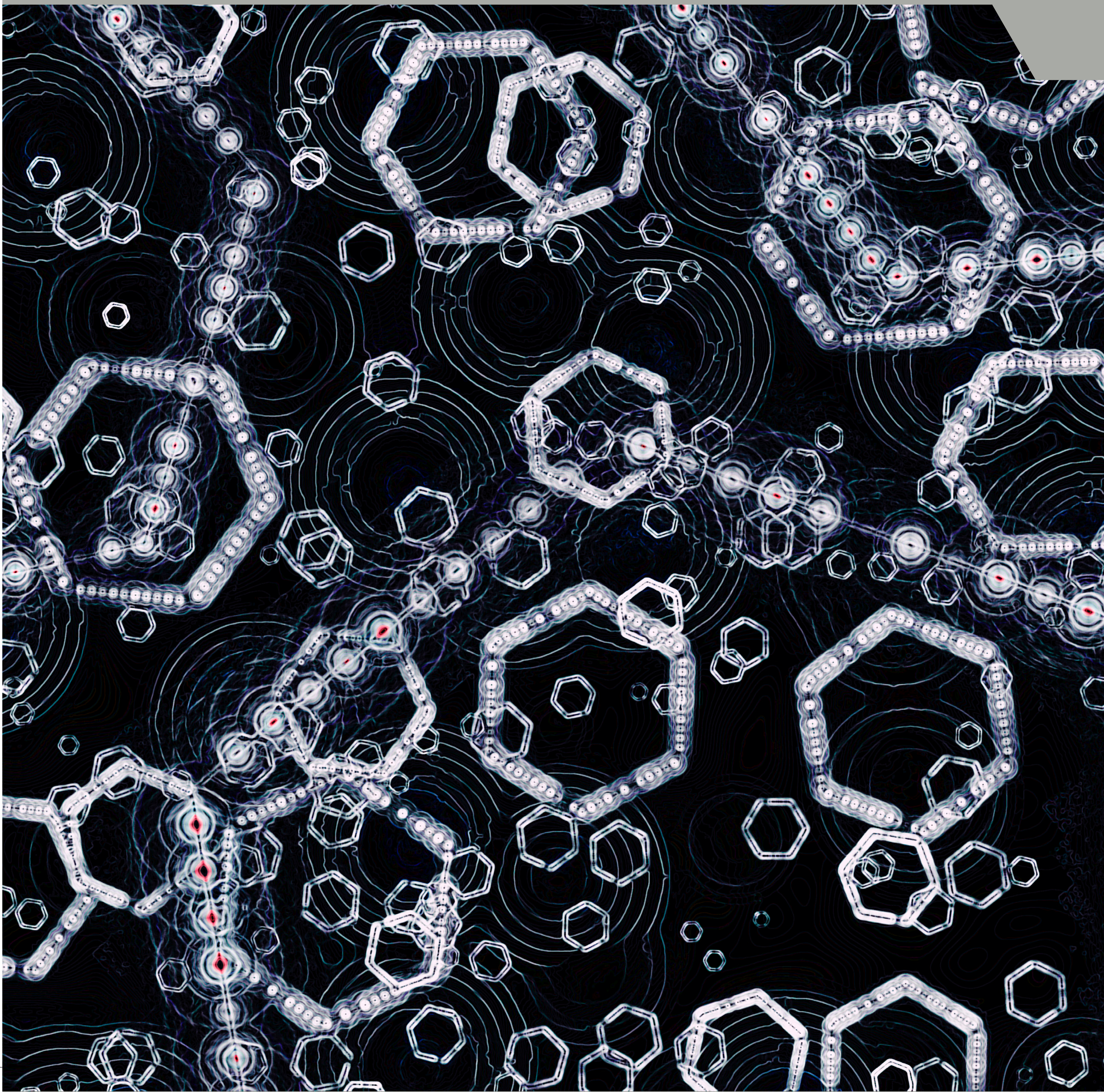
GRAPHENE FLAGSHIP

Funded by the European Union

GRAPHENE FLAGSHIP
Annual Report 2018



Ana Reguero demonstrates the leading edge of Aernova's graphene composite airplane wing at the European Commission annual review.
Credit: Johan Bodell/Chalmers

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From the Director

Over the past year, the Graphene Flagship consortium has made great progress towards its overarching goal of taking graphene from academic laboratories to society. As technologies mature, the issue of reproducibility and manufacturability is becoming more prominent – breakthroughs in this direction include the quality monitoring and characterisation techniques based on terahertz measurements developed by the Technical University of Denmark and the fabrication of large graphene composites for aerospace applications by Aernnova, Grupo Antolin, UC3M and Airbus. Other great achievements include chemical vapour deposition (CVD) growth of very high quality graphene for electronics applications, developed, through different approaches, by teams at RWTH and the Istituto Italiano di Tecnologia.

WHY THE GRAPHENE FLAGSHIP?

The defining feature of a flagship is long-term funding. This has proven to be an efficient way to take advanced concepts from early stages of development to maturity. Graphene Flagship partners have already released dozens of products on the market and launched several new companies to commercialise the results of their work. We see that a value network of new and old, large and small enterprises is being established in Europe as a direct outcome of the Graphene Flagship.

LOOKING FORWARD

The coming year will bring with it several exciting developments. Most concretely, we must prepare the third core project of the Graphene Flagship, where we will further increase our effort in applied research and development while maintaining strong support for fundamental research. A new initiative, an experimental pilot line for graphene-based electronics, optoelectronics and sensors will be set up to address the manufacturing challenges. We will also start the work to prepare the continuation of the Graphene Flagship beyond 2023 and into the Horizon Europe era.

Jari Kinaret, Director of the Graphene Flagship

The Graphene Flagship is research, innovation and collaboration. The Graphene Flagship is Europe!

As a Future and Emerging Technology (FET) Flagship funded by the European Commission, the Graphene Flagship is, by definition, a massive project: bringing together 145 academic and industrial partners in 21 countries. The Graphene Flagship, however, is much more than the sum of its parts. One billion euros of funding in the hands of 145 individual institutions may have facilitated research and innovation on a small scale, but by combining these players into one project with the broader goal of bringing graphene and related materials into commercial applications, the European Commission created a mechanism capable of overcoming some of the obstacles commonly faced by new technologies.

Some things can only be accomplished in a large project. Firstly, it takes many years of continuous work to create a new technology. Secondly, to reach such an ambitious goal you need to involve people and organizations with different competencies, some working on materials production, others on using the materials to make individual components and finally someone who integrates the components in systems such as cars, airplanes or communication networks. If one separates the different elements into independent projects, nothing happens, as everyone is waiting for everyone else: for instance, the component manufacturer does not dare to engage in a project if the materials supply is not secured or if there are no system integrators that will buy the components that the project would develop. Developing a new technology is risky, and in Europe no single company or country can assume the risk alone, we need to work together.

By creating the FET Flagships, the European Commission assumed some of the risk of developing new technologies, and in so doing paved the path for Europe to take a major role in the ongoing technological revolution.

"The Graphene Flagship, now halfway through its ten-year programme, is uniquely positioned to take emerging graphene-based technologies from the lab to fab; the Executive Board is charged with turning this vision into a reality. We have assessed many of the scientific breakthroughs and can see their potential commercial application in a variety of applications and as such, we will strive to realise future graphene-based products by increasing the number of spearhead projects, industrial partners and business development activities."

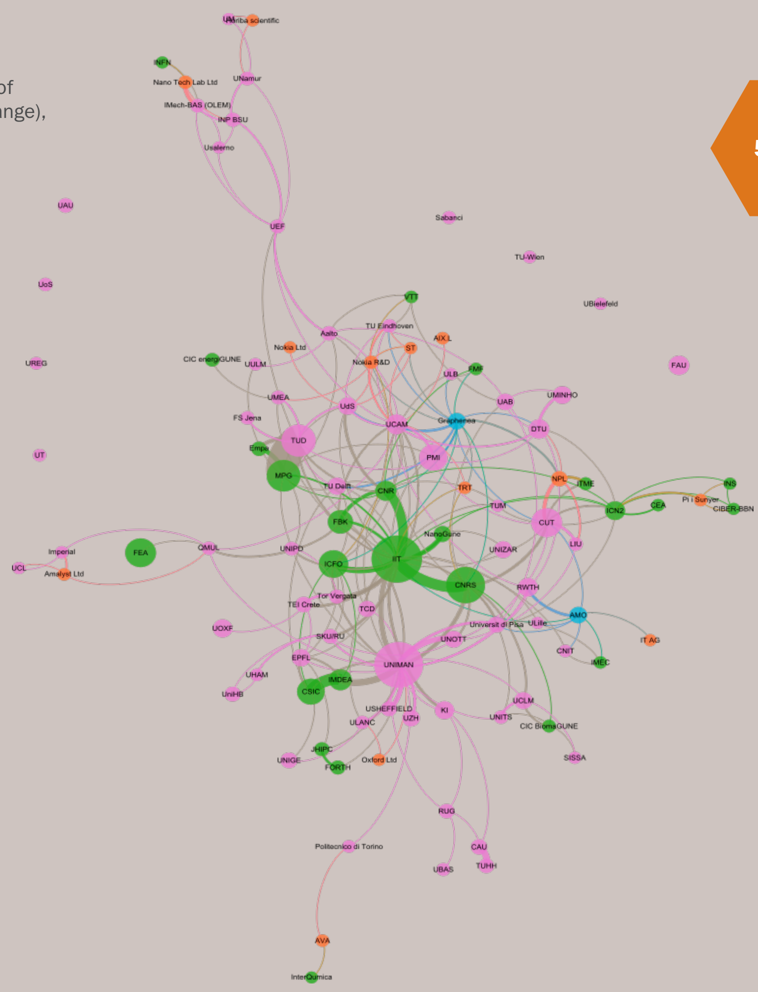
Ken Teo, Graphene Flagship Executive Board Chair

"The particular strength of the Graphene Flagship is in the synergetic development of the fundamental and applied research. New and fresh scientific results are getting translated swiftly into applications, as is now happening with graphene membranes. There are still a lot of new things going on: a vast portfolio of two dimensional (2D) materials and their heterostructures, magnetic 2D materials, controlling electronic properties of 2D materials by twisting them, etc. The strong and permanent dialog between fundamental and applied research, secured by the Graphene Flagship is key to the success of the whole project."

Konstantin Novoselov, Graphene Flagship Strategic Advisory Council Chair

"The Graphene Flagship's division structure enables an efficient collaboration between researchers in the different work packages on common challenges and thus avoids replication of tasks and speeds up the progress."

Daniel Neumaier, Division 3 Leader



Joint-publications between Core1 partners. Node colours indicate types of organisations: Higher Education Institutions (purple), Large company (orange), Small and Medium enterprise (blue) or other (green).

The Breakdown

DIVISION 1: ENABLING SCIENCE AND MATERIALS
This division provides foundations of science and develops materials for the Graphene Flagship.

DIVISION 2: HEALTH, MEDICINE AND SENSORS
This division provides coherence and focus in the development of graphene and 2D material technologies on interaction with living organisms, whether it is for the determination of safety limitations, development of advanced medical technologies or enhancing our capabilities for accurate and sensitive sensing.

DIVISION 3: ELECTRONICS AND PHOTONICS INTEGRATION
The work in this division will find applications in communication, sensors, Internet of Things and energy. It addresses key high-tech domains, which will have a significant impact on the European economy and society.

DIVISION 4: ENERGY, COMPOSITES AND PRODUCTION
This division is addressing applications at high TRL (4–5 or above) in the strategic fields of energy and composites where there is a large expectation that graphene and other 2D materials will have the most significant commercial impacts in the short to medium term.

DIVISION 5: PARTNERING DIVISION
The partnering division brings the added value of the associated members and partnering projects to the Graphene Flagship, enabling new possibilities both in research and in technological implementation of graphene and related materials.

DIVISION 6: ADMINISTRATION AND SERVICES
The work packages in this division provide services that support the overall goals of the Graphene Flagship from management and dissemination to market research and outreach as well as work on innovation, standardisation and validation services.

145
PARTNERS

31
PARTNERING PROJECTS

87
ASSOCIATED MEMBERS

21
COUNTRIES

Work Package Leader:
Kari Hjelt

Work Package Deputy:
Francesco Bonaccorso

Innovation

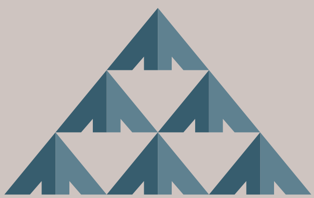
"Innovation is at the core of the Graphene Flagship's mission to create business impact from graphene technologies. In 2018 we have witnessed the move from materials research towards component development and system-level integration. Our focus is in strengthening our cooperation with industry stakeholders to increase technology readiness levels. The spearhead projects play a major role in this effort. Furthermore, our business developers are key players in creating the network connecting our research efforts to industry. Their tasks range from scouting the recipients for our technologies to being messengers from industry when it comes to industry trends, needs and roadmaps. They arrange workshops and help teams to create business models."

Kari Hjelt, Graphene Flagship Head of Innovation

GRAPHENE PHOTODETECTORS

Stemming from the Graphene Flagship framework, Emberion has developed photodetector modules that can detect light in the visible to short-wave infrared ranges. Emberion has unique skills in combining graphene and nanostructured optical absorbers with custom-designed read-out integrated circuits (ROIC), which allows high-performance infrared detector products for a broad range of wavelengths from visible light to the thermal range. They provide products that are highly cost competitive with superior performance and can be used for various applications such as machine vision, night vision, spectrometry and thermography.

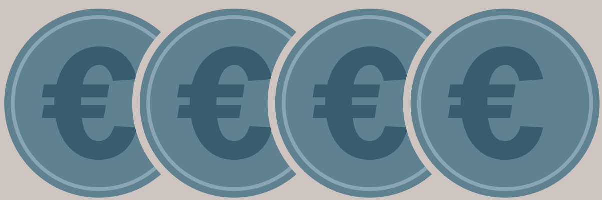
6
SPEARHEADS



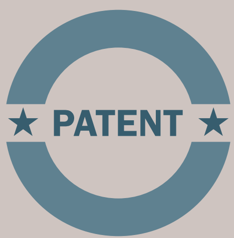
46
PRODUCTS LAUNCHED

9
SPIN-OFF COMPANIES

€100M
EXPECTED VALUE OF GRAPHENE MARKET BY 2020



25
PATENTS GRANTED



€150–550M
EXPECTED VALUE OF GRAPHENE MARKET BY 2025

Our focus is in strengthening our cooperation with industry stakeholders to increase technology readiness levels."

Kari Hjelt

BEDIMENSIONAL

BeDimensional, a spin-off of Graphene Flagship member Istituto Italiano di Tecnologia, is dedicated to the development of innovative products based on graphene and other two-dimensional crystals. BeDimensional has unique know-how in producing two-dimensional crystals on an industrial scale maintaining high quality standards, i.e. few-layer thick, at competitive cost. The use of high-quality 2D crystal flakes allows the development of high-performance products for a broad range of applications, ranging from printed electronics, to composites and energy, with superior performance compared to the state-of-the-art.

IIT's Energy Day combined lectures and workshops.
Credit: Duilio Farina, IIT

ENERGY DAY @ IIT

On 18 April 2018, the Graphene Flagship sponsored a Graphene Connect event organised jointly by the Istituto Italiano di Tecnologia (IIT) Graphene Labs and the Ticass Consortium (Genova, Italy). The Energy Day workshop brought together representatives of the research, industry and academic communities as well as policy-makers and end-users at large in order to share information and discuss overlapping roadmaps and fringe innovation in the energy storage domain. "Industry, inside and outside the perimeter of the Graphene Flagship, is very interested in the future applications of 'our' 2D material in the Energy world," says Fabrizio Tubertini, Graphene Flagship business developer for energy applications.

Credit: BeDimensional

Business Developers

Each business developer serves a specific graphene application area and helps to identify industry needs and how graphene can address them.

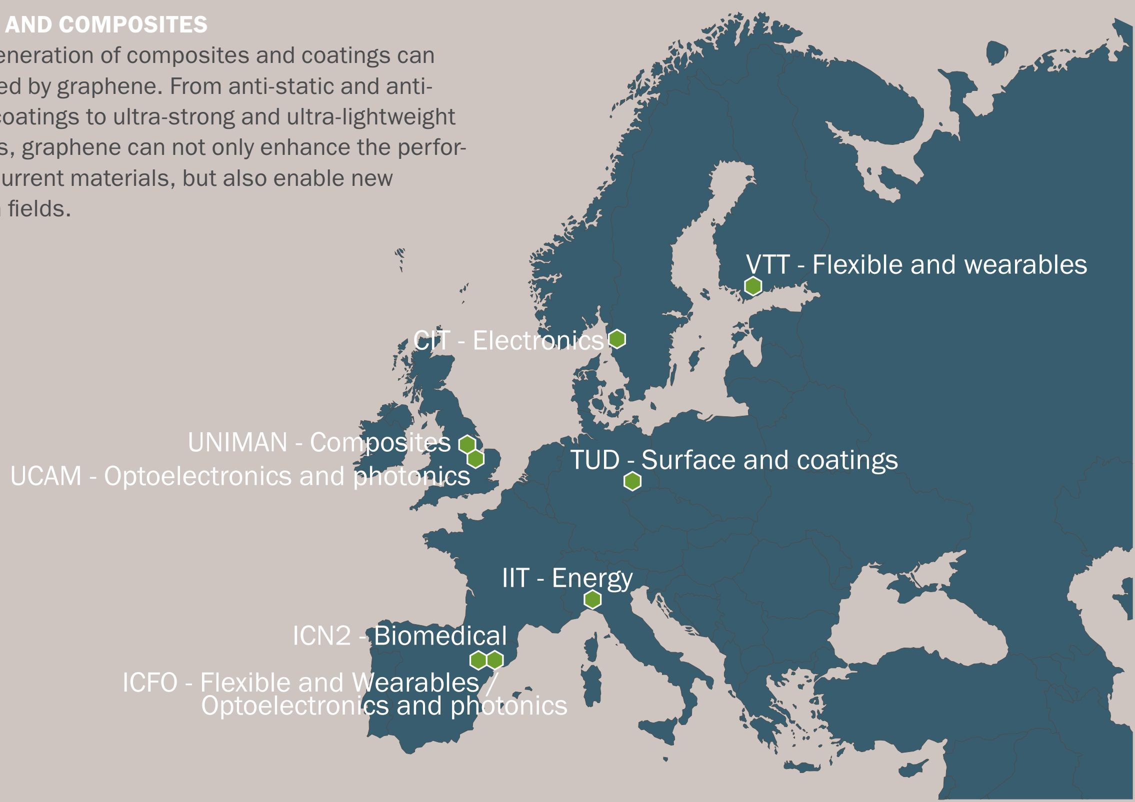
ELECTRONICS
Graphene has much to offer the next generation of electronics technology from chips and interconnects for data communication to flexible screens for wearable technology. With miniaturisation being a major driving factor of the electronics industry, graphene's thinness coupled with its high room temperature conductivity shows great promise.

BIOMEDICAL
Graphene is paving the way for novel diagnosis and treatments, thanks to its unique properties, such as high surface area, electron mobility, and functionalisation potential. These are all favourable features for biomedical technologies. For example, graphene is an excellent platform for drug delivery due to its surface area, and couples as a biosensor, due to its high electrical conductivity.

COATINGS AND COMPOSITES
The next generation of composites and coatings can be enhanced by graphene. From anti-static and anti-corrosion coatings to ultra-strong and ultra-lightweight composites, graphene can not only enhance the performance of current materials, but also enable new application fields.

