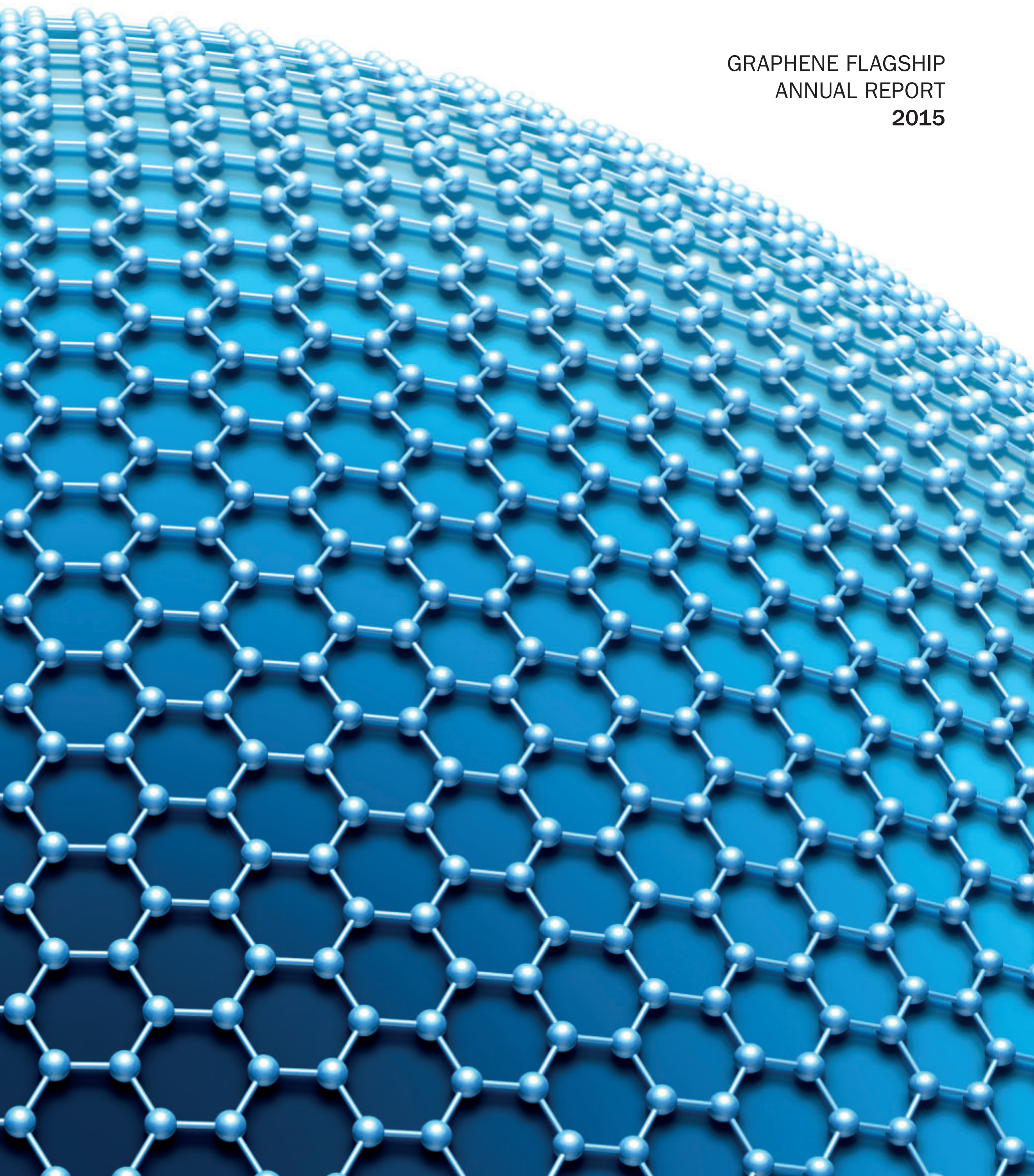
GRAPHENE FLAGSHIP

GRAPHENE FLAGSHIP ANNUAL REPORT 2015



"In the coming year we are about to embark upon new targets and new challenges to strengthen our Flagship as we move into the first Core Project of the Horizon 2020 phase."

As the second year of the Graphene Flagship draws to a close we have arrived at a significant milestone: the ramp-up phase is finished, and with three quarters of the Flagship's journey still ahead we are about to embark upon new targets and new challenges to strengthen our Flagship as we move into the first Core Project of the Horizon 2020 phase.

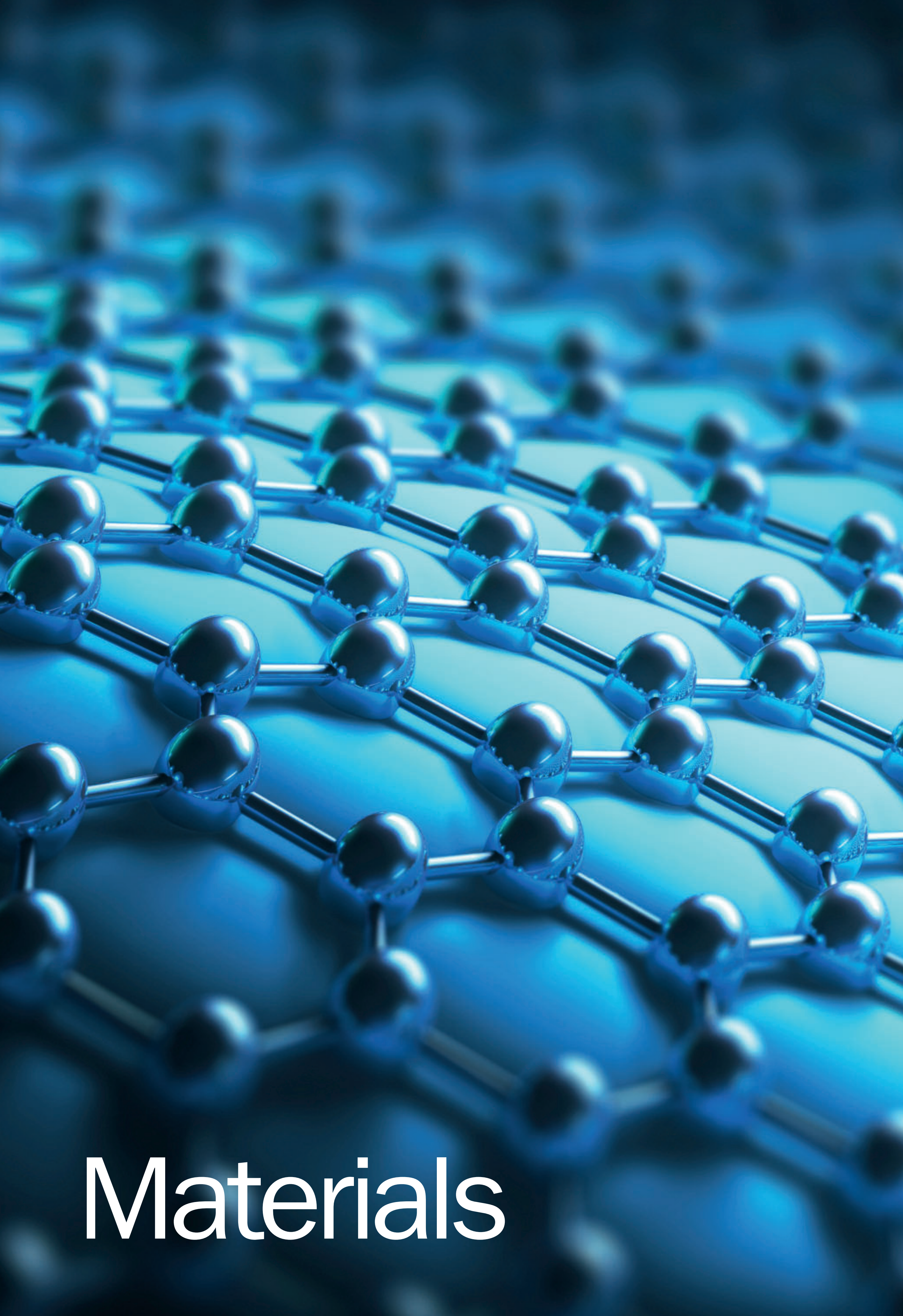
The ramp-up phase has been a success by all accounts. We have in many cases greatly exceeded the goals that we set to ourselves for the number of publications, industrial collaborations etc., and laid a solid foundation for the coming years. We have made many breakthroughs that are described under the different work packages in this report. Among the general highlights from the last year I would like to mention our Science and Technology Options Assessment Workshop at the European Parliament, the largest ever Graphene Week conference in Manchester, and our presence in the 100,000 visitors strong Mobile World Congress in Barcelona.

