GRAPHENE
FLAGSHIP

Funded by
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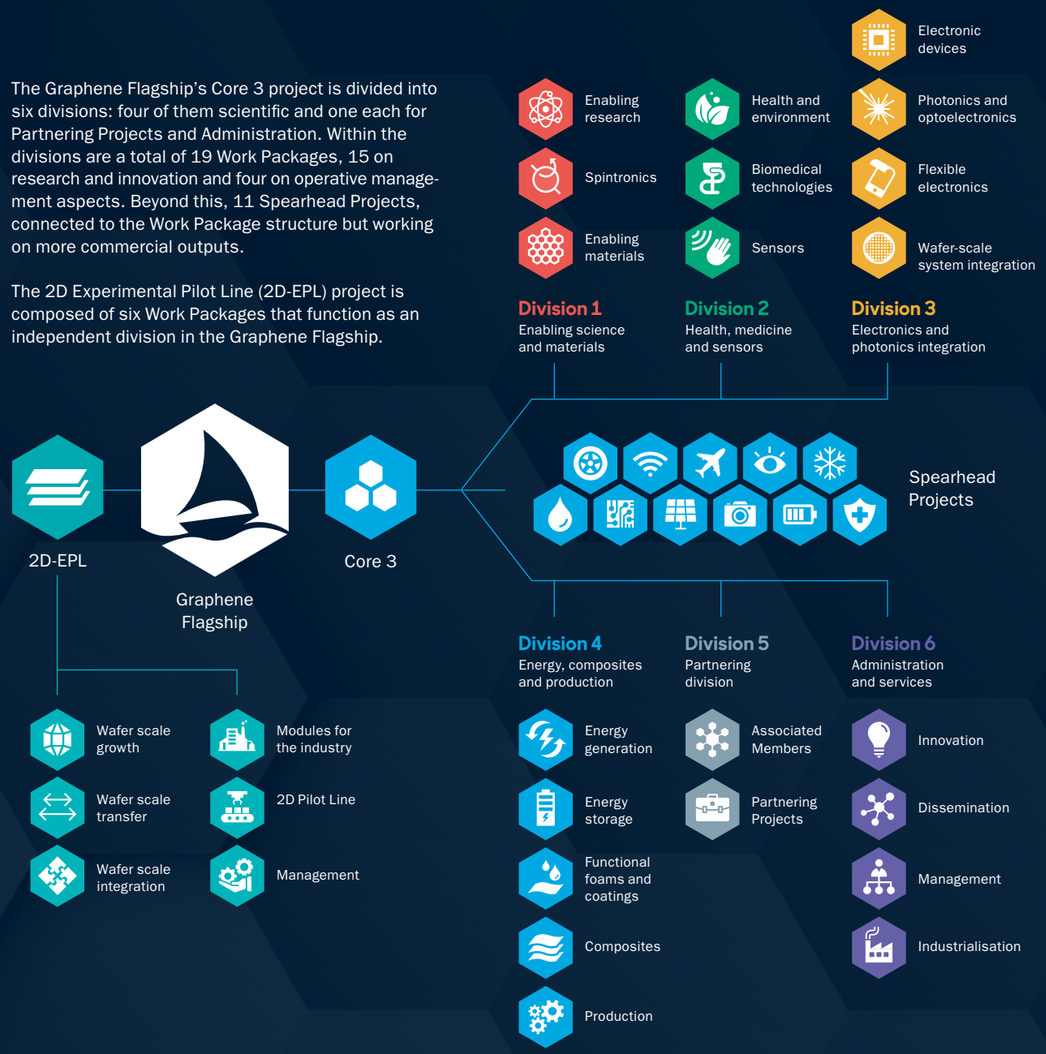
Annual Report 2021

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.



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Top:
Graphene Flagship Director, Jari Kinaret, explains the value of graphene in products produced by the project to European Commission Executive Vice President Margrethe Vestager. Credit: Rebecca Waters

Above:
Director General for DG Connect at the European Commission, Roberto Viola, and Graphene Flagship Director, Jari Kinaret, opened Graphene Week 2021 with a look to the future of graphene in Europe. Credit: Alexandra Csuport

Left:
Jari Kinaret, Graphene Flagship Director, in a panel discussion at Graphene Week 2019. We look forward to returning to in person events in 2022. Credit: Vesa Laitinen

From the Director

The past year has tested and demonstrated the resilience of the Graphene Flagship in times when the pandemic made life quite difficult for many of us. We have developed and implemented new ways of working that have allowed us to continue our work, taking graphene and related materials from laboratories to society.

HIGHLIGHTS

One of this year's success stories is linked to aerographene foams. They were initially the subject of rather fundamental research but have now developed into applied research on high-power actuators pursued by a team at the Christian Albrecht University in Kiel. The Spearhead Project AEROGrAFT, led by Lufthansa Technik, is also using them to create a new type of air filter.

Another example of successful technology transfer is the company INBRAIN Neuroelectronics that aims to commercialize the graphene-based electrodes that were developed by the Graphene Flagship's Biomedical Technologies Work Package. INBRAIN has received over €17 million in private funding to date, proving the high level of confidence investors have in this technology.

The applications pursued by Lufthansa Technik and INBRAIN are but two examples of the diverse impacts of the Graphene Flagship's achievements. There are many others, in fields ranging from novel batteries to composite materials for the automotive and aviation industries, or new ways to help autonomous vehicles sense their environment under low visibility conditions. The presence of graphene in these devices may not always be obvious to the consumer, but it does not need to be, it is quite enough to know that we are contributing to a safer and more sustainable society.

WHAT'S IN STORE

In 2022 we will see the Graphene Flagship take further steps on the path to real-world applications. One area where we are putting a lot of emphasis is the manufacturability of electronic and photonic devices based on graphene and related materials. Our 2D Experimental Pilot Line (2D-EPL) will launch its first multi-project wafer run in 2022 allowing customers to test device fabrication outside the laboratory-style development facilities. The general theme of manufacturability and reproducibility will gain importance across most of the Graphene Flagship's work now that the Horizon 2020 part of our voyage is nearing its end.

Portrait of Graphene Flagship Director Jari Kinaret. Credit: Oscar Mattsson

> Achieving manufacturability and reproducibility will gain importance now that the Horizon 2020 part of our voyage is nearing its end."

COLLABORATION

The Graphene Flagship has demonstrated the power of European collaboration. We have brought together some 170 organizations from across Europe to work side-by-side towards common goals. The consortium has evolved over the years from a collection of primarily academic partners to one that is now equally divided between commercial actors on one side and academic and research institutes on the other. This collaboration allows us to tackle challenges that no individual country or organization would be able take on by themselves.

Furthermore, the Graphene Flagship combines the strengths of many organizations to create something that is more than just a sum of its parts. In a nutshell, one could say that the academic partners are good at identifying what is doable while the commercial partners are better at deciding what is worth doing. Bringing them together enables us to work on the intersection, topics that are both doable and worth doing, and that creates win-win situations for all concerned – not only for our partners but for all Europeans.

Jari Kinaret
Graphene Flagship Director

Charting a course to success

Launched in 2013, the Graphene Flagship is a large collaborative research and innovation project funded by the European Commission, as well as the EU member states and associated countries. The project aims to create and commercialise new technologies based on graphene and related layered materials. Through an ecosystem of research, innovation and collaboration, the Graphene Flagship will lead the transition from academic laboratories to society in the form of new graphene-enabled products, new companies and new employment opportunities.

Initially, the consortium was dominated by academic partners. However, today our team is evenly divided between universities and research institutes and industrial partners, from key sectors like aerospace, automotive, energy and sustainability. Moreover, we've recently incorporated a new project, the 2D Experimental Pilot Line, the first foundry to integrate graphene and related materials into semiconductor platforms, further contributing to the shift toward industrial applications. This evolution of the consortium is one clear indication that the Graphene Flagship is on course to reach its target and create the impacts envisioned over ten years ago.

ALL ABOARD

Collaboration is central to the Graphene Flagship's success. Within our core consortium, nearly 170 academic and industrial partners in 22 countries work side-by-side to bring graphene and related materials to society. Their work is supported by over 90 Associated Members throughout Europe, often funded through national and regional agencies, or self-financed on commercial terms.

Our collaborations extend beyond Europe through a series of yearly International Workshops with Australia, China, Japan, Korea and the United States. They allow us to identify key challenges, discuss ways to overcome them and learn from each other in ways that make all of us reach our goals more efficiently than we would alone. At the heart of our work is the belief that research is a global activity that does not, and should not, respect political or geographical borders. By working together, we can achieve much more than we would in isolation.

LOOKING BACK

Ten years ago, when we planned the Graphene Flagship, the activity around graphene was mostly academic, and impact was created through publications in journals like Science and Nature. Thus far we have published nearly 5,000 publications, cited approximately 200,000 times. While keeping our academic passion, over the years we have consciously steered the Graphene Flagship towards more applied topics, moving our focus to other performance indicators such as patents, companies created, and products launched. For example, our 11 industrially led Spearhead Projects pursue specific commercially motivated applications in areas like autonomous driving, clean water and air, more efficient batteries, and new systems for aviation. All of these showcase our success.

Graphene Flagship partners have 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 commercially, which is yet another indicator that the Graphene Flagship is delivering on its promise.

ON THE HORIZON

The current European Commission funding instrument, Horizon 2020, will end in 2023, replaced by Horizon Europe. The Graphene Flagship will evolve further to match the new structure for European research and innovation, but the important work that we are doing to commercialise graphene and related materials will continue.

Over the next 18 months, we will celebrate the successes we have achieved through excellent research, cutting-edge innovation, and most importantly, open collaboration. We will see our Spearhead Project's goals come to fruition, new products and spin-off companies emerge and a new course charted into Horizon Europe.

The Graphene Flagship in numbers

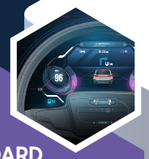
The Graphene Flagship is research, innovation and collaboration. Since the project kicked-off in 2013, it has evolved to embrace a higher proportion of industrial partners and a stronger commitment to innovation. Moreover, we've expanded our networks outside the Core Consortium, to collaborate with over 100 Associated Members and Partnering Projects in EU Member States.

Spearheads – Where Innovation meets Industry

The Graphene Flagship Spearhead Projects are industry-led initiatives working to increase the technology readiness level (TRL) of graphene-based technologies. These projects collaborate closely with the rest of the project to maximise the impact of the Graphene Flagship in the innovation ecosystem and the European economy.

GRAPHIL

GRAPHIL filters are being tested to ensure they comply with the EU drinking Water Directives and guarantee their compatibility with food and drinking applications. Commercialisation of the first water filters will likely arrive before the end of 2022.



G+BOARD

G+BOARD's future activities will focus on the development and validation of automotive components with a higher TRL value. By 2023 these technologies will be integrated into a concept car for Stellantis – the automotive manufacturing corporation formed by Fiat Chrysler and the PSA Group.

CIRCUITBREAKERS

Self-lubricating metal-graphene coatings have successfully been produced and validated in a laboratory. Now, the team aims to scale up the plating technology and validate the coating solution in product settings via demonstrator tests and environmental trials, to achieve TRL 5.

METROGRAPH

METROGRAPH builds on the achievements of the Photonics and Optoelectronics and Wafer-Scale Integration Work Packages, which facilitated the demonstration of fast and efficient modulators and detectors. A prototype should be ready by early 2023.

GRAPES

Currently, the GRAPES graphene-perovskite-silicon tandem technology works on small area devices. By the end of the project, the team will upscale prototype modules to wafer size, with efficiencies higher than 23%, greater than the most powerful silicon module on the market.

AEOGRAFT

The AEROGrAFT team improved the generation of aerographene foams with a newly developed continuous exfoliation reactor. In the future, AEROGrAFT material systems could enable the development of filters with different characteristics and properties that could be useful for other sectors that require air filtration.

GBIRCAM

The GBIRCAM project is developing a unique industrial camera and image sensor to enable affordable, high performance hyperspectral imaging. Cameras with visible, short-wave infrared and middle-wave infrared pixels open new machine-vision applications.

AUTOVISION

Autovision will enable (semi) autonomous cars to operate under adverse ambient conditions. The team aims to build a TRL 6 demonstrator, which will progress imaging technology and steer future specifications through a customer-driven process.

GREENBAT

GrEEnBAT aims to scale up the fabrication of silicon/graphene composite electrodes for anodes in lithium-ion batteries and to develop a fully functional battery module for automotive applications. The first prototypes, made in 2021, are now under evaluation.

GICE

The GICE team is working on a slat for the wings of large aircraft, a rotor blade for helicopters and an air inlet, all tailored to the needs of their industrial partners. GICE aims to achieve a TRL above 4 by 2023 and expects market-ready technology two to five years later.

SAFEGRAPH

SafeGraph produced a first regulatory roadmap for complex electronic GRM devices for medical and consumer applications. SafeGraph partners plan to collaborate with Horizon Europe consortia and explore new methods for characterising advanced GRMs.

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Towards market-ready products

Led by companies, the Graphene Flagship Spearhead Projects target high-technology readiness level (TRL) prototypes or products, supporting sustainable innovation in Europe.

All these projects exploit the academic and industrial partnerships created by the Graphene Flagship to bring graphene and related materials into devices close to market application. The close interaction between Work Packages, Spearhead Projects, Associated Members and Partnering Projects ensures that nobody works in a silo. Ideas are developed and implemented together, making the most of the wide-ranging expertise present in the Graphene Flagship: unity is strength.

GRAPHIL

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

GRAPHIL is developing graphene-enabled water filters for household sinks, portable water purifiers and points-of-entry water treatment devices. These products will provide access to safe and clean water, reducing the need for bottled water.

THIS YEAR'S PROGRESS

Looking for the best options for filtering materials, GRAPHIL focused on polysulfone (PSU) and polyethersulfone (PES) hollow fibre membranes coated with graphene oxide (GO). The team tested different water filters made with PSU-GO composites in the presence of microbiological and emerging contaminants. In the lab environment, the best performing material was a PSU-GO composite with 3.5% GO. This demonstrated high removal by adsorption of several pollutants, including the antibiotic ciprofloxacin; heavy metals like lead, chromium and copper; fluorinated substances (including PFAS); as well as microbiological contaminants.

The team published their results in different peer-reviewed journals, covering topics such as the coating of PES hollow fibre with GO, the possibility to prepare GO nanosheets with a 2-step method, and the outstanding properties of GO for water treatment.

COLLABORATIONS

GRAPHIL is working with the SafeGraph Spearhead Project to examine regulatory compliance. GRAPHIL also collaborates with the HSB Living Lab, who partners with Graphene Flagship partner Chalmers University of Technology, for on-field testing of filters for shower wastewater recycling.

Further collaborations with the Dissemination and Industrialisation Work Packages are helping to prepare the market launch of GRAPHIL products.

WHAT'S IN STORE

GRAPHIL filters are being tested to ensure they comply with the EU Drinking Water Directive, to be compatible with food and drinking applications. It is important to ensure GO does not migrate into the water. GRAPHIL industrial partners, including Graphene Flagship partners Medica, Polymem and Icon Lifesaver, have been actively involved in the manufacturing process, moving the products towards higher technology readiness levels (TRL). The first water filters will likely go to market before the end of 2022.

Above:
Medica showcased its work on the GRAPHIL Spearhead Project at the Aquatech Exhibition in Amsterdam.
Credit: Sofia Järbur

Below:
A lab-scale prototype of GRAPHIL filters under testing.
Credit: Medica SpA

FUN FACT

GRAPHIL showcased its prototypes at the Aquatech Exhibition 2021 in the Netherlands and gained a lot of interest and follow-up contacts.

PARTNERS

Chalmers University of Technology, Sweden
Icon Lifesaver, UK
Medica, Italy
National Research Council, Italy
Polymem, France
University of Manchester, UK

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

A G+BOARD steering wheel demonstrator with integrated heating capabilities showing the differences between traditional copper wiring and a GRM-based approach. Credit: Stellantis

G+BOARD is producing an integrated copper-free dashboard for vehicles, featuring conductive patterns, sensors and devices based on graphene and related materials. These include multi-functional graphene and reduced graphene oxide. The team is working to replace the copper wiring and buttons currently used in car dashboards, thus reducing the number of production steps and decreasing vehicle weight, whilst improving aesthetics, perceived quality and recyclability. G+BOARD focuses on two applications exploiting graphene electrical properties: graphene-based heating elements for the steering wheel and dashboard drawers with sensors and wires enabled by graphene and related materials.

THIS YEAR'S PROGRESS

In 2021, G+BOARD produced a high technology readiness level (TRL) demonstrator of a steering wheel that integrates a graphene-based functional polymeric coating as a heating element. This coating is an energy efficient system, acting both as a Joule heater and heat spreader. Consequently, it heats faster and more homogeneously than traditional wire heating systems.

COLLABORATIONS

The collaborations with various Graphene Flagship Work Packages facilitated and accelerated G+BOARD's tasks. For example, G+BOARD collaborates with The Composites Work Package on the production of graphene-polypropylene composites, as well as with the Production and Industrialisation Work Packages.

The Graphene Flagship industrial value chain will accelerate the time-to-market after the end of the project.

WHAT'S IN STORE

G+BOARD's future activities will focus on the development and validation of automotive components with a higher TRL value. A patent application is also under evaluation. By the end of Core 3, the new technologies will be integrated into a concept car for Stellantis – the automotive manufacturing corporation formed after a 50-50 merger agreement between Fiat Chrysler and the PSA Group.

FUN FACTS

Graphene is a good functional filler because of its aspect ratio, enabling effective conduction at low percentage content. This allows one to process materials more effectively than by existing technologies and to maintain the required characteristics. Recyclability is improved by reducing the number of hybrid metal-plastic parts, such as copper cables. Fewer components and cables also lead to easier assembly.

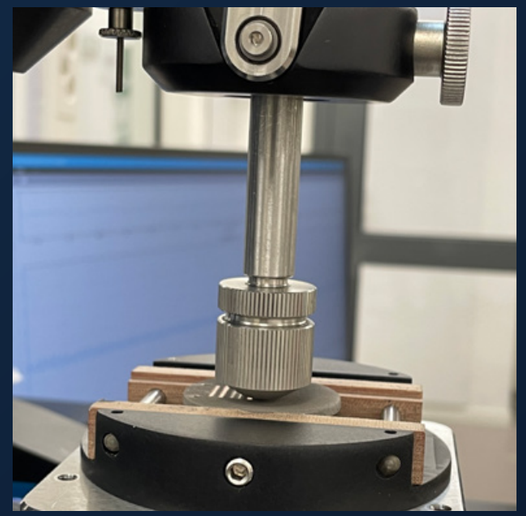
G+BOARD technologies could be exploited in several automotive components: GRM-based heating elements could be adapted to seats and gear knobs, and GRM-based sensing and wiring capabilities could be inserted in door panels, consoles and steering wheels.

PARTNERS

Avanzare, Spain
Bioage, Italy
Fiat Research Centre, Italy
FORTH, Greece
Nanesa, Italy
National Research Council, Italy
SPAC, Italy
The University of Cambridge, UK

Circuit-Breakers

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



A friction and wear test setup (tribometer) for a steel substrate with self-lubricating Me-GRM-based coating versus a stainless-steel ball. Credit: Su Zhao, ABB

Low-voltage air circuit-breakers (also known as LVCBs) are common protection devices in the electric grid. The mechanism that drives their operation between open and closed positions is usually lubricated with grease. However, ageing of the grease is known to cause failures and requires costly, time-based maintenance and re-greasing. The CircuitBreakers Spearhead Project aims to demonstrate first-of-its-kind, maintenance-free LVCBs by replacing grease lubrication in the drive mechanism with self-lubricating composites that combine metals and graphene, either in the form of coatings or sintered parts.

THIS YEAR'S PROGRESS

CircuitBreakers successfully optimised a multilayer metal-graphene coating that meets specified targets for adhesion, friction, wear and corrosion. Our Spearhead Project also upscaled the electroplating process to 100 litres, showing consistent and promising results. Graphene-enabled circuit breakers, coated with this new technology, have better performance when compared to greased components used for reference. These results encouraged the team to work on a patent application.

COLLABORATIONS

Optimising the materials has been an iterative process, which required good communication and fast feedback loops. Chalmers University of Technology, University of Rome Tor Vergata and FORTH explored specific graphene pre-treatment methodologies, while working with the companies Nanesa and Graphmatech on the optimization of performance and process stability.

These two SMEs led the development of composite coatings with the support from ABB and the academic researchers.

WHAT'S IN STORE

Self-lubricating metal-graphene coatings were produced and validated in the lab environment, technology readiness level (TRL) 4. Now, the team is working on scaling up the plating technology and validating the coating solution in product settings via demonstrator tests and environmental trials, aiming for TRL 5.

From a business perspective, the coating solution will be sufficient for a maintenance-free circuit breaker. A decision about the sintering activities will be taken in the spring of 2022, since they may offer possibilities for eliminating grease in a wider product range.

FUN FACTS

Nanesa has signed a formal cooperation agreement with industrial-scale electroplater LEM S.r.l., to facilitate the upscaling of metal-GRM coating.

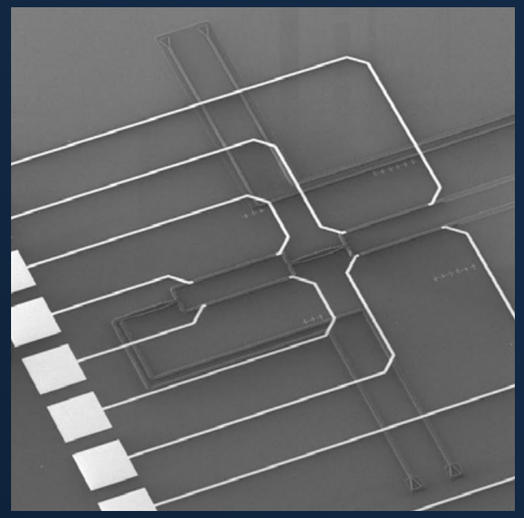
CircuitBreakers' technology could also be applied to sliding electric contacts, owing to its good electrical and corrosion properties.

PARTNERS

ABB Corporate Research, Sweden
Chalmers University of Technology, Sweden
FORTH, Greece
Graphmatech, Sweden
Nanesa, Italy
The University of Manchester, UK
The University of Rome Tor Vergata, Italy

METROGRAPH

Project Leader
Paola Galli, Nokia, Italy
Industrial Leader
Nokia, Italy
Project Deputy
Vito Sorianello, CNIT, Italy



A Mach-Zehnder modulator.
Credit: CNIT, InPhoTec

The METROGRAPH Spearhead Project will contribute to the improvement of internet networks and 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 metropolitan networks (10–500 Km), 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 GSymbols/s with each symbol carrying up to 6 bits depending on the modulation format used. These innovative circuits, and the established platform of silicon photonics, ensure maximum efficiency, low power consumption, low cost and a small footprint.

THIS YEAR'S PROGRESS

METROGRAPH achieved outstanding results in electro-absorption modulators with bandwidths exceeding 30 GHz. Optical data streams were detected with two different modulation schemes On-Off-Keying (OOK) and four-level pulse amplitude modulation (PAM4), where PAM-4 effectively doubles the total capacity of a connection compared to the usual mechanism used in OOK communications. The team reached 105 Gbit/s in the OOK scheme and 120 Gbit/s in the PAM-4, setting the state-of-the-art for graphene photodetectors.

The design of these customised electrical integrated circuits for graphene photonics chips brought the project forward.

COLLABORATIONS

METROGRAPH builds upon the achievements of the Graphene Flagship's Photonics and Optoelectronics and Wafer-scale Integration Work Packages. The collaboration with Photonics and Optoelectronics facilitated the demonstration of fast and efficient modulators and detectors. The project requires 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.

WHAT'S IN STORE

The target technology readiness levels (TRL) are 5 to 6. Future commercialisation of this technology will build on the collaborative work with the Photonics and Optoelectronics, Wafer-Scale Integration Work Packages and the 2D-Experimental Pilot Line. The plan is to demonstrate a METROGRAPH prototype by the first quarter of 2023. Then, integration within a network line card in the second quarter. After that, METROGRAPH will be able to assess the reliability of several modules.

FUN FACT

METROGRAPH's wafer-scale techniques are compatible with silicon photonics production processes, which will facilitate the ramp-up required for product commercialisation.

PARTNERS

CNIT, Italy
Finisar II-VI, Germany
IIT, Italy
imec, Belgium
Nokia Solutions and Networks, Germany
Nokia Solutions and Networks, Italy
The University of Cambridge, UK

GRAPES

Project Leader
Marina Foti, Enel Green Power, Italy
Industrial Leader
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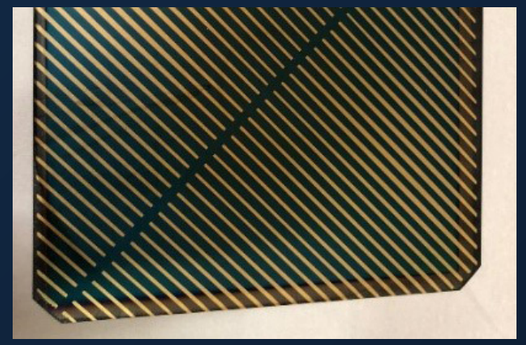


A prototype of a GRM-based perovskite/Si tandem device on an M2 wafer. Credit: University of Rome Tor Vergata

Silicon solar cells are gradually reaching their theoretical efficiency limits, while perovskite cells have emerged as low-cost alternative for high-efficiency photovoltaics. By exploiting graphene and related materials, the GRAPES Spearhead Project aims to combine silicon and perovskite technologies to design, fabricate and characterise innovative tandem solar cells. This unique combination can push performance and stability to new record levels, leading to the cost-effective fabrication of stable photovoltaic panels. Graphene-enabled solar panels could achieve levelized costs of energy – lifetime costs divided by energy production, less than 20 €/MWh.

THIS YEAR'S PROGRESS

Over the past year, GRAPES has worked on new graphene-perovskite-silicon tandem solar cells produced at temperatures below 200°C. The efficiency of the new mechanically stacked device increased from 24% to 26.7%. Researchers also developed compatible and stable materials for the connection and encapsulation of the top and bottom sub-cells. The top sub-cell is a semi-transparent perovskite-based solar cell engineered with graphene and related materials, while the bottom sub-cell is a commercially available silicon hetero-junction provided by Graphene Flagship industrial partner Enel Green Power.

The team is also working on microinverters used to convert direct current into alternating current, optimised for Maximum Power Point Tracking (MPPT), a technique that maximizes energy extraction.

COLLABORATIONS

Facilitated by the Graphene Flagship, the direct connection between academic and industrial partners allows faster troubleshooting and the development of innovative solutions based on layered materials. The connection with the Industrialisation Work Package resulted in a roadmap that highlights the use of graphene-enabled perovskite solar cells for space applications.

WHAT'S IN STORE

Currently, the GRAPES graphene-perovskite-silicon tandem technology works on small area devices (0.54 cm^2). By the end of the project, this will be upscaled to wafer size, with efficiencies greater than 23%, higher than the most efficient silicon module currently on the market.

The installation of these prototype modules with adapted inverters and a performance monitoring system will demonstrate their reliability and outdoor performance. This will inform the wider industry of this application's potential and move graphene-enabled perovskite technologies closer to industry.

From a business perspective, the coating solution will be sufficient for a maintenance-free circuit breaker. A decision about the sintering activities will be taken in the spring of 2022, since they may offer possibilities for eliminating grease in a wider product range.

FUN FACT

GRAPES devices will be realised in an industrial environment (manufacturing readiness level ≥ 6) and tested by using accelerated lifetime tests, under real outdoor conditions (technology readiness level ≥ 6).

PARTNERS

Enel Green Power, Italy
Greatcell Solar Italia, Italy
Hellenic Mediterranean University, Greece
SIEMENS, Germany
Swiss Federal Institute of Technology, Lausanne, Switzerland
The University of Cambridge, UK
University of Rome Tor Vergata, Italy

AEROGrAFT

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

The main objective of the AEROGrAFT Spearhead Project is to build a sustainable and innovative air filtration system for passenger aircraft. Thanks to graphene, this will provide an optimal level of cabin air quality combined with options for smart self-cleaning and sterilisation.

Our team is developing a filtration system made of aerographene foams, which consist of an ultra-light, low-density material with unique mechanical and electrical characteristics.

THIS YEAR'S PROGRESS

AEROGrAFT improved the generation of aerographene foams with a newly developed continuous exfoliation reactor. It resulted in the upscaling of exfoliated graphene production from 10 to 250 grams per day. Beyond quantity, Graphene Flagship researchers managed to improve its quality as well. We can now fabricate foams 50 cm^3 in size with high reproducibility and homogeneity.

Another significant success in 2021 is the development of aerographene filter materials with innovative smart characteristics, such as the ability to monitor the filter status and some environmental conditions.

AEROGrAFT also evaluated different system integration options, certification requirements and developed a first demonstrator of the aerographene filter system.

