

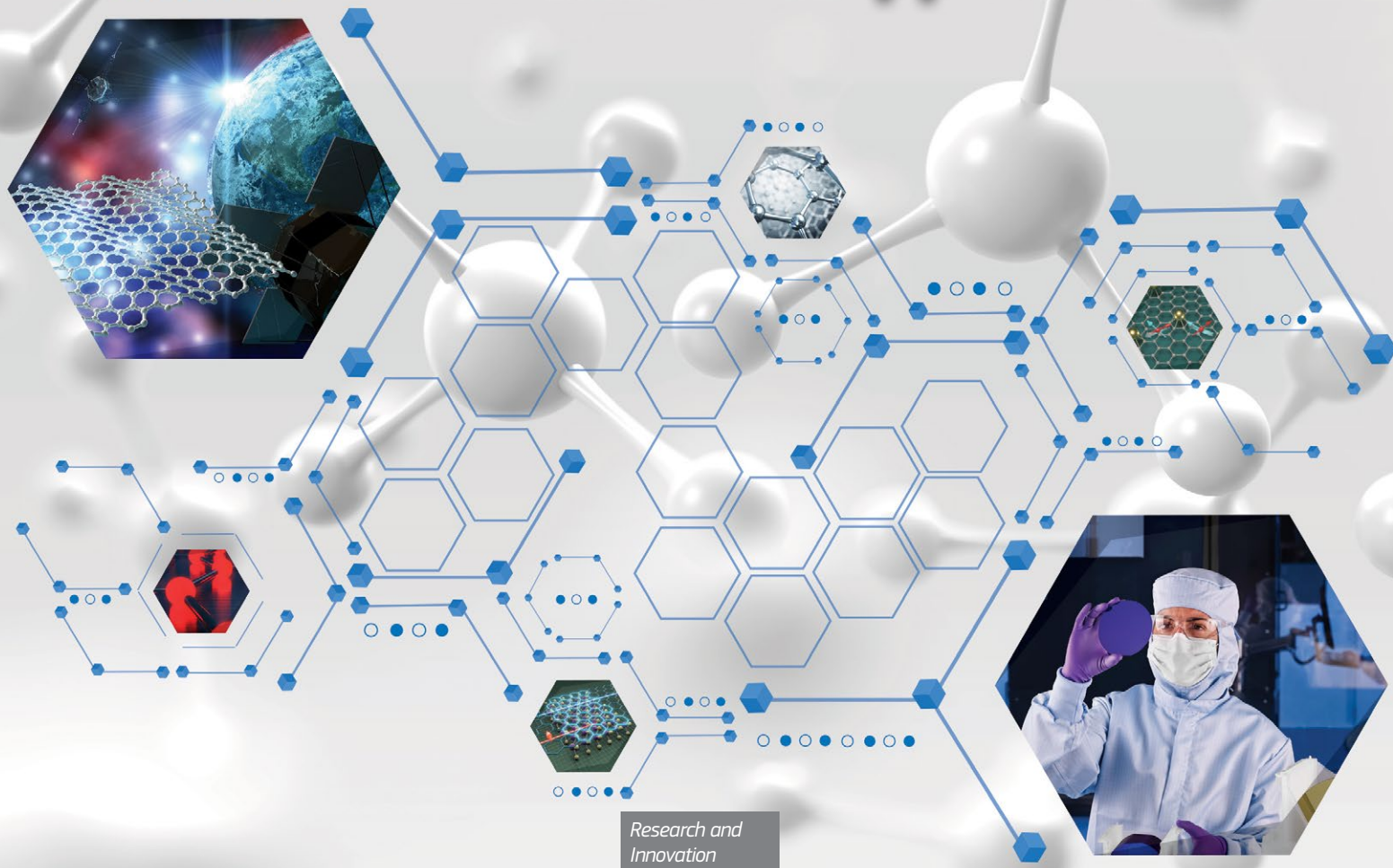


CORDIS Results Pack on graphene

A thematic collection of EU-funded research and innovation results

January 2019

Graphene and 2D materials on track to innovative applications



Research and
Innovation

Contents

3

Europe's investment in graphene

5

Graphene's versatility extends to space applications

7

Graphene's spectacular performance in high-speed optical communications

9

Taking graphene mass production to the next era

11

Novel graphene-based materials

13

Graphene makes low-dimensional spintronics viable at room temperature

15

Biomedical advances through use of graphene

17

Graphene quantum dot detectors for next-generation health-monitoring wearables

19

Using graphene as a supercharged magnifying glass

21

Using graphene for flawless tunnelling accelerometers

23

LbL technology applied to graphene oxide

25

Graphene-reinforced polymers ready for commercialisation

Editorial

Graphene is a two-dimensional atomic crystal made up of carbon atoms arranged in a hexagonal lattice. At one atom thick, graphene is the thinnest known compound, as well as the strongest compound discovered (between 100 and 300 times stronger than steel), the lightest known material (with one square metre weighing approximately 0.77 milligrams), and extremely flexible.

A material for the future

This **CORDIS Results Pack** showcases 12 articles on 6 ambitious cutting-edge EU research projects funded under the EU's Seventh Framework Programme (FP7) and Horizon 2020 research programmes relevant to graphene and 2D materials. Of these, seven articles cover different aspects of the Graphene Flagship.

The Graphene Flagship, the EU's biggest research initiative, with a budget of EUR 1 billion, represents a new form of joint, coordinated research initiative on an unprecedented scale. Through a combined academic-industrial consortium, the research effort covers the entire value chain, from materials production to components and system integration, aiming to exploit the unique properties of graphene.

An introduction to graphene outlines work conducted by the Flagship, including collaboration with the European Space Agency (ESA) on the use of graphene in space applications, such as light propulsion and thermal management. Researchers also used optoelectronic communication systems to provide fast data for the future. The large-scale production of graphene for commercial market applications involved scaling up manufacturing to industrial scale, whilst maintaining consistency, high quality and cost-efficiency.

Scientists investigated chemical processing and functional applications of graphene and graphene-related materials for engineering new molecular structures with unique properties. Graphene spintronics utilised both electron charge and spin at room temperature to create new possibilities for information-processing and storage. Finally, the Flagship has investigated the use of graphene for biomedical applications to develop innovative medical devices and sensors for detecting, treating and managing nervous system diseases.

European graphene research doesn't all fall under the remit of the Flagship, and researchers are using alternative EU funding mechanisms to undertake other projects. GRAPHEALTH produced the next generation of wearable sensors, while GRASP applied interactions between graphene and light to quantum computing and biomedicine. GraTA developed tunnelling accelerometers for use in machine vibration monitoring. HIGRAPHEN created dense polymer composites for use in optoelectronics and energy storage. PolyGraph (working closely with the Graphene Flagship) studied graphene-reinforced polymers for use in the aeronautics and automobile sectors.

Europe's investment in graphene

The world's first two-dimensional material, graphene, possesses unique and outstanding properties. A major EU-funded initiative has developed the material and its application in a myriad of new technologies.

Graphene is a familiar material: the 'lead' in pencils is actually graphite, which comprises many layers of graphene stacked on top of each other. Following the isolation of a single atomic layer for the first time in 2004 by Andre Geim and Konstantin Novoselov at the University of Manchester, scientists have discovered that individual graphene layers possess exceptional properties. These properties include the highest thermal conductivity of any known material, plus very high strength and electrical conductivity. Furthermore, graphene is impermeable, transparent and flexible, and combinations of these properties can be applied to many different areas.