The number of partners in the Flagship has doubled since we started in October, 2013, and more than 150 partners will participate in the first Core Project under Horizon 2020 – probably the largest number of partners during the entire voyage of the Flagship. In the coming year we will start planning the next Core Project, which will require setting priorities and focusing on the most promising directions.

In the Horizon 2020 phase, the Flagship will comprise both the European Commission funded Core Project and a set of Partnering Projects funded by member states and other organisations. We will be working together with the Partnering Projects to realise the overall goal of the Flagship, boosting economic growth and sustainable development in Europe through the creation of a new disruptive technology.

I am looking forward to another productive and exciting year, discovering new science and creating new technologies together with the entire crew of the Graphene Flagship!

Prof. Jari Kinaret
Director of the Graphene Flagship



Materials

Researchers from the Graphene Flagship have been making great progress on two of the key challenges for large-scale manufacturing of graphene-based products – access to large quantities of high-quality uniform graphene and on-demand tailoring of graphene properties.

Prof. Mar Garcia Hernandez

WORK PACKAGE LEADER
Prof. Mar Garcia Hernandez,
CSIC Spanish National Research Council, Spain

WORK PACKAGE DEPUTY
Prof. Jonathan Coleman,
Trinity College Dublin, Ireland

Prof. Mar Garcia Hernandez, the Materials Work Package Leader from CSIC (Instituto de Ciencia de Materiales de Madrid) outlines some of these exciting steps forward. *"Great progress has been made on various fronts within the work package. Synthesising graphene directly onto a Germanium substrate or producing very high quality graphene on various polar and non polar faces of SiC can both be very useful for the integration of graphene in conventional CMOS technologies. Looking at other 2D materials, easy spectroscopic characterisation techniques have been developed along with new synthesis protocols enabling the ability to tailor their properties. For example, we have reported a process to synthesise semiconducting transition metal dichalcogenides monolayers at scale, tailor the bandgaps of nanoribbons and even Synthesisation BN on 4" wafers or carbon membranes which have excellent filtering properties."*

One group of Flagship scientists, upon focusing their energies on graphene synthesis, were able to grow graphene directly onto dielectric substrates including glass, quartz and silica. This important breakthrough allows graphene to be used without the need to transfer it from the substrate used for its growth (often metallic) onto a dielectric substrate for integration into devices: a process which degrades the graphene material and harms its performance. This direct growth was achieved through remote electron cyclotron resonance plasma assisted chemical vapor deposition and produces mostly monolayer continuous graphene sheets. Importantly the scientists have applied for a patent to protect this novel technique[(1)]. The size and nucleation density of these graphene sheets can be effectively controlled by varying the deposition time and pressure; and their perfect hexagonal shape suggests their single crystal nature.

Commenting on this exciting research Prof. Hernandez says *"This is a very important first step towards the direct growth of graphene on materials that are technologically relevant for the integration of Graphene on Si based electronics. It also opens up the possibility of having large surfaces coated with graphene enabling smart windows or ultra-thin heaters."*

[(1)] Spanish Patent Pending Application nº P201530864

Health and Environment

As all groups within the Flagship move towards the goal of transitioning graphene from the laboratory and into commercialised products, nanosafety has never been more important. The mission of the Work Package Health and Environment is to assess and resolve health and toxicity issues associated with graphene and other 2D materials and to enable integration of graphene with biomedical applications.

Prof. Maurizio Prato

WORK PACKAGE LEADER
Prof. Maurizio Prato,
University of Trieste, Italy

WORK PACKAGE DEPUTY
Prof. Alberto Bianco, CNRS
National Centre for Scientific
Research, France

Over the past year researchers from within the group have made big steps forward on both of these goals. However, before the biological interactions can be studied, an important hurdle needs to be overcome as the Work Package Leader, Prof. Prato from the University of Trieste in Italy, who is also a member of the Graphene Flagship Executive Board, explains:

"As a first achievement of this last year of intense research, we have established an original protocol for the production of graphene that can be easily dispersed in water and allows an easier development of the biological studies."

This relatively simple sounding improvement has paved the way for many different biological studies into the health and toxicity issues surrounding graphene. For example, using these water dispersions, researchers from within the Flagship have published work[(1)] which provides a previously unavailable pharmacological understanding of how graphene oxide (GO) sheets are transported within the body of a mouse; primarily accumulating in the spleen and excreted in the urine.

Also, work package researchers have shown for the first time that is is possible to interface untreated graphene with neuron cells whilst maintaining the integrity of these vital cells[(2)]. This result is a significant first step towards using graphene to produce better deep brain implants which can both harness and control the brain. The work, published in the journal ACS Nano, was a truly interdisciplinary collaboration between the University of Trieste in Italy, the University Castilla-La Mancha in Spain and the Cambridge Graphene Centre, with nanotechnologists, chemists, biophysicists and neurobiologists all playing an important role.

Prof. Prato, commented that *"We are currently involved in frontline research in graphene technology towards biomedical applications, exploring the interactions between graphene nano- and micro-sheets with the sophisticated signalling machinery of nerve cells. Our work is only a first step in that direction."*

Prof. Ferrari, Director of the Cambridge Graphene Centre, and Chair of the Graphene Flagship Executive Board, stated that *"The Flagship will support biomedical research and development based on graphene technology with a new work package and a significant cash investment from 2016. These initial results show how we are just revealing the tip of an iceberg when it comes to the potential of graphene and related materials in bio-applications."*

(1) Jasim D. A., et al.,
Chem. Sci., 6, 3952 (2015)

(2) Fabbro A., et al.,
ACS Nano, 10 (1), 615 (2016)

Fundamental Science

Fundamental Science underpins everything that is done at the Graphene Flagship. With a strong foundation researchers can not only take current results out of the laboratory and begin the commercialisation process but they can also work on the next generation of scientific studies.

Prof. Vladimir Falko

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

WORK PACKAGE DEPUTY
Dr Alberto Morpurgo, University of Geneva, Switzerland

Thus research is undertaken in the Graphene Flagship not only on the fundamental principles of graphene but also on other 2D materials, which when coupled together are able to produce multifunctional heterojunctions which can be used, for example, as electric logic and memory devices.

Over the past year researchers from the Graphene Flagship have demonstrated superconducting electric currents in graphene whose electron waves, when encapsulated in a Josephson junction, can support dissipationless current. This has the potential for graphene-based Josephson junctions to be used in ultrasensitive magnetometers, voltmeters and as advanced circuits applicable to quantum information processing.