COLLABORATIONS

All academic and industrial partners involved in AEROGrAFT have been constructively working together since the beginning of the project. By focusing on the same goal, insights from one partner have been continuously looped back to support other partners' developments, leading to an agile and intense collaboration inside the Spearhead project.

Within the Graphene Flagship, AEROGrAFT is also collaborating with the Functional Foams and Coatings Work Package to develop new types of aeromaterials.

WHAT'S IN STORE

AEROGrAFT focusses on developing a fully functional aircraft system, including equipment qualification and certification. Our team is looking forward to the next steps, dealing with detailed system design and qualification, performance testing and validation, and certification elaboration.

Above:
Aircraft in the Lufthansa hangar. Credit: Lufthansa Technik

Below:
We aim to build a sustainable and innovative air filtration system for passenger aircraft. Credit: Lufthansa Technik

FUN FACT

AEROGrAFT material systems could enable the development of filters with different characteristics and properties, useful for other sectors that require air filtration, beyond the aerospace industry.

PARTNERS

Christian-Albrechts University of Kiel, Germany
Lufthansa Technik, Germany
Naturality, France
PhiStone, Germany
Sixonia Tech, Germany
Technische Universität Dresden, Germany

GBIRCAM

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

The GBIRCAM Spearhead Project is developing a unique industrial camera and image sensor to enable the production of an affordable, high performance hyperspectral imaging system. Cameras with visible, short-wave infrared (SWIR) and middle-wave infrared (MWIR) pixels pave the way toward new machine-vision applications in several industries, including plastic recycling, textile sorting, mining and food quality analysis. Other applications for this image sensor include surveillance in fog and smoke conditions and various environmental monitoring applications, such as the detection of CO_2.

GBIRCAM is working on the CMOS readout circuitry with an array of 80x60 superpixels directly on its surface. One superpixel consists of three sub-pixels to detect visible, SWIR and MWIR/LWIR light. All the sub-pixels use graphene field-effect transistors (GFETs) for charge detection and amplification. The integration of GFET on CMOS circuitry has been completed successfully.

This first-of-its-kind sensor allows simultaneous imaging and detection in the range of visible light and infrared with one focal plane array. Camera electronics, mechanics, software and the integrated circuits are ready and fully tested for further experiments.

THIS YEAR'S PROGRESS

The GBIRCAM team created readout integrated circuits (ROICs) tailored to the GFET-based superpixels and tested them with the camera electronics provided by Emberion. Both visible and SWIR light sensitive pixels have been fabricated on the GFET pixels. Thus, different building blocks, including a pyroelectric thin film transducer, are ready for integration into demonstrators and the final prototype.

The team also created a technology description document for broadband products based on customer requirements, and analysed the application domains for broadband wavelength sensing, such as mining, gas sensing, hyperspectral imaging for recycling, surveillance, food sorting and remote sensing opportunities.

COLLABORATIONS

GBIRCAM's collaboration is shaped around the manufacturing flow of building the superpixel image sensor, integrating it into the camera system, and performing different measurements and testing. Emberion in Finland is responsible for the ROIC and camera system development, while Emberion in the UK works on the image sensor pixel design and fabrication.

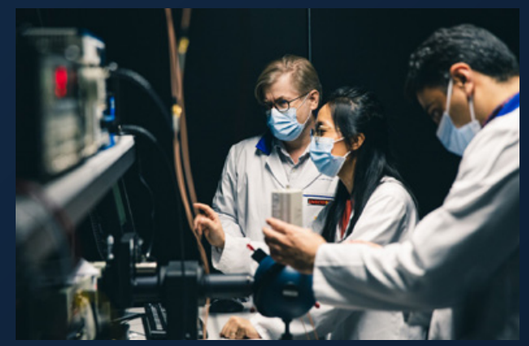


Image sensor testing in Emberion's laboratory.
Credit: Emberion Oy

Graphenea Semiconductor has transferred high quality graphene on ROIC wafers. VTT developed wafer post-processing, graphene patterning, infrared-sensitive materials and infrared characterisation, especially for the MWIR/LWIR pixels. The University of Cambridge developed MWIR/LWIR pixels and large-scale integration of GFETs on the ROIC. GBIRCAM is also one of the pilot projects in the 2D-Experimental Pilot Line (2D-EPL), with the VTT team participating in the project.

WHAT'S IN STORE

The project is now focusing on completing the final demonstrator: a high-quality GFET on a fully processed CMOS wafer with image sensor electronics. The work will be done in collaboration with all the Spearhead Project partners and supported by the 2D-EPL. The final product should be ready by the end of the project.

FUN FACT

The strong business focus of this project has already attracted a lot of interest. The technology has been presented at several trade fairs, including Photonics West 2020, Chii 2020, European Photonics Industry Consortium (EPIC) conferences, Defence and Security Equipment International (DSEI) 2021 and Vision '21.

PARTNERS

Emberion OY, Finland
Emberion Ltd., UK
Graphenea Semiconductor, Spain
The University of Cambridge, UK
VTT, Finland

Autovision

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

The Autovision Spearhead Project will allow (semi)autonomous cars to operate under adverse ambient conditions. It aims to develop the equipment and processes required to scale up the manufacturing of graphene-based infrared image sensors for advanced driver assistance systems. The same technology could also find applications in all-weather operation of extended reality (a combination of augmented, virtual and mixed reality), as well as enhance the capabilities of service robots through multispectral vision.

Our project has developed a wafer-scale graphene manufacturing process, demonstrating the integration of graphene-based, wide-spectrum pixels on CMOS test-chips with a low-resolution test array.

THIS YEAR'S PROGRESS

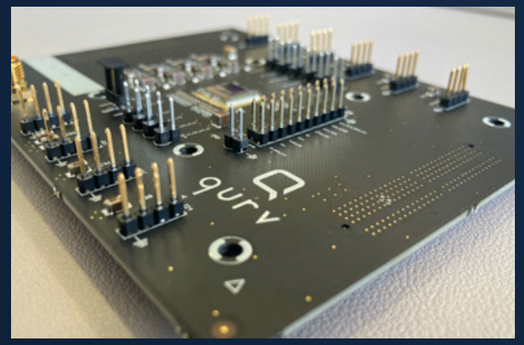
Autovision achieved two important milestones on the road to scaling up graphene-based electronic devices, which will allow these products to become economical and reach widespread adoption. The first is the development of a tool for semi-automated graphene delamination. Second is the delamination of graphene onto an opaque glass wafer, used as a carrier to transfer graphene to its target wafer substrate.

COLLABORATIONS

The Autovision project leverages technologies developed in the 2D-Experimental Pilot Line, and vice versa. The involvement of Aixtron and imec in both projects facilitates the use of the technology developed in the Wafer-scale Integration Work Package for the advancement of Autovision's manufacturing process. Autovision also benefits from close interactions with the Photonics and Optoelectronics Work Package, gaining insights on the development of photodetector technologies based on layered materials.

WHAT'S IN STORE

The integration of a graphene-based image sensor into a camera is the main challenge for 2022. The results of the camera system benchmark planned for late 2022 and early 2023 will be instrumental in communicating to automotive manufacturers. The team aims to build a technology readiness level (TRL) 6 demonstrator, which will serve to progress discussions on the relevance of the imaging technology and steer future specifications through a customer-driven process. The ultimate goal is to accelerate business development, boost customer engagement and optimise resource allocation.



Above:
A 300 mm glass carrier wafer with graphene ready for bonding onto a target wafer. Credit: imec

Below:
A board with Qurv's wide-spectrum image sensor test chip. Credit: Qurv Technologies S.L.

FUN FACT

Autovision's first evaluations with large manufacturers in Europe focused on comparing visual, small-wave and long-wave IR cameras in dark and dusty environments, where dirt road driving is the primary challenge.

PARTNERS

Aixtron, UK and Germany
ICFO, Spain
imec, Belgium
Qurv Technologies, Spain
Veoneer, Sweden

GrEEnBAT

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

The GrEEnBAT Spearhead Project aims to scale up the fabrication of innovative silicon-graphene composite electrodes for lithium-ion batteries. Silicon works as an active material in anodes, increasing lithium-ion batteries' energy density by more than 20%, but 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, helping to achieve the targeted cycle life. The team will fully develop functional battery modules for electric vehicles.

THIS YEAR'S PROGRESS

Our team made significant progress this year and achieved all its targets for the upscaling of battery materials and electrodes to manufacture the first proof-of-concept 21700 prototype cells. These are rechargeable lithium-ion cells 21 mm in diameter and 70 mm in length. Thanks to silicon-graphene composites, GrEEnBAT could maintain an enhanced energy density, 20% higher than state-of-the-art cells with graphite in the anode. GrEEnBAT also improved the cycling performance by more than 60%.

The first proof-of-concept prototypes were fabricated and are undergoing comprehensive evaluation and testing. Additional iterations are planned for 2022, ending with a design-freeze of the battery cell.

COLLABORATIONS

The project 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.

WHAT'S IN STORE

Although significant advances have been achieved, battery life and a high number of cycles are still the main challenge to the introduction of silicon-graphene composites in lithium-ion batteries. Beside the cycling stability, the cost target for automotive cells remains a major challenge. GrEEnBAT is confident it 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 TRL 6.

Above:
GrEEnBAT aims to fully develop functional battery modules for electric vehicles. Credit: Adobe Stock

Below:
A 21700 cylindrical battery prototype.
Credit: Christoph Stangl, VARTA

FUN FACT

The automotive industry has very stringent requirements for batteries. GrEEnBAT technology could also be adapted to less-demanding applications in consumer electronics, power tools and other wireless products.

PARTNERS

BeDimensional, Italy
BMW, Germany
CEA, France
VARTA Microbattery, Germany
VARTA Innovation, Austria

GRAPHENE FLAGSHIP ANNUAL REPORT 2021

GICE

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

Ice accumulation is a major issue for aircraft. Graphene-based de-icing offers an alternative, low-weight, highly efficient and versatile solution, expected to decrease power and fuel consumption. The GICE Spearhead Project is working on a slat for the wings of large aircraft, a rotor blade for helicopters and an air inlet, all tailored to the needs of industrial partners, primarily Graphene Flagship partners Airbus Helicopters and Sonaca.

THIS YEAR'S PROGRESS

GICE demonstrated the production capabilities of graphene-related materials in the desired form, quantity and quality this year. Our team even successfully described the materials' physical and chemical characteristics.

Our project worked on improving electrical conductivity, thermal conductivity and heating power density of graphene-based heater elements. GICE demonstrated that heater elements perfectly adapt to the sheet resistance range specified by Airbus and Sonaca.

Moreover, our team made progress in designing, manufacturing and testing different sensors for humidity and ice, also based on graphene and related materials.

COLLABORATIONS

GICE collaborates with the SAFEGRAPH Spearhead Project to assess the lifecycle analysis (LCA) and CO_2 footprint of graphene production methods and heater mat manufacturing processes.

WHAT'S IN STORE

In the coming year, GICE will select the best candidate for the integration of its system into large aircraft slats, helicopter rotor blades and air inlets. GICE aims to achieve a technology readiness level (TRL) above 4 by the end of the current project and to produce a market-ready technology two to five years later.

Above:
Helicopter flight tests in blowing snow conditions. Credit: Airbus Helicopters

Below:
A lab test of GRM-based ice sensor technology at the Free University of Brussels. Credit: Dario Farina, Free University of Brussels

FUN FACT

GICE team will use a small-scale icing wind tunnel to assess the performance of graphene-based humidity and ice sensors and heaters.

PARTNERS

Airbus Helicopters, France
FIDAMC, Spain
FORTH, Greece
Free University of Brussels, Belgium
Nanesa, Italy
National Research Council (CNR), Italy
Sonaca, Belgium
The University of Cambridge, UK
Versarien, UK

SafeGraph

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

The SafeGraph Spearhead Project delivers a set of guidelines supporting other Spearhead Projects and the Graphene Flagship in achieving the essential regulatory compliance for their new products. This will accelerate the path to market, saving Graphene Flagship 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

Over the past year, SafeGraph produced a first regulatory roadmap for complex electronic devices containing graphene and related materials (GRMs) for medical and consumer applications. This identified some initial gaps in current regulations, leading to the implementation of contingency measures to ensure our materials will safely reach the marketplace.

Our team modelled the impact of GRMs 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.

COLLABORATIONS

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. SafeGraph exploits the know-how accumulated by Spearhead Projects WearGraph and Chemsens during the Graphene Flagship's previous Core 2 phase, as well the ongoing work of GRAPHIL and GICE in Core 3.

SafeGraph has close links with the Graphene Flagship's Health and Environment and Industrialisation Work Packages and the Horizon 2020 projects Sunshine and Harmless, to share information on industrial case studies and regulatory compliance.

SafeGraph is a facilitator for regulatory compliance, accelerating the market launch of innovative and safe graphene-based products.

WHAT'S IN STORE

SafeGraph will work to develop new opportunities for GRMs. Our project has already collaborated with the Health and Environment Work Package to conduct in vitro skin sensitisation tests of WearGraph's final products produced for the end of Core 2. The results will be directly applicable to other innovative graphene-enabled wearables.

FUN FACT

SafeGraph plans to explore new methods for characterising advanced GRMs.

PARTNERS

Chalmers Industriteknik, Sweden
EMPA, Switzerland
TEMAS Solutions, Switzerland
University of Castilla La Mancha, Spain
University of Natural Resources and Life Sciences, Austria
University of Trieste, Italy

Sailing on international waters

An overview of our most successful collaborations with researchers in China, Korea and Japan

The Graphene Flagship brings graphene and layered materials out of the lab and into commercial applications. Because we're funded by the European Commission, we want to secure a major role for Europe in the technological revolution, catalysing the transformation to a more sustainable future through research, innovation and collaboration. And it's precisely this collaborative spirit that motivates our exploration beyond our continent.

Since the kick-off of the project in 2013, we have established strong partnerships with research teams in Asia, Australia and the US, among others. These efforts to venture and sail across oceans has generated innovative outcomes, and further accelerated the technology readiness level of graphene-based solutions.

The success of our international partnership is only possible through multidisciplinary collaborations across institutions, coordinated by Graphene Flagship partner European Science Foundation, in France. Beyond that, many international institutions around the world contribute to making this initiative possible, including key government-funded agencies and leading industrial companies.

Our international Graphene Flagship workshops are probably the most important part of these international collaborations. Organised jointly between researchers in Europe and abroad, the workshops foster the exchange of exciting experiences and interesting ideas, all related to the latest advances in the field of graphene and layered materials. After many prosperous years of in-person events, visiting cities like Sydney, Dresden, Shanghai, San Sebastian, Tokyo, Beijing, Seoul, Helsinki and Copenhagen, the COVID-19 pandemic forced a transition to online conferences. Despite the challenges posed by very different time zones, the Graphene Flagship and its international collaborators managed very well during the past few years,

"Open exchanges advance research, and long-term partnerships like the EU-Japan collaboration play a key role for the entire community of graphene and layered materials."

Christoph Stampfer
Chair of the Graphene Flagship
EU-Japan workshop

co-hosting several meetings that connected hundreds of people. Some argue that, compared to conventional conferences, the current online alternatives hinder collaboration. However, the reality is remote conferences enhance diversity, accessibility and flexibility – everybody is welcome, wherever they connect from. Graphene Week 2021 demonstrated the huge potential of organising scientific events online; our international workshops showcased similar accomplishments.

In 2021, we celebrated three international workshops, in collaboration with researchers in Korea, Japan and China. The first one took place on 29 September, closely following the Graphene Flagship annual conference. Inaugurated by programme chair Paolo Samori, from Graphene Flagship partner the University of Strasbourg, France, this 6th EU-Korea workshop focused on the production of graphene and layered materials, as well as methods to better tune and characterise their properties. Sustainability was ever-present in the discussions, which covered graphene inks for printed, paper-based circuitry and electronics and highly stable graphene oxide solutions for efficient batteries and supercapacitors, among other things. Some of these applications are already transferred into commercial products thanks to the collaboration with Korean companies. Maybe because of the pandemic, and the growing needs in biomedical testing, the conversation

"Our insightful workshops catalyse cross-activities for advanced applications in optoelectronics, sensing and energy, paving the way to commercialisation."

Paolo Samori
Chair of the Graphene Flagship
EU-Korea workshop

covered new devices for portable, point-of-care sensors based on graphene and layered materials.

Beyond properties like flexibility, sensitivity and high conductivity, graphene provides an attractive alternative in terms of cost – as demonstrated by the bacterial detectors developed by Graphene Flagship spin-off Graphenica Lab, based in Spain. In previous in-person workshops, researchers identified biochemical sensing as an important topic to explore; surely these interesting discussions will continue during the next meet-up. Furthermore, the international team will keep exploring other opportunities in the field of energy generation and storage, two technologies where graphene could provide enhanced performance, paving the way to more sustainable solutions to the current climate crisis.

Barely a month later, the 5th EU-Japan workshop took place. Workshop chair Taiichi Otsuji, from Tohoku University, in Japan, gave the opening address, which was followed by ten invited talks by researchers in both academia and industry. The event covered electronics, photonics, spintronics and more – exploring the possibilities of graphene and layered materials in these fields. According to our own Graphene Flagship roadmapping efforts, these applications lay distant in our nautical charts, however their outcomes will certainly revolutionise telecommunications with unprecedented speeds, bandwidths and performances. Nowadays, our digital devices account for approximately 2% of the global greenhouse gas emissions, a trend that keeps growing with the popularity of on-demand content, cloud storage and cryptocurrencies. Graphene could contribute to cutting carbon emissions in this sector, enabling better solutions for clean energy generation and storage, but especially providing more efficient electronics.

The Graphene Flagship and its recently launched 2D Experimental Pilot Line focus on low-cost, scalable integrated circuits to provide innovative telecommunication solutions that operate at high data rates and optimal performance with minimal energy requirements, thus reducing the environmental impact. Besides, the EU-Japan collaboration explored the continuation of exchange programmes between the two regions, which proved extremely effective in the past. On top of the existing Graphene Flagship mobility grants, Japanese researchers announced new contributions to these activities through a new grant by the JSPS – "Science of 2.5 Dimensional Materials" – funded until 2026. After almost three years without in-person gatherings, the group expects to meet again soon.

Finally, the year closed with a successful online event between researchers in the EU and China, attended by over 50 people. Xinliang Feng, the programme chair from Graphene Flagship partner TU Dresden, Germany, highlighted the great value of early career researchers to scientific progress and innovation. Young sailors in the vast graphene field plant the seeds to exciting future collaborations; much like Feng himself when he moved from Shanghai to Germany to start his doctoral studies. Among other topics, the discussions turned around the production of high-quality graphene, as well as other layered materials, such as molybdenum disulfide and manganese bismuth telluride. The latter is a revolutionary quantum material with extraordinary properties in power generation and sustainable refrigeration – however some challenges lay ahead in terms of production and stability, which were addressed during the workshop. Other innovative materials include the amorphous versions of graphene and boron nitride, which have led to many commercial applications from industrial leaders like Samsung and LG. In addition to fundamental research, the participants also exchanged opinions about applicability, which focused mostly on the development of new electronic devices. For example, layered materials could provide alternatives to silicon in transistors, modulators and gate insulators. Moreover, combining layered materials like ingredients in a sandwich yields heterostructures with new properties and possibilities. In this field, transistors with sheets of indium selenide provide high performance and high mobility, both ideal properties for the development of flash memory cells. The collaborations will continue to further enhance microscopy and nano-imaging techniques, to better characterise these new materials and to overcome the current challenges in the production and growth of large-area substrates. Everyone seems excited by the prospects ahead and looks forward to meeting again in 2022.

Whether it happens in-person or online, the Graphene Flagship will keep strengthening international collaborations in the near future, supporting workshops, exchange programmes and cross-country cooperation. Diversity is paramount to the advancement of science. Collaborative networks support science, increasing opportunities and accelerating the path to market applications.

"It is always exciting to be part of these workshops, meet international colleagues in the field of 2D materials and follow the latest scientific advances. We look forward to upcoming events which we will soon start to organise and will be held later this year, two of them next to the Graphene Week 2022."

Isabella Vacchi
Graphene Flagship European Alignment and International Collaboration Team

"China is a key player in graphene applications, and their experience it is also very interesting for mutual exchange and collaboration."

Xinliang Feng
Chair of the Graphene Flagship
EU-China workshop

Enabling Research

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

Work Package Deputy
Alberto Morpurgo, The University of Geneva, Switzerland

> We're investigating twistronics – where different layered materials are stacked forming different angles, which results in properties like superconductivity."
>
> **Vladimir Fal'ko**
> Work Package Leader

Graphene... with a twist

To push innovation in graphene and layered materials, we must understand their behaviour. Therefore, the Enabling Research Work Package focuses on understanding the most fundamental properties of these materials, exploring beyond the single one-atom-thick layer of graphene and venturing into new possibilities. Among these, we're investigating twistronics – where different layered materials are stacked forming different angles, which results in properties like superconductivity. Moreover, we study the possibilities of layered materials in ferroelectric and magnetic devices, with applications in electronics.

THIS YEAR'S PROGRESS

In the field of twistronics, our focus has been to develop new ultra-high vacuum technologies to manufacture tailor-made heterostructures, always controlling the twist angle. We're now preparing a patent for our innovative preparation protocols, which enable an unprecedented control of 0.2 degrees. Such precision will help our researchers discover new twisted combinations of graphene and layered materials, beyond the original 'magic angle' superlattice. Among other things, we've shown that twirled stacks of hexagonal boron nitride and transition metal dichalcogenides enable tuneable ferroelectric effects.

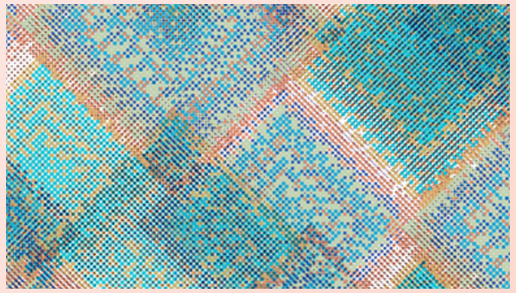
Another key advance in twistronics led us to the discovery of quantum anomalies in twisted bilayer graphene. These include states that range from Mott insulators to superconductors – and we've used these effects in devices such as electronic junctions. Besides preparing new materials, our Work Package has also developed new technologies to study them more efficiently, which is key to advance our understanding of layered materials. These include a totally new method for identifying atomically thin layers, as well as advances in scanning thermal microscopy to better study twisted bilayers, heterostructures and even combinations of layered materials with materials like polymers and semiconductors.

We also explore the potential of graphene and layered materials to enable new functionalities in electronics, photonics and other technologies. That's why we're also interested in the magnetic properties of layered materials, which could lead to applications in data storage. Beyond the traditional materials, our Work Package has explored layered versions of manganese, cobalt and niobium sulfides, as well as chromium bromide. Some of these devices exhibit 100% magnetoresistance, opening new possibilities for sensors, navigation, hard drives and much more.

To further expand our knowledge, we also carry out computational modelling of properties like magnetism, charge density and superconductivity, and measure the effects of interlayer coupling with tools like photoluminescence, infrared spectroscopy and Raman scattering. Combined, these strategies help us predict promising phenomena and better assess the potential of twisted heterostructures in real-life applications.

UPCOMING CHALLENGES

After developing innovative methods for the assembly of heterostructures – with or without a twist – the Enabling Research Work Package will focus on further refining this technology. We'll improve homogeneity, cover larger areas and enhance our control of the twist angle beyond the state-of-the-art. In this line, another key milestone will include synthetic approaches ready for glove-box environments, which will democratise access to these innovative materials. In the future, we will further study the quantum and optical effects of twistronics in graphene bi- and tri-layers, as well as "sandwiches" with hexagonal boron nitride and other layered materials. Finally, in the next years of the Graphene Flagship project, we'll aim to fully understand the relationships between charge transfer and magnetism in layered materials, particularly metal halides. In general, we'll delve into anything that seems unexpected and interesting for the progress of the field.



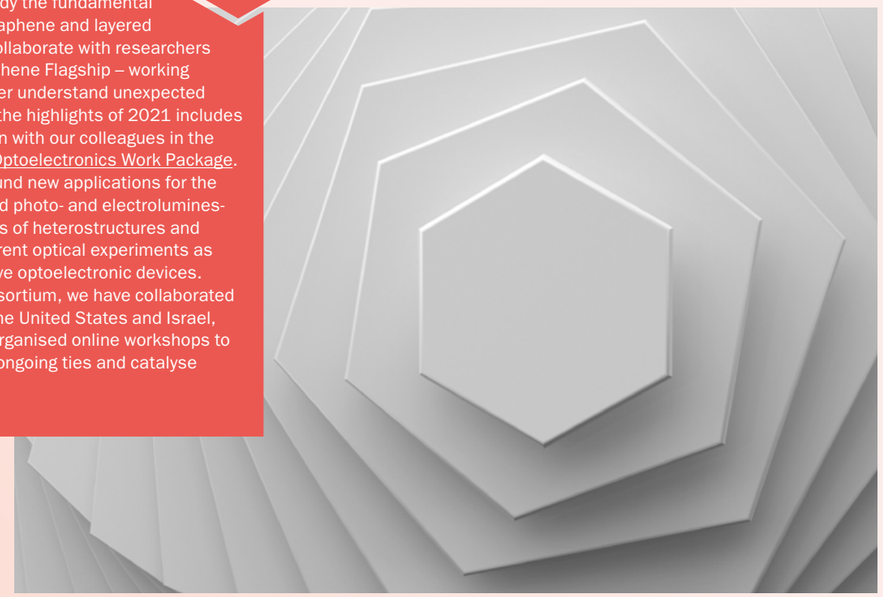
The advances in twistronics have found Moiré patterns and twisted combinations of graphene and layered materials beyond the original 'magic angle' superlattice. Credit: Adobe Stock

Studying the magnetic properties of graphene and layered materials could lead to applications in data storage. Credit: Adobe Stock

COLLABORATION

Because we study the fundamental properties of graphene and layered materials, we collaborate with researchers across the Graphene Flagship – working together to better understand unexpected effects. One of the highlights of 2021 includes the collaboration with our colleagues in the Photonics and Optoelectronics Work Package. Together, we found new applications for the newly discovered photo- and electroluminescence properties of heterostructures and developed different optical experiments as well as innovative optoelectronic devices. Beyond our consortium, we have collaborated with groups in the United States and Israel, with whom we organised online workshops to strengthen our ongoing ties and catalyse cooperation.

Our technologies to manufacture tailormade heterostructures for twistronics control the angle with an unprecedented precision of 0.2 degrees. Credit: Adobe Stock



References
Xu, S. et al. Nature Phys. 2021, DOI: 10.1038/s41567-021-01172-9.
De Vries, F. K. et al. Nature Nanotechnol. 2021, DOI: 10.1038/s41565-021-00896-2.
Woods, C. R. et al. Nature Commun. 2021, DOI: 10.1038/s41467-020-20667-2

Spintronics

Work Package Leader
Stephan Roche, ICN2, Spain

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

We explore the potential of graphene and layered materials, including emerging magnetic two-dimensional materials, for spintronics applications."

Stephan Roche
Work Package Leader

A new spin on magnetic devices

Spintronics studies the spin of electrons and its associated magnetic effects. This field finds applications in logic devices, electronics and information storage, to cite a few examples. The Spintronics Work Package investigates how to integrate graphene and other layered materials into spintronic applications. Recent developments by the Graphene Flagship include new technologies for non-volatile memory – the type of computer memory that retains information even after power supplies are turned off, like hard-drives.

THIS YEAR'S PROGRESS

At the beginning of Core 3, the Work Package created a dedicated task force to develop new combinations of layered materials and magnetic materials. Current memory technologies already exploit the latter, but graphene and related materials widen the possibilities, often demonstrating superior performance. A successful example of this integration includes the incorporation of both graphene and tungsten disulfide layers in magnetoresistive RAM (MRAM) stacks. Graphene Flagship partner imec, Belgium, supplied the wafers and partner Graphenea, Spain, transferred the graphene and other layered materials onto them. The resulting products showcased high quality and interesting magnetic properties.

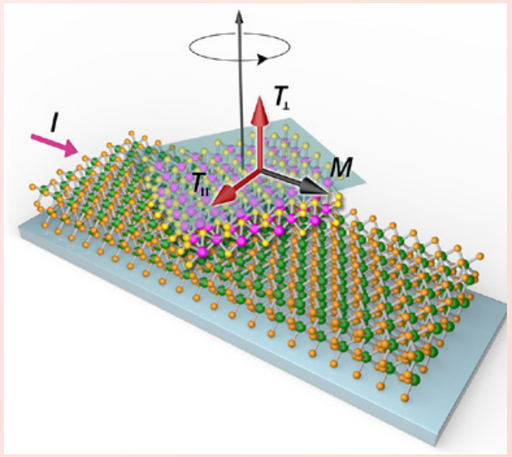
Another breakthrough was the demonstration of all-electrical spin logic gates that work at room temperature. These have applications in spin communications, as well as for magnets used in reading and writing digital information. Combining graphene with layered anti-ferromagnets yielded gigantic magnetic proximity effects of up to 170 teslas.

