Chalmers cleanroom.

Experimental demonstration of spin-orbit torque spintronic memory
Spin-orbit torque (SOT) magnetisation switching without the need for external magnetic fields and low power consumption is essential for next-generation energy-efficient non-volatile spintronic memory technologies. The discovery of 2D materials above room temperature holds promise for such SOT phenomena because of their unique and tuneable magnetic properties. 2DSPIN-TECH researchers demonstrated energy-efficient, field-free and deterministic switching using a non-trivial magnetic order of such 2D magnets up to room temperature. They also discovered the coexistence of ferromagnetic and antiferromagnetic orders present in some material compositions, inducing an intrinsic exchange bias and canted perpendicular magnetism. These findings revealed efficient SOT phenomena of canted magnet up to room temperature and their usefulness in spintronic devices.[4]

Finally, scientists have made van der Waals heterostructures of spin-orbit material and magnetic material, showing that they can efficiently control magnetisation dynamics for spin-based memory. In this study, researchers combined Fe_3GaTe_2 (a magnetic material) with $TaIrTe_4$ (a topological Weyl semimetal) to form a heterostructure. They demonstrated that this structure allows for SOT switching at room temperature, meaning it can control magnetic states without needing an external magnetic field.[9] Detailed measurements indicate the presence of a significant out-of-plane spin torque, which is essential for efficient spintronic devices. By tuning the temperature and electronic properties of $TaIrTe_4$, researchers found that the strength of the spin-orbit torque could be adjusted. These results show that 2D heterostructures provide a promising route for energy-efficient, field-free and tuneable SOT-based spintronic memory technologies.

DISSEMINATION AND EXPLOITATION

The objective of dissemination and exploitation is to make the project results and 2D-based magneto resistive random-access memory (MRAM) technology known to relevant stakeholders, audiences and attract potential customers in the future. Three courses related to 2D materials or spintronics have been given, and more than 100 students enrolled for the courses. Seminars and an internal workshop have been organised to spread knowledge to younger scientists within the consortium. The principal investigators (PIs) from the project are actively attending national and international conferences as invited speakers or giving oral presentations. To this point, the partners have attended more than 30 conferences. 12 articles have been published in peer reviewed journals.

A stakeholder analysis has been carried out, and a stakeholders candidate list was created by assessing their interest and importance for the project. By sharing our website, LinkedIn and Graphene Flagship Annual Report, the stakeholders can follow the progress of the project and have better understanding of what we are doing. In the coming years, interviews and workshops will be arranged with the stakeholders to obtain feedback and suggestions.

Most 2DSPIN-TECH partners attended Graphene Week 2024, and in the exhibition area, 2DSPIN-TECH had its own booth to present the project with flyers, a roll-up and video. Some of the researchers have expressed the willingness to have future collaborations with partners from 2DSPIN-TECH.

Saroj Dash at Graphene Week in Prague.

Spintronic discussions after workshop.

2DSPIN-TECH has invited three FlagEra projects MINERVA, MNEMOSYN and MagicTune as partnering projects within the framework of the Graphene Flagship. By connecting the partners from these projects, it is expected to generate more discussion and collaboration in the future.

POWERED BY THE GRAPHENE FLAGSHIP

In 2024, 2DSPIN-TECH hosted a workshop during Graphene Week. The purpose of the workshop was to invite researchers outside of the project consortium to present the recent progress of spintronic study and its applications, especially in the areas related to 2D materials. The event attracted more than 100 people, even though not everyone was working in this area. The participants were curious about this new technology and tried to understand the working mechanism behind it. This generated dialogue and knowledge sharing among the speakers, partners from 2DSPIN-TECH project and other researchers, and potential collaborations were brought up and discussed.

SAILING FORWARD

Recent advancements and studies are limited to exfoliated flakes. Scalable growth of 2D SOM and magnets with high-quality vdW magnetic heterostructures need to be explored. The project will continue to maximise out-of-plane orbit spin polarisation and optimise the 2D SOM/graphene/FM heterostructures to obtain the SOT functionality of an all 2D magnetic memory at room temperature.

1. doi.org/10.1038/s41467-024-48872-3
2. DOI 10.1088/2053-1583/ad59b4
3. https://advanced.onlinelibrary.wiley.com/doi/full/10.1002/adma.202205226
4. https://doi.org/10.48550/arXiv.2308.13408
5. https://advanced.onlinelibrary.wiley.com/doi/full/10.1002/adma.202209113
6. https://pubs.acs.org/doi/full/10.1021/acsnano.3c07462
7. https://www.nature.com/articles/s41699-024-00447-y
8. https://arxiv.org/abs/2501.06160
9. https://arxiv.org/abs/2408.13095

2D Materials of Tomorrow

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Ankara University
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2DSPIN-TECH

SAFARI

Safe and sustainable by design MXenes and MXenes/graphene hybrids

THE SAFARI PROJECT focuses on producing MXenes creating a new combination of 2D materials by the hybridisation of MXenes and graphene. Those materials are unique because they are both thermally stable and excellent conductors of electricity, making them ideal for a variety of end user applications.

The project incorporates the Safe and Sustainable by Design (SSbD) framework at every stage, advancing the development of 2D materials with sustainable methods. The framework proposed by the European Commission provides guidelines for the innovation of chemicals and materials towards a green and sustainable transition.

