GRAPHENE FLAGSHIP

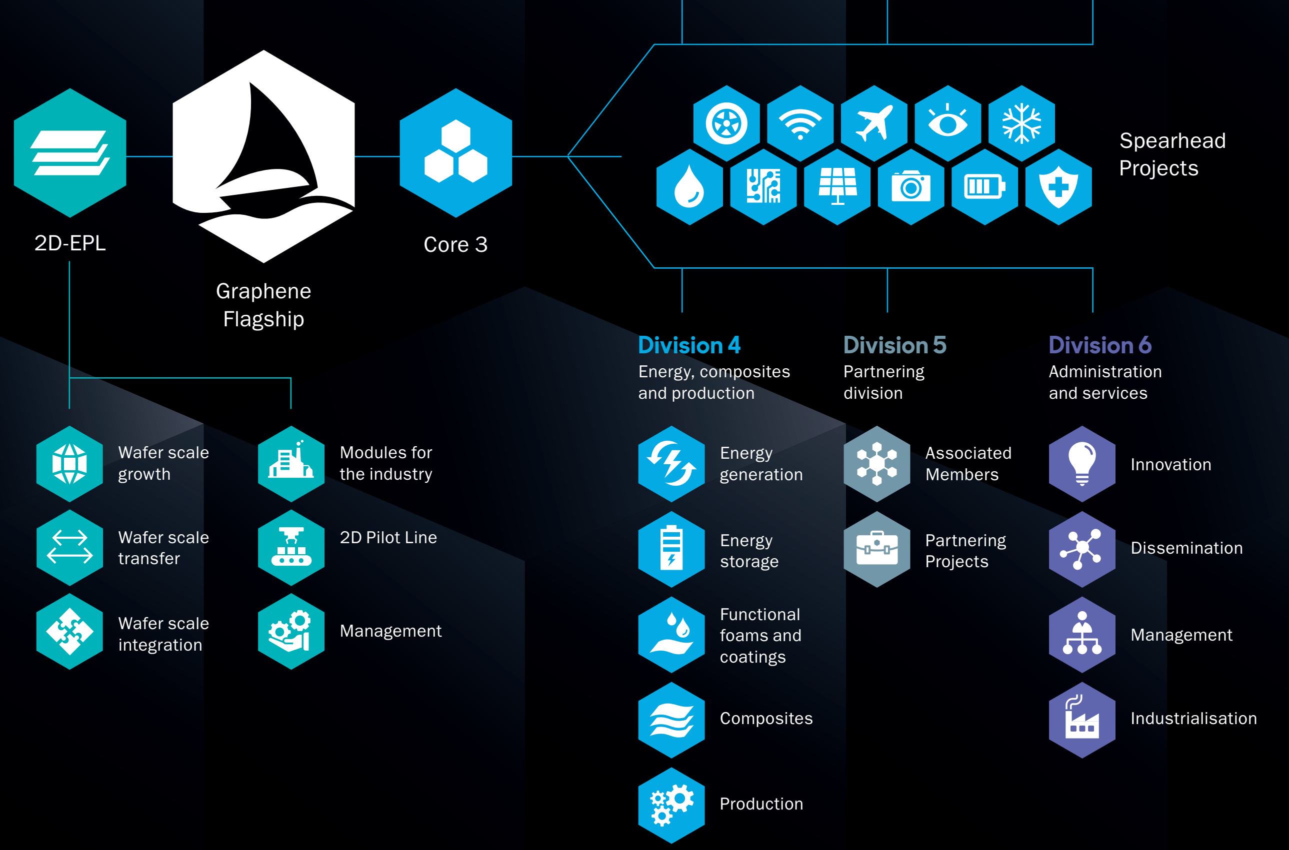
Funded by the European Union

Annual Report 2022

How we work

The Graphene Flagship's Core 3 project is divided into six divisions: four of them scientific and one each for Partnering Projects and Administration. Within the divisions are a total of 19 Work Packages, 15 on research and innovation and four on operative management aspects. Beyond this, 11 Spearhead Projects, connected to the Work Package structure but working on more commercial outputs.

The 2D Experimental Pilot Line (2D-EPL) project is composed of six Work Packages that function as an independent division in the Graphene Flagship.



Cover image
Artistic impression of the surface of a graphene microphone membrane. Credit: Midjourney and Peter Steeneken

Contents

Top
2014: 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

Above
Jari Kinaret prepares to kick off the Graphene Flagship's ten-year anniversary at Graphene Week 2022. Credit: Juliane Haerendel, Graphene Flagship

Left
2013: Jari Kinaret, Director of the Graphene Flagship, presents Neelie Kroes, Vice-President of the EC in charge of Digital Agenda, a graphene-enhanced wafer at the award ceremony when the Graphene Flagship was announced. Credit: European Commission

From the Director

Portrait of Graphene Flagship Director Jari Kinaret.

A general theme over the past year has been a continued shift in focus from academic "hero devices", statistical outliers that give spectacular but not easily reproducible results, to more industrially relevant results. Examples of these are larger electronic circuits based on molybdenum disulphide for 6G communication systems and graphene detectors operating at the terahertz range at room temperature.

It is fair to say that while applications for graphene and related materials have appeared on the market quite quickly in many areas, such as composite materials, the transition from laboratories to the real world has been slower in electronics. Now with the launch of the first multi-project wafer runs offered by our 2D Experimental Pilot Line project, we see that transition taking place. There are still some issues that need to be resolved before the large-scale production of electronics and photonics based on two-dimensional materials is commonplace, but we are well on our way there.

> The most important factor behind the Graphene Flagship's success has been the longevity of the endeavour."

A DECADE STRONG

The Graphene Flagship launched a 10th anniversary at Graphene Week 2022 that will culminate with a final celebration of project results at Graphene Week 2023. As I reflect on the past ten years, I am very proud of the fact that we have created a community that brings academic and industrial partners together to create new technologies, or to substantially change existing technologies in fields ranging from composite materials to energy, electronics and medical technologies. If we look back at where we were ten years ago, the evolution has been phenomenal. Now the production of graphene and related materials is an industrial activity rather than one involving graduate students in academic laboratories peeling small flakes of graphene off graphite stones using sticky tape. We know much more about the properties of these materials, including their health and environmental effects, and we have begun to create substantial economic and technological impact through both our start-ups such as BeDimensional, Qurv and INBRAIN, and large industrial partners like ABB, Airbus and others. In short, we are delivering on the promises we made ten years ago.

The most important factor behind the Graphene Flagship's success has been the longevity of the endeavour. The results that we have produced would not have been possible without trust: firstly, trust that the new technology was real and not just hype, and secondly trust between organisations in the consortium. Building either type of trust takes time, several years, which is beyond the reach of typical three-year research projects. If one aims at something more than incremental results, if one wants to truly impact the state-of-the-art, a long project period is much more important that a large project budget.

ON THE HORIZON

With the Graphene Flagship Core 3 project coming to a close in September 2023, we see some changes on the wind. Many of the Graphene Flagship's activities will continue under Horizon Europe but organised as several research and innovation actions bound together by a small coordination and support project. The first projects were announced in March 2023, but further projects will be selected later this year and in 2024. This will undoubtedly result in some changes in the Graphene Flagship consortium and the way decisions are taken, but I expect that the concrete work to bring graphene and related materials to real world applications will continue in much the same way as today.

Jari Kinaret
Graphene Flagship Director

GRAPHENE CELEBRATES 10

> The Graphene Flagship has acted as leverage in setting up businesses such as start-ups and spin-offs and showed to be an authority when it comes to graphene related research worldwide."
>
> **Nordine Es-Sadki**
> Case Study on Graphene Flagship in H2020 framework

Over the past ten years, the Graphene Flagship has grown from a primarily academic project focused on a single, remarkable material to an increasingly industry-forward project focused on market applications of a whole family of two-dimensional and layered materials. In September 2022 we launched a year-long celebration of the project's results to highlight the incredible journey the Graphene Flagship has undertaken.

The Graphene Flagship was funded to ensure that Europe would maintain its lead in graphene research and innovation following the scientific breakthrough of graphene's isolation at the University of Manchester. The European Commission launched the unprecedented long-term and large-scale Flagship research initiatives to tackle major challenges in science and technology, bringing positive changes that benefit society and the economy and advance European leadership in technology and industry. A decade on, we are proud to say that the Graphene Flagship has delivered on its promise.

FROM ATOMS TO TONNES

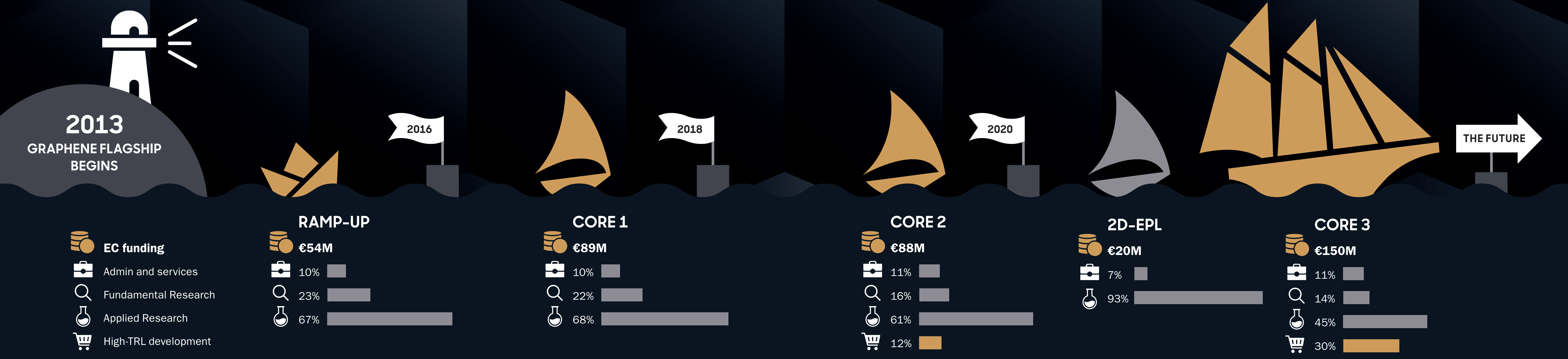
"It's amazing what we achieved in such a limited period of time with respect to what is required by technologies to develop from the lab to the factory floor," says Graphene Flagship Science and Technology Officer Andrea C. Ferrari. "Over the past ten years, we have gone from graphene flakes of the size of one micron to 300 mm wafer-scale production." Over the years we have consciously steered the Graphene Flagship towards more applied topics, and focus has moved from measuring publications to other indicators such as applied and granted patents, new companies created and products launched to the market. The launch of our 11 industry-led spearhead projects which pursue specific commercially motivated applications in areas like autonomous driving, clean water and air, more efficient batteries and new systems for aviation in 2020 was a clear milestone on our commercialisation journey. We have seen a progression toward more applied research and the development of high technology readiness level (TRL) demonstrators that are close to market. In fact, high TRL development now makes up 30 percent of the Graphene Flagship's budget, whereas these activities were non-existent before 2018.

Graphene Flagship partners have also created over a dozen new companies in areas such as photonics, medical technologies and materials production, which have jointly received tens of millions of euros of private funding. They continue to grow and evolve under commercial terms, which is yet another indicator that the Graphene Flagship is delivering what it promised – bringing graphene products out of the lab and closer to the public.

CELEBRATING TEN-FOLD IMPACT

While the success stories of the Graphene Flagship spin-off companies, SMEs, graphene producers and large industrial partners provide anecdotal evidence of the project's accomplishments (see page 58), concrete numbers also show that the Graphene Flagship has outperformed the benchmarks set by the average European-funded research project by a factor of ten. The Graphene Flagship can boast 346 patent applications with 83 patents granted as of September 2022, a volume 13 times higher per 1K€ invested than shorter research projects. Similarly, our more than 4,900 publications and 212,000 citations in academic journals are ten times higher than for a typical project.

One of the key goals for the Graphene Flagship was to create a commercial ecosystem for graphene and related materials, helping to grow the European economy through the creation of new industries and jobs. To properly assess the Graphene Flagship's economic impact, we commissioned a report from WifOR an independent economic research institute. By analysing our project outputs, growth in key European industries and the distribution of the original investment by the European Commission, WifOR was able to estimate the project's impact. Based on a total investment of €1.4 billion in European projects for graphene and related materials, the Graphene Flagship contributed a gross value added of €5.9 billion and helped to create 81,622 jobs global labour market. The Graphene Flagship has yielded an impact 14.5 times higher than the European Commission's direct investment in the project of €401 million over the past ten years. The full economic report will be released in the first half of 2023.



The Graphene Flagship has delivered on its promise, scaling up graphene production from atoms to tonnes and bringing it into the market with real products. Credit: Graphene Flagship

A PROMISE FULFILLED

"The formation of the business development function, creation of spearheads and active collaboration between work packages and external stakeholders have all had a profound effect on the results and success of the project," says Graphene Flagship Head of Innovation Kari Hjelt. Given the 106 products created, 17 spin-off companies launched and the increase of industrial partners in the project from 30% in 2013 to 47% in 2022, our commercialisation efforts are on the right track.

"We have fulfilled the vision for our initial ten years," Ferrari adds. "In particular we have firmly demonstrated that graphene is not a curiosity for the lab but is a true enabler for new technologies."

"As I reflect on the past ten years, I am very proud of the fact that we have created a community that brings academic and industrial partners together to create new technologies, or to substantially change existing technologies in fields ranging from composite materials to energy, electronics and medical technologies," says Graphene Flagship Director Jari Kinaret. "If we look back at where we were ten years ago, the evolution has been phenomenal."

SAILING TOWARD NEW HORIZONS

In October 2023, the Core 3 project will end, and the Graphene Flagship will kick off a new initiative under Horizon Europe, the European Commission's financial instrument from 2021–2027. The 2D Experimental Pilot Line project will continue to be funded through Horizon 2020 for another year. With this transition, the structure of the Graphene Flagship initiative will also change. Rather than a single project, the initiative will be organised into separately funded Research and Innovation Actions and Innovation Actions (RIA/IAs) connected by a Coordination and Support Action (CSA).

> The Graphene Flagship has yielded an impact 14.5 times higher than the European Commission's direct investment in the project"

Several key partners in the Graphene Flagship's Administrative and Services Division are now in the planning stages of what will become the Horizon Europe CSA project, ensuring continuity as it evolves and transforms. The success of this CSA is a testament to the success of the current project and its management. To date six RIAs and one IA have been selected across composites, photonics, energy and biomedical areas. Further calls will close later in 2023 and 2024, but the results of this preliminary call show that there has been enormous growth in the 2D materials (2DM) community in Europe over the last ten years. The calls had many more applicants than anticipated, highlighting the success of the Graphene Flagship in strengthening Europe's position in 2DM research and innovation and creating a strong value chain for GRM commercialisation. As the Graphene Flagship continues its voyage, it will evolve and adapt to a widening European 2DM landscape. The important work on graphene that was launched a decade ago, however, will continue to move forward creating new technologies, industries and products in its wake.

Spearheading market-ready results

The Graphene Flagship Spearhead Projects develop graphene-enabled prototypes into commercial applications.

The Graphene Flagship Spearhead Projects are industry-led initiatives aimed at increasing the technology readiness level (TRL) of graphene-based technologies. Our commitment to the Spearhead Projects is unshakeable: one third of the Graphene Flagship's current funding is invested into these ventures, a bold move to maximise the impact of the project in the innovation ecosystem and the European economy.

All these projects foster industrial and academic partnerships to bring graphene out of the lab and into real-world applications. Continuous dialogue among the Work Packages, Spearhead Projects and Partnering Division creates a collaborative environment, where nobody works in a silo. In the following pages you will learn about the prototypes being developed by each of our 11 Spearhead Projects, how their work has benefitted from a decade of Graphene Flagship research and innovation and the collaborations that have propelled these technologies closer to market.

TECHNOLOGY READINESS LEVELS EXPLAINED

TRL 1 – Basic principles observed
TRL 2 – Technology concept formulated
TRL 3 – Experimental verification of the concept
TRL 4 – Technology tested in the laboratory
TRL 5 – Technology checked in a relevant environment
TRL 6 – Technology tested in a relevant environment
TRL 7 – Test of a system prototype in real life situation
TRL 8 – System is complete and qualified
TRL 9 – System works in an operational environment

Scan the QR code to watch our Spearhead Project videos

GRAPHIL

Project Leader
Letizia Bocchi, Medica SpA, Italy
Industrial Leader
Medica SpA, Italy
Project Deputy
Manuela Melucci, National Research Council (CNR-ISOF), Italy

Showcase of prototypes at Graphene Week.
Credit: Juliane Haerendel, Graphene Flagship

GRAPHIL is aimed at developing a new generation of water filters employing a polymeric membrane enriched with graphene. The composite material obtained should enhance filters' capabilities to remove emerging chemical contaminants from water.

BUILDING ON THE PAST

Enthusiasm for graphene water filters has been sustained and grown over the past decade in large part due to the material's promising properties. The development of graphene-enabled water filters could provide greater access to safe and clean water, and these filters could come to be used in a range of different contexts.

Indeed, researchers working on GRAPHIL have already identified a wide range of purposes for which these innovative filters made of polymer-graphene composite material could be used. These include household installation for drinking water purification, such as in sinks; portable water purifiers; industrial water purification; water quality monitoring, involving the removal of specific contaminants; and refinement or enhancement of traditional water treatment.

The GRAPHIL Spearhead Project, launched in Core 3, developed a new composite material made from hollow fibre and graphene oxide. It is anticipated that this new composite will be used in the GRAPHIL products destined for market.

The work done to develop this new composite has been substantial. The production process of hollow fibre containing graphene had to be optimised and adapted to the presence of the advanced material. Once the composite was obtained, its characterisation involved many aspects. Safety of the material was proved by no release of graphene at the actual known limit of detection (0.1 ppb). Performance, meanwhile, was achieved via focus towards lead, PFAS, antibiotics and microbiological contaminants.

THIS YEAR'S PROGRESS

In 2022, the GRAPHIL team focused on the scale-up production of composite membranes and on the optimisation of the assembly process of finished, real-size products. Reaching real scale assembly capabilities has been a top priority.

As part of these efforts, samples of the composite were distributed among customers for field testing. This use of samples offered a highly effective means of gathering a wide range of data regarding how the composite membrane functions across various contexts. Results collected so far reported a satisfying removal of selected contaminants in certain concentration ranges.

Tests are extending into 2023 to increase volume and lifetime knowledge.

COLLABORATION WITH THE GRAPHENE FLAGSHIP

Being a part of the Graphene Flagship has made a significant positive impact on the work of GRAPHIL.

Medica SpA, GRAPHIL's industrial leader, only became part of the Graphene Flagship during Core 3 – however, being a part of the Graphene Flagship even for this short period of time has led to positive opportunities. For a medium-sized company like Medica, being a part of the Graphene Flagship has brought extensive collaboration and networking possibilities. It has also supported the company in its work to amplify the growth of the Medica Water Division.

More broadly, thanks to the Graphene Flagship, it was possible to reach a wide range of stakeholders relevant to GRAPHIL, as well as to garner widespread expressions of interest including from beyond Europe. The collaboration between Work Packages and partners has proven a source of great improvement and growth – and such collaboration would not have been possible without the specific structure and focus areas of the Graphene Flagship. Indeed, some of the meetings and interactions that occurred during Graphene Week, for instance, helped develop business possibilities for GRAPHIL.

At this point, it is not easy to measure direct returns in terms of business generated and potential turnover, given the extent of GRAPHIL's impact will take time to realise. This will become more obvious once GRAPHIL's products have been accepted by end-users. Nevertheless, current progress suggests a bright future for GRAPHIL.

G+BOARD

Project Leader
Brunetto Martorana, Fiat Research Centre, Italy
Industrial Leader
Fiat-Chrysler Automobiles, Italy
Project Deputy
Vincenzo Palermo, National Research Council (CNR), Italy

G+BOARD is producing an integrated copper-free automotive dashboard for vehicles, consisting of a glovebox and steering wheel. The dashboard will feature conductive patterns, sensors and devices based on multi-functional graphene or reduced graphene oxide.

BUILDING ON THE PAST

Since its inception in April 2020, the G+BOARD project has been working to replace the copper wiring and buttons currently used in car dashboards. It is forecast that this will reduce the number of production steps involved in manufacturing dashboards and decrease vehicle weight, while also improving aesthetics, quality and recyclability.

These are a steering wheel whose heating elements make use of graphene and related materials; and a dashboard drawer using graphene and related materials in sensing and wiring capabilities. The multi-functional properties of graphene and layered materials will be used to modify selectively the electrical conductivity of the dashboard polymer material. This can allow for internal signal transport and wireless conductive circuits by replacing traditional copper wiring with integrated conductive paths, as well as sensors and switches to enable better communication between the driver and the environment. Over the past few years, G+BOARD has focused on developing two automotive applications exploiting graphene's electrical properties.

Graphene and related materials could also be exploited in other automotive components such as heating elements for seats and gear knobs, and sensing and wiring capabilities for door panels, consoles and gear knobs.

G+BOARD has defined the technical requirements for these components, identifying the proper materials in accordance with their intended applications and targets. G+BOARD also formulated new polymer compounds based on graphene and layered materials and carried out testing and characterisation. Laser process optimisation, new design strategies and specifications of innovative components and activities on electronics and connections integration have all been carried out.

As a result, final prototypes are in development in collaboration with Tier 1 and Tier 2 suppliers with the aim of releasing a product customisable for specific automotive models by the end of the project.

THIS YEAR'S PROGRESS

In 2022, G+BOARD carried on with the development of new components with integrated graphene and related materials and brought these components closer to the industrial process. Small series production has been done in the Stellantis Plant, realising glovebox drawer components that will be used for the final validation phases and for the final demo production.

Stellantis Restraint Group have been involved in the preliminary industrialisation of the heated steering wheel components. In collaboration with the entire partnership, a small pre-series of these components will be produced for demo realisation. This means that in effect, the products generated by our Spearhead Project will have reached the market by the project's end in 2023. Specifically, the new technologies will be integrated into a concept car for Stellantis vehicles. The car's introduction to the market will be linked to the development timeline of a new vehicle. To reach the market, necessary customisation phases specific to target models will be required.

We have also scaled up our outreach activities. As of 2022, the G+BOARD consortium has already presented the preliminary results and project targets at 11 conferences, generating high interest from industrial entities.

A preliminary draft of our patent is also under evaluation.

COLLABORATION WITH THE GRAPHENE FLAGSHIP

Being a part of the Graphene Flagship has been key to G+BOARD's success. Indeed, collaborating with other Core 3 partners and Work Packages has made our work easier and quicker to execute.

As examples, the Graphene Flagship enabled us to collaborate with various Work Packages on the process adopted to produce to produce graphene and related materials, polypropylene and composites composed of these materials and to characterise them.

The consortium's network and its connections with the industrial value chain also promises to accelerate the speed with which G+BOARD products reach the market. In short, participation and collaboration with the Graphene Flagship improved the scientific general knowledge on graphene and related materials in our project and increased our network of contacts at academic and industrial levels, facilitating the setup of new collaborations.

Circuit-Breakers

Project Leader
Anna Andersson, ABB, Sweden
Industrial Leader
ABB, Sweden
Project Deputy
Francesco Bertocchi, Nanesa, Italy

CircuitBreakers aims to demonstrate a first-of-its-kind, maintenance-free low-voltage air circuit-breakers (LVCB) by replacing grease lubrication in the drive mechanism with self-lubricating metal–graphene (Me-GRM) composites, either in the form of coatings or as sintered parts.

BUILDING ON THE PAST

LVCBs are common protection devices in the electric grid. The mechanism that drives the breaker open/close operation within the grid is grease lubricated; however, aging of the grease is known to cause failures. Consequently, LVCBs require costly time-based maintenance and regreasing breaks.

Since its launch in 2020, CircuitBreakers has aimed to optimise Me-GRM materials with high solid lubricating properties, develop a large-volume manufacturing process and demonstrate complete LVCB prototypes according to standard requirements.

Researchers involved in CircuitBreakers have developed a self-lubricating multilayer Me-GRM composite coating technology on a pre-industrial scale, as well as a cost-efficient electrodeposition process. Nanesa led on this work, with support from ABB, FORTH, the University of Manchester and other partners.

This coating technology can be applied to selected wear parts in the breaker's mechanical drive system, thus eliminating the need for problematic grease lubrication. The developed solution has been validated in the lab, as well as in a first component functionality demonstrator test. A second demonstrator test for another component functionality is currently ongoing, as is a revision of the business plan and supply-chain analysis. A full prototype test on the product-level, meanwhile, is planned for April 2023.

THIS YEAR'S PROGRESS

In 2022, CircuitBreakers researchers have successfully accomplished upscaling of the multilayer Me-GRM coating solution meeting specified targets for adhesion, friction, wear and corrosion, at a pre-industrial scale. The first component demonstrator has been completed and the coating solution has been validated. Additionally, three patent applications have been submitted by Nanesa and ABB.

Self-lubricating Me-GRM coatings have successfully been produced and validated in a lab environment at technology readiness level (TRL) 4, as well as in product-like settings such as demonstrator tests and environmental trials (TRL 5).

Upscaling of the process technology – on which Nanesa is collaborating with industrial-scale electroplater LEM Industry – is also progressing well.

These results are especially exciting given the range of applications that could come of the CircuitBreakers project. The main application is the drive mechanism in LVCBs, but the technology can be considered for sliding electric contact applications owing to good electrical and corrosion properties, in addition to good wear and friction behaviour.

COLLABORATION WITH THE GRAPHENE FLAGSHIP

Most of the activity and the innovative ideas developed as part of the CircuitBreakers project have been elaborated during previous phases of the Graphene Flagship.

During Core 2, ABB and Nanesa formed a strong collaboration, exploring possibilities with new graphene-based electroplating-technology, wherein they evaluated multifunctional Me-GRM composite coating concepts and their usefulness for different applications and properties – including electrical, thermal, abrasion resistance, corrosion resistance, ageing resistance and solid lubrication. The research centres involved – University of Manchester, FORTH, CNR, Chalmers University of Technology and University of Rome Tor Vergata – supported this phase with characterisations and optimisation. Nanesa also involved LEM to facilitate the scale-up process from lab to industrial production. The role of the Graphene Flagship has been crucial for the birth and the growth of this business opportunity.

During Core 3, ABB also introduced the start-up Graphmatech to the project, to aid in the development of sintered self-lubricating Me-GRM composites for the breaker-application. ABB and Graphmatech had previously collaborated on similar topics with funding via Swedish SIO Graphene, and here within the Circuitbreakers project – and with support from the Graphene Flagship – the collaboration has continued to explore alternatives to electroplating to offer self-lubricating Me-GRM concepts to eliminate grease in a wider product range (higher loads). Graphmatech is presently collaborating with the Swedish university Högskolan Väst on a plasma-spray coating concept for this purpose.

METROGRAPH

Project Leader
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METROGRAPH advanced technologies will contribute to the improvement of internet networks, as well as make them more sustainable. Thanks to graphene-enabled optical and wide-bandwidth communications, people will have better access to information for education, work, healthcare and more.

METROGRAPH's optical transceivers with graphene-based photonic integrated circuits will operate in metros, as well as in longer reach long-haul segments. Matrices of high-quality and high-mobility graphene single crystals are transferred onto silicon wafers to achieve high-performance modulators and photodetectors with a base modulation rate of 64 Gbaud (a unit of measurement for speed communication). These innovative circuits and the established platform of silicon photonics ensure maximum efficiency, low power consumption, low cost and small footprint.

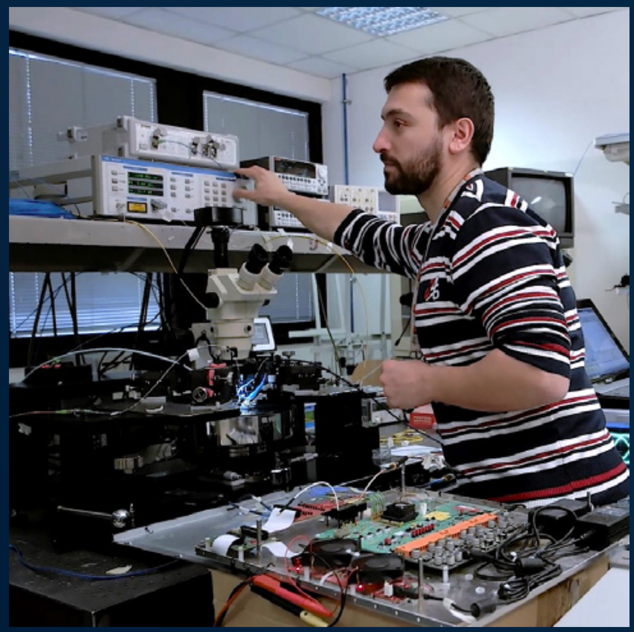
THIS YEAR'S PROGRESS

The METROGRAPH team has achieved outstanding results in electro-absorption modulators with bandwidths exceeding 30 GHz. Optical data streams were detected with two different modulation schemes (NRZ and PAM-4) and reached 105 Gbit/s in the NRZ scheme and 120 Gbit/s in the PAM-4: state-of-the-art detection results for graphene photodetectors. PAM-4 can potentially double the bandwidth of a connection compared to usual mechanism used in serial communications (NRZ).

Furthermore, the design of customised electrical integrated circuits for graphene photonics chips brought the project forward.

COLLABORATIONS

METROGRAPH builds upon the achievements of Graphene Flagship Work Packages for Photonics and Optoelectronics and Wafer-scale System Integration. The collaboration with Photonics and Optoelectronics facilitated the demonstration of fast and efficient modulators and detectors. The project requires complex photonic circuits with several graphene devices that must work with the same performance to obtain more advanced functions. These include complex modulation, coherent mixing and bitrate.



Top
Researcher at CNIT while testing METROGRAPH photonic chips.
Credit: CNIT

Bottom
Test bench at CNIT's labs for graphene modulators.
Credit: CNIT

WHAT'S IN STORE

The target technology readiness level for the project is 5–6. Future commercialisation of this technology may be the result of the achievements of the collaborative work with Work Packages for Photonics and Optoelectronics, Wafer-scale System Integration and the new 2D-Experimental Pilot Line. The plan is to demonstrate a METROGRAPH prototype in 2023 followed by integration within a network line card. In a successive phase, METROGRAPH plans to start to assess the reliability of several modules.

GRAPES

Project Leader
Marina Foti, 3SUN, Italy
Industrial Leader
3SUN, Italy
Project Deputy
Antonio Agresti, University of Rome Tor Vergata, Italy

Silicon solar cells (SiSCs) are gradually reaching their theoretical upper power conversion efficiency (PCE) limit. At the same time, perovskite (PSK) solar cells have emerged for low-cost (<0.28 €/W) and high-efficiency (>25%) photovoltaics. The GRAPES Spearhead Project aims to combine these two technologies for the design, fabrication and characterisation of graphene and related materials-based perovskite/silicon tandem solar cells.

By exploiting 2D materials, the GRAPES team aims to boost the performance and stability of perovskite cells to a new record level and fabricate cost-effective, stable photovoltaic panels based on GRM-PSK/Si tandem technology.

BUILDING ON THE PAST

GRAPES project, a continuation of the Core 2 SolarFarm Spearhead Project, has the potential to reshape the energy sector. Primary applications of GRAPES technology involve the installation of efficient and cheap terrestrial PV plants as well as, in the near future, the possibility of exploring the proposed technology for space applications in satellites.

The past few years have been busy for GRAPES. We have long been working on developing large area perovskite devices fitting the standard silicon wafer dimensions. During Core 3, we demonstrated the use of interface engineering based on 2D materials as an efficient tool for trap passivation and energy level alignment in perovskite devices by mitigating the performance losses induced by the scaling-up process.

During this phase of the project, we also developed an efficient perovskite top cell (realised separately from the commercial Si device), optimised to work in synergy with the Si wafer-sized cell. This demonstrated the integration of graphene and 2D materials as a pivotal step for driving semi-transparent perovskite solar cell efficiency; stabilising its performance in outdoor working conditions; and scaling up the production process from lab-prototypes (2.5x2.5 cm^2) to large area dimension devices (15.6x15.6 cm^2, M2 wafer size) compatible with the machines composing the 3SUN production line. All the production processes for the perovskite solar cells have been demonstrated to be scalable and fully embeddable in a pilot line production process. Moreover, we already demonstrated state-of-the-art power conversion efficiency (>29%) on two-terminal mechanically stacked tandem devices, employing the 2D material engineered perovskite top cell coupled with the bifacial Si industrial bottom cells, which can exploit the radiation reflected by the ground (albedo).

THIS YEAR'S PROGRESS

Over the past year, we developed an ad-hoc lamination procedure employing semi-transparent ionomer foils, compatible with the temperature and pressure constrains imposed by the perovskite technology, to fabricate > 1 m^2 perovskite/Si tandem panels employing the commercialized Si bottom cell produced in an industrially relevant environment. The 3SUN production line was dismounted in September 2022 for building the new 3-gigawatt line, which will be operative at the beginning of 2024. The new production line will embed a perovskite/silicon production pilot line and will be able to definitively demonstrate the industrialisation of this technology.

By consequence, products developed by the GRAPES project are drawing increasingly close to the market. These innovative devices will be realised in an industry-relevant environment (pilot line, MRL ≥ 6) and the panels fabricated with these tandem solar cells, will be tested by using accelerated lifetime tests and under real outdoor conditions (MRL ≥ 6), while reducing the Levelized Cost of Energy (LCOE) below 20 €/MWh.

Companies involved in the GRAPES project for the development of the perovskite/Si tandem panel production lines are 3SUN (formerly Enel Green Power prior to June 2022) and Greatcell Solar, while SIEMENS is in charge for developing micro-inverters for the installation of the final tandem panel in a solar farm located at the Hellenic Mediterranean University in Heraklion (Crete, Greece).

COLLABORATION WITH THE GRAPHENE FLAGSHIP

Collaborations among various Graphene Flagship partners have been pivotal to the success of the GRAPES project.

The low-cost and high-throughput production of the 2D materials (performed by BeDimensional, a Graphene Flagship spin-off), combined with the use of cheap printing techniques for perovskite technology – together with the development of dedicated equipment by several companies involved in the Graphene Flagship (Greatcell Solar, SIEMENS) or external (Cicci Research) – allowed the GRAPES project to put forward a new generation technology able to exceed commercialised ones in terms of performance and advantageous production costs.

More broadly, the Graphene Flagship brought together a wide range of academic and industrial partners for future collaborations in several research fields.

AEROGrAFT

Project Leader
Philip Herberger, Lufthansa Technik, Germany
Industrial Leader
Lufthansa Technik, Germany
Project Deputy
Rainier Adelung, Christian-Albrechts
University of Kiel, Germany

The AEROGrAFT Spearhead Project aims to build a sustainable, innovative air filtration system for passenger aircraft. Our team is developing a filtration system made of lightweight filter materials based on graphene foams, which possess unique mechanical and electrical characteristics. By using graphene, we can turn conventional filters into an active system, providing new functionalities such as monitoring of environmental conditions, sterilisation of pathogens and self-cleaning, in addition to the effective passive removal of contaminants.

BUILDING ON THE PAST

Conventional air filtration systems are based on fibrous mats and rely on the passive removal of air contaminants (such as viruses, bacteria and dust) from the air stream passing through them. Therefore, they need to be replaced regularly.

Over the past ten years, the Graphene Flagship has worked to investigate how graphene might play a role in improving air filtration systems. Launched in 2020, AEROGrAFT aims to provide air filters with smart operating functions for an enhanced cabin air quality.

Over the past few years, our partners have worked to upscale underlying processes to large-scale aerographene foams. While at the beginning of Core 3 only lab-scale aerographene foams of around 1 cm^3 were available, the consortium has developed new processes, meaning we can now produce aerographene foams several cm3 in size and in various geometries, while simultaneously decreasing time and energy consumption.

In terms of potential applications, we developed a system to replace conventional HEPA filters in aircraft with the new AEROGrAFT air filtration system. It is striking to consider how much research and development has occurred within our project for us to reach this point. We began with development of laboratory-scale material samples over functional templates and a first functional small-scale demonstrator – and now, our project's underlying technology has been published in one of the top-ranked journals in the field of materials science, and our European patent is currently being transferred to the international level.

Beyond aviation, these filters can also be employed in other sectors, such as automotive and transportation. They can also ensure sterile working conditions in pharmaceutical production.

Our work has delivered exciting results beyond our Spearhead Project, in the automotive sector.

THIS YEAR'S PROGRESS

AEROGrAFT has seen several major accomplishments this year. These include the design and fabrication of a small-scale filter system demonstrator; the design of a large-scale system test facility based on a real aircraft system environment; and the successful aerographene material qualification according to RTCA/DO-160G requirements.

