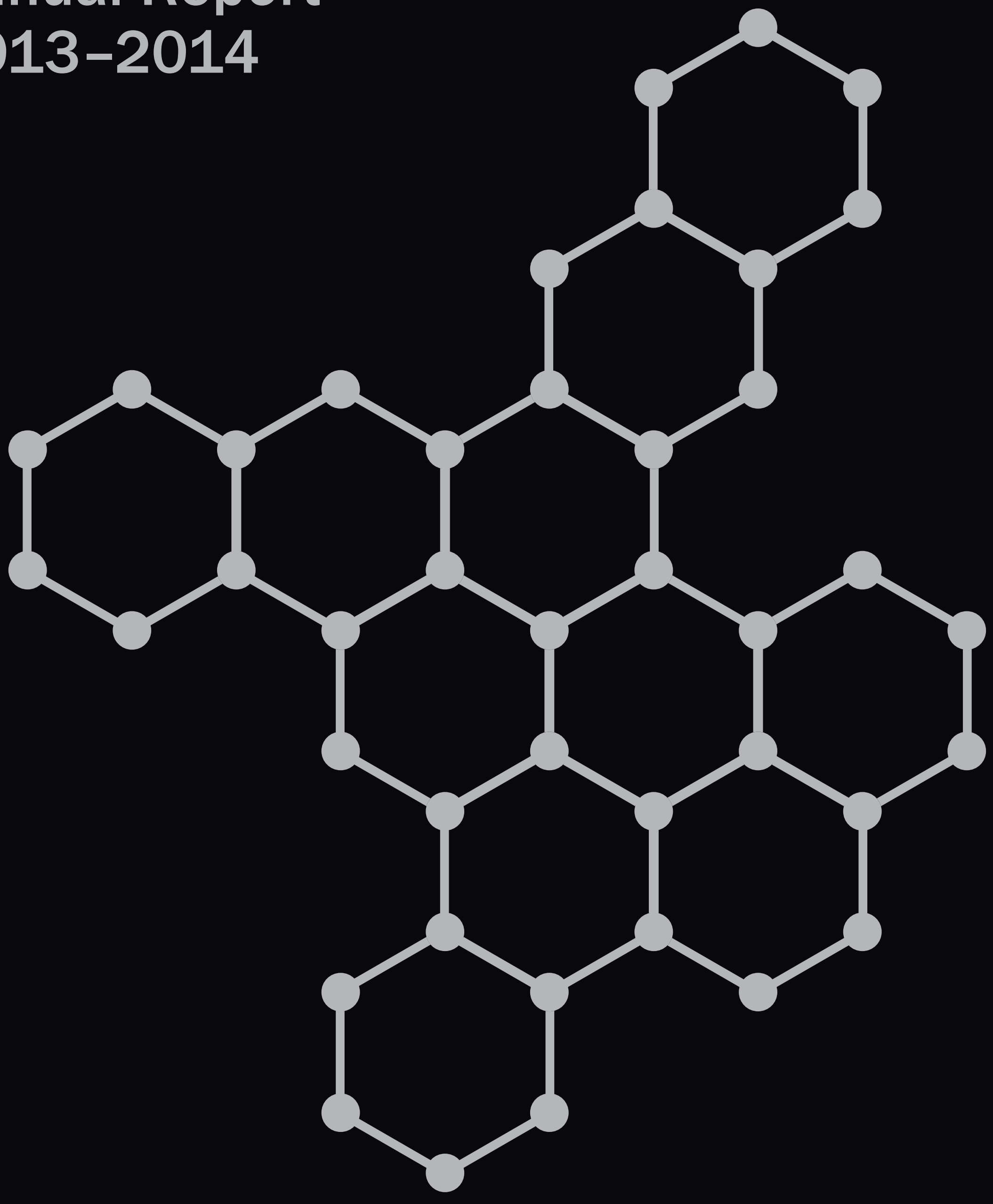
Graphene Flagship
One Year On

Annual Report
2013–2014



GRAPHENE FLAGSHIP

The journey so far

A recent independent assessment has confirmed that the Graphene Flagship is firmly on course, so we can be very proud of our accomplishments during the first year.

Launched in October 2013, the Graphene Flagship has now been sailing for a little over a year. Much has been achieved in this short time, yet we are only a tenth of the way on a voyage that we hope will take graphene and related materials from academic laboratories into society.

The Graphene Flagship is the first endeavor of its kind. Part of the first year has been about establishing routines within the research community, and between the flagship and the European Commission and EU member states. We have been learning the ropes, so to speak.

Among the key events during the year was an expansion of the Graphene Flagship through a competitive call, as a result of which the consortium now includes 142 partners in 23 countries. Our collaboration with member states included a joint transnational call, through which national and regional funding agencies contribute €11 million to research that complements the EC-funded project.

