GRAPHENE MAGAZINE

2021 EDITION

GRAPHENE UNLEASHED

See how graphene could revolutionise energy storage and cameras in our latest visual features

MEET THE SCIENTISTS

Exclusive interviews with Graphene Flagship pioneers, early-career researchers and more

VIDEO SHOWCASE

Watch brand-new video footage of Graphene Flagship commercial products, from motor lube to neural interfaces

ENTER THE LAB

SEE GRAPHENE FLAGSHIP RESEARCH IN ACTION

Funded by the European Union

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On the cover: A peek inside Graphene Flagship partner AMO's lab. Learn more on **page 34**. Credit: AMO

Check out the Graphene Flagship events website to stay updated on all our upcoming events

... for a full schedule of events in 2022

Returning live

- Graphene Week 2022
- Graphene Study 2022

Digital programming on the Graphene Hub

- Diversity in Graphene
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- Standardisation workshops
- International workshops
- Pioneering 2D materials for the semiconductor industry

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FROM THE EDITOR

By: Tom Foley

Graphene Flagship research is sailing ahead at full speed, and 2021 is shaping up to be an excellent year for graphene.

The past year of science has shown that graphene can keep aircraft ice-free, protect ships from erosion, map brain activity and enable faster internet connections on our smartphones. This is on top of a whole host of other results and milestones from the Graphene Flagship's talented and devoted Europe-wide consortium.

In this year's edition of Graphene Magazine, we're putting the spotlight on the hard-working researchers who kept the ship sailing through stormy seas. Inside, read exclusive interviews with the scientists who built the Graphene Flagship from the ground up, as well as the ambitious newcomers whose careers in graphene have only just set sail.

The future is bright, and we can't wait to see where the tides will take us. The 2D Experimental Pilot Line, the Graphene Flagship's initiative to incorporate graphene into wafer-scale semiconductor manufacturing, has just celebrated its first birthday, and our eleven industry-led Spearhead Projects are coming to fruition. Many of our spin-off companies have reasons to celebrate, too – like INBRAIN Neuroelectronics, which received a €14M investment this year and recently partnered with pharmaceutical giant Merck. Read on to hear these success stories and more.

So put on your lab coat and goggles and get ready to enter the lab: in this magazine, step into three real Graphene Flagship laboratories for an exclusive look at the research that goes on behind closed doors. See inside Medica, AMO and the Cambridge Graphene Centre, three Graphene Flagship partners with cutting-edge facilities, all of whom are developing next-generation technologies. We also created video brochures for five of our favourite Graphene Flagship products – dive in now and see them in action.

On behalf of the Graphene Flagship, thank you for reading our magazine. We are so excited to tell you about our year of discovery, and we hope that you enjoy hearing it.

Warm wishes,

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Tom Foley, Editor

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IT ALL STARTED WITH STICKY TAPE

FROM DREAMS AND WONDER TO IMPACTFUL PRODUCTS

By: Fernando Gomollón-Bel

Graphene: an ideal material for invisible cat hammocks and space elevators. Or at least, that was what the hype would have led you to believe. A few years ago, the public excitement for graphene was overwhelming. And it made sense. Scientists had discovered something stronger than steel and more conductive than copper, yet flexible, transparent and thousands of times thinner than a human hair.

So, when the Graphene Flagship officially launched in 2013, the bar was understandably set rather high. But thanks to their unshakeable passion and commitment, our researchers managed to exceed expectations. Although making a hammock out of graphene to support the weight of a cat still remains a far-off challenge, today, Europe counts on world-leading graphene technologies enabled by the Graphene Flagship that attract private investments and propel innovation into the future.

GREAT STRIDES

Graphene has evolved tremendously since those first few Friday evening experiments with sticky tape. Nowadays, thanks to the Graphene Flagship, we manufacture graphene on a large scale using intricate production methods like chemical vapour deposition or liquid phase exfoliation. Moreover, the additional €20 million in funding granted to the 2D Experimental Pilot Line will guarantee successful knowledge transfer to the semiconductor industry.

The past fifteen years also unveiled some unexpected surprises. As it turns out, graphene itself is its own family of materials. Different technologies yield pristine one-atom-thick carbon sheets, few-layer graphene flakes, or graphene oxide – a product that combines carbon and oxygen atoms. These distinct substances exhibit different properties, opening up a new world of possibilities.

For instance, crystalline graphene excels in electronics and photonics applications, paving the way to new technologies in computing and telecommunications. On the other hand, graphene oxide powers innovative batteries, sensors, conductive inks and much more. Recent discoveries by Graphene Flagship scientists suggest that graphene oxide could even have therapeutic properties. A model study showed that, when injected into specific regions of the brain, graphene oxide silences the neurons responsible for anxious behaviour, soothing the symptoms of stress and worry.

Our scientists even spiced up graphene by introducing some exotic physical properties. When one layer of graphene is twisted at just the right angle, or mixed with certain other materials, graphene suddenly reveals unusual hidden behaviours like superconductivity. This discovery will likely lead to new quantum technologies, including ultra-safe encryption and faster computers.

TO INFINITY AND BEYOND

But what about the space elevator? Very much like the invisible hammock, this turned out to be a futuristic lucubration by eccentric dreamers. Nevertheless, the Graphene Flagship continues to explore the final frontier, pushing technologies for space exploration ever-forward.

In 2017, our scientists embarked in a zero-gravity adventure to test the potential of graphene in different space applications. They experimented with graphene-enabled solar sails: an efficient method to propel spacecraft using only light. Then, embarking on a parabolic flight operated by the European Space Agency, Graphene Flagship researchers studied the benefits of graphene-enabled satellite heat pipes. These devices are paramount to the survival of electronics in space, as temperatures can reach 200 °C when facing the sun. Graphene's excellent heat-transfer capabilities can improve the efficiency of heat pipes and, consequently, bolster the durability and performance of satellites, probes and spaceships.

The flashpoint of these exploratory endeavours came about in 2019, when graphene finally ventured into outer space. Our experiment – which shared a MASER rocket with three other prototypes – tested the printing of graphene-based inks under zero-gravity conditions. On Earth, graphene inks have found applications in batteries, sensors and gauges, among other things. The Graphene Flagship wondered if we could print these in space, to enable new self-sufficient eco-systems for future space missions.

These advances resulted in several patent applications and garnered the interest of many industry-leading companies. They also inspired further functionalities in aeronautics. Now, companies like AIRBUS and Lufthansa Technik coordinate Graphene Flagship Spearhead Projects to bring the technological advantages of graphene to commercial aircraft. We expect to see these results by 2023.

So far, our researchers have truly shined at delivering on their promises, and we fully expect to see this continue into the future.

The flashpoint of these exploratory endeavours came about in 2019, when graphene finally ventured into outer space. Our experiment, which shared a MASER rocket with three other prototypes, tested the printing of graphene-based inks under zero-gravity conditions."

2023

We expect to see results from our aerospace-focused Spearhead Projects like AEROGrAFT and GICE by 2023.

GRAPHENE 101

ALL ABOUT GRAPHENE AND ITS MANY FORMS

By: Letizia Diamante

The Graphene Flagship is racing to find the most efficient and effective ways to make graphene and its derivatives, as well as to establish new standards and lead the way to commercialisation. In fact, graphene's market penetration is on the rise, with a projected year-on-year growth rate of 40% by 2025.

Welcome to the world of graphene. On these pages, learn about the different forms of graphene, how they are made, and what they can do.

GRAPHENE

CONDUCTIVE, FLEXIBLE AND STRONG

Graphene is a one-atom-thick sheet of bonded carbon atoms with a hexagonal structure, like chicken wire. Even when it is not one-atom-thick, the material still retains some of the unique properties of the single-layer form. This is called multi-layer graphene, and it has similar properties to graphene up to a thickness of about 10 layers.

One way to make graphene is to break down natural or artificial graphite, which consists of stacked graphene layers bonded weakly by van der Waals forces. This can be done using mechanical, thermal or liquid-phase exfoliation: the act of ripping layers off the bulk material. Liquid phase exfoliation just celebrated its 10th anniversary!

Single-layer graphene is used for high-end technical applications like supercapacitors, solar cells and semiconductors. Multi-layer graphene is used in applications like composites, where the need for a carefully tailored electronic structure is less important.

Alternatively, graphene can be deposited onto a substrate from a carbon-rich source, such as methane, using a method called chemical vapour deposition (CVD). This can produce high-quality single-layer versions of graphene, suitable for high-performance applications in photonics, sensing and wafer-scale electronics.

Graphene's properties far exceed those of its mother material, graphite. Just as you have no doubt experienced when writing with a pencil, graphite is naturally brittle – and yet graphene is one of the strongest materials in the world. It is also transparent, elastic and flexible.

Products containing single-layer and multi-layer graphene have been released to the market in several forms, including powders, solutions, inks and pastes. Functionalised graphene could even remove heavy metal pollutants from water.

GRAPHENE OXIDE

THE WATER-LOVING GRAPHENE

Graphene oxide is made by treating graphite with strong oxidisers like sulphuric acid, alongside a catalyst like potassium permanganate and sodium nitrate. These procedures add oxygen atoms to its surface and make the material hydrophilic, meaning it can be dispersed in water.

Plus, depending on the ratio between the number of carbon and oxygen atoms, graphene oxide films can either be a conducting or insulating material.

Graphene oxide is important for a broad range of applications like biomedicine, fire protection, energy storage and composites. It is also used to make transparent films for flexible electronics, solar cells and chemical sensors such as drug tests, and there are promising trends in healthcare.

We can even build 3D structures out of graphene and graphene oxide flakes, like aerogels for conductive inks or a chrysalis that makes magnesium batteries more sustainable.

REDUCED GRAPHENE OXIDE

THE ECONOMICALLY VALUABLE GRAPHENE

Scientists can reduce graphene oxide to make a different, economically valuable material. Laser-scribing, chemical, thermal or electrochemical reduction are all viable techniques for converting graphene oxide into reduced graphene oxide. Although reduction does not remove all oxygen groups from the material's surface, it does partially restore graphene's electron transfer properties.

Reduced graphene oxide can also be functionalised to endow it with new properties suitable for a variety of commercial applications, such as electrochemical sensing.