As a result of these achievements and others, our products are now moving closer to the market. A large-scale functional demonstrator, including ~7500 cm^3 of aerographene, will be constructed and will be one of the largest, if not the largest, active and functional graphene foam-based devices in Europe. Our demonstrator will be tested within a real aircraft system environment. To do this, a specific test stand has been designed and is currently about to be constructed based on a 20 m Airbus A320 aircraft segment. Extensive system performance and certification tests are providing a base for future product development, and we aim to reach technology readiness level 6 during our project's remaining time.

COLLABORATION WITH THE GRAPHENE FLAGSHIP

Collaborating with the Graphene Flagship has proven fruitful right from the start. Already in the ramp-up phase of the project, the Aerographite material was evaluated as suitable for aviation technology. It was further developed into different variants at Christian-Albrechts University of Kiel, involving different nanomaterials.

Close collaboration between Graphene Flagship Partners Kiel University and Technical University of Dresden began during Core 1. Together, the partners developed an innovative and up-scalable method for the fabrication of extremely porous and lightweight aerographene, characterised by a unique set of thermal, electrical and mechanical properties. , Both partners started to identify possible use cases for aerographene in the scope of Core 2 – including air filtration.

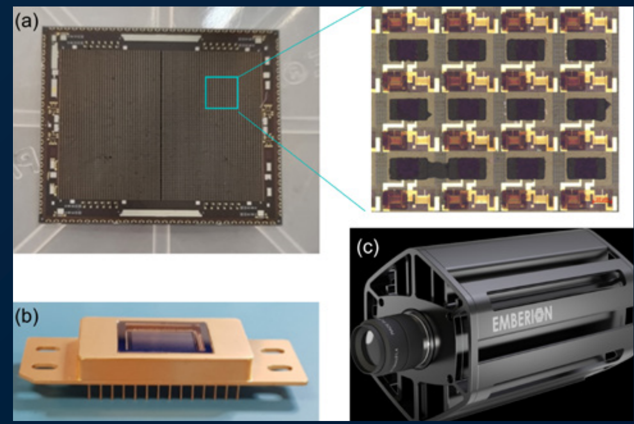
With Lufthansa Technik AG as an industrial end user – and together with spin-offs Sixonia Tech and PhiStone– these fundamental findings are currently being transferred into an innovative and active air filtration system.

The extensive Graphene Flagship network has led to the development of other aeromaterials – such as ones based on 2D hexagonal boron nitride and MXenes – in collaboration with Graphene Flagship partners from The University of Cambridge, UK and Trinity College Dublin, Ireland, with applications in energy efficient lighting and energy storage.

For us it is a fact that without the funding, support and collaborative environment of the Graphene Flagship, we would certainly not have been able to make such significant progress in our research.

GBIRCAM

Project Leader
Tapani Ryhänen, Emberion, Finland
Industrial Leader
Emberion, Finland
Project Deputy
Aapo Vartula, VTT, Finland



(a) Image sensor integrated circuit with a focal plane array of 80x60 superpixels. (b) Packaged image sensor. (c) Camera prototype using an 80x60 superpixel image sensor. Credit: Tapani Ryhänen

The Graphene Broadband Infrared Imager for Camera Systems (GBIRCAM) Spearhead Project revolves around developing an image sensor and camera system for the simultaneous detection of visible (vis), short-wave infrared (SWIR) and mid-wave infrared (MWIR) wavelengthss.

BUILDING ON THE PAST

GBIRCAM image sensor is based on colloidal quantum dots, titanium sesquioxide and pyroelectric transducers coupled to graphene transistors. The focal plane sensors are directly integrated on a complementary metal-oxide-semiconductor (CMOS)-integrated circuit chip hosting readout electronics. Meanwhile, the image sensor in a 28-pin metal package is integrated into Emberion's camera core and mechanics. A PC user interface for the camera has also been implemented.

The broadband imaging (400 nm – 5000 nm) enabled by GBIRCAM's camera has a variety of possible uses, such as plastic and textile sorting. For example, the camera possesses a superior ability to distinguish between materials, including black plastic.

The image sensor could also help with surveillance in fog and smoke conditions, as well as with monitoring applications, such as the detection of CO_2. The use of the camera's infrared imaging technologies in industrial process control and recycling, meanwhile, can enable more efficient use of resources, thereby fostering circular economies.

Initially,we focused on producing visible to SWIR industrial cameras. The novel image sensor technology under development by GBIRCAM is designed to be easily integrated into Emberion's commercially available camera platform,and will be based on an 80x60 array of "superpixels" with three wavelength components. In the commercialisation phase, we will address the pixel resolution – such as VGA resolution.

THIS YEAR'S PROGRESS

In 2022, GBIRCAM made substantial progress towards bringing its products closer to market. Two demonstrators were completed in 2022: a 10x8 superpixel (vis, SWIR, MWIR pixel) demonstrator with prototype electronics and software, and an 80x60 superpixel (vis, SWIR, MWIR pixel) demonstrator with full camera mechanics, electronics and software that will form the basis of the final project demonstrator.

We are developing high-quality graphene field-effect transistors on the fully processed CMOS wafers for the final demonstrator. We have also designed, fabricated, tested and demonstrated complete, fully-integrated demonstration cameras, including camera mechanics, camera core electronics, camera embedded SW, image sensor packaging, image sensor CMOS ROIC and processed superpixel sensors.

GBIRCAM's products are consequently closer to market than ever before, and the project's work with partner Emberion shows great promise. GBIRCAM prototypes are developed to be compatible with Emberion's camera products and use several common hardware and software components: for example, the readout integrated circuit has been designed to be directly compatible with Emberion's camera core. Commercialisation, in partnership with Emberion, looks likely to become a reality.

COLLABORATION WITH THE GRAPHENE FLAGSHIP

Concepts for photonic devices based on graphene transducers were one of the main motivations for Nokia research to become involved in the Graphene Flagship, including in its earliest stages. Nokia's initial focus was on flexible electronics, sensors, photonics and on different energy sources for mobile phone technologies. Thanks to the network created by the Graphene Flagship, Nokia was able to carry out research together with key Graphene Flagship partners such as The University of Cambridge, Aalto University, VTT and Graphenea.

In 2014, a business incubation project inside Nokia started building business concepts that led to the formation of a spin-off company: Emberion Oy, in 2016. The spin-off was created with the purpose of making photodetectors, image sensors and cameras based on graphene and nanomaterials. The company subsequently became a member of the Graphene Flagship.

Ultimately, the Graphene Flagship has created a network of collaborations without which it would not have been possible for small companies such as Emberion and Graphenea to interact with leading research teams from The University of Cambridge and VTT.

Autovision

Project Leader
Stijn Goossens, Qurv Technologies, Spain
Industrial Leader
Qurv Technologies, Spain
Project Deputy
Steven Brems, imec, Belgium

The Autovision Spearhead Project is aimed at enabling semi-autonomous cars to operate under adverse ambient conditions. It is strongly focused on scaling up the manufacturing of graphene-based infrared image sensors for advanced driver systems. This same technology could also find applications in all-weather operation of extended reality, as well as improve the capabilities of service robots by providing them with multispectral vision.

BUILDING ON THE PAST

Since its inception in April 2020, the Autovision Spearhead Project has worked to develop a wafer-scale wide spectrum image sensor process to show high volume manufacturing feasibility and a complementary metal-oxide-semiconductor (CMOS) integrated wide spectrum (Vis+SWIR) camera based on a graphene and colloidal quantum dot pixel stack. The Spearhead Project will use these technologies to benchmark SWIR imaging against other sensor technologies for computer vision under adverse weather conditions in an automotive use case scenario.

Autovision has demonstrated integration of graphene-based wide-spectrum pixels on CMOS test-chips with a low-resolution test-array. Qurv has developed the electronics for an evaluation kit based on wide-spectrum CMOS test-chips – and customers from different fields have shown great interest in acquiring the evaluation kit.

Given tooling is essential in the development of a high-volume manufacturing process, Autovision's focus has recently been on developing a semi-automated graphene delamination tool. Furthermore, a delamination of graphene to a carrier substrate has been demonstrated, thereby tackling a challenging step towards wafer-scale manufacturing feasibility.

A wafer-scale graphene back-end-of-line integration process flow has also been designed and is currently being implemented. Process development has been running in imec's 200 mm pilot line.

THIS YEAR'S PROGRESS

This year has been an exciting one for Autovision. The project has been working to solve the scale-up challenge of graphene-based electronic devices, which will allow graphene-based products to benefit from economies of scale for widespread adoption. The major milestone of 2022 was the start of wafer-scale process development in imec's 200 mm pilot foundry.

Consequently, products developed by Autovision are closer than ever to reaching the market.

Furthermore, Qurv – an ICFO spin-off launched September 2020 – developed an evaluation kit compatible with Autovision's 2D material-based pixel technology. This kit has helped to progress discussions on the relevance of the imaging technology and steer future specifications through a customer-driven process. The end goal is the acceleration of business development, increased customer engagement, and resource allocation efficiency – all of which Autovision appears on track to maximise.

COLLABORATION WITH THE GRAPHENE FLAGSHIP

The Graphene Flagship has enabled the European graphene ecosystem to exchange ideas effectively and work together on relevant challenges – and the Autovision Spearhead Project has benefited from being a part of this large and talented group. In this working group, academic and industrial researchers with a background in 2D material growth and device integration learnt together to tackle the challenges of upscaling high-quality 2D material-based electronic devices. The cross-fertilisation between the Wafer-scale System Integration Work Package, the 2D Experimental Pilot Line and Autovision has also been valuable in advancing the wafer-scale integration of graphene.

A specific example of successful collaboration between Autovision and other Graphene Flagship partners is with Graphenea. Graphenea has supplied CVD graphene to Autovision's partners, which will enable the demonstration of 200 mm back-end-of-line integration of GFETs.

Exhibiting at the Mobile World Congress Graphene Flagship pavilion, for instance, allowed ample interaction with a diverse group of stakeholders: from potential customers, to suppliers, to policy makers.

Indeed, involvement in the Graphene Flagship ultimately enabled us and all our partners to build relevant networks within the graphene community. These networks will enable future research and support future partnerships for us all.

GrEEnBAT

Project Leader
Stefan Koller, VARTA Innovation, Austria
Industrial Leader
VARTA Innovation, Austria
Project Deputy
Andrea Gamucci, BeDimensional, Italy

The GrEEnBAT Spearhead Project seeks to scale up the fabrication of innovative silicon-graphene composite electrodes for lithium-ion batteries. This project has the aim of fully developing functional battery modules for electric vehicles.

BUILDING ON THE PAST

Since the GrEEnBAT project's inception in April 2020, the team has been working to develop functional battery modules for electric vehicles – a challenging and valuable task.

Silicon works as an active material in anodes, increasing lithium-ion batteries' energy density by more than 20%; however, volume changes during charging and discharging typically lower the batteries' cyclability. For this reason, GrEEnBAT uses graphene as a mechanical and electrically conducting framework that can maintain the structural stability of the electrode, and thereby help to achieve the targeted cycle life.

As is often the case in research and development, GrEEnBAT did not develop as a straight-forward project. Over the course of the project, we had to change our initial plans for the active material or the cell format to achieve the results we ultimately attained. Thanks to these changes, however, we are now highly confident of our project's ability to deliver a technology that will change the future of mobility.

In terms of bringing this technology to market, battery life and a high number of cycles still pose key challenges to the introduction of silicon-graphene composites in lithium-ion batteries. From the beginning of the project to the end of 2022, however, we have been able to increase the cycle life of the silicon-based batteries by more than 100%, from ~300 to ~650 full cycles. Other than this, the cost target for automotive cells remains a major challenge – however, the GrEEnBAT team is confident that we can overcome this hurdle. The final cell will be a so-called A-Sample, which implies that basic parameters such as recipe, design and format will be very similar to the marketable device. In terms of technology readiness level, the final product will reach TRL6.

THIS YEAR'S PROGRESS

In 2022, several milestones were met for the GrEEnBAT project. These include the successful upscaling milestone of the silicon/graphene composite, as well as the design freeze for the automotive next-generation battery. Here, VARTA's proprietary multi-pin design for 21700 cells was selected as the cell format. This design is already well proven and used for commercial products and now serves as proof-of-concept for

Manufactured 21700 coils.

VARTA's very first high-energy automotive cell, which is based on silicon/graphene composites.

We are consequently closer than ever before to developing a new, high-energy cell in an electric vehicle that ensures a high driving range at a reasonable shelf life. GrEEnBAT technology could also be adapted to applications in consumer electronics, power tools and other wireless products.

COLLABORATION WITH THE GRAPHENE FLAGSHIP

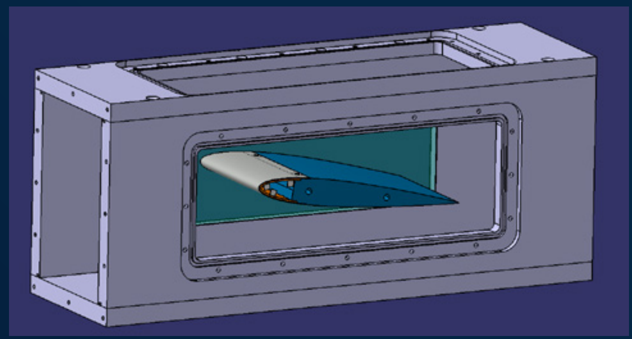
Our involvement in the Graphene Flagship has tremendously increased our scientific networking activities. Within the last ten years, we collaborated with ~50 different companies and research institutions related to the Graphene Flagship – either direct Partners, Partners from different Work Packages, or Associated Members of the project.

Collaborating with the Graphene Flagship has proven enormously beneficial for our project. GrEEnBAT is built upon results obtained during previous phases of the Graphene Flagship. Our current results would not have been possible without the Graphene Flagship and the close and open cooperation with the partners involved in previous energy storage research.

Indeed, over the past ten years, our view of graphene-related materials has evolved. While it was initially seen as a promising graphite replacement in lithium-ion batteries, it has now emerged as an exceptional conductive and structural additive that will enable the market introduction of next-generation silicon-based lithium-ion batteries. With the use of graphene, partners within the Graphene Flagship have developed and manufactured batteries that, compared to conventional lithium-ion cells, offer up to 25% higher energy density with comparable cycle lives. This result would not have been possible without the Graphene Flagship's structure and support.

GICE

Project Leader
Fabien Dezitter, Airbus Helicopters, France
Industrial Leader
Airbus Helicopters, France
Project Deputy
Guillaume Fievez, Sonaca, Belgium



A small-scale demonstrator was subjected to tests in the Airbus iCORE Icing Wind Tunnel to assess the performance of GRM technologies for de-icing applications. Credit: Airbus

The GICE Spearhead Project exists to advance graphene-based ice protection and ice sensing technologies to high technology readiness levels (TRLs). It aims to produce three demonstrators for specific applications, tailored to the needs of GICE's industrial partners: primarily Airbus and Sonaca. These demos are a slat for large aircraft, a rotor blade for helicopters and an air inlet.

BUILDING ON THE PAST

The decade of work on graphene and related materials in the Graphene Flagship has enabled us to develop technologies that could have a marked impact on aircraft safety and air travel. Ice accumulation on wings, propellers and other aircraft surfaces can be extremely dangerous, and graphene-based de-icing systems can offer an alternative low-weight, efficient and versatile solution.

An exciting by-product of our work is the potential our research has for making air travel more sustainable and environmentally friendly. Lowering power consumption and greenhouse gas emissions are essential aspects of the GICE project, launched in April 2020 to capitalise on research and innovation work in these areas. Our graphene-based technology, together with an optimised architecture for ice protection systems, is expected to contribute to reducing weight and power consumption by 30–40% in helicopters. For large aircraft, integrating ice protection onto the wings will enable better natural laminar flow or hybrid laminar flow, which will also decrease power and fuel consumption.

During Core 3 specifically, GICE reached TRL 3 with feasibility demonstrations of technology bricks – namely, heater mat and ice sensor technologies. We are getting much closer to being able to integrate graphene-based technologies in full scale demonstrators. Moreover, we anticipate being able to produce market-ready technologies two to five years from now, following necessary validation in relevant environments.

THIS YEAR'S PROGRESS

Our Spearhead Project has seen several major accomplishments this year. We have demonstrated versatility of graphene and related material (GRM)-based heater element technologies, important integral properties of electrical conductivity, thermal conductivity, heating power density and the stability of thermal and heating properties over time. These investigations confirmed the ability of GRM heater elements to adapt to resistance sheet range as specified by Airbus and Sonaca.

Specifically, GRM heater mat and ice sensor technologies were integrated in a small-scale demonstrator (NACA0012) and icing wind tunnel tests were performed within the Airbus iCORE Icing Wind Tunnel to assess the performance of GRM technologies, which allowed us to demonstrate TRL 3 maturity, or feasibility. New tests in the iCORE icing wind tunnel are planned to speed up the development of graphene-based heater mats and ice sensor solutions and their integration in aeronautic components.

COLLABORATION WITH THE GRAPHENE FLAGSHIP

The Graphene Flagship has enabled the GICE project to benefit from various excellent collaborations. During the project, we began collaborating with researchers from another Spearhead Project, SafeGraph, who are exploring the main regulatory needs of graphene-enabled technologies. During the last year of the GICE project, we have been working even more closely alongside SafeGraph to assess life cycle assessment (LCA) and the CO_2 footprint of graphene production processes and heater mat manufacturing processes.

Moving forward, our researchers will be focusing on the challenge of integrating graphene-based technologies developed as part of this project within three demonstrators for specific applications – these include the aforementioned wing leading edge for large aircraft, the rotor blade for helicopters and the air inlet. The work performed within the GICE project will pave the way for future research to further mature graphene-based technologies for ice protection applications.

SafeGraph

Project Leader
James Baker, TEMAS Solutions, Switzerland
Industrial Leader
TEMAS Solutions, Switzerland
Project Deputy
Peter Wick, EMPA, Switzerland

SafeGraph delivers a set of guidelines to support other Spearhead Projects and the Graphene Flagship to achieve essential regulatory compliance for their new products. This will accelerate the path to market, saving our partners time and money prior to commercialisation. SafeGraph applies concepts of regulatory affairs, risk assessment, (eco)toxicology, as well as physical and environmental chemistry, to assess the main regulatory needs of graphene-enabled medical devices, food contact materials, aerospace composites and wearable electronics.

THIS YEAR'S PROGRESS

SafeGraph has produced its first regulatory roadmap for complex electronic devices containing graphene and related materials (GRMs) for medical and consumer applications. This roadmap has already allowed the identification of some initial gaps in current regulations regarding graphene and related materials. This immediately led to the implementation of contingency measures to ensure our materials will safety reach the marketplace.

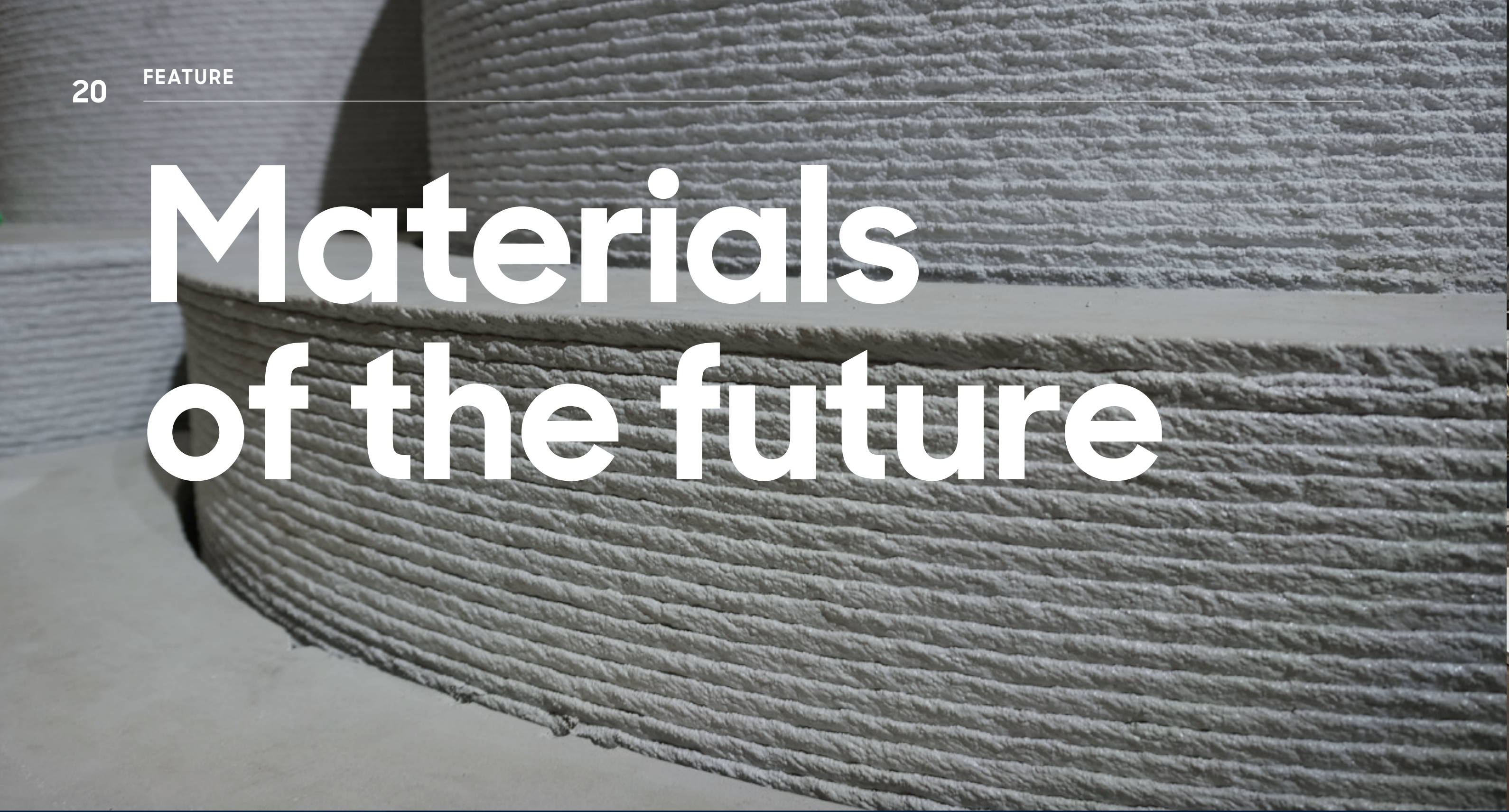
The Spearhead Project also modelled the impact of graphene and related materials at the end of their life cycle, including their release in European surface waters, natural urban soils and sludge treated soils. The model included a time interval between 2004 and 2030, a major achievement with implications far beyond this project.

SafeGraph partners will continue to develop new opportunities for graphene and related materials. For example, SafeGraph collaborated with Graphene Flagship Work Package for Health and Environment to conduct *in vitro* skin sensitisation tests of WearGraph's final products. The results obtained during these case studies will be directly applicable to other innovative graphene-enabled wearables. Where possible, SafeGraph's results will form the basis of new Horizon Europe projects, establishing a long-lasting legacy for the Graphene Flagship.

COLLABORATION WITH THE GRAPHENE FLAGSHIP

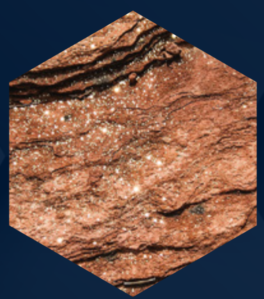
SafeGraph is a facilitator for regulatory compliance. It assists other Graphene Flagship Work Packages and Spearhead Projects, accelerating the market launch of innovative graphene-based products. In particular, SafeGraph depends on collaboration with successful Graphene Flagship Spearhead Projects from our previous funding phase, like WearGraph and Chemsens, as well as ongoing projects GRAPHIL and GICE.

Furthermore, the SafeGraph Spearhead Project established links with the Graphene Flagship Work Packages for Health and Environment, Industrialisation, and external Horizon 2020 projects, such as Sunshine and Harmless, to share information on industrial case studies and regulatory compliance.



Materials of the future

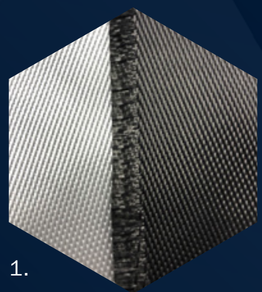
Trace amounts of graphene and other layered materials are often sufficient to enhance the properties of other materials. Graphene Flagship researchers add graphene to metals, plastics and other materials, to make them stronger, lighter, conductive and so forth. Whether embedded, layered or sprayed, graphene introduces new properties to existing products or allows the development of new ones. It also reduces the amount of material required to achieve the same performance, or to raise performance to previously unattainable levels.



GRAPHENE AND METALS – TACKLING FUTURE COPPER SHORTAGES

As the globe becomes increasingly electrified, the demand for metals, particularly copper, will grow by an order of magnitude over the next several decades. On the flip side, a shortage of 10 million tonnes of copper is projected by 2030. Graphene Flagship Associated Member GraphMaTech, Sweden, aims to reduce the need for copper, replacing a portion of it with graphene. Compared with copper alone, copper-graphene composites perform better on several metrics, including hardness, Young's modulus and tensile strength at room temperature. Furthermore, graphene fillers maintain copper's mechanical properties and reduce electromigration effects, which can cause circuits to fail or lose connection.

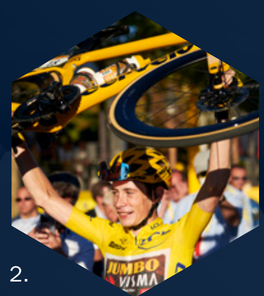
"We have developed technologies to integrate graphene in metals, with the ambition to improve metal-graphene composites. We can boost the property of metallic materials, which means that less metal is needed in certain applications. We are focusing on electrification applications and looking at using graphene-metals that are hydrogen-compatible for the hydrogen economy of the future," said Mamoun Taher, GraphMaTech AB's CEO during the "Enabling the green transition with graphene technology" webinar organised by Graphene Flagship Innovation Work Package on 27 October 2022.



1.

GRAPHENE AND GLASS FIBERS – ADDING NEW FUNCTIONALITIES

Graphene Flagship Associated Member Grafren AB, Sweden, is direct coating glass fibres with graphene flakes to improve their properties. Conventional graphene paint- or binder-based coating approaches are not applicable to glass fibres. Graphene and glass fibres must be integrated on the nanoscale level, assembling and arranging graphene flakes on the fibres' surface. "We coat the glass fibres using graphene flakes in a unique way. The resulting coating resembles a snake's skin, with a lot of flakes arranged on the fibres' surface and overlapping with each other," explains Grafren's CEO Erik Khranovskyy. The team has successfully demonstrated the fabrication of lightweight and soft e-textiles – electrically conductive fabrics – using the same approach.



2.

GRAPHENE AND RUBBER – WINNING THE GOLD MEDAL AT THE TOUR DE FRANCE 2022

Conventional rubber, whether natural or synthetic, must undergo a chemical cross-linking reaction to harden. These properties can be further enhanced during manufacture by adding compounding ingredients. Graphene oxide is one of them: it can both crosslink and reinforce rubber. It can increase rubber's ability to withstand prolonged abrasion and improve rubber's tensile and tear strength, fire retardancy and thermal resistance.

Graphene Flagship Associated Member Vittoria Spa, Italy, applied graphene to its race tyres, obtaining improved results in terms of speed and rolling performance (+5%), grip (+8%), and puncture resistance (+19%) and durability. Vittoria's second-generation graphene compound (Graphene 2.0) won numerous Grand Tour races, as well as European, French, German, Austrian, Russian, Brazilian and Pan-American Cross-Country MTB championships. In 2022 alone, Vittoria's graphene enhanced race tyres were the fastest for bikes of all types, winning races such as Le Tour de France (road), UCI World Gravel Championships, as well as UCI World Mountain Bike Championships in Cross Country, and UCI World Track Championships, showing class leading performance across diverse disciplines as well as terrain.

GRAPHENE AND CONCRETE – MORE GRAPHENE, LESS CEMENT

Graphene-enhanced concrete is 2.5 times stronger and 4 times less water permeable than standard concrete. It uses much less cement to deliver the desired strength. Since cement production is the main cause of CO_2 emissions in the construction industry, graphene-enhanced concrete is expected to reduce these emissions by 30%.

In March 2022, Graphene Flagship Partner Versarien unveiled the world's first 3D printed construction with graphene-enhanced admixture, trademarked as Cementene™. Later in 2022, Versarien collaborated with designer Steuart Padwick to use Cementene™ to create Island Steps, a 3D-printed cement-free structure, which was presented at Design London.

3.

GRAPHENE AND TEXTILES – WEAVING CONDUCTIVE YARNS

The researchers in the Graphene Flagship's Flexible Electronics Work Package are developing graphene-enriched conductive polyester (polyethylene terephthalate, PET) yarns. The team follows a collaborative approach: the Finnish Institute VTT receives graphene-based layered materials from the University of Cambridge (UK), and compounds it with PET. Afterwards, the material is spun and woven into fabric by the German company Trevira GmbH. If techno-economically successful, this material is expected to become a new type of lightweight conductive yarn.

Captions

1. Graphene coated glass fibre vs bare glass fibre. Credit: Grafren AB
2. Jonas Vingegaard wins the Tour de France 2022 riding on Vittoria spa's graphene race tyres. Credit: Vittoria Spa
3. Graphene-enriched fabric works as a pressure sensor and was applied to the shoe soles. Credit: Trevira

Learn more about graphene products
https://graphene-flagship.eu/innovation/products/

GRAPHENE FLAGSHIP ANNUAL REPORT 2022

Enabling Research

Work Package Leader
Vladimir Fal'ko, University of Manchester, UK

Work Package Deputy
Alberto Morpurgo, University of Geneva, Switzerland

Long-term funding, provided by the Graphene Flagship, has enabled us to perform agile open-ended research, addressing new needs and seizing unexpected opportunities, enabling us to achieve fast, valid, high-quality results"

Vladimir Fal'ko
Work Package Leader

Exploring new areas of graphene and related materials research

The Enabling Research Work Package has investigated physical properties of mono- and few-layer graphene, reaching the extreme limits of material purity and electronic transport performance, and exploring the influences of substrates and environments.

THE LAST 10 YEARS

The researchers in this Work Package have developed methods for the transfer of ultraclean graphene in inert atmosphere, followed by encapsulation into hexagon boron nitride (hBN), to create quantum dots and quantum wire circuits based on bilayer graphene with electrostatically controlled spatially modulated band gaps.

The team has worked on Moiré superlattice minibands, which arise when some layered materials are stacked on top of each other with a slight rotation between the layers. We have found a route towards modifying the electronic properties of graphene in highly aligned graphene-hBN heterostructures and twisted few-layer graphene structures.

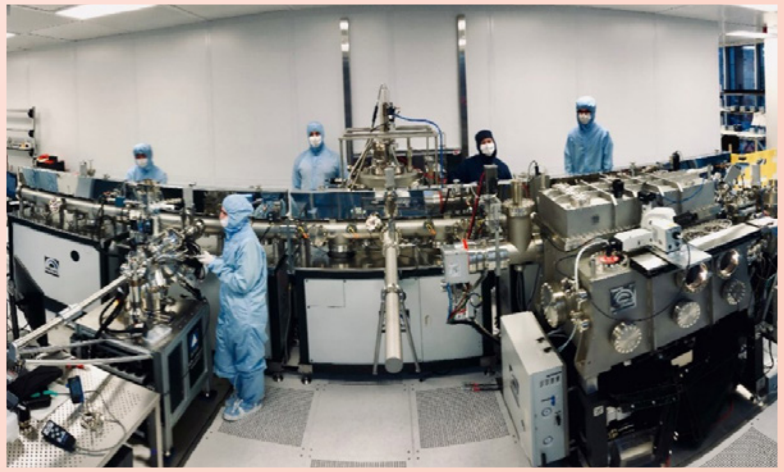
Over the years, the scope of the Enabling Research Work Package broadened onto a wide range of 2D materials: semiconductors (such as transition metal dichalcogenides, indium selenide and gallium selenide) and magnetic layered materials. We developed robotic transfer in glove-box environments and ultra-high vacuums, enabling the fabrication of atomically thin films and heterostructures. Their characterisation and multiscale modelling led to the detailed understanding of their magneto-transport, optical and optoelectronic properties. By controlling the alignment of consecutive layers in the assembled structures, we can implement new materials design, leading to the observation of Moiré superlattice minibands in such structures and the creation of ferroelectric interfaces.

THIS YEAR'S PROGRESS

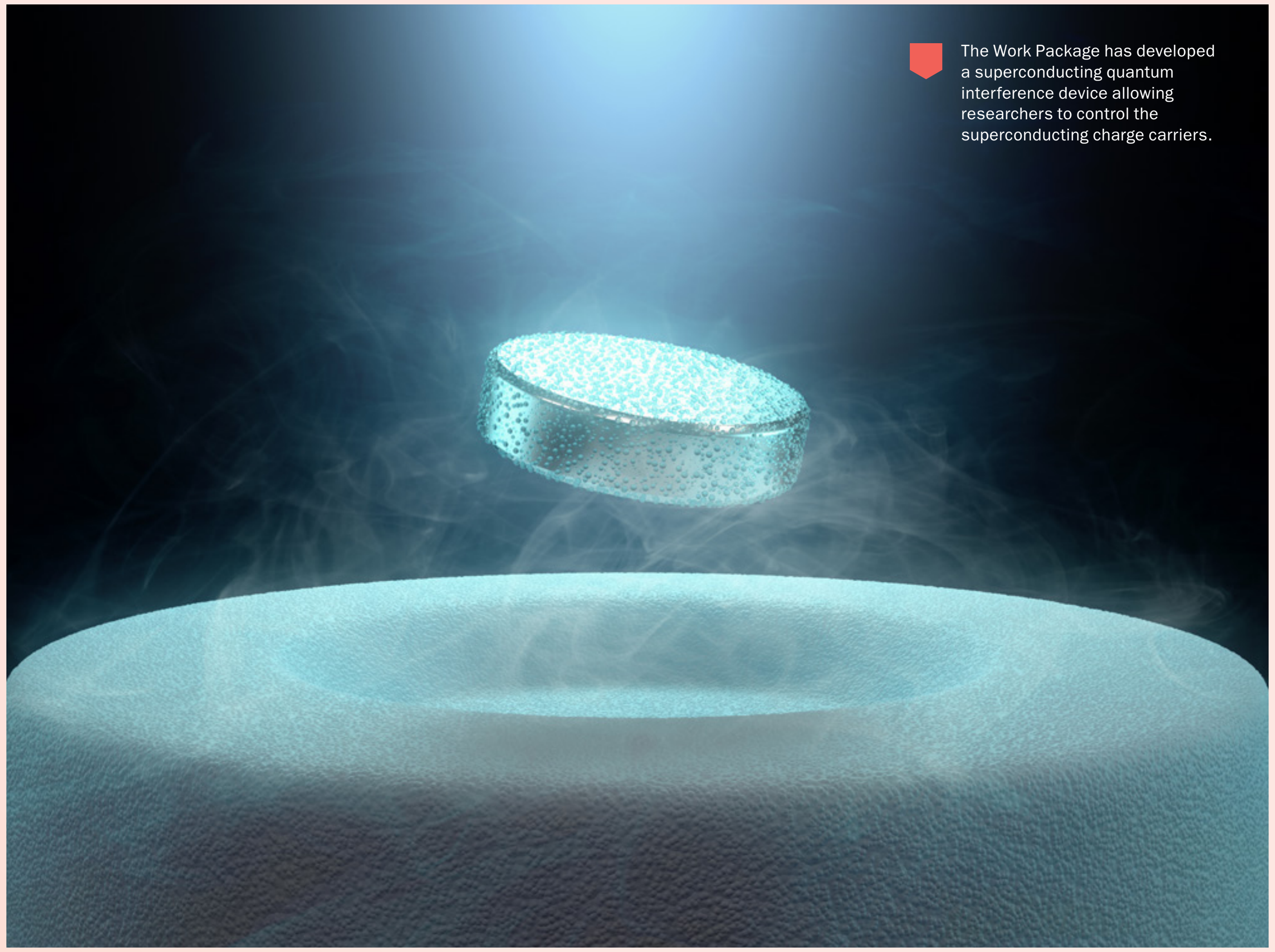
In 2022 the researchers in the Enabling Research Work Package have created a superconducting quantum interference device (SQUID) using magic-angle twisted bilayer graphene. The researchers were able to control the superconducting charge carriers in the device, measure the inductance and study the current-phase relation of one of the junctions in the device. This can lead to the development of new devices, such as phase-slip junctions and high kinetic inductance detectors.

The researchers also looked closely at the magnetism of chromic sulfide bromide (CrSBr), which could be interesting in the production of new kinds of electronic devices. They found that at low temperatures, the magnetic fluctuations of the material slowed down and the magnetic fields started to change direction in a continuous way. At around 140 K, the magnetic properties change, and the material becomes antiferromagnetic, while at about 40 K, the spin freezes. They believe that the behaviour they observed is caused by a mix of different factors, including the shape of the material and the types of atoms in it.