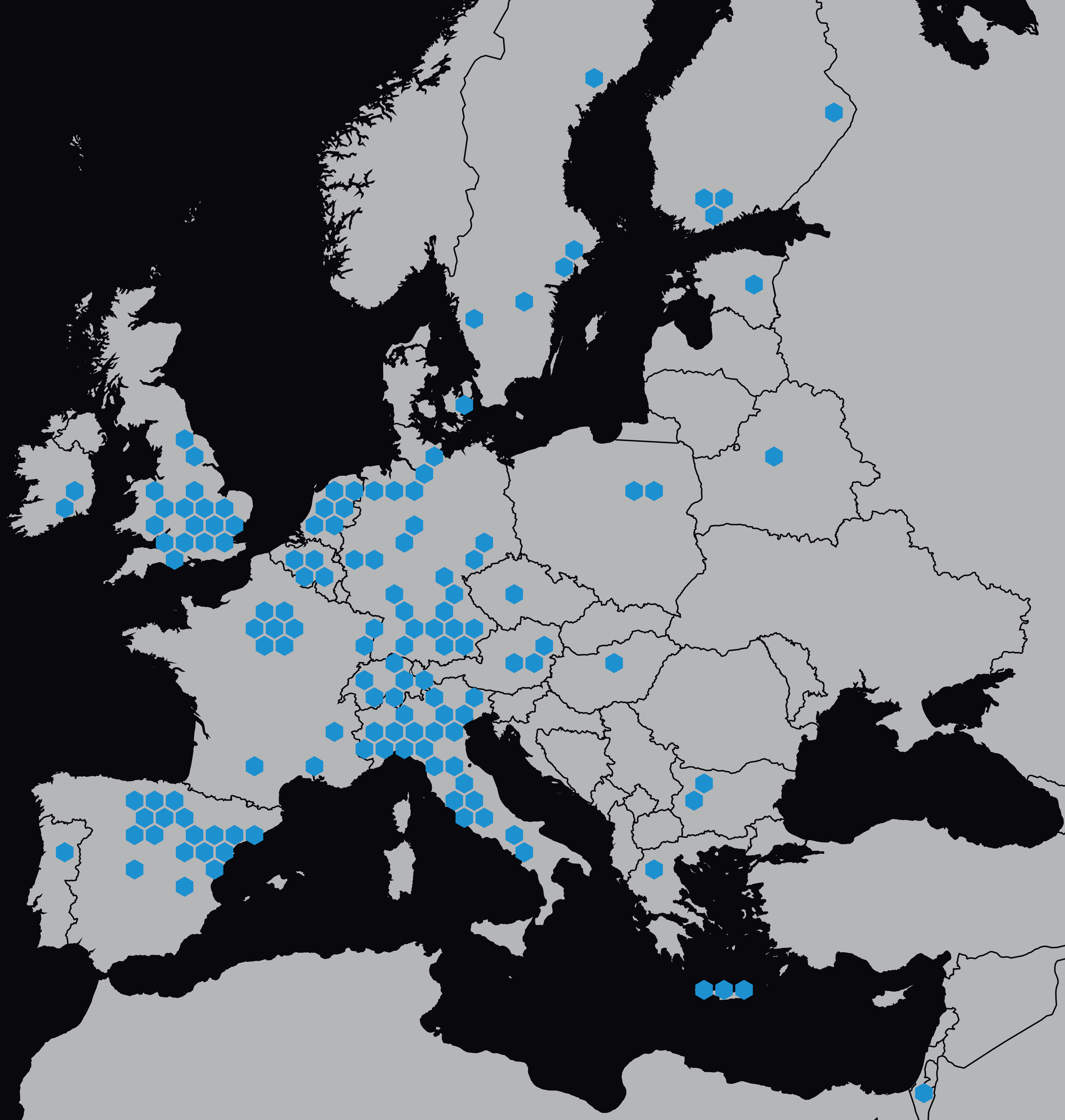
Already during the first year, the Graphene Flagship has made a substantial impact in the science and technology of graphene and related materials. We have more than 300 peer-reviewed papers to our name, have filed several patent applications, and given more than 600 public presentations of our work. All this while still in the ramp-up phase, with a budget half that of the steady state.

We are now planning the next phase of the Graphene Flagship, in which we will use the larger budget to introduce new topics such as biomedical technologies, and to strengthen the industrial component of our work. That said, excellent science continues to be the driving force of the flagship.

A recent independent assessment has confirmed that the Graphene Flagship is firmly on course, so we can be very proud of our accomplishments during the first year. The following pages highlight some of the flagship's science and technology achievements to date.

Prof. Jari Kinaret
Director of the Graphene Flagship

142 partners in 23 countries



The Graphene Flagship consortium consists of 142 academic and industrial research partners located across 23 countries. For the full list, see inside cover.

A €9 million competitive call launched by the flagship in late 2013 attracted a total of 218 proposals, representing 738 organisations from 37 countries.

As a result of the call, the Graphene Flagship doubled in size, with the addition of 66 new partners from 19 countries, six of which were new to the consortium.

Italy and Germany have the highest number of partners in the Graphene Flagship (23 each), followed by Spain (18), UK (17) and France (13).

Over one third (34%) of new partners are companies, mainly SMEs, showing the growing interest of economic actors in graphene. In the initial consortium this ratio was 20%. In total, 14% of flagship partners are now SMEs.

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GRAPHENE FLAGSHIP

Materials

Industrial-scale production of two-dimensional materials is the first step in their exploitation, and two of the Graphene Flagship's science and technology work packages are devoted to materials production. One of the research teams focuses on volume production of high-quality, uniform graphene, together with the tailoring, or chemical functionalisation, of graphene and other 2D materials.

There are various ways of producing graphene and related materials. Chemical vapour deposition, for example, yields relatively pure, defect-free graphene, but it requires high temperatures and controlled conditions. Depending on the application, other methods may be better suited to industrial production of layered materials.

Flagship scientists have demonstrated a scalable form of the production technique known as liquid-phase exfoliation. Jonathan Coleman, a professor of applied physics at the AMBER centre of Trinity College Dublin, outlines this simple process, which may be described informally as the kitchen-sink approach to graphene production …

> Our aim was to develop a new method for producing high-quality graphene in liquids, and we found that we could do this using high-shear mixers. These work by using spinning blades to make the liquid rotate at high speed. This in turn causes graphene sheets to slide off graphite crystals suspended within the liquid.

> Surprisingly, we found that this technique produced graphene at higher rates than most other methods. It is particularly useful, as industrial shear mixers can be bought commercially, making scale-up relatively straightforward. In addition, the method can be used to produce sheets of 2D materials, including boron nitride and molybdenum disulphide. Such materials will be useful in a range of applications, from printed electronics to energy generation.