The goal of the EU-funded [Graphene Flagship](#) is to bring graphene and related materials (GRMs) out of the laboratory into society in the form of exciting and versatile new products. The Flagship aims to contribute to Europe's economic growth through the creation of new employment opportunities.

Significant funding

This is the EU's largest research initiative; with a duration of 10 years and a budget of EUR 1 billion, it represents a new form of joint coordinated research at an unprecedented scale. It is funded jointly by the European Commission, Member States and Associated Countries, with over 150 research groups across 23 countries involving academia, research institutes and industry. "Research efforts cover the entire value chain from materials production to component technologies, and system integration ranging from electronics or optoelectronics to composite materials, batteries and coatings," notes Dr Jari Kinaret, Director of the Graphene Flagship.

In the current phase of the Flagship programme (known as Core2) running between 2018 and 2020, six spearhead projects





Research efforts cover the entire value chain, from materials production to component technologies, and system integration ranging from electronics or optoelectronics to composite materials, batteries and coatings.

are being conducted. These projects focus on a wide range of application areas, but all aim to develop new or improved products with GRMs. The move towards a higher technology readiness level is evident after partner organisations launched six spin-off companies based on their work, securing more than EUR 20 million in risk capital funds.

“It is quite difficult to choose the highlights among individual results,” says Prof. Kinaret. “But I would mention extremely rapid communication systems such as very fast photodetectors and a photonic switch for 5G communication systems.” Additional examples include a combination of different upscalable technologies for producing graphene flakes through electrochemistry or shear exfoliation, both of which have already been commercialised.

lighter cars and airplanes to be produced. Furthermore, we are developing a wide range of sensors for environmental and medical applications.”

Graphene’s unique thermal and strength properties make it ideal for improving the performance of aerospace and satellite applications. When combined with composites or plastics, graphene performs exceptionally well in terms of overall strength, material strength and thermal conductivity. Graphene is also useful in novel diagnosis and treatment applications such as drug delivery and biosensors.

Europe is now a major player in graphene revolution. “By taking graphene from the realm of academic laboratories and into society, Graphene Flagship aims to generate economic growth, new jobs and new opportunities for Europeans as both investors and employees,” concludes Prof. Kinaret.

Major benefits

The initiative also promotes sustainability, with researchers working on several technologies related to renewable energy. “For example, we are developing a solar farm in Crete, and energy storage technologies that are crucial for electromobility,” explains Prof. Kinaret. “More generally, many of the technologies we are working on reduce energy consumption by enabling

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COORDINATED BY

Chalmers University of Technology, Sweden

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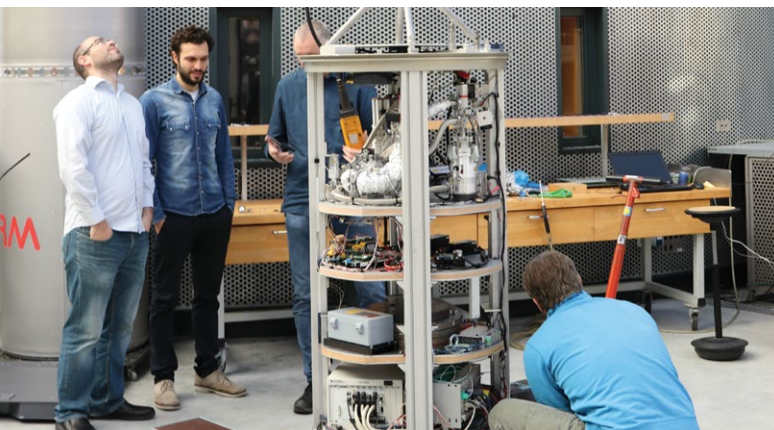
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Graphene's versatility extends to space applications

In an ingenious set of experiments, European teams have tested graphene under microgravity conditions for the first time. The exciting results provide a valuable foundation for developing graphene devices for use in space.



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Graphene has unique mechanical, electrical and thermal properties, inspiring researchers to explore the usefulness of this two-dimensional lattice of pure carbon.

Researchers and students in the Graphene Flagship research initiative, in collaboration with ESA, have found additional potential for the material that renders it suitable for use in space applications including light propulsion and thermal management. Results produced from this well-orchestrated synergy constitute the first step towards expanding the frontiers of graphene research.

Sailing in space with graphene

Breakthrough Starshot is a Breakthrough Initiatives research and engineering project that aims to develop a proof-of-concept fleet of light-sail spacecraft that will reach the Alpha Centauri star system within 20 years of launch.

A team of Graphene Flagship graduate students from the Delft Technical University in Netherlands participating in [ESA Education's Drop Your Thesis!](#) programme took a first step towards this ambitious goal. The programme offered them the chance to perform an experiment in microgravity at the Center of Applied Space Technology and Microgravity (ZARM) Drop Tower in Bremen, in order to test graphene's potential as a solar sail material in spacecraft propulsion.

To create microgravity conditions, a capsule containing cameras, lasers and graphene was allowed to fall down a 150-metre tower, leading to 4.5 seconds of weightlessness. The radiation pressure from shining high-power laser light onto the graphene membrane caused the sail to move. The team measured this displacement with a microscope to determine the thrust on the graphene sails.

"For effective propulsion, the light sail must have a large surface and be as light as possible. Graphene satisfies these requirements, as it is very light and strong, and can be expanded over a large area," notes Prof. Andrea Ferrari (University of Cambridge (UK)), Science and Technology Officer of the Graphene Flagship.

Graphene spreads the heat

Researchers from Graphene Flagship partner institutes the Free University of Brussels (ULB) (Belgium), the University of Cambridge (UK), the Bologna Unit of the Italian National Research Council (CNR) (Italy), and Leonardo (Italy) designed an experiment to test how graphene-based coatings can improve the efficiency of satellite cooling systems by utilising the material's unique thermal properties.



The experiments showed that graphene improved the capillary pressure of the fluid in the metallic wick by 40 %, and the evaporation rate by 800 %.

Prof. Ferrari explains: "Graphene is being used in what are called loop heat pipes, which are pumps that move fluid without the need for any mechanical parts. This is very important for space operations because there is no wear and tear as well as no need for maintenance. For example, loop heat pipes can transport heat from hot electronic systems in satellites out into space."

The material was brought aboard a parabolic flight in Novespace Zero-G aircraft, where microgravity conditions are created for intervals of about 24 seconds at a time. The team conducted 6 flights, each making 31 parabolic arcs, for a total of over 1 hour in microgravity.

"The graphene aboard endured the environment and performed well. The experiments showed that graphene improved the capillary pressure of the fluid in the metallic wick by 40 %, and the evaporation rate by 800 %," notes Prof. Ferrari.

Both experiments were an exceptional display of the manifold potential of graphene, which has now extended its boundaries by establishing its usefulness in space. Based on the encouraging results, the Flagship is continuing to develop and optimise graphene devices for applications in real-space conditions.

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Graphene's spectacular performance in high-speed optical communications

Integrating graphene sheets into silicon photonics could form the basis for next-generation data communications. Researchers from the Graphene Flagship initiative have pushed the technology closer to application by demonstrating the world's first high-speed graphene-based data communication at a data rate of 50 Gb/s.