Finally, the Work Package has demonstrated proof-of-principle field-effect transistors made with mono- or few-layer molybdenum disulphide. The device exhibits a pronounced hysteresis, which means that it could be a promising avenue for the development of new types of electronic and optoelectronic devices with built-in memory functions.

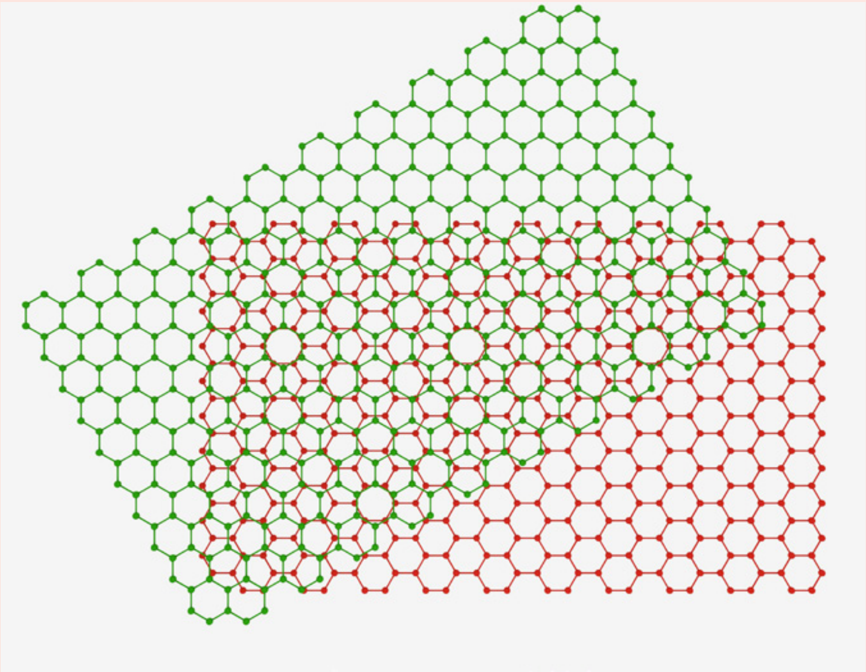


The world's first UHV 2DM press, for integrated dry transfer, characterisation and device fabrication in ultra-high vacuum. Credit: University of Manchester



The Work Package has developed a superconducting quantum interference device allowing researchers to control the superconducting charge carriers.

Moiré superlattice minibands arise when some layered materials are stacked on top of each other with a slight rotation between the layers.



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Spintronics

Work Package Leader
Stephan Roche, ICN2 and ICREA, Spain

Work Package Deputy
Kevin Garello, Commission for
Atomic and Alternative Energies (CEA), France

The Spintronics Work Package has established Europe as a global leader in spintronics based on layered materials and opened the road towards further developments for the next ten years."

Stephan Roche
Work Package Leader

Developing novel spin device paradigms

The Spintronics Work Package has achieved an unquestionable international leadership in discovering new spin transport phenomena by combining different types of layered materials into van der Waals heterostructures, fabricating some of the most complex device architectures and establishing state-of-the-art knowledge and prediction of novel spin device paradigms.

THE LAST 10 YEARS

In its initial phase, the Spintronics Work Package addressed key questions, such as the origin of spin relaxation mechanisms in graphene. Thanks to studies marrying theoretical simulations and advanced device fabrication, the Work Package investigated spin transport efficiency limitations in CVD-grown graphene materials and mitigated them to achieve the upper limit of spin diffusion length at room temperature. In its second phase, the Work Package monitored proximity effects between graphene and other two-dimensional materials, making graphene "magnetic" or spin-dependent responsive. Major scientific breakthroughs were achieved, such as room-temperature spin current generation and demonstration of electric field control. Finally, the Work Package has pushed the frontier of knowledge by integrating layered materials into advanced non-volatile memory technologies: the first demonstration of large-scale integration of graphene into a magneto-resistive random-access memory (MRAM) stack.

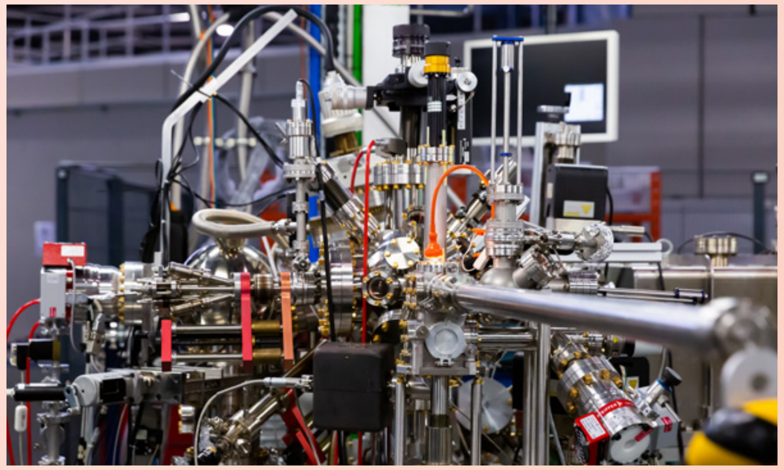
The increased relevance of our collaborations with several companies, such as Singulus Technologies and Graphenea, and reasearch institute imec, have played a key role in exploring the co-integration of layered materials with conventional magnetic materials used in commercial memory technologies. The roadmap established by this Work Package in collaboration with companies like Samsung, Global Foundries and THALES highlights the need for further efforts, funding and consolidated support to keep transferring knowledge towards real applications.

THIS YEAR'S PROGRESS

In 2022 the Spintronics Work Package developed several spintronic devices that were published in top level journals. For example, researchers worked on spin-valves that avoid conventional, air-sensitive magnetic contacts. The new device uses the spin properties of electrons in graphene to create a spin signal via the interaction of graphene with an antiferromagnetic material called chromium sulphide bromide. Using graphene for both the generation and transport of the spin signal helped to avoid a common problem in spintronics, that is "conductivity mismatch" which is a difference in electrical resistance between different parts of the device.

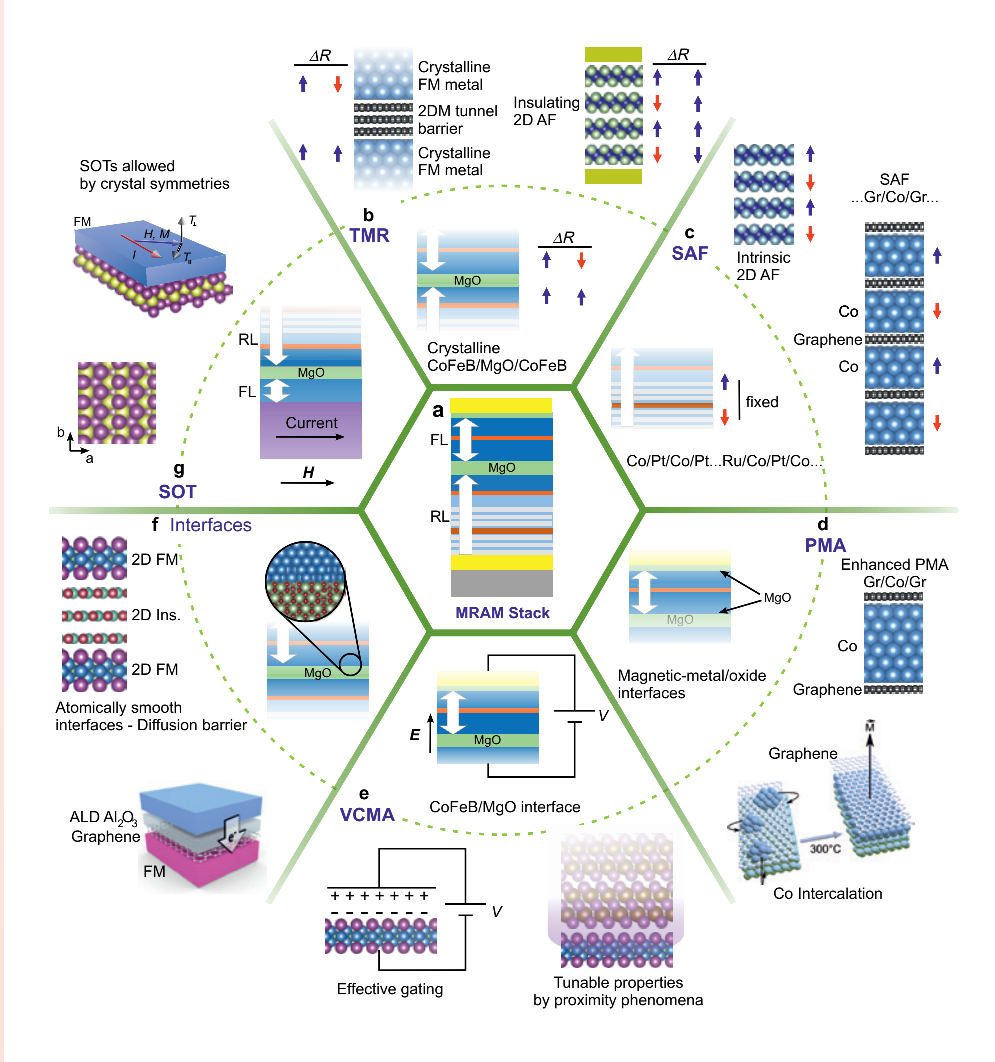
New inverted spin-valve devices made from CVD-grown bilayer graphene and hexagonal boron nitride (hBN) were also developed and performed more than twice as well as the best bilayer graphene spin valves at room temperature. It showed spin lifetimes of up to 5.8 ns, a spin diffusion length of up to 26 µm at room temperature and high charge carrier mobility.

A Perspective article in Nature was also published to highlight the prospects and challenges of non-volatile spintronic memories.

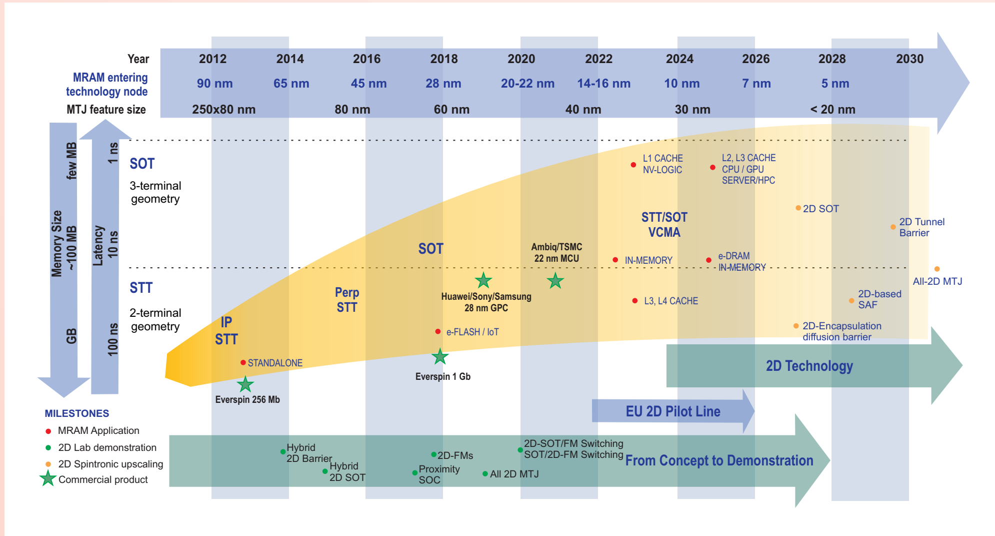


Experimental spintronics equipment at the ALBA scientific research laboratory.

Visualisation of all technical advantages of 2D materials for improving the functioning of memory building blocks. Credit: Nature



Spin torque memory technology roadmap. Credit: Nature



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GRAPHENE FLAGSHIP ANNUAL REPORT 2022

Enabling Materials

Work Package Leader
Mar García-Hernández, CSIC, Spain

Work Package Deputy
Jonathan Coleman, Trinity College Dublin, Ireland

We have formed a transversal group that has contributed enormously to the general success of the Graphene Flagship. We have provided state-of-the-art materials that other Work Packages can use."

Mar García-Hernández
Work Package Leader

Synthesising and characterising layered materials

The Enabling Materials Work Package has developed scalable synthetic routes for the synthesis and characterisation of layered materials. The team has optimised the properties of these materials to the point of matching the ones of pristine mechanical exfoliated materials.

THE LAST 10 YEARS

Ten years ago, high-quality graphene was usually isolated mainly through mechanical exfoliation of graphite, which was hard to scale up. This prompted us to develop scalable synthetic routes, including chemical vapour deposition (CVD), liquid phase exfoliation, ultra-high vacuum surface synthesis, electrochemical exfoliation, etc. We have mastered our scalable methods to produce high-quality, transferable graphene at a wafer scale, matching the properties exhibited by mechanically exfoliated materials.

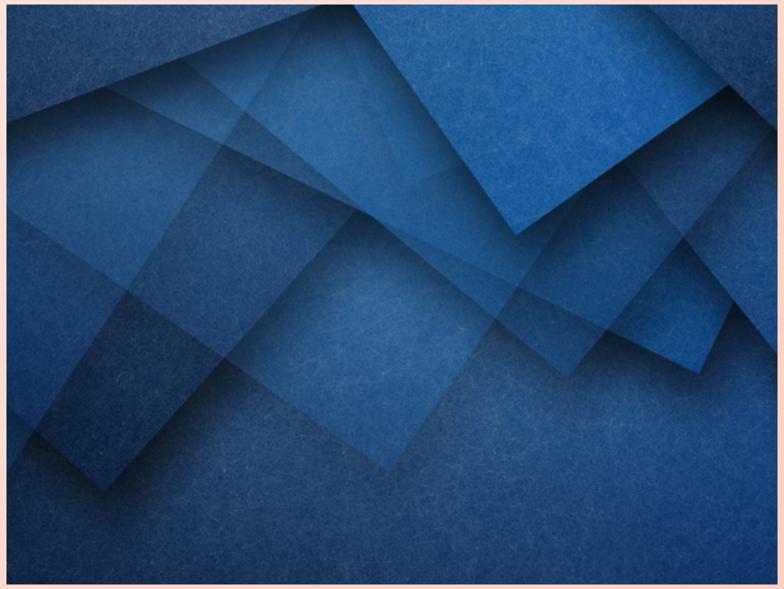
The discovery of graphene was the beginning of a new era. Thousands of exfoliable, bidimensional materials with intriguing and useful properties have been developed and used to build functional heterostructures and devices for electronics, spintronics or optoelectronics. For example, we have mastered the synthesis of hexagonal boron nitride and transition metal dichalcogenides and stacked them to create heterostructures. We are also scaling up the production of homostructures which can be twisted at predetermined angles to obtain new phenomena that are absent in a single layer. We are also optimising the growth of graphene nanoribbons with tailored geometry and the synthesis of 2D polymers and metal–organic frameworks (MOFs). Finally, we have been able to exfoliate non-layered materials using liquid-phase exfoliation and epitaxial growth of ultrathin layers.

During the last three years, the Enabling Materials Work Package has contributed to more than 70 joint publications.

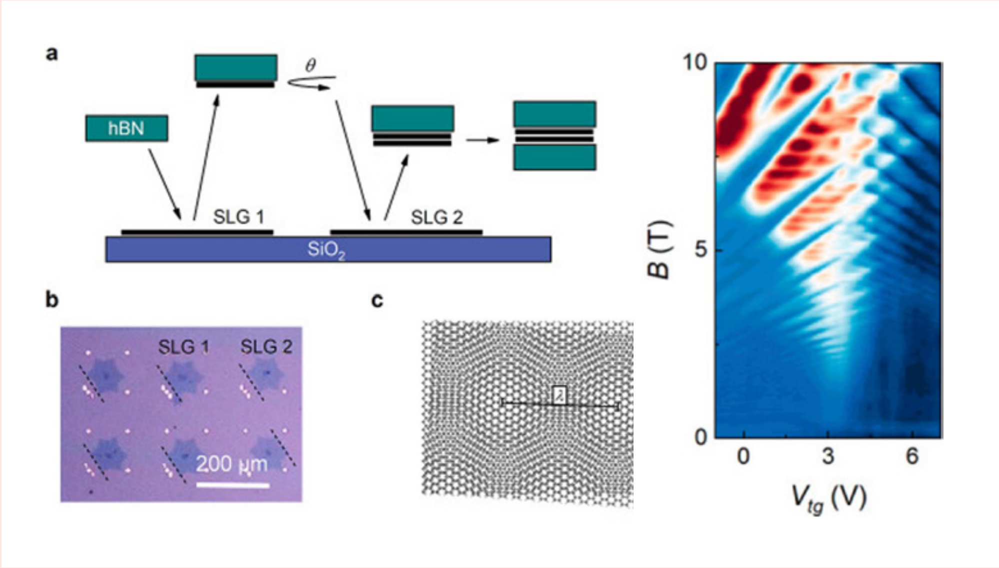
THIS YEAR'S PROGRESS

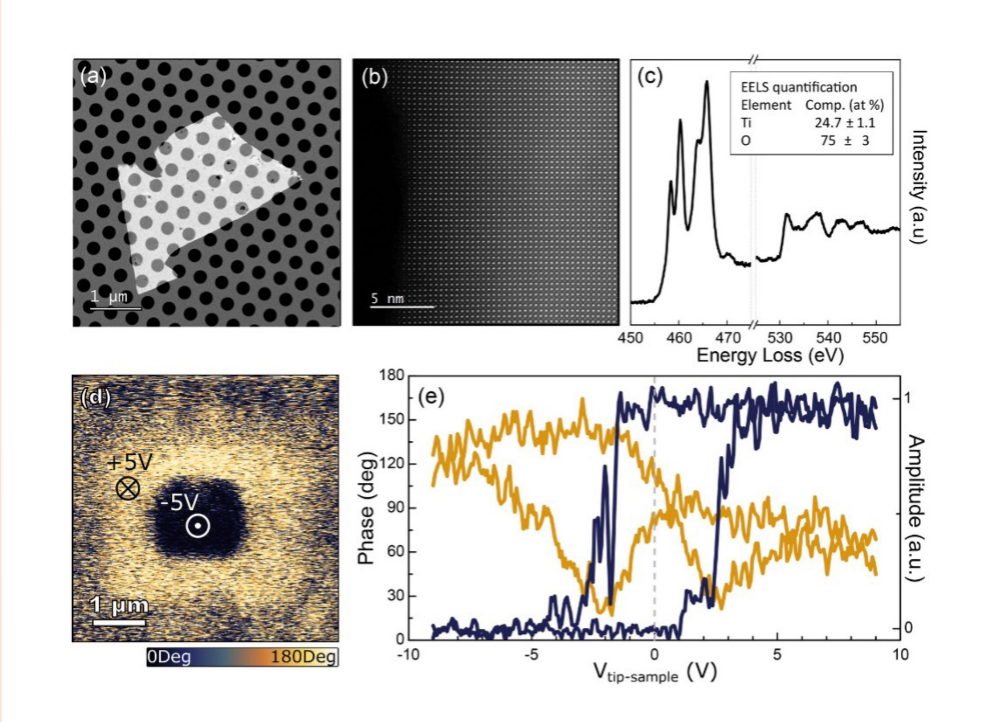
In 2022, the Enabling Materials Work Package worked on the production of twisted bilayer graphene using CVD-grown single graphene layers which were then assembled into a twisted bilayer structure. This represents a proof-of-concept demonstration for future large-scale assemblies.

Furthermore, the researchers published their results on field-effect transistors made of single-layer molybdenum disulphide and a thin dielectric layer of barium titanate (BaTiO3). The mobilities of these devices are much higher than the ones of devices made with other dielectrics, such as silicon dioxide, and comparable to hexagonal boron nitride. Thanks to the demonstrated hysteresis of the current vs gate voltage, which disappears when the device is heated above a certain temperature, these tools could be applied to future memory storage devices.



GRAPHENE FLAGSHIP ANNUAL REPORT 2022





Above
(a) Schematics of the dry pick-up process with stacking of separated CVD-grown graphene crystals. (b) Optical microscopy image of CVD SLG crystals on SiO$_2$/Si. The dashed lines indicate their crystallographic alignment. (c) The θ-rotated graphene sheets form a moiré pattern with periodicity λ. Right: Longitudinal resistance measured as a function of Vtg and B, at Vbg = −60 V (left panel, T = 2.5 K) and Vbg = +60 V (right panel, T = 4.2 K). Nano Letters 22 (13), 5252-5259, (2022)

Below
Structural, chemical, and ferroelectric characterization of freestanding BaTiO$_3$ (BTO) thin films. (a) Z-contrast scanning transmission electron microscopy (STEM) low-magnification image of a 30 nm freestanding BTO flake transferred over a holey Si$_3$N$_4$ membrane. (b) Atomic resolution image showing the atomically sharp edge of the BTO flake viewed along the [001] direction. (c) Electron energy loss spectra of the TiL2,3 and OK edges acquired over the freestanding BTO flake. (d) PFM phase image on a 40 nm thick BTO flake after ferroelectric domain engineering by pooling a box-in-box pattern with tip voltages of +5 V and −5 V. (e) Local PFM amplitude (orange) and phase (black) hysteresis curves acquired on the transferred BTO flake. Nano Letters 22 (18), 7457-7466, (2022)

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Safety by design paves the way to a sustainable project

As the drive to commercialise graphene continues, it is important to thoroughly research and understand all factors that could influence its safety. The Graphene Flagship project has a dedicated Health and Environment Work Package to study the impact of graphene and layered materials on human health, as well as their impact on the environment. Because of this, safety by design is a core part of the Graphene Flagship's innovation journey.

The most crucial factor for assessing the toxicology of a material is to fully characterise it with safety in mind. To this end, the Graphene Flagship published a detailed safety assessment of graphene and layered materials and its effects on human health and the environment. The study investigates various methods of production and characterisation and considers a number of different materials whose biological effects depend on their inherent properties.

"One of the key messages is that this family of materials has varying properties, and thus displays varying biological effects. It is important to emphasise the need not only for a systematic analysis of well-characterised graphene-based materials, but also the importance of using standardised *in vitro* or *in vivo* assays for safety assessment," explains lead author Bengt Fadeel from the Karolinska Institute, a Graphene Flagship partner in Sweden.

"This review correlates the physicochemical characteristics of graphene and layered materials to their biological effects. A classification based on the lateral dimensions, number of layers and carbon-to-oxygen ratio allows us to describe the parameters that can alter graphene's toxicology. This can orient the future development and use of these materials," explains Alberto Bianco, from Graphene Flagship partner CNRS, France, deputy leader of the Health and Environment Work Package.

> Ethics is about learning the art of questioning. Do I involve all the stakeholders? Do I take into account all of the stakeholders?"
>
> **Norberto Patrignani**
> The Graphene Flagship Ethics Advisory Board

The paper gives a comprehensive overview of all aspects of graphene's impact on health and the environment, focusing on the potential interactions of graphene-based materials with key target organs including the skin, lungs, immune system, cardiovascular system, gastrointestinal system, central nervous system and reproductive system, as well as a wide range of other organisms including bacteria, algae, plants, invertebrates and vertebrates in various ecosystems.
"One cannot draw conclusions from previous work on other carbon-based materials, such as carbon nanotubes, and extrapolate this to graphene. Graphene-based materials are less cytotoxic when compared to carbon nanotubes and graphene oxide is readily degradable by cells of the immune system," Fadeel comments.

Andrea C. Ferrari, Science and Technology Officer of the Graphene Flagship, adds that "understanding any potential health and environmental impacts of graphene and layered materials has been at the core of all Graphene Flagship activities since day one. This review provides a solid guide for the safe use of these materials, a key step towards their widespread utilisation, as laid out by our Innovation and Technology Roadmap."

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MEET OUR ETHICS ADVISORY BOARD

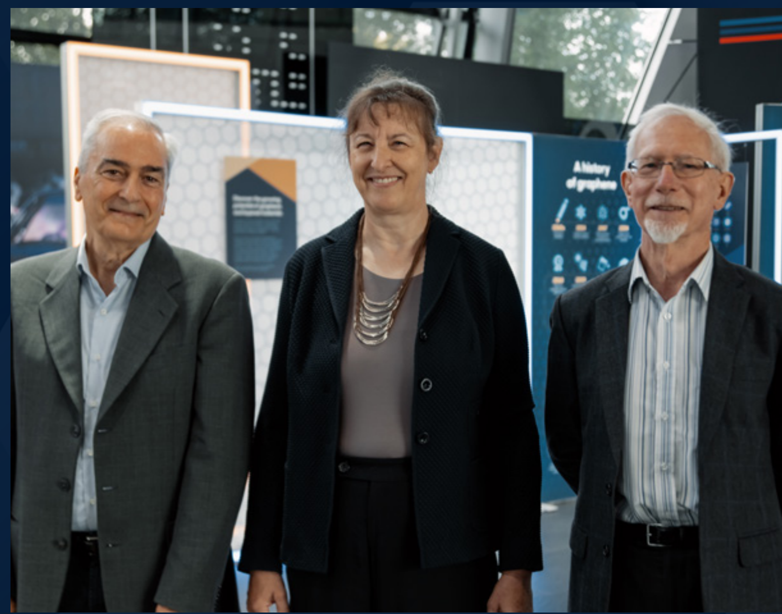
The Graphene Flagship values ethics in all aspects of the project, from research topics to societal implications. The Graphene Flagship's Ethics Advisory Board advises partners on matters relating to ethical research and innovation, sustainability and responsible by design research.

"Ethics and the responsible push to research and innovation, isn't simply a question of ticking the boxes when you fill in your grant application, or when you're submitting a paper for publication," says Advisory Board member Steven Savage a consultant for the Swedish Defence Research Agency.

"Ethics is about learning the art of questioning. Do I involve all the stakeholders? Do I take into account all of the stakeholders?" adds Norberto Patrignani Senior Associate Lecturer of "Computer Ethics" at Graduate School of Politecnico di Torino, Ethics Expert for the EU Commission and Scientific Advisor for Loccioni (Ancona, Italy).

"The EthIcs Advisory Board supports the Graphene Flagship by providing input into research activities," says Ursula Hohlneicher of AstraZeneca, Sweden. "We have reviewed the work packages that are part of the Core 3programme, and in some cases provided input to ensure that responsible research aspects were taken into account."

"We are also engaging with scientists to discuss ethical questions at conferences, and we've held the popular 'ethics gym' which is an opportunity to learn more about ethical research and how to ask the right questions," Hohlneicher adds.



The Graphene Flagship Ethics Advisory Board.
Left to right: Norberto Patrignani, Ursula Hohlneicher and Steven Savage.
Credit: Juliane Haerendel, Graphene Flagship

Health and Environment

Work Package Leader
Maurizio Prato, University of Trieste, Italy

Work Package Deputy
Alberto Bianco, CNRS Strasbourg, France

We are proud to be able to say that our Work Package has contributed enormously to reassuring the public on the safety of GRMs"

Maurizio Prato
Work Package Leader

Ensuring the safe and environmentally friendly commercialisation of graphene

The main objective of the Health and Environment Work Package is to evaluate the safety profile of graphene and related materials (GRMs) with regard to health and the environment in relation to their production, handling, manufacturing and use.

THE LAST 10 YEARS

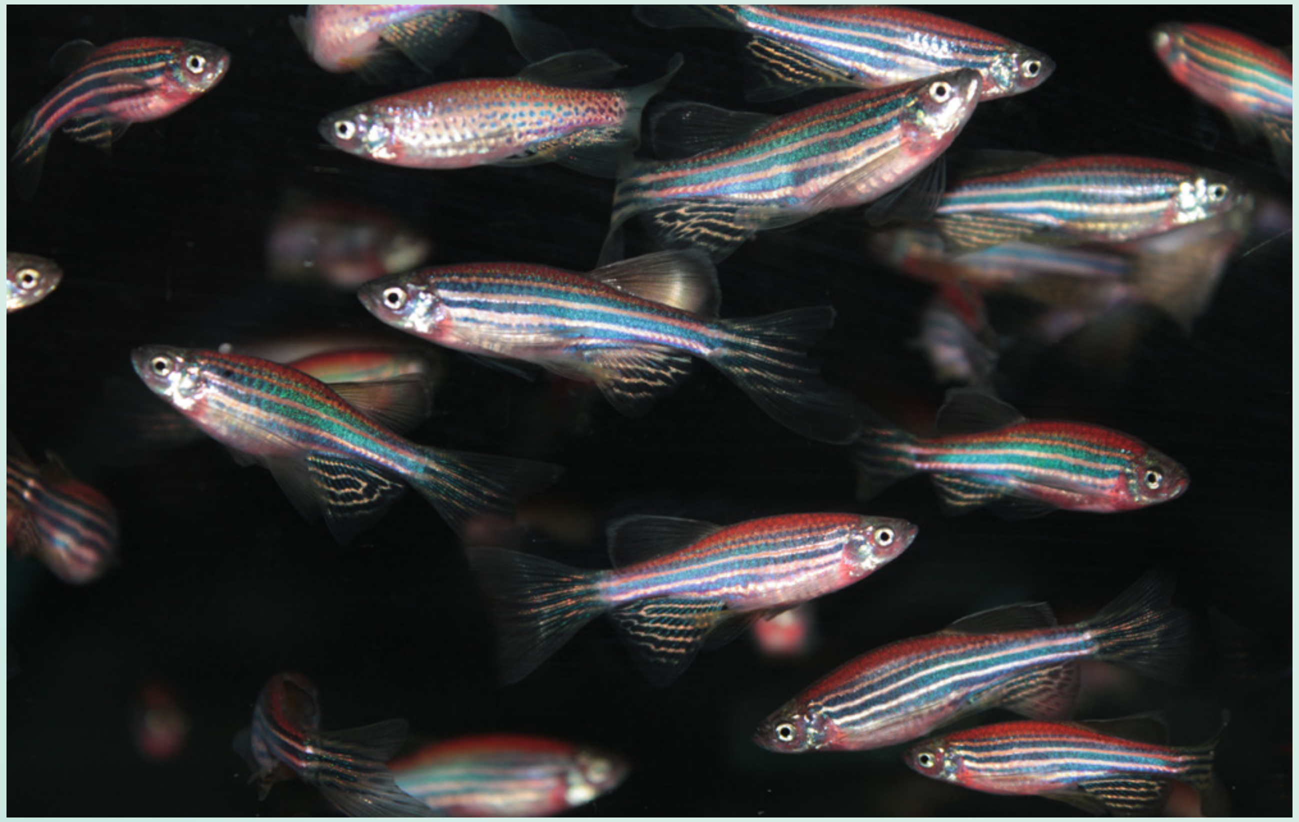
The Health and Environment Work Package has been responsible for performing a series of *in vitro* and *in vivo* studies to prove the safety of GRMs use, identify possible risks and propose solutions for avoiding these risks. During the ramp-up phase of the project, we began to evaluate the impact of graphene oxide and few-layer graphene using several *in vitro* and *in vivo* models, including lung, kidney, gastrointestinal tract, skin, immune system, brain, plants, algae, and aquatic organisms. In Core 1, we expanded the studies on the assessment of the life cycle of GRMs and their (bio)degradability. During Core 2, we enlarged the toxicity studies to other layered materials and evaluated the impact of composites containing graphene that underwent a process of degradation, mimicking their aging, to understand possible risks related to their disposal. Finally, in Core 3 we addressed the issue of occupational health and hazards to workers in daily contact with these materials. Researchers evaluated the applicability of the Organization for Economic Cooperation and Development (OECD) guidelines to GRMs in view of the European Union's Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and future commercialisation of graphene materials. We believe that this comprehensive evaluation of the impact of graphene and layered materials has been fundamental to the protection of human health and the environment as well as to the current and future commercial applications of these materials.

Our review article on health and safety of graphene-based materials (see page 28) published in 2018 and co-authored by all the partners in the Health and Environment Work Package scores in the top 1% of the academic field of Materials Science, according to the Web of Science. Other Graphene Flagship Work Packages and various companies have been interested in the results of these studies. For example, the University of Castilla-La Mancha, Spain, created with the spin-off company BioGraph Solutions in 2019 with the aim of producing graphene and 2D materials free of any type of contaminants and suitable for physiological media.

THIS YEAR'S DEVELOPMENT

This year's most important achievements were published in Nature Nanotechnology. The study shows that the gut microbiome needs to be taken into consideration when evaluating the impact of graphene and related materials, specifically graphene oxide (GO). Using zebrafish as a model, the researchers showed that GO modulates the composition of the gut microbiome. Furthermore, using germ-free zebrafish, the authors found that GO in combination with certain microbial metabolites triggered the induction of an innate immune response. This study has shown that GO can influence the crosstalk between the microbiome and immune system, thus opening a new horizon with respect to layered material-host interactions.

Additionally, a joint paper coordinated by Graphene Flagship Partner EMPA reported on the toxicological impact of reduced GO-reinforced composites.



Researchers tested the effect of graphene oxide on zebrafish gut and immune system.

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Biomedical Technologies

Work Package Leader
Kostas Kostarelos, The University of Manchester, UK and ICN2, Spain

Work Package Deputy
Serge Picaud, Sorbonne University, France

Coordinating the first-ever clinical investigation for graphene-based technologies is challenging, complex and thrilling.”

Kostas Kostarelos
Work Package Leader

Graphene biosensors for biomedical applications

The [Biomedical Technologies Work Package] innovates and pushes the technological boundaries for the engineering and biological performance of neural interface devices for the diagnostics and treatment of neuropathologies.

THE LAST 10 YEARS

The Biomedical Technologies Work Package became part of the Graphene Flagship at the start of Core 1 with 14 partners. We focused on the utilisation of different types of graphene and other layered materials in the design of devices for the management of neuropathologies. During Core 1 and Core 2, we concentrated on the development and initial preclinical proof-of-concept studies of graphene-based neural interface technologies for the central and peripheral nervous system. The goal was to identify the most promising applications to take forward in the clinical translation pipeline.

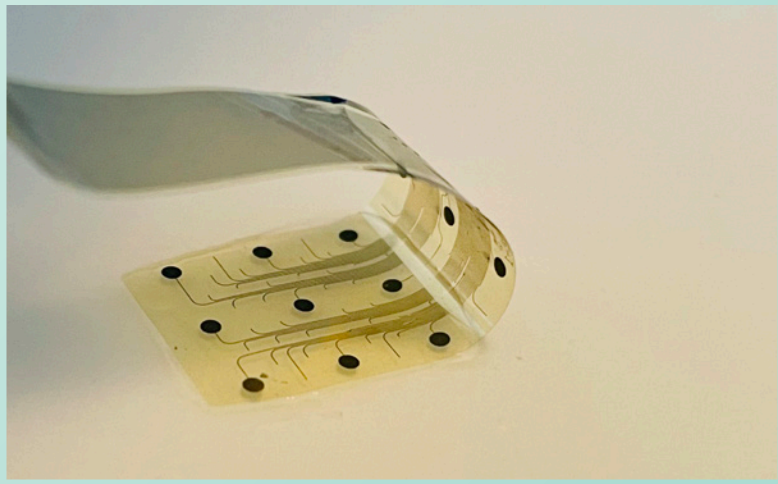
The Work Package has grown to incorporate 18 partners and, more importantly, has evolved to advance the most promising technologies to higher TRL levels. During Core 3, the role of our industrial and clinical partners has become increasingly important to ensure the translation of these technologies by industry and adoption by clinics. For example, the spin-off company [INBRAIN Neuroelectronics] was created in 2020 and raised more than €17.5M in venture capital investment to champion the clinical translation of our graphene-based technologies for the benefit of patients suffering from serious neuropathologies.

Critical research highlights include high-profile publications detailing graphene-based field-effect transistor (GFET) technologies in Nature Communications and Nature Nanotechnology. We will culminate Core 3 with a world-first: the first in-human clinical study of graphene-based electrocorticography (ECoG) microelectrode arrays in patients undergoing brain cancer resection surgery performed at NHS Royal Salford Hospital, UK.