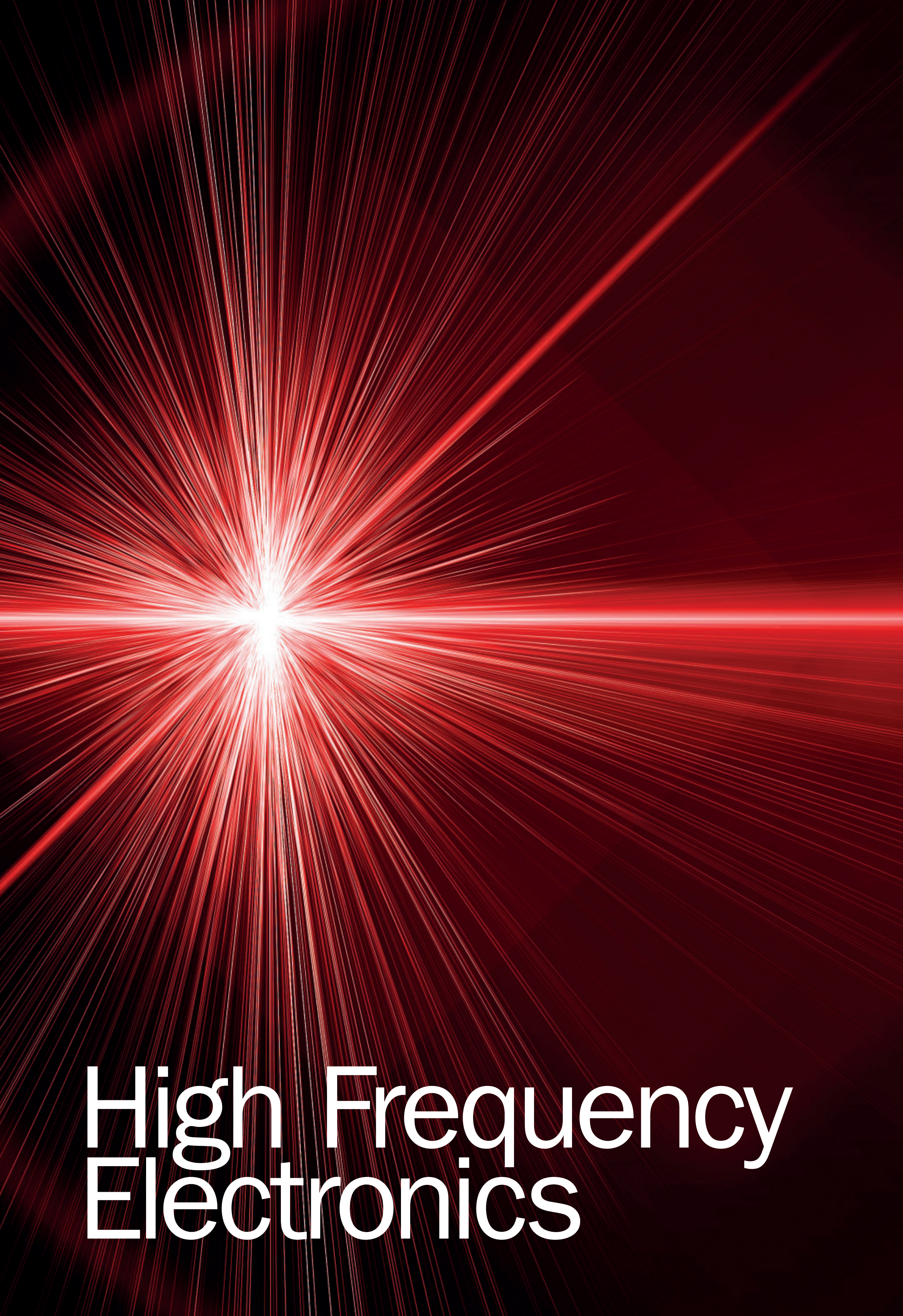
A Josephson junction, made by sandwiching a thin layer of non-superconducting material between two superconducting layers, allows, in certain circumstances, a Cooper electron pair to tunnel through the insulating middle layer without meeting any resistance. This resistance-free current is allowed up to a critical level at which point an alternating voltage is set up across the junction and it is the ability to measure this change that is used in applications of Josephson junctions.

This work, emerging from the Graphene Flagship teams lead by Lieven Vandersypen (Kavli Institute of Nanoscience, TU Delft), Andre Geim and Vladimir Falko (National Graphene Institute, the University of Manchester) was published in the journals Nature Nanotechnology[(1)] and Nature Physics[(2)]. In talking to Srijit Goswami, a member of Vandersypen's group, he said *"This work allows us to unravel new physics related to the interplay between superconductivity and the relativistic behaviour of electrons in graphene. With this technology we can study and exploit graphene Josephson junctions in a new, exciting regime."*

Vladimir Falko, who leads this work package, said *"A superior electronic transport quality of graphene encapsulated in hexagonal boron nitride offers great potential for developing new device concepts, and we shall investigate further the prospects for SQUIDs made of superconductor-graphene-superconductor junctions to compete with the standard aluminum/aluminum-oxide tunnel junction SQUID technology."*

[(1)] Calado V. E., et al.,
Nature Nanotech., 10, 761 (2015)

[(2)] Shalom M. B., et al.,
Nat. Phys., Dec (2015)



High Frequency Electronics

Dr Daniel Neumaier

Researchers from the Work Package High Frequency Electronics are focusing on producing graphene-based high-performance electronics technologies operating at gigahertz frequencies and above. This allows the potential for on-chip-systems to increase the functionality and decrease the cost of electronic systems.

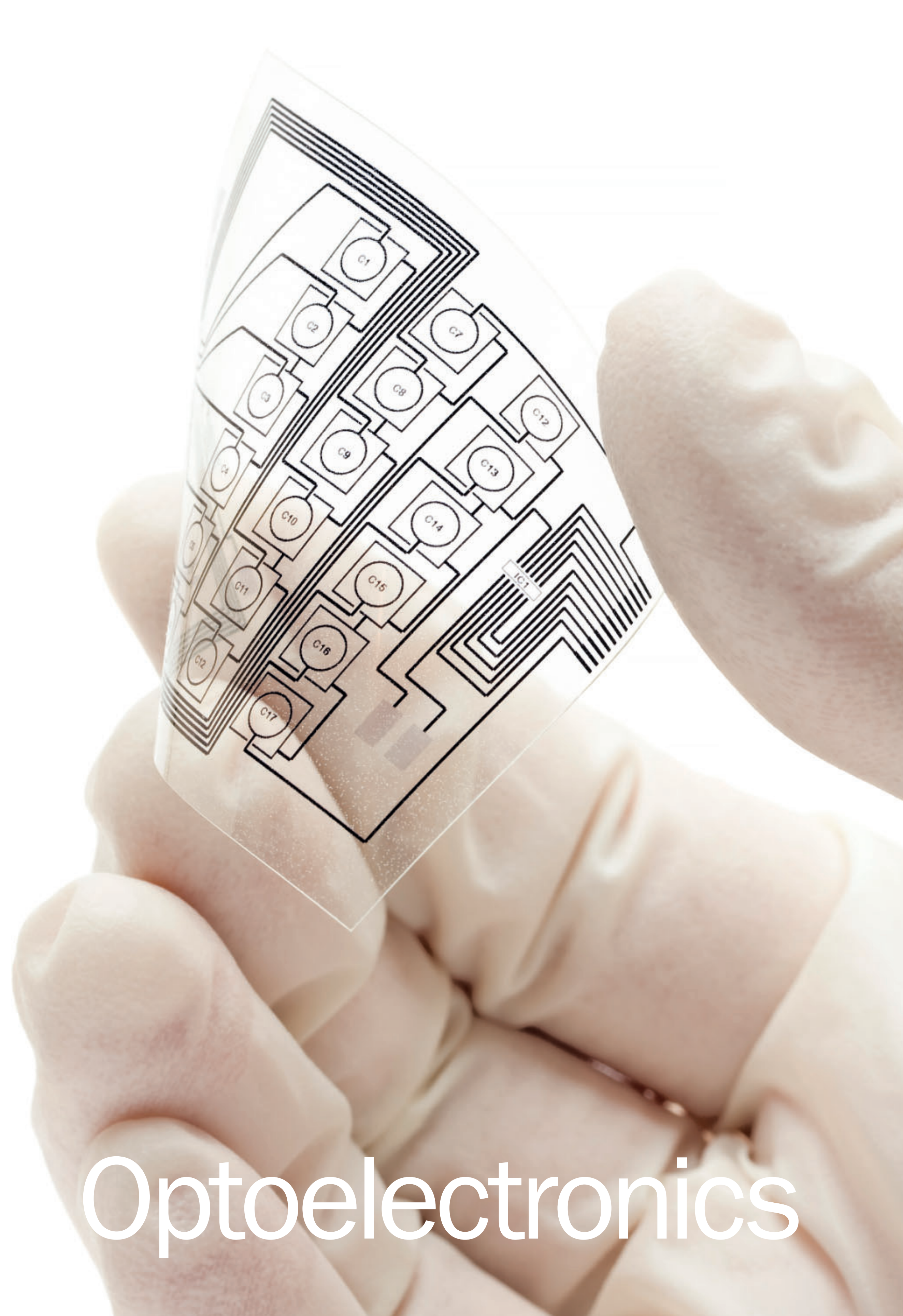
WORK PACKAGE LEADER
Dr Daniel Neumaier, AMO GmbH, Germany