FLEXIBLE AND WEARABLES
Ubiquitous computing and its integration with accessories such as bands, watches, glasses, clothing and implants, have resulted in an enhanced intra- and interconnectivity among humans and their environment. This future is on our doorstep thanks to recent technological advancements but requires a step-change in the building blocks of wearable technologies. Graphene and related materials (GRMs) are, due to their inherent properties, extremely suitable for such devices.

ENERGY
As the global population expands, the demand for energy production and storage constantly increases. Solar cells, batteries, super capacitors, hydrogen production and fuel cells are all areas where GRMs can make a difference. These could be used to produce new devices or integrate into current ones to boost their performance.



Work Package Leader:
Thomas Reiss

Work Package Deputy:
Alexander Tzalenchuk

Industrialisation

Work Package Industrialisation contributes directly to the Graphene Flagship's goal of facilitating and accelerating the uptake of graphene and related materials (GRMs) for industrial and commercial applications through its core activities: identifying, exploring and evaluating graphene application opportunities, improving trust and confidence in GRMs, enabling innovation, developing standards, communicating the outcomes transparently via the samples and materials database (SMDB) and providing information and raising awareness regarding quality control as well as fabrication and characterisation standards.

VALIDATION

The validation service, established at the beginning of core 2, has proven to be extremely successful. The role of validation, carried out by work package members coming from authorized national measurement institutes and facilities, is to give objective data on real GRMs and GRMs-enhanced devices. Provided with reliable validated data, the users make confident decisions on the suitability of graphene for their application, benchmark its properties against the existing solutions and explore options for identifying the right suppliers. Within the first three months of its launch, 23 validation requests from different partners of nine different work packages of the Graphene Flagship have been raised. About a quarter of the requests have already been completed and the requesters have been provided with detailed validation results reports. The other validation requests are in progress. Most requests came from the work packages enabling research, wafer scale systems integration, functional foams and coatings as well as polymer composites. By the establishment of the service, a significant contribution to enhancing trust and confidence on GRMs-based innovations could be made. This will also further the position of the Graphene Flagship as a key site not only of excellent graphene research but also on GRMs-based innovation.

80+
PROMISING APPLICATION AREAS ANALYSED

23
VALIDATION REQUESTS

40+
DETAILED INNOVATION ROADMAPS

SERVING
9
WORK PACKAGES

ROADMAP

Over the past year, Work Package Industrialisation has implemented a new method for conducting focused value chain analyses of promising GRMs applications. The approach consists of three main steps: the first step comprises the elaboration of a GRMs-based value chain starting from the assessment of promising application areas within the overview roadmap. The second step focuses on identifying the key stakeholders along the value chain. The third step is the joined elaboration of the different stages of the value chain including specific KPIs and milestones.

In 2018 three topics have been elaborated upon following this scheme:

- Graphene-based materials for next generation neural interfaces
- Perovskite solar cells using GRMs materials
- Integrated graphene-based photonics for data communication

In some cases, the outcomes of these analyses have already been taken up directly by industry-led consortia in order to implement this innovation approach. An example is the perovskite solar cell topic where a team was set up including researchers and industries, covering the whole value chain starting from material preparation until system integration.

> "Work Package Industrialisation is working on the macro level, considering entire industries and aiming at connecting and advancing innovation communities."
>
> **Thomas Reiss**

STANDARDISATION

The aim of standardisation within Work Package Industrialisation is to promote the industrialisation of GRMs by providing consensus-based accepted standards for the properties and characterisation of GRMs, GRMs-enabled components and systems. Industrial players need standardised materials and processes in order to integrate these new materials and devices into their innovation activities. Accomplishments include the establishment and operation of the Graphene Flagship standardisation committee and in particular the establishment of links to the international standardisation bodies, most importantly the IEC/TC113 "nanotechnology for electrotechnical products". These activities brought Europe into a leadership position as measured by the number of standardisation project leads.

The standardisation activity builds upon the validation activity of the work package as well as existing developments in the international standardisation community. It strongly depends on the input from the technical work packages and in particular from the spearhead projects.

30%

OF ALL INTERNATIONAL GRMS-RELATED STANDARDISATION PROJECTS ARE LED BY EUROPE

80%

OF THESE HAVE BEEN INITIATED BY GRAPHENE FLAGSHIP MEMBERS

SAMPLES AND MATERIALS DATABASE

The samples and materials database (SMDB) has been further developed and integrated into the Graphene Flagship intranet. It now includes a larger range of parameters, methods and standards and provides valuable information to its users. A full integration of the workflows for the validation service with the SMDB is being elaborated.

INDUSTRIALISATION VS INNOVATION

The activities of Work Packages Industrialisation and Innovation are complementary: Industrialisation looks at the big picture, elaborating strategic target areas for innovation via the technology and innovation roadmap and providing key requirements and prerequisites for innovation based on GRMs, namely trust and confidence in GRMs-enabled products by providing validation services and developing international standards. Thereby Work Package Industrialisation is working on the macro level, considering entire industries and aiming at connecting and advancing innovation communities. Work Package Innovation translates the strategic target areas identified in Industrialisation into concrete innovation actions.
In this sense, Innovation is working on a micro level promoting competitive advantages of individual actors and companies. Within this work package, business developers may work with a specific company on a specific innovation project on a confidential basis.

Management and Dissemination Events

Women in Graphene

The Graphene Flagship demonstrates its commitment to creating a more diverse scientific community through its Women in Graphene initiative, designed to provide a support network and role models for women in the graphene community.

"The Women in Graphene career development days help equip attendees with the inspiration, support and knowledge to pursue their career goals in the realm of materials science," explains Siân Fogden, event organiser. In 2018 the Graphene Flagship held two Women in Graphene events. At the Women in Science and Graphene Workshop held at AstraZeneca in Gothenburg, Sweden, on 8 March, speakers highlighted the importance of diversity to successful research and development projects and ways to identify suppression techniques and combat them. The Women in Graphene session held on 11 September during Graphene Week in San Sebastián, Spain, presented the life lessons of three graphene scientists, highlighting the diverse paths each took to overcome their individual career challenges.

Ethical Research and Innovation

The Graphene Flagship's Ethical Advisory Board provides input on the project's activities to ensure that the ethical implications of technologies developed by the Graphene Flagship are considered.

In 2018, the Graphene Flagship also hosted a session

Women in Graphene creates a support network for women and encourages diversity in science. Credit: arri studioa

The poster session at Graphene Week gives researchers a chance to showcase their work. Credit: arri studioa

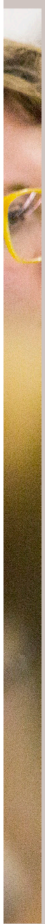
on Sustainable Research and Innovation at Graphene Week highlighting the concepts, methods and tools required to ensure that the research conducted and the innovations created by the project address society's needs and anticipate, as far as possible, unintended effects.

International Workshops

Over the past year, the Graphene Flagship held a series of International Workshops designed to encourage the exchange of experiences, practices and ideas between Europe and other countries including the United States, Korea, Japan, Australia and China. Specifically, the workshops attempt to identify research challenges that need to be addressed by the research community.

The workshops have also identified a need to address challenges relating to standardisation, material validation and other obstacles to industrialisation.

As part of its international outreach, the Graphene Flagship offers mobility grants to students looking to travel to other countries to learn from their experience or take advantage of research equipment available at other facilities. The US, Korea and Japan also offer mobility grants to their students.



Graphene Study

Through Graphene Study, its school for early career researchers, the Graphene Flagship helps to develop the future of graphene research. Two Graphene Study event's were held in 2018. Titled *2D materials for environment and energy applications,* the summer edition explored experimenters' techniques in studying energy and environmental applications for graphene, mainly filtration and energy storage technologies. The winter edition, titled *Structural characterisation of graphene-based materials,* provided delegates with a strategic overview of the most common techniques and methodologies available to determine the nature, composition and behaviour of 2D materials. These events allow early career researchers to network with more experienced ones and to form relationships that could help them further their research and careers.

Graphene Week

Each year the Graphene Flagship hosts its annual conference showcasing the latest innovations and leading-edge technology and research on graphene. This event brings together over 700 graphene experts from 50 countries to exchange information and explore the hottest topics in the field. Targeted workshops highlight trending topics, its Exhibition Hall allows companies to showcase their products and services, related to graphene and related materials, and the Graphene Innovation Forum provides a platform for industry and researchers to exchange information concerning the future of graphene as they enter the market.

Graphene Marketplace

Graphene Marketplace is an initiative to promote graphene applications among industrial partners. On 17 October 2018, Leonardo, one of the Graphene Flagship's largest industrial partners, hosted the event *"Graphene: revolution is coming to Earth… and Space."* The goal of the event was to promote the many applications of graphene internally among Leonardo's researchers and engineers and to explore the use of graphene to sustain Leonardo's competitiveness.

Nobel Laureate Konstantin Novoselov speaks at the Graphene Marketplace in Milan. Credit: Leonardo Company

Work Package Leader:
Alex Jouvray

Work Package Deputy:
Tamara Blanco

Production

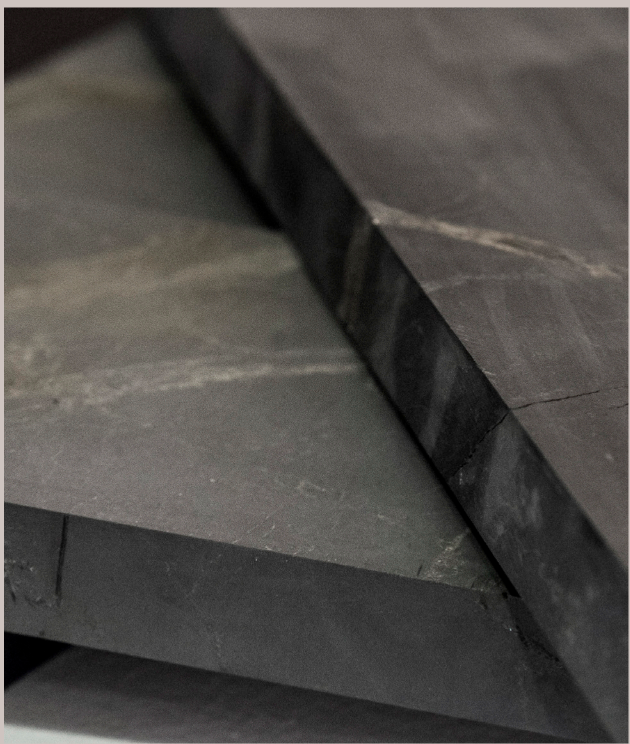
The Graphene Flagship's Production Work Package aims to establish industrial scale processes to enable the mass production of graphene and related materials (GRMs) for diverse markets. Only with the development of cost-effective production techniques will graphene-based products make the jump from the laboratory to the factory floor. The work package aims to develop manufacturing techniques suitable for aerospace, automotive and (opto)electronics industries where the multifunctional nature of GRMs can be used to their full potential.

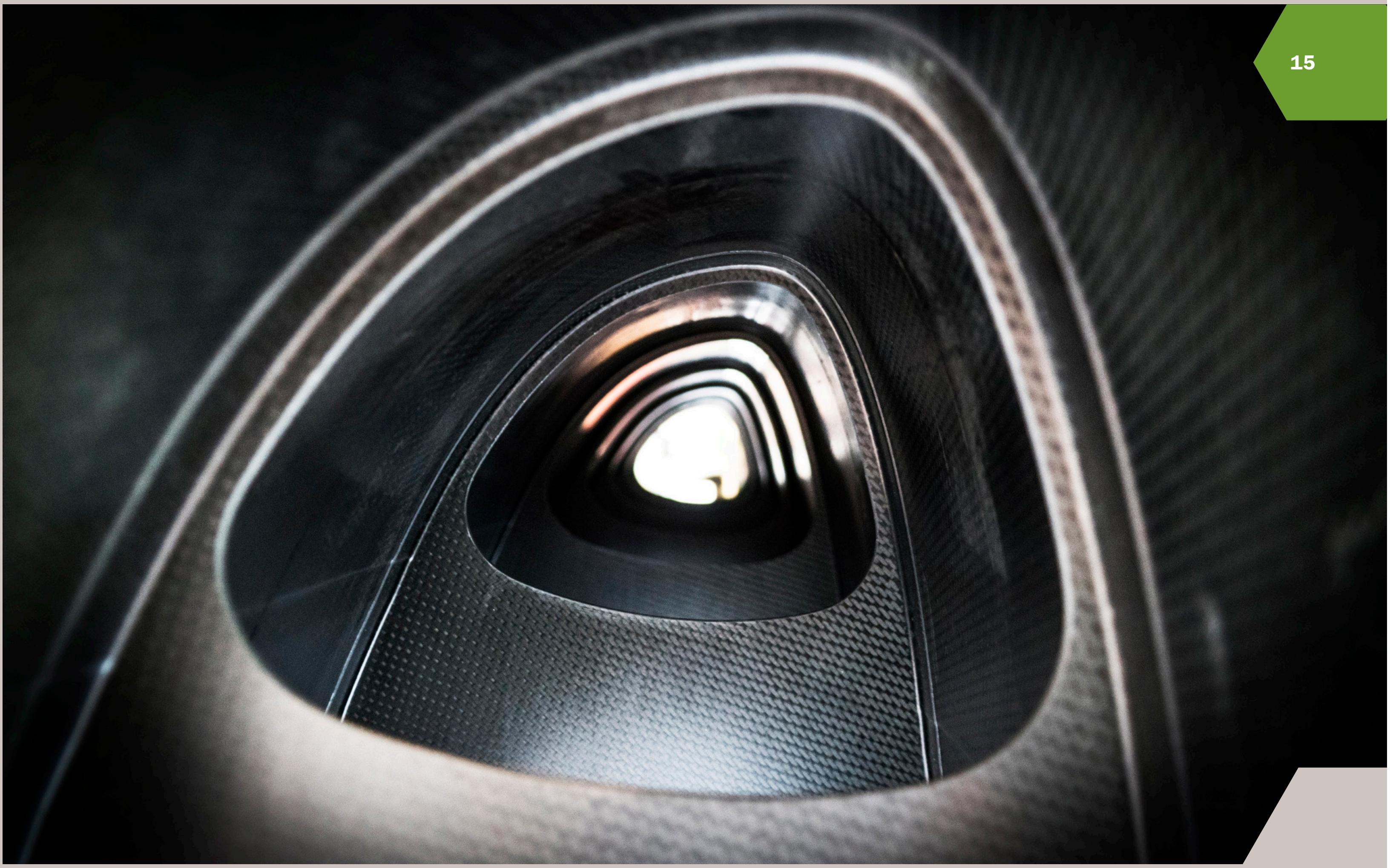
YEAR IN REVIEW

During the last year, the Production Work Package focused on the development of diverse products such as graphene-based transparent electrodes for UV-LEDs and graphene coatings for copper wires used in low voltage domestic and industrial wiring. The work package demonstrated and qualified flame-retardant graphene coatings for building and automotive industries. In this instance, the thermal properties of graphene are being used to quickly dissipate heat, decelerating the burning and melting of the materials being tested. The addition of these graphene based materials into building materials means that they are a safer alternative to current materials. The addition of graphene to plastics for use in the automotive industry could also increase vehicle safety. The graphene produced by this work package's advanced production processes is also used by other work packages within the Graphene Flagship.

Over the course of the last year, the work package also assessed the impact and electrical performance of resin transfer moulded carbon fibre/graphene related resin composites for aerostructures. Grupo Antolin, Aernnova, UC3M and Airbus produced a leading edge for an Airbus A350 horizontal tail using graphene. The leading edge is the part of the airplane wing or tail plane that first contacts the air, and as such it must possess excellent mechanical and thermal properties. Graphene increased the mechanical properties, making it thinner and de-

Beginning with graphite stone from their Swedish mines (left), Talga produces a water-based dispersion of few layered graphene and a dry graphene nanoplatelet powder (right). Credit: Alexandra Csuport





Graphene increased the mechanical properties of the leading edge, making it thinner and decreasing its weight while maintaining its functionality. Credit: Johan Bodell/Chalmers

> "The large scale of the Graphene Flagship allows different partners to work together. This enables the faster development of new technologies and products that otherwise wouldn't be possible."
>
> **Alex Jouvray**

creasing its weight while maintaining its functionality. This will result in significant fuel saving, with cost and emissions reductions over an aircraft's lifetime.

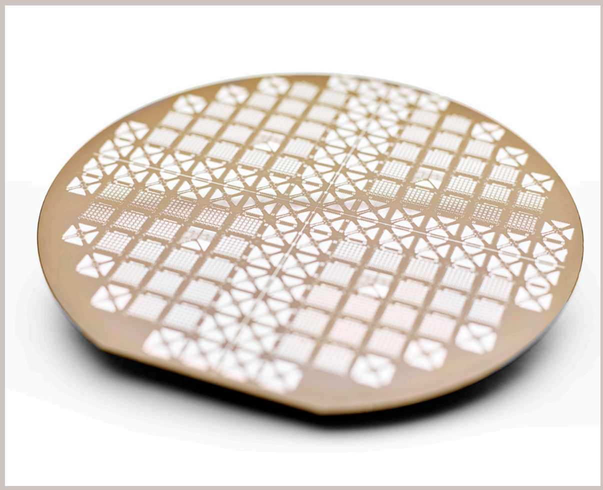
LOOKING FORWARD

Alex Jouvray, work package leader from Aixtron Ltd., United Kingdom, commented further on the plans for next year: "We will continue to develop different technologies to reach higher technology readiness levels and launch new products."

WHY THE GRAPHENE FLAGSHIP?

"The large-scale nature of the Graphene Flagship project is important. It allows different partners to work together, increasing the network-effect of the project. This enables the faster development of new technologies and products that otherwise wouldn't be possible," said Jouvray.

Graphene Flagship partner Graphenea produces four, six and eight inch wafers. Credit: Graphenea



Work Package Leader:
Costas Galiotis

Work Package Deputy:
Ian Kinloch

Composites

The Composites Work Package focuses on the best way to combine graphene and related materials (GRMs) with other materials to enable their use on the macroscopic level. The inherent properties of GRMs can provide additional functionality to other materials, adding electrical or thermal conductivity, decreasing weight or increasing mechanical strength. This work package focuses on applications in sectors including aerospace, automotive and energy generation.

As the Graphene Flagship moves onwards in its journey to take graphene from the laboratory and into innovations suitable for commercialisation, the Composites Work Package has intensified its efforts to increase the involvement of its industrial partners such as Airbus, Fiat, ABB, BASF, Avanzare and Nanesa to help move research efforts to a higher technology readiness level.

YEAR IN REVIEW

Over the last year, the Composites Work Package developed a new generation of high-quality masterbatches that will facilitate the widespread diffusion of GRMs into the plastics industry. Functionalisation strategies have also been implemented in the masterbatches to allow tailoring of the GRMs properties to specific applications and to the needs of industrial users. This included the development of a thermoplastic automotive 'smart' dashboard with conductive patterns and sensors based on GRMs.

Also developed is a heating module containing GRMs that will be employed in the aviation and automotive industries. This module has proven resistant to both fire initiation and propagation by adding GRMs in thermoplastic and thermosetting polymers. The use of graphene

A new generation of high-quality masterbatches has been developed that will facilitate the widespread diffusion of GRMs into the plastics industry. Credit: Johan Bodell/Chalmers

> “Concentrated research efforts that involve both academic and industrial institutions provide an important paradigm shift for future research.”
>
> **Costas Galiotis**

as an additive in thermoplastic elastomers has been shown to increase the dielectric constant leading to higher actuator efficiency, while the stiffness was increased 130% compared to the pristine polymer.

Another highlight is the incorporation of MoS_2 flakes, introduced at various concentrations, into an elastomeric matrix to produce novel piezoresistive sensors with a negative gauge factor. The work package also worked on the production of high-performance cooling systems while at the same time reducing metal corrosion by mixing GRMs with other additives and nano-additives such as metallic powders.