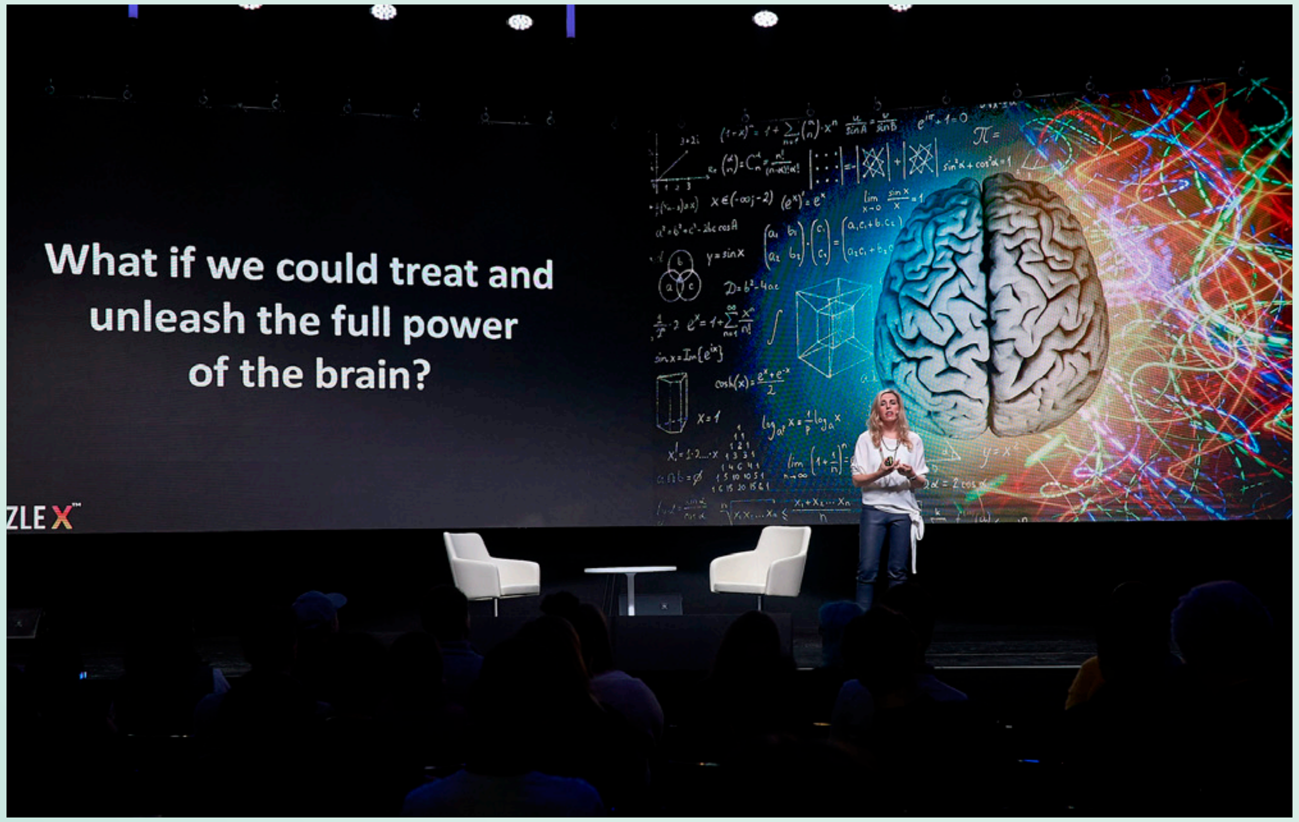
THIS YEAR'S PROGRESS

Multi Channel Systems GmbH, an industrial partner in the Biomedical Technologies Work Package, developed new tools to record brain electrical activity via GE2100 head stages. These are all-in-one solutions for amplifying, recording and analysing preclinical *in vivo* data from GFET probes with 16 or 32 channels, 24-bit resolution and 50 kHz sampling rate. The GE2100 HS16 and HS32 are currently technology readiness level (TRL) 8 and are planned to be marketed in 2023.

INBRAIN Neuroelectronics and its subsidiary INNERVIA Bioelectronics signed a strategic collaboration programme with Merck, Germany, to develop next-generation bioelectronics. G.tec medical engineering GmbH worked on a biosignal amplification and acquisition system with graphene-based electrodes, which is used to decode signals from GFETs.



INBRAIN graphene-based, high-resolution cortical brain interface. Credit: INBRAIN Neuroelectronics



INBRAIN Neuroelectronics' CEO Carolina Aguilar presents the possibilities for future brain research. Credit: INBRAIN Neuroelectronics

The INBRAIN Neuroelectronics team. This Graphene Flagship spin-off company exemplifies the project's commercialisation progress. Credit: INBRAIN Neuroelectronics

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GRAPHENE FLAGSHIP ANNUAL REPORT 2022

Sensors

Work Package Leader
Peter Steeneken, TU Delft, The Netherlands

Work Package Deputy
Sanna Arpiainen, Infineon Technologies AG, Germany

The performance of devices based on graphene and related materials is outstanding and is expected to be comparable to or even better than commercial products."

Peter Steeneken
Work Package Leader

Developing state-of-the-art graphene sensors

The Sensors Work Package has evolved significantly over the past ten years and transcended from basic graphene research in laboratories to a level where different sensors are being incorporated in a CMOS platform for demonstration.

THE LAST 10 YEARS

Starting from graphene, we have engaged with other layered materials, including transition-metal dichalcogenides (TMDs), which have promising applications in future electronics. We have used thermally assisted conversion (TAC) – a methodology that needs relatively low temperatures to produce various combinations of TMD materials and is compatible with semiconductor fabrication processes.

The Work Package has developed gas sensors that are more compact and efficient than current solutions and show high sensitivity to low quantities of gas, such as carbon dioxide. In 2018, we reported an outstanding multifunctional sensor based on platinum diselenide that can detect toxic gases, gas pressure and infrared radiation.

Amidst the COVID-19 pandemic, the Work Package redirected its research efforts to develop new biomedical sensors that utilise graphene technologies and created prototypes that can detect the virus spike protein in saliva samples with a single step, providing results in minutes.

Our graphene microphones outperformed state-of-the-art devices in high sound sensitivity. In 2022, we created graphene-enabled microphones using transferless graphene, which was directly grown on the desired substrates.

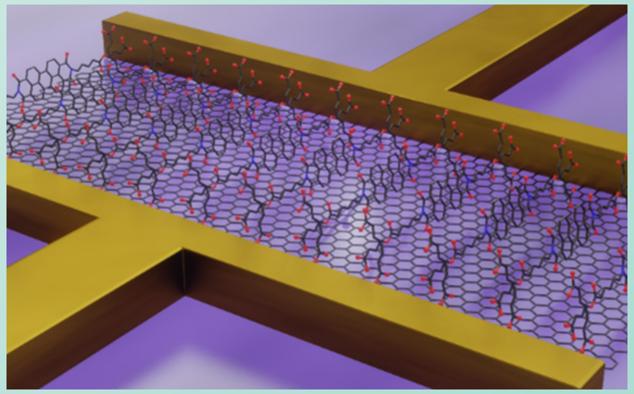
We have also worked closely with members of the 2D-Experimental Pilot Line to develop large-area integration methods, which will hopefully increase the technology readiness levels (TRLs) of our different technologies. Our focus is now concentrated on the sensors' reproducibility, uniformity, stability, yield and scalability to move these devices to higher TRLs.

THIS YEAR'S PROGRESS

The Work Package continued to make progress on pressure, air and biosensors. An extensive analysis of material and device variations was performed to improve the yield of TMD piezoresistive pressure sensors and their integration with CMOS.

The Sensors Work Package continues a strong collaboration with Infineon on graphene-enabled microphones and gas sensors. Benchmarking demonstrated that these microphones have record performance against commercial devices and literature, and wafer-scale transferless graphene membranes for microphones have been tested in industrial setups.

In the field of biosensing, the Work Package improved functionalisation methods for biosensors and developed a device that detects vitamin B12 by optical localised surface plasmon resonance. Furthermore, a new type of antibiotic susceptibility sensing method based on bacterial nanomotion was developed and led to the creation of a new TU Delft spin-off, SoundCell.



Functionalised GFET biosensor. Credit: Universität der Bundeswehr München

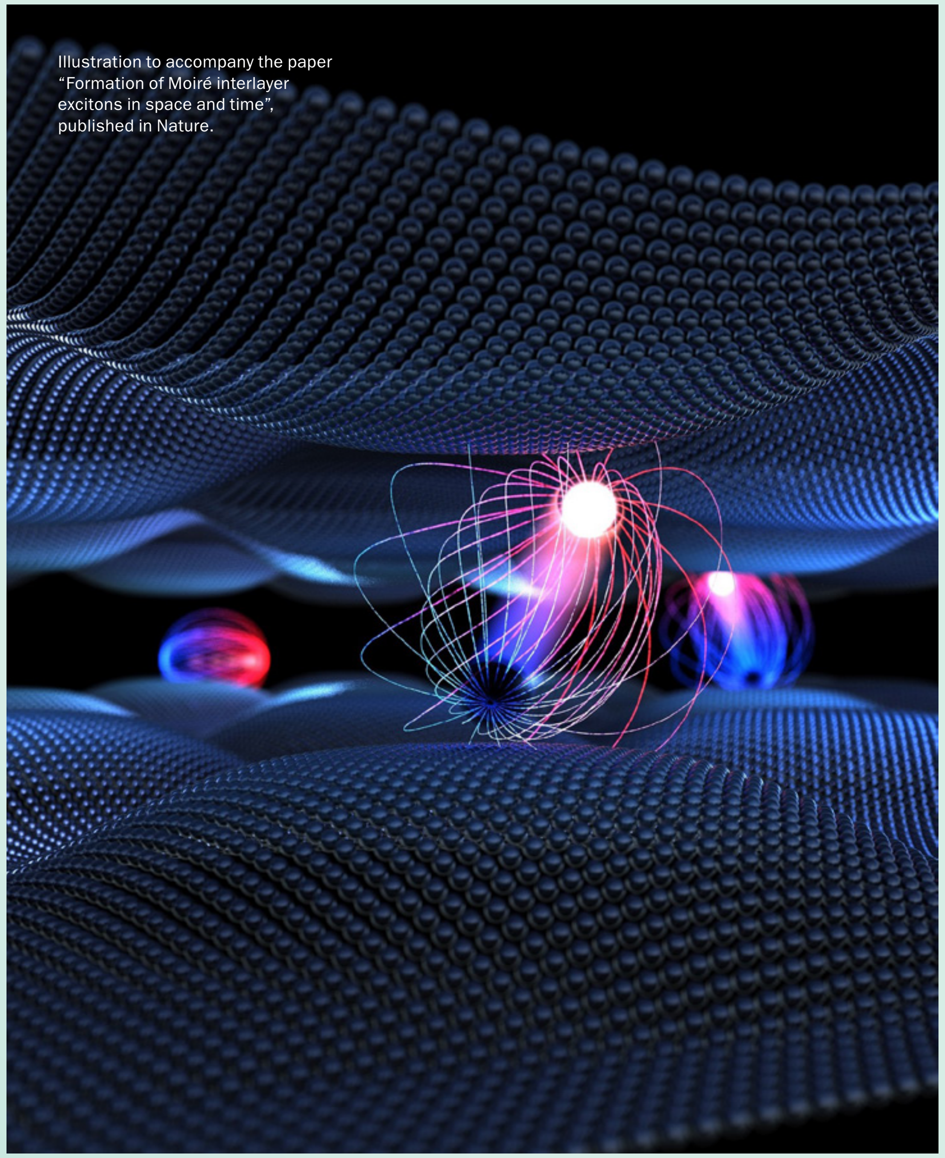
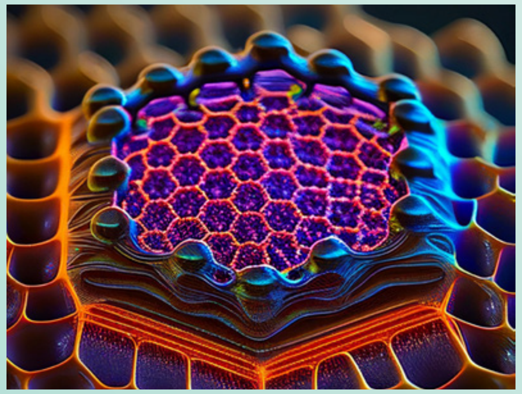
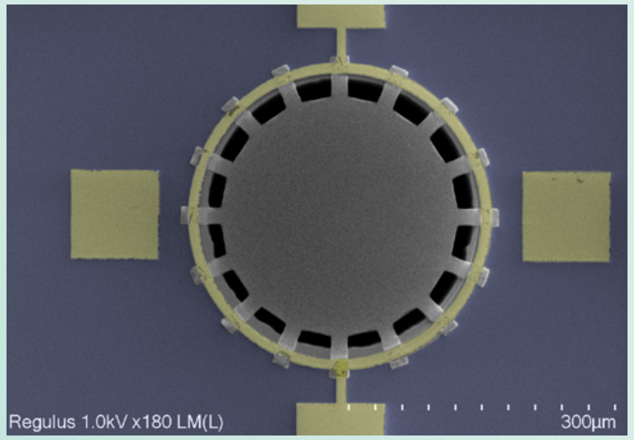


Illustration to accompany the paper "Formation of Moiré interlayer excitons in space and time", published in Nature.



Artistic impression of the surface of a graphene microphone membrane. Credit: Midjourney and Peter Steeneken



Transferless 7 nm thick multilayer graphene membranes with diameters ranging from 85–155 to 300 µm can be used to detect sound and outperform commercially available MEMS microphones. Credit: ACS Appl. Mater. Interfaces

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Rosłoń, I. E. et al. Nature Nanotechn. 2022, DOI: 10.1038/s41565-022-01111-6

Life cycle assessment of graphene and related materials

Graphene can be produced using a range of methods, but what are the most sustainable options? To answer this question, Graphene Flagship researchers published three studies related to the sustainable production of graphene related materials and their life cycle assessment – the best tool to evaluate the environmental footprint of a product or material.

> The integration of graphene-enabled products in everyday life needs to be compatible with the circular economy principles."

Cinzia Casiraghi
University of Manchester, UK

REVIEWING DIFFERENT PRODUCTION METHODS

The different production methods for graphene related materials (GRMs) can vary depending on your choice of reactants, solvents and processing parameters. For this reason, even small adjustments in the manufacturing process can decrease the environmental footprint of GRMs.

Led by Cinzia Casiraghi, researchers from Graphene Flagship Partner University of Manchester, UK, and colleagues from the University of Milano-Bicocca, Italy, found that the environmental impact of chemical oxidation/reduction and exfoliation techniques can be significantly improved through higher acid and solvent recovery rates. Chemical vapour deposition (CVD) methods can become more sustainable through higher heat transfer efficiencies and more efficient consumption of precursor gases (ideally derived from renewable feedstock, such as biomass). Finally, the environmental footprint of GRM growth on silicon – an energy-intensive process by design – benefits from the use of renewable energy sources.

"The life cycle assessment (LCA) allows us to identify opportunities for improvement along the life cycle of material production processes. For example, our analysis of GRM production shows that hotspots will vary depending on the production route, this could either be the carbon source, the energy requirements, or the choice of solvents and reagents needed," LCA expert Rosa Cuéllar-Franca from the University of Manchester explained during her webinar entitled "Life cycle environmental impacts of graphene production" organised by the Innovation Work Package on 6 October 2022.

The study also highlights the need to improve the type and quality of data associated to graphene production. It will be increasingly important to compare different production routes and applications, as graphene reaches the market.

THE BALL MILLING PROCESS

In another study, LCA experts from Graphene Flagship Partner EMPA, Switzerland, measured LCA-relevant data for the ball milling process – a method used to exfoliate graphite into few-layer graphene. They compared 38 lab-scale pathways to producing single and few layer graphene and graphene oxide. They focused on cradle-to-gate LCA, which considers the sustainability of a product from its resource extraction (cradle) to the factory gate, before it reaches the consumer.

"Our analysis shows that graphene-based materials can be environmentally beneficial in some applications, but there is a need for more accurate data on manufacturing steps to identify the most interesting options," says Didier Beloin-Saint-Pierre from EMPA.

APPLYING LCA TO THE FIRST GRAPHENE-ENABLED SOLAR FARM

The cradle-to-gate LCA and environmental profile of the first solar farm based on perovskite solar panels enabled by graphene and other layered material was evaluated by researchers from Graphene Flagship Partners Hellenic Mediterranean University, Greece, University of Rome Tor Vergata, Greatcell Solar Italia SRL, IIT, National Research Council and BeDimensional SpA, Italy.

"The team demonstrated the commercial potential of this technology in terms of both energy and environmental performance. The environmental footprint is lower than the present European electricity mix, and even better than some of the energy mix scenarios foreseen by the European energy roadmap 2050," says Emmanuel Kymakis, from the Hellenic Mediterranean University.

LOOKING AT THE FUTURE

Rosa Cuéllar-Franca points out that these efforts are only the beginning towards understanding the environmental impacts of GRM production: "The major challenge is the lack of data on the commercial production of GRMs to conduct representative LCA studies, which is not surprising considering the cutting-edge nature and competitiveness of the field. LCA studies requires highly sensitive information that companies might not be willing to share openly."

> It is very important to discuss sustainable development of advanced materials at the early stages of their commercial exploitation."

Cinzia Casiraghi
University of Manchester, UK

Furthermore, most LCA studies on GRMs are from cradle-to-gate rather than cradle-to-grave, which excludes the application and end-of-life stages. It is recommended that future studies consider the full life cycle of these materials, especially their application and functionality aspects, as this will allow us to properly understand their actual benefits. "For example, the relatively high environmental impacts of producing a material could be compensated by an extended service life of an enhanced product with such material," explains Cuéllar-Franca.

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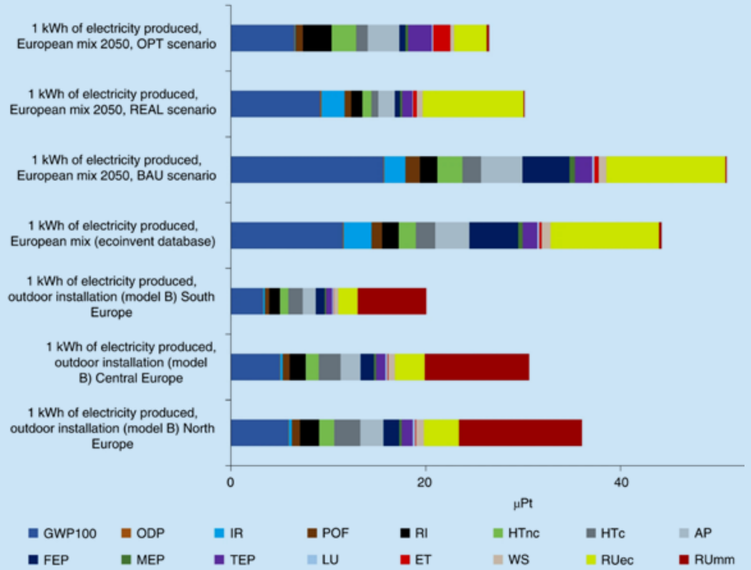
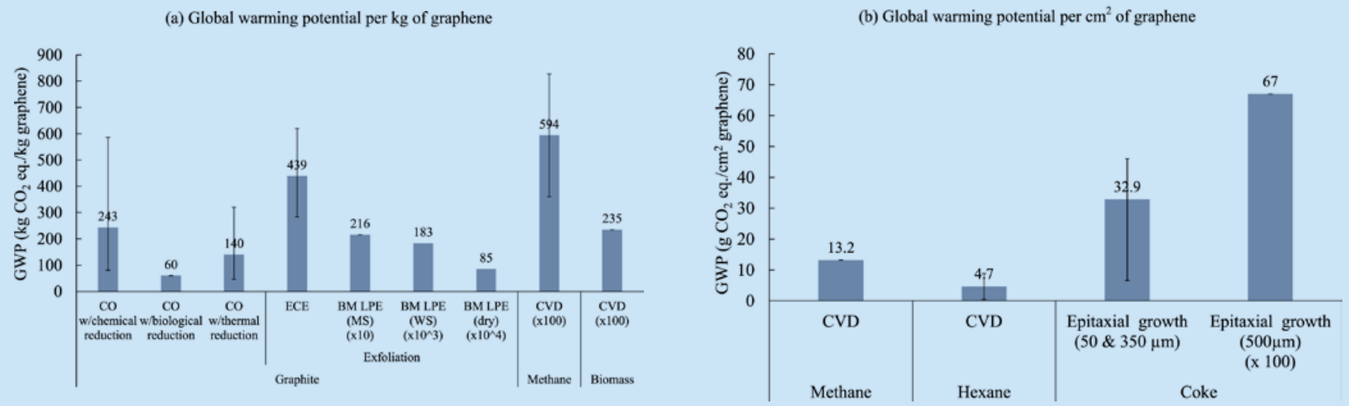


Environmental footprint of optimised graphene-enabled solar farm (Model B) if installed in North, Central and South Europe, current European electricity mix (Ecoinvent), and 2050 European electricity mix based on business-as-usual (BAU), realistic (REAL) and optimistic (OPT) scenarios. Perovskite-graphene panels installed in South Europe have the lowest environmental impact. The Environmental Footprint 2.0 method used to perform LCA considers the following 16 environmental categories: Climate change (GWP100), ozone depletion (ODP), ionising radiation (IR), photochemical ozone formation (POF), respiratory inorganics (RI), non-cancer human health effects (HTnc), cancer human health effects (HTc), acidification terrestrial and freshwater (AP), eutrophication freshwater (FEP), eutrophication marine (MEP), eutrophication terrestrial (TEP), land use (LU), ecotoxicity freshwater (ET), water scarcity (WS), resource use, energy carriers (RUec) and Resource use, mineral and metals (RUmm). Credit: Nature Energy



Global warming potential (GWP) for several graphene production processes, expressed (a) per kg graphene and (b) per cm² graphene. Ball milling (BM) results are reported in melamine solution (MS), water solution (WS) and on a dry basis. Epitaxial growth results are reported in terms of the SiC wafer thickness. CO: chemical oxidation; ECE: electrochemical exfoliation; LPE: liquid phase exfoliation; CVD: chemical vapour deposition. Credit: 2D Mater. 2021

Electronic Devices

Work Package Leader
Daniel Neumaier, AMO, Germany

Work Package Deputy
Gianluca Fiori, University of Pisa, Italy

Our new technologies can open new scenarios in the field of electronics and be the key for the much-needed shift towards next-generation high-performance and low-power devices."

Daniel Neumaier
Work Package Leader

Sustainable more than Moore devices

The Electronic Devices Work Package strives to obtain sustainable devices with improved capabilities and performance that go beyond the established Moore's Law using graphene and other layered materials.

THE LAST 10 YEARS

Over the last 10 years, the Electronic Devices Work Package has moved its focus from the development of critical process technologies to the realisation of different integrated circuits for logic, radio frequency electronics and flexible electronics. This increase in complexity was only possible by laying the foundations at the beginning of the Graphene Flagship, putting sufficient effort toward fabricating reliable and reproducible devices.

Over time, the focus has moved from graphene to other layered materials, such as semiconducting transition metal dichalcogenides (TMDs), especially molybdenum disulphide (MoS_2), which have great potential for electronic applications.

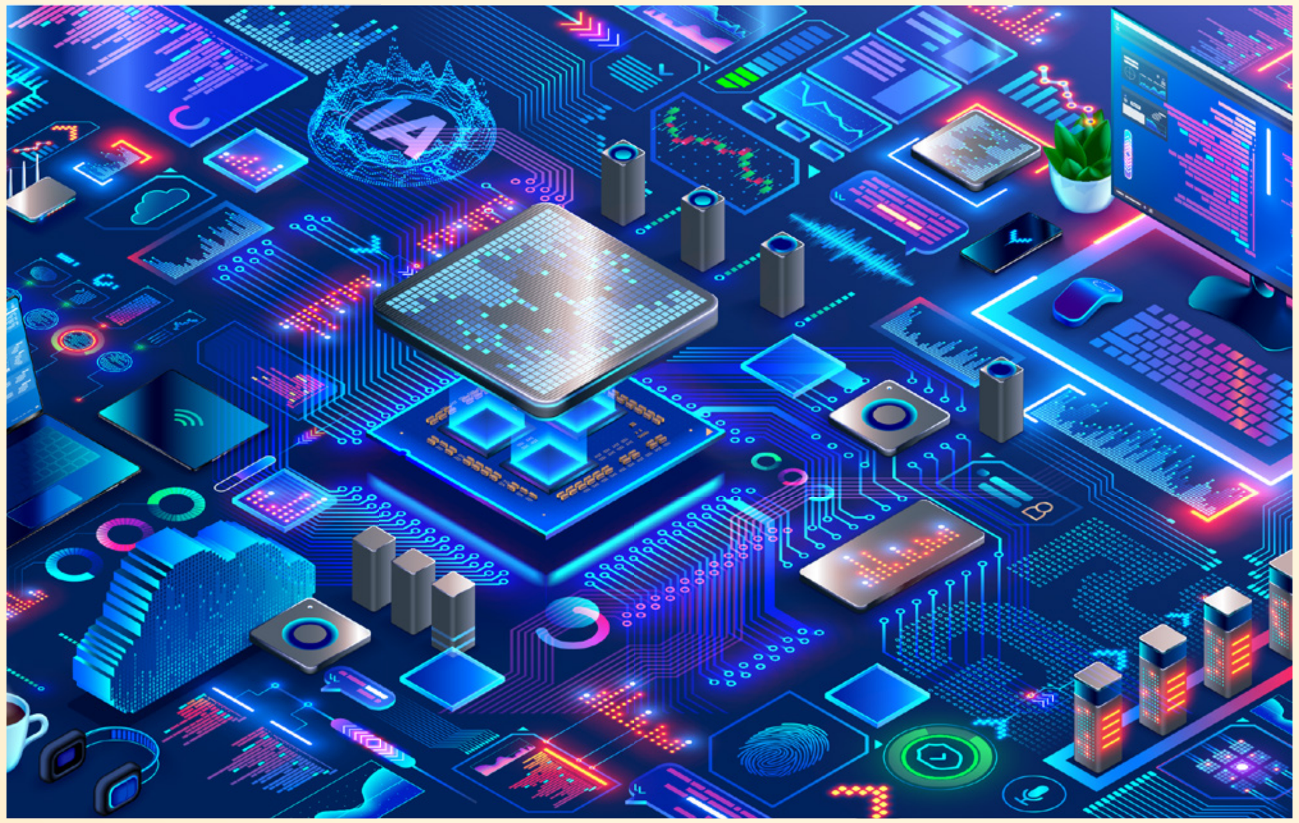
Thanks to the versatility of layered materials, we modelled and demonstrated how to print traditional CMOS devices onto flexible substrates, such as paper, for environmentally friendly electronics. Other advances include high data-rate communication links, new Hall sensors for position sensing and electronic devices for biomedical applications.

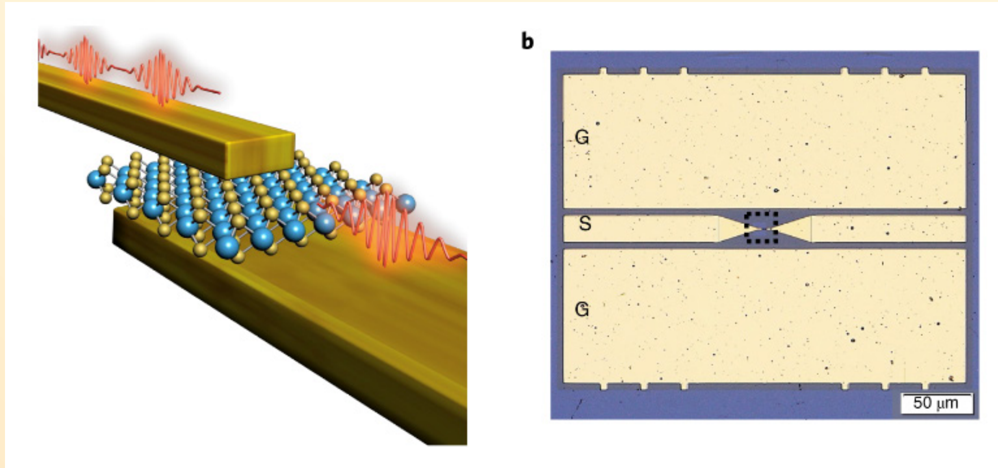
In addition, the Work Package experienced a clear transition from focusing on "hero devices" to the optimization of the reproducibility and reliability of fabrication processes, to progress the large-scale production of electronic devices in Europe.

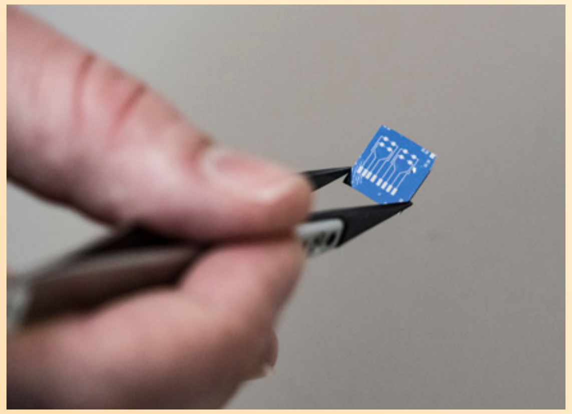
THIS YEAR'S PROGRESS

The know-how acquired this year around the reliability and reproducibility of our transistors put these technologies a step ahead in the realisation of complex circuits based on layered materials. This is a huge result, inconceivable ten years ago. In particular, the researchers also improved the stability of graphene-based field-effect transistor devices by adjusting the energy level of the charge carriers, so that they are less likely to interact with the defects in the insulator without needing to reduce the total number of defects.

The Electronic Devices Work Package made progress in non-volatile resistive switching made from monolayer molybdenum disulphide in a metal-insulator-metal structure, which could be used to create analogue switches for high-frequency communications. They can operate at 100–500 GHz frequencies, which correspond to the 6G communication band. Finally, we reported that hexagonal boron nitride (h-BN) can be used as a barrier layer between MoS_2 and a commonly used encapsulation layer, aluminium oxide (Al_2O_3). This barrier layer prevents charge transfer from Al_2O_3 to MoS_2 and helps to protect MoS_2 from environmental factors. The resulting devices are more stable and show lower hysteresis.







Top
A simplified illustration of a radio frequency switch with a vertical metal–insulator–metal structure and monolayer MoS_2 as the resistive switching insulator (left). Optical microscopy image of a fabricated monolayer MoS_2 radio frequency switch where the dashed box shows the vertical metal–insulator–metal structure (right).
Credit: Nature Electronics

Left
An early chip produced by the Electronic Devices Work Package. Credit: Johan Bodell, Chalmers University of Technology

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GRAPHENE FLAGSHIP ANNUAL REPORT 2022

Photonics and Opto-electronics

Work Package Leader
Frank Koppens, ICFO, Spain

Work Package Deputy
Andrea C. Ferrari, The University of Cambridge, UK

We have seen new applications of graphene emerging almost unpredictably.”

Frank Koppens
Work Package Leader

Fast solutions for data-transmission, image sensing and terahertz detection

The Photonics and Optoelectronics Work Package focuses on research areas and high technology readiness level (TRL) activities that provide fast solutions for data-transmission, image sensing technologies and terahertz (THz) detection at room temperature, which are difficult to achieve with traditional electronic and optical technologies.

THE LAST 10 YEARS

As graphene has evolved from components to application-tailored prototypes over the past decade, the objectives of the Work Package have followed the same trajectory. We launched several spin-offs (i.e., Camgraphic, Emberion, Cambridge Raman Imaging and Qurv) stemming from the research and development efforts of the Work Package. These meet the needs of different industries, and target optical sensors, imaging systems and data communications.

In particular, Cambridge Raman Imaging is developing a coherent Raman microscopy platform, based on the graphene-enabled dual wavelength fibre laser source, that can differentiate between cancer and healthy tissues. Preliminary chemometric data of tumour tissue samples have been acquired and the product is expected to be launched as soon as the end of 2023, targeting the market of cellular process analysis in academia and pharma/biotech industry. Then the product will evolve into a clinical scanner to assess tissue biopsies and support histopathologists in the process of diagnosing cancer.

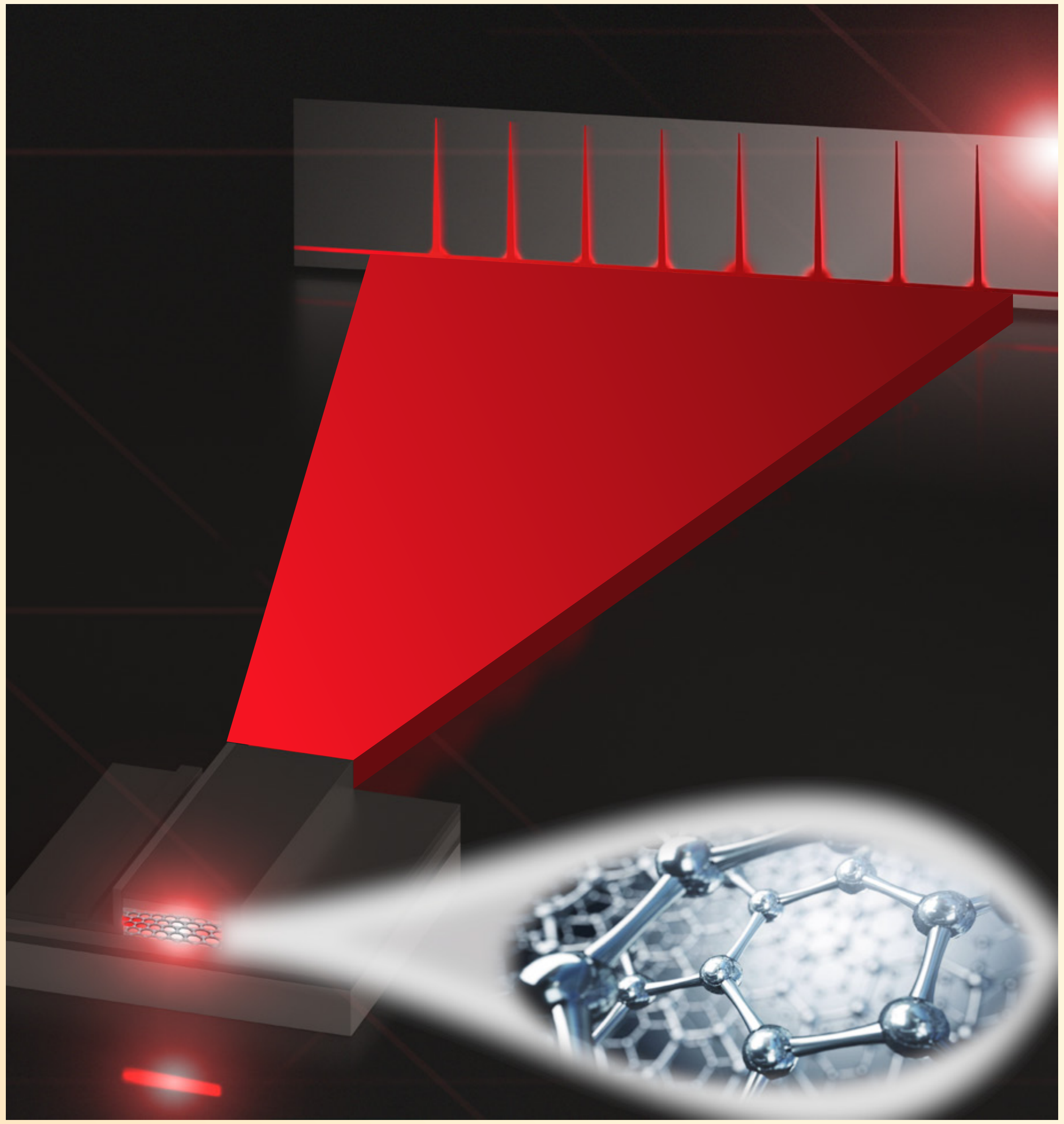
During Core 3, some of the activities with higher TRL moved to the Graphene Flagship Spearhead Projects linked to data communication and broadband image sensors. In the Work Package, we aim to develop the best performing building blocks, while the work carried out in the Spearheads focuses on engineering innovative solutions. By the end of 2023, we aim to surpass state-of-the-art devices and target end-user specifications with the motivation to advance the TRL of these systems even further in the future.

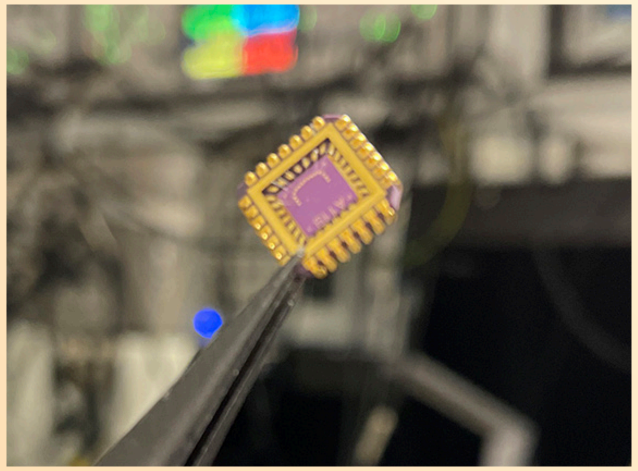
THIS YEAR’S PROGRESS

Over the past year, the researchers in the Photonics and Optoelectronic Work Package worked on THz lasers and detectors. They produced a THz quantum cascade laser (QCL) working at 55% of its total possible range of frequencies. This ability, known as “comb operation”, is useful for detecting harmful gases and explosives and can be applied to infrared imaging systems to detect medical conditions, breath analysers and a variety of other sensing and spectroscopic applications.