The Graphene Flagship programme aims to act as a catalyst for the development of groundbreaking applications by bringing together academia and industry to take this versatile material into society within 10 years. The importance of integrating graphene in silicon photonics was evident in the joint results produced by the collaboration between Flagship partners AMO GmbH (Germany), the National Inter-University Consortium for Telecommunications (CNIT) (Italy), Ericsson (Sweden), Ghent University (Belgium), the Institute of Photonic Sciences (ICFO) (Spain), imec (Belgium), Nokia (Germany and Italy), the Vienna University of Technology (TU Wien) (Austria) and the University of Cambridge (UK).

One-chip wonder

Silicon has been widely hailed as suitable for monolithic integration for photonics. However, increasing the speed and reducing the power and footprint of key components of silicon photonics technology has not been achieved in a single chip, to date. But graphene — with its capacity for signal emission, modulation and detection — can be the next disruptive technology to achieve this.

"Graphene offers an all-in-one solution for optoelectronic technologies," notes Daniel Neumaier

from AMO GmbH, Leader of the Graphene Flagships Division on Electronics and Photonics Integration. Its tuneable optical properties, high electrical mobility, spectrally broadband operation and compatibility with silicon photonics allow monolithic integration of phase and absorption modulators, switches and photodetectors. Integration on a single chip can increase device performance and substantially reduce its footprint and fabrication cost.

Not entirely stuck on silicon

Light modulation and detection are key operations in photonic integrated circuits. Lacking a bandgap, graphene makes broadband light detection with a single material possible as it absorbs uniformly across a broad range in the visible and infrared spectrum. The 2D material also displays electro-absorption and electro-refraction effects that can be used for ultrafast modulation.

Instead of relying on the expensive silicon-on-insulator wafer technology widely used in silicon photonics, Graphene Flagship researchers proposed a more convenient configuration. This consisted of a pair of single-layer graphene (SLG) layers, a capacitor consisting of an SLG-insulator-SLG stack



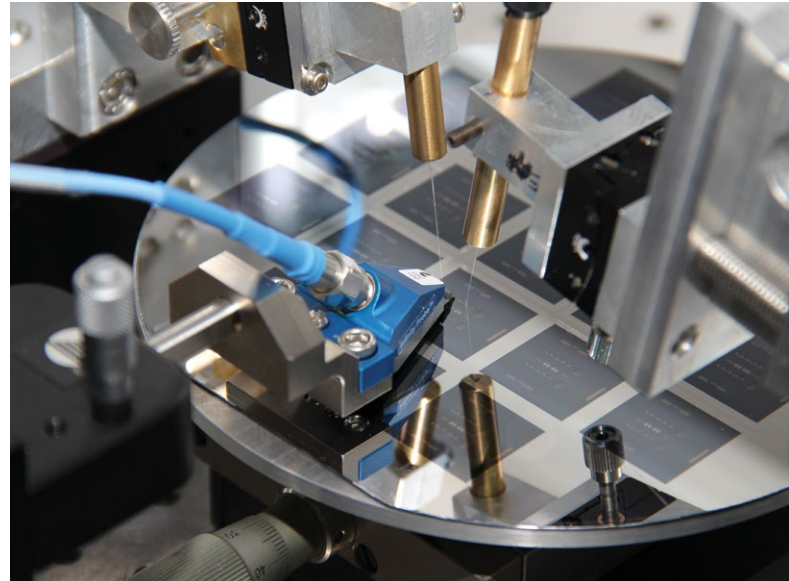
Offering high speeds and high rates of data-streaming, graphene-based photonic devices are key for the next generation of data transfer.

on top of a passive waveguide. "Such an arrangement boasts several advantages compared to silicon photonic modulators," explains Neumaier. As he further outlines, modulator fabrication does not rely on the waveguide material or the electro-absorption and electro-refraction modulation mechanisms. In addition, replacing germanium photodetectors with SLG removes the need for the fairly costly modules of germanium epitaxy and the accompanying specialised doping processes.

Silicon nitride (SiN) provided a good substrate for synthesising graphene, enabling high carrier mobility, transparency over the visible and infrared regions and perfect compatibility with silicon and complementary metal-oxide semiconductor (CMOS) technologies. As a passive waveguide platform, SiN facilitates laser integration and fibre coupling to the waveguide, thereby enabling the design of miniaturised devices.

A bright future for graphene-based photoelectronics

Tapping into the potential of graphene, researchers successfully demonstrated data communication with graphene photonic components up to a data rate of 50 Gb/s. A graphene-based modulator processed the data on the transmitter side of the network, encoding an electronic data stream to an optical signal. On the receiver side, a graphene-based photodetector converted the optical modulation into an electronic signal. "These results are a promising start for using graphene-based photonic devices in next-generation data communications," Neumaier concludes.



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Taking graphene mass production to the next era

Graphene's unique combination of properties paves the way for a wide variety of applications, from energy and electronics to biomedical devices and aircraft. To meet these increasing demands, researchers have to scale up graphene production to industrial scale.

Traditionally, graphene production takes place through processing of graphite or chemical vapour deposition (CVD) methodologies, each resulting in different material properties and quality. Although CVD is a scalable approach, it only generates monolayers of high-quality graphene suitable for semi-conductor applications.

The Graphene Flagship Production Work Package led by Dr Alex Jouvray of [Aixtron Ltd](#) in the UK, focuses on the mass production of graphene for commercial market applications. The idea is to scale up the manufacturing processes of CVD and bulk graphene to industrial scale in a cost-effective manner, whilst maintaining consistency and high quality. "Our ultimate goal is to establish an industrial graphene supply chain in Europe that can support the diverse applications of graphene," explains Dr Jouvray. Work package partners include an industrial equipment manufacturer (Aixtron Ltd), commercial producers of graphene (Avanzare Innovacion Tecnologica SL, Graphenea SA and Grupo Antolin-Ingenieria SA) and graphene end users such as Airbus Operations SL and Aernnova.

Production methodologies

Graphene processing methods such as exfoliation, sonication and plasma treatment break the graphite in a controlled manner, generating graphene flakes. The exfoliation method can produce extremely high-quality graphene flakes, but it is not scalable to the industrial scale. On the other hand, plasma treatment and sonication can produce very large amounts of graphene oxide, reduced graphene oxide and graphene nanoplatelets that serve as additives to plastics, can be incorporated in glass-reinforced

polymers or in concrete to confer strength and thermal conductivity. In addition, these graphene-related materials are suitable for coatings and printing applications.

Researchers have successfully developed a methodology for large-scale deposition of graphene onto foil alongside a tiling technology that transfers high-quality graphene on large-area substrates. In addition, Avanzare has increased graphene production to tonnes per year, serving as a supplier for other Graphene Flagship partners.

Novel graphene-based products

Apart from graphene production and deposition systems, significant effort has also been dedicated to the qualification of graphene-based products in a real-life environment. A number of products containing graphene have been brought to market, such as tennis rackets, automotive headliners, and a wide range of graphene-related materials. The Production Work Package specifically targets the automotive, aerospace and optoelectronic industries.

By adding graphene into a polymer composite, scientists have generated a flame-retardant plastic with potential application in the automotive and building industries. Incorporation of such



Our ultimate goal is to establish an industrial graphene supply chain in Europe that can support the diverse applications of graphene.



smart materials alongside efficient fire-detection systems can undoubtedly enhance building safety. At the same time, given the increasing problem of road vehicle fires, flame-retardant materials will help enhance road safety.