Some of these advances rely on the creation of heterostructures, 'sandwiches' of different layered materials. Beyond graphene, hexagonal boron nitride and tungsten diselenide, these devices also use mono-dimensional ferromagnetic contacts, which enable the creation of lateral spin valves. These interfaces allowed unprecedented demonstrations, including room temperature spin-to-charge conversion and imprinted magnetism. The results exceed even the best predictions for Core 3. The Spintronics Work Package was remarkably productive over the past 18 months, publishing 40 papers.

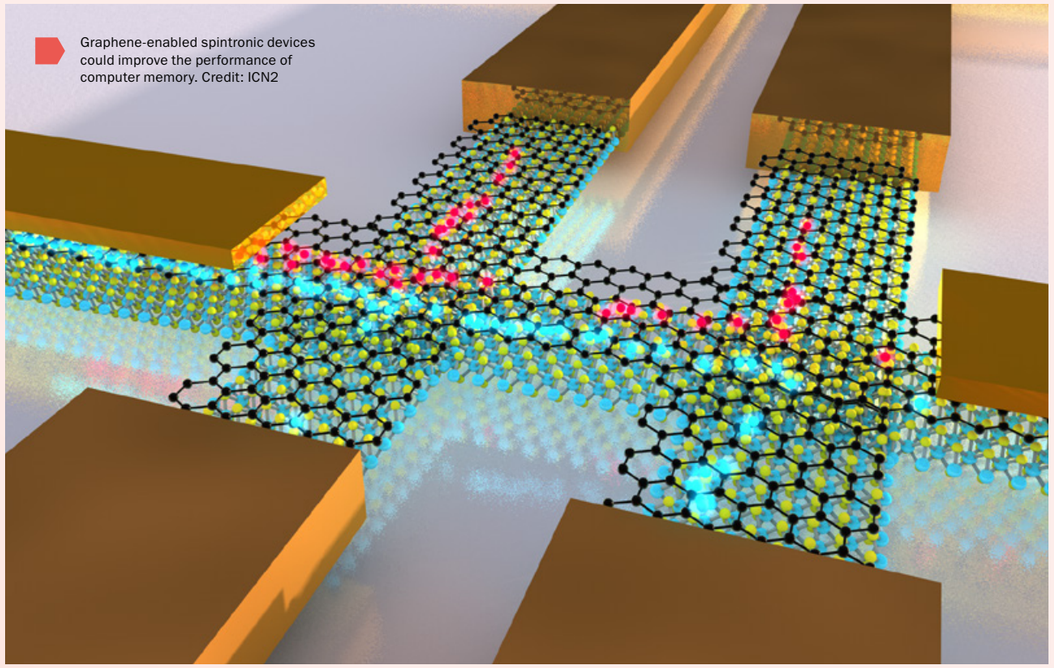
The challenge now is progressing towards higher technology readiness levels (TRL). Further work on integration, validation and large-scale manufacturing will ensure we grow to TRL 4 and 5, taking graphene-enabled spintronic technologies one step closer to the market. Spintronics holds the key to low-power computing devices, from embedded memories to applications for the upcoming Internet of Things.

UPCOMING CHALLENGES

We pushed the state-of-the-art in spintronics forward, thanks to research, innovation and collaboration. However, we have not yet progressed to market applications. For this reason, we established close cooperation mechanisms with the 2D-EPL, in particular imec, to accelerate the fabrication of pre-patterned wafers, readily designed to deposit layers of materials and magnetic stacks for MRAM technologies. Other efforts will focus on the validation of large-scale assembly processes, propelling our developments to TRL 5 and beyond.



Stacked into "heterostructures", graphene and layered materials offer great possibilities in spintronics. Credit: ICN2



Graphene-enabled spintronic devices could improve the performance of computer memory. Credit: ICN2

COLLABORATION

Our Work Package maintains regular information exchanges with the other Division 1 Work Packages, all in charge of fundamental studies of graphene and layered materials. Collaborations with other divisions and the 2D Experimental Pilot Line (2D-EPL) have directly impacted the development of new magnetic devices, in particular the creation of reliable deposition methods for large-scale manufacturing. Through mechanisms like FLAG-ERA, the Spintronics Work Package also collaborates with different Associated Members and takes part in various Partnering Projects, such as H2O, SoGraphMem and MECHANIC. The latter carries out multiscale simulations to further explain experimental results by Graphene Flagship researchers, and new publications are already undergoing peer review.

Our Work Package produced pre-patterned wafers, readily designed to deposit layers of materials and magnetic stacks for MRAM. Credit: Liam Briese, Unsplash

References
Ghiasi, T.S. et al. Nature Nanotechnol. 2021, DOI: 10.1038/s41565-021-00887-3.
Sierra, J.F. et al. Nature Nanotechnol. 2021, DOI: 10.1038/s41565-021-00936-x.
Hallal, A. et al. Nano Lett. 2021, DOI: 10.1021/acs.nanolett.1c01713

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Enabling Materials

Work Package Leader
Mar García-Hernández, CSIC, Spain

Work Package Deputy
Jonathan Coleman, Trinity College Dublin, Ireland

> Our major challenge is the large-scale synthesis of materials without defects, aiming at perfection."
>
> **Mar García-Hernández**
> Work Package Leader

Synthesis and production of perfect layered materials

The isolation of graphene triggered the interest in many other layered materials. The Enabling Materials Work Package studies them and investigates new optimised manufacturing methods. The solutions developed within the Graphene Flagship enable a variety of applications, such as sensors, batteries, and (opto)electronics.

THIS YEAR'S PROGRESS

One promising layered material is molybdenum disulfide, which has extraordinary electronic properties. Our Work Package has developed new production methods to grow high-quality molybdenum disulfide directly onto sapphire wafers – later used to create reprogrammable logic circuits and other electronic devices. We also designed efficient methods to manufacture layers of tin phosphide (SnP_3), ideal for boosting the capacity of lithium-ion batteries. Thanks to liquid-exfoliated tin phosphide sheets, the Graphene Flagship created batteries with record-breaking energy densities.

The Enabling Materials Work Package also combines different layered compounds, like ingredients in a sandwich, to yield unprecedented properties and applications. For example, encapsulating graphene into slices of hexagonal boron nitride creates samples with excellent electronic properties, easily manufactured in large scales using methods like chemical vapour deposition.

Our fundamental approach allows us to push the boundaries of layered materials and yield ground-breaking discoveries. In 2021, we pioneered the synthesis of nanographene spin chains – mono-dimensional materials that use hydrocarbon *triangulene* as building blocks. We also functionalised graphene with small peptides that specifically recognise HCV – the virus behind hepatitis C. The materials developed by the Graphene Flagship feature high tuneability beyond this type of sensors – other applications include the detection of different biomarkers and antiviral coatings, key in the fight against pathogens like SARS-CoV-2.

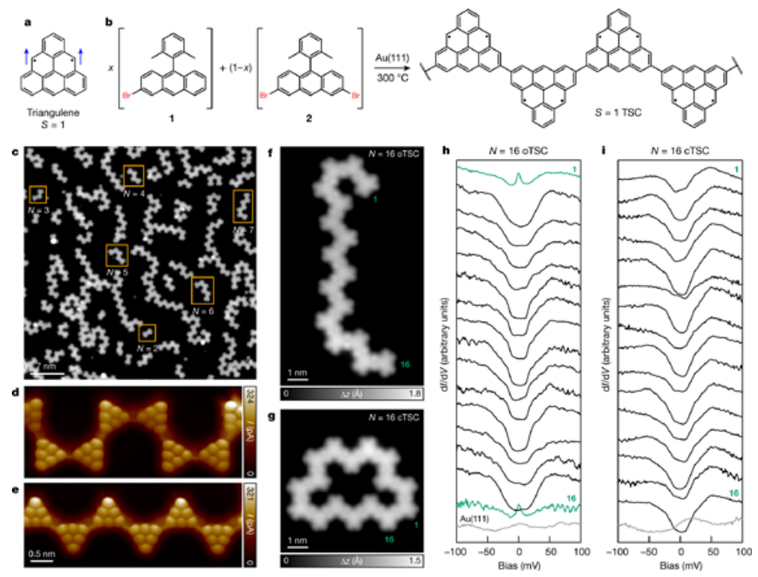
Now, the biggest challenge ahead is the large-scale synthesis of new layered materials, ideally without any defects. Our goal is perfection – however this is a major task that will still require years of research and innovation. Beyond this, the Enabling Materials Work Package will keep exploring the fundamental properties of novel layered materials, as well as designing new characterisation methodologies.

We want to keep enlarging the catalogue of layered materials, fully understand their properties and develop more innovative applications.

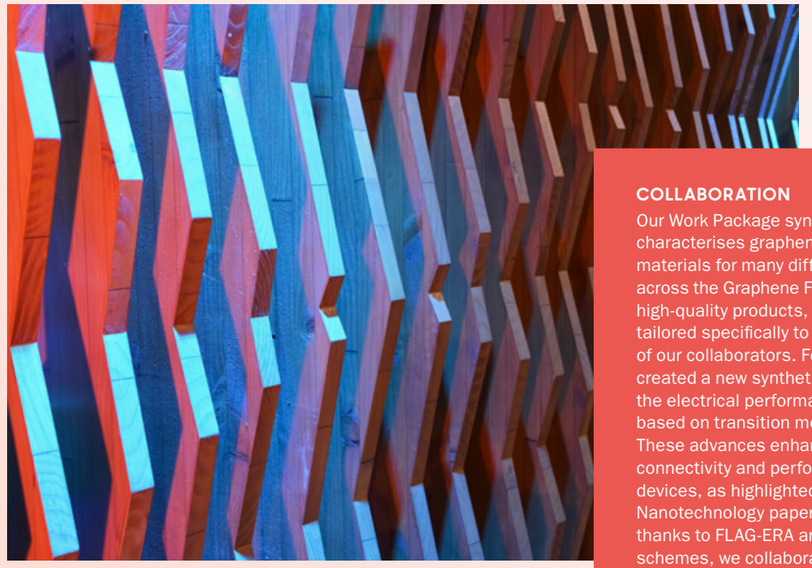
UPCOMING CHALLENGES

We want to expand the catalogue of layered materials. Our Work Package will keep focusing on the characterisation and functionalisation of graphene and related materials, to better understand their properties and develop innovative applications. One of our major challenges is the large-scale synthesis of materials without defects, which will require huge efforts over the next few years. Additionally, the exploration of new physics – such as topologically protected states – are sure to lead to fascinating effects and outcomes.

The isolation of graphene in 2004 triggered the discovery of many different layered materials for applications in sensors, batteries and electronics. Credit: Clark Van Der Berken, Unsplash



In 2021 we pioneered the synthesis of nanographene spin chains, which use triangulene building blocks to create monodimensional materials. Credit: Nature Publishing Group



The Enabling Materials Work Package combines different layered compounds, like ingredients in a sandwich, to yield unprecedented properties and applications. Credit: Jeremy Bezanger, Unsplash

COLLABORATION

Our Work Package synthesises and characterises graphene and related materials for many different partners across the Graphene Flagship. We provide high-quality products, as well as protocols tailored specifically to meet the demands of our collaborators. For example, we created a new synthetic strategy to boost the electrical performance of devices based on transition metal dichalcogenides. These advances enhanced the electronic connectivity and performance of electronic devices, as highlighted in a recent Nature Nanotechnology paper. Furthermore, thanks to FLAG-ERA and their different schemes, we collaborate with several Graphene Flagship Associated Members and Partnering Projects. Our cooperative spirit is reflected in over 60 peer-reviewed publications and six patents granted during the first half of Core 3.

References
Mishra, S. et al. Nature 2021,
DOI: 10.1038/s41586-021-03842-3.
Marega, M. et al. Nature 2020,
DOI: 10.1038/s41586-020-2861-0.
Ippolito, S. et al. Nature Nanotechnol. 2021,
DOI: 10.1038/s41565-021-00857-9

GRAPHENE FLAGSHIP ANNUAL REPORT 2021

Graphene breeze

New technologies to fight air pollution

Air pollution is the biggest environmental risk to human health, according to the WHO, killing seven million people worldwide each year. Therefore, the European Commission has set a target of reducing premature deaths caused by air pollution by half before 2030. Linked to the pursuit of this goal, researchers at the Graphene Flagship are exploring the potential of graphene in applications like sensors, coatings and foams.

> Graphene technologies like compact NO_2 sensors and photocatalysts represent an exciting step towards making urban environments cleaner and safer for their inhabitants."

The term air pollution means the alteration of the indoor or outdoor environment by chemical, physical or biological contaminants. Typical sources include petrol and diesel vehicles, industrial plants and fires. The most common pollutants of concern include gases like carbon monoxide, nitrogen oxides (or NOX) and sulfur dioxide, as well as particulate matter. Air pollution is damaging to both the environment and public health, increasing the number of fatalities due to stroke, heart disease, chronic obstructive pulmonary disease, lung cancer and acute respiratory infections.

Despite much progress in reducing air pollution over the last 30 years, levels in some parts of Europe remain unacceptably high, with over 350,000 premature deaths caused by air pollution in 2021 – that's almost 10% of overall deaths. Around 90 per cent of European city dwellers are exposed to harmful levels of air pollution, and with Europe's urban population growing and ageing – therefore becoming more sensitive to air pollution – this threat to public health is only going to become more urgent.

Governments and organisations around the world are making tackling air pollution their top priority. As well as European targets, several of the United Nations' sustainable development goals (SDGs) specifically address this issue, for example substantially reducing the number of deaths and illnesses from air pollution, or reducing the environmental impact of cities by improving air quality.

At the Graphene Flagship, research is underway to utilise the properties of graphene and layered materials in a new generation of sensors, foams and coatings that can all contribute to either monitoring air-quality or helping to improve it.

MONITORING AIR QUALITY WITH GRAPHENE

Air quality can change dramatically even within small areas, for example one street may be within safe levels, while the next dramatically exceeds them. To help governments improve air quality within a particular city, accurate pollution mapping is needed – after all, understanding a problem is the first step towards solving it. One option is small, cost-effective sensors that could be installed around the city and provide real-time data. These sensors could even be integrated into mobile devices or wearables, informing individuals and enabling them to make personal decisions when it comes to air pollution, such as changing walking routes or wearing a mask if needed.

As part of the Graphene Flagship, researchers have developed this kind of air quality sensor, which utilizes the properties of graphene to create compact, low-energy sensors able to detect nitrogen dioxide in real time. The project is a collaboration between Graphene Flagship Partners at the National Physical Laboratory, UK, and Chalmers University of Technology, Sweden, alongside colleagues at the Advanced Institute of Technology, UK, Royal Holloway University, UK, and Linköping University, Sweden.

90%

Around 90 per cent of European city dwellers are exposed to harmful levels of air pollution, and with Europe's urban population growing and ageing – therefore becoming more sensitive to air pollution – this threat to public health is only going to become more urgent.

Nitrogen dioxide gas, produced by burning fossil fuels, causes airway inflammation which can lead to breathing problems and asthma attacks. Research even links exposure to nitrogen dioxide, and other NOX, to childhood obesity and dementia. Usually, air pollution is monitored using chemiluminescence, requiring large and expensive lab equipment, and metal oxide detectors, which lack sensitivity. By contrast, this new graphene-based sensor is both small and accurate, reporting pollutant levels based on changes in its electrical resistance.

When nitrogen dioxide from the air is absorbed by the graphene layer within the sensor, electrons are withdrawn from the graphene changing its resistance changes. This produces a recordable signal, using very simple electronics. The device's simplicity means that small, commercially available sensors can easily be adapted and upgraded, using graphene-enabled sensors.

SMOG NO MORE

Graphene isn't just useful to help us better understand air pollution in our towns and cities, it can help us reduce it too. Photocatalysts, such as titania, degrade nitrogen oxides when exposed to sunlight, oxidising them into inert or harmless products. As the reaction is activated by solar light, it neither consumes the photocatalyst or requires an additional power source, making it an effective way to depollute the environment. These photocatalysts can be applied to the surfaces of buildings and thereby decrease the amount of nitrogen oxides in the air, as well as resulting in a self-cleaning, smog-eating coating.

Graphene Flagship researchers, coordinated by Italcementi, of HeidelbergCement Group, Italy, have developed a graphene-titania composite that's much more powerful than titania alone. By performing liquid-phase exfoliation to create graphene in the presence of titania nanoparticles – using only water and atmospheric pressure – the team created a new graphene-titania nanocomposite that when applied as a coating can passively remove pollutants from the air. The graphene titania composite was found to be 40 per cent more effective than titania alone, and in powder form can be applied to different materials, including concrete.

Air pollution is one of the biggest threats to public health faced by Europe. But, as with any problem facing society, research and innovation may hold an answer. Graphene technologies like compact NO_2 sensors or photocatalysts either fill a gap in the market or make an existing product much more effective. Fully commercialising these technologies represents an exciting step towards making urban environments cleaner and safer for their inhabitants.

Graphene Flagship researchers have developed a new kind of air quality sensor, which utilizes the properties of graphene to create compact, low-energy devices that detect nitrogen dioxide in real time.

Time zero.
Photocatalytic panel exposed outdoors. The purple section is treated with a pollutant (Rhodamine B). A small plexigalss roof protects the treatment from being washed away by the rain.

Three weeks later.
The purple color has disappeared. The pollutant has been degraded by the action of the photocatalyst under solar light.

Health and Environment

Work Package Leader
Maurizio Prato, University of Trieste, Italy

Work Package Deputy
Alberto Bianco, CNRS, France

It is important to understand the potential toxicity, if any, of graphene and related materials."

Maurizio Prato
Work Package Leader

Towards safe and sustainable graphene and related materials

While we are on the path to market applications, the Graphene Flagship must evaluate the effects of graphene and related materials on human health and the environment. To this end, the Health and Environment Work Package studies the potential risks that could arise from these new materials.

THIS YEAR'S PROGRESS

Our Work Package works to ensure the production of safe and sustainable graphene and related materials. In the past year, we evaluated the materials' interactions with many different natural barriers, such as the skin, lungs and kidneys, among others. We closely follow the safety rules established by the Organisation for Economic Cooperation and Development (OECD), the international standard in the testing of chemical substances. Moreover, we have worked with the OECD to develop new regulations and procedures for layered materials. These cover aspects like skin irritation, and more complex issues like neurotoxicity and immunotoxicity. It is crucial to consider safety before releasing commercial products.

We also focus on the sustainable production of graphene and related materials. When it comes to graphene manufacturing, we want to avoid hazardous materials and chemicals that could pose a threat to the environment. Graphene Flagship partner University of Castilla-La Mancha, Spain, created the spin-off Biograph Solutions to produce graphene following green chemistry methods, suitable for uses with biological tissues. Their patented technology yields clean materials, free of contaminants like metals, acids and organic compounds.

The commercial uses of graphene and related materials keep growing. Therefore, this field needs a comprehensive evaluation of their potential impact on human health and the environment. Over the past few years, the Graphene Flagship has investigated many new layered materials, all different from each other. We must also uncover any relationships between chemical structure and biological activity. Then, we will understand if any physical and chemical properties have links to potentially harmful effects.

UPCOMING CHALLENGES

Currently, the biggest challenge for the Health and Environment Work Package is the application of OECD guidelines for graphene and related materials. Every new material requires new adaptations and modifications, and our Work Package strives to further develop regulations to ensure the appropriate registration of layered materials. Eventually, these rules will guarantee further commercialisation of graphene-enabled products and industrial production on a large scale.

Our research ensured the production of sustainable materials, avoiding hazardous chemicals that threaten the environment. Credit: Marcie Kennedy, Unsplash

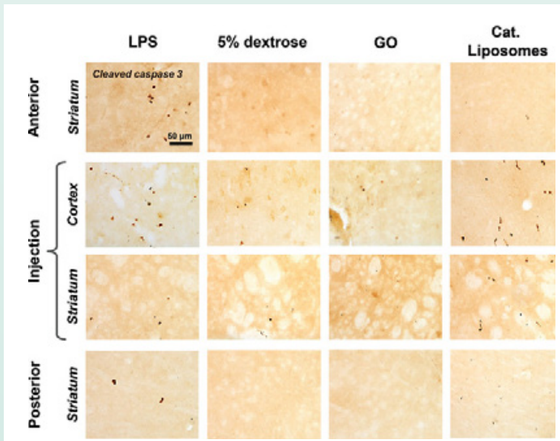
We evaluate the interactions of graphene and layered materials with the brain, lungs and kidneys, among others. Credit: Milad Fakurian, Unsplash

We believe our comprehensive evaluations are crucial for the protection of human health, the environment, and future applications of graphene and related materials."

COLLABORATION

Collaboration is fundamental to the Health and Environment Work Package. We work with OECD and other regulatory agencies to ensure graphene and layered materials meet the highest standards in terms of safety and sustainability. We also actively collaborate within the Graphene Flagship, particularly with partner companies like Avanzare, Spain, and BeDimensional, Italy. The former provided us with reduced graphene oxide composites for safety studies, which showed that exposure to these types of materials is safe and the health effects are negligible. The latter provided samples of hexagonal boron nitride, currently undergoing different tests. The results will provide insights on the environmental impact of layered materials.

References
Portioli, C. et al. Small 2020, DOI: 10.1002/smll.202004029.
Di Mauro, G. et al. Nanomaterials 2021, DOI: 10.3390/nano11092161



Preliminary studies indicate graphene oxide nanosheets mitigate inflammation in brain procedures, without any cytotoxic effects. Credit: Wiley

Biomedical Technologies

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

Work Package Deputy
Serge Picaud, Sorbonne University, France

> Graphene Flagship spin-off INBRAIN has grown to become a full partner and raise over €17 million in capital investments, breaking industry records in Europe.”
>
> **Kostas Kostarelos**
> Work Package Leader

Graphene biosensors for biomedical applications

Graphene has unique properties. In our Work Package, we make the most of them to develop innovative biomedical technologies. For example, we use graphene’s ability to interact with electro-active cells and tissues in the body for medical monitoring, diagnosis and neuropathic therapy, among other things.

THIS YEAR’S PROGRESS

One of our highlights in 2021 was the partnership with INBRAIN Neuroelectronics. This company, which spun off from the Graphene Flagship at the beginning of Core 3, has grown to become a full partner and to raise over €17 million in capital investments, breaking industry records in Europe. With INBRAIN, we develop graphene-based neural interfaces and other devices to record brain activity. These intelligent high-resolution neuroelectronic systems enable effective real-time brain mapping and minimally invasive brain resection applications.

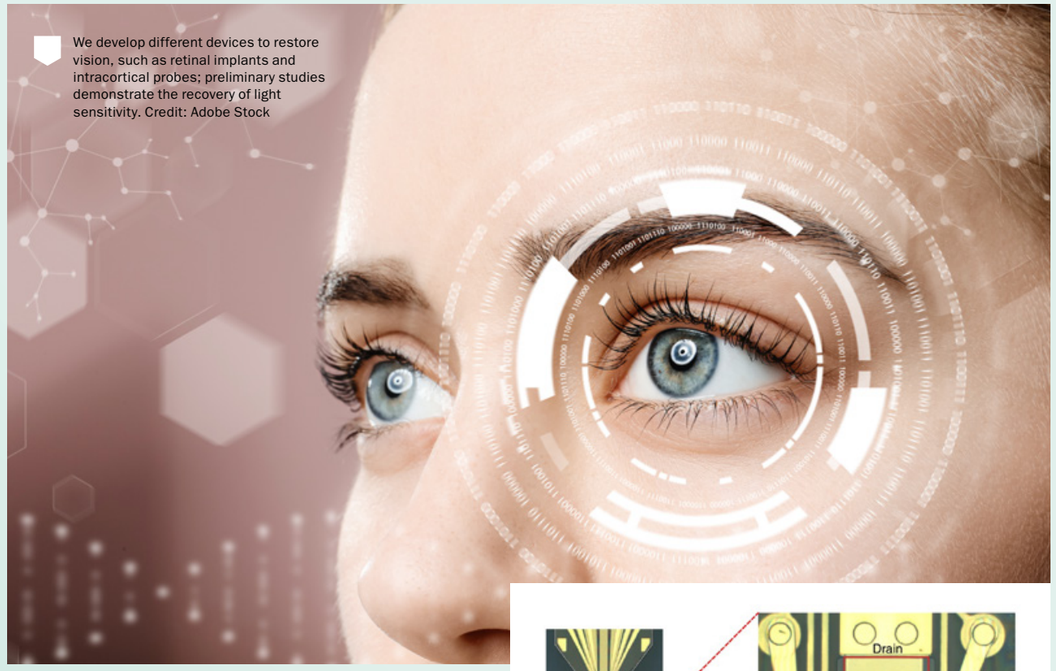
Graphene also offers outstanding opportunities in the detection and recording of slow brain waves. Our graphene microtransistors have overcome many technical challenges and will accelerate the discovery of new biomarkers related to neurological disorders, among them strokes and epilepsy. Within our efforts to commercialise graphene-enabled devices, the Biomedical Technologies Work Package patented this technology and licensed it to a leading company in the biomedical sector. Experts in neurology have claimed this graphene-enabled sensing technology will provide unprecedented insights into brain activity, thus opening new possibilities in both diagnostics and treatments.

Beyond the brain, graphene-based biomedical devices find other applications. For example, our Work Package partners develop different devices to restore vision, such as retinal implants and intracortical probes. Graphene electrodes will mimic natural photoreceptors, stimulating the optic nerve and transmitting information and images towards the visual cortex. So far, the technology is still undergoing in vivo tests in small animals, like rats and minipigs. These will yield valuable insights on biocompatibility and have already provided promising outcomes. Preliminary studies demonstrate the recovery of light sensitivity. Plus, our researchers have optimised the surgery procedures for implantation, ensuring safety.

Recently, our Work Package also discovered the potential of graphene to sooth anxiety – inhibiting the negative effects of post traumatic stress disorder. In a model study, injecting graphene oxide into a specific region of the brain silenced the neurons responsible for anxious behaviour. Tested in mice, this work provides another great demonstration of the therapeutic potential of graphene. Further studies will combine graphene with other molecules, to take advantage of its specificity for applications in drug delivery.

UPCOMING CHALLENGES

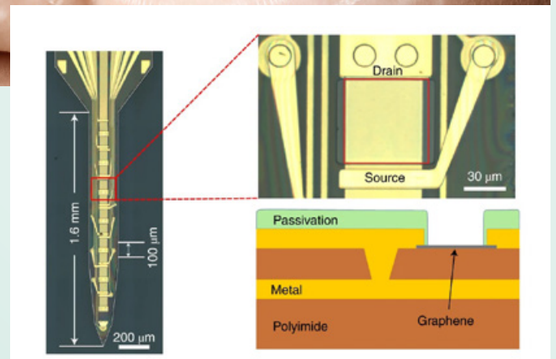
In the biomedical field, standardisation and validation will become crucial conditions towards commercialisation. The Biomedical Technologies Work Package wants to lead these efforts. For this reason, we funded the Graphene Flagship REACH/ECHA Working Group to liaise between researchers, manufacturers and the European Chemicals Agency (ECHA) and speed up the transition to market. So far, we’re preparing and filing three different documents for the registration of graphene-based materials, and we will further work in the coming years to accelerate the adoption of our biomedical technologies. Moreover, we’ll work on drafting regulatory recommendations to increase the rate of clinical translation. Hopefully, clinical trials will advance in the next few years, advancing towards the approval of graphene-enabled medical technologies in different fields.

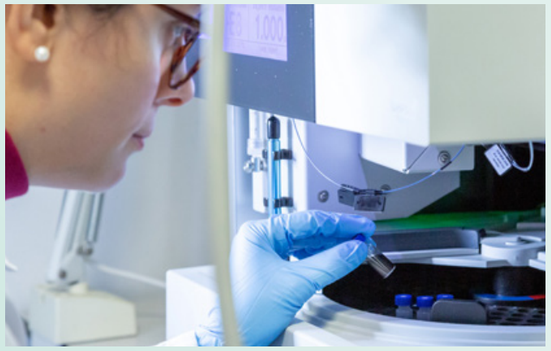


We develop different devices to restore vision, such as retinal implants and intracortical probes; preliminary studies demonstrate the recovery of light sensitivity. Credit: Adobe Stock

COLLABORATION

Besides the collaboration within our own Health, Medicine and Sensors Division, the Biomedical Technologies Work Package closely collaborates with many other parts of the Graphene Flagship. Together with the Electronic Devices and Flexible Electronics Work Packages, we develop devices for biomedical applications – the advantages of graphene enable high conductivity, sensitivity and flexibility, all key properties for innovative med-tech solutions. Graphene can be used to create miniaturised brain sensors, around 40,000 times smaller than platinum-based alternatives, with better resolution and biocompatibility. We also collaborated with the FLAG-ERA Partnering Project GRAFIN, to study graphene-enabled neuroprotheses and kicked off the FLAG-ERA Partnering Project RESCUE, which will develop graphene-based electrodes for spinal cord rehabilitation. We look forward to exciting results!