The process is detailed in a paper published in *Nature Materials*. It has gained considerable media attention, and Professor Coleman is a popular public speaker. His research group has signed a licensing agreement with UK-based chemical manufacturer Thomas Swan Ltd., with a view to scaling production, and making materials produced with the technique available to industry.

This technique produced graphene at higher rates than most other methods, and produced sheets of 2D materials that will be useful in a range of applications, from printed electronics to energy generation.

Deputy work package leader Prof. Jonathan Coleman.

Industrial mixer used for producing graphene flakes by shear exfoliation. © Trinity College Dublin. Portrait: © Samuel Sanchez, El País.

Work Package 1: Materials
Work package leader: Prof. Mar Garcia Hernandez, CSIC Spanish National Research Council, Spain
Deputy leader: Prof. Jonathan Coleman, Trinity College Dublin, Ireland

Article: Paton et al., Scalable production of large quantities of defect-free few-layer graphene by shear exfoliation in liquids, Nature Materials 13, 624 (2014); doi:10.1038/nmat3944

Health and environment

Environmental and health effects of engineered materials are of concern to the general public, regulatory authorities, industry, and the materials science community responsible for their creation. Health and safety can never be separated from technology development, and so Graphene Flagship researchers are assessing the safety of graphene and related materials. The small size and unique properties of 2D materials pose potential risks to human health and the environment.

Resolving safety and toxicity issues associated with graphene and related materials will not only be beneficial when it comes to their integration into structural composites and electronics – they will also be critical in biomedical applications, and especially devices which interface directly with biological cells and tissues.

As a first step, flagship researchers have created a classification system for 2D materials. Classification is based on the number of layers and lateral length of 2D material sheets, and the oxygen content of the materials relative to that of carbon.

During the first year of the flagship, researchers carried out experimental studies of graphene dispersion in cell cultures. This is not an easy task, as graphene is hydrophobic, and cannot be dispersed in water without the help of additives that reduce the surface tension of the liquid. Maurizio Prato, an organic chemist at the University of Trieste, comments on the results…

> Initial studies of cellular uptake and the toxicity of graphene and graphene oxide using primary human macrophages and rodent neuronal cells have shown low impact on cell viability and dose-dependent cellular activation. With aquatic microorganisms and terrestrial algae, the observed effects are rather limited.

As the development of graphene and related 2D materials progresses, health and environmental research will increase in line with it. Risk assessments of 2D materials will be disseminated widely, so that we can all be confident as to their safety.

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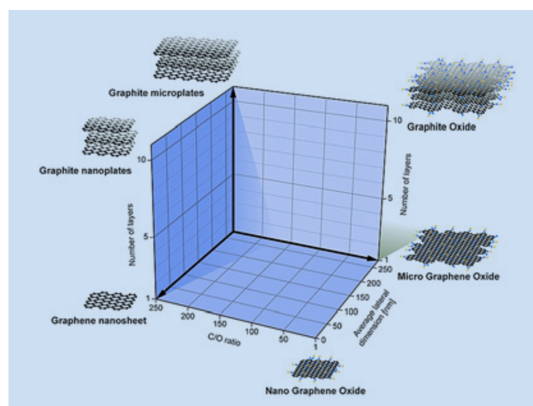
Work package leader Prof. Maurizio Prato.



Classification of graphene according to the number of layers, oxygen content and dimensions. © 2014 Wiley-VCH Verlag.

Work Package 2: Health and Environment
Work package leader: Prof. Maurizio Prato, University of Trieste, Italy
Deputy leader: Prof. Alberto Bianco, CNRS National Centre for Scientific Research, France

Article: Wick et al., Classification framework for graphene-based materials, Angew. Chem. Int. Ed. 30, 7714 (2014); doi: 10.1002/anie.201403335

Fundamental science

Applied science and technology can only advance when built on a solid fundamental science base. The Graphene Flagship – a project committed to the development of practical technologies based on graphene and related materials – has integrated basic scientific research into its programme.

Flagship researchers are investigating the mechanisms that determine and may limit the potential of graphene and related materials in electronic and optoelectronics applications. They are also developing a second generation of graphene-based structures for electronic devices that goes beyond the established complementary metal oxide semiconductor (CMOS) field effect transistor.

During the first year, flagship scientists investigated van der Waals superstructures of graphene and hexagonal boron nitride (hBN). Known also as white graphite for its optical transparency, hBN is a perfect insulator, with a crystal structure similar to that of graphene. In contrast to bulk composites, such structures are bonded by weak polarisation of atomic orbitals, known as van der Waals interactions. This does not require lattice matching between consecutive crystalline layers, thereby preserving the individual physical properties of all the layers involved.

Lancaster University physicist Vladimir Falko describes novel electronic components based on superstructures of graphene and hBN…

> // By manufacturing hBN-graphene-hBN-graphene-hBN superstructures with ultra-thin boron nitride layers, flagship research teams created prototypes for ultra-thin capacitors in which the electrically conducting graphene is used for metallic electrodes, and the insulating properties of hBN allows us to reach the desired device thickness of 5–10 nanometres. A similar material, with only three to four atomic layers of hBN placed between graphene electrodes, gives us a prototype for the thinnest vertical tunnelling transistor, with strongly non-linear current-voltage characteristics. This type of transistor is suitable for generating high-frequency electromagnetic fields.

Fundamental science studies carried out by Graphene Flagship researchers will broaden the range of functional applications of graphene and hybrid superstructures in post-CMOS electronics.

