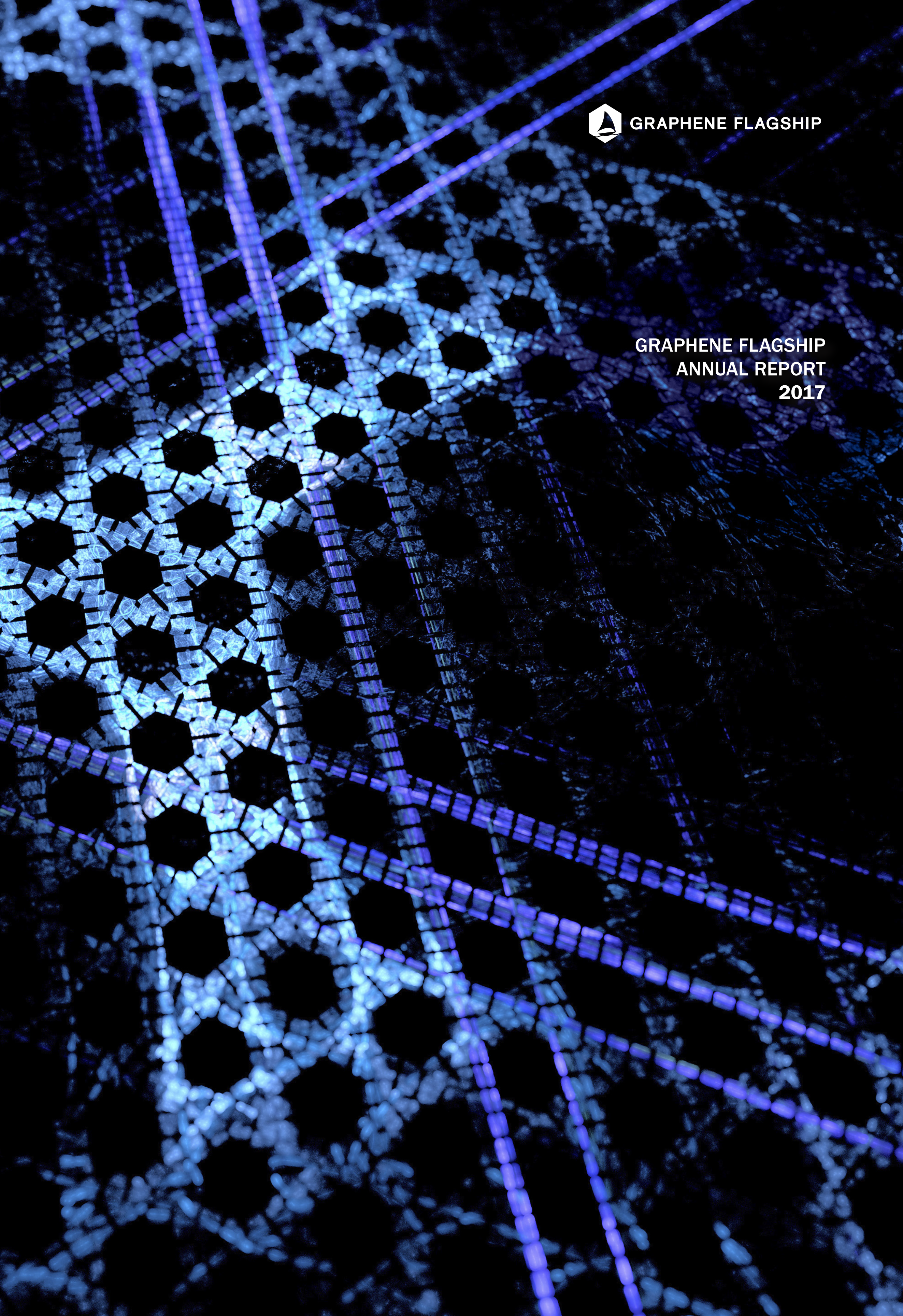


GRAPHENE FLAGSHIP

GRAPHENE FLAGSHIP ANNUAL REPORT 2017

The year 2017 was an important milestone for the Graphene Flagship. It brought about many breakthroughs, both planned and unplanned, and clearly demonstrated that the Flagship is well on track to deliver upon its promises.

Many of the breakthroughs are presented in the following technical parts of this annual report, but I would like to mention two of them. The first one is a result of our planned activities in electronics and optoelectronics and comprises several related but distinct results: graphene as an enabler for very fast optical/electrical communication systems. The photodetector and modulator developed in the Photonics and Optoelectronics and Wafer Scale System Integration Work Packages show record-breaking performance and are being developed further as key components in, e.g., data switches in 5G communication technologies. This breakthrough is a result of long-term, goal-oriented research involving several academic and industrial partners – the Flagship in action.

The other breakthrough that I have in mind is completely different in its character. You cannot find it mentioned in any of our task descriptions: it was a serendipitous discovery. In the Health and Environment Work Package, researchers found [1] that few-layer graphene flakes kill monocytes, a type of immune cell. This sounds like bad news until you realize that the proliferation of those cells lies behind one type of leukemia and the discovery may lead to a new type of cancer therapy. Research cannot be planned in detail, and we must always maintain a basic research component even when the center of gravity of the Flagship moves to higher technology readiness levels.

This said, in the coming years the Flagship must increasingly focus on those areas where it has the highest potential to create positive impact in Europe. We must rely on our combined expertise and place our bets to maximize the payoff to our funders, the European tax-payers.

Jari Kinaret
Director of the Graphene Flagship

[1] J. Russier *et al., Angew. Chem. Int. Ed.* **56**, *3014 (2017)*

Introduction

The Graphene Flagship is focused on translating quality research into material innovation based on graphene and related materials (GRMs). Through connecting the European research community, the Flagship is taking GRM technologies from research laboratories into practical applications.

The large-scale and long-term nature of the Future and Emerging Technology Flagships is crucial for establishing a broad collaboration that utilises interdisciplinary and Europe-wide synergies. The Graphene Flagship is an anchoring point for GRM research and development in Europe, accelerating research through strong networks and collaborations.

INNOVATING WITH INDUSTRY

In its mission to bring GRM innovation to the market, the Graphene Flagship creates networking opportunities that raise awareness of GRMs within European industries. By holding workshops focused on specific topics and industry needs, experts in research and industry have the opportunity to meet and discuss. Collaborative innovation projects bridging academia and industry are bringing GRM technologies to consumer markets. The Flagship regularly exhibits prototypes and products at international trade fairs to engage a wide industry audience.

INTERNATIONAL COLLABORATION

European research is taking place in a global context. Building bridges and sharing knowledge and experience is of fundamental importance to the Flagship. The Graphene Flagship organises the annual Graphene Week, one of the most influential conferences on GRMs worldwide – a truly international event where researchers from all corners of the world present and discuss the latest in GRM research. The Graphene Flagship also collaborates with counterpart organisations in the US, Japan, Korea and China.

NEXT GENERATION OF RESEARCH

The Graphene Flagship actively works to create activities specially designed to stir curiosity and promote scientific excellence within the younger generation. An annual school, Graphene Study, encourages scientific developments and enables younger-researchers to engage with experts across different research topics. The Flagship has also developed playful and interactive exhibitions to show young audiences the wonders of graphene and science.

KEY FIGURES

- 158 partners
- 23 countries
- 18 partnering projects
- 73 associated members
- 39% Academia
- 22% Research org.
- 39% Industry
- 1400+ scientific publications
- 37 patents applied
- €381 million Projected EC-funding under FP7 and Horizon 2020
- 23000+ citations
- 17 products launched
- 6 spin-off companies
- 1252 people involved
- ♂ 70%
- ♀ 30%

Figures as of September

Enabling Research

Graphene and related materials (GRMs) have potential in a wide range of applications, with more yet to be discovered. Research within the Graphene Flagship's Enabling Research Work Package is focused on exploring new concepts for exploiting these properties towards different applications, such as novel electronics, optoelectronics and quantum technologies.

Vladimir Falko

Lithium-ion batteries rely on the transport of lithium between electrolytes and electrodes. Battery electrodes for solid-state batteries require solid materials that can simultaneously conduct electrons and allow the motion of ions. However, these materials are quite rare, and lithium-ion batteries typically contain mixed-phase electronic and ionic conductors.

Flagship researchers working at the Max Planck Institute for Solid State Research and CNR have uncovered interesting mechanics of lithium diffusion in bilayer graphene [1]. They found that lithium ions readily penetrate the bilayer and travel deeply into the graphene sheets, even in areas that are not in direct contact with the electrolyte. This work shows that graphene can act as a true solid-state conductor of both electrons and ions.

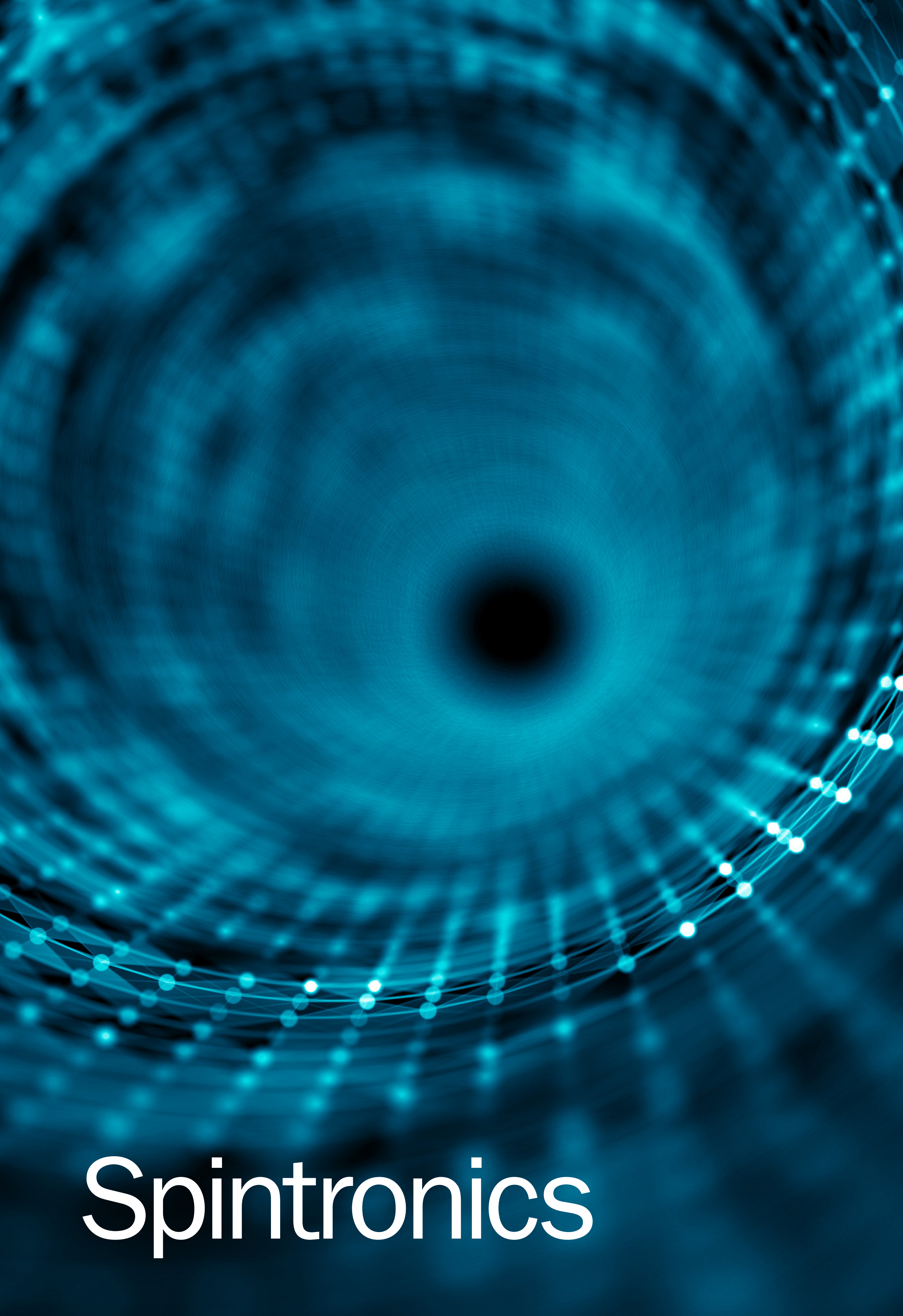
The diffusion of lithium into bilayer graphene is one of the fastest diffusion processes ever observed – faster than the diffusion of table salt into water. The process is reversible, indicating potential in high-performance, all-solid-state lithium ion batteries that can be charged rapidly.

