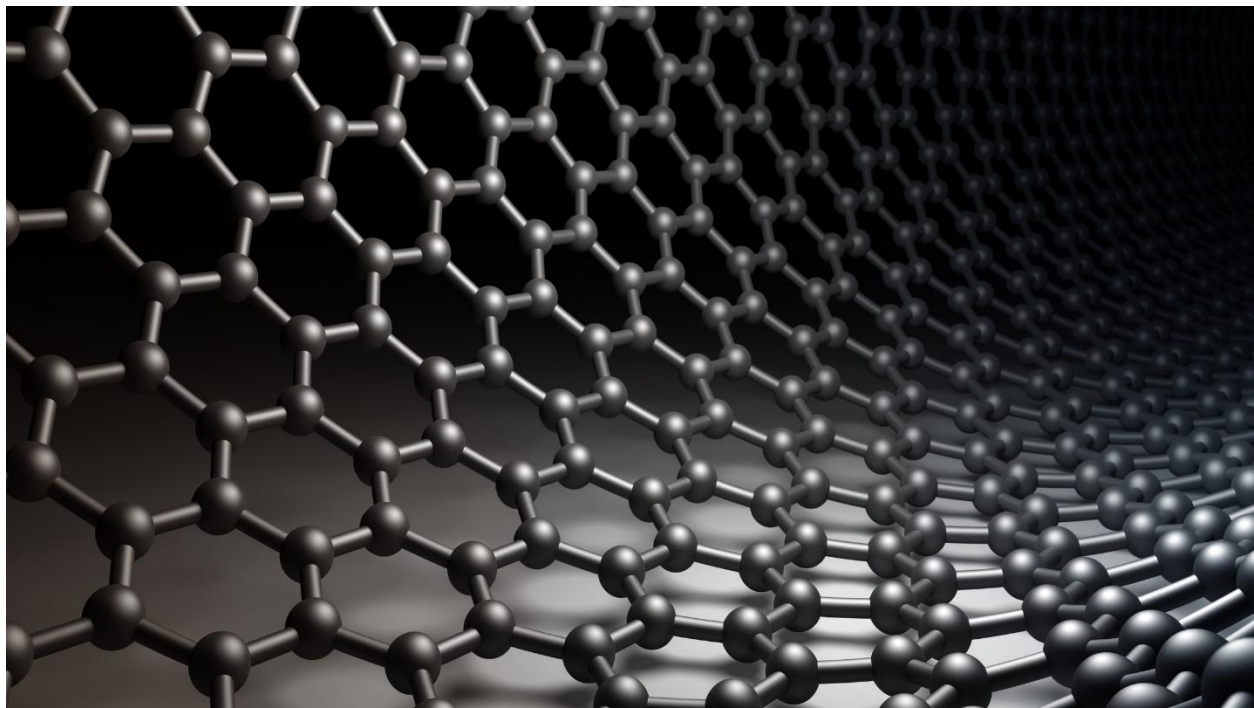
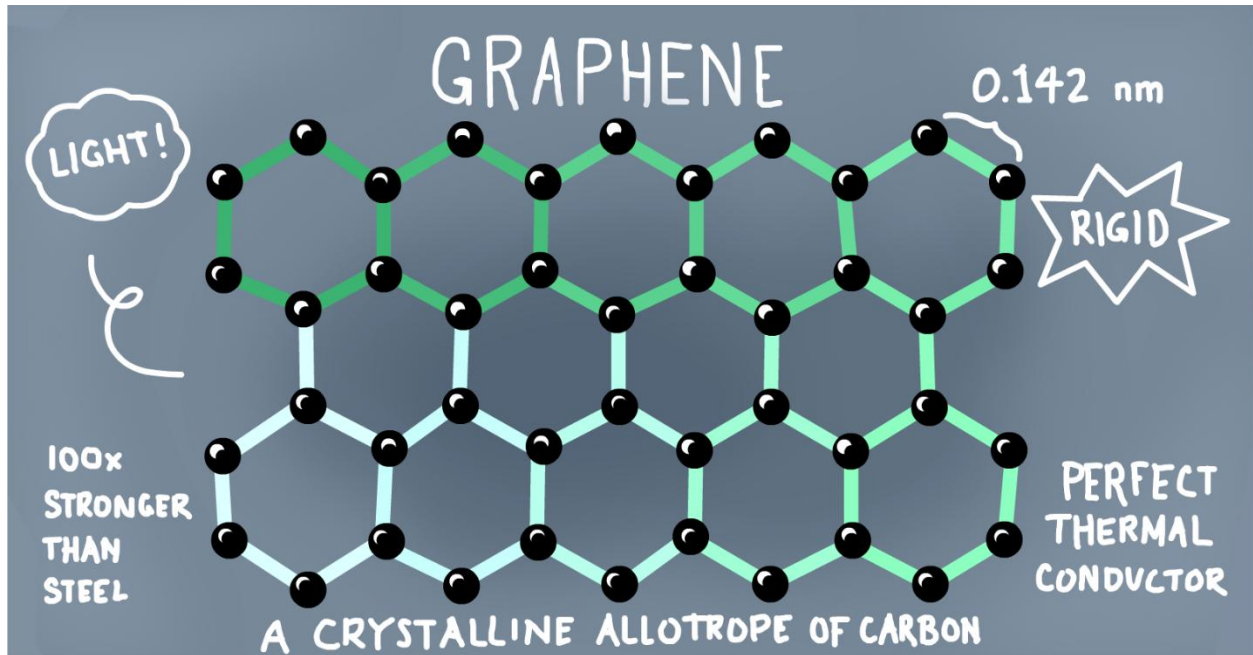


CARBON GRAPHENE and CARBON NANOTUBE



20 Years Ago, Two Physicists Made A Groundbreaking Discovery That Changed Technology Forever

Twenty years ago this October, two physicists at the University of Manchester, Andre Geim and Konstantin Novoselov, published a [groundbreaking paper](#) on the “electric field effect in atomically thin carbon films”. Their work described the extraordinary electronic properties of graphene, a crystalline form of carbon equivalent to a single layer of graphite, just one atom thick.

Around that time, I started my doctorate at the University of Surrey. Our team specializes in the electronic properties of carbon. Carbon nanotubes were the latest craze, which I was happily following. One day, my professor encouraged a group of us to travel to London to attend a talk by a well-known science communicator from the University of Manchester. This was Andre Geim.

We were not disappointed. He was inspiring for us fresh-faced PhD students, incorporating talk of wacky Friday afternoon experiments with levitating frogs before getting on to atomically thin carbon. All the same, we were skeptical about this carbon concept. We couldn’t quite believe that a material effectively obtained from pencil lead with sticky tape was really what it claimed to be. But we were wrong.

The work was quickly copied and reproduced by scientists across the globe. New methods for making this material were devised. Incredible claims about its properties made it sound like something out of a Stan Lee comic. Stronger than steel, highly flexible, super-slippery and impermeable to gases. It is a better electronic conductor than copper and a better thermal conductor than diamond. It is also practically invisible and displays a host of exotic quantum properties.

Graphene was hailed as a revolutionary material, promising [ultra-fast electronics](#), [supercomputers](#) and [super-strong materials](#). More fantastical claims have included [space elevators](#), [solar sails](#), [artificial retinas](#), and even [invisibility cloaks](#).

Just six years after their initial work, Geim and Novoselov were awarded the [Nobel Prize in Physics](#), further fueling the enthusiasm around this wonder

stuff. Since then, hundreds of thousands of academic papers have been published on graphene and related materials.

But not everyone is on board. Skim through the comments section of any popular article on the material, and you'll quickly find the sceptics. We have endured decades of empty promises about the real-world impact of graphene, they complain. Where are the game-changing products to enrich our lives or save the world from climate change, they ask?

So, has graphene been a resounding success or a damp squib? As is so often the case, the reality is somewhere in between.

Graphene's ups and downs

In terms of public perception, it's fair to say that graphene has been held to an impossible standard. The popular media can certainly exaggerate science stories for clicks, but academics – including myself – are not immune from over-egging or speculating about their pet projects either. I'd argue this can even be useful, helping to drive new technologies forward. Equally, though, there can be a backlash when progress looks disappointing.

Having said that, disruptive technologies such as cars, television or plastic all required decades of development. Graphene is still a newcomer in the grand scheme of things, so it's far too early to reach any conclusions about its impact.

What has quietly occurred is a steady integration of graphene into numerous practical applications. Much of this is thanks to the [Graphene Flagship](#), a major European research initiative coordinated by Chalmers University of Technology in Sweden. This aims to bring graphene and related materials from academic research to real-world commercial applications, and more than 90 products have been developed over the past decade as a result.

These include blended plastics for high-performance [sports equipment](#), more durable [racing tyres](#) for bicycles, [motorcycle helmets](#) that better distribute impact forces, [thermally conductive coatings](#) for motorcycle components, and [lubricants](#) for reducing friction and wear between mechanical parts.

Graphene is finding its way into [batteries](#) and [supercapacitors](#), enabling faster charging times and longer life spans. Conductive graphene inks are now used to manufacture [sensors](#), [wireless tracking tags](#), [heating elements](#), and [electromagnetic shielding](#) for protecting sensitive electronics. Graphene is even used [in headphones](#) to improve the sound quality and as a more efficient means of transmitting heat in [air-conditioning units](#).

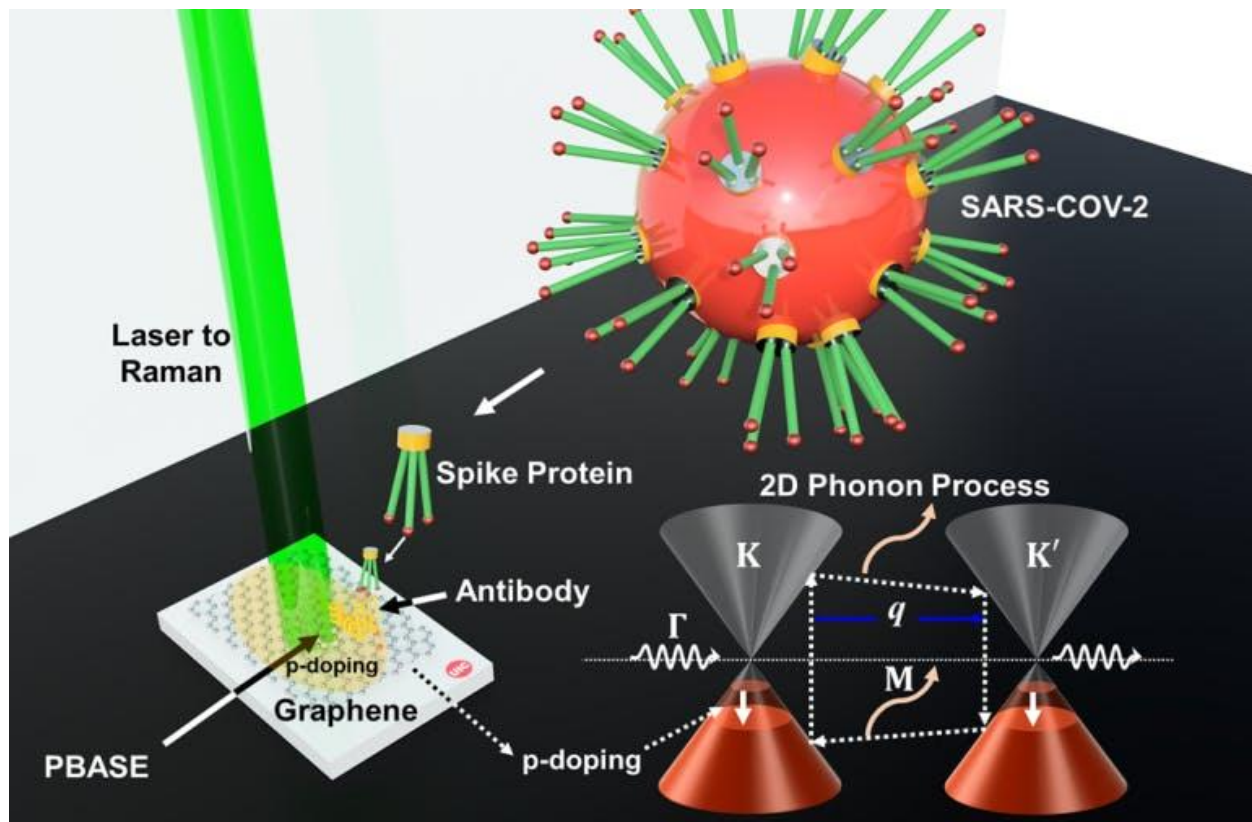
Graphene oxide products are used for [desalination](#), [wastewater treatment](#), and purification of [drinking water](#). Meanwhile, a range of graphene materials can be bought off the shelf for use in countless other products, and major corporations, including [SpaceX](#), [Tesla](#), [Panasonic](#), [Samsung](#), [Sony](#) and [Apple](#), are all rumored or known to be using them to develop new products.

From promise to practicality

The impact of graphene on materials science is undeniable. The impact on consumer products is tangible but not as visible. Once a material is embedded in a working product, there is little need to keep mentioning it, and proprietary concerns can make companies reluctant to get into details in any case. Consumers can, therefore, be blissfully unaware that their car, mobile phone, or golf club contains graphene and most probably don't care as long as it works.

As production methods improve and costs decrease, we can expect graphene to become ever more widely adopted. Economies of scale will make it more accessible, and the range of applications is likely to continue to expand.

Personally, after two decades, I still get excited when I try it out for something new in the lab. While I may be guilty of having contributed to the initial hype, I remain optimistic about graphene's potential. I'm still waiting for my ride on a space elevator, but in the meantime, I'll take comfort in the fact that graphene is already helping to shape a better future – quietly and steadily.



Graphene: The ‘wonder material’

Jan. 3, 2022

Innovative discoveries have helped to overcome existing challenges when using graphene.

An illustration of the graphene-based COVID-19 spike protein detection process developed at the University of Illinois. The white rectangle represents the substrate with graphene functionalized with SARS-CoV-2 antibody (shown in yellow). When this graphene detector interacts with the virus’ spike protein in a COVID-positive sample, its atomic vibration frequency changes.

[View Image Gallery](#)

Graphene has been hailed a “wonder material,” given its potential in a growing pool of applications and industries, from quantum computing (also see “Getting edgy with graphene”) to healthcare. But it’s also a bit unassuming. While it’s the thinnest material in the world at just one atom-thick, graphene is among the strongest at roughly 200X stronger than steel.

A monolayer of carbon atoms arranged in a hexagonal lattice, graphene’s most common use has been to form graphite, which is comprised of stacked graphene layers held together by van der Waals forces—essentially the backbone of pencils and lubricants. Moving beyond those historical uses, graphene is advancing into a jack of all trades.

Let’s take a look at how researchers are finding exciting new uses for this wonder material.

Gas sensors

As its potential applications escalate, graphene is playing a pivotal role in enhancing chemical sensors and imagers. Graphene-based sensors work by measuring alterations in the electrical conductivity of the material, and also by absorbing a gas molecule on the graphene's surface, which acts as donors or acceptors of electrons. The benchmarked parameters of graphene sensors include sensitivity, selectivity, response and recovery time, and detection limit.

According to the Graphene Council, scientists have found that the material can measure quantum-scale changes in conduction. It "boasts the benefit of being an extremely low-noise material. Because of this, even at the limit of no carriers and a few extra electrons, graphene's carrier concentration is able to change considerably." Additionally, graphene enables the creation of four-probe devices on monocrystals, basically guaranteeing eradication of "any influence of the contact resistance in limiting sensitivity."

Healthcare, biomedical research

Promising results from lab experiments at the University of Illinois Chicago show that a graphene-based sensor can quickly spot COVID-19 (see figure). [Published in *ACS Nano*](#), the research involved "modification of the dopant density and the phononic energy of antibody-coupled graphene when it interfaces with SARS-CoV-2 spike protein."

Researchers created the sensor by combining sheets of graphene and an antibody developed to target the spike protein. Using a Raman spectrometer, they measured the sheets' atomic-level vibrations after exposing them to samples of artificial saliva that were COVID-positive and others that were COVID-negative. Those vibrations changed when they treated it with the positive sample; there was no change with the negative sample—the changes became evident in less than 5 minutes.

According to the study, the graphene chemo-phononic system identified the SARS-CoV-2 spike protein at a detection limit of about 3.75 fg (force exerted by gravitation) per milliliter in artificial saliva, and about 1 fg (force exerted by gravitation) per milliliter in phosphate-buffered saline. "It also exhibited selectivity over proteins in saliva and MERS-CoV spike protein. Since the change in graphene phononics is monitored instead of the phononic signature of the analyte, this optical platform can be replicated for other COVID variants and specific-binding-based bio-detection applications."

The researchers note that carbon atoms in graphene are bound by chemical bonds, the elasticity and movement of which can produce resonant vibrations (phonons—the "collective excitation in a periodic, elastic arrangement of atoms or molecules in condensed matter"). This leads to very accurate measurements. When the SARS-CoV-2 molecule interacted with graphene, those resonant vibrations changed "in a quantifiable way."

The promising takeaway is that the potential for early detection of future variants could lead to earlier, quicker administration of treatments and a higher rate of successful recovery.

Dentistry

Graphene is also employed in dentistry-related studies, as well as some procedures. In research [published in *Applied Materials Today*](#), a team at Okayama University in Japan has found that graphene oxide (GO, a graphene nanomaterial) and functionalized GO “has provided outstanding results in antimicrobial action, regenerative dentistry, bone tissue engineering, drug delivery, physicomaterial property enhancement of dental biomaterials, and oral cancer treatment.” Graphene nanomaterials have exhibited unique optical, mechanical, and physiochemical properties that are specifically benefitting dental research. Overall, the researchers note, GO has a number of “chemically reactive functional groups on its surface, which facilitate interaction with DNA, proteins, polymers, and biomolecules” and shows great promise for biomedicine.

Across multiple studies, the researchers have developed GO for “biofilm and caries prevention as well as implant surface modification and as a quorum sensing inhibitor,” thanks to graphene’s antibiofilm and antiadhesion properties.

Specifically, graphene has proven beneficial for tissue engineering for treatments such as restoration of missing teeth. While most artificial biomaterials such as collagen lack “tissue-inductive activities,” scaffolds created using GO have prompted bone formation five times faster than has been possible with collagen scaffolds.

There’s promise for dental implants as well with graphene helping address the issue of leaking seals at the hard and soft tissue interfaces, which often leads to bacterial infections. [In an *AZO Materials* contribution](#), biotechnology researcher Dr. Priyom Bose said, “the healing process must be accelerated and bacterial colonization must be prevented. When graphene is coated with titanium substrate, its hydrophobic character imparts a self-cleaning effect on its surfaces, which enables a reduction in the adhesion of dental pathogens.”

Endodontic procedures such as root canals involve bioactive cement for the management of perforation, pulp capping, and retrograde root filling. Bose notes that graphene nanosheets improve the mechanical property of the bioactive cement.” For restorative dentistry and periodontology (the study of teeth’s supporting structures as well as diseases and conditions that affect them), fluoride graphene boosts the mechanical and antibacterial properties of glass ionomers, which are commonly used in restorative dentistry. It also “decreases microcracks in the internal structure and protects it from erosion and disintegration by microbial invasion.”

Quantum computing

A team at Nagoya University in Japan has been dabbling in graphene, with a biomedical tie but for the purpose of potentially advancing the next generation of quantum computing. The researchers developed this technique as the human brain can process highly complex data (such as images) more efficiently than existing computer architectures with limited processing speeds.

The team has designed graphene/diamond junctions that mimic the characteristics of biological synapses as well as key memory functions. In a study [published in *Carbon*](#), they demonstrated “optoelectronically controlled synaptic functions using junctions between vertically aligned graphene and diamond.” The junctions essentially mimic biological synaptic functions, “such as the production of ‘excitatory postsynaptic current’”—the charge induced by neurotransmitters at the synaptic membrane—when they stimulated it by optical pulses. They were also found to exhibit other basic brain functions, including the transition from short-term to long-term memory.

“Our brains are well equipped to sieve through the information available and store what's important,” says Dr. Kenji Ueda, a researcher in the Department of Materials Physics at Nagoya who led this study. “We tried something similar with our [vertically aligned graphene and diamond] arrays, which emulate the human brain when exposed to optical stimuli. This study was triggered due to a discovery in 2016, when we found a large optically induced conductivity change in graphene-diamond junctions.”

Ueda adds that this study offers a better understanding of “the working mechanism behind the artificial optoelectronic synaptic behaviors, paving the way for optically controllable brain-mimicking computers and better information-processing capabilities than existing computers.”

Considering these existing applications—and the continued interest in further research—it is easy to understand how graphene is truly becoming the wonder material.

Getting edgy with graphene

The next generation of devices is right around the corner—and we have a new phase of graphene to thank.

A team at Purdue University (West Lafayette, IN) has demonstrated that graphene’s viscous fluid can boost unidirectional electromagnetic “edge waves,” which are “linked to a new topological phase of matter and symbolize a phase transition in the material. With this, light travels in only one direction along the edge of the graphene material, making it “robust to disorder, imperfections, and deformation.”

The researchers used graphene because of its electrical conduction properties.

All of this has the potential to boost all-optical processing, as well as quantum information processing, computing, and networking, and interconnects between quantum and classical computing systems.

“There is a lot of interest right now in trying to build interconnections between our quantum systems and classical systems,” says researcher Zubin Jacob, the Elmore associate professor of electrical and computer engineering at Purdue; he worked alongside postdoctoral researcher Todd Van Mechelen and graduate research assistant Wenbo Sun on this study. “[Quantum systems] are basically information processing nodes that can beat classical systems. These [quantum systems] are the next generation of devices we are going to have.”

He notes, however, that quantum systems are very complex and may not be able to stand on their own. “They will need to be interfaced with existing supercomputers and hardware systems to communicate information in one direction back and forth.” Basically, “you want the information to preferentially flow in whichever direction you want.” Interconnects and a topological circulator device (cylindrical one-way signal routers developed by the Purdue team) allow this (see figure), unlike an isolator, which isolates the signal in one direction but not the other.

“Instead of just two systems, like A and B, just think of three ports: one, two, and three,” Jacob says. “So, you’re interfacing three signals in your cell phone or three antennas, for example, and so forth. That’s our circulator. You want information to go from one to two, two to three, and three to one, but not the other way around. The information circulates between whichever routes you choose, but not the other way around.”

Topological circulators are crucial devices for a variety of systems, and show potential for on-chip, all-optical processing because they are “a fundamental building block in integrated optical circuits.” However, they are large and bulky, whereas the processing chip is very small. This presents a problem, according to the researchers.

“We can’t fit hundreds of thousands of them on a small chip,” Jacob says. “We are trying to really miniaturize all of this. And the idea is we need signals to go from one port to another, but not backward. But this is very difficult to achieve if your system is really small. If you wanted a future device where you needed these circulators jam-packed on the chip, you want to make it really small. This is not possible because these devices require a magnetic field, a large and bulky magnet, and large cables to be routing the signal. And these signals are generally electromagnetic signals.”

He adds that his team, in searching for new approaches to shrinking the topological circulators, realized that the secret is charge plus electron fluid plus Hall viscosity—it is the electron fluid and graphene that are charged. This presents a special (new) viscosity that is not related to friction. “Instead of causing energy to dissipate, friction means there’s some heating going on; there is some dissipation going on. This is special because there is no dissipation associated with [Hall viscosity].”

“What we have shown is that it is indeed possible to rethink how these devices work, and approach this technology in a different way,” Jacob says, “and actually make it 10X or 100X smaller than what exists today.”

Graphene, called the miracle material, has taken its place among the global rush industry. Today, there has been a great enhancement in graphene rush globally.

To begin exploring the applications and uses of graphene, it's important to understand [what is graphene](#). Graphene is a material composed of pure carbon, similar to graphite but with unique characteristics that make it extraordinarily light and strong. It's a single layer of carbon atoms arranged in a hexagonal lattice pattern, which gives it remarkable properties that have captured the attention of scientists and industry professionals alike. A sheet of one square meter of graphene weighs 0.77 milligrams. Its strength is 200 times greater than that of steel and its density is similar to that of carbon fiber. All these make it resist high bending forces without breaking. It is one of the most conductive materials for electricity and heat, which makes it the perfect material for electronics and many other industries. For many experts, **graphene is the material of the future**. Its scientific definition and possible application areas can be considered somewhat complex, but the truth is that the properties of this material open a new horizon in the world of technology.

[Nanografi presents top-quality graphene solutions](#) and research area for enhanced projects, productions, and technology. In this blog, you can profoundly explore the present and the potential uses and applications of graphene.

Introduction

Its applications are virtually unlimited and promise to revolutionize many fields: from electronics and computing to construction or even health. You can find nearly **all applications and uses of graphene in this list** – some already commercialized, some need years to materialize.

Guide to 60 Uses and Applications of Graphene

- **Graphene's Applications in Energy Industry:** Items 1-6
- **Graphene's Applications in Medicine:** Items 7-22
- **Graphene's Applications in Electronics:** Items 23-34
- **Graphene's Applications in Food Industry:** Items 35-39
- **Graphene's Applications in Sports:** Items 40-45
- **Other Applications of Graphene:** Items 46-60

Uses and Applications of Graphene

Graphene has a wide range of potential applications and uses due to its exceptional mechanical, electrical, and thermal properties. It is used in electronics, energy storage, sensors, coatings, composites, biomedical devices and many other. Its high surface area and biocompatibility make it an attractive material for drug delivery and tissue engineering applications. Graphene's unique properties make it a promising material for many future technologies.

In this below, **discover the cutting-edge world of graphene** and its limitless possibilities, **from current uses to future innovations**.

Graphene Uses and Applications in Energy Industry

1. Graphene in Solar Cells

The idea of developing lighter, flexible and transparent solar cells has been around for a while but finding the material which has all the properties and able to carry the current was the issue. Indium Tin Oxide has been used because it was transparent, however it was not flexible therefore the cell had to remain stiff.

In 2017, researchers from MIT have managed to apply and **use graphene succesfully on a solar cell**. When they compared the graphene solar cell with others made of Aluminum and Indium Tin Oxide, they saw that it was as good as the ITO cell, and a little worse than Al one in terms of current densities and power conversion efficiencies. However, it is expected for a transparent cell to perform lower than Aluminum-based, which is nontransparent.

Although electrical properties were not a breakthrough, a solar cell that can be installed on any kind of surface (cars, clothes, paper, and cell phones, etc.) which is flexible and transparent was developed. Moreover, other scientists are trying to find out if graphene solar cells can generate energy from raindrops, which theoretically looks possible.

2. Graphene Batteries

Graphene enhanced Li-ion batteries show incredible characteristics such as longer lifespan, higher capacity, and faster charging time as well as flexibility and lightness, so that it could be used in wearable electronics.

3. Graphene in Nuclear Power Plants

Heavy water used in nuclear power plants to cool the reactors is both costly to produce and causes a million tons of CO₂ emissions during production. Researchers from University of Manchester have discovered that there is a **greener and low-cost method to produce heavy water: graphene membranes**. Team leader Dr. Lozada-Hidalgo believes that this innovation is extremely important and its introduction to the nuclear industry will be soon even though this industry is usually skeptical about new technologies.

4. Graphene in Thermoelectric

Seebeck effect is defined as a thermoelectric effect occurring when heat is applied to one of the two dissimilar electric conductors (or semiconductors) to move the electrons from the hot part to the cooler part and produce electricity. However, the energy generated by this method is really small, usually quantified by microvolts. Still, it is believed that it can be used to benefit from the heat generated by the engines, which is practically wasted. Graphene can be used to increase the Seebeck effect created by Strontium Titanate, almost up to 5 times.

5. Graphene in Alcohol Distillation

Graphene's physical properties is so interesting and unique that, it would let large water molecules to pass through but stop Helium molecules which could leak through glass. Andre Geim (one of the inventors of Graphene) and Rahul Nair from Manchester University have tried sealing a bottle of vodka with graphene membrane that they have developed, and discovered that graphene could distill ethanol effectively even at room temperature and without the vacuum needed for distillation methods. This area of utilization can be employed in alcoholic beverages, fuel, water purification and so on.

6. Graphene in Fuel Cells

Even hydrogen atoms, known as the smallest atom, cannot pass through Graphene. In another research, Sir Andre Geim and his team have tested if protons would be blocked by graphene or not. Suprisingly, protons could pass through graphene. This property would improve fuel cells performance by lowering the fuel crossover which is a major problem with fuel cells that decreases durability and efficiency.

Graphene Uses and Applications in Medicine

7. Graphene in Drug Delivery

Functionalized graphene can be used to carry chemotherapy drugs to tumors for cancer patients. Graphene based carriers targeted cancer cells better and reduced and decreased toxicity of the effected healthy cells. Drug delivery is not limited to cancer treatment, anti-inflammatory drugs have also been carried by graphene & chitosan combinations and yielded promising results.

8. Graphene in Cancer Treatment

Graphene can also detect cancer cells in the early stages of the disease. Moreover, it can stop them from growing any further in many types of cancer by intervening the correct formation of the tumor or causing autophagy which leads to the death of cancer cells.

9. Graphene in Gene Delivery

Gene delivery is a method used to cure some genetic diseases by bringing foreign DNA into cells. Graphene Oxide modified by Polyethyleneimine can be used for these purposes is expected to show low cytotoxicity, as it did in the drug delivery case.

10. Graphene in Photothermal Therapy

Photothermal therapy (PTT) is a approach used to eliminate abnormal cells in the targeted area of the body by irradiating a special agent which creates heat capable of destructing those cells. Graphene oxide increases effectiveness of PTT by a number of ways. First, it can be used to carry chemotherapeutic drugs to the tumor cells while they are being exposed to PTT simultaneously. Combining chemo and PTT like this is more effective than using one of these approaches alone. A nanocomposite of reduced graphene oxide (QD-CRGO) can be used during PTT for bioimaging of the cancer cells. Moreover, in their research, a group of scientists from Texas Tech and Texas A&M University have shown that using graphene oxide functionalized with biocompatible porphyrin as a platform for PTT for brain cancer have killed more cancer cells than PTT alone, while giving no harm to the healthy cells.

11. Graphene in Diabetes Monitoring

Scientists from the University of Bath have developed a blood glucose monitoring test which does not pierce the skin, unlike currently used finger prick tests. This patch, including a graphene sensor, is able to work on a small area containing at least one hair follicle. It detects the glucose by pulling it from the fluid present between the cells. This does not only end the painful methods of blood sugar monitoring, but is also expected to increase the accuracy of the results.

12. Graphene in Dialysis

Graphene membranes are not only useful for the energy, nuclear and food industries. A group of researchers from MIT showed that graphene can be used to filter the blood from wastes, drugs and chemicals as well. Graphene's superiority in this case is that it is 20 times thinner than traditional membranes which leads to significant decrease in the time spent in the dialysis for the patients.

13. Graphene in Bone and Teeth Implantation

Hydroxyapatite, a form of calcium apatite, is a material used as a synthetic bone substitute for regenerated bone and dental tissues. **Graphene, combined with Hydroxyapatite** and Chitosan, have shown increase in the strength, corrosion resistance, flexibility and mechanical & osteogenic properties of the substitute when compared to HAp alone.

14. Graphene in Tissue Engineering and Cell Therapy

Bones are not the only tissue graphene can cure. Certain forms of graphene were shown to be compatible with human osteoblasts and human mesenchymal cells, showing similar properties with the cells' physiological microenvironment. Cells grown with this method demonstrated better growth, proliferation, and differentiation while being ineffective on the cells' viability. Stem cells are especially important in tissue reengineering to improve the lives of people with neuronal disorders or neurodegenerative diseases.

15. Graphene UV Sensors

UV sensors are used for detecting dangerous levels of ultra-violet radiation which can lead to skin problems or even cancer. However, it is not the only use of UV sensors, they are used in the military, optical communication, and environmental monitoring as well. On its own, graphene may not present a high photoresponsivity but when it is combined with other materials, they create flexible, transparent, environmentally-friendly and low-cost UV sensors which will lead to technologies such as wearable electronics in the close future.

16. Graphene for the Brain

Mysteries about the brain haven't been revealed completely yet. A graphene-based technology may allow scientists to uncover many of the unknowns by recording brains electrical activity. This new device is able to hear the frequencies below older technologies' limits, and it doesn't interfere with the functioning of the brain. Besides research on how the brain works, the technology can help the scientists to understand the reasons behind epilepsy seizures and develop treatments for the patients. Moreover, discovering more about the brain could lead to developing new Brain-Computer interfaces which are used in many areas including control of prosthetic limbs.

17. Graphene in HIV Diagnosis

Despite all the improvements, there are many drawbacks on current HIV diagnosis methods. They can either detect the antibodies in the body nearly a month later the patient was infected, or they can detect the virus itself however these methods take some time to process themselves and more expensive when compared to the antibody method. A biosensor made of silicon or **graphene, containing Gold Nanoparticles** was developed by Spanish National Research Council, which targets p24, an antigen found on HIV. **The new method can detect the virus only a week** after being infected and at levels 100,000 times lower than what the current tests can notice. Moreover, results of the test are ready within 5 hours of being tested.

18. Graphene Biosensors

One of the advantages of graphene is its ability to detect minimal amounts of substances. Even a single molecule in a large volume can be detected with it. Biosensors made of graphene, graphene oxide or reduced graphene oxide show ultrasensitive properties when

detecting DNA, ATP, dopamine, oligonucleotides, thrombin, and different atoms. There are several medical companies that already sell medical sensors made with graphene.

19. Graphene Bactericide

Graphene is a magnificent bactericidal material as it avoids the generation of microorganisms, such as bacteria, viruses, and fungi, by damaging their cell membranes between its outer layers. When compared to different derivatives of Graphene, Graphene Oxide and reduced Graphene Oxide shows the best antibacterial effects. GO can also be used as a compound with silver nanoparticles to increase antibacterial properties even further.

20. Graphene in Birth Control

Graphene has all the properties that is desired in a condom: it is flexible, extra strong and extremely thin. Researchers from Manchester University have worked on developing a “supercondom” made of graphene and latex combined. The research has received many funding, including one from Bill and Melinda Gates Foundation.

21. Graphene in Deaf-Mute Communication

A group of Chinese scientists have developed a wearable, bio-integrated device that can translate sign language into text and spoken language. The device uses graphene’s incredible conductivity and flexibility properties.

22. Graphene in Body Scans

Unlike X-rays, T-waves which can be used for body scanning are harmless to human body. However, there is a catch. T-waves, or THZ radiation, is hard to both detect and generate. The good news is, with the help of some modifications and other materials, CVD graphene can detect THZ radiation successfully. This will not only lead to safer body scans, but also incredibly faster internet in the future.

Graphene Uses and Applications in Electronics

23. Graphene in Generating Light

Researchers at MIT have discovered that when light hits the surface of graphene, it’s slowed down and the photons started moving in a speed very close to the speed of electrons which increases when moving on graphene. This coincidence makes it possible to break the light barrier for electrons and creates light. The advantage of this method over the conventional ways of generating light such as fluorescent or LEDs is that it’s expected to be more efficient, faster, compact and controllable, and it looks like generating light from graphene

will be a key milestone in developing even smaller, faster and more efficient computer chips.

24. Graphene Transistors

The new supertransistors, which replace silicon with graphene, can increase the speed of computers up to one thousand times when compared to current technology. Increasing speed of computers is a crucial step for many technologies to be able to improve, including but not limited to blockchain, simulations of the outer space, robots, and stock markets.

25. Graphene in Waterproof Electronics

One of the main problems of electronic devices which people are afraid of is being dropped to water. Instead of covering the device with tight-fitted screws, graphene proposes a great solution for this problem. Engineers from Iowa State University print the circuits of the device with graphene flakes because graphene is transparent, strong and conducts electricity. Graphene flakes are arranged in a specific order and non-conductive binders are used to combine them which improved the conductivity. As in the most application areas, graphene again puts a great solution to this problem.

26. Graphene in Wearable Electronics

Researchers are looking for new ways to power wearable devices. One of the outstanding ways is flexible batteries printed on a fabric with graphene. This enables people to wear their batteries and power their smartphones or other devices, literally. If this can be achieved, it will be an environmentally friendly and smart e-textile that can store energy. Carrying heavy power-banks or chargers will be history by the invention of this amazing idea.

27. Graphene for Touchscreens

Indium tin oxide (ITO) is the commercial product used as transparent conductor of the smartphones, tablets, and computers. Researchers from the Rice University have developed a graphene-based thin film to be used in touchscreens. It is found that graphene-based thin film beats ITO and any other materials in terms of performance because it has lower resistance and higher transparency. Thus, Graphene is the new candidate material for the replacement of ITO.

28. Graphene in Flexible Screens

The world of technology would be one of the great beneficiaries of the standardization of graphene as a material to incorporate in products such as smartphones or tablets. It would be the definitive step to advance in the world of smartphones.

Recently, a Chinese company has produced a bendable smartphone with a graphene touch screen. Since one layer of graphene is strong, light, transparent and very conductive, it

meets all the requirements for the production of smartphones. The smartphone of the Chinese company has the ability to wrap a twist completely, and it weighs only 200 grams which propose a perfect convenience for usage. However, production of graphene is expensive at an industrial scale relative to other materials used in smartphones. Researchers are looking for ways to produce graphene at lower costs. When this problem and some others are solved, old phones seem to be replaced by these flexible smartphones in the future. **Nanografi's Europe Horizon 2020 winner project: Green Graphene**, producing **top-tier Graphene** with environmentally friendly methods and lowest costs.

29. Graphene in Hard Drives and Memories

Usually, graphene is not considered magnetic, at least not in a controllable or useful way. In 2015, researchers from U.S. Naval Research Laboratory have found a way to turn graphene into a reliable and controllable electromagnetic material. If this innovation is used in hard drives, it is expected to have a capacity almost a million times greater than what we use today.

30. Graphene in Elastic Robots

A team of researchers has developed a gel that is sensitive to near infrared light so that it could be used in numerous applications when creating flexible or elastic robotic parts. The snake-like robots created with this method are able to change its form without any forces from the outside. Their future applications can vary from search-and-rescue to medical operations.

31. Graphene as a Superconductor

Scientists have discovered that graphene can also be used as a superconductive material. Two layers of Graphene can conduct the electron without any resistance. This can be accomplished by twisting these two layers of graphene at a 'magic angle' which is 1.1° . Most of the superconductive materials show their properties at temperatures close to absolute zero. Even High temperature superconductive materials relative to usual ones can work at around -140°C . In other words, these superconductive materials require a huge energy for cooling. If graphene can be used as a superconductive material at temperatures close to room temperature, there will be a huge revolution for many application areas.

32. Graphene in Optoelectronics

Researchers are working on a new material for the optical communications since energy and power requirement increase as the time passes. A research conducted by the collaboration of different universities has shown that integrating graphene with silicon can beat current silicon photonic technology. How can it beat the current state of art? Because devices made by graphene are cheaper, simpler and work at high-scale wavelengths.

Apparently, graphene will present a low-energy optical telecommunication and many other convenient optical systems.

33. Graphene in Optical Sensors

Graphene has a lot of breakthroughs in industry and science owing to its super properties. Researchers tried to shrink the light to make optical sensors smaller. Recently, the Institute of Photonic Sciences(ICFO) in Barcelona, with the collaboration of Graphene Flagship team, conducted a study which explains the reduction of light down to just a single atom thick which is thought to be impossible by many researchers. This discovery will lead to a huge step in ultra-small optical sensors and switches.

34. Graphene Security Sensors

One of the first practical and real applications of graphene was security labels. Instead of the bulky sensors that many stores use, the sensors made with graphene are smaller, more aesthetic, able to bend without creating a damage on the circuit, and cost only a couple cents per tag.

Graphene Uses and Applications in Food Industry

35. Graphene in Food Packaging

Graphene can also be used as a coating material because it prevents the transfer of water and oxygen. Graphene membranes can be used in food or pharmaceutical packaging by keeping food and medicines fresh for longer time. It may seem a simple application, but it can dramatically reduce the amount of food waste people throw away every day.

36. Graphene in Water Purification

Normally, water purification is not a simple process and feasibility of the process depends on how heavily the water is contaminated. An Australian scientist has found [**a low-cost technique to purify water at one step**](#). Soybean-based graphene, which is also called 'GrapHair', is used as a filter. This filter can make the dirtiest water drinkable. it is more efficient, cheaper and environmentally friendly compared to other methods.

37. Graphene in Desalination

Approximately, 97.5% of the total water present on the planet is salty. It does not matter how many wells we excavate, only 2.5% of the total is fresh water. The filters based on meshes that use graphene have yielded amazing results. The University of Manchester

employed graphene to make filtering sieve that has higher density and permit the water particles to pass but prevents the salts.

38. Graphene in Crop Protection

Graphene is a great material for sensors. Micro-sized sensors can be produced thanks to graphene's unique structure. It can detect whether a molecule is dangerous or not for the environment. These **sensors can be used in food industry, especially in crop protection**. Farmers can track and detect dangerous and harmful gasses to crop and they can determine the ideal areas for the growth of the crop depending on the atmospheric conditions, and even the moisture level and "thirst" of the plants with the help of graphene sensors.

39. Graphene for Food Security

Studies done by US Rice University have shown that laser-induced graphene can be applied to various substances such as wood, bread, coconut, etc. It may seem like a substance with a pattern on it printed with ink, but it is not. The laser carburizes the material and carburized material is converted into graphene. Any pattern that is desired can be achieved by this technique. Issues that are related to food security can be overcome by this technique.