THE VALIDATION SERVICE

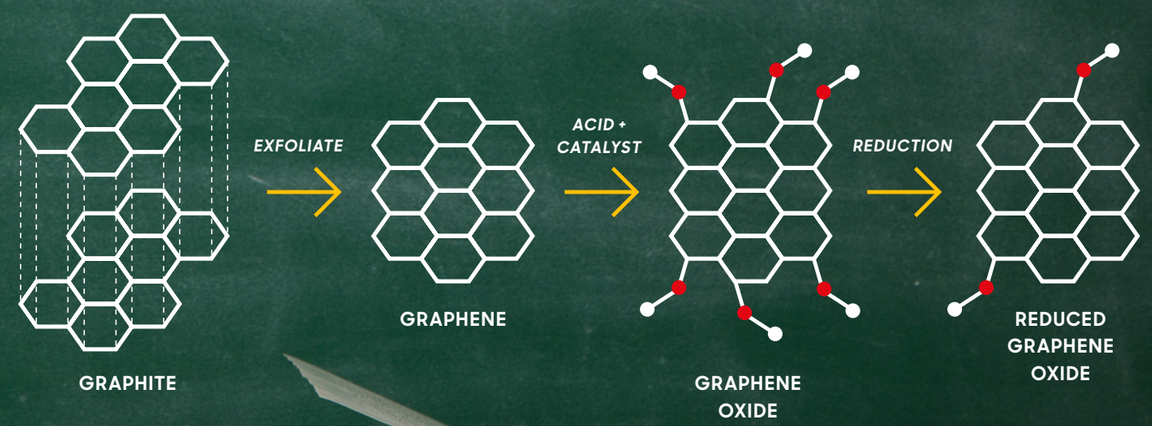
QUALITY CONTROL

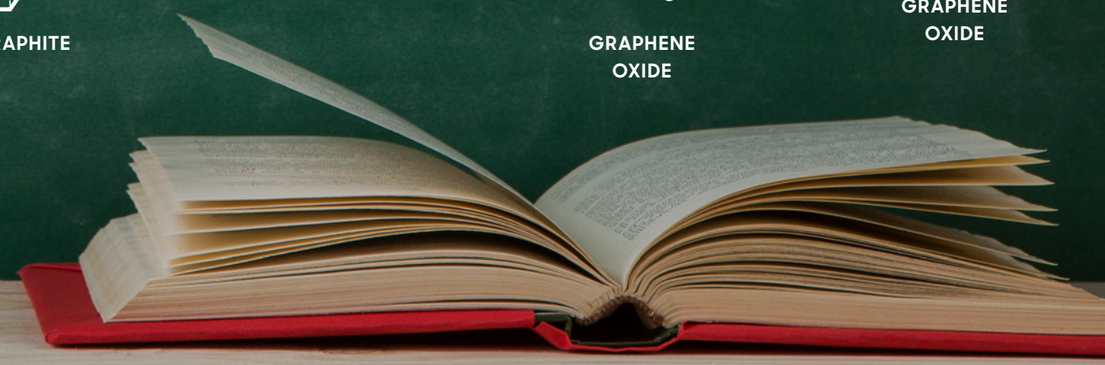
If a material is to have applications in industry, its quality and composition need to be reliable and reproducible, and it must be made from consistent source materials. To help with these needs, the Graphene Flagship Validation Service offers a set of tests including structural, mechanical, optical, thermal, electrical, magnetic, chemical and lifecycle measurements to assess and validate the performance of graphene-based devices and materials.

Clients of the Validation Service receive a detailed report from authorised institutions: Graphene Flagship partners the National Physical Laboratory in the UK, the University of Zaragoza in Spain and LNE in France.

LOOKING FOR A SUPPLIER?

Finding a supplier who can meet all of your desired specifications can be difficult. To solve this challenge, Graphene Flagship Partnering Project SIO Grafen published a list of worldwide graphene suppliers and whether they are REACH certified.





ENTER THE LAB

MEDICA

Welcome to Medica: the Graphene Flagship partner that coordinates the Graphil Spearhead Project. In these labs, scientists are researching graphene and related materials – especially graphene oxide – to enrich the polymeric matrix of polysulfone and polyethersulfone hollow fibres, which are used for water filtration.

Adding graphene to these fibres enables new filters that can remove both microbiological and chemical contaminants from drinking water. Graphil aims to exploit the high surface area of graphene and layered materials, which gives it a strong affinity to many of the contaminants found in unsafe water. This affinity enables new filters that remove contaminants by adsorption.

1

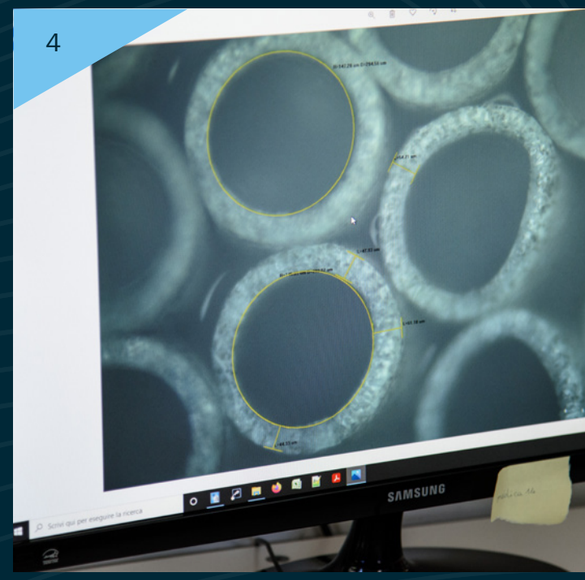
Using an overhead stirrer to mix a polysulfone casting solution blended with graphene oxide. It must be thoroughly mixed to ensure homogeneous dispersion of the polymer. Graphene oxide makes the mixture completely black. You can clearly see how viscous it is.

2

Pouring the polysulfone-graphene oxide casting solution onto a rheometer sample plate to measure its viscosity, which can affect the hollow fibre spinning process. It needs to be carefully controlled for each batch.

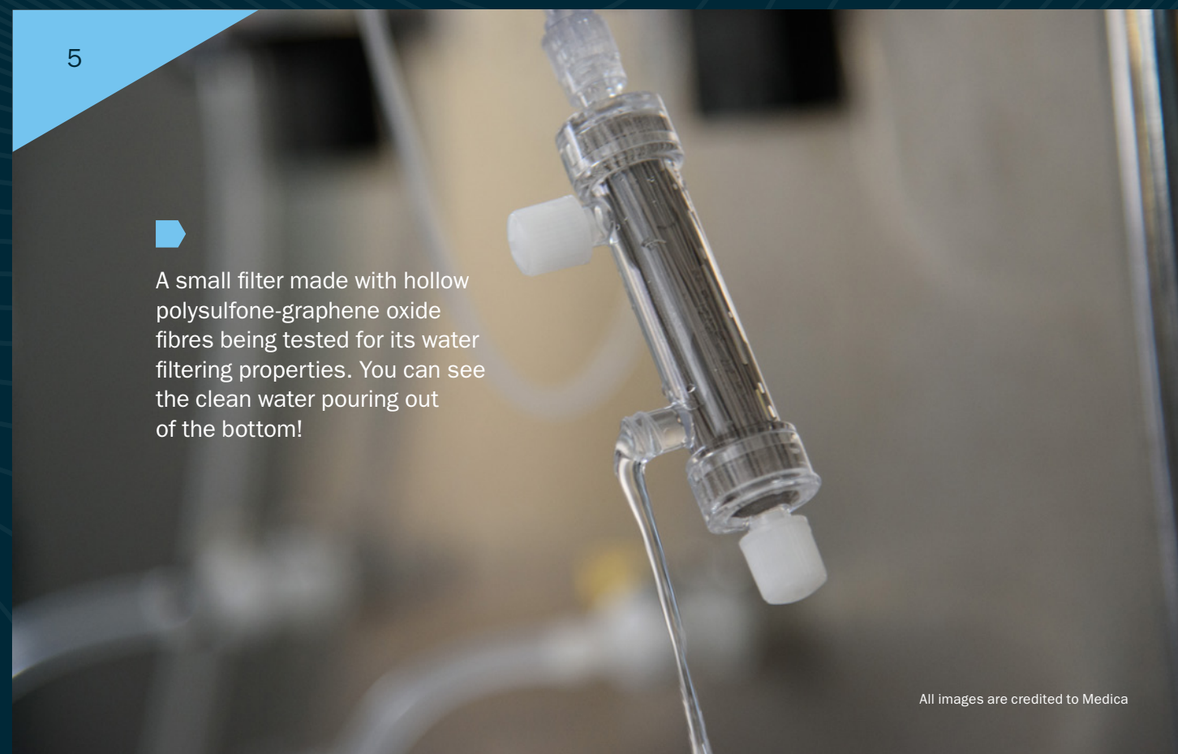
3

The casting solution is spun into fibres at a dedicated plant using a process called phase inversion. The fibres are then made into bundles and small filters for lab-scale testing. The grey colour indicates the presence of graphene oxide.



4

A cross-section of the fibres made with an optical microscope during the spinning process. A small sample is collected and checked for size and morphology.



5

A small filter made with hollow polysulfone-graphene oxide fibres being tested for its water filtering properties. You can see the clean water pouring out of the bottom!

All images are credited to Medica

IN THE NEWS

GRAPHENE SOARS TOWARDS THE MARKETPLACE IN THESE TOP STORIES

By: Francesco Bonnacorso

The year 2021 was an unusual one, with life just starting to get back to normal in many places around the world. But this did not get in the way of new innovations from Graphene Flagship members, Partnering Projects and Spearhead Projects around Europe. Here, Francesco Bonaccorso, Deputy Head of Innovation for the Graphene Flagship, looks back at four of the most-read graphene stories from the last year.

Read on to learn about how graphene could give us faster mobile phones, safer aircraft and seafaring vessels, and even a new construction material that replicates human bone.

COMING IN HOT

In Top Gun, the 1980s action drama about fighter pilots, Tom Cruise's arch-rival was nicknamed the Iceman. This is actually not too far from the truth: it is absolutely vital to protect aircraft from ice formation due to the super-cold temperatures high up in the sky. In fact, in the worst cases, ice accumulation in the airframe and engine resulted in numerous fatal accidents in aviation history. Fortunately, graphene is an ideal material to keep aircraft parts ice-free, with no impact on the aerodynamic properties.

Various partners of the Graphene Flagship are working on graphene-based ice protection technologies for aircraft. One Graphene Flagship Spearhead Project is developing a graphene-based thermoelectric ice protection system: GICE. Here, an ultra-thin conductive coating layer of aero-graphene foam is applied to aircraft components.

Because of graphene's homogenous heat distribution properties, heat flows evenly throughout the layer when a current is applied, which can be controlled precisely for optimum ice protection. This keeps aircraft parts ice free without affecting the aerodynamic properties, and prevents ice from dangerously inhibiting an aircraft's controls. Iceman, be afraid!

HARD AS BONE

What do seashells and human bones have in common? They are both functionally graded materials comprised of sandwiched layers, with properties that gradually vary between each layer. Now, Graphene Flagship Partnering Project CERANEA, comprising researchers from a wide range of institutes in countries such as Hungary, Germany and Slovakia, is exploring ceramics and graphene to develop new possibilities for bone-like materials.

CERANEA's researchers replicated bone-like structures by altering the amounts of graphene in ceramic-graphene composites, mimicking different porosities in the process. Placing foam-like graphene at the top of the structure enables it to support 3,000 times its own weight.

By exploiting conventional powder technologies, with additional industry-standard processes like hot isostatic pressing to enhance the ceramic density, scientists can produce composite materials ranging in size from approximately 1 to 10 microns. This allows CERANEA to manufacture functionally graded materials of differing layers and varying compositions: usually five to 30 per cent graphene by weight. Not only does this make bone reconstruction possible, the use of artificial materials like these holds exciting possibilities for biomedical implants.