Vladimir Falko (University of Manchester), leader of the Enabling Materials Work Package, said: ***"These results are significant both for potential applications and for gaining fundamental insights into transport processes that were not previously available. The techniques presented here will prove very useful in further investigations involving other layered materials, and should provide new insights that can be of use in developing innovative technologies that exploit fundamental properties."***

WORK PACKAGE LEADER
Vladimir Falko, University of Manchester, United Kingdom

WORK PACKAGE DEPUTY
Alberto Morpurgo, University of Geneva, Switzerland

[1] M. Kühne *et al., Nat. Nanotechnol.* **12**, 895 (2018)



Spintronics

Graphene and related materials have strong potential in spintronic applications, driving the Graphene Flagship's quest for novel ways to control currents of electron spins. As well as charge, electrons possess the property of spin, an intrinsic angular momentum that can be detected and manipulated with a magnetic field.

Bart van Wees

WORK PACKAGE LEADER
Bart van Wees, University of Groningen, The Netherlands

WORK PACKAGE DEPUTY
Stephan Roche, Catalan Institute of Nanotechnology (ICN2), Spain

Spintronics is expected to lead to further advances in a new generation of non-volatile memories, as well as information processing technologies including quantum computing. However, spin currents are very difficult to generate, guide and manipulate. For practical applications, it is crucial to be able to control spin currents using all-electrical means at room temperature.

This year, Flagship researchers demonstrated key building blocks for spin manipulation at room temperature, bringing disruptive spintronics technologies several steps closer.

Flagship researchers working at the University of Groningen demonstrated that it is possible to inject highly polarised spin currents into graphene, and that the degree and direction of polarisation can be further controlled by applying a voltage [1] – an essential component for spin control. In a graphene device covered with two layers of hexagonal boron nitride, the researchers observed unprecedented spin current injection and transport even at room temperature.

Spin transistors are devices that allow or block the flow of spin currents based on electrical input signals. Researchers from Chalmers University of Technology demonstrated a room-temperature field-effect spin transistor in a graphene and molybdenum disulphide device [2], bringing all-electrical, room-temperature spintronics closer to applications.

In a landmark achievement that demonstrates how collaboration within the Graphene Flagship is increasing the pace of scientific progress, researchers from across the Flagship predicted and experimentally verified a new spintronics phenomenon. Publishing theory and experimental work simultaneously, researchers from ICN2, the Autonomous University of Barcelona, the University of Groningen, and the University of Regensburg demonstrated giant anisotropy in spin lifetimes in layered devices of graphene and transition metal dichalcogenides [3, 4, 5]. This finding reveals that spin currents with different polarisations have dramatically different behaviour, and spin filtering of certain polarisation is possible at room temperature.

Stephan Roche, deputy leader of the Spintronics Work Package, commented, ***"The progress achieved during Core 1 makes us optimistic for Core 2. The outcomes and success should generate a high value in the industrial environment once technology integration in fab environment is demonstrated. Our commitment to the Flagship community and European stakeholders is to shorten the time between knowledge generation and its practical use in real concrete applications."***

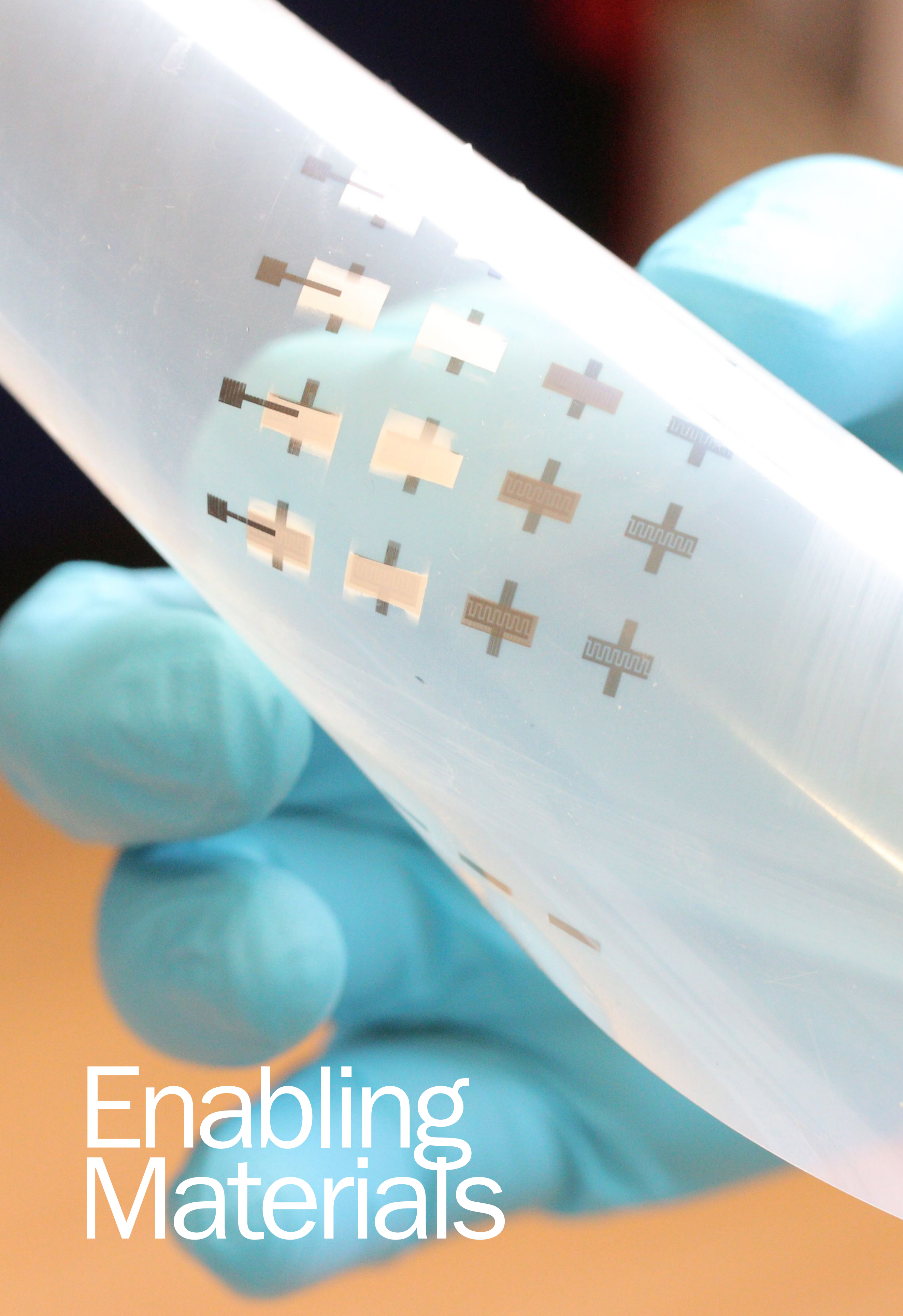
[1] M. Gurram, *et al., Nat. Commun.* **8**, 248 (2017).

[2] A. Dankert, S. Dash, *Nat. Commun.* **8**, 16098 (2017).

[3] L. Antonio Benítez *et al., Nat. Phys.* **14**, 303 (2018)

[4] T. S. Ghiasi *et al., Nano Lett.* **17**, 7528 (2017)

[5] A. W. Cummings *et al., Phys. Rev. Lett.* **119**, 206601 (2017)



Enabling Materials

The Graphene Flagship's push for technology advancement based on graphene and related materials (GRMs) is rooted in a strong understanding of their material properties. Optimising GRMs for different applications and developing scalable synthesis routes is a key focus on the route to new technologies.

Mar Garcia-Hernandez

WORK PACKAGE LEADER
Mar Garcia-Hernandez, Spanish National Research Council (CSIC), Spain

WORK PACKAGE DEPUTY
Jonathan Coleman, Trinity College Dublin, Ireland

Printed electronics is an important avenue of research for low-cost and high-volume applications, particularly in adding smart functionality, such as sensing, into everyday objects. GRMs are highly promising for printed electronics due to their excellent electronic properties and ease of processing into printable inks.

Graphene Flagship researchers from Trinity College Dublin and Bundeswehr University Munich have developed all-printed electronic devices using GRM inks – including transistors [1]. Transistors are the building blocks of modern electronics and are essential for any kind of logic circuit. Therefore, fully-printed transistors are highly attractive.

Jonathan Coleman, deputy leader of the Enabling Materials Work Package, was involved in the work. ***"This is the first time all-printed, all nanosheet transistors have been achieved and opens the door to developing printed electronic devices from layered materials. It is a nice example of how basic materials synthesis and processing can lead directly to applications,"*** he said.

In some electronic applications, it is necessary to modify graphene's electrical properties by opening up a gap in the electronic band structure. Thin nanoribbons of graphene have such a band; however, bottom-up methods to synthesise graphene nanoribbons tend to produce very short ribbons that cannot be used in electronic devices. Researchers working at the Swiss Federal Laboratories for Materials Science and Technology have produced a field effect transistor based on longer graphene nanoribbons produced in a bottom-up process [2]. These transistors exhibit excellent switching behaviour and the results are promising for densely packed, high-performance logic devices.

Another method of tailoring the electronic properties of graphene as well as enlarging its application scope is functionalisation – attaching different molecular groups to the graphene structure. However, pristine graphene is chemically inert, making selective and controllable covalent functionalisation highly challenging.

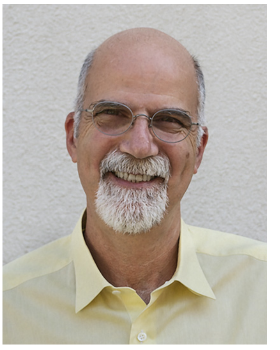
A new method for chemical functionalisation has been developed by researchers at CSIC by first introducing single-atom hole defects in the graphene lattice by ion irradiation [3]. The desired functional molecules bond to these highly reactive holes, providing excellent control over the degree of functionalisation. Importantly, the electrical properties of graphene are not degraded, enabling this functionalised graphene to be used in high-performance sensors, field-effect transistors and other electronic devices.

[1] A. G. Kelly *et al., Science* **356**, 69 (2017)

[2] J. P. Llinas *et al., Nat. Commun.* **8**, 633 (2017)

[3] R. A. Bueno *et al., Nat. Commun.* **8**, 15306 (2017)

Health and Environment



Maurizio Prato

The Graphene Flagship is committed to responsible development of technologies based on graphene and related materials (GRMs). Within the Health and Environment Work Package, potential risks to humans, animals and the environment are assessed to guide the development of safe materials and technologies.

WORK PACKAGE LEADER
Maurizio Prato, University of Trieste, Italy

WORK PACKAGE DEPUTY
Alberto Bianco, National Centre for Scientific Research (CNRS), France

For human health, there are several possible routes of exposure to through use of GRM-based technologies or in their manufacturing processes: skin contact, inhalation and ingestion. Flagship researchers have conducted studies into the effects of various GRMs on different skin cells to understand potential health risks and inform safety-by-design approaches.

Researchers from the University of Trieste, the University Castilla-La Mancha and CIC BiomaGUNE have studied the effects of different types of graphene or graphene oxide (GO) flakes on skin cells [1]. The researchers found that skin cells were damaged only after contact with very high concentrations and extended exposure times, indicating an acceptable biocompatibility after both short and long-term exposure. These results indicate that the cytotoxicity of these graphene-based materials is lower than other carbon-based nanomaterials such as nanotubes.

"We have found that graphene is not devoid of safety concerns. However, the amounts that are necessary to stimulate a reaction, at the skin level, are so high and the exposure so persistent, that these conditions are very unlikely to occur," said Maurizio Prato, leader of the Health and Environment Work Package.