Graphene Uses and Applications in Sports

40. Graphene in Shoes

Graphene sneakers? Yes, although in this case it is not used purely, other composite materials take advantage of it. In fact, it is claimed that a sole made of pure graphene could last hundreds of years. University of Manchester and sports brand Inov-8 developed a shoe using graphene which increases the outsoles' strength and flexibility properties by 50%. These shoes are more durable and absorb the impacts which could damage the bones and joints.

41. Graphene in Helmets

An ideal helmet would be strong, resistant to impact, durable, comfortable, and light. Graphene is incredibly strong, light, and flexible. It's even used in bulletproof vests, so it can definitely resist impacts. With these properties, graphene is commercially used in motorbike helmets.

42. Graphene in Tires

Graphene is also used to make smarter tires and sports bike components. Adding graphene to bike's tires apparently increases the puncture resistance and velocity, decreases rolling resistance and makes them way lighter, stronger, faster, and more resilient.

43. Graphene Clothes

The use of graphene fibers in fabrics offers antibacterial, and anti-static clothes which can preserve the heat and block UV. These fabrics can be used to create outdoor sportswear, pajamas for children that repel soil bacteria, or even household furniture to prevent the development of bacteria on its surface.

44. Graphene Rackets

Graphene can improve the energy distribution and weight of the racket while increasing the service speed and stability. Tennis equipment manufacturer Head have already developed a series of commercially available racket enhanced with graphene, named "Graphene 360" which is already used by tennis stars like Novak Djokovic and Sascha Zverev.

45. Graphene Electronic Tattoos and Fitness Tracking

Graphene Electronic Tattoo (GET) is developed by scientists at the University of Texas. First, they are more resistant to moisture, have a greater elasticity - with the ability to grow or shrink up to 40%, have a total thickness of 463 ± 30 nm, and have optical transparency of approximately 85%. They are like a second skin. These tattoos can be used to track heart rate, temperature, hydration levels, oxygen saturation and even the level of exposure to UV. Their application areas can vary from fitness tracking to medicine.

Other Uses and Applications of Graphene

46. Graphene and Silk

Researchers in China have conducted a research to enhance the properties of silk which has already great characteristics. Silkworms eat white mulberry leaves. Researchers sprayed a solution having 0.2 percent graphene on the leaves and let the silkworms eat that leaves. Findings were promising because commercial silkworms fed by graphene sprayed leaves give ten times more than what a usual silkworm can. While it is uncertain how much of the graphene is digested by silkworms, this study will have a positive effect on smart clothing which is a hot topic of the recent years.

47. Graphene in Cement

Potential application areas of graphene expand as the time passes. One of the important potential usages of graphene is construction industry because graphene is strong and light at the same time which is perfect for construction. It can be used instead of steel, but

strength and weight are not the only parameters. Graphene's the main problem is that crack propagates very fast in graphene which can cause catastrophic failures. Researchers are trying to find ways for using graphene in construction. A group of researchers from University of Exeter used graphene in cement as a reinforcement material and tested. As a result, 2.5 times stronger and 4 times less water permeable concrete was obtained which proves that **graphene can be a great reinforcement material in construction**.

48. Graphene in Insulation

Graphene can be used as a superconductor or insulator material when two sheets of graphene are arranged at a magic angle. Most of the metal parts of the cars, ships or planes suffer from rusting. When graphene is combined with paint, it can be a great insulation material for creating rust-free surfaces. Another application can be coating of bricks and stones. In this way, water-proof houses can be constructed.

49. Graphene in Speakers and Headphones

A speaker converts electricity into sound by vibrating a membrane in the air. Graphene is used to make lightweight and great rigidity membranes. Moreover, headphones use a small diaphragm reinforced with graphene. GrapheneQ, a headphone developed by the company ORA Sound is lighter and smaller, and at the same time it can reach louder and higher quality sounds with less energy.

50. Graphene in Photography

Due to its exceptional properties and high sensitivity to ultraviolet, visible and infrared lights, graphene seems to be one of the ideal materials to push digital photography and any discipline where optical modulators and photoreceptors are involved. Cameras' sensors enhanced with graphene and quantum dot can be smaller and lighter while achieving greater resolution levels than any small sensor could up until now.

51. Graphene in Automotive

The extraordinary strength and hardness of graphene, coupled with its flexibility, is perfect to start creating cars that are immune to shocks. Moreover, accident-proof vehicles could also be created. This would result in a direct decline in road mortality. Graphene cars, which we may see in the showrooms within a decade, are also expected to be cheaper and lighter.

52. Graphene in Airplanes

Scientists from UK have designed an airplane that includes **graphene in the carbon-fiber coating of the aircraft's wings**. The model plane, Prospero, was lighter since it was enough to cover the wings with only one layer of the improved composite. It consumes less fuel, resists impact better, and has lower environmental costs as well.

53. Graphene Paints

Every painter knows it very well: humidity is the number one enemy of painting. Graphenstone is a company that makes graphene painting solutions. The result? The light bounces better, protects barrels and basements, absorbs 120 grams of CO₂ per square meter and is able to withstand the corrosion derived from contact with metals.

54. Graphene in Ballistics

Kevlar is used in the manufacturing of bulletproof vests, helmets and protective clothing and even weapons. But graphene has much greater malleability and is medically safer in case of accident and contact with the bloodstream. Moreover, Kevlar and graphene composites are lighter to wear, and increases heat absorption for the protection of the fibers, when compared to Kevlar on its own.

55. Graphene in Military Protective Equipment

One of the future uses that have been raised for graphene is destined for the arms industry. In particular, its usefulness would be aimed at shielding and protection. It could be used in making helmets, bulletproof vests, and many more accessories. It could, in fact, **graphene will be a determining material for the future of police forces and armies.**

56. Graphene in Thermal and Infrared Vision

A great advance that we could see is the development of graphene lenses that allows thermal and infrared vision. The graphene allows manufacturing such ultrathin devices with a built-in camera that gives the user an infrared and thermal vision. Something that until now we have only seen in science fiction movies.

57. Graphene in Machinery Lubricants

Industrial machines mostly suffer from friction because friction affects the durability, strength, efficiency and working life of the machines negatively. To minimize these effects, solid or liquid lubricants are used. Recently, graphene, which has countless potential application areas, has started to shine out on this subject. Why graphene? Because it offers perfect friction and wear properties compared to conventional materials. It can also serve as solid or liquid lubricant. In addition, having a great chemical inertness, smooth and densely packed surface makes graphene a great lubricant material.

58. Graphene in Corrosion Protection for Glass

One of the application areas of graphene is that it can be used as a coating material for glass. Although glass is a high resistant material to corrosion, it can corrode under some conditions such as high humidity or extreme pH values. Also, durability of the glass can be vital in some areas such as pharmaceutical or optical industries. It prevents any type of

failure such as corrosion, oxidation, electromagnetic radiation. Graphene with high transparency and high chemical inertness can be a promising material for the protection of glass.

59. Graphene in Radiation Shielding

Scientists have been trying to keep the radiation at minimum since it is very dangerous for human health. For this purpose, a variety of materials can be used as a shielding material to radiation but there are many parameters that affects the efficiency of shielding. **Graphene is known as a weak radiation absorber**, but scientists have found that it can be a great shielding material when it is used in multi-layered form which are graphene slabs. Graphene is an outstanding material for this purpose thanks to its low manufacturing cost, light weight and high efficiency compared to any other shielding materials.

60. Graphene for Anti-corrosion Oil and Gas Pipes

Underwater pipes used to carry oil or gas is subject to corrosion over time, as CO₂ and water is able to get through the outer layers sometimes. Repairing them is costly, and if they break due to the corrosion, they would release the content which may be toxic to aquatic life. Researchers from the University of Manchester and the technology firm TWI have developed a coating with graphene nanoplatelets and tested it under the temperature and pressure conditions the pipes would face under the sea. The result was that, CO₂ permeability was decreased by 90%, and lowered the permeability of other corroding agents as well.

Could not find an application of graphene that you know of? Or saw one which is outdated and no longer valid? Graphene is an emerging material with magnificent properties and tens of research about it is started or resulted every day, so we may have missed one.

Conclusion

In conclusion, graphene is an extraordinary material that has sparked a global rush in industry. It's composed of pure carbon and possesses remarkable properties, including its strength, lightweight, and conductivity. Graphene has endless potential applications in electronics, energy storage, sensors, coatings, composites, and biomedical devices. Its high surface area and biocompatibility make it an attractive material for drug delivery and tissue engineering applications. **Nanografi offers high-quality graphene and nanotechnology solutions** to enhance a range of projects, productions, and technologies. Overall, graphene's unique properties offer an exciting new frontier in technology and have the potential to revolutionize many industries in the future.

A reminder: Graphene is called the “wonder material” for a reason. There are tons of research about it which are not published yet, but may change the world tomorrow. On the other hand, some of the potential applications we list here may be disproven in the future

either. For this reason, we cannot claim that this list includes all applications of graphene, but unquestionably, it is one of the most inclusive lists of the applications of graphene you can find online.

Breakthrough in fine-tuning electron behavior can unlock best quantum materials

Breakthrough in fine-tuning electron behavior can unlock best quantum materials

Researchers at Loughborough University have developed a method that allows scientists to optimize electron behavior to create advanced quantum materials.

The way electrons act directly influences the quality and capabilities of quantum materials.

This is because factors such as electron motion, spin, and energy levels determine properties like thermal conductivity, electrical efficiency, charge transfer, quantum coherence, and the performance of data storage and processing in quantum computing applications.

However, fine-tuning [electron](#) behavior has been a challenge. For instance, for years, scientists have been aware that materials like strontium ruthenate (SrRuO_3) or bilayer [graphene can lead](#) to the development of superior quantum applications.

Still, they couldn't use these materials as there wasn't any practical approach to control the complex behavior of their electrons. In their new study, the Loughborough University team claims to have overcome this challenge.

The significance of High-order Van Hove singularities

According to the researchers, there are special points in a material's electronic structure where many energy levels of electrons bunch together unusually densely. These singularities are called High-order Van Hove singularities (HOVHS) and occur in the material's band structure, which describes [how electrons behave](#) and move.

Unlike regular Van Hove singularities, which happen when the energy levels are locally flat or have a simple shape, HOVHS involve more complex shapes, leading to an even higher concentration of electrons at specific energies.

This can amplify certain physical effects, such as [superconductivity](#) or magnetism, making HOVHS important in advanced material research.

"Scientists are keen to explore how HOVHs can be manipulated to fine-tune a material's properties. However, understanding of HOVHs remains limited, including determining where they occur in materials and the factors that drive their formation," the study authors [said](#).

Based on the Feynman-Hellmann theorem, the authors developed a method that allowed them to successfully detect and examine HOVHs using some theoretical and computational models.

The Feynman-Hellmann theorem is a concept in quantum mechanics that helps relate how the energy of a system changes when you slightly change a parameter of the system.

Using HOVHs to fine-tune quantum materials

The researchers used their method on strontium ruthenate (Sr_2RuO_4) and discovered the presence of HOVHs on its surface. Their study revealed that due to certain rotations in the material's structure, HOVHs are only limited to the Sr_2RuO_4 surface and absent elsewhere.

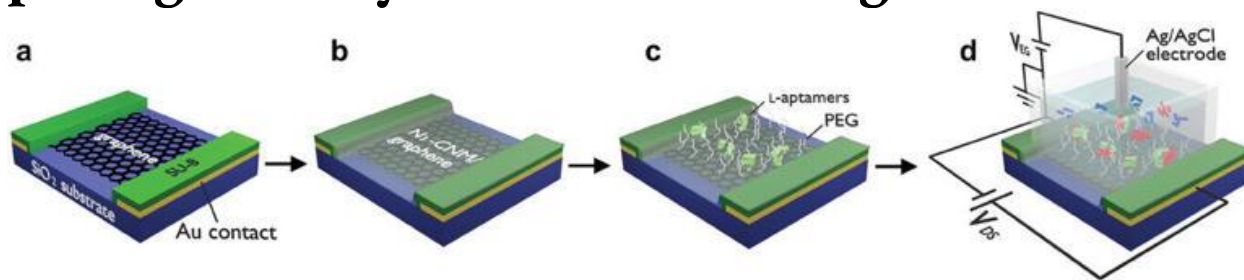
They suggest that using the information from their study, they can predict how modifying the surface structure of Sr_2RuO_4 can affect its [quantum properties](#). Moreover, these results may apply to other quantum materials as well.

“Thanks to our research, it is now possible to envision methods to create these types of singularities to alter the material’s electronic and magnetic properties,” [Joseph Betouras](#), one of the study authors and a professor at Loughborough University, said.

“This could, for example, enable the creation of superconductors—materials where electrons flow without resistance—at temperatures approaching room temperature,” he added.

The [study](#) is published in the journal *Nature Communications*

Chemists develop graphene-based biosensor, paving the way for advanced diagnostics



Schematic illustration of the fabrication steps of the I-AP/PEG-CNM GFET sensors. Credit: Advanced Materials (2024). DOI: 10.1002/adma.202407487

Two-dimensional materials such as graphene are not only ultrathin, but also extremely sensitive. Researchers have therefore been trying for years to develop highly sensitive biosensors that utilize their properties.

Graphene-based field-effect transistors, for example, could register the tiniest changes in the electronic properties caused by the molecules when they interact with this atomically thin layer. However, the hypersensitivity of the material has so far stood in the way of the practical realization of this idea.

Scientists at Friedrich Schiller University Jena, Germany have now developed a way to overcome this obstacle, potentially paving the way for a revolution in

diagnostics. They have [published](#) their findings in the research journal *Advanced Materials*.

Just like other biosensors, a graphene-based biosensor requires a functionalized surface on which only specific molecules can attach. If, for example, a specific biomarker is to be detected from a blood or saliva sample, a corresponding counterpart—a so-called capture molecule—must be applied to the sensor surface.

The problem: "If graphene is functionalized directly, its electronic structure changes unfavorably," explains Prof. Dr. Andrey Turchanin from the University of Jena. "Graphene is then no longer graphene—the specific electronic properties that you actually want to utilize are then no longer available." Parameters that make up the high sensitivity of such a biosensor—for example the mobility of the charge carriers—are too strongly influenced.

Functionalization thanks to a molecular intermediate layer

However, Turchanin and his team, together with partners from industry, research and medicine, have now developed a method to functionalize graphene without interference. "We have applied a molecular carbon membrane to the graphene, which is just as thin as graphene at one nanometer. This intermediate layer is dielectric, which means that it does not conduct electricity," explains Turchanin.

"Both components are connected to each other by so-called van der Waals forces and form a heterostructure that we were able to functionalize without affecting the electronic properties of the graphene."

This is because chemically active functional groups can be applied to the molecular intermediate layer without interference, to which any number of different capture molecules can be attached. When the desired counterparts attach, they transmit the electric field to the graphene, which changes the electrical signals in this material without affecting its properties.

Investigation of complex clinical samples

As capture molecules, the researchers equipped the chemically active functional group on the molecular intermediate layer with artificially produced aptamers that can bind specific molecules in a very targeted manner. They also functionalized the carbon nanomembrane with a protein-repellent layer of polyethylene glycol, a synthetic polymer that is often used in medicine. It prevents something from adsorbing on the surface that is not wanted. In this way, the biomarkers sought can be found in a complex biological sample.

With this experimental set-up, the experts in Jena succeeded in detecting chemokines—a certain group of proteins that play an important role in the human immune system and can therefore play a major role as biomarkers in the diagnosis of illnesses.

"Thanks to the cooperation with a medicine laboratory in the Netherlands, we used samples from nasal swabs of real patients for these experiments," says Andrey Turchanin. "What's more, the graphene sensors we developed can be used to find not just one biomarker, but hundreds," adds Dr. David Kaiser, the first author of the publication.

More sensitive, faster, cheaper

"This research result could be groundbreaking for the diagnostics of the future, because we have been able to remove a major hurdle on the way to a graphene-based biosensor that is far more effective than anything currently used in normal clinical application areas," says Kaiser. "It is much more sensitive, significantly faster—the results are available in around five minutes—and cost-effective if it is produced in large quantities."

The measuring principle is purely electrical—changes in the electrical current alone indicate whether the biomarkers being sought have been found. Accordingly, such a biosensor can be easily integrated into everyday clinical practice in conjunction with a handy point-of-care device. "It's probably even possible with our mobile phones," says Turchanin.

More information: David Kaiser et al, Ultrasensitive Detection of Chemokines in Clinical Samples with Graphene-Based Field-Effect Transistors, *Advanced Materials* (2024). DOI: [10.1002/adma.202407487](https://doi.org/10.1002/adma.202407487)

Provided by Friedrich Schiller University of Jena

Nanopatterned graphene enables infrared 'color' detection and imaging

UCF NanoScience Technology Center Professor Debashis Chanda sits near an infrared camera image of himself in his lab. Chanda and his research group of UCF students developed a new long wave infrared detection technique. (Photo courtesy of Debashis Chanda). Credit: Debashis Chanda

University of Central Florida (UCF) researcher Debashis Chanda, a professor at UCF's NanoScience Technology Center, has developed a new technique to detect long wave infrared (LWIR) photons of different wavelengths or "colors."

The research was recently [published](#) in *Nano Letters*.

The new detection and imaging technique will have applications in analyzing materials by their spectral properties, or spectroscopic imaging, as well as thermal imaging applications.

Humans perceive primary and secondary colors but not infrared light. Scientists hypothesize that animals like snakes or nocturnal species can detect various wavelengths in the infrared almost like how humans perceive colors.

Infrared, specifically LWIR, detection at room temperature has been a long-standing challenge due to the weak photon energy, Chanda says.

LWIR detectors can be broadly classified into either cooled or uncooled detectors, the researcher says.

Cooled detectors excel in high detectivity and fast response times but their reliance on cryogenic cooling significantly escalates their cost and restricts their practical applications.

In contrast, uncooled detectors, like microbolometers, can function at room temperature and come at a relatively lower cost but exhibit lower sensitivity and slower response times, Chanda says.

Both kinds of LWIR detectors lack the dynamic spectral tunability, and so they can't distinguish photon wavelengths of different "colors."

Chanda and his team of postdoctoral scholars sought to expand beyond the limitations of existing LWIR detectors, so they worked to demonstrate a highly sensitive, efficient and dynamically tunable method based on a nanopatterned graphene.

Tianyi Guo is the lead author of the research. Guo completed his doctoral degree at UCF in 2023 under Chanda's mentorship. This newly discovered method is the culmination of the research that Guo, Chanda and others in Chanda's lab have performed, Chanda says.

"No present cooled or uncooled detectors offer such dynamic spectral tunability and ultrafast response," Chanda says. "This demonstration underscores the potential of engineered monolayer graphene LWIR detectors operating at room temperature, offering high sensitivity as well as dynamic spectral tunability for spectroscopic imaging."

The detector relies on a temperature difference in materials (known as the Seebeck effect) within an asymmetrically patterned graphene film. Upon light illumination and interaction, the patterned half generates hot carriers with greatly enhanced absorption while the unpatterned half remains cool. The diffusion of the hot carriers creates a photo-thermoelectric voltage and is measured between the source and drain electrodes.

By patterning the graphene into a specialized array, the researchers achieved an enhanced absorption and can further electrostatically tune within the LWIR spectra range and provide better infrared detection. The detector significantly surpasses the capabilities of the conventional uncooled infrared detectors—also known as microbolometers.

"The proposed detection platform paves the path for a new generation of uncooled graphene-based LWIR photodetectors for wide ranging applications

such as consumer electronics, molecular sensing and space to name a few," Chanda says.

More information: Tianyi Guo et al, Spectrally Tunable Ultrafast Long Wave Infrared Detection at Room Temperature, *Nano Letters* (2024). DOI: [10.1021/acs.nanolett.4c03832](https://doi.org/10.1021/acs.nanolett.4c03832)

Provided by University of Central Florida

Nitrogen-Doped Graphene for High-Performance Ultracapacitors and the Importance of Nitrogen-Doped Sites at Basal Planes

- [Hyung Mo Jeong](#)[†]
- [Jung Woo Lee](#)[†]
- [Weon Ho Shin](#)[†]
- [Yoon Jeong Choi](#)[†]
- [Hyun Joon Shin](#)[‡]
- [Jeung Ku Kang](#)^{*†§}
- [Jang Wook Choi](#)^{*§}

Abstract

Although various carbon nanomaterials including activated carbon, carbon nanotubes, and graphene have been successfully demonstrated for high-performance ultracapacitors, their capacitances need to be improved further for wider and more challenging applications. Herein, using nitrogen-doped graphene produced by a simple plasma process, we developed ultracapacitors whose capacitances ($\sim 280 \text{ F/g}_{\text{electrode}}$) are about 4 times larger than those of pristine graphene based counterparts without sacrificing other essential and useful properties for ultracapacitor operations including excellent cycle life (>200000), high power capability, and compatibility with flexible substrates. While we were trying to understand the improved capacitance using scanning photoemission microscopy with a capability of probing local nitrogen-carbon bonding configurations within a single sheet of graphene, we observed interesting microscopic features of N-configurations: N-doped sites even at basal planes, distinctive distributions of N-configurations between edges and basal planes, and their distinctive evolutions with plasma duration. The local N-configuration mappings during

plasma treatment, alongside binding energy calculated by density functional theory, revealed that the origin of the improved capacitance is a certain N-configuration at basal planes.

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Investigation on mechanical and thermal behaviour of graphene bonded carbon/Kevlar hybrid fabric polymer composites

- [Venkateswara Babu Peddakondigalla,](#)
- [Vasavi Boggarapu,](#)
- [Rajani Doppalapudi,](#)
- [Phani Pooja N. &](#)
- [Aruna Y.](#)

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Abstract

The present research is aimed to understand the influence of graphene-reinforced carbon/Kevlar hybrid fabric epoxy composites. Samples HG0, HG2, HG4, and HG6 are fabricated using four layers of fabric mat and with varying graphene weight percentage as 0, 2, 4, and 6 wt.%, respectively. Mechanical characterizations such as hardness, tensile, and flexural strength were individually assessed. Thermal stability is evaluated through thermogravimetric analysis. Composite HG6 with high filler loading showed 71% and 114.4% greater tensile and flexural strength compared to unfilled HG0 specimen. Similarly, HG6 exhibited greater thermal stability. Inclusion of graphene particles in higher concentration improved the interfacial bonding between fibre/matrix/filler system. Fracture surfaces are analysed using scanning electron microscopy to understand the failure mechanisms.

Introduction

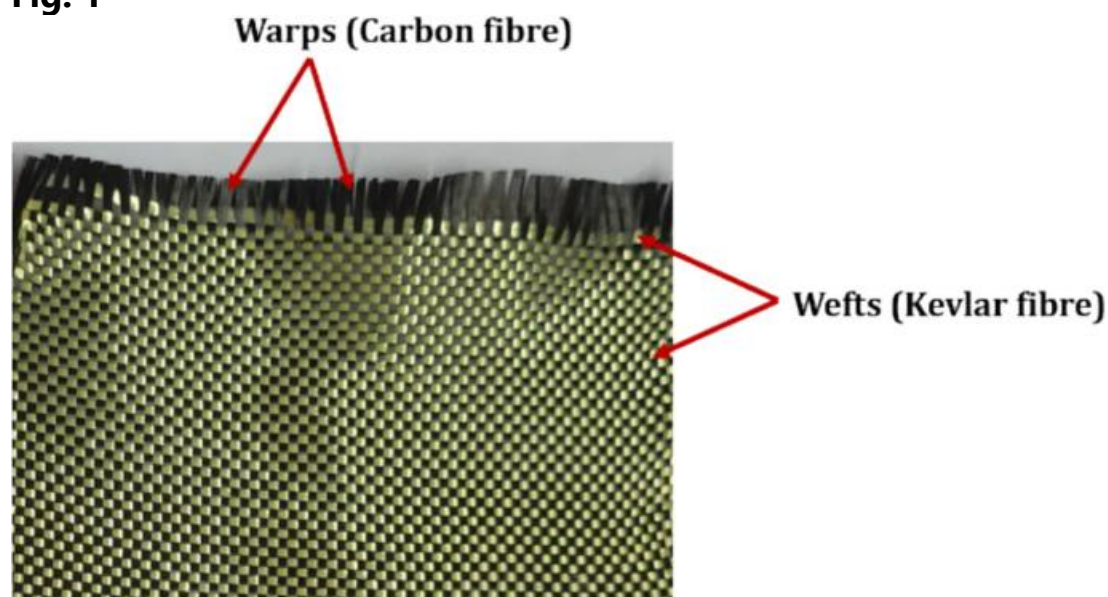
Polymer composites are extensively utilized for structural applications in automotive, chemical, and medical industries owing to their lighter weight components that are combined with superior thermal, mechanical, and chemical properties [1,2,3,4]. Polymer matrix particularly epoxy resin is commonly employed as structural adhesive by reinforcing with different types of fibres and fillers. Epoxy-based composites possess high specific strength, fabrication ease, chemical resistant, and less cost. These composites find their applications in aircraft engine blades, pipe lines for petroleum refining, high speed vehicles, and impeller blades [5,6,7]. Polymer composites strengthened with fibres often referred as fibre-reinforced composites (FRPs) exhibit excellent mechanical strength, but they are weakened owing to brittle nature of matrix material. To overcome such drawback, appropriate micro or nano filler is added to develop fibre/matrix/filler system [8,9,10]. Kevlar fibres exhibit high strain and neither melt or decompose at higher temperatures ($> 450\text{ }^{\circ}\text{C}$). Carbon fibres are popularly used for aerospace applications owing to good specific strength and stiffness [11, 12]. Hybridization of two fibres can enhance compressive strength, impact toughness, weight reduction, and strain capability of composite laminates. Although better properties were reported with hybridization, yet the further improvements are necessary to meet varied design conditions [13, 14]. Thus, filler particles are added to obtain beneficial effects to hybrid fibre composite configurations. In the current industrial scenario, carbon-based particles such as carbon nanotubes, carbon black, graphene, and graphite emerged as novel filler materials. Integration of graphene particles into the epoxy resins showed promising results by enhancing the properties of composite materials [15,16,17]. Graphene particles comprise two-dimensional carbon atoms in mono layers. Due to this, better dispersibility can be achieved with polymer matrices. Besides, they are able to improve mechanical and thermal properties, damping characteristics and corrosion resistance of composites [18,19,20]. A study presented by Alexopoulos et al. [21] proved that addition of graphene nano particles increased the tensile and fracture toughness of epoxy composites by 15% and 12%, respectively. Another study by Salom et al. [22] showed the enhanced storage modulus in graphene/epoxy composite materials at optimum filler loading. At higher concentration, the properties tend to decrease. Li et al. [23] stated in his literature review that incorporating graphene layers in polymer matrices improve their mechanical characteristics.

Cho et al. [24] added graphene particles to carbon fibre/epoxy composites and observed 16% and 18% increase in compressive and in plane shear strengths respectively. Moreover, graphene also enhanced tensile, flexural, and impact strengths of glass fibre/epoxy composites as reported by Aswathnarayan et al. [25]. The interfacial interaction between graphene and fibres improves the structural stability of epoxy composites. From the literature, it was observed that limited research was reported on graphene-based fibre-reinforced composites. On the other hand, hybridization of fibres was presented by researchers, but the studies pertaining to hybrid fabric was not explored so far. Thus, the novelty of present research lies in utilizing the hybrid fabric mat comprising carbon as warp and Kevlar as weft in epoxy matrix along with graphene particles. Such fibre/matrix/filler composite configuration is experimentally tested to understand the mechanical and thermal characteristics.

Materials and methods

Hybrid mat as shown in Fig. 1 comprises carbon as warp and Kevlar as weft 200 gsm taken as fibre material. Graphene having an average particle size of 15 μm with 99% purity is chosen as filler. Epoxy resin LY-556 is utilized as a polymeric matrix along with a curing agent HY-951. Properties of raw materials used in the fabrication process are given in Table 1.

Fig. 1



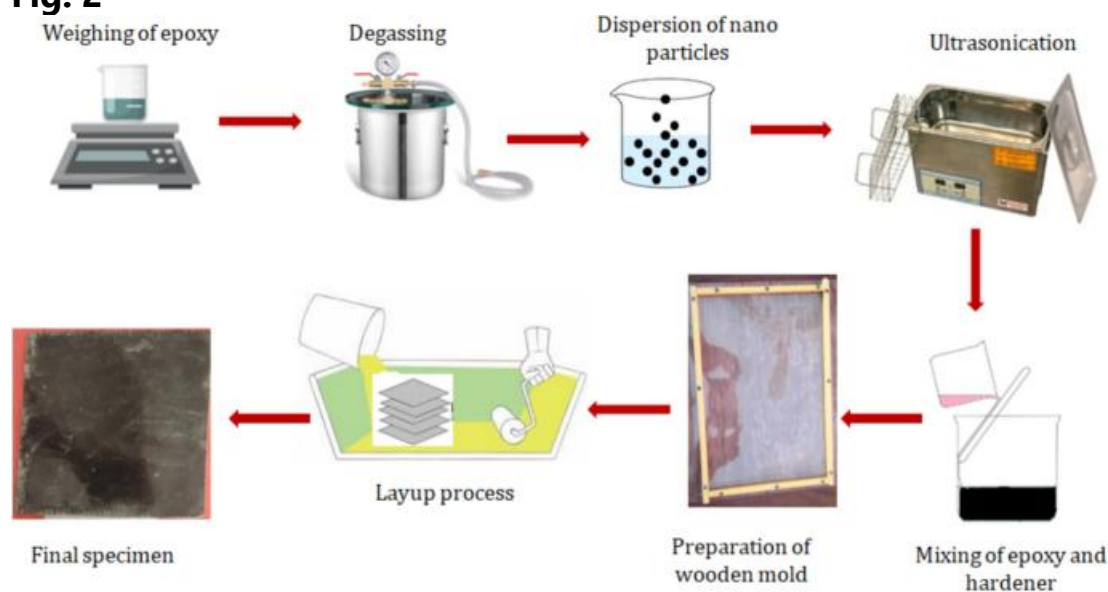
Carbon/Kevlar hybrid fabric mat

Table 1 Properties of raw materials

Fabrication of hybrid composites

Initially, the hybrid fabric mat was cleaned using acetone to remove any dust particles present on it. It was then dried at 60 °C in a vacuum oven for 3 h to remove the moisture completely. Degassing of epoxy resin was done to eliminate the air bubbles. Graphene taken in different weight percentages (0, 2, 4, and 6%) was added to epoxy in individual containers. To ensure uniform dispersion of graphene in epoxy, the containers were subjected to ultrasonic bath sonicator as supplied by Samarth Electronics by maintaining a temperature of 60 °C for 3-h duration. After sonication, the curing agent was added to the epoxy mixture in 10:1 ratio. The composites were fabricated in a wooden mould of volume $200 \times 200 \times 4 \text{ mm}^3$ through lay-up lamination process. Four layers of hybrid fabric mat were placed in a wooden mould, and then epoxy mixture was added to it. Samples were left out for curing at room temperature for 72 h. Composite fabrication is represented through Fig. 2. Composites were designated as HG0, HG2, HG4, and HG6 which corresponds to filler weight percentage.

Fig. 2



Schematic diagram for composites fabrication

Hardness

Hardness of composite specimens is evaluated on RS Scientific FMV1-MC-AT micro Vicker's hardness testing apparatus present at Vellore Institute of Technology, Andhra Pradesh. Samples were tested following ASTM E384-17 standard by applying a load of 1 kg for a dwell period of 15 s. For each composite, three readings were taken, and their mean value was noted. Hardness number in terms of HV is calculated using the formulae reported in the literature [26].

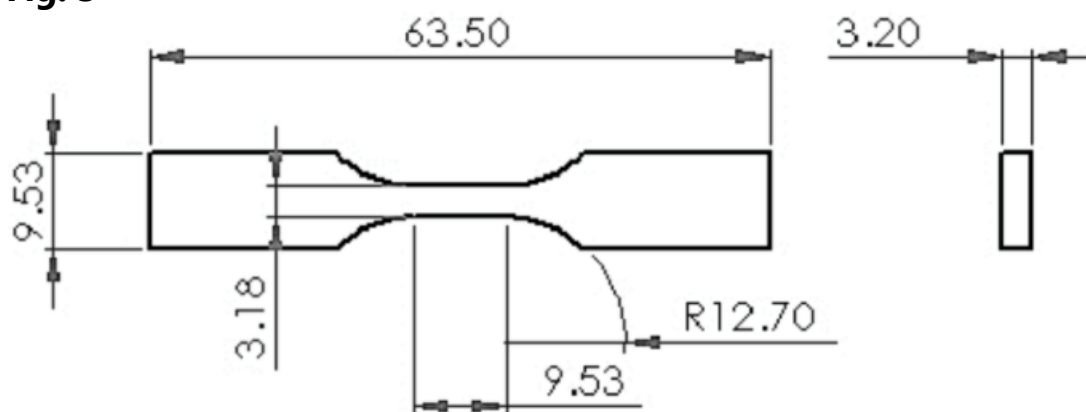
Thermogravimetric analysis

Thermogravimetric analysis (TGA) is performed on PerkinElmer thermal analyser available at Vellore Institute of Technology, Andhra Pradesh, to understand the thermal stability. Specimens were heated in the inert atmosphere from 30 °C to 700 °C maintaining a constant rate of 15 °C min⁻¹, and the corresponding weight loss (in %) was recorded.

Mechanical testing

Mechanical strength in terms of tensile and flexural was evaluated on Tinius Olsen H10KL UTM facility available at Vellore Institute of Technology, Andhra Pradesh, following the ASTM D638 and D790 standards respectively. For tensile testing, ASTM D638 type V sample having overall length of 63.5 mm and a width and gauge length of 9.53 as displayed in Fig. 3 was utilized. Crosshead strain rate of UTM is maintained constant at 1 mm/min⁻¹. Three identical specimens from each composite were tested, and their average value is adopted for result analysis. After testing, the surface of fractured samples was analysed under SEM to understand failure mechanisms.

Fig. 3



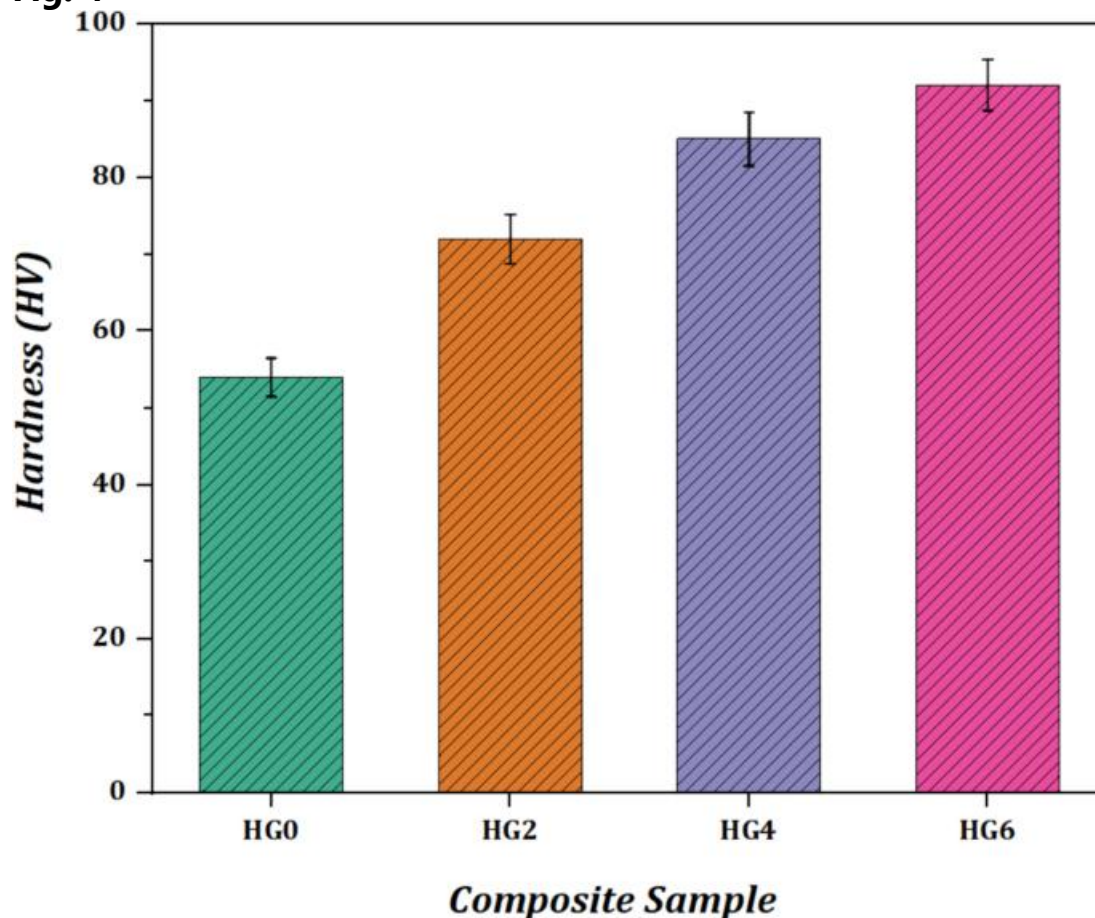
ASTM D638 standard figure for tensile testing

Results and discussion

Hardness

Vickers hardness (in HV) of all composite samples is shown in Fig. 4. Results depicted that specimen filled by 6% graphene, i.e. HG6, exhibited high hardness number of 92 HV compared to other composites due to better dispersion of filler particles and their bonding with the fibre and matrix. Nearly 27.7% increment in hardness was observed from HG2 to HG6. As the filler loading is increased, the interparticle distance in the matrix decreases which provide resistance to indentation [27]. Thus, the composite specimen HG6 with more filler particles displayed greater hardness. On the other hand, HG0 having 0% graphene exhibited least hardness of 54 HV due to weak bonding between fibre and epoxy. Hardness improved by 33.3%, 57.4%, and 70.3% for HG2, HG4, and HG6, respectively, as compared to HG0.

Fig. 4

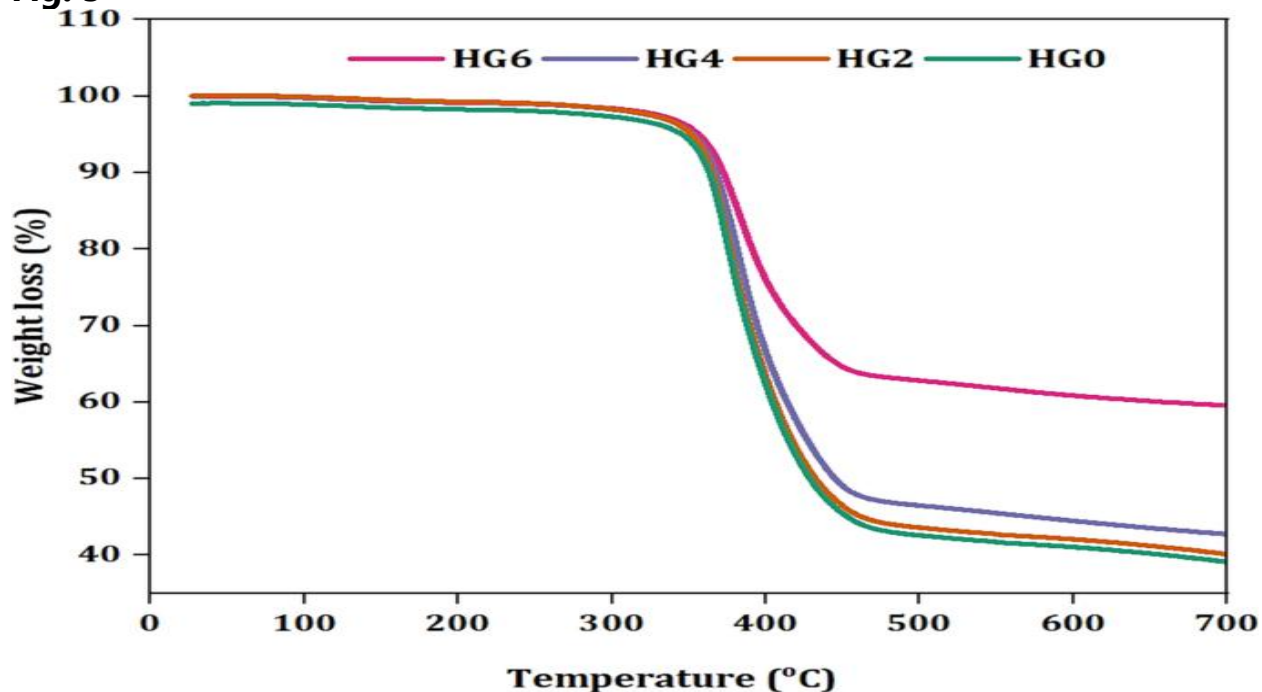


Vickers hardness of composite laminates

Thermogravimetric analysis

TGA analysis was performed in the nitrogen atmosphere, and the obtained results are represented in Fig. 5. From the curves, it was evident that early degradation of composites took place around 330–350 °C. During this temperature, the moisture and wax in the samples evaporate and resulted in maximum weight loss [28]. On further increase in temperature, the decomposition of polymer chains was initiated. The presence of graphene significantly affected the thermal stability of hybrid carbon/Kevlar epoxy composite laminates. Sample HG6 exhibited greater stability with 59.6% residue which indicates its more char formation, while HG0 possess least thermal stability and formed 39.1% of solid residue. Likewise, the char formation in the composites HG4 and HG2 was observed as 42.7% and 40.3%, respectively. Increasing sequence of thermal stability of all samples follow the order as HG6 > HG4 > HG2 > HG0. Greater stability of HG6 is mainly due to better thermal response and dispersibility of graphene particles in the epoxy. Moreover, the aromatic rings present in the Kevlar were highly cross linked with the epoxy which also effects the thermal stability [29].