The Graphene Flagship partnered with Talga, an industry-leading battery anode and graphene additive company. Talga developed a new patent-pending graphene additive product, called Talcoat™, designed to enhance the anticorrosion performance of protective coating on marine vessels without the ecological damage.

The graphene phone has the potential to use the full bandwidth of the 5G network: up to five times faster than 4G."

BON VOYAGE

Billions of euros are spent on technologies to protect marine vessels, like ships, tankers and their equipment against water's harmful effects. Rain and stormy seas cause the structures of vessels to corrode heavily, which necessitates spending on repairs and replacement materials. What's more, the traditional method of protection, where epoxy primer is applied to a ship's entire structure, causes damage to the ocean's ecology over time.

This is why the Graphene Flagship partnered with Associated Member Talga, an industry-leading battery anode and graphene additive company. Talga developed a new patent-pending graphene additive product, called Talcoat™, designed to enhance the anticorrosion performance of protective coating on marine vessels without the ecological damage.

Talcoat has already been applied to two active commercial cargo ships in what's believed to be the world's largest application of graphene, and the sea trials have reported positive results. Graphene also shows strong potential as a coating material for other products.

SPEED DIAL

Because of its unique properties, graphene is about to step out of the field of material science and into the spotlight of mobile phone technology. Indeed, it could make phones of the future faster.

Using graphene-based photonics, the Graphene Flagship's 5G Spearhead Project developed a way to transmit data at speeds of up to 56 gigabits per second, much faster than an ethernet connection. This new method of data transfer is faster, consumes less energy and results in fewer transmission errors than current 4G connections.

The ultimate purpose of this initiative is to demonstrate an ultra-high capacity transmitter and receivers for 5G communications using graphene. The project has already demonstrated transmission speeds of 50 Gb per second from an electro-absorption modulator and 56 Gb per second from a transmitter. This means the graphene phone has the potential to use the full bandwidth of the 5G network: up to five-times faster than 4G. Projects like these represent significant steps towards justifying large-scale commercial interest in graphene, going into 2022 and beyond.

THE GRAPHENE SOLUTION

AN ERA OF INNOVATION

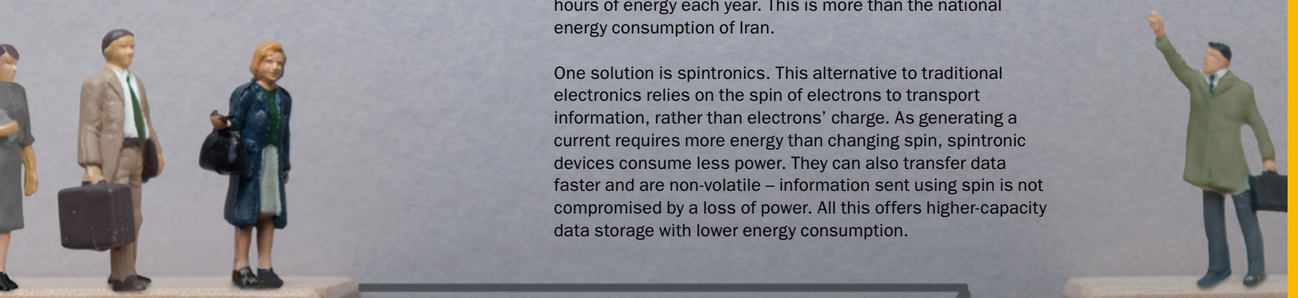
By: Kari Hjelt

Since graphene's discovery, researchers have found hundreds of potential applications for this incredibly versatile material. From brain implants to treat neurological disorders, to the next generation of smart textiles, products enabled by graphene and related materials promise to disrupt individuals, industries and societies. In this article, Kari Hjelt, Head of Innovation at the Graphene Flagship, looks at three examples.

PUT A SPIN ON IT

In today's world, data is king. But the ever-increasing demand for faster data processing and data storage capabilities led to a dramatic rise in energy consumption, as well as the accompanying concerns about the environmental impact of data processing. The world's data is stored in physical locations – data centres, which globally use an estimated 200 terawatt hours of energy each year. This is more than the national energy consumption of Iran.

One solution is spintronics. This alternative to traditional electronics relies on the spin of electrons to transport information, rather than electrons' charge. As generating a current requires more energy than changing spin, spintronic devices consume less power. They can also transfer data faster and are non-volatile – information sent using spin is not compromised by a loss of power. All this offers higher-capacity data storage with lower energy consumption.



Where does graphene come in?

Spin devices based on graphene and related materials drastically outperform conventional materials when transferring spin information at room temperature. The Graphene Flagship's Spintronics Work Package aims to demonstrate the efficient integration of related materials into spintronic devices to improve their speed, energy and cost.

Sophisticated graphene-enabled spintronic devices could open the door to the design of exceptionally energy-efficient memory technologies, reducing the environmental impact and cost of data storage around the world.

These examples showcase that graphene's significance is not limited to research and academia. Instead, it is a powerful solution to major real-world problems.

21%

Transportation is responsible for 21% of global CO_2 emissions.

ON THE ROAD

Passenger cars account for 60% of Europe's total CO_2 emissions from road transport. With the European Union setting strict targets to limit transport emissions, it is vital to reduce the environmental impact of passenger cars now more than ever.

There are two ways to achieve this goal: making cars more efficient by reducing their weight, and switching to renewably powered electric vehicles.

The first is possible using lightweight materials for vehicle frameworks – something that can be achieved through strong and light hierarchical fibre composites, made with graphene sheets just a few billionths of a metre thick, as a nano-additive. Research undertaken by the G+BOARD Spearhead Project also uses graphene to develop lighter and greener car dashboards, replacing the need for copper wiring.

The second, encouraging the uptake of electric vehicles, falls under the remit of Spearhead Project GREENBAT. Electric vehicles are becoming more and more popular, but many drivers are concerned about the availability of charging points, the limited range and high cost. GREENBAT's research will help electric vehicles become the norm by using graphene's properties to create high-performance automotive batteries. The focus of their innovation is the cell's negative electrode, made from a silicon-graphene composite developed during earlier Graphene Flagship research.

These batteries will perform as well as the projected state-of-the-art models in 2025, helping scientists and engineers in the automotive industry to make long-range, cost-effective electric vehicles a reality.

CLEAN AND SAFE

A major problem facing the twenty-first century is readily accessible safe and clean drinking water. Even in Europe, the number of contaminants released into the environment rises every day. Worse, no existing technology can remove all these contaminants from our drinking water.

To solve this issue, a new generation of water filters is needed: an innovation that Spearhead Project GRAPHIL hopes achieve. GRAPHIL's compact filtration systems will be easily connected to a household sink, or able to be used as a portable device. They aim to keep costs sustainable.

GRAPHIL's filters use polymeric hollow fibre membranes blended with graphene. They remove both microbiological and inorganic contaminants by combing membrane filtration and absorption mechanisms.

GRAPHIL expect to have a market-ready product by 2024: one that should make clean, contaminant-free water accessible for all.

BATTERIES UNLEASHED

CUTTING-EDGE ENERGY STORAGE TECHNOLOGIES PIONEERED BY THE GRAPHENE FLAGSHIP

By: Tom Foley

SUPER-HIGH CAPACITY

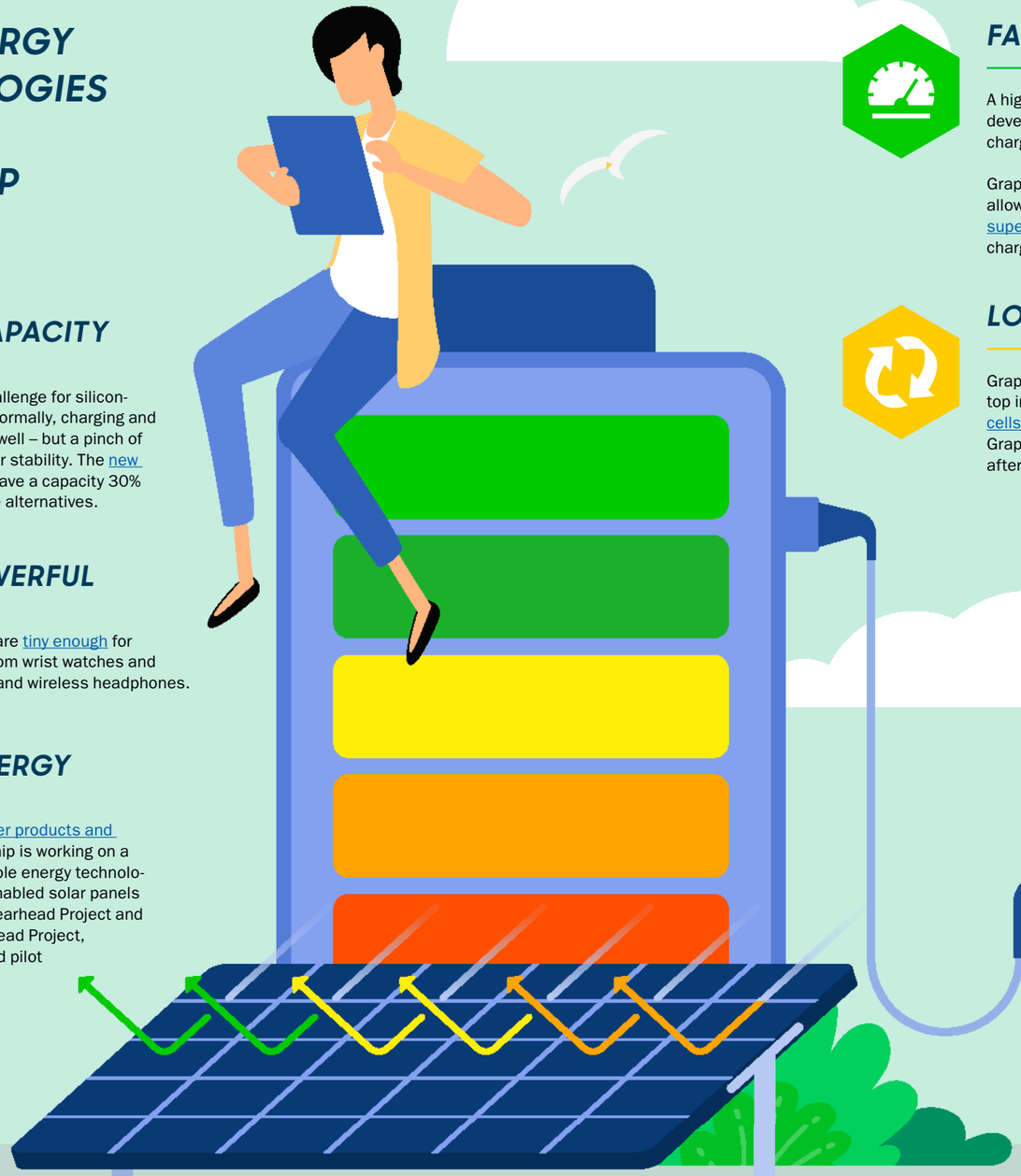
Graphene solved a critical challenge for silicon-based lithium-ion batteries. Normally, charging and discharging causes them to swell – but a pinch of graphene vastly improves their stability. The new graphene-enabled batteries have a capacity 30% higher than currently available alternatives.