Above:
Graphene brain sensors are approximately 40,000 times smaller than platinum-based alternatives, with better resolution and biocompatibility. Credit: Nature

Below:
We discovered the potential for graphene to sooth anxiety – inhibiting the negative effects of post-traumatic stress disorder. Credit: IIT

References
Bonaccini Calia, A. et al. Nature Nanotech. 2021, DOI: 10.1038/s41565-021-01041-9.
Franceschi Biagioni, A. et al. Biomaterials 2021, DOI: 10.1016/j.biomaterials.2021.120749.
García-Cortadella, R. et al. Nature Commun. 2021, DOI: 10.1038/s41467-020-20546-w

Sensors

Work Package Leader
Peter Steeneken, TU Delft, The Netherlands

Work Package Deputy
Sanna Arpiainen, VTT, Finland

> We improved the performance and integration of our sensors and started making graphene micro-phones using *transferless* graphene."
>
> **Peter Steeneken**
> Work Package Leader

The feeling of new applications

Graphene is a one-atom-thick layer of carbon atoms. This provides a unique sensitivity to changes in the environment, which the Sensors Work Package studies to develop high-performance sensors with a variety of applications, from detecting infectious diseases, to piezoresistive devices for microphones and speakers.

In our Work Package, we investigate and develop sensors that exploit the unique properties of graphene and layered materials, such as sensitivity, conductivity and tuneability. For example, we used platinum diselenide to create a multifunctional sensor, which switches between the detection of toxic gases like ammonia and the detection of infrared radiation. This hybrid device suggests how different combinations of layered materials, as well as different topologies and structures, will lead to miniaturised devices for the sensing of chemicals and light.

THIS YEAR'S PROGRESS

Amidst the COVID-19 pandemic, the Sensors Work Package steered the research efforts to focus on new graphene-enabled sensors for biomedical applications. We envisioned functionalisation methods to anchor graphene to proteins and antibodies, specific to different pathogens and diseases. Some of these devices target the coronavirus' spike protein, offering solutions that yield effective, quantitative, quick results, without the need for hazardous reagents in the process. Our first prototypes detect the spike protein from saliva in only one step, offering results in a matter of minutes.

Our Work Package is deeply committed to sustainability. Amongst other applications, graphene-enabled sensors excel at the detection of carbon dioxide, one of the greenhouse gases that more heavily contributes to the current climate crisis. By creating heterostructures – sandwiches – of graphene and other layered materials, Graphene Flagship researchers have developed detectors for carbon dioxide, more compact and efficient than current solutions. Beyond environmental applications, CO_2 detectors could also become an effective tool to tackle the pandemic. Good carbon dioxide detectors help monitor air quality, promoting proper ventilation procedures, therefore reducing transmission rates for coronavirus and other diseases.

Graphene also allows for ultimate force sensitivities in high-performance pressure sensors, microphones and accelerometers. In 2021, we created graphene-enabled microphones using transferless graphene, a material directly grown onto the desired substrates. We work to integrate all these devices on traditional CMOS silicon technologies, thus ensuring compatibility with state-of-the-art electronics and low-cost readout devices.

UPCOMING CHALLENGES

Our main challenge in the Sensors Work Package is achieving full integration with CMOS devices. This means ensuring that graphene-enabled sensors transfer their readings successfully to traditional electronic devices, maximising the performance and the marketability of products. Graphene and layered materials have the potential to miniaturise all sorts of sensors, ready for applications in mobile phones, wearables and the Internet of Things, providing valuable information about everyday situations.

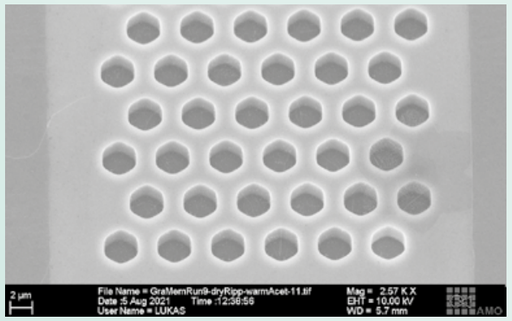
A researcher preparing a graphene-enabled sensor for laboratory measurements.
Credit: RWTH Aachen University and Martin Braun

A researcher studying graphene samples under the microscope.
Credit: RWTH Aachen University and Martin Braun

> We develop innovative sensors that exploit the unique properties of graphene and related materials to improve performance and enable new functionalities."

COLLABORATION

Collaboration with other Graphene Flagship partners has brought graphene-enabled sensors to much higher maturity levels. To name one example, our work with the Enabling Materials Work Package has yielded novel functionalised sensors for different applications, including biomedicine and gas detection. We also work closely with members of the 2D Experimental Pilot Line to develop large-area integration methods, which will hopefully increase the technology readiness levels of our different technologies.



Scanning electron microscopy shows suspended monolayer graphene in one of the sensors developed by Graphene Flagship partner RWTH Aachen University.
Credit: RTWH Aachen University and Sebastian Lukas

References
Lukas, S. et al. Adv. Funct. Mater. 2021, DOI: 10.1002/adfm.202102929.
Idili, A. et al. ACS Sens. 2021, DOI: 10.1021/acssensors.1c01222.
Prechtl, M. et al. Adv. Funct. Mater. 2021, DOI: 10.1002/adfm.202103936.
Quellmalz, A. et al. Nature Commun. 2021, DOI: 10.1038/s41467-021-21136-0

GRAPHENE FLAGSHIP ANNUAL REPORT 2021

The layered materials' trove

Graphene and layered materials put an end to the treasure hunt for rare earths and scarce materials, paving the way to sustainable electronics

On the isolated coast of southwest Greenland, the abandoned mining town of Ivigtut is eerily baron. The site was once home to a prosperous mine and was one of the world's few sources of cryolite, a material used to refine aluminium, make pesticides and insecticides, and give fireworks their yellow colour. Then in 1987, the mine simply ran out.

Ivigtut mine's demise and abandonment is a reminder of how global demand can quickly outstrip earth's natural resources. Today, we are experiencing the same imbalance in the supply of rare minerals and the scale of their demand in the electronics industry. However, graphene and layered materials could alleviate this challenge, tackling the global material crisis.

RAW MATERIAL RESERVES

Among the very rarest of materials used in electronics are tantalum, gallium, indium and rare earths like europium and neodimium, among a host of others. These elements are found in naturally occurring minerals that, like cryolite, cannot be recreated or replaced. Moreover, many are only present in miniscule quantities in the Earth's crust.

The applications of these materials are unbelievably widespread. In fact, you are within just a few inches of at least one of these materials, working away to allow your smartphone or laptop to operate. What's more, they are increasingly used in developing environmental technologies such as solar panels and batteries for electric vehicles (EVs).

The scarcity of these materials is already causing a huge surge in their cost. The price of lithium, used in modern day batteries, has increased by 150 per cent since September 2020. Holmium, used to make magnets and alloys for sensors and actuators, has more than doubled in price; other rare earths like neodymium and praseodymium, minerals used in magnets, motors and wind turbines, have seen an increase of 73 per cent in a single year.

> The scarcity of some materials is already causing a huge surge in their cost. The price of lithium, used in modern day batteries, has increased by 150 per cent since September 2020."

Costs are rising, but what happens when these raw mineral reserves run out, or become too expensive to use? Ivigtut's depletion caused a collapse of the town's mining community, but the potential of stopping the world's electronics manufacturing industry – and the public's insatiable desire for new electronics – is almost incomprehensible.

EXPLORING NEW OPTIONS

While the recent data appears catastrophic, the scarcity of these rare materials is not a new concern. China, which is home to more than 90 per cent of rare mineral refining, claims that supplies of rare earth elements such as dysprosium, neodymium and lanthanum – coveted for their conductive properties and commonly used in computers – could be exhausted in just 20 years.

Some sceptics have argued that the concern about diminishing availability of rare metals is misplaced, suggesting increased mining could discover untapped reserves. While that's possible, it cannot be relied upon.

Meanwhile, industry experts elsewhere have called for tougher rules on recycling of electronics, hoping to make better use of the rare metals in disused technology. In a recent report, European project Cewaste explained that recycling should be mandatory for the crucial raw materials present in electronics.

But, even if the industry did have a robust recycling mandate in place, shouldn't we be looking for better, more easily obtainable alternatives?

> The world's electronics industry must continue thriving to serve our growing population and help develop technologies for a greener future. We're confident that graphene is the answer."

GRAPHENE FOR ELECTRONICS

The Graphene Flagship has been exploring the potential of graphene for electronics since the project's inception almost a decade ago. Boasting impressive flexibility, strength and conductive properties that surpass the potential of copper, the material has much to offer an industry that is currently grappling with ever-escalating costs of other metals.

"[Graphene] is the thinnest material, making it an excellent choice for new sensing devices," explained Maria Smolander, research team leader from Graphene Flagship partner VTT, Finland. "It's also a more sustainable solution, as graphene-based circuits can be printed without requiring rare or precious metals."

In fact, a recent study has proved the potential of graphene for use in touch screen sensors. Researchers demonstrated the fabrication of organic light-emitting diodes (known as OLEDs) with a monolayer of graphene in the anode. This method replaced the use of indium tin oxide, a key part of touch screens that is currently listed as a critical raw material in Europe.

This study is a promising breakthrough – and a necessary discovery should the world need to wean itself from rare minerals in electronics. Despite the potential, there are some barriers to widespread adoption of graphene for electronics.

Crucially, wafer-scale integration of graphene is necessary for the electronics industry to transition to commercial use of graphene. This process will be accelerated by initiatives such as the European Commission's 2D Experimental Pilot Line, part of the Graphene Flagship, which is dedicated to the improvement and scaling-up of the wafer-scale integration process.

CHANGE FOR THE FUTURE

Finding alternatives to rare minerals is crucial for the future of the electronics industry – and for the planet. The International Energy Agency calculated that, if the world is to reach net zero greenhouse gas emissions in 2050, the demand for critical materials and rare earths will be six times higher than it is today.

In fact, demand for lithium alone will be 40 times higher in 2040 because of its use in batteries – crucial for EVs and other energy storage applications.

While it's likely that many of earth's rare minerals will follow the fate of cryolite and become decimated in time, the world's electronics industry must continue thriving to serve our growing population and help develop technologies for a greener future. We're confident that graphene is the answer.

800

There are 800 million tons of recoverable graphite on earth

15th

Carbon is the 15th most abundant element in the Earth's crust

Electronic Devices

Work Package Leader
Daniel Neumaier, AMO, Germany

Work Package Deputy
Gianluca Fiori, University of Pisa, Italy

> Nearly all of our results come from collaboration, this is one of the biggest advantages of the Graphene Flagship."
>
> **Daniel Neumaier**
> Work Package Leader

Chips and bits with integrated graphene

Traditional silicon electronics have almost reached their maximum potential. Moore's Law predicts the number of transistors in an integrated circuit doubles every year, however cost and power consumption keep growing and physical limitations hinder the development of faster and denser devices. Graphene and layered materials opened a new space in electronics, paving the way to a more-than-Moore scenario of disruptive technologies for digital applications. The Electronic Devices Work Package focuses on these advances.

THIS YEAR'S PROGRESS

Our aim is to develop new fabrication processes to exploit the properties of graphene and layered materials in electronic applications. In particular, we explore logic circuits, wireless communications and flexible electronics, all in close collaboration with other Graphene Flagship Work Packages. To achieve this, we combine the excellent conductive properties of graphene with other layered materials such as transition metal dichalcogenides and hexagonal boron nitride acting as semiconductors and insulators, respectively. The different layers enable the creation of heterostructures with hybrid properties and use in devices with unprecedented features and new applications in electronics.

Thanks to the versatility of layered materials, we demonstrated how to print traditional CMOS devices onto flexible substrates like paper. The Graphene Flagship is fully committed to developing more sustainable solutions, and graphene-enabled inkjet-printed circuitry can fulfil the need for environmentally friendly electronics. A step forward in sustainable transistors was possible, thanks to our technology that enables printing all the main building blocks of electronics, such as inverters, logic gates and latches; all highly recyclable and produced at very low costs.

Other advances include high data-rate communication links, new Hall sensors for position sensing, and electronic devices for biomedical applications. All these make the most of the electronic properties of graphene and layered materials. Furthermore, the Electronic Devices Work Package also investigates the underlying physics of these phenomena, to better understand the potential of layered materials in real-world applications.

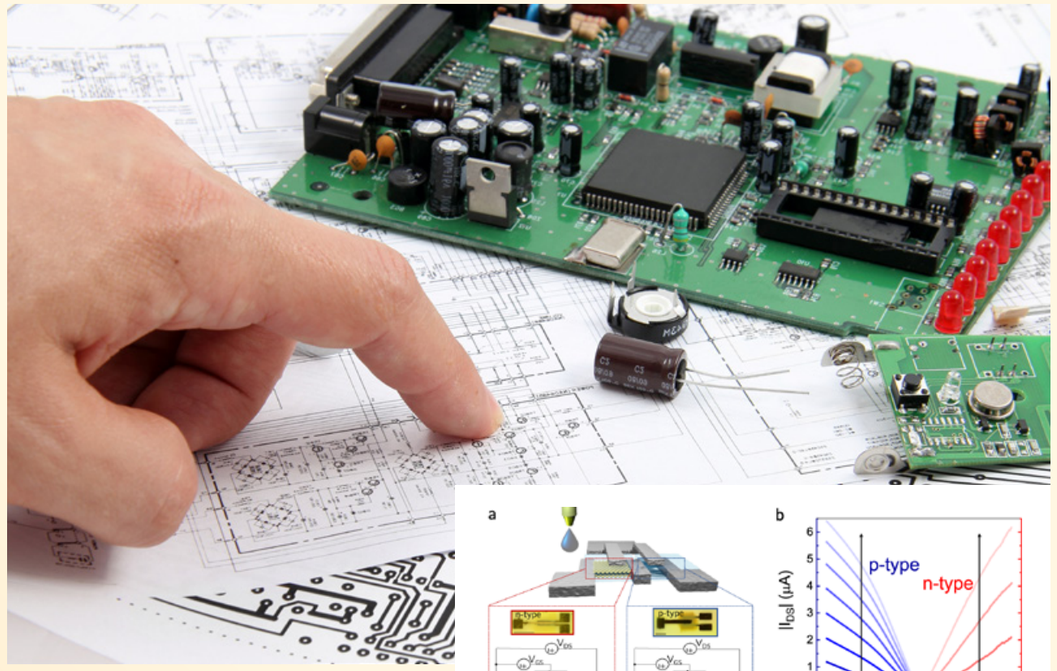
Moving forward, our Work Package will focus on improving the manufacturing process of graphene-enabled electronics. We will address issues related to reliability, stability and reproducibility, making sure that our technologies are ready for European manufacturing lines. Complex systems featuring graphene and layered materials may become standard in future electronics.

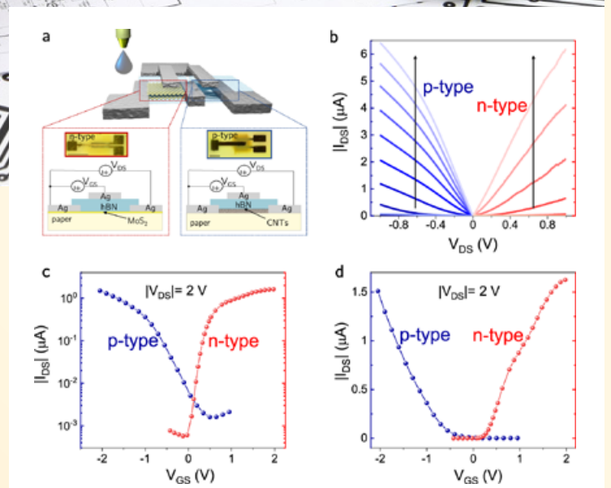
UPCOMING CHALLENGES

Sometimes, transistors based on transition metal dichalcogenides present unwanted hysteresis, a physical effect detrimental to their performance. We solved this issue, mostly thanks to the complementary skills and competencies within our Work Package and the cooperative environment within the Graphene Flagship. Our main challenges are related to increasing the reliability of graphene-enabled electronic devices, reducing performance variations and boosting the stability under stress. We will hopefully solve these and hit the market, demonstrating the competitiveness of graphene and layered materials for electronics.

COLLABORATION

In the Graphene Flagship, collaboration is one of the biggest assets. Nearly all the results that our Work Package has published come from the collaboration of two or more institutions within the project, as well as Associated Members and Partnering Projects, often funded via FLAG-ERA. In addition, we foster strong interactions with other Work Packages and the 2D Experimental Pilot Line. These collaborations help us to create better solutions to challenges like processing and reliability. A good example is the creation of new devices that link radiofrequency and optical communications, which we developed side-by-side with the Photonics and Optoelectronics Work Package.

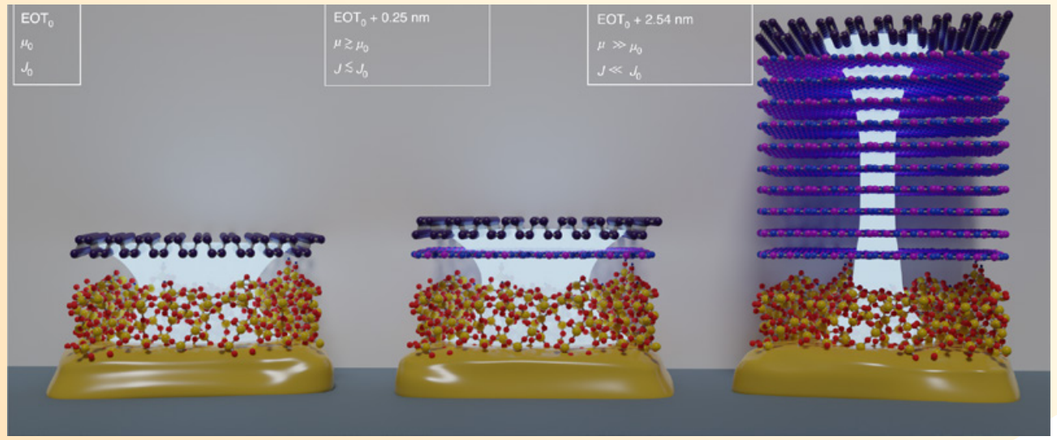




Above:
Our graphene-enabled inkjet-printed circuitry will undoubtedly fulfil the need for environmentally friendly electronics. Credit: Adobe Stock

Right:
Transistors with graphene and molybdenum disulfide could boost the performance of electronics. Credit: Nature Publishing Group

Below:
Heterostructures – the combination of different layered materials – showcase great performance, as well as unprecedented features for electronics. Credit: Nature Publishing Group



References
Knobloch, T. et al. Nature Electr. 2021, DOI: 10.1038/s41928-021-00672-z.
Montanaro, A. et al. Nature Commun. 2021, DOI: 10.1038/s41467-021-22943-1.
Brunetti, I. et al. NPJ 2D Mater. Appl. 2021, DOI: 10.1038/s41699-021-00266-5

Photonics and Opto-electronics

Work Package Leader
Frank Koppens, ICFO, Spain

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

The Graphene Flagship is an ideal platform for harvesting the knowledge from world-leading researchers in Europe and accomplishing ambitious goals, otherwise impossible."

Frank Koppens
Work Package Leader

Graphene for high-speed communications

Photonics studies light and its interactions with matter. When combined with electronics, we get the subject of the Photonics and Optoelectronics Work Package. This comprehensive field develops devices to source, control and detect light for different applications, mostly in telecommunications and sensing. A key advantage of graphene and layered materials in optoelectronics is their record-breaking efficiency, which will enable faster solutions for data-transmission, as well as more sustainable solutions for reducing its carbon footprint.

THIS YEAR'S PROGRESS

Our Work Package creates new components with graphene and layered materials. Beyond telecom and datacom, some interesting applications include image sensing arrays for night-vision and autonomous driving, and innovative sensors for new medical imaging technologies.

This past year, we developed new terahertz detectors with high frequency range, used in different devices for sensing and imaging. Thanks to the work carried out within the Graphene Flagship, including advances in scalability and chemical vapour deposition, terahertz technologies are moving towards higher technology readiness levels (TRL). Other highlights include new electro-absorption modulators that outperform silicon-based alternatives, and other competitors. These types of components could enhance the performance and stability of optoelectronic devices, creating new opportunities in the design of innovative systems. The Photonics and Optoelectronics Work Package also demonstrated the possibilities of hexagonal boron nitride for gas detection in the mid-infrared, using phonon-enhanced sensing. This boosts the sensitivity of carbon dioxide detectors, devices that have become crucial in the monitoring of air quality.

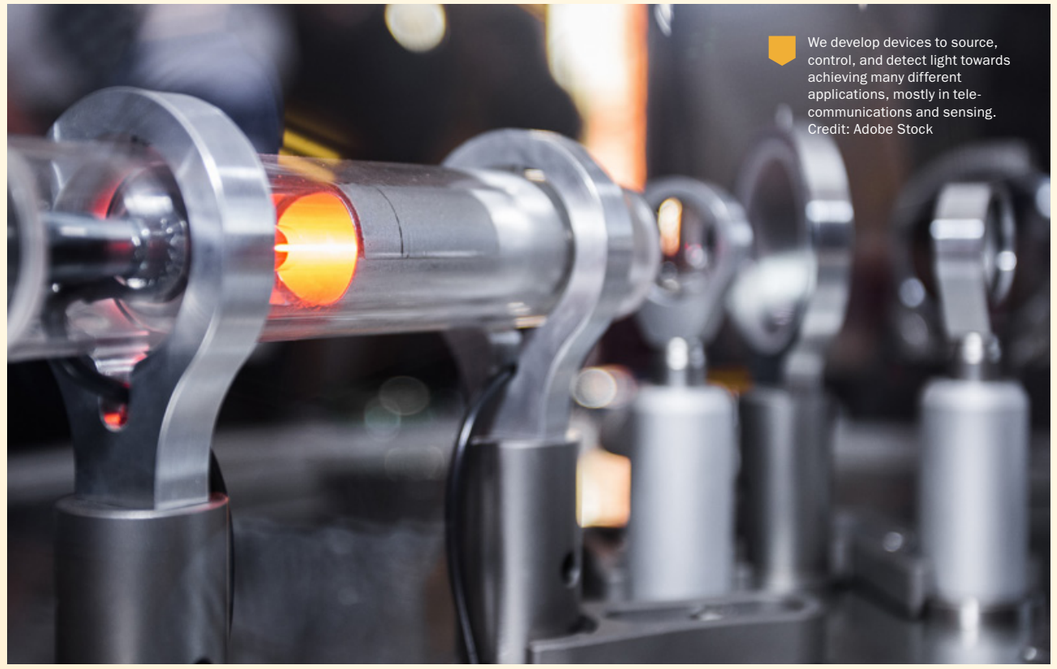
We have exported most of our high-TRL technologies to Graphene Flagship Spearhead Projects – three of which are closely linked to our Work Package – and new spin-off companies. For example, Qurv Technologies, based in Barcelona, creates innovative image sensors in the short-wave infrared using both graphene and quantum dots. These devices work alongside traditional CMOS components, thus enabling low-cost and high-yield manufacturing processes. Cambridge Raman Imaging uses graphene-enabled fibre lasers to better detect cancer and other diseases. Their technology outperforms the competition in terms of both accuracy and price; and should become widely available between 2023 and 2025. Graphene Flagship Associated Member CamGraPhIC is developing novel modulators and transceivers for the future of 5G and 6G communications.

Despite having so many technologies and products close to the market and having filed 20 patents in Core 3, our Work Package is also deeply committed to fundamental science. We strive to understand the physical phenomena behind our highly efficient devices. One of our key achievements in 2021 was fully theoretical – we created a multiphysics model to simulate the electronic, heat and optical properties of our graphene-enabled components.

In future years, we will further advance our most promising optoelectronic technologies, as well as design creative demonstrators to highlight the commercial value of our discoveries and keep engaging key industrial partners in their commitments to graphene and layered materials.

UPCOMING CHALLENGES

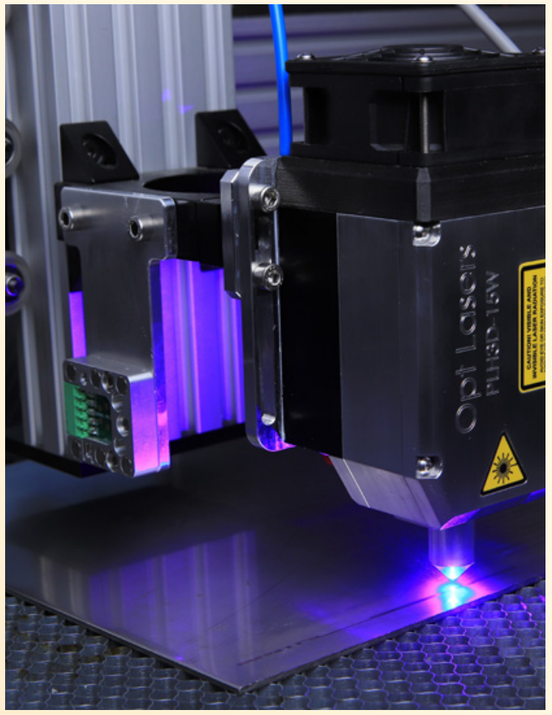
The Photonics and Optoelectronics Work Package aims to develop the best performing optoelectronic devices, to serve as building blocks for further engineered solutions within the Graphene Flagship Spearhead Projects. Beyond the scope of Core 3, our main challenge is delivering specific technological implementations with increased TRLs and enhanced market uptake. We will need to overcome technical hurdles, as well as work hard to develop new sets of standards, and find investors and manufacturers. Some of these goals will be met in collaboration with the 2D Experimental Pilot Line, while others will require reinforced communication efforts and the application of open science strategies.



We develop devices to source, control, and detect light towards achieving many different applications, mostly in telecommunications and sensing. Credit: Adobe Stock

COLLABORATION

The Graphene Flagship is an ideal platform for harvesting the knowledge from world-leading researchers in Europe and accomplishing ambitious goals, otherwise impossible. These goals can be reached working together with our industrial partners and Associated Members. Thanks to this collaborative environment, we get access to fabrication and testing facilities and a unique collection of expertise that helps enhance the promising performance of our optoelectronic devices. Extensive connections with high-tech spin-offs, key industry players and our own Graphene Flagship Spearhead Projects pave the way towards commercialisation of graphene-enabled products.



With graphene and layered materials, photonics and optoelectronics will enable faster solutions for data-transmission, as well as more sustainable solutions to reduce its carbon footprint. Credit: Opt Lasers, Unsplash

References
Bareza, N.J. et al. ACS Photonics, 2022, DOI: 10.1021/acsphotonics.1c01254.
Agarwal, H. et al. Nature Commun. 2021, DOI: 10.1038/s41467-021-20926-w.
Asgari, M. et al. ACS Nano. 2021, DOI: 10.1021/acsnano.1c06432

GRAPHENE FLAGSHIP ANNUAL REPORT 2021

Flexible Electronics

Work Package Leader
Maria Smolander, VTT, Finland

Work Package Deputy
Henri Happy, University of Lille, France

> Thanks to the properties of graphene and layered materials, we can develop flexible and stretchable devices for many applications.”
>
> **Maria Smolander**
> Work Package Leader

Graphene... ready to wear!

The properties of graphene and layered materials enable the Flexible Electronics Work Package to develop flexible and wearable devices for many applications, ranging from wireless communications to solutions to monitor health and wellbeing.

We have a strong commitment to sustainability. Graphene can be a green alternative to the scarce raw materials traditionally used in electronics. We also focus our efforts on making devices with high recyclability, avoiding the ever-growing problem of waste accumulation. Thanks to low-emission manufacturing methods and the versatility of graphene-inks, we have developed several electronic devices using renewable substrates, like paper. This paves the way to eco-friendly electronics.

THIS YEAR'S PROGRESS

Some promising results from the Flexible Electronics Work Package include graphene-enabled flexible devices for health applications. In particular, we developed electrodes covered in CVD-graphene to measure heart rate, even detecting a full electrocardiogram, providing information on the rhythm and electrical activity of the human heart. Our Work Package also works on new ways of interacting with digital devices, such as flexible touchpads. Much like the screens on smartphones, these graphene-enabled sensors interpret capacitive and force inputs and translate those into electrical pulses.

These graphene-enabled electrodes have been patented and perform better than traditional solutions. More importantly, they offer high-quality readings without the application of medical gels, which aligns with our sustainability efforts, reducing unnecessary products and offering higher reusability in medical settings. Already at technology readiness levels (TRL) 4 and 5, we believe these devices will soon be commercialised thanks to the Graphene Flagship's innovation and business development efforts.

Many other flexible electronic devices could hit the market, all exploiting graphene and related materials. The Flexible Electronics Work Package has developed a graphene-based yarn that is already undergoing large-scale production trials. This material was incorporated in textiles and wearables as a proof-of-concept for integrated electronics.