The project's main activities begin with the production of two main types of MXenes – Ti3C2 and Cr2C – which are then hybridised with graphene to form advanced 2D material structures. The materials and hybrid formulations are then tested in relation to their properties, structure and perfor-mance.

However, the project is not only creating new materials; but also guaranteeing they are safe for people and for the environ-ment along the design phase and the material production cycle. This is due to the SSbD methodology used for the materials production which ensures that the materials are non-toxic and eco-friendly. To this end, the partners are assessing the toxicological and eco-toxicological profiles of the materials produced.

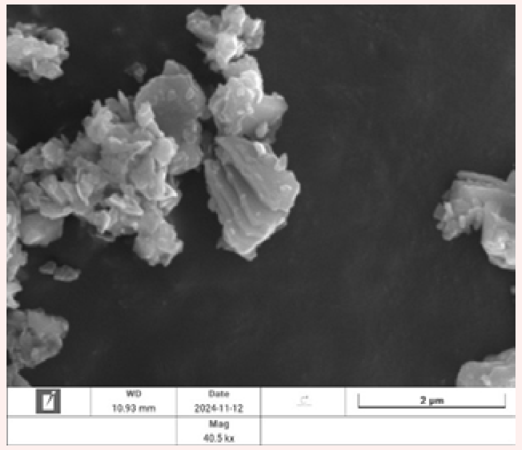
As a final stage, the project explores the MXenes and hybridisa-tion formulation of MXenes and graphene in practical applica-tions, such as biosensors, conductive inks and shielding against electromagnetic interference (EMI).
In a nutshell, the SAFARI project is making advancements in innovative, safe and versatile materials for modern applica-tions.

HIGHLIGHTS FROM 2024

Our partner Poznański Institute of Technology produced the first samples of MXenes. The samples produced contain impurities and residues from the MAX phase (the raw material for MXenes production). Analysis and classification of the impurities was the second step for the materials produced. Creative Nano also conducted an elaborative investigation on how to purify the MXenes, remove the remaining MAX phase starting material and further delaminate flakes to increase the interlayer spacing and enhance electrical properties of MXenes. Additionally, a procedure was defined to develop MXene thin film composites with polymeric materials such as PVA, PVP, PEI etc., allowing for the incorporation of metal ions (Cu) and small organic molecules (such as the molecules of (3-Aminopropyl) triethoxysilane (APTES). These films can be used directly as electrodes while other applications for these composites are being investigated. Below, you can see the image showing the structure of the MXenes produced.

2024 marked the first year of the SAFARI project, bringing a sense of accomplishment through our collaborative efforts within the consortium. A lot of satisfaction came from focusing on innovative technologies based on graphene and reduced graphene oxide, aiming at limiting negative impact on environment. Among our successes was also an active involvement in the Graphene Flagship actions, integrating SAFARI partners into the vibrant and dynamic European ecosystem of advanced materials."

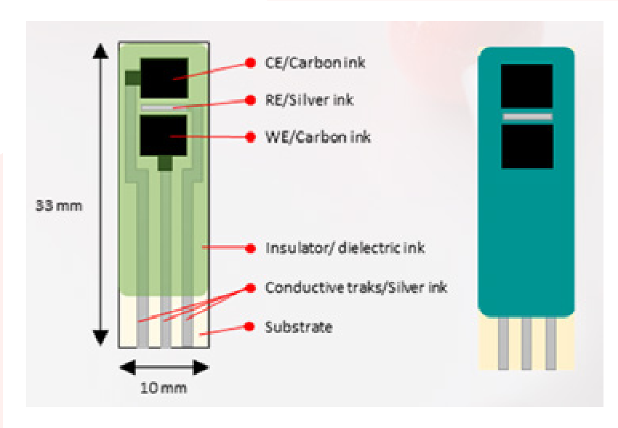
Dariusz Garbiec
Łukasiewicz – Poznański Instytut Technologiczny, Project Coordinator



SEM image illustrating accordion-like structure of MXenes. Credit: Creative Nano.

As mentioned above, ensuring the safety and sustainability of the materials used in MXenes production is SAFARI's key focus, aligning with the SSbD. The framework consists of four steps of assessment: 1) Hazard assessment, 2) Human health and safety aspects, 3) Human health and environmental aspects and 4) Environmental sustainability.

During the project´s first year, the partners ISQ Group, University of Burgos and Metrohm DropSens successfully worked in parallel on different aspects of this framework, which included assessing the human, physical and environmental hazards associated with the materials being developed in the project. The advanced methods for the assessment used in the project include tools such as QSAR models or *in vitro* assays. Additionally, questionnaires were designed to gather informa-tion about potential exposure scenarios during the processes and materials development. These measures aim at ensuring the safety and well-being of workers while advancing the development of innovative and sustainable materials.



Electrochemical sensor design developed by Metrohm DropSens. Credit: Daniel Izquierdo Bote

When it comes to SAFARI´s end user applications, Metrohm DropSens designed a preliminary version of the electrochemi-cal sensors, fundamental for measuring substances like glucose and lactate, essential for the biosensor applications under development in SAFARI for biomedical and healthcare applications.

DISSEMINATION AND EXPLOITATION

AXIA Innovation leads the SAFARI project communication strategy, aiming to fully engage stakeholders and effectively convey the project´s goals and achievements. During the first year, the project created five press releases, two newsletters, a project brochure and a roll-up banner, ensuring the project developments reached a wide audience.