Fig. 5

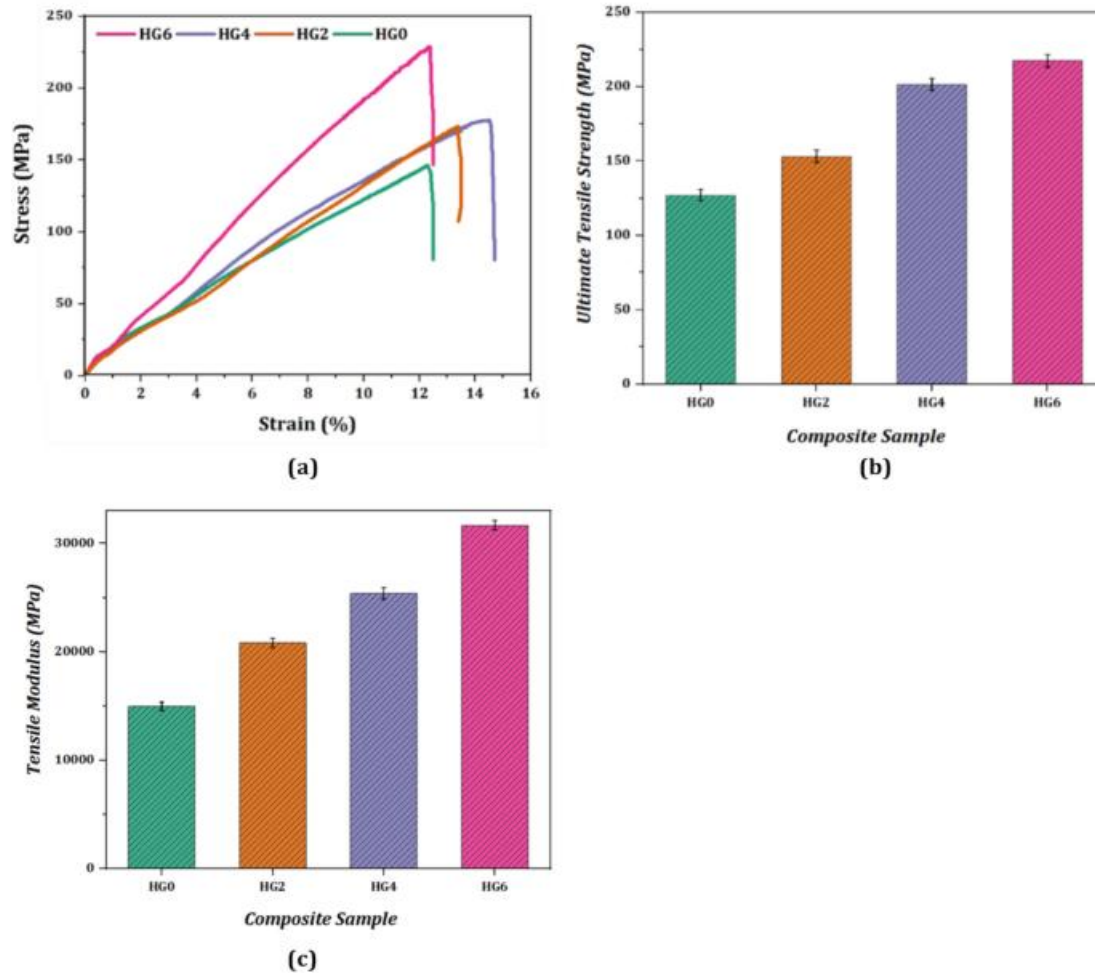


TGA curves of composite samples

Mechanical testing

Figure 6a–b represents the tensile stress–strain graph and ultimate tensile strength (in MPa) of composites. The specimens showed a linear variation indicating their nature as brittle. Addition of graphene particles further increased the brittleness and improved the tensile strength of hybrid carbon/Kevlar epoxy composites [30]. Highest strength of 217.2 MPa was shown by HG6, while the least strength of 126.9 MPa exhibited by HG0 among all composite configurations. Composites with graphene particles displayed superior strength due to their dispersibility and better load carrying capability. The tensile strength was improved by 41.8% as graphene content increased from 2 to 6%. Further, the increment of 20.62%, 58.6, and 71% was observed for HG2, HG4, and HG6 compared to HG0 composites. The increasing sequence of tensile strength of all specimens follows the order as $HG6 > HG4 > HG2 > HG0$. On the other hand, tensile modulus for the sample HG6 was also reported to be higher as evident from Fig. 6c.

Fig. 6

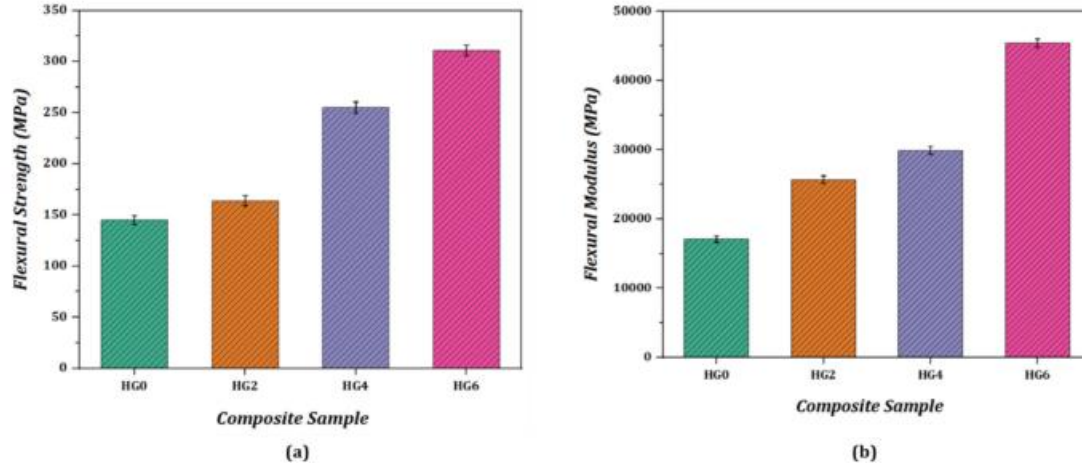


a Tensile stress–strain graph. **b** Ultimate tensile strength. **c** Tensile modulus of all samples

Flexural strength (in MPa) corresponding to all the composites is represented in Fig. 7a. Samples showed increased strength with an increase in graphene particles. Flexural strength improved by 114.4% as filler content increased from 0 to 6% as observed from HG0 to HG6. Almost 55.48% increment in strength is seen from HG2 to HG4, while the flexural strength was marginally increased to 21.9% from HG4 to HG6. Among all fabricated samples, the higher and lower flexural strengths were displayed by HG6 and HG0 which was reported as 145 MPa and 311 MPa, respectively. Furthermore, flexural modulus for the sample HG6 was found to be higher as can be displayed in Fig. 7b. All the mechanical results are provided with error bars which represent the standard deviation. From the results obtained, it can be concluded that the improved interfacial force between fibre and matrix can be attained by inclusion of graphene particles which results in superior mechanical strength

[31, 32]. In the present study, hybrid carbon/Kevlar fabric mat was utilized which can replace the individual mat usage and obtain significant improvement in mechanical properties of fibre-reinforced polymer composites.

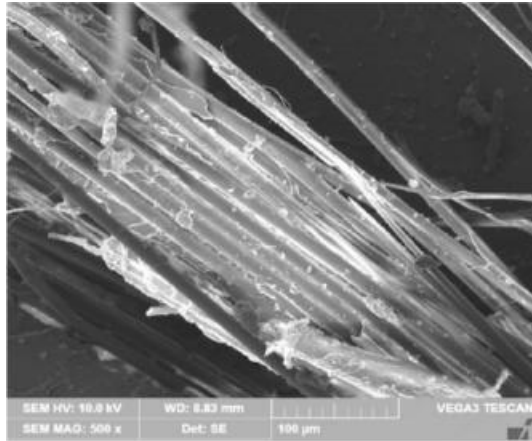
Fig. 7



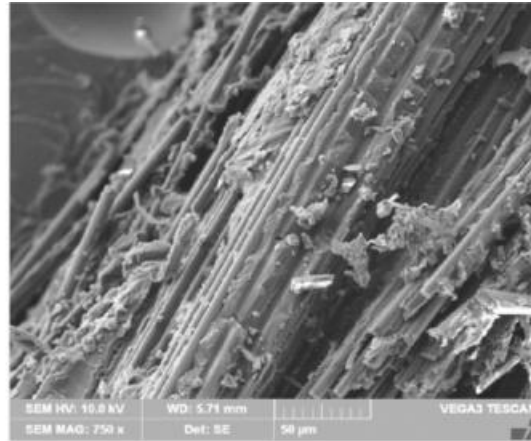
a Flexural strength. **b** Flexural modulus of composite samples

The SEM images shown in figure resemble the brittle fracture of all composite samples. As the filler loading increased from 2 to 6%, graphene particles formed as continuous networks on the fibre surface as assessed from Fig. 8a, b. Due to this, the sample HG6 showed improved interfacial bonding among fibre/matrix/filler which significantly affected its mechanical strength. Besides, the images also reveal the uniform dispersion of filler particles in the composites due to ultra-sonication process during fabrication. Thus, agglomeration was not detected in the images. Figure 8c, d represents the fracture images of HG2 and HG6 subjected to tensile loading respectively. Due to lower filler content, surface of sample HG2 failed by weak interface bonding and fibre pull-out [33]. Along fibre direction, the uneven breakage occurred, while the fibre cracking lowered in the case of HG6 compared to HG2 due to more graphene particles present in the composite (see Fig. 8d).

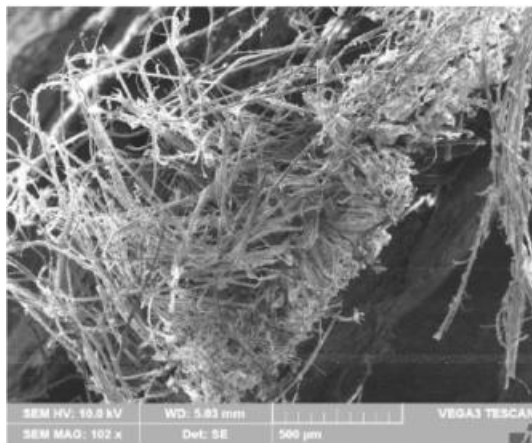
Fig. 8



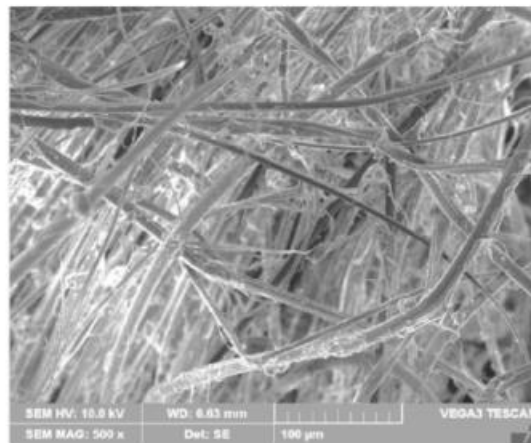
(a)



(b)



(c)



(d)

a–d SEM micrographs of fractured HG2 and HG6 samples

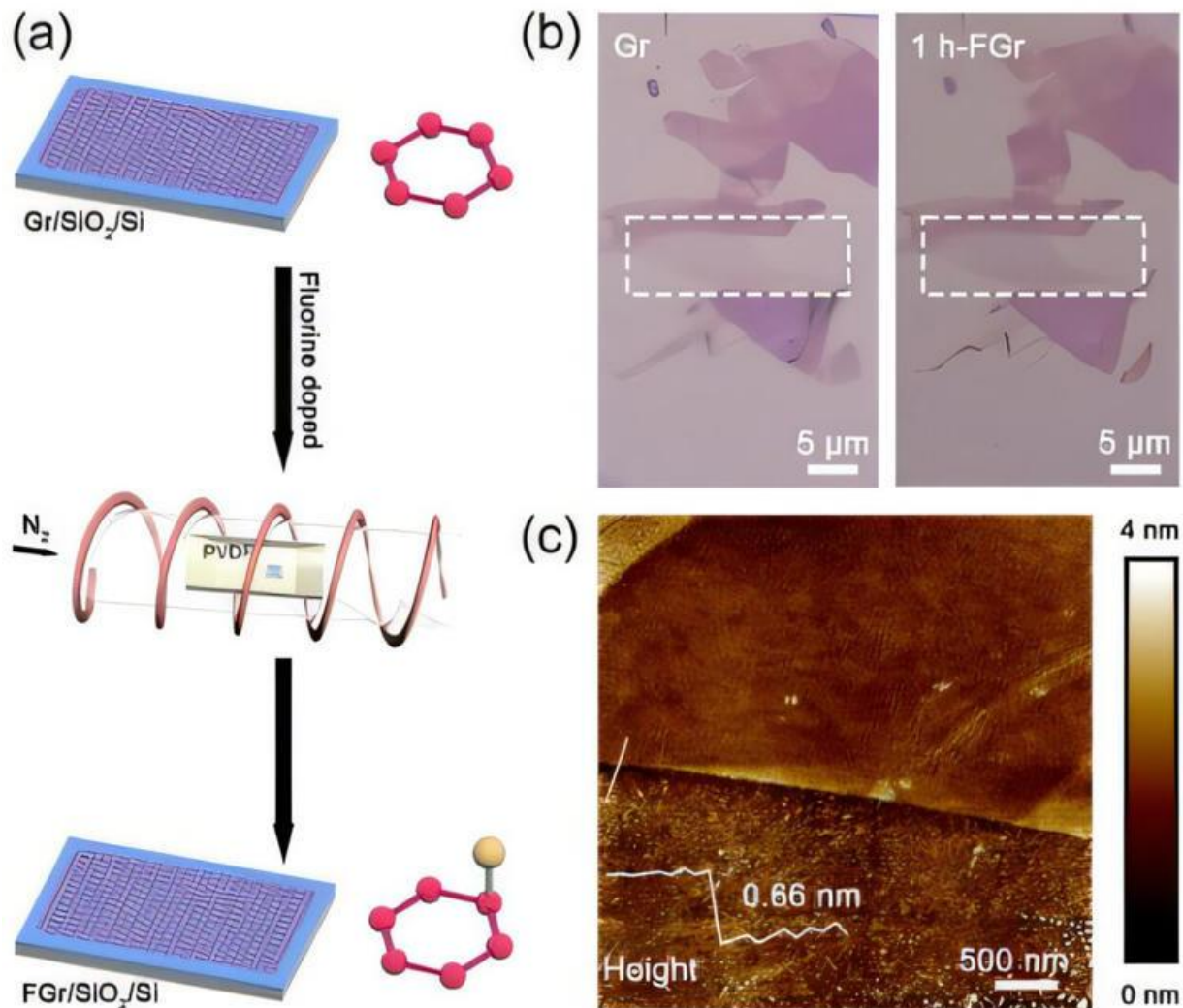
Conclusions

Epoxy composites comprising four layers of hybrid carbon/Kevlar fabric mat with varying weight percentage of graphene particles were fabricated through lay-up lamination technique. Specimens were mechanically tested to understand their tensile and flexural strength. Based on results obtained, the following observations were summarized below.

- Inclusion of graphene particles within hybrid carbon/Kevlar fabric significantly improved thermal stability and tensile and flexural strengths of composite laminates.
- Mechanical strength of composites increases with an increase in filler content due to the improved interfacial bonding between fibre/matrix/filler which resulted in greater load transfer.

- The sample HG6 with high filler loading exhibited 71% and 114.4% greater tensile and flexural strength respectively, as compared to unfilled HG0 composite.
- Thermal stability and hardness of HG6 were greater among all the specimens.
- SEM images reveal the uniform dispersion of graphene particles in the composite system. Besides, the samples have shown brittle fracture.

Fluorination strategy unlocks graphene's potential for optoelectronic and energy applications



Characterization of the Gr and FGr. Credit: Applied Physics Letters (2024). DOI: 10.1063/5.0197942

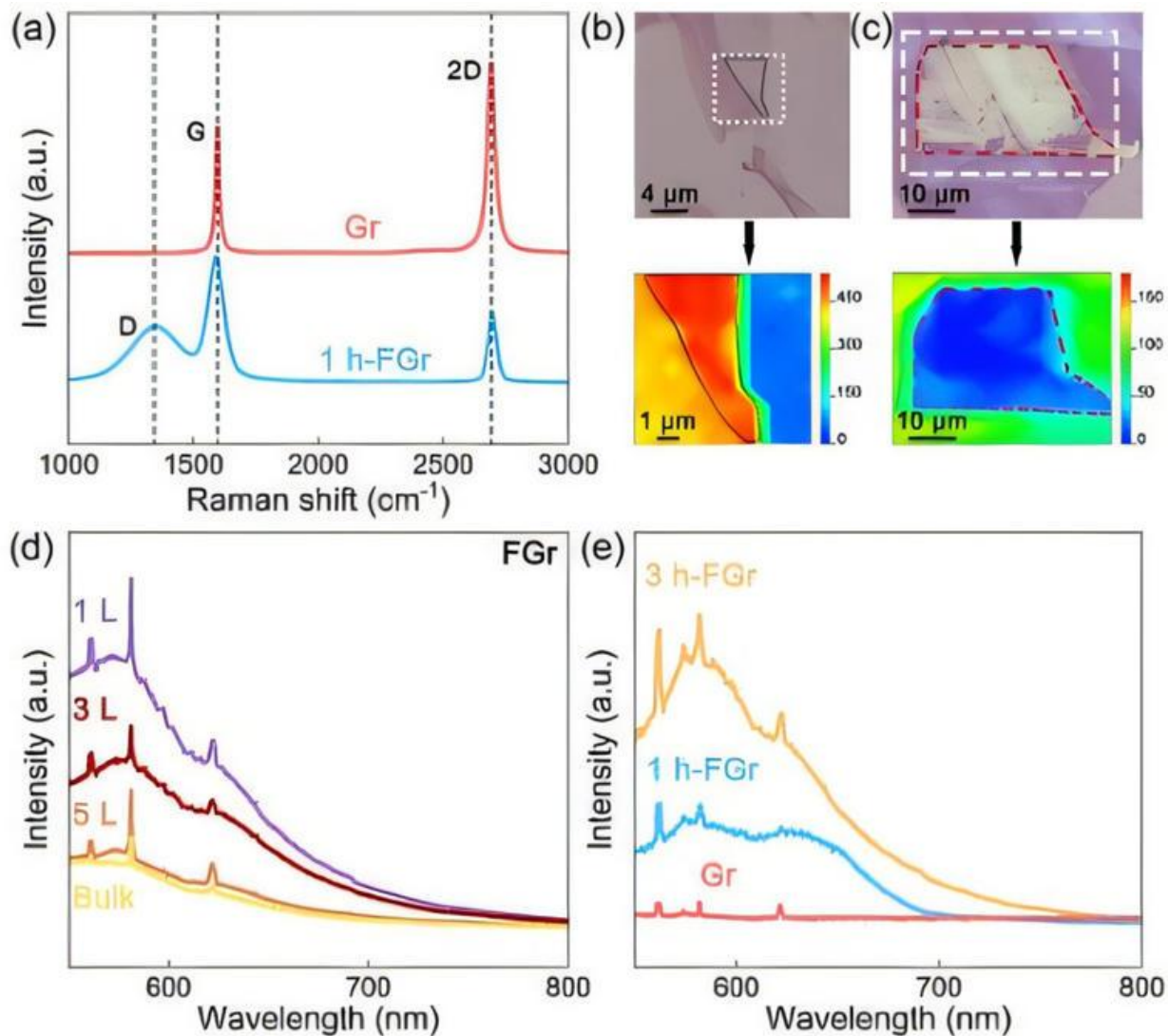
Researchers from Tohoku University and collaborators have developed a weak fluorination strategy to address the zero-bandgap limitation of graphene. [Details of the research](#) were published in the journal *Applied Physics Letters*.

In most electronic materials, a "gate," i.e., a bandgap, exists that can either stop or allow electricity to pass. This is how we control electricity in things like

computers or phones. But graphene has no such gate, meaning it conducts electricity continuously and cannot be turned off.

To counteract this, scientists have often added a small amount of fluorine atoms to graphene, slightly changing its structure and introducing a bandgap, without damaging its core advantages. Fluorination, however, relies on the use of hazardous chemicals, rendering it dangerous and impractical to apply on a large scale.

"We developed an environmentally-friendly approach, one where we utilized fluoropolymers under controlled conditions to achieve selective fluorination," said Dr. Yaping Qi, assistant professor at Tohoku University. "This advancement also enables enhanced photoluminescence and tunable transport properties while maintaining high carrier mobility, making graphene more applicable for use in optoelectronic and energy devices."



Raman and PL of the Gr and FGr. Credit: Applied Physics Letters (2024). DOI: 10.1063/5.0197942

Qi and her colleagues used advanced techniques, including photoluminescence (PL) mapping and Raman spectroscopy, to analyze how fluorination changes graphene's structure and optical properties. Their tests showed that fluorinated graphene has improved light-emitting abilities, making it promising for use in LEDs, sensors, and other energy technologies.

This work also connects to recent developments in van der Waals (vdW) heterostructures, which are created by layering different 2D materials to achieve multiple functions. Such structures have potential uses in memory storage, artificial intelligence, and photoelectric devices.

"The integration of fluorinated graphene into vdW heterostructures opens up exciting possibilities, especially for flexible electronics and systems that can perform multiple tasks at once," said Dr. Xichan Gao, a co-author and assistant professor at the Advanced Institute for Materials Research (AIMR) at Tohoku University.

"This research demonstrates how environmentally friendly processing can significantly improve the functional properties of graphene," adds Qi.

"Combining fluorination with strain engineering opens new possibilities for the development of scalable, high-performance 2D materials, providing a pathway to enhance graphene's practical utility while maintaining a focus on safe and scalable material processing techniques."

More information: Yue Xue et al, Photoluminescence and transport properties of fluorinated graphene via a weak fluorination strategy, *Applied Physics Letters* (2024). DOI: [10.1063/5.0197942](https://doi.org/10.1063/5.0197942)

Provided by Tohoku University

In a significant breakthrough, researchers at the [University of Copenhagen](#), working with [Ruhr University Bochum](#), have solved a persistent issue in quantum research. They can now control two quantum light sources instead of just one.

While this might seem trivial to those unfamiliar with quantum mechanics, it's a monumental step forward. This advancement allows the creation of [quantum mechanical entanglement](#), a phenomenon that holds immense potential for commercial technology applications.

Illustration of two a chip comprising two entangled quantum light sources. (CREDIT: NBI)© The Brighter Side of News

Controlling two quantum light sources is crucial in quantum physics. Researchers worldwide have long sought to develop stable quantum light sources and achieve entanglement—a phenomenon with almost sci-fi properties where two

light sources can instantly affect each other, even over large distances. Entanglement forms the basis of [quantum networks](#) and is central to developing efficient quantum computers.

Researchers from the Niels Bohr Institute recently published their findings in the [Journal Science](#). According to Professor Peter Lodahl, a key researcher in this project, this is a critical step toward advancing quantum technology and "quantizing" computers, encryption, and the internet.

"We can now control two [quantum light sources](#) and connect them. It might not sound like much, but it's a major advancement and builds upon the past 20 years of work. By doing so, we've revealed the key to scaling up the technology, which is crucial for the most groundbreaking of quantum hardware applications," says Professor Lodahl, who has been researching in this area since 2001.

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This innovation happens on a nanochip, barely larger than a human hair, developed by the researchers over recent years.

Professor Lodahl's group focuses on quantum technology using photons, light particles, to transport quantum information. Despite being a leader in this field, they could only control one light source at a time until now due to the sensitivity of these sources to external noise. The new research has succeeded in creating two identical [quantum light sources](#).

"Entanglement means that by controlling one light source, you immediately affect the other. This makes it possible to create a whole network of entangled quantum light sources, all of which interact with one another, and which you can get to perform [quantum bit operations](#) in the same way as bits in a regular computer, only much more powerfully," explains postdoc Alexey Tiranov, the lead author of the article.

A quantum bit can be both a 1 and 0 simultaneously, leading to processing power far beyond today's computer technology. According to Professor Lodahl, 100 photons from a single [quantum light source](#) contain more information than the world's largest supercomputer can process.

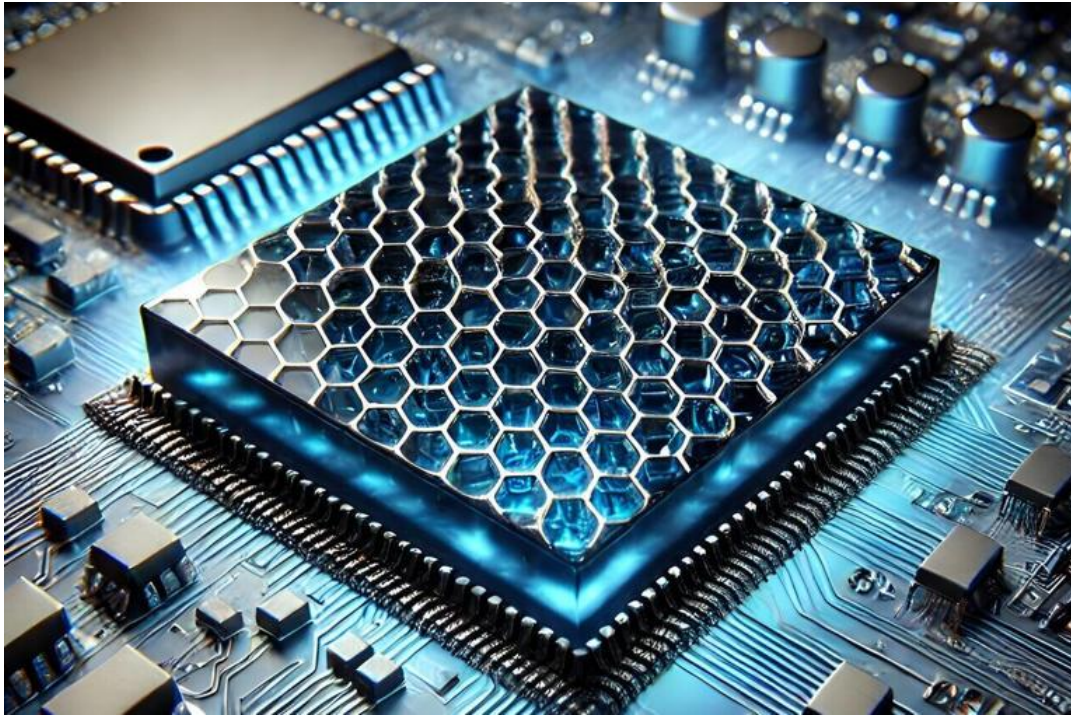
Using 20-30 entangled quantum light sources could potentially build a universal error-corrected quantum computer—the ultimate "holy grail" of quantum technology. Large IT companies are investing billions in this pursuit.

The biggest challenge was moving from controlling one to two quantum light sources, which required developing extremely quiet nanochips and precise control over each light source. Now, with this breakthrough, the fundamental [quantum physics research](#) is established. The task now is for other entities to build upon this work and apply quantum physics to technologies like computers, the internet, and encryption.

Photon emission is the hallmark of light-matter interaction and the foundation of photonic quantum science. (CREDIT: Science)© The Brighter Side of News

"It is too expensive for a university to build a setup where we control 15-20 quantum light sources. So, now that we have contributed to understanding the [fundamental quantum physics](#) and taken the first step along the way, scaling up further is very much a technological task," says Professor Lodahl.

The research was conducted at the Danish National Research Foundation's "Center of Excellence for Hybrid Quantum Networks (Hy-Q)" and is a collaboration between Ruhr University Bochum in Germany and the University of Copenhagen's Niels Bohr Institute.



Symbolic illustration of a graphene layer on a microchip. In combination with a heavy-metal thin film and ferromagnetic monolayers, graphene could enable spintronic devices. Credit: Dall-E/Helmholtz Association of German Research Centres

Spintronics uses the spins of electrons to perform logic operations or store information. Ideally, spintronic devices could operate faster and more energy-efficiently than conventional semiconductor devices. However, it is still difficult to create and manipulate spin textures in materials.

Graphene, a two-dimensional honeycomb structure built by carbon atoms, is considered an interesting candidate for spintronic applications. Graphene is typically deposited on a thin film of heavy metal.

At the interface between graphene and heavy metal, a strong spin-orbit coupling develops, which gives rise to different quantum effects, including a spin-orbit splitting of energy levels (Rashba effect) and a canting in the alignment of spins (Dzyaloshinskii-Moriya interaction). The spin canting effect is especially needed to stabilize vortex-like spin textures, known as skyrmions, which are particularly suitable for spintronics.

Now, however, a Spanish-German team has shown that these effects are significantly enhanced when a few monolayers of the ferromagnetic element cobalt are inserted between the graphene and the heavy metal (here: iridium). The samples were grown on insulating substrates, which is a necessary prerequisite for the implementation of multifunctional spintronic devices exploiting these effects.

The research is [published](#) in the journal *ACS Nano*.

"At BESSY II, we have analyzed the electronic structures at the interfaces between graphene, cobalt and iridium," says Dr. Jaime Sánchez-Barriga, a physicist at HZB. The most important finding: contrary to expectations, the graphene interacts not only with the cobalt, but also through the cobalt with the iridium.

"The interaction between the graphene and the heavy metal iridium is mediated by the ferromagnetic cobalt layer," Sánchez-Barriga explains. The ferromagnetic layer enhances the splitting of the energy levels.

"We can influence the spin-canting effect by the number of cobalt monolayers; three monolayers are best," says Sanchez-Barriga.

This result is supported not only by experimental data, but also by new calculations using density functional theory. The fact that both quantum effects influence and reinforce each other is new and unexpected.

"We were only able to obtain these new insights because BESSY II offers extremely sensitive instruments for measuring photoemission with spin resolution (Spin-ARPES). This leads to the fortunate situation that we can determine the assumed origin of the spin canting, i. e., the Rashba-type spin-orbit splitting, very precisely, probably even more precisely than the spin canting itself," emphasizes Prof. Oliver Rader, who heads the "Spin and Topology in Quantum Materials" department at HZB.

There are only a very few institutions worldwide that have instruments with these capabilities. The results show that graphene-based heterostructures have great potential for the next generation of spintronic devices.

More information: Beatriz Muñiz Cano et al, Rashba-like Spin Textures in Graphene Promoted by Ferromagnet-Mediated Electronic Hybridization with a Heavy Metal, *ACS Nano* (2024). DOI: [10.1021/acsnano.4c02154](https://doi.org/10.1021/acsnano.4c02154)

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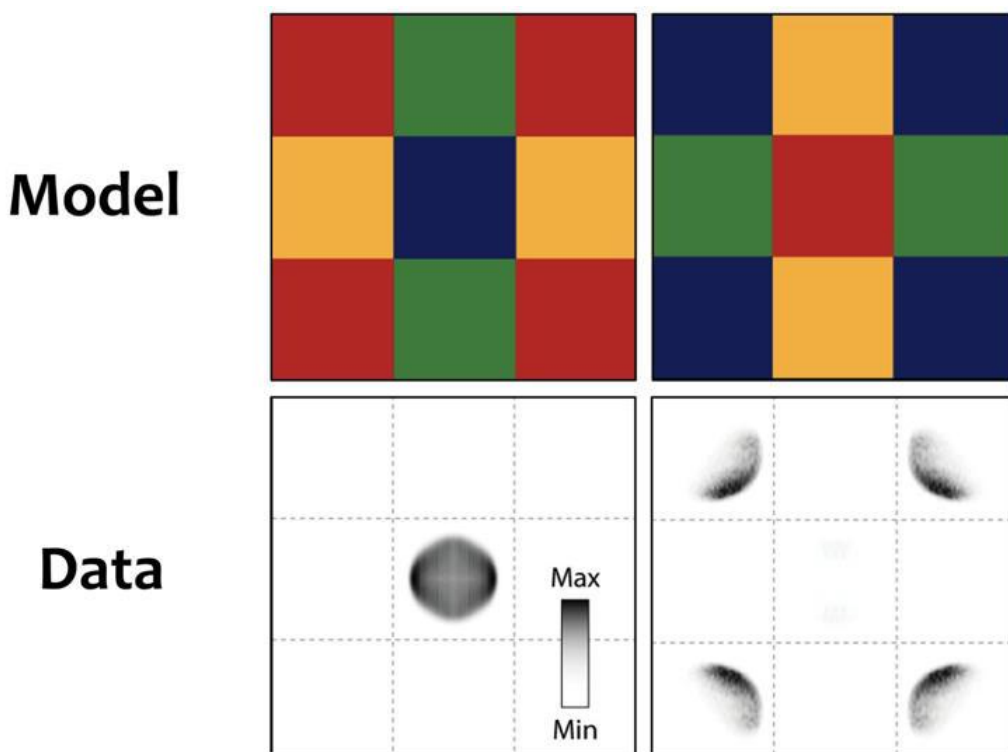


Image illustrating four-source interference, which is similar to the mechanism of condensed matter dark states Credit: Chung et al

Dark states are quantum states in which a system does not interact with external fields, such as light (i.e., photons) or electromagnetic fields. These states, which generally occur due to interferences between the pathways through which a system interacts with an external field, are undetectable using spectroscopic techniques.

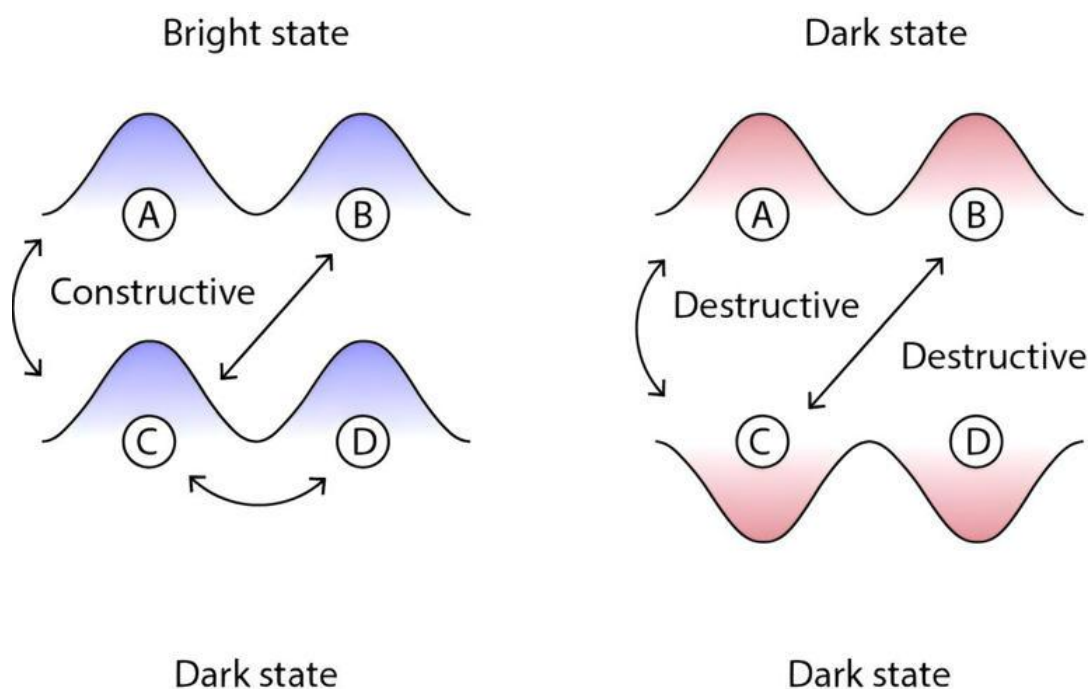


Image illustrating four kinds of electron states in solids with two pairs of sublattices indexed A, B, C, and D. Palladium diselenides, cuprate superconductors and lead halide perovskites have unique crystal symmetries known as multiple glide-mirror symmetries. These symmetries make all the electrons simplified into only four kinds shown in blue, red, yellow, and green in the picture. The blue is only the bright state, and red, yellow, and green are dark states. As you can easily identify by comparing the model and data, only the blue could be observed in angle-resolved photoemission spectroscopy. Credit: Chung et al

Researchers at Yonsei University in South Korea and other institutes recently discovered some undetectable condensed-matter dark states in palladium diselenide, a quantum system with two pairs of sublattices in its primitive cell.

Their observations, outlined in a [paper](#) published in *Nature Physics*, could have interesting implications for the study of materials, quantum states and correlated phenomena.

"Angle-resolved photoemission spectroscopy is a powerful experimental technique for physicists to understand how electrons behave in solids," Keun Su Kim, Professor of Physics at Yonsei University and co-author of the paper, told Phys.org.

"From experience, it has been well known that not all the electrons are detected by angle-resolved photoemission spectroscopy. In other words, some electrons are detectable but the others are not."

For a long time, physicists assumed that the inability to detect some electrons using spectroscopic techniques was associated with the methods used to conduct experiments, rather than the intrinsic properties of materials.

However, in previous studies examining simple elemental materials with one pair of sublattices, such as graphene and black phosphorus, Kim and his colleagues showed that this elusiveness is in fact closely linked to the intrinsic properties of materials.

"We have dug into this problem to extend it to materials with two pairs of sublattices and found that there are some electrons that cannot be detected in any experimental conditions," Kim said. "Simply speaking, we could see experimental signals only for electrons expected to be detectable (bright states) and could not see any experimental signals for electrons expected to be undetectable (dark states)."

To carry out their experiments, the researchers employed a technique known as angle-resolved photoemission spectroscopy. This widely used experimental technique leverages the photoelectric effect first discovered by Albert Einstein to gather information about the electronic structure of materials.

Essentially, Kim and his colleagues irradiated their samples with a high-energy photon beam. This beam of energy ejected some electrons from the sample, allowing them to collect information about the energy and momentum they exhibited while still in the sample.

"In this work, we studied three materials, palladium diselenides (PdSe_2), cuprate superconductors ($\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ or Bi-2212), and lead halide perovskites (CsPbBr_3)," Kim explained. "An important common property of these three materials is that they have certain crystal symmetries (multiple glide-mirror symmetries) that make all the electrons in the solid samples characterizable as one of four types."

Essentially, the researchers found that electrons in quantum systems with two pairs of sublattices can be characterized into four different categories. One of these types of electrons could be detected using angle-resolved photoemission spectroscopy, while the other three types were undetectable, as they were in dark states.

"It is just a possibility for now, but our result offers a new way to explain one of the long-standing issues in the study of high-temperature superconductivity, called the 'Fermi arc,'" Kim said. "Our nature is too complex to include everything in the theoretical model, and often you need to make a choice about what to include and what to exclude for approximation. Strictly speaking, there are sublattices in the unit structure of cuprate superconductors, but these sublattices have been overlooked so far."



Group members conducting angle-resolved photoemission spectroscopy experiments at synchrotron radiation Credit: Advanced Light Source, US, and Diamond Light Source, UK.

The recent work by this team demonstrates the existence of dark states in various quantum systems with two pairs of sublattices, including palladium diselenides, cuprate superconductors and lead halide perovskites. In the future, it could have important implications for the study of these materials, potentially broadening the understanding of their underlying physics.