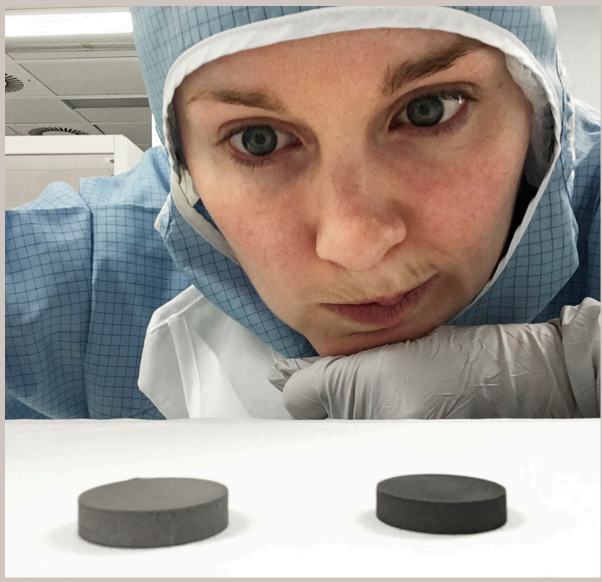
LOOKING FORWARD

The Composites Work Package aims to produce two different large-scale masterbatches which can be exploited by end users. There is a plan to test a loop heat pipe system in orbit on a mini satellite whilst also developing a full-size prototype for further testing. The development of GRMs-enhanced carbon fibre reinforced composites, will be intensified, employing thermoplastic or thermosetting matrices for the aviation and automotive sectors. This has the aim of implementing GRMs matrices in a product in aeronautical or automotive fields in the short to medium term.

With its focus on industrially relevant composite applications and work with industrial partners, there have been many success stories to emerge from the Composites Work Package. Costas Galiotis, work package leader from FORTH, Greece commented, “Interquimica successfully produced GRMs reinforced plastic with improved flammability resistance. Similarly, Avanzare managed to enhance the thermal conductivity of plastic by 1000% with GRMs, at a competitive market cost which was complemented by a pilot extrusion run. CRF exploited the electrical properties of GRMs with polymeric matrix for sensing and wiring applications. Nanesa developed an aluminium foam with a copper-graphene coating product for thermal dissipation. AIRBUS, in collaboration with CNR and Nanesa, integrated graphene-based heaters in carbon fibre reinforced polymer panels for anti-icing applications in aircrafts.”

WHY THE GRAPHENE FLAGSHIP?

“Concentrated research efforts that involve both academic and industrial institutions provide an important paradigm shift for future research,” said Galiotis. “FORTH evaluated the performance of an integrated commercial graphene/polymer heating system employed for medical applications. The University of Cambridge developed a new masterbatch production technique of polymer/graphene composites with uniform dispersion of flakes by microfluidisation. The University of Cambridge in collaboration with Leonardo, Université Libre de Bruxelles and National Research Council of Italy also developed loop heat pipes for space applications which, when tested in microgravity, showed approximately 1.5 times improvement in vapour production compared to the reference wick.”



Samples from the loop heat pipe tested in zero gravity.
Credit: Meganne Christian

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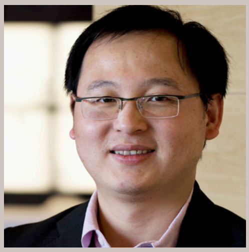
https://www.graphene.cam.ac.uk/news/100-yield-scalable-production-of-conductive-graphene-inks



Work Package Leader:
Xinliang Feng

Work Package Deputy:
Paolo Samori

Functional Foams and Coatings

The Functional Foams and Coatings Work Package is dedicated to the chemical processing and functional applications of graphene and related materials (GRMs) with a focus on nanocomposite thin films, coatings and porous foam structures for environmental applications. Focusing on large scale processing methods, they aim to implement GRMs in applications in flexible electronics, supercapacitors, batteries, fuel cells, photocatalysts, membranes, anticorrosion and desalination/water purification.

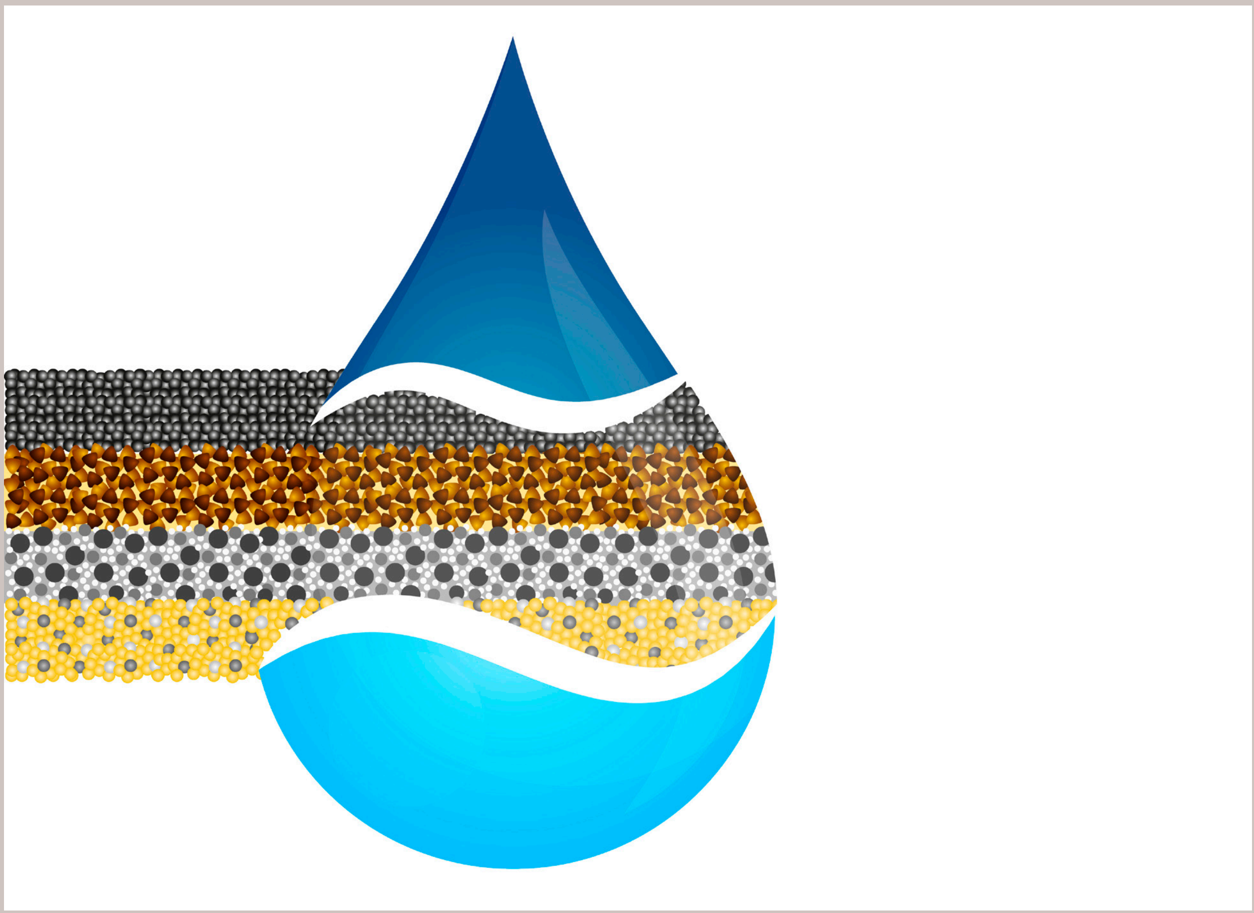
YEAR IN REVIEW

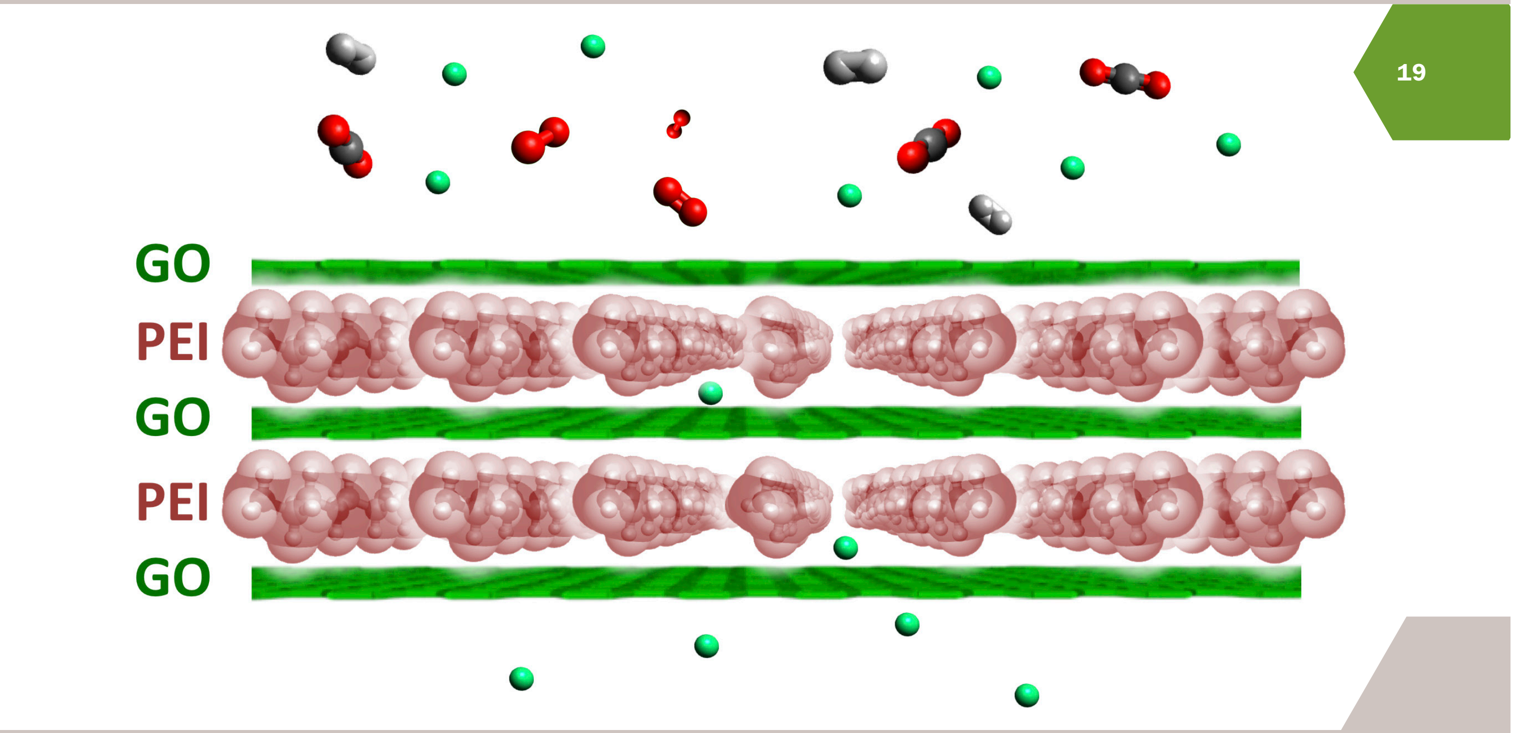
Over the course of the last year, the work package has seen success in key areas, with potential to move forward the goal of GRMs commercialisation:

- The work package developed protocols for scalable production of high quality, chemically functionalised GRMs, including an electrochemical exfoliation method. Functionalised GRMs were further processed into porous structures and coatings for applications including water and air purification and smart coatings.

- For water purification, two strategies were developed to both prepare potable water for human consumption and to produce water for agricultural and industrial applications. The first strategy focussed on the development of filter membranes, based on porous GRMs, able to remove different pollutants, such as heavy metals and organic substances. The second approach addressed the need for an energy efficient and low-

Two strategies have been developed to prepare potable water for human consumption and to produce water for agricultural and industrial applications.





PEI molecules, constrained between graphene oxide nanosheets, can be used for gas separation. Credit: American Chemical Society

> "We have developed a new infiltration technique, with high capacity, to produce aero-graphene with high surface area, ultra-light weight and high conductivity."
>
> **Xinliang Feng**

cost desalination process and used high-capacity deionisation electrodes based on GRMs inks.

- Air purification is another area of focus. To help cut down the air pollutants released into the atmosphere, the work package is looking at how GRMs can be used in clean fuels like hydrogen. They also developed a novel water splitting catalyst for an electrolyser device to efficiently produce clean hydrogen from different water sources (e.g. seawater) and worked on catalysts that can clean the air pollutants using sunlight.

- The development of smart coatings plays an important part in this work package, for graphene-based anticorrosion coating, pressure sensors and wearable devices. The work package is also involved with two Spearhead Projects (SHPs). SHP WearGRAPH focuses on the integration of textile-based wearable devices for energy conversion and storage. SHP CHEMsens focuses on the production of modular, multi-analyte bio-chemical sensing.

LOOKING FORWARD

Over the course of the next year, the Functional Foams and Coatings Work Package will focus on producing up-scaled processes to enable commercialisation. This will include developing a process for 50g/day of functionalised GRMs, establishing a large-scale production route for aero- GRMs materials via infiltration and lab scale production of water splitting catalysts (5g/day) for hydrogen production. There are also plans to achieve purification of water from contaminates using graphene filter membranes (90% organic and heavy metal removal) and desalination of sea-water up to 60% by graphene-based capacitive deionisation. The SHPs will focus on demonstrator development. CHEMsens plans to develop a graphene-based plaster, able to detect biological data on human skin and WearGRAPH a textile-integrated platform demonstrator with energy harvesting and energy storage functionality that will be used to power a wearable application.

"We have developed a new infiltration technique, with high capacity, to produce aero-graphene with high surface area, ultra-light weight and high conductivity. This is a candidate for developing self-cleaning aircraft air-filters, due to its high porosity, low weight and excellent electrical/thermal conductivities," said Xinliang Feng, work package leader from the Technical University of Dresden, Germany. "We also developed many new technologies and products which have wider significance within the Graphene Flagship. These include an anticorrosion coating of stainless-steel plates in bipolar fuel cells (a cross activity with the Energy Generation Work Package) and the development of conductive graphene inks for electronic and energy applications (a cross activity with the Photonics and Optoelectronics and Energy Storage Work Packages."

Work Package Leader:
Vittorio Pellegrini

Work Package Deputy:
Teófilo Rojo

Energy Storage

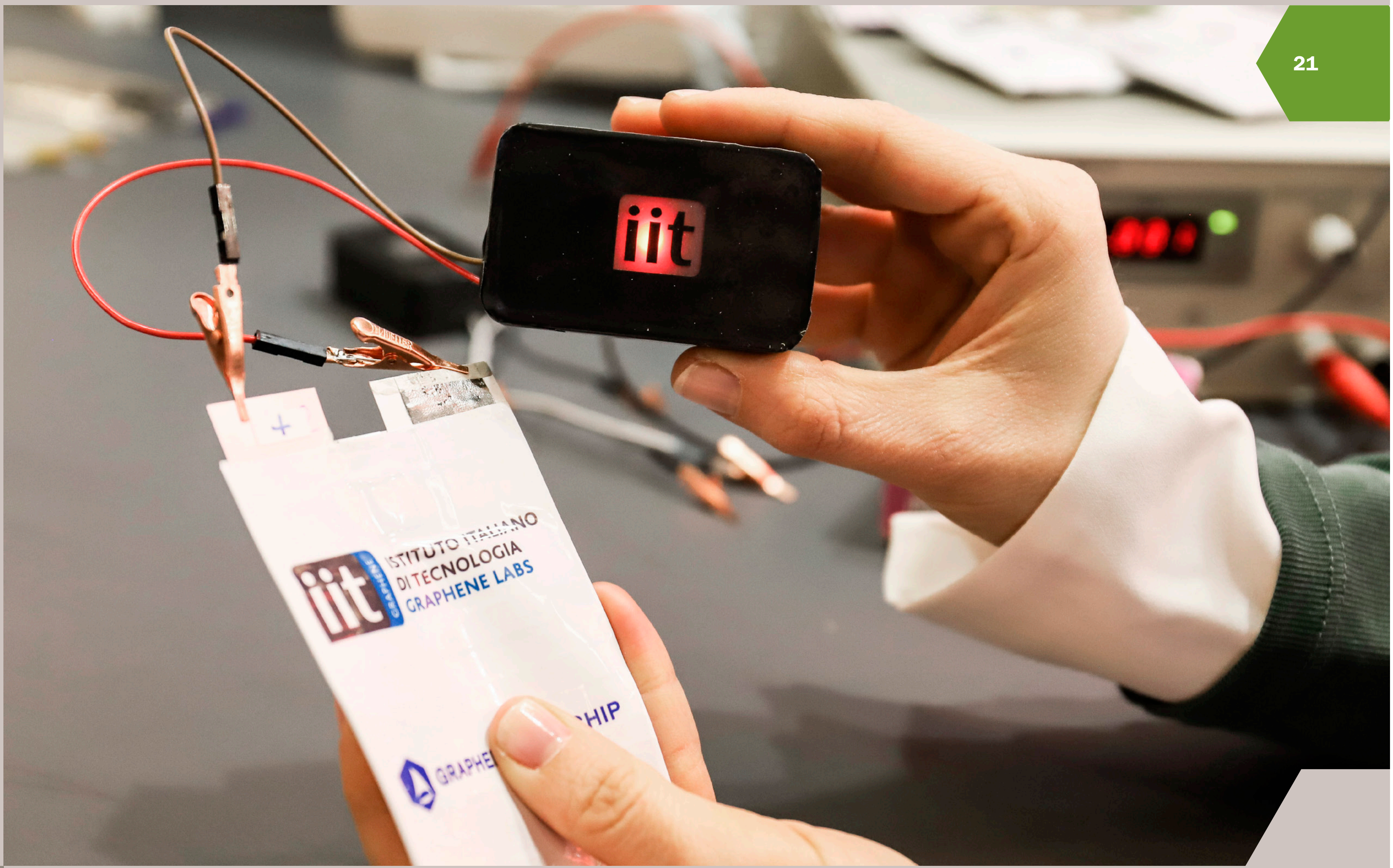
As societal demands for energy increases, so does the need to produce this energy in a renewable manner. The ability to create better energy storage solutions will not only become more important as humans continue to demand more out of their portable electronic devices and electric vehicles, but it will also enable the growing renewable energy market. Graphene and related materials have an excellent opportunity in this ever-growing market, due to their excellent electrical conductivity, mechanical strength and high surface-to-weight ratio. By exploiting these strengths, the Energy Storage Work Package is focused on commercially relevant technologies and materials for batteries, supercapacitors and hydrogen-storage systems.

YEAR IN REVIEW

Over the course of the last year, the work package has developed many new energy storage solutions including silicon-graphene anodes for lithium-ion batteries.

The focus of the work package has always been on industrially relevant energy storage solutions and this year saw the Graphene Flagship partners Thales and M-Solv develop a large-scale spray coating tool capable of meeting the high-volume manufacturing requirements

Thales and M-Solv have developed a large-scale spray coating tool capable of meeting the high-volume manufacturing requirements for high power graphene supercapacitors. Credit: Fernando Gomollón-Bel



Graphene has the potential to greatly increase the energy storage of supercapacitors. Credit: Sophia Lloyd

> "In a field like energy storage, relevant applications require long-lasting research and development activities including optimisations, validations and certifications."
>
> **Vittorio Pellegrini**

for high power graphene supercapacitors. Graphene has the potential to greatly increase the energy storage of supercapacitors as it can be used to increase the active surface area of the electrodes and therefore enable it to store more electrostatic charge. By incorporating graphene into supercapacitors, Thales significantly increased the storage potential of supercapacitor devices. Thales also developed a spray coating technique to deposit the graphene electrode onto a variety of substrates, allowing them to develop a fully flexible device. Thales then collaborated with M-Solv (leaders in developing tools for deposition) to scale up their spray coating technique. They developed a tool able to produce the supercapacitors with a high degree of reproducibility due to inline, real-time characterisation techniques developed for the tool.