Our social media presence has been remarkable, with more than 75 posts shared across platforms. Updates on social media have helped inform diverse audiences about the project, highlighting its objectives, significance and impact in the field of 2D materials. Thanks to these efforts, we´ve already gained over 500 followers on our social media channels, reaching 50% of our committed communication target for followers within the first year.

Beyond the project's strong social media engagement, SAFARI partners submitted a research article, had an internal training session on intellectual property management and exploitation and actively took part in over ten events to showcase the project research results.

CONFERENCE HIGHLIGHTS

The SAFARI project was showcased at major conferences, presenting the last research results and further enhancing its visibility and engagement within the research and development communities. Some of the key events attended include:

LOPEC 2024 in Munich
SAFARI partners from the Danish Technological Institute, Creative Nano and AXIA Innovation attended the leading event on flexible, organic and printed electronics. The event took place from 5–7 March 2024 in Munich, Germany, bringing together participants from application development to research across all continents in the high-tech metropolis of Munich. At the conference, SAFARI partners explored and mapped advancements in the scientific, technological and economic aspects of electronics. The partners' focus was on the electronic market, particularly in areas aligned with SAFARI´s applications, such as conductive printable inks and electro-magnetic shielding coatings.

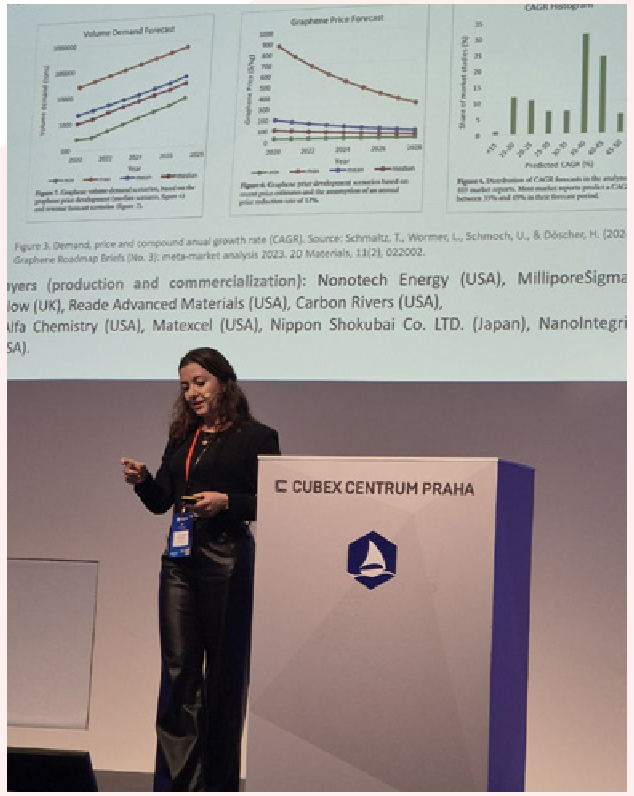
Grzegorz Kubicki at his oral presentation. Credit: SAFARI.

Materials Week 2024 in Cyprus
Grzegorz Kubicki from the Research Group of Materials Engineering (Ponański Institute of Technology) presented the work titled "Circularity of MAX Phases: From Worn Parts and Broken Samples to 2D Functional Mate-rials", highlighting an innovative approach for reusing MAX phases. The presentation was an effective way to disseminate about the project to several stakeholders. in addition, his participation was important to gain knowledge, since Grzegorz Kubicki also attended two training courses on:

- Integration & Balance of SSbD Categories from an Industry Perspec-tive, and
- Harmonisation, Standardisation & Validation of Test- and Characteri-sation-Methods.

Graphene Week 2024 in Prague
SAFARI actively contributed to Graphene Week by hosting a session, presenting a poster and delivering an oral presenta-tion, covering the SSbD aspects specific to 2D materials.

- **Session on Safe and Sustainable by Design.** The session was led by SAFARI´s coordinator, Dariusz Garbiec, who guided the talks and discussions on the design and innovations in relation to the sustainability aspects of 2D materials.
- **Invited Oral Presentation.** Jaqueline de Godoy from our partner AXIA Innovation delivered an invited talk titled "Market application of MXenes and graphene" The presenta-tion highlighted insights from potential commercial areas for expansion of the 2D materials produced within the SSbD framework.
- **Poster presentation.** Axia Innovation presented the poster titled "Market application of MXenes and graphene produced



Oral presentation by AXIA Innovation.
Credit: Myrto Pelopida

through a Safe and Sustainable-by-Design framework". The poster was the result of the exploitation of the key results of the project developed up to date by Jaqueline de Godoy, Myrto Pelopida, Georgios Maris and Ioanna Deligkiozi.

Safe and Sustainable by Design Bootcamp in Greece
From 22–25 October 2024, Carlos Bernárdez Casás and Valeria Acevedo García from the AIMEN Technology Centre were in Thessaloniki, Greece for the 2nd SSbD Bootcamp. The event, organised by the European Commission and the Aristotle University of Thessaloniki (AUTH) focused on an in-depth understanding of the SSbD framework and the stage-gate innovation process, demonstrating real-life applications. Carlos Bernárdez Casás notes: "It was a good opportunity to improve our knowledge within the whole framework of the SSbD, not only the sustainability part which is carried out by AIMEN throughout the SAFARI project, but also in other aspects of the innovation process."