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

Highlighting a common theme seen throughout the Flagship in the last year Dr Daniel Neumaier says *"In the past year we have made substantial progress in developing and optimising the process technology for handling graphene. This allows us now to explore and exploit the unique properties and potential of graphene devices in more complex RF circuits and systems."* Speaking of the last year in the work package Dr Neumaier outlines *"In Work Package High Frequency Electronics researchers with different backgrounds ranging from circuit design, material science, RF testing to device modeling and development are brought together in order to cover the whole value chain. This vertical approach enables us to fully implement the new possibilities in the final systems."*

As high speed communication becomes more and more important to society, whether through fibre-optic cables or via wireless transmission, more research and development must be undertaken to keep up with societal demand. Flagship researchers have been focusing on the practical aspect of a means to better downshift the received high frequency signal from GHz to MHz. In a paper soon to be published, Alberto Montanaro of the French electronic systems company Thales and others present a graphene-based device capable of optoelectronic mixing at a frequency of 30 gigahertz. By combining a 30-GHz intensity-modulated optical signal with a 29.9-GHz electrical signal, the Flagship researchers achieve frequency downconversion to 100 MHz. The experimental results could lead to advances in optoelectronics for radar and wireless-communication systems.

Speaking about this exciting advancement Dr Neumaier says *"Microwave-photonics, the processing and generation of RF signals by optical means, is currently a very dynamic field, bringing together the advantages of optics and RF-electronics for future communication systems. Because of its outstanding electronic and opto-electronic properties, together with the CMOS-compatibility, graphene could become the enabling material for on-chip microwave photonics."*



Optoelectronics

Optoelectronics is based on the study of how light and electronic materials interact. Researchers from the Graphene Flagship are using the unique optical properties of graphene as an enabling material for optoelectronic applications. From lasers and optical switches, to wireless communication and energy harvesting, graphene will play an important role within the optoelectronics field.

Prof. Frank Koppens

WORK PACKAGE LEADER
Prof. Andrea Ferrari, University of Cambridge, United Kingdom

WORK PACKAGE DEPUTY
Prof. Frank Koppens, Institute of Photonic Sciences, Spain

One of the key optoelectronics applications of graphene is the broadband detection of light. In order to demonstrate the applicability of this technology, researchers from the Graphene Flagship collectively implemented a graphene chromatic eye (GCE). This is an apparatus where multiple graphene-based photodetectors are integrated to acquire ultra-wide spectral information, from UV to far-IR. For all wavelengths, the sensitivity of the chromatic eye should be sufficient to perceive signals generated in a normal environment, such as indoor ambient light, an IR beam from a remote control, or the thermal radiation from a human body. The GCE is packaged and operated as a single polychromatic sensor with ambient intelligence, meaning that it can discriminate different light patterns by analysing their spectral fingerprint.

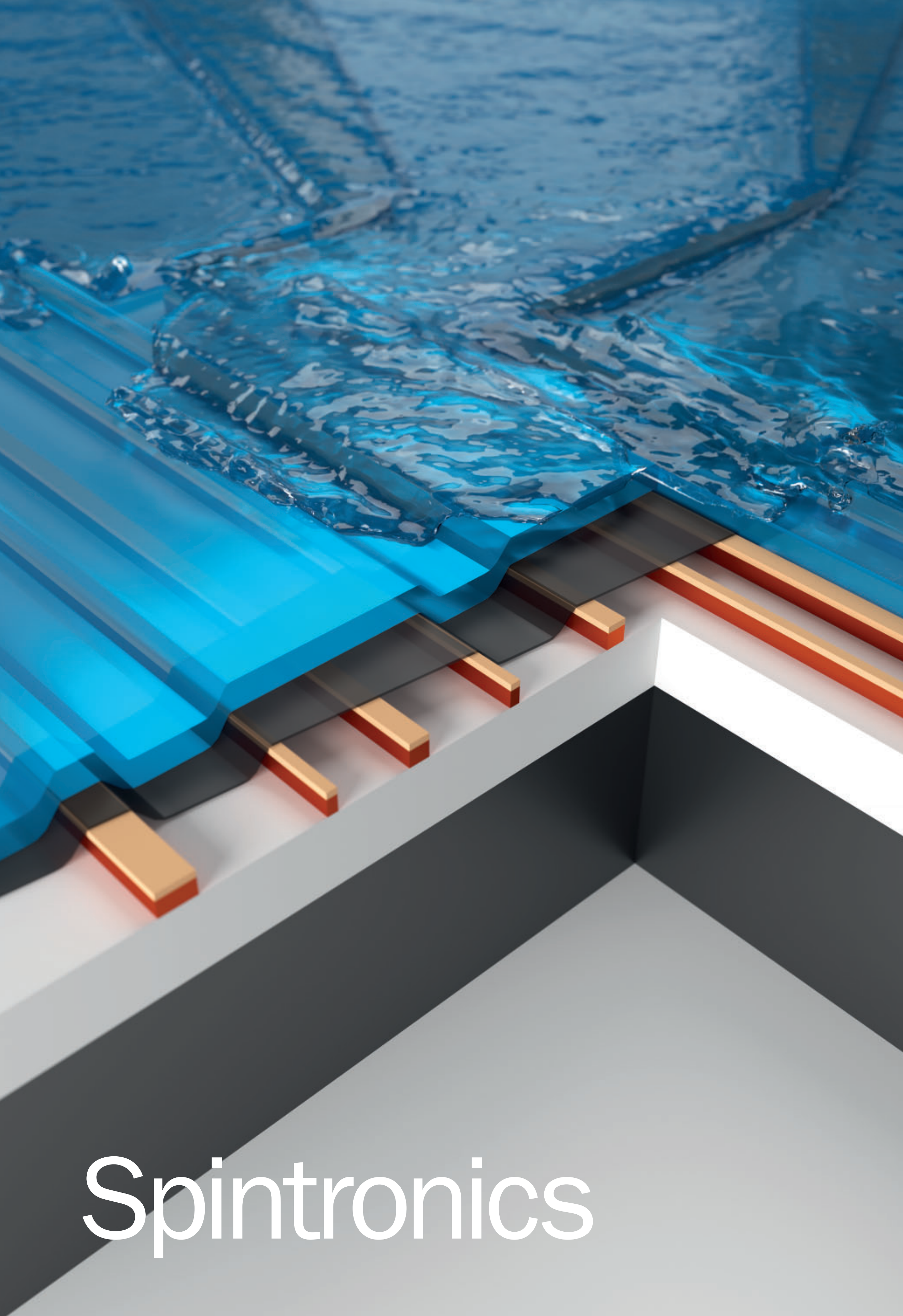
Speaking about the GCE, Prof. Frank Koppens (from ICFO – The Institute of Photonic Sciences) said *"This represents the fundamental building block for future imaging technologies aiming to augment our visible reality with its several invisible components."*

THE GRAPHENE PAVILION AT THE MOBILE WORLD CONGRESS

With his strong application based focus, Prof. Koppens, Deputy Leader of the Work Package Optoelectronics managed to secure a collaboration with the GSMA which is a group that represents the interest of those working in the mobile industry. This led to the inaugural Graphene Pavilion at the Mobile World Congress (MWC) – a GSMA event and an unparalleled opportunity to showcase graphene.