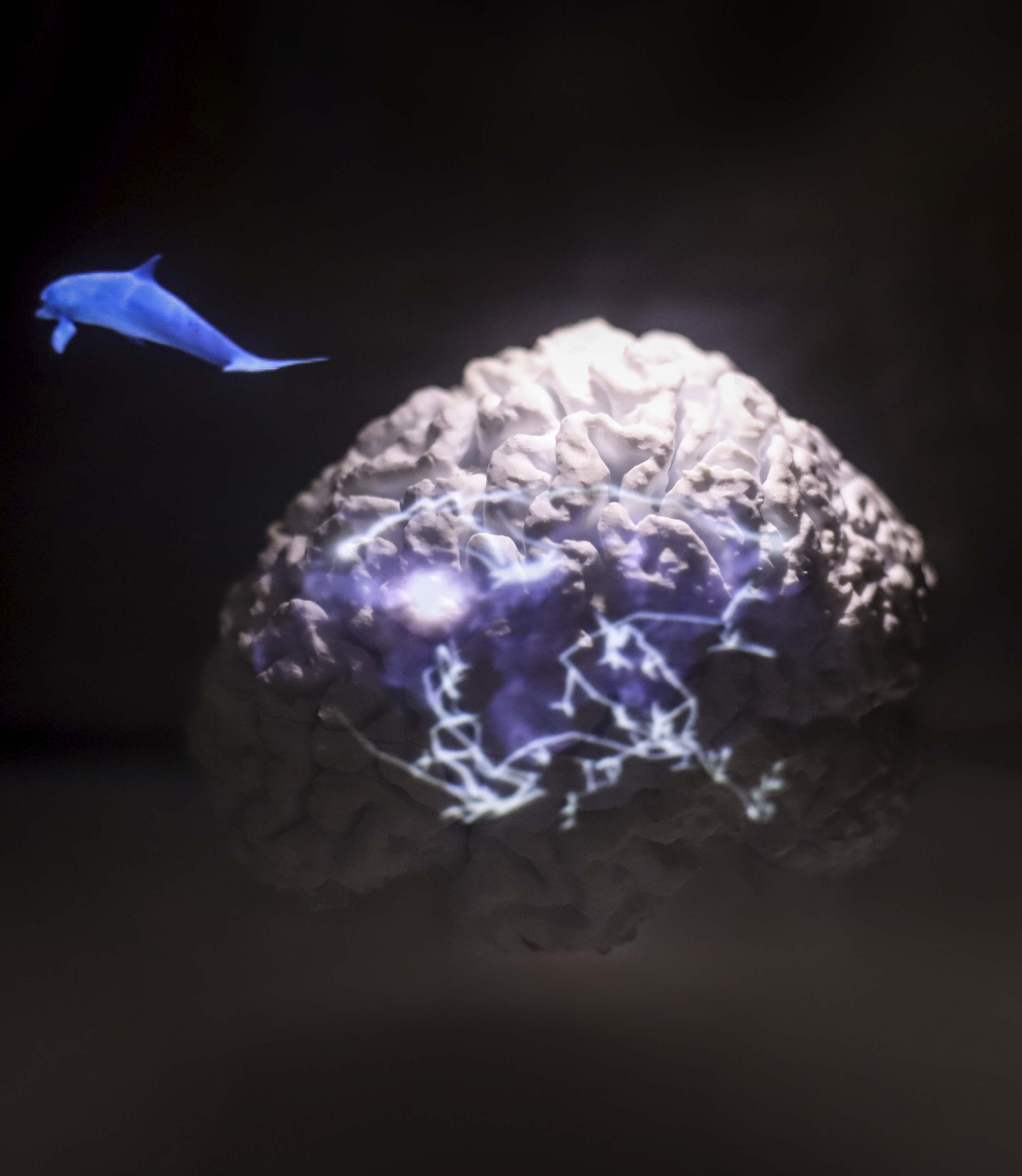
One important aspect of understanding the effect of GRMs in the human body is the immune response, the body's first line of defence against foreign materials. Research from Flagship scientists working at Karolinska Institute and the University of Manchester has shown that graphene oxide (GO) can be rapidly degraded by human neutrophil cells, part of the body's immune response [2]. Further, the researchers also investigated the effect of the by-products of this degradation on lung cells, finding that the degraded GO is non-toxic for human lung cells and does not cause damage to DNA.

GO is more reactive than pristine graphene and can be more easily functionalised, making it highly attractive for a range of applications including biomedicine and drug delivery, antimicrobial coatings and water purification. Flagship researchers working at University of Strasbourg, CNRS and the University of Manchester have demonstrated that biodegradation of GO by enzymes is strongly dependent on the type of functionalisation and can be enhanced using specific functional groups [3]. This opens the path to designing safer GRMs that break down more readily in the environment.

[1] M. Pelin *et al., Sci. Rep.* **7**, 40572 (2017)

[2] S. P. Mukherjee *et al., Nanoscale* **10**, 1180 (2018)

[3] R. Kurapati *et al., 2D Mater.* **5** 015020 (2018)



Biomedical Technologies

The excellent electrical and chemical properties of graphene combined with its biocompatibility provide exciting opportunities for new biomedical applications. Research within the Graphene Flagship's Biomedical Technologies Work Package is focused on developing clinically-relevant devices and therapies as well as advanced neural interfaces for neuroscience research applications.

Kostas Kostarelos

WORK PACKAGE LEADER
Kostas Kostarelos, University of Manchester, United Kingdom

WORK PACKAGE DEPUTY
Jose Garrido, Catalan Institute of Nanoscience and Nanotechnology (ICN2), Spain

Electrically active neural implants are a promising approach for treatment of a wide range of different sensory and motor disorders with neurological origins. Neural implants can act as interfaces between the brain and external devices, by recording, monitoring and stimulating brain activity. Such brain-machine interfaces could be used to intervene with central nervous system motor functions, for example, for better control of prosthetic limbs or communication with devices.

Neural interface devices currently in use are generally designed to perform a single function – either record or stimulate brain activity – and are typically large in size. Graphene and related materials (GRMs) offer several benefits as novel components for the engineering of neural interfaces [1], including multifunctionality and biocompatibility. Researchers within the Graphene Flagship are exploring how GRMs can improve different types of flexible neural interface devices.

The flexibility of graphene means that the implants can conform to the surface of the brain, offering a more efficient interface between the active substrate and the brain. Graphene's intrinsic low noise is highly promising for high-sensitivity neural implants that can detect neural activity at the level of μV, enabling detection of subtle and previously unexplored neuronal activity. Graphene's sensitivity also means that the implant's active sites can be very small, allowing arrays of probes with high spatial resolution.

Flagship researchers working at ICN2, CSIC, CIBER and IDIBAPS have reported flexible neural implants with very low noise levels [2]. Using a flexible array of graphene field-effect transistors, the implants successfully detected slow-wave activity, synchronous epileptic activity and audio-visual responses in rats, matching the performance of state-of-the-art platinum electrode implants.

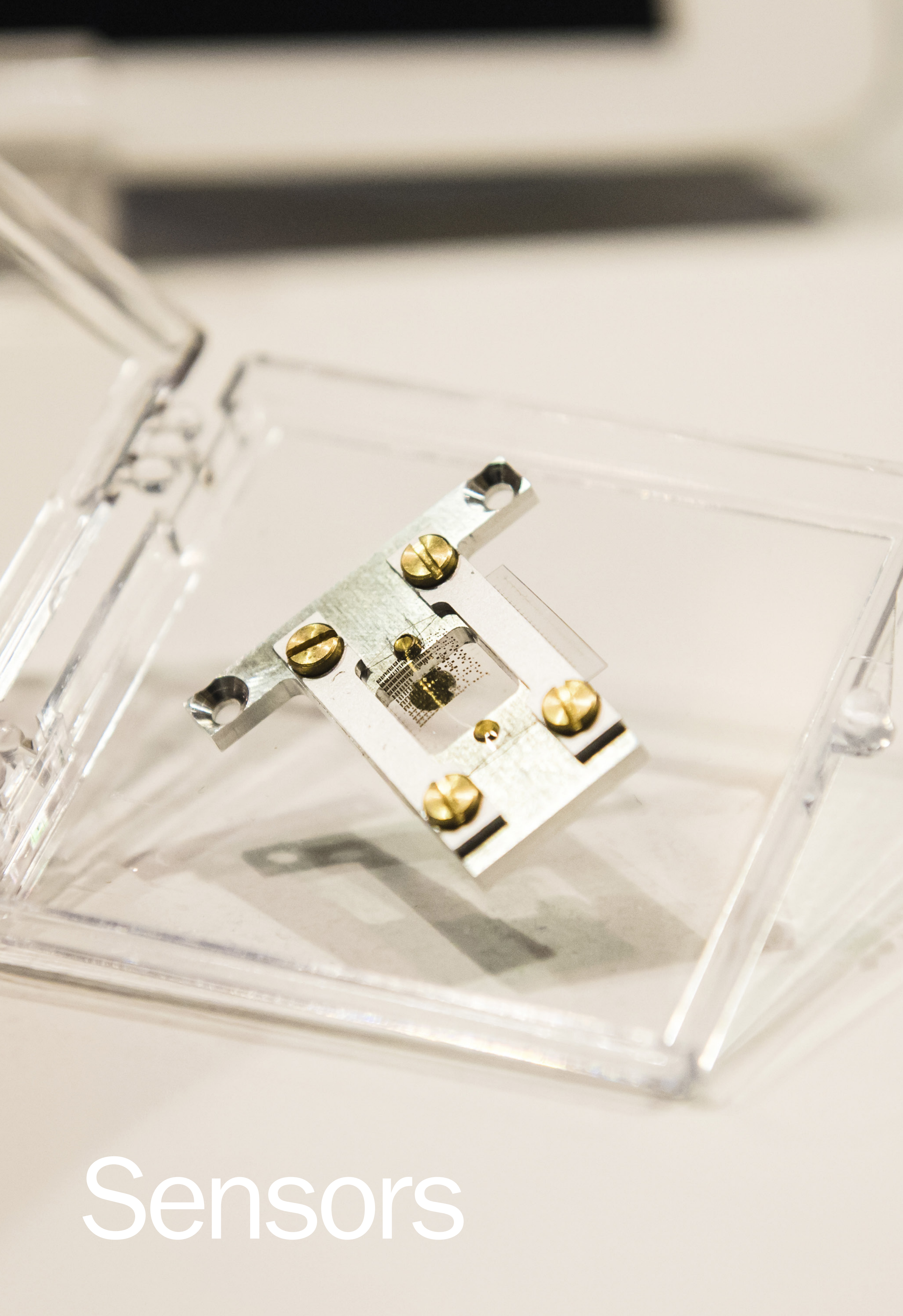
Graphene is also being explored as a novel platform for the local delivery of therapeutic molecules with encouraging early results [3]. Functionalisation of graphene and graphene oxide can tailor their properties and enable their use as carriers of therapeutic molecules, while their biosensing, optical and photothermal properties are also being exploited for combinatory interventions.

Kostas Kostarelos (University of Manchester), leader of the Biomedical Technologies Work Package, said: ***"Graphene presents exciting opportunities for biomedicine. In the Core 2 phase, we will continue to focus on the preclinical development of advanced types of neural interface devices using GRMs, with the aim to take them closer towards clinical applications."***

[1] K. Kostarelos *et al., Adv. Mater.* **2017**, 1700909 (2017)

[2] C. Hébert *et al., Adv. Funct. Mater.* **2017**, 170 3976 (2017)

[3] M. Vincent *et al., Gene Ther.* **24**, 123 (2017)



Sensors

Graphene's excellent electrical properties and sensitivity to its environment make it ideal for a range of sensing applications. As sensors become increasingly important in our daily lives – with the rise of the Internet of Things and automated processes – the Graphene Flagship is exploring new ways of sensing the environment around us.


Herre van der Zant

WORK PACKAGE LEADER
Herre van der Zant, Delft University of Technology , The Netherlands

WORK PACKAGE DEPUTY
Sanna Arpiainen, VTT Technical Research Center of Finland, Finland

Targeting detection of pollutant gases, researchers at the University of Tartu have developed an "electronic nose" based on graphene sensors. Mimicking the workings of the human nose, the electronic nose consists of an array of graphene-based gas sensors functionalised by pulsed laser deposition. With different functionalisation, each sensor can be made to respond differently – producing a unique response profile that allows gases and pollutants to be identified. A working prototype of the electronic nose was presented at the Tallinn Digital Summit in September 2017.

As well as the type of gas, detecting changes in gas pressure is also significant. Researchers working at Delft Technical University have developed on-chip pressure sensors capable of sensing pressure changes down to 25 mbar [1]. Using graphene membranes suspended over quartz-based substrates, the pressure sensors exploit capacitive effects to deliver an all-electrical readout. These highly sensitive gas pressure sensors are ideal for small, low-power applications including the Internet of Things and monitoring industrial processes.