The development of graphene-reinforced structures for aerospace applications is of great significance. Graphene confers improved mechanical properties and conductivity to composites. Engineers and scientists from Airbus, Aernnova and Grupo Antolin have developed a prototype aircraft component using graphene-based composite materials that provides lightning-strike protection at reduced weight.

Until recently, graphene was largely confined to a research environment. "In the Production Work Package, graphene development is entirely driven by industry, and the material and equipment producers have to adhere to strict development and quality control protocols," Dr Jouvray notes.

With graphene rapidly becoming the material of the 21st century, the industry has to keep up with production processes. Dr Jouvray believes that the Graphene Flagship will "create an industry-driven ecosystem for graphene and its related products, thereby expanding potential applications".

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Novel graphene-based materials

Pollution is a serious issue in many parts of the world, especially in urban areas. Using novel graphene-based materials, researchers from the Graphene Flagship Functional Foams and Coatings Work Package have provided solutions to tackle environmental contamination, among other applications.

Widespread enthusiasm about the applications of graphene in industry has been hampered by high-cost, scalability and quality bottlenecks. Various methodologies have been tested, which either leave defects in the resulting material or suffer from limited yield. Therefore, there is a pressing need to produce high-quality graphene at large scale with novel functionalities.

The Functional Foams and Coatings Work Package, led by Prof. Xinliang Feng of the Technical University of Dresden in Germany, focuses on the chemical processing and functional applications



Electrochemical exfoliation and functionalisation of graphite will help bridge the gap between materials science and practical applications.

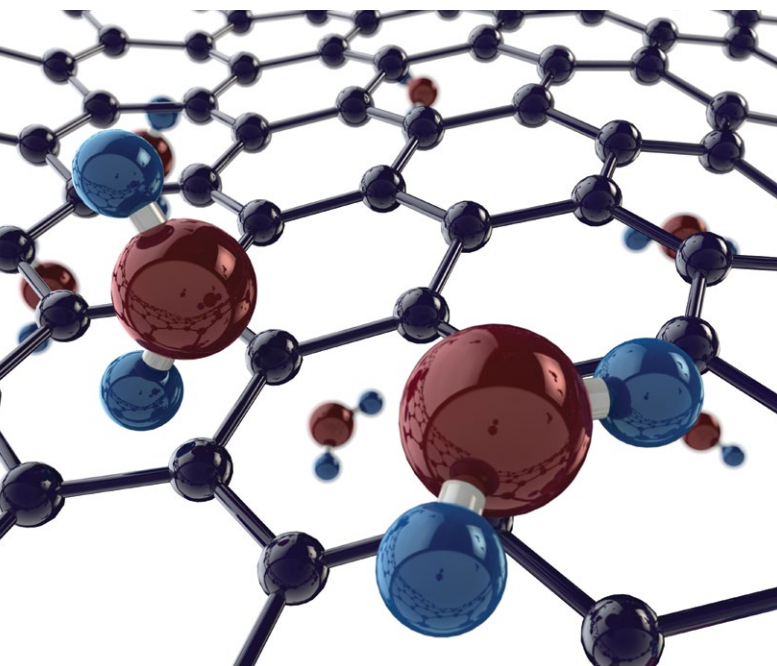
of graphene and graphene-related materials (GRMs). “Our aims are to create porous structures such as foams and membranes, mainly for filtration, and functional thin films for various applications,” explains Dr Martin Lohe, Group Leader of Innovation & Industry at the University of Dresden.

Upscaling graphene production

Researchers have successfully developed a graphene production process in the laboratory based on electrochemical exfoliation, that generates high-quality graphene with tremendously improved yield. It involves the use of an electrolyte and an electrical current that drive structural expansion within minutes or hours under ambient conditions. Electrochemical exfoliation is also ecofriendly and can be adapted to natural carbon resources.

The most significant advantage of this method is that graphene with tuneable properties can be produced simply by changing the starting material and the conditions of the process. As a result, the graphene can be tailor-made, depending on the given application.

Scientists had to overcome certain obstacles, mainly associated with the tendency of high-quality graphene to stack back together. To address this problem, they used functionalising agents that resulted in highly conductive, yet water-dispersible graphene. At the same time, this approach increased yield and material stability.



Novel applications of graphene

Functionalisation of graphene renders it suitable for a wide range of applications such as indoor and outdoor photocatalysis, desalination and purification, energy storage and chemical sensors. Partners of the Functional Foams and Coatings Work Package have produced graphene inks used in fully printed sensors and energy storage devices.

Novel applications of the Graphene Flagship GRMs include water purification strategies such as filtration and desalination. The latter offers a promising prospect for sustainable, energy- and cost-efficient production of clean water from brackish and sea-water sources. GRMs are also suitable for use in catalyst systems for hydrogen production, and in the form of foams for lighting purposes and as fast heating elements. Importantly, graphene is also used to extend the capacity of titanium oxide to break down certain pollutants. Graphene-cement composites with titanium oxide can be utilised as photocatalytic coatings in smart buildings that can clean air in our cities and destroy water pollutants.

The numerous scientific achievements of the work package are highlighted by the number of patent applications, awards and scientific publications. It is worth noting the 25 current collabo-

rations with industrial partners and the two spin-off companies that have emerged, promoting production methodologies and graphene-based products to market.

Furthermore, the results and nanocomposite materials produced in this work package are shared with other parts of the Graphene Flagship, for use in working devices in fields like printed electronics, sensors, fuel and solar cells. This will advance graphene applications further, beyond current technologies. Commenting on the electrochemical exfoliation and functionalisation of graphite, Prof. Feng is confident that "it will help bridge the gap between materials science and practical applications".

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Graphene makes low-dimensional spintronics viable at room temperature

Graphene Flagship researchers produced graphene-based spintronics devices that utilise both electron charge and spin at room temperature. Demonstrating the spin's feasibility for bridging distances of up to several micrometres, results open up new possibilities for integrating information-processing and storage in a single chip.

From its very inception, the Graphene Flagship programme saw the potential of spintronics devices made from GRMs. Researchers from different universities successfully showed that it is possible to manipulate graphene's spin properties in a controlled manner at room temperature. These results inspire new directions in the development of spin-logic devices and quantum computing. "With miniaturisation a major driving force behind the electronics industry, graphene opens new possibilities for compacting spin-logic operations with magnetic memory elements in a single platform," notes Catalan Institution for

Research and Advanced Studies (ICREA) Research Professor Stephan Roche, who has been leading the Graphene Flagships Spintronics Work Package since its inception.



With miniaturisation a major driving factor of the electronics industry, graphene opens new possibilities for compacting spin-logic operations with magnetic memory elements in a single device.