SMALL BUT POWERFUL

Graphene-enabled coin cells are tiny enough for small personal electronics, from wrist watches and wearable devices to car keys and wireless headphones.

RENEWABLE ENERGY

… leads to cleaner and greener products and devices. The Graphene Flagship is working on a number of pioneering renewable energy technologies, such as the graphene-enabled solar panels developed by our GRAPES Spearhead Project and the recent Solar Farm Spearhead Project, which led to an unprecedented pilot installation in Greece.



GOING THE DISTANCE

Graphene Flagship scientists are developing an advanced automotive battery based on an innovative graphene-silicon composite anode. It boasts a lifetime of 1000 cycles: a total driving range of 450,000 km, which will be competitive with state-of-the-art lithium batteries in 2025.

FASTER CHARGE RATES

A high-power graphene-based battery prototype developed by our Batteries Spearhead Project can charge and discharge in only six minutes.

Graphene's excellent electrical properties also allow for super-fast energy transfer: graphene supercapacitors enable rapid and portable device charging and store up to 100 times more energy.

LONGER LIFETIMES

Graphene Flagship scientists at VARTA and other top institutions developed graphene-enhanced coin cells that can withstand over 300 recharge cycles. Graphene helps batteries to retain their properties after heavy-duty use, improving their lifetime.

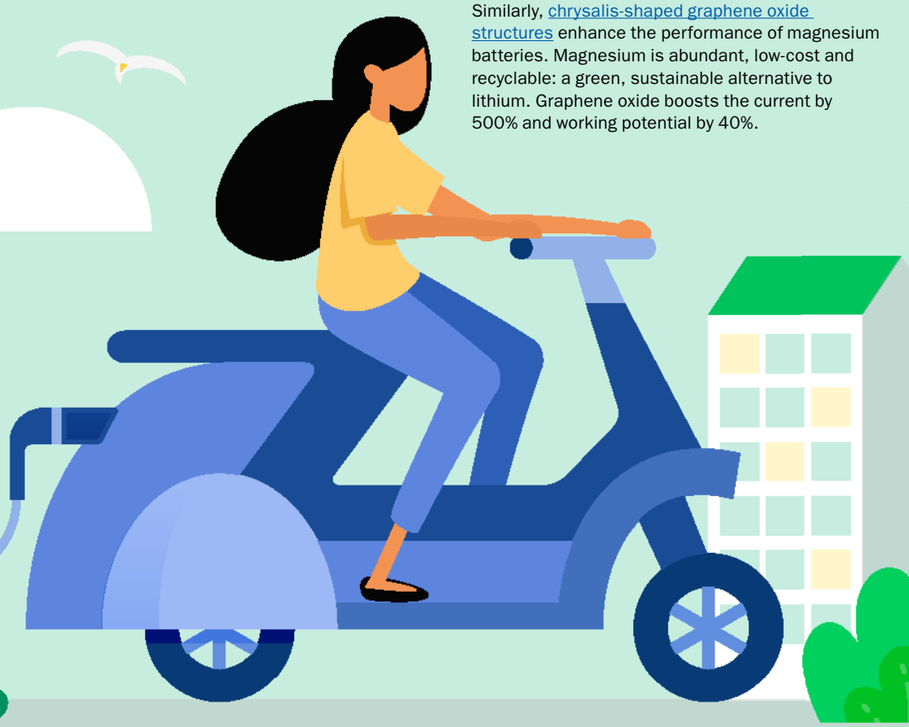
30%

VARTA's graphene-based batteries have capacities up to 30% higher than traditional alternatives.

ENVIRONMENTALLY FRIENDLY

Graphene Flagship scientists transformed a graphene-based ink into an aerogel cathode for sodium-air batteries. The ink and batteries are recyclable, don't require organic solvents or toxic components, and can be recharged 50 times with 94% efficiency.

Similarly, chrysalis-shaped graphene oxide structures enhance the performance of magnesium batteries. Magnesium is abundant, low-cost and recyclable: a green, sustainable alternative to lithium. Graphene oxide boosts the current by 500% and working potential by 40%.



THE RISE OF GRAPHENE FLAGSHIP SCIENTISTS

PIONEERING RESEARCHERS SHARE THEIR STORIES

By: Fernando Gomollón-Bel

About ten years ago, researchers across Europe started to mobilise. The European Commission had just announced a visionary idea: heavily funded, long-term projects to catapult innovative technologies out from the lab and onto the market. Graphene, recently awarded the Nobel prize in Physics, was an ideal candidate.

Four of our inspirational investigators were among the first to join this ambitious endeavour: Xinliang Feng, Mar García-Hernández, Vincenzo Palermo and Amaia Zurutuza. They joined the project with bright ideas, a keen sense of enthusiasm and the unwavering will to succeed. Now, after a decade of proud research and cutting-edge results, their careers have all flourished aboard the Graphene Flagship, and they are pleased to tell their story.

AN AMBITIOUS JOURNEY BEGINS

Zurutuza was working in Scotland, as a researcher for a pharmaceutical company, when a job advert caught her attention. Near her hometown in the Basque Country, a brand-new scientific start-up company needed bright new minds to develop reliable, reproducible methods to manufacture a new material: graphene.

“I applied for the role of Scientific Director, even though my background came from a totally different field,” she explains. And it was the right choice. Soon after that interview, Zurutuza became the Chief Scientific Officer of Graphenea – one of the founding members of the Graphene Flagship consortium. “And the rest is history,” she adds.

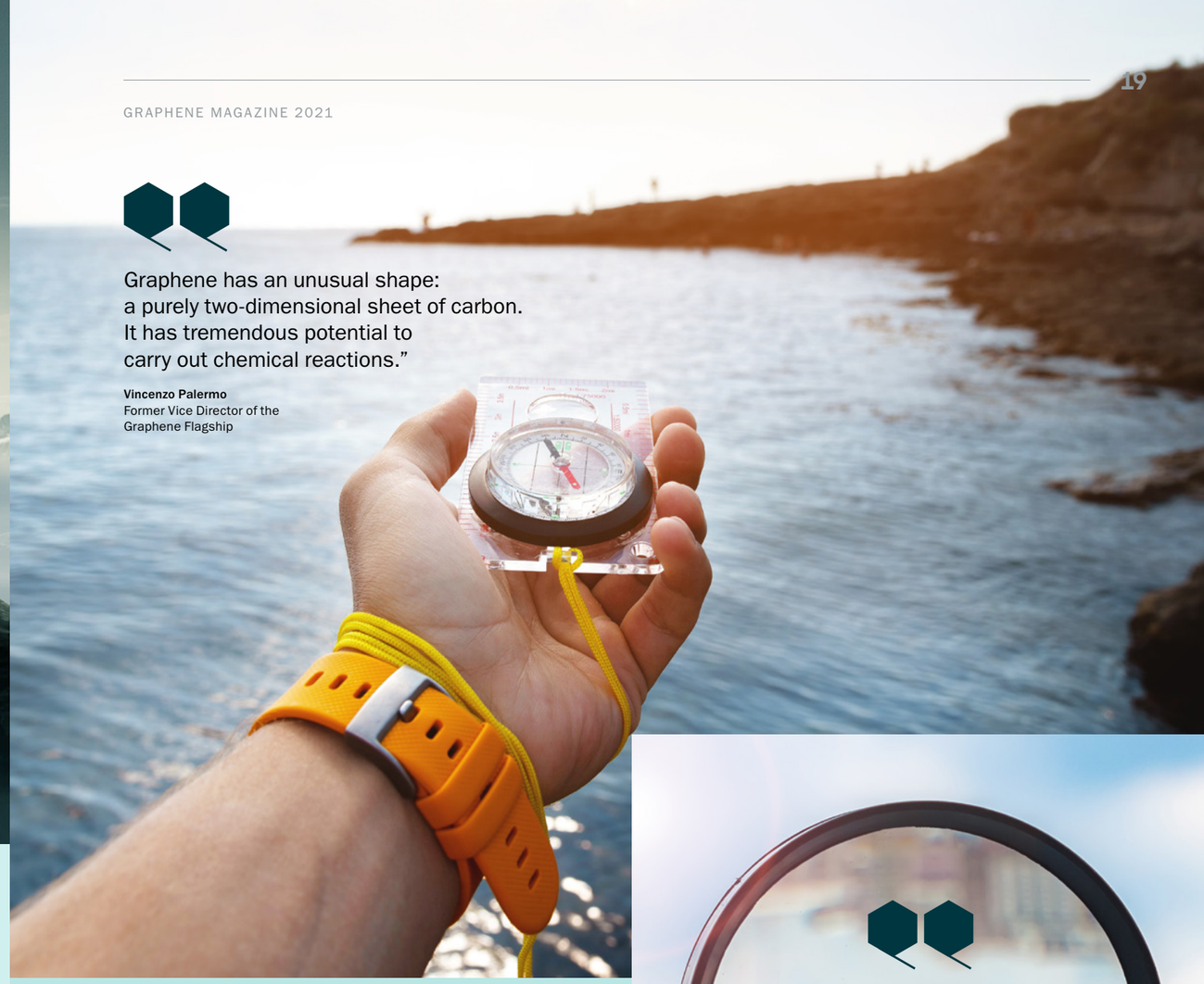
Palermo and Feng entered the world of graphene fascinated by its possible applications in chemistry. “Graphene has an unusual shape: a purely two-dimensional sheet of carbon,” explains Palermo. “It has tremendous potential to carry out chemical reactions,” he says. This singular structure enables the synthesis of new layered materials that, combined like ingredients in a sandwich, yield mixtures with weird and wonderful flavours and properties.

A NEW ERA FOR DISCOVERY

Although graphene was traditionally exfoliated – peeled coat after coat – from graphite, Feng envisioned a bottom-up approach instead, like a chemical jigsaw. Using advanced synthetic methods, Feng and his team merged polycyclic aromatics into monoatomic layers of carbon. “These systems are unattainable just using physical methods,” says Feng. “Plus, we can chemically modify graphene to tailor its functional groups, yielding designs with unique shapes and lengths,” he continues.

“Graphene is like the Swiss army knife of materials,” says García-Hernández, who explains that graphene is a truly multi-faceted material with a huge array of useful applications. “Its true charm lies in its unrivalled combination of different properties,” she adds. But despite the many advances pioneered by the Graphene Flagship, García-Hernández believes that the real breakthroughs are still around the corner.