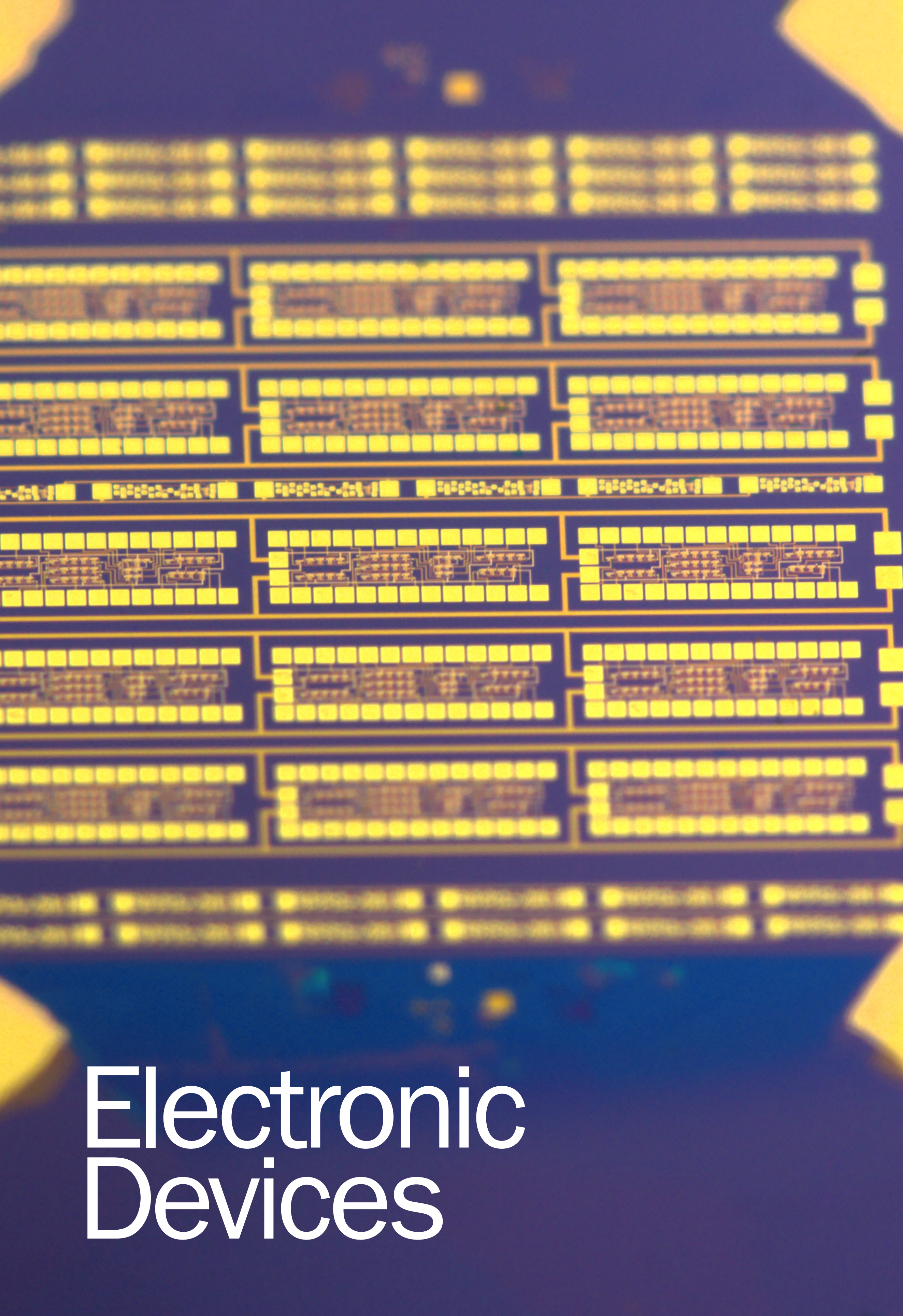
Graphene oxide readily absorbs water and is ideal for humidity sensing. Using printed graphene oxide on printed graphene RFID antennas, researchers at the University of Manchester produced a humidity sensor that can be monitored wirelessly [2]. The absorption of water by the graphene oxide affects the response of the antenna, allowing wireless sensing without a power source.

Industry partner Prognomics Ltd. is focussing its efforts to take graphene-based biosensors to the market. Multiplexed prototypes have been developed for applications such as point-of-care detection of cardiac biomarkers. This is a significant step towards quasi-real time diagnostic aids for early detection of myocardial infarction, enabling more effective and efficient intervention.

"These exciting developments once again confirm the potential that graphene offers for sensor solutions; the next phase is to transfer these proof-of-principle experiments to real applications," said Herre van der Zant (TU Delft), leader of the Sensors Work Package.

[1] D. Davidovikj *et al., ACS Appl. Mater. Interfaces* **9**, 43205 (2017)

[2] X. Huang *et al., Sci. Rep.* **8**, 48 (2018)



Electronic Devices

Translating the excellent electronic properties of graphene and related materials (GRMs) into new technologies surpassing the current state-of-the-art is the aim of the Flagship's Electronic Devices Work Package. Targeting high performance and high frequency electronic devices, researchers across the Graphene Flagship have made progress in several key areas this year.

Daniel Neumaier

WORK PACKAGE LEADER
Daniel Neumaier, AMO, Germany

WORK PACKAGE DEPUTY
Herbert Zirath, Chalmers University of Technology, Sweden

In a landmark result, researchers from Vienna University of Technology created a microprocessor based on molybdenum disulphide (MoS_2), a layered transition metal dichalcogenide. With 115 MoS_2 transistors, this processor is the most complex GRM circuit to date [1].

"This is a crucial step towards application, reaching a new integration level, and demonstrating the reproducibility and maturity of the technology," said Daniel Neumaier, leader of the Electronic Devices Work Package. ***"Future work needs to concentrate on increasing the performance on a single device level and further increasing the integration level."***

High frequency electronics cover frequencies from microwave to terahertz and have applications in the Internet of Things, communications, medical imaging, security and energy harvesting. High frequencies require different generation, modulation and detection schemes compared to lower frequency radiation. Researchers in the Graphene Flagship are developing high frequency components for integrated electronics. Researchers at RWTH Aachen and AMO have demonstrated an integrated microwave receiver entirely fabricated on glass that can receive and process complex digital communication signals at 2.45 GHz [2].

Researchers from Chalmers University of Technology have developed a flexible terahertz detector capable of detecting frequencies between 330-500 GHz [3]. Built on flexible plastic substrate, the detector could be ideal for high speed communication in the Internet of Things and wearable electronic devices.

An important issue for high frequency electronics is keeping the components cool during operation. Research from UPMC Sorbonne, ICFO and other Flagship partners has shown a new and extremely efficient cooling mechanism for graphene-based nanoelectronics [4,5]. With a hexagonal boron nitride (hBN) substrate, phonon vibrations in graphene transistors are transferred into the hBN, leading to strong cooling effects. ***"This result shows that excellent current saturation in graphene transistors can be achieved using hyperbolic phonon cooling – an important and previously unsolved issue for exploiting graphene transistors in RF applications,"*** said Neumaier.

[1] S. Wachter *et al., Nat. Commun.* **8**, 14948 (2017)

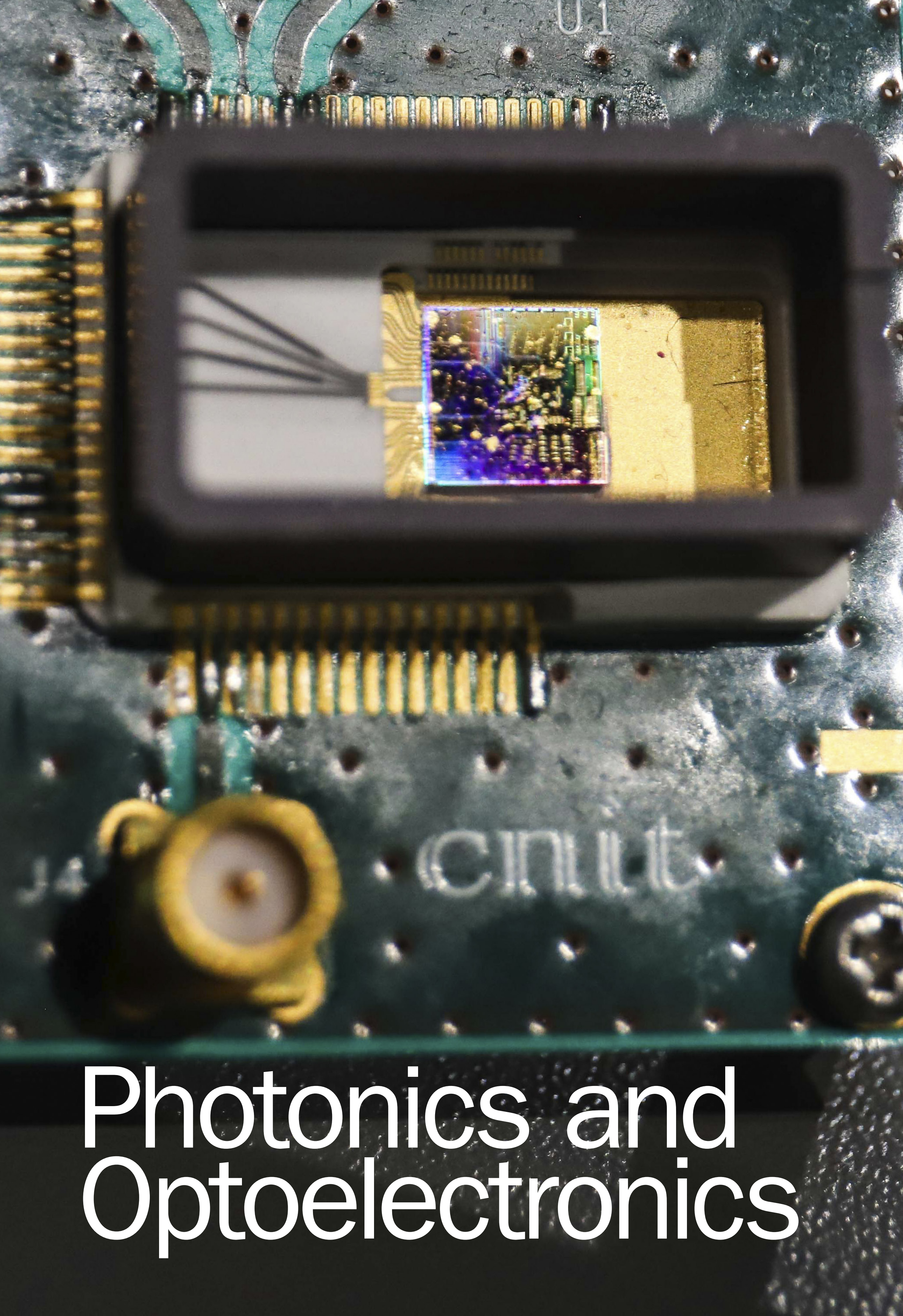
[2] M. Saeed *et al., Nanoscale* **10**, 93 (2017)

[3] X. Yang *et al., Appl. Phys. Lett.* **111**, 021102 (2017)

[4] W. Yang, *et al., Nat. Nanotechnol.* **13**, 47 (2018)

[5] K. J. Tielrooij, *et al., Nat. Nanotechnol.* **13**, 41 (2018)

Photonics and Optoelectronics



Graphene's combination of electrical and optical properties is exciting for a range of photonics and optoelectronics applications, in which light is manipulated, detected and controlled electrically. A key focus of the Graphene Flagship's Photonics and Optoelectronics Work Package is the use of graphene-based technologies to send and receive optical data signals.


Frank Koppens

WORK PACKAGE LEADER
Frank Koppens, Institute of Photonic Sciences (ICFO), Spain

WORK PACKAGE DEPUTY
Andrea Ferrari, University of Cambridge, United Kingdom

Ultrafast photodetectors are needed for next generation and 5G optical communications systems. Researchers from AMO have demonstrated detectors with a measured bandwidth of more than 76 GHz [1] – suitable for data transfer rates of more than 100 Gb/s. In fact, the measured bandwidth was limited by the experimental set-up, meaning these devices could be used to detect significantly larger data rates. A key feature of this result is the 6"-wafer-based fabrication, providing a clear route to integration with existing silicon communications systems.

Information is encoded into optical data streams by modulation of light. It is therefore extremely important to be able to modulate light very quickly for fast data rates. Using a graphene-silicon device, Flagship researchers working at CNIT, IMEC and the University of Cambridge have developed a phase modulation platform operating at 5 GHz, allowing a data rate of 10 Gb/s [2]. These optical modulators are highly efficient and comparable or better than state-of-the-art silicon-based technologies, giving error-free transmission up to 50 km.