The team also reported room temperature detectors for THz frequencies using CVD-grown, large-area, single-layer graphene, integrated in antenna-coupled field effect transistors. The device showed quick responses (around 5 nanoseconds) and low levels of background noise.

Finally, the scientists discovered a way to generate a photovoltage perpendicular to the usual electron flow by shining circularly polarized light on a bilayer graphene device. This new energy source can be used for detecting small amounts of light and energy, which could have important applications in fields like infrared and terahertz sensing, space imaging, medical imaging and material inspection for security purposes.





Device prepared by the Photonics and Optoelectronic Work Package.
Credit: ICFO

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GRAPHENE FLAGSHIP ANNUAL REPORT 2022

Flexible Electronics

Work Package Leader
Maria Smolander, VTT, Finland

Work Package Deputy
Henri Happy, University of Lille, France

We started with ideas that transformed into concepts close to commercial exploitation."

Maria Smolander
Work Package Leader

Developing graphene-based wearable electronics

The Flexible Electronics Work Package takes advantage of the unique properties of layered materials for conductive fabrics as well as elastic and stretchable electronic devices.

THE LAST 10 YEARS

From the beginning of the Graphene Flagship, the target application for graphene-based flexible electronics has been wearable electronics – a megatrend in today's world. Initially, we focused on bendable and light-weight devices, but our recent efforts have been directed towards elastic electronics for conformable devices, such as skin patches. We have also successfully tackled the modification of textile fibres with graphene for e-textiles.

Our aim has been to investigate the use of graphene in applications where substantial amounts of conductive materials are required, such as printed conductors and heat dissipating materials. Given the increasing number of connected items, the Work Package has continuously tackled high-performance, flexible devices and semiconductors based on transition-metal dichalcogenides (TMDCs), providing the advantage of high-performance devices in flexible structures.

The Work Package has had a strong industrial component. We are actively working to patent graphene-based materials and components for flexible electronics. GRM-elastomers by Printed Electronics Ltd are currently integrated in different demonstrators in collaboration with Interactive Wear AG to enable commercial exploitation. Furthermore, Novalia has designed demonstrators based on graphene and related materials (GRMs) and paper-based substrates, which can be exploited in devices like sensors, biodegradable electrodes and anticounterfeit features.

THIS YEAR'S PROGRESS

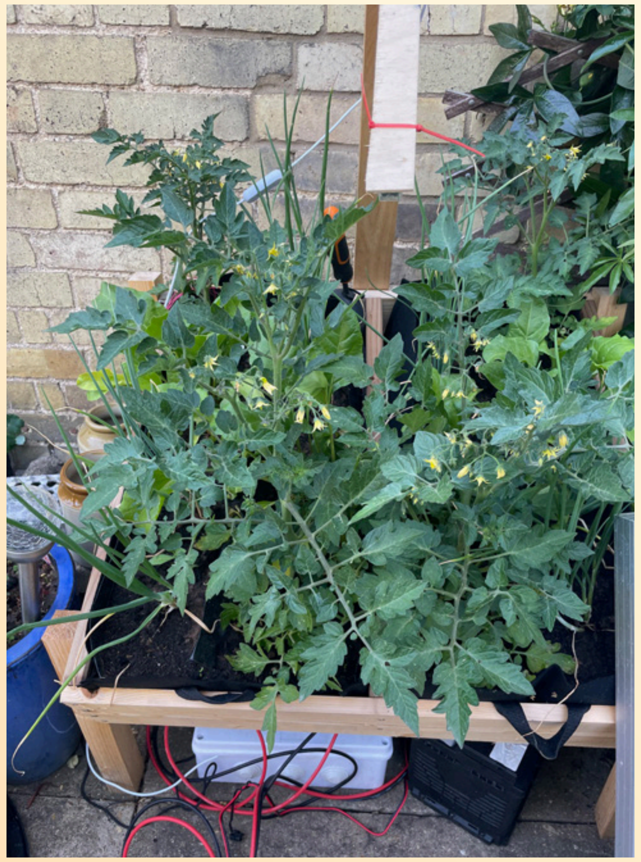
Our team developed a GRM-based conductive polyester (PET) yarn with exceptional performance and durability. We have seamlessly integrated GRMs production with compounding, spinning and weaving processes to create this advanced material. Our ongoing focus is to utilise this material in the development of wearable pressure sensors. As a society, we face an increase in e-waste and the overuse of rare materials. The Flexible Electronics Work Package has increased its efforts towards the use of sustainable technologies through a careful selection of materials, as well as the use of low-energy processing methods, such as printing-based additive methods.

Furthermore, we have successfully developed GRM-elastomers that are washable, and printed stretchable conductors that remain stable even after 1,000 strain cycles. We have also explored various ground-breaking concepts, including paper-based loudspeakers and plant electrodes, which have been developed and tested with positive results. For example, the team is testing GRM- and paper-based biodegradable electrodes that are buried in the soil and powered by solar panels to promote the growth of tomatoes, onions and beetroot: electrically stressed plants appear to grow slightly faster and taller, flowering and fruiting sooner than the control.

Tickets with GRM for anticounterfeit technology.
Credit: Novalia

Resistance measurement in e-fabric woven with yarn produced by Trevira, another company involved in this Work Package.
Credit: Interactive Wear

Graphene-based dry electrodes for ECG measurement.
Credit: VTT



GRM electrodes in the soil make plants grow slightly faster and taller.
Credit: Novalia

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Wafer-scale Integration

Work Package Leader
Amaia Zurutuza, Graphenea Semiconductor, Spain

Work Package Deputy
Camilla Coletti, Fondazione Istituto Italiano di Tecnologia, Italy

Europe can now demonstrate graphene-based wafer-scale photonic and electronic components, something that ten years ago was truly out of reach."

Amaia Zurutuza
Work Package Leader

Graphene meets silicon wafers

The aim of the Wafer-scale Integration Work Package is to bring graphene integration maturity from the laboratory to semiconductor manufacturing plants, or "fabs".

THE LAST 10 YEARS

The incorporation of graphene into electronic and photonic components can enhance their performance in terms of size, power and energy efficiency. It is also the next step to enabling graphene-based commercial products. However, integrating graphene into mature manufacturing processes within the semiconductor industry is not an easy undertaking.

The Work Package was established in Core 1 to address the integration challenges that hindered the successful implementation of graphene in industry, mainly focussing on the manufacture of electronic and photonic integrated devices. Over the course of eight years, the Work Package has made significant progress in improving the manufacturing and fabrication of graphene materials (including steps such as contacting, patterning and encapsulation). Efforts have also been made to enhance the wafers' scale, which increased from 50 mm up to 200 mm, and the quality of graphene.

One of the great advantages of the Graphene Flagship for our Work Package has been the long-term collaborations between research institutes, universities and companies. This has enabled tremendous progress in our work. Through collaboration, researchers from academia and industry have been able to tackle and solve relevant problems and ultimately move one step closer to graphene industrialisation. It also built a European ecosystem around graphene and layered materials.

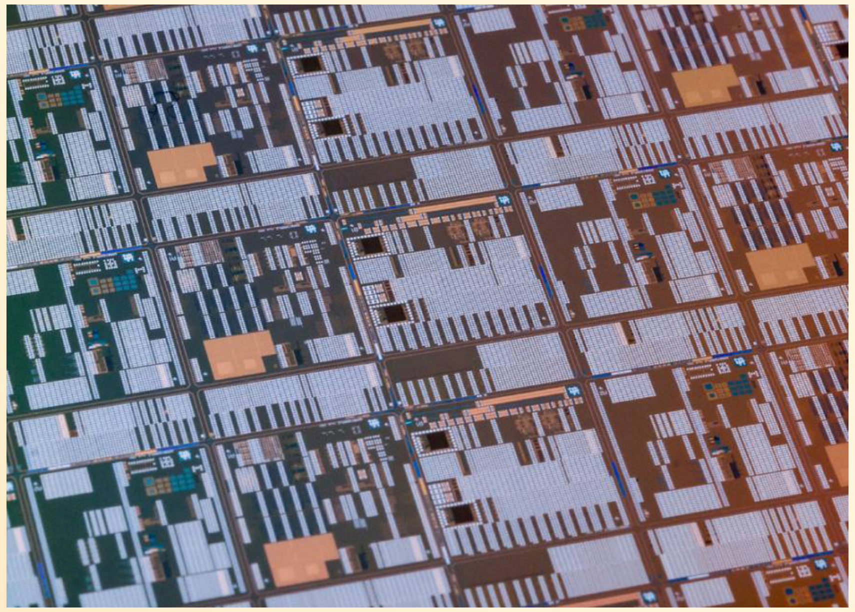
LAST YEAR'S PROGRESS

The Wafer-scale Integration Work Package's efforts focused on Hall sensors as electronic components and electro-absorption modulators as photonic components.

In 2022, the researchers transferred 200 mm CVD graphene on a 300 mm waveguide containing wafers in imec's 300 mm CMOS platform, achieving high uniformity and yield. The process met the semiconductor industry's metal contamination requirements for back-end-of-line, with a concentration of iron and copper contaminants lower than 1012 atoms/cm^2 on 200 mm CVD graphene. Additionally, CVD graphene deposited on various substrates, such as aluminium oxide and silicon dioxide, showed improved charge carrier mobility values of 10,000 cm^2/Vs.

Furthermore, the Work Package has developed graphene-enabled electro-absorption modulators with data-rate of 20 Gbps and high-speed photodetectors with data-rate up to 120 Gbps. These advances demonstrate the potential for energy-efficient photonic components using graphene technology.

A look inside imec's cleanroom.
Credit: imec



A development wafer from imec.
Credit: imec

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Graphene Flagship's Meganne Christian was chosen as one of the ESA's new astronauts

Selected from among 22,500 candidates, industrial chemist Christian can now accomplish her dream

"I always try to find people who are doing great things and try to learn as much as I can from each of them. My favourite example is the Italian astronaut Samantha Cristoforetti… who knows, maybe one day I will work with her!" said Meganne Christian during a Graphene Flagship's interview in 2021. Her comment turned out to be prescient, for on 23 November 2022, the European Space Agency (ESA) announced her name among the new class of ESA astronauts. Selected from more than 22,500 applicants from across Europe, this new class includes five career astronauts, 11 members of an astronaut reserve (including Christian), and one astronaut with a disability.

Christian is a researcher at Graphene Flagship Partner the National Research Council (CNR), Institute for Microelectronics and Microsystems (IMM), Italy. She moved to Europe from Australia and she has been involved in the Graphene Flagship's Work Packages for Composites and Functional Foams and Coatings since 2014.

"The whole reason I wanted to move to Europe was that it's really the centre of things, it's really a great point of collaboration. I thought that being part of the Graphene Flagship would be a perfect opportunity to really take advantage of this," says Christian. "In 2014, I decided to change my life and move to Bologna, Italy. It was pretty much the beginning of the Graphene Flagship. I remember going to Graphene Study, attending my first Graphene Week and presenting at my first Work Package meetings. Now I am a task leader, so I can say I've kind of grown together with the Graphene Flagship and that's been a really exciting experience."

During this time, she has taken part in two parabolic flight campaigns, in 2017 and 2021, to test graphene coatings in loop heat pipes destined for use as thermal management systems in satellites. These graphene wicks were tested in a collaboration between Graphene Flagship Partners Université Libre de Bruxelles (Belgium), University of Cambridge (UK), and CNR-IMM.

During her sabbatical at the Concordia Station in Antarctica, Christian connected via Skype in order to explain her research aims to the Graphene Week 2019 audience. "I would like to set up a laboratory for the use of nanomaterials in extreme environments, such as Antarctica and space. The conditions of Antarctica and space are not too different in some respects, after all," she said during the interview. She later presented a poster on '2D materials for research in extreme environments' during Graphene Week 2022.

"I've been fascinated by the ways that material science of nanomaterials, graphene and 2D materials can help facilitate research in extreme environments. For example, the boots I used in Antarctica were bulky and heavy. Ideally, we could incorporate 2D materials to insulate them and have some passive (or perhaps even active) heating to make them a lot lighter and more practical to use," explains Christian.

Colleagues from across the Graphene Flagship community were excited to hear of the news of Christian's selection as an astronaut.

"Meganne is a space enthusiast, and I am very happy to have had the opportunity to work with her on the development of loop heat pipes for space applications. I am even happier to have coordinated two parabolic flights that could be considered the 'appetizer' of her brilliant career ahead as an ESA astronaut. I am proud and happy for her, and I know she fully deserves to go to space one day," says Graphene Flagship Space Champion Carlo Iorio from the Université Libre de Bruxelles.

Meganne Christian from National Research Council (CNR), Institute for Microelectronics and Microsystems (IMM), Italy, was selected as an ESA astronaut reserve in November 2022. Credit: Graphene Flagship

The 17 members of the 2022 ESA astronaut class. Meganne Christian is the third from the left on the first line. Credit: ESA

"Meganne has always been a highly motivated scientist. I still remember her first job interview at CNR, which she gave from a car in Australia due to the time difference! We were also together in Toulouse for our first flight in zero gravity, on the "Zero-G" Airbus of ESA; I hope to watch her next flight soon, this time in space. Well done, Meganne!" says Vincenzo Palermo, Director of the Institute for Organic Synthesis and Photoreactivity, CNR (Italy).

"It requires a great deal of hard work and perseverance to become an astronaut. The ESA seeks out not only individuals with strong scientific backgrounds such as Meganne's, but also people who are dedicated, resilient, resourceful and good team players. To be selected as one of the ESA's new cohort is not only a well-deserved opportunity for Meganne, but also a reflection of her character and of her appetite for growth that she has cultivated over the years, and which the Graphene Flagship has sought to foster. As an entire community, the Graphene Flagship is immensely proud of her achievements and wishes her every success," says Jari Kinaret, Director of the Graphene Flagship.

"People have always been at the core of the Graphene Flagship. Over the years young scientists have developed into world-leading professionals thanks to the work done within the project and benefiting from all the support activities we provided. Space is the next frontier for graphene and related materials. The Graphene Flagship has pioneered its application and space qualification, with experiments and plans involving drop towers, parabolic flights, sounding rockets, lunar rovers and the international space station. Meganne was part of the first ever zero-G campaign organized to test graphene-enabled loop heat pipes in zero-G. We are immensely proud to see her selected as an ESA astronaut. Her experience in graphene and related materials will place her in a unique position to inform the space community about their potential," says Andrea C. Ferrari, Graphene Flagship Science and Technology Officer. All our researchers are stars in our eyes, and the possibility of one of them venturing into outer space, to further research and exploration goals benefitting the global community, fills us with pride. On behalf of the Graphene Flagship: many congratulations again, Meganne. We are so excited to see where the future will take you.

GRAPHENE FLAGSHIP ANNUAL REPORT 2022

Energy Generation

Work Package Leader
Emmanuel Kymakis, Hellenic Mediterranean University, Greece

Work Package Deputy
Aldo di Carlo, University of Rome Tor Vergata, Italy

A new generation of scientists was trained, becoming proficient in a hot field with profound implications for the future of mankind.”

Emmanuel Kymakis
Work Package Leader

Next gen solar cells

The Energy Generation Work Package addresses different approaches for energy harvesting: harnessing the energy of the sun with large-area photovoltaics and producing hydrogen with water electrolysers.

THE LAST 10 YEARS

This ten-year journey allowed us to bridge the gap between laboratory prototypes and up-scaled demonstrations, targeting applications in large-area solar panels for on-grid electricity generation, and flexible solar modules to power Internet of Things (IoT) devices. We developed various graphene and related materials (GRMs) and integrated them with perovskite solar cells to enhance both stability and efficiency. Technical issues that had slowed down the photovoltaics upscaling process have been resolved, including the replacement of noble metals, the processing of titanium dioxide at low temperatures and the optimisation of laser patterning. Moreover, GRM-based conductive pastes and novel encapsulants led to stable and efficient modules with low capital expenditure (CAPEX).

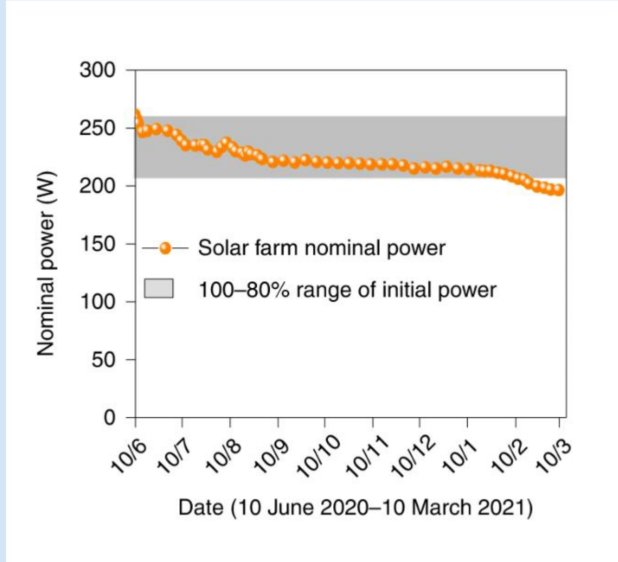
On the fuel cell front, we developed graphene-enabled supports for electrocatalysis. Initially, they were meant to promote only the oxygen reduction reaction, but at a later stage, electrocatalysts featuring a graphene-based support were also developed to promote the hydrogen evolution reaction and the oxygen evolution reaction at low-temperatures. We also devised graphene-based anticorrosion coatings, as well as easily scalable solid-state and liquid-based approaches to obtain enough inexpensive graphene. The resulting demonstrators showed an outstanding performance and durability in the electrochemical processes.

THIS YEAR’S PROGRESS

The Energy Generation Work Package’s effort led to the world’s first outdoor demonstration of a solar farm with 4.5 m^2 graphene–perovskite panels. These delivered a peak power exceeding 250 W and demonstrated a remarkable stability: only a 20% reduction in the performance over eight months. Gathered in an open data repository, all experimental data will be of interest to the photovoltaics industrial sector and will lay the groundwork for commercialisation targets. We reached high technology readiness levels (TRLs); TRL 6 in the solar farm demonstration, TRL 4-5 in the transparent conductive electrodes based on exfoliated graphene hybrids, and TRL 5 in the fully printed, flexible perovskite solar modules with stabilised output power for indoor applications. Finally, a life cycle assessment (LCA) model indicated that this technology might compete with those calculated for European 2050 electricity mix scenarios.

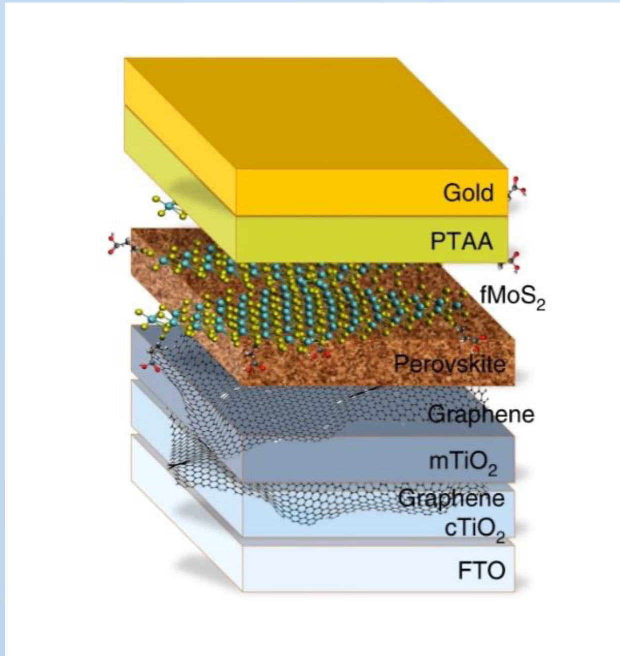
We devised graphene-enabled electrocatalysts that promote key processes for the operation of fuel cells and electrolysers, exhibiting a performance and durability beyond the state-of-the-art. These are also free from or with minimal concentrations of strategic elements, such as platinum group metals.

The GRM-enabled functional components, mostly supports and electrocatalysts, have already been synthesised in batches of 5-100 grams and could easily be scaled up. Such functional components are already available on the market for demo purposes and sampling by one of our industrial partners, BRETON.



The deployment and performance of the perovskite modules in a PV system. a) 4.5 m^2 metal halide perovskite modules installed on Crete (Greece). b) Nine months of outdoor performance data. Credit: Nature Energy

The solar panel consists of several layers: glass with fluorine-doped tin oxide (FTO), compact titanium dioxide (TiO_2) with graphene, mesoporous TiO_2 with graphene, perovskite, $fMoS_2$, poly(triarylamine) and gold. In the scale-up and sustainable mass production of this technology, gold can be replaced with an alternative material, such as graphene, other carbon materials or cheap metals. Credit: Nature Energy



The single fuel cells are assembled into a short stack demonstrator. Credit: BRETON SpA

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GRAPHENE FLAGSHIP ANNUAL REPORT 2022

Energy Storage

Work Package Leader
Vittorio Pellegrini, BeDimensional, Italy

Work Package Deputy
Daniel Carriazo, CIC energiGUNE, Spain

We are excited to develop materials in a research environment, and then assemble and test them in an industrial environment."

Vittorio Pellegrini
Work Package Leader

Improving supercapacitor and battery life and charging times

The Energy Storage Work Package explores the benefits of graphene and layered materials in batteries and supercapacitors to improve their capabilities, accelerating charging rates and lifetime extension.

THE LAST 10 YEARS

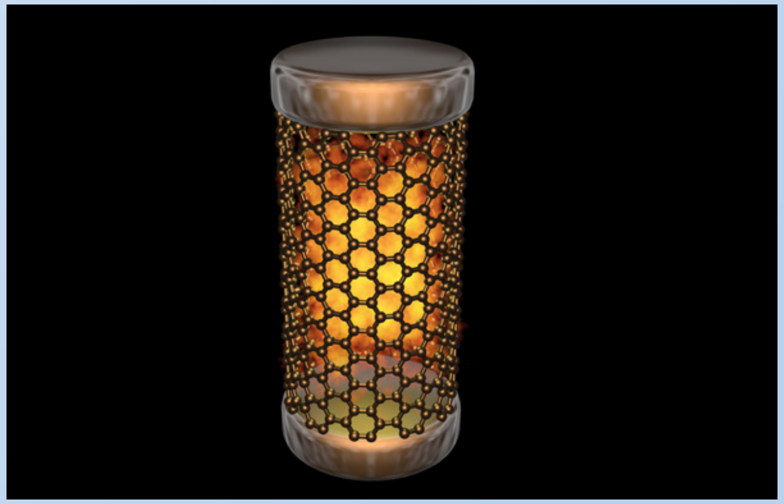
Over the past decade, our Work Package has identified a technology that can solve the issue of silicon degradation during lithium-ion battery cycling. We have developed silicon-graphene composites as anodes for lithium-ion batteries and challenged issues related to quality control and standardisation thanks to the collaboration between industrial partners and research institutes.

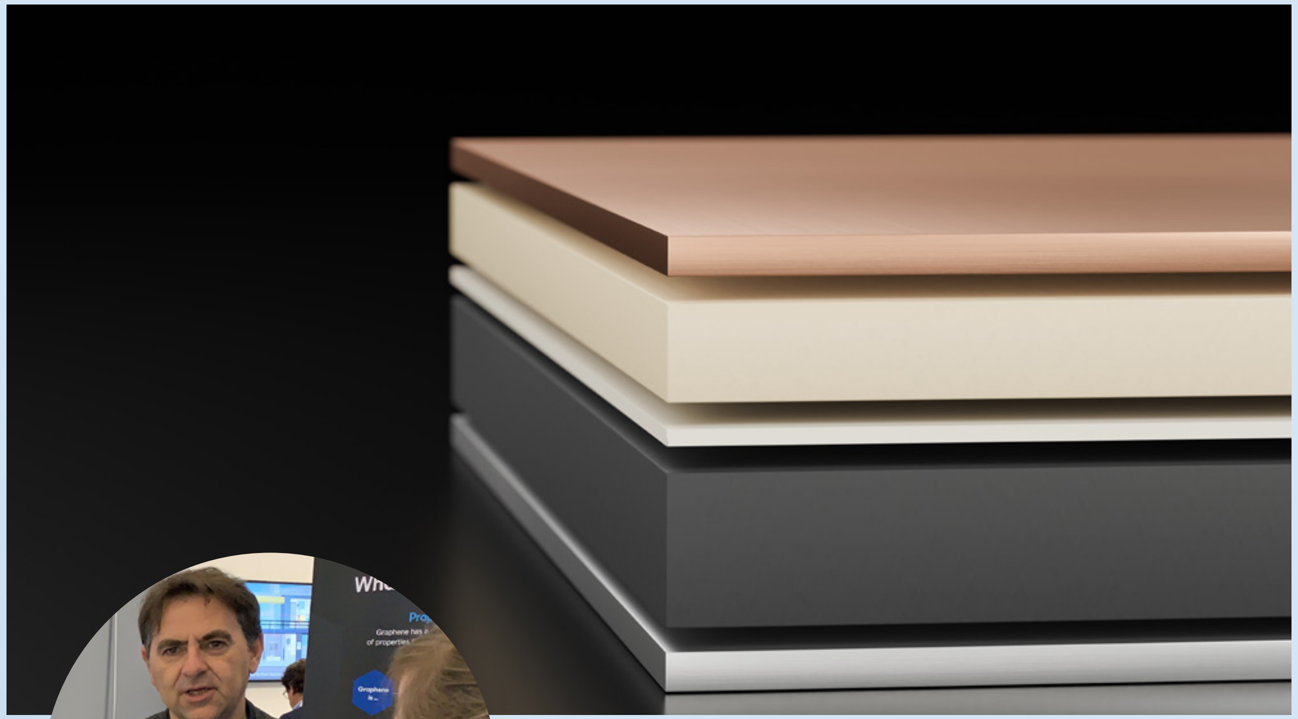
We also worked on graphene-based dispersions optimised for the realisation of supercapacitor and micro-supercapacitor electrodes, by spray coating or ink-jet printing. They have technology readiness levels (TRL) of 5 and 4, respectively. The activity evolved from research studies and lab tests to prototyping and industrial scale-up. These dispersions can be produced in large quantities by Graphene Flagship Partner companies, such as Graphenea, Sixonia and BeDimensional. During the last ten years, our Work Package progressively explored other storage technologies, such as solid-state lithium-ion, lithium-sulphur and metal-air batteries, as well as hybrid capacitors. Although there are no commercially available lithium-sulphur or secondary metal-air batteries, and the implementation of graphene to overcome some of their limitations is still at the fundamental stages, we have improved the stability and cyclability of these cells. In this respect, we hope to present TRL 3-4 demonstrators by the end of the project.

THIS YEAR'S PROGRESS

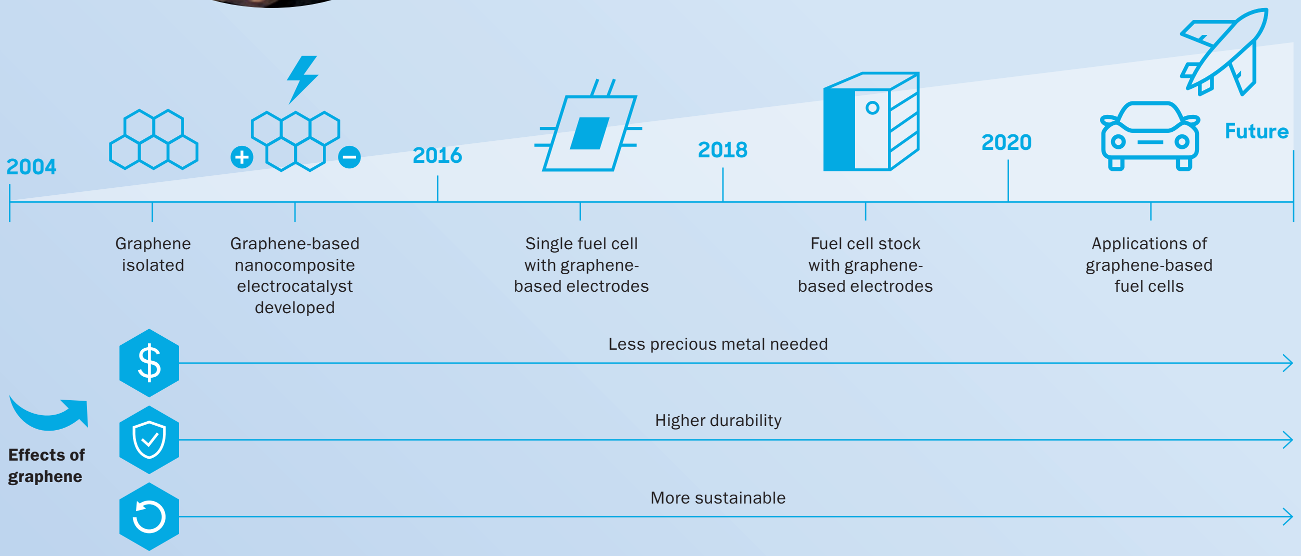
Some representative works published in 2022 include the development of lithium-ion hybrid supercapacitors showing maximum energy density of 133 Wh/kg at 142 W/kg and 51 Wh/kg at 25,600 W/kg. It could be discharged in approximately one minute and could withstand more than 19,000 charge-discharge cycles.

We have also synthesised and optimised graphene-based electrodes for lithium-sulphur batteries, which enabled the assembly of a lithium-sulphur 20 cm^2 pouch cell demonstrator showing specific capacities over 1200 mAh/g and areal capacities of 3.5 mAh/cm^2. This shows the material's aptitude for delivering outstanding results under real-world conditions. Finally, we have investigated the use of graphene nanoplatelets with polytetrafluoroethylene (PTFE) in cathodes for sodium-air batteries. The cathode processed with 10 wt% of PTFE binder presented the best charge-discharge cycle life of 142 cycles areal capacities of at 0.2 mA/cm^2 and 0.5 mAh/cm^2. This represents an interesting development in electrochemical storage devices that involve oxygen gas.





Work Package leader Vittorio Pellegrini at Enlit Europe, a tradeshow focused on the entire energy value chain, held 29 November – 1 December 2022 in Frankfurt, Germany. Credit: Anastasia Papanicolaou, Graphene Flagship



The effects of graphene on energy storage technology since graphene was first isolated in 2004

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Functional Foams and Coatings

Work Package Leader
Xinliang Feng, Technical University of Dresden, Germany

Work Package Deputy
Paolo Samorì, University of Strasbourg, France

We cannot wait to see our technologies on the market in the next five to ten years. These sustainable materials can compete with the state-of-the-art technologies and hold the potential to address global challenges, especially water scarcity, air pollution and human health monitoring."

Xinliang Feng
Work Package Leader

New materials to tackle sustainability challenges

The Functional Foams and Coatings Work Package took significant steps forward on the functionalisation and processing of graphene and related materials (GRMs) into porous structures, such as foams and membranes, coatings for environmental applications like water and air purification, anticorrosion coatings and environmental monitoring devices. These address the United Nations' Sustainable Development Goals to fight against the shortage of drinkable water, the increase of air pollution and the lack of proper health monitoring.

THE LAST 10 YEARS

The Work Package has faced some challenges in upscaling functionalised GRMs and their industrial-level processing into foams and coatings. However, these have been successfully addressed and two spin-offs were established, namely Sixonia Tech and BeDimensional.

BeDimensional's anticorrosion paint based on two-dimensional hexagonal boron nitride and Sixonia Tech's graphene inks are already on the market.

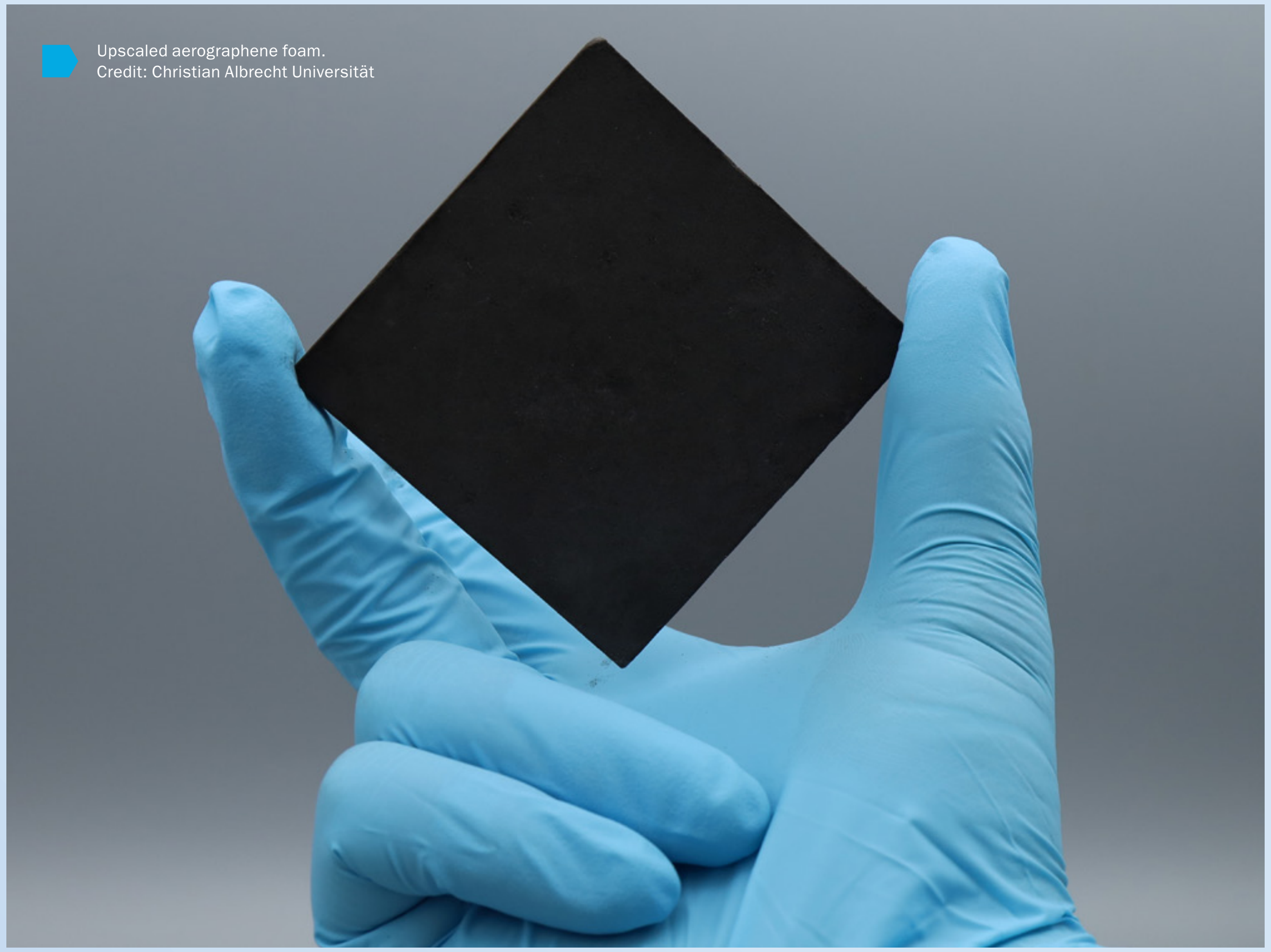
We filed several patents and coordinated several non-disclosure agreements to discuss graphene-based foams with various European companies, especially in the automotive and aviation sectors.

We have also worked on membranes for water filtration and sensors for environmental and health applications. Finally, we have collaborated with the Spearhead Project GrEEnBaT, led by Varta Micro Innovation, to work on graphene-enabled energy storage solutions.

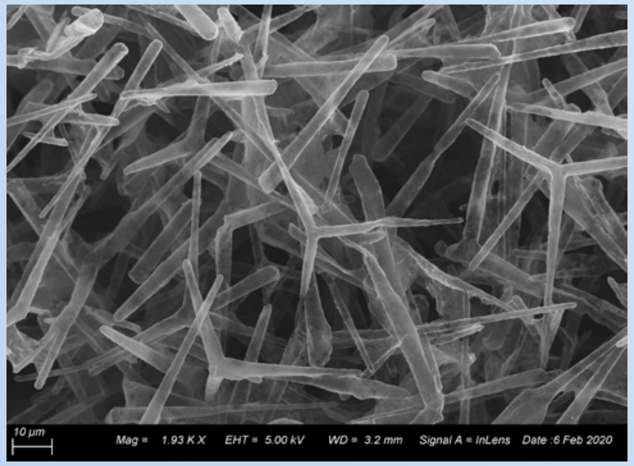
LAST YEAR'S PROGRESS

This year we published our progress in developing membranes for reverse electrodialysis – a technique that could capture the osmotic energy available from the difference in the salt concentration between seawater and fresh water. Traditional membranes, such as commercial ion-exchange membranes, suffer from inadequate ion transport abilities, while layered materials have emerged as promising alternatives to generate electricity. These thin membranes made of imine-based 2D polymers display excellent ionic conductivity and high selectivity, resulting in power density of 53 W/m^2, which is one order of magnitude higher than traditional ion-exchange membranes.