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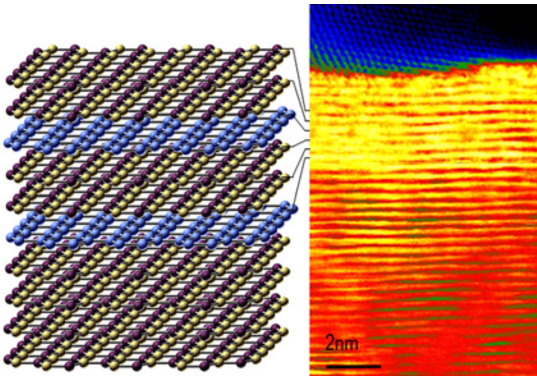
Work package leader
Prof. Vladimir Falko.



Hexagonal boron nitride/graphene superstructures with ultra-thin boron nitride layers. ©Vladimir Falko.

Work Package 3: Fundamental Science of Graphene and 2D Materials Beyond Graphene
Work package leader: Prof. Vladimir Falko, University of Lancaster, United Kingdom

Deputy leader: Dr. Alberto Morpurgo, University of Geneva, Switzerland
Article: Mishchenko et al., Twist-controlled resonant tunnelling in graphene/boron nitride/graphene heterostructures, Nature Nanotech 9, 808 (2014); doi:10.1038/nnano.2014.187

High-frequency electronics

On-chip integration of different electronic components has in recent times been a major driving force in electronics. This is certainly the case with high-frequency electronics, which covers devices operating from microwave through to terahertz frequencies. Integrating components into systems-on-a-chip can at the same time boost performance and reduce fabrication cost.

Graphene and related materials can be used to construct high-performance electronic devices, and they may also be incorporated into heterostructures based on silicon CMOS technology and plastic substrates. Moving from single devices to complex integrated circuits on different platforms is the most demanding task when it comes to unlocking the potential of graphene and related 2D materials in electronics.

Flagship researchers are developing and optimising scalable processes for the construction of high-frequency devices. For example, they have made available a fabrication platform for a full monolithic microwave integrated circuit process, the key components of which include graphene-based field-effect transistors and diodes, along with metal-based thin-film resistors, inductors and capacitors.

Daniel Neumaier, an engineer working with AMO GmbH in Aachen, says …

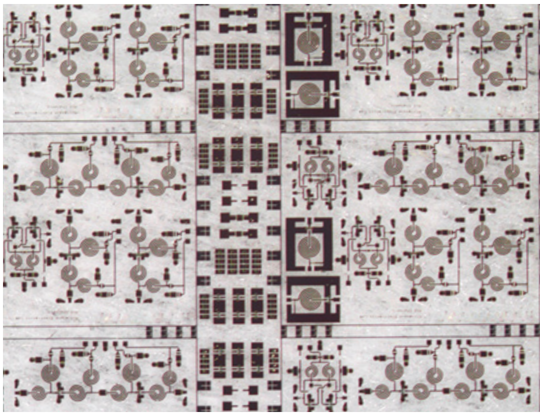
> // The flexibility of implementing graphene devices into various systems is a major advantage compared with established semiconductors. I believe that this will be the key enabler for the success of graphene in electronic devices.

Flagship researchers have designed a first major demonstrator circuit: a receiver for the microwave W-band (75–115 GHz). The design is based on graphene field-effect transistors, using a fabrication technology transferable to either silicon or plastic substrates.

Receivers in this frequency range are commonly used for radar applications and satellite communications. Their application in the consumer electronics sector is currently limited by cost, mainly related to expensive fabrication of boron-nitrogen group semiconductor devices. Graphene-based electronics will play an important role in enabling the widespread use of this technology.

// The flexibility of implementing graphene devices into various systems is a major advantage compared with established semiconductors.

Work package leader Dr. Daniel Neumaier.



Integrated Circuits and Test Structures based on Graphene Field Effect Transistors. © Daniel Neumaier, AMO.

Work Package 4: High Frequency Electronics
Work package leader: Dr. Daniel Neumaier, AMO GmbH, Germany
Deputy leader: Prof. Herbert Zirath, Chalmers University of Technology, Sweden

Article: Fiori et al., Electronics based on two-dimensional materials, Nature Nanotech 9, 768 (2014); doi: 10.1038/nnano.2014.207

Optoelectronics

Photonics and optoelectronics target the integration of electronics and light, and here flagship researchers are exploiting the unique optical properties of graphene and related materials. Among other things, they are working on applications in long-haul communications, optical interconnects, wireless communications, security and surveillance, environmental monitoring and energy harvesting.

Andrea Ferrari, director of the Cambridge Graphene Centre, comments on the achievements of flagship researchers in photonics and optoelectronics …

// We have assembled a world leading team in optical technologies based on graphene and related materials. With almost 90 publications and over 10 prototypes in the first year, the optoelectronics effort has seen major advances in light-based technologies.

// Advances made by flagship researchers include ultrafast lasers with unprecedented speed and spectral tunability, and which work over the broadest wavelength range of any other material. We have also created flexible, transparent detectors able to capture light with unsurpassed efficiency.

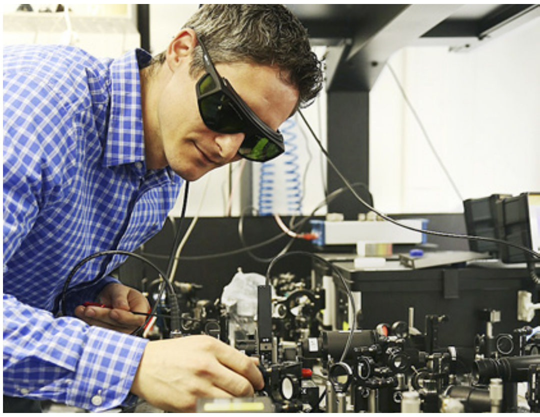
// In exploiting surface plasmons – electron oscillations which propagate along the interface between conducting and insulating materials – we have developed chemical detectors with four orders-of-magnitude better performance than conventional solutions.