Graphene’s ultra-thin structure is extremely sensitive to any changes in its surroundings, from small molecules to shining beams of light. This gives graphene tremendous potential in sensing applications. “These advantages will revolutionise optoelectronics and telecommunications,” García-Hernández



> Graphene has an unusual shape: a purely two-dimensional sheet of carbon. It has tremendous potential to carry out chemical reactions.”
>
> **Vincenzo Palermo**
> Former Vice Director of the Graphene Flagship

says. Graphene will empower technological breakthroughs in terms of energy efficiency, the optimisation of resources and sustainability. “Miniaturising means saving,” she explains. And she’s right – what could be smaller than transparent pieces of one-atom-thin carbon layers?

Further down the line, these capabilities will transform biomedical technologies, too. “We could also make responsive actuators using graphene. These would be fast and highly responsive, enabling doctors to rapidly respond to complications,” says García-Hernández.

“The immense importance of biosensors became evident during the pandemic,” adds Zurutuza. Beyond COVID-19, the possibilities are endless – when properly functionalised, graphene detects bacteria, viruses and even cancer. A remarkable example of this comes from Graphene Flagship spin-offs INBRAIN Neuroelectronics and Grapheal, which both attracted considerable private investments in 2021.

INBRAIN develops graphene-enabled neural interfaces that are more sensitive but less invasive than current technologies. Read more about INBRAIN’s successes on **page 21**. Grapheal responded to the coronavirus by refocusing their research pipeline from wound monitoring to COVID testing, developing new and accurate point-of-care tests for SARS-CoV-2. Both companies are progressing towards clinical studies, and their technologies could hit the market soon.

> The immense importance of biosensors became evident during the pandemic.”
>
> **Amaia Zurutuza**
> Chief Scientific Officer of Graphene Flagship partner Graphenea

We can chemically modify graphene to tailor its functional groups, yielding designs with unique shapes and lengths."

Xinliang Feng
Graphene Flagship Work Package Leader
for Functional Foams and Coatings

Graphene is like the Swiss army knife of materials. Its true charm lies in its unrivalled combination of different properties."

Mar García-Hernández
Graphene Flagship Work Package Leader
for Enabling Materials

LOOKING FORWARD

Just like the blossoming careers of our pioneering scientists, their graphene-based technologies were also enabled by the unique ecosystem fostered by the Graphene Flagship.

And this goes beyond just funding: the true secret to successful research is supporting fruitful and worthwhile collaborations between researchers across different countries, institutions and disciplines. "My career grew alongside the project," says Feng. "We all learnt so much about graphene and related materials, from physics and fundamentals to applications and innovations," he adds.

It is thanks to the Graphene Flagship that many graphene-enabled products are already commercially available. "Their impact on our everyday life is still limited, but technological revolutions take time," explains Palermo. Nevertheless, he is certain that graphene will transform the European innovation landscape. "Materials improve our lives and our planet," he adds. See videos of Graphene Flagship products in action on **page 32**.

Mixing and matching layered materials like graphene is a way to create completely new cutting-edge composites. For instance, García-Hernández studies methods to grow graphene on silicon, glass, sapphire, and even paper. There is a world of opportunities to explore ahead of us.

ADVICE FOR THE NEW GENERATION

These pioneers are now established, recognised graphene experts across Europe. We asked them what advice they would give to our young and early career scientists. Is there a secret to personal scientific success?

Together, they agreed that the most important qualities are curiosity, passion and perseverance. "It's great to start your career being curious about something new," explains Feng.

Then comes the fight for funding. Genius is mostly hard work, but proposals require dedication and determination. Keeping your dreams alive takes persistence, but it pays off. "Curiosity and passion drive scientific discovery," says García-Hernández. "The very story of graphene's discovery is the perfect example," she adds. For all four of these pioneering scientists, the Graphene Flagship has been a fantastic experience.

Overall, 'pursue your ambitions' is the take-home message. And Zurutuza makes a very convincing argument: "just go for it!"

THE FUTURE OF NEURAL INTERFACING

INBRAIN NEUROELECTRONICS PARTNERS WITH MERCK

By: Fernando Gomollón-Bel

After just two years in business, Graphene Flagship spin-off INBRAIN Neuroelectronics' success story keeps on growing. In early 2021, they announced a record-breaking investment of over €14 million, and they recently partnered with Merck, one of the largest pharmaceutical companies in the world, to develop the next generation of bioelectronics.

INBRAIN was launched by Graphene Flagship partners ICN2 and ICREA and quickly attracted significant interest from competitive calls and venture capital. They make graphene-based biomedical devices to diagnose and treat neurological disorders, motivated by the huge social and economical cost of these diseases.

Graphene enables flexibility, sensibility and biocompatibility in INBRAIN's bioelectronic devices, unlike traditional solutions – which impose restrictions in terms of resolution, miniaturisation and patient rejection. Furthermore, thanks to the other extraordinary properties of graphene, they are also programmable and can charge wirelessly.

The Graphene Flagship ecosystem was key to the development of these innovative technologies. ICN2 collaborated with other partners in the project, like the University of Manchester, to test the biocompatibility and toxicity of these devices and validate the discoveries *in vitro* and *in vivo*.

"Minimally invasive electronic therapies represent a revolutionary alternative," said INBRAIN's CEO Carolina Aguilar in a press statement. Graphene offers a real opportunity to understand how our brain works, and use this knowledge to optimise and personalise medical treatment. The potential to revolutionise the medtech industry is outstanding.

On top of this, INBRAIN recently expanded its business to create INNERVIA, a new company that will work hand-in-hand with leading pharmaceutical company Merck to develop smart bioelectronics to treat chronic diseases. This partnership highlights the interest of key industrial players in graphene technologies.

Laura Matz, Chief Science and Technology Officer at Merck, explained: "We aim to accelerate developments in the emerging field of bioelectronics by boosting the novel modality of selective neurostimulation." Through this novel association, digital personalised diagnostics and treatments are one step closer.

Kari Hjelt, the Graphene Flagship's Head of Innovation, adds: "This collaboration showcases the unique innovation landscape created in Europe by initiatives like the Graphene Flagship, and certainly sheds light on the possibilities of graphene for other bioelectronic applications."

INBRAIN's technologies could improve the diagnosis and treatment of brain disorders like Parkinson's and epilepsy

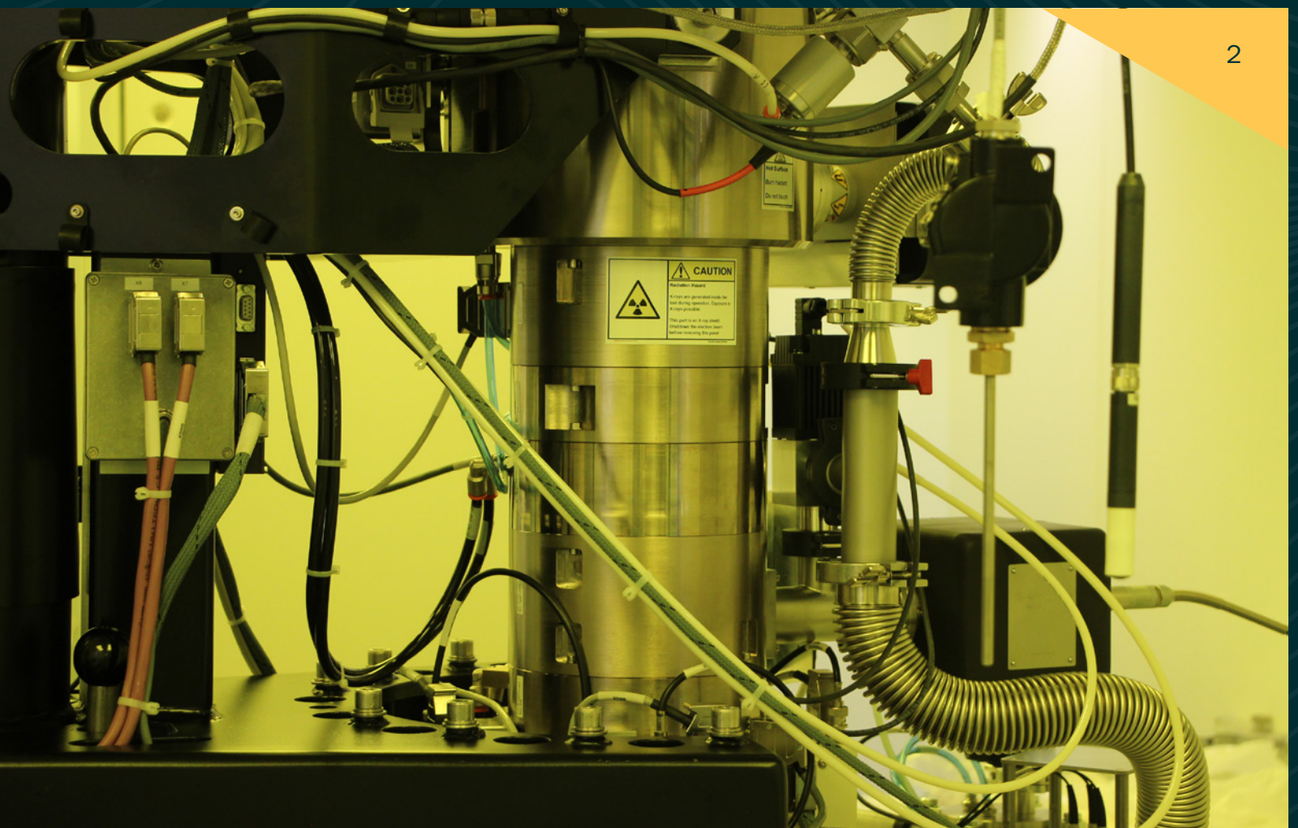
ENTER THE LAB

CAMBRIDGE GRAPHENE CENTRE

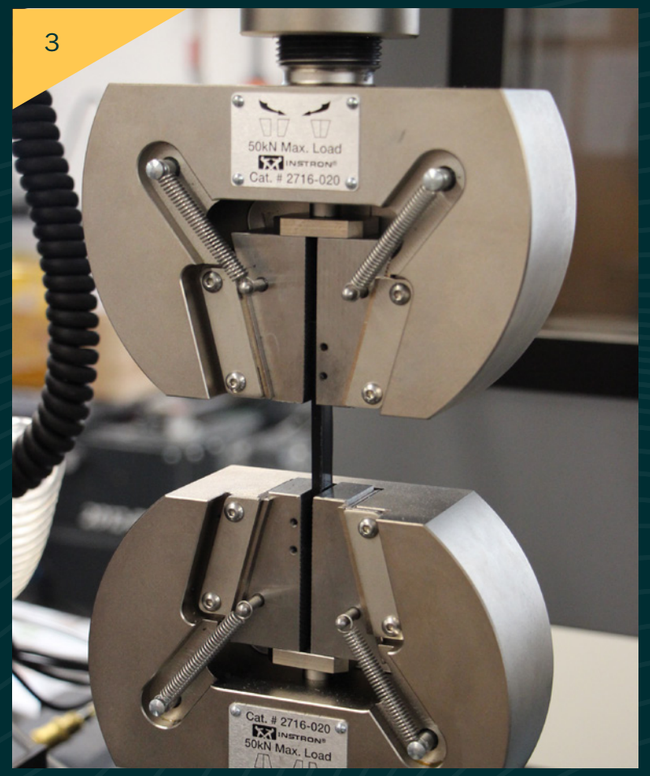
Welcome to the Cambridge Graphene Centre, part of the University of Cambridge. Here, Graphene Flagship researchers investigate the science and technology of graphene, carbon allotropes, layered crystals and hybrid nanomaterials.