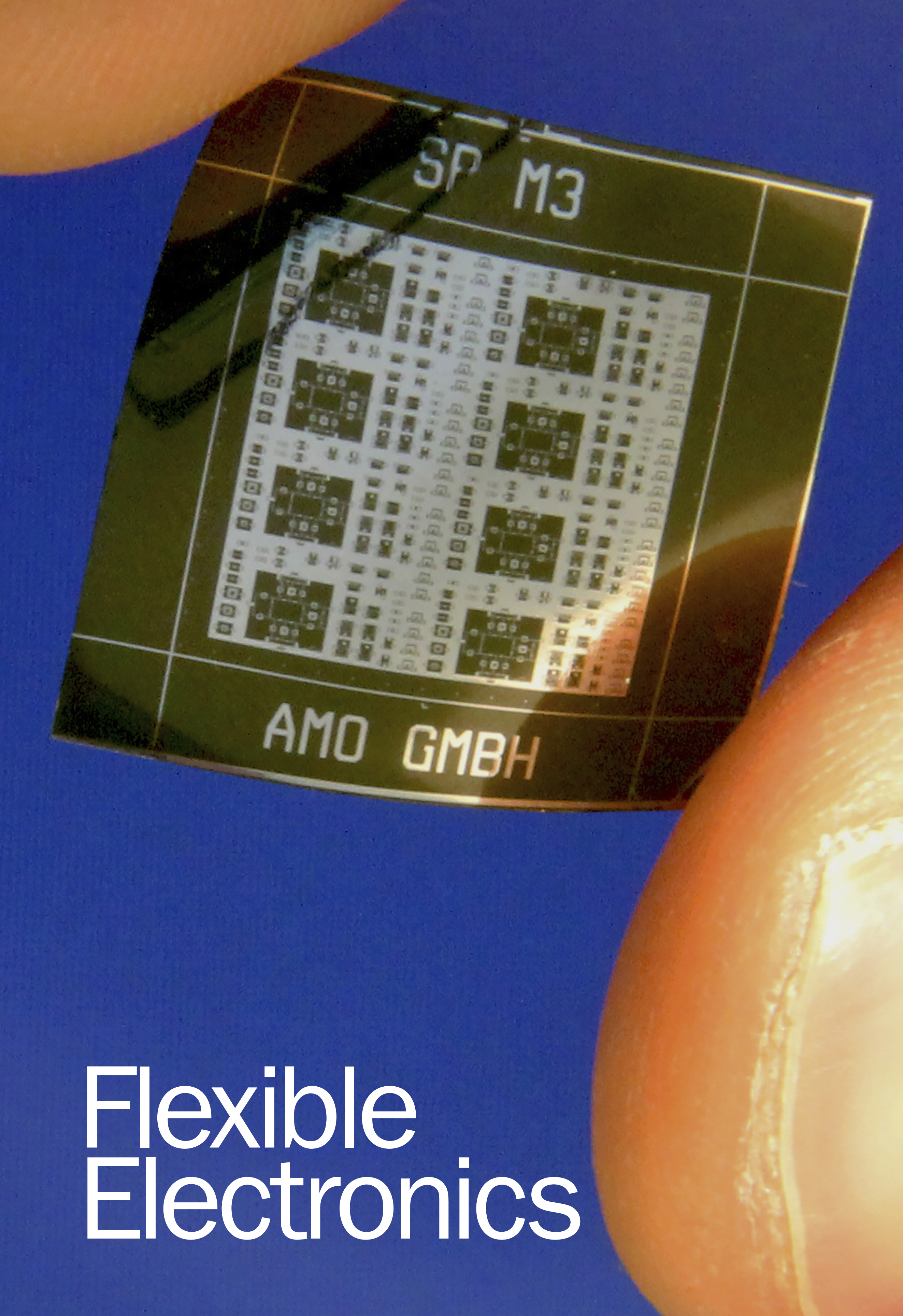
A significant result from the past year is the use of graphene in a CMOS-compatible, broadband camera sensor. Using off-the-shelf read-out-integrated-circuit (ROIC), researchers at ICFO demonstrated a highly sensitive graphene-based camera using back-end-of-line electronics integration technologies [3]. The 388 × 288-pixel sensor is capable of hyperspectral imaging over an extremely wide spectrum, detecting ultraviolet, visible and infrared light. These compact sensors are ideal for automotive applications such as self-driving cars as well as portable spectrometers for food safety and quality checking.

Frank Koppens (ICFO), leader of the Photonics and Optoelectronics Work Package, said: ***"It's really exciting to see that the first graphene-based photodetection device is making it to the market this year. Together with several 5G demos at the Mobile World Congress and even at the Ericsson exhibition stand, we can see more and more market pull."***

[1] D. Schall *et al., J. Phys. D: Appl. Phys.* **50**, 124004 (2017)

[2] V. Sorianello *et al., Nat. Photonics* **12**, 40 (2017)

[3] S. Goossens *et al., Nat. Photonics* **11**, 366 (2017)



Flexible Electronics

Henrik Sandberg

Flexible electronics is an area of strong market interest. The flexibility of graphene and related materials (GRMs) offers unique opportunities to develop fully flexible devices. This year has seen a combination of cross-Flagship results that demonstrate real progress towards flexible electronics.

WORK PACKAGE LEADER
Henrik Sandberg, VTT Technical Research Center of Finland, Finland

WORK PACKAGE DEPUTY
Sebastiano Ravesi, ST Microelectronics, Italy

The development of flexible electronics has several challenges including material performance and function, production and processing using industry-accepted techniques and cost. During the last year, developments in flexible functional devices and materials processing methods have brought fully flexible electronic devices several steps closer.

Flexible electronics are of increasing interest for wearable technologies and the Internet of Things. At Mobile World Congress 2018, Flagship partners RWTH Aachen, AMO, the University of Cambridge and Novalia presented several different types of flexible circuits – building blocks for fully flexible devices. As well as logic circuits, they also presented a microwave-frequency wireless communication receiver, ideal for connecting flexible devices to networks.

For fully flexible electronics, flexible power solutions are required. Using a patented electrochemical exfoliation technique (see Functional Foams and Coatings, p30-31), researchers at TU Dresden developed flexible, all-solid-state graphene-based supercapacitors [1]. These supercapacitors showed excellent energy and power density and could be produced at scale to satisfy power requirements for some flexible electronics.

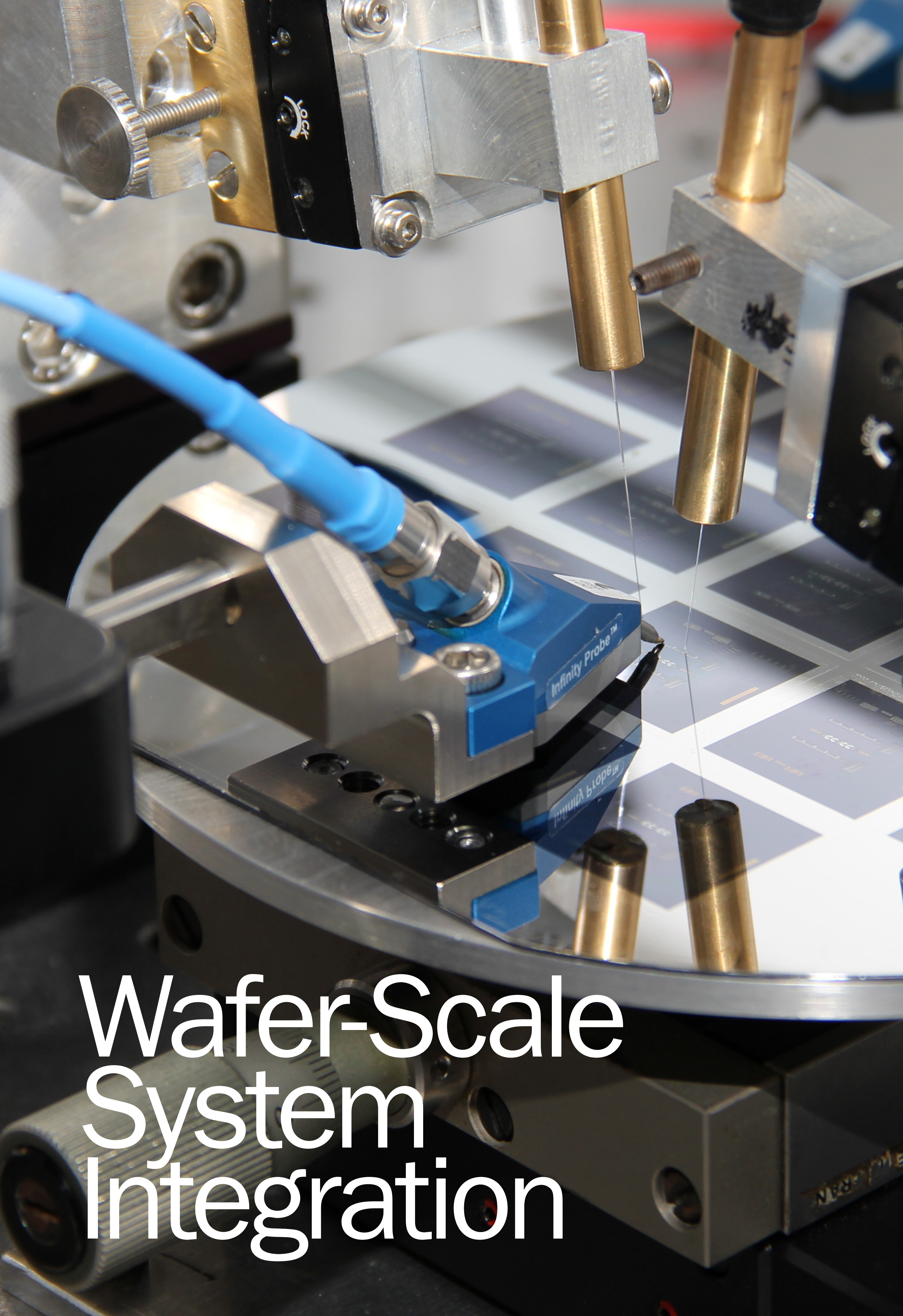
To scale flexible electronics technologies, production methods that preserve the strong properties of GRMs alongside their flexibility are essential. There have been significant advances in printed electronics this year using different GRMs (see Enabling Materials, p10-11), and these methods will be suitable for high-volume, low-cost applications such as smart packaging. Several sensor applications for wearables or large area, low cost applications utilising GRMs processed from dispersions were also displayed at Mobile World Congress 2018. Particularly for the wearable technology markets, methods to produce flexible integrated electronics are essential. Researchers at Aalto University have devised a method to transfer wafer-scale graphene films for processing into flexible electronic devices [2]. The versatility of this technique was demonstrated with wearable touch panels, a strain sensor and a self-powered triboelectric sensor.

Henrik Sandberg (VTT), leader of the Flexible Electronics Work Package, said: ***"There has been much progress in flexible electronics towards wearable devices, especially focussing on sensing functionality and autonomous devices, requiring no wired connection for power supply or data transmission. New advances in hybrid integration technologies for combining exfoliated and grown GRM together with mainstream microelectronics components and novel power generation and storage have brought us closer to flexible electronics applications."***

[1] H. Li *et al.*, *Adv. Energy. Mater.* **7**, 1601847 (2017)

[2] M. Kim *et al.*, *2D Mater.* **4**, 035004 (2017)

Wafer-Scale System Integration



Integration with silicon-based electronics is essential to take advantage of graphene's potential for high-performance electronics. Developing processing methods to take graphene research out of the laboratories and into silicon-electronic processing foundries is the focus of the Wafer-Scale System Integration Work Package.


Marco Romagnoli

WORK PACKAGE LEADER
Marco Romagnoli, CNIT, Italy

WORK PACKAGE DEPUTY
Cedric Huyghebaert, IMEC, Belgium

This year, Flagship researchers have made great progress in the scaling of graphene processing on wafer-based electronic and photonic chips, particularly within optical communications. The rise in data communication and the Internet of Things are placing higher and higher demands on communication infrastructure. Aiming at 5G and beyond, graphene has real potential for next-generation communication systems.

The Graphene Flagship is accelerating GRM-based innovation by partnering with leading industry figures. A Flagship collaboration involving partners in Ericsson, Nokia, CNIT, IMEC, AMO, RWTH Aachen, the University of Cambridge and ICFO are developing new technologies for data communications. One of the results of this collaboration is a prototype of an ultra-fast photonic switch, designed for 5G networks operating at 100 Gb/s. The fully packaged switch prototype was exhibited to an audience of telecommunications experts at the Ericsson stand at Mobile World Congress 2018.

Also on display at Mobile World Congress 2018 was a fully-integrated graphene data link, produced by CNIT, IMEC, AMO and RWTH Aachen. This link is the first integrated transceiver in which all electro-optical operations are achieved using graphene: a graphene-based modulator encodes electronic data onto an optical signal, while a graphene photodetector receives the signal and converts it back into an electronic signal. Operating at 25 Gb/s per channel, the graphene data link matches the state-of-the-art in photonics. These excellent results are pointing the way towards high-performance, graphene-based telecommunications systems.

This year also saw key results in integrating optical detectors with wafer processing systems. Flagship industry partner Emberion this year launched a digital, single-pixel photodetector module that illustrates the maturity of graphene-based photosensors. The hyperspectral sensor operates in the short-wave infrared-ultraviolet spectral ranges and is marketed for industrial sensing applications. The commercial production of integrated photodetectors is a significant milestone for the Graphene Flagship.

Marco Romagnoli (CNIT), leader of the Wafer Scale System Integration Work Package, said: ***"This year, we have demonstrated the global relevance for graphene in this field. Next, we have to engineer all aspects of our devices to show graphene can compete in technology and costs."***

Energy Generation

Developing sustainable power sources is a key issue for our technology-driven society. Due to their excellent electrical properties, GRMs present excellent opportunities in new power sources. Researchers in the Graphene Flagship are developing this potential into large-scale and industrially viable technologies that will satisfy the growing demands for electrical power.