Material imperfections are not to blame any more

Graphene extends the area of spintronics inter-device communication from nanometres to micrometres at low energy cost. Although initial theoretical predictions estimated spin lifetimes of around a microsecond in the material,

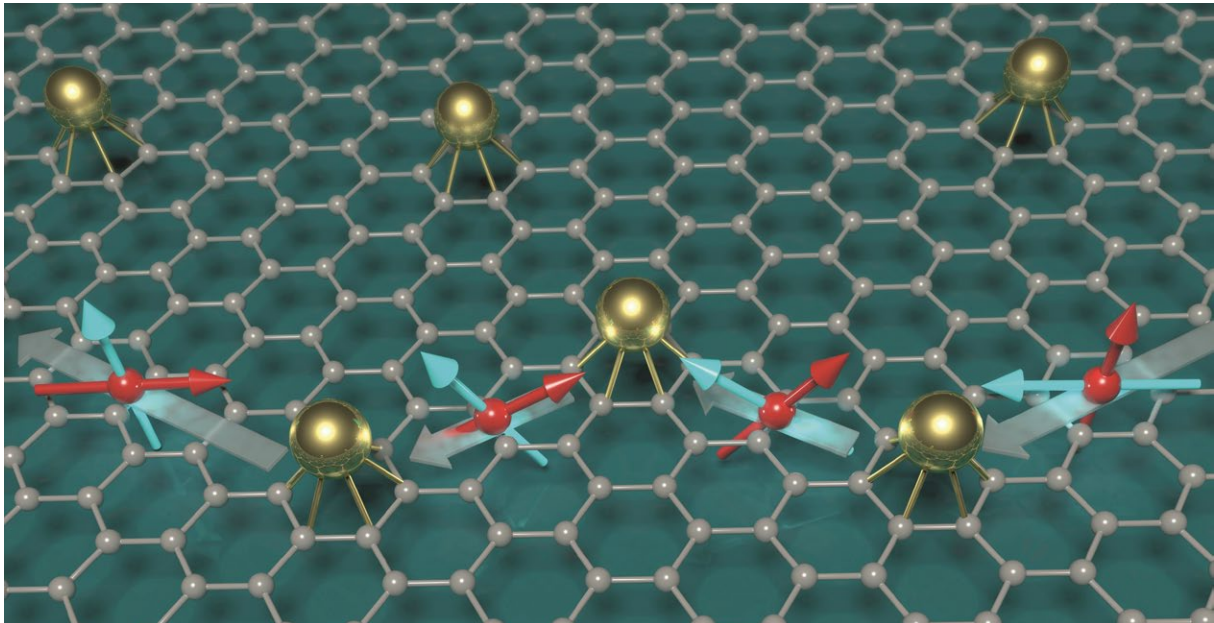
previous experiments have shown a few nanoseconds at best. This puzzling discrepancy initially suggested that the material's impurities and defects are primarily responsible for spin relaxation. However, Flagship researchers have challenged these conventionally conceived mechanisms of spin relaxation, and proposed several new ones that are unique to graphene.

In particular, they observed that the rate at which spins relax in systems composed of graphene and transition metal dichalcogenides (TMDCs) strongly depends on whether they are pointing in or out of the graphene plane. "Graphene interfaced with a TMDC could serve as a spin filter, since the transfer of spin information depends on the initial spin polarisation of the injected electrons, enabling new low-power spin-transistor concepts," explains Prof. Roche.

Importantly, experiments were carried out at room temperature and are particularly important for externally manipulating electron spins in graphene.

The ultimate switch

Given that graphene can maintain spin coherence over sufficiently long distances, integrating it with another layered material in which spin is maintained for considerably lesser time can result in fabrication of a spin field-effect transistor-like device.



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Combining graphene with molybdenum disulfide (MoS₂) (where spin lasts for picoseconds), Flagship researchers demonstrated that it is possible to control where the spin can go by using a gate voltage. “This combination of graphene with another thin 2D material with contrasting spintronic properties enables the creation of a spin switch,” observes Prof. Roche.

Researchers have chosen MoS₂ due to its low-spin lifetime stemming from its strong spin-orbit coupling. Importantly, this material mix worked at room temperature.

Increasing spin signals

From studies of the literature, conductance mismatch has been identified as a key factor that could substantially reduce spin injection from ferromagnets into semiconductors.

The Flagship team showed that they could greatly improve the efficiency of the injection and detection of spin electrons into graphene, by using a sandwich of materials. This consisted of a boron nitride insulator in-between the graphene layer and the ferromagnetic spin injector/detector electrodes.

In the device produced, polarisation increased up to 70 % with voltage, challenging textbook wisdom that only ferromagnets

can influence spin polarisation. Instead, quantum tunnelling was found to affect spin polarisation in the devices. In particular, spin bridged a distance of 10 micrometres in more than 3 nanoseconds at room temperature.

“The use of graphene and other 2D materials for advancing next-generation spin torque-based memories (such as STT-MRAM and SOT-MRAM) is also extremely appealing, and has stimulated imec to take the lead of the consortium and work on their large-scale integration in the fab environment,” says Kevin Garelo, WP leader and imec researcher leading the emerging magnetic advanced memory concepts research.

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Biomedical advances through use of graphene

The increasing demand for healthcare services requires novel solutions. Graphene is paving the way, with technologies capable of detecting, treating and managing diseases of the nervous system with the aid of neural implants.

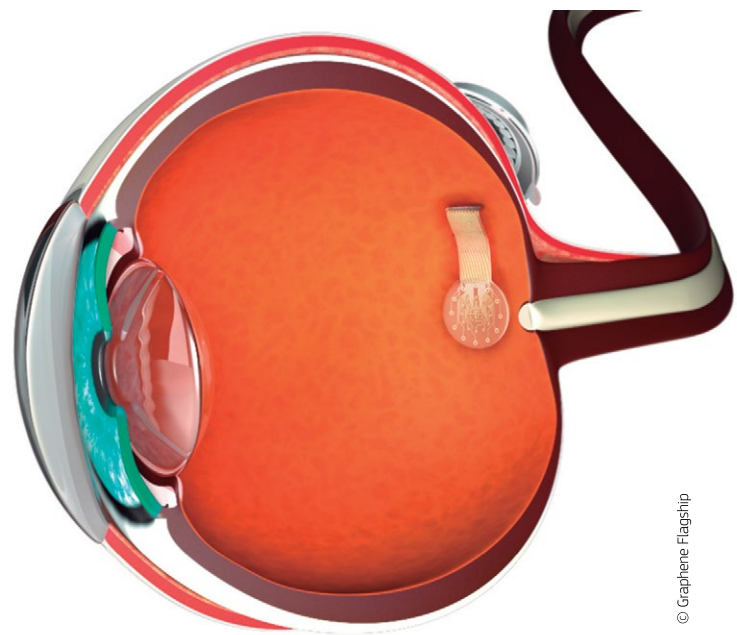
Graphene is the thinnest, strongest — but at the same time lightest — substance, impermeable to molecules but amenable to chemical modification. Alongside its high surface area and biocompatibility, these unique properties render graphene a very promising starting material for a variety of biomedical applications.

The Graphene Flagship's Biomedical Technologies Work Package, led by Prof. Kostas Kostarelos at the [Nanomedicine Lab](#) of the University of Manchester (UK) and Prof. Jose A Garrido of the Catalan Institute of Nanoscience and Nanotechnology (Spain), explores the use of GRMs in the design of neural implant devices for recording and stimulating electrical activity, combined with localised drug delivery. As Prof. Kostarelos explains, "The aim of this Work Package is to develop the next generation of neural implants that combine recording and stimulation functionalities, together with therapeutic capabilities."

Neural implants have emerged as a promising approach for detecting, monitoring and treating (via electrical stimulation) a number of different sensory and motor disorders of the central and peripheral nervous system. These implants serve as the interface between the neural tissue, nerve fibres or individual neurons and external devices, used to record, monitor and stimulate brain activity to intervene with central nervous system functions.