In these labs, scientists are working to integrate graphene into smart devices based on flexible and transparent substrates, developing new energy storage technologies enabling them to work wirelessly and autonomously. The passionate researchers are also working to print, process and optimise inks based on graphene and other carbon nanomaterials, among a whole host of other cutting-edge research pursuits.

An atomic layer deposition system inside the Cambridge Graphene Centre cleanroom. This thin film deposition technique is key to making semiconductor devices.



An X-ray photoelectron spectrometer used to identify the elemental composition of materials and their electronic structures. These measurements show which elements are present in a sample, and which other elements they are bonded to.



Scientist Yarjan Samad inspects a graphene product undergoing lyophilisation, also known as freeze-drying. This is a low-temperature process to remove water from a sample.

Tensile testing using a mechanical wedge action grip. Scientists at the Cambridge Graphene Centre conduct tests like this to measure the mechanical properties of the materials they produce.

An anechoic chamber to test antennae and RFID sensors and detectors. Shout as loud as you want – no one can hear you in here.

All images are credited to the Cambridge Graphene Centre

ONE YEAR OF THE 2D-EPL

By: Rebecca Waters

In October 2020, the Graphene Flagship launched a second project funded by the European Commission: the 2D Experimental Pilot Line (2D-EPL). This project is working to establish a European ecosystem for the prototype production of graphene and related material (GRM)-based electronics, photonics and sensors.

Cedric Huyghebaert, a research manager for Nano Applications Material Engineering at imec in Belgium, leads the 2D-EPL project. Here, he offers his thoughts on the purpose of the project, its accomplishments over this first year and the future of the 2D-EPL within the Graphene Flagship and beyond.

Cedric Huyghebaert, 2D-EPL Division Leader
Credit: Graphene Flagship

What was the motivation behind the 2D-EPL project?

2D materials have shown wonderful performance in many devices targeting different application fields. Nevertheless, despite the promising properties of 2D materials, new technology needs to be developed in order to bring 2D materials to mass production. Bridging the gap between GRM processes in the lab and silicon processing in the semiconductor industry is a big challenge, and requires coordinated action between processing sites, tool vendors and material suppliers to take the first steps in that direction. I saw the 2D-EPL as an opportunity to jump into this adventure and make Europe the place where 2D materials would become a semiconductor technology.

How did you personally become involved in the project?

I was involved in the project from the beginning. As the Deputy Leader of the Graphene Flagship's Wafer-scale System Integration Work Package, I had a good view of the key challenges that would need to be addressed, and I made a list of possible solutions. I then reached out to people and companies from within the Graphene Flagship and beyond to see if they shared my analysis, and to find out if they could contribute to these solutions. Based on their feedback we began to form a consortium – and a project, which is now the 2D-EPL as we know it today.

How does a collaborative project like the 2D-EPL help to advance the state-of-the-art?

The 2D-EPL allows us to bring together the entire supply chain for the successful integration of 2D materials. The injection of EU money reduces the risks for the participants by supplying a large portion of the investment necessary to bridge the gap between demonstrating 2D materials in the lab and building up robust 2D technology.

One year on, what has the 2D-EPL project accomplished?

The first year of the project was critical to establishing the structure and infrastructure of the project. It was an important year where the seeds of success were planted and started to grow, but the output is not yet visible to the external world. We finalised the design of the first commercial 300 mm growth tool for graphene, hexagonal boron nitride and transition metal dichalcogenides – two other GRMs. The parts have been ordered, and the tool will be manufactured in the coming year.

In the meantime, we processed the first lot with transferred tungsten diselenide through the fab, and made the first double-gated transistors below 50 nm in a fab flow relying on standard semiconductor equipment. Last but not least, we stabilised a 200 mm graphene device flow, with a yield above 80%, allowing us to open a multi-purpose wafer call capable of meeting customer requirements.

What are the next steps for the 2D-EPL?

The next steps are to improve the stability of our integration flows and to prepare for upscaling to 200 and 300 mm for some of the improved flows we demonstrated in the labs. This is in addition to starting to explore the possibilities for collaboration with our customers.

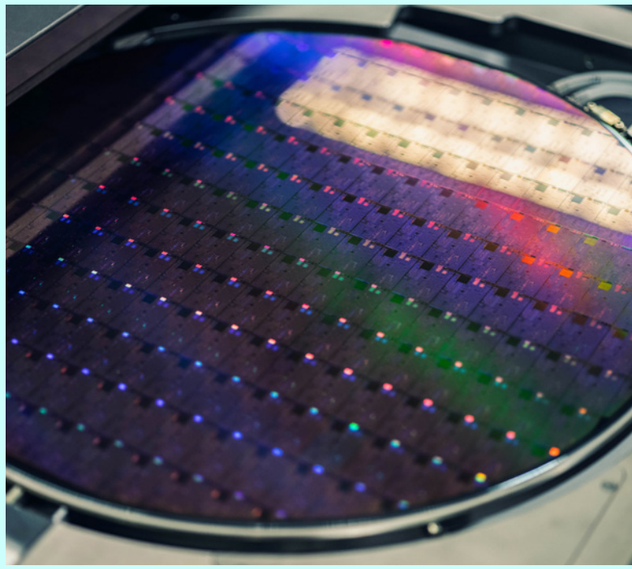
What does the future hold for the 2D-EPL beyond the four-year EC funding?

My hope is that 2D materials will be adopted by the semiconductor industry. There are plenty of potential applications in the sensors, datacom, photonics and electronics fields, but the integration of 2D materials lacks maturity. The 2D-EPL is the big opportunity to take some key steps forward, and to demonstrate to the industry that there is a demand for 2D co-integration with silicon. Finally, if the funding window is too short to convince industry, the infrastructure built by the 2D-EPL will offer opportunities to continue fine-tuning the integration more specifically for different application fields. In the 2D-EPL, we are focused on the development of a generic integration module. But more tuning will be needed to optimise the performance for different application fields.

What is your favourite thing about 2D materials for wafers?

I'm just fascinated by the fact that it's possible to transfer a monolayer of material over such a large area. The aspect ratio of that is really gigantic. The control that is required to do so is just amazing.

> The first year of the project was critical to establishing the structure and infrastructure of the project.
>
> **Cedric Huyghebaert**
> Division Leader



The 2D-EPL will soon launch its first multi-purpose wafer runs, producing graphene integrated silicon wafers. Credit: imec

80%

In the last year, the 2D-EPL stabilized a 200 mm graphene device flow with a yield above 80%.

COMING SOON

MPW RUN 1

The 2D-EPL will launch its first multi-purpose wafer run early next year. This run is mainly intended for graphene sensors and will be offered by AMO GmbH.

The baseline process is a GFET including a top/bottom contact with an optional local or global back gate, optional encapsulation and an optional graphene-area opening. The design of the device can be adjusted within the specifications listed on the 2D-EPL website.

A ROYAL FLUSH

MAKING GRAPHENE FROM SEWAGE SLUDGE AND WASTE

By: Tom Foley

Graphene will soon be produced from the unwanted waste collected from cities and towns. In a new collaboration, Graphene Flagship partner Graphenea have joined Circular Biocarbon: an initiative to develop a biorefinery that recycles urban waste into value-added products like graphene and more.

We spoke to Amaia Zurutuza, Graphenea's Chief Scientific Officer, who told us how Graphene Flagship scientists could soon benefit from green and sustainable recycled graphene.

Please can you tell us a bit about the project?

This is a first-of-a-kind flagship biorefinery to increase the value of the organic fraction from municipal solid waste and sewage sludge. The refinery will convert organic waste into high added-value products like graphene.

Circular Biocarbon will work towards a sustainable bioeconomy based on their vision: circular waste treatment in urban centres.

How could it benefit the Graphene Flagship?

Like the Graphene Flagship, Circular Biocarbon is also funded by the European Commission. The project is aligned with the EU's commitment to promote a circular and green bioeconomy and encourage sustainable development.

Obtaining graphene from urban waste will promote a circular economy for graphene-based products, and decrease our dependence on fossil fuels. Graphene Flagship scientists will be able to use green graphene in their applications, making their research and products more environmentally sustainable.

> The refinery will treat all the biowaste produced by a medium-size city – a bold step towards circular waste treatment and a great way to obtain green materials"
>
> **Amanda Zurutuza**
> Chief Scientific Officer at Graphenea

How does the treatment method work?

The biorefinery is organised through a pool of cascading innovative technologies. After pre-treatment, mixed urban waste streams undergo anaerobic processing in an oxygen-free environment. The refinery will treat all the biowaste produced by a medium-size city. This is a bold step towards waste treatment models, as well as being a great way to obtain green, bio-based materials.

Can you tell us about the graphene produced by the refinery?

Graphenea produces 200 mm wafer-scale graphene using chemical vapour deposition. The biorefineries should be able to match that. Our idea is to use this green graphene to make night vision cameras and graphene-based devices for telecommunications in 5G technology and beyond.

How soon will we see this up-and-running?

The biorefineries are being built in in Zaragoza, Spain, and Milan, Italy, and will run for three years. Construction begins in 2022.

CAMERAS UNLEASHED

GRAPHENE CAMERAS TEST FOOD QUALITY, SEE IN THE DARK, SENSE OBSTACLES AND MORE

By: Tom Foley

CHEMICAL SENSING AND FOOD SAFETY

Graphene Flagship partner Emberion's graphene-based cameras detect both visible and infra-red light, and could make low-cost imaging technology more accessible to businesses. The cameras can quickly analyse organic products and are now the focus of our GBIRCAM Spearhead Project. Similarly, Graphene Flagship partner ICFO developed graphene-based hyperspectral image sensors that can sense harmful substances in the food we eat, and even detect counterfeit drugs.

SELF-DRIVING CARS

Image sensors based on graphene quantum dots are sensitive, fast and low-cost. Graphene Flagship partner Qurv leads the AUTOVISION Spearhead Project, our latest initiative to develop a high-resolution graphene-based image sensor for autonomous vehicles, ready for industrial uptake. The graphene-based sensor detects obstacles and road curvature, even in rain or fog.

NIGHT VISION

With graphene, cameras can 'see' wavelengths beyond visible light. This means they can detect obstacles or provide vision in low-light conditions. On top of night-vision applications, these cameras complement smartphone cameras with thousands of individual photodetectors that improve image quality, thanks to their super-sensitivity to infra-red and ultra-violet light.

MEDICAL IMAGING

A medical microscope based on graphene is under development to detect and diagnose tumours. Graphene-based ultrafast lasers generate real-time digital images of tissue samples using a technology called Raman spectroscopy. Doctors use this to differentiate between healthy and diseased tissue, or to visualise tumours as they respond to treatment.