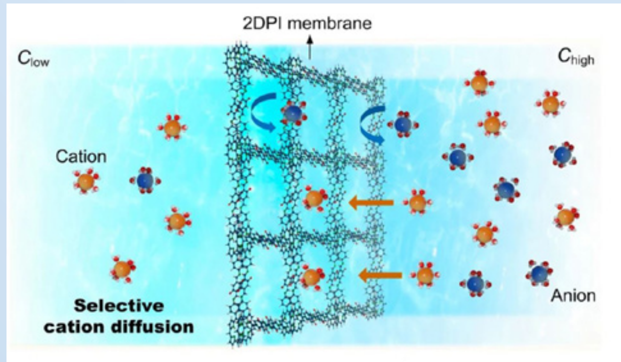
The team also published a method to develop single crystals of charged two-dimensional polymers made of pyridinium cations and BF4 anions. The crystals have a thickness that can be adjusted between 2 and 30 nm and can be as large as 120 square micrometres. They show excellent chloride ion selectivity and output power density, superior to those of graphene and boron membranes.



Upscaled aerographene foam.
Credit: Christian Albrecht Universität



A scanning electron microscopy image of graphene foam used in the AEROGrAFT Spearhead Project's air filters. Credit: Christian Albrecht Universität



Fully crystalline imine-based 2D polymer (2DPI) membranes can combine excellent ionic conductivity and high selectivity for osmotic energy conversion.
Credit: Nature Communications

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GRAPHENE FLAGSHIP ANNUAL REPORT 2022

Composites

Work Package Leader
Costas Galiotis, FORTH, Greece

Work Package Deputy
Ian Kinloch, The University of Manchester, UK

The Graphene Flagship is a huge repository of knowledge and strong collaboration, including well defined value chains and opportunities for graphene and layered materials."

Costas Galiotis
Work Package Leader

Nanomaterials raise the bar for composite materials

The Composites Work Package aims to develop high technology readiness level (TRL) systems covering a range of applications in aerospace, automotive, materials processing and production.

THE LAST 10 YEARS

At the onset of the Graphene Flagship's "ramp-up" phase in 2013, our Work Package was classified as "Nanocomposites" and was primarily focused on fundamental research to improve the processing, integration, characterisation, modelling and performance of graphene and related materials (GRMs) as nano-inclusions in composites. At the start of Core 1 in 2016, the Work Package changed its name to "Polymer Composites" and shifted its focus to the development of high-performance GRM/polymer-based composites with enhanced multi-functionalities, which was one of the major challenges at that time. Issues related to geometric dimensions and dispersion characteristics of GRM into matrices were tackled and resolved. In Core 2, the Work Package, then titled "Composites", brought to the fore other categories of materials, such as ceramic and metal matrix composites, as well as hybrid GRM/fibre composites, a major expansion in the work on all families of composite materials of broad industrial interest.

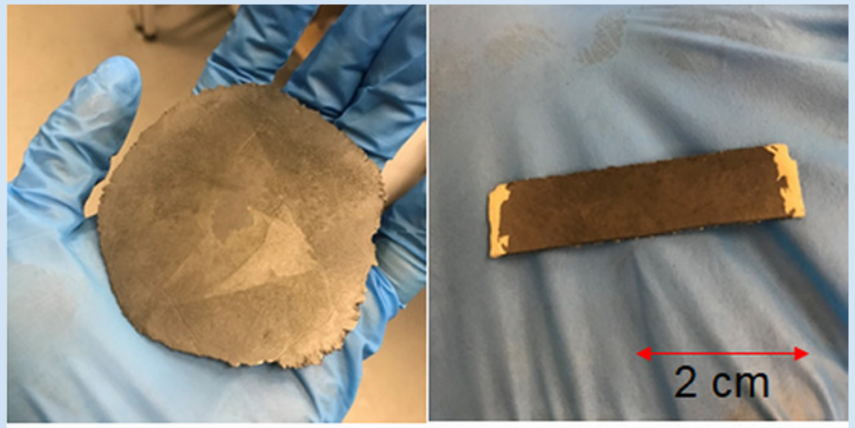
In Core 3, the Composites Work Package has established three internal value chains for the polymer/chemical industry, automotive and aerospace sectors. The researchers aim to develop high TRL systems based on prototypes and demonstrators of tomorrow's everyday life products. Up to now, 11 prototypes with TRLs between 4 and 7 have been completed, including 3D-printed GRM-based flexible/wearable sensing devices, ultra-concentrated GRM/polymer master batches (MBs) with applications in the packaging and automotive industry, conductive injection moulded GRM composite components for sensor elements, a smart ice detection system for the aerospace sector and GRM coatings on metal components (e.g. fin radiators, brake disks and callipers) for the automotive industry.

THIS YEAR'S PROGRESS

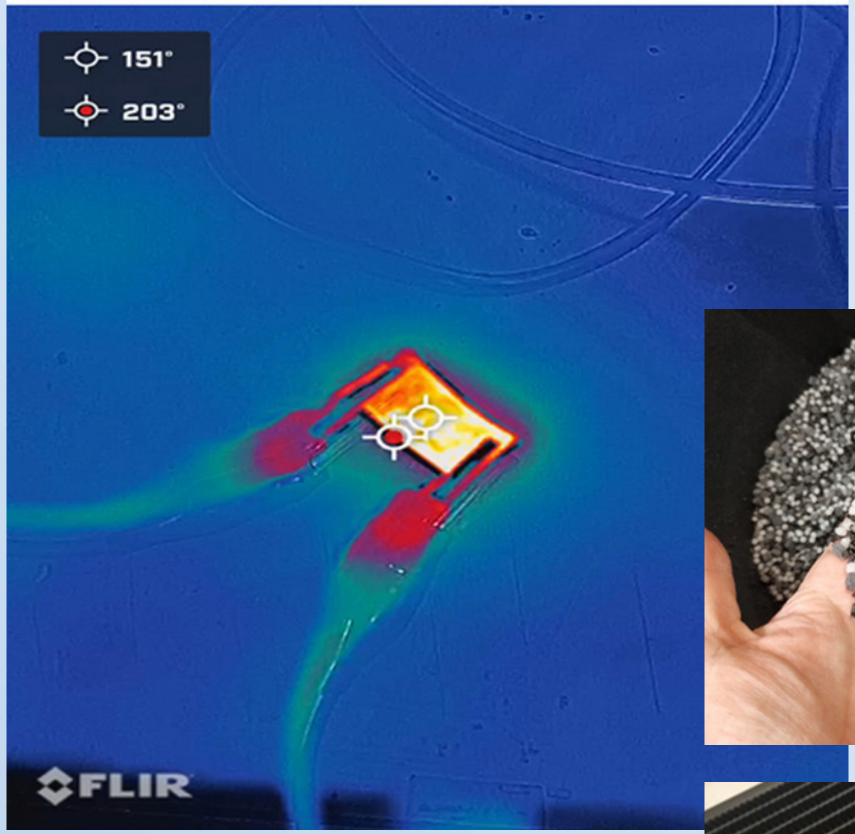
In 2022, the Composites Work Package has produced ultra-concentrated GRM/polymer MBs, which were successfully tested at an injection plant for a Tier-2 automotive industry supplier and showed a drastically improved thermal dissipation. The introduction of GRMs in polymer composites contributes to mechanical performance improvement and small amounts of GRMs were found to improve the recyclability of polyamide and polypropylene fibre composites.

BeDimensional developed six different types of MBs that can be employed in various areas, such as energy storage and conversion, paints and coatings, and composites. The University of Cambridge and Université Libre de Bruxelles have been granted two IP licences.

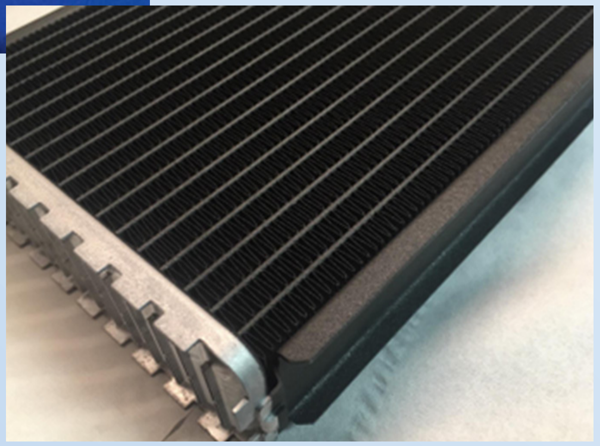
Among the papers published by our Work Package this year, we can highlight a new type of nanocomposites, where a small amount (0.06%) of graphene induces improvements in stiffness, strength and toughness. Additionally, graphene makes the composite material more resistant to gas permeation, thus a good candidate for flexible gas barriers. We also reported a new resistive field grading material with a network of zinc oxide (5 vol %) in a rubber matrix, which is better than other materials for controlling the flow of electricity in high-voltage cable systems. Finally, we discovered that the titanium carbide MXene ($Ti_3C_2T_x$) is a good candidate for reinforcing polymer materials: the mechanical performance of this MXene is not very sensitive to the thickness of the flakes and can be functionalised to make stronger bonds with the polymer and improve the mechanical strength of these materials.



Hot pressed graphene-PEEK powder form films with high conductivity and added functionality made by The University of Cambridge. Credit: The University of Cambridge



Ultra-concentrated GRM/Polymer masterbatches produced by Avanzare at industrial scale. Credit: Avanzare



Nanesa's thermal GRM coating on a radiator. Credit: Nanesa

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Production

Work Package Leader
Alex Jouvray, Aixtron, UK

Work Package Deputy
Julio Gómez-Cordón, Avanzare, Spain

The work on fire retardants and fire sensing GRMs remains to date some of the more innovative, and likely underrated, work on GRMs. It has the potential to displace metal in favour of GRMs in several well-established markets such as large chemical reactors, pipes, metal structure and more."

Alex Jouvray
Work Package Leader

Providing commercial quality graphene

The Production Work Package is mostly driven by the Graphene Flagship's industrial partners which develop both graphene and related materials (GRMs) and GRM applications. This Work Package also provides commercial quality graphene to the rest of the Graphene Flagship.

THE LAST 10 YEARS

This Work Package has been fortunate to have continuity in both its key partners and its development areas over the past decade. We have focused on producing high-quality, reproducible GRMs for aerospace and aerostructures. We improved manufacturing processes – particularly the roll-to-roll production of CVD graphene – and scaled these processes up.

Furthermore, we are demonstrating the viability of GRMs. We have tried to understand how GRMs can provide significant benefits over traditional metal materials in large chemical reactors, pipes and in fire retardants. This work was well documented in Core 2, when the excellent fire retardancy properties of the GRM developed by Avanzare were demonstrated. This material can be applied as a coating to existing structures to not only prevent fire, but also to detect fire.

Over the last ten years, the Work Package has developed its capabilities in terms of production volumes, quality (and traceability) of material produced and range of product offering. Most manufacturing challenges for GRMs from the start of the project have now been overcome.

Being largely driven by industrial partners, several products and prototypes have been released to the market over the course of the Graphene Flagship project. For example, the bicycle lubricant GXT-Bike and the graphene-based synthetic additive for the treatment of engine oil GXT-LUBE can be purchased on Amazon.

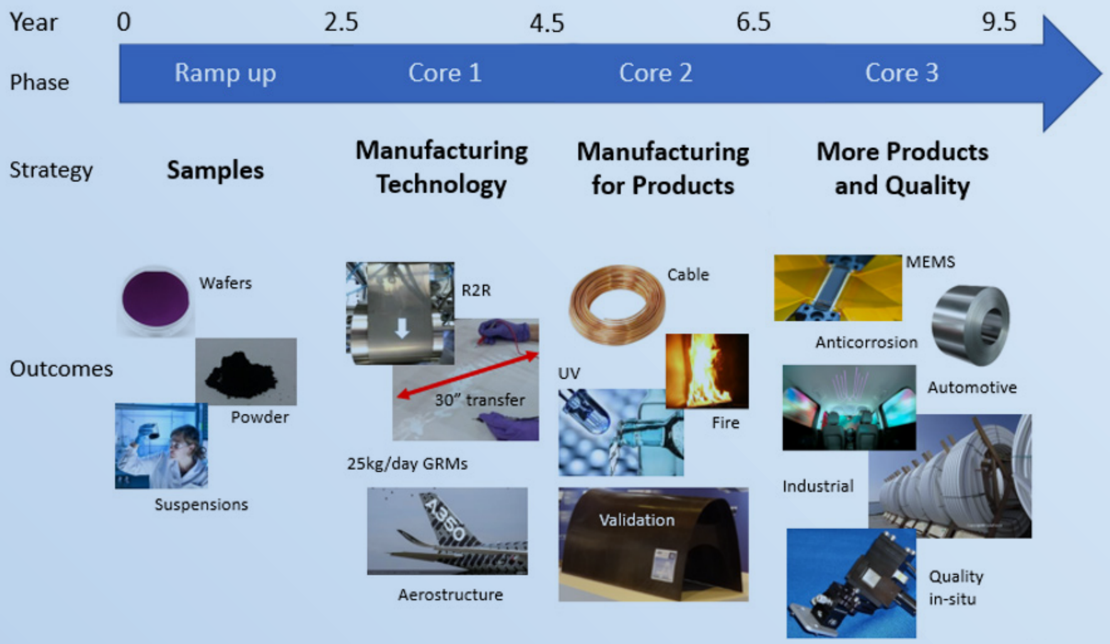
THIS YEAR'S PROGRESS

We have made significant technical progress in the development of GRM-based UV-C LED lights for disinfection with increased power conversion. In particular, we demonstrated LED processes on 50 mm wafers.

The team has also characterised graphene-based wire coatings via in-line metrology and achieved composite laminates using resin transfer moulding and Graphene Flagship partner Evonik Operations' (non-porous) resins for aerospace applications. In low-velocity impact tests, the performance improvement of resins with 0.4% GRM reached 23% higher strength and 30% less damage area when compared with non-GRM resins. We worked on GRMs as an alternative to metal structures for fire sensing capabilities in large and high diameter pipes and a corrosion-free chemical reactor for potentially explosive atmospheres (ATEX), organic solvents, etc.

A non-metal chemical reactor for potentially explosive atmospheres, based on graphene composites to gain electrical conductivity, fire retardancy and anticorrosion properties. Credit: Julio Gómez-Cordón, Avanzare

Graphene-based composite pipe, with electrical conductivity, fire retardancy and sensing properties. Credit: Julio Gómez-Cordón, Avanzare



The Production Work Package's strategy from the ramp-up phase of the Graphene Flagship until the current Core 3.

Business Success Stories

Point of use water filters from Medica SpA, who is leading the Graphene Flagship Graphil Spearhead Project. Credit: Sofia Järbur, Graphene Flagship

Over the last 10 years, the number of companies and industries involved in the Graphene Flagship increased considerably. Large companies, spin-offs and SMEs have come aboard our community as Graphene Flagship Partners or Associated Members. Over the course of the Graphene Flagship, the proportion of industrial partners among our collaborators increased from 30% in 2013 to 47% in 2022. Here a small selection of nine projects that are bringing graphene to the next level.

INCREASING CONSUMER CONFIDENCE IN TAP WATER WITH GRAPHENE-ENABLED FILTERS

Graphene Flagship Partner Medica SpA, Italy, produces a compact water filter, exploiting the best of two materials: hollow fibre membranes to eliminate microbiological contaminants (i.e. bacteria, viruses, endotoxins) and graphene oxide to remove emerging contaminants (i.e. drugs, antibiotics, pesticides, heavy metals and personal care by-products) from water.

"We tested the first graphene filter in 2015 with researchers from Graphene Flagship Partner National Research Council (CNR) in Bologna. Even though our first filters tested worked for just one hour, we saw the potential. The filter could capture contaminants from water thanks to its high contact surfaces and chemical affinity with many different chemical species," says Letizia Bocchi, Medica's Research Laboratory Manager and leader of the Spearhead Project Graphil.

BRIDGING THE GAP BETWEEN GRAPHENE'S QUALITY AND PROCESSABILITY

Graphene Flagship Partner Sixonia Tech GmbH's proprietary technique is an electrochemical exfoliation method where few-layer graphene is derived from graphite and functionalised with the desired chemical groups at the same time. Spun off from Graphene Flagship Partner Technische Universität Dresden in Germany, Sixonia has continuously doubled its turnover every year since its launch in 2017.

> "These companies are trailblazers of innovation in the Graphene Flagship, charting new paths. May their ingenuity, resourcefulness and passion continue to lead the way forward."

Kari Hjelt
Graphene Flagship Head of Innovation

"One of the primary challenges with graphene has been its tendency to re-stack back to graphite during processing. Sixonia is addressing this issue by functionalising graphene just enough to make it processable, while retaining graphene's features, such as electrical conductivity," says Martin Lohe, co-founder and CEO of Sixonia.

IMPROVING OPTICAL COMMUNICATION FOR FASTER DATA TRAFFIC

Graphene Flagship Associated Member CamGraPhiC's mission is to boost optical telecommunications for several fields, such as 5G and edge computing, to support optical telecommunications, advanced sensors, artificial intelligence, quantum photonics and space applications, among others. With offices in the UK and Italy, CamGraPhiC is now developing the first building blocks to demonstrate the capabilities of graphene-integrated photonics. They aim to be the first in the market to deliver 1600 gigabits per second.

"Important requirements for the next-generation components are high speed, small size, low cost, low power consumption and flexibility. CamGraPhiC is developing graphene-integrated photonics to satisfy all these requirements," says CamGraPhiC's CTO Alessio Pirastu.

Cambridge Raman Imaging is working on a technology that enables quick and cost-effective cancer diagnosis. Credit: Cambridge Raman Imaging

TOWARDS SAFER DRIVING IN ADVERSE WEATHER CONDITIONS

Graphene Flagship Partner Qurv Technologies, Spain, is developing new sensors to unlock computer vision applications with unprecedented levels of performance, reliability and function. Qurv's technology captures UV, visible and infrared photons and is based on a graphene-enabled pixel stack integrated with CMOS circuits. "Our technology provides benefits in different markets. One of Qurv's target markets is automotive. In the Graphene Flagship Spearhead Project AUTOVISION, we explore the potential of graphene-based wide spectrum image sensors to allow autonomous cars to see better in adverse conditions," says Qurv's CTO Stijn Goossens, leader of AUTOVISION.

INTEGRATING GRAPHENE IN FAB PRODUCTION LINE PROCESSES

Headquartered in Germany, Aixtron has 35 years of experience in deposition systems. It is present in seven countries, with around 700 employees. Active in several Graphene Flagship Work Packages, a Spearhead Project and the 2D-Experimental Pilot Line (2D-EPL), Aixtron works on growth and transfer tools.

More recently, both Aixtron Ltd and Aixtron SE are involved in helping the 2D-EPL improve and scale up the production of graphene and other layered materials. This includes the growth and subsequent transfer of these materials to target wafers.

"Our goal is to provide the tools to produce high-quality graphene at 300 mm wafer-scale and develop new strategies to enable its integration into existing fab production line processes," says John Walker, development engineer and project leader at Aixtron Ltd in Cambridge, UK.

TRANSFORMING CANCER DIAGNOSIS

Graphene Flagship Partner Cambridge Raman Imaging (CRI), Italy and UK, is developing a technology to diagnose cancer quickly and at affordable costs. The instrument measures the molecular composition of unstained tissue biopsies using coherent Raman – a microscopy technique that differentiates molecules by the way they vibrate. It is the first application of fast Raman imaging to the clinical field. The Raman measurements are then directly fed into an artificial intelligence (AI) programme that differentiates healthy and tumour tissues and provides tumour subtype classification.

"We aim to develop a medical device that is capable of automatically analysing unstained tissues, differentiating normal versus neoplastic tissues with an accuracy higher than 98%, and differentiating and grading histologic subtypes with an accuracy higher than 90%. Our instrument will offer an accuracy comparable to the existing clinical protocols, but it will be much faster and more objective," says CRI's CEO and CTO Matteo Negro.

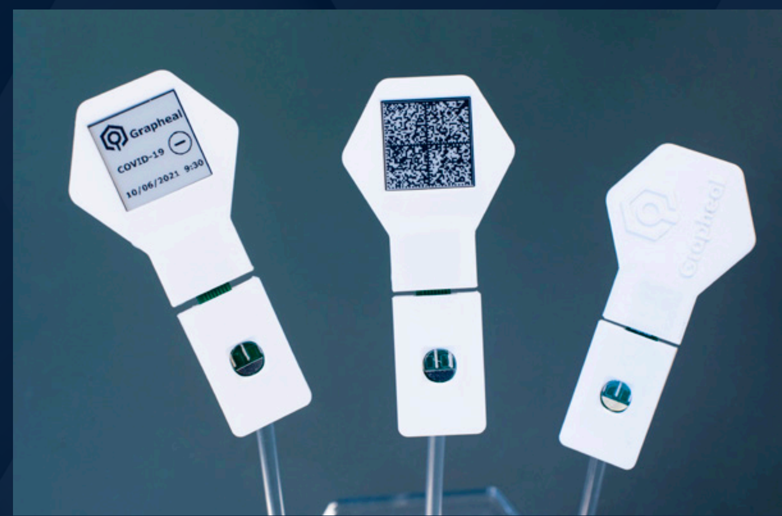
REMOVING GREASE FROM CIRCUIT BREAKERS WITH METAL-GRAPHENE COMPOSITES

Led by the Swedish-Swiss multinational corporation ABB, Graphene Flagship Spearhead Project Circuitbreakers investigates the use of metal-graphene composites to produce maintenance-free low voltage circuit breakers – devices connected to the distribution grid that open and close an electrical circuit during faults.

"Today we are at a stage where we are becoming very confident about graphene as a material for mechanical lubrication. That's why we have scaled up our intention, we aim to increase the technology readiness level and achieve successful applications," says ABB's research team manager, Santanu Singha.

GRAPHENE-ENABLED SENSORS FOR WOUND MONITORING, PATHOGEN DETECTION AND MORE

The rapid testing of COVID-19, TestNTrace, won the prestigious CES 2022 Innovation Award in Las Vegas. It was developed for COVID-19 by Graphene Flagship Associated Member Grapheal, France, but can be adapted to other applications. "TestNTrace shows the result in three minutes or less. It takes advantage of the contactless communication technology, that is already present in every smartphone. The collected data are GDPR compliant," says Grapheal's CEO Vincent Bouchiat. Previously, Grapheal developed the smart plaster WoundLAB: a pH sensor to monitor wound evolution without opening the bandage. Preclinical studies have shown that it is biocompatible and does not affect the wound, so the team will start the first clinical trials on a pilot study in diabetic patients.



Grapheal's TestNTrace was devised for the rapid testing of COVID-19 and won the prestigious CES 2022 Innovation Award in Las Vegas. Credit: Grapheal

Innovation

Head of Innovation
Kari Hjelt, Chalmers Industriteknik, Sweden

Work Package Deputy
Francesco Bonaccorso, BeDimensional, Italy

Overall our Work Package was a catalyst in the evolution of the Graphene Flagship from basic research to economic impact."

Kari Hjelt
Work Package Leader

Driving the commercialisation of graphene

Our goal in the Innovation Work Package is to create stronger links between Graphene Flagship researchers and external market opportunities. We aim to maximise the project's innovation potential through the creation of new ventures and spin-offs, the commercialisation of products and services based on of graphene and related materials (GRMs) through partnerships, as well as providing support in licensing intellectual property rights. We have a strong focus on business development, knowledge management and knowledge transfer.

THE LAST 10 YEARS

The Innovation Work Package has transformed its work from small, strategy and governance focused efforts to actively driving the Graphene Flagship's commercialisation efforts on an operational level. The formation of the business development function, creation of the Spearhead Projects and active collaboration with other Work Packages and external stakeholders have had a profound effect on the results and success of the project. Overall, our Work Package was a catalyst in the evolution of the Graphene Flagship from basic research to economic impact.

Early innovation work focused on outreach events to help increase the visibility of graphene and the project. As the Graphene Flagship has progressed, the innovation efforts have evolved to be more concrete. Direct contact with large industrial players, emerging SMEs in the graphene value chain and spin-off companies drive the commercialisation of project outputs.

The Business Developers have played a key role in helping to launch spin-off companies and to attract private investment, which has reached a total of nearly €100M across our 17 spin-offs. Work Package Innovation also helped to select the six Core 2 and 11 Core 3 Spearhead Projects, significantly increasing industrial participation in the Graphene Flagship and growing the volume of high technology readiness level (TRL) development to 12 percent of the project's budget in Core 2 and up to 30 percent in Core 3.

THIS YEAR'S PROGRESS

The Innovation Work Package acts as a booster and enabler for the technical Work Packages. These actions include several activities. First, we offer business development support for the Work Packages and Spearhead Projects with eight Business Developers located at key Partner sites and organized thematically on the most promising application areas. Second, we provide support on intellectual property (IP) rights, new ventures, commercialised products and services and licensed technologies. Next, we ensure continued alignment between the Industrialisation Work Package's technology and innovation roadmap (TIR) and the Graphene Flagship's innovation objectives and strategies, as well as innovation policy and management support. Finally, we facilitate industry outreach activities including Innovation Workshops and webinars on various technical and industrial themes contributing to a structured overview of industry needs and preferences stemming both from these workshops and mapping efforts.

In 2022 the Innovation Work Package organised the Graphene Innovation Forum at Graphene Week in Munich, Germany. The Innovation Forum presents a dedicated programme on the commercialisation of GRMs for industry attendees at the Graphene Flagship's annual conference. It is an opportunity to hear about the successful implementation of graphene from both start-ups and larger corporations. The Graphene Flagship Spearhead Projects and Business Developers presented their views on the challenges and opportunities for GRM applications. This year's event gathered nearly 100 attendees and was followed by a networking break bringing stakeholders from industry and academia together to exchange ideas for GRM innovations. The Work Package also organized four webinars, including a series on sustainability of graphene.

The Graphene Flagship attended two tradeshows in 2022: Enlit Europe, focusing on the European Energy transition, and ILA Berlin, an aeronautics exhibition. Head of Innovation Kari Hjelt is on the Graphene Flagship's Tradeshow Committee, and helped ensure that graphene is visible where the most promising application areas can be exploited. The Business Developers collaborated with the Dissemination Work Package in the selection of Partners, Associated Members, products and technologies to showcase at these shows. They also attended to help explain the commercial potential of GRMs in their application areas and act as spokespeople for the Graphene Flagship. At Enlit, Piero Gamarra, our Business Developer for energy applications, was interviewed for a podcast on how graphene will jump out of the lab and into commercial applications for the energy sector.

The Innovation Work Package at Graphene Week 2022. Credit: Juliane Haerendel, Graphene Flagship

Business Developers Ali Shaygan Nia and Piero Gamarra attended the Enlit Europe tradeshow to explain the commercial potential of GRMs for energy applications. Credit: Anastasia Papanicolaou, Graphene Flagship

Spearhead leaders discuss the next steps for graphene commercialisation in a panel discussion during the Innovation Forum at Graphene Week 2022. Credit: Juliane Haerendel, Graphene Flagship

Dissemination

Head of Dissemination
Rebecca Waters, Chalmers University of Technology, Sweden

Work Package Deputy
Letizia Diamante, The University of Cambridge, UK

> Dissemination creates visibility for the remarkable work being done every day across the Graphene Flagship, helping people understand graphene and its potential."
>
> **Rebecca Waters**
> Work Package Leader

Building a community around graphene and related materials

The Dissemination Work Package ensures that the Graphene Flagship's work is visible and accessible to its many stakeholders. Our website, social media, marketing materials and annual reports help spread the news about the latest breakthroughs, establishing the Graphene Flagship as the source for information on graphene and related materials (GRMs). Our tradeshows and exhibitions help promote the project's commercialisation goals, while our scientific and diversity events work to foster a community for those working across the entire GRM value chain, from the lab to the factory floor.

THE LAST 10 YEARS

As a service Work Package, Dissemination has evolved in step with the Graphene Flagship over the past decade. In the beginning, the goal was to help people understand what graphene is, why it is unique and how it can be applied to critical applications that touch all our lives. As the Graphene Flagship has become more established and graphene has become widely known, our mission has shifted to sharing the project's broader commercialisation message, success stories and exciting GRM applications.

Community building has always been a key component for Dissemination. The collaborations between academia and industry; Partners, Associated Members and the global community; and between producers and suppliers are a big part of what makes the Graphene Flagship successful. Over the years Dissemination has developed events that bring people together to share information, network and become inspired. Graphene Week, the project's annual conference taken over from the European Science Foundation at the start of the Graphene Flagship, is the oldest graphene conference, connecting graphene researchers and industry for 18 years. Our activities for early career researchers have also been important community builders, both to foster the next generation of graphene thought leaders and to facilitate connections between our junior and senior members.

Diversity and inclusion are also a foundation of our dissemination efforts. The Women in Graphene initiative, kicked off in Core 1 was made up of a series of events tailored to supporting women scientists in the Graphene Flagship. In Core 3, we expanded and rebranded the initiative to Diversity in Graphene and shifted our goal to celebrating diversity, build a welcoming community and raising awareness of the challenges faced by underrepresented groups in all STEM fields, in particular those in the GRM community. Today the initiative includes skills training through our Career Day programmes, a mentoring programme to provide one-on-one support and career coaching in addition to our regular events featuring inspirational talks from members of our community .

THIS YEAR'S PROGRESS

The past year was marked by the return to in person events. Graphene Week 2022, held at the awe-inspiring BMW Welt in Munich, Germany, 5-9 September, brought together graphene researchers and industry to an unprecedented level. Focusing on "Where science meets business," the conference hosted several industry outreach events, including the Innovation Forum, a special session by the business networking company Bayern Innovativ and the first ever in person 2D Experimental Pilot Line workshop providing "An industry perspective on CMOS integration."

At the Graphene Week, the Dissemination team kicked off a year-long celebration of the Graphene Flagship's decade of 2D materials innovation. The Open Forum featured a panel discussing the success of the project, and a pavilion was constructed to showcase our accomplishments in key application areas. A series of videos highlighting the Spearhead Projects was also prepared for this exhibition. The pavilion remained at BMW Welt over the weekend, inviting the thousands of people who visit the venue daily to learn about graphene and interact with our demos.

Tradeshows were also back in 2022, and the Graphene Flagship exhibited at both ILA Berlin and Enlit Europe in Frankfurt, Germany. ILA Berlin, one of the main European tradeshows for the aerospace sector, took place 22–26 June and gathered around 550 exhibitors and more than 72,000 visitors. Here we showcased key applications for graphene in aircraft and in space, including demonstrations of our GICE ice protection system and AeroGRaFT's air filter unit. Enlit Europe, a show dedicated to the energy transition, took place from 29

The Dissemination team.
Credit: Graphene Flagship

November to 1 December 2022 and attracted 700 exhibitors and 11,000 visitors. Graphene-based solar cells, graphene-enhanced circuit breakers and inkjet-printed supercapacitors were showcased at our booth located inside a dedicated EU project zone.

In addition to our work highlighting the Graphene Flagship's decade of success, we commissioned an economic impact report from WifOR Institute, an independent economic research institute, to provide concrete data on the European Commission's return on its Graphene Flagship investment. (See page 4.) A full report will be published soon with figures illustrating the impact our project has had on Europe and the global economy.

Over the next year, Dissemination will continue to celebrate the Graphene Flagship's 10-year anniversary, culminating in Graphene Week 2023 in Gothenburg, Sweden. The project has accomplished great things over the past decade, and Dissemination has been there every step of the way to share our successes with the graphene community, Europe and the world! Looking forward to Horizon Europe, Dissemination will continue to play a key role in the Graphene Flagship initiative, and some of our team will continue to our work in the Coordinating and Support Action that will launch in October 2023. We look forward to reshaping our dissemination activities to match the latest evolution of the project.

The Graphene Flagship pavilion at Graphene Week showcased key graphene applications.
Credit: Juliane Haerendel, Graphene Flagship

GRAPHENE FLAGSHIP ANNUAL REPORT 2022

Management

Work Package Leader
Jari Kinaret, Graphene Flagship Director, Chalmers University of Technology, Sweden

Head of Administration
Macarena Muñoz-Ruiz, Chalmers University of Technology, Sweden

The Graphene Flagship is currently celebrating its tenth year. We are consequently taking stock of the project and considering both how far it has come, and where the project's research and collaborations will go next."

Jari Kinaret
Work Package Leader

Charting a course to success

The Management Work Package ensures that Graphene Flagship outputs are properly monitored and reported on, coordinates the governing bodies and liaises with the European Commission. Our team also facilitates the growth of the project through the partnering mechanism, expressions of interest and the addition of new initiatives like the Spearhead Projects and 2D Experimental Pilot Line (2D-EPL).

THE LAST 10 YEARS

The effective management of the Graphene Flagship has been a key factor in the project's success. From the start, Management has ensured that the consortium had the tools it needed for growth and collaboration. The Work Package has developed infrastructure to help the partners share data, report their work efficiently and receive project updates. The Management team has updated the Graphene Flagship's governance structure to keep up with the growth of the project as it has increased in size and complexity. There have been a total of 231 different partners in the Graphene Flagship over the past ten years, including some in competitive market positions. Management has been instrumental in finding pathways to collaboration, even when relations have been challenging.

In a case study on the Graphene Flagship performed as part of an evaluation on excellent science in the European Framework Programmes for Research and Innovation, independent evaluators found the Management Work Package work to be exemplary: "The Graphene Flagship coordination was effective and able to engage stakeholders in the graphene related fields. It has furthermore shown to be able to adapt and adjust, when necessary, with activities following trends in graphene related research and other societal challenges such as recently devoting a study on the links with graphene and the UN SDGs."

Furthermore, the evaluation claims: "[The] partnering mechanism can be considered as a successful mechanism to widen participation, promote alignment and contribute to the advancement of graphene related material research in a coordinated way in Europe." 1 Management has had a strong commitment to fostering collaborations outside the project. The partnering mechanism has been instrumental in open the door to collaborations with European universities, industry and research projects working on complementary research and development activities.

Likewise, the Graphene Flagship extends its network internationally through multidisciplinary collaborations across institutions, coordinated by Graphene Flagship partner European Science Foundation, in France. International workshops, organised jointly between researchers in Europe and abroad, foster the exchange of ideas and research collaborations overseas. Collaborations have been established with the USA, Australia, Korea, Japan and China.

THIS YEAR'S PROGRESS

In 2022, Management split its time between coordination and collaboration tasks. We coordinated the second half of the Core 3 internal assessment, an exercise that examines the Work Packages' future plans and allows evaluators to give suggestions in time for the project to adjust. The team also organised the first in-person Annual Meeting since Core 2, allowing time for networking and socialising (an important factor in fostering new collaborations). Furthermore, the European Science Foundation produced two key deliverables. The first deliverable analysed the "European funding landscape on graphene and 2D materials" which revealed, among other things, that the member states honoured their agreements to co-fund graphene research and innovation activities. The "PPs and AM Integration Report" on Partnering Projects' and Associated Members' collaborations with Core 3 partners showed a clear path for Associated Members to become project Partners.

Collaborations within and without the project were an important part of the Management team's work in 2022. Internally, the team collaborated with the Innovation and Industrialisation Work Packages to develop a product and prototypes database. This has helped us to analyse the full impact of the Graphene Flagship and to better support and promote Partners' commercialisation efforts. Management has also helped to keep the consortium informed about upcoming funding opportunities: sharing call information and helping partners plan beyond Core 3. Collaborations with other large European projects allowed us exchange best practices, plan for collaborations outside our current work and exploit synergies in our work.

Our International Workshops resumed in-person with EU-US and EU-Korea meetings being held at Graphene Week 2022. Meetings Australia, Korea and Japan are already planned for 2023, along with the launch of a new International Workshop series with Singapore. These workshops encourage an exchange of ideas and foster collaborations that help advance research and innovation. Strengthening connections and collaborations on graphene and related materials research between Europe and the rest of the world has never been more important.

The next year will be critical for the Management Work Package as we close Core 3, coordinate the final review and plan for the future.

Head of Administration Macarena Muñoz-Ruiz at the Annual Meeting in Dublin, Ireland. Credit: Graphene Flagship

Klaus Ensslin, Director of the National Center of Research on "Quantum Science and Technology" at ETH Zurich kicks off the EU-US Workshop in Munich, Germany. Credit: Juliane Haerendel, Graphene Flagship

References
Es-Sadki, N. (2023). Case study on FET Graphene Flagship. Evaluation study on Excellent Science in the European Framework Programmes for Research and Innovation. Phase 1 Final Study report. European Commission. Directorate-General for Research and Innovation.