5th International Workshop on Spark Plasma Sintering in France
Dariusz Garbiec, Łukasiewicz – Poznański Institute of Technology, was invited to chair the opening session at the 5th International Workshop on Spark Plasma Sintering. Furthermore, he delivered the presentation titled "SPS-synthesised MAX phases: processing and applications" presenting the project's work.

Electronica Fair 2024 in Munich
From 12–15 November 2024, the world's leading trade fair and conference in electronics happened in Munich, Germany. Jaqueline de Godoy and Myrto Pelopida from AXIA Innovation were at the fair networking, presenting the innovations under the SAFARI project and getting immersed in the last advancements on the electronics field.

SSbD24 Conference in Switzerland
The SSbD24 conference, organised by the Swiss Federal Laboratories for Materials Science and Technology (EMPA), was held in Monte Veritá from 11–15 November 2024. Carla Martins from our partner ISQ Group held a presentation on "Addressing the SSbD steps to the development of hybrid formulation of MXenes and graphene". The conference focus was on the practical application of the SSbD framework, bringing together experts from various fields to discuss methods and tools for sustainable design.

SAFARI newsletters
Our newsletters, part of our grey literature, are available electronically to our audiences. Through these updates, all interested parties can stay informed about all advancements in the SAFARI project.

- **First newsletter, August 2024.** This issue introduced the project´s structure, goals and key technologies. It detailed SAFARI´s innovative technologies, our main contributions and the user applications we are testing, all framed within the Safe and Sustainable by Design Framework being applied. Additionally, we introduced our partners, provided details on events attended and on the cooperation with the Graphene Flagship.
- **Second Newsletter, December 2024.** This edition focused on the milestones and deliverables, highlighting the progress made by each partner. It also showcased the development of our partnership with the Graphene Flagship, highlighting the project´s participation on the Graphene Week and other key milestones achieved.

Exploitation activities
On 12 December 2024, AXIA Innovation hosted a workshop focused on Exploitation and Intellectual Property Rights (IPR) Management. The workshop provided an overview of Horizon Europe Rules governing exploitation activities, which are an integral part of Horizon Europe funded projects. In addition, specific rules and objectives of the SAFARI project related to its exploitation strategy were presented, along with key terminology in the field.

The workshop was also theoretically insightful in terms of intellectual property rights protection within Horizon Europe-funded projects. Other topics covered in the workshop included the existing forms of intellectual property protection means, as well as the strategies for mapping and safeguarding the project´s outcomes.

Based on the insights and knowledge gained in the training, partners replied to a questionnaire that is being used to design the exploitation routes for each partner who has a key exploitable result within the project.

A key result of the exploitation activities in the first year was the preliminary market landscape study of graphene and MXenes hybrids conducted by AXIA Innovation. This study was presented as a poster and invited for an oral presentation at Graphene Week 2024.

POWERED BY THE GRAPHENE FLAGSHIP

The Graphene Flagship has played an important role in aligning the actions of the SAFARI project with the overall strategy for 2D materials development in Europe. SAFARI actively participates in working group meetings focused on innovation and dissemination activities, roadmapping and standardisation to ensure alignment and conjunct contributions.

Additionally, the project is collaborating with other Graphene Flagship projects. Currently, SAFARI collaborates closely with 2D-BioPAD, MUNASET and GRAPHERGIA, showcasing the versatility of 2D materials for applications in biomedical applications. Specifically, SAFARI is contributing with knowledge on the development of biosensors for glucose and lactate detection having MXenes and graphene hybrids as the sensing material.

SAFARI partners at Graphene Week 2024.
Credit: Kateřina Antoš

Furthermore, SAFARI is exchanging knowledge with the ARMS project on how to improve the use of the sustainability framework in both projects. Carlos Bernárdez Casás from AIMEN Technology Centre noted that exchanges with the ARMS project are creating valuable insights for applying the SSbD framework. The discussions between SAFARI and ARMS are helping to move forward with the work under development in parallel by both projects.

Furthermore, in 2024 our collaboration with the Graphene Flagship led to SAFARI´s active participation in Graphene Week 2024. Specifically, our coordinator from Lukasiewicz – Poznanski Institute of Technology moderated a parallel session to share knowledge on the development of 2D materials with the SSbD Framework. Furthermore, AXIA Innovation presented a poster on Marked Applications of MXenes and 2D materials produced through a SSbD Framework. Furthermore, Jaqueline de Godoy from AXIA innovation was invited to give an oral presentation on the Market Scenarios for 2D materials.

SAILING FORWARD

As the project enters its second year, our partners are focusing on key goals across all areas. "The SAFARI project's goals for 2025 are clear," says project coordinator, Dariusz Garbiec. "First, our aim is to be one of the first in the world to produce MXenes from Cr_2AlC, at present, Ti_3AlC_2 is mainly used as a precursor. Second, this year, we plan to develop an upscaled production line for MXenes, which will be an important step in the development of this material, as well as a major milestone allowing its further application in sensors or EMI shielding."