The Graphene Pavilion, coordinated by the Graphene Flagship and ICFO, with the support of GSMA, embraced five technological and innovative fields within the mobile world: display technologies, wearables, Internet of Things, energy transmission and storage, and data communications. This year the MWC attracted more than 100,000 mobile industry professionals to witness the launch of new products and applications as well as scouting out new commercial trends and evaluating market niches for innovative products, services and applications that could inspire new technologies. Over four days of non-stop activity, the Graphene Pavilion featured 12 companies and 12 research centres showcasing graphene-based demos and applications to a continuous stream of visitors, press and companies interested in seeing graphene at work in operational prototypes.

Prof. Koppens, who was also the Science and Technology Curator of the Graphene Pavilion and chair of the Conference Session, said *"We now have working prototypes which is a huge step. Whether this will 'tip' or not depends on industry joining us for the integration into real products and further pursuing economical ways of mass producing these products. From what we have seen at MWC, industry may now be ready to take this important step."*



Spintronics

Exploiting the detection and manipulation of electron spin, researchers from the Graphene Flagship are looking to increase the efficiency and diversity of the practical uses for spintronics. A new generation of graphene based ‘spintronic’ devices will be smaller, more versatile and more robust than those currently making up silicon chips and circuit elements.

Prof. Stephan Roche

These ‘spintronic’ devices harvest the fact that information can be stored (written) into spins in a particular spin orientation, up-spin or down-spin, or any superposition of them. Targets of the Graphene Flagship range from low-power and tunable high-frequency nanoscale oscillators (used in space communication or radar vehicles) to innovative logic gates and spin-based memories.

The Work Package Spintronics Deputy Prof. Stephan Roche from ICN Catalan Institute of Nanotechnology, Spain, outlined 3 different technical milestones achieved by the work package over the last year.

MILESTONE 1: The optimisation of CVD-grown graphene-based devices is essential for the development of practical spintronic applications, and has been the focus of intense efforts inside the Work Package. An advanced transfer technique has been reported by the consortium[1], allowing both reusing the copper substrate of the CVD growth and making devices with mobilities as high as 350,000 $cm^2 V^{-1} s^{-1}$, thus rivalling exfoliated graphene, with ballistic transport exceeding 28 micrometres[2]. Additionally, we achieved the largest spin lifetimes of 12 nanoseconds ever measured in graphene non-local spin valve devices.

MILESTONE 2: The role of electron-hole puddles for different substrates (SiO_2 and hBN) in understanding the charge density dependence of spin lifetime has been ascertained theoretically. The values of spin lifetime, together with the dependence in energy have been related with the strength of puddles, leading to a conventional Dyakonov-Perel relaxation mechanism for graphene supported on silicon-oxide or to a pure dephasing mechanism for graphene on hBN substrate[3].

MILESTONE 3: A magnetic proximity effect induced by Yttrium-Iron garnet on graphene has been revealed and quantified for the first time using Hanle spin precession measurements. An exchange coupling field of about 0.2 Tesla was found to alter the spin transport in graphene at room temperature. This opens new perspective for magnetic gating in graphene devices[4].”

Prof. Roche also outlined how the Graphene Flagship is developing spintronics through industrial partnerships *“By working with NanOsc AB from Sweden we have defined the case of graphene-based spin nanoscillators (used for instance in radar communication) as a practical device to be implemented and benchmarked compared to current commercial technologies. The advances made by the consortium in 2015 are paving the way to optimising the technology developed at NanOsc AB in the next phase. We believe that more industry will join the consortium in the next phases and benefit from our consortium excellence and capability to transfer knowledge and technologies to practical devices.”*

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

WORK PACKAGE DEPUTY
Prof. Stephan Roche, ICN Catalan Institute of Nanotechnology, Spain

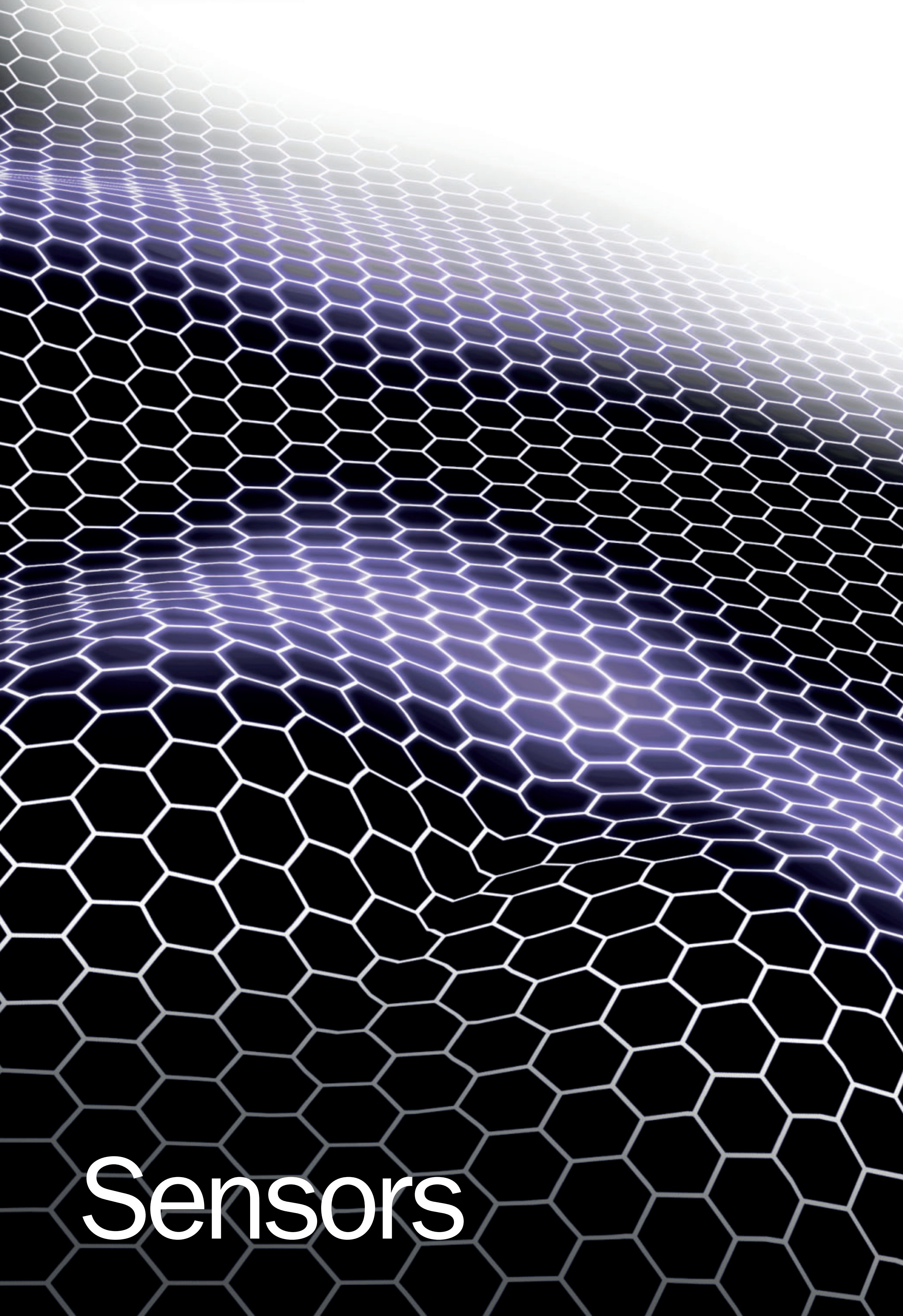
(1) Banszerus L., et al., Sci. Adv. 1, e1500222 (2015)

(2) Banszerus L., et al., Nano Lett., 16, 1387 (2016)

(3) Van Tuan D., et al. Sci. Rep., 6, 21046 (2016)

(4) Roche S., et al., 2D Materials, 2, 030202 (2015)

(5) Leutenantsmeyer J. C., et al., (submitted to Nat. Phys.)