Emmanuel Kymakis

WORK PACKAGE LEADER
Gerard Gebel, French Alternative Energies and Atomic Energy Commission (CEA), France

WORK PACKAGE DEPUTY
Emmanuel Kymakis, Technological Educational Institute of Crete, Greece

Perovskite solar cells (PSCs) are highly promising as next-generation solar power sources with very high efficiency at converting sunlight into electricity. Flagship researchers are making excellent progress in improving the long-term lifetime and performance, while at the same time reducing the production cost of PSCs using GRMs. PSCs are constructed of different layers – in the photoactive perovskite layer, electron-hole pairs are generated by absorption of solar energy, and the electrons and hole are separated. The photogenerated holes and electrons should be efficiently transported from the perovskite layer to the hole/electron transporting materials in order to prevent their recombination. Careful engineering of the interfaces of the perovskite layer with the hole/electron transporters using GRMs improves the solar cell performance and stability.

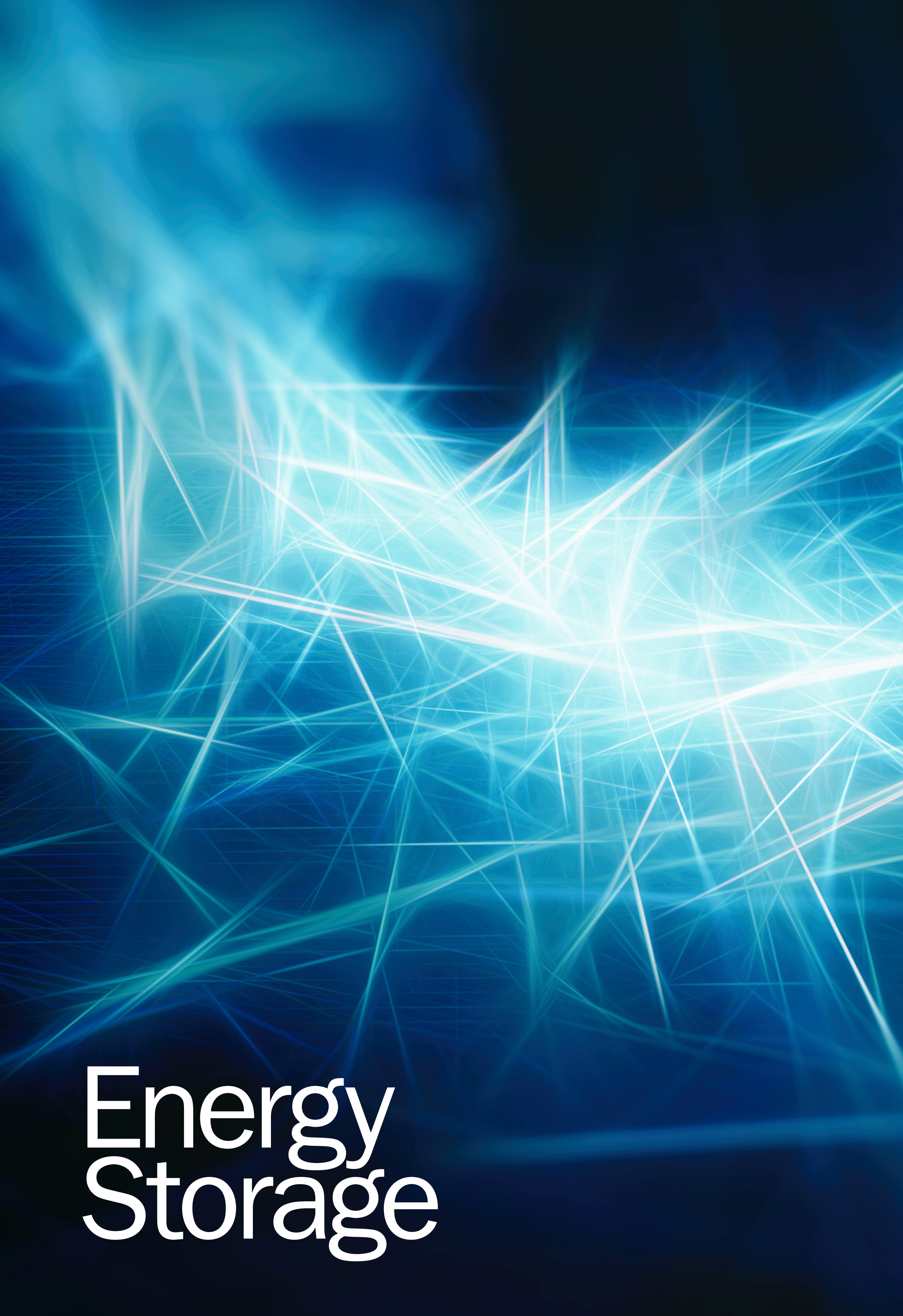
Researchers working at TEI Crete, FORTH, CNR-ISM and the Italian Institute of Technology have demonstrated large-area PSCs with an improved long-term lifetime, retaining 80% of their initial efficiency after 568 hours continuous operation in ambient conditions [1]. This result was achieved using flakes of the layered transition metal dichalcogenide, molybdenum disulphide (MoS_2) as an interlayer between the hole transport layer and the perovskite absorber. Importantly, the addition of the MoS_2 interfacial layer improved the scalability of the solar cell fabrication.

Materials cost of solar cells is a significant issue, and standard hole-transport materials significantly increase the device cost. In a landmark result, researchers from EPFL demonstrated PSCs with efficiency over 20% using a low-cost hole-transport material [2], by adding a reduced graphene oxide spacer layer between the hole transport material and the gold electrode, to stabilise the interface. These devices retained 95% of their initial efficiency after 1000 h of continuous illumination.

Emmanuel Kymakis (TEI Crete), deputy leader of the Energy Generation Work Package, said: ***"These results reveal the beneficial role of GRMs as a fascinating toolbox for mastering the interface properties of the devices, paving the way for the large-scale commercial deployment of graphene-PSCs. In this context, efforts will be focused on the future industrialization of this emerging technology through the establishment of a pilot production line and a 1 kWp GRM-perovskite solar farm in Crete."***

[1] G. Kakavelakis *et al., Adv. Energy Mater.* **2018**, 1702287 (2018)

[2] N. Arora *et al., Science* **358**, 768 (2017)


Energy
Storage

The rise of electric vehicles and the Internet of Things is driving demand for energy storage solutions with high capacity and long lifetimes. Research within the Flagship's Energy Storage work package focuses on developing high-performance batteries and supercapacitor technologies using scalable methods suitable for commercialisation.

Vittorio Pellegrini

WORK PACKAGE LEADER
Vittorio Pellegrini, Italian Institute of Technology (IIT), Italy

WORK PACKAGE DEPUTY
Teofilo Rojo, CIC EnergiGUNE, Spain

Silicon anodes are highly promising for next-generation lithium-ion battery technologies, as they have high energy capacity, but stability remains a barrier to commercialisation. Now, Flagship researchers have overcome this barrier by developing methods for combining few-layer graphene and silicon nanoparticles yielding high performance silicon-graphene anodes. The highly stable anodes maintain 92% of their energy capacity over 300 charge-discharge cycles, with a high maximum capacity of 1500 mAh per gram of silicon [1]. Based on these results, the researchers have realised working full-cell prototypes combining these innovative anodes with commercial cathodes to reach promising energy density values well above 400 Wh/kg.

Importantly, the methods used to produce the silicon-graphene anodes is cost-effective, scalable and compatible with commercial battery electrode fabrication methods. In the Core 2 phase of the Graphene Flagship, a Spearhead project will focus on realising pre-industrial production of a silicon-graphene-based lithium ion battery.

A second key objective for the Energy Storage work package during the Core 1 phase was the development of a spray deposition tool capable of scaling up the fabrication of graphene electrodes for use in supercapacitors and batteries. This tool, designed and built by M-SOLV, has now been installed at the Thales Research and Technology site in Palaiseau. The spray-deposition platform is capable of depositing up to 2 l/min of well-dispersed graphene and other nanomaterials on an area of 300 cm^2, a significant leap forward in scale.

The spray-deposition fabrication method can produce supercapacitors with very high power densities [2]. A spray-deposition technique was also used to fabricate flexible supercapacitors, which were displayed at Mobile World Congress 2018. The high power and long charge-discharge lifetimes of graphene-based supercapacitors are ideal for applications in the automotive industry and the Internet of Things.

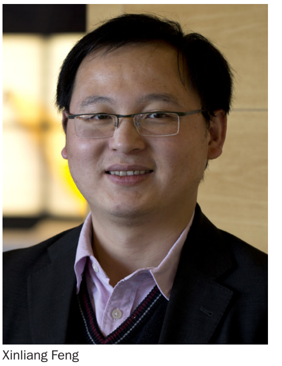
"The results jointly achieved by the partners of the Energy Storage Work Package represent the building blocks for the next phase of the activity, where we want to scale-up our technologies and focus on specific applications," said Vittorio Pellegrini (Italian Institute of Technology), leader of the Energy Storage Work Package.

[1] E. Greco *et al., J. Mater. Chem A* **5**, 19306 (2017)

[2] A. Ansaldo *et al., ChemNanoMat* **2017**, 436 (2017)

Functional Foams and Coatings

Researchers within the Functional Foams and Coatings Work Package are developing new chemical processing and functionalisation methods to deliver GRMs at high-quality and large-scale. These methods open up commercial and technological applications in various sectors, including sensors electronics, photocatalysis, anticorrosion, energy applications and more.


Xinliang Feng

WORK PACKAGE LEADER
Xinliang Feng, Technical University of Dresden, Germany

WORK PACKAGE DEPUTY
Paolo Samori, University of Strasbourg, France

Atmospheric pollution is a significant problem, particularly in urban environments. Some pollutants can be broken down by ultraviolet light in the presence of a photocatalyst such as titanium dioxide (TiO_2). GRMs can extend this photocatalytic activity into the visible range, speeding-up the breakdown of pollutants. Researchers from Italcementi, the University of Bologna, the Israel Institute of Technology and the University of Cambridge have developed and patented effective photocatalysts based on mixtures of GRMs and TiO_2 [1]. These photocatalytic materials are ideal cement additives for smart buildings to enable reduction of urban pollution via self-cleaning cement.

Building on recent work, researchers at TU Dresden have further developed electrochemical methods to produce solution processable, high-quality graphene. Using electrical currents, graphite electrodes can be exfoliated into graphene flakes dispersed in solution. Due to its low cost, speed and high-quality results, electrochemical exfoliation is highly promising for large-scale production of graphene, and yield can be further increased using alternating currents and two graphite electrodes [2,3]. Additionally, it is possible to functionalise the graphene simultaneously with exfoliation [4]. A spin-out company has been established to commercialise these patented production methods.

Aerographite foams have been found to have excellent mechanical and electrical properties and are of interest for a number of applications including energy. Researchers from Kiel University and Hamburg University of Technology have shown that a network of aerographite tetrapods can be used as a lightweight, high-performance electrode for supercapacitors [5]. This work opens possibilities for low-cost and lightweight electrodes with excellent energy and power densities.

Xinliang Feng (TU Dresden), leader of the Functional Foams and Coatings Work Package, said: ***"Our work targets scalable development of GRMs with chemical processing and functionalisation, which hold the potential for a broad range of applications in the fields of coatings and foams. In the last year, remarkable progress has been achieved towards the electrochemical production of functionalised graphene, indoor and outdoor photocatalysis, desalination, energy storage and chemical sensors."***

[1] European Patent No. EP16159215.9.

[2] S. Yang *et al. Angew. Chem. Int. Ed.* **56**, 6669 (2017).

[3] German Patent Application No. 10 2017 207 045.5.

[4] German Patent Application No. 10 2017 223 892.5.

[5] O. Parlak *et al. Nano Energy* **34**, 570 (2017).

Polymer Composites

Composites containing graphene and related materials (GRMs) can be engineered to provide multifunctional benefits, including enhanced mechanical strength, thermal and electrical conductivity and lightness. Research in the Graphene Flagship's Polymer Composites Work Package focuses on developing high-performance composites with a specific target towards applications in large-scale industries such as aerospace, automotive and energy generation.


Costas Galiotis

WORK PACKAGE LEADER
Costas Galiotis, FORTH, Greece

WORK PACKAGE DEPUTY
Ian Kinloch, University of Manchester, United Kingdom

Achievements this year include a rudder for the Airbus A380, designed by Airbus and produced by FIDAMC using carbon fibre- and graphene-embedded epoxy resin; an automotive oil pan developed by CRF using compression moulding technology; and the development of fire-retardant polymers by Avanzare, Interquímica and Nanesa via the addition of GRMs and innovative graphene-papers. Additionally, a collaborative effort from Université libre de Bruxelles, the University of Cambridge, and CNR, working with industry partner Leonardo, demonstrated remarkable improvements in metal wicks for loop heat pipes for heat management in satellites and aerospace applications using graphene coatings.