The detectors can measure signals in the mid-infrared and terahertz regions of the electromagnetic spectrum, and this will have great potential for security applications. The challenge now is to integrate the devices into a scalable platform compatible with the established CMOS technology for silicon-based transistors.

Systems integration of optoelectronic devices developed by flagship researchers will enable high-speed data transmission with low power consumption, and thus overcome the main optical interconnect challenges of cost and energy efficiency. Graphene and related materials will then become the technology of choice for chip-to-chip and eventually on-chip communications.

// With almost 90 publications and over 10 prototypes in the first year, the optoelectronics effort has seen major advances in light-based technologies.

Work package leader
Prof. Andrea Ferrari.



Dr. Valentin Wittwer of the Cambridge Graphene Centre characterising graphene-based saturable absorbers for ultrafast lasers. © University of Cambridge.

Work Package 5: Optoelectronics
Work package leader: Prof. Andrea Ferrari, University of Cambridge, United Kingdom
Deputy leader: Prof. Frank Koppens, Institute of Photonic Sciences, Spain

Article: Koppens et al., Photodetectors based on graphene, other two-dimensional materials and hybrid systems, Nature Nanotech. 9, 780 (2014)

Spintronics

Electronics is based on the manipulation of electric charges, but it can go further than that. Electrons also possess the quantum mechanical property known as spin, which is a form of intrinsic angular momentum. An example of a device which exploits spin is the read head on a magnetic hard drive.

Graphene Flagship researchers are looking to unlock the potential of electron spin using graphene and related materials. In particular they are targeting efficient room temperature spin injection and detection, and also spin gating and manipulation in spintronic devices. Spin transport mechanisms in graphene-based devices are being explored using a number of different material and device fabrication techniques.

Bart van Wees, a physicist at the Zernike Institute of Materials in Groningen, talks about the record spin lifetimes achieved by flagship researchers…

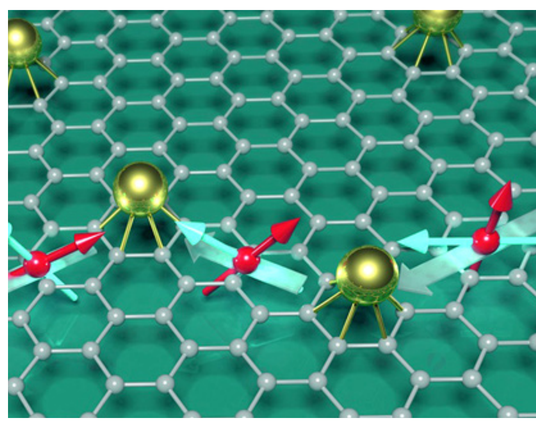
> By optimising device fabrication through the encapsulation of graphene between boron-nitride layers, and engineering the best conditions for spin injection and detection, our researchers have reported the largest spin lifetimes – a few nanoseconds – ever measured at room temperature. The associated long distances over which spin information can be transported demonstrate the capability of graphene-based spintronic devices for practical applications.

This enhancement of spin lifetime by several orders of magnitude over the state-of-the-art was obtained by optimising material quality and device integration processes. Achieving such long spin lifetimes at room temperature is an essential step toward the further engineering of efficient spin gating or manipulation functions, which constitute the main targets and challenges for the flagship in the next phase. The practical use of graphene-based spintronics for targeted applications will now be evaluated.

On the theoretical side, flagship researchers have begun to unravel several spin relaxation mechanisms and phenomena which make spin dynamics in graphene unique. This is a challenge which demands a full quantum dynamics treatment, beyond conventional and semi-classical approximations.

> Researchers have begun to unravel several spin relaxation mechanisms and phenomena which make spin dynamics in graphene unique.

Work package leader
Prof. Bart van Wees.



Electron spin/G lattice. © Bart van Wees.

Work Package 6: Spintronics
Work package leader: Prof. Bart van Wees, University of Groningen, the Netherlands
Deputy leader: Prof. Stephan Roche, ICN Catalan Institute of Nanotechnology, Spain

Article: Guimarães et al., Controlling spin relaxation in hexagonal BN-encapsulated graphene with a transverse electric field, Phys. Rev. Lett. 113, 086602 (2014); doi: 10.1103/PhysRevLett.113.086602

Sensors

Sensors cover a multitude of applications and device types, and among the physical properties of interest for sensing are pressure, sound waves, mass, force, electromagnetic radiation and biological processes. Graphene Flagship researchers are developing devices over a whole range of applications.

Suspended graphene membranes are a starting point and a key focus for flagship researchers. In such free-hanging layers, electrical and mechanical degrees of freedom are strongly coupled. This offers unique opportunities for implementing graphene-based sensors, based on their mechanical properties.

Biosensors are of particular interest to biophysicist Cees Dekker and his colleagues at the Kavli Institute of NanoScience in Delft. Dekker's group was among the first to study the movement of DNA through solid-state nanopores, using membranes made of silicon nitride, and the researchers have since been working with graphene monolayers in order to improve DNA sequencing. They have shown that single molecules of DNA in water can be pulled through a graphene nanopore and, critically, that each molecule can be detected as it passes through the pore.

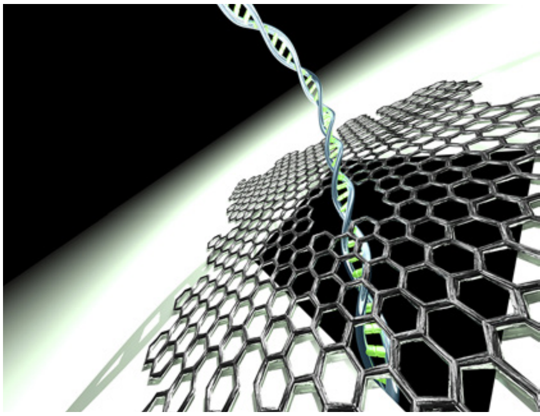
> // Translocation of DNA through a nanopore in order to determine its base sequence is a 25-year-old idea that has very recently led to the first commercial devices based on protein nanopores in lipid bilayers, which are relatively fragile.