We are also very proud of our paper-based electronics developments. This sustainable alternative to traditional silicon chips has found uses in security systems, screens, photo-detectors and much more. We look forward to further developing the technology. It could speed up authentication processes, thanks to graphene-enabled tickets and documents directly printed with features like RFID. With a TRL between 7 and 8, these advances could become commercial realities before 2023.

UPCOMING CHALLENGES

Large surfaces pose challenges for graphene-enabled wearables. We need better solutions for printing, as fabrics and textiles keep high conductivity when used in large areas. For now, we are focusing our efforts on applications that require smaller areas, such as heating and sensing – both have shown promise and advanced functionalities. In the future, we could also tackle these problems, exploiting different devices working in parallel. With multi-sensor systems and strategies, we could cover wider surfaces, then process the data retrieved using software-based approaches.

Graphene-enabled technologies enable inkjet-printed flexible electronic circuits and RFID tags for applications in security, the food industry and gaming. Credit: Novalia, Graphene Flagship

The properties of graphene and layered materials enable flexible and wearable devices for many applications. Credit: Adobe Stock

COLLABORATION

Collaboration with Work Packages from other Graphene Flagship divisions is paramount to the success of the Flexible Electronics Work Package. For example, the Enabling Materials Work Package provides novel exfoliation approaches for graphite and layered materials. These have been used in heating devices with applications in the Spearhead Project GICE. Since some of our flexible devices aim at medical applications, we collaborate closely with the Health and Environment Work Package to ensure graphene-enabled electrodes and sensors comply with all current safety regulations. Our constant exchanges within our division fostered advances in the field of electronics, successfully producing key components printed on paper. Our presence in the Innovation Work Package in the form of VTT's Business Developer for Flexible and Wearable Applications ensures rapid market implementation, providing market overviews, and triggering new partnerships with Graphene Flagship Associated Members.

A respiration sensor based on printed graphene. Credit: IAW

Graphene-enabled technologies enable inkjet-printed flexible electronic circuits and RFID tags for applications in security, the food industry and gaming. Credit: Novalia, Graphene Flagship

References
Conti, S. et al. Nat. Commun., 2021, DOI: 10.1038/s41467-020-17297-z.
Kim, M. et al. Appl. Surf. Sci., 2021, DOI: 10.1016/j.apsusc.2021.149410

GRAPHENE FLAGSHIP ANNUAL REPORT 2021

Wafer-scale Integration

Work Package Leader
Marco Romagnoli, CNIT, Italy

Work Package Deputy
Amaia Zurutuza, Graphenea, Spain

* Amaia Zurutuza became Work Package leader in 2022.

We develop processes to integrate graphene into silicon foundries.”

Marco Romagnoli
Work Package Leader

Silicon: the perfect pairing for graphene

All the exciting applications for graphene in electronics and optoelectronics heavily rely on a successful integration with traditional silicon devices. Therefore, the Wafer-scale Integration Work Package develops the processes to incorporate graphene and related materials into silicon foundries’ manufacturing pipelines. Our work is key to attaining the Graphene Flagship’s primary goal, taking graphene from the lab… to the fab!

THIS YEAR’S PROGRESS

In the world of electronics, wafers are thin slices of semiconductor materials – usually crystalline silicon. Our Work Package optimises the fabrication process to cover silicon with layers of graphene and related materials, to achieve different properties for a variety of applications. This requires the optimisation of different steps: growth of graphene, transfer and encapsulation. In the past year, we improved all these techniques to achieve record-breaking results in terms of uniformity and carrier mobility, two factors directly correlated to the quality of graphene-enabled devices.

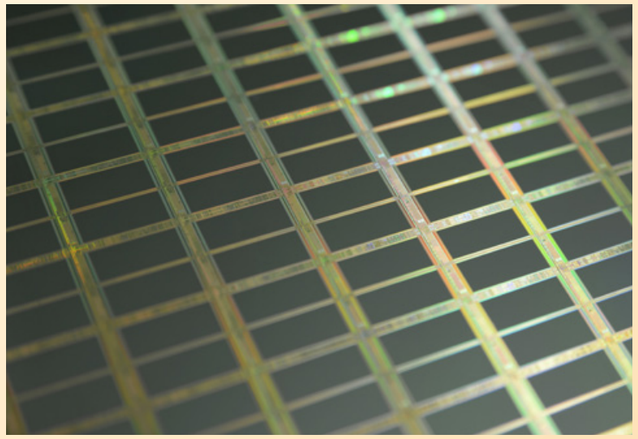
We demonstrated a wafer-scale method for building single crystal matrices on silicon and silicon nitride. These structures have applications in electronics, optoelectronics and photonics; among these optical- and electro-absorption modulators and ultrafast detectors. The reproducibility of this approach is outstanding. We also develop customised tools for graphene-based wafer scale platforms, including transfer and delamination devices.

Thanks to the collaborations between academia and industry, fostered by the project, most of the processes developed within our Work Package have already reached the European market. For example, Graphene Flagship partner Graphenea, Spain, commercialises wafer-scale graphene field effect transistors (GFET). Graphene Flagship partners Aixtron, Germany, and DTU, Denmark, have developed an innovative roll-to-roll system to deposit graphene on 100mm-wide flexible substrates, now close to commercialisation.

Overall, the Wafer-scale Integration Work Package has consistently increased the technology readiness level (TRL) of different technologies to manufacture graphene-enabled devices in a reproducible and reliable manner. Our work paves the way to applications like high-performance photonic circuits for telecom and datacom and innovative image sensors for multispectral applications.

UPCOMING CHALLENGES

The Wafer-scale Integration Work Package strives to improve current processes even further. Our researchers will optimise all the operations required for the integration of graphene and silicon. We will work on the encapsulation of graphene, as the preservation of this one-atom-thick material throughout the different fabrication steps is key. Graphene must keep its excellent properties to guarantee applications in telecom, datacom, sensors and many more.



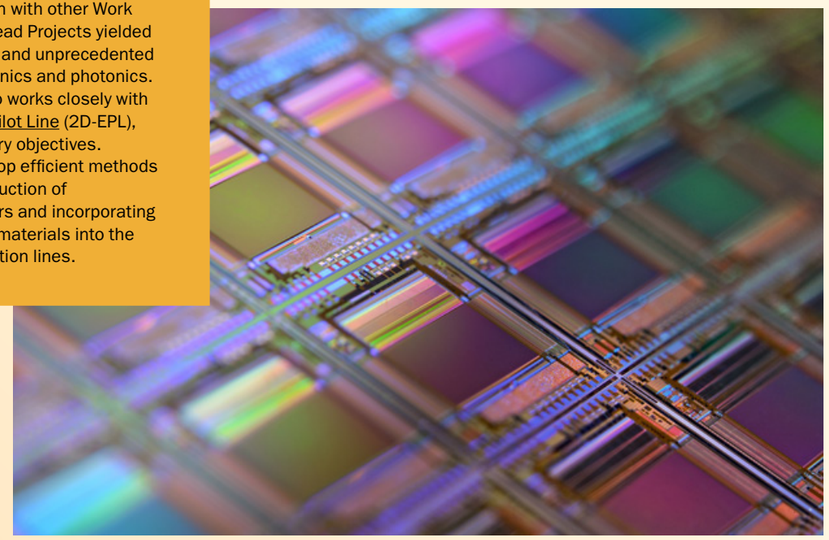
In the world of electronics, wafers are thin slices of semiconductor material; we develop customised tools to manufacture graphene-based wafers, including transfer processes and delamination devices.
Credit: Laura Ockel, Unsplash

The Wafer-scale Integration Work Package develops suitable processes to incorporate graphene and related materials into the different manufacturing pipelines of silicon foundries.
Credit: Adobe Stock

COLLABORATION

The collaborations with industrial partners like Graphenea and Aixtron have enabled the development of commercial solutions for graphene-enabled electronics. The fruitful cooperation with other Work Packages and Spearhead Projects yielded unique demonstrators and unprecedented results in (opto)electronics and photonics. Our Work Package also works closely with the 2D Experimental Pilot Line (2D-EPL), towards complementary objectives. Together, we will develop efficient methods for scaling-up the production of graphene-coated wafers and incorporating graphene and layered materials into the semiconductor fabrication lines.

We pave the way to applications like high performance photonic circuits for telecom and datacom and innovative image sensors for multispectral applications.
Credit: Laura Ockel, Unsplash



References
Marconi, S. et al. Nature Commun., 2021, DOI: 10.1038/s41467-021-21137-z.
Giambra, M.A. et al. ACS Nano, 2021, DOI: 10.1021/acsnano.0c09758.
Wu, C.H. et al. Symposium VLSI Circuits, 2021, DOI: 10.23919/VLSICircuits52068.2021.9492495

GRAPHENE FLAGSHIP ANNUAL REPORT 2021

You've got the power

The graphene technologies improving battery performance

By 2030, it is expected that over 50% of cars produced will be partly or wholly electric. Automotive brand Jaguar recently announced that, from 2025, it will only sell electric cars. With many other big names, from Volvo Cars to Ford, implementing similar strategies, electric vehicles (EVs) look set to revolutionise our roads. But there is a limiting factor – batteries. So much so, in fact, that the term range anxiety has been coined, a name for the specific fear that your EV won't reach its destination before running out of power. Thankfully, Europe's leading scientists are researching ways to improve battery life and performance. Here we explore some of the latest graphene-based battery technology across different industries.

Batteries are one of the key innovations that define the current technological era. They enabled the development of everything from mobile devices to renewable energy generation, as well as EVs. But, even today's state-of-the-art lithium-ion batteries (LIBs) have their limitations. The ideal battery would have more charge cycles, longer life-span, faster recharging, higher energy density and lower cost than today's LIBs on the market. In addition, safety, recyclability and environmental impact must always be considered carefully.

One avenue of research that could create the batteries of the future is the use of new materials; advanced types of carbon, such as graphene. It is important to tackle this challenge from different fronts, covering both technological and performance optimisation as well as more fundamental concepts. In the former, we can exploit graphene additives that increase the power performance of LIBs. In the latter, we investigate novel graphene-based materials for Na+-ions in sodium-ion batteries (SIBs) or for sulfur in lithium-sulfur (Li-S) batteries. The Graphene Flagship has been looking into how introducing graphene and layered materials can improve batteries' performance, with some startling results.

READY TO BUY

Some of our industrial members have been working with and selling carbon-based materials for several years. For example, Graphene Flagship Associate Member OCSiAl produces highly conductive nano-materials to improve battery performance. One of their top products, TuballTM, is ideal for battery applications. More than 90% of their customers request their Tuball Batt dispersions, which they offer in N-Methyl-2-pyrrolidone (NMP) or in water, for the manufacturing of LIB cathodes and anodes, respectively. Their product can be directly poured into the slurry mixing process of the battery manufacturer.

ON THE ROAD SOON

One of the Graphene Flagship's Spearhead Projects – industry-led initiatives to bring graphene technology closer to commercialisation – is Graphene Enabled High-Energy Batteries for Automotive Applications (GrEEnBat). The GrEEnBat project aims to create a working battery module for automotive applications, using silicon-graphene composite anodes in LIBs, able to compete with the projected state-of-the-art available in 2025.

> The Graphene Flagship has been looking into how introducing graphene and layered materials can improve batteries' performance, with some startling results."

> Graphene is also making waves in smaller scale batteries – for electronic devices such as watches, wearable devices and headphones."

Over the last year, the project has focussed on upscaling the production of high-quality anode materials to the tonne-per-year scale, and improving the electrodes' areal capacity, and thereby energy density and cyclability, i.e. life-span. The researchers have also worked on optimising their electrode recipes, electrolyte formulations and cell designs.

STARTING SMALL

Graphene is also making waves in smaller scale batteries – for electronic devices such as watches, wearable devices and headphones. Silicon-based anodes in LIBs are one promising alternative to the traditional graphite, in theory offering a much-improved storage capability. But in practice there have been challenges with using silicon as the active material – as it is charged and discharged, its volume expands and contracts, leading to stresses and fracturing in the anode, ultimately causing the battery to fail after too few cycles to be of any commercial interest.

However, researchers within the Graphene Flagship have found a way to solve this in coin cell batteries; a tiny amount of graphene stabilises the anode during the charge and discharge cycle by handling the silicon expansion.

50%

By 2030, it is expected that over 50% of cars produced will be partly or wholly electric.

2025

Automotive brand Jaguar recently announced that, from 2025, it will only sell electric cars.

TRYING TO REPLACE LITHIUM

As demand for rechargeable batteries continues to grow, it increases the strain on lithium resources and ultimately increases the cost of the raw materials. Compared to lithium metal batteries – the "Holy Grail" of many battery R&D efforts – using magnesium metal anodes renders a battery much less prone to form dendrites, which can cause short circuits and, in rare cases, battery fires. The drawback? Poor practical cell performance, largely due to the lack of suitable cathodes.

To solve this, Graphene Flagship researchers have developed a brand-new cathode material that could lead to more powerful, longer-lasting batteries for mobile devices. The material combines the properties of vanadium with graphene oxide to create a cathode with improved chemical and electrochemical stability, as well as kinetics. The resulting rechargeable coin-cell, thus a lab-level proof-of-concept device, can operate with significantly higher currents (i.e. power outtakes), an often limiting factor of magnesium-based batteries. At the same time, it offers somewhat higher cell voltage than competing chemistries.

Another metal that Graphene Flagship researchers are working on is sodium. Despite being far from commercial application, a new anode material concept for sodium-ion batteries based on "Janus" graphene stacks has been recently published by Graphene Flagship partner Chalmers University of Technology in Sweden.

Whether you're considering batteries for EVs, electronics or other applications, the key concerns of performance, cost and sustainability remain the same. Through the collective effort of global researchers and scientists, graphene has proven its potential to solve some of the issues that limit batteries today. Batteries may well have defined the current technological era thus far, but with these new technologies on their way to commercialisation, it is exciting to see what the future will hold.

For more information on the Graphene Flagship's research into battery technology, click here.

GRAPHENE FLAGSHIP ANNUAL REPORT 2021

Energy Generation

Work Package Leader
Emmanuel Kymakis, Hellenic Mediterranean University, Greece

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

We will bridge the gaps between laboratories and industry, ensuring graphene-enabled photovoltaics and electrolysers can reach the market."

Emmanuel Kymakis
Work Package Leader

Graphene-enhanced solar cells

The world is facing an ever-growing energy crisis. Graphene and related materials could help alleviate this problem by becoming part of new technologies to harvest electricity in clean and sustainable ways. The Energy Generation Work Package tackles this challenge with two different approaches, targeting both on- and off-grid applications. Thanks to the collaborations fostered by the Graphene Flagship, we bridge the gaps between research laboratories and industry, ensuring graphene-enabled photovoltaics and electrolysers can reach the market.

THIS YEAR'S PROGRESS

The main on-grid technology we are developing is graphene solar cells. Our Work Package has developed several solutions for large-area photovoltaics. Graphene-enabled solar panels have demonstrated efficiencies of up to 14.1% and do so more sustainably by eliminating the need for noble metals. Our work with Graphene Flagship industrial partner BeDimensional, Italy, led to the discovery of an innovative encapsulant that increases the stability and efficacy of our devices at a very low price. We operate the world's first solar farm infrastructure based on graphene and related materials, located in Crete, Greece. We also developed processes to print graphene-based photovoltaics onto flexible substrates. Our prototypes have passed indoor tests and reached technology readiness level (TRL) 5, with possible deployment for portable electronics and Internet-of-Things devices.

Another approach lays in the design of graphene-based electrolysers for the production of green hydrogen. In this same line, we also develop fuel cells – devices that achieve the opposite reaction, the conversion of hydrogen into water and clean energy. Thanks to graphene and layered materials, we reduced the dependence on critical materials, such as indium and platinum. Hydrogen could store the excess energy of intermittent renewable sources, like solar and wind, then provide it for applications in transportation and industry, among others.

Graphene-enabled electrolysers and fuel-cells show higher activity and durability than most currently available competitors. The Energy Generation Work Package has already exceeded its original expectations, screening different solutions for the hydrogen economy, with some of them deployed into working demonstrators. Graphene Flagship partner Breton, Italy, tested these technologies in pre-industrial batches, hitting TRLs 5-6.

With almost 50 peer-reviewed publications, 14 patents and applications and 10 prototype energy-generation devices, our Work Package is well on track to deliver on the Graphene Flagship's original promises. Graphene and green energy make the perfect couple.

UPCOMING CHALLENGES

Graphene technologies will compete with current alternatives at lower costs. In the case of graphene-enabled solar cells, we still need to work on better processes to scale-up processes efficiently, which will require cheaper raw materials and more economical manufacturing, especially in terms of energy consumption. For electrolysers and fuel-cells, the challenges are greater. So far, the industrial batches of catalysts and coatings still exhibit lower performance than lab-based experiments. We must optimise the scale up procedures to fully integrate graphene into these devices. The collaborations enabled by the Graphene Flagship, including the Spearhead Projects and the FLAG-ERA networks, will accelerate the improvement of graphene-enabled technologies for energy generation.

Our industrial collaborations have yielded an innovative encapsulant that increases the stability and efficacy of graphene-enabled solar panels at a very low price. Credit: Raphael Cruz, Unsplash

COLLABORATION

The Energy Generation Work Package partners with teams across the Graphene Flagship and beyond. We have strong collaborations with the Enabling Materials Work Package to develop functionalised graphene and layered materials with customised properties, with the Energy Storage Work Package to create more efficient power-banks and with the Composites Work Package to craft combinations of materials to encapsulate our solar cells. We also take advantage of our collaborations with FLAG-ERA to work with different Partnering Projects, such as LASERGRAPH and PeroGaS. Together, we look into the fabrication of electrodes with lasers and the formulation of hybrid perovskite-graphene composites.

Graphene-enabled solar panels have demonstrated efficiencies of up to 14.1% and eliminated the need for noble metals, often scarce materials. Credit: Markus Spiske, Unsplash

References
Mariani, P. et al. ACS Appl. Mater. Interfaces, 2021, DOI: 10.1021/acsami.1c02626.
Rogdakis, K. et al. Energy Environ. Sci., 2021, DOI: 10.1039/D0EE04013D.
Polyzoidis, C. et al. Adv. Energy Mater., 2021, DOI: 10.1002/aenm.202101854

Energy Storage

Work Package Leader
Vittorio Pellegrini, BeDimensional, Italy

Work Package Deputy
Daniel Carriazo, CIC energiGUNE, Spain

Our collaborations within the Graphene Flagship target large-scale production of graphene coatings, focusing on environmentally friendly approaches."

Vittorio Pellegrini
Work Package Leader

Long-lasting graphene to recharge our batteries

The Energy Storage Work Package explores the benefits of graphene and layered materials in batteries and supercapacitors. The former store electrical charge for the long run; the latter store energy for quick, energetic deliveries, which comes in handy in electronics, transportation and many other applications.

We aim to improve the capabilities of these devices, accelerating charging rates and extending their lifetime. We also target additional features, such as improved mechanical properties and heat resistance. These advances have already led to improved performance under extreme environmental conditions, which could eventually trigger innovative applications in different industrial sectors. We have also developed batteries and supercapacitors that withstand bending and folding, providing new opportunities for flexible electronics and wearables. Graphene – and other layered materials – offer opportunities to enhance well-established electrochemical energy storage solutions, including Nobel prize-winning lithium-ion batteries and double-layered supercapacitors. Layered materials also provide advantages for newer technologies, such as lithium-sulfur batteries and metal-air batteries. Still under development, these devices could yield unprecedented storage capacities. Beyond consumer electronics, high-performance batteries could transform the energy landscape, becoming a solution for the intermittence of renewable sources like solar and wind generators.

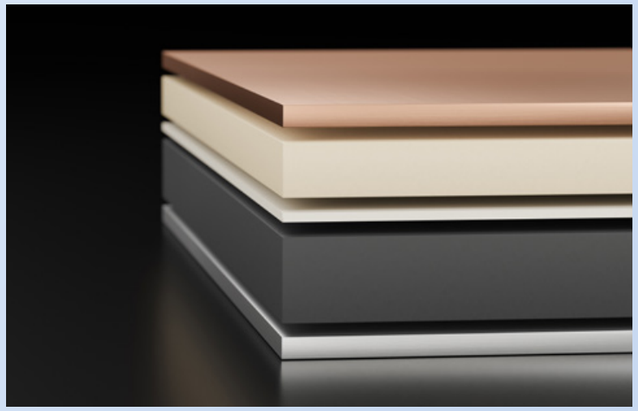
THIS YEAR'S PROGRESS

Some successes over the past year include improving the mechanical stability and an enhanced powered density in different types of supercapacitors. We functionalised graphene with different chemical groups, such as phosphates, to diversify the possibilities and develop innovative applications in energy storage. Other examples include new graphene-coated current collectors to improve the performance of lithium-sulfur batteries and better sodium-air batteries incorporating exfoliated graphite films.

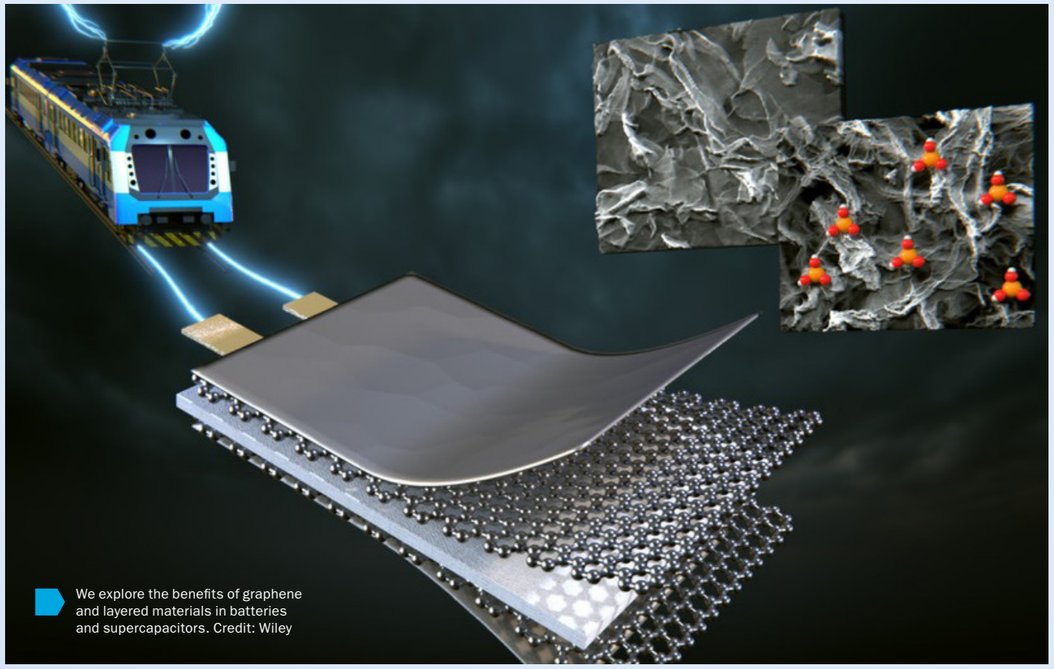
Most of our technologies already cover technology readiness levels (TRL) between 3 and 6. In the next few years, we will focus on validating our technologies under real environmental conditions and developing new working demonstrators and prototypes to attract the interest of European industry. Thanks to our collaborations with the Spearhead Project GrEEnBat, led by Varta Microinnovation, we will enable the most advanced applications for graphene-enabled energy storage solutions.

UPCOMING CHALLENGES

Our biggest challenge is continuing to raise the TRL of our graphene-enabled batteries and supercapacitors. We will work on standardisation and certification processes, required by the battery market, which has high demands in terms of safety and stability of the products. The validation of device prototypes at industrial levels requires significant investments. Our collaborations with leading manufacturing companies in Europe will expedite these procedures, eventually shortening the time to market and making our discoveries available to end users soon.



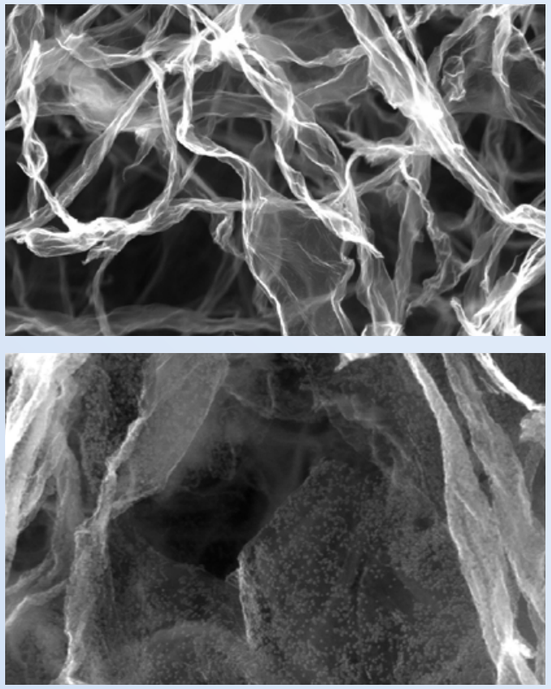
Graphene – and other layered materials – offer opportunities to enhance well-established electrochemical energy storage solutions, including Nobel prize-winning lithium-ion batteries and double-layer supercapacitors. Credit: Adobe Stock



We explore the benefits of graphene and layered materials in batteries and supercapacitors. Credit: Wiley

COLLABORATION

Our Work Package's collaborations within the Graphene Flagship target large-scale production of graphene coatings, focusing on environmentally friendly approaches. This win-to-win collaboration between the Energy Storage and Functional Foams and Coatings Work Packages exploits water-based graphene solutions to spray different types of electrodes that are then used in batteries and supercapacitors. The versatility of this method enables applications onto large surfaces, meeting industry standards. We also established a strong collaboration with Associated Member Elkem, Norway, and an external company, Wacker Chemie, Germany, to develop new graphene-silicon anodes for batteries. This combination proved very successful in increasing battery capacities, and we look forward to further advances in the field.



Graphene and layered materials accelerate batteries' charging rates and extend their lifetime, as well as improve mechanical properties and heat resistance. Credit: CIC energiGUNE

References
Moreno-Fernández, G. et al. Batteries Supercaps, 2021, DOI: 10.1002/batt.202100038.
Enterría, M. et al. Small, 2021, DOI: 10.1002/smll.202005034.
Romaní-Vázquez, A. et al. Nanoscale, 2021, DOI: 10.1039/D1NR03960A.
Abouali, S. et al. 2D Mater. 2021, DOI: 10.1088/2053-1583/abe106

GRAPHENE FLAGSHIP ANNUAL REPORT 2021

Functional Foams and Coatings

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

Work Package Deputy
Paolo Samorì, University of Strasbourg, France

> Using graphene and layered materials, we create innovative foams and coatings for environmental applications."
>
> **Xinliang Feng**
> Work Package Leader

Sustainable solutions with graphene and layered materials

The Graphene Flagship objectives align with the United Nations' Sustainable Development Goals (SDG), as well as the European Green Deal and Horizon Europe Missions. The Functional Foams and Coatings Work Package investigates how to combine graphene and layered materials into functional products, such as foams and coatings, for environmental applications.

For example, we designed graphene-enabled membranes for water filtration, in line with SDG 6 for Clean Water and Sanitation. Our graphene foams combine very high porosity with attractive properties like conductivity and both thermal and mechanical stabilities. Thanks to graphene, we could provide easy access to drinkable water. Our Work Package also investigates new processes for water desalination and wastewater treatment. These systems use other layered materials like titanium carbide, which provides tuneability in terms of surface properties. We patented this technology, as it could find applications in other areas, like in air purification.

The Functional Foams and Coatings Work Package also designs new graphene-enabled products against corrosion. Responsible for around 3.5% of losses to the global GDP, corrosion reactions also yield unwanted chemical substances that are often toxic and contaminant. With layered materials like graphene and hexagonal boron nitride, our partners BeDimensional, Italy, and Sixonia, Germany, have developed paints and inks to fight corrosion in different industrial settings.

Furthermore, we investigate the uses of graphene foams and coatings in highly efficient sensors. Our researchers have created different tailored materials for health and environmental applications, including networks of graphene and layered materials and functionalised substances with highly tuneable properties. Some of these sensors have already started clinical trials and will likely keep advancing through the pipeline in the coming years.

From the beginning of the Graphene Flagship, we optimised our technologies for each step in the value chain, including end-users in leading industries. We have pushed towards higher technology readiness levels (TRL) between six and seven, filing patents and coordinating non-disclosure agreements with different companies, especially in the automotive sector, a pillar of the European economy.

Soon, the increased production of graphene and layered materials will lower their cost, catalysing the transformation of the technological market. Our Work Package combined high-impact research with real-life applications which are sustainable and environmentally friendly.

UPCOMING CHALLENGES

We developed highly functional technologies for applications in water purification, air filtration, protective coatings, and sensing, among others. We want to tackle societal issues with graphene and layered materials. Our biggest challenge is bridging the gap with industry and introducing our technologies into the European market. While some issues with cost, trust, and standards remain, the Graphene Flagship will further work to guarantee the success of layered materials.