Sensors

As our society becomes increasingly data driven the ability to sense is increasingly important. Sensing has a huge variety of forms and researchers within the Graphene Flagship are focusing on many different types of sensors ranging from sounds waves, pressure, mass, force and microwave all the way to single molecule biosensors.

Prof. Herre van der Zant

WORK PACKAGE LEADER
Prof. Herre van der Zant,
Technical University of Delft,
The Netherlands

WORK PACKAGE DEPUTY
Prof. Pertti Hakonen,
Aalto University, Finland

This year, researchers from the Graphene Flagship have developed a small, robust, highly efficient squeeze film pressure sensor. Pressure sensors are the most prolific of the membrane based mechanical sensors and are present in most mobile handsets. Conventional pressure sensors feature a membrane that is several hundred nanometers thick. By replacing this with a graphene membrane would not only allow the sensor to decrease in size but also significantly increase its responsiveness. Researchers from the Graphene Flagship have shown that by placing a graphene membrane over a gas cavity at ambient pressure they can increase the lifetime of the sensor by cutting out the need for an impermeable reference cavity at stable reference pressure. The paper, published in Nano Letters [1], demonstrates a reproducible sensor that has a 4MHz resonance frequency shift and follows the squeeze film model between 8 and 200 mbar. This leads to an increase in responsivity of between 5-45 times of conventional pressure sensors over an area that is 25 times smaller.

Discussing this work is the paper's lead author, Robin Dolleman (from the Technical University of Delft, The Netherlands). *"After spending a year modelling various systems the idea of the squeeze-film pressure sensor was formed. Funding from the Graphene Flagship provided the opportunity to perform the experiments and we obtained very good results. We built a squeeze film pressure sensor from 31 layers of graphene, which showed a 45 times higher response than silicon based devices, while reducing the area of the device by a factor of 25. Currently, our work is focused on obtaining similar results on monolayer graphene."*

The work package was explained further by Prof. Herre van der Zant (from the Technical University of Delft, The Netherlands), *"This work package focuses on using the unique properties of graphene to make sensors. Graphene is, of course, very thin and has a very high surface area and it's this unique property that means we can start to make better sensors. In only a few years from now we expect to see the first examples of graphene sensors in your mobile phone and other applications. We are excited by the new results of the squeeze film pressure sensors and how it will be used in applications in the future."*

[1] Dolleman R. J., et al., Nano Lett., 16, 568 (2016)

Flexible Electronics

Graphene, being flexible, thin and ultra strong is an obvious choice for flexible electronics and researchers with the Graphene Flagship have been working hard to turn its potential into a reality.

Dr Stefano Borini

WORK PACKAGE LEADER
Dr Stefano Borini, NOKIA R&D, United Kingdom

WORK PACKAGE DEPUTY
Dr Sebastiano Ravesi, STMicroelectronics, Italy

Over the last year researchers have made huge advances in the development and benchmarking of graphene and related materials on flexible substrates. Through extensive device prototyping and testing they are taking the first steps towards system integration.

Production of functional graphene inks has allowed for printing onto plastic substrates, for both circuit tracks and sensing elements which show a promising combination of performance and mechanical stability. Different types of printed sensors, including strain gauges and infrared detectors, have been demonstrated. All have competitive figures of merit, with a gauge factor of 17 in the case of flexible strain sensors.

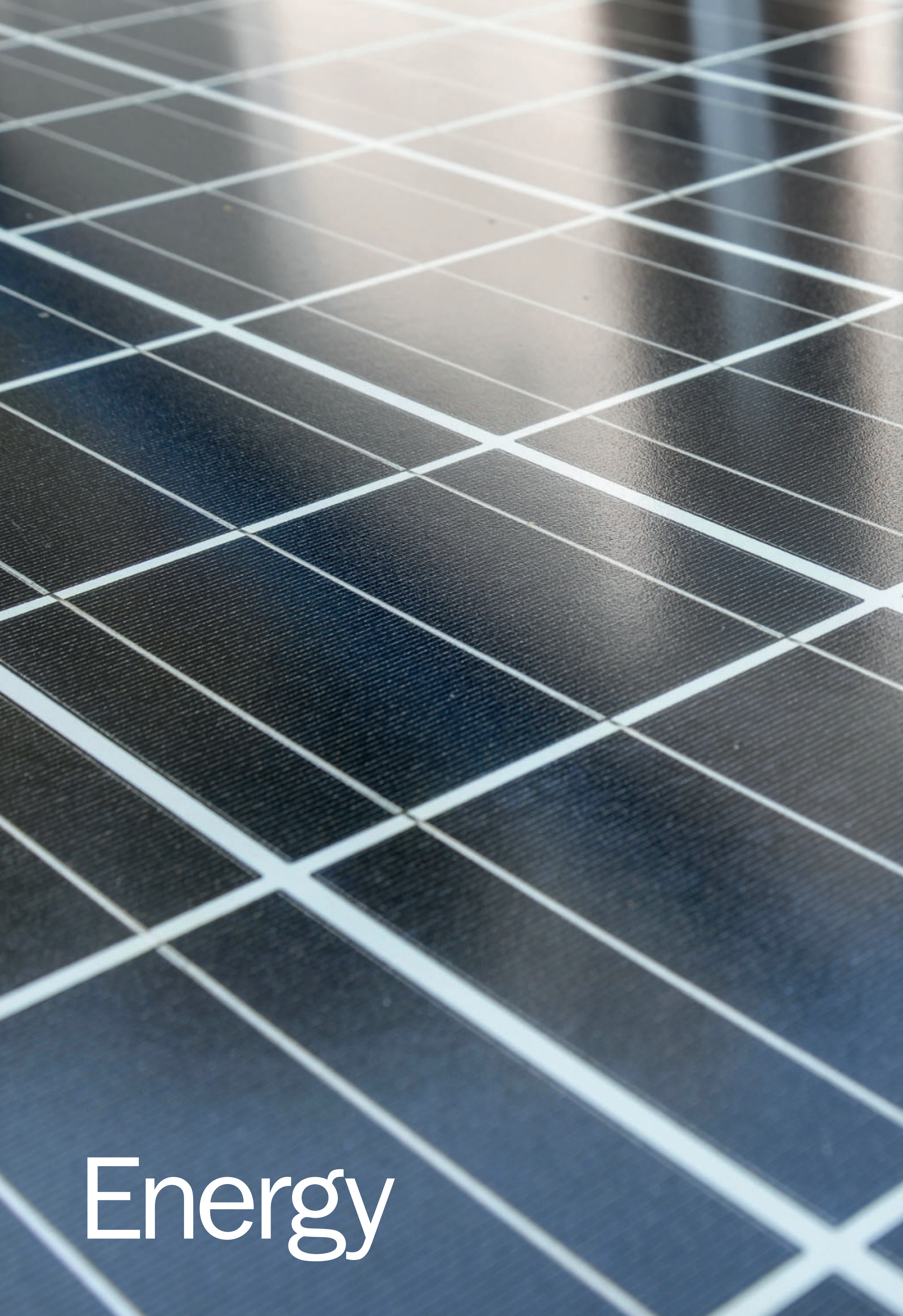
Processes for depositing large-area CVD graphene on plastics have been developed, and these have been optimised for a number of applications. By controlled doping of graphene on plastics, for example, researchers have produced a transparent conductor with superior mechanical stability under bending. At the wafer scale, they have also manufactured graphene field-effect sensors with integrated microfluidics.

Radio-frequency components are another focus of activity, and RF transistors with a maximum frequency of 13 GHz have been produced on the polyimide film Kapton. Such devices retain their functionality under static bending, and display long-term stability when subject to fatigue cycles.