Safe by Design

PROJECT COORDINATOR
Dariusz Garbiec, Poznanski Institute of Technology, Poland

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University of Burgos, Spain
ITENE Research Center, Spain
ISQ Group, Portugal
AIMEN Technology Center, Spain
Danish Technology Institute, Denmark
Israel Aerospace Industries Ltd., Israel
ThinkWorks BV, Netherlands
AXIA Innovation GmbH, Germany
Metrohm DropSens SL, Spain

Associated Members
Graphenest SA
Avanzare Innovacion Tecnologica SL
Sabanci University

SAFARI

Association Mechanism

THE GRAPHENE FLAGSHIP Association Mechanism offers the possibility for projects and organisations to join the initiative as Associated Members or Partnering Projects. The aim of this mechanism is to promote broader exchanges and an inclusive environment within the 2DM community, as well as ensure the continuity of national and international collaborations established in past project phases. The focus of this mechanism is on promoting synergies and mutual benefits, some of which may include expanding the network and establishing new collaboration opportunities and partnerships. Associated Members and Partnering Projects benefit from networking and collaboration opportunities with a broad scientific community, and as a consequence, increased visibility of their research and innovation outcomes. Below are highlights from some of the Graphene Flagship's 32 Associated Members and 11 Partnering Projects.

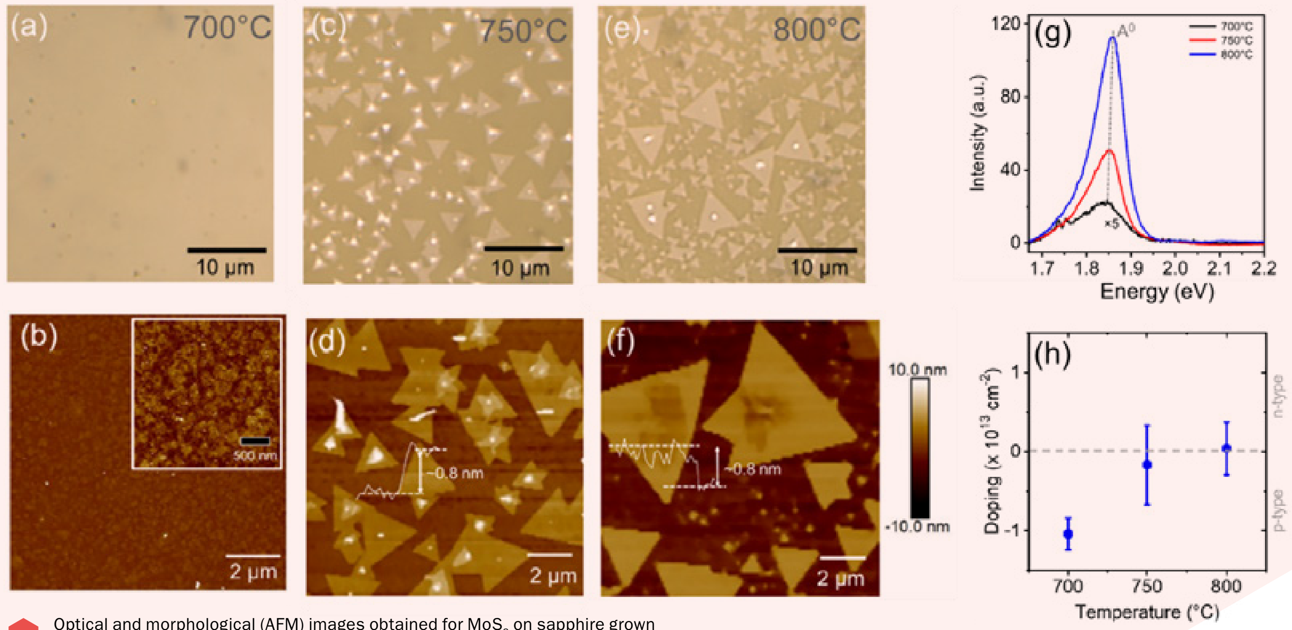
PARTNERING PROJECT: 2DINTEGRATE

FOCUS: ELECTRONICS AND PHOTONICS

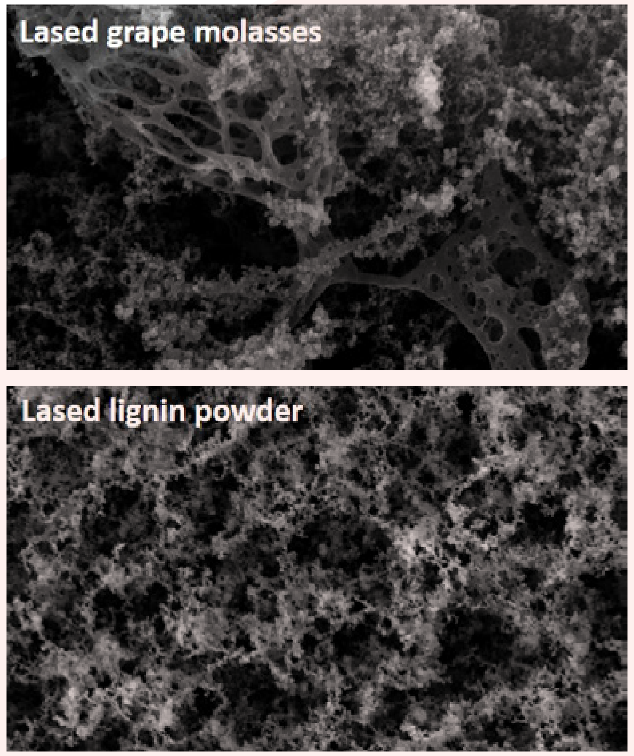
In 2024, the partners of the project 2DIntegratE (http://2dintegrate.imm.cnr.it/), demonstrated a cost-effective and semiconductor-fab compatible approach to produce monolayer MoS_2 with tailored crystalline quality, strain, doping and light emission properties by sulphurisation of pre-deposited MoOx films on sapphire at temperatures (Ts) from 700 to 800 °C. The increase of Ts resulted in the transition from a continuous nanocrystalline film to a distribution MoS_2 domain with micrometer size, accompanied by a strong (25 times) enhancement of the photoluminescence intensity. Furthermore, the doping of MoS2 evolved from a strong p-type doping (~1×1013 cm-2) after Ts=700 °C to a low n-type doping (~0.04×1013 cm-2) after Ts=800 °C.