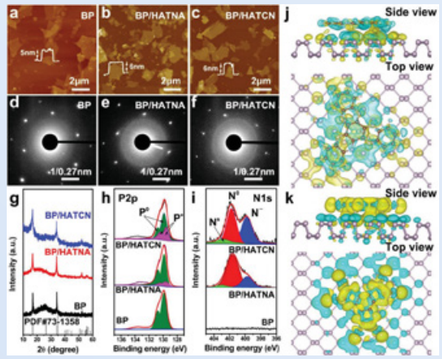
Most of our technologies already cover technology readiness levels (TRL) between 3 and 6. In the next few years, we will focus on validating our technologies under real environmental conditions and developing new working demonstrators and prototypes to attract the interest of European industry. Thanks to our collaborations with the Spearhead Project GrEEnBat, led by Varta Microinnovation, we will enable the most advanced applications for graphene-enabled energy storage solutions.

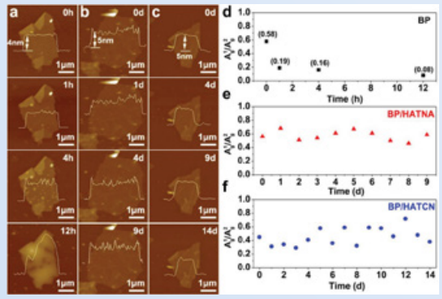
Our Work Package investigates how to combine graphene and layered materials into functional products, such as foams and coatings, for environmental applications. Credit: Adobe Stock

COLLABORATION

In the Functional Foams and Coatings Work Package, collaboration enabled innovations in pressure sensors and health monitoring devices. These developments include institutions within the Graphene Flagship, as well as external teams, involved in real-life tests and clinical trials. Our industrial partners facilitated TRL growth and helped us adapt our lab prototypes to the needs of both manufacturers and end users.

> We work on purification technologies, anticorrosion coatings and highly efficient sensors for pressure and humidity."





Heterostructures with layered materials like black phosphorus enhanced carrier mobility and stability, for applications in electronics. Credit: Wiley

References
Ippolito, S. et al. Nature Nanotech., 2021, DOI: 10.1038/s41565-021-00857-9.
Shi, H. et al. Adv. Mater., 2021, DOI: 10.1002/adma.202105694.
Shi. H. et al. Angew. Chem. Int. Ed., 2021, DOI: 10.1002/anie.202015627.
Schütt, F. et al. Mater. Today, 2021, DOI: 10.1016/j.mattod.2021.03.010

Composites

Work Package Leader
Costas Galiotis, FORTH, Greece

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

The close collaboration between our partners, which include academic institutions, SMEs, and large multinational industries, led to a smooth evolution of our activities."

Costas Galiotis
Work Package Leader

New materials for aerospace, automotive and energy

Composites combine individual materials to achieve unprecedented properties. The Composites Work Package couples graphene and layered materials with plastics, fibres and metals for innovative applications in industrial sectors such as aerospace, automotive and energy. We also develop custom composites for manufacturing, connecting academia and industry.

THIS YEAR'S PROGRESS

Among other applications, our Work Package used graphene and layered materials to reinforce carbon fibre plastics. This confers additional properties, such as increased stability, making graphene composites ideal for automotive components. Different combinations lead to tuneable functionalities and increased sustainability. Some of our graphene-based composites have found applications as fire retardants; others have increased recyclability, aligned with the United Nations' Sustainable Development Goals (SDG) and the European Green Deal.

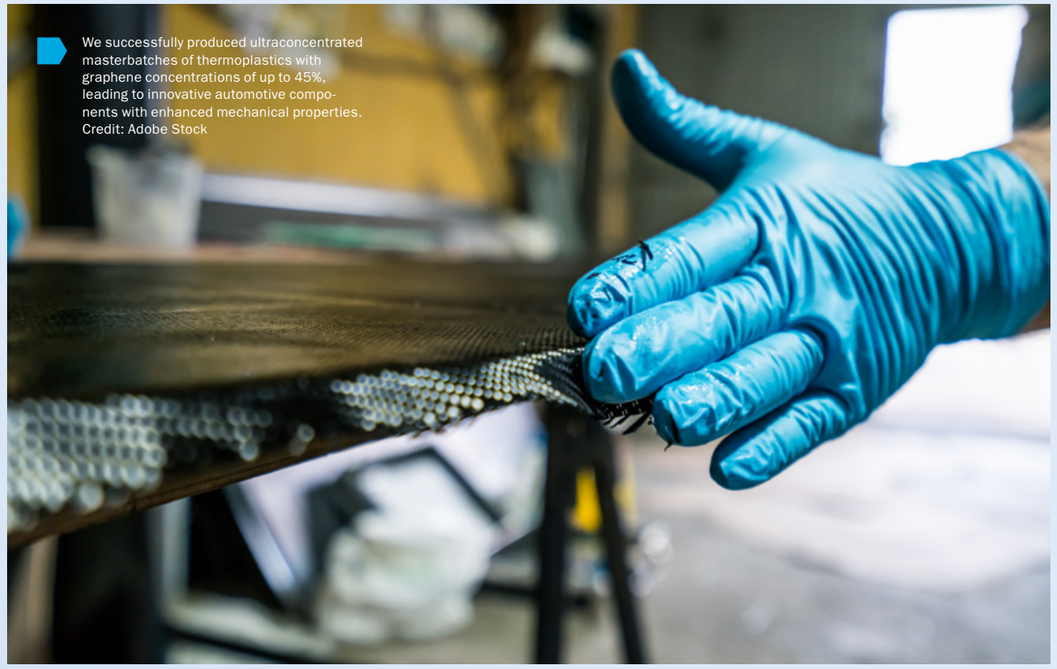
The Composites Work Package successfully produced ultraconcentrated masterbatches of thermoplastics with graphene concentrations up to 45%. This led to the creation of innovative automotive components, which enhanced various mechanical properties. We further tested these materials thanks to our collaborations with the Graphene Flagship Spearhead Projects G+BOARD and GICE. In particular, the latter focuses on expanding the possibilities of graphene-enabled composites for the mechanical protection of aircraft. Some of these technologies have attained high technology readiness levels (TRL) between 6 and 7.

Other products and prototypes are also close to market. These include graphene-based composites for injection moulding manufacturing lines with applications in sensing, with a TRL 5, and composites for 3D printing, which showcase ideal properties for flexible and wearable electronic devices at TRL 4. The different advances were only possible thanks to the 15 collaborations established with industrial partners. These symbiotic relationships have advanced methods for processing, production and characterisation of composites based on graphene and layered materials.

Graphene-enabled composites also show great promise for energy generation and distribution. Through different partnerships with other Graphene Flagship researchers, our Work Package worked on 3D-printed batteries, innovative circuit breakers, energy management systems and applications for electro-magnetic shielding. We contributed to the development of the next generation of lightweight, recyclable graphene-enabled composites. Cost reduction and simple repairs to further enhance sustainability were also investigated.

UPCOMING CHALLENGES

The close collaboration between partners in our Work Package, which include academic institutions, SMEs, and large multinational industries, led to a smooth evolution of our activities. The main challenge ahead is meeting the sustainability goals within the SDG and the European Missions in Horizon Europe, to bring innovative solutions to the greatest societal challenges. Our team will address issues around manufacturing, processability and production. We look forward to establishing internal value chains and standardised methods to overcome obstacles.

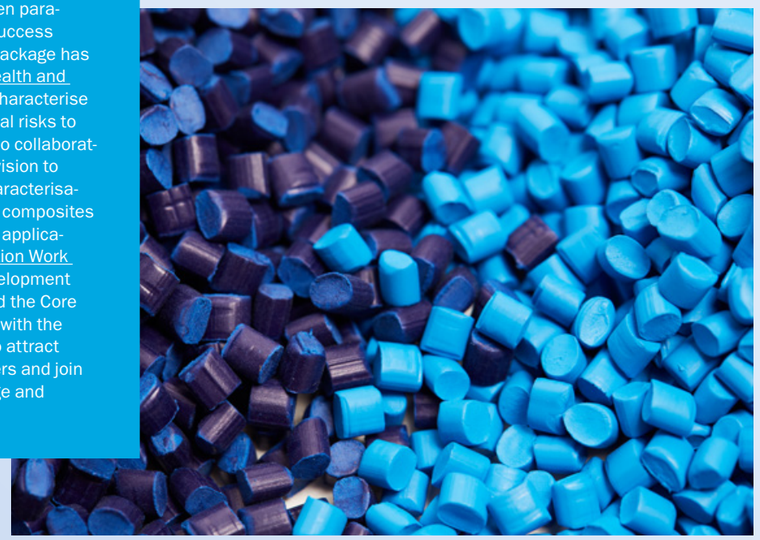


We successfully produced ultraconcentrated masterbatches of thermoplastics with graphene concentrations of up to 45%, leading to innovative automotive components with enhanced mechanical properties. Credit: Adobe Stock

COLLABORATION

Collaboration has enabled the establishment of many new fields and ventures for graphene-enabled composites. The knowledge transfer mechanisms within the Graphene Flagship have been paramount. To highlight just some success stories, our Composites Work Package has closely collaborated with the Health and Environment Work Package to characterise composites and assess potential risks to health and environment. We also collaborated with other partners in our division to advance manufacturing and characterisation methods, including various composites and components for aerospace applications. The links with the Innovation Work Package boosted business development and patent applications. Beyond the Core Consortium, the collaborations with the Partnering Division helped us to attract several new Associated Members and join two Partnering Projects: Grasage and Mechanic.

Composites combine individual materials to achieve unprecedented properties; we couple graphene and layered materials with plastics, fibres, metals and more. Credit: Adobe Stock



References
Pavlou, C. et al. Nature Commun., 2021,
DOI: 10.1038/s41467-021-24970-4.
Cao, J. et al. ACS Appl. Mater. Interfaces, 2021,
DOI: 10.1021/acsami.0c21699.
Sgouros, A. et al. ACS Appl. Mater. Interfaces, 2021,
DOI: 10.1021/acsami.0c18774

Production

Work Package Leader
Alex Jouvray, Aixtron, UK

Work Package Deputy
Julio Gómez-Cordón, Avanzare, Spain

All graphene materials produced by our industrial partners are available on the market today."

Alex Jouvray
Work Package Leader

Getting graphene ready for the market

The Production Work Package mostly consists of industrial partners with a common goal: to develop new products with graphene and layered materials. We focus on applications where layered materials make a difference, providing unique properties and functionalities. Our team has the challenging task of providing commercial quality graphene to the rest of the Graphene Flagship.

The products developed by our Work Package have a range of applications in different industrial sectors. We designed a graphene-enabled UV lamp for air, water and surface disinfection; innovative systems for the in-line monitoring of graphene production; high-quality graphene coatings for copper wires, as well as lubricating appliances; and multifunctional materials with corrosion protection and fire-retardant properties.

THIS YEAR'S PROGRESS

Some of our accomplishments in 2021 include the study of graphene-coated copper wires. Graphene Flagship researchers analysed the effects on ageing and degradation, demonstrating an improvement in conductivity of 3.5% when compared to pristine copper. We also developed the roll-to-roll production of monolayer CVD graphene onto polymer substrates, key for applications in flexible electronics and wearables. The system exploits the latest advances in terahertz spectroscopy for in-line monitoring and quality assessment. We also manufactured large-scale prototypes of pipes with customised properties enabled by graphene and layered materials. These tailored features include fire resistance and capabilities for sensing.

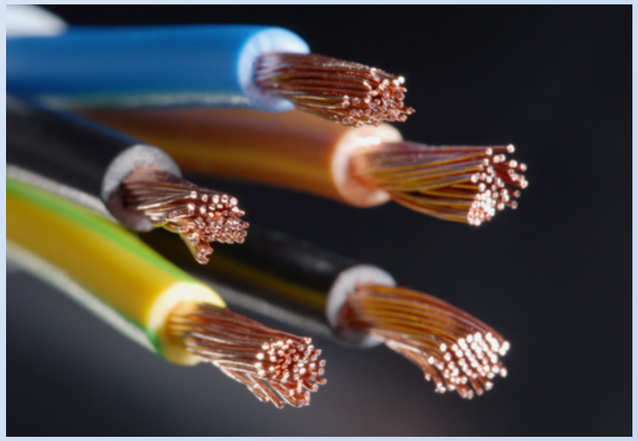
Although applications are our main focus, the Production Work Package also carries out fundamental research. For example, we studied how graphene and layered materials improved the mechanical properties of copper wires and coatings, gaining insights for the development of better evidence-based solutions.

All the graphene-enabled materials and products manufactured by our industrial partners are currently commercially available. Our activities progress as planned, and our researchers have overcome the major challenges encountered so far. We solved the difficulties posed by the dispersion of graphene and related materials in composites for aerospace and scaled up the production of innovative solutions for lubrication.

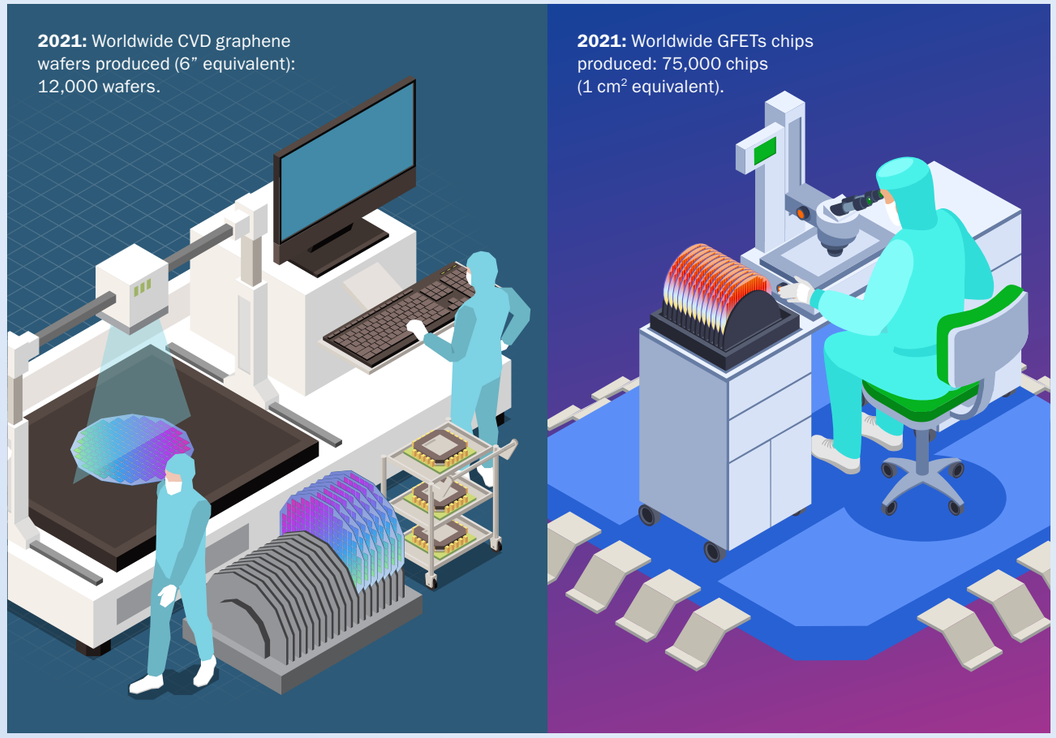
Some prototypes still require improvements to reach the market. Nevertheless, we are confident that many of these innovative applications for graphene and layered materials will become commercial products by the end of 2023.

UPCOMING CHALLENGES

Beyond the regular challenges of commercialising new products, our Work Package faces additional problems derived from the complexity of qualifications and regulations in certain industrial sectors. In the automotive industry, product approvals often take over two years, and in the aerospace industry this can take up to a decade. The Graphene Flagship had foreseen the convoluted pipelines, and has always invested in efficient roadmapping, validation and standardisation. We are on the path towards making graphene and related materials a commercial reality.

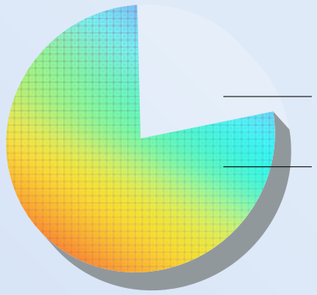


Graphene-coated copper wires have demonstrated an improvement in conductivity of 3.5% when compared to naked copper. Credit: Adobe Stock



COLLABORATION

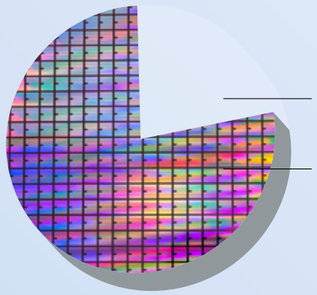
The Graphene Flagship environment provides a uniquely wide network of partners to collaborate with, both in industry and academia. Although the COVID-19 pandemic hindered some of our networking activities, our Work Package remained an active team-player in the consortium, ensuring that our knowledge and resources were shared effectively. The main highlight over the past year was our partnership with the Composites Work Package, which led to new tests and the qualification of graphene-enabled panels for the aerospace industry. In this field, graphene offers increased mechanical properties, such as strength and resilience, at very low weight, which leads to the reduction of carbon emissions and more sustainable aircraft.



Bulk graphene produced in Europe

Non-GF
23%

GF Partners
77%



Revenue of European Graphene companies

Non-GF
27%

GF Partners
73%

References
Stojanovic, G.M. et al. IEEE Sensors J., 2021, DOI: 10.1109/JSEN.2021.3078692.
Nekrasov, N. et al. Nanomaterials, 2021, DOI: 10.3390/nano11010226

GRAPHENE FLAGSHIP ANNUAL REPORT 2021

Innovation Success Stories

Above: Artistic representation of graphene for energy storage. Credit: Martin Pykal, CATRIN

Since its inception, the Graphene Flagship has focused on both fundamental science and technological innovation. This cross-pollinating environment favours the creation of spin-off companies and the collaboration between academic and industrial groups in both SMEs and big companies. Here you can find a selection of key innovation developments from 2021 that bring graphene products closer to the market.

> The journey from laboratory to factory floor and the creation of business opportunities have been the main drivers for our programme since the beginning."
>
> **Kari Hjelt**
> Graphene Flagship Head of Innovation

"These success stories cement the fact that innovation and results are emerging from the Graphene Flagship. The journey from laboratory to factory floor and the creation of business opportunities have been the main drivers for our programme since the beginning. We start to see the fruits of the European Commission and our partners' long-term support," says Kari Hjelt, Graphene Flagship Head of Innovation.

INBRAIN NEUROELECTRONICS SECURES MILLIONS IN FUNDING

In 2021, INBRAIN Neuroelectronics received a €14.5M Series A investment, one of the biggest rounds in the Spanish MedTech industry, co-led by Asabys Partners and Alta Life Sciences, and joined by Vsquared Ventures, a DeepTech-focused early-stage venture capitalist based in Munich; TruVenturo GmbH, Germany's most successful tech and life science company builders; and CDTI, at the Spanish Ministry of Science and Innovation.

INBRAIN Neuroelectronics is a spin-off company of Graphene Flagship partners the Catalan Institute of Nanoscience and Nanotechnology (ICN2) and ICREA, Spain. Established in 2019, INBRAIN Neuroelectronics develops graphene-based neural implants for personalised therapies in brain disorders, to overcome the current limitations of metal-based neural devices. INBRAIN will use this year's investment, including an investment from ICF Venture Tech II, to begin clinical trials in humans.

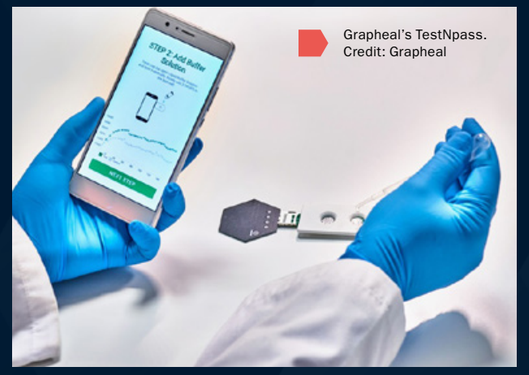
INBRAIN also signed a collaboration with Merck, a leading science and technology company, to develop the next generation of graphene bioelectronics for vagus nerve therapies, which will target severe chronic diseases with high unmet medical needs. This collaboration will combine Merck's data science, clinical, regulatory and quality expertise with INBRAIN's technical know-how in the development of graphene interfaces, device development and signal processing for clinical applications.

QURV TECHNOLOGIES: THE NEW SPIN-OFF SPECIALISED IN IMAGE SENSOR TECHNOLOGIES

This year, Graphene Flagship partner ICFO in Barcelona, Spain, launched the spin-off Qurv Technologies to develop graphene-enabled wide-spectrum image sensor technologies for next-generation computer vision, which could find application in autonomous cars and robots. Qurv has created a 'plug-and-play' manufacturing approach, making it more widely compatible and accessible than current alternatives. The company takes advantage of the unique electronic properties of graphene and light sensitisers made of quantum nanoparticles, to achieve the efficient detection of a broad range of wavelengths – from ultraviolet to infrared light – with a single device. This graphene-based sensor replaces traditional costly alternatives based on indium gallium arsenide, paving the way to short-wave infrared imagers up to 1,000 times cheaper.

Qurv is also the leader the Graphene Flagship Spearhead Project Autovision, and Stijn Goossens, Qurv's CTO is on the 2D-EPL's Industrial Advisory Board.

> These success stories cement the fact that innovation and results are emerging from the Graphene Flagship."
>
> **Kari Hjelt**
> Graphene Flagship Head of Innovation



Grapheal's TestNpass. Credit: Grapheal

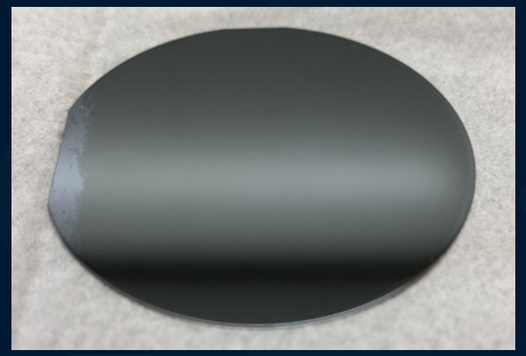
GRAPHEAL WINS CES 2022 INNOVATION AWARD

Graphene Flagship Associated Member Grapheal launched TestNpass – a graphene-enabled, digital, diagnostic "test strip" – and received the "Best in Innovation" award at the Consumer Electronic Show (CES) 2022 in the United States of America. Medtech spinoff of Graphene Flagship partner CNRS-Grenoble, France, Grapheal is the only start-up awarded this prestigious prize in the healthcare category this year, and TestNpass is the first graphene biosensor to obtain such an award.

TestNpass screens for the presence of biomarkers, e.g. antigens related to COVID-19, in body fluids and delivers the results in a time-stamped, encrypted RFID tag, which is tamper-proofed by facial recognition control. It provides a secure, biometric health pass in less than 5 minutes, which is ideal for rapid and repeated screening in high traffic areas and large venues. Digital results are encrypted and do not need to be shared over the internet to be valid, making the system fully compliant with strict data protection laws.

TWO-DIMENSIONAL CHEMISTRY TOWARDS NEW GRAPHENE DERIVATIVES

Partnering Project 2DChem filed a patent application related to the preparation of nitrogen-doped graphene in 2020, then published in 2021. This material displays a well-balanced set of parameters, ideal for supercapacitor electrodes. Its extraordinary density, paired with its capacity to absorb ions from the electrolyte, results in an ultrahigh volumetric energy density – higher than any previously reported carbon or graphene-based supercapacitor materials. The highest value of volumetric energy density reached almost 170 Wh/L at volumetric power density of 5.2 kW/L. Beyond its applications in energy storage devices, this material can be applied to sensing and catalysis.



FIELD-EFFECT TRANSISTORS WITH ORGANIC SEMICONDUCTORS

Partnering Project H2O demonstrated wafer-scale (3-inch) fabrication of high-quality transferable organic semiconductor (OSC) nanosheets with thickness down to 15 nm, which enables the realization of various heterojunction devices. The invention was filed as a patent application (10 2021 107 057.0) in German Patent and Trade Mark Office (GPTO). The team also released OSC films that can be transferred onto arbitrary substrates without losing their crystalline quality, and realized a manifold of field-effect transistors, by transferring OSC nanosheets (p-type) onto prefabricated electrodes and transition-metal dichalcogenide monolayers (n-type).

Above: H2O's pentacene nanosheet transferred onto a 3-inch Si wafer. Credit: Sirri Batuhan Kalkan. Modified from npj 2D Materials and Applications 5:92 (2021)

Members of the INBRAIN Neuroelectronics team. Credit: INBRAIN

Innovation

Work Package Leader
Kari Hjelt, Chalmers Industriteknik, Sweden

Head of Administration:
Francesco Bonaccorso, BeDimensional, Italy

> Our Work Package has a strong impact shaping the Graphene Flagship's commercialisation strategy."
>
> **Kari Hjelt**
> Work Package Leader

Catalysing industrial innovation

Our goal in the Innovation Work Package is to create stronger links between Graphene Flagship researchers and external market opportunities. We try to maximise the project's innovation potential through the creation of new ventures and spin-offs, the commercialisation of products and services 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.

THIS YEAR'S PROGRESS

Over the past year, our Business Developers have continued to make strong contributions to the creation of start-ups within the Graphene Flagship. Notably, Qurv Technologies spun off from Graphene Flagship partner ICFO, Spain, and became a Graphene Flagship partner in 2021. Qurv was founded to develop graphene-enabled wide-spectrum image sensor technologies for next-generation computer vision applications, and now leads the Spearhead Project AUTOVISION. The business developers continue to support other recently formed spin-off companies like Grapheal and INBRAIN Neuroelectronics, both medtech companies that have received significant investments from private investors. Business Developers also attend industry events and organize workshops to raise visibility for graphene applications. These activities are also instrumental to lead generation, which has been very high this year.

The Innovation Work Package played a key role in the evaluation and selection of the current Spearhead Projects, which have significantly boosted the Graphene Flagship's collaboration with industry in the current funding phase.

We've also added new tasks related to the collection and validation of Graphene Flagship patent data. Among other things, we've evaluated the project's outputs in terms of patents and patent applications since its launch in 2013. This work has demonstrated the true impact that the Graphene Flagship in the European industrial landscape. Together, the developments seen over 2021 demonstrate the growing momentum in bringing graphene from laboratories to the factory floor and into the hands of consumers.

Our Work Package offers a whole host of video courses and resources covering a range of topics, including intellectual property, patenting, start-up creation, technology transfer, venture capital and more.

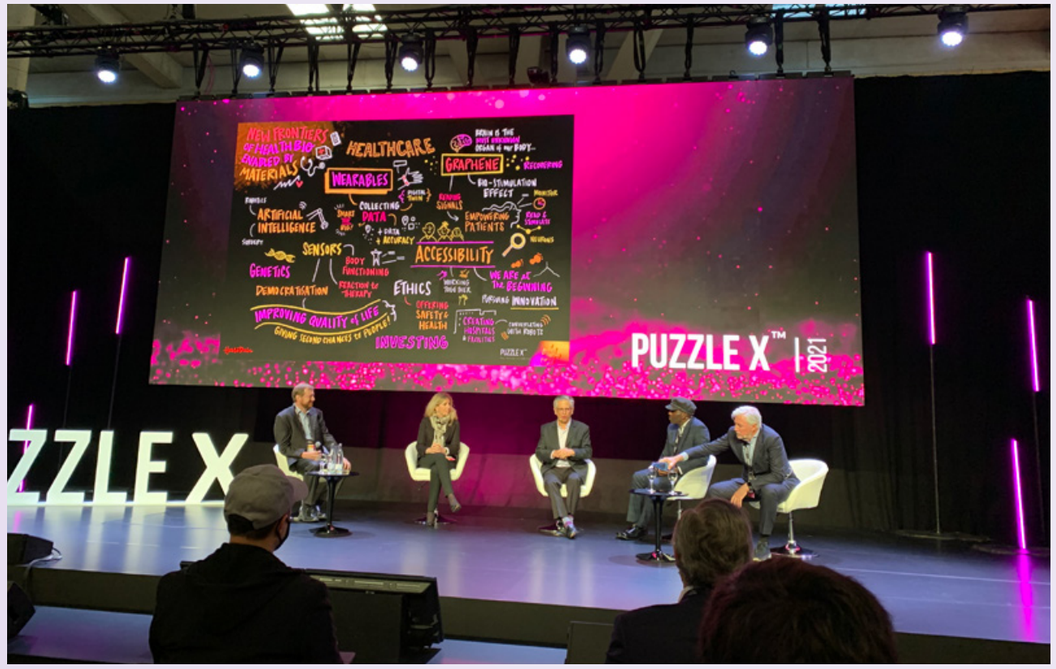
The Innovation Education and Training Platform serves as a central training hub for Graphene Flagship researchers looking to bolster their professional careers in scientific innovation and academic entrepreneurship.