> // Flagship researchers are now exploring next-generation nanopore sequencing devices. We employ graphene for both its monolayer thin quality, which allows the ultimate resolution, and its intrinsic conductance, leading to novel sensing modalities.

Dekker and his colleagues have extended the principle in order to study more elaborate constructs such as DNA-protein complexes. Apart from investigating the translocation of such molecules, the researchers employ a combination of nanopores and optical tweezers to locally exert and measure the forces involved. Moreover, protein-coated artificial pores are being used to mimic the biological nuclear pore complex, testifying to the versatility of nanopore sensors.

> // Researchers have shown that single molecules of DNA in water can be pulled through a graphene nanopore and, critically, that each molecule can be detected as it passes through the pore.

Prof. Cees Dekker.



Schematic illustrating the translocation of DNA through a graphene nanopore. © Kavli Institute of NanoScience.

Work Package 7: Sensors
Work package leader: Prof. Herre van der Zant, Technical University of Delft, the Netherlands
Deputy leader: Prof. Pertti Hakonen, Aalto University, Finland

Article: Schneider et al., Tailoring the hydrophobicity of graphene for its use as nanopores for WA translocation, Nat. Commun. 4, 2619 (2015); doi: 10.1038/ncomms3619

Flexible electronics

Conventional silicon-based electronics is inherently inflexible, but flexible circuits based on graphene and other 2D materials open up a plethora of possibilities that will complement and enhance established technologies. They will enable such things as rollable displays, textiles with embedded sensors, electronic devices moulded to fit their environment, and more.

Flagship partners are investigating and assembling all the required technology enablers for flexible electronics. These include the development of suitable materials and processes, and system integration of flexible components.

Flexible solutions for energy, radio-frequency electronics and sensing have been studied during the first year of the flagship, with demonstrator devices based on graphene and related materials realised. Another first-year highlight is the e-reader display developed by the Cambridge Graphene Centre together with printed electronics specialist Plastic Logic/FlexEnable Ltd.

When it comes to the field of flexible electronics as a whole, flagship partners are addressing the issue of scalable manufacturing of flexible graphene-based devices. A fundamental milestone has been successfully achieved: the fabrication of flexible graphene transistors on six-inch wafers.

Sebastiano Ravesi, a technology development specialist with STMicroelectronics in Catania, comments on the potential of and challenges surrounding graphene and related materials in flexible electronics…

// We believe that graphene could enable many applications in the so-called 'More Than Moore' area, adding valuable features to the silicon-based CMOS platform, and, especially, to smart systems integration on flexible substrates for wearable electronics and the Internet of Things.

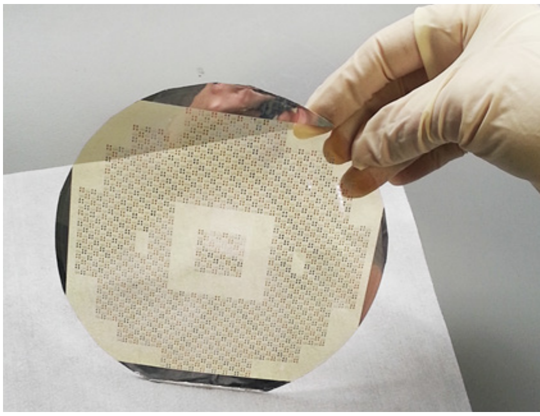
// In order to reduce the time to market, we are tackling all the challenges to integrate graphene in manufacturing. This includes large-area processing on flexible and silicon substrates, and cross-contamination and metrology issues in factory environments. We have also fabricated large-area field-effect transistors on plastic substrates, to be used as sensing devices integrated within fully flexible smart systems.

The scalable manufacturing capability of which Ravesi speaks paves the way to industrially relevant applications of graphene and related materials in flexible electronics.

Work Package 8: Flexible Electronics
Work package leader: Dr. Jani Kivioja, NOKIA Research Center, United Kingdom
Deputy leader: Dr. Sebastiano Ravesi, STMicroelectronics, Italy

// In order to reduce the time to market, we are tackling all the challenges to integrate graphene in manufacturing.

Deputy work package leader Dr. Sebastiano Ravesi.



Flexible graphene-based transistors on a six-inch wafer. ©STMicroelectronics.

Energy

Graphene and related materials have many potential applications in energy conversion and storage. Two-dimensional crystals combine high electrical conductivity with physical flexibility and a huge surface to weight ratio. Such qualities make them highly suitable for storing electric charge in batteries and supercapacitors, and as catalysts in solar and fuel-cell electrodes.

Flagship researchers are very active in this area, and the interest from industry is strong. Work done during the first year includes material functionalisation (graphene can be produced in a variety of forms, each of them with physical and chemical properties that can be tuned for specific energy applications).

Etienne Quesnel, a materials scientist based at the French Alternative Energies and Atomic Energy Commission in Grenoble, points to the value and complementary nature of graphene in energy applications …

> // We are convinced that innovative technologies will emerge from our ability to understand and control the electrochemical properties of graphene, and to fully integrate graphene with the materials used today in energy applications.