The wide tunability of doping and PL of MoS_2 by the sulphurisation temperature can be exploited to engineer material properties for different specific applications. The results of these studies have been published in APL.

https://doi.org/10.1063/5.0214274



Optical and morphological (AFM) images obtained for MoS_2 on sapphire grown at 700 °C (a,b), 750 °C (c,d), and 800 °C (e, f). PL spectra (g) and doping dependence (h) on the sulfurisation temperature. Credit: 2DIntegratE



The two biomass materials investigated as precursors, liquid grape molasses (left) and an aqueous suspension of lignin powder (right). Credit: EMPHASIS

PARTNERING PROJECT: EMPHASIS

FOCUS: ENERGY

EMPHASIS works to create substantial impact on energy storage systems solutions for applications ranging from consumer goods to electrification of transport and reduction of emissions. 3D graphene-like electrode materials are being prepared by laser-assisted decomposition from biomass-derived precursors. Two different laser approaches are being developed, a simultaneous transformation and deposition of the laser-assisted graphene flakes via the LEST method and a direct laser-assisted graphene production approach. Two biomass materials are investigated as precursors: liquid grape molasses and an aqueous suspension of lignin powder. Various flexible substrates have been employed to synthesise laser-assisted graphene-like active materials on both single and planar-type interdigitated supercapacitor electrodes. In all cases the produced active materials are of high-quality few layer turbostratic graphene with superior conductivity, high C/O and sp2/sp3 ratio of carbon content. The performance of a microflexible supercapacitor fabricated using the above approaches, with the exception of using Kapton polymer as a carbon precursor instead of biomass, was measured to be among the highest reported in the literature for interdigitated supercapacitors based on laser-grown graphene.

https://doi.org/10.1038/s41699-022-00331-7
https://doi.org/10.1021/acsanm.3c05387

PARTNERING PROJECT: MINERVA

FOCUS: 2D MATERIALS OF TOMORROW

The MINERVA project, involving several partners including the University of Lyon, the Catalan Institute of Nanoscience and Nanotechnology (ICN2), Uppsala University and UCLouvain, made significant strides in 2024 in the synthesis and characterisation of amorphous boron nitride (aBN) thin films. The team successfully optimised chemical vapour deposition (CVD) parameters to grow aBN films with controlled thicknesses on silicon and copper substrates. These films were thoroughly analysed, with the cross-plane thermal conductivity measured at around 0.3 W.m-1.K-1 and film thicknesses accurately determined via X-ray reflectometry. The research also involved theoretical studies, including machine-learning potentials for hydrogen- and carbon-modified aBN, as well as *ab initio* simulations to explore the material's electronic and dielectric properties. The team also began developing patterned substrates for future 2D material growth, intending to benchmark these films for future applications. Since the project's inception, nine publications have been released.

The Polygraph project team.
Credit: Polygraph

PARTNERING PROJECT: POLYGRAPH

FOCUS: ENERGY

Partnering project Polygraph, which is being implemented at Associate Member Institute of Chemistry, Technology and Metallurgy (ICTM) in Belgrade, Serbia, has spent 2024 making strides in the development of laser-induced graphene (LIG). LIG has shown prospects as an exciting material for electrodes and various types of sensors, due to its facile production process and sensitivity to a number of parameters, including substrate bending, environmental pH, bacteria, viruses and sound waves.

Polygraph is a focused effort to produce LIG on a number of biocompatible synthetic polymers, for use in wearable sensors. In the first project year, 2024, Polygraph members published a research article on laser induction of graphene on Poly(dimethylsiloxane)/Triton composites, and another article on blood oxygen saturation estimation with a LIG respiration sensor. The researchers are continuing work to fabricate and characterise LIG on a number of biologically important biocompatible polymers. In collaboration with Graphene Flagship Associate Members from TU Delft, the team at ICTM published a notable paper on quantifying stress distribution in ultra-large graphene drums through mode shape imaging.

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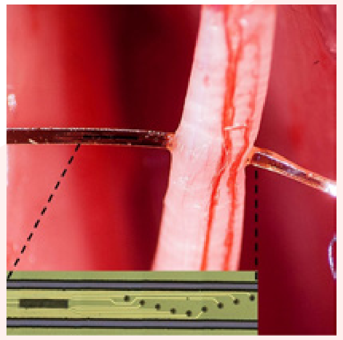


Implant of a graphene-based electrode in the peripheral nerve. Insight of the graphene active electrodes (black dots) on a polymide substrate electrode. Credit: UAB and ICN2.