Innovative graphene-based devices

Research activities of leading scientists across Europe involved in the Graphene Flagship project have focused on materials engineering, implant technology and functionality for applications in the fields of neurology, ophthalmology and surgery. Their aim is to implement these devices for the diagnosis and treatment of various diseases like epilepsy, Parkinson's, blindness, rheumatoid arthritis and diabetes.



© Graphene Flagship

Graphene is a versatile substrate that can take many forms with different properties, excellent for generating 2D materials that can be used in recording and stimulation devices. The electrical conductivity and flexibility of SLG nanosheets greatly facilitate the recording of electrical activity in neuronal tissue with high fidelity.

For electrical stimulation of the nervous system — as in the case of Parkinson's patients who are unresponsive to levodopa — scientists have chosen reduced graphene oxide. Graphene oxide produces flexible yet porous nanoscale substrates of high capacitance, capable of providing stimulation for longer periods. Partners in this work package are exploring the technology to develop a retinal implant for people who have lost their sight



The aim of this work package is to develop the next generation of neural implants that combine recording and stimulation functionalities, together with therapeutic capabilities.

due to retinal disease. A camera collects images from the environment and converts them into electrical stimulation, delivered through graphene microelectrodes.

Furthermore, the tuneable characteristics of suspension graphene and its capacity to be functionalised with oxygen can be exploited for drug delivery. Anti-inflammatory drugs, neurotransmitters or neural attractants are linked to hydrogel-coated graphene sheets and released at different speeds upon implantation.

based on the extraordinary properties of graphene which make it ideal for recording and stimulating neural tissues in pathological diseases like Parkinson's and epilepsy.

"Undoubtedly, graphene is paving the way for novel diagnosis and treatments, helping to improve the quality of life for millions of patients globally" concludes Prof. Kostarelos. In view of the future, he emphasises that "collaboration with industry is essential to guide innovations and direct research efforts towards the most commercially promising applications".

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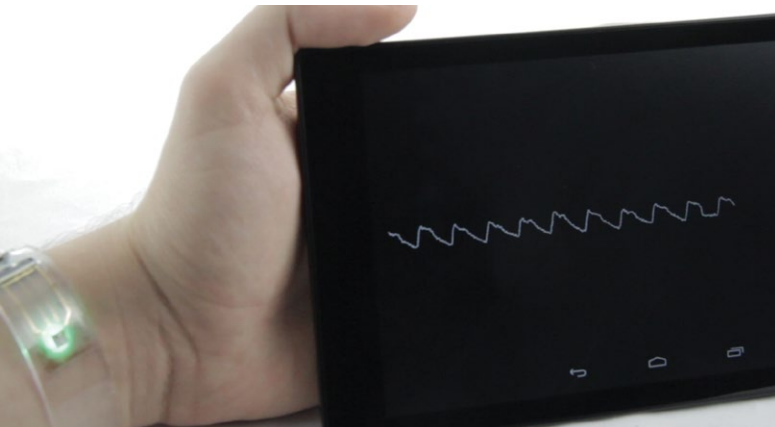
The future of graphene in the biomedical field

Research in the use of graphene and 2D materials for biomedical applications is expanding in diverse fields ranging from monitoring wearable devices to drug delivery and cancer diagnostics. Research work in the Biomedical Technologies Work Package is



Graphene quantum dot detectors for next-generation health-monitoring wearables

Bulky health monitoring systems could soon become a thing of the past, thanks to new devices developed under the GRAPHEALTH project. In fact, these devices could help shape future flexible electronics and smart wearable markets.



© GRAPHEALTH

Health monitoring, especially during exercise, was one of the very first applications allowing smart wearables to graduate from an appealing technological concept to actual, marketable products. However, extended health monitoring to detect all kinds of health markers quickly tends to become bulky. This means that, until now, engineers have had to find the best compromise between functionality and comfort: only a limited number of components could be integrated, making the whole system much less appealing than it could be.

A solution, according to Dr Frank Koppens from the Spanish Institute of Photonic Sciences (ICFO), lies in the inherent properties of graphene quantum dot (GQD) detectors — photodetectors with characteristics derived from graphene and semi-conducting

quantum dots. GQD detectors would indeed enable the development of a flexible, compact and wearable system for constant monitoring of consumer health and muscle health of athletes during exercise or after injury.

“Our photodetector is very sensitive to light for a very broad wavelength range, from 300 to 2 200 nm. And most importantly, it is flexible,” stresses Dr Koppens. “This is made possible by the fact that the detector can be placed on basically any flexible substrate. It’s just a few hundred nanometres thick, so it’s excellent for integration into wearable sensors.”

The use of graphene is key here, as it provides for an ultra-thin conductor with extremely high conductivity properties, notably electronic mobility. Furthermore, graphene can easily be transferred to flexible substrates and can cover relatively large areas.

“It works as follows,” Dr Koppens explains. “Light, be it from a LED device or from the environment, enters the skin, after which it interacts with the tissue and blood vessels. There, it is partially absorbed, but also partially bounces off the skin, in which case it can be picked up by the detector. Now, if the blood veins expand and contract due to heartbeat, the photodetection signal will modulate as well. In other words, the heartbeat is directly visible from the photodetection signal.”

This, of course, is just an example. The technology, which was developed under the GRAPHEALTH (Hybrid quantum dot and graphene wearable sensor for systemic haemodynamics

and hydration-monitoring) project, has demonstrated its capacity to be used for the likes of oxygen-monitoring as well. Other important health markers will also soon be detectable. The GRAPHEALTH photodetector is compatible with current flexible electronic manufacturing processes, which means industry should not expect major investment costs.

“We have made several prototype wearable devices — including one for the wrist and a patch that is more like a thin sticker



Our photodetector is very sensitive to light for a very broad wavelength range, from 300 to 2 200 nm. And most importantly, it is flexible.

— and we have shown that these can be produced with scalable large-area graphene,” enthuses Dr Koppens.

Now that the project has come to an end, Dr Koppens and his team intend to make the GRAPHEALTH system more versatile by integrating more health markers. They also want to develop a completely integrated health patch, which would include not only the patch itself but also the electronics, wireless power transfer and wireless data transfer.

“It’s difficult to make any predictions regarding potential commercialisation, as flexible electronics and wearables are very young markets. We can create a very large range of different wearables, and integration into existing wearables, such as combining with a smart watch, can also be considered. The challenge now is to make wise choices on which application to focus exactly,” Dr Koppens concludes.

PROJECT

GRAPHEALTH - Hybrid quantum dot and graphene wearable sensor for systemic hemodynamics and hydration monitoring

COORDINATED BY

University of Naples Federico II, Italy

FUNDED UNDER

H2020

PROJECT WEBSITE

N/A



Using graphene as a supercharged magnifying glass

The complex interactions between graphene and light are now much better understood thanks to work under the GRASP project. The outcomes of the four-year research lay the groundwork for future technologies exploiting nonlinear optical effects.

Besides their importance in the understanding of fundamental physics, nonlinear optical effects are also key to vital applications such as quantum computing, biomedicine or all-optical switching. But there are still many obstacles to exploiting their full potential, one of these being the actuation of nonlinear optical effects at ultra-low powers and on chip-scale devices.

“This is indeed one of the outstanding challenges in optics,” says Prof. Dr Darrick Chang, Group Leader on Theoretical Quantum-Nano Photonics at ICFO. “Realising nonlinear optical effects typically requires large laser intensities, and the resulting power

consumption — or the size of the power sources required — often makes it impractical to realise on small scales, such as for portable devices.”