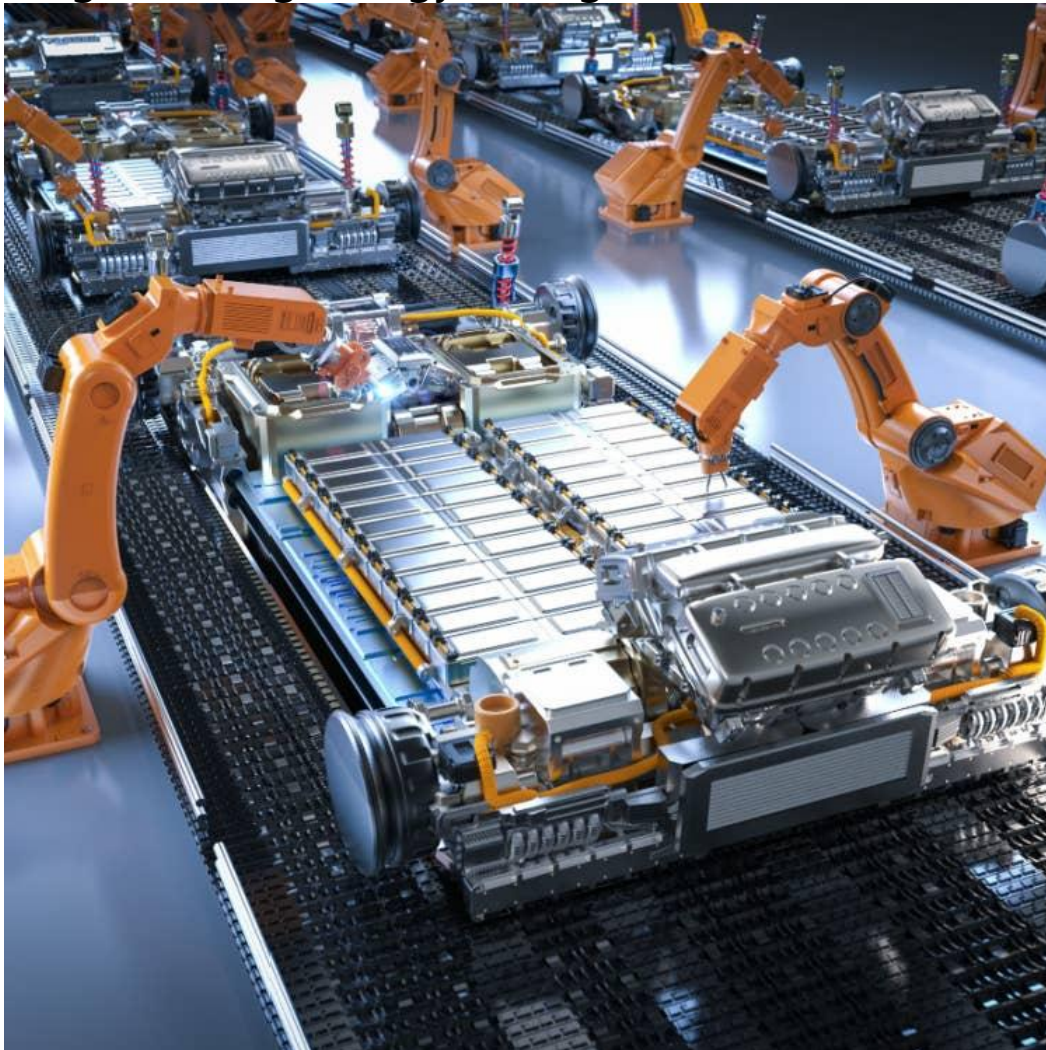
"Our findings pose the question of whether it is really OK to leave out sublattices in the unit structure of cuprate superconductors when interpreting angle-resolved photoemission spectroscopy data collected from these materials," Kim added. "Our plan for future research is to dig into the Fermi arc problem of

cuprate superconductors in the same context but more deeply. We already have some promising results and are working on the next paper."

More information: Yoonah Chung et al, Dark states of electrons in a quantum system with two pairs of sublattices, *Nature Physics* (2024). DOI: [10.1038/s41567-024-02586-x](https://doi.org/10.1038/s41567-024-02586-x)

Breakthrough graphene technology revolutionizes battery safety and performance

Graphene enhances lithium-ion battery safety with superior heat management, paving the way for safer, longer-lasting energy storage solutions.



Swansea University researchers have developed a revolutionary graphene foil that enhances lithium-ion battery safety. (CREDIT: Shutterstock)

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Researchers from Swansea University, in collaboration with [Wuhan University of Technology](#) and [Shenzhen University](#), have developed a breakthrough technique for

producing large-scale graphene current collectors. This new advancement could significantly improve lithium-ion battery (LIB) safety and performance, addressing critical challenges in energy storage technology.

The findings, published in [Nature Chemical Engineering](#), outline the first successful approach for creating defect-free graphene foils on a commercial scale, an achievement that could reshape the future of battery technology.

Graphene, a material known for its exceptional properties, now promises extraordinary thermal conductivity in current collectors. The graphene foils developed by this team can conduct heat at up to $1,400.8 \text{ W m}^{-1} \text{ K}^{-1}$ —almost ten times greater than traditional copper and aluminum current collectors used in lithium-ion batteries.

This enhanced conductivity plays a crucial role in efficiently managing the intense heat generated within high-energy [lithium-ion batteries](#), such as those used in electric vehicles.



A scalable graphene current collector featuring high thermal and electrical conductivity has been developed to address the crucial thermal problems in lithium-ion batteries. (CREDIT: Swansea University)

Dr. Rui Tan, a co-lead author from [Swansea University](#), highlights the importance of this development, stating, "Our method allows for the production of graphene current collectors at a scale and quality that can be readily integrated into commercial battery manufacturing."

This not only improves battery safety by efficiently managing heat but also enhances energy density and longevity.” By replacing traditional metal collectors, graphene-based collectors offer a safer alternative by preventing the buildup of extreme heat, which can lead to battery failure and even fires or explosions.

One of the most significant challenges in [battery technology](#) is preventing thermal runaway—a dangerous condition in which a battery generates excessive heat that it cannot dissipate, leading to potential failure. These new graphene foils are designed to dissipate heat more effectively, reducing the likelihood of thermal runaway.

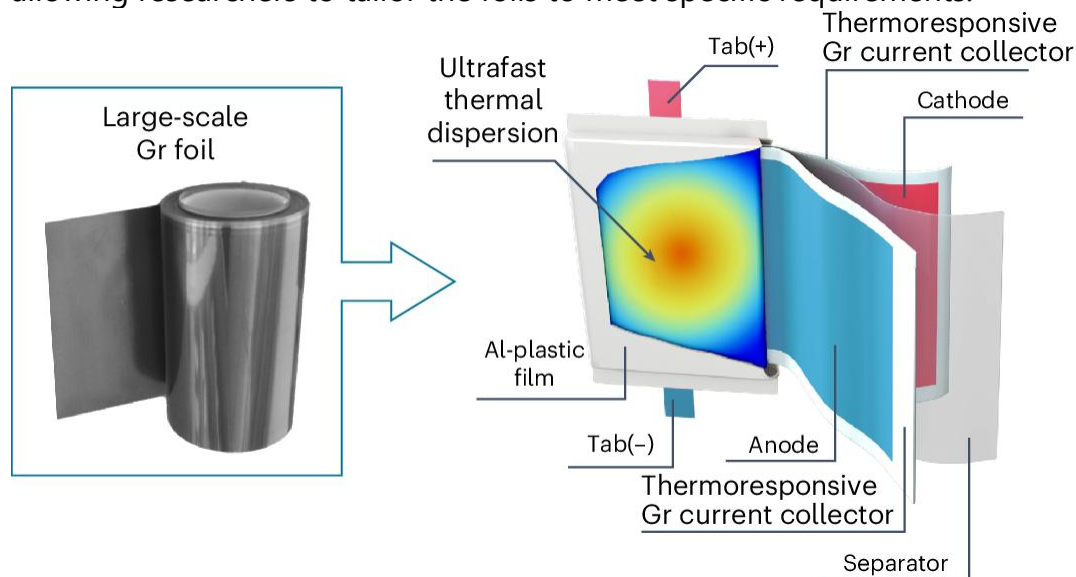
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“Our dense, aligned graphene structure provides a robust barrier against the formation of flammable gases and prevents oxygen from permeating the battery cells, which is crucial for avoiding catastrophic failures,” explained Dr. Jinlong Yang, another co-lead author from Shenzhen University.

Beyond heat management, these graphene foils show remarkable durability. In a key demonstration, the researchers produced a 200-meter-long graphene foil with a thickness of just 17 micrometers. This foil retained high [electrical conductivity](#) even after being bent over 100,000 times, showcasing its flexibility and resilience. Such durability makes the material suitable not only for batteries but also for flexible electronics and other advanced applications.

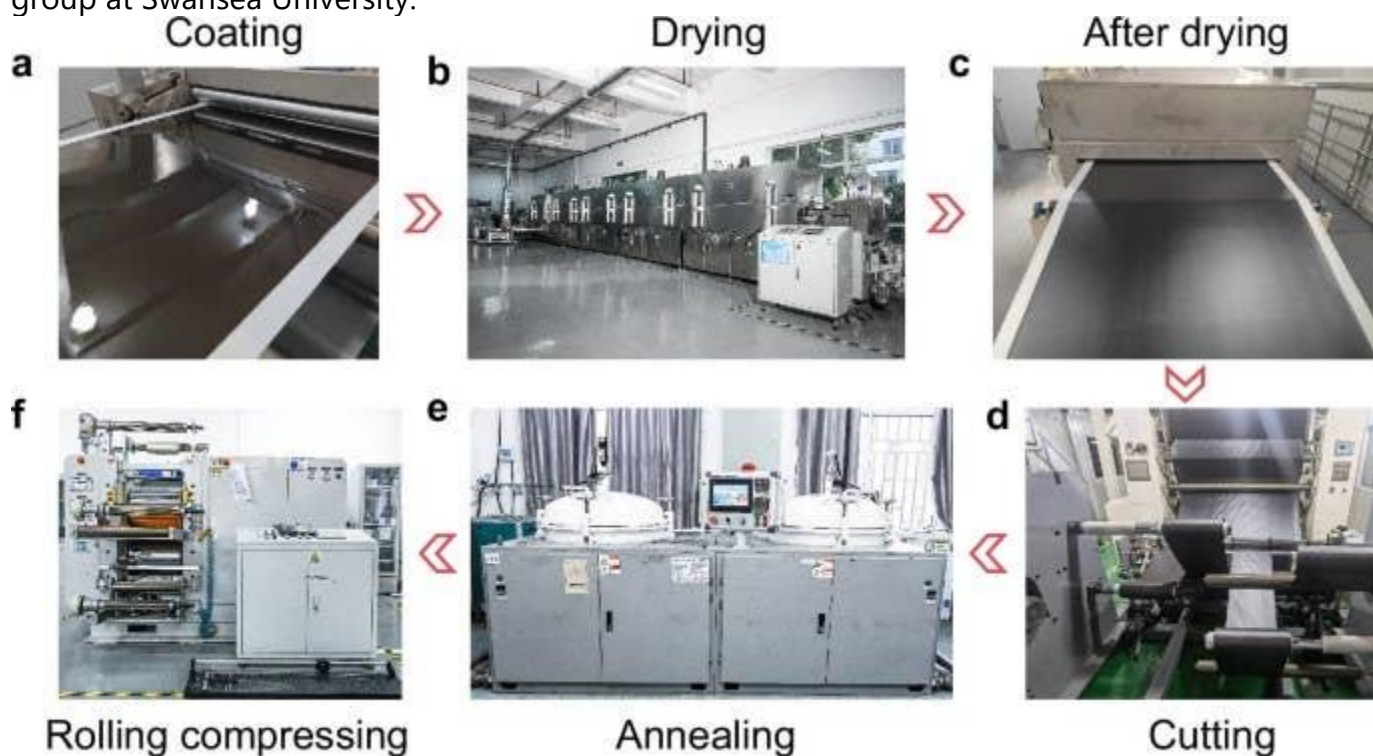
The scalability of this process marks a significant leap for graphene applications. The technique enables the production of graphene foils in customizable thicknesses, allowing researchers to tailor the foils to meet specific requirements.



Graphite cells integrated with these temperature-responsive foils show faster heat dissipation, eliminating the local heat concentration and circumventing the fast exothermic aluminothermic and hydrogen-evolution reactions. (CREDIT: Nature Chemical Engineering)

For instance, thicker foils could enhance durability in high-stress applications, while thinner foils might be ideal for situations requiring lighter materials. This adaptability opens doors for safer, more efficient energy storage systems across a range of sectors. Looking forward, the impact of this innovation could be substantial, especially in industries like [electric vehicles](#) and renewable energy systems, where efficiency and safety are paramount. These graphene foils could improve battery safety, energy density, and overall performance, making them an attractive option for electric vehicle manufacturers who prioritize safety and longevity.

The research team is continuing to refine this technology with ongoing efforts aimed to reduce the thickness of graphene foils even further while enhancing their mechanical properties. The team is also exploring additional applications for this material, including redox flow and sodium-ion batteries, with support from Professor Serena Margodonna's group at Swansea University.



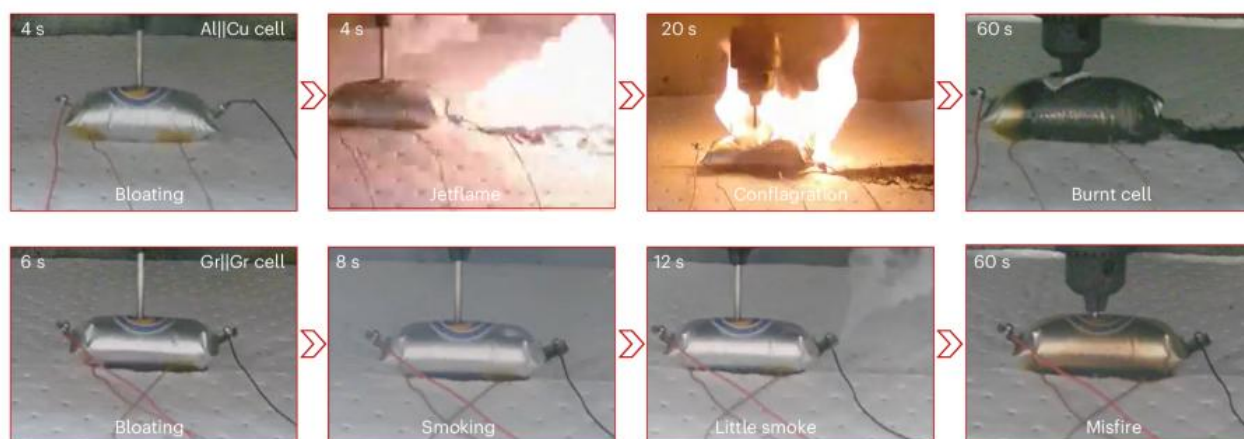
Fabrication of the large-area Gr using GO+3wt.% PEA precursor. (CREDIT: Nature Chemical Engineering)

Thermal runaway is one of the most pressing safety issues in lithium-ion batteries. When the internal temperature of a battery exceeds a critical threshold, the battery can begin to produce heat faster than it can dissipate it. This can lead to a cascade of exothermic reactions, resulting in [battery failure](#). Traditional metal current collectors, such as

aluminum and copper, are limited in their ability to transfer heat efficiently, making them inadequate for high-energy-density batteries.

The newly developed graphene current collectors address these limitations. Their high thermal conductivity enables rapid heat transfer, which helps to maintain safe operating temperatures within the battery cells. As a result, the battery's internal structure remains stable, preventing the chemical reactions that lead to thermal runaway. Graphene's unique structure not only serves as a robust thermal conductor but also acts as a barrier to oxygen, further enhancing the battery's safety profile.

In practical applications, lithium-ion batteries with these graphene foils demonstrated faster heat dissipation. This helps prevent local heat concentration within [battery packs](#), a primary contributor to thermal failure. Batteries equipped with these graphene current collectors were able to maintain stable temperatures, avoiding the fast exothermic reactions that can occur with aluminum and copper foils. This characteristic makes graphene current collectors ideal for high-performance applications, especially in electric vehicles, where safety standards are stringent.

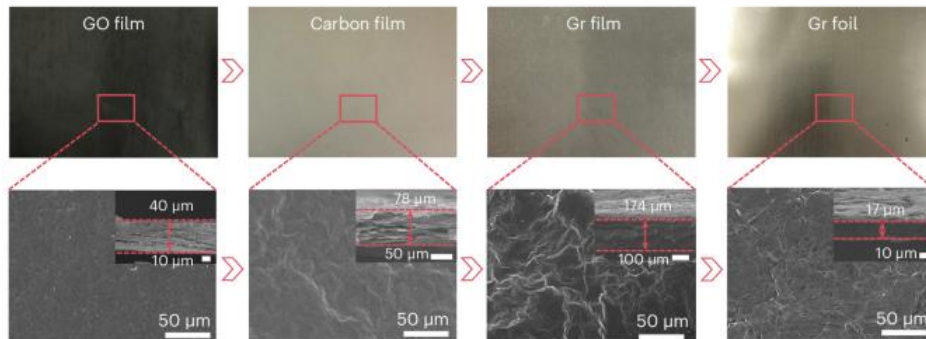
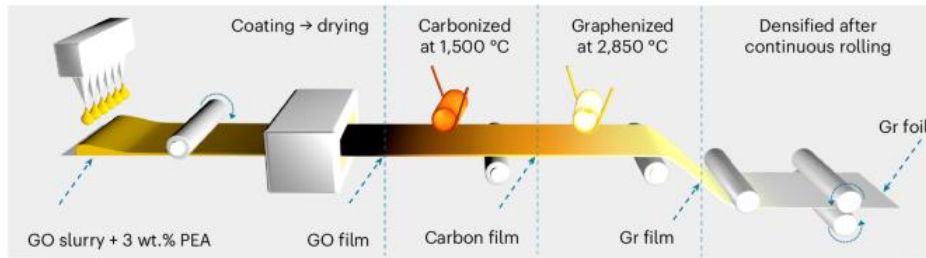


Safety performance and mechanism analysis of pouch cells during thermal runaway. (CREDIT: Nature Chemical Engineering)

Overall, this innovative approach offers a solution to one of the most significant challenges in battery technology. Graphene foils are not just a laboratory success; they are ready for commercial production on a large scale. By enabling the fabrication of these foils in lengths ranging from meters to kilometers, this technology promises to drive the next generation of energy storage solutions.

The potential of graphene in this role extends beyond [lithium-ion batteries](#). The researchers are exploring applications in other types of batteries, like sodium-ion and redox flow batteries, where high thermal conductivity and flexible design are advantageous.

With this development, the research team has paved the way for safer, more efficient batteries. This is a crucial advancement as the world moves toward renewable energy and electric mobility, both of which demand high-performance, reliable, and safe energy storage solutions.



Fabrication of the large-area Gr foil. (CREDIT: Nature Chemical Engineering)

The innovation not only addresses safety concerns but also offers practical solutions for extending battery lifespan and optimizing energy use in various applications.

Note: Materials provided a

Tiny graphene-based magnetic devices could lead to much smaller — and way more powerful — processors in the future© Yuichiro Chino via Getty Images

Researchers have developed a technique that could enable the extreme miniaturization of computing components, paving the way for compact and high-performance devices.

The smaller the transistors and logic gates in a processor, the more computing power can be packed into a smaller area. But the physical constraints of silicon mean we are reaching the limits of how small these components can be.

However, a new technique, involving ultrafast switching between spin states in 2D magnets — to represent the switching between the binary states of 1 and 0 — can lead to much denser and more power-efficient components.

This technique is enabled by a new type of magnetic tunnel junction (MTJ) — a material structure that acts as a data storage device in a computing system. The scientists sandwiched chromium triiodide (a 2D insulating magnet) between layers of graphene and sent an electrical current through it to dictate the magnet's orientation within the individual chromium triiodide layers.

Harnessing these MTJs could mean packing more computing power into a chip than was previously deemed possible — while consuming much less energy during the switching process. The researchers published their findings in a new study published May 1 in the journal [Nature Communications](#).

In the paper, the scientists demonstrated that 2D magnets can be polarized to represent binary states — the 1s and 0s of computing data — paving the way for highly energy-efficient computing.

Harnessing spintronics for faster computing

Precisely controlling the magnetic phase of 2D materials is a crucial step in spintronics (controlling an electron's spin and the associated magnetic moment). By precisely controlling the current, the new technique can change the spin states in chromium triiodide using the current's polarity and amplitude. This is possible because the compound is ferromagnetic (it is magnetic and can attract magnets in a similar way to iron). This compound is also a semiconductor — a material that has a conductivity that falls between a metal and an insulator.

A key enabling component for spintronics is the MTJ — two ferromagnetic layers separated by an insulating barrier. Controlling an MTJ's spin state is a technique that is already used in various computer components, such as the read heads of hard drives. But precisely controlling the thickness of its constituent layers and their quality of their interfaces with each other has proved challenging.

Materials must withstand the high current densities of at least 10 million amps through an area approximately the size of fingernail — but also meet the demands of device miniaturization and energy efficiency. For comparison purposes, a typical bolt of lightning is 1,000 to 300,000 amps.

"This paper is about the fact that you can have two possible states of the tunneling current; spin-parallel and anti-parallel," [Adelina Ilie](#), a reader in physics at the University of Bath in the U.K. specializing in 2D magnets, told LiveScience. "If there are two defined states, they can be used as logic gates in a computer."

Much greater energy efficiency for future AI systems

The scientists created the 2D van der Waals (chromium triiodide) magnets, then layered atomically thin flakes of graphene, hexagonal boron nitride and chromium triiodide on top of each other to form tunnel junction devices — which they chilled to [near absolute zero](#). They simultaneously passed an electrical current through the material and measured it using a sourcemeter in 16-millisecond bursts.

They noted that the voltage underwent random switching between the levels, corresponding to the spin-parallel and spin-antiparallel states within chromium triiodide, with the switching direction determined by the polarity and amplitude of the current. The duration for each magnetic state was typically 10 milliseconds, while the switching time between the two states was in the order of microseconds (a microsecond is onemillionth of a second).

"These states are not exactly stable," explained Ilie. "What actually happens is that the current goes from one state to another, back and forth stochastically, but the average of time it stays more in one state or another, depending on the voltage. This gives us two states that we can select deterministically."

The two states, which can be used as logic gates, enable operation at a much smaller scale than was previously possible. Using this technology, manufacturers

could create computer chips with greater processing power. But the need for near absolute-zero operating temperatures means implementing futuristic devices practically would be challenging.

"What makes this kind of work different is that it looks like the energy needed to go from one state to another is a magnitude lower than in conventional magnetic tunnel junctions," concluded Ilie. "With new technologies like generative AI, which increase power consumption tremendously, it won't be possible to keep up, so you need devices that are energy efficient."

Researchers at Tsinghua University in China have developed a new photonic chip that processes, transmits, and reconstructs images in nanoseconds.

The chip achieves this feat by skipping the optical to electronic data conversion deployed by conventional chips.

Machine vision is an evolving field in which cameras, sensors, and algorithms work in tandem to make sense of the world around them and perform specific tasks. In the past, technology relied on moving this data over long distances, where it can be analyzed and appropriate responses taken and executed.

"The world is entering an AI era, but AI is very time- and energy-exhaustive," said Lu Fang, associate professor at the Department of Electronic Engineering at Tsinghua University in China. In a fast-moving world, machine vision now demands that data is processed on the device, called edge computing, to aid faster decision-making.

"The growth of edge devices, such as [smartphones](#), intelligent cars and laptops has resulted in explosive growth of image data to be processed, transmitted and displayed. We are working to advance machine vision by integrating sensing and computing in the optical domain," Fang added.

Doing away with optical-electro conversions

Edge tasks like autonomous driving are slowed by millisecond optical-to-electronic conversions.

“Capturing, processing and analyzing images for edge-based tasks such as autonomous driving is currently limited to millisecond-level speeds due to the necessity of optical-to-electronic conversions,” said Fang.

Currently, images captured by machine vision devices need to be transferred from their optical nature to electronic versions for the computers to make sense of the data.

Under Fang’s guidance, the researchers have built an optical parallel computational array (OPCA) chip with a sensing-computing array made using ring resonators. This design allows the [photonic chip](#) to convert an optical image into a two-dimensional representation of its light intensity that can be guided onto the chip using a micro-lens array.

The OPCA chip has a processing bandwidth of up to a hundred billion pixels and a response time of just six nanoseconds.

The new intelligent optical computational array (OPCA) chip performs end-to-end image processing, transmission and reconstruction by integrating sensing and computing on one chip. Image credit: Wei Wu, Tsinghua University© Provided by Interesting Engineering

All optical neural network

Since the data is processed as light signals, the researchers used them to develop an all-optical neural network and deploy it for classification tasks typically carried out on the edge.

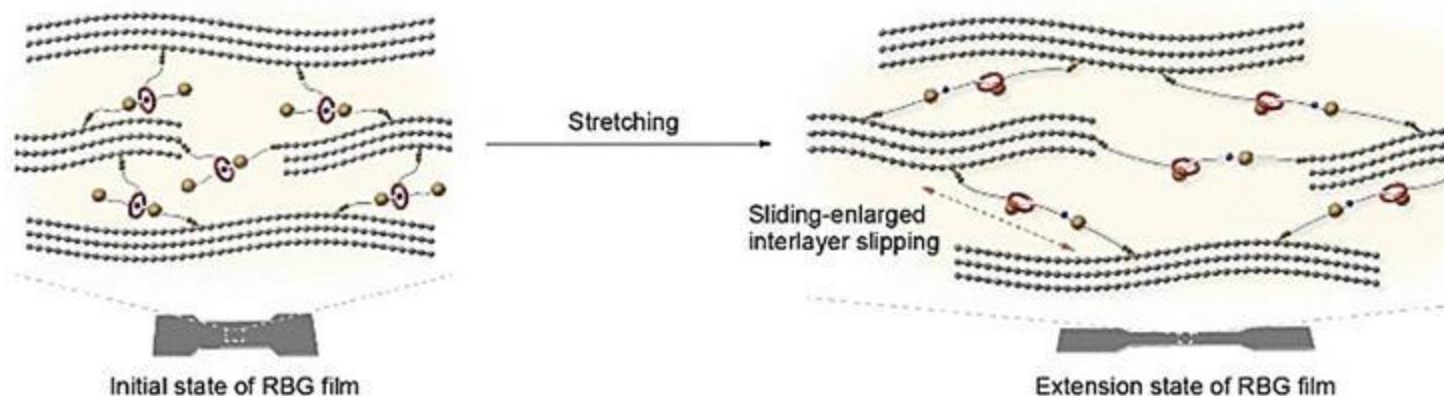
“Because each sensing-computing element of this chip is reconfigurable, they can each operate as a programmable neuron that generates light modulation output based on the input and weight,” added Fang in the [press release](#).

“The neural network connects all the sensing-computing neurons with a single waveguide, facilitating an all-optical full connection between the input information and the output.”

The research team deployed the chip for tasks such as [image classification](#) of hand-drawn images and image convolution to demonstrate how the chip works. In the latter approach, a filter is used on an image to extract certain features from it.

The successful completion of these tasks demonstrates that the chip architecture is competent in handling such tasks. In the future, the research team aims to increase the overall size of the OPCA chip and improve the neural network's processing capacity to bring it closer to commercial usage.

The research findings were published in the journal [Optica](#).



Credit: Angewandte Chemie International Edition (2024). DOI: 10.1002/anie.202404481© Provided by Phys.org

Layers of carbon atoms in a honeycomb array are a true supermaterial: their unusually high conductivity and favorable mechanical properties could further the development of bendable electronics, new batteries, and innovative composite materials for aeronautics and space flight. However, the development of elastic and tough films remains a challenge.

In the journal [Angewandte Chemie](#), a research team has now introduced a method to overcome this hurdle: they linked graphene nanolayers via "extendable" bridging structures.

The special capabilities of microscopic graphene nanolayers often drop off when the layers are assembled into foils, because they are only held together by relatively weak interactions—primarily hydrogen bonds.

Approaches that attempt to improve the mechanical properties of graphene foils by introducing stronger interactions have only been partially successful, leaving particular room for improvement in the stretchability and toughness of the materials.

A team led by Xuzhou Yan at Shanghai Jiao Tong University (China) took a new approach: they cross-linked graphene nanolayers with mechanically interlocked molecules whose building blocks are not chemically linked, but rather inseparably spatially entangled. The researchers chose to use rotaxanes as their links.

A rotaxane is a "wheel" (a large ring-shaped molecule) that is "threaded" onto an "axle" (a molecular chain). Bulky groups cap the axles to prevent the wheels from coming unthreaded. The team built their axle with a charged group (ammonium) that holds the wheel in a specific position.

A molecular "anchor" (OH group) was attached to both the axle and wheel by a linker. The graphene was oxidized to make graphene oxide, which forms a variety of oxygen-containing groups on both sides of the graphene layer. These include carboxyl groups, which can bind to the OH groups (esterification). This reaction allows the wheel and axle to cross-link the layers, after which the graphene oxide is reduced back to graphene.

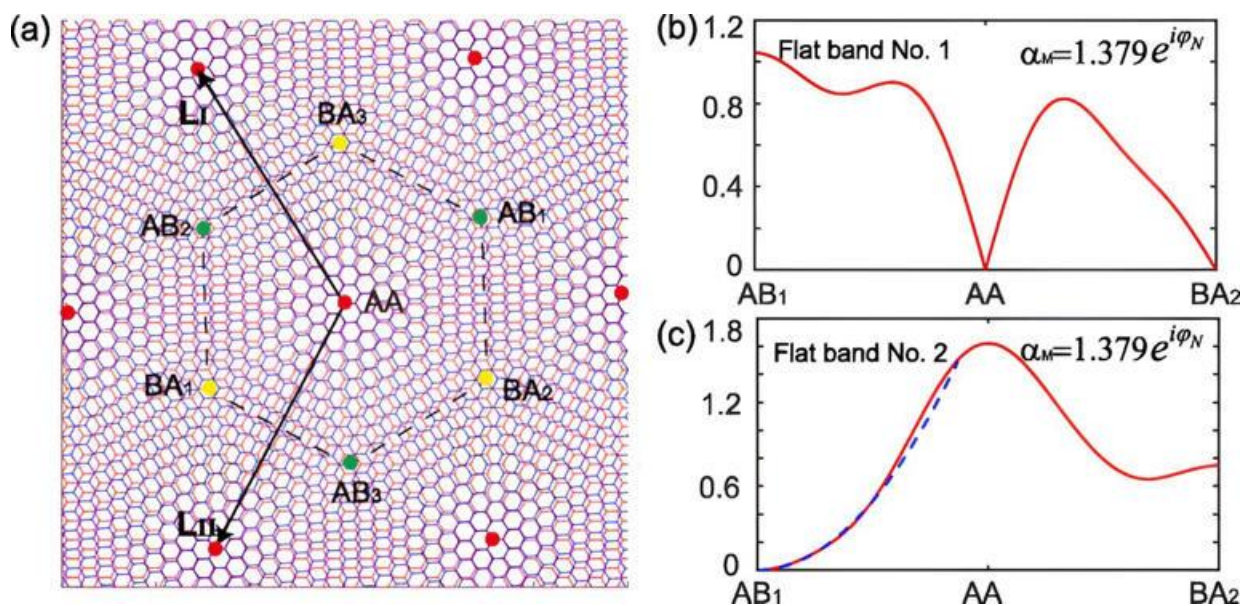
When these films are stretched or bent, the attractive forces between the wheel and the ammonium group on the axle must be overcome, which increases the tensile strength. Increased stress eventually causes the axle to be pulled through the wheel until it "strikes" the end cap. This motion lengthens the rotaxane-bridges, allowing the layers to slide across each other, which significantly increases the stretchability of the film.

Flexible electrodes made from this graphene-rotaxane foil could be stretched up to 20% or bent repeatedly without being damaged. They also retained their high electric conductivity. Only stretching by over 23% led to fracture.

The new foils were considerably stronger than foils without rotaxanes (247.3 vs. 74.8 MPa), as well as more elastic (23.6 vs. 10.2%), and tougher (23.9 vs. 4.0

MJ/m³). The team also built a simple "grasping tool" with mechanical joints that were equipped with and actuated by the new foils.

More information: Chunyu Wang et al, A Stretchable and Tough Graphene Film Enabled by Mechanical Bond, *Angewandte Chemie International Edition* (2024). DOI: [10.1002/anie.202404481](https://doi.org/10.1002/anie.202404481)



Credit: Physical Review Letters (2024). DOI: 10.1103/PhysRevLett.132.246401

Magnetic fields can engineer flat bands in twisted graphene layers to create a new playground for exotic physics, RIKEN physicists have shown.

The exotic properties of graphene—a single layer of carbon atoms in a hexagonal lattice—are now well established. Electrons effectively move through graphene as if they have no mass. This is an exciting prospect for creating electronic devices with functionalities beyond those of silicon.

But things get even weirder when two or more layers of graphene are combined.

Whenever two sheets with a repeating pattern are placed on top of each other, a much larger pattern emerges when one sheet is rotated. Two layers of graphene also exhibit this so-called moiré pattern.

This leads to a dramatic change in properties. For example, at specific twisted angles, by adjusting electron number, the bilayer graphene can exhibit behaviors of a correlated insulator as well as superconductivity.

Now, Ching-Kai Chiu and Congcong Le, both at the RIKEN Interdisciplinary Theoretical and Mathematical Sciences (iTHEMS), and co-workers have shown that twisted bilayer graphene can become an even richer playground for exotic physics by using a spatially varying magnetic field. Their study is [published](#) in *Physical Review Letters*.

Graphene's unique band structure gives rise to its special electronic properties. "Graphene is renowned for having a band structure with a linear relationship between an electron's energy and momentum at certain points," explains Chiu.

Having two layers of graphene twisted at an angle alters these bands. "In twisted bilayer graphene, at certain 'magic' twist angles, these bands evolve into flat bands because the interlayer coupling between the layers is adjusted to the right spot," says Chiu.

In these flat bands, the kinetic energy of electrons is minimized, so the interactions between electrons become the dominant force. Intense electron–electron interactions lead to numerous strongly correlated electronic phenomena such as unconventional superconductivity.

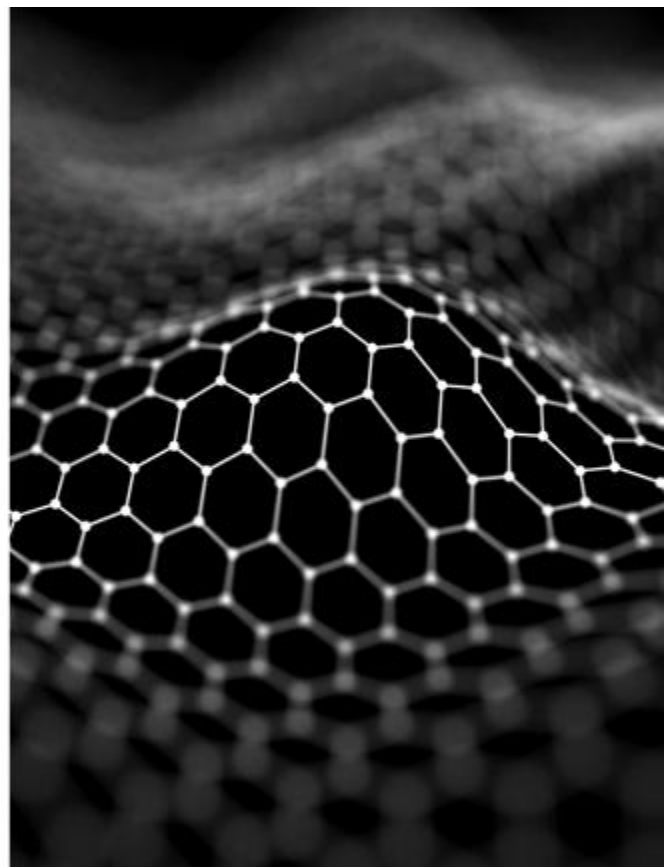
"The discovery of strongly correlated electrons in magic-angle twisted bilayer graphene devices has both shocked and excited the physics community," notes Le.

These flat bands are two-fold degenerate: that is, two different quantum states have the same energy. Chiu and the team have now mathematically shown that introducing a spatially alternating magnetic field gives rise to additional magic angles and flat bands that are quadruply (four-fold) degenerate.

"This higher degeneracy could potentially lead to even more correlated phenomena," says Le. "And the magnetic phase offers an additional novel degree of freedom to tailor the electronic band structure."

The search is on to find other materials that exhibit these phenomena. "We will systematically search for new platforms that host flat bands," says Chiu.

More information: Congcong Le et al, Double and Quadruple Flat Bands Tuned by Alternative Magnetic Fluxes in Twisted Bilayer Graphene, *Physical Review Letters* (2024). DOI: [10.1103/PhysRevLett.132.246401](https://doi.org/10.1103/PhysRevLett.132.246401). On arXiv: DOI: [10.48550/arxiv.2210.13976](https://doi.org/10.48550/arxiv.2210.13976)



Dark electrons discovered in solids for 1st time in superconductor breakthrough

Until now scientists believed that dark electrons, electrons associated with the quantum state of matter, simply don't exist in solid materials.

However, a new study from researchers at South Korea's Yonsei University reveals that solid materials do contain dark electrons. They also conducted an experiment, providing evidence that indicate the presence of such electrons.

According to the researchers, the findings from their study can explain why some materials exhibit [superconductor-like properties](#) under specific conditions. It will also allow scientists to develop novel superconductor materials.

The mystery of dark electrons

Scientists are able to detect regular electrons using various spectroscopy techniques because they can absorb a photon's energy, allowing atoms and molecules to absorb light.

Dark electrons, on the other side, are fundamental particles [that form dark matter](#). They don't interact with photons and any other electromagnetic forces, and therefore scientists can't detect their presence using spectroscopy methods.

Since dark electrons don't interact with light particles, [dark matter which is around 27 percent](#) of the universe, is also unable to absorb light and therefore remains invisible.

While some scientists consider dark electrons to be hypothetical particles, many others believe that materials around us also contain electrons in a dark state that is hidden from us. For the first time, scientists have solid evidence suggesting that the latter is true.

Finding the hidden electrons

Many previous studies that aimed to find dark electrons used materials such as graphenes that had only one pair of sublattices, a specific repeating arrangement of a subset of atoms within the larger crystal structure of a material.

However, the researchers chose materials with two pairs of sublattices for their study. This is because they could deduce the number of total electrons (including both regular and dark) in the sublattices of such materials.

"We studied three materials, palladium diselenides (PdSe_2), cuprate superconductors ($\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ or Bi-2212), and lead halide perovskites (CsPbBr_3)," Keun Su Kim, one of the study authors and a physics professor at Yonsei University, [said](#).

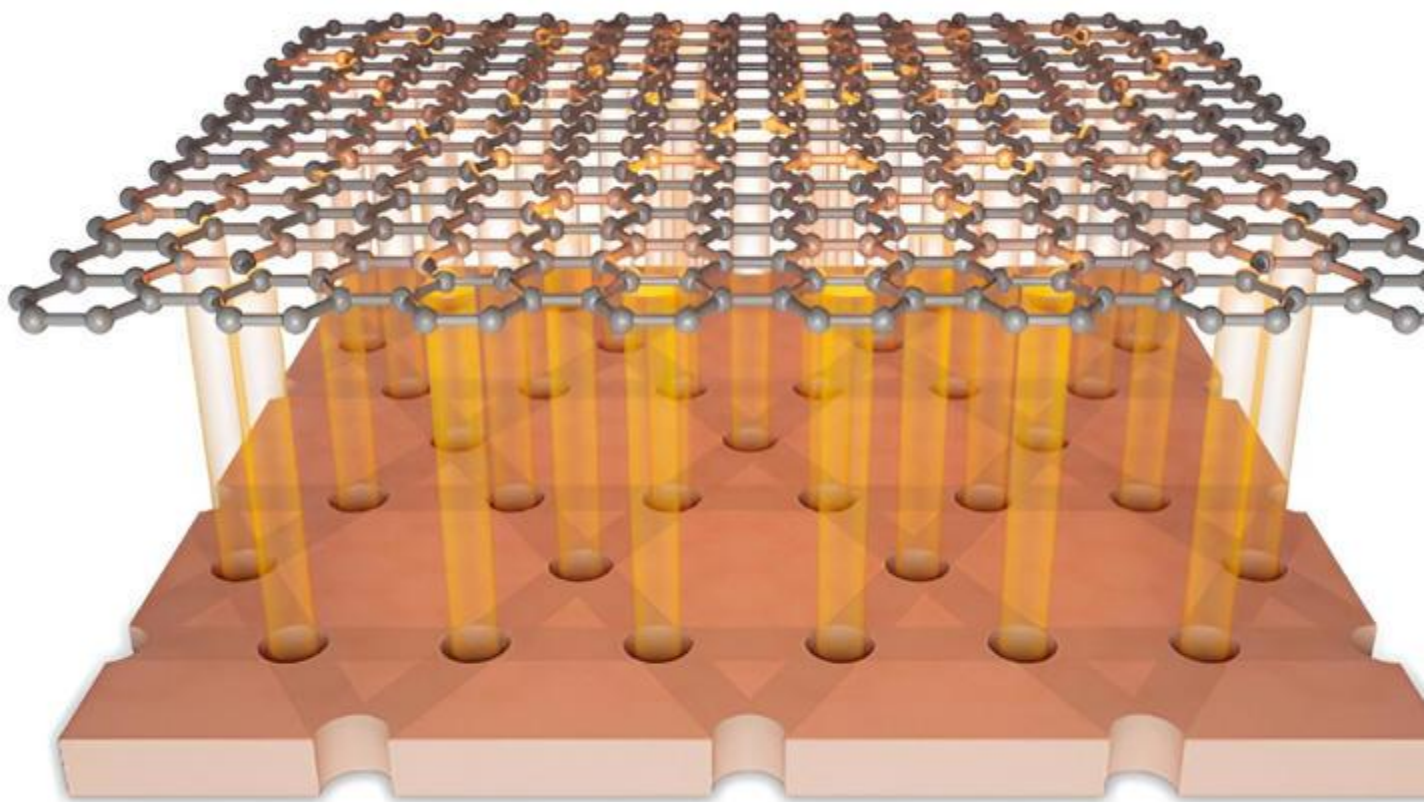
The study authors knew that materials with two pairs of sublattices in their quantum state have four types of electrons. However, when they used angle-resolved photoemission spectroscopy (ARPES), a technique used for studying electrons in solid materials, they obtained a different result.

ARPES involves photons striking a material's surface and causing the emission of electrons ([photoelectric effect](#)). It revealed the presence of only one type of electron. This meant that the remaining three types of electrons didn't interact with the photos, suggesting they were in a dark state.

"We could see experimental signals only for electrons expected to be detectable (bright states) and could not see any experimental signals for electrons expected to be undetectable (dark states)," Kim said.

Although further research is required to confirm these findings, this experiment does highlight the significance of sublattices when it comes to studying dark electrons.

"Our results suggest that the sublattice degree of freedom, which has been overlooked so far, should be considered in the study of dark electron-related phenomenon and optoelectronic characteristics," the study authors added.