GRAPHENE FLAGSHIP ANNUAL REPORT 2022

Industrialisation

Work Package Leader
Alexander Tzalenchuk, National Physics Laboratory, UK

Work Package Deputy
Thomas Reiss, Fraunhofer ISI, Germany

Europe needs to establish enhanced innovation sovereignty, which is more resilient, with robust value chains for essential services and products. Guidance and orientation for GRM-based innovation with a holistic perspective are essential. We can offer this perspective."

Alexander Tzalenchuk
Work Package Leader

Building confidence in graphene and related materials

The Industrialisation Work Package is critical to the Graphene Flagship's commercialisation mission. Its roadmapping work helps the project explore market opportunities and provides general market and competition intelligence. Furthermore, its validation and standardisation services create trust and confidence in graphene and related materials. Last, but not least, its activities facilitate networking between industry and academia, a keystone of the Graphene Flagship's success.

THE LAST 10 YEARS

From the launch of the Graphene Flagship, Industrialisation has played an important role in guiding the project towards market needs via innovation roadmaps and our innovation interface investigation concept. In fact the Work Package's Technology and Innovation Roadmaps have been remarkably accurate resources to determine the most promising markets and applications for graphene and related materials (GRMs) and have been used to determine the best path forward. While the GRM market is expanding, there are still obstacles to growth. The outcomes of the roadmap work also show the lack of application-oriented and traceable material quality standards of graphene.

The Industrialisation Work Package has worked to establish a coherent industrial workflow towards GRM-based innovation involving key requirements for the adoption of new materials in industry: trust, confidence, reliability of material properties via validation and standardisation. The aim of the validation service is to provide confidence in graphene and related materials to enable a quicker transition of graphene products to market using authorised national measurement institutes and facilities world renowned for their excellence, independence, integrity and impartiality.

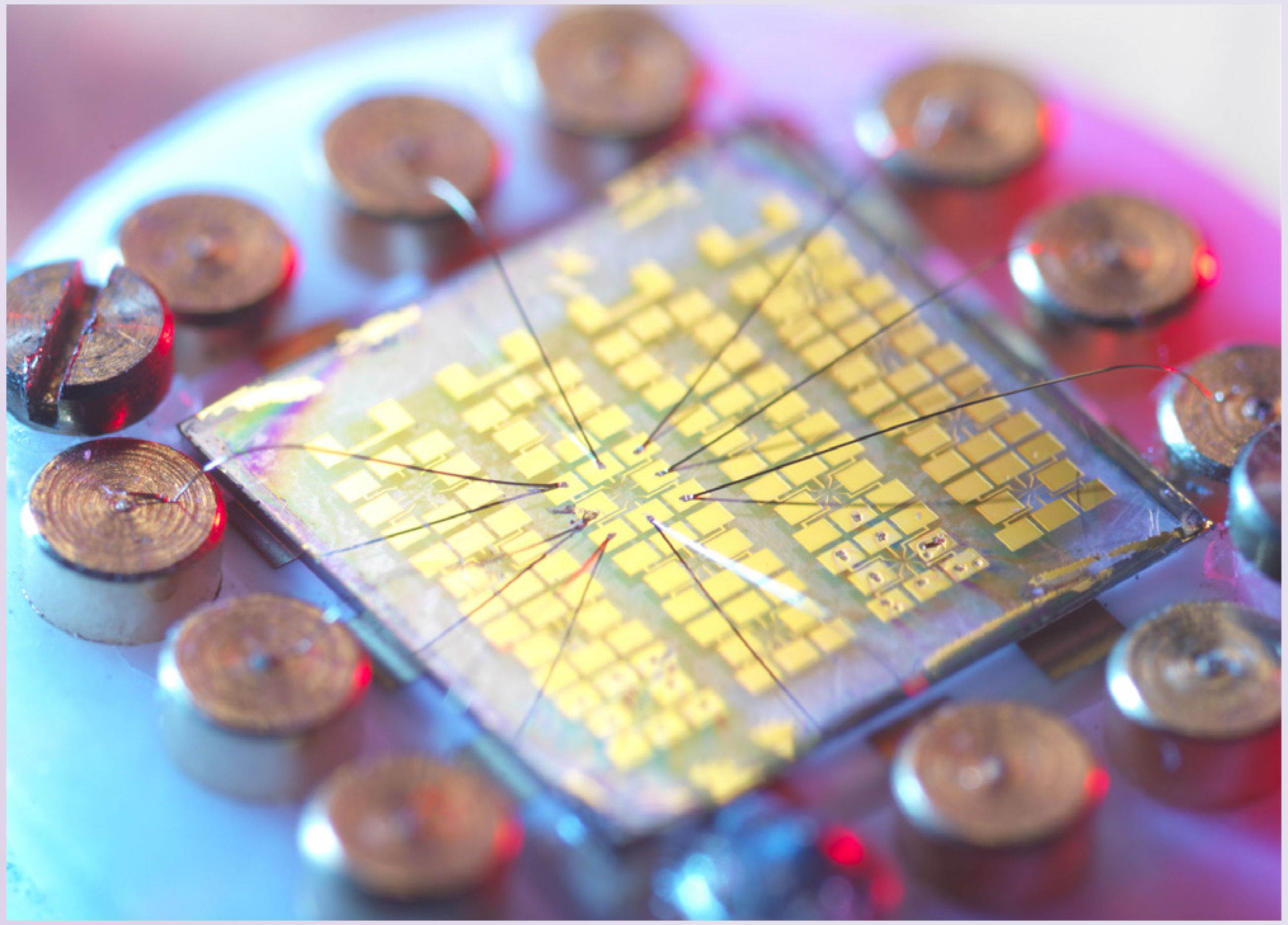
The Graphene Flagship Standardisation Committee (GFSC) has been part of the Graphene Flagship from its inception, but now that the project is closer to commercialisation, interest from industry is increasing. The GFSC works with both the IEC and ISO in a formal and informal capacity and has ensured a strong European voice in both bodies. In the IEC, 50 percent of all graphene projects are being led by European scientists. Within that, the GFSC is leading 70 percent, giving us a strong voice in graphene standardisation.

The Samples and Materials Database (SMDB) is a tool curated for the Graphene Flagship community, to help Partners exchange samples and materials, and to gather information on their use. In 2021 a new SMDB was developed as a stand-alone application that will continue to be available after the end of Core 3. Chalmers University of Technology personnel, in collaboration with the Industrialisation Work Package, developed the best way to collect data with new and relevant Key Control Characteristics (KCCs), a more user-friendly layout and improved search functionality. Currently, the SMDB has over 50 samples/materials, from 6 Partners, which are available on request. All Graphene Flagship Core 3 partners have full access to the SMDB, 2D-EPL partners and Associated Members have read access.

THIS YEAR'S PROGRESS

Over the past year, the roadmapping team has performed new in-depth explorations of future GRM value chains though focus investigations into two novel topics: thermal management and cement. They have also completed comprehensive revisions of the batteries and neural interfaces roadmaps. Case studies on supercapacitors for space will provide information for a future roadmap.

The Validation Service, available free-of charge to Graphene Flagship partners, continues to be popular, with 59 validation requests received and 35 completed to date. Four novel tests related to chemical and thermomechanical analyses of lubricants were developed by the Laboratoire National de Métrologie et d'Essais (LNE), France, in response to industry needs. The National Physical Laboratory (NPL), UK, Universidad de Zaragoza, Spain and CNR, Italy contributed to three VAMAS interlaboratory comparisons in 2022.



Graphene device under test at NPL.
Credit: NPL

80

The Roadmap team has consulted more than 80 stakeholders via interviews, workshops over the past decade.

Thurid Gspann, the Chair of the Graphene Flagship Standardisation Committee, took part in the Graphene Week 2022 exhibition.
Credit: Juliane Haerendel, Graphene Flagship

As of 2022, 16 standardisation projects are being led by GFSC members, and seven of them have been published. Five technical leads and their core team have received the Graphene Flagship Standardisation Certificate in acknowledgement of their contributions toward new standards.

Looking forward, there is an ever-growing need for the Industrialisation Work Package's services. Post-covid and in light of the war in Ukraine, Europe will need to establish enhanced innovation sovereignty, which is more resilient, having established robust value chains for essential services and products (health, food, energy, communication, etc.). Guidance and orientation for GRM-based innovation with a holistic perspective are essential. We can offer such a perspective.

Building bridges

An interview with Ana Helman on the connections and collaborations at the core of the Graphene Flagship

Ana Helman – currently the Managing Director of the European Centre for Quantum Sciences at the University of Strasbourg in France – served for nine years as the European Alignment Officer for the Graphene Flagship. Working as part of the Management Work Package at the European Science Foundation (ESF), Helman oversaw coordination actions between the EU, various national programmes and international collaborations with countries such as USA, South Korea, Japan, China and Australia.

We sat down with her to talk about her journey with the Graphene Flagship, the various milestones achieved and her aspirations for graphene and the project.

> I have been very grateful of the many opportunities that the Graphene Flagship has offered me to grow professionally and personally. From a more general perspective, having such a large community working together towards common objectives can only be beneficial as it accelerates the scientific and technological advances in a quite spectacular way."
>
> **Ana Helman**

LAUNCHING THE GRAPHENE FLAGSHIP

Ana Helman's journey with the project began when Graphene Flagship Director Jari Kinaret approached her in 2010 with the initial idea for the Flagship. At that time, she was the programme coordinator at the European Science Foundation, in charge of managing the collaborative EUROCORES research programme on graphene, called EuroGraphene.

At that time EuroGraphene was already supported by 15 national funding agencies across Europe. A network of funders had been established, and they were able tap into this network. Helman was invited to join EuroGraphene's first launch meeting at the University of Strasbourg. The discussions and brainstorming sessions that transpired in this first meeting led to ideas on how to bring together the graphene community. A proposal for the Graphene Flagship pilot was then submitted by a consortium of nine partners in response to a call by the European Commission (EC). The proposal was approved and funding for a Coordination and Support Action was obtained. Helman had two main responsibilities. Firstly, to provide an interface between the national funders and the research community. And secondly, to identify the main initiatives at the national level where they could build a Europe-wide network of researchers and organisation. This was a perfect role for her given her varied experiences in both academia and industry. It was through these interactions that the Graphene Flagship was born.

The plan was for the funding from the European Commission to be integrated with contributions from the EU Member States. This was a new concept. Consequently, there were multiple meetings and discussions to ensure both coherence and flexibility to facilitate research in a rapidly evolving ecosystem. It was Helman's role to work with the stakeholders – national funders, the EC and Graphene Flagship Management – to create a succinct framework to allow them to come together.

The FLAG-ERA NET was also established in the initial phase of the Flagship programme to bring together multiple national and regional funding agencies to support the two Flagships: the Graphene Flagship and the Human Brain Project. They agreed to regularly launch dedicated calls for funding in synergy with the Flagships. This has been crucial to keeping the dialogue between the EC and nationally funded parts of the Flagships alive. Additionally, Helman and her team introduced the possibility for individual organisations to join the Graphene Flagship as Associated Members. Her work here proved extremely successful for attracting companies, and in particular small- and medium-sized enterprises (SMEs) under the Flagship umbrella. This further assimilated the synergy between academia and industry.

CONNECTING WITH RESEARCH AND INDUSTRY GLOBALLY

Multiple countries globally were also investing and launching programmes on graphene research around the same period. Hence the idea of a large-scale European initiative on graphene attracted a lot of interest and was very well received by the international research community. These constellations of graphene research clearly put graphene on the map as a new and important emerging technology. This consequently gave the Graphene Flagship strong international visibility.

International visibility expanded collaborations between researchers in Europe and the rest of the world. Regular International Workshops were established to deepen research and further identify promising avenues for research and collaborations. Helman and her team at ESF, played an integral role in providing organisational support for these workshops and establishing links with a growing number of countries.

ACCOMPLISHMENTS

When asked about her accomplishments, Helman attributed the success of the Graphene Flagship to the long-term perspective – which sets it apart from typical three-year EC-funded research initiatives – that drove invaluable research and communication in this area. This has allowed the Graphene Flagship to build a strong and resilient community that has and will continue to develop activities and facilitate research which will result in strong and important impact over time. She also credits the Graphene Flagship's success to great teamwork, which sometimes included long but always constructive discussions between the various subgroups within the project – management, administration and scientific divisions. This has been integral to overcoming varied challenges.

LOOKING AHEAD

When asked about her thoughts on the Graphene Flagship's future, she explains that the first ten years of work through research and implementation have now started to bear fruit. Hence it would be interesting and important to have these findings assessed and measured independently. (See page 4 for preliminary data from one such assessment.) She is also extremely grateful for the opportunities that the Graphene Flagship has afforded her. She adds that having such a large community working together towards common objectives can only be beneficial as it accelerates the scientific and technological advances in a quite spectacular way. Graphene and related materials and technologies are now branching out to many different application areas. And the research, industry and funding communities are responding accordingly. She says it will be exciting to see the new research and findings that will come out of these collaborations ten years on.

On a personal level, Helman emphasises and celebrates the lifelong impacts and mobility opportunities that have arisen from the various interactions between junior and established researchers that the Graphene Flagship has facilitated. She herself is one such beneficiary. She reiterates that she will definitely use the many skills and knowledge attained over the past ten years at the Graphene Flagship in her new role as the Managing Director of the European Centre for Quantum Sciences at the University of Strasbourg in France. We wish her all the best in her future endeavours.

Partnering Division

Division Leader
Yuri Svirko, University of Eastern Finland, Finland

Division Deputy
Jan Erik Hanssen, Graphitene Ltd, UK

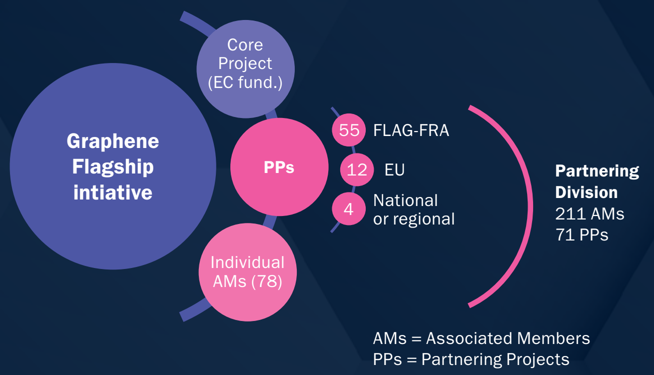
Yuri Svirko
Division Leader

The integration of the Associated Members (AMs) and Partnering Projects (PPs) within the Graphene Flagship can be considered a successful example of joint European research and technological advancement, bringing research organisations involved in complementary activities funded under national and European projects, and SMEs and companies in the field of graphene and related materials (GRMs) under the same umbrella. Overall, there are high expectations for 2D materials, as evidenced by the level of funding at European and national level and other investments. This has created a European network composed of many different actors, involved in the Graphene Flagship initiative and beyond, which has contributed to the advancement of GRM research towards market-ready products.

As of 1 January 2023, the Graphene Flagship Partnering Division numbers 112 Associated Members, out of which 49 are individual Associated Members, and the rest belong to one of 33 Partnering Projects.

Below we present the 2022 highlights from a small selection of Associated Members and Partnering Projects.

Partnering Division from Core1 through January 2023



INSTITUTE FOR HIGH PERFORMANCE MICROELECTRONICS (IHP)

ASSOCIATED MEMBER AND CORE PARTNER

The Institute for High Performance Microelectronics (IHP, Germany) began as an individual Associated Member in Core 1 and Core 2, and became an Associated Member of the Partnering Project 2DHetero (hBN/Graphene 2D Heterostructures: from scalable growth to integration) – a project that aims to develop graphene/hexagonal boron nitride heterostructures on substrates compatible with silicon microelectronics – in Core 3. Subsequently it joined the Core Partners in the 2D-EPL project. The Institute develops graphene-based electronic and photonic devices which it stives to integrate with the IHP's core BiCMOS technologies. Graphene-related research activities include the development of a toolbox of technological processes required for graphene device fabrication in a 200 mm silicon wafer pilot line, accompanied by metrology methods that provide feedback in the fabrication process.

UNIVERSITY OF EASTERN FINLAND

ASSOCIATED MEMBER

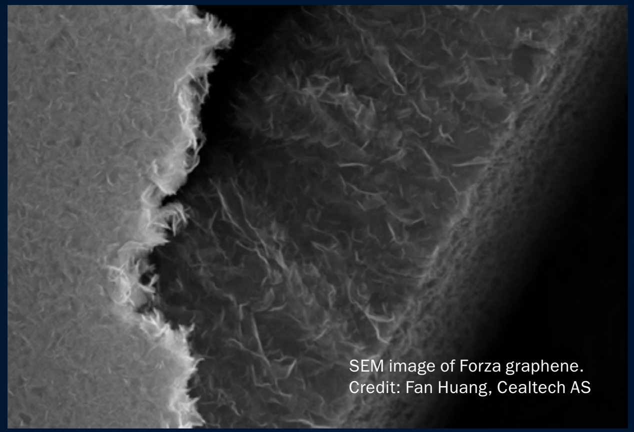
The University of Eastern Finland (Finland) was a Core Partner organisation in FP7 and Core 1. Then it became an Associated Member, taking part to the Partnering Projects CoExAN (Collective Excitations in Advanced Nanostructures) and DISETCOM (Dirac Semimetals based Terahertz Components). The research group looks at the application of layered materials in THz photonics, in collaboration with Core Partners and Associated Members of the Graphene Flagship with a synergistic effect. The complementary expertise of Associated Members supports the rapid evolution of the Core project and enables new opportunities in both fundamental research and technological implementation of GRM.

UNIVERSITY OF NOVA GORICA

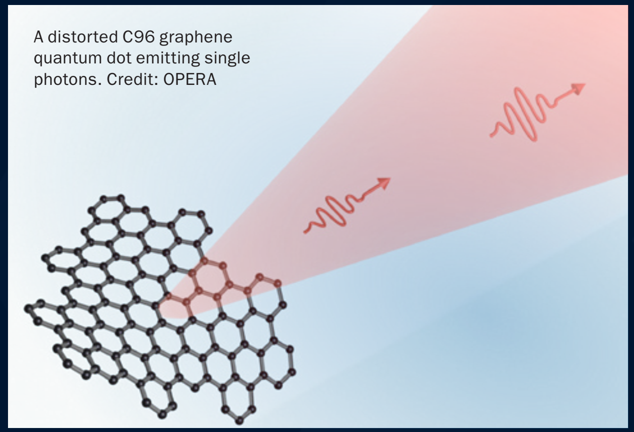
ASSOCIATED MEMBER

The University of Nova Gorica (Slovenia) has been an Associated Member since Core 1, and has been involved in several Partnering Projects like MX-OSMOPED (MXene–organic semiconductor blends for high-mobility printed organic electronic devices), NanoElMem (Designing new renewable nano-structured electrode and membrane materials for direct alkaline ethanol fuel cell), PROSPECT (PatteRned cOatings based on 2D materials benzoxazine reSin hybrids for broad range Pressure detECTion) and DIMAG (Electrically controlled ferromagnetism in 2-dimensional semiconductors).

Over the last ten years, the Laboratory of Organic Matter Physics of the University has made great strides in mastering the fabrication and characterization of electric charge transport in field-effect devices based on blends between organic semiconductors and micron-size flakes of layered materials. The team, in collaboration with Graphene Flagship Partners University of Strasbourg, Technische Universität Dresden, Chalmers University of Technology and several Associated Members, has performed successful experiments to elucidate the electronic properties of charge carrier transport at the interface between organic semiconductor molecules and flakes of graphene, reduced graphene oxide and MXenes.



SEM image of Forza graphene. Credit: Fan Huang, Cealtech AS



A distorted C96 graphene quantum dot emitting single photons. Credit: OPERA

SIGNAL

PARTNERING PROJECT

The SiGNAL project (Silicon-Graphene Nanoengineered Anode for Li-ion battery) aims at integrating graphene and silicon for future anodes of lithium-ion batteries to address the increasing demand for higher energy density batteries. In this project, the teams from CealTech, the Institute for Energy Technology and the University of Oslo are using an exclusive license from California Institute of Technology (Caltech) and their own patent pending Forza technology to meet industrial requirements necessary for commercialisation. Furthermore, in 2022, the Research Council of Norway selected CealTech as one of the 18 innovative companies for Offshore Northerns Seas (ONS) Innovation Park, which showcases exciting technologies related to some of the challenges facing the energy industry today.

OPERA

PARTNERING PROJECT

The OPERA project (Nanographene for quantum technologies) is mastering the synthesis, studies and theoretical understanding of graphene materials with perfectly defined structures and on-demand designed properties. OPERA gathers partners with complementary skills in chemical synthesis, theory/modelling, spectroscopy and quantum optics. In 2022, the consortium has been able to reveal the quantum states at the origin of the emission of single graphene quantum dots, synthesized by bottom-up chemistry and composed of 96 carbon atoms. Likewise, the OPERA members have measured the vibrational fingerprints of these graphene quantum dots. Finally, a breakthrough in their synthesis led to highly soluble graphene quantum dots with unprecedentedly high fluorescence quantum yield (up to 95%).

- Liu, T. et al. Nanoscale 2022, DOI: 10.1039/D1NR08279E
- Liu, T. et al. J. Chem. Phys. 2022, DOI: 10.1063/5.0083282

MARGO

PARTNERING PROJECT

The MARGO (Maxillofacial bone regeneration graphene oxide) project develops bio-inspired surfaces for the reconstruction of face and jaw bones. In particular, it aims to build a prototype of an integrated 3D printer with a laser activation system that allows patient-tailored grafts with optimized antibacterial and pro-osteogenic features. The project is coordinated by the Nonlinear Photonics Laboratory at the Physics Department of the University Sapienza of Rome (Italy), whose researchers have worked on graphene oxide in the field of bioengineering since 2016. The members of MARGO project regularly participate to Graphene Flagship events, to share achievements and key-results in the applications of graphene.

- Palmieri, V. et al. Appl. Surf. Sci. 2023, DOI: 10.1016/j.apsusc.2022.156315

GRAPHENEST

INDIVIDUAL ASSOCIATED MEMBER

Graphenest (Portugal) teamed up with Delta Tecnic (Spain) to develop a family of compounds for electrical and, particularly, electromagnetic (EMI) shielding applications. The current materials used for cable shielding are usually rigid, heavy meshes or highly overlapped and expensive metal-based foils. Graphene provides a lot of advantages and excellent EMI shielding on a wide range of frequencies, especially at high and very high ranges, which is essential for 5G and 6G communications. The material produced by the two companies opens the unprecedented possibility of achieving top-notch shielded energy and data cables much more rapidly: a partial or complete replacement of the metal braiding speeds up the production at least 40 times, extruding at a velocity of 200 meters/min instead of braiding at 5 metres/min. Graphenest is also involved in the NeuroStimSpinal Partnering Project, which aims to advance treatments in spinal cord injury, using graphene-enabled scaffolds and electrical stimulation, and has established links with the Graphene Flagship's Biomedical Technologies Work Package.

In production

A step-by-step look at the 2D-EPL's first multi-project wafer run

The 2D Experimental Pilot Line (2D-EPL) is a Graphene Flagship project created to address the challenges of establishing reliable fabrication processes for high-volume production of graphene and related materials (GRM) based electronics, photonics and sensors. Part of this process is the development of multi-project wafer (MPW) runs in which customer designs are included as dies on joint wafers. This article will take us through the manufacturing steps involved in the 2D-EPL's first MPW run. Future runs will operate in a similar fashion, though they will be tailored to different applications and build on the experience of past runs.

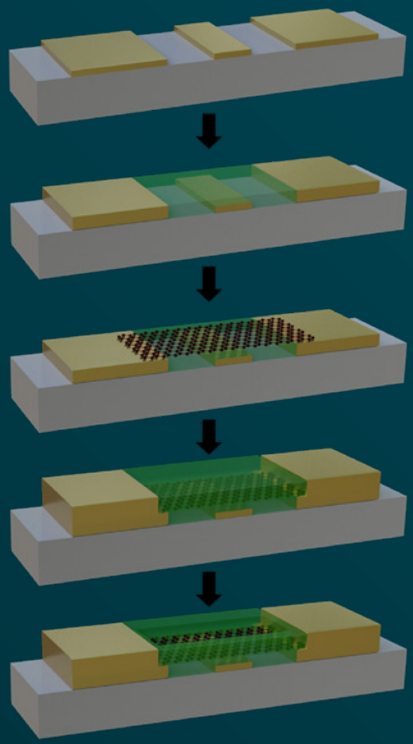
STEP 1
Back gate and contacts

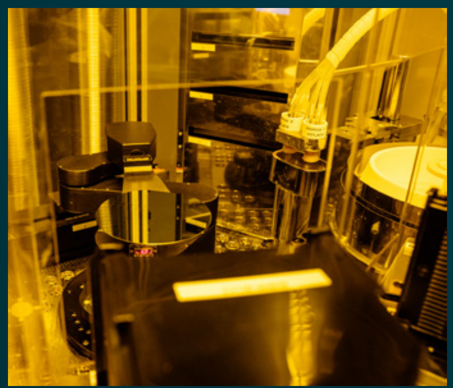
STEP 2
Dialectic

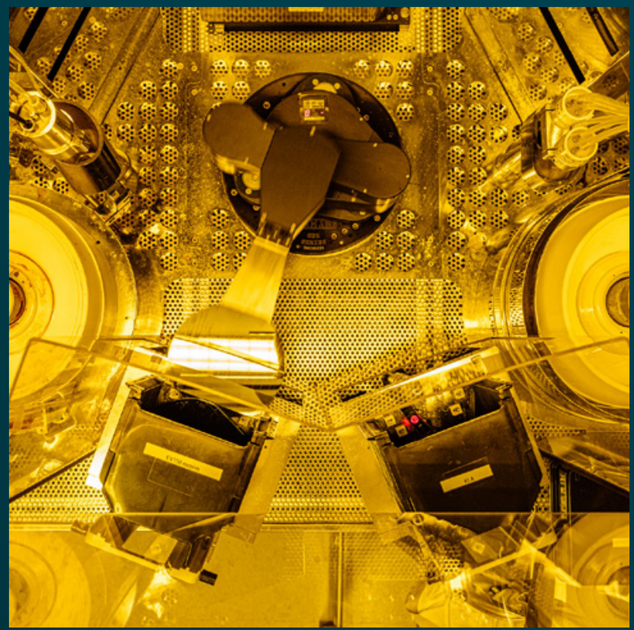
STEP 3
Graphene transfer and patterning

STEP 4
Contacts and encapsulation

STEP 5
Opening of encapsulation

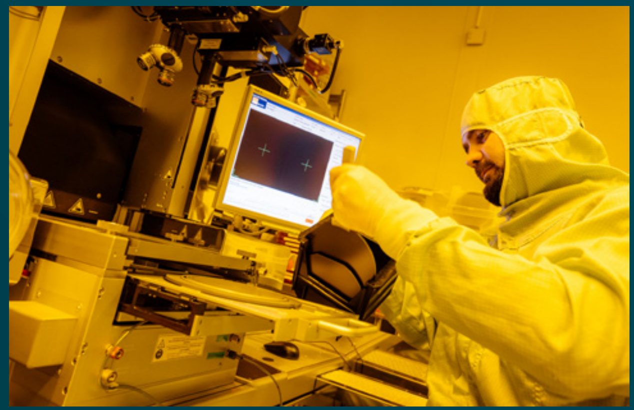






Wafer coating & development

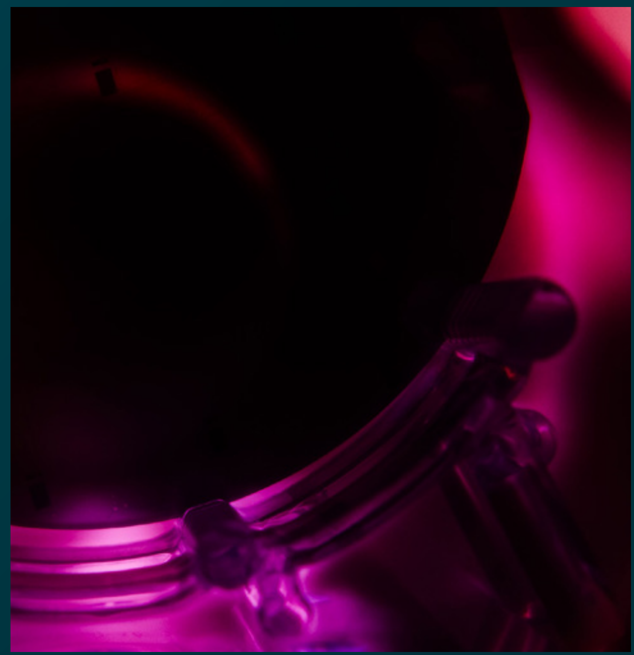
STEP 1
BACK GATE AND CONTACTS
The fabrication process includes several metallisation steps to deposit the back gate as well as the bottom and the top contacts. Each metallisation step is formed by four sub-steps (coating, UV contact lithography, development, metal evaporation, and lift-off).



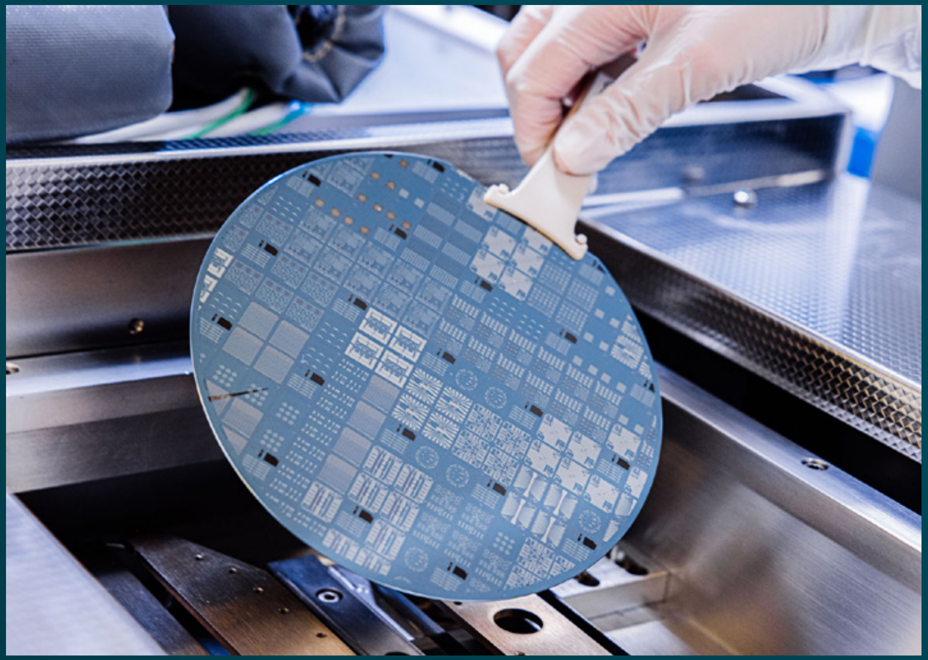
UV contact lithography

STEP 2
DIELECTRIC DEPOSITION
The gate dielectric (Al2O3-layer) is deposited using atomic layer deposition (ALD).

STEP 3
GRAPHENE TRANSFER AND PATTERNING OF GRAPHENE
The graphene is grown by Graphenea (Spain), who then transfer it onto the wafer. After the transfer, the wafers are sent back to AMO where it is patterned in the desired shape using reactive ion etching and plasma etching.



GRAPHENE FLAGSHIP ANNUAL REPORT 2022

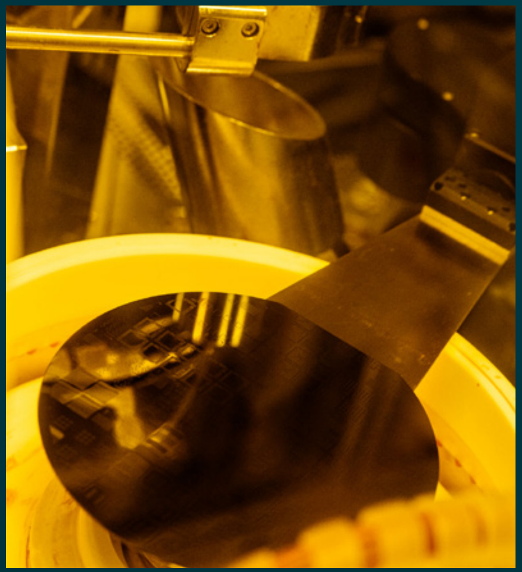


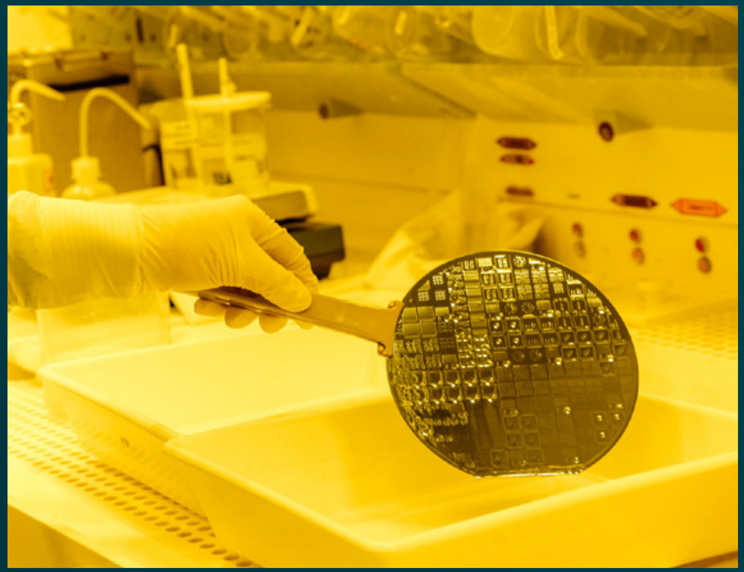
STEP 4
CONTACTS AND ENCAPSULATION

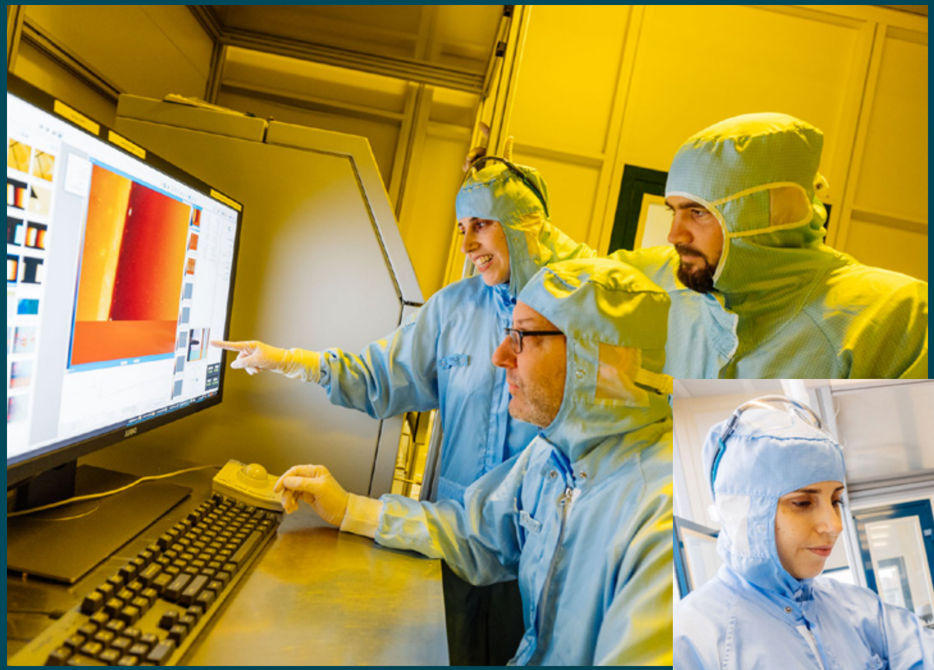
After graphene is patterned, the wafers undergo a final metallization step when the top contacts are fabricated, followed by encapsulation with Al_2O_3.

STEP 5
OPENING OF ENCAPSULATION

For encapsulation, the wafer goes through another round of coating, lithography, development, evaporation and lift-off to open the contact pads and the graphene area of the sensors.







STEP 6
TESTING

Finally, the wafers are extensively tested using optical microscopy, Raman spectrocopy, as well as electrical measurements on test devices.

GRAPHENE FLAGSHIP ANNUAL REPORT 2022

Wafer Scale Growth

Michael Heuken
Work Package Leader

Work Package Leader
Michael Heuken, AIXTRON, Germany

Work Package Deputy
Amaia Zurutuza, Graphenea Semiconductors, Spain

Developing systems to scale up the growth of 2D materials

The Wafer Scale Growth Work Package aims to scale up the growth of high-quality single crystalline graphene and related 2D materials to 300 mm substrates and to provide the 2D films for the 2D Experimental Pilot Line (2D-EPL) processes.