UPCOMING CHALLENGES

Our main challenge is to maximise the impact of the Spearhead Projects and the new 2D Experimental Pilot Line. These projects represent the Graphene Flagship outputs with the highest technology readiness levels (TRL).

As this funding cycle ends, the new funding structure in Horizon Europe, with discrete and diverse projects, poses synergy challenges for the coordination of innovation efforts. We'll ensure a special care to our existing initiatives to maintain momentum and maximise market penetration of graphene-enabled products.

Kari Hjelt, Graphene Flagship Head of Innovation, explores the PuzzleX exhibition. The Innovation Work Package enjoyed the easing pandemic restrictions to meet in person at this future materials forum. Credit: Sofia Öiseth, Chalmers Industriteknik.

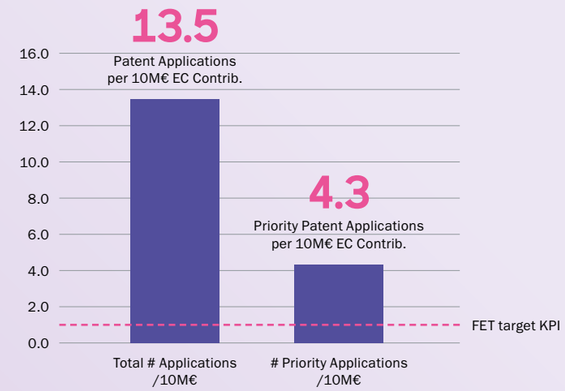


Carolina Aguilar, CEO & co-founder of Graphene Flagship spin-off company INBRAIN Neuroelectronics joins a panel on new materials for biomedicine at PuzzleX. Credit: Sofia Öiseth, Chalmers Industriteknik

COLLABORATION

The Innovation Work Package relies on collaborations across the project. We collaborate regularly with the Dissemination Work Package to produce innovation events, contribute to the preparation of tradeshows and exhibitions and much more. Moreover, our Business Developers interact regularly with their designated Work Packages and Spearhead Projects helping to identify commercialisation opportunities and market potential in emerging technologies. Throughout this funding phase, we have also worked with the Management Work Package to improve the reporting processes for different outputs, from patents and inventions to commercial products and prototypes. Together with the Industrialisation Work Package, we elaborate the Technology and Innovation Roadmap and plan the Innovation Forum at the Graphene Flagship's annual conference, Graphene Week.

Our Work Package has a strong impact shaping the Graphene Flagship's commercialisation strategy through its role within the Spearhead Projects, its support in spin-off creation and its work to connect academics with companies interested in exploiting their research results.



Graphene Flagship Patent Application KPIs exceed EC FET benchmark

The legal basis of Horizon 2020 specifies a list of compulsory Key Performance Indicators (KPIs) to be considered in its evaluation and monitoring system. For Future and Emerging Technology projects, the EC has set a benchmark of 1 patent application per €10M of funding.

For the period October 2013 – March 2020, the inventive output of the Graphene Flagship exceeded this benchmark, whether calculating from the total number of patent applications (13.5/10M€) or the number of priority patent applications (4.3/10M€).

GRAPHENE FLAGSHIP ANNUAL REPORT 2021

Dissemination

Work Package Leader
Rebecca Waters, Chalmers University of Technology, Sweden

Head of Administration:
Fernando Gomollón-Bel, University of Cambridge, UK

The Dissemination Work Package serves the entire Graphene Flagship family, making collaboration a cornerstone of our work."

Rebecca Waters
Work Package Leader

Making a splash with graphene

The Dissemination Work Package spreads the word about the Graphene Flagship. Our events, website, media outreach, social media and tradeshow participation target different stakeholders and inform them about the latest research and innovation developments on graphene and related materials.

THIS YEAR'S PROGRESS

Despite the ongoing pandemic, our team was not idle in 2021. The limitations on travel and in person gatherings forced a transition to digital events. Surprisingly, these alternatives offered increased accessibility to early career researchers and international participants, increasing the overall reach of our events over the last year.

Graphene Week 2021, held online, was a particular success. Our opening "Inspiration Day" programme was a collaboration with the European Commission, who provided speakers for our Diversity in Graphene, Sustainability and Horizon Europe sessions. On top of that, we designed innovative digital sessions for poster presentations, bringing small groups together to present in a topic-oriented round table discussion – the initiative proved successful in terms of attendance. Additionally, a special session on alternative career paths for researchers provided inspiration for early career researchers in the audience.

Our industrial outreach activities also went digital over the past year. The Graphene Flagship attended several digital tradeshows and exhibitions with booths and speakers at Enlit Europe, EuroNanoForum and the European Space Conference.

In early November, we returned to in-person exhibitions, putting together a joint booth at Aquatech in Amsterdam with Graphene Flagship partner Medica, who leads the GRAPHIL Spearhead Project. It was great to see people in person again; and GRAPHIL's graphene water filters generated a lot of interest among leading manufacturers.

To further improve our industrial outreach and support our industrial partners, our Work Package produced a series of five professional product videos highlighting exciting graphene products already available on the market. We hope to produce another round of videos with new products launched before the end of 2023.

Resources like the Graphene Flagship Annual Report, the Graphene Magazine and various infographics produced for these publications have helped to increase visibility for the project and created a wealth of marketing resources available to Graphene Flagship spokespeople when highlighting the success of the project.

With so much happening in the Graphene Flagship over the past year, it is no surprise that we reached – even exceeded – our social media milestones in the past year. We continue to engage a broad community through our **@GrapheneEU** accounts, it's an effective way to share our news with the world. We've strengthened our social media efforts with targeted videos, infographics and campaigns around sustainability, the Graphene Flagship Spearhead Projects, graphene-enabled products and applications, as well as diversity and inclusion. This strategy has generated interest and discussion around graphene and layered materials, but most especially on important issues for our community.

DIVERSITY IN THE SPOTLIGHT

A particular highlight over the past year has been our Diversity in Graphene initiative. At the Graphene Flagship, we are committed to supporting inclusion, increasing visibility of different gender and sexual identities, race and disabilities. We're proud to have created a support network for project participants from underrepresented groups. Our digital events over the past year have presented a broad range of issues in Diversity, Equality and Inclusion to both increase awareness and provide visible role models to our community, for inspiration and support. The Graphene Flagship Mentoring Programme, which launched in 2020, was a great success. Its participants found an excellent way to discuss workplace challenges, exchange ideas and plan for the future. The second edition of the programme is already underway.

Division 6
A collaborative community

UPCOMING CHALLENGES

The next 18 months present the challenge of showcasing the full breadth of the Graphene Flagship's accomplishments. With funds from its Horizon 2020 programme, the European Commission invested in graphene, an idea, a new material to strengthen research, industry and society. Now, the Dissemination team will work to showcase the return on investment delivered by the Graphene Flagship.

Graphene Week host **Jane Powel**, Dissemination Work Package Deputy **Fernando Gomollón-Bel** and Head of the Gender Equality Sector in DG Research and Innovation at the European Commission **Mina Stareva** discuss gender issues in science during the Diversity in Graphene session at Graphene Week.

COLLABORATION

The Dissemination Work Package serves the entire Graphene Flagship consortium, making collaboration a cornerstone of our work. We reach out regularly to project participants for news on their progress, but we also create events like Graphene Week to facilitate collaboration among our partners through knowledge exchange and networking. Our collaborations extend beyond the consortium, working with other European initiatives to gain insights and visibility and reaching out to the global research and innovation community.

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

We coordinated another successful project review this year, with the preparation, attention to detail and structure specifically noted by the reviewers.”

Jari Kinaret
Work Package Leader

Coordinating the fleet of partners

The Management Work Package is instrumental in keeping the Graphene Flagship on course. We ensure that project outputs are properly monitored and reported on, coordinate the governing bodies and liaise 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).

THIS YEAR’S PROGRESS

Our Work Package has opened new avenues for collaboration over the past year. At Graphene Week 2021, we coordinated with the European Commission to create a session on the funding opportunities of Horizon Europe. Marie-Alexandra Neouze from FLAG-ERA, Jean-Marie Auger from the European Commission’s DG Connect and our Graphene Flagship Director Jari Kinaret addressed the relevant calls on graphene published by the European Commission and how they will impact our community.

Moreover, we pioneered the establishment of the REACH/ECHA Working Group, which coordinates the communication between the Graphene Flagship and different regulatory stakeholders, such as the European Chemical Agency (ECHA), the European Union Observatory on Nanomaterials (EUON) and the Graphene Reach Registration Consortium (GRRC). In 2021, we organised several meetings to enhance cooperation with ECHA and EUON, creating new ways to share knowledge about the safety – and potential toxicity – of graphene and related layered materials. This Working Group also liaised with the GRRC, a consortium of companies which is currently managing the REACH registration of graphene. As the graphene market grows and more industries incorporate it into their processes and products, REACH registration will be key issue for the manufacturing and importing of graphene within the EU. Thus, the Working Group organised a webinar to inform Graphene Flagship industrial partners about the progress of graphene registration and its relevance to a long-term perspective.

In addition to these newer initiatives, the Management Work Package oversaw another successful project review. The preparation, attention to detail and structure of the month 18 review were specifically noted by the reviewers. Additionally, we also organised an internal assessment of half the Graphene Flagship Work Packages to help plan the evolution of the project through and beyond the current funding phase, including the transition into Horizon Europe, the new funding framework from the European Commission.

The European Science Foundation (ESF), France, one of our Work Package partners, also analysed the funding system and finalised its report on Graphene Flagship data collaborations, both of which will prove useful in assessing the impact of the project. Based on these results, ESF concluded that the Partnering Division and Partnering Mechanism have heavily contributed to the success and impact of the Graphene Flagship initiative.

NEW FACES, NEW SKILLS

Over the past year, our Work Package has had the unique situation of having half its team on maternity leave at one time or the other. As a result, the team has had an influx of new temporary members, each bringing new perspectives and skills. We’ve taken advantage of this opportunity to grow, learn and adapt processes to take advantage of our new strengths. Many frequent Graphene Flagship collaborators will have noticed new faces around the Management team, and we’re proud to welcome five “Graphene Babies” to the Graphene Flagship family.

UPCOMING CHALLENGES

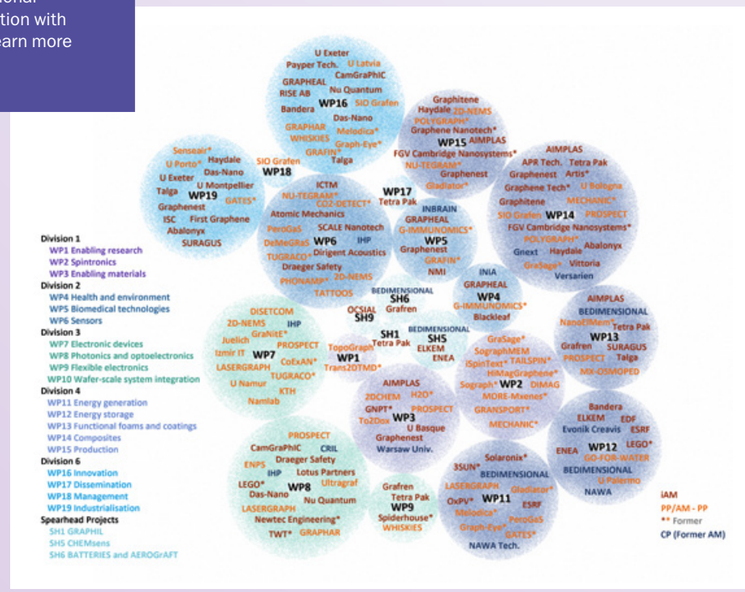
Looking towards the horizon, the Management Work Package will sail into uncharted waters. Over the next year and a half, we will need to coordinate the close of the ten-year project funded by Horizon 2020 and chart a new course into Horizon Europe. The Horizon Europe ecosystem changes how graphene research and innovation is funded by the European Commission, with the current Graphene Flagship splitting into separate, topic-based projects, only loosely coordinated by a central project.

The Horizon Europe session at Graphene Week, organized by the Management Work Package, addressed the relevant calls on graphene for the next European Commission funding cycle.

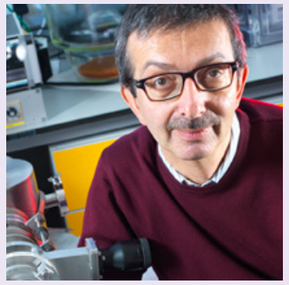
COLLABORATION

Aside from coordinating the Graphene Flagship core partners, our Work Package is also at the heart of all external collaborations. Through the partnering mechanism, we facilitate collaboration with Partnering Projects and Associated Members throughout Europe, and International Workshops encourage collaboration with researchers around the world (learn more on page 20).

This map shows the numerous interactions between current and former Associate Members and Partnering Projects and Core Project Work Packages and Spearhead Projects.



Industrialisation



Work Package Leader
Alexander Tzalenchuk, National Physics Laboratory, UK

Work Package Deputy
Thomas Reiss, Fraunhofer ISI, Germany

> Following the covid pandemic, Europe may require the Graphene Flagship to shift its strategies, setting up robust value networks which support Europe's innovation sovereignty."
>
> **Alexander Tzalenchuk**
> Work Package Leader

Plotting the route to commercialisation

The Industrialisation Work Package explores application opportunities for graphene and related materials based on market needs through the Technology and Innovation Roadmap. A prerequisite for industrial uptake of graphene technologies is trust and confidence in these technologies. Therefore, starting from the most promising applications, we validate the properties of graphene and layered materials and devices. This provides objective data on the characteristics of real GRMs thereby supporting users in making confident decisions on the suitability of the materials for their needs. Next, we develop international standards for properties and characterisation of graphene and layered materials, as well as graphene-enhanced components, devices and systems. Finally, we communicate the outcomes transparently to the whole Graphene Flagship community via the Sample and Materials Database (SMDB).

THIS YEAR'S PROGRESS

Over the past year, our Work Package has successfully established an industrial workflow. When it comes to roadmapping, we were forced to reinvent the format of our workshops to allow for the same types of intensive exchange with industry in an online format. Online consultations of industrial stakeholders allowed us to explore three new topics, such as microelectromechanical systems (MEMS) for sensors, antimicrobial surfaces and the applications of graphene photovoltaics in space. The roadmapping team also had the first in a series of roadmap briefs published.

Within our validation efforts, our partners contributed to three VAMAS interlaboratory comparisons, helping to set criteria for harmonised measurements, testing, specifications and standards for advanced materials. The team also developed new services to characterise lubricants containing graphene additives. The Graphene Flagship Validation Service increasingly supports industrial partners with very different types of measurements, often for a variety of parameters on the same samples as well as repeat measurements as their technology improves.

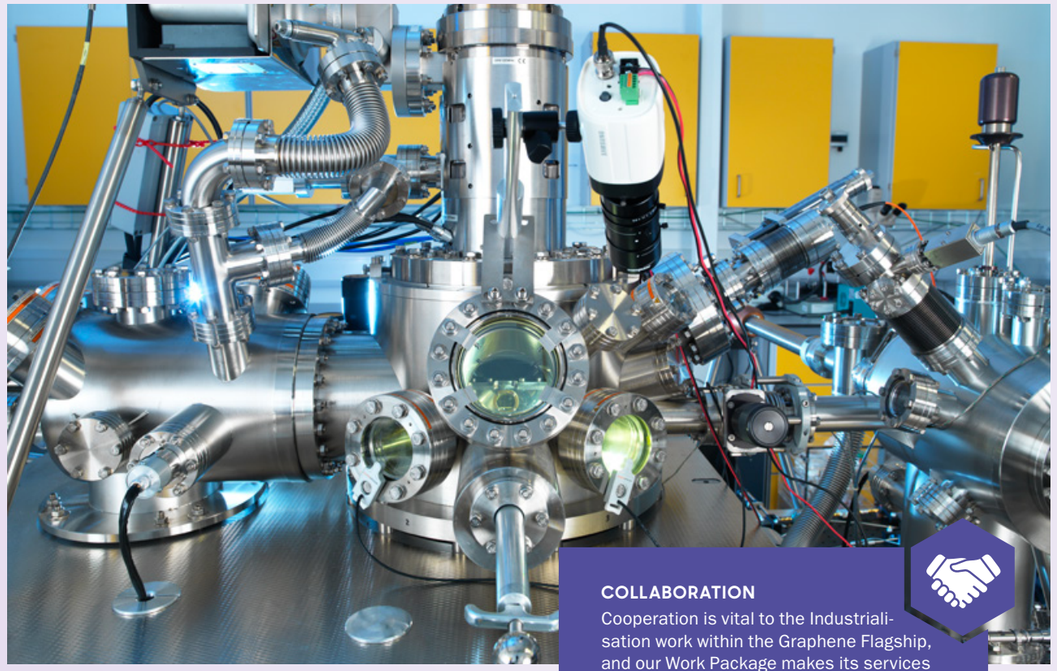
Moreover, our standardisation team made great strides over the past year. Graphene Flagship partner Karlsruhe Institute of Technology, Germany, leads the standardisation task, with Thurid Gspann as Chair of the Graphene Flagship Standardization Committee. This team has grown to include 47 members and led a total of 16 standardisation projects, doubling the number from our previous funding period. A growing number of standardisation projects required industry leads, and five Graphene Flagship Associated Members specifically joined our Graphene Flagship project to work on standardisation strategies. We also completely redeveloped the SMDB, which is now available to end users as a stand-alone application, structured according our systematic of standards.

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.

WHAT'S IN STORE

Following the COVID-19 pandemic, Europe may require the Graphene Flagship to shift its strategies towards health and safety, becoming more resilient and setting up robust value networks to support Europe's innovation sovereignty. In this context, guidance and orientation are crucial – and the work of our Industrialisation Work Package, through its Technology and Innovation Roadmap activities, becomes paramount.

Along with the rest of the Graphene Flagship, we see a fundamental challenge in the fragmentation of the established ecosystem for the project after the end of this funding phase, which would create far less impact and jeopardize Europe's leading role in graphene innovation.



A nanoprobe tool used in the validation service at NPL. Credit: NPL

COLLABORATION

Cooperation is vital to the Industrialisation work within the Graphene Flagship, and our Work Package makes its services available to all stakeholders, from project partners and Associated Members to interested parties outside the consortium. Below are some concrete examples of collaborations that impacted the Work Package's work in the past year.

We've gathered intelligence to support the identification and selection of most relevant topics for roadmap focus investigations, and Graphene Flagship partner Fraunhofer ISI, Germany, carried out an extensive survey of consortium members and external stakeholders. In total, they received 135 completed responses, which were analysed and refined. Then, the team engaged in the exploration of novel topics using our established 3I strategy – that is innovation, interface and investigation.

Motivated by demand from one of our Graphene Flagship industrial partners, the National Laboratory of Metrology and Testing in France developed new services for lubricants containing graphene additives, including new chemical analysis for the determination of pH, ash content and other features. All these strategies were adapted from existing ISO standards.

Partnering Division

Division Leader
Yuri Svirko, University of Eastern Finland, Finland

Division Deputy
Jan Erik Hanssen, Graphitene Ltd., UK

Yuri Svirko
Division Leader

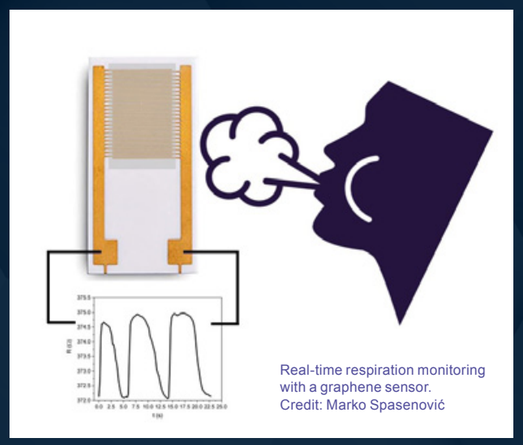
The Partnering Division expands the technological and research expertise of the Graphene Flagship with Partnering Projects and Associated Members working on a breadth of graphene and related materials topics, ranging from basic science to devices at high technology readiness levels (TRL).

"Strong and well-established collaborations between Partnering Division teams and Core Partners strengthen the Graphene Flagship," says Partnering Division Leader Yuri Svirko, from Graphene Flagship Associated Member the University of Eastern Finland.

As of 31 December 2021, the Graphene Flagship counted 114 Associated Members, 45 individual Associated Member and 40 Partnering Projects, all participating in the Partnering Division.

COLLABORATION

Graphene Flagship Partners, Associated Members and Partnering Projects form close collaborations via the exchange of knowledge and samples. For example, researchers from Associated Member ICTM (Institute of Chemistry, Technology and Metallurgy) in Serbia visited Graphene Flagship partner Delft University of Technology in the Netherlands, part of the Graphene Flagship's Sensors Work Package, to produce suspended graphene membranes with large diameters. They are planning to publish their results on the mechanical properties of these membranes and devise graphene-enabled microphone prototypes. These were benchmarked against commercial microphones, in consultation with the Associated Member Dirigent Acoustics based in Serbia.

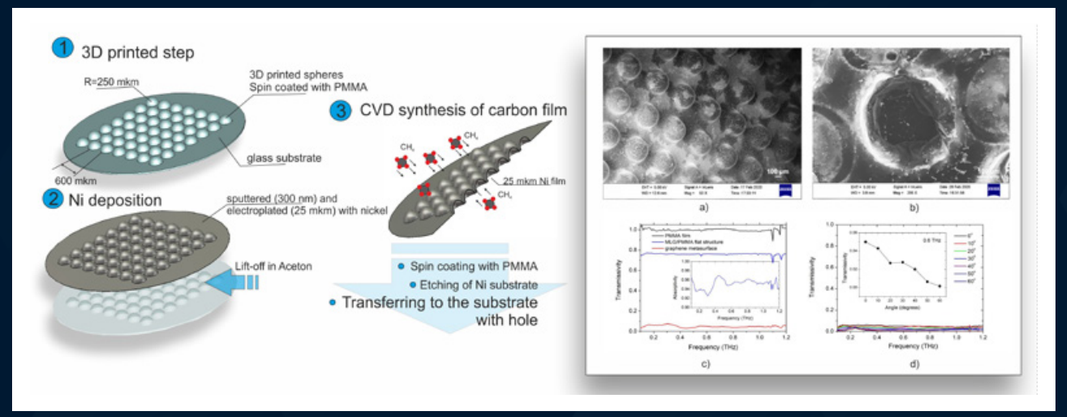


Real-time respiration monitoring with a graphene sensor. Credit: Marko Spasenović

INSTITUTE OF CHEMISTRY, TECHNOLOGY AND METALLURGY (ICTM)

ASSOCIATED MEMBER

Associated Member ICTM (Institute of Chemistry, Technology and Metallurgy), Serbia, produced an ultrafast humidity sensor exploiting graphene that can operate as a real-time respiration monitor or finger proximity detector. While commercial humidity sensors are far too slow, graphene enables real-time breath detection and has the advantage of being flexible and transparent, paving the way to integration into hospital respiratory masks. Finger proximity detection for touchless panels, controlled by hovering, was also demonstrated. The work was performed as part of project GramulSen, funded by the Republic of Serbia's Science Fund.



DiSetCom's fabrication of all-graphene "bubble wrap" metasurface: (1) 3D printing of polymer hemispheres array on glass substrate, (2) Ni deposition, and (3) CVD of graphene on the top of corrugated Ni layer, followed by spin coating with nm-thick PMMA and wet etching of the Ni catalytic substrate.

RISE RESEARCH INSTITUTE OF SWEDEN AB

ASSOCIATED MEMBER

RISE worked on a method to produce highly concentrated (~3g/L) printable starch-graphene inks in aqueous media. This eco-friendly and cost-efficient approach has potential for the scalable production and integration of conductive graphene inks for applications in printed and flexible electronics. RISE validated the photonic annealing of the starch-graphene ink for rapid post-processing of printed films and demonstrated the role of starch as a dispersing agent for graphene in water. The photonic pulse energy enhances the electrical properties of the printed graphene patterns, achieving an electrical conductivity of around 2.4 × 104 S/m.

DAS-NANO

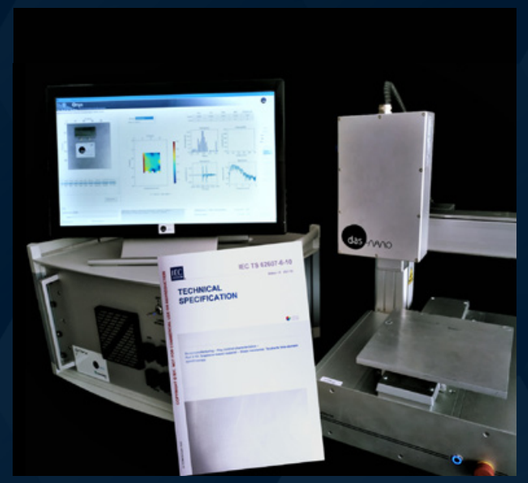
ASSOCIATED MEMBER

das-Nano co-led the writing of the IEC technical specification 62607-6-10:2021, in line with its commitment to the standardisation of terahertz technology. das-Nano's project manager Elena Taboada received the IEC 1906 Award in recognition of her outstanding individual commitment to the development of this document. Published by the International Electrotechnical Commission (IEC), this technical specification deals with the measurement of sheet resistance of graphene-based materials by terahertz time-domain spectroscopy. The method can be used for statistical process control, comparing graphene films produced by different suppliers, or obtaining information on microscale imperfections. das-Nano's Onyx – the first system on the market intended for the non-destructive, fast characterization of graphene and other materials' electrical properties using Terahertz waves – complies with IEC TS 62607-6-10.

COSTRUZIONI MECCANICHE LUIGI BANDERA

ASSOCIATED MEMBER

The R&D department of Bandera SpA confirms its commitment to researching new methods of extruding polymers and biopolymer compounds with graphene and other layered materials. From 0.3 to 3,000 kg/h, Bandera SpA offers the entire spectrum of extrusion possibilities both in flat die or blown film technology, available with coating, spray, multilayer, recycling and purification technologies for innovative applications and products.



The IEC technical specification booklet and das-Nano's Onyx system. Credit: das-Nano

ETMOS

PARTNERING PROJECT

ETMOS optimized gold-assisted exfoliation and transfer of monolayer MoS_2 membranes to insulating substrates, providing insights into vibrational, electronic and optical emission properties. The project developed gold-assisted mechanical exfoliation to separate large area (mm^2 to cm^2) monolayers of MoS2 and other transition metal dichalcogenides from bulk crystals, by exploiting the strong interaction between gold and chalcogen atoms. The resulting layers exhibit excellent electronic and optoelectronic properties, comparable to monolayers obtained by traditional mechanical exfoliation. This can pave the way to the realization of layered material heterostructures over a large area.

DISETCOM

PARTNERING PROJECT

By combining 3D printing, electroplating and chemical vapour deposition, DiSetCom fabricated "bubble wrap" polymer membranes covered with multilayered graphene, working as a broadband terahertz (THz) absorber, with more than 95% absorptivity in the frequency range spanning from a few hundreds of GHz to 1.2 THz. This fabrication technique can also be employed in other applications that require free-standing corrugated graphene/polymer membranes.

GRAPHENE FLAGSHIP ANNUAL REPORT 2021

Pilot Line for the Future

Establishing an ecosystem for integrated 2D materials in the semiconductor industry.

The 2D Experimental Pilot Line (2D-EPL), a €20 million project launched in October 2020 to integrate 2D materials into silicon wafers, is the culmination of many of the Graphene Flagship's efforts to bring graphene and related materials (GRMs) out of the lab and into commercial applications. With this project we address the industrialization challenges of achieving reliable fabrication processes for high-volume production.

"By developing a European pilot line for the processing of graphene and related materials, we aim to bring these innovative materials from the academic laboratories to the semiconductor production lines, making them compatible with the standards in the industry. Moreover, we want to offer early access to experimental pilot line production to the innovative graphene community in Europe and abroad. The pilot line will allow them to scale up the production of their innovative devices based on GRMs," explains Cedric Huyghebaert, division leader for the 2D-EPL project, and programme manager for exploratory material and module integration at imec, Belgium.

BUILDING A FOUNDATION

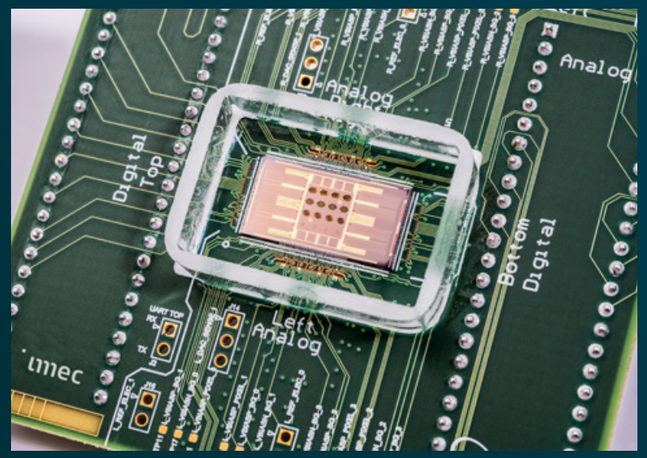
The first year of the project was critical to establishing the structure and infrastructure of the project. It was an important year where the seeds of success were planted and started to grow, but the output is not yet visible to the external world. We finalised the design of the first commercial 300 mm growth tool for graphene, hexagonal boron nitride and transition metal dichalcogenides – two other GRMs. The tool will be manufactured in the coming year.