The kagome-type artificial superlattice. Credit: Shuai Wang et.al

A research team has introduced a novel method for selectively tuning electronic bands in graphene. Their findings, [published](#) in *Physical Review Letters*, showcase the potential of artificial superlattice fields for manipulating different types of band dispersions in graphene.

Traditional band engineering methods, such as heterostructures, interfacial strain, and alloying, have limitations, particularly in providing in situ and continuous control over the engineered band structures. The advent of van der Waals (vdW) materials, especially graphene, has opened new avenues for band structure

engineering through gating and moiré heterostructures, which can modify energy bands and lead to various emergent physical phenomena.

The primary challenge lies in the precise control and manipulation of band structures to achieve specific electronic properties. Previous methods have been less flexible and lacked the ability to actively and selectively modify dispersion characteristics of bands.

To address the challenges, this research introduces a paradigm-shifting method of band engineering by creating an artificial kagome superlattice to manipulate the Dirac bands in graphene. The kagome superlattice is designed with a large period of 80 nm, which is pivotal for folding and compressing various high-energy bands into a low-energy regime that can be experimentally observed and manipulated.

The study's key innovation lies in the use of a high-order potential within the kagome superlattice. This potential allows for the reconstruction of band structures through different contributions, leading to dispersion-selective band modulation. The researchers fabricated the artificial lattice device using standard van der Waals assembly techniques and electron beam lithography, creating a kagome-lattice pattern that functions as a local gate for the graphene.

By independently adjusting the voltage applied to the local gate and the doped silicon substrate, the researchers were able to finely control both the strength of the artificial potential and the carrier density in the graphene. The high-order kagome potential enabled the researchers to observe and manipulate the redistribution of spectral weight among multiple Dirac peaks.

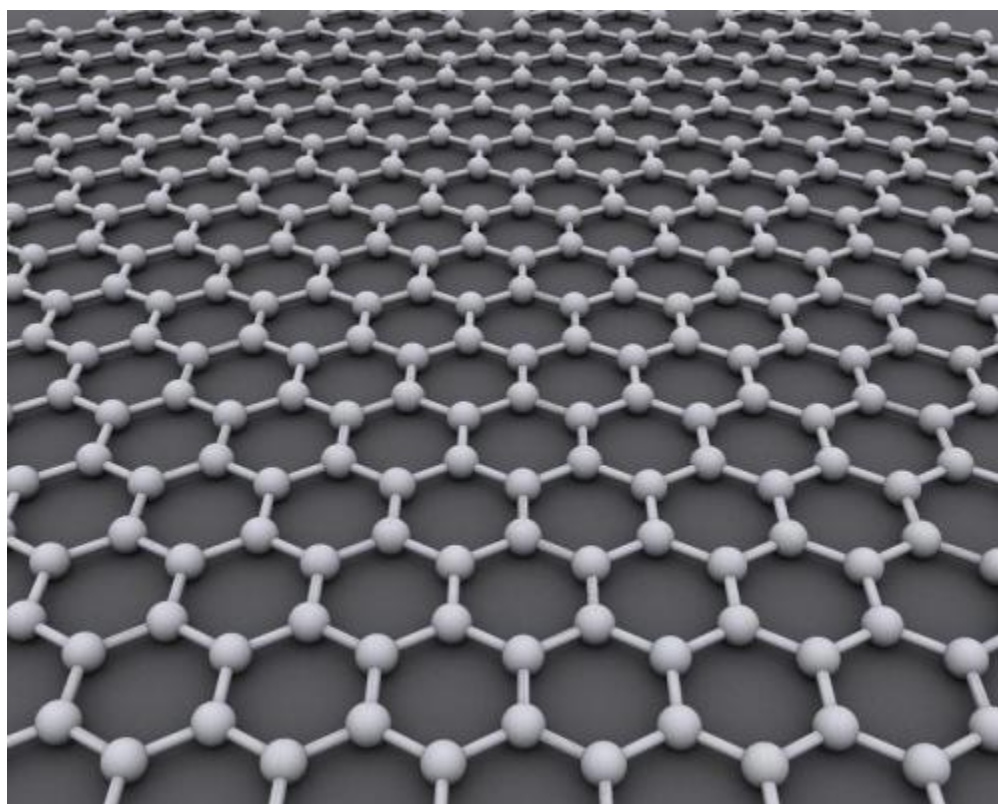
Furthermore, the application of a magnetic field was shown to effectively weaken the superlattice's impact on the band structure, reactivating the intrinsic Dirac band. This finding provides an additional knob for controlling the electronic properties of the material.

In conclusion, the innovative approach presented in the study, leveraging an artificial kagome superlattice, offers unprecedented control over band structure engineering. This method not only advances the field's capacity for precise manipulation of electronic properties but also opens new avenues for the discovery of novel physical phenomena and materials with designed functionalities.

The team was led by Prof. Zeng Changgan from the University of Science and Technology of China (USTC) of the Chinese Academy of Sciences (CAS), who collaborated with Prof. Sheng Junyuan from Wuhan University and Prof. Francisco Guinea from IMDEA Nanociencia in Spain.

More information: Shuai Wang et al, Dispersion-Selective Band Engineering in an Artificial Kagome Superlattice, *Physical Review Letters* (2024). DOI: [10.1103/PhysRevLett.133.066302](https://doi.org/10.1103/PhysRevLett.133.066302)

Provided by University of Science and Technology of China



Credit: AlexanderAIUS/Wikipedia/CC BY-SA 3.0

Twenty years ago this October, two physicists at the University of Manchester, Andre Geim and Konstantin Novoselov, published a [groundbreaking paper](#) on the "electric field effect in atomically thin carbon films." Their work

described the extraordinary electronic properties of graphene, a crystalline form of carbon equivalent to a single layer of graphite, just one atom thick.

Around that time, I started my doctorate at the University of Surrey. Our team specialized in the electronic properties of carbon. Carbon nanotubes were the latest craze, which I was happily following. One day, my professor encouraged a group of us to travel to London to attend a talk by a well-known science communicator from the University of Manchester. This was Andre Geim.

We were not disappointed. He was inspiring for us fresh-faced Ph.D. students, incorporating talk of wacky Friday afternoon experiments with levitating frogs, before getting on to atomically thin carbon. All the same, we were skeptical about this carbon concept. We couldn't quite believe that a material effectively obtained from pencil lead with sticky tape was really what it claimed to be. But we were wrong.

The work was quickly copied and reproduced by scientists across the globe. New methods for making this material were devised. Incredible claims about its properties made it sound like something out of a Stan Lee comic. Stronger than steel, highly flexible, super-slippery and impermeable to gases. A better electronic conductor than copper and a better thermal conductor than diamond, as well as practically invisible and displaying a host of exotic quantum properties.

Graphene was hailed as a revolutionary material, promising [ultra-fast electronics](#), [supercomputers](#) and [super-strong materials](#). More fantastical claims have included [space elevators](#), [solar sails](#), [artificial retinas](#), even [invisibility cloaks](#).

Just six years after their initial work, Geim and Novoselov were awarded the [Nobel Prize in Physics](#), further fueling the enthusiasm around this wonder stuff. Since then, hundreds of thousands of academic papers have been published on graphene and related materials.

But not everyone is on board. Skim through the comments section of any popular article on the material, and you'll quickly find the skeptics. We have endured decades of empty promises about the real-world impact of graphene, they complain. Where are the game-changing products to enrich our lives or save the world from climate change, they ask.

So has graphene been a resounding success or a damp squib? As is so often the case, the reality is somewhere in between.

Graphene's ups and downs

In terms of public perception, it's fair to say that graphene has been held to an impossible standard. The popular media can certainly exaggerate science stories for clicks, but academics—including myself—are not immune from over-egging or speculating about their pet projects either. I'd argue this can even be useful, helping to drive new technologies forward. Equally, though, there can be a backlash when progress looks disappointing.

Having said that, disruptive technologies such as cars, television or plastic all required decades of development. Graphene is still a newcomer in the grand scheme of things, so it's far too early to reach any conclusions about its impact.

What has quietly occurred is a steady integration of graphene into numerous practical applications. Much of this is thanks to the [Graphene Flagship](#), a major European research initiative coordinated by Chalmers University of Technology in Sweden. This aims to bring graphene and related materials from academic research to real-world commercial applications, and more than 90 products have been developed over the past decade as a result.

These include blended plastics for high-performance [sports equipment](#), more durable [racing tires](#) for bicycles, [motorcycle helmets](#) that better distribute impact forces, [thermally conductive coatings](#) for motorcycle components, and [lubricants](#) for reducing friction and wear between mechanical parts.

Graphene is finding its way into [batteries](#) and [supercapacitors](#), enabling faster charging times and longer life spans. Conductive graphene inks are now used to manufacture [sensors](#), [wireless tracking tags](#), [heating elements](#), and [electromagnetic shielding](#) for protecting sensitive electronics. Graphene is even used [in headphones](#) to improve the sound quality, and as a more efficient means of transmitting heat in [air-conditioning units](#).

Graphene oxide products are being used for [desalination](#), [wastewater treatment](#) and purification of [drinking water](#). Meanwhile, a range of graphene

materials can be bought off the shelf for use in countless other products, and major corporations including [SpaceX](#), [Tesla](#), [Panasonic](#), [Samsung](#), [Sony](#) and [Apple](#) are all rumored or known to be using them to develop new products.

From promise to practicality

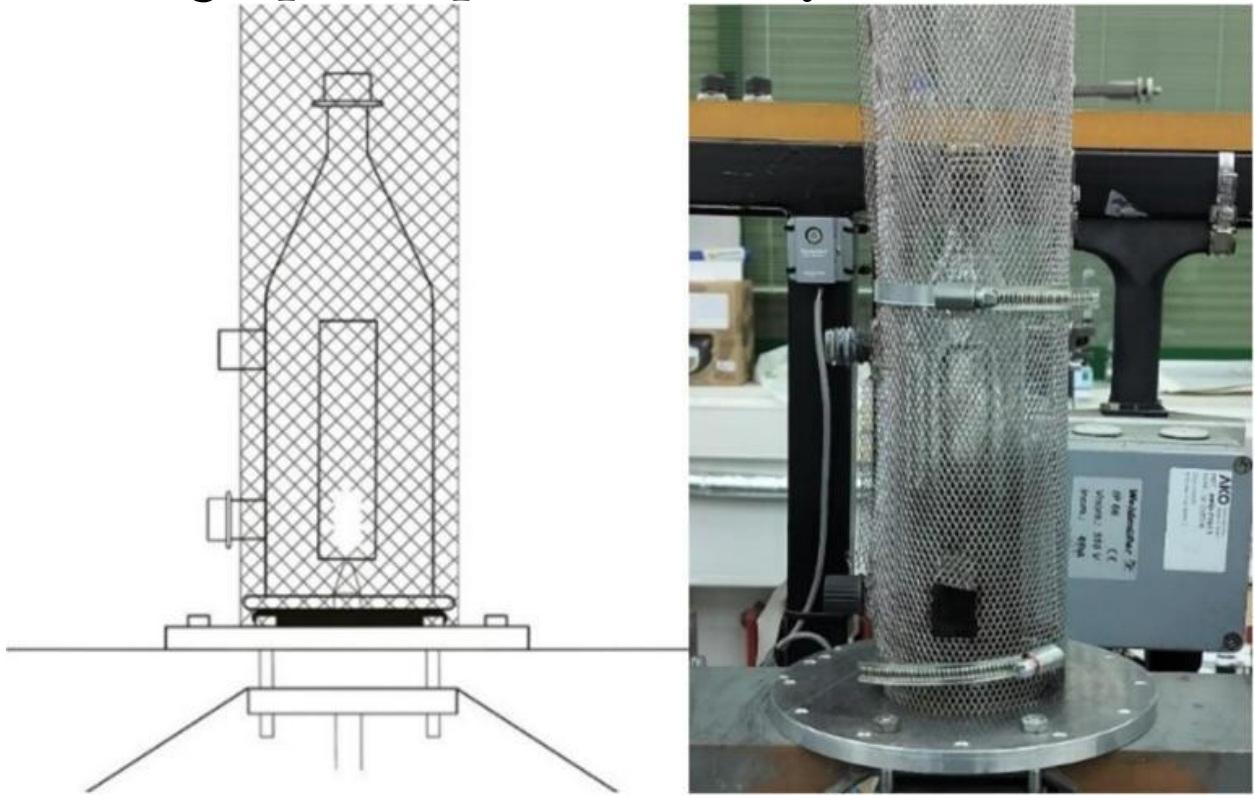
The impact of graphene on materials science is undeniable. The impact on consumer products is tangible, but not as visible. Once a material is embedded in a working product, there is little need to keep mentioning it, and proprietary concerns can make companies reluctant to get into details in any case. Consumers can therefore be blissfully unaware that their car, mobile phone, or golf club contains graphene, and most probably don't care, as long as it works.

As production methods improve and costs decrease, we can expect graphene to become ever more widely adopted. Economies of scale will make it more accessible, and the range of applications is likely to continue to expand.

Personally, after two decades, I still get excited when I try it out for something new in the lab. While I may be guilty of having contributed to the initial hype, I remain optimistic about graphene's potential. I'm still waiting for my ride on a space elevator, but in the meantime, I'll take comfort in the fact that graphene is already helping to shape a better future—quietly and steadily.

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A new plasma-based technological design boosts graphene production by more than 22%



Shielded TIAGO torch reaction chamber: conceptual illustration (left) and realized prototype (right). Credit: Chemical Engineering Journal (2024). DOI: 10.1016/j.cej.2024.155088

Harder than a diamond, stronger than steel, as flexible as rubber and lighter than aluminum. These are just some of the properties attributed to graphene. Although this material has sparked great interest in the scientific community in recent years, there is still no cheap and sustainable enough method for its high-quality manufacturing on an industrial scale.

A research team from the University of Córdoba (UCO) has just [published](#) a new prototype in the journal *Chemical Engineering Journal* that could precisely represent a great step forward towards the large-scale production of this material, first synthesized in 2004, with those responsible winning a Nobel Prize six years later.

This new technological design, which has already been registered for evaluation as a patent and is based on a previous patent of the team itself, increases the production of graphene by more than 22%, with the process maintaining the high quality that characterizes graphene synthesized with this technology.

The work is based on plasma technology, a partially ionized gas often referred to as the fourth state of matter. Although there are natural plasmas, such as lightning and the Northern Lights, they can also be artificially generated in a laboratory.

One of its great advantages, highlighted the study's lead author, Francisco Javier Morales, is that "it is a highly energetic medium that is capable of breaking down organic molecules very easily." Specifically, the team used this plasma torch to break down ethanol and rearrange the molecule's carbon atoms, resulting in the creation of graphene.

A Faraday cage to optimize energy

Although this graphene synthesis process is already protected under the group's patent, the study's novel innovation is its great increase in graphene production thanks to the process's energy optimization.

As explained by the team's principal investigator, Rocío Rincón, previous studies by the group had shown that almost 43% of the energy supplied was dissipated and went to waste. This is a clear example of how, as is often the case in science, one finding leads to another, and applied research is built on the foundations of basic research.

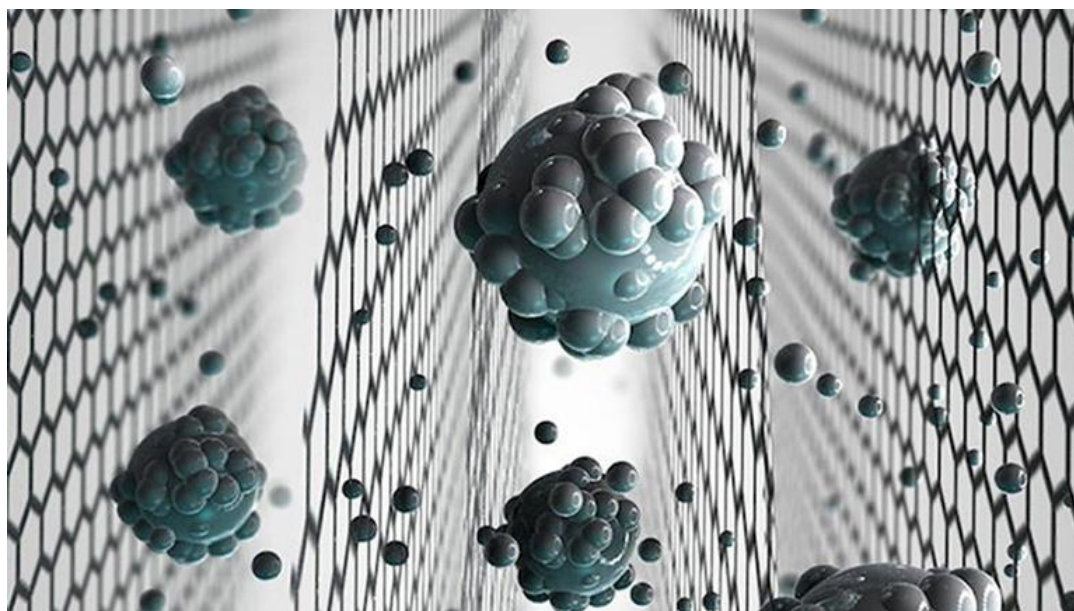
To avoid, precisely, this valuable loss of energy, around the plasma the research team built a Faraday cage, a metal mesh that acts as an electromagnetic shield, similar to the one used by microwaves to insulate the system from the outside. In this way, according to the results of the study, while 4.3 milligrams of graphene were previously generated per minute and watt, with this new shielding, which takes maximum advantage of the plasma energy, 5.2 milligrams are produced with the same amount of time and power.

The study was carried out by the Plasma Innovation Laboratory research group at the University of Cordoba, in collaboration with the Chemical Institute for Energy and the Environment (IQUEMA), which was partly responsible for the evaluation of the quality of the graphene produced.

More information: F.J. Morales-Calero et al, Increasing the production of high-quality graphene nanosheet powder: The impact of electromagnetic shielding of the reaction chamber on the TIAGO torch plasma approach, *Chemical Engineering Journal* (2024). DOI: [10.1016/j.cej.2024.155088](https://doi.org/10.1016/j.cej.2024.155088)

Provided by University of Córdoba

UK-Saudi deal to make 'miracle material' at scale



Graphene has been described as the world's first two-dimensional material.

A deal has been struck for the world's first commercial production of carbon fibre enriched with graphene in a new project led by a UK company in Saudi Arabia.

Manchester firm Graphene Innovations Manchester (GIM) has agreed to construct a factory in the Gulf state to manufacture the advanced "wonder" material for use in the kingdom's huge [plans to build futurist eco-cities in the desert](#).

About £250m could be invested in building a research and innovation hub in Greater Manchester as part of the deal and more than 1,000 jobs could be created.

Dr Vivek Koncherry, GIM chief executive, said producing the material at scale had the potential "to change every aspect of our lives".



The factory will be built in Saudi Arabia with the backing of investors© BBC

Scientists describe graphene as a nanomaterial that is effectively two-dimensional, because the hexagonal lattice structure that makes it up is only one atom thick.

About 200 times stronger than steel, it has been praised for its "amazing properties" and excitement built over its future use when it was discovered by scientists at the University of Manchester in 2004.

- [Graphene: 20 years of a 'miracle' made in Manchester](#)

The deal between GIM and Saudi-based investors Organized Chaos to build the factory and see investment return to the UK was heralded by UK Prime Minister Sir Kier Starmer on a trip to the Gulf State on Sunday.



Dr Vivek Koncherry said the advanced material would be produced at scale© GIM

The first machine constructing the material is already operational, with the factory expected to be up and running by the end of 2025, Dr Koncherry said.

He studied graphene as a student at the University of Manchester and was supported to set up his company by the university's National Graphene Institute.

Dr Koncherry said the material could "change the world" by enabling new building techniques, lighter materials for aviation and space explorations.

"My idea is to rapidly develop products that can solve global problems like climate change, water shortage, plastic pollution, because the world is facing so many challenges, we can't wait anymore."

His company plans to build the first factory producing graphene enriched carbon fibre in the UK by 2026, he said.

Professor James Baker at the university's Graphene Engineering Innovation Centre, said the deal was a "significant development".

He said the commercialisation of the material was evidence of a "tipping of new products and applications being developed for the market".

How Carbon Nanotubes Will Change the World

9 Ways Carbon Nanotubes Just Might Rock the World

Nanotubes have been billed as the key to curing cancer, building space elevators, and creating real-world Spidermen. Whether they're totally tubular or just an overhyped pipe dream remains to be seen.

Oh carbon nanotubes, is there anything you can't do?

Nanotubes can be envisioned as one-atom thick sheets of carbon that have been rolled into tubes. Researchers know that when things get that small, they act a little weird, and labs around the world are now racing to capitalize on [nanotubes](#)' strange properties. With their extraordinary strength and fascinating knack for conducting electricity and heat, nanotubes are finding applications in everything from cancer treatments to hydrogen cars. These structures of carbon may be tiny—a nanotube's diameter is about 10,000 times smaller than a human hair—but their impact on science and technology has been enormous.

Here, we count down nine of the most enticing possibilities for these giants on the Lilliputian stage. They probably won't all pan out, but if nanotubes fulfill just a few of these predictions, they'll be worth the buzz.

9. X-traordinary X-rays A new nanotube-based imaging system could take sharper, faster pictures that trump today's X-rays and CT scans. Researchers from the University of North Carolina say their device will be especially useful for imaging organs that are perpetually in motion, like the heart and lungs.

In a traditional X-ray machine, a filament emits electrons when it is heated above a certain threshold, and those electrons fly through the body and hit a metal electrode on the other side, creating images; CT scans produce three-dimensional images by rotating the electron source. But [the new system](#) uses an array of carbon nanotubes that emit hundreds of electrons simultaneously as soon as voltage is applied to them. The system is faster than a regular X-ray machine because there are no filaments to

warm up, and the multiple nanotube emitters can also take pictures from many different angles without moving.

8. Helping the Hydrogen Car Cars powered by hydrogen fuel cells have been a clean energy dream for years, but they've been held back largely by the expense of making fuel cells. The Department of Energy estimates that half of a fuel cell's price tag comes from the platinum catalyst used to speed up the reaction that produces energy. But in February a team of researchers found that bundles of carbon nanotubes doped with nitrogen form a **more efficient and more compact catalyst**.

While carbon nanotubes are currently fairly expensive to produce, researchers note that the price has been plummeting. Researchers from the University of Dayton, Ohio note that nanotube production costs have fallen 100-fold since 1990, while no such price reductions are likely with platinum, a limited natural resource.

7. Diagnosis Via Nanotube Spanish researchers say nanotubes can even help with an embarrassing medical problem, and have **created a biosensor** that can diagnose yeast infections (the irritating fungal infections that can take hold on the genitals). The scientists say their gadget provides a quicker diagnosis than today's typical method, in which a cell sample is taken and cultured in the lab to look for the presence of the *Candida albicans* fungus.

The researchers built a transistor that contains carbon nanotubes and antibodies programmed to attack the *Candida* yeast cells. When a cell sample is put on the biosensor, the interaction between the yeast and the antibodies changes the electric current of the device. The extremely conductive nanotubes record the change and allow researchers to measure how much yeast is present.

6. The Smallest Chips in the Land Nanotubes could even spell the end of a building block of our modern world: the silicon-based computer chip. Several research groups have found ways to "unzip" carbon nanotubes to produce **atom-thick ribbons of graphene**. Like silicon, graphene is a semiconductor, but the nano-sized ribbons could be used to pack much more processing power on every computer chip.

Researchers have made graphene ribbons before, but never as easily—previously the ribbons were cut from larger graphene sheets, which offered little control over their size and shape. In contrast, unzipping nanotubes is a precise process. One research group first stuck the nanotubes to a polymer film, then used argon gas to etch away a strip from each tube to produce the nanoribbons.

5. Turn It Up! The next application could make for a noisier world: Chinese researchers have found a way to make flexible, **paper-thin loudspeakers** out of nanotube sheets. The scientists say the technology could be used to add an auditory dimension to anything from clothing to magazines—and to prove their point, they put one on a waving flag.

The nanospeakers don't generate sound like conventional speakers, which make noise by vibrating the surrounding air molecules. Instead, they harness a phenomenon called the thermoacoustic effect, which is how lightning produces thunder. When an electric current runs through the nanotube sheets, they heat and expand the air near them, creating sound waves.

4. Taking Lessons from the Gecko Real-world Spidermen could one day scamper up walls thanks to an **adhesive made of carbon nanotubes**. The substance mimics the design of gecko feet, which are covered in millions of tiny hairs that each end in a profusion of spatula-shaped tips. The lizards can defy gravity and walk up sheer surfaces because when those tiny tips are close to a surface, they induce a strong attractive force that operates on the atomic scale, known as the **van der Waals force**.

The nanotech version of this system is a glue that is ten times stickier than the gecko's feet. Researchers made arrays of vertically aligned nanotubes that were topped with shorter nanotube bits, like branching treetops. The adhesive worked on a variety of surfaces, including slick glass and rough sandpaper, but its hold could easily be broken by those who knew the trick. Just like a gecko lifting its foot away from the wall, researchers pulled the glue pad away at a 90-degree angle so that only the tips of the branching nanotube bits were touching the surface, and it easily came away.

3. Flexible, Bendable Electronics Imagine a **computer screen that could be bent**, folded in half, and even crumpled like a sheet of newspaper, without affecting its function in the slightest. Researchers at the University of Tokyo took a step in that direction in May when they constructed a display made of organic light-emitting diodes (OLEDs) paired with a rubbery, nanotube-based conductor.

The organic compounds in an OLED system emit light when an electric current is passed through them, and they need no backlight, making them thinner than traditional displays. As nanotubes are natural semiconductors, they channel the electricity to the organic compounds. Researchers can envision enough technological applications to fill a World's Fair, including everything from food packages with interactive displays to artificial skin for robots and coatings for airplanes that would check the craft for wear and tear.

Low-cost, large-scale fabrication could be around the corner: The researchers used a cheap industrial printing process to deposit the nanotubes on a rubbery surface.

2. Space Elevator, Going Up Carbon nanotubes are renowned for their superior strength, and in March researchers from the University of Texas manipulated that property to **create a material** that is simultaneously strong, stretchy, and nearly as light as air. The researchers made an aerogel (a low-density solid) out of nanotubes, and found that it was as strong as steel. Meanwhile, applying voltage to the material made it stretchier than rubber.

What possible uses could the world find for such a material? One idea is to fashion nanotube ropes to act as cables for a **space elevator**, which could lift astronauts, cargo, or even tourists into orbit. The **62,000-mile-long cables** would have to be strong and flexible so they wouldn't break when buffeted by atmospheric storms and space debris, but light enough so they wouldn't collapse under their own weight.

1. Tumor Blitz The tiny tubes could even end up as must-haves in cancer hospitals one day. In a recent **study**, researchers injected carbon nanotubes into kidney tumors in mice, and then directed a near-infrared laser at the tumors. The tubes responded to the laser blast by vibrating, which created enough heat to kill surrounding tumor cells.

In the group that received the highest dose of nanotubes followed by a 30-second laser treatment, the tumors shrank and completely **disappeared in 80 percent of the mice**. The procedure didn't appear to damage the animals' internal organs, and left only a slight burn on the skin. But researchers haven't yet proven that nanotubes are safe and non-toxic, and say that much more research must be done before such procedures are ready to be tested in humans.

Carbon nanotubes – what they are, how they are made, what they are used for

Content

What are carbon nanotubes?

Carbon allotropes

Electrical properties of carbon nanotubes

Properties of carbon nanotubes

Difference between carbon nanotubes and carbon nanofibers

Who discovered carbon nanotubes?

How are carbon nanotubes made?

Applications of carbon nanotubes and their uses

– Materials

– Catalysis

– Transistors

– Sensors

– Nano inks

– Electrodes

– Displays

– Buckypaper

– Optoelectronic and photonic applications

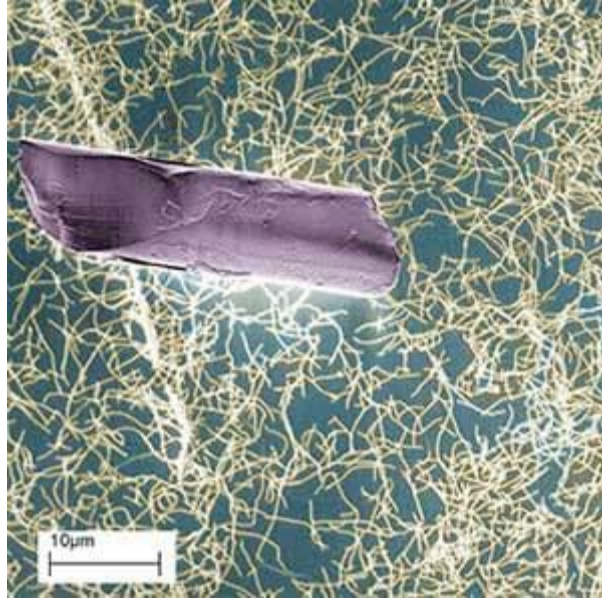
– Nanomedicine and biotechnology

– Filtration

Frequently Asked Questions (FAQs) about carbon nanotubes

What are carbon nanotubes?

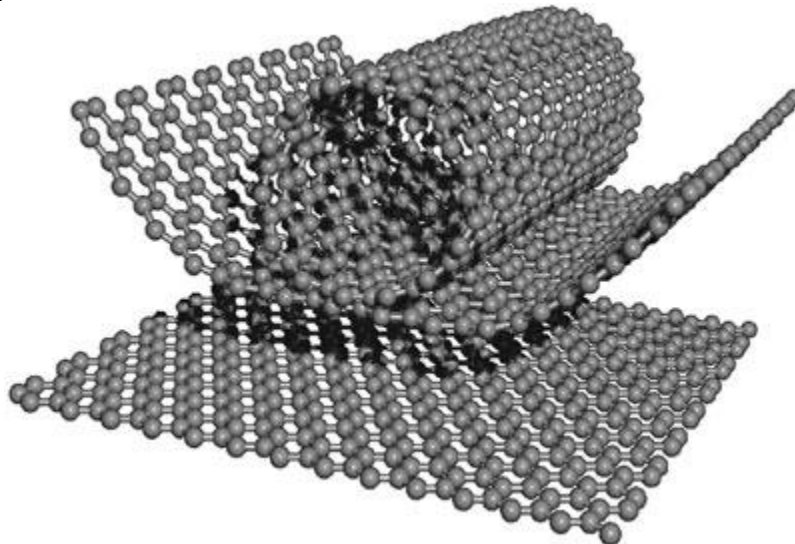
Carbon nanotubes (CNTs) are cylindrical molecules that consist of rolled-up sheets of single-layer carbon atoms (graphene). They can be single-walled (SWCNT) with a diameter of less than 1 nanometer (nm) or multi-walled (MWCNT), consisting of several concentrically interlinked nanotubes, with diameters reaching more than 100 nm. Their length can reach several micrometers or even millimeters.



The purple structure is a human hair fragment, with a diameter of about 80 to 100 thousand nanometers and in the background is a network of single-walled carbon nanotubes. (Image: Jirka Cech)

Like their building block graphene (Why not read our extensive tutorial on [graphene](#) – which includes a fantastic infographic), CNTs are chemically bonded with sp^2 bonds, an extremely strong form of molecular interaction.

This feature combined with carbon nanotubes' natural inclination to rope together via van der Waals forces, provide the opportunity to develop ultra-high strength, low-weight materials that possess highly conductive electrical and thermal properties. This makes them highly attractive for numerous applications.



Schematic of how graphene could roll up to form a carbon nanotube.

Carbon allotropes

Carbon is the fourth-most-abundant element in the universe and, depending on the arrangements of carbon atoms, takes on a wide variety of forms, called *allotropes*. Carbon allotropes exhibit unique properties of strength and electrical conductivity.

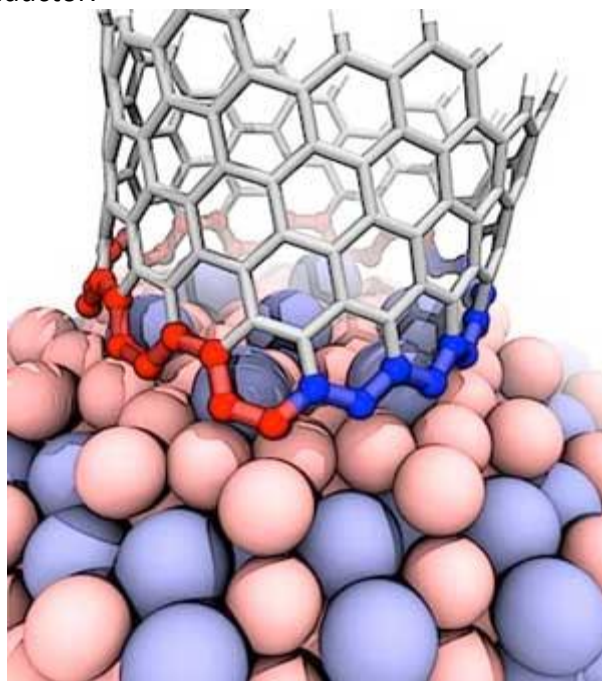
Solid carbon at room temperature has two classical structures: diamond and graphite. In 1985 the discovery of the existence of a third and new carbon allotrope containing sixty perfectly symmetrically arranged carbon atoms (also known as C₆₀, fullerene, or buckyballs) meant a major breakthrough and opened a novel field of carbon nanochemistry. Then, in 1991, carbon nanotubes were discovered and graphene in 2004.

Electrical properties of carbon nanotubes

The rolling-up direction (rolling-up or *chiral* vector) of the graphene layers determines the electrical properties of the nanotubes. Chirality describes the angle of the nanotube's hexagonal carbon-atom lattice.

Armchair nanotubes – so called because of the armchair-like shape of their edges – have identical chiral indices and are highly desired for their perfect conductivity. They are unlike *zigzag* nanotubes, which may be semiconductors. Turning a graphene sheet a mere 30 degrees will change the nanotube it forms from armchair to zigzag or vice versa.

While MWCNTs are always conducting and achieve at least the same level of conductivity as metals, SWCNTs' conductivity depends on their chiral vector: they can behave like a metal and be electrically conducting; display the properties of a semi-conductor; or be non-conducting. For example, a slight change in the pitch of the helicity can transform the tube from a metal into a large-gap semiconductor.



This illustration shows the interface between a growing carbon nanotube and a cobalt-tungsten catalyst. The atomic arrangement of the catalyst forces the nanotube to quickly transition from

zigzag (blue) to armchair (red), which ultimately grows a nanotube . (Image: Evgeni Penev/Rice University)

Properties of carbon nanotubes

Apart from their electrical properties, which they inherit from graphene, CNTs also have unique thermal and mechanical properties that make them intriguing for the development of new materials:

- their mechanical tensile strength can be 400 times that of steel;
- they are very light-weight – their density is one sixth of that of steel;
- their thermal conductivity is better than that of diamond;
- they have a very high aspect ratio greater than 1000, i.e. in relation to their length they are extremely thin;
- a tip-surface area near the theoretical limit (the smaller the tip-surface area, the more concentrated the electric field, and the greater the field enhancement factor);
- just like graphite, they are highly chemically stable and resist virtually any chemical impact unless they are simultaneously exposed to high temperatures and oxygen - a property that makes them extremely resistant to corrosion;
- their hollow interior can be filled with various nanomaterials, separating and shielding them from the surrounding environment - a property that is extremely useful for nanomedicine applications like drug delivery.

All these properties make carbon nanotubes ideal candidates for electronic devices, chemical/electrochemical and biosensors, [transistors](#), electron field emitters, lithium-ion batteries, white light sources, hydrogen storage cells, cathode ray tubes (CRTs), electrostatic discharge (ESD) and electrical-shielding applications.

Difference between carbon nanotubes and carbon nanofibers

Please note that carbon nanotubes are different than carbon nanofibers (CNFs). CNFs are usually several micrometers long and have a diameter of about 200 nm. Carbon fibers have been used for decades to strengthen compound but they do not have the same lattice structure as CNTs. Instead, they consist of a combination of several forms of carbon and/or several layers of graphite, which are stacked at various angles on amorphous carbon (where atoms do not arrange themselves in ordered structures). CNFs have similar properties as CNTs, but their tensile strength is lower owing to their variable structure and they are not hollow inside. For starters, you could watch these five short videos about carbon nanotubes:

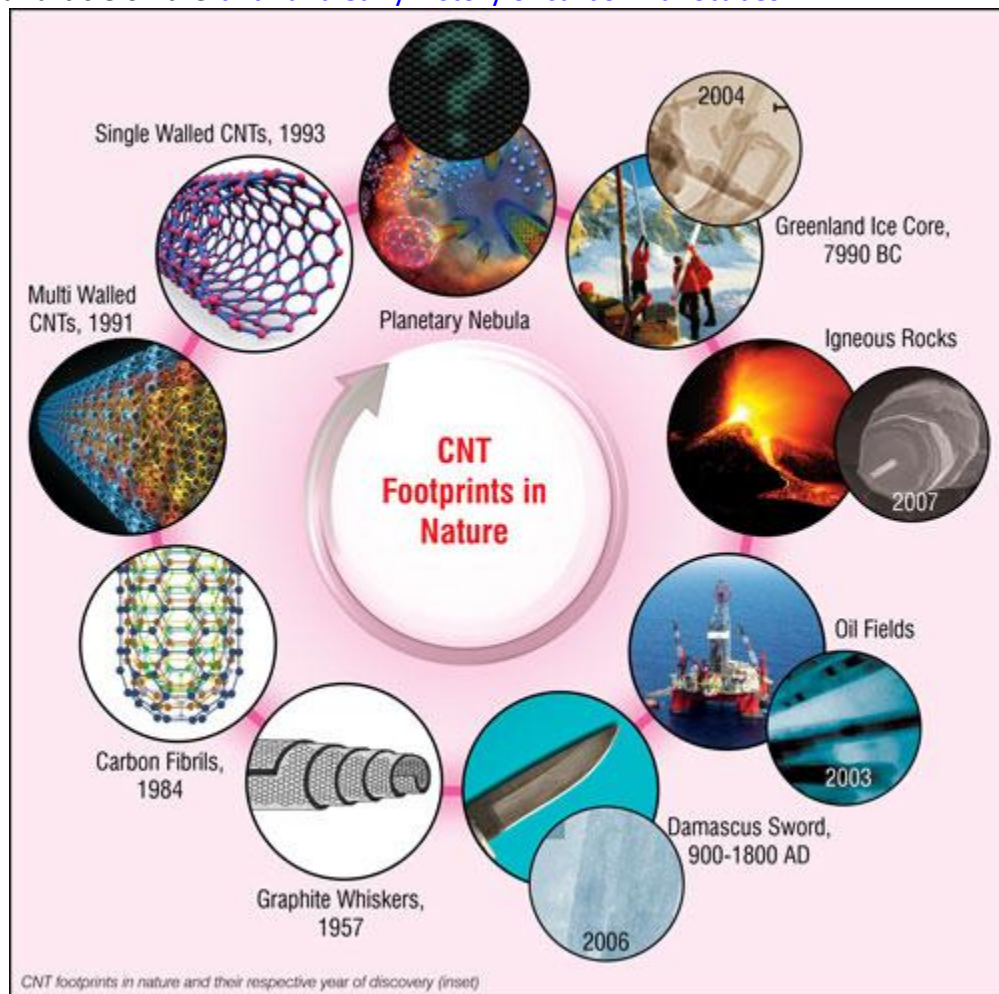
Who discovered carbon nanotubes?

Thousands of papers are being published every year on CNTs or related areas and most of these papers give credit for the discovery of CNTs to Sumio Iijima who, in 1991, published a ground-breaking paper in *Nature* ("[Helical microtubules of graphitic carbon](#)") reporting the discovery of multi-walled carbon nanotubes.

On taking a cursory look at the scientific literature, one might get the impression that Iijima is the de facto discoverer of carbon nanotubes. Of course, there is no doubt that he has made two

seminal contributions to the field, however a careful analysis of the literature suggests that certainly he is not the first one who has reported the existence of CNTs.

An editorial in the journal *Carbon* ("[Who should be given the credit for the discovery of carbon nanotubes?](#)") tried to clear the air by describing the chronological events that led to the discovery of carbon nanotubes. By delving deeper into the history of carbon nanotubes, it becomes quite apparent that the origin of CNTs could be even pre-historic in nature (read more here in our article on the [birth and early history of carbon nanotubes](#)).



CNT footprints in nature and their respective year of discovery (inset). (click on image to enlarge)

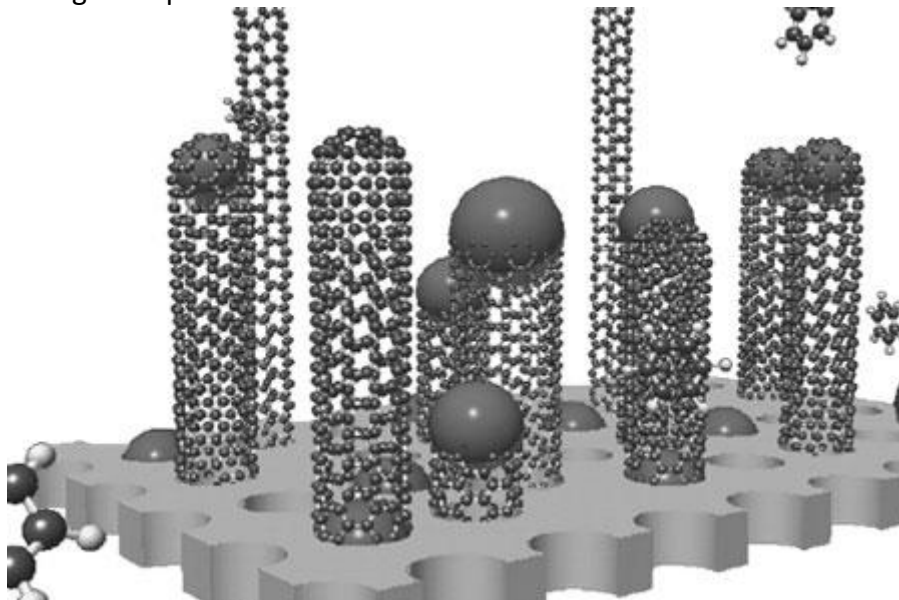
How are carbon nanotubes made?