LOOKING FORWARD

Over the next year the work package is looking to demonstrate lithium-ion batteries with graphene and silicon anodes created with techniques that are more industrially relevant. Also planned is the continuation of the work on the spray coating to produce a roll-to-roll machine for supercapacitor electrode deposition.

Vittorio Pellegrini, work package leader from IIT Graphene Labs, Istituto Italiano di Tecnologia, Italy commented. "Our work package continues to strive towards production relevant applications in a real industrial environment in the field of energy storage. This will have an important impact on European companies such as Thales, BMW, VARTA, Fiat and help to stimulate the need of high-quality graphene production currently being commercialised by the Graphene Flagship's spin-off companies."

WHY THE GRAPHENE FLAGSHIP?

"In a field like energy storage, relevant applications require long-lasting research and development activities including optimisations, validations and certifications. A large-scale funding model is an ideal opportunity compatible with the long time-to-market of these technologies," commented Pellegrini.

Work Package Leader:
Gérard Gebel

Work Package Deputy:
Emmanuel Kymakis

Energy Generation

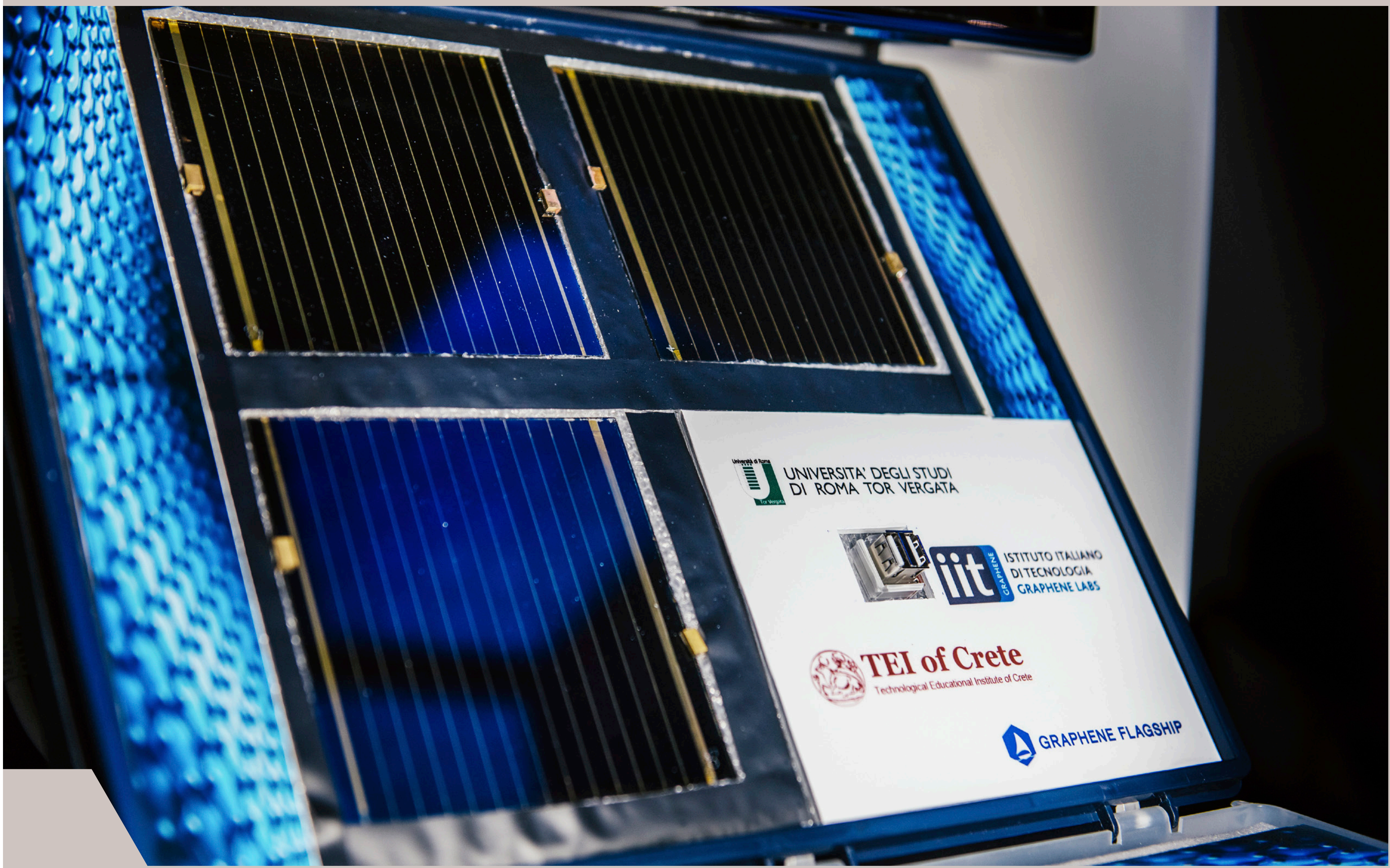
As the world moves to a more connected, digitally-driven future, the demand for electrical power will continue to increase. Not only does the world need to produce more power, but it needs to do so in a sustainable and environmentally sound manner. The Energy Generation Work Package focuses on using graphene and related materials (GRMs) to create world-leading solar and fuel cells that can be used in an industrial environment.

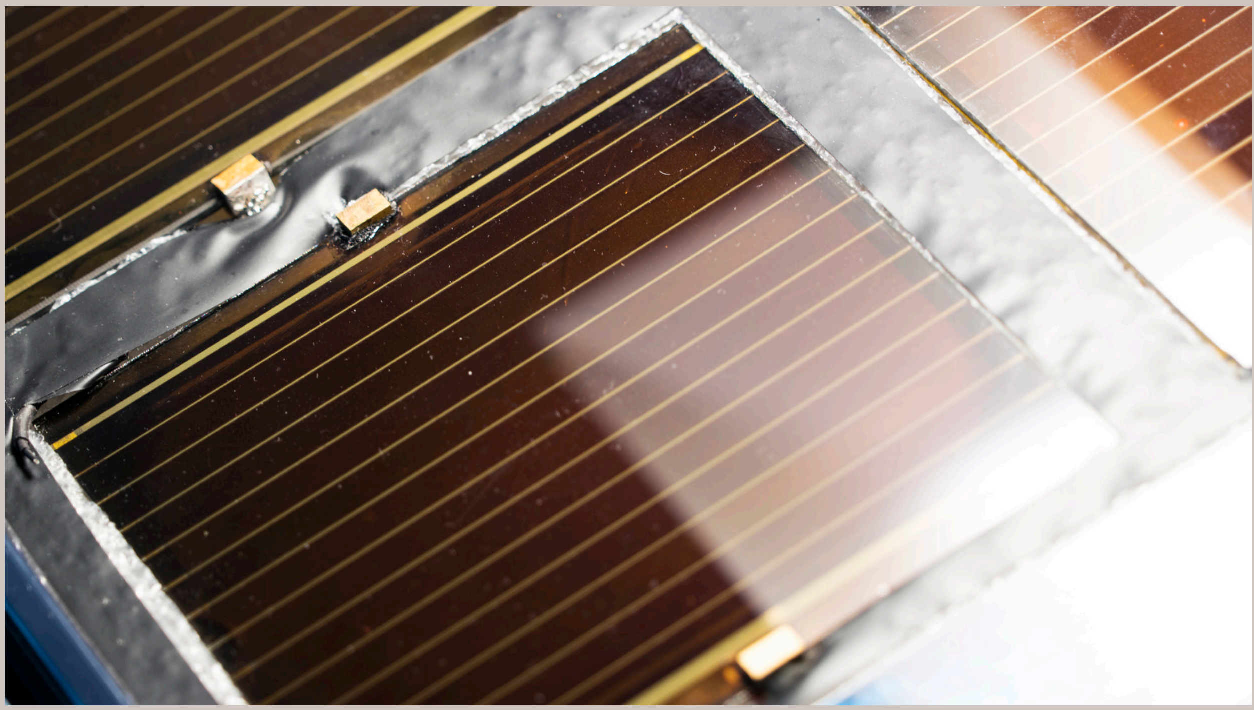
YEAR IN REVIEW

Over the last year, the Energy Generation Work Package produced efficient solar cells with a demonstrated manufacturing technique. Large-area perovskite solar cells have been produced with high performance and operational stability. To improve the triangle of efficiency, stability and cost for these solar cells the Graphene Interface Engineering (GIE) laboratory achieved high throughput fabrication via automated spray coating. GIE also developed a method to formulate GRMs with tailored properties.

"GIE achieved three world records: mesoscopic perovskite solar cells with efficiency over 20%, inverted perovskite solar cells with efficiency around 17% and the most efficient perovskite solar module was produced

Graphene and related materials boost the stability and efficiency of solar cells. Credit: Alexandra Csuport





Creating large area perovskite solar cells with high power efficiency and long lifetime is possible thanks to graphene.
Credit: Johan Bodell/Chalmers

> By bringing together researchers from different disciplines, the Graphene Flagship creates an unprecedented level of collaboration and community building in Europe."
>
> **Gérard Gebel**

within a collaboration between UTV, IIT and TEIC, presented at the Mobile World Congress," said Gérard Gebel, work package leader from French Alternative Energies and Atomic Energy Commission (CEA), France. "These achievements, coupled with the upscaling of GRMs ink production and deposition, may have a significant impact on the commercialisation of perovskite photovoltaics".

GIE also demonstrated that MoS_2 quantum dots, anchored to the functional site of reduced graphene oxide in perovskite solar cells can homogenise the deposition of charge transport layers onto the perovskite active layer and increase the efficiency.

Over the last year, developments in fuel cell technology have also emerged. New GRMs based on low platinum content electrocatalysts (ECs) have been developed and patented. The synthesis of these ECs was upscaled and transferred to partners to produce large-scale membrane electrode assemblies. New anticorrosion coatings on the metallic support of bipolar plates were developed and tested in terms of conductivity and lifetime.

LOOKING FORWARD

Moving forward, the plan is to use the work package's key technology base to continue on an industrialisation path. There are plans to establish a pilot production line to demonstrate GRMs-based photovoltaic modules (>200 cm^2) with efficiency >14% and a long-term operational lifetime. These large area modules will be assembled in solar panels and integrated into a solar farm, which will allow performance monitoring under real operational conditions in order to provide a realistic forecast of their lifetime, while at the same time identifying and tackling potential environmental risks.

The main objective of the fuel cell work is to upscale the electrocatalysts and large area membrane electrode assembly to produce a stack of few kWs (>5 kW). GRMs-based anticorrosion coatings in actual fuel cell systems will also be prepared and tested.

WHY THE GRAPHENE FLAGSHIP?

"To achieve our ambitious objectives and technology development targets, the large-scale collaboration seen in the Graphene Flagship mobilises synergies and establishes collaboration across various partnering organisations. By bringing together researchers from different disciplines, the Flagship creates an unprecedented level of collaboration and community building in Europe. Through its long duration, the Graphene Flagship enables the participating research groups to build up expertise and create durable links," commented Gebel.

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Spearheads

The Spearhead initiative was introduced in 2017 with the second core project. The Spearheads are market-motivated, industry-led targeted sub-projects that aim at creating prototypes (technology readiness level 6 or above) in areas where graphene-related technologies have an edge over competing approaches. In the third core project, the spearhead program will be expanded to comprise about 30% of the Graphene Flagship's funding from the European Commission.

"This is a bold move that shows our firm commitment to maximising the impact of the Graphene Flagship," says Graphene Flagship Director Jari Kinaret. "During Core 2, six spearhead projects are pursuing goals related to energy generation and storage, optoelectronics, and flexible and wearable electronics. In Core 3 we expect to have ten spearheads covering automotive, aerospace, energy and photonic applications."

PRINTABLE SENSORS INTEGRATED WITH RFID ANTENNA

This spearhead aims to create a platform to manufacture sensors of various physical parameters linked with RFID antennas. The platform will be built by combining different 2D materials into heterostructures operating as sensors (strain, humidity, light, etc.) and by making remotely readable radiation detectors. For easier scalability, the sensors/detectors could be printed or deposited into laminates in a sequential process with printing/depositing graphene antennas.

TECHNOLOGY OF SILICON GRAPHENE LITHIUM-ION BATTERIES FOR LARGE SCALE PRODUCTION

The main goal of this spearhead is to advance in pre-industrial production of silicon/graphene composites and their subsequent processing into lithium-ion batteries for high-energy and high-power applications, which can be disruptive for the current generation of accumulators.

Graphene antennas present interesting possibities. Credit: Alexandra Csuport

> This is a bold move that shows our firm commitment to maximising the impact of the Graphene Flagship."
>
> **Jari Kinaret**

In the first six months of the project, the partners successfully proceeded in material upscaling and are now able to produce quantities in the range of >100 grams of silicon/ graphene composite per week. Electrode development of this material is ongoing, first results are very promising (220 full cycles, ~390 Wh/L) and almost achieved the interim targets. The next steps will include further upscaling of all relevant process steps, like electrode fabrication on semi-automatic equipment.

MULTIFUNCTIONAL PLASTER SENSOR FOR HUMAN SKIN, BASED ON FUNCTIONALIZED GRAPHENE

The goal of this spearhead is to develop a modular, multi-analyte sensor platform based on graphene and related materials to enable sensitive and reliable (bio)chemical sensors for health monitoring. The activity within the spearhead has already led to the development of a pressure sensor for health monitoring. In particular, the controlled functionalization of graphene with soft and compressible molecules yielded the fabrication of a highly-sensitive pressure sensor for the efficient detection of heart beats. This result was published in Advanced Materials, 2019, 31, 1804600.

GRAPHENE-PHOTONICS INTEGRATED CIRCUITS FOR THE 5G ERA

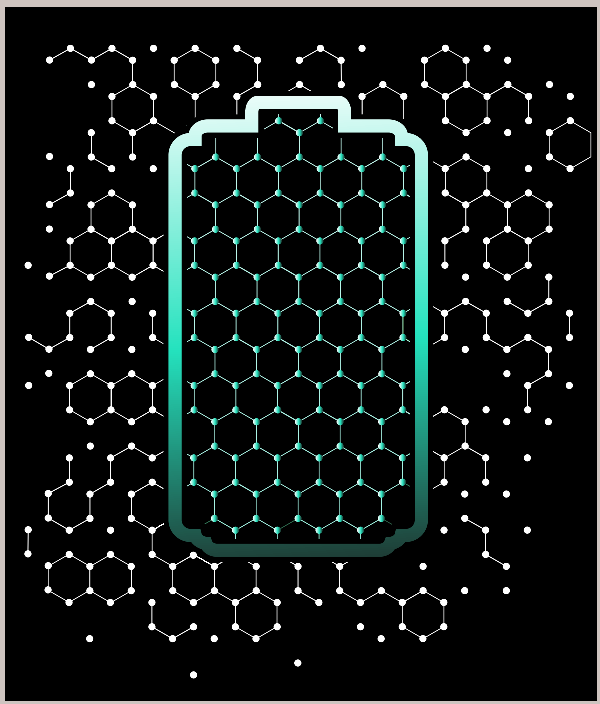
This spearhead project targets the development of a fully integrated transceiver, where graphene, Si photonics and high-speed electronics are integrated and validated in a real transmission system. This product prototype is crucial to validating the spearhead's performance and for the demonstration of a versatile, low-power consumption, high-speed data/tele-communication system with relevant cost reduction.

SELF-POWERED GRAPHENE-BASED TEXTILE FOR WEARABLE ELECTRONICS

The goal of this spearhead is to produce self-powered graphene-based textile for wearable devices for energy generation and storage based on graphene and related materials. In particular, we will develop a multifunctional, wearable device combining graphene-based solar cell, triboelectric nanogenerator and supercapacitor. Wearable electronics can guarantee a series of benefits and advanced features towards healthcare and medical to fitness and wellness, infotainment and more. This spearhead will develop graphene-based self-powered systems for wearable electronics up to a pre-industrialisation stage.

GRAPHENE-PEROVSKITE SOLAR FARM

This spearhead targets the development of graphene-perovskite photovoltaics up to TRL 6, underpinning the future industrialisation of this emerging technology.
A batch pilot production line will be designed via solution processes, of both opaque and semi-transparent G-PE panels. GRMs will be used for graphene interface engineering as well as for contacts, replacing gold, which is expensive and can induce fast cell degradation. Opaque panels will be used as stand-alone PV devices for power plants. Semi-transparent modules will be considered for both building integrated PVs and as retrofitting of conventional Si based PV (four terminal tandem configuration). This project will bring the manufacturing readiness level of G-PE modules from MRL 3 to 6. G-PE panels will be then used for a field test by constructing a 1 kWp 10 m^2 solar farm in the island of Crete, a site that combines favourable climate conditions and very high solar irradiation. Energy production will also be compared with other PV technologies. Thus, the main objective of the SP will be the realisation of the first solar farm with graphene-perovskite panels fabricated with a batch pilot line.
Energy production will also be compared with other PV technologies.



Work Package Leader:
Marco Romagnoli

Work Package Deputy:
Cedric Huyghebaert

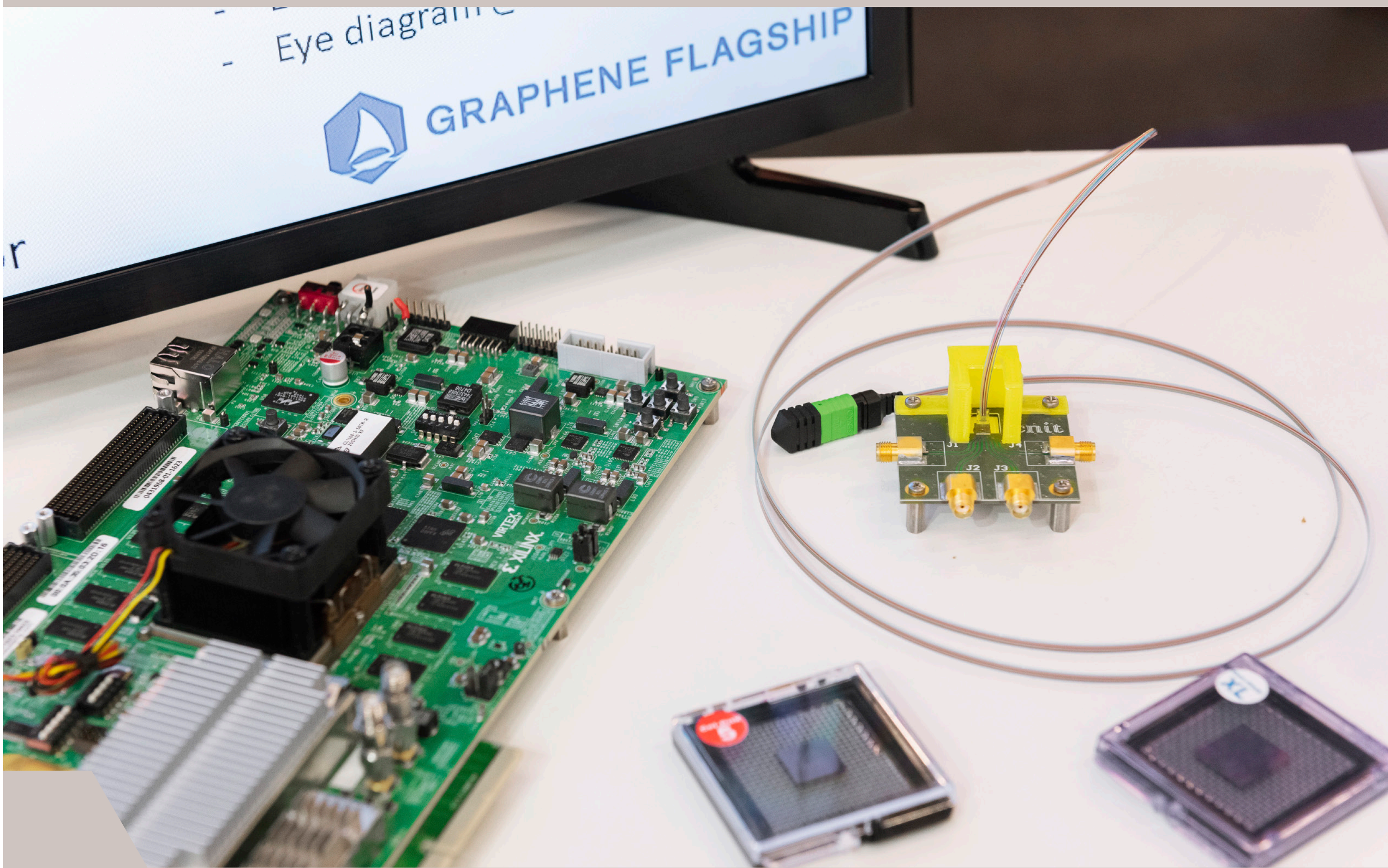
Wafer-Scale System Integration

Wafer-scale system integration of graphene and related materials (GRMs) with silicon-based electronics is crucial to enabling a wide range of applications in photonics, optoelectronics and high frequency electronics. The Graphene Flagship has developed a wide range of devices that will only see real industry uptake when their production can be reliably and reproducibly completed at the wafer-scale. It is then that we will see these innovations in real consumer electronics.