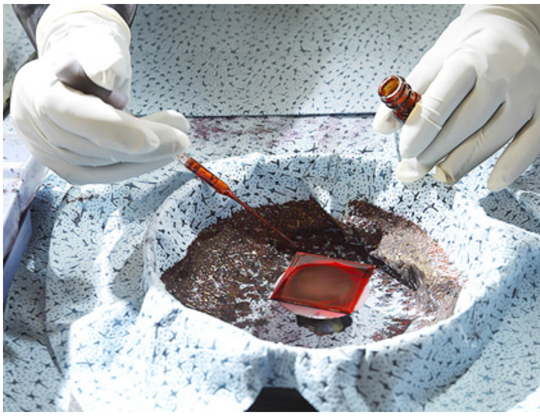
> // Organic solar cells with better efficiency are one goal. Modelling helps predict how laser-assisted chemical modification of graphene surfaces can improve photovoltaic performance, and experimental confirmation of theory opens the way to more efficient, flexible solar cells.

> // As for batteries, commercial graphene-coated copper foils are a smart way of manufacturing novel flexible battery systems which meet mobile application requirements.

The interest in 2D materials for energy applications comes not only from their properties, but also the possibility of producing and processing them in large quantities, in a cost-effective manner. Printable inks, for example, are the gateway to the realisation of new-generation electrodes in energy storage and conversion devices. The challenge ahead is to demonstrate a disruptive technology in which 2D materials not only replace traditional electrodes, but, more importantly, enable whole new device concepts.

// We are convinced that innovative technologies will emerge from our ability to understand and control the electrochemical properties of graphene.

Work package leader
Dr. Etienne Quesnel.



Researchers at work in the CEA-Liten labs, Grenoble, France. © Avavian/reproduced by courtesy of CEA-Liten.

Work Package 9: Energy
Work package leader: Dr. Etienne Quesnel, CEA French Alternative Energies and Atomic Energy Commission, France

Deputy leader: Dr. Vittorio Pellegrini, Italian Institute of Technology, IIT Graphene Labs, Italy
Article: Bonaccorso et al., Graphene, related two-dimensional crystals, and hybrid systems for energy conversion and storage, Science 347, 6217 (2015)

Nanocomposites

Much attention is given to the properties of graphene in its pure, defect-free form, but when exploiting graphene in the real world, we must consider such things as application context, manufacturing cost and scalability. That can mean combining graphene with other materials in composites.

Graphene-based composites are at present the only commercially available forms of graphene. The number of products containing such composites is ever increasing, but the performance of commercial products should be improved to match what can be achieved in the laboratory.

Vincenzo Palermo, leader of the Advanced Materials unit at the Institute for Organic Synthesis and Photoreactivity in Bologna, describes the work of flagship scientists in the development of graphene-based composites …

// In the first year of the flagship, we have studied how to improve the processing, interaction and performance of monoatomic sheets of graphene or graphene oxide in three-dimensional composites. We have developed methods to model sheet size and orientation, and measure in-situ their mechanical behaviour. We have also studied how graphene behaves under stress, such as when compressed into a composite, or used as reinforcement in microstructures.

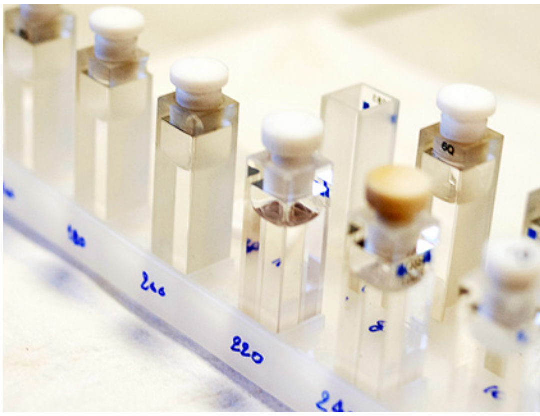
// Graphene can interact with other materials, not only to reinforce them, but also generate new properties and functions. Thanks to their high surface area, mechanical strength, flexibility and chemical versatility, graphene-based nanosheets can be used as ultra-thin scaffolds, and combined with other materials to enhance their properties.

Flagship researchers have created two-dimensional composites of graphene oxide with silica, hematite and conductive polymers. These have been used to produce metal-free catalysts in fuel cells, exhibiting superior performance to that of conventional platinum-based catalysts. Graphene-based composites can reduce cost and enhance lithium storage in batteries. They can also be used to build photosensors comparable to state-of-the-art inorganic devices based on silicon, and high-performance supercapacitors.

There is practically no limit to the number of possible 2D composites based on a graphene backbone structure. Chemistry can then be used to modify them according to application requirements.

// There is practically no limit to the number of possible 2D composites based on a graphene backbone structure.

Work package leader
Dr. Vincenzo Palermo.



Thin sheets of graphene dissolved in solution to be re-assembled with other materials to create nanocomposites for mechanics, batteries, capacitors, sensors or electronics. © Institute of Organic Synthesis and Photoreactivity.

Work Package 10: Nanocomposites
Work package leader: Dr. Vincenzo Palermo, CNR National Research Council, Italy
Deputy leader: Dr. Xinliang Feng, Max Planck Society, Germany

Article: Wei et al., Nitrogen-Doped Carbon nanosheets with size-defined mesopores as highly efficient metal-free catalyst for the oxygen reduction reaction, Angew. Chem. Int. Ed. 53, 1570 (2014); doi: 10.1002/anie.201307319

Production

There are various ways of producing graphene and its derivatives, but successful commercial exploitation will depend on being able to produce the materials cost effectively on a large scale. One group of flagship researchers is focusing on bulk production of graphene films at equipment and material levels, and the evaluation of production scalability, reproducibility and cost. The work is aligned with other material production projects funded by the European Commission through its NMP programme.

For graphene-based products to become a reality, a strategic alignment with end-use customers is required. Three industrial partners of the Graphene Flagship – AIXTRON, Graphenea and Grupo Antolin – are working with others on the commercial-scale manufacture of graphene products. An example of this alignment is the close interaction between AIXTRON, Graphenea and Philips on the development of graphene films for flexible organic light-emitting diodes.