Three main methods are currently available for the production of CNTs: arc discharge, laser ablation of graphite, and chemical vapor deposition (CVD).

In the first two processes, graphite is combusted electrically or by means of a laser, and the CNTs developing in the gaseous phase are separated. All three methods require the use of metals (e.g. iron, cobalt, nickel) as catalysts.

CVD process

The CVD process currently holds the greatest promise, since it allows the production of larger quantities of CNTs under more easily controllable conditions and at lower cost. In the CVD process, manufacturers can combine a metal catalyst (such as iron) with carbon-containing reaction gases (such as hydrogen or carbon monoxide) to form carbon nanotubes on the catalyst inside a high-temperature furnace.



Schematic view of CNT growth on catalyst particles during CVD. First, small secondary catalyst particles of the size of a CNT diameter develop, on which the nanotubes start growing. The catalyst particle is either at the top or at the bottom of the emerging nanotube. Growth will stop if the catalyst particle is deactivated through the development of a carbon envelope.

(Image: © Royal Society of Chemistry)

The CVD process can be purely catalytic or plasma-supported. The latter requires slightly lower temperatures (200-500°C) than the catalytic process (up to 750°C) and aims at producing 'lawn-like' CNT growth.

Purification

Even though synthetic techniques have been improved to obtain high-purity carbon nanotubes, the formation of byproducts containing impurities such as metal encapsulated nanoparticles, metal particles in the tip of a carbon nanotube, and amorphous carbon has been an unavoidable phenomenon, because the metal nanoparticles are essential for the nanotube growth.

These foreign nanoparticles, as well as structural defects that occurred during synthesis, have the unfortunate implication that they modify the physico-chemical properties of the produced carbon nanotubes.

That's why carbon nanotubes need to be purified with the help of various methods such as acid treatment or ultrasound at the end of the production process.

Applications of carbon nanotubes and their uses

CNTs are well-suited for virtually any application requiring high strength, durability, electrical conductivity, thermal conductivity and lightweight properties compared to conventional materials.

Currently, CNTs are mainly used as additives to synthetics. CNTs are commercially available as a powder, i.e. in a highly tangled-up and agglomerated form. For CNTs to unfold their particular properties they need to be untangled and spread evenly in the substrate.

Another requirement is that CNTs need to be chemically bonded with the substrate, e.g. a plastic material. For that purpose, CNTs are functionalized, i.e. their surface is chemically adapted for optimal incorporation into different materials and for the specific application in question.

Carbon nanotubes can also be spun into fibers, which not only promise interesting possibilities for specialty textiles but may also help realize a particularly utopian project – the [space elevator](#). (HIGHLY UNFEASIBLE—G.K.W.)

Materials

Carbon nanotube enabled nanocomposites have received much attention as a highly attractive alternative to conventional composite materials due to their mechanical, electrical, thermal, barrier and chemical properties such as electrical conductivity, increased tensile strength, improved heat deflection temperature, or flame retardancy.

These materials promise to offer increased wear resistance and breaking strength, antistatic properties as well as weight reduction. For instance, it has been estimated that advanced CNT composites could reduce the weight of aircraft and spacecraft by up to 30%.

These composite materials already find use in

- sporting goods(bicycle frames, tennis rackets, hockey sticks, golf clubs and balls, skis, kayaks; sports arrows)
- yachting (masts, hulls and other parts of sailboats)
- textiles (antistatic and electrically conducting textiles ('smart textiles'); bullet-proof vests, water-resistant and flame-retardant textiles)
- automotive, aeronautics and space (light-weight, high-strength structural composites)
- industrial engineering (e.g. coating of wind-turbine rotor blades, industrial robot arms)
- electrostatic charge protection (for instance, researchers have developed electrically conducting and flexible [CNT film specifically for space applications](#)) and radiation shielding with CNT-based nanofoams and aerogels.



CNT fabric stopped a 9MM, jacketed round in controlled ballistics testing. This material shown is roughly the same thickness as six stacked business cards. (Source: Nanocomp Technologies)

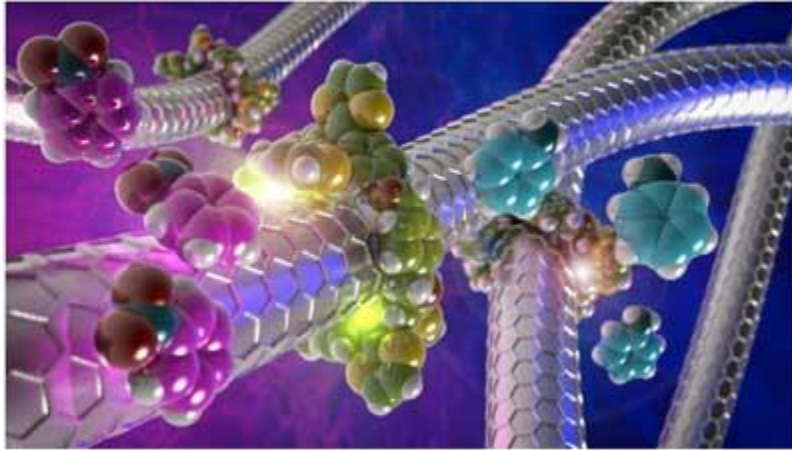
Catalysis

What makes carbon nanotubes so attractive for catalysis is their exceptionally high surface area combined with the ability to attach essentially any chemical species to their sidewalls. Already, CNTs have been used as catalysts in many relevant chemical processes, however, controlling their catalytic activity is not easy.

Initially, carbon nanotubes have been combined with molecules via very strong bonds (covalent bonds) that lead to very stable compounds. Such connection, however, implies a change in the structure of the nanotube and therefore in its properties.

It would be analogous to nailing an advertisement to a post using a thumbtack: the union is strong, but it leaves a hole in both the advertisement and the post. Weak non-covalent forces have also been used, which keep the structure of the nanotubes intact, but typically yield kinetically unstable compounds. The comparison in this case would be to tape the advert to the post. Neither the advertisement nor the post is damaged, but the union is much weaker.

To overcome this issue, researchers already are developing methods for the chemical modification of carbon nanotubes by mechanical bonding, the first example of [mechanically interlocked carbon nanotubes \(MINTs\)](#). This type of compounds is as stable as covalent compounds, but at the same time as respectful of the initial structure as the non-covalent compounds.



Positive and negative regulation of carbon nanotube catalysts through encapsulation within macrocycles. (Image: Emilio M. Pérez, IMDEA)

Transistors

Despite the rise of graphene and other two-dimensional (2D) materials, semiconducting single-walled carbon nanotubes are still regarded as strong candidates for the next generation of high-performance, ultra-scaled and thin-film transistors as well as for opto-electronic devices to replace silicon electronics (read more: ["20 years of nanotube transistors"](#)).

One of the crucial questions is if CNT transistors can offer performance advantages over silicon at sub-10 nm lengths.

There have been mixed opinions in the nanoelectronics community regarding whether or not CNT transistors would maintain their impressive performance at extremely scaled lengths.

Some argued that the very small effective mass of the carriers would contribute to a tunneling phenomena that would cause the devices to breakdown around 15 nm – an opinion supported by the few theoretical studies that explored nanotube devices at such dimensions.

Meanwhile, others remained convinced that the ultrathin body of single-walled carbon nanotubes – only 1 nm in diameter – would allow for excellent transistor behavior even down to the sub-10 nm range.



Schematic of a sub-10 nm carbon nanotube transistor configuration. (Image: Aaron Scott, Southern Illinois University)

So far researchers have achieved only promising experimental results and at this point there remain numerous challenges related to integrating CNT transistors into industrial-scale chip manufacturing.

Sensors

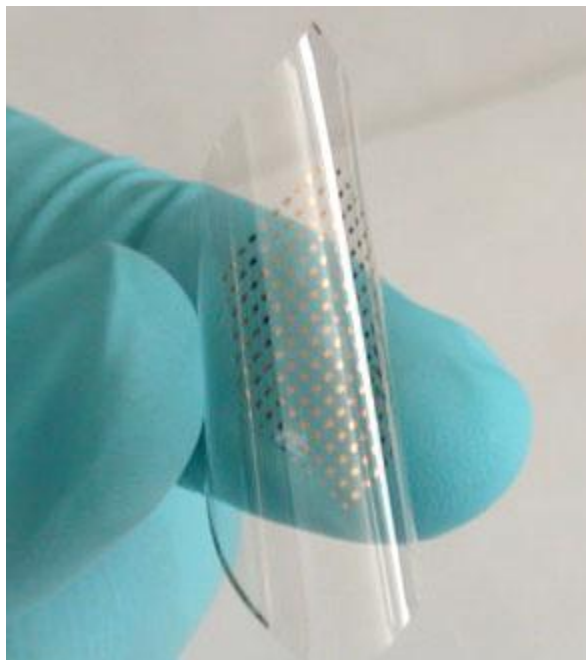
The [group](#) of Cees Dekker paved the way for the development of CNT-based electrochemical nanosensors by demonstrating the possibilities of SWCNTs as quantum wires and their effectiveness in the development of field-effect transistors.

Many studies have shown that although CNTs are robust and inert structures, their electrical properties are extremely sensitive to the effects of charge transfer and chemical doping by various molecules.

Most sensors based on CNTs are field effect transistors (FET) – although CNT are robust and inert structures, their electrical properties are extremely sensitive to the effects of charge transfer and chemical doping by various molecules. CNTs-FETs have been widely used to detect gases such as greenhouse gases in environmental applications.

The functionalization of CNTs is important for making them selective to the target analyte. Different types of sensors are based on molecular recognition interactions between functionalized CNT and target analytes.

For instance, researchers have developed [flexible hydrogen sensors](#) using single-walled carbon nanotubes decorated with palladium nanoparticles.



Example of a flexible hydrogen sensor fabricated with single-walled carbon nanotubes. (Image: Dr. Sun/Argonne)

Nano inks

Ink formulations based on CNT dispersions are attractive for printed electronics applications such as transparent electrodes, RFID tags, thin-film transistors, light-emitting devices, and solar cells (read more: "[Conductive nanomaterials for printed electronics applications](#)").

Electrodes

Carbon nanotubes have been widely used as electrodes for chemical and biological sensing applications and many other electrochemical studies. With their unique one-dimensional molecular geometry of a large surface area coupled with their excellent electrical properties, CNTs have become important materials for the molecular engineering of electrode surfaces where the development of electrochemical devices with region-specific electron-transfer capabilities is of paramount importance.

Displays

Given their high electrical conductivity, and the incredible sharpness of their tip (the smaller the tips' radius of curvature, the more concentrated the electric field, the higher field emission), carbon nanotubes are considered the most promising material for field emitters and a practical example are CNTs as electron emitters for field emission displays (FED).

Field emission display (FED) technology makes possible a new class of large area, high resolution, low cost flat panel displays. However, FED manufacturing requires CNT to be grown in precise sizes and densities. Height, diameter and tip sharpness affect voltage, while density affects current.

Buckypapers

Buckypapers could find numerous applications: As one of the most thermally conductive materials known, buckypaper could lead to the development of more efficient heat sinks for chips; a more energy-efficient and lighter background illumination material for displays; a

protective material for electronic circuits from electromagnetic interference due to its unusually high current-carrying capacity; or switchable surfaces (see: ["Nanotechnology paper for switchable surfaces"](#)).

Optoelectronic and photonic applications

While individual nanotubes generate discrete fine peaks in optical absorption and emission, macroscopic structures consisting of many CNTs gathered together also demonstrate interesting optical behavior.

For example, a millimeter-long bundle of aligned MWCNTs emits polarized incandescent light by electrical current heating and SWCNT bundles are giving higher brightness emission at lower voltage compared with conventional tungsten filaments.

Nanomedicine and biotechnology

Carbon nanomaterials such as nanotubes or graphene not only are widely researched for their potential uses in industrial applications, they also are of great interest to biomedical engineers working on nanotechnology applications.

There is considerable interest in using CNTs for various biomedical applications. The physical properties of CNTs, such as mechanical strength, electrical conductivity, and optical properties, could be of great value for creating advanced biomaterials.

Carbon nanotubes can also be chemically modified to present specific moieties (e.g., functional groups, molecules, and polymers) to impart properties suited for biological applications, such as increased solubility and biocompatibility, enhanced material compatibility and cellular responsiveness.

Nitrogen-doped carbon nanotubes for instance have been developed for drug delivery applications (["Nanoparticle-corked carbon nanotubes as drug delivery vehicles"](#)).

However, the issue of cytotoxicity of CNTs is an area that has already attracted much research interest and has not resulted in a definitive answer yet. Given the inconclusive state of these nanotoxicology studies researchers says that more systematic biological evaluations of CNTs having various chemical and physical properties are warranted in order to determine their precise pharmacokinetics, cytotoxicity, and optimal dosages.

Filtration

High-flow membranes are an important part of future energy-efficient water purification.

Already, researchers have demonstrated efficient water transport in carbon nanotubes with openings of less than one nanometer.

When embedded in fatty membranes, the nanotubes squeeze entering water molecules into a single file chain, which leads to very fast transport. The flow was 10 times faster than in wider carbon nanotubes and 6 times faster than in the best biological membrane, a protein called aquaporin (read more: ["Filtering water better than nature"](#)).

Carbon nanotubes also have been used to demonstrate protective textiles with ultra breathable membranes. These membranes provide rates of water vapor transport that surpass those of commercial breathable fabrics like GoreTex, even though the CNT pores are only a few nanometers wide.

Crucially, they also provide protection from biological agents due to their very small pore size, less than 5 nanometers wide. Biological threats like bacteria or viruses are much larger and typically more than 10-nm in size.

In order to make these membranes also protect from chemical agents, which are much smaller in size, researchers modified the CNT surfaces with chemical-threat-responsive functional groups. These functional groups will sense and block the threat like gatekeepers on the pore entrance (read more: "['Second skin' protects soldiers from biological and chemical agents](#)").

Frequently Asked Questions (FAQs) about carbon nanotubes

What are Carbon Nanotubes?

Carbon Nanotubes, or CNTs, are cylindrical nanostructures composed entirely of carbon atoms. These tubes have extraordinary mechanical, electrical, thermal, optical, and chemical properties, which makes them suitable for various applications in nanotechnology, electronics, optics, and other fields of materials science.

How are Carbon Nanotubes Made?

Carbon Nanotubes are generally produced using three methods: Arc Discharge, Laser Ablation, and Chemical Vapor Deposition (CVD). Among these, CVD is the most popular due to its lower cost and higher scalability.

What are the Types of Carbon Nanotubes?

Carbon Nanotubes come in two main types: Single-Walled Carbon Nanotubes (SWCNTs) and Multi-Walled Carbon Nanotubes (MWCNTs). The SWCNTs have a single layer of carbon atoms, while MWCNTs consist of multiple concentric layers of carbon atoms.

What are the Properties of Carbon Nanotubes?

Carbon Nanotubes possess unique properties. They are incredibly lightweight yet stronger than steel, have high thermal conductivity, excellent electrical conductivity, and exhibit unique optical properties. These attributes make them suitable for various technological applications.

What are the Applications of Carbon Nanotubes?

Carbon Nanotubes have diverse applications in many fields, including electronics, materials science, and nanotechnology. They are used in making transistors, batteries, energy storage devices, sensors, and even medical devices. In materials science, they are used for strengthening composite materials.

Are Carbon Nanotubes Safe?

The safety of Carbon Nanotubes is still under investigation. Although they have vast potential for use in various fields, their impact on human health and the environment is not fully understood. Some studies suggest they can be harmful if inhaled, similar to asbestos fibers. Thus, appropriate safety measures should be taken when handling them.

What is the Current Research on Carbon Nanotubes?

Research on Carbon Nanotubes is extensive, focusing on developing new applications, improving production methods, and studying their properties. Additionally, researchers are studying the potential environmental and health impacts of Carbon Nanotubes to ensure their safe usage.

Can Carbon Nanotubes Conduct Electricity?

Yes, Carbon Nanotubes are excellent conductors of electricity. They can carry a high current density without being damaged, making them useful in various electronics applications.

Can Carbon Nanotubes be Used in Medicine?

Yes, Carbon Nanotubes have potential applications in medicine. Their unique properties make them useful for drug delivery, tissue engineering, and as components in medical devices. However, more research is needed to ensure their safety and effectiveness in these applications.

What is the Future of Carbon Nanotubes?

The future of Carbon Nanotubes looks promising, with extensive research exploring their applications in various fields. Their unique properties could revolutionize electronics, medicine, energy storage, and materials science. However, ensuring their safe use is a critical area for future research.

Are Carbon Nanotubes Expensive?

The cost of Carbon Nanotubes can vary greatly depending on their quality, type, and production method. Generally, high-quality Carbon Nanotubes are expensive due to the complexity of their production process. However, as production methods improve, costs may decrease in the future.

How are Carbon Nanotubes Used in Electronics?

In electronics, Carbon Nanotubes are used in transistors, sensors, and other components due to their excellent electrical conductivity and unique electronic properties. They may also play a critical role in developing smaller, faster, and more energy-efficient electronic devices in the future.

What is the Environmental Impact of Carbon Nanotubes?

The environmental impact of Carbon Nanotubes is not fully understood. While they offer significant potential benefits, there are concerns about their potential to harm the environment if not properly disposed of or recycled. Research is ongoing to understand their environmental impact and develop safe handling and disposal methods.

Can Carbon Nanotubes be Recycled?

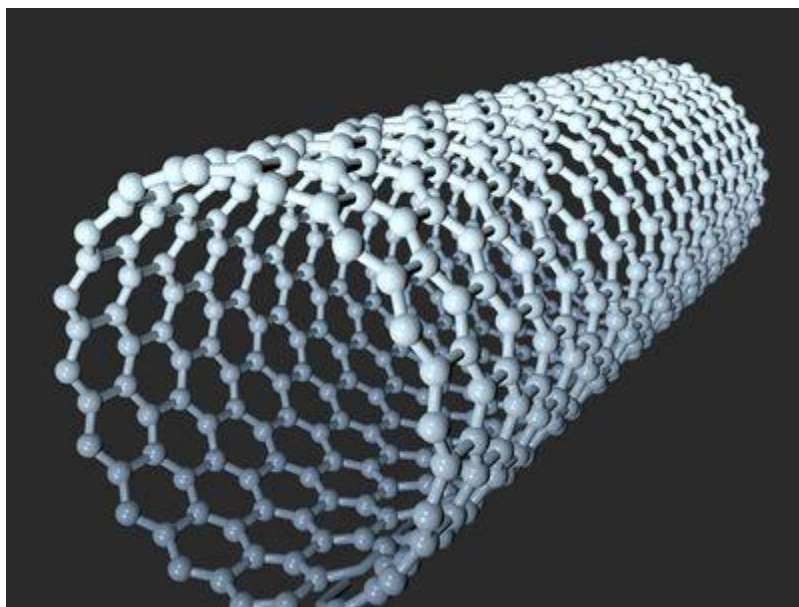
Research is ongoing to develop methods for recycling Carbon Nanotubes, especially given their potential environmental impact. While some progress has been made, effectively recycling Carbon Nanotubes and maintaining their unique properties remains a significant challenge.

What is the Role of Carbon Nanotubes in Energy Storage?

Carbon Nanotubes have significant potential in energy storage. They are used in supercapacitors and batteries due to their high surface area, electrical conductivity, and chemical stability. They can enhance energy storage devices' performance, making them more efficient and capable of storing more energy.



By [Michael Berger](#) – Michael is author of three books by the Royal Society of Chemistry: [Nano-Society: Pushing the Boundaries of Technology](#), [Nanotechnology: The Future is Tiny](#), and [Nanoengineering: The Skills and Tools Making Technology Invisible](#)
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[carbon nanotube](#) Illustration of a carbon nanotube.

carbon nanotube

carbon nanotube, nanoscale hollow tubes composed of carbon atoms. The cylindrical carbon molecules feature high aspect ratios (length-to-diameter values) typically above 10^3 , with diameters from about 1 nanometer up to tens of nanometers and lengths up to millimeters. This unique one-dimensional structure and [concomitant](#) properties endow

carbon nanotubes with special natures, rendering them with unlimited potential in [nanotechnology](#)-associated applications. Carbon nanotubes are members of the [fullerene](#) family. Although the first fullerene molecules were discovered in 1985, it was not until Sumio Iijima reported his findings in 1991 about needlelike carbon tubes in *Nature* that carbon nanotubes came to public awareness.

Since then, carbon nanotubes with various structures have been discovered. According to the number of graphic shells, they are mainly categorized as single-walled (SWNTs) and multi-walled carbon nanotubes (MWNTs). The carbon nanotubes reported by Iijima were MWNTs synthesized by arc discharge methods. Two years later, two sets of researchers working independently—Iijima and Toshinari Ichihashi, along with Donald S. Bethune and his colleagues at [IBM](#)—synthesized SWNTs, using transition-metal catalyzed arc discharge.

A SWNT can be described as a long tube formed by wrapping a single graphene sheet into a cylinder with diameter of about 1 nanometer, the ends of which are capped by fullerene cages. The fullerene structures, with alternating structures of five hexagons [adjacent](#) to one pentagon, form the surface with desired curvature to enclose the volume. The sidewalls of carbon nanotubes are made of graphene sheets consisting of neighboring hexagonal cells. Other [polygon](#) structures, such as pentagons and heptagons, [constitute](#) defects of sidewalls. The cylindrical sidewalls can be produced from different rolling directions to make SWNTs with distinct structures and properties. Due to cylindrical symmetry, there are only a handful of methods that are effective in making seamless cylinders, and they are characterized by the chiral vectors with integer indices (n , m). To establish the chiral vector, two atoms in the graphene sheet are selected, with one serving as the origin of the vector pointing toward the other [atom](#). The [graphene](#) sheet is then rolled in a way that allows the two [atoms](#) to coincide. Under these circumstances, the chiral vectors form a plane perpendicular to the longitude direction of nanotubes and the lengths of the chiral vectors are equal to the circumference. Three different types of SWNTs are distinctly characterized, named “zigzag” ($m = 0$), “armchair” ($n = m$), and “chiral.” These structural variations result in differences in electrical conductivity and mechanical strength.

MWNTs are concentrically aligned SWNT assemblies with different diameters. The distance between adjacent shells is about 0.34 nanometer. MWNTs differ from SWNTs not only in their dimensions, but also in their corresponding properties. Various techniques have been developed to produce carbon nanotubes in sizable quantity, high yield, and purity, while maintaining a reasonable cost. Well-developed techniques include arc discharge, [laser](#) ablation, and chemical vapor [deposition](#) (CVD), and most processes involve costly [vacuum](#) conditions.

Arc discharge was initially used for the synthesis of fullerenes. In a typical experimental setup, a chamber filled with low-pressure (50 to 700 mbar) [inert gas](#) ([helium](#), [argon](#)) is where the reaction takes place. Two carbon rods are placed end-to-end as the electrodes, separated by a few millimeters, and a [direct current](#) of 50 to 100 A (driven by a potential difference of 20 V) generates a high discharge temperature to [sublime](#) the [negative](#)

[electrode](#), leaving soot where carbon nanotubes are found. This method is the most common way to synthesize carbon nanotubes and perhaps the easiest way. The quality of carbon nanotubes depends on the uniformity of plasma arc, [catalysts](#), and the selection of filling gases. A mixture of carbon nanotubes is usually produced; thus, purification processes are needed to remove the fullerenes, [amorphous](#) carbon, and catalysts.

Laser ablation was first employed to produce carbon nanotubes in 1995. A pulsed or continuous laser is used to vaporize a [graphite](#) (or graphite [metal](#) mixture) target in a 1,200 °C (2,200 °F) oven filled with inert gas at a pressure of 500 torr. [Carbon](#) vapors cool down rapidly during expansion, and carbon atoms quickly condense to form tubular structures with the help of [catalyst](#) particles. MWNTs can be synthesized when pure graphite is vaporized, and SWNTs are grown from graphite-transition metal ([cobalt](#), [nickel](#), etc.) mixtures. The method is primarily used to synthesize SWNTs with high selectivity and in a diameter-controllable way by tailoring reaction temperatures. The resulting products are usually in the form of bundles. Laser ablation is the most costly technique due to the involvement of expensive lasers and high power input.

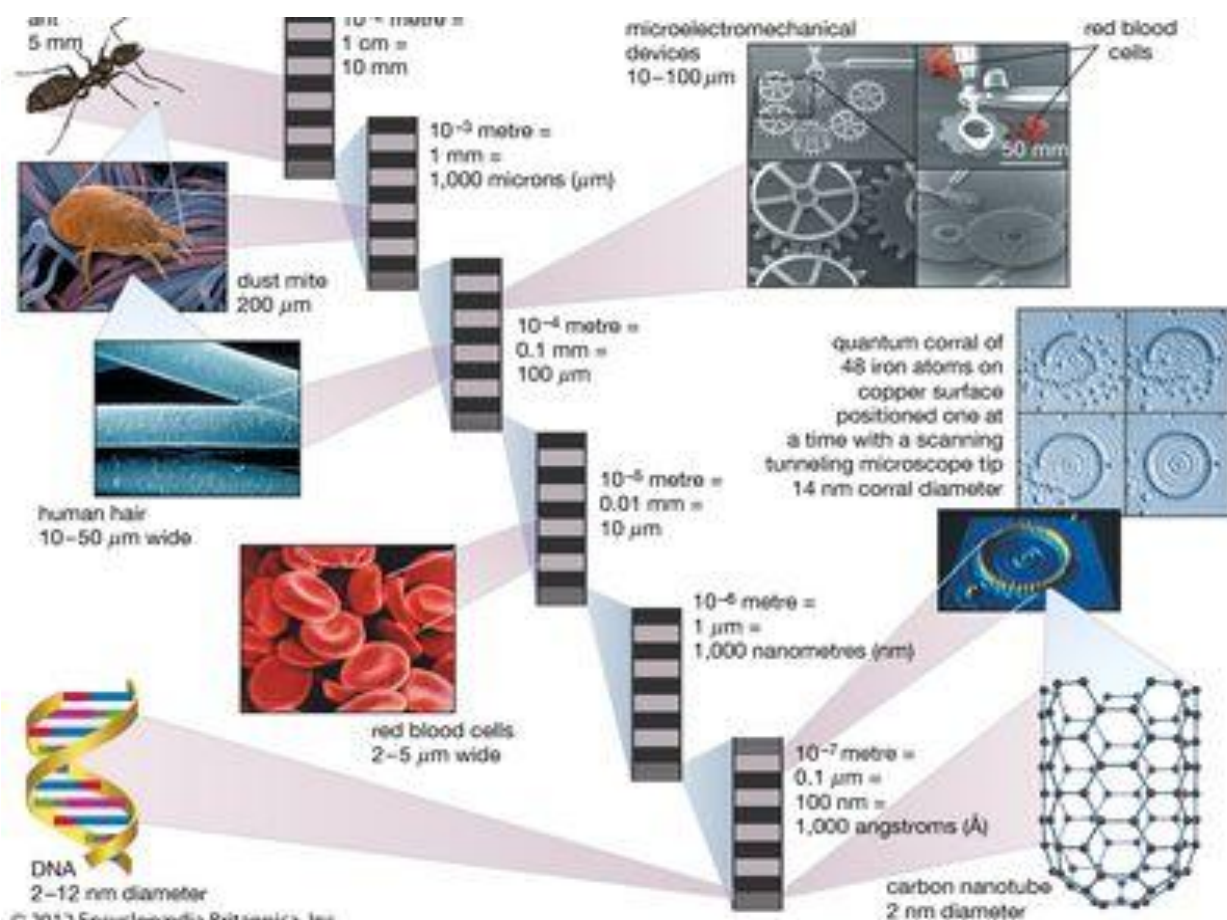
Chemical vapor deposition (CVD) is the most promising way to produce carbon nanotubes on an industrial scale. This process [utilizes](#) high energy (600–900 °C [1,100–1,650 °F]) to atomize gaseous carbon sources, such as [methane](#), [carbon monoxide](#), and [acetylene](#). The resulting reactive carbon atoms diffuse toward a catalyst-coated substrate and condense to form carbon nanotubes. Well-aligned carbon nanotubes can be synthesized with precisely controlled [morphology](#), provided that proper reaction conditions are maintained, including preparation of substrates, selection of catalysts, etc.

Novel chemical, electrical, and mechanical properties absent in other materials have been discovered in carbon nanotubes. Pristine carbon nanotubes are inert to most chemicals and need to be grafted with surface functional groups to increase their chemical reactivity and add new properties. For SWNTs, electrical conductivity is dependent on the chiral vector and independent of the length as determined by [quantum mechanics](#). Considering a chiral vector with indices (n , m), carbon nanotubes are metallic when $n = m$ or $(n - m) = 3i$ (i is an integer) and semiconducting in other cases. Along the longitude directions, carbon nanotubes show superior mechanical strength, with the highest known [tensile strength](#) and elastic modulus among known materials.

As for thermal properties, carbon nanotubes outperform [diamond](#) as the best thermal conductor. Applications of carbon nanotubes are aimed to make use of their unique properties to solve problems at the nanoscale. Their high surface area, together with the unique ability to carry any chemical [compounds](#) after surface modification, offers carbon nanotubes the potential to be used as nanoscale catalyst supports with high catalytic reactivity and chemical sensors. They are known to be the best field emitters due to their sharp tips, which can concentrate [electric field](#) easily, enabling them to emit electrons at low voltages.

This property has special applications in [field emission](#) flat-panel displays and cold-cathode [electron guns](#) used in microscopes. In nanoelectronics, SWNTs have been used to fabricate [transistors](#) that can function at room temperature and are potential candidates for devices operating at terahertz (THZ) frequencies. Engineering materials using carbon nanotubes as additives have exhibited capability to make plastic composites with [enhanced](#) electrical conductivity and mechanical strength. For biomedical applications, carbon nanotubes show promise as vehicles for targeted drug-delivery and [nerve cell](#) regeneration. However, their future success in bio-related applications is highly subject to the toxicity study, which is still in an early stage.

Some researchers have become concerned about the health risks involving carbon nanotubes, which according to lab research seem to pose a danger to human health that is similar to [asbestos](#). In particular, exposure to carbon nanotubes has been associated with [mesothelioma](#), a [cancer](#) of the lung lining. If inhaled, it is believed that nanotubes can scar lung tissues in a manner similar to asbestos fibers, a cause for concern because nanotubes are already used in many common products, such as [bicycle](#) frames, automobile bodies, and tennis rackets. Potential health risks are relevant not only to those involved in manufacturing but also to the general public, and little research has been conducted to determine if risks to human health are created when products containing nanotubes are crushed or incinerated in a waste dump.



The powers of 10 Examples from biological and mechanical realms illustrate various “orders of magnitude” (powers of 10), from 10^{-2} meter down to 10^{-7} meter.(more)

nanotechnology

nanotechnology, the manipulation and manufacture of materials and devices on the scale of atoms or small groups of atoms. The “nanoscale” is typically measured in nanometres, or billionths of a metre (*nanos*, the Greek word for “dwarf,” being the source of the prefix), and materials built at this scale often exhibit distinctive physical and chemical properties due to [quantum mechanical](#) effects. Although usable devices this small may be decades away (see [microelectromechanical system](#)), techniques for working at the nanoscale have become essential to electronic [engineering](#), and nanoengineered materials have begun to appear in consumer products. For example, billions of microscopic “nanowhiskers,” each about 10 nanometres in length, have been molecularly hooked onto natural and [synthetic](#) fibres to impart stain resistance to [clothing](#) and other fabrics; zinc oxide nanocrystals have been used to create invisible sunscreens that block ultraviolet light; and silver nanocrystals have been embedded in bandages to kill bacteria and prevent infection.



How spider-inspired tools could revolutionize nanofiber handling Spider combs inspire a new tool for handling sticky nanofibres.

Possibilities for the future are numerous. Nanotechnology may make it possible to manufacture lighter, stronger, and programmable materials that require less energy to produce than conventional materials, that produce less waste than with

conventional [manufacturing](#), and that promise greater fuel [efficiency](#) in land [transportation](#), ships, aircraft, and space vehicles. Nanocoatings for both [opaque](#) and translucent surfaces may render them resistant to corrosion, scratches, and radiation. Nanoscale electronic, magnetic, and mechanical devices and systems with unprecedented levels of [information processing](#) may be fabricated, as may chemical, photochemical, and biological sensors for protection, health care, manufacturing, and the environment; new photoelectric materials that will enable the manufacture of cost-efficient solar-energy panels; and molecular-semiconductor hybrid devices that may become engines for the next revolution in the information age. The potential for improvements in health, [safety](#), [quality of life](#), and conservation of the [environment](#) are vast.

At the same time, significant challenges must be overcome for the benefits of nanotechnology to be realized. Scientists must learn how to manipulate and characterize individual [atoms](#) and small groups of atoms reliably. New and improved tools are needed to control the properties and structure of materials at the nanoscale; significant improvements in computer simulations of atomic and molecular structures are essential to the understanding of this realm. Next, new tools and approaches are needed for assembling atoms and molecules into nanoscale systems and for the further assembly of small systems into more-complex objects. Furthermore, nanotechnology products must provide not only improved performance but also lower cost. Finally, without [integration](#) of nanoscale objects with systems at the micro- and macroscale (that is, from millionths of a metre up to the millimetre scale), it will be very difficult to exploit many of the unique properties found at the nanoscale.

Overview of nanotechnology



Discover how progress in nanotechnology aid scientists to understand and apply the concept of particle engineering, specifically in the field of pharmacology
Examining how breakthroughs in nanotechnology are enabling scientists to better understand and apply concepts of particle engineering, specifically in the field of pharmacology.

Nanotechnology is highly interdisciplinary, involving physics, chemistry, [biology](#), [materials science](#), and the full range of the [engineering disciplines](#). The word *nanotechnology* is widely used as shorthand to refer to both the science and the [technology](#) of this emerging field. Narrowly defined, nanoscience concerns a basic understanding of physical, chemical, and biological properties on atomic and near-atomic scales. Nanotechnology, narrowly defined, employs controlled manipulation of these properties to create materials and functional systems with unique capabilities.

In contrast to recent engineering efforts, nature developed “nanotechnologies” over billions of years, employing enzymes and [catalysts](#) to organize with [exquisite](#) precision different kinds of atoms and molecules into complex microscopic structures that make life possible. These natural products are built with great [efficiency](#) and have impressive capabilities, such as the [power](#) to harvest [solar energy](#), to convert minerals and water into living cells, to store and process massive amounts of data using large arrays of nerve cells, and to replicate perfectly billions of bits of information stored in molecules of deoxyribonucleic acid ([DNA](#)).

There are two principal reasons for qualitative differences in material behaviour at the nanoscale (traditionally defined as less than 100 nanometres). First, [quantum](#) mechanical effects come into play at very small dimensions and lead to new physics and chemistry. Second, a defining feature at the nanoscale is the very large surface-to-volume ratio of these structures. This means that no [atom](#) is very far from a surface or interface, and the behaviour of atoms at these higher-energy sites have a significant influence on the properties of the material. For example, the reactivity of a [metal catalyst](#) particle generally increases appreciably as its size is reduced—macroscopic [gold](#) is chemically inert, whereas at nanoscales gold becomes extremely reactive and catalytic and even melts at a lower temperature. Thus, at nanoscale dimensions material properties depend on and change with size, as well as [composition](#) and structure.

Using the processes of nanotechnology, basic industrial production may veer dramatically from the course followed by steel plants and chemical factories of the past. Raw materials will come from the atoms of abundant elements—carbon, hydrogen, and silicon—and these will be manipulated into precise configurations to create nanostructured materials that exhibit exactly the right properties for each particular application. For example, carbon atoms can be bonded together in a number of different geometries to create variously a fibre, a tube, a molecular coating, or a wire, all with the superior strength-to-weight ratio of another carbon material—diamond. Additionally, such material processing need not require smokestacks, power-hungry industrial [machinery](#), or intensive human labour. Instead, it may be accomplished either by “growing” new structures through some combination of chemical catalysts

and [synthetic](#) enzymes or by [building](#) them through new techniques based on patterning and self-assembly of nanoscale materials into useful predetermined designs. Nanotechnology ultimately may allow people to fabricate almost any type of material or product allowable under the laws of physics and chemistry. While such possibilities seem remote, even approaching nature's virtuosity in energy-efficient fabrication would be revolutionary.

Even more revolutionary would be the fabrication of nanoscale machines and devices for incorporation into micro- and macroscale systems. Once again, nature has led the way with the fabrication of both linear and rotary molecular motors. These biological machines carry out such tasks as muscle [contraction](#) (in organisms ranging from clams to humans) and shuttling little packets of material around within cells while being powered by the recyclable, energy-efficient fuel [adenosine triphosphate](#). Scientists are only beginning to develop the tools to fabricate functioning systems at such small scales, with most advances based on electronic or magnetic [information processing](#) and storage systems. The energy-efficient, reconfigurable, and self-repairing aspects of biological systems are just becoming understood.

The potential impact of nanotechnology processes, machines, and products is expected to be far-reaching, affecting nearly every conceivable information technology, energy source, agricultural product, medical device, [pharmaceutical](#), and material used in [manufacturing](#). Meanwhile, the dimensions of electronic circuits on semiconductors continue to shrink, with minimum feature sizes now reaching the nanorealm, under 100 nanometres. Likewise, magnetic memory materials, which form the basis of [hard disk](#) drives, have achieved dramatically greater memory density as a result of nanoscale structuring to exploit new magnetic effects at nanodimensions. These latter two areas represent another major trend, the evolution of critical elements of microtechnology into the realm of nanotechnology to [enhance](#) performance. They are immense markets driven by the rapid advance of information technology.

Milestones in the development of nanotechnology

Visionaries

In a lecture in 1959 to the American Physical Society, "There's Plenty of Room at the Bottom," American Nobelist [Richard P. Feynman](#) presented his audience with a vision of what could be done with extreme miniaturization. He began his lecture by noting that the [Lord's Prayer](#) had been written on the head of a pin and asked, *Why cannot we write the entire 24 volumes of the Encyclopædia Britannica on the head of a pin? Let's see what would be involved. The head of a pin is a sixteenth of an inch across. If you magnify it by 25,000 diameters, the area of the head of the pin is then equal to the area of all the pages of the Encyclopædia Britannica. Therefore, all it is necessary to do is to reduce in size all the writing in the Encyclopædia by 25,000 times. Is that possible? The resolving power of the eye is about 1/120 of an inch—that is roughly the diameter of one of the little dots on the fine half-tone reproductions in the Encyclopædia. This, when you demagnify it by 25,000 times, is still 80 angstroms in diameter—32 atoms across, in an ordinary metal. In other words, one of those dots still would contain in its area 1,000 atoms. So, each dot can easily be*

adjusted in size as required by the photoengraving, and there is no question that there is enough room on the head of a pin to put all of the Encyclopædia Britannica.

Feynman was [intrigued](#) by biology and pointed out that

cells are very tiny, but they are very active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvelous things—all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small which does what we want—that we can manufacture an object that maneuvers at that level!

He also considered using big tools to make smaller tools that could make yet smaller tools, eventually obtaining nanoscale tools for directly manipulating atoms and molecules. In considering what all this might mean, Feynman declared,

I can hardly doubt that when we have some control of the arrangement of things on a small scale we will get an enormously greater range of possible properties that substances can have, and of different things that we can do.

Perhaps the biggest barrier to following these [prophetic](#) thoughts was simply the immediate lack of tools to manipulate and visualize matter at such a small scale. The availability of tools has always been an enabling aspect of the advance of all science and technology, and some of the key tools for nanotechnology are discussed in the next section, [Pioneers](#).

Starting with a 1981 paper in the *Proceedings of the National Academy of Sciences* and following with two popular books, *Engines of Creation* (1986) and *Nanosystems* (1992), American scientist [K. Eric Drexler](#) became one of the foremost advocates of nanotechnology. In fact, Drexler was the first person anywhere to receive a Ph.D. in molecular nanotechnology (from the Massachusetts Institute of Technology). In his written works he takes a molecular view of the world and [envisions](#) molecular machines doing much of the work of the future. For example, he refers to “assemblers,” which will manipulate individual atoms to manufacture structures, and “replicators,” which will be able to make multiple copies of themselves in order to save time dealing with the billions of atoms needed to make objects of useful size. In an article for [Encyclopædia Britannica’s 1990 Yearbook of Science and the Future](#), Drexler wrote:

Cells and tissues in the [human body](#) are built and maintained by molecular machinery, but sometimes that machinery proves inadequate: viruses multiply, cancer cells spread, or systems age and deteriorate. As one might expect, new molecular machines and computers of subcellular size could support the body’s own mechanisms. Devices containing nanocomputers interfaced to molecular sensors and effectors could serve as an augmented [immune system](#), searching out and destroying viruses and cancer cells. Similar devices programmed as repair machines could enter living cells to edit out viral DNA sequences and repair molecular damage. Such machines would bring surgical control to the molecular level, opening broad new horizons in [medicine](#).