YEAR IN REVIEW

Over the course of the last year, there has been a focus on the transfer of graphene to silicon-wafers and wafer-scale processes to fabricate graphene-based devices. This includes the continued development of a tool for graphene transfer onto wafers (from 100 to 300 mm). Demonstrations of photonic integrated devices as modulators and/or detectors which illustrate the preservation of electron mobility upon the integration processes have been created. To further this development and enable this process to be used in a manufacturing plant, a tool based on THz absorption was developed to measure

Wafer-scale system integration of graphene with silicon-based electronics is crucial to enabling a wide range of applications. Credit: Alexandra Csuport



> Only a large-scale partnership provides an ecosystem able to respond to many questions arising during technology developments."
>
> **Marco Romagnoli**

mobility on wafer-scale and for on line diagnostics of process quality.

"Developed within the Wafer-Scale System Integration Work Package, the THz absorption tool to map, at the wafer-scale, the carrier mobility of graphene is an important and innovative achievement," said Marco Romagnoli, work package leader from CNIT, Italy. "All of the innovations developed are intended for wafer-scale production of graphene-based devices to be incorporated into consumer electronics."

LOOKING FORWARD

Over the next year, the work packages goals centre around:

- Integration of wafer-scale graphene growth and transfer onto an automated cluster tool. The aim is to remove particulate contamination, a common source of defects and variability, which will result in improved quality and consistency of the material and device performance.

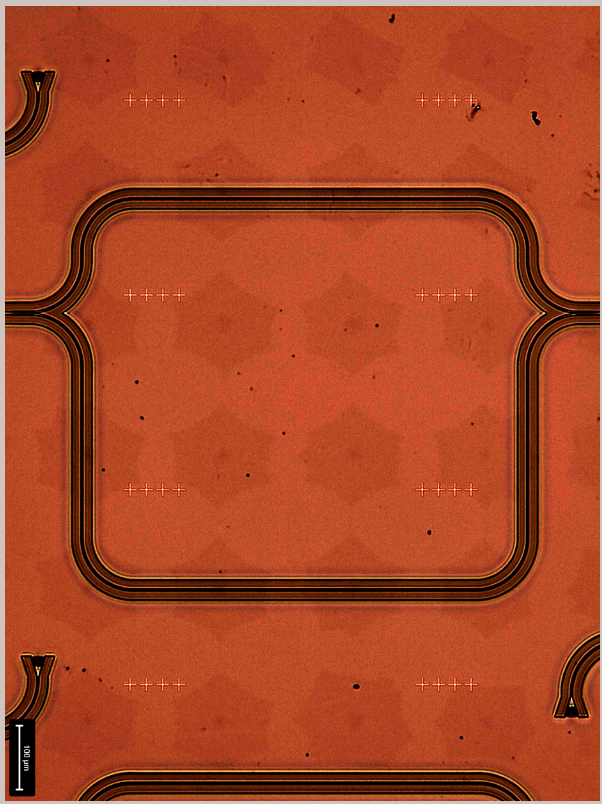
- Quality monitoring by THz measurements, further developments will include the integration of the fabrication process flow for graphene devices.

- Fine-tuning high-quality growth and transfer of suitable encapsulant/encapsulants for specific applications. This activity will be scaled in combination with higher mobility graphene up to 200 or 300 mm wafers.

- Developing single crystal matrix growth and transfer based on stamping, aiming to achieve high mobility after transfer and no degradation after encapsulation with a dielectric.

WHY THE GRAPHENE FLAGSHIP?

"The large scale of the Graphene Flagship is of extreme importance for the success of this work package because only a large-scale partnership provides an ecosystem able to respond to many questions arising during technology developments," said Romagnoli.



Graphene arrays on photonic waveguides. Credit: Vaidotas Miseikis

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Press release: "IMEC reports for the first time direct growth of 2D materials on 300 mm wafers… Imec is the first to demonstrate a full 300 mm monolayer 2D material transfer" at International Electron Devices Meeting (IEDM) 2018

Stamping of arrayed graphene crystals on silicon photonics circuits

Work Package Leader:
Henrik Sandberg

Work Package Deputy:
Matteo Bruna

Flexible Electronics

As market interest in flexible electronics continues to increase, the potential of graphene and related materials (GRMs) to enable new applications continues to grow. Their excellent electrical and mechanical properties make GRMs ideal for flexible electronics. The Flexible Electronics Work Package targets not only technologies for flexible devices, but also efficient manufacturing processes that will enable their large-scale adoption.

YEAR IN REVIEW

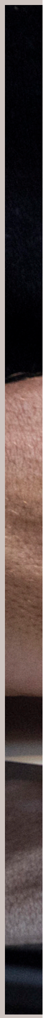
Over the last year there have been exciting results that show real progress in the field of flexible electronics device creation and manufacturing:

- Electronics modules to interface with distributed sensors (including motion, pressure and physical parameters) whilst also developing deposition and patterning techniques for conductors onto textiles and other stretchable material have been developed.
- A curved (thermoformed) high performance touch interface, based on CVD graphene and polycarbonate, was developed for automotive dashboards. A low-cost paper display with capacitive input sensors using electroluminescent technology was created and implemented into a game board prototype.
- GRMs dispersions were developed along with the processing parameters for various substrates and patterns enabling printing onto elastomers and textiles. Methods that combine printing and CVD graphene in device manufacture and basic devices were also developed.
- Flexible X-ray detector arrays with an OTFT back plane, a graphene/quantum dot photodetector and a scintillator film were defined and tested.
- Low noise, high gain flexible amplifiers were developed and whilst optimising MoS_2 growth, transfer and processing, suitable transition metal dichalcogenides and thin film transistors were also developed, defining the energy solutions for such systems.

LOOKING FORWAD

Looking ahead to the next year, the work package targets autonomous wearable devices to measure and analyse the vital signs of the human body. This will include a user interface based on display elements and touch sensitive surfaces and also formability/mouldability of this approach. The work in the automotive industry will continue with the creation of mouldable printed flexible layers for touch sensitive panels in an automotive dashboard using GRMs. The materials processing needed for the paper display will continue to be developed, while a prototype for the flexible X-ray detector array will be demonstrated.

Graphene is well suited to printing conductive tracks and areas onto flexible surfaces, such as plastic sheets, paper or fabrics. This shirt integrates graphene-based, electrically conductive areas that function as capacitive touch sensitive electrodes. Credit: Alexandra Csuport



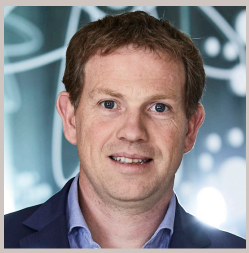
This wearable epidermal sensor grid can be used as the basis for a wide variety of wearable autonomous devices. Credit: Johan Bodell/Chalmers

> “Prototypes of flexible devices created and displayed at a variety of public events have been successful in raising awareness of the capabilities of GRMs for flexible electronics.”
>
> **Henrik Sandberg**

Henrik Sandberg, work package leader from VTT Technical Research Centre of Finland Ltd., commented on the prototypes and demonstrations developed: “Prototypes which show examples of flexible electronic devices have been created and displayed at a variety of public events including Mobile World Congress. These demos, including sensor matrices and shoe insoles, paper based interactive boards and wireless devices such as RFID and NFC devices, have been successful in raising awareness of the capabilities of GRMs for flexible devices.”

WHY THE GRAPHENE FLAGSHIP?

“The solution processing technology developed has already been useful in many other Work Packages within the Graphene Flagship,” said Sandberg. “The large scale of the Flagship consortium has offered us an unprecedented opportunity to interact with a very large network. The long time frame for the collaborations have been important and productive for the continued development of flexible devices.”



Work Package Leader:
Frank Koppens

Work Package Deputy:
Andrea C. Ferrari

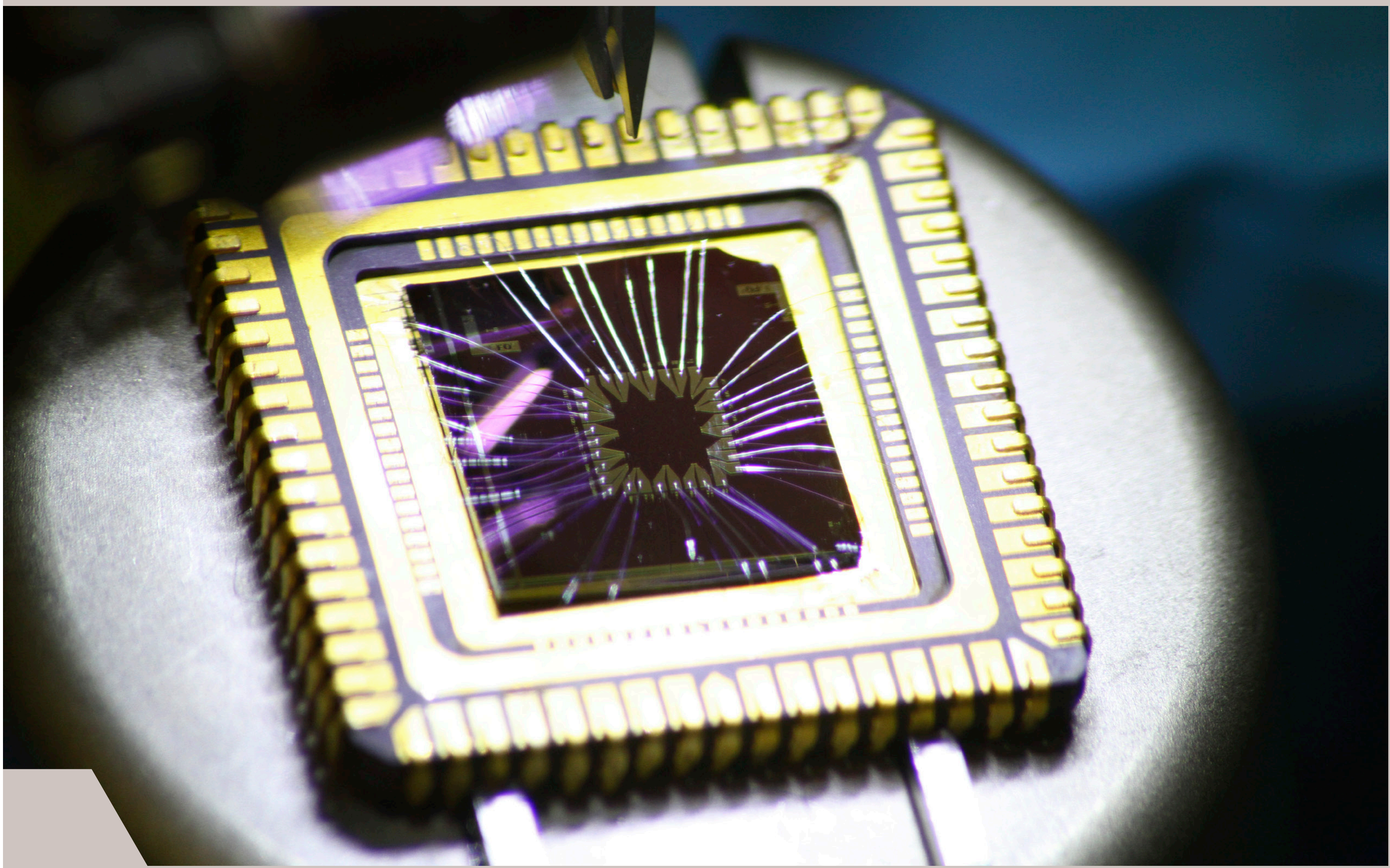
Photonics and Optoelectronics

The manipulation, detection and control of light is at the heart of our communications network. The goal of the Photonics and Optoelectronics Work Package is to develop graphene and related materials (GRMs) based components for photonic and optoelectronic applications and to integrate them into photonic circuits, imaging arrays and optical sensors. The generation of graphene-based devices to send and receive optical data can enable ultra-wide bandwidth communications coupled with low power consumption, with potential to surpass the needs of 5G, Internet of Things (IoT) and Industry 4.0. Graphene photonics offers advantages in both performance and manufacturing over the state-of-the-art. Graphene can ensure modulation, detection and switching performances meeting all the requirements for the next evolution in photonic device manufacturing

YEAR IN REVIEW

With a focus on the creation of fast, ultra-wide bandwidth communication technologies, the work package demonstrated the fastest, silicon waveguide integrated photodetectors with a bandwidth >128 GHz for ultrafast optical communication. Importantly for its commercialisation potential, the photodetectors are based on graphene grown by chemical vapour deposition which is compatible with wafer scale production methods.

An array of infrared photodetectors. Credit: Koppens group, ICFO



> Several start-up companies have already been created based on technology from our work package, the Graphene Flagship structure is the ideal opportunity to overcome the valley of death for high-level applications."

Frank Koppens

The researchers were also able to record a high bandwidth of 180 Gb/s.

The Photonics and Optoelectronics Work Package, in collaboration with the Wafer-Scale System Integration Work Package, developed a vision for the future of graphene-based integrated photonics, with strategies for improving power consumption, manufacturability and wafer-scale integration in a paper published in Nature Review Materials. This provides a roadmap for graphene-based photonics devices surpassing the technological requirement for the evolution of datacom and telecom markets driven by 5G, IoT and Industry 4.0.

The work package also developed a room-temperature terahertz detector with record high detectability and speed. The detection of light at terahertz frequencies is important for a large range of applications such as medicine, security, quality testing and chemical spectroscopy. Crucially, this graphene-based detector fulfils the current lack of room-temperature detectors that are simultaneously sensitive and fast.

LOOKING FORWARD

Over the course of the next year, the work package will develop a CMOS-integrated array of terahertz detectors and demonstrate a scalable graphene photonic integrated circuit for the 5G era that will permit selectable modulation formats for both datacom and telecom applications. They are targeting data rates up 672 Gbit/s on a single fiber.

With the push towards higher technology readiness levels, Frank Koppens, work package leader from ICFO, Spain, commented, "We have a very strong innovation potential. Photonics and optoelectronics technologies have unique advantages compared to existing technologies and the demand from the market is clear. Every component in this work package is benchmarked with existing technologies. Graphene and related materials optoelectronics integrated with Si-CMOS builds on well-developed technology and shows a clear competitive advantage to non-Si semi-conductors that are not easily integrated with Si-CMOS."

Andrea C. Ferrari, work package deputy leader from the University of Cambridge, UK, added, "This work package continues to deliver state-of-the-art results in all key branches of photonics and optoelectronics. This validates the huge potential of GRMs in this area. The following year will be crucial to meet industrially relevant targets, which could propel several work package technologies towards applications. In particular, our focus on the use of scalable approaches, and the close collaboration with other work packages, are the key elements underpinning the strength of our developments."

WHY THE GRAPHENE FLAGSHIP?

"Several start-up companies have already been created based on technology from our work package and more will follow. The Graphene Flagship structure is the ideal opportunity to overcome the valley of death for these high-level applications. Its well-coordinated efforts towards joint goals is a unique opportunity to bring high-level devices to the market," said Koppens. "Having set the work package goals to solve concrete problems, identified by end-users, associated members and industrial partners, has been crucial to our success."

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Work Package Leader:
Daniel Neumaier

Work Package Deputy:
Herbert Zirath

Electronic Devices

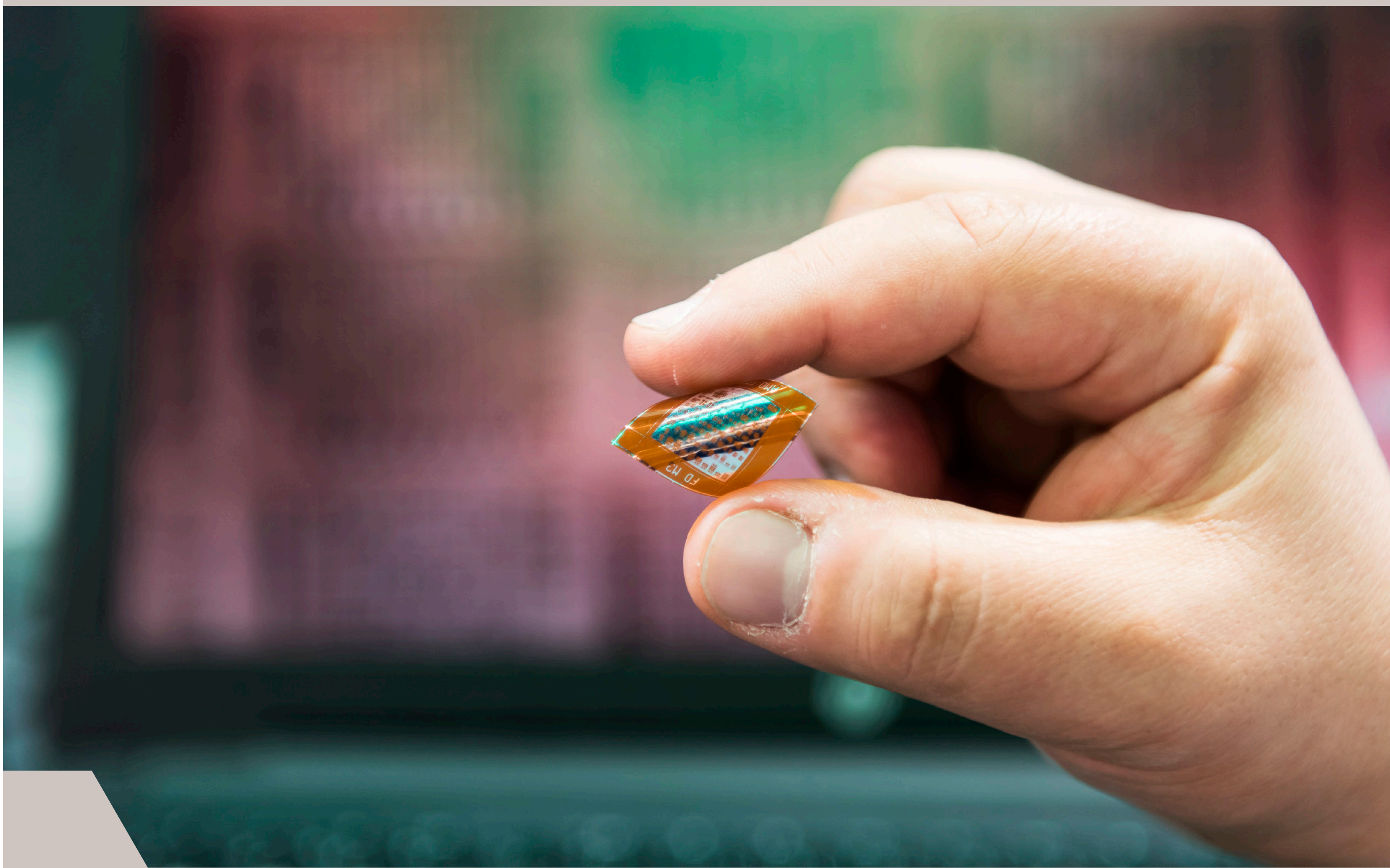
The Graphene Flagship Electronic Devices Work Package has one unifying aim: to turn the unique properties of graphene and related materials (GRMs) into high performance electronic devices that can significantly outperform state-of-the-art technologies. This will enable new and innovative technology solutions for future wireless communication, data processing, 5G, Internet of Things, low power electronics and sensor systems.