PARTNERING PROJECT: RESCUEGRAPH

FOCUS: BIOMEDICAL

Loss of sensory and motor functions as a result of spinal cord injury, peripheral nerve injury or amputation affects several million people worldwide. Neuroprostheses represent an advanced solution to restore or substitute the lost sensory and motor functions. The RESCUEGRAPH project is aimed at exploring the potential of graphene-based technologies in neural interfaces to help improve the performance of motor neuroprostheses. Taking advantage of intrinsic properties of graphene, such as biocompatibility, electrical performance and easy integration within elastic substrates, flexible polyimide devices with graphene microelectrodes have been fabricated with the ability to record and stimulate the nervous system with lower current needed and with high selectivity. The contact of the graphene material with neural tissue or neurons does not generate damage, thus demonstrating its biocompatibility. This technology can become a new standard for future advanced neural implants towards clinical applications.

The development and *in vivo* assessment of the graphene-based electrodes has been reported in the following papers with the participation of partners ICN2 and Universitat Autònoma de Barcelona (UAB).

https://doi.org/10.1038/s41565-023-01570-5
https://doi.org/10.1002/advs.202308689

It is strategically important for Sweden to nurture and connect young researchers."

Samuel Lara Avila
Chalmers University of Technology

PARTNERING PROJECT: SIO GRAFEN

FOCUS: COORDINATION AND SUPPORT

SIO Grafen has actively facilitated the 2D Graduate Network throughout 2024. This national network for young researchers in 2D materials started off as a feasibility study in 2021. The network turned into a strategic project in 2023 and continues onwards. The goals are to spread knowledge, exchange ideas and build a national structure that promotes collaboration between young researchers, academia and industry in Swedish 2D innovation. Today, the network consists of over 40 younger researchers, with seven universities represented.

Young researchers taking part in SIO Grafen's 2D Graduate Network. Credit: SIO Grafen

"It is strategically important for Sweden to nurture and connect young researchers. An active network within a common area creates opportunities for interdisciplinary exchanges and collaborations. It broadens the perspective and potential of younger researchers; therefore, it is also a contributing factor to the sustainable development of Swedish graphene innovation," says Samuel Lara Avila, Associate Professor in Quantum Device Physics, Microtechnology and Nanoscience at Chalmers University of Technology.

Lara Avila leads the 2D Graduate Network for SIO Grafen together with Jens Eriksson, Linköping University, and Nazanin Emami, Luleå University of Technology. And the work will continue. SIO Grafen aims to have more than ten universities represented and over 50 active members in the network by the end of 2025.

ASSOCIATE MEMBER: UNIVERSITY OF MINHO

FOCUS: ELECTRONICS AND PHOTONICS

Over the past year, the University of Minho's activity was mainly concentrated in the field of plasmonics of 2D materials. We demonstrated that the graphene monolayer, encapsulated into hexagonal boron-nitride (hBN) layer, is able to sustain mixed phonon-plasmon polaritons, in which dispersion curves exist both inside and outside Reststrahlen bands of hBN. These modes can be excited by photocurrent and be revealed as peaks in photocurrent spectrum in the structure, where the graphene-hBN stack is deposited on top of a periodic array of metal bars. Along with our collaborators, we developed the semi-analytical method to predict the positions of polaritonic peaks, using dispersion relations for acoustic modes and single layer graphene ones and applying total phase increase conditions over one period of the structure.

https://doi.org/10.1364/JOSAB.514255
https://doi.org/10.1038/s41467-024-52838-w

ASSOCIATE MEMBER: VERSARIEN

FOCUS: BIOMEDICAL

Over the last 12 months, Versarien (previously a Core 3 partner as part of the GICE spearhead) has made significant strides in low-carbon construction, energy storage and electronics, securing key commercial contracts and grant funding. Versarien's Cementene™ technology is advancing sustainable concrete solutions, with large-scale trials underway. Versarien subsidiary Gnanomat is developing Gnanocaps technology, driving innovation in energy storage, securing significant grant funding and strategic contracts with major companies. Versarien's growing partnerships in South Korea and technology licensing has also led to the recent launch of a CVD graphene-based biosensor platform for rapid point-of-care diagnostics through a distribution agreement. Versarien CEO Dr. Stephen Hodge continues to play a crucial role in graphene regulation, maintaining his position in the re-formed Graphene Flagship REACH-ECHA committee to address regulatory challenges and support industry adoption.

Versarien CEO Dr. Stephen Hodge spoke as part of the Innovation Forum at Graphene Week in Prague. Credit: Kateřina Antoš

Versarien's pilot plant based in Madrid. Credit: Versarien

Versarien's Gnanocaps technologies for energy storage. Credit: Versarien

On the horizon

HAVING WORKED ON the periphery of the Graphene Flagship activities at Chalmers University of Technology – working with the Chalmers Graphene Centre, serving on the steering board of the Swedish 2D-Tech Centre of Excellence and acting as Director for Chalmers' Materials Science Area of Advance – I now look forward to stepping into a lead role for the initiative.