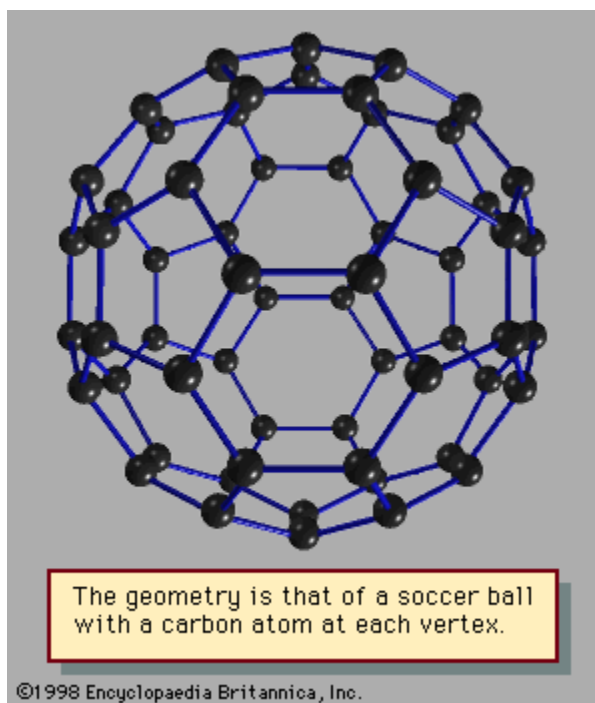
Drexler’s futurist visions have stimulated much thought, but the assembler approach has failed to account for the strong influence of atomic and molecular forces (i.e., the chemistry) at such dimensions. The controversy surrounding these popularizations, and

the potential dangers of entities such as intelligent replicators (however remote), have stimulated debate over the [ethical](#) and societal [implications](#) of nanotechnology.

Pioneers

A number of key technological milestones have been achieved by working pioneers. [Molecular beam epitaxy](#), invented by Alfred Cho and John Arthur at [Bell Labs](#) in 1968 and developed in the 1970s, enabled the controlled [deposition](#) of single atomic layers. This [tool](#) provided for nanostructuring in one dimension as atomic layers were grown one upon the next. It subsequently became important in the area of [compound semiconductor device](#) fabrication. For example, sandwiching one-nanometre-thick layers of nonmagnetic-sensor materials between magnetic layers in computer disk drives resulted in large increases in storage capacity, and a similar use of nanostructuring resulted in more energy-efficient [semiconductor lasers](#) for use in [compact disc](#) players.

In 1981 [Gerd Binnig](#) and [Heinrich Rohrer](#) developed the [scanning tunneling microscope](#) at IBM's laboratories in Switzerland. This tool provided a revolutionary advance by enabling scientists to image the position of individual atoms on surfaces. It earned Binnig and Rohrer a [Nobel Prize](#) in 1986 and spawned a wide variety of scanning probe tools for nanoscale observations.



[structure of buckminsterfullerene](#) The structure of buckminsterfullerene (C_{60}).

The observation of new carbon structures marked another important [milestone](#) in the advance of nanotechnology, with Nobel Prizes for the discoverers. In 1985 [Robert F. Curl, Jr.](#), [Harold W. Kroto](#), and [Richard E. Smalley](#) discovered the first [fullerene](#), the third known form of pure carbon (after diamond and graphite). They named their discovery [buckminsterfullerene](#) ("buckyball") for its resemblance to the geodesic domes

promoted by the American architect [R. Buckminster Fuller](#). Technically called C_{60} for the 60 carbon atoms that form their hollow spherical structure, buckyballs resemble a football one nanometre in diameter (see figure). In 1991 [Sumio Iijima](#) of [NEC Corporation](#) in Japan discovered [carbon nanotubes](#), in which the carbon ringlike structures are extended from spheres into long tubes of varying diameter. Taken together, these new structures surprised and excited the imaginations of scientists about the possibilities of forming well-defined nanostructures with unexpected new properties.

The scanning tunneling microscope not only allowed for the imaging of atoms by scanning a sharp probe tip over a surface, but it also allowed atoms to be “pushed” around on the surface. With a slight bias voltage applied to the probe tip, certain atoms could be made to adhere to the tip used for imaging and then to be released from it. Thus, in 1990 Donald Eigler spelled out the letters of his company’s logo, [IBM](#), by moving 35 xenon atoms into place on a nickel surface. This demonstration caught the public’s attention because it showed the precision of the emerging nanoscale tools.

Properties at the nanoscale

At nanoscale dimensions the properties of materials no longer depend solely on [composition](#) and structure in the usual sense. Nanomaterials display new phenomena associated with quantized effects and with the preponderance of surfaces and interfaces.

Quantized effects arise in the nanometre regime because the overall dimensions of objects are comparable to the characteristic wavelength for fundamental excitations in materials. For example, electron [wave functions](#) (see also [de Broglie wave](#)) in semiconductors are typically on the order of 10 to 100 nanometres. Such excitations include the wavelength of [electrons](#), [photons](#), [phonons](#), and [magnons](#), to name a few. These excitations carry the [quanta](#) of energy through materials and thus determine the [dynamics](#) of their [propagation](#) and transformation from one form to another. When the size of structures is comparable to the [quanta](#) themselves, it influences how these excitations move through and interact in the material. Small structures may limit flow, create wave interference effects, and otherwise bring into play [quantum](#) mechanical selection rules not apparent at larger dimensions.

Electronic and photonic behaviour

Quantum mechanical properties for confinement of electrons in one dimension have long been exploited in solid-state [electronics](#). Semiconductor devices are grown with thin layers of differing composition so that electrons (or “holes” in the case of missing electron charges) can be confined in specific regions of the structure (known as quantum wells). Thin layers with larger energy bandgaps can serve as barriers that restrict the flow of charges to certain conditions under which they can “tunnel” through these barriers—the basis of resonant tunneling [diodes](#). [Superlattices](#) are periodic structures of repeating wells that set up a new set of selection rules which affect the conditions for charges to flow through the structure. Superlattices have been exploited in cascade lasers to achieve far infrared wavelengths. Modern telecommunications is

based on semiconductor lasers that exploit the unique properties of quantum wells to achieve specific wavelengths and high [efficiency](#).

The propagation of [photons](#) is altered dramatically when the size and periodicity of the [transient](#) structure approach the wavelength of visible light (400 to 800 nanometres). When photons [propagate](#) through a periodically varying dielectric constant—for example, semiconductor posts surrounded by air—quantum mechanical rules define and limit the propagation of the photons depending on their energy (wavelength). This new behaviour is [analogous](#) to the quantum mechanical rules that define the motion of electrons through crystals, giving bandgaps for semiconductors. In one dimension, compound semiconductor superlattices can be grown epitaxially with the alternating layers having different dielectric constants, thus providing highly reflective mirrors for specific wavelengths as determined by the repeat distance of layers in the superlattice. These structures are used to provide “built-in” mirrors for vertical-cavity surface-emitting lasers, which are used in communications applications. In two and three dimensions, periodic structures known as photonic crystals offer additional control over photon propagation.

Photonic crystals are being explored in a variety of materials and periodicities, such as two-dimensional hexagonal [arrays](#) of posts fabricated in compound semiconductors or stacked loglike arrays of [silicon](#) bars in three dimensions. The dimensions of these structures depend on the wavelength of light being [propagated](#) and are typically in the range of a few hundred nanometres for wavelengths in the visible and near infrared. Photonic crystal properties based on nanostructured materials offer the possibility of confining, steering, and separating light by wavelength on unprecedented small scales and of creating new devices such as lasers that require very low currents to initiate lasing (called near-thresholdless lasers). These structures are being extensively investigated as the tools for nanostructuring materials are steadily advancing. Researchers are particularly interested in the infrared wavelengths, where dimensional control is not as [stringent](#) as at the shorter visible wavelengths and where optical communications and chemical sensing provide motivation for potential new applications.

Magnetic, mechanical, and chemical behaviour

Nanoscale materials also have size-dependent magnetic behaviour, mechanical properties, and chemical reactivity. At very small sizes (a few nanometres), magnetic nanoclusters have a single magnetic domain, and the strongly coupled magnetic spins on each [atom](#) combine to produce a particle with a single “giant” spin. For example, the giant spin of a ferromagnetic iron particle rotates freely at room temperature for diameters below about 16 nanometres, an effect termed [superparamagnetism](#).

Mechanical properties of nanostructured materials can reach exceptional strengths. As a specific example, the introduction of two-nanometre [aluminum oxide precipitates](#) into thin films of pure nickel results in yield strengths increasing from 0.15 to 5 gigapascals, which is more than twice that for a hard bearing steel. Another example of exceptional mechanical properties at the nanoscale is the carbon nanotube, which exhibits great strength and stiffness along its longitudinal axis.

The preponderance of surfaces is a major reason for the change in behaviour of materials at the nanoscale. Since up to half of all the atoms in [nanoparticles](#) are surface atoms, properties such as electrical transport are no longer determined by solid-state bulk phenomena. Likewise, the atoms in nanostructures have a higher average energy than atoms in larger structures, because of the large proportion of surface atoms. For example, catalytic materials have a greater chemical activity per atom of exposed surface as the [catalyst](#) is reduced in size at the nanoscale. Defects and impurities may be attracted to surfaces and interfaces, and interactions between particles at these small dimensions can depend on the structure and nature of [chemical bonding](#) at the surface. Molecular monolayers may be used to change or control surface properties and to mediate the interaction between nanoparticles.

Surfaces and their interactions with molecular structures are basic to all [biology](#). The intersection of nanotechnology and [biotechnology](#) offers the possibility of achieving new functions and properties with nanostructured surfaces. In this surface- and interface-dominated regime, biology does an [exquisite](#) job of selectively controlling functions through a combination of structure and chemical forces. The transcription of information stored in genes and the selectivity of biochemical reactions based on chemical recognition of complex molecules are examples where interfaces play the key role in establishing nanoscale behaviour. Atomic forces and chemical bonds dominate at these dimensions, while macroscopic effects—such as convection, turbulence, and momentum (inertial forces)—are of little consequence.

Nanotechnology research

Nanomaterials

As discussed in the section [Properties at the nanoscale](#), material properties—electrical, optical, magnetic, mechanical, and chemical—depend on their exact dimensions. This opens the way for development of new and improved materials through manipulation of their nanostructure. Hierarchical assemblies of nanoscale-engineered materials into larger structures, or their incorporation into devices, provide the basis for tailoring radically new materials and machines.

Nature's assemblies point the way to improving structural materials. The often-cited [abalone](#) seashell provides a beautiful example of how the combination of a hard, brittle inorganic material with nanoscale structuring and a soft, “tough” organic material can produce a strong, durable nanocomposite—basically, these nanocomposites are made of [calcium carbonate](#) “bricks” held together by a glycoprotein “glue.” New engineered materials are emerging—such as polymer-clay nanocomposites—that are not only strong and tough but also lightweight and easier to recycle than conventional reinforced plastics. Such improvements in structural materials are particularly important for the [transportation industry](#), where reduced weight directly translates into improved fuel economy. Other improvements can increase [safety](#) or decrease the impact on the [environment](#) of fabrication and recycling.

Further advances, such as truly smart materials that signal their impending failure or are even able to self-repair flaws, may be possible with composites of the future.

Sensors are central to almost all modern control systems. For example, multiple sensors are used in automobiles for such **diverse** tasks as engine management, emission control, security, safety, comfort, vehicle monitoring, and diagnostics. While such traditional applications for physical sensing generally rely on microscale sensing devices, the advent of nanoscale materials and structures has led to new electronic, photonic, and magnetic nanosensors, sometimes known as “smart dust.” Because of their small size, nanosensors exhibit unprecedented speed and sensitivity, extending in some cases down to the detection of single molecules. For example, nanowires made of carbon nanotubes, **silicon**, or other semiconductor materials exhibit exceptional sensitivity to chemical species or biological agents. Electrical current through nanowires can be altered by having molecules attached to their surface that locally perturb their electronic band structure. By means of **nanowire** surfaces coated with **sensor** molecules that selectively attach particular species, charge-induced changes in current can be used to detect the presence of those species. This same strategy is adopted for many classes of sensing systems. New types of sensors with ultrahigh **sensitivity and specificity** will have many applications; for example, sensors that can detect cancerous tumours when they consist of only a few cells would be a very significant advance.

Nanomaterials also make excellent filters for trapping heavy metals and other pollutants from industrial wastewater. One of the greatest potential impacts of nanotechnology on the lives of the majority of people on Earth will be in the area of economical water desalination and purification. Nanomaterials will very likely find important use in fuel cells, bioconversion for energy, bioprocessing of **food** products, waste remediation, and pollution-control systems.

A recent concern regarding nanoparticles is whether their small sizes and novel properties may pose significant health or environmental risks. In general, ultrafine particles—such as the carbon in photocopier toners or in soot produced by combustion engines and factories—have **adverse** respiratory and cardiovascular effects on people and animals. Studies are under way to determine if specific nanoscale particles pose higher risks that may require special regulatory restrictions. Of particular concern are potential carcinogenic risks from inhaled particles and the possibility for very small nanoparticles to cross the blood-brain barrier to unknown effect. Nanomaterials currently receiving attention from health officials include carbon nanotubes, buckyballs, and cadmium selenide **quantum** dots. Studies of the absorption through the skin of titanium oxide nanoparticles (used in sunscreens) are also planned. More far-ranging studies of the toxicity, transport, and overall fate of nanoparticles in ecosystems and the environment have not yet been undertaken. Some early animal studies, involving the introduction of very high levels of nanoparticles which resulted in the rapid death of many of the subjects, are quite controversial.

Biomedicine and health care

Drug delivery

Nanotechnology promises to impact medical [treatment](#) in multiple ways. First, advances in nanoscale particle design and fabrication provide new options for drug delivery and [drug therapies](#). More than half of the new drugs developed each year are not water-soluble, which makes their delivery difficult. In the form of nanosized particles, however, these drugs are more readily transported to their destination, and they can be delivered in the conventional form of pills.

More important, nanotechnology may enable drugs to be delivered to precisely the right location in the body and to release drug doses on a predetermined schedule for optimal treatment. The general approach is to attach the drug to a nanosized carrier that will release the [medicine](#) in the body over an extended period of time or when specifically triggered to do so. In addition, the surfaces of these nanoscale carriers may be treated to seek out and become localized at a disease site—for example, attaching to cancerous tumours. One type of [molecule](#) of special interest for these applications is an organic dendrimer. A dendrimer is a special class of polymeric molecule that [weaves](#) in and out from a hollow central region. These spherical “fuzz balls” are about the size of a typical protein but cannot unfold like proteins. Interest in dendrimers derives from the ability to tailor their cavity sizes and chemical properties to hold different therapeutic agents. Researchers hope to design different dendrimers that can swell and release their drug on exposure to specifically recognized molecules that indicate a disease target. This same general approach to nanoparticle-directed drug delivery is being explored for other types of nanoparticles as well.

Another approach involves gold-coated nanoshells whose size can be adjusted to absorb light energy at different wavelengths. In particular, infrared light will pass through several centimetres of body tissue, allowing a delicate and precise heating of such capsules in order to release the [therapeutic](#) substance within. Furthermore, antibodies may be attached to the outer [gold](#) surface of the shells to cause them to bind specifically to certain tumour cells, thereby reducing the damage to surrounding healthy cells.

Bioassays

A second area of intense study in [nanomedicine](#) is that of developing new diagnostic tools. Motivation for this work ranges from fundamental biomedical research at the level of single genes or cells to point-of-care applications for health delivery services. With advances in [molecular biology](#), much diagnostic work now focuses on detecting specific biological “signatures.” These analyses are referred to as bioassays. Examples include studies to determine which genes are active in response to a particular disease or [drug](#) therapy. A general approach involves attaching fluorescing dye molecules to the target biomolecules in order to reveal their concentration.

Another approach to bioassays uses semiconductor nanoparticles, such as cadmium selenide, which emit light of a specific wavelength depending on their size. Different-size particles can be tagged to different receptors so that a wider variety of distinct

colour tags are available than can be distinguished for dye molecules. The [degradation](#) in fluorescence with repeated excitation for dyes is avoided. Furthermore, various-size particles can be [encapsulated](#) in latex beads and their resulting wavelengths read like a [bar code](#). This approach, while still in the exploratory stage, would allow for an enormous number of distinct labels for bioassays.

Another nanotechnology variation on bioassays is to attach one half of the single-stranded complementary DNA segment for the genetic sequence to be detected to one set of [gold](#) particles and the other half to a second set of gold particles. When the material of interest is present in a solution, the two attachments cause the gold balls to agglomerate, providing a large change in optical properties that can be seen in the colour of the solution. If both halves of the sequence do not match, no [agglomeration](#) will occur and no change will be observed.

Approaches that do not involve optical detection techniques are also being explored with nanoparticles. For example, magnetic nanoparticles can be attached to antibodies that in turn recognize and attach to specific biomolecules. The magnetic particles then act as tags and “handlebars” through which magnetic fields can be used for mixing, extracting, or identifying the attached biomolecules within microlitre- or nanolitre-sized samples. For example, magnetic nanoparticles stay magnetized as a single domain for a significant period, which enables them to be aligned and detected in a [magnetic field](#). In particular, attached antibody–magnetic-nanoparticle combinations rotate slowly and give a distinctive magnetic signal. In contrast, magnetically tagged antibodies that are not attached to the biological material being detected rotate more rapidly and so do not give the same distinctive signal.

[Microfluidic systems](#), or “labs-on-chips,” have been developed for biochemical assays of minuscule samples. Typically cramming numerous electronic and mechanical components into a portable unit no larger than a [credit card](#), they are especially useful for conducting rapid analysis in the field. While these microfluidic systems primarily operate at the microscale (that is, millionths of a metre), nanotechnology has contributed new concepts and will likely play an increasing role in the future. For example, separation of [DNA](#) is sensitive to entropic effects, such as the [entropy](#) required to unfold DNA of a given length. A new approach to separating DNA could take advantage of its passage through a nanoscale array of posts or channels such that DNA molecules of different lengths would uncoil at different rates.

Other researchers have focused on detecting signal changes as nanometre-wide DNA strands are threaded through a nanoscale pore. Early studies used pores punched in membranes by viruses; artificially fabricated nanopores are also being tested. By applying an [electric potential](#) across the membrane in a liquid [cell](#) to pull the DNA through, changes in ion current can be measured as different repeating base units of the [molecule](#) pass through the pores. Nanotechnology-enabled advances in the entire area of bioassays will clearly impact health care in many ways, from early detection, rapid clinical analysis, and home monitoring to new understanding of molecular biology and genetic-based treatments for fighting disease.

Assistive devices and tissue engineering

Another biomedical application of nanotechnology involves assistive devices for people who have lost or lack certain natural capabilities. For example, researchers hope to design retinal implants for vision-impaired individuals. The concept is to implant chips with photodetector arrays to transmit signals from the retina to the brain via the [optic nerve](#). Meaningful spatial information, even if only at a [rudimentary](#) level, would be of great assistance to the [blind](#). Such research illustrates the tremendous challenge of designing hybrid systems that work at the interface between inorganic devices and biological systems.

Closely related research involves implanting nanoscale neural probes in brain tissue to activate and control motor functions. This requires effective and stable “wiring” of many electrodes to neurons. It is exciting because of the possibility of recovery of control for motor-impaired individuals. Studies employing neural stimulation of damaged [spinal cords](#) by electrical signals have demonstrated the return of some locomotion. Researchers are also seeking ways to assist in the regeneration and healing of bone, skin, and cartilage—for example, developing [synthetic](#) biocompatible or biodegradable structures with nanosized voids that would serve as templates for regenerating specific tissue while delivering chemicals to assist in the repair process. At a more sophisticated level, researchers hope to someday build nanoscale or microscale machines that can repair, assist, or replace more-complex organs.

Information technology

Semiconductor experts agree that the ongoing shrinkage in “conventional” electronic devices will inevitably reach fundamental limits due to [quantum](#) effects such as “tunneling,” in which electrons jump out of their prescribed circuit path and create atomic-scale interference between devices. At that point, radical new approaches to [data](#) storage and information processing will be required for further advances. For example, radically new systems have been imagined that are based on [quantum computing](#) or biomolecular computing.

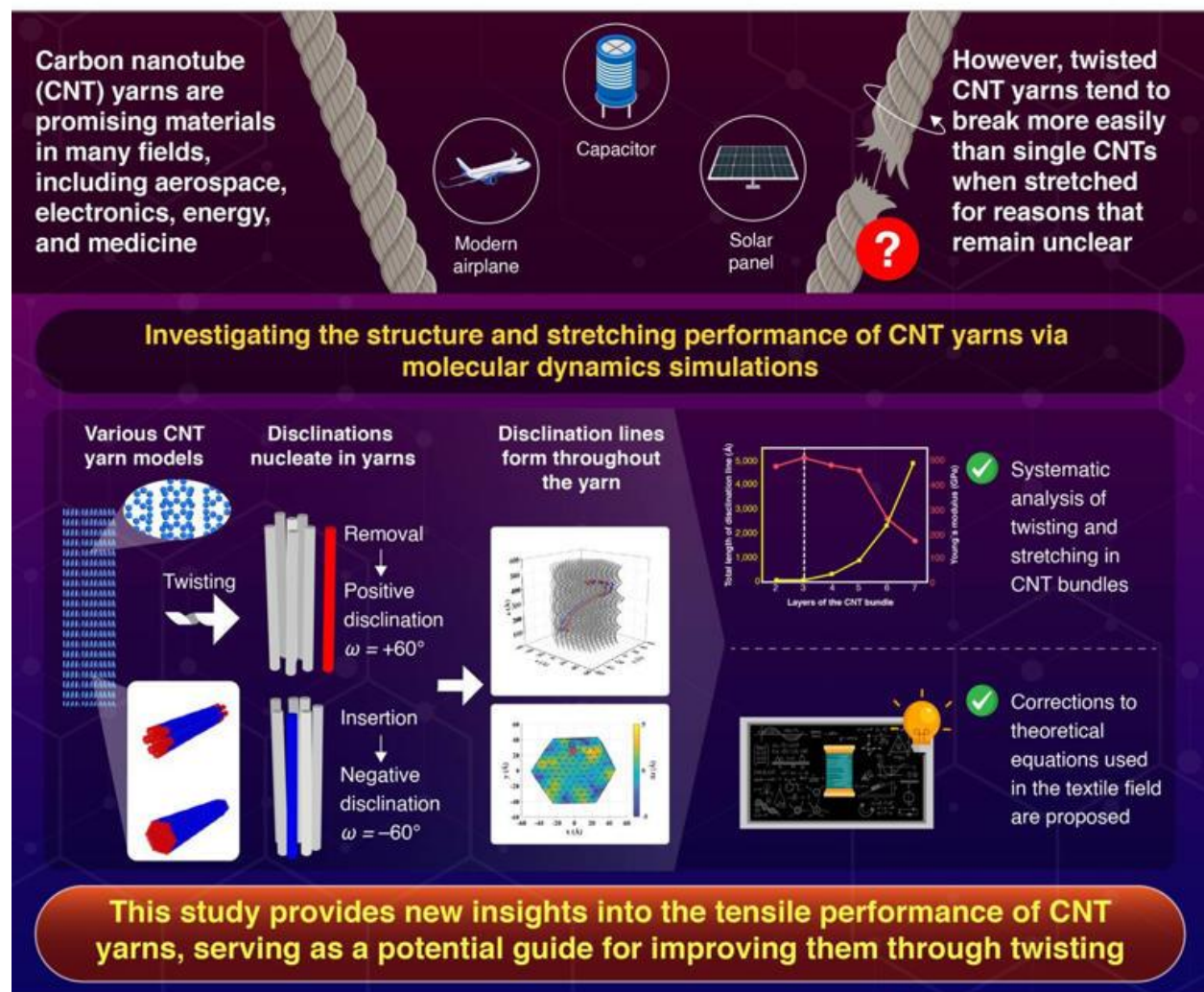
Molecular electronics

The use of molecules for electronic devices was suggested by Mark Ratner of [Northwestern University](#) and Avi Aviram of IBM as early as the 1970s, but proper nanotechnology tools did not become available until the turn of the 21st century. Wiring up molecules some half a nanometre wide and a few nanometres long remains a major challenge, and an understanding of electrical transport through single molecules is only beginning to emerge. A number of groups have been able to demonstrate molecular switches, for example, that could conceivably be used in [computer memory](#) or logic [arrays](#). Current areas of research include mechanisms to guide the selection of molecules, architectures for assembling molecules into nanoscale gates, and three-terminal molecules for transistor-like behaviour. More-radical approaches include [DNA computing](#), where single-stranded DNA on a [silicon](#) chip would encode all possible variable values and complementary strand interactions would be used for a parallel

processing approach to finding solutions. An area related to molecular electronics is that of organic thin-film [transistors](#) and light emitters, which promise new applications such as video displays that can be rolled out like wallpaper and flexible electronic newspapers.

New insights into mechanical weakness of twisted carbon nanotube yarns

Insights on the Mechanical Properties of Carbon Nanotube Yarns



Nucleation of disclinations in carbon nanotube bundle structures under twisting loads

T. Lu, X.-W. Lei*, T. Fujii (2024) | *Carbon* | 10.1016/j.carbon.2024.119287

This study provides new insights into the tensile performance of CNT yarns, serving as a potential guide for improving them through twisting. Credit: Tokyo Tech© Provided by Phys.org

Aside from being an essential building block for life, carbon is being actively researched due to its versatility as an engineering material. Carbon nanotubes (CNTs), in particular, have demonstrated tremendous potential for aerospace, semiconductor, and medical applications, mostly owing to their high strength and low weight.

Since CNTs are typically short, they need to be weaved into bundles or yarns to expand their practical uses. However, scientists have noted that CNT bundles (CNTBs) and CNT yarns both exhibit a much lower tensile strength than single CNTs when they undergo twisting—this drop in stretching performance can even reach several orders of magnitude! The worst part is that, despite research efforts, the reasons behind this phenomenon remain unclear.

In a recent study [published in *Carbon*](#) on 30 May 2024, a research team led by Associate Professor Xiao-Wen Lei from Tokyo Institute of Technology, Japan, sought to solve this puzzle. By combining molecular dynamics (MD) simulations and the Delaunay triangulation algorithm, they shed light on what could be happening inside CNTBs as they are twisted.

The researchers designed several CTNB models and setups for the MD simulations, considering different numbers of CNT layers, CNT lengths, twisting angles, and twisting force profiles. After running the simulations, they carefully analyzed how the CNTBs reacted to the stretching before and after twisting.

By observing the cross-section of the twisted CNTBs, the team revealed that the poor mechanical performance of CNTBs and CNT yarns may be caused by what's known as "wedge disclinations." To understand what these are, one should first know that CNTs naturally arrange themselves in hexagonal patterns when bundled. A disclination refers to a defect in this pattern, whereby either a CNT is missing from the group of six (positive disclination) or an additional CNT is inserted to form an arrangement of seven (negative disclination).

Based on the simulations, the researchers found that when the CNTBs were twisted, disclinations arose due to local CNT rearrangements. These disclinations formed long, curved disclination lines in CNTBs with more layers. Most importantly, these lines appeared to have a direct effect on the behavior of the CNTBs upon mechanical stretching.

"We observed that the presence of disclination lines resulted in a decrease in the Young's modulus of the CNTBs, with longer disclination lines corresponding to a lower Young's modulus. The appearance of disclination lines in twisted CNTBs may thus be one of the key reasons for the decline in the mechanical properties of the CNT yarns," explains Lei.

Taken together, the findings of this study help explain some of the current limitations of CNTBs and hint at potential solutions to realize high-performance CNT yarns through twisting.

"Leveraging insights gained from understanding the correlation between microscopic internal stacking structural changes and mechanical properties caused by the introduction of lattice defects in materials could pioneer a new academic field related to computational materials science," highlights Lei. "We ultimately aim for our research to contribute to the realization of a smart, sustainable, and prosperous society in the near future."

With any luck, the current challenges associated with CNTs will soon be addressed so that these amazing materials help us push the state of the art further.

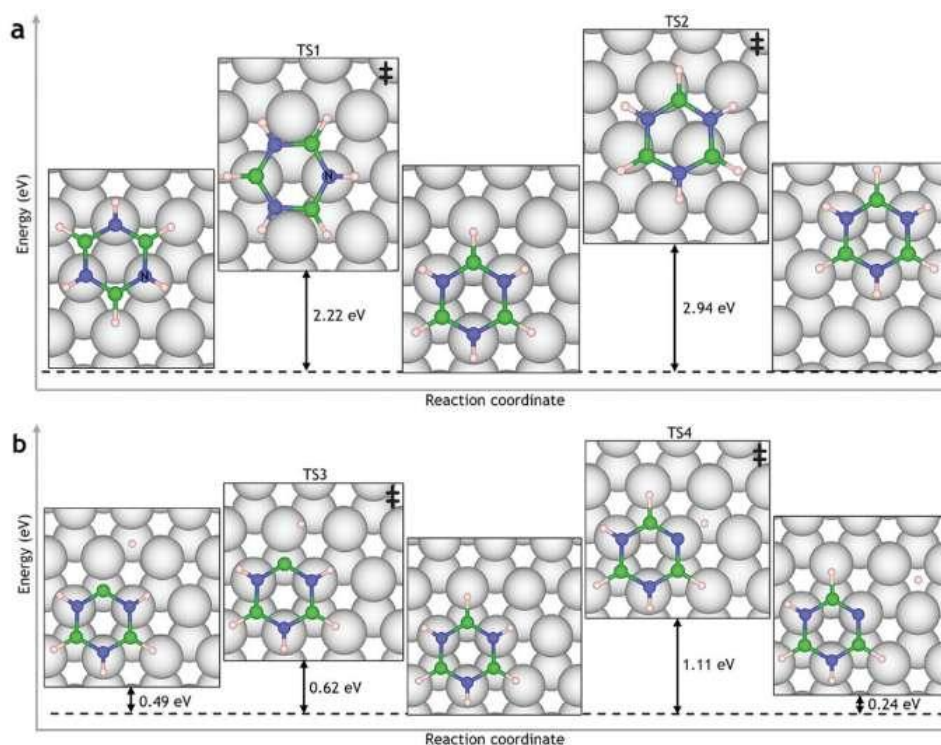
More information: Tong Lu et al, Nucleation of disclinations in carbon nanotube bundle structures under twisting loads, *Carbon* (2024). DOI: [10.1016/j.carbon.2024.119287](https://doi.org/10.1016/j.carbon.2024.119287)

Provided by Tokyo Institute of Technology

JANUARY 8, 2025

Decoding 2D material growth: White graphene insights open doors to cleaner energy and more efficient electronics

by [University of Surrey](#)



Diffusion routes of borazine on Ru(0001) illustrate that borazine moves by a pivoting motion alternating between HCP and FCC sites as it diffuses across the surface. In terms of hydrogen removal from borazine, b) shows that B-dehydrogenation is the kinetically favored product, while N-dehydrogenation is thermodynamically favored. Credit: *Small* (2025). DOI: 10.1002/sml.202405404

A breakthrough in decoding the growth process of hexagonal boron nitride (hBN), a 2D material, and its nanostructures on metal substrates could pave the way for more efficient electronics, cleaner energy solutions and greener chemical manufacturing, according to new research from the University of Surrey [published](#) in the journal *Small*.

Only one atom thick, hBN—often nicknamed "white graphene"—is an ultra-thin, super-resilient material that blocks electrical currents, withstands extreme temperatures and resists chemical damage. Its unique versatility makes it an invaluable component in [advanced electronics](#), where it can protect delicate microchips and enable the development of faster, more efficient transistors.

Going a step further, researchers have also demonstrated the formation of nanoporous hBN, a novel material with structured voids that allows for selective absorption, advanced catalysis and enhanced functionality, vastly expanding its potential environmental applications. This includes sensing and filtering pollutants—as well as enhancing advanced energy systems, including hydrogen storage and electrochemical catalysts for fuel cells.

Dr. Marco Sacchi, lead author of the study and Associate Professor at Surrey's School of Chemistry and Chemical Engineering, said, "Our research sheds light on the atomic-scale processes that govern the formation of this remarkable material and its nanostructures. By understanding these mechanisms, we can engineer materials with unprecedented precision, optimizing their properties for a host of revolutionary technologies."

Working in collaboration with Austria's Graz University of Technology (TU Graz), the team—led by Dr. Marco Sacchi, with the theoretical work performed by Dr. Anthony Payne and Dr. Neubi Xavier—combined density functional theory and microkinetic modeling to map the growth process of hBN from borazine precursors, examining key molecular processes such as diffusion, decomposition, adsorption and desorption, polymerization, and dehydrogenation.

This approach enabled them to develop an atomic scale model that allows for the material to be grown at any temperature.

The insights from the theoretical simulations align closely with experimental observations by the Graz research group, setting the stage for controlled, high-quality production of hBN with specific designs and functionality.

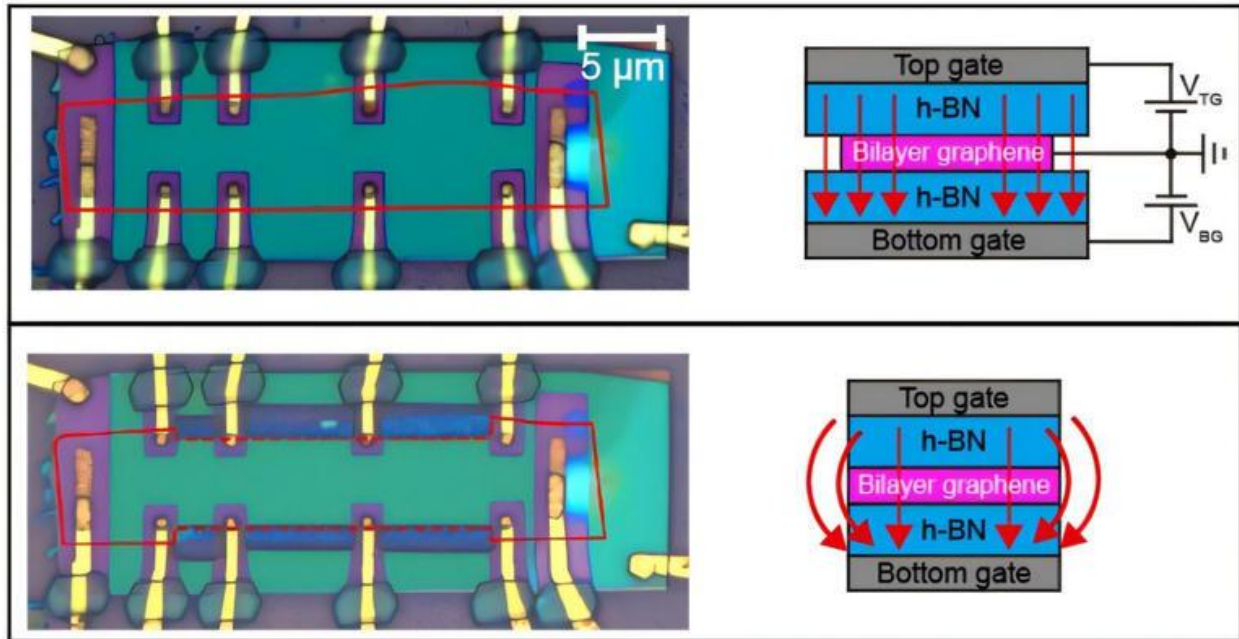
Dr. Anton Tamtögl, lead researcher on the project at TU Graz, said, "Previous studies have neither considered all these intermediates nor such a large parameter space (temperature and particle density). We believe that it will be useful to guide chemical vapor deposition growth of hBN on other metallic substrates, as well as the synthesis of nanoporous or functionalized structures."

More information: Anthony J. R. Payne et al, Unravelling the Epitaxial Growth Mechanism of Hexagonal and Nanoporous Boron Nitride: A First-Principles Microkinetic Model, *Small* (2025). DOI: [10.1002/sml.202405404](https://doi.org/10.1002/sml.202405404)

Journal information: *Small*

Provided by [University of Surrey](https://www.surrey.ac.uk)

Hidden transport pathways in graphene confirmed, paving the way for next-generation device design



Photos and schematic of the edge etching of the bilayer graphene device, before and after the process. Credit: POSTECH

Electron transport in bilayer graphene exhibits a pronounced dependence on edge states and a nonlocal transport mechanism, according to a study led by Professor Gil-Ho Lee and Ph.D. candidate Hyeon-Woo Jeong of POSTECH's Department of Physics, in collaboration with Dr. Kenji Watanabe and Dr. Takashi Taniguchi at Japan's National Institute for Materials Science (NIMS).

The findings are [published](#) in the journal *Nano Letters*.

Bilayer graphene, comprising two vertically stacked graphene layers, can exploit externally applied electric fields to modulate its electronic band gap—a property essential for electron transport. This distinctive feature has drawn considerable attention for its prospective role in "valleytronics," an emerging paradigm for next-generation data processing.

By capitalizing on the "valley," a quantum state in an electron's energy structure that functions as a discrete data storage unit, valleytronics enables faster, more

efficient data handling than conventional electronics or spintronics. With its tunable band gap, bilayer graphene stands as a foundational platform for advanced valleytronics research and device innovation.

A central concept in valleytronics is the "Valley Hall Effect (VHE)," which describes how electron flow is selectively channeled through discrete energy states—known as "valleys"—within a given material. Consequently, a remarkable phenomenon called "nonlocal resistance" emerges, introducing measurable resistance in regions lacking direct current flow—even in the absence of conduction paths.

While much of the current literature regards nonlocal resistance as definitive proof of the VHE, some researchers posit that device-edge impurities or external factors—such as manufacturing processes—may also produce the observed signals, leaving the debate over VHE's origins unresolved.

To ascertain the definitive source of nonlocal resistance in bilayer graphene, the joint POSCO-NIMS research team fabricated a dual-gate graphene device, enabling precise band gap control. They subsequently compared the electrical characteristics of pristine, naturally formed graphene edges with those artificially processed using Reactive Ion Etching.

The finding revealed that nonlocal resistance in naturally formed edges conformed to theoretical expectations, while etching-processed edges exhibited nonlocal resistance exceeding those values by two orders of magnitude.

This discrepancy indicates that the etching procedure introduced extraneous conductive pathways unrelated to the VHE, thereby explaining why a reduced band gap had been observed in prior measurements of bilayer graphene.

"The etching process, a vital step in device fabrication, has not received sufficient scrutiny, particularly regarding its impact on nonlocal transport," commented Hyeon-Woo Jeong, the paper's first author.

"Our findings underscore the need to reexamine these considerations and offer crucial insights for advancing valleytronics device design and development."

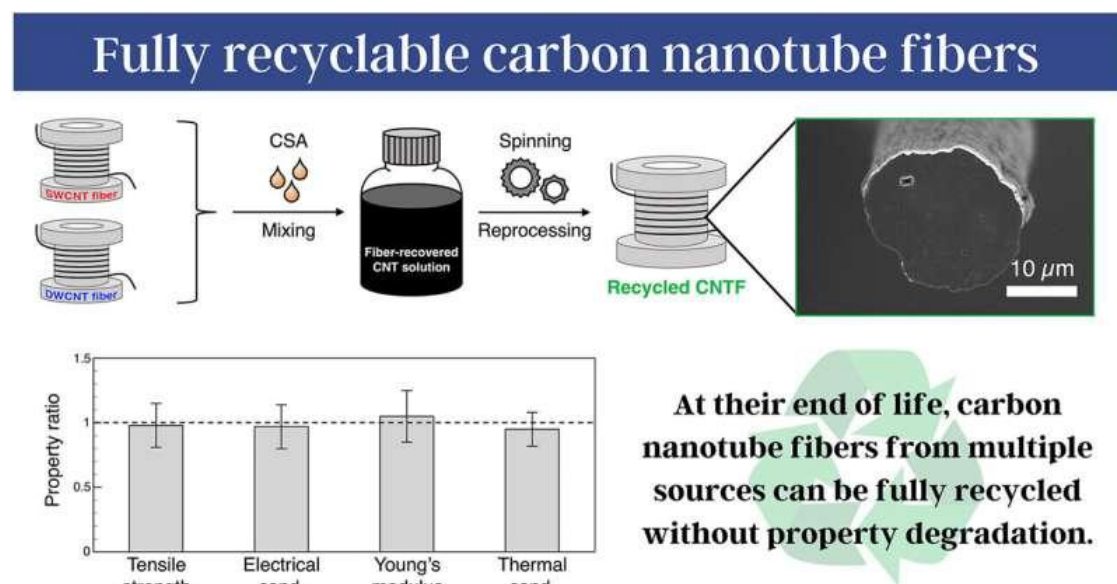
More information: Hyeon-Woo Jeong et al, Edge Dependence of Nonlocal Transport in Gapped Bilayer Graphene, *Nano Letters* (2024). DOI: [10.1021/acs.nanolett.4c02660](https://doi.org/10.1021/acs.nanolett.4c02660)

Provided by Pohang University of Science and Technology

JANUARY 13, 2025

Fully recyclable carbon nanotube fibers have far-reaching implications for manufacturing across sectors

by [Rice University](#)



Credit: *Carbon* (2024). DOI: 10.1016/j.carbon.2024.119899

In a significant step toward creating a sustainable and circular economy, Rice University researchers have [published](#) a study in the journal *Carbon* demonstrating that carbon nanotube (CNT) fibers can be fully recycled without any loss in their structure or properties. This discovery positions CNT fibers as a sustainable alternative to traditional materials like metals, polymers and the much larger carbon fibers, which are notoriously difficult to recycle.