In the meantime, we processed the first lot with transferred tungsten disulfide through the fab and made the first double-gated transistors below 15 nm in a fab flow relying on standard semiconductor equipment. Last but not least, we stabilised a 200 mm graphene device flow, with a yield above 90%, allowing us to open a multi-project wafer (MPW) run call capable of meeting customer requirements.

FIRST IN LINE

This first run will be produced by AMO GmbH's 400 square metre, state-of-the art cleanroom. Target applications are bio, gas, or chemical sensors, hall sensors or photodetector applications, taking advantage of graphene's extreme sensitivity to the environment. The baseline process is a graphene field effect transistor (GFET), with several customization options.

The MPW run offers participants a unique chance to acquire GFETs on dies manufactured to their own designs. The cost of production is shared between the 2D-EPL project and the customer, meaning that companies, universities and research institutes can access this technology at a much lower price point. At this time, the quantities available are suited for prototyping, research and development.



Above
A multimodal CMOS multi-electrode array.
Credit: imec

SCALING UP

The next steps for the project are to improve the stability of our integration flows and to prepare for upscaling to 200 and 300 mm for some of the improved flows we demonstrated in the labs. This is in addition to starting to explore the possibilities for collaboration with our customers.

The results from our first multi-project wafer run call will help us understand our key customers and their needs as well as the expected demand for these services. Each wafer run will build on those before it.

"Electronics based on 2D materials can be a real vehicle for Europe to gain shares in the high-tech sector, but what is needed is the development of a whole ecosystem around this topic – from tool and material developers to potential customers. This is what the 2D-EPL is trying to achieve. At AMO, we are really excited to contribute our experience and our fabrication capabilities to this major project," says Max Lemme, scientific director of AMO GmbH.

How we work

1. DEVELOPMENT OF TOOLS AND METARIALS

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

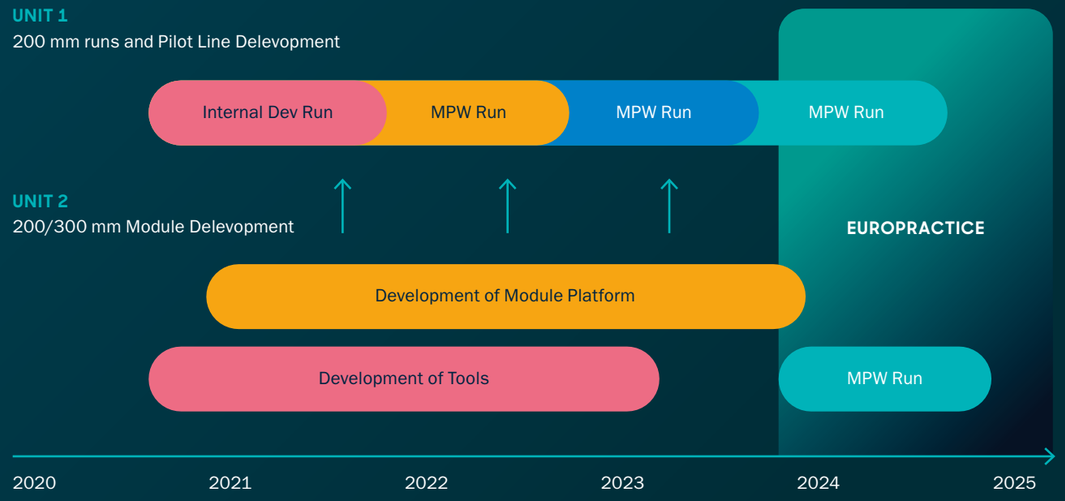
2. DEVELOPMENT OF MODULE AND PLATFORM

VTT · imec · AMO · ihp solutions

3. MULTI-PURPOSE WAFER RUNS

VTT · imec · AMO · ihp solutions

COORDINATOR: CHALMERS



Wafer Scale Growth

Michael Heuken
Work Package Leader

Work Package Leader
Michael Heuken, AIXTRON, Germany

Work Package Deputy
Amaia Zurutuza, Graphenea Semiconductors, Spain

Developing a new deposition system for 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

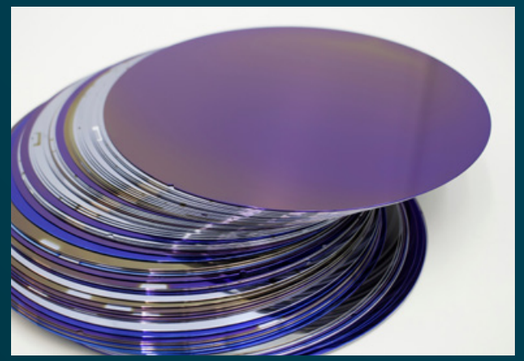
In this first year of the project, a new deposition system for the growth of 2D materials has already been designed and will be built and delivered to project partner imec in 2022. This prototype system is an essential part of the 2D-EPL, as it will allow the production of the highest quality 2D-material-based 300 mm wafers for the production of optoelectronic devices in the semi-industrial form factor. This system will be capable of controlled and uniform growth of 2D materials like graphene, hBN and transition metal dichalcogenides (TMDCs) like WS2 on sapphire and metal catalyst substrates in a fully automated way.

The biggest accomplishment this year is staying on track with all Work Package objectives despite the challenges of the Covid pandemic working conditions and long lead-times on components. The Work Package has 77 people working on process developments and plant development; the reduced interactions in remote work conditions and a lack of access to labs slows progress on assembly and testing.

Unexpectedly, our work on the design phase of the prototype development led to a technology change from a planetary reactor type to a close-coupled showerhead reactor type. This change should allow for an improved control of the growth of GRMs.

COLLABORATION

Within the ecosystem of the Graphene Flagship, there is an intensive knowledge exchange and discussions on 2D material growth and characterization which is fruitful for further technology developments and process investigations.



Above
This Work Package will scale up the growth of high-quality single crystalline graphene for use in 2D-EPL processes.

Below
Our Work Package develops new methods to integrate graphene and layered materials, and graphene-based microelectronic components, into silicon fabrication lines for next-generation computing technologies. Credit: imec

WHAT'S IN STORE

The new 300 mm prototype deposition system for 2D materials, being developed by our Work Package, will be TRL level 7. It will be an essential part of achieving the 2D-EPL's goal of establishing an ecosystem that is integrated in a commercial semiconductor foundry (TRL 7-8). After the project, work will continue on the prototype system to develop a commercial product for CMOS market application.

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

Making large-scale and high-quality graphene and MX2

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

The Work Package is working with two different kinds of materials: graphene and transition metal dichalcogenides (TMDCs) and thus developing two transfer solutions. For graphene we are investigating wet methods. For TMDCs we are developing a mechanical process. Both approaches require a carrier layer, therefore we also develop cleaning protocols to deliver a clean, intact layer. Finally, the target's specifications are also investigated to ensure compatibility with the 2D material.

This is the first year of the project, so we are still in development. The products, graphene and TMDCs, on specific substrates have been designed. Tools for their production are under construction and will be validated in relevant environments in the next steps of the project.

In the past year we also identified water intercalation as being crucial for the delamination of monolayer MoS2 from sapphire and a 300 mm debonder was designed to achieve this goal. We evaluated several adhesives for the different types of transfer that were needed. A debonding prototype to remove the glass carrier at the end of the production process was also built.

COLLABORATION

Cooperation between the 2D-EPL partners is crucial to our success. The electrochemical delamination of graphene being a challenge, AIXTRON has produced a new tool that will etch the subtract on which graphene is being grown. This will allow us to automate the transfer of graphene to 200 mm wafers very soon.

Concerning the delamination of TMDC, the collaboration between imec and SUSS led us to design a mechanical delamination tool that provides the option of using water at the interface between the growth carrier and the material.

Above
imec researchers working on the debonder prototype. Credit: imec

WHAT'S IN STORE

The cleaning of the 2D layer on the target wafer is under investigation, and we are working toward optimised polymer residue removal. The process needs to preserve the integrity of the layer and its properties.

Furthermore, the Work Package is working on two separate delamination tools specific for TMDCs and graphene. An impressive feat in and of itself! These should be delivered in the coming year. With these tools we want to make these 2D materials available for the industry.

Video: Learn more about our work on bonding.

FUN FACT

The first prototype of the TMDC debonder is a tabletop home built tool! It was designed and tested during the Covid pandemic lockdown that prevented us from working in our labs. However, despite the challenges, that's how the role of water in the delamination process was unveiled, working on 2-inch wafers.

Wafer Scale Integration

Miika Soikkeli
Work Package Leader

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

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

Developing processes for the fabrication of sensing, electronics or photonics devices

The work done in the 2D Experimental Pilot Line's (2D-EPL) Wafer Scale Integration Work Package will develop the processing steps needed for the fabrication of graphene and other 2D material-based devices, such as field effect transistors. This includes the optimization of the material patterning, contacting and passivation from the environmental effects. A significant effort is also being placed on quality control development to ensure high stability and quality of the devices.

Above
Work Package Deputy, Mindaugas Lukosius, works in the IHP cleanroom. Credit: IHP

THIS YEAR'S PROGRESS

The definition of quality control protocols has been an important step during the first year of the 2D-EPL. Our Work Package has established common key control characteristics and protocols to enable all project partners to provide clear and transparent comparison and reporting. The work was done in collaboration with Graphene Flagship's standardization committee and the International Electrotechnical Commission (IEC) to move forward with the standardization of the protocols.

The biggest technological accomplishments this year were the demonstration of TMDC based transistors on 300 mm wafers and GFETs integrated with a CMOS readout on 200 mm wafers. The scientific accomplishments include advances in the interface optimization between graphene and Si wafer substrates and dielectric deposition on graphene and TMDC layers.

COLLABORATION

Partners are well connected across 2D-EPL and Core 3 Work Packages. Inside the 2D-EPL GSEMI provides graphene on 150 mm and 200 mm wafers to AMO and VTT, and micro resist technology in the Wafer Scale Transfer Work Package is developing custom resist to be utilized for graphene patterning in our Work Package. AMO and imec also work in the Wafer-scale System Integration Work Package of the Core 3 project. VTT is utilizing the processes developed by our Work Package to enhance the graphene field effect transistor integration efforts in the Core 3 Sensors Work Package and the GBIRCAM spearhead project. imec is also part of the Autovision and METROGRAPH spearhead projects which benefit from our development efforts.

WHAT'S IN STORE

The processes developed by our Work Package are intended for use in the multi-project wafer (MPW) runs, which will launch in 2022. They will also be made available directly to the pilot line partners. The partners have already established stable process flows in the pilot line sites that can be utilized in the product development for customers, bringing our technologies directly to industry. The first MPW runs will focus on providing services for companies interested in graphene-based sensors. Further process optimization, in the coming years, will enable higher electrical quality of the devices in the future. The later MPW runs will include electronics and the integration of devices on top of CMOS readout wafers.

The main technological challenges for our Work Package are in achieving stable processes with high electrical quality in the 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 the 2D material specific processing steps is crucial to ensure devices with high electrical quality because even high-quality material growth and transfer is easily hindered by suboptimal process flows.

Modules for the Industry

Daniel Neumaier
Work Package Leader

Work Package Leader
Daniel Neumaier, AMO, Germany

Work Package Deputy
Sanna Arpiainen, VTT Technical Research Centre of Finland, Finland

Bringing the multi-project wafer runs to life

The 2D Experimental Pilot Line (2D-EPL) project's Modules for the Industry Work Package will develop dedicated fabrication processes for sensing, electronics and photonics applications, and prepare and perform multi-project wafer (MPW) runs which will be offered to external clients. The MPW runs will fabricate graphene-based devices for external clients (companies, research centres and universities) based on their individual designs. This will enable us to test and validate the process technology developed in the 2D-EPL.

THIS YEAR'S PROGRESS

In the past year, our Work Package has worked with the Wafer Scale Integration Work Package to apply the processes that they have developed to our upcoming MPW runs. Work has also been performed with the 2D Pilot Line and Management Work Packages to resolve the administrative and dissemination processes involved in launching the first MPW run.

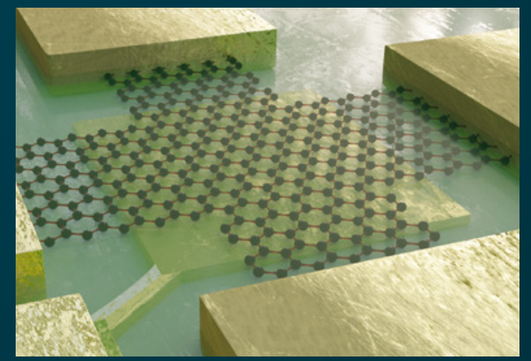
COLLABORATION

An important aspect of the 2D-EPL in general, and for our Work Package specifically, is the interaction with the Industrial Advisory Board, a group of individuals from influential European companies who provide input on the most relevant application areas for the 2D-EPL. This group is also instrumental in helping to promote the MPW runs amongst their networks.

WHAT'S IN STORE

In 2022 the first and second MPW run will launch focusing on sensor applications using graphene field effect devices. The chips from this MPW run could be used for a number of possible sensors: bio-sensors, 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. Completing the first MPW run will be our biggest challenge in the coming year. At this point it is unclear how many and what types of clients the project will receive.

Moving forward, the key challenge for our Work Package will be to properly address the needs of the MPW run clients and to maximize the impact of the 2D-EPL project. In total four or five MPW runs are planned and the lessons from one run will be used to improve subsequent runs.



Above
A sensor device schematic fabricated in the first multi-project wafer run. Credit: AMO

Below
A scientist working on a chip housing in the AMO cleanroom. Credit: AMO

2D Pilot Line

Work Package Leader
Cedric Huyghebaert, imec, Belgium

Work Package Deputy
Max Lemme, AMO GmbH, Germany

* Inge Asselberghs became Work Package leader in 2022.

Securing the 2D-EPL's future

The 2D Pilot Line Work Package supports the 2D Experimental Pilot Line's (2D-EPL) development. It is responsible for defining the multi-project wafer (MPW) runs and disseminating the results of the project, as well as creating a business model that will make the pilot line available to European R&D players in a sustainable way.

THIS YEAR'S PROGRESS

The first year of the project was critical to establishing the structure and infrastructure of the 2D-EPL. One key part of this infrastructure was the establishment of the Industrial Advisory Board, a group of ten experts from influential European semiconductor and electronics companies that help the 2D-EPL identify its client needs and industry trends. In parallel, the 2D-EPL allows them to have an inside track on recent progress and will provide them with insights on the maturity of the GRM integration, helping them in adopting future technologies.

In the past year we also took the preliminary steps towards launching our first MPW run, with the completion of the first process definition kits. A microsite for the 2D-EPL was also established on the Graphene Flagship website to allow clients to request further information and apply to the MPW runs. The wafer run call will be open the first half of 2022 and will run in the third quarter.

The Work Package also established a logo and brand identity for the 2D-EPL that illustrate the link to the project's roots in the Graphene Flagship, while remaining independent enough to stand alone when the 2D-EPL's European Commission funding comes to an end.

The streamlined 2D wordmark is created as a seamless line which gives the logo a unique and recognizable appearance.

The gap between the 2 and D clarifies the beginning and end of the line. It also provides a higher level of detail.

The connecting line represents the journey from laboratory to factory, the environments In which the 2D-Experimental Pilot Line is active. The line can be animated, buliding up the 2 and D, to create a logo with a movement forward.

The arrowhead has a 30 and -30 degree angle that comes from the hexagon. The same shape as used for the Graphene Flagship logo.

Above
Just as the 2D-EPL has emerged from the infrastructure created by the European Commission funded Graphene Flagship, the 2D-EPL brand was born from the Graphene Flagship graphic identity but given its own identity with which to go forward beyond its EU funding in 2024.

The Industrial Advisory Board and Steering Committee keep the 2D-EPL partners aligned and ensure the work completed is compatible with the project and the industry's needs.

WHAT'S IN STORE

The next year will be an exciting one for our Work Package, with two MPW run calls opening and the first run taking place before the end of the year. The lessons from this wafer run will help us to understand the 2D-EPL's average customer, the scope and size of the runs and the overall outside interest in the project. Future actions will be tailored to take advantage of this information.

COLLABORATION

As a service Work Package, we are a cornerstone to collaborations in the project. The dissemination efforts link all the Work Packages and partners through a common website, social media and events. In particular, our quarterly workshops have provided a medium for increasing the project's visibility and creating a natural gathering point for the community. Future in person events will increase the networking opportunities afforded by these workshops.

Management

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

Work Package Deputy
Veronique de Halleux, Imec, Belgium

Kicking off the project with expert ease

The goal of the Management Work Package is to implement the 2D Experimental Pilot Line (2D-EPL) project in an efficient manner. It plans and coordinates the project's actions, but also facilitates the 2D-EPL's interactions and collaborations with the Graphene Flagship's Core project and with the European Commission.

THIS YEAR'S PROGRESS

In this first year of the project, our work in establishing a foundation for the 2D-EPL has been critical. We began with an internal kickoff meeting with introductions from all the Work Package leaders to ensure that everyone started from the same understanding of the tasks at hand. The Industrial Advisory Board members, who provide the project with valuable industry insights, were also invited to join the kickoff and share their perspectives on the importance of the project.

The Work Package was able to draw on its experience from managing the Graphene Flagship core project to effectively establish the internal tools necessary to run the 2D-EPL efficiently and exploit synergies between partners. The 2D-EPL's first European Commission review was also managed smoothly, benefiting from Chalmers' ten years of experience running the Graphene Flagship.

COLLABORATION

The interactions and synergies created by the Graphene Flagship are at the heart of its success. By bringing diverse partners working on similar problems together, we help them to solve the problems of how to apply graphene and other layered materials more easily. Thus, it was only natural for the European Commission to create the 2D-EPL within the framework of the Graphene Flagship where it could benefit from the knowledge and resources of the core project and share its successes in return.

The timing is also critical. Many applications and products rely on semiconductor chips, and the global shortage of these chips has exposed a weakness in Europe's industrial ecosystem. Europe has an overall global semiconductors production market share of less than 10% and is heavily dependent on third-country suppliers. The European Commission has made a commitment to remedy this shortcoming with the European Chips Act. The work of the 2D-EPL will not only create more infrastructure for the creation of semiconductor chips in Europe, but it can also improve the state of the art. Combining graphene and 2D materials with silicon could enhance the potential of electronic technologies traditionally based on silicon.

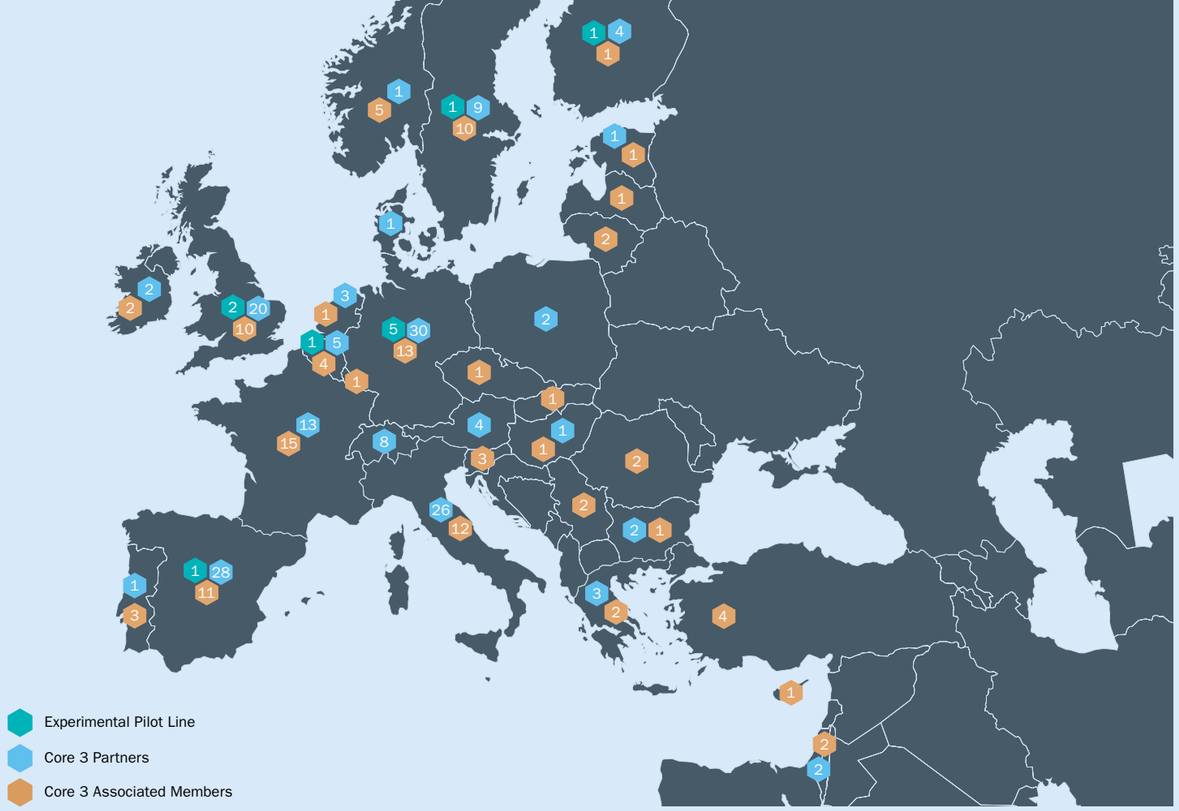
WHAT'S IN STORE

Over the next year, the Management Work Package will continue to keep the 2D-EPL on course. As the multi-project wafer runs launch, new challenges and opportunities will arise.

CALL OPEN: MULTI-PROJECT WAFER RUN 1

The 2D-EPL project has launched its first multi-project wafer (MPW) run where universities, research institutes and companies can include their designs as dies on joint wafers. The first run is mainly intended for graphene sensors and will be offered by AMO GmbH.

Why apply?
- Customizable chips
- Short turn around
- Flexible process flows
- Direct communication channels
- Experienced partners
- Feasibility consulting



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
- Karlsruhe Institute of Technology
- 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 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
- CONFINIS AG
- 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

UNITED KINGDOM
- Aixtron Ltd
- Cambridge Raman Imaging Ltd
- Composites Evolution Ltd
- Emberion Ltd
- FlexEnable Ltd
- Icon Lifesaver Ltd
- Imperial College London
- Novalia Ltd
- National Physical Laboratory – NPL
- 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

CYPRUS
- Delta Nano Ltd

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
- Marsielle University
- NEURRINNOV SAS
- Synchrotron Soléil
- University Claude Bernard Lyon
- University of Montpellier

GERMANY
- Dräger Safety AG
- Center for Solar Energy and Hydrogen Research
- International Standards Consulting GmbH
- Jülich Research Centre GmbH
- Ludwig Maximilians University
- 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 Hamburg

GREECE
- OTENET
- University of Patras

HUNGARY
- Budapest University of Technology and Economics

IRELAND
- Optrace Ltd
- 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 Cagliari
- University of Bologna
- University of Rome Sapienza
- Vittoria SpA

LATVIA
- University of Latvia

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

LUXEMBOURG
- OCSIAL Sarl

NETHERLANDS
- Institute of Molecules and Materials,
- Radboud University

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

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
- Linköping University
- RISE Research Institutes of Sweden AB
- Royal Institute of Technology – KTH
- SenseAir
- Uppsala University

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

UNITED KINGDOM
- Atomic Mechanics Ltd
- CamGraPhIC Ltd
- First Graphene Ltd
- Footfalls & Heartbeats Ltd
- Graphitene Ltd
- Haydale Ltd
- Nu Quantum Ltd
- Payper Technologies Ltd
- University of Brighton
- University of Exeter

Looking to the Horizon

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

> We need to expand and confidently branch out in many areas of science and technology. The only limit is our imagination.”

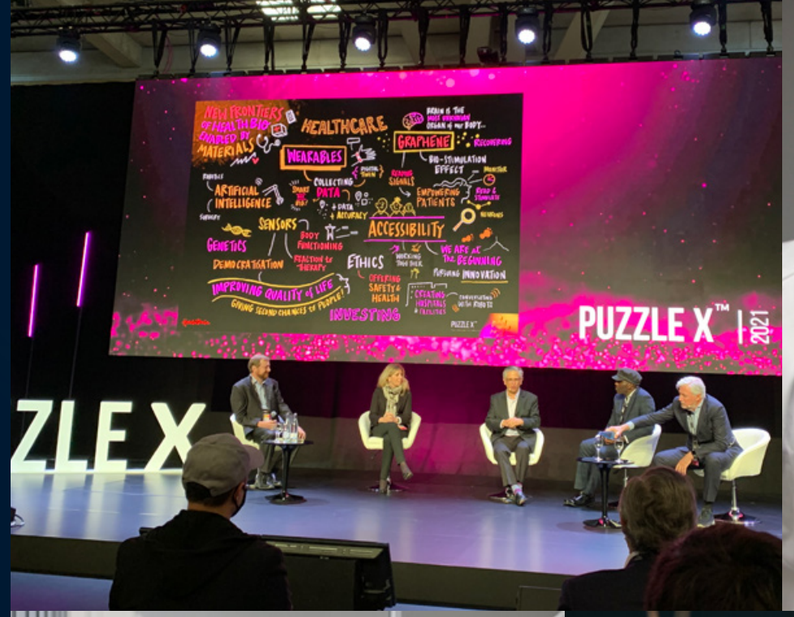
The past year posed many challenges, but the improvement of the COVID-19 situation in Europe provided further impetus to the Graphene Flagship’s work. Our Partners and Associated Members have embraced remote collaboration, making interactions, in some respects, more frequent than in pre-pandemic times. Now, we look forward to establishing new ways of working, whereby online interactions will continue to ensure quick progress, while a return to in-person meetings will allow the direct human contact that we missed so much over the past two years.

The Graphene Flagship has progressed from strength to strength in delivering cutting edge science and technology, firmly keeping Europe as the world leader in graphene and related materials. The engagement of leading European companies, such as Nokia, Ericsson, Nvidia, Airbus, ABB, Lufthansa, BMW, Varta, Sonaca, Aixtron, Siemens, Enel Green Power and Veoneer, to cite a few, ensures the relevance of our work for future technologies. It is crucial that we keep listening to their feedback, to effectively align our plans with the needs of European industry, keeping science and technology, not bureaucracy, as our leading beacon. We also cannot forget the ever-increasing number of small and medium enterprises engaged in the Graphene Flagship, including many start-ups, initiated by scientists in the project. We need to celebrate, not hamper, this entrepreneurial spirit. The Graphene Flagship-related start-ups plant the seeds upon which our technology grows, and they are essential in covering the gap between lab-based research and mass production in large companies.

We are now heading towards the final 18 months of the Horizon 2020-funded phase of the Graphene Flagship. It was in 2010 that the initial proposal was submitted, followed by a pilot phase and then the kick off in October 2013. The Graphene Flagship is set to continue into Horizon Europe, the next European Commission research and innovation funding instrument. Most importantly, it is set to have significant influence in a variety of European programmes and initiatives. Layered quantum materials are now part of the Quantum Flagship, and graphene-based batteries are studied in the Battery 2030+ initiative. Several European Innovation Council grants are supporting graphene and related material-based technologies, and the European Research Council keeps funding fundamental and disruptive research based on layered materials. It was exciting to see graphene and related materials included in the recently presented European Chips Act proposal, aiming at recovering Europe’s capabilities and resilience towards supply chain disruptions. This shows that the efforts we put in investigating wafer-scale graphene technologies, either as films or single crystal arrays, are paying off. Renewed effort should go to their development and transfer to industry. Now it is not a time to stop.

Moving forward, the “graphene for graphene’s sake” work cannot continue. We need to expand and confidently branch out in many areas of science and technology, where graphene and related materials can now claim a rightful spot alongside more established materials platform technologies, but with greater potential to address key performance and sustainability issues. The only limit is our imagination.

Andrea C. Ferrari
Graphene Flagship Science and Technology Officer



The Graphene Flagship is research, innovation and collaboration

Funded by the European Commission, the Graphene Flagship aims to secure a major role for Europe in the ongoing technological revolution, helping to bring graphene innovation out of the lab and into commercial applications. The Graphene Flagship gathers over 170 academic and industrial partners from 22 countries, all exploring different aspects of graphene and layered materials.

Bringing diverse competencies together, the Graphene Flagship facilitates cooperation between its partners, accelerating the timeline for industry acceptance of graphene technologies. 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.

Funded by
the European Union

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