When it comes to flexible RF antennas, researchers have demonstrated printed graphene dipole antennas with decent performance in UHF and >2 GHz frequency ranges. Again in the wireless domain, first prototypes of flexible Near-Field Communication (NFC) antennas based on graphene paper have been built. These could provide a very competitive solution for flexible RFID tags.

Researchers have taken the idea of flexible electronics even further and have designed and realised an electronic platform for the integration of flexible components. The platform is an essential enabler for the fast prototyping of flexible components and their gradual integration into functional flexible systems.

Work Package Leader Stefano Borini of Nokia Research in Cambridge said *"Materials experts are working together with components manufacturers and system integrators, delivering flexible demonstrators and prototypes with potential impact in several emerging fields such as wearables and the Internet of Things."*



Energy

As the global population expands the need for energy production and storage grows constantly. Researchers from the Work Package Energy are focusing on producing graphene based devices to meet this demand including solar cells, batteries, supercapacitors as well as hydrogen storage and fuel cells.


Dr Etienne Quesnel

2015 was a particularly fruitful year for the Work Package Energy producing many proof of concept devices. The challenge ahead is to demonstrate that the exploitation of graphene and related two-dimensional crystals, either as materials that stand alone or integrated into other materials to form functional composites, can indeed boost the performance of energy devices. Whilst also triggering the development of disruptive technologies meeting the future needs of industry.

Using the existing approaches developed for solar cells and electric storage devices, whilst at the same time utilising emerging technologies, such as those related to lithum-oxygen batteries, various energy conversion and storage devices (1) have been produced. By integrating graphene, which provides surfaces with well controlled electro-chemical and electronic properties, these devices can have increased stability and higher energy capacity (~10 times in some cases) enabling commercial exploitation. Over the last year researchers from the work package have produced organic solar cells with integrated doped reduced graphene oxide materials that demonstrates conversion efficiencies up to 9%, a value among the best performance demonstrated so far for single junction OPV devices (2). They have also replaced platinum with graphene in dye-synthetized solar modules leading to a more efficient, cost-effective and environmentally-friendly solar device (3).

Regarding energy storage, a gain in power efficiency of at least 1 order of magnitude is obtained by replacing the industry-standard activated carbon with reduced graphene oxide in supercapacitor electrodes. In the short term, this approach could open the way to a new generation of much better performing supercapacitors. In the longer term the recent lithium-oxygen battery demonstrator, which integrates porous electrodes made of reduced graphene oxide (4), could lead to high capacity batteries.

Speaking of these findings Etienne Quesnel from CEA French Alternative Energies and Atomic Energy Commission, France said *"The major lesson of these findings is that the integration of graphene and related materials is not only a way to improve existing technologies but also an exceptional key enabling technology to address very challenging societal issues like very high capacity energy storage or flexible devices."*

WORK PACKAGE LEADER
Dr Etienne Quesnel, CEA French Alternative Energies and Atomic Energy Commission, France

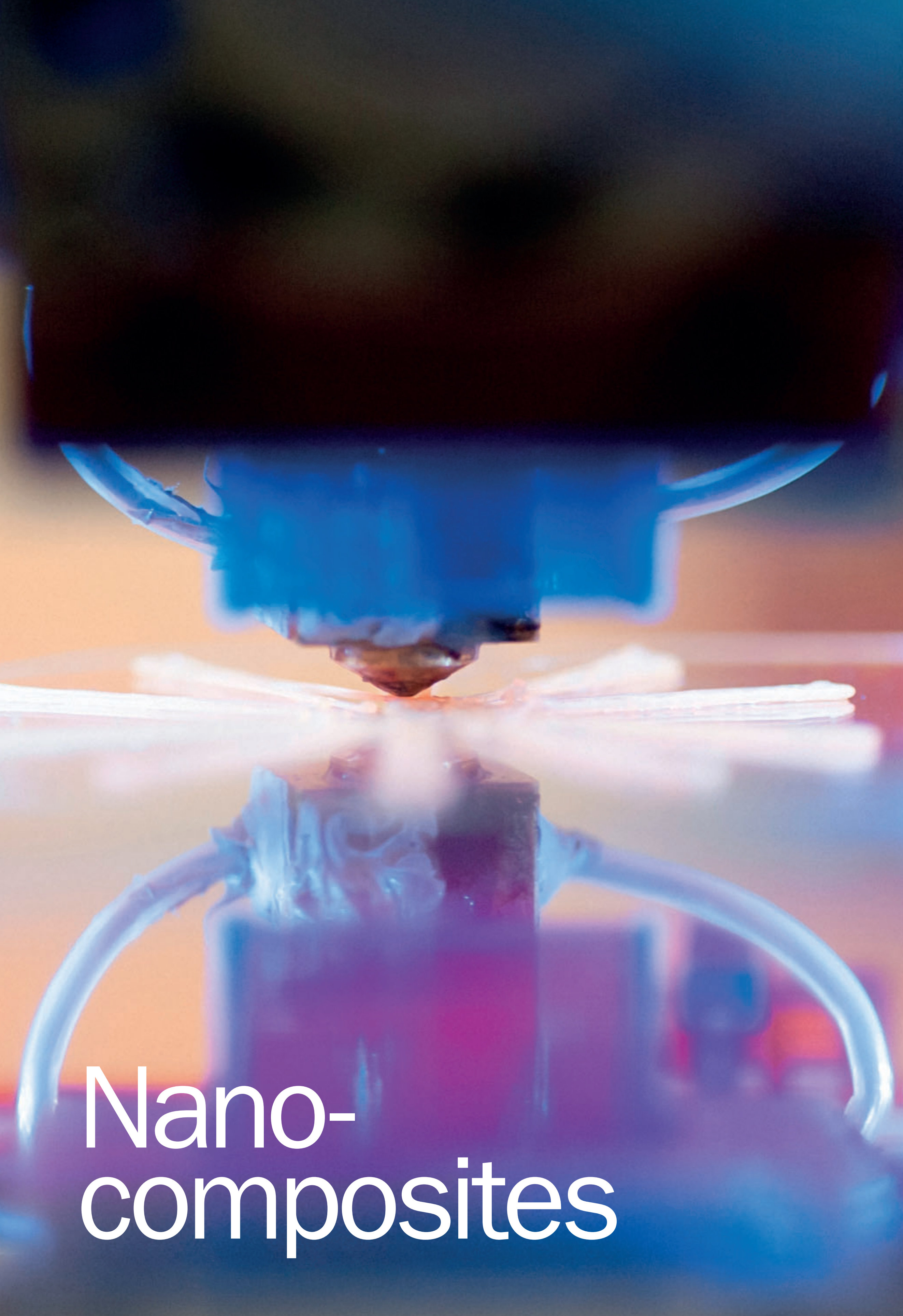
WORK PACKAGE DEPUTY
Dr Vittorio Pellegrini, Italian Institute of Technology, IIT Graphene Labs, Italy

(1) Quesnel E., et al., 2D Mater. 2, 030204 (2015)

(2) Konios D., et al., J. Mater. Chem. A, 4, 1612 (2016)

(3) Casalucci S., et al., Nanoscale (2016)

(4) Liu T. et al., Science, 350, 6260, 530 (2015)



Nano-composites

The Work Package Nanocomposites is focused on transferring the exceptional properties of graphene from the nanoscale to useful macroscopic materials. Alongside developing practical applications for graphene-based composites in different industrial fields, much effort has been undertaken to truly understand how graphene and other 2D materials work in complex systems.