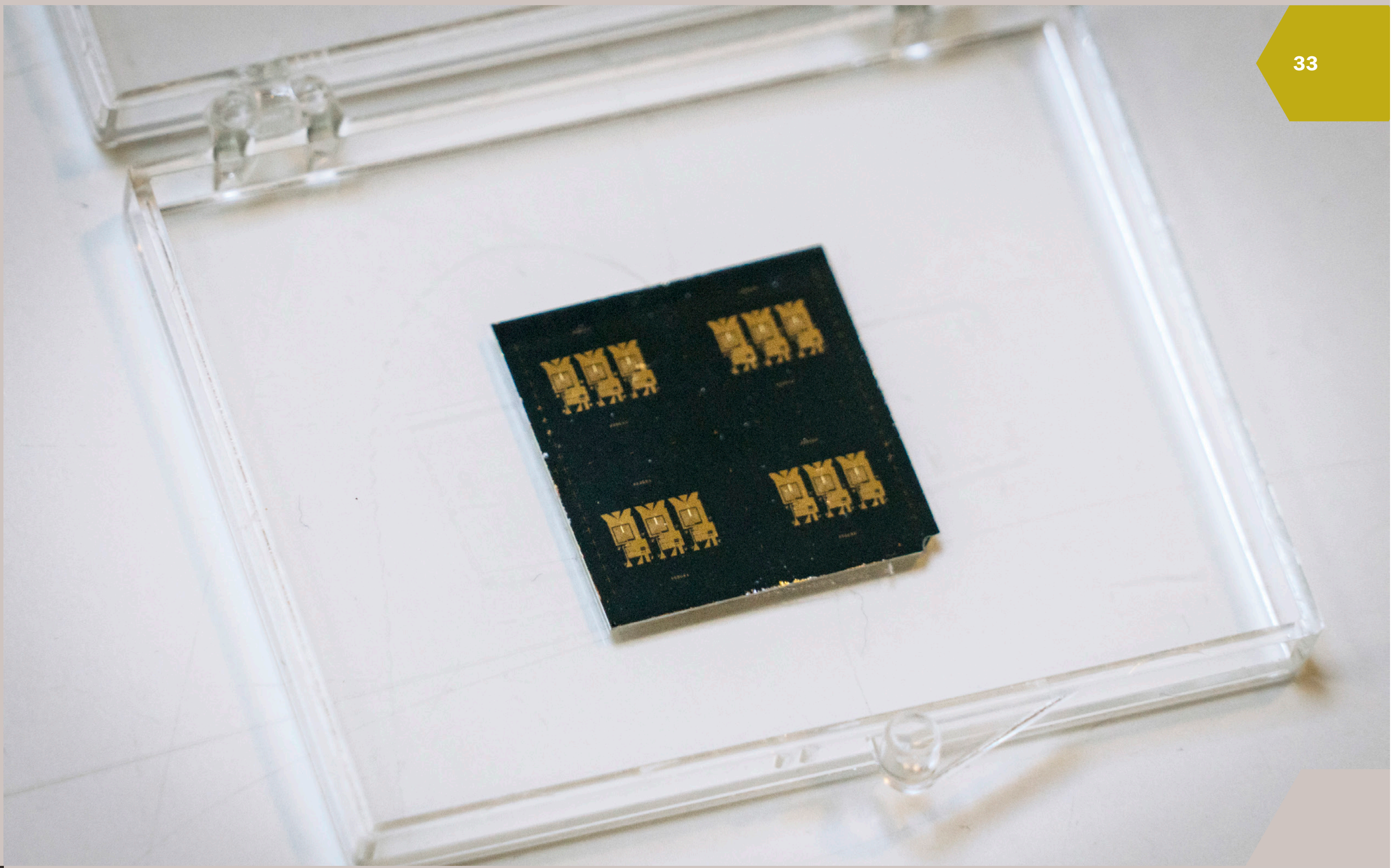
YEAR IN REVIEW

Over the last year there has been a focus on two key areas: the exploration of the intrinsic limits of graphene-based electronic devices, and the demonstration of key building blocks for wireless communication. A key result of the first domain was the demonstration of hyperbolic phonon cooling in devices. In order to achieve this key result, using the highest quality graphene was of optimum importance, something made possible due to collaborations within the Graphene Flagship. Success in demonstrating this has important implications in radio-frequency electronics.

In the second domain, there has been a realisation of an integrated circuit for up-conversion mixing in the 6–12 GHz band, which is a key operation for wireless communication. Also produced was one of the first demon-

Flexible chips will usher in a new era of flexible electronics. Credit: Alexandra Csuport





A 200 GHz graphene mixer and IF amplifier. Credit: Johan Bodell/Chalmers

> We provide an important contribution to the technology required in many work packages working with electronic devices, such as sensors, photodetectors and flexible devices."
>
> **Daniel Neumaier**

strators for more complex integrated circuits, showing performance on par with the state-of-the-art technology. As society faces an unprecedented expansion of connectivity and communications, the Electronic Devices Work Package is constantly looking for ways in which GRMs can meet the demands of an ever-changing electronics landscape.

LOOKING FORWARD

Over the next year, the work package is targeting the completion of a WiFi communications receiver operating at 90 GHz along with a flexible logic for sensor readouts. Significant progress is also planned on process technology for transition metal dichalcogenide-based logic devices that will involve better control and reproducibility of critical device parameters.

WHY THE GRAPHENE FLAGSHIP?

"We provide an important contribution to the technology required in many work packages working with electronic devices, such as sensors, photodetectors and flexible devices," says Daniel Neumaier, work package leader from AMO GmbH, Germany, on collaborations within the Graphene Flagship. "We have been able to work together to provide solutions for electric contacts, interfaces and encapsulation. The interaction with other work packages on these issues is highly efficient and is an important part of working inside the Graphene Flagship. The large environment of the Flagship ensures that all aspects of research are covered, and the outcome of the research can be utilised by as many other researchers as possible."

Work Package Leader:
Peter Steeneken

Work Package Deputy:
Sanna Arpiainen

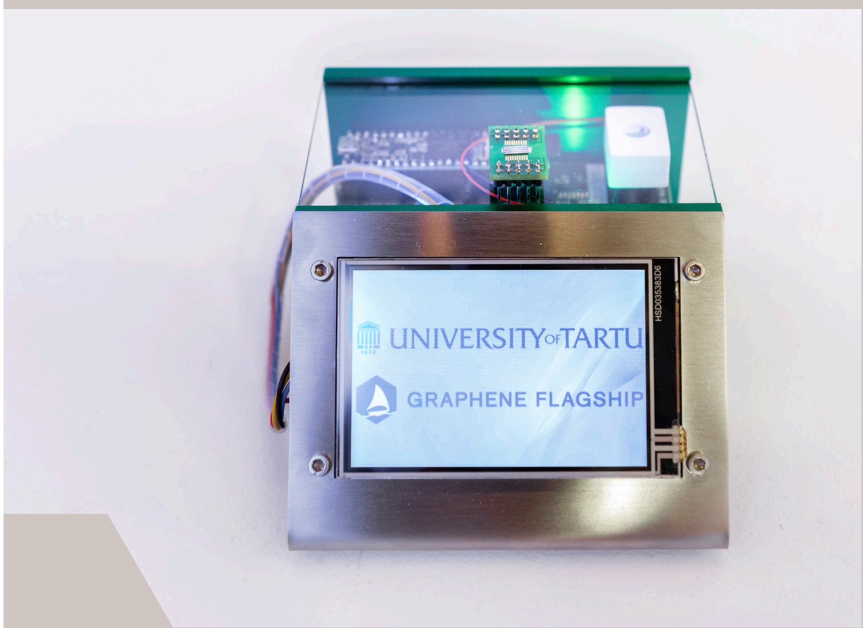
Sensors

Graphene is highly sensitive to its environment, making it an ideal material for sensing applications. As we move towards a data driven future, sensors will play an increasingly important part in all of our lives. They will provide the backbone for the Internet of Things, providing the information for both environment and health monitoring, whilst also enabling further automation by sensing everything from gasses and biomolecules to pressure and radiation.

YEAR IN REVIEW

Over the course of the last year, the Sensors Work Package developed new types of sensing technologies. This includes a fast and reliable point-of-care biodiagnostic graphene biosensor platform which analyses serum and blood samples for cardiac markers of coronary thrombosis that requires instant hospital care. This sensing platform, made with a collaboration between VTT and Prognomics, could be used in ambulances to differentiate heart attacks from less severe heart pain. VTT also demonstrated a proof-of-concept for oriented single-step functionalisation of graphene with antibody fragments; and ICN2 developed a lateral flow, paper-based biosensor using graphene quantum dots for signal amplification with high stability and quantum yield.

A single module air pollution detector with four functionalised graphene gas sensors. Credit: Alexandra Csuport



With a focus on sensing at scale, scientists demonstrated wafer level processing of graphene biosensors with high yield and stability. Methods were also developed to scale up the fabrication of graphene-based plasmonic sensing technology using large scale nano-imprint lithography. A new technique for direct patterning and transfer of graphene to almost any substrate (PET, paper, nitrocellulose, glass, fabric, silicon, skin, etc.) was developed, with several advantages (higher electrical signal, one step functionalisation) compared with classic carbon screen-printed electrodes.

This work package also developed a number of high-end technology demonstrators, showing the graphene and related material (GRMs) potential for sensing applications, including:

- A single module air pollution detector with four functionalised graphene gas sensors.
- A battery-powered capacitive pressure sensor consisting of 10,000 membranes in parallel reached a sensitivity outperforming state-of-the-art sensors.
- A piezoresistive pressure sensor with record gauge factor using the transition metal dichalcogenide $PtSe_2$.
- A demonstrator for biosensing of cardiac markers at the point-of-care using functionalised graphene.

LOOKING FORWARD

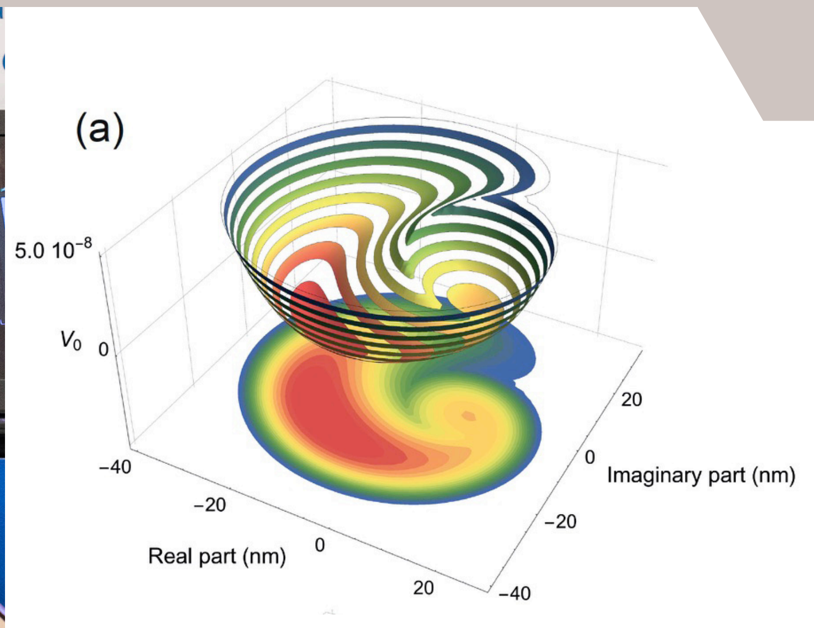
Over the course of the next year the work package will strive to increase the technology readiness level of all of its most prominent developments. This will include raising sensitivity and selectivity of the gas, bio and physical sensors. In addition, studies will take place to enable the sensors to be fully integrated with CMOS electronics. A multiplexed biosensor matrix with monolithic CMOS readout will be developed and will allow a dramatic increase in statistics in bioanalysis and the development of full bioassay on a single chip.

Optimised hybrid graphene-metal graphene-based plasmonic sensing technology surfaces which operate in reflection/total internal reflection will be devised and fabricated. These will enable direct bio-functionalisation in a liquid environment and integration with microfluidic channels for quantitative biomarker detection.

“The industrialisation of graphene components will be advanced by the CMOS integration of the sensor matrices, showing the compatibility and stability of graphene

> The industrialisation of graphene components will be advanced by the CMOS integration of the sensor matrices, showing the compatibility and stability of graphene sensors in industrial sensing platforms.”
>
> **Peter Steeneken**

A battery-powered capacitive pressure sensor consisting of 10,000 membranes. Credit: Alexandra Csuport



Simulation of the nonlinear dynamics of a graphene mechanical resonator. Credits: Pierpaolo Belardinelli and Farbod Alijani, TU Delft

sensors in industrial sensing platforms,” commented Peter Steeneken, work package leader from Technische Universiteit Delft (TuDelft), The Netherlands. The industrial adaptation of graphene biosensors relies on the demonstration of the high sensitivity and specificity in real sample matrices. Engineering of bioreceptors enables the optimisation of the biosensor performance.”

WHY THE GRAPHENE FLAGSHIP?

“Large projects enable efficient technology exchange and collaboration between different players in the European graphene community,” Steeneken commented. “We have good links to other work packages and Associated Members/Partnering Projects, which help to extend our knowledge beyond the borders of the Graphene Flagship. The synergy, knowledge sharing and long-term funding in the Flagship is very important for the continuity of our project. Building on the vast knowledge base that has been created during the last years in the Graphene Flagship clearly accelerates our output.”

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Work Package Leader:
Kostas Kostarelos

Work Package Deputy:
Jose A. Garrido

Biomedical Technologies

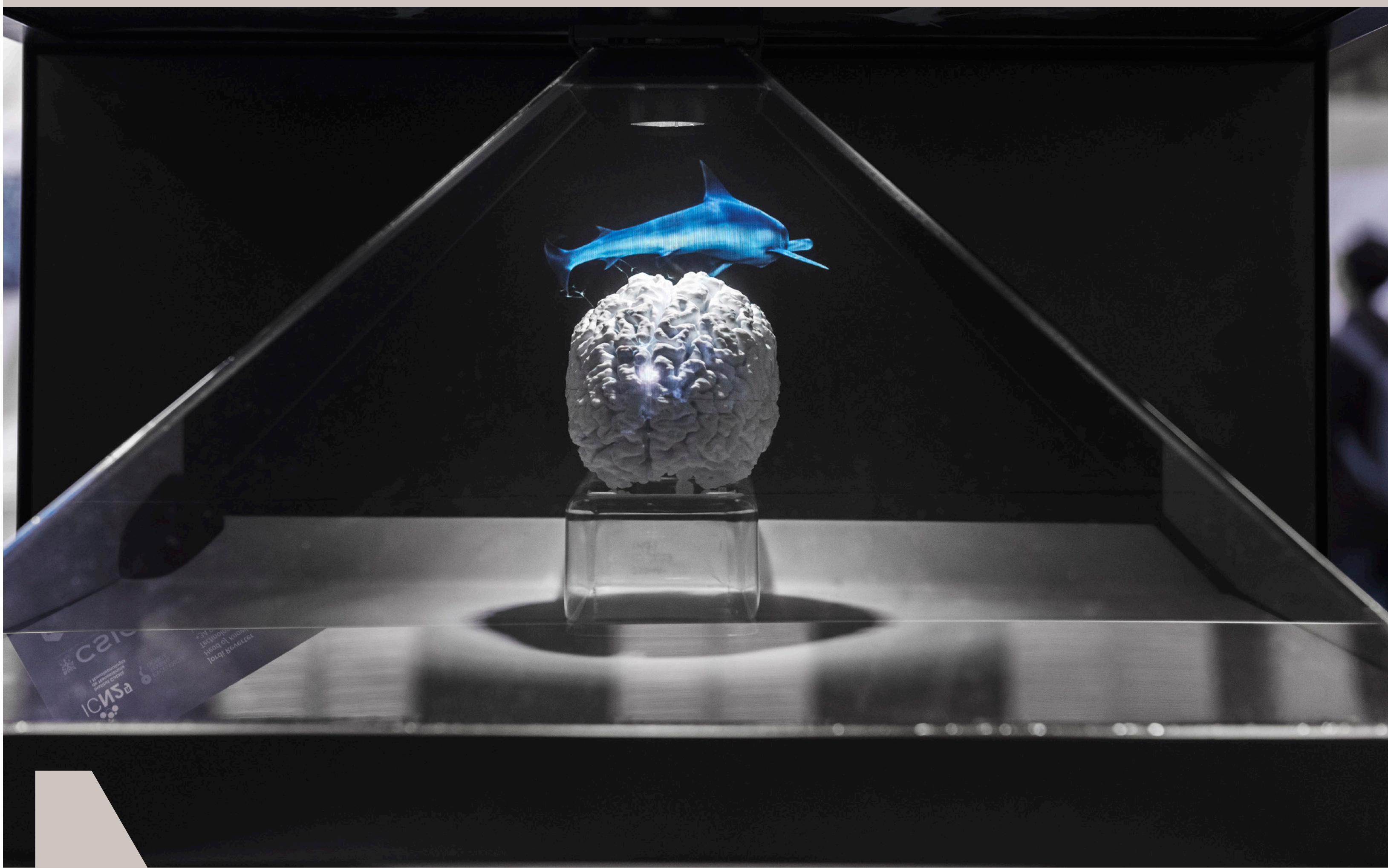
The Graphene Flagship's Biomedical Technologies Work Package aims to develop medical devices using graphene and related materials as well as advanced tools to monitor and influence the nervous system. This work package explores the use of graphene and related materials (GRMs) in the design of neural implants for recording and stimulating electrical activity, combined with localised drug delivery.

"Our work package is highly multidisciplinary, composed of engineers, chemists, neuroscientists and clinicians. In order to perform multidisciplinary research with such a large consortium, large-scale funding, such as that provided by the Graphene Flagship structure, is necessary," said Jose A. Garrido, work package deputy leader from Catalan Institute of Nanoscience and Nanotechnology (ICN2), Spain. "During the past three years, we demonstrated that graphene-based devices can have important applications in neuroscience. This work package contributed to pushing the state-of-the-art of the technology worldwide."

YEAR IN REVIEW

The success stories and technological breakthroughs over the past year are numerous. Here we highlight

Graphene Flagship researchers have developed a sensor that records brain activity at extremely low frequencies and could lead to new treatments for epilepsy. Credit: ICN2



Flexible arrays of graphene solution-gated field effect transistors can be used to monitor brain activity. Credit: Alexandra Csuport

> We have demonstrated that graphene-based devices can have important applications in neuroscience, pushing the state-of-the-art of the technology worldwide."
>
> **Jose Garrido**

three papers on neural implants and on the understanding of how graphene can be used at the cutting edge of this field.