THIS YEAR'S PROGRESS

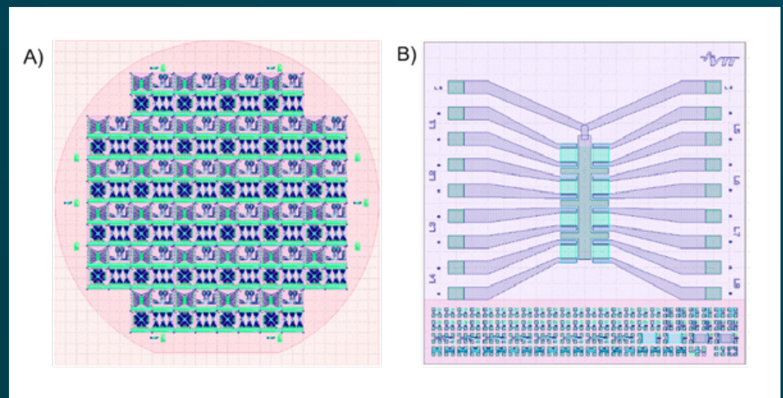
Over the past year AIXTRON completed the new 300 mm MOCVD (metal-organic chemical vapour deposition) system for the growth of 2D materials, and final testing will be performed by 2D process demonstration in 2023 at imec where the tool will be allocated. This system will be a key component for the flexible R&D and prototype production of 2D materials in the semi-industrial form factor on the wafer sizes up to 200 and 300 mm used by 2D-EPL partners.

The work package also performed research and optimisation of growth of transition metal dichalkogenides (TMDCs) on sapphire and graphene on catalytic CuNi (111)/sapphire, Cu (111)/sapphire and Cu foil-based substrates on 200 mm and 300 mm wafers. Another outstanding achievement was the development of the growth of high-quality graphene on Cu foils by Graphenea Semiconductors, which allowed fabrication of graphene field effect transistor (GFET) devices by VTT and AMO demonstrating graphene mobility of >2,400 cm²/Vs on 200 mm wafers.

BUILDING ON THE GRAPHENE FLAGSHIP FOUNDATION

AIXTRON, Graphenea, imec and AMO have been important Graphene Flagship partners from the beginning. They have benefited from the collaboration under the framework of the Graphene Flagship and the 2D-EPL thanks to the creation of an ecosystem where the partners can develop the 2D technology in much faster time frame as compared to the separate efforts.

Close collaboration between 2D-EPL partners (AIXTRON, Graphenea, imec, AMO, VTT and IHP) in the 2D materials area and good alignment with Core 3 Graphene Flagship work packages and spearheads have paved the way for our success. In turn, AIXTRON's 300 mm system will be a key component in the development of the 2D-Experimental Pilot Line.



GFET devices (128 chips measured) on a 150 mm wafer by VTT fabricated using graphene grown on 200 mm Cu foils by Graphenea. Credit: Graphenea Semiconductors

FUTURE CHALLENGES

The main challenge in the coming year will be the start-up of the AIXTRON 300 mm 2D system at imec, including the qualification of initial processes. The main goal for 2023 is therefore to demonstrate initial growth of 2D material on 200 mm and 300 mm substrates with this system. This target is still achievable despite present delays linked to the necessity of additional thorough system testing before delivery to improve the stability of the software.

IMPACT

Our work promises to impact various industries. CVD growth of graphene on 200 mm and 300 mm wafers will be valuable in various applications such as biosensors, sensors, IR cameras and telecommunications. The target application for MOCVD growth of TMDC layers on wafers up to 300 mm is for use as channel materials in ultra-scaled CMOS transistors. Furthermore, TMDC layers (like WS_2, MoS_2, etc.) are named for neuromorphic computing and spintronic applications in the literature.

Wafer Scale Transfer

Marie-Emanuelle Boulon
Work Package Leader

Work Package Leader
Marie-Emmanuelle Boulon, imec, Belgium

Work Package Deputy
Thomas Rapps, SUSS MicroTec Lithography, Germany

Improving transfer processes for higher-quality 2D materials

The Wafer Scale Transfer Work Package is developing a module to transfer high-quality 2D materials from the growth wafer to a target wafer for the 2D Experimental Pilot Line (2D-EPL).

THIS YEAR'S PROGRESS

Over the past year, the Wafer Scale Transfer Work Package achieved its objectives concerning the target material and the demonstration of the delamination of MX2 from sapphire. The collaboration between the partners was fruitful with a large number of wafers being exchanged among us, including those used in the first multi-project wafer (MPW) run.

A mechanical debonder tool was constructed by SUSS MicroTec Lithography for the delamination of MX_2 at 200- and 300 mm scale. Since experimental research showed that water intercalation is needed to facilitate the delamination process, the debonder tool is equipped with two water hoses that can introduce water at the crack propagation front to enable a reliable debond process. A drying arm was also engineered to dry both the top and bottom wafers after the opening of the stack. This arm can move along the wafers flushing N2 gas in both top and bottom directions.

BUILDING ON THE GRAPHENE FLAGSHIP FOUNDATION

Our work package has benefitted from the Graphene Flagship's work on wafer-scale integration with partners on both graphene supply and wafer preparation tasks bringing their expertise from the Core project. We have also built upon the foundations of collaboration in the 2D-EPL with processes relying on wafer exchanges and interconnected workflows.

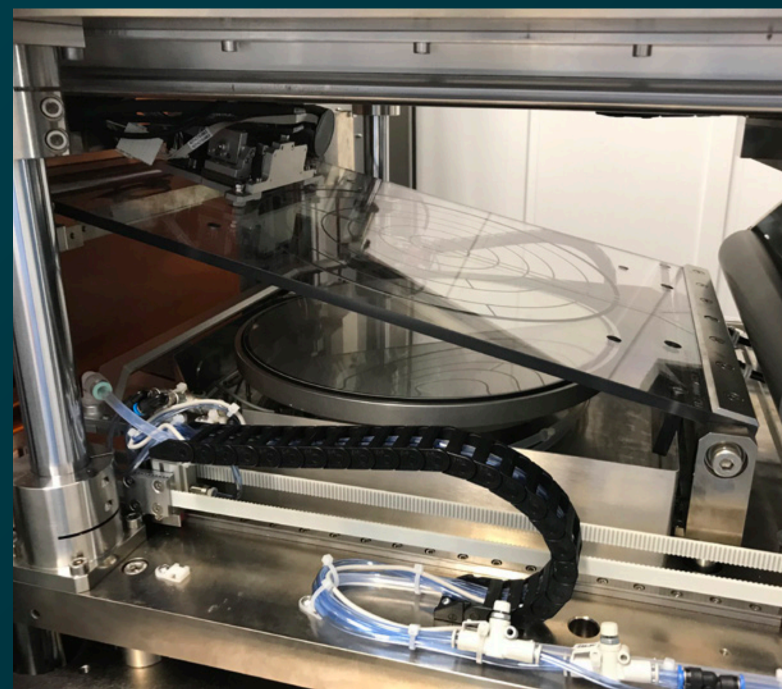
FUTURE CHALLENGES

Over the next year we will address some remaining challenges in the wafer scale transfer process. The new SUSS delamination tool will allow us to upscale the transfer of MX_2 grown epitaxially to 200 mm wafers. We will also test new polymers on MX_2 to assess their delamination properties and hope to simplify the cleaning process while maintaining their intrinsic properties and high mobility. Finally, we will develop a process to improve the copper foil quality to allow higher quality of graphene to be grown on it.

IMPACT

The work performed by the Wafer Scale Transfer Work Package will increase the quality of graphene and other 2D materials on wafers, accelerating the adoption of 2D materials for electronics, photonics and optoelectronics devices. These devices will benefit from 2D material properties allowing for more-than-more processing capabilities.

The SUSS 2D layer transfer module for the 200 mm and 300 mm MX_2 delamination process. Credit SUSS MicroTec Lithography



Wafer Scale Integration

Work Package Leader
Miika Soikkeli, VTT Technical Research Centre of Finland, Finland

Work Package Deputy
Mindaugas Lukosius, IHP – Leibniz Institute for high Performance Microelectronics, Germany

Miika Soikkeli
Work Package Leader

Developing processes for the fabrication of field effect transistors

The work done in the 2D Experimental Pilot Line's Wafer Scale Integration Work Package aims to develop the process steps needed for the fabrication of graphene and other 2D material-based devices such as field effect transistors. This includes for example the optimization of the active patterning, contacting and passivation module development. A significant effort is also placed on the quality control development to ensure process stability and unified parameter extraction for the devices.

THIS YEAR'S PROGRESS

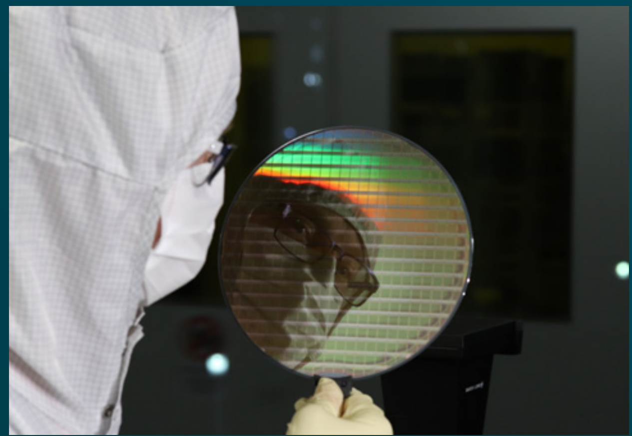
Our work package's biggest technological accomplishments over the past year are related to developments in dielectric deposition. We have demonstrated a way to deposit high-quality dielectrics with plasma enhanced atomic layer deposition (PEALD) processes on graphene without noticeable channel property degradation. In addition to this, the uniformity of the seeding layer has improved by using a modified atomic layer deposition process relying on physisorption for oxide gate stack deposition on transition-metal dichalcogenide (TMDC) channels.

The processes developed are being utilized in the multi-project wafer (MPW) runs and are also available directly from the pilot line partners. The partners have already established stable process flows in the pilot line sites that can be utilized in product development for customers.

The first MPW runs focused on providing services for companies interested in graphene-based sensors. Further process optimization will enable higher electrical quality and higher complexity of the devices in the future. The upcoming MPW runs will include electronics and integration of devices on top of CMOS readout wafers.

FUTURE CHALLENGES

One specific challenge that we have addressed is the verification and development of quality control protocols. These have been performed by analysing the uniformity of the determined key control characteristics and yield for graphene- and TMDC-based devices fabricated on 150 mm, 200 mm and 300 mm wafers. This has been an important step towards standardised devices over the last year. The work has also continued in collaboration with Graphene Flagship's standardisation committee and International Electrotechnical Commission (IEC) to move forward with the standardisation of the protocols.



Our work package focuses on the development of processes for graphene FET CMOS readout integration. Credit: VTT

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

IMPACT

The processes developed in the Wafer Scale Integration Work Package can be utilised in the fabrication of devices for sensing, electronics or photonics applications with graphene. The processes developed for TMDC-based devices can be utilised for logic-type of applications. Likely, the first application area where we see potential impact is in bio- and gas-sensing applications as well as in infrared (IR) cameras.

Modules for the Industry

Work Package Leader
Daniel Neumaier, AMO, Germany

Work Package Deputy
Olli-Pekka Kilpi, VTT Technical Research Centre of Finland, Finland

Daniel Neumaier
Work Package Leader

Launching the multi-project wafer runs

The Modules for the Industry Work Package of the 2D Experimental Pilot Line (2D-EPL) project is developing fabrication processes for sensing, electronics and photonics applications. The main outcome of our work is the preparation and execution of multi-project wafer (MPW) runs which are offered to external clients. In the MPW runs, graphene-based devices are fabricated for external clients (companies, research centres and universities) based on their individual designs. This enables us to test and validate the process technology developed in the 2D-EPL. In 2022, our first MPW run with a total of 14 clients was completed by 2D-EPL partner AMO with a focus on sensors. A second run by VTT is currently in production with a total of 10 clients participating.

BUILDING ON THE GRAPHENE FLAGSHIP FOUNDATION

Our work package, and the 2D-EPL as a whole, has relied heavily on the technology developed within the Graphene Flagship Core projects over the past years. Being part of the Graphene Flagship also provided the right visibility to make the first MPW run a success.

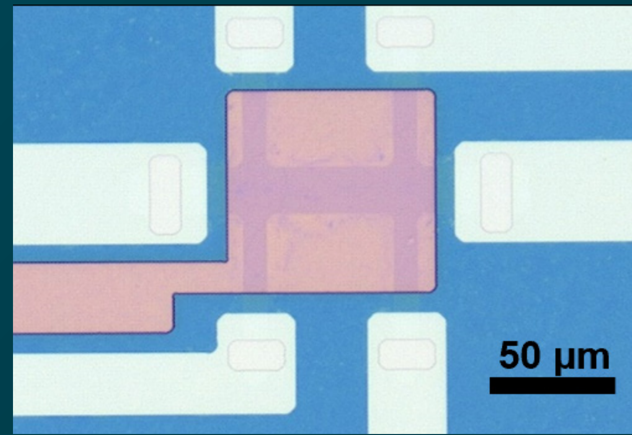
Collaboration is a key component of the Graphene Flagship ecosystem. Within the 2D-EPL, our work package mainly collaborates with the Wafer Scale Integration Work Package, where specific processes are developed then adopted for the MPW runs. We also collaborate closely with the 2D Pilot Line and Management Work Packages where the administrative issues of the MPW runs are handled.

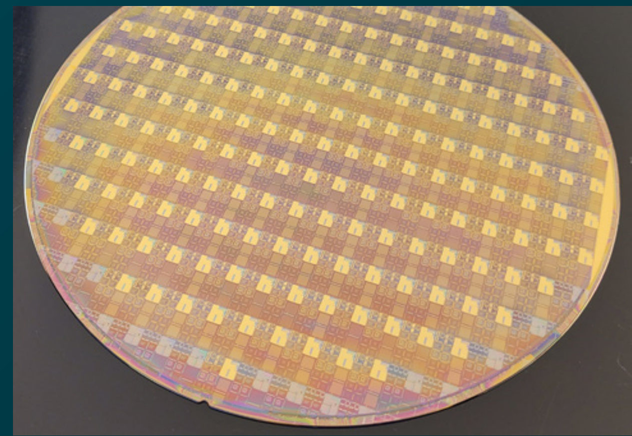
An important aspect of the 2D-EPL in general, and for our work package specifically, is the interaction with the Industrial Advisory Board, which provides input on the most relevant application areas and helps to advertise the MPW runs.

We are also in continuous discussion with the Core 3 Spearhead Projects to receive their input for process module designs according to their specific needs.

FUTURE CHALLENGES

A key challenge in the future will be to increase the reproducibility of device fabrication. This challenge has been clear for many years, but its importance has significantly increased with the MPW runs. Process and device reliability will therefore be the next big challenge to address.





Above
One of the 130 four-point measurement reference devices distributed across the wafer, fabricated during the MPW run and used for quality control. Credit: AMO

Below
A CMOS readout wafer for graphene-based biosensors, gas sensors and pressure sensors designed in the Core 3 Sensors Work Package are fabricated using the 2D-EPL processes. Credit: VTT

IMPACT

The first MPW run focused on sensor applications using graphene devices (GFET). Possible type of sensors included in the MPW run are biosensors, light sensors, Hall-sensors or chemical sensors. In photonics, the applications are in sensing and telecom, and in electronics we are developing processes for novel transistor technologies based on 2D semiconductors, with TMDC-based transistors for reference device.

2D Pilot Line

Inge Asselberghs
Work Package Leader

Work Package Leader
Inge Asselberghs, imec, Belgium

Work Package Deputy
Max Lemme, AMO GmbH, Germany

Laying the track for the MPW runs

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

The team at AMO responsible for producing the first 2D-EPL wafers. This run was an important milestone for the project.

THIS YEAR'S PROGRESS

The launch of two multi-project wafer (MPW) runs have been at the center of the 2D Pilot Line Work Package activities over the past year. Not only in administering the application portal and promoting the runs through social media and articles in key industry publications, but also as a running theme in the workshops organized throughout 2022.

The first MPW run, by AMO, attracted 35 requests and resulted in 14 paying customers who received their orders in December. This run was mainly intended for graphene sensors and will lay the groundwork for more complex co-integrated runs later in the project. The second run, by VTT, received 28 requests resulting in ten paying customers and is currently in production. Customer feedback and the partner's experiences executing these two MPW runs have already yielded insights to creating a more efficient workflow and improving the Pilot Line processes.

The work package also organized a series of events to help spread information about the 2D-EPL and promote the MPW runs. Over the last year, we continued our "Pioneering 2D materials for semiconductor industry" workshop series including an in-person edition at Graphene Week 2022 in Munich, a hybrid workshop integrated in a photonics event in Aachen, Germany and an in-person session at the Graphene 2022 conference in Aachen. We also co-hosted a three-part webinar series with EUROPRACTICE highlighting the MPW runs. This collaboration helped us to reach a broader audience made up of people already interested in EUROPRACTICE's pilot lines, but perhaps less familiar with 2D materials and the advantages of their wafer-scale integration.

BUILDING ON THE GRAPHENE FLAGSHIP FOUNDATION

Synergies with the Graphene Flagship's Core project have boosted the 2D-EPL's success. The visibility of the project and the contacts established over the past decade have strongly helped in the successful launch of our first MPW runs. The dissemination experience brought to the project also helped in efficiently launching the 2D-EPL marketing, communications and events strategies needed for a project of this type.

FUTURE CHALLENGES

As the 2D-EPL technologies mature, the next challenge will be to attract a broader customer base to the MPW runs. This will require both an examination of what features are required to meet the needs of commercial players and a more refined promotional strategy, targeting the relevant industries. With each MPW run we will continue to fine tune our workflows and processes, moving toward more commercial outputs. Another challenge will be to find the right format and timing for continuing the "Experimental Pilot Line" towards a "Pilot Line", and finally to enable technology transfer into foundry and semiconductor manufacturers.

Management

Jari Kinaret
Work Package Leader

Work Package Leader
Jari Kinaret, Chalmers University of Technology, Sweden

Work Package Deputy
Veronique de Halleux, imec, Belgium

Coordinating the project and its collaborations

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

The 2D-EPL came together at imec for its first in-person review giving our community a chance to connect, network and plan for the future. Credit: Graphene Flagship

THIS YEAR'S PROGRESS

Over the past year, the Management Work Package has coordinated both an internal assessment, looking at the project's future plans, and a full review looking at its progress so far.

Internal assessments are a forward-looking exercise used to plan the evolution of Graphene Flagship activities through and beyond the 2D-EPL, including into Horizon Europe. In this year's assessment, external experts found the 2D-EPL project had made impressive progress toward establishing a 2D materials-based technology ecosystem that could form the basis for the next phase of the program. The assessors encouraged the 2D-EPL to outline plans and opportunities for the EPL that build on the successes of the current project.

The project's first in-person review, which took place at imec in Leuven, Belgium, in December was a fantastic opportunity for everyone to come together after having launched the project during the Covid lockdown. The reviewers found that the project is proceeding well and gave many valuable recommendations for the future. A window tour of the imec clean room gave the reviewers a chance to see the 2D-EPL work in action.

The Management Work Package facilitated both activities, ensuring that all the materials were on time and consistent and that the appropriate experts were involved. These efforts resulted in the smooth and effective running of both events.

BUILDING ON THE GRAPHENE FLAGSHIP FOUNDATION

The 2D-EPL benefits from the experience and infrastructure developed for the Graphene Flagship Core projects over the last decade. This has made it easy for the project to focus on the main objectives of the 2D-EPL, without having to take time to establish these processes at the launch of the project. The easy collaborations with the Core project and the European Commission build on the foundations already laid.

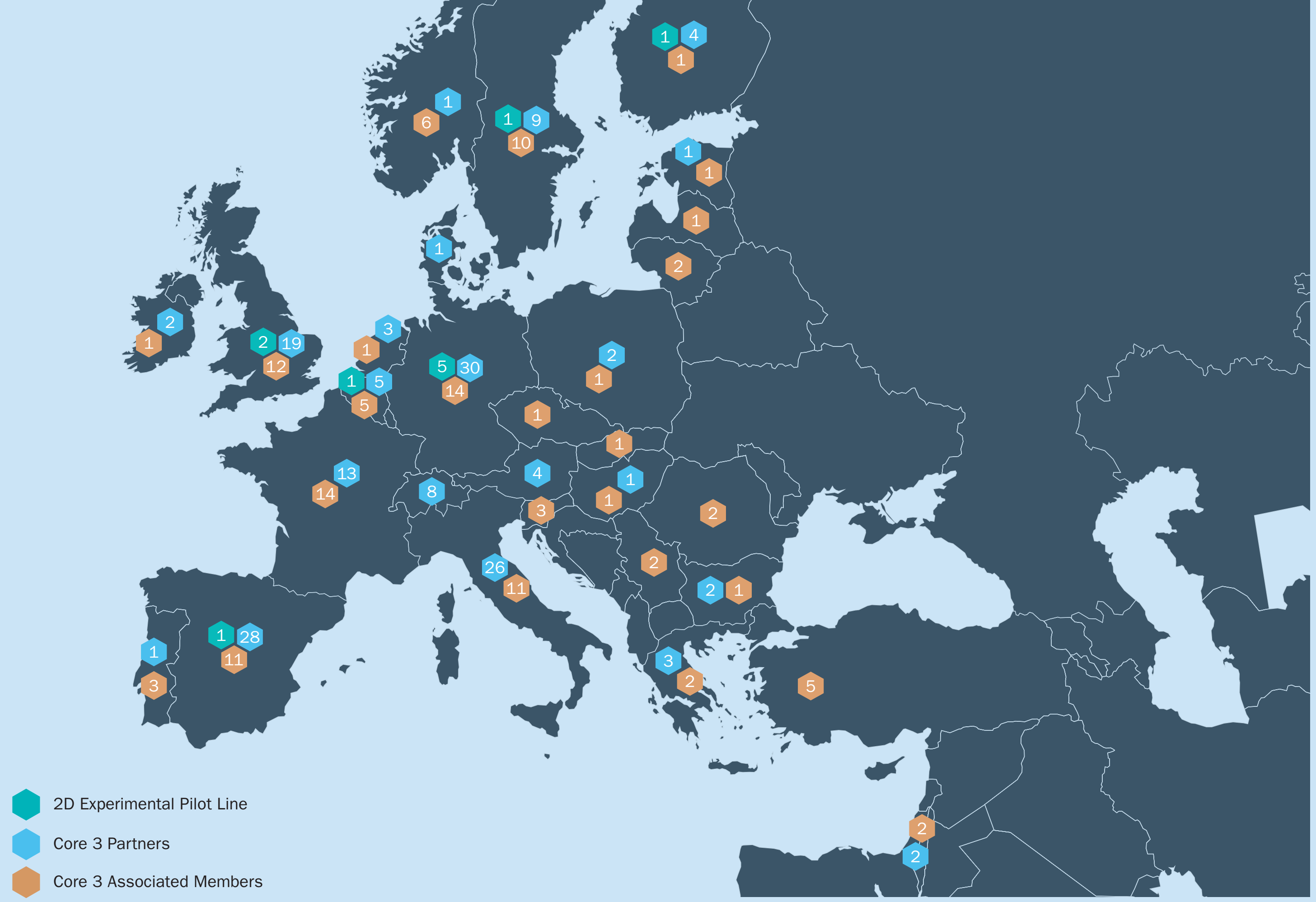
FUTURE CHALLENGES

In the coming months, the Management Work Package will prepare for the period after the Graphene Core 3 project has ended and the 2D-EPL is still running. We are also already looking forward to the Horizon Europe phase and assessing how a future 2D materials pilot line can build upon the experiences of the 2D-EPL.

CALL OPEN: MULTI-PROJECT WAFER RUN 3

The 2D-EPL's third MPW run is mainly intended towards electronics but can also include sensor devices and will be provided by AMO GmbH. The design of the device can be adjusted within the specifications. The offered device structure is a GFET consisting of the following fabrication steps:

- Back gate
- Dielectric deposition & vias opening
- Fabrication of adhesion pads
- Wafer scale graphene transfer & patterning
- Top contact fabrication
- Encapsulation & vias opening



- 2D Experimental Pilot Line
- Core 3 Partners
- Core 3 Associated Members

2D Experimental Pilot Line

BELGIUM
- Interuniversity centre for micro-electronics – imec

FINLAND
- Technical Research Centre of Finland – VTT OY

GERMANY
- AIXTRON SE
- AMO GmbH
- Leibniz Institute of Innovative Microelectronics – IHP
- micro resist technology GmbH
- SUSS MicroTec GmbH

SPAIN
- Graphenea SL

SWEDEN
- Chalmers University of Technology

UNITED KINGDOM
- Aixtron Ltd
- Oxford Instruments Ltd

Core 3 Partners

AUSTRIA
- Guger Technologies OG
- Technical University of Vienna
- University of Natural Resources and Life Sciences, Vienna
- Varta Innovation GmbH

BELGIUM
- Interuniversity Centre for Microelectronics – imec
- National Society of Aerospace Constructions – SONACA SA
- Toyota Motor Europe NV
- Catholic University of Leuven
- Free University of Brussels

BULGARIA
- Institute of Mechanics, Bulgarian Academy of Sciences
- Research and Development of Nanomaterials and Nanotechnology Ltd

DENMARK
- Technical University of Denmark

ESTONIA
- University of Tartu

FINLAND
- Aalto University
- Emberion OY
- Finnish Institute of Occupational Health AG
- Technical Research Centre of Finland – VTT OY

FRANCE
- Airbus Helicopters SAS
- National Centre for Scientific Research – CNRS
- Commission for Atomic and Alternative Energies – CEA
- European Science Foundation – ESF
- National Institute of Health and Medical Research – INSERM
- National Laboratory of Metrology and Testing – LNE
- NAWA Technologies
- Pixium Vision
- Polymem SA
- Thales
- University of Strasbourg
- University of Lille
- Sorbonne University

GERMANY
- Airbus Defence and Space GmbH
- BASF SE
- BMW AG
- Bundeswehr University Munich
- Christian-Albrechts University of Kiel
- Evonik GmbH
- Finisar GmbH
- Fraunhofer Society
- Friedrich-Alexander University of Erlangen-Nürnberg
- Friedrich-Schiller University of Jena
- AMO GmbH
- Infineon Technologies AG
- Interactive Wear AG
- Lufthansa Technik AG
- Max Planck Society for the Advancement of Science
- Multi Channel Systems GmbH
- Nokia Solutions and Networks GmbH
- Phi-Stone AG
- RWTH Aachen
- Siemens AG
- Singulus Technologies AG
- Sixonia Tech GmbH
- Technical University of Dresden
- Trevira GmbH
- University of Augsburg
- University of Hamburg
- University of Marburg
- University of Regensburg
- University of Ulm
- Varta Micro Battery GmbH

GREECE
- Greek Foundation for Research and Technology – FORTH
- Hellenic Mediterranean University
- University of Ioannina

HUNGARY
- Centre for Energy Research, Hungarian Academy of Sciences – MTA EK

IRELAND
- Boston Scientific Ltd
- Trinity College Dublin

ISRAEL
- Mellanox Technologies Ltd
- Israel Institute of Technology – Technion

ITALY
- BeDimensional SpA
- Bioage SRL
- Breton SpA
- Bruno Baldassari & Fratelli SpA
- Fiat Research Centre SpA
- National Research Council – CNR
- Interuniversity National Consortium for Telecommunications – CNIT
- Dallara Automobiles SpA
- Enel Green Power SpA
- Graphene-XT SRL
- Greatcell Solar SRL
- Italian Institute of Technology – IIT
- Italcementi SpA
- Leonardo SpA
- Medica SpA
- Nanesa SRL
- Nokia Solutions and Networks SpA
- Polytechnic University of Milan
- International School for Advanced Studies – SISSA
- SPAC SpA
- STMicroelectronics SRL
- University of Padova
- University of Rome Tor Vergata
- University of Salerno
- University of Trieste
- University of Pisa

NETHERLANDS
- Delft University of Technology
- Eindhoven University of Technology
- University of Groningen

NORWAY
- CrayoNano AS

POLAND
- Lukasiewicz Research Network – Institute of Microelectronics and Photonics Polytechnic University of Warsaw
- Politechnika Warszawska

PORTUGAL
- University of Minho

SPAIN
- Airbus Operations SL
- ArcelorMittal SA
- Autonomous University of Barcelona
- Avanzare SL
- Barpimo SA
- Casals Cardona SA
- CIBER-BBN
- CIC biomaGUNE
- CIC energiGUNE
- CIC nanoGUNE
- DIPC
- FIDAMC Foundation
- Tecnalia Foundation
- Graphenea SL
- Grupo Antolin SA
- ICFO
- ICN2
- IDIBAPS
- IMDEA Nanociencia
- Inbrain Neuroelectronics SL
- INTERQUIMICA
- INIA
- Naturality
- Qurv Technologies SL
- Spanish National Research Council – CSIC
- University of Madrid – Carlos III
- University of Castilla-La Mancha
- University of Zaragoza

SWEDEN
- ABB AB
- Chalmers Industrial Technology
- Chalmers University of Technology
- Ericsson AB
- Graphmatech AB
- Karolinska Institute
- NanOsc AB
- Umeå University
- Veoneer Sweden AB

SWITZERLAND
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- EMPA
- Schaffhausen Institute of Technology AG
- University of Zurich
- University of Geneva
- Swiss Federal Institute of Technology in Lausanne – EPFL
- Swiss Federal Institute of Technology in Zurich – ETH
- TEMAS Solutions GMBH

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- Aixtron Ltd
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- Imperial College London
- Novalia Ltd
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- Printed Electronics Ltd
- Prognomics Ltd
- Queen Mary University of London
- University of Cambridge
- University of Manchester
- University of Nottingham
- University of Sheffield
- University of Warwick
- University College London
- University of Lancaster
- Versarien plc

Core 3 Associated Members

BELGIUM
- Ampashield NV
- Catholic University of Leuven
- Ghent University (UGent)
- University of Mons
- University of Namur

BULGARIA
- Institute of Microbiology, Bulgarian Academy of Sciences

CZECH REPUBLIC
- Palacký University of Olomouc

ESTONIA
- SCALE Nanotech

FINLAND
- University of Eastern Finland

FRANCE
- 2CRSi
- Aix Marseielle University – CINaM
- BLACKLEAF
- Carbon Waters
- ENS Paris Saclay – Aimé Cotton Laboratory
- European Synchrotron Radiation Facility – ESRF
- France Electricity – EDF
- French Institute for Research in Computer Science and Automation
- Grapheal
- Hummink
- NEURRINNOV SAS
- Synchrotron Soléil
- University Claude Bernard Lyon
- University of Montpellier

GERMANY
- Akhetonics
- Dräger Safety AG
- Center for Solar Energy and Hydrogen Research
- International Standards Consulting GmbH
- Jülich Research Centre GmbH
- Karlsruhe Institute of Technology
- Mjr Pharmjet GmbH
- Namlab GmbH
- NMI Natural and Medical Sciences Institute at the University of Tübingen
- Helmholtz Centre for Materials and Energy – HZB
- SURAGUS GmbH
- TALGA GmbH
- Technical University of Munich
- University of Freiburg

GREECE
- OTENET
- University of Patras

HUNGARY
- Budapest University of Technology and Economics

IRELAND
- Technological University of Dublin

ISRAEL
- Bar Ilan University
- Simtal nano coatings

ITALY
- National Agency for New Technologies, Energy and Sustainable Economic Development – ENEA
- Fortore Energia SpA
- GSNET SRL
- Luigi Bandera SpA
- Optosmart SRL
- Sacred Heart – Catholic University
- Tetra Pak SpA
- University of Palermo
- University of Bologna
- University of Rome Sapienza
- Vittoria SpA

LATVIA
- University of Latvia

LITHUANIA
- Centre for Physical Sciences and Technology – FTMC
- TERAVIL Ltd

NETHERLANDS
- Radboud University

NORWAY
- Abalonyx AS
- CealTech AS
- Elkem AS
- Institute for Energy Technology
- LayerOne
- University of Oslo

POLAND
- nanoEMI Technologies Ltd

PORTUGAL
- Graphenest
- Stemmatters
- University of Aveiro

ROMANIA
- EPI-SYSTEM SRL
- Transylvania University of Brasov – UTBV

SERBIA
- Dirigent Acoustics
- Institute for Chemistry, Technology and Metallurgy – ICTM

SLOVAKIA
- Slovak Academy of Sciences

SLOVENIA
- Jožef Stefan Institute (JSI)
- University of Ljubljana
- University of Nova Gorica

SPAIN
- AIMPLAS
- ALBA-CELLS
- CIDETEC
- Complutense University of Madrid
- das-Nano SL
- Gnanomat SL
- Lotus Partners
- Regemat3D SL
- University of Alicante
- Centre for Research in Biological Chemistry and Molecular Materials, University of Santiago de Compostela – CIQUS
- University of the Basque Country

SWEDEN
- APR Technologies
- Bright Day Graphene AB
- GRAFREN AB
- Graphensic
- Karlstad University
- RISE Research Institutes of Sweden AB
- Royal Institute of Technology – KTH
- SMENA Catalysis AB
- Tenutec AB
- Uppsala University

TURKEY
- Ankara University
- Boğaziçi University
- Izmir Institute of Technology
- Integrated Manufacturing Technologies Research and Application Centre, Sabanci University
- Nanografen

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- CamGraPhIC Ltd
- Colloids Ltd
- First Graphene Ltd
- Footfalls & Heartbeats Ltd
- GraphEnergyTech Ltd
- Graphitene Ltd
- Haydale Ltd
- Nu Quantum Ltd
- Payper Technologies Ltd
- University of Brighton
- University of Exeter

Onward!

Portrait of Graphene Flagship Science and Technology Officer Andrea C. Ferrari.

> This is the time to celebrate our success, since it is on a scale unprecedented by other EU projects."

The recent "Evaluation study on Excellent Science in the European Framework Programmes for Research and Innovation" tasked by the European Commission (EC) to review the Graphene Flagship activities states that the number of patent applications per 10M euros funding was 13 times higher than the benchmark for H2020, concluding that, "The Graphene Flagship has successfully delivered on the objectives as set out in the beginning of the FET programme of excellent science and excellent innovation."

We have been together for ten years and successfully executed one of the most ambitious projects ever funded by the European Union (EU). We delivered new science, new technologies, patents, spin-offs and products on the market. We propelled Europe to the forefront of science and technology in graphene and related materials. We leveraged the funding received by the EU to produce an economic impact far superior to that of the direct EU support. We engaged all large European companies relevant for the application areas we targeted.

I wish to congratulate all the Graphene Flagship Partners and Associated Members for helping deliver what will remain one of the biggest success stories in EU funded projects!

It is important that this community continues in the new phase of the Graphene Flagship in Horizon Europe. Other forms of collaborations are possible, and we need to place a renewed impetus on ensuring that what we achieved is not wasted. Graphene and related materials are now ready to enter multiple sectors, from spintronics to biomedicine, sensors to flexible and wearable devices, electronics and photonics to energy harvesting, generation and storage, composites, coatings, and many more.

Layered materials are finding their way into other areas. Layered Quantum Materials, the class of layered materials displaying non-trivial quantum phenomena, are a quickly expanding and emerging area of study, not just in terms of fundamental science. They constitute a new platform for quantum technologies, for example as on-chip photon sources for quantum information applications. Chip-compatible and scalable quantum devices based on layered quantum materials could lead to new functionalities, which may revolutionize the way we compute and communicate, eventually leading to new industries.

Graphene and related materials are also making their way into space applications, in collaboration with the European Space Agency and other national and international space agencies. A spacecraft carrying a lunar rover with graphene-based composites is now orbiting the moon, with a landing planned at the end of April.

This is the time to celebrate our success, since it is on a scale unprecedented by other EU projects. We need to ensure the creation of a European Partnership to foster the progress of emerging materials. We need to establish an effective industrial association so that European industry remains at the forefront of the exploitation of graphene and related materials, maximising economic and innovation growth. We need to engage with all communities that now stand to benefit from the introduction of graphene and related materials in their value chain.

Onward!

Andrea C. Ferrari
Graphene Flagship Science and Technology Officer
The University of Cambridge

The Graphene Flagship celebrates a decade of 2D materials innovation

Funded by the European Commission in 2013, the Graphene Flagship has brought graphene innovation out of the lab and into commercial applications. Bringing diverse competencies from 170 academic and industrial partners in 21 countries together, the Graphene Flagship facilitates cooperation between its partners, accelerating the timeline for industry acceptance of graphene technologies.

With applications in everything from energy and transportation to electronics and biomedicine, graphene and other 2D materials are changing the way we live and work. The European Commission's FET Flagships enable research projects on an unprecedented scale. With €1 billion budgets, the Graphene Flagship, Human Brain Project and Quantum Flagship serve as technology accelerators, helping Europe to compete with other global markets in research and innovation.

With an additional €20 million investment, the European Commission has now funded the creation of an experimental pilot line for graphene-based electronics, optoelectronics and sensors.

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