Dr Vincenzo Palermo

WORK PACKAGE LEADER
Dr Vincenzo Palermo, CNR National Research Council, Italy

WORK PACKAGE DEPUTY
Dr Xinliang Feng, Max-Planck Society, Germany

Discussing the progress of the work package over the last year is its Leader Dr Vincenzo Palermo, from CNR National Research Council, Italy, *"A main task we pursued this year was to strengthen the collaboration and interactions with the other Flagship Work Packages to create added value through a strong exchange of materials, samples and information. As an example, we provided composite materials for batteries, flexible antennas, and biological studies. We also tested composite materials for other groups.*

Working in collaboration with AVANZARE, a supplier of high-performance nanomaterials, they were able to produce a dispersion of graphene in styrene which is used in polyester thermoset resins. The conductivity obtained with the addition of graphene allows the use of these resins with explosion risk fluids as well as in vessels and pipes used in the chemical and petrochemical industries. Another product, created in partnership with AVANZARE, is a highly electrically conductive composite in pellet form suitable for 3D printing – a major emerging market."

Work Package Nanocomposites, alongside Nokia and Work Package Flexible Electronics, presented prototypes of working flexible NFC antenna and flexible printed sensors at the Mobile World Congress in Barcelona – a great result and testament to collaborative working.

Other important results for Work Package Nanocomposites include a partnership with Talga Advanced Materials GmbH who are working to transfer the electrochemical exfoliation of graphene out of the lab and into their pilot plant in Germany, where the high quality graphene they produce will have many possible applications in the field of composites for flexible and printable electronics.

Research done within this work package, recently published in Science [(1)], has observed the onset of superlubricity in graphene nanoribbons sliding on a surface, unraveling the role played by ribbon size and elasticity. This important finding opens up the development potential of nanographene frictionless coatings. With researchers from Work Package Materials and Work Package Health and the Environment also involved, this result is a shining example of the inter-disciplinary, cross-collaborative approach to research undertaken within the Flagship.

[(1)] Kawai S., et al., Science, 351, 6276, 957 (2016)

Production

Production is unique amongst the Graphene Flagship's technical work packages in that it focuses on technology development to enable cost effective and large scale production in the future. The three principal goals of Work Package Production are to provide material samples, help form links to Europe's Nanosciences, Nanotechnologies, Materials and New Production Technologies programmes, and to deal with standardisation matters.


Dr Ken Teo

WORK PACKAGE LEADER
Dr Ken Teo, Aixtron Ltd., United Kingdom

WORK PACKAGE DEPUTY
Dr Nalin Rupesinghe, Aixtron Ltd., United Kingdom

Production is a highly collaborative work package with a strong industry focus. Lead by AIXTRON and working with Graphenea, Grupo Antolin and ANT, much has been achieved in commercial scale graphene production.

Dr Ken Teo from AIXTRON, who is the Work Package Leader, outlines the work undertaken in the last year: *"AIXTRON as an equipment supplier has been able to reduce CVD graphene production costs by optimisation of growth recipes and improvement of reactor design, which makes CVD graphene attractive in wide ranging applications."*

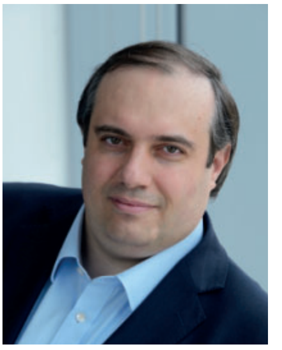
Graphenea, a graphene producer, has worked very closely with IMEC, AMO and ICFO in order to overcome issues that arise when fabricating graphene devices and by collaboration with TU Delft has been able to better define the required graphene material for sensor applications.

Grupo Antolin has developed an easy and eco-friendly means to obtain good quality graphene en-masse using ball-milling for the exfoliation of GANF® carbon nanofibres through interaction with melamine, whose structure helps to favour graphene exfoliation under ball-milling conditions. This process avoids the use of strong acids and high vacuum chambers, while the solvents used can be recovered and recycled."

There are so many potential uses of graphene and only with scalable and cost efficient production techniques can graphene thrive. This year collaboration within Work Package Production saw Spanish automotive interiors specialist, and Flagship partner, Grupo Antolin SA work in collaboration with Roman Kayaks to develop an innovative kayak that incorporates graphene into its thermoset polymeric matrices. The use of graphene and related materials results in a significant increase in both impact strength and stiffness, improving the resistance to breakage in critical areas of the boat. Pushing the graphene canoe well beyond the prototype demonstration bubble, Roman Kayaks chose to use the K-1 kayak in the Canoe Marathon World Championships held in September in Gyor, Hungary where the Graphene Canoe was really put through its paces.

"In the Graphene Flagship project, Work Package Production works as a technology enabler for real-world applications," says Dr Teo. "Here we show the world-first K-1 kayak (5.2 meters long), using graphene related materials developed by Grupo Antolin. We are very happy to see that graphene is creating value beyond traditional industries."

“As we move to the first Core Project, we must optimise and streamline our administrative structures and focus our goals towards higher technology readiness levels.”



Prof. Andrea Ferrari

With the ramp-up phase coming to an end, the Graphene Flagship graduates to the next level. After the expansion with the Open Call, Expressions of Interest and the Joint Translational Call, and with an increasing number of Associate Members and Partnering Projects, we are seeing the vision of this large and unique programme taking shape.

The results achieved to date truly define the state of the art in the science and technology of graphene, layered materials and hybrid systems. With hundreds of publications in the top international journals, tens of patents and an ever increasing number of invention disclosures, spin outs and prototypes, the Flagship is steadily moving forward on the roadmap to exploitation. The huge success of our presence at the Mobile World Congress clearly shows that the leading industries take very seriously the potential of our work.

As we move to the first Core Project, we must optimise and streamline our administrative structures and focus our goals towards higher technology readiness levels. The new work packages on Wafer-Scale System Integration and Biomedical Applications show that we are not afraid of facing our challenges head on, while always seizing new opportunities. We will always encourage the creation of new concepts, the discovery and the understanding of new science, to keep our work fresh and relevant.

We need to keep innovation as our driving force. We need to identify key areas where to focus our resources. We need to maximise complementarity research, while ensuring critical mass in the priority areas. We cannot shy away from difficult, strategic decisions. The new divisional structure embodies our vision of a truly collaborative project, with horizontal and vertical integration between different tasks, so to increase our impact.

The decisions and directions we will take in first Core Project will show that graphene really means business.

Prof. Andrea C. Ferrari
Chair of The Graphene Flagship Executive Board

Graphene Flagship partners

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Guger Technologies OG
Varta Micro Innovation
Vienna University of Technology

BELGIUM
Catholic University of Louvain
University of Namur
Université libre de Bruxelles
IMEC

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

BELARUS
Belarusian State University

CZECH REPUBLIC
J. Heyrovsky Institute of Physical Chemistry

DENMARK
Technical University of Denmark
LEGO*

ESTONIA
University of Tartu

FINLAND
Aalto University
Nokia Finland
University of Eastern Finland
VTT Technical Research Centre of Finland

FRANCE
Atherm
CEA French Alternative Energies and Atomic Energy Commission
CNRS National Centre for Scientific Research
ESF European Science Foundation
Horiba Scientific
Laboratoire national de métrologie et d'essais
Pixium Vision
Polymem
Thales
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University of Lille 1
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UPMC Sorbonne Universités

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Centro Ricerche Fiat S.C.p.A. (CRF)
CNIT
CNR National Research Council
Delta-Tech S.p.A.
Dyesol Headquarters
FBK Bruno Kessler Foundation
Gripp 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
Selex ES Ltd.
ST Microelectronics
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Avanzare
The Biomedical Research Networking center in Bioengineering, Biomaterials and Nanomedicine (CIBER-BBN)
CIC energiGUNE
CIC NanoGUNE
CSIC Spanish National Research Council
Graphenea
Grupo Antolin
ICFO Institute of Photonic Sciences
ICN Catalan Institute of Nanotechnology
Institut d'Investigacions Biomèdiques August Pi i Sunyer (IDIBAPS)
IQ Interquimica
nvision systems & technologies
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Graphensic*
Karolinska Institute
Linköping University
Umeå University

SWITZERLAND
EMPA Swiss Federal Laboratories for Materials Science and Technology
ETH Swiss Federal Institute of Technology Zurich
Imerys*
University of Basel
University of Geneva
University of Zurich

TURKEY
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