- A paper summarising the fabrication of flexible arrays of graphene solution-gated field effect transistors and their use for monitoring brain activity. This provides a benchmark with respect to standard passive electrodes used to monitor the activity within the brain.
- A paper demonstrating the impact of single layer graphene on the communication between neurons. This describes how single-layer graphene under cultures of neurons can influence the membrane characteristics, resulting in an augmented neuronal activity.
- An article summarising the impact of graphene solutiongated field effect transistors and how they can be used to map infraslow cortical activity *in vivo*.

LOOKING FORWARD

The work package plans, by the end of March 2020, to complete several chronic studies in order to understand the impact of long-term implantation of graphene based neural probes. The main objectives are to assess both the impact of the implant on the tissue and the change of the implant functionality with time.

Thinking in both the short and mid-term, Garrido anticipates the future innovations to appear from the work package: "In the short term (1–2 years), I hope that the development of novel tools (neural probes for monitoring and stimulating nervous activity) reaches the neuroscience research market. In the mid-term (2–4 years), we should be able to demonstrate our neural probes in first-of-its-kind human trials. This will allow us to break the ceiling for using graphene in clinical settings, opening up graphene use to investors in the fields of health and medial devices."

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Work Package Leader:
Maurizio Prato

Work Package Deputy:
Alberto Bianco

Health and Environment

As the Graphene Flagship continues its drive to commercialise graphene and related materials (GRMs) technologies it is important that all safety aspects are thoroughly researched and understood. The Health and Environment Work Package targets safety by design as a core part of innovation.

Fulfilling a fundamental role within the Graphene Flagship, to assess the potential risks associated with the development of GRMs, the findings from the Health and Environment Work Package play a crucial role in technology development across all the technical work packages.

Alberto Bianco, work package deputy leader from CNRS National Centre for Scientific Research, France, stated, "One of the objectives of our work package is to explore appropriate chemical strategies to enhance the biodegradability of GRMs. Towards this goal, we demonstrated that artificial enzymes based on appropriate DNA sequences can be an alternative to natural peroxidases (like the plant enzyme horseradish peroxidase) for the oxidation and degradation of graphene oxide (GO). Our results open new possibilities for the degradation of GRMs."

YEAR IN REVIEW

Graphene has long been thought of as an important material for neuroengineering; however, research into how graphene interacts with neural tissue is still in its

Artificial enzymes based on appropriate DNA sequences can be an alternative to natural peroxidases for the degradation of graphene oxide.

Experiments have shown that the acidic properties of GO affect pollen performance in seed plants.

> "Graphene might represent an unconventional tool to gain insights into genuine biological processes."
>
> **Maurizio Prato**

infancy. "Over the past year, we have been able to show that single layer graphene, when engineered on an insulating glass substrate, is able to tune neuronal excitability. Graphene properties might thus affect neuronal information processing through its physical interaction with the biological environment. This indicates that graphene might represent an unconventional tool to gain insights into genuine biological processes," said Maurizio Prato, work package leader from University of Trieste, Italy.

"A particularly important aspect in graphene technology is the impact of GRMs on the environment," continued Prato. "GO is among the most active GRMs, since it causes widely varying effects on the vegetative body of seed plants. In addition, GO is prepared under strongly acidic conditions with this acidity being maintained in most commercial products. In a study on the reproductive process, the effects of GO on pollen germination and pollen tube elongation were investigated. The results reveal that GO affects the intracellular pH homeostasis with experiments showing that the main factor influencing pollen performance is the acidic properties of GO. This might affect the reproductive process of numerous seed plants thus being relevant from an environmental point of view."

LOOKING FORWARD

Over the next year, this work package will investigate GRMs' impact on both health and environment, monitoring effects on the skin, lungs, intestines, brain, plant pollination and fertilisation, and aquatic ecosystems.

WHY THE GRAPHENE FLAGSHIP?

"The large-scale funding of the Graphene Flagship allows us to conduct our research in a highly competitive way, putting us firmly at the forefront of discovery and innovation within the field of toxicology investigation for both health and the environment," said Bianco. "Safety issues related to technologically advanced materials such as graphene represent an important matter and the results of research in this area should not be assumed. Our research points to a clear indication of biodegradability of GRMs, which is important information. However, more work is needed to fully understand the effects of GRMs on health and the environment."

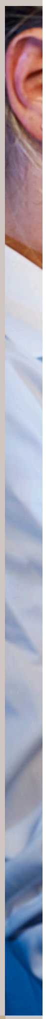
Work Package Leader:
Mar García-Hernández

Work Package Deputy:
Jonathan Coleman

Enabling Materials

A thorough understanding of the material properties of graphene and related materials (GRMs) is key as the Graphene Flagship moves forward with its goal of developing these technologies into commercialised products. The focus of the Enabling Materials Work Package is GRMs synthesis, in order to understand and then optimise the relationship between synthesis parameters and material properties, as an essential part of the commercialisation journey. Coupling this understanding with heterostructure formation allows the tuning of electronic, structural, optical and electrochemical properties, which, in turn, make GRMs suitable for different applications. All of the synthesis routes developed and optimised within this work package are looked at through the lens of scalability for commercialisation, and its wide-reaching outlook supports all other Graphene Flagship work packages.

"The whole Graphene Flagship will benefit from our developments in GRMs synthesis," said Mar García-Hernández, work package leader from CSIC, Consejo Superior de Investigaciones Cientificas, Spain. "Without scalable synthesis protocols for producing high quality materials, the large-scale production of devices will not be possible. In order to achieve this, we need to continue understanding the growth mechanisms for the best possible materials, not yet commercially available, to be



Materials research is an important milestone towards production.

Understanding and optimizing the relationship between synthesis parameters and material properties is an essential part of the commercialisation journey. Credit: Graphenea

> “The whole Graphene Flagship will benefit from our developments in GRMs synthesis.”
>
> **Mar García-Hernández**

used in other work packages involved in specific applications.”

As the Graphene Flagship sails on, the number of layered materials investigated constantly increases. These have different properties and combining them together in heterostructures (with or without graphene) gives us the ability to create a huge array of devices with unique properties suitable for a wide range of applications. Before any device created from GRMs heterostructures can be commercialised, the constituent materials must be able to be produced in a fast, controlled, scalable way.

YEAR IN REVIEW

The focus of the Enabling Materials Work Package over the last year has been on achieving ultra-flat films of hexagonal boron nitride (h-BN) and transition metal dichalcogenides whilst controlling the number of layers (from 1 to 10) over a large area. Combining these with graphene allows for the production of heterostructures. These have many potential applications in electronics, optoelectronics and energy harvesting and conversion.

The many GRMs synthesis methods developed have resulted in patenting and licensing. It is this link to commercialisation that is a key goal of the Graphene Flagship.

LOOKING FORWARD

Over the course of the next year, this work package aims to build on its h-BN synthesis success to grow ultra-flat thick h-BN that can be used as a substrate in devices. The stability of several other layered materials and their corresponding devices to develop encapsulation schemes to prolong their working lifetime will also be explored.

WHY THE GRAPHENE FLAGSHIP?

The strength of the Graphene Flagship and its large-scale funding model comes from its collaborative work. “The quality of our research would have been impossible without Graphene Flagship funding and the synergies developed between the many different groups,” said García-Hernández.

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Work Package Leader:
Kevin Garello

Work Package Deputy:
Stephan Roche

Spintronics

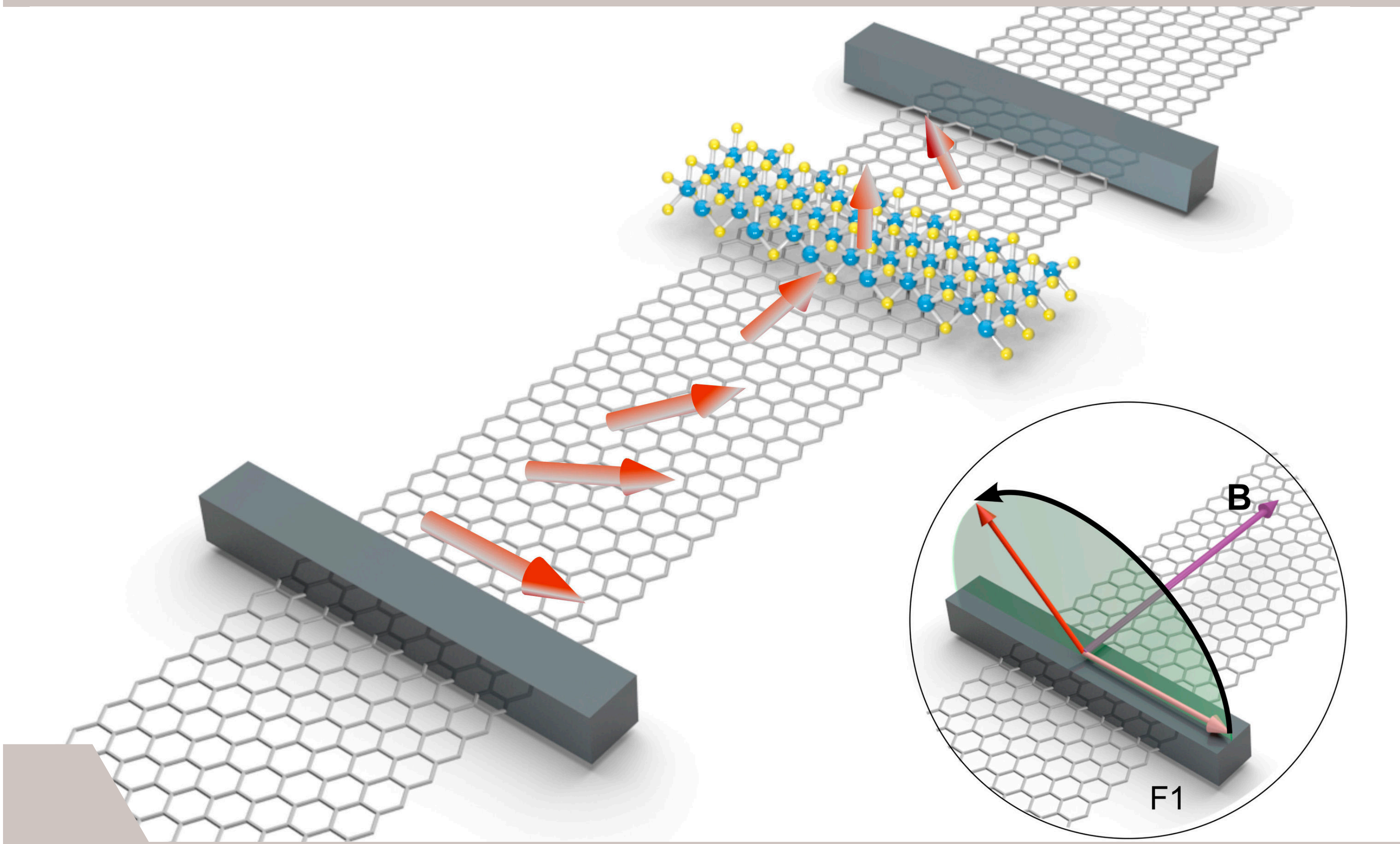
Graphene's long spin lifetime and high electron mobility make it appealing for spintronic applications. The Graphene Flagship's Spintronics Work Package aims to develop new spintronics technologies using graphene and related materials (GRMs). These range from novel spin device functionalities to advanced non-volatile memories, as well as information processing technologies including quantum computing, with a direct impact on the Internet of Things and memory markets. The fundamental ingredients for spintronics devices are the efficient creation, manipulation and detection of spin currents. For practical applications, it is crucial to be able to control spin currents using all-electrical means at room temperature.

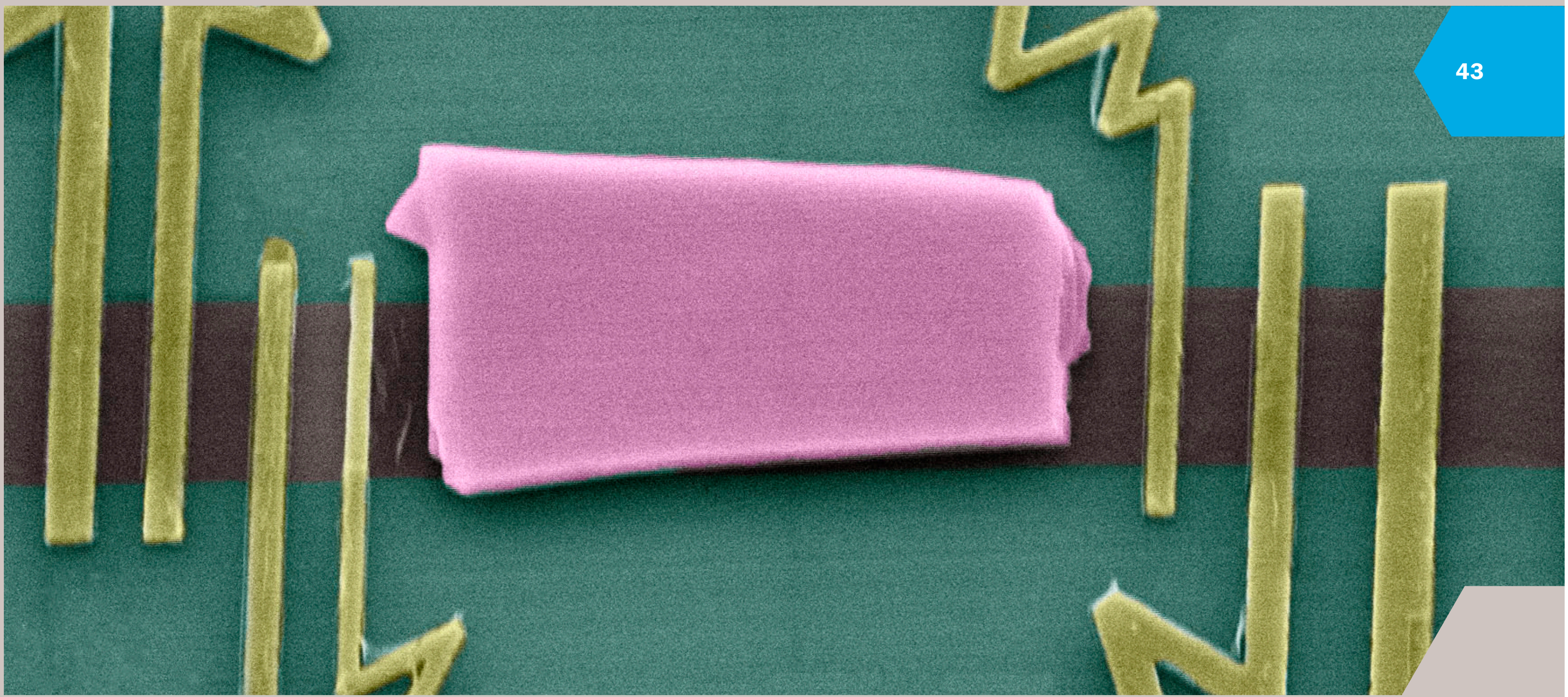
YEAR IN REVIEW

Over the course of the last year the Spintronics Work Package has seen many technology breakthroughs as well as a change in leadership to make it more applications focused. ICREA Research Professor Stephan Roche, work package deputy leader from ICN2 Catalan Institute of Nanosience and Nanotechnology, Spain, explains. "The agreement for IMEC to take the lead is an accomplishment which validates the strategic knowledge obtained by our consortium to envision disruptive aspects of existing technologies (memories) by integrating GRMs in state-of-the-art MRAM technology."

Focusing on spintronic principles towards applications, the work package targeted efficient spin injection and

Probing spin current anisotropy in graphene heterostructures upon magnetic field orientation engineering. Credit: Dámaso Torres (ICN2)





A scanning electron microscope micrograph of a fabricated device showing the graphene topological insulator heterostructure channel.
Credit: Dmitrii Khokhriakov, Chalmers

> "Pushed to move towards higher technology readiness levels, our theoretical work has been strongly oriented towards realistic modelling of complex materials and towards a systematic support of experimental activities."
>
> **Stephan Roche**

detection by designing specialised device architectures, using hexagonal boron nitride stacks as a tunnel barrier. Using CVD graphene, they were able to record very long room temperature spin diffusion.

Working on the potential application for non-volatile memories (MRAM), large tunnel magnetoresistance in vertical/two-dimensional stacks of hexagonal boron nitride or graphene and magnetic materials was reported. Linking this with advanced modelling, it was possible to understand more about the phenomena, and this resulted in the first devices.

Control and manipulation of spin is important when looking to produce spintronics devices used in logic and computing. This included producing graphene heterostructures with record room temperature mobility and theoretically predicted and experimentally confirmed that these heterostructures can be tailored with out-of-plane polarization several orders of magnitude longer than for in-plane polarization.

Focusing on how graphene spintronics can be used in a very real sense, the work package developed a method to synthesize large graphene flakes (>100 nm) in which they were able to obtain the longest spin diffusion length at room temperature. A method for using these graphene flakes in nano-oscillators which would eventually be commercialised by Graphene Flagship consortium member NanOsc is currently being developed.

LOOKING FORWARD

Looking ahead to the next year, the work package will continue to develop graphene-based spintronics memory technologies using the strong foundation they have built over the previous years. This includes developing scalable materials and industrially-relevant technology processes to determine the conditions for most efficient room temperature control of spin current formation and advancing MRAM memories developed at imec.

Having already found that predictive modelling plays a crucial role in benchmarking the best heterostructures for a given spin transport effect, work will also be undertaken to perform the first complete simulation of spin torque efficiency in realistic models of complex layered materials-based heterostuctures.

WHY THE GRAPHENE FLAGSHIP?

"Our work package demonstrated its scientific leadership in terms of fundamental research, evidenced by the discovery of novel spin transport phenomena together with the understanding of the highly complex physics of spin devices. Pushed to move towards higher technology readiness levels, our theoretical work has been strongly oriented towards realistic modelling of complex materials and towards a systematic support of experimental activities, with large number of joint publications realised within the synergies developed inside the Graphene Flagship," said Roche.