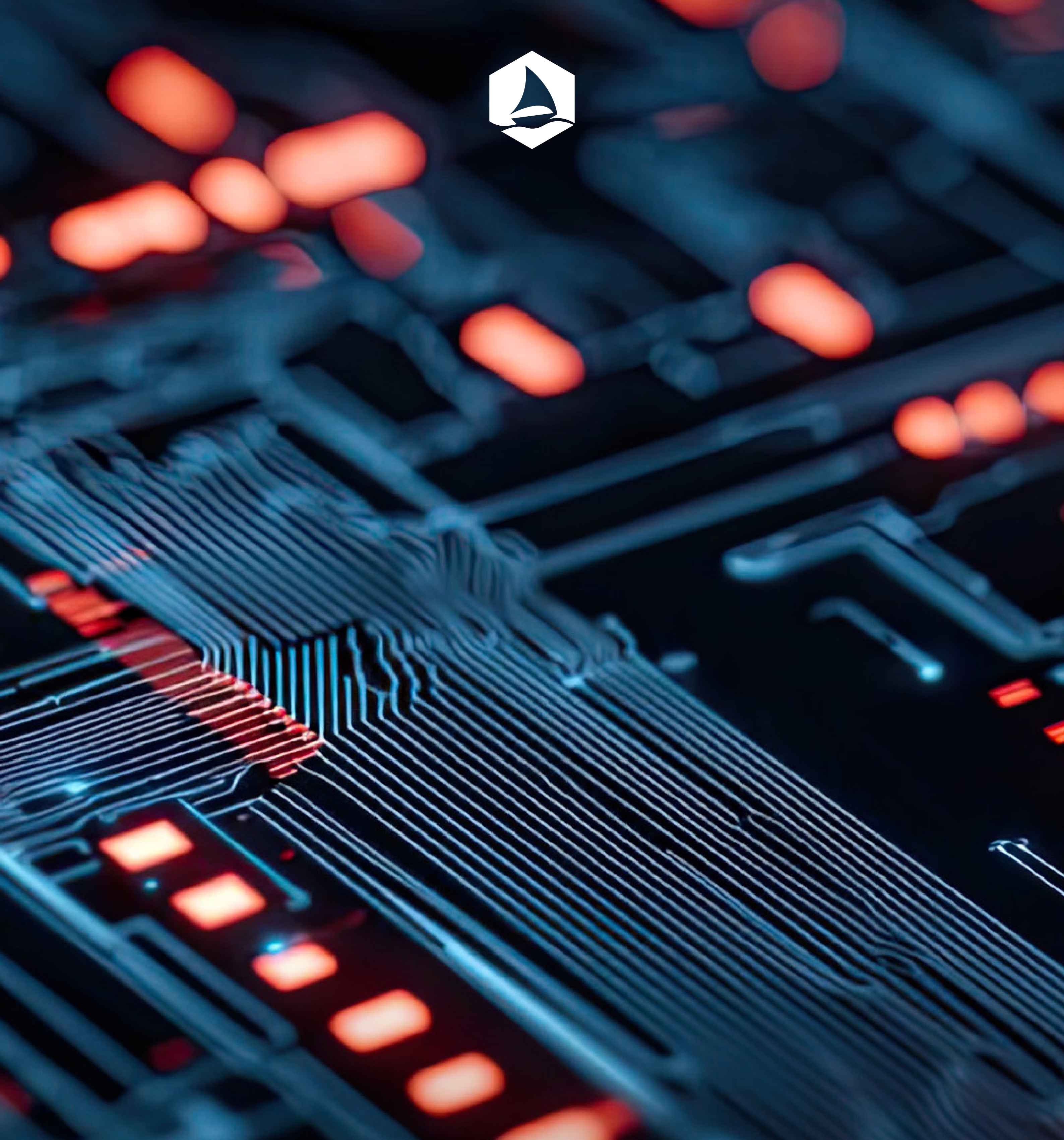
As the Graphene Flagship continues to advance Europe's leading role in 2D materials research and innovation, its strategic importance continues to grow. The next years will be pivotal in establishing the Graphene Flagship as the European leader in 2D materials both as part of the IAM4EU public-private partnership (learn more on page 8) and in the larger scope of innovative advanced materials. The years of experience brought by the Graphene Flagship community will be critical here as will a clear view of future opportunities. It is important for the community to remain open to new ideas, applications for the initiative's past work and ways of working within the European Commission's future frameworks.

The Graphene Flagship has established a solid foundation for the future. Its participation in IAM-I (the Innovative Advanced Materials Initiative) which will govern IAM4EU, ensures a strong voice in support of 2D materials research and innovation in the partnership. Planning at Science and Technology Fora has given the Graphene Flagship a strong platform, identifying the key areas for promising future work. Furthermore, work is underway to leverage the experience of key members of the Graphene Flagship Core projects to ensure that the whole community (past and present) is represented. In the next year, the IGFC (Initial Graphene Flagship Community) is being established to provide an avenue through which these experts can share their insights and voice their wishes for the future of the initiative.

In the next year, I will be working with the GrapheneEU CSA, the RIA/IA projects and the European Commission to ensure that the Graphene Flagship is positioned for success in the future. I encourage you to reach out to me if you have any ideas or concerns, and I look forward to getting to know you all better at Graphene Week in Vicenza, Italy!

Maria Abrahamsson
Graphene Flagship Director

I look forward to working more closely with the Graphene Flagship community and building on its tradition of bringing science out of the lab and into applications that can solve some of society's pressing challenges."



What is the Graphene Flagship?

Bringing together 126 academic and industrial partners and 49 Associated Members in 13 research and innovation projects and 1 coordination and support project, the Graphene Flagship initiative 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 ten years of the Graphene Flagship, is funded by the European Commission's Horizon Europe research and innovation programme.

Visit graphene-flagship.eu

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Flavia Maia

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