The ultimate goal would be to see nonlinear effects at the level of single quantum particles of light, and pursuing this objective is well worth the trouble. It would notably enable the best possible performance and wide deployment of classical nonlinear devices, whilst facilitating disruptive quantum information protocols that cannot be realised on classical platforms.



It is with this objective in mind that the GRASP (Graphene-Based Single-Photon Nonlinear Optics) project kicked off in 2014. "The goal of the project was to investigate whether a relatively new and exotic material — graphene — could allow pulses of light to interact with each other at much lower power," he explains. The graphene path is fundamentally new in nonlinear optics, but Prof. Dr Chang and his team believed that the material's unique properties would allow even single particles of light to attain the required intensities to actuate nonlinear processes.

"One of the unique properties of graphene, which was both theoretically predicted and then experimentally observed, was that it could effectively focus or spatially confine light to extremely small length scales. We could use the analogy of a magnifying glass, which makes it possible to focus light from the sun into a small spot, making the light intense enough to even burn a piece of paper," Prof. Dr Chang explains.

In this analogy, graphene could be viewed as a supercharged magnifying glass. It can squeeze light into a space millions of times smaller than the best magnifying glasses or lenses money could ever buy, and the resulting intensities would be high enough to actuate nonlinear optical processes.

The GRASP project was able to observe nonlinear effects originating from this magnifying-glass effect for the first time. This is particularly remarkable considering that graphene is just a single atom thick, whereas standard nonlinear optical devices involve bulky materials. Whilst the ultimate goal of developing a completely new generation of technology based on nonlinear optical devices that can operate at ultra-low powers is still some distance away, the consortium's work is a significant step in this direction.



One of the unique properties of graphene, which was both theoretically predicted and then experimentally observed, was that it could effectively focus or spatially confine light to extremely small length scales.

"Of course, much more work must be done for graphene to become a mature technology for nonlinear optics. But we developed a lot of important building blocks that set the ground for further work. This includes seeing nonlinear optical effects in graphene due to strong light confinement for the first time, learning to fabricate graphene with higher material quality, constructing new devices that can confine fields not millions, but billions of times better than the best lenses, and getting a better understanding of the complex interactions between graphene and light," Prof. Dr Chang says.

Whilst it's probably too early to speculate on specific routes toward commercialisation, the use of graphene for widely deployable, chip-scale classical and quantum nonlinear optical technologies is now much more conceivable.

Which explains why Prof. Dr Chang intends to pursue this work: "Having established the important building blocks needed, our goal is to continue along this exciting line of research, and begin to put these building blocks together, and realise basic but real devices in the coming years."

PROJECT

GRASP - Graphene-Based Single-Photon Nonlinear Optics

COORDINATED BY

Institute of Photonic Sciences (ICFO), Spain

FUNDED UNDER

FP7-ICT

PROJECT WEBSITE

grasp-fet.eu



Using graphene for flawless tunnelling accelerometers

A European Research Council (ERC) Proof of Concept grant is enabling Aalto University to work on a novel concept for a tunnelling accelerometer, using graphene's unique properties. If successful, the project could appeal to industries producing high-precision applications.

Accelerometers are used in a wide range of applications, from navigation systems in aircrafts to motion-sensing in cars and portable electronic devices. But the most demanding applications require high-resolution accelerometers which are both very large and extremely expensive to manufacture.

For such applications, which include the likes of microgravity measurements, acoustic measurements and seismology, the use of tunnelling accelerometers might seem self-evident. A giant step ahead of their conventional counterparts, they can be produced at much lower cost whilst providing unmatched precision. Yet their commercialisation is still hindered by a complex fabrication process and long-term instability.

Enter the GraTA (Graphene Tunneling Accelerometer) project, which is developing a first-of-its-kind — and already patented — tunnelling accelerometer design using graphene. Its technical advantages, which include smaller size, wider bandwidth, simpler fabrication and natural stability, are already turning heads within industry. Among other things, it could enable the production of high-end sensors based on graphene.

Prof. Dr Pertti Hakonen, who is in charge of the project, discusses his tunnelling accelerometer concept, its development process and prospects for commercialisation.



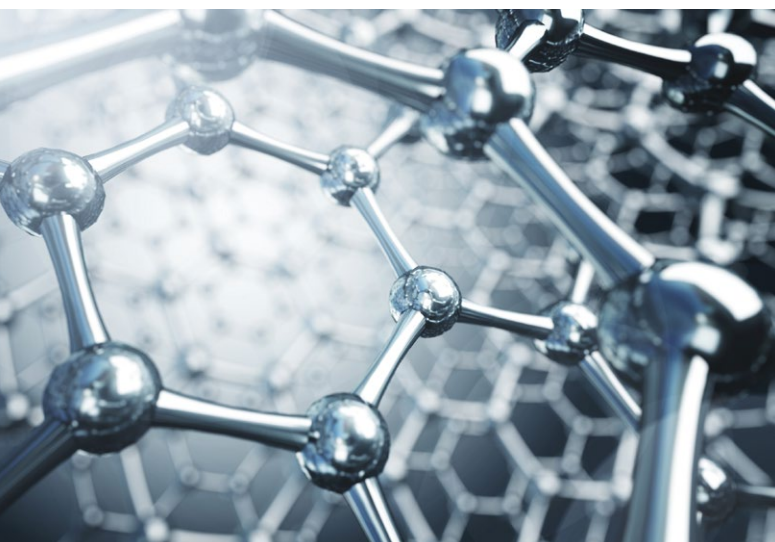
With the key intellectual property rights (IPR) filed and more field data being collected, we are on the right track towards the goal of commercialisation.

What shortcomings of tunnelling accelerometers were you aiming to tackle with this project?

The lack of long-term stability of silicon-based, metal-coated tunnelling sensors is the main shortcoming we tried to overcome. The sensitivity and bandwidth will be improved as well.

Why do you think graphene can offer a suitable solution to achieve this objective?

Graphene is known to have superior mechanical properties (light, strong, robust carbon crystal) and good electrical conductivity (no need for metal coating). We are experienced in dealing with details such as tension in graphene microelectromechanical systems (MEMS) structures. The nature of the material and our know-how make the graphene accelerometer a potential solution.



What were the main difficulties you faced in making these new graphene accelerometers a reality?

The manufacturability (and reproducibility) is the main challenge when switching from lab samples to future accelerometers to be called a product.

What would you say have been your most important achievements so far?

We have proven that the tiny gap is not prone to collapse, even in air, which is crucial for its reliability. The core patent has been filed, and one more with related materials is on the way.

What do you still need to do before the end of the project?

We need to build more prototypes which are properly packaged, and collect more data out of the lab.

What kind of sensor applications do you have in mind?

Machine vibration monitoring — the most widespread method to determine the health of rotating equipment — would be an example. This is valuable for safety and smart maintenance in modern industry, especially in the era of the Internet of things.

How close would you say you are to potential commercialisation?

This is hard to say. Commercialisation takes much longer and requires different means than what we had available for our research work in the lab environment. However, with the key IPR filed and more field data being collected, we are on the right track towards the goal of commercialisation.