OLEDs are increasingly common in mobile device displays and lighting systems, and there is significant potential for market growth. Flagship partners have added mechanical flexibility to OLEDs, thus paving the way to foldable and rollable products. When used as the transparent electrode in OLEDs, graphene has the advantage of superior mechanical flexibility, improved light extraction, and compatibility with a wide range of flexible substrates.

In addition to thin film graphene, the partners are also working on graphene in powder form. Upscaling graphene powder production is also a key factor for the success of graphene in the automotive, aerospace and construction industries. Grupo Antolin has developed a method for producing its GRAnPH products, graphene oxide and other graphene-related materials from carbon nanofibres grown by the floating catalyst method at the tonne scale. This will provide the high volumes required by these and other industries at a competitive cost.

During the first year, flagship partners formed a number of important partnerships with European companies, with a view to bringing concepts to reality through the creation of value chains.

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Work package leader
Dr. Ken Teo.

Production of 6-inch graphene on an AIXTRON BM Pro system. These are transferred onto flexible polyethylene naphthalate substrates by Graphenea, and then integrated into a flexible organic light-emitting diode (13 × 13 cm) by Philips. © Aixtron Ltd.

Work Package 11: Production
Work package leader: Dr. Ken Teo, Aixtron Ltd., United Kingdom
Deputy leader: Dr. Nalin Rupesinghe, Aixtron Ltd., United Kingdom

Graphene Flagship partners

The Graphene Flagship consists of 142 academic and industrial research groups in 23 countries (see map, inside cover).

Austria
- 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

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 S.A
- Thales
- Université Montpellier 2 Sciences et techniques
- University of Lille 1
- University of Strasbourg
- UPMC Sorbonne Universités

Germany
- Alcatel Lucent
- AMO
- BASF
- Chemnitz University of Technology
- CNM Technologies GmbH
- Dresden University of Technology
- EPCOS AG
- Fraunhofer IAF
- Friedrich-Alexander University Erlangen-Nuremberg
- Hamburg University of Technology
- Karlsruhe Institute of Technology
- Max Planck Society
- Philips Technology GmbH
- RWTH Aachen University
- Technical University Munich
- TU Dortmund University
- Ulm University
- University of Augsburg
- Bielefeld University
- University of Bremen
- University of Freiburg
- University of Hamburg
- University of Kiel
- University of Regensburg

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
- Breton S.p.A.
- Centro Ricerche Fiat S.C.p.A. (CRF)
- CNIT
- CNR National Research Council
- Delta-Tech S.p.A.
- Dyesol Headquarters
- FBK Bruno Kessler Foundation
- 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
- Selex ES Ltd
- ST Microelectronics
- University of Bologna
- University of Padova
- University of Pisa
- University of Salerno
- University of Trieste
- University of Tor Vergata

The Netherlands
- Delft University of Technology
- Philips
- Radboud University Nijmegen
- University of Groningen
- Eindhoven University of Technology
- DSM Ahead BV

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 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
- Repsol
- Tecnalia Research and Innovation
- University of Castilla-La Mancha
- The University of Zaragoza

Sweden
- Chalmers University of Technology
- Chalmers Industrial Technology
- Ericsson
- Karolinska Institute
- Linkoping University
- Umea University

Switzerland
- EMPA Swiss Federal Laboratories for Materials Science and Technology
- ETH Swiss Federal Institute of Technology Zurich
- École Polytechnique Fédérale de Lausanne
- University of Basel
- University of Geneva
- University of Zurich

Turkey
- Sabanci University

United Kingdom
- Amalyst Ltd.
- Aixtron Ltd.
- BAE Systems
- G24 Power Ltd
- Imperial College London
- Lancaster University
- Nokia R&D
- NPL National Physical Laboratory
- Oxford Instruments
- Queen Mary University of London
- University College London
- University of Cambridge
- University of Manchester
- The University of Nottingham
- University of Oxford
- University of Sheffield
- University of Sunderland

Mapping the road ahead

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Every one of the science and technology work packages achieved its milestones, and often exceeded the relevant key performance indicators.

This short brochure attempts to summarise the many achievements of Graphene Flagship partners over the first year. Our target was to make a start with this unprecedented effort in translational technology, to turn early-stage discoveries into new products, and advance 2D materials innovation to the point where it becomes attractive for further industrial development.

The flagship's Executive Board has faced many challenges along the way. These range from the definition of topics for the open call and member states' joint transnational call, to agreeing a governance structure for the steady-state phase from 2016 onwards.

Every one of the science and technology work packages achieved its milestones, and often exceeded the relevant key performance indicators. The collective effort of flagship partners has now provided us with a clear roadmap for the years ahead. This was published recently as an open-access document in the journal Nanoscale.

It is our great duty to ensure that the work of the flagship community is disseminated to audiences both specialist and general. This has been achieved through successful exhibitions, both at conferences and museums, as well as at Graphene Schools open to all.

We have also staged Graphene Connect workshops, with existing and prospective industrial partners joining academic researchers to discuss topics ranging from composites and energy to flexible electronics and high-speed data connections. These are some of the many application areas in which graphene and related materials are expected to have a disruptive impact. Our innovation and alignment activities have ensured wide participation, and the engagement of funding agencies and technology transfer offices across Europe.

At the end of its first year of operation, the Graphene Flagship has created a cohesive research and development community, and we are confident that Europe still leads in the science of graphene and related materials. We must now keep up the pace, so that Europe can benefit from new technologies and job creation driven by an emerging graphene economy.

Prof. Andrea Ferrari
Chair of the Executive Board of the Graphene Flagship

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