Work Package Leader:
Vladimir Fal'ko

Work Package Deputy:
Alberto Morpurgo

Enabling Research

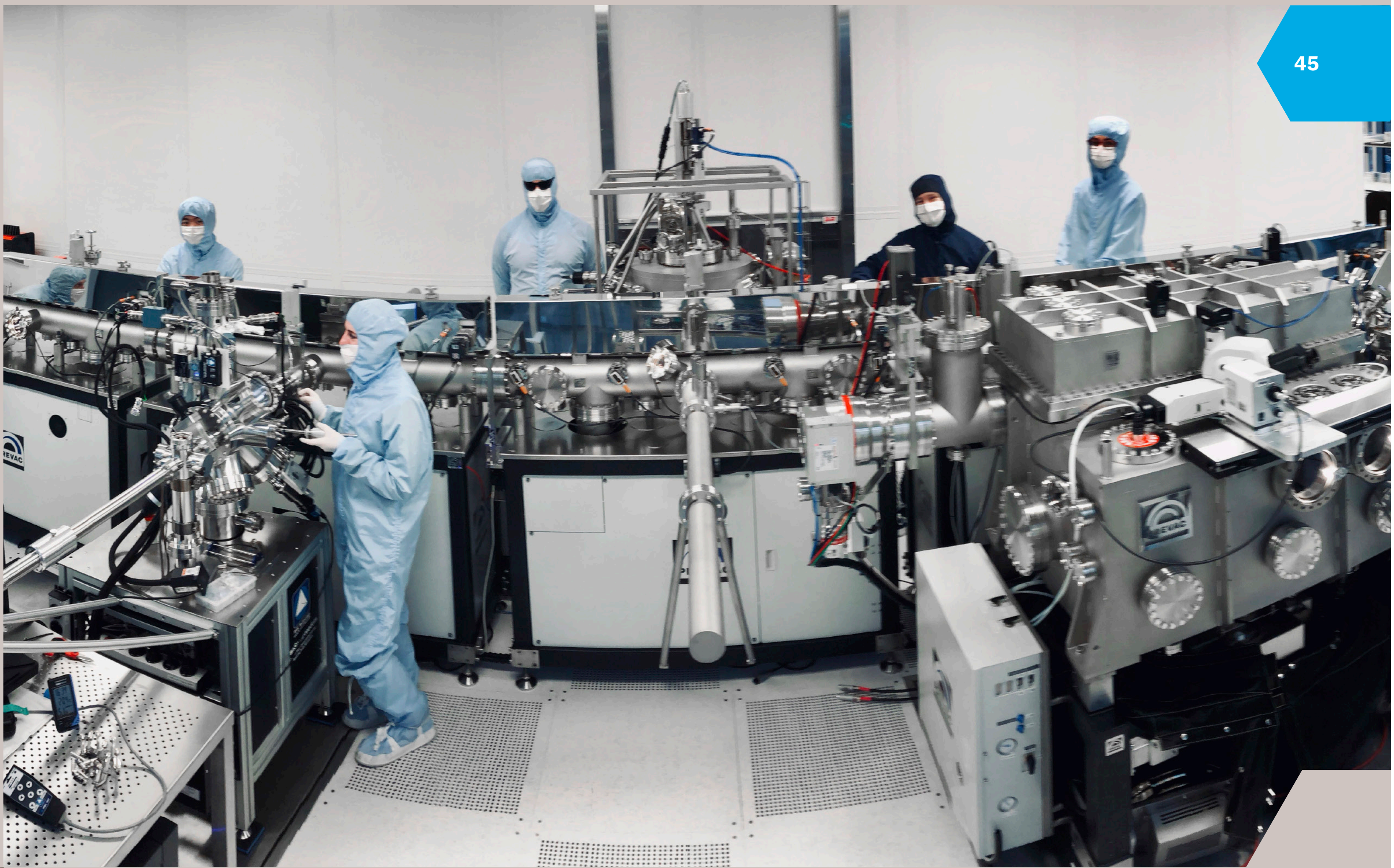
Understanding the fundamental properties of graphene and related materials (GRMs) from both a physical and chemical perspective is key to enabling them to reach their potential in future applications. The Graphene Flagship's Enabling Research Work Package studies these fundamental properties so that they can be exploited in new device architectures.

"Knowledge developed by our work package on the properties of GRMs and their heterostructures is passed on to the other work packages to strengthen and help underpin their research and innovation," said Vladimir Falko, work package leader from the University of Manchester, UK.

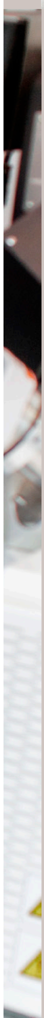
YEAR IN REVIEW

Researching the fundamental properties of graphene has led to the development of new and interesting characterisation techniques which have helped to open the graphene world up for others. A collaboration between Oxford Instruments, the National Physical Laboratory and the National Graphene Institute has seen the development of a quantum resistance standard, now ready for commercialisation. This is a turnkey solution which enables the measurement of graphene's electrical resistance with unprecedented accuracy. This will have far reaching benefits for calibration and metrology services worldwide.

The National Graphene Institute is working to improve our understanding the fundamental properties of graphene and related materials.
Credit: The University of Manchester



An integrated ultra-high vacuum instrument for dry transfer and characterisation of GRMs. Credit: Roman Gorbachev @ National Graphene Institute, the University of Manchester



> Knowledge developed by our work package on the properties of GRMs and their heterostructures is passed on to the other work packages to strengthen and help underpin their research and innovation."
>
> **Vladimir Falko**

"Also developed is an integrated ultra-high vacuum instrument for dry transfer and characterisation of GRMs, ready to supply bespoke heterostructures for Graphene Flagship partners," said Falko.

At the core of this work package is the study of GRMs' fundamental properties. Heterostructures formed by layers of graphene and other materials, such as hexagonal boron nitride and transition metal dichalcogenides, enable the production of devices with electronic properties that differ from those of the constituent materials. Studying the Moire superlattice effect, which leads to the unique electronic properties of these materials, widens the potential for their use in designer electronics.

In the last year, this work package has also focused on bilayer graphene. By introducing a bandgap in bilayer graphene, researchers were able to study quantum transport in electrostatically defined circuits.

Focusing not only on graphene but also on other related materials, researchers were able to predict and experimentally show the inter-subband transitions in few-layer transition metal dichalcogenides, which has opened a new range of infrared and terahertz applications.

LOOKING FORWARD

Considering the upcoming year, Falko describes how the work package will build on the successful foundations they have laid: "Over the next year we plan to take our research into transition metal dichalcogenides heterostructures forward to observe the Moire superlattice minibands of excitons. Continuing our work on gapped bilayer graphene we hope to understand the electronic properties of electrostatically controlled quantum dots within its structure."

This work package also hopes to control the lithiation of graphene microstructures, which could ultimately improve the cycling stability of the next generation of lithium-ion batteries.

Division Leader:
Andrey Turchanin

Division Deputy:
Yuri Svirko

Partnering Division

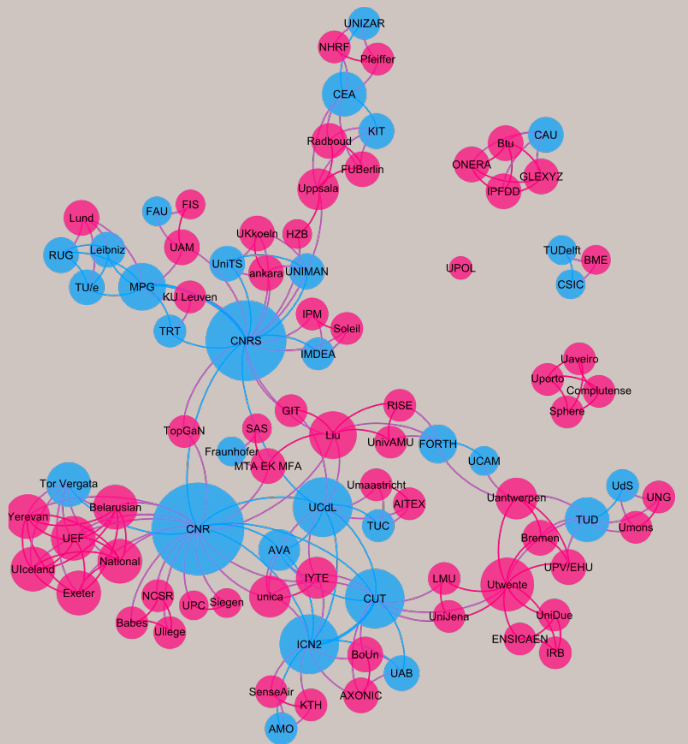
“The partnering projects and associated members, with their complementary expertise, bring a great added value to the Graphene Flagship, enabling new possibilities both in research and in technological implementation of graphene and related materials. The number of associated members nearly equals the number of Core Project members, building a network with unprecedented expertise and potential for scientific excellence and industrial innovation in Europe,” says Andrey Turchanin, partnering division leader from Friedrich Schiller University Jena, Germany.

COEXAN

In 2018 CoExAn measured optical conductivity of silicon nanosheets epitaxially grown on the optically transparent Al_2O_3(0001). The study will open the route to new photonic and plasmonic devices, also integrated with other two-dimensional materials such as graphene. ”Silicene, the Silicon-based analogous of graphene, is predicted to possess a slightly buckled honeycomb structure with massless Dirac fermions when in its free-standing form,” says Project Coordinator Olivia Pulci. “In order to fully exploit the properties of this new 2D material, it would be important to integrate it into electronic and optical devices without losing its features. The search for a suitable substrate is of paramount importance. A small step towards this goal is represented by this combined experimental and theoretical study, suggesting that sapphire may be a good candidate as an inert and transparent substrate for silicene growth.”

H2O

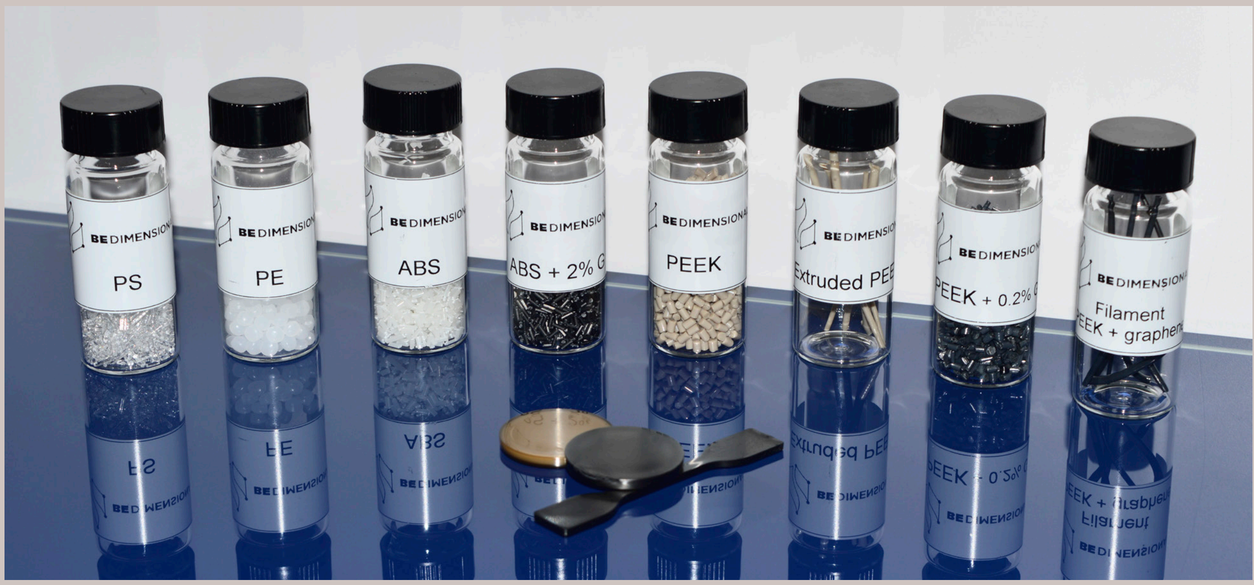
The H2O project investigates heterostructures based on established 2D materials like graphene or transition metal dichalcogenides (TMDs) with the recently developed free-standing nanolayers of organic semiconductors aiming to create novel electronic and optoelectronic devices. Based on a collaboration with the Core Project (Ulm University), H2O reported in 2018 on a new synthesis method for lateral heterostructures composed of organic and inorganic nanosheets and on an optimized chemical vapour deposition growth of TMD monolayers. The grown TMD monolayers have a structural quality comparable to the samples obtained by mechanical exfoliation of the respective bulk crystals.



The scientific network and collaborations within the Partnering Division reveal a complex structure with several Core Project institutions (blue bubbles) and Associated Members (pink bubbles) forming clusters throughout the entire network.

TAILSPIN

High quality graphene nanoribbons epitaxially grown on the sidewalls of silicon carbide (SiC) mesa structures stand as key building blocks for graphene-based nanoelectronics. Such ribbons display 1D single-channel ballistic transport at room temperature with exceptionally long mean free paths. Using spatially-resolved two-point probe (2PP) measurements, the TAILSPIN project has selectively accessed and directly imaged a range of individual transport modes in sidewall ribbons. The signature of the independently contacted channels is a sequence of quantised conductance plateaus for different probe positions. These result from an interplay between edge magnetism and asymmetric terminations at opposite ribbon edges due to the underlying SiC structure morphology. The findings demonstrate a precise control of transport through multiple, independent, ballistic tracks in graphene-based devices, opening intriguing pathways for quantum information device concepts.



Graphene-based additives in plastics are a growing rapidly due to new scalable production processes. Credit: Bandera, IIT/BeDimensional

ULTRAGRAF

In the past year, Ultragraf performed studies on the non-linear optical properties of graphene flakes in highly concentrated suspensions of NMP, which can be deposited and desiccated on a substrate. The most relevant result is that the saturable absorption of these deposits is huge, because the flakes can easily pile-up up to approximately 60 layers, keeping their individual properties. This system can serve as a saturable absorber for mode-locked lasers. Few layers of CDV grown graphene have already been used for that purpose, but this system is easier to fabricate, more economical and allows a larger number of layers to be stacked. The studies were performed at 800 nm with a femtosecond Titatium: Sapphire laser, and are now being extended to the telecommunications wavelength range.

GRANITE

The GraNitE project aims at the development of a hybrid technology based on graphene/Nitride semiconductors heterostructures, with a wide range of potential applications, in the fields of high-frequency electronics, optoelectronics and sensing. One of the main targets of the project is the demonstration of a hot electron transistor (HET) with a graphene base and the emitter made with the Al(Ga)N/GaN heterojunction. Such a device relies on the ballistic transit of hot electrons across the atomically thin base and has the potential to operate at THz frequency. However, proper choice of the emitter and base-collector barrier materials is necessary to achieve the theoretical performances.

BANDERA

Graphene-based additives in plastics are a growing rapidly due to the new scalable production processes (e.g. shear mixing, microfluidization) suitable for industrial production, via several technologies (moulding, extrusion, coating, printing, lamination, 3D printing, etc.). Grapholymer is a project that allows the development of products and production processes that combine polymers/biopolymers and graphene for advanced solutions in the fields of smart recyclable / biodegradable packaging, advanced food-wrapping, organic substrates, agriculture coverage, and many others everyday products. Bandera and IIT/BeDimensional have developed new compounds with a large variety of polymers with graphene that could be scaled up to industrial productions. Bandera facilities are open to testing industrial extrusion production up to 3,000 kg/h.

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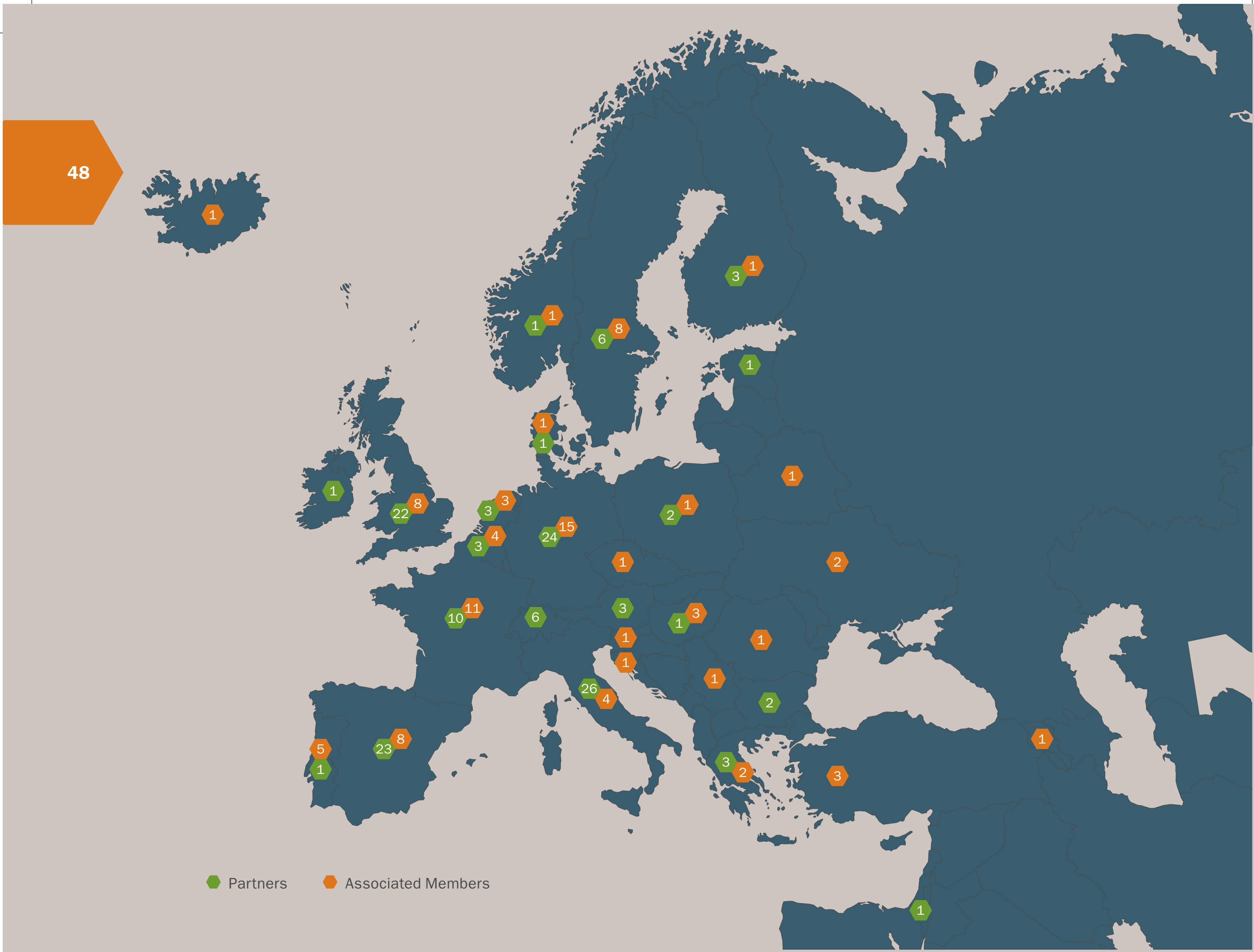

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Andrea C. Ferrari, Graphene Flagship Science and Technology Officer

Science and Technology Outlook

We are now in the second half of the 10-year Graphene Flagship project. The preparations for Core 3 are underway and another 11 spearhead projects will launch in April 2020, with topics ranging from advanced batteries to high speed communications, de-icing, air and water filtration, advanced imaging devices, novel circuit breakers and tandem solar cells, as well as health and safety regulations.

The increasing number of companies engaged in the Graphene Flagship—including many start-ups related to work done by partners or associate members—is a testimony to the Flagship's progress towards its goal of developing graphene applications.

At the same time, many new discoveries and findings show that applications do not come at the price of fundamental research but, on the contrary, the continuous progress in our understanding of the properties of graphene and related materials underpins our drive for their widespread use.

Over the years the Graphene Flagship has evolved with a healthy turnover of partners, and many more will join us in Core 3. Our presence at trade shows and exhibitions, such as Mobile World Congress, help us to expand our industry outreach. Marketplace events, like those organized with Airbus and Leonardo, as well as the many roadmapping and innovation workshops, provide guidance for our progress and ensure that we target issues relevant to European industry.

Our wider dissemination events and conferences, targeting students, experienced scientists, policy makers and the wider public, secure a healthy exchange of ideas, while at the same time training the next generation of scientists and engineers.

As science and technology officer, I am proud of what we have achieved thus far. The next challenge will be to ensure the continuation of the Graphene Flagship for at least another Core project, following Core 3, as planned in our original vision. At the same time, we should continue to support and welcome companies wishing to invest in and exploit our technologies, starting with those created by our partners.

! CAPTIONS:

1. Industry events like Mobile World Congress also present an excellent opportunity to speak with the press. Credit: Alexandra Csuport

2. Tours of Graphene Flagship start-up Graphenea, conducted during Graphene Week in San Sebastian, Spain, highlight graphene production processes. Credit: arri studioa

3. The Exhibit Hall at Graphene Week allowed businesses working on graphene products to showcase their work. Credit: arri studioa

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GRAPHENE FLAGSHIP

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 by 2023. The Graphene Flagship gathers nearly 150 academic and industrial partners from over 20 countries, all exploring different aspects of graphene and related 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.

Learn more at graphene-flagship.eu

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