Costas Galiotis (FORTH), leader of the Composites Work Package, said: ***"In Core 1 we have made great progress towards the incorporation of graphene into commercial products; furthermore, new graphene composite formulations have emerged with enhanced multifunctionality."***

Flagship researchers working at the University of Manchester have developed a high-precision model to determine the mechanical effects of adding graphene nanoplatelets to polymers with different Young's moduli [1], providing a strong step towards full understanding of the mechanical properties of graphene polymers. The key variables are the aspect ratio, orientation and the degree of stress transfer between the graphene and the polymer.

One factor affecting the degree of reinforcement in graphene-polymer composites is the presence of wrinkles in the graphene. Researchers from FORTH found that the formation of wrinkles in graphene sheets embedded in polymers does not necessarily have an adverse effect on the load-bearing capabilities of such composites [2,3]. In particular, by designing composites that contain graphene with large wavelength wrinkling, the stress transfer from the polymer to the graphene can be improved, paving the way for affordable multi-layer graphene composites with higher stress-transfer efficiency.

Adding GRMs to composite materials often provides multifunctional benefits. Research involving Flagship scientists from CSIC and Queen Mary University of London showed that adding graphene oxide and carbon nanotubes can lead to electrically conductive rubbers with enhanced strength, as well as icephobic properties [4]. These composites are highly promising as multifunctional, frost-resistant rubbers for the automotive and aviation sectors.

[1] R. J. Young *et al., Comp. Sci Technol.* **154**, 110 (2018)

[2] C. Androulidakis *et al., Nanoscale* **9**, 18180 (2017)

[3] C. Androulidakis *et al., Appl. Mater. Interfaces* **9**, 26593 (2017)

[4] L. Valentini *et al., Comp. Sci Technol.* DOI: 10.1016/j.compscitech.2018.01.050 (2018)

Production

Ken Teo

To bring graphene-based technologies to market, full-scale industrial processes are needed. The Production Work Package focusses on establishing manufacturing capabilities for technologies based on graphene and related materials (GRMs).

WORK PACKAGE LEADER
Ken Teo, Aixtron, United Kingdom

WORK PACKAGE DEPUTY
Tamara Blanco, Airbus, Spain

"By bringing together the very best manufacturing companies in Europe into a value chain, the Production Work Package aims to enable large scale manufacturing of GRMs and their end products," said Ken Teo (AIXTRON), leader of the Production Work Package.

Several key results have been achieved this year by companies working within the Graphene Flagship. Targeting applications in flexible and large-area electronics, AIXTRON have demonstrated large-scale deposition of graphene onto foil in a roll-to-roll process, opening up possibilities for integrating graphene growth into inline manufacturing processes. Graphenea have developed a transfer technology based on tiling to achieve high quality graphene on large area substrates. Avanzare have increased the scale of production of GRMs to tonnes per year; their material is used by Flagship partners to develop applications in composites and energy storage.

One key sector where graphene is expected to make a significant impact is in aerospace applications. Graphene can give multifunctional benefits to composites, including increased mechanical properties and conductivity. To protect against lightning strikes, the composite structures of aircraft contain metal meshes or have embedded conductive wires. Graphene-containing composites could provide lightning-strike protection with the advantage of a simplified production process and weight reduction.

This year, a team comprising engineers and scientists from Airbus, Aernnova and Grupo Antolin have developed a prototype aircraft component using a graphene-based composite material. A section of the horizontal tail plane leading edge (HTPLE) of the Airbus A350 XWB was manufactured using industry standard resin transfer moulding of a graphene-based composite. The performance of this prototype component will be validated through electrical, mechanical and impact testing during the Core 2 phase.

Several different types of GRMs (provided by Grupo Antolin) were dispersed at different concentrations into the high-performance epoxy resin for optimisation. The main challenge was the size of the GRMs themselves, which needed to be small enough to disperse evenly within the hierarchical carbon-fibre thermoset composite. Additionally, the concentration of the GRMs could affect the resin during the injection process. Notably, adding the GRMs did not adversely affect the viscosity of the resin, allowing the GRM-containing resin to be injected during the resin transfer moulding process of the prototype aerostructure.

Innovation

"The Graphene Flagship's principal mission is to take technologies based on graphene and related materials from the laboratory to commercial applications. With this quest innovation has become a key focus of the Flagship.

During Core 1 we continued to witness the potential of graphene-based technologies to create market disruptions and transformational innovations.

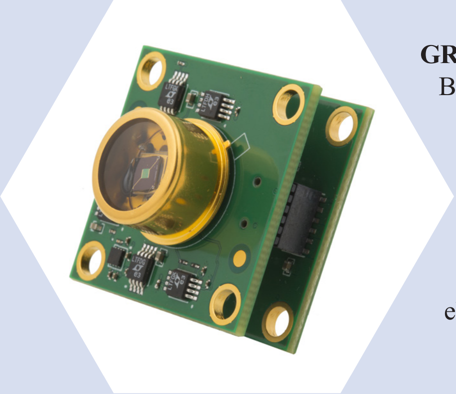
In the next phase we continue to move from materials research towards component development and system-level integration. Our focus is in combining technology push and market pull by working with industry stakeholders to increase technology readiness levels."

Kari Hjelt, Chalmers Industriteknik
Head of Innovation

PRODUCTS

COMMERCIALISING COMPOSITES

Composites applications are among the most mature markets for graphene, with several commercial products already available from Flagship partners. This year, Flagship Partner IIT and Associated Member BeDimensional worked with leading Italian footwear company Fadel to develop Freshoes, shoes with graphene-containing insoles. The insoles, made from polyurethane with added graphene, improve the thermal properties of the shoes, keeping feet comfortable in hot weather.



GRAPHENE LIGHT SENSORS

Based on research conducted within the Flagship framework, Emberion launched a fully packaged photodetector module that can detect light in the visible to short-wave infrared ranges. Aimed at industrial applications including spectrometry, gas detection and power measurements, the low-noise, high-sensitivity detectors are now available for Emberion's customer base. This product is the Flagship's first commercial launch exploiting graphene's unique electro-optical properties.

BRINGING INNOVATION TO INDUSTRY

MOBILE WORLD CONGRESS – MEETING GRAPHENE

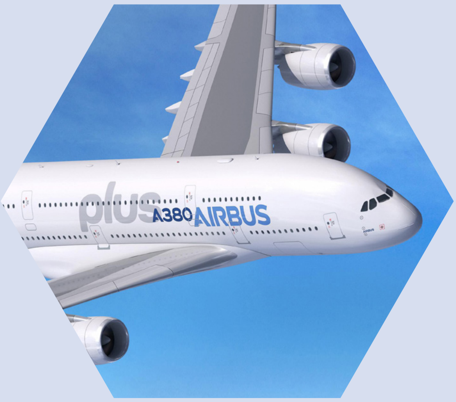
The Graphene Flagship had a strong presence at the 2018 edition of Mobile World Congress, the premier international trade show focused on high-tech and mobile applications. The Graphene Pavilion collected prototypes from 27 partners, demonstrating graphene technologies to a broad audience including senior-level industry representatives The Flagship also held a successful networking event – Meeting Graphene – bringing together industry experts for networking and in-depth discussion.

MEDICA – GRAPHENE CONNECT

Medica is the largest medical trade fair worldwide, focused on innovations in healthcare and biomedicine. At the 2017 edition in Düsseldorf, the Graphene Flagship exhibited a selection of graphene-based biomedical devices to an audience of medical professionals. Alongside the exhibition, the Flagship organised a Graphene Connect workshop focussed on Biomedical Technologies – an opportunity for the medical community to discover more about the biomedical potential of graphene.

AIRBUS MARKETPLACE

The strong potential of graphene for the aeronautics industry was recognised early on by Airbus, a multinational aeronautics company with a long history of embracing materials innovation. In May 2017, Airbus partnered with the Graphene Flagship to hold a Graphene Marketplace symposium where Flagship partner companies showcased demonstrators and prototypes for aeronautic applications.



COLLABORATION WITH EUROPEAN SPACE AGENCY

A cross-Flagship collaboration involving researchers from the Université libre de Bruxelles, the University of Cambridge, CNR National Research Council and industry partner Leonardo have partnered with the European Space Agency to explore the potential of graphene in space applications. In a series of microgravity parabolic flights, the collaboration tested graphene-based coatings for loop-heat pipes – heat management systems used in satellites. This work is being further developed to improve loop heat pipes for commercial space applications.

Partnering Division

"A growing number of Associated Members and Partnering Projects are supporting the Graphene Flagship, enabling an excellent alignment of GRM research across Europe and helping to realise an unprecedented network of industrial and academic partners."

Stefano Borini

DIVISION LEADER
Stefano Borini, Graphitene, UK

DIVISION DEPUTY
Oguz Gülseren,
Bilkent University, Turkey

G-IMMUNOMICS: The G-IMMUNOMICS project investigates the potential health and environmental concerns of graphene-based materials. A large-scale analysis [1] of the effects of graphene-oxide (GO)-based nanomaterials on the immune response of 15 different cell types showed that amine functionalisation improves GO biocompatibility. Using single-cell mass cytometry, the high-throughput method simultaneously identified multiple immune response markers at single-cell level, helping to characterise the complicated interactions between GO and immune cells.

2Dfun: The aim of the 2Dfun project is to develop new techniques for high-volume manufacturing of electronic devices based on GRMs. A method to grow insulating thin films on top of transition metal dichalcogenides (TMDCs) was developed by first depositing small quantities of silicon dioxide [2]. This method will be an essential building block for TMDC-based chip devices. 2Dfun research also found that electrical properties of interfaces of TMDCs on insulators are strongly affected by the production method [3], allowing tuning of the electrical properties of layered GRM devices.

2D-CHEM: For many uses, including biomedical and composite applications, it is useful to add chemical groups to change graphene's chemical properties. The 2D-CHEM project develops scalable synthesis methods to produce graphene-derivatives from fluorographene, a stable and easily synthesised precursor. Such graphene-derivatives include those functionalised with amine, carboxyl, hydroxyl and aromatic functional groups [4, 5, 6]. Significantly, hydroxyl-functionalised graphene shows room-temperature magnetic properties and could be interesting for spintronics applications.

NU-TEGRAM: The aim of the NU-TEGRAM project is to develop porous graphene-polymer-composite membranes for nanofluidics applications. These membranes are expected to provide advantages in water purification and biomedical applications. NU-TEGRAM researchers have developed large-area porous graphene-polymer membranes that can be fabricated to scale [7]. Pores are created in graphene on a polymer support, while selective etching of microchannels in the polymer support increases flow for high-efficiency filtering.

GRIFONE: The GRIFONE project is developing new routes towards the fabrication of electronic devices composed of layers of graphene and semiconducting materials such as metal oxides. Using a combined approach of modelling, transmission electron microscopy and atomic force microscopy, investigating the growth dynamics of these electronic devices is helping to develop controllable production methods compatible with industrial fabrication methods [8].

[1] M. Orecchioni *et al., Nat. Commun.* **8**, 1109 (2017)

[2] H. Zhang *et al., Chem. Mater.* **29**, 6772 (2017)

[3] V. Afanas'ev *et al., ECS Trans.* **80**, 191 (2017)

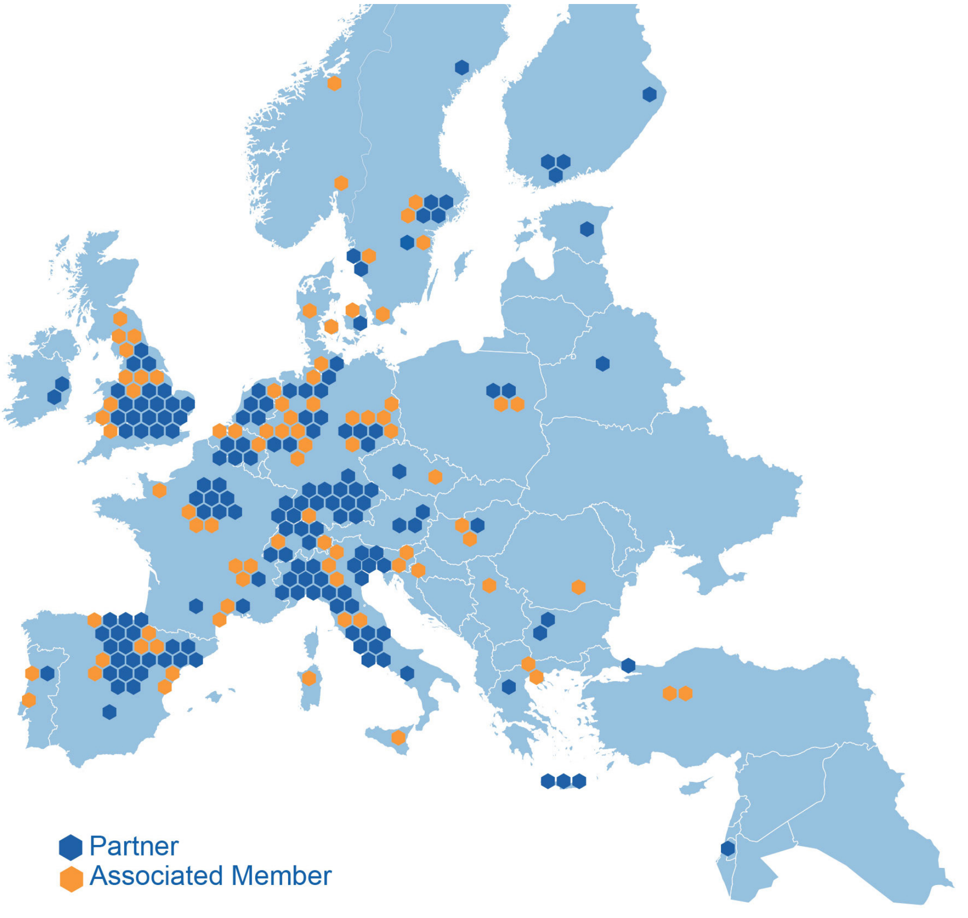
[4] J. Tuček *et al., Nat. Commun.* **8**, 14525 (2017)

[5] D. D. Chronopoulos *et al., Chem. Mater.* **29**, 926 (2017)

[6] A. Bakandritsos *et al., ACS Nano* **11**, 2982 (2017)

[7] L. Madauß *et al., Nanoscale* **9**, 10487 (2017)

[8] A. Kakanakova *et al., Invited Presentation at* XL ENFMC Brazilian Physical Society Meeting, Armação dos Búzios, Brazil, August 27-31, 2017



Partners

AUSTRIA
Guger Technologies OG
Varta Micro Innovation
Vienna University of Technology

BELARUS
Belarusian State University

BELGIUM
University of Namur
Université libre de Bruxelles
IMEC

BULGARIA
Bulgarian Academy of Sciences, Institute of Mechanics
Nano Tech Lab Ltd.