IMAGE RECOGNITION

A chip based on the layered material tungsten diselenide emulates a human eye, recognising and interpreting what it sees. This technology is used for facial recognition in smartphone cameras, like highlighting faces in the camera app. The new chip processes images a thousand times faster than conventional machine vision, using significantly less power – saving battery life.

LONG-RANGE COMMUNICATION

Graphene Flagship scientists developed a graphene-based optoelectronic mixer, a key component in telecom and datacom devices, that could make long-range communications cheaper and more sustainable – as well as accelerating their uptake into 5G and 6G industry. A new graphene-based optical receiver for wide-spectrum communication, developed by Graphene Flagship industrial partners Nokia and Finisar, is the focus of the METROGRAPH Spearhead Project.

SCIENTISTS IN THE SPOTLIGHT

THREE GRAPHENE FLAGSHIP SCIENTISTS SHARE THEIR STORIES AND SUCCESSES

By: Letizia Diamante

MARINA FOTI

Marina Foti works on the Solar Innovation Team at Enel's 3SUN factory in Italy. She also leads the Graphene Flagship Spearhead Project GRAPES, where she aims to use graphene and layered materials to enhance the properties of solar cell technologies.

The Graphene Flagship boasts a trove of multidisciplinary skills and a range of talents across many facets of science and technology. From theoretical physics to business developers, and from industrial experts to chemists, the Europe-wide consortium is fuelled by ambitious projects and the transfer of knowledge between experts at all stages in their careers. In this article, meet three of them, and find out why they are so proud to sail with the Graphene Flagship.

> The new graphene technologies applied to photovoltaics will lead to more efficient and reliable solar cells."
>
> **Martina Foti**
> GRAPES Spearhead Project Leader

Please can you tell us about GRAPES?

Since silicon solar cells are approaching their upper limits, we are looking into new possibilities and materials. The GRAPES project aims to design, fabricate and characterise a new type of solar cells based on silicon and perovskite, combined with graphene and related materials. Silicon and perovskites absorb a wide range of wavelengths over the spectrum, while graphene helps to improve the perovskite's stability and protects it from humidity and environmental contamination.

How will this benefit society?

For both solar panels and wind turbines, we have seen an outstanding and unprecedented decrease in the levelised cost of energy (LCOE): the average cost to generate electricity over a plant's lifetime. According to the International Renewable Energy Agency, the LCOE for solar photovoltaics fell by 82% between 2010 and 2019, for onshore wind by 39%, and for offshore wind by 29%.

These reductions make renewable energies much more cost-competitive or in some cases even cheaper than fossil fuels. The new graphene technologies applied to photovoltaics will lead to more efficient and reliable solar cells. This will address several of the UN's Sustainable Development Goals and contribute to the uptake and spread of renewable, affordable and clean energy.

ARNE QUELLMALZ

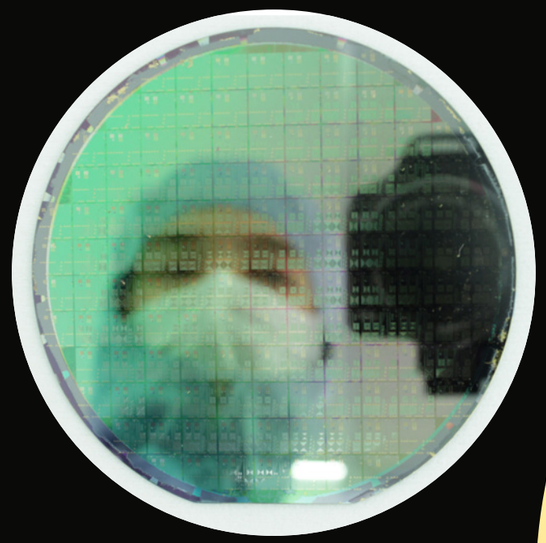
Arne Quellmalz is a PhD student at Graphene Flagship Associated Member KTH Royal Institute of Technology, Sweden. He is developing technologies to replace the current, bulky and energy-consuming gas sensors. In 2018, he joined Graphene Flagship Partnering Project CO2-DETECT, funded by the FLAG-ERA Joint Transnational Call in 2017, to integrate graphene into air quality sensors.

Why is graphene so useful for air quality sensing?

Many gases, like carbon dioxide and hydrocarbons such as methane, absorb infra-red light. This phenomenon allows us to determine the concentration of a gas by measuring the intensity of the light as it passes through. Graphene and other layered materials are promising candidates to make miniaturised photodetectors because they absorb light very strongly and can be combined with semiconductor substrates.

What is your proudest moment so far?

The recent publication of our work in Nature Communications was a big milestone for me! I was very happy to see that it attracted a lot of attention in both academia and relevant industries, which proves that we are trying to solve an important problem.



Arne Quellmalz takes a photo of himself wearing full cleanroom gear in a wafer's reflection. Credit: Arne Quellmalz

ANA HELMAN

Ana Helman is a Science Officer at the European Science Foundation – Science Connect, France, and works in the Graphene Flagship as the European Alignment Officer. She coordinates and aligns the Graphene Flagship Core Project with national and international research initiatives, such as FLAG-ERA, an ERA-NET co-fund action that supports the Graphene Flagship and the Human Brain Project.

How did you get to where you are today?

It was a steady climb. After graduating with my PhD in electronics, I started my career as a researcher at Philips Research Laboratories in the Netherlands. It was here where I realised just how much I enjoyed working in an international team, collaborating with several different countries. I also really valued seeing the 'bigger picture' of how research was done at a cross-European level. In 2008, I started working at the ESF, and there I discovered what it truly meant to manage research programmes and advance research from a different perspective.

What was the biggest milestone in your career?

I am honoured to have been involved in the Graphene Flagship since its inception, and that over the years, I contributed to shaping and developing the project. Seeing the Graphene Flagship evolve from a small-scale project to the huge Europe-wide initiative it is today has been so meaningful and worthwhile!

> Graphene and other layered materials are promising candidates to make miniaturised photodetectors because they absorb light very strongly and can be combined with semiconductor substrates."
>
> **Arne Quellmalz**
> PhD Student, KTH, Sweden

> Seeing the Graphene Flagship evolve from a small-scale project to the huge Europe-wide initiative it is today has been so meaningful and worthwhile!"
>
> **Ana Helman**
> Science Officer at ESF – Science Connect

VIDEO PRODUCT GALLERY

SEE GRAPHENE FLAGSHIP PRODUCTS IN ACTION

By: Tom Foley

Nothing shows progress better than cutting-edge products on the marketplace. Over the past year, Graphene Flagship scientists have been hard at work accelerating the development of their graphene-based technologies, getting them out of the lab and into the hands of consumers.

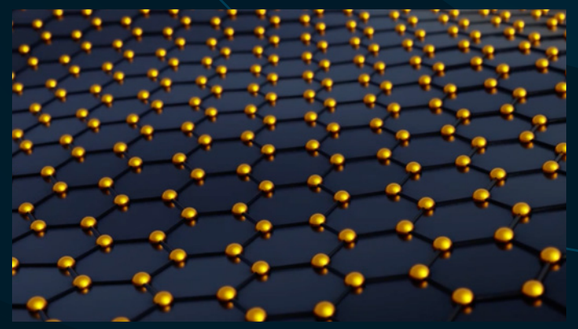
Watch these video brochures now to learn about five of our favourite Graphene Flagship products.

GRAFREN

ELECTRICALLY CONDUCTIVE FABRIC

Smart clothes that can monitor human health parameters, control pain or regulate temperature could all be possible with Grafren's new graphene-based electrically conductive fabric. The fabrics are soft, comfortable, breathable and lightweight – useful for biomedical applications as well as sports, virtual reality and gaming.

grafren.se

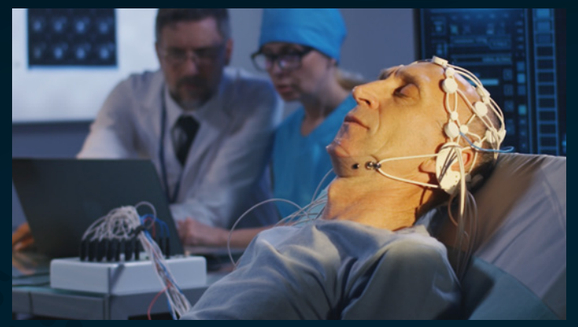


GRAPHENE-XT

GXT LUBE

GXT lube reduces wear and tear in diesel and petrol engines. Graphene's layered structure makes it a very strong lubricant – its atom-thin layers can easily slip and slide against each other, making it an excellent choice to keep engines running for longer.

graphene-xt.com



INBRAIN NEUROELECTRONICS

CHECKERS BRAIN INTERFACE

INBRAIN uses graphene to develop intelligent, high-resolution neuroelectronic systems for real-time brain mapping. In the Checkers Brain Interface, graphene acts as an electronic skin, enabling perfect contact with the surface of the brain whilst being less invasive than current brain interface technologies.

inbrain-neuroelectronics.com

GRAPHENEA SEMICONDUCTOR

GRAPHENE FIELD-EFFECT TRANSISTOR

The graphene field-effect transistor developed by Graphenea detects virtually any biomarker, and could be used to test for COVID-19, MERS, the Zika virus and even the common flu. Graphenea offers a variety of different sensing products that can be configured to test for several diseases at once.

graphenea.com

GRAPHEAL

TESTNPASS

The new generation of digital biosensors is here. TestNPass is a portable COVID-19 test that connects to a free smartphone app using near-field communication. The digital health pass app on your phone interprets your test results on-the-go, providing fast and accurate information without sharing any data online.

grapheal.com

ENTER THE LAB

AMO

Welcome to the cleanroom at Graphene Flagship partner AMO, Germany. Here, scientists are hard-at-work developing new electronic and photonic devices, finding new ways to integrate their fabrication processes into conventional semiconductor processing lines for applications in computing.

This is a critical step in the transition from lab to fab – one of the key goals of the Graphene Flagship and the 2D Experimental Pilot Line.

Graphene is a two-dimensional material, so it is completely flat. In principle, graphene is perfectly compatible with silicon wafer processing. But, because it is so thin, it is extremely sensitive to its environment. This is the main challenge for scientists integrating graphene into silicon wafers.

Scientists at AMO and other Graphene Flagship institutions recently had a breakthrough. They used a technique called plasma-enhanced atomic layer deposition to encapsulate wafer-scale graphene, maintaining graphene's excellent performance. This could help researchers to manufacture wafer-scale graphene-based sensors in the future.

1

Sputter deposition is a standard method in semiconductor processing to efficiently deposit metals. Here, a wafer is being loaded into a sputter coater to fabricate ohmic contacts to a graphene transistor – one of the key steps in GFET technologies.