PROJECT

GraTA - Graphene Tunneling Accelerometer

COORDINATED BY

Aalto University, Finland

FUNDED UNDER

H2020

PROJECT WEBSITE

N/A



LbL technology applied to graphene oxide

An EU-funded project has successfully demonstrated that graphene oxide can be assembled with other materials to produce dense polymer composites. This breakthrough could lead to applications in optoelectronics and energy conversion, among others.

Graphene is often presented as a supermaterial for its out-of-the-ordinary strength, thinness, conductivity and optical properties. But its potential reaches a whole other level when combined with other materials of different natures. By creating these hybrid materials, graphene properties can be tweaked. This provides researchers with new and exciting prospects for applications, and it can also guarantee better integration of graphene in devices.

With this in mind, Dr Sergio Moya from the Center for Cooperative Research in Biomaterials (CIC biomaGUNE) kick-started the HIGRAPHEN (Hierarchical Functionalization of Graphene for Multiple device fabrication) project in March 2014. Using layer-by-layer technology — a simple procedure for the functionalisation of surfaces based on the stepwise deposition of oppositely-charged molecules or materials — he aimed to develop a versatile, generic procedure for the fabrication of hybrid devices coupling graphene with polymeric, organic and inorganic materials.

“The driving force behind layer-by-layer (LbL) assembly is the electrostatic interaction between the assembled components,” Dr Moya explains. “Initially, this technique has been developed for the assembly of polyelectrolytes, that is, polymers with multiple charged monomers. But it has since been extended to multiple components: LbL film polyelectrolytes can be combined with nanoparticles, with lipids, cells, graphene oxide, etc. It offers a simple and powerful way to engineer interfaces while avoiding covalent chemistry, and it has potential in many applications — from nanofiltration membranes to optoelectronic devices, smart coatings, and drug delivery.”

The project went a step further by specifically focusing on the combination of graphene oxide with metal and metal oxide nanoparticles, as well as polyelectrolytes, whilst contemplating potential applications in energy storage and catalysis. Although the LbL technique is widely used in surface engineering and



thin film fabrication, HIGRAPHEN's use of LbL to assemble heterogeneous components with graphene oxide is particularly innovative.

Dr Moya and his team first proceeded by synthesising different nanomaterials such as zinc selenide (ZnSe) quantum dots, magnetic nanoparticle, and electroactive polymers like poly-aminobenzylamine (PABA), before integrating them into LbL



It has potential in many applications — from nanofiltration membranes to optoelectronic devices, smart coatings, and drug delivery.

films with multiple components including graphene oxide. The HIGRAPHEN team then integrated the assemblies into macroscopic anticorrosive coatings and devices for optoelectronic applications and energy conversion.

“One of the main challenges we faced was to obtain a dense arrangement of graphene oxide in combination with polymers. This led to the development of different approaches to coat the graphene oxide and combine it with nanoparticles,” says Dr Moya.

Overall, the project’s most important outcome is the demonstration that graphene oxide can be assembled to produce dense polymer composite, and that it can be easily integrated with metal nanoparticles for catalysis. Whilst HIGRAPHEN will only

draw to a close in March 2018, Dr Moya says that project partners are already pursuing interesting new research directions based on project outcomes for device fabrication and catalytic applications.

PROJECT

HIGRAPHEN - Hierarchical Functionalization of Graphene for Multiple device fabrication

COORDINATED BY

Center for Cooperative Research in Biomaterials (CIC biomaGUNE), Spain

FUNDED UNDER

FP7-PEOPLE

PROJECT WEBSITE

personal.cicbiomagune.es/smoya/higraphen/index.html



Graphene-reinforced polymers ready for commercialisation

A four-year development process has led to the identification of the most suitable materials and production techniques for graphene-based coatings, adhesives and composites. Once the graphene market reaches maturity, these new products could appeal to a vast range of industries.



© PolyGraph

To this day, graphene remains expensive enough to discourage its large-scale incorporation into commercial products. But this hasn't been preventing researchers across Europe from moving forward with the development of materials and production techniques that can pique industry interest as larger batches of graphene become available at a lower cost.

The PolyGraph (Up-Scaled Production of Graphene Reinforced Thermosetting Polymers for Composite, Coating and Adhesive Applications) project is one of these pioneering ventures. By bringing together 14 partners, including small and medium-sized enterprises (SMEs), companies, universities and


a research centre, the project aimed to deliver industrial-scale quantities of graphene-reinforced thermosetting polymers.

"We tried to look at different ways to improve the thermo-mechanical and electrical properties of coatings, additives and composites," explains Maria Konstantakopoulou, Development Engineer at project coordinating company Coventive Composites. Once the target performances were defined, the team picked suitable polymers, outlined a range of graphite and graphene grades, and identified suitable exfoliation and dispersion techniques that would eventually allow them to scale up production whilst ensuring that graphene remained well-distributed in the final product.

As Ben Hargreaves, coordinator of PolyGraph, explains, the idea was to produce "on a scale that would be viable for other companies, enabling them to consider integrating our solution in their current or future products". Large-scale conversion of composite materials indeed remains an obstacle to market adoption.

Once project partners became able to produce as much as 100 kg of graphite and 25 kg of graphene per batch, new horizons opened up.

Many different composite materials were produced by the project consortium, and were then evaluated for their electrical conductivity and mechanical properties. The most promising coatings, adhesives and composites were used in demonstrator parts, respectively an aerospace structural element, a coated aerospace radome/fairing element, and a rear seat back panel for


We tried to look at different ways to improve the thermomechanical and electrical properties of coatings, additives and composites.

automotives. Benefits include better structural behaviour, weight reduction, aesthetics, electrical properties and fire retardation.

“One of the main advantages of the graphene-reinforced composites resulting from this research and development process lies in their electrical properties, making them suitable for electromagnetic interference (EMI) shielding or for the de-icing of wind turbines,” Konstantakopoulou points out.

Waiting for the right opportunity

Gary Foster, who acted as project manager on PolyGraph, explains that commercial perspectives vary strongly for each of the three materials. “On the coating side, project partner HMG Paints can pretty much go straight to production because what we developed is not too far away from the products that they currently sell. Adhesives, on the other hand, are a bit more price-sensitive. It doesn’t mean our partners won’t be using those materials, but they just wait for the right moment in time where people will want that product.”

The third product, a pre-impregnated composite fibre or pre-preg, was particularly important for Coventive Composites, as Hargreaves highlights: “Pre-preg development wasn’t originally programmed into the project as heavily as what we ultimately ended up doing. We also looked at other production techniques like infusion, but early work made it clear that pre-preg was going to be the optimum technique.” Both he and Foster agree that the company should now focus on finding the right niche

market for this composite, and that future efforts should focus on finding out what potential customers need and how the product can be refined to meet their expectations.

Until then, the team will be looking at the evolution of graphene. “There is a need for a certain level of generalisation,” Foster explains. “For example, if we want to use our product in the aerospace sector, customers will need certain fundamental data from graphene producers that currently they are not able to provide. These are obstacles that we cannot overcome on our end.”

With this in mind, the PolyGraph consortium has been working closely with the Graphene Flagship, creating a link between academics and industry so that the former’s research better matches the needs of the latter. Eventually, this would allow Coventive Composites to bring to market innovative solutions for the likes of EMI shields or the de-icing of wind turbine blades.

PROJECT

PolyGraph - Up-Scaled Production of Graphene Reinforced Thermosetting Polymers for Composite, Coating and Adhesive Applications

COORDINATED BY

NetComposites Limited, United Kingdom

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polygraphproject.eu



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