CZECH REPUBLIC
J. Heyrovsky Institute of Physical Chemistry

DENMARK
Technical University of Denmark

ESTONIA
University of Tartu

FINLAND
Aalto University
Emberion OY
University of Eastern Finland
VTT Technical Research Centre of Finland

FRANCE
CEA French Alternative Energies and Atomic Energy Commission
CNRS National Centre for Scientific Research
ESF European Science Foundation
Horiba Jobin Yvon S.A.
Institut National de la Santé et de la Recherche Médicale
Laboratoire National de Métrologie et d'Essais
Pixium Vision
Polymem
Thales S.A.
Université catholique de Louvain
University of Lille
University of Montpellier
University of Strasbourg
UPMC Sorbonne Universités

GERMANY
AMO
BASF SE
Bielefeld University
Bosch
Chemnitz University of Technology
CNM Technologies GmbH
Dresden University of Technology
Fraunhofer-Gesellschaft
Friedrich-Alexander University Erlangen-Nuremberg
Friedrich Schiller Universität Jena
Hamburg University of Technology
Infineon Technologies AG
Institut für Korrosionsschutz Dresden (IKS)
Karlsruhe Institute of Technology
Max Planck Society
Nokia Solutions and Networks GmbH
RF 360 Europe Gmbh
RWTH Aachen University
Technical University Chemnitz
Technical University Dresden
Technical University Munich
Ulm University
University of Augsburg
University of Bremen
University of Freiburg
University of Hamburg
University of Kiel
University of Regensburg
University of Ulm
Universität der Bundeswehr München

GREECE
FORTH Foundation for Research and Technology - Hellas
Technological Educational Institute of Crete
University of Crete
University of Ioannina

HUNGARY
Research Centre for Natural Sciences, Hungarian Academy of Sciences

IRELAND
Trinity College Dublin
University College Dublin

ISRAEL
Technion - Israel Institute of Technology

ITALY
Alcatel-Lucent Italia
Breton S.p.A.
Centro Ricerche Fiat S.C.p.A. (CRF)
CNIT
CNR National Research Council
Delta-Tech S.p.A.
Finmeccanica
FBK Bruno Kessler Foundation

Fondazione Edoardo Amaldi
Greatcell Solar Italia S.r.l.
Grinp S.r.l.
IIT Italian Institute of Technology
INFN - National Institute for Nuclear Physics
Italcementi Group
Libre S.r.l.
Nanesa
Polytechnic University of Milan
Polytechnic University of Turin
Scuola Internazionale Superiori di Studi Avanzati
STMicroelectronics S.r.l.
University of Bologna
University of Padova
University of Pisa
University of Salerno
University of Trieste
University of Tor Vergata

POLAND
Institute of Electronic Materials Technology
University of Warsaw

PORTUGAL
University of Minho

SPAIN
Airbus
Autonomous University of Barcelona
Avanzare
The Biomedical Research Networking Center in Bioengineering, Biomaterials and Nanomedicine (CIBER-BBN)
CIC BiomaGUNE
CIC energiGUNE
CIC NanoGUNE
CSIC Spanish National Research Council
Fundación IMDEA Nanociencia
Fundación para la Investigación, Desarrollo y Aplicación de Materiales Compuestos
Graphenea
Grupo Antolin-Ingenieria S.A.
ICFO Institute of Photonic Sciences
ICN2 Catalan Institute of Nanoscience and Nanotechnology
Institut d'Investigacions Biomèdiques August Pi i Sunyer (IDIBAPS)
Institute of Emerging Chemical Technologies Rioja
Internacional de Composites S.A.
N Vision Systems & Technologies S.L.
Repsol
Tecnalia Research and Innovation
University of Castilla-La Mancha
The University of Zaragoza

SWEDEN
ABB
Chalmers University of Technology
Chalmers Industrial Technology
Ericsson AB
Karolinska Institute
Linköping University
NanOsc AB
Umeå University

SWITZERLAND
École Polytechnique Fédérale de Lausanne (EPFL)
EMPA Swiss Federal Laboratories for Materials Science and Technology
ETH Zurich Swiss Federal Institute of Technology
University of Basel
University of Geneva
University of Zurich

THE NETHERLANDS
Delft University of Technology
DSM Ahead BV
Eindhoven University of Technology
Stichting Katholieke Universiteit
University of Groningen

TURKEY
Sabanci University

UNITED KINGDOM
Aixtron Ltd.
Amalyst Ltd.
Emberion Ltd.
FlexEnable Ltd.
Galvani Bioelectronics Ltd.
Imperial College Science, Technology and Medicine
Lancaster University
M-Solv Ltd.
Nokia Solutions and Networks UK Ltd.
Novalia Ltd.
NPL Management Ltd.
Oxford Instruments
Prognomics Ltd
Queen Mary University of London
University College London
University of Cambridge
The University of Manchester
The University of Nottingham
University of Oxford
The University of Sheffield
University of Sunderland

Associated Members

BELGIUM
Catholic University of Leuven
Toyota Motor Europe
University of Antwerp

CROATIA
Institute Ruder Boskovic

CZECH REPUBLIC
Palacky University Olomouc

DENMARK
LEGO
National Research Centre for the Working Environment
Newtec Engineering A/S

FRANCE
Electricité de France (EDF)
European Synchrotron Radiation Facility
National Graduate School of Engineering & Research Center in Caen
Nawa Technologies
ONERA
Owens Corning Chambery International
SAIREM SAS
Soleil Synchrotron
T-Waves-Technologies (TWT)

GERMANY
Brandenburg Technical University
Dräger Safety AG & Co. KGaA
Evonik Creavis GmbH
IHP GmbH
Jacobs University of Bremen
Leibniz Institute for Polymer Research
Leibniz Institute of Surface Modification
Leibniz University of Hanover
SURAGUS GmbH
TALGA Advanced Materials GmbH
Trevira GmbH
University of Duisburg-Essen
University Hospital Cologne
University of Konstanz
University of Ruhr Bochum
University of Siegen

GREECE
Aristotle University of Thessaloniki
Organic Electronic Technologies

HUNGARY
Budapest University of Technology and Economics
Technical Physics and Materials Science, Centre for Energy Research, Hungarian Academy of Science (MTA EK MFA)

ITALY
3SUN S.r.l.
BeDimensional
GNext
Green Capital Alliance
Instituto P.M. srl
Quanta System
University of Sassari

THE NETHERLANDS
Brains On-line
University of Twente

NORWAY
Abalonyx
Norwegian University of Science and Technology

POLAND
CEZAMAT
TopGaN
Warsaw University of Technology

PORTUGAL
GLEXYZ
Graphenest

ROMANIA
International Center of Biodynamics

SERBIA
Institute of Physics in Belgrade

SLOVENIA
University of Maribor
University of Nova Gorica

SPAIN
AIMPLAS
Autonomous University of Madrid
Graphene Nanotech
Graphene Tech S. L.
National Institute for Agricultural and Food Research and Technology (INIA)
Polytechnic University of Catalonia
University of the Basque Country
Walter Pack

SWEDEN
APR Technologies
Graphensic
KTH Royal Institute of Technology
Lund University
SP Sveriges Tekniska Forskingsinstitut

SWITZERLAND
Imerys
Solaronix AS

TURKEY
Ankara University
Bilkent University

UNITED KINGDOM
ARTIS
BAE Systems (Operations) Ltd.
Eksagon Group Ltd
FGV Cambridge Nanosystems Ltd.
Graphitene Ltd.
Haydale Limited
Institute for Occupational Medicine
NetComposites
Oxford Photovoltaics Ltd.
Robnor Resins Ltd.
Versarien

Andrea C. Ferrari

With the end of Core 1, we are approaching the half-way point of the ten-year Graphene Flagship. Looking back at the science and technology roadmap it is encouraging to see that we are on track with the planned work and translation from laboratories to the factory floor.

An increasing number of patent applications are being submitted by Flagship Partners and Associate Members. Licensing agreement have been signed, products are on the market and several spin-off companies have been launched. The Flagship is now present in major trade-shows, such as the Mobile World Congress, Medica and Composites Europe, besides having leading contributions in all the scientific conferences in Europe and worldwide.

GRMs are at the centre of an ever increasing number of initiatives worldwide. With thousands of materials available that can be combined amongst themselves, there is an almost endless set of possibilities available for future investigation. The Graphene Flagship continues to study the fundamental properties of these new materials and materials combinations, leading the development of both new science and new applications.

In Core 2 the Flagship will be organized around six spearhead projects, with clear and well-defined objectives – application oriented and motivated by market opportunities. Working groups and task forces will take a central role in tackling bottlenecks or key issues so as to achieve synergistic solutions for the benefit of all partners.

We are on the verge of creating a new GRM-based technology. What was a vague hope in 2010, when the coordination action that led to the Graphene Flagship started, and a detailed plan when the Flagship set sail in October 2013, is now steadily becoming a reality.

We need to keep our course steady. We need to consolidate the collaborations and partnership between academic and industrial members of the Flagship. We need to recognize that the Graphene Flagship is enabling European researchers to be at the forefront of science, technology, innovation and industrialization of GRMs, and make the most of this unique opportunity.

Andrea C. Ferrari
Science and Technology Officer

GRAPHENE ROADMAP

THE FUTURE OF GRAPHENE APPLICATIONS

	COMPOSITES	ENERGY	DATACOM
BEFORE 2023	Functional coating and surface modification Structural materials Multifunctional construction materials	Fast-charging batteries	5G, wireless networks
2023 – 2028	Water treatment and desalination	Supercapacitors for warehouse logistics Flexible solar cells	Advanced network infrastructures
AFTER 2028		Fuel cells for transportation	6G and beyond, wireless networks On-chip optical data

	ELECTRONICS	SENSORS AND IMAGING	BIOMEDICAL TECHNOLOGIES
BEFORE 2023	High frequency electronics Low-cost printable electronics	Photodetectors and physical/ chemical sensors Broadband CMOS cameras and spectrometers	
2023 – 2028	Flexible devices		Neural interfaces
AFTER 2028	Spin-logic devices		Drug delivery Bioelectronic medicine

Funded by
the European Union

The Graphene Flagship was launched by the European Union in 2013 as part of its largest research initiative ever. With a budget of €1 billion it represents a new form of joint, coordinated research initiative on an unprecedented scale. The overall goal of the Graphene Flagship is to take graphene from the realm of academic laboratories into European society, facilitating economic growth and creating new jobs in the space of ten years. Through a combined academic-industrial consortium consisting of more than 150 partners in over 20 European countries, the research effort covers the entire value chain, from materials production to components and system integration, and targets a number of specific goals that exploit the unique properties of graphene.

Learn more at graphene-flagship.eu

GRAPHENE FLAGSHIP

graphene-flagship.eu
twitter.com/grapheneca
facebook.com/GrapheneFlagship
youtube.com/user/GrapheneFlagship
instagram.com/grapheneflagship
linkedin.com/company/graphene-flagship

CONTENT AND CONCEPT BY
WORK PACKAGE DISSEMINATION:
Sophia Lloyd
Rebecca Waters
Eugenia Vranjancu
Photo page 14 by Sophia Lloyd