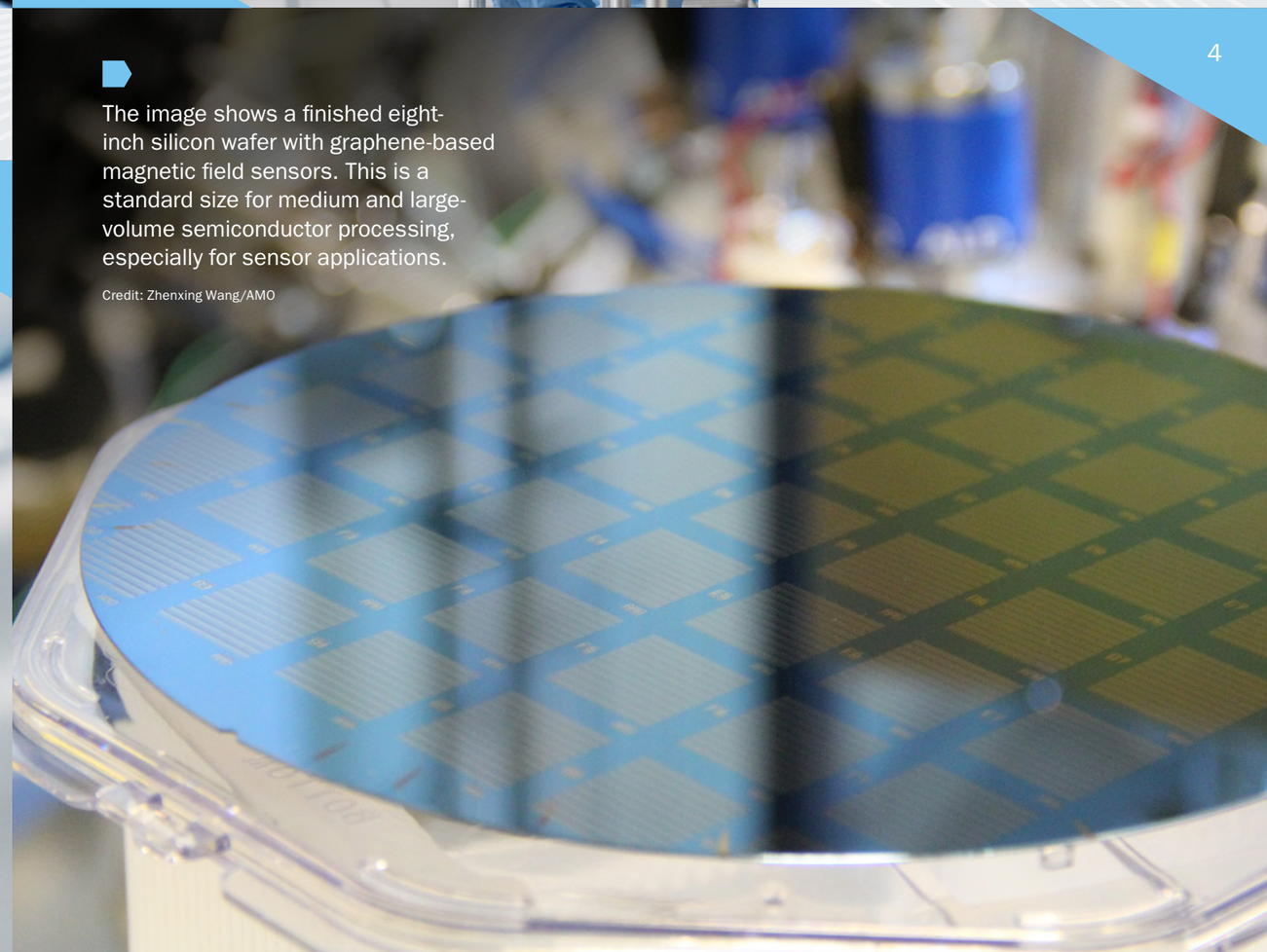
3

"Graphene is a two-dimensional material, so it is completely flat. In principle, graphene is perfectly compatible with silicon wafer processing. But, because it is so thin, it is extremely sensitive to its environment. This is the main challenge for scientists integrating graphene into silicon wafers."

A scientist wire-bonding graphene chips to connect them to the semiconductor package. This is the housing of a semiconductor chip that allows it to be plugged into a circuit board. This is the final processing step in AMO's cleanroom, and afterwards, the chip will look just like something you'd find in your computer.

2

AMO researchers studied the electrical measurements of graphene-based magnetic field sensors. In this picture, the researchers are analysing and discussing their results in order to qualify the performance of their sensors.



4

The image shows a finished eight-inch silicon wafer with graphene-based magnetic field sensors. This is a standard size for medium and large-volume semiconductor processing, especially for sensor applications.

Credit: Zhenxing Wang/AMO

All images are credited to AMO unless otherwise stated

BRIGHT FUTURES

WHAT'S NEXT FOR GRAPHENE?

By: Fernando Gomollón-Bel

As Physics Nobel Laureate Niels Bohr used to say: "it's difficult to make predictions, especially about the future."

Indeed, forecasting forthcoming breakthroughs is a complicated matter. For this very reason, the Graphene Flagship funds comprehensive roadmapping efforts within our Industrialisation Work Package. Our researchers study the state-of-the-art developments based on graphene technologies, analyse the market, and then provide strategic guidance on commercial uptake and industrial impact.

At the beginning of the project, our roadmapping team predicted a number of applications before 2020. Among them were graphene composites, inks and printable electronics. All of these dreams have come true, and our online product gallery showcases several success stories – from motorcycle helmets and tennis rackets to thermal coatings and cooling solutions. If you haven't already, check out the brand-new video product gallery on **page 30** to see footage of our latest products in action.

Some of these developments surpassed our highest expectations: notably, graphene-enabled sensors and detectors. Such positive results foretell triumphs in the fields of photonics, electronics and spintronics, supported by the launch of Graphene Flagship spin-off companies in these areas: Emberion, Qurv Technologies, CamGraphIC and CRIL.

Another unexpected accomplishment arrived in the field of graphene-enabled biomedical technologies. In 2021 alone, our spin-offs Grapheal and INBRAIN received over €16 million in private investments. Experts believe that graphene could revolutionise the medtech industry thanks to its unique flexibility, conductivity and biocompatibility.

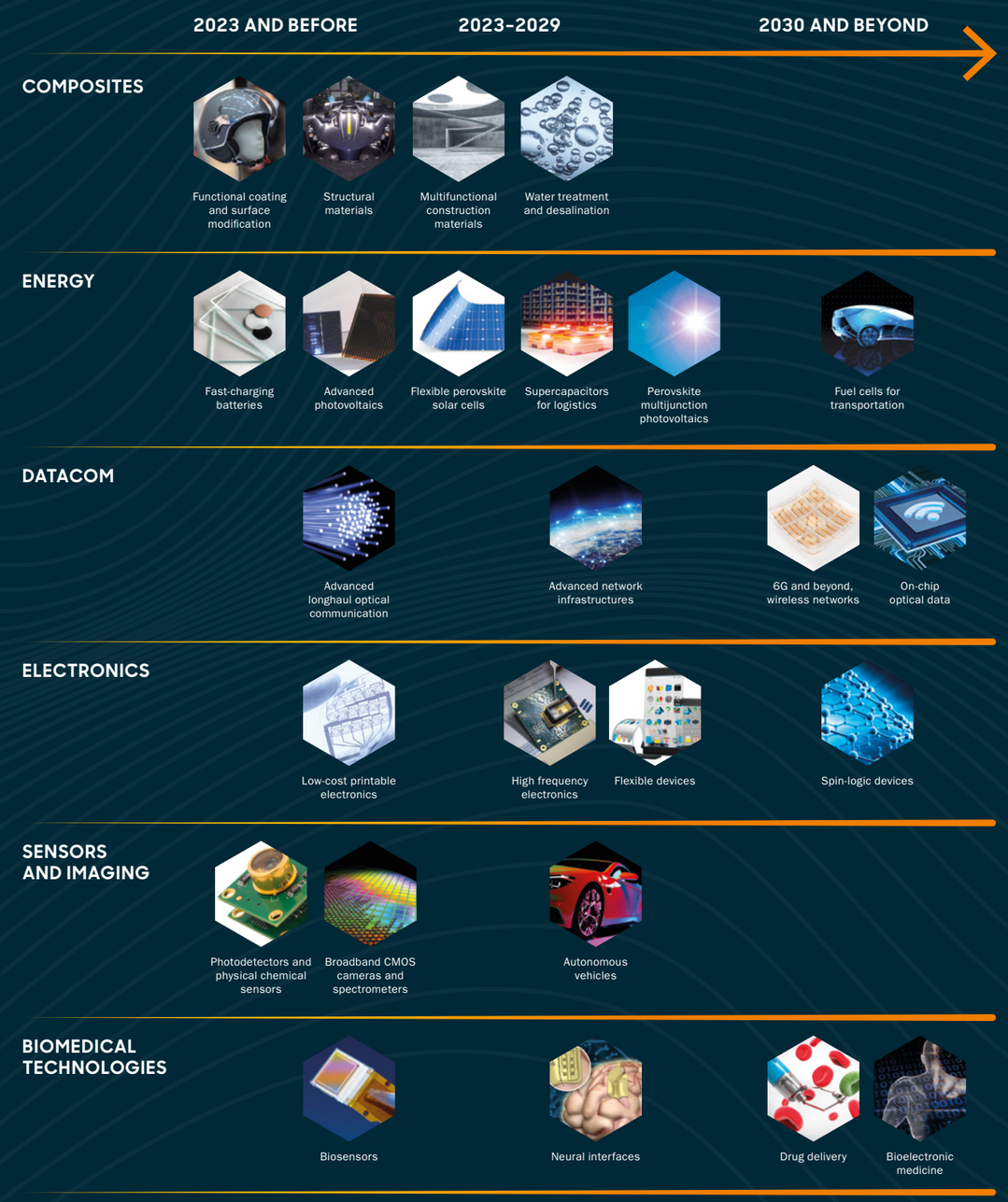
> In 2021 alone, our spin-offs Grapheal and INBRAIN received over €16 million in private investments. Experts believe that graphene could revolutionise the medtech industry thanks to its unique flexibility, conductivity and biocompatibility.

Combined with advances like artificial intelligence and biometrics, graphene-enabled biosensors and medical devices are set to outperform existing solutions. Currently, Graphene Flagship researchers are carrying out clinical trials. If these prosper, time-to-market will shrink, and graphene-based medical solutions will reach patients sooner than anybody anticipated.

The latest market analyses all agree that graphene's value will reach €600 million by 2030. Beyond just papers, patents and projects, this truly illustrates the success of the Graphene Flagship. We have established an innovative ecosystem that fosters collaboration between academia and industry, and consolidated Europe's leadership in the field of graphene and related materials. And it all blossomed from a chunk of graphite and a piece of sticky tape.

Now, graphene is a world-leading industry – with many more surprises yet to come.

TECHNOLOGY & INNOVATION ROADMAP



GRAPHENE WEEK

SAVE THE DATE: GRAPHENE WEEK 2022

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