"Recycling has long been a challenge in the materials industry—metals recycling is often inefficient and energy-intensive, polymers tend to lose their properties after reprocessing and carbon fibers cannot be recycled at all, only downcycled by chopping them up into short pieces," said corresponding author Matteo Pasquali, director of Rice's Carbon Hub and the

A.J. Hartsook Professor of Chemical and Biomolecular Engineering, Materials Science and NanoEngineering and Chemistry.

"As CNT fibers are being [scaled up](#), we asked whether and how these new materials could be recycled in the future so as to proactively avoid waste management problems that emerged as other engineered materials reached large-scale use. We expected that recycling would be difficult and would lead to significant loss of properties. Surprisingly, we found that [carbon nanotube](#) fibers far exceed the recyclability potential of existing engineered materials, offering a solution to a major environmental issue."

Credit: Rice University

The research team used solution-spun CNT fibers created by dissolving fiber-grade commercial CNTs in chlorosulfonic acid, a widely used industrial solvent. Because end-of-life recycling invariably brings together materials that were manufactured by different companies in different processes, it was important to assess the effect of multiple material sources on the fiber manufacturing process and fiber properties.

Fibers made from different types of CNTs produced by different manufacturers were initially processed into separate single-source virgin fibers, then recycled by combining them and mixing in chlorosulfonic acid. Surprisingly, mixing the two fibers led to complete redissolution and no sign of separation of the two source materials into different liquid phases. This redissolved material was spun into a mixed-source recycled fiber that retained the same structure and alignment of the virgin fiber.

"By using two different sources of carbon nanotubes, we ensured that our [recycling process](#) was representative of real-life conditions," said co-first author Michelle Durán-Chaves, a graduate student in chemistry. "Remarkably, the recycled fibers demonstrated equivalent mechanical strength, electrical conductivity, thermal conductivity and alignment, which is unprecedented in the field of engineered materials."

Rice researchers unveil 'surprising' breakthrough in carbon nanotube recycling, paving way for sustainable materials. Credit: Brandon Martin/Rice University.

The research revealed several significant findings that position CNT fibers as a promising material in the journey toward [sustainable practices](#). Foremost among these is the full recyclability of CNT fibers. Unlike traditional materials, particularly polymers and [carbon fibers](#) that degrade in quality during recycling, CNT fibers retain 100% of their original properties after being recycled.

"This preservation of quality means CNT fibers can be used and reused in demanding applications without compromising performance, thus extending their lifecycle and reducing the need for new raw materials," said co-first author Ivan R. Siqueira, a recent doctoral graduate in Rice's Department of Chemical and Biomolecular Engineering who is now associate professor of mechanical engineering at the Pontifícia Universidade Católica in Rio de Janeiro.

Equally significant is the efficiency of the recycling process. The researchers demonstrated that CNT fiber recycling is notably more efficient than traditional recycling methods for

metals and polymers, which often involve high energy use, hazardous chemicals or labor-intensive sorting.

CNT fibers, however, can be recycled without sorting as fibers from various sources can be combined to produce high-quality recycled materials. Once these materials reach scale, this simple recycling process will significantly reduce waste, energy consumption and carbon dioxide emissions associated with materials manufacturing.

"The ability to fully recycle CNT fibers has broad implications for industries like aerospace, automotive and electronics," Durán-Chaves said. "We hope this could pave the way for fully recyclable composites in aircraft, vehicles, civil infrastructures and more, ultimately reducing environmental impacts across a wide range of sectors."

Other co-authors of the paper include Rice graduate alumni Oliver Dewey, now of DexMat; Steven Williams; Cedric Ginestra, now of LyondellBasell; Yingru Song, now a postdoctoral fellow at Purdue University; Rice undergraduate alumnus Juan De La Garza, now of Axiom Space; and Geoff Wehmeyer, assistant professor of mechanical engineering.

More information: Ivan R. Siqueira et al, Fully recyclable carbon nanotube fibers, *Carbon* (2024). DOI: [10.1016/j.carbon.2024.119899](https://doi.org/10.1016/j.carbon.2024.119899)

Journal information: *Carbon*

Provided by [Rice University](https://www.rice.edu/)

Scientists observe and control ultrafast surface waves on graphene

Imagine standing by a lake and throwing a stone into the water. Waves spread out in circular patterns and can reflect at obstacles and boundaries. Researchers at the University of Regensburg, in collaboration with colleagues from Milan and Pisa, have recreated this everyday phenomenon in a fascinating miniature world: They observed the propagation of waves—not on water but in an "electron sea"—using one of the fastest slow-motion cameras on the nanoscale. The study is [published](#) in *Nano Letters*.

Such electron seas are typically found on the surfaces of metals or materials with metallic properties. In this case, the material was graphene—a so-called two-dimensional material composed of a single layer of carbon atoms. Instead of a stone, the scientists used laser pulses, focusing them on a sharp metallic tip positioned just above the material's surface.

"The light sets the electrons in the tip in motion," explains Simon Anglhuber from the Institute of Experimental and Applied Physics of the UR. The resulting oscillations exert a force on the electrons in graphene.

This generates a circular electron density wave that propagates through the graphene beneath the tip. The wave can reflect off the edges of the sample and travel back to the tip. These reflections can then be measured optically by reversing the previous process and converting the electron wave back into light. By precisely moving the tip over the sample, the researchers could record a film showing the wave's oscillation at various locations over time.

High-precision analysis of wave motion

The new technique allows for the direct observation of electron wave propagation in both space and time. This was achieved with a resolution on the nanometer scale—relevant for modern semiconductor technologies—and a temporal resolution in the femtosecond range. In terms of temporal resolution, the method can be compared to an ultra-fast slow-motion camera with a frame rate of over 10 trillion frames per second.

The result is a highly precise analysis of wave motion, including its speed, damping, and frequency, without requiring complex computational transformations. Notably, the researchers observed a distinction between the propagation of the wave's center of mass and the propagation of individual wave peaks and troughs. By precisely measuring these two speeds, it is possible to infer the properties of the material through which the waves are propagating.

In their experiments, the researchers compared graphene samples produced by different methods and found significant differences in wave propagation, which were linked to variations in sample quality. These findings are expected to contribute to the development of better samples for use in optoelectronic devices, such as highly sensitive light sensors.

Remarkably, the method also works for heavily damped electron waves in the so-called terahertz and mid-infrared range—a spectral region between our 5G network and visible light that has been difficult to access so far.

Ultrafast control of surface waves

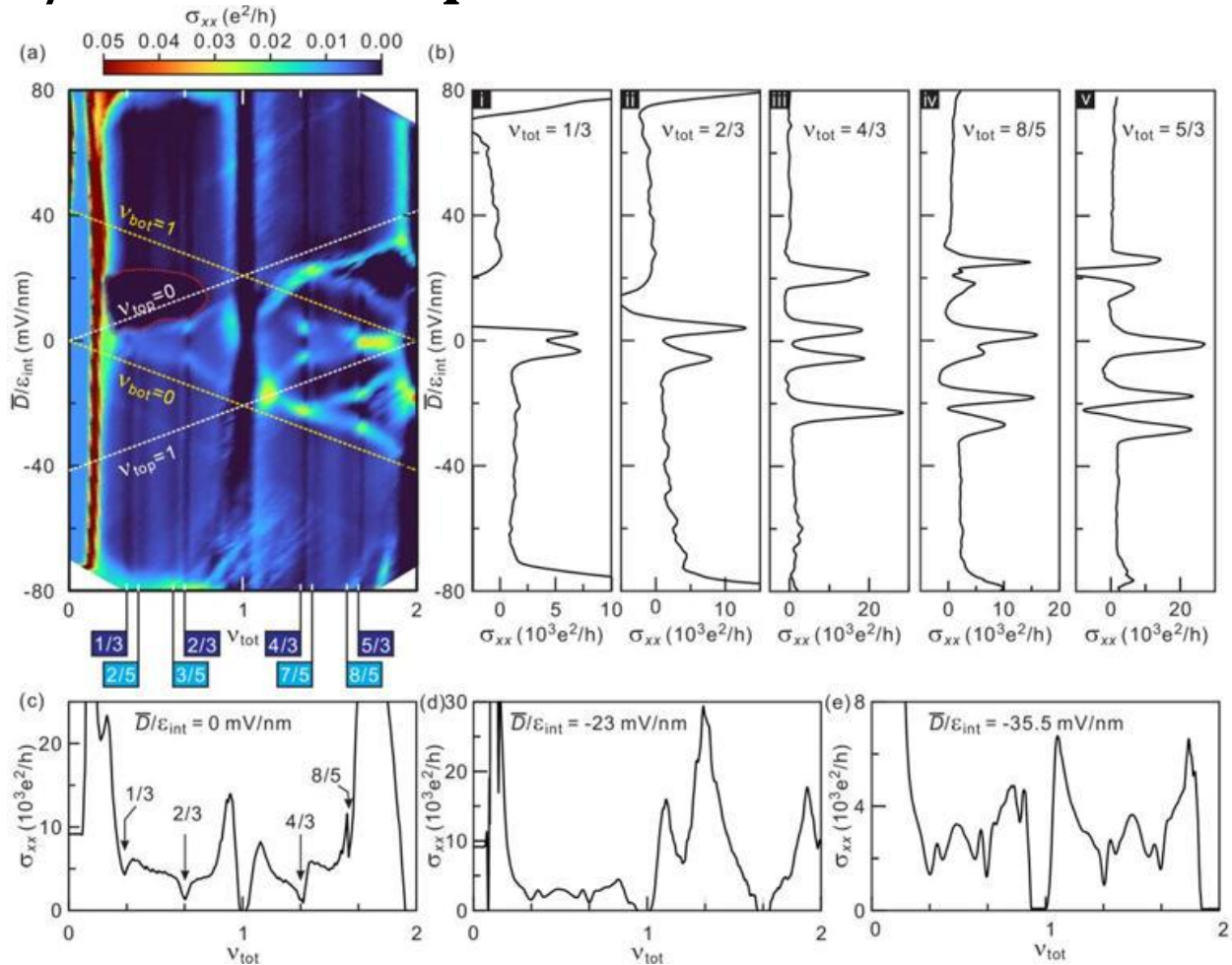
As a final step, the researchers used another laser pulse to deliberately perturb the electron sea in the graphene sample while the electron wave was propagating. By including the second laser pulse, they were able to selectively weaken the wave. This not only allows for observation of the waves and insights into the material in its static form but also enables control and ultrafast alteration of material properties.

This direct control of electron density waves could be a key step toward developing new electronic components with clock speeds more than a thousand times faster than current electronics.

More information: Simon Anglhuber et al, Spacetime Imaging of Group and Phase Velocities of Terahertz Surface Plasmon Polaritons in Graphene, *Nano Letters* (2025). DOI: [10.1021/acs.nanolett.4c04615](https://doi.org/10.1021/acs.nanolett.4c04615)

Provided by Universität Regensburg

Electrons in twisted graphene form novel 1/3 fractional quantum Hall state



The longitudinal conductivity σ_{xx} recorded on device D1 as a function of total filling ν_{tot} and displacement field $\bar{D}/\epsilon_{\text{int}}$ for a fixed magnetic field of 19 T and at a temperature of 30 mK. Credit: Nature Communications (2025). DOI: 10.1038/s41467-024-55486-2

A research team discovered a quantum state in which electrons move in a completely new way under a twisted graphene structure. The unique electronic state is expected to contribute to the development of more efficient and faster electronic devices. It may also be applicable to technologies such as quantum memory, which can process complex computations.

Quantum physics is a crucial theory that attempts to understand and explain how atoms and particles interact and move in nature. Such an understanding serves as the basis for designing new technologies that control or utilize nature at the microscopic level. The research conducted holds significance in discovering the

quantum state, which is difficult to implement with conventional semiconductor technologies, and in greatly expanding future possibilities for quantum technologies.

Graphene is a material as thin as a piece of paper and is made of carbon atoms. This study utilized a unique structure comprising two slightly twisted layers of graphene, observing a new quantum state. When compared to two transparent films, each film has regular patterns, and when they are rotated slightly, the patterns overlap to reveal new patterns.

The research team revealed that these new patterns create completely different rules for governing the movement of electrons, preventing electrons from crossing from one layer to another while creating strong interactions (Coulomb interactions) between the layers. The paper is [published](#) in the journal *Nature Communications*.

Electron Microscope Hack to see Graphene

In particular, the research team discovered a new electronic state called "1/3 fractional quantum Hall state." This state is unique because electrons move as if in three parts, which is completely different from their conventional movement. This state arises from strong interactions between electrons as they push and pull each other between the layers. It was theoretically proven using a Monte Carlo simulation, which demonstrated its physical implications.

Professor Gilyoung Cho at KAIST said, "Our discovery of a fractional quantum Hall state in new materials could contribute significantly to the development of quantum computer technologies."

Professor Youngwook Kim at DGIST added, "This study is the outcome of close collaboration with NIMS in Japan and the Max Planck Society for the Advancement of Science in Germany. More notably, we used the Max Planck Society's high-magnetic-field experimental equipment to obtain key data, and our international collaboration opened up new possibilities. We will continue our research to implement similar conditions in an environment where there is no magnetic field."

This study was led by Youngwook Kim at DGIST and Ph.D. student Seyoung Jin at POSTECH.

More information: Dohun Kim et al, Observation of $1/3$ fractional quantum Hall physics in balanced large angle twisted bilayer graphene, *Nature Communications* (2025). DOI: [10.1038/s41467-024-55486-2](https://doi.org/10.1038/s41467-024-55486-2)

Provided by Daegu Gyeongbuk Institute of Science and Technology

Plastic supercapacitors could solve energy storage problems



Illustration of a PEDOT film on a graphene sheet that can be used in supercapacitors to store large amounts of energy. Credit: Maher El-Kady

Plastics have shaped our modern world and changed the way we live. For decades, they have been primarily used in electronics for their excellent insulating properties. But in the 1970s, scientists accidentally discovered that some plastics can also conduct electricity. This finding revolutionized the field and opened the door to applications in electronics and energy storage.

One of the most widely used electroconductive plastics today is called PEDOT, short for poly(3,4-ethylenedioxythiophene). PEDOT is a flexible, transparent film often applied to the surfaces of photographic films and electronic components to protect them from static electricity. It is also found in touch screens, organic solar cells and electrochromic devices, such as smart windows that switch from light to dark at the press of a button.

However, PEDOT's potential for energy storage has been limited because commercially available PEDOT materials lack the electrical conductivity and surface area needed to hold large amounts of energy.

UCLA chemists are addressing these challenges with an innovative method to control the morphology of PEDOT to grow nanofibers precisely. These nanofibers exhibit exceptional conductivity and expanded surface area, both of which are crucial for enhancing the energy storage capabilities of PEDOT.

This approach, described in a paper [published](#) in *Advanced Functional Materials*, demonstrates the potential of PEDOT nanofibers for supercapacitor applications.

Unlike batteries, which store energy through slow chemical reactions, supercapacitors store and release energy by accumulating electrical charge on their surface. This allows them to charge and discharge extremely quickly, making them ideal for applications requiring rapid bursts of power, such as regenerative braking systems in hybrid and electric vehicles and camera flashes. Better supercapacitors are, therefore, one route to reduced dependence on fossil fuels.

The UCLA chemists produced the new material through a unique vapor-phase growth process to create vertical PEDOT nanofibers. These nanofibers, resembling dense grass growing upward, dramatically increase the material's surface area, allowing it to store more energy. By adding a drop of liquid containing graphene oxide nanoflakes and ferric chloride on a graphite sheet, the researchers exposed this sample to a vapor of the precursor molecules that eventually formed the PEDOT polymer.

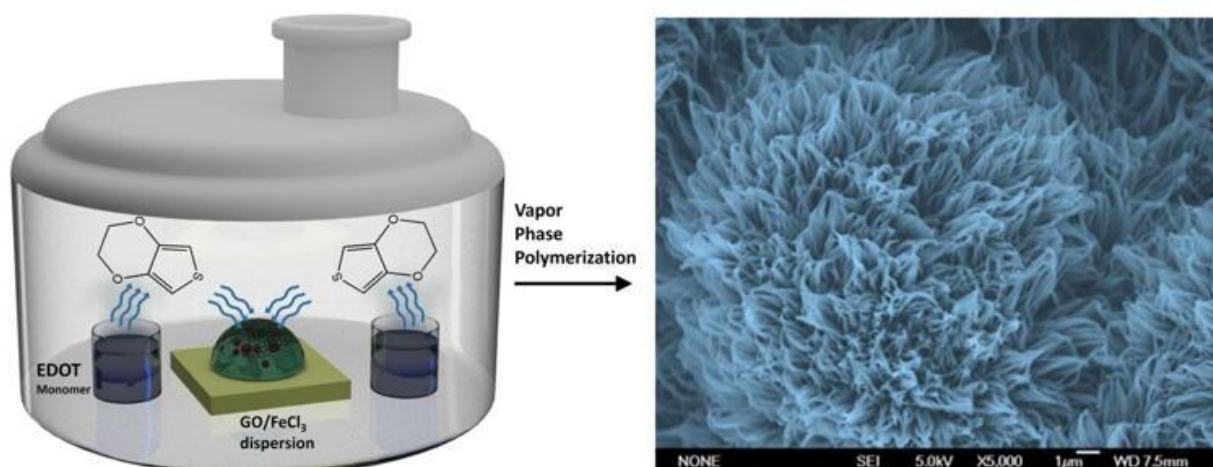
Instead of developing into a very thin, flat film, the polymer grew into a thick, fur-like structure, significantly increasing the surface area compared to conventional PEDOT materials.

"The material's unique vertical growth allows us to create PEDOT electrodes that store far more energy than traditional PEDOT," said corresponding author and UCLA materials scientist Maher El-Kady. "Electric charge is stored on the surface of the material, and traditional PEDOT films don't have enough surface area to hold very much charge. We increased the surface area of PEDOT and thereby increased its capacity enough to build a supercapacitor."

The authors used these PEDOT structures to fabricate supercapacitors with excellent charge storage capacity and extraordinary cycling stability, reaching nearly 100,000 cycles. The advance could pave the way for more efficient energy storage systems, directly addressing global challenges in renewable energy and sustainability.

"A polymer is essentially a long chain of molecules built out of shorter blocks called monomers," said El-Kady. "Think of it like a necklace made from individual beads strung together. We heat the liquid form of the monomers inside a chamber. As the vapors rise, they react chemically when they come in contact with the surface of the graphene nanoflakes. This reaction causes the monomers to bond and form vertical nanofibers. These nanofibers have a much higher surface area, which means they can store much more energy."

The new PEDOT material has shown impressive results, exceeding expectations in several critical areas. Its conductivity is 100 times higher than that of commercial PEDOT products, making it far more efficient for charge storage. What's even more remarkable is that the electrochemically active surface area of these PEDOT nanofibers is four times greater than that of traditional PEDOT. This increased surface area is crucial because it allows for much more energy to be stored in the same volume of material, significantly boosting the performance of supercapacitors.



An example of how EDOT monomer vapors react with a droplet of graphene oxide and ferric chloride to form PEDOT nanofibers. Credit: Maher El-Kady and Musibau Jimoh

Thanks to the new process, which grows a thick layer of nanofibers on the graphene sheet, this material now has one of the highest charge storage capacities for PEDOT reported to date—more than 4,600 milliFarads per square centimeter, which is nearly one order of magnitude higher than conventional PEDOT.

On top of that, the material is incredibly durable, lasting through more than 70,000 charging cycles, far outlasting traditional materials. These advances open the door for supercapacitors that are not only faster and more efficient but also longer-lasting, which are essential qualities for the renewable energy industry.

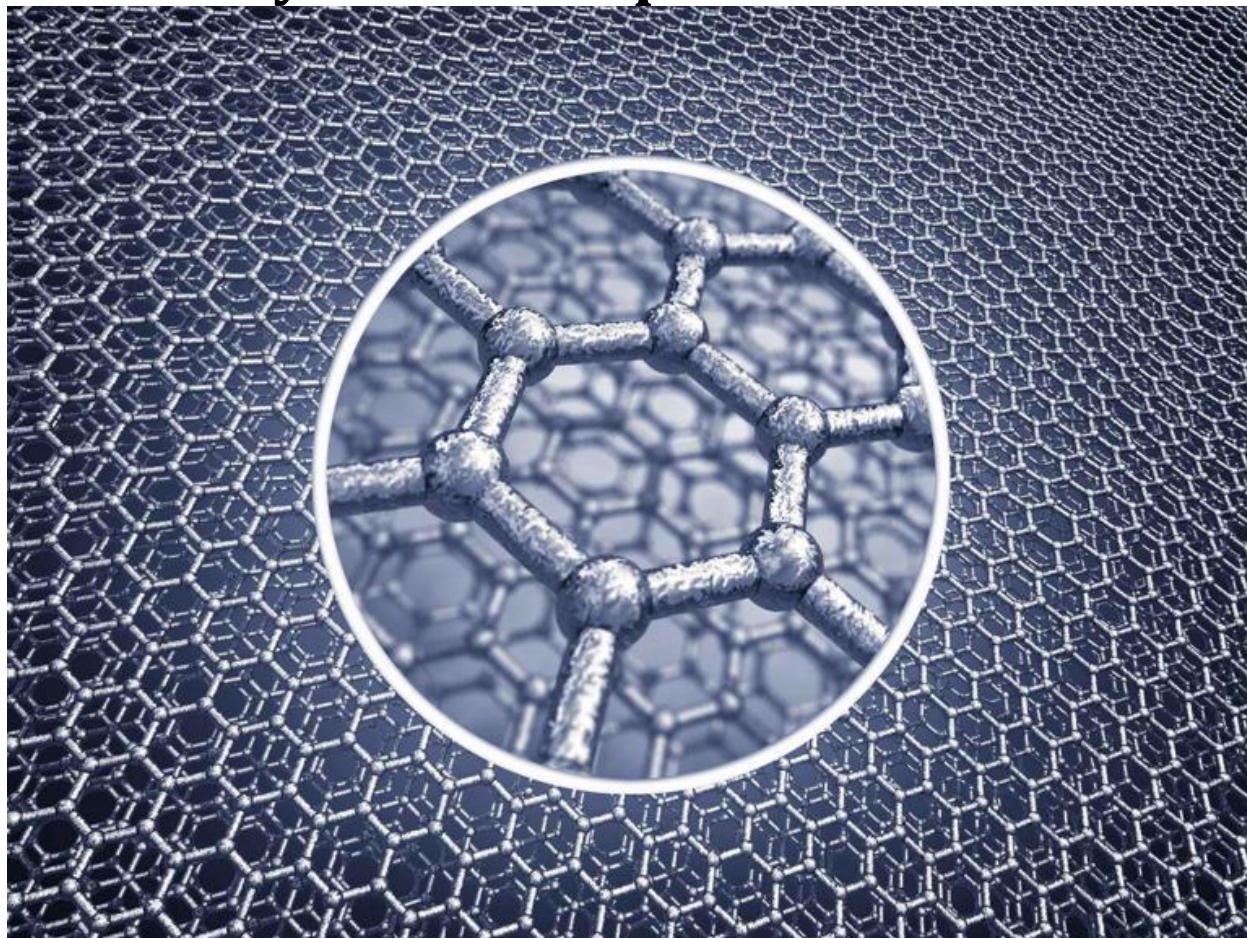
"The exceptional performance and durability of our electrodes shows great potential for graphene PEDOT's use in supercapacitors that can help our society meet our energy needs," said corresponding author Richard Kaner, a UCLA distinguished professor of chemistry and of materials science and engineering, whose research team has been at the forefront of conducting polymer research for over 37 years.

As a doctoral student, Kaner contributed to the discovery of electrically conductive plastic by his advisors Alan MacDiarmid and Alan Heeger, who later received a Nobel Prize for their work. Other authors on the study include Musibau Francis Jimoh, Gray Carson and Mackenzie Anderson, all of whom are also at UCLA.

More information: Musibau Francis Jimoh et al, Direct Fabrication of 3D Electrodes Based on Graphene and Conducting Polymers for Supercapacitor Applications, *Advanced Functional Materials* (2024). DOI: [10.1002/adfm.202405569](https://doi.org/10.1002/adfm.202405569)

Provided by University of California, Los Angeles

What is Synthetic Graphite?



What is Synthetic Graphite? ©nobeastsofierce / Shutterstock© Investing News Network

The [outlook for the graphite market](#) is promising due to its usage in the battery industry and energy storage applications, as well as steel-making.

With China dominating the natural graphite market, synthetic graphite is poised to capitalize on rising demand for graphite in the technologies.

Understanding what synthetic graphite is and how it differs from natural graphite is important for investors, as each industry typically needs a specific type of graphite. Here's a look at the synthetic graphite market and what it has to offer.

In this article

What is synthetic graphite?

[Synthetic graphite](#) is an industrial material that is artificially made from hydrocarbon precursors. It is able to withstand high temperatures and corrosion.

Those points make it a great option for highly specialized industries that need predictable results from carbon materials, such as metal fabrication, solar panels, electric vehicle batteries and grid-scale energy storage systems.

What are the uses of synthetic graphite?

Synthetic graphite uses cover a variety of applications, including energy storage applications and steel manufacturing, and its particular uses are dependent on its form.

Synthetic graphite typically comes in two forms: [electrodes](#) and graphite blocks. The form of synthetic graphite directly determines which industries it will be used in.

- **Electrodes:** Synthetic graphite electrodes are primarily created using petroleum coke as a precursor and are almost exclusively found in electric-arc furnaces — these furnaces are used for melting steel and iron, and producing ferroalloys.
- **Graphite blocks:** Synthetic graphite blocks, or isotropic graphite, are primarily used for energy storage in the solar industry. These blocks are made using the same petroleum coke process as electrodes, but differ slightly in the structure of the coke used.

- **Secondary synthetic graphite:** Secondary synthetic graphite is a by-product material of synthetic graphite production, and it is typically yielded as a powder. This by-product is considered a low-cost graphite material and some forms of it can compete with natural graphite in applications like brake linings and lubricants.

- **Primary synthetic graphite:** Primary synthetic graphite is typically manufactured in powder form and used for high-end lithium-ion batteries. However, it is more expensive to produce and can cost the same amount as manufacturing an electrode. Unlike its secondary counterpart, primary synthetic graphite is not a by-product material.

How is high-performance battery-grade synthetic graphite made?

Battery-grade synthetic graphite is made from heat-treating at very high temperatures a blend of lower purity carbon-based raw materials with coal tar pitch, petroleum coke or oil. This creates a uniform carbon structure suited for high performance, long-lasting electric vehicle batteries.

Is synthetic graphite better than natural graphite?

As for how synthetic graphite [compares](#) to natural graphite, synthetic graphite is purer than natural graphite in terms of carbon content and tends to behave more predictably. This makes synthetic graphite a better option than natural for use in high-performance applications that require higher efficiency and reliability such as lithium-ion batteries for electric vehicles.

On the flip side, as the process is energy intensive, synthetic graphite production can be significantly more expensive than that of natural graphite, and the environmental impact of synthetic graphite is worse as well.

"Synthetic graphite anode production can be over four times more carbon intensive than natural graphite anode production, due to its use of energy and fossil fuels as a feedstock," [according to Benchmark](#).

These higher economic and environmental costs for producing synthetic graphite has led graphite end users to substitute natural graphite for synthetic graphite in battery anodes.

How big is the synthetic graphite market?

The global synthetic graphite market size is expected to come in at US\$3.41 billion in 2025, [according to Mordor Intelligence](#), and is projected to growing at a CAGR of 6.83 percent to reach more than US\$4.74 billion by 2030.

In terms of overall graphite demand, Benchmark Mineral Intelligence expects to see a supply deficit from growth in the battery sector moving forward.

Tony Alderson, price and data analyst at Benchmark Mineral Intelligence, [told the Investing News Network](#), "the currently announced supply is simply not enough to meet the forecasted demand out to 2034, with both (synthetic and natural graphite) reaching deficits of over 600,000 tpa, which are only set to widen out to 2040."

As a whole, it appears graphite's future is bright. However, synthetic graphite will still face somewhat of an uphill battle. For one, improvements in natural graphite purity are helping it enter the nuclear technology and high-end battery markets, which have typically been owned by synthetic graphite.

Price will certainly continue to be a determining factor in the competition between natural and synthetic graphite. [Data from S&P Global Market Intelligence](#) shows that processing synthetic graphite is three times as energy intensive as processing natural graphite, which translates into higher costs for the artificial material.

Going forward, higher synthetic graphite prices are expected, as are higher natural graphite prices, as demand rises and electric vehicle battery manufacturers vie for the limited supply outside of China.

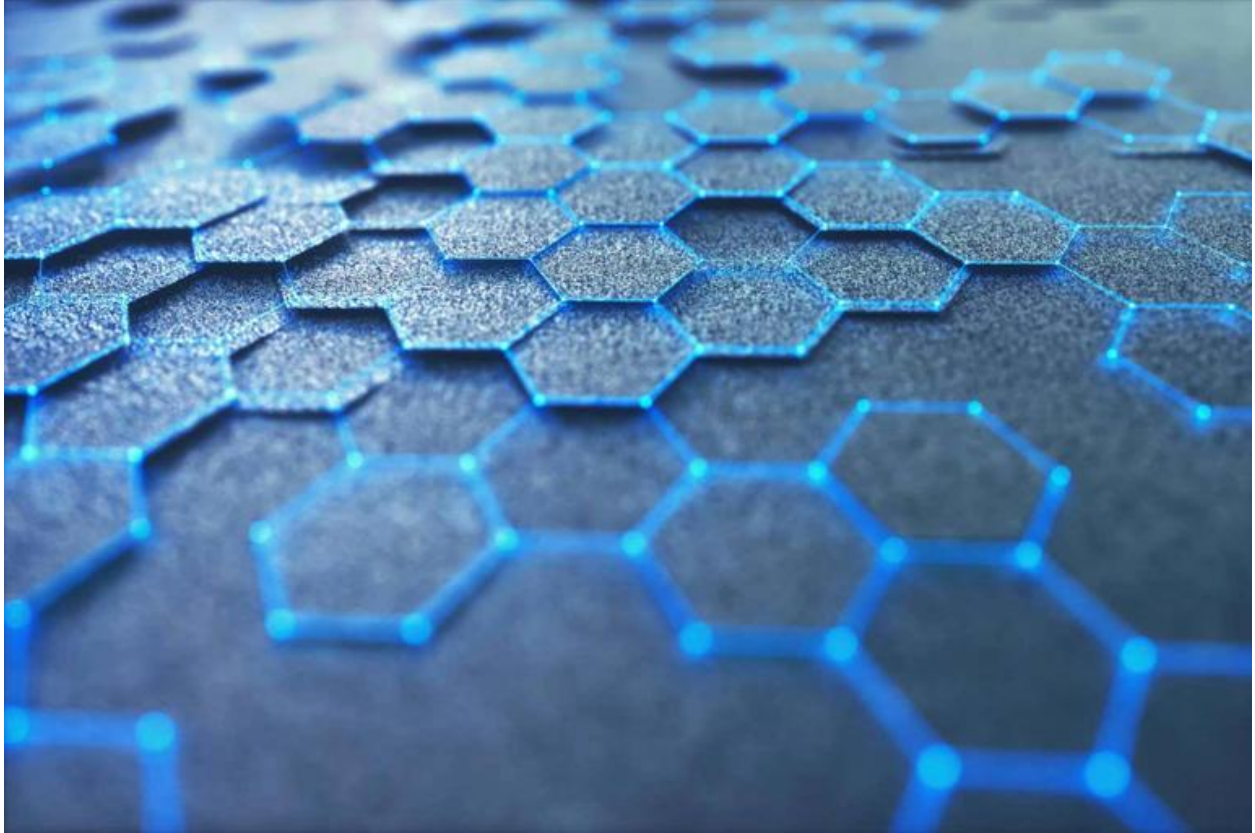
"We see China continuing to operate at a surplus over the next decade because of its existing capacity, but the rest of the world still looks to need more capacity for both natural and synthetic anodes if it wants to meet its own demand," [James Willoughby](#), senior research analyst for Graphite, Energy Transition & Battery Raw Materials at Wood Mackenzie, told the Investing News Network.

Synthetic graphite stocks

The global synthetic graphite market is "partially consolidated" and dominated by a handful of major companies, according to a [report by Mordor Intelligence](#). The top five players in this space are:

- **GrafTech International (NYSE:EAF)** is a leading large-scale manufacturer of high-quality graphite electrode products essential to the production of electric arc furnace steel.
- **BTR New Material Group (BJSE:835185)** is a Chinese manufacturer of cathode and anode materials for the lithium-ion battery industry.
- **Resonac Holdings' (TSE:4004)** graphite business unit manufactures several graphite products, including synthetic graphite electrodes. It has six graphite facilities globally, including one in South Carolina, US.
- **Ningbo Shanshan Technology (SHA:600884)** manufactures components of lithium-ion batteries, including cathode and anode materials, in China and internationally. Its graphite anode segment contributes a significant amount of global anode production.
- **Imerys (EPA:NK)** is a French multinational firm that provides mineral products, including synthetic graphite, to various industries.

Layered graphene has revealed a strange new kind of superconductivity



Strange properties manifest in ultra-thin materials like graphene Science Photo Library/Alamy

Why do cold thin sheets of carbon offer no resistance to electric currents? Two experiments are bringing us closer to an answer – and maybe even to practical room-temperature superconductors.

[Kin Chung Fong](#) at Northeastern University in Massachusetts was stunned when another physicist, [Abhishek Banerjee](#) at Harvard University, told him a number over dinner. They were studying different aspects of graphene – sheets of carbon only one atom thick – but both made the same estimate about how hard it should be for an electric current flowing through graphene to suddenly change.

Room-temperature superconductors: Here's everything you need to know

Past experiments have shown that very cold stacks of two or three layers of graphene can superconduct, or perfectly conduct electricity without resistance and energy loss, if some of the sheets are rotated by a special angle. But why this

happens remained mysterious. The two physicists thought the property they estimated at dinner, called kinetic inductance, might illuminate the answer.

“The feeling was like when you are in a wood hiking [through] the forest, and suddenly you find, well, wait a minute, I’m not the only person in this deep forest,” says Fong.

Together with other colleagues, they turned their idea into two experiments. One group measured kinetic inductance for two layers of stacked-and-twisted graphene; a second group focused on three layers.

[Joel Wang](#) at the Massachusetts Institute of Technology, who was in the group that worked on two-ply graphene, says that measuring kinetic inductance had previously been prohibitively difficult. Because multilayer graphene is so slight and tiny, standard techniques for measuring its superconducting currents – such as exposing it to particles or magnetic fields – produced excessively weak signals. Instead, both teams had to innovate a setup where the tiny graphene flakes were exposed to microwaves while the researchers slowly varied properties like temperature, which must be kept very low for superconductivity to occur at all.

We know that multilayer graphene superconducts because the electrons inside of it pair up, and these pairs flow in currents more easily than individual particles. But electrons typically repel each other. How exactly the particles come together and what properties these pairs have is still not understood.

“Theory is [running] behind experiments here,” says [Miuko Tanaka](#) at the University of Tokyo, who was also in the two-ply group.

For two layers of graphene, her team found that the superconducting current is much “stiffer” – it resists change more – than in any conventional theory of superconductivity. They traced this anomaly back to something called quantum geometry. Specifically, the shape of the electrons’ wavefunctions, which encode all their properties and possible behaviours, seemed to drive this exotic type of superconductivity.

The exotic quantum effects found hiding inside ultra-thin materials

In trilayer graphene, researchers found surprising similarities between the kinetic inductance of their sample and the behaviour of a family of completely different

superconductors – ones that maintain their special properties at much higher temperatures.

Because of this, both Banerjee and Tanaka say these experiments may do more than shed light on why graphene superconducts – they could also reveal key ingredients for room-temperature superconductors. Physicists have been searching for such materials for decades in the hope that using them could radically decrease the energy consumption of many devices.

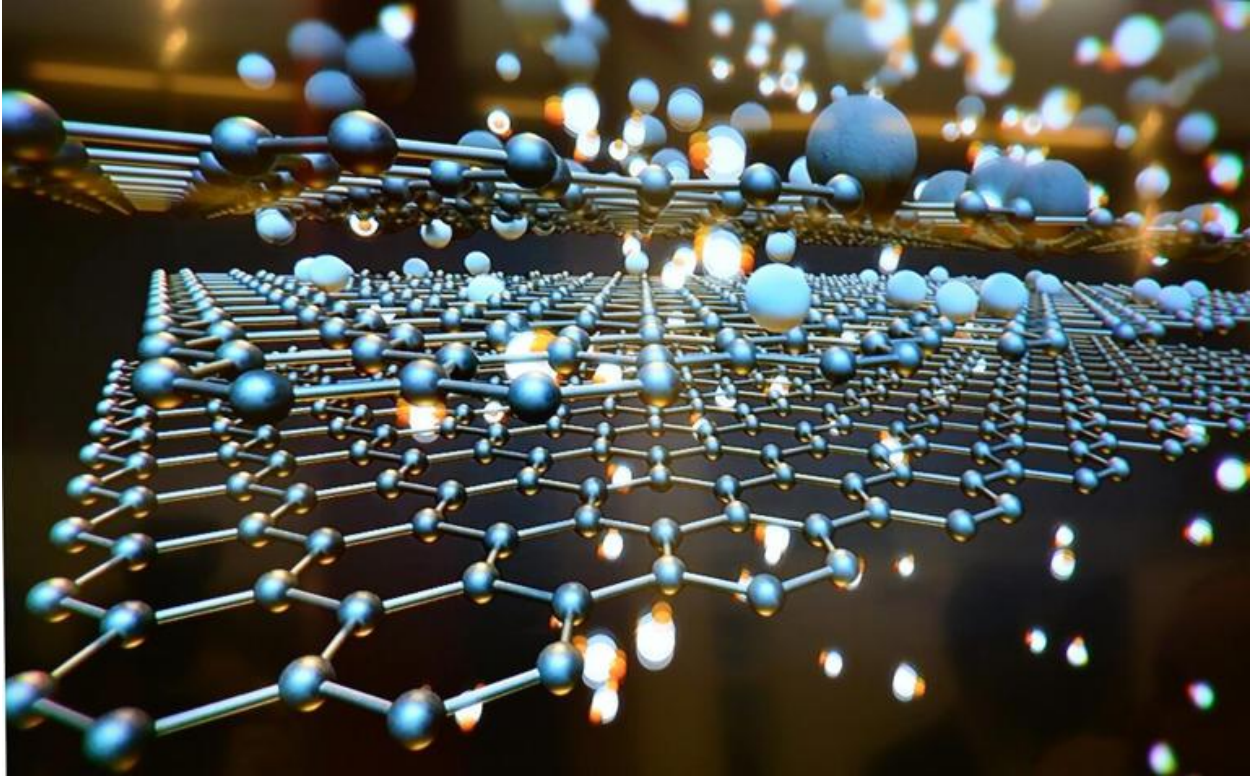
“We are finding interesting laws which seem to emerge in both these material systems. Maybe what we are uncovering is something deeper,” says Banerjee. Both teams are planning on performing similar experiments with other very thin superconductors. “Recently, there have been so many new two-dimensional superconductors that are interesting, surprising and kind of unusual,” says [Zeyu Hao](#), also at Harvard University.

In the meantime, his colleague [Mary Kreidel](#), now at NASA Jet Propulsion Laboratory in California, already has an application in mind for stacked-and-twisted graphene. She is working on particle detectors for space missions, many of which use superconductors. They could be made smaller and lighter – a crucial advantage in space flight – if they were made from multilayer graphene, she says.

Journal reference:

Nature DOI: [10.1038/s41586-024-08494-7](https://doi.org/10.1038/s41586-024-08494-7), DOI: [10.1038/s41586-024-08444-3](https://doi.org/10.1038/s41586-024-08444-3)

Physicists measure a key aspect of superconductivity in 'magic-angle' graphene



Superconducting materials are similar to the carpool lane in a congested interstate. Like commuters who ride together, electrons that pair up can bypass the regular traffic, moving through the material with zero friction.

But just as with carpools, how easily electron pairs can flow depends on a number of conditions, including the density of pairs that are moving through the material. This "superfluid stiffness," or the ease with which a current of electron pairs can flow, is a key measure of a material's superconductivity.

Physicists at MIT and Harvard University have now directly measured superfluid stiffness for the first time in "magic-angle" graphene—materials that are made from two or more atomically thin sheets of graphene twisted with respect to each other at just the right angle to enable a host of exceptional properties, including unconventional superconductivity.

This superconductivity makes magic-angle graphene a promising building block for future quantum-computing devices, but exactly how the material superconducts is not well-understood. Knowing the material's superfluid stiffness will help scientists identify the mechanism of superconductivity in magic-angle graphene.

The team's measurements suggest that magic-angle graphene's superconductivity is primarily governed by quantum geometry, which refers to the conceptual "shape" of quantum states that can exist in a given material.

The [results](#), which are reported in the journal *Nature*, represent the first time scientists have directly measured superfluid stiffness in a two-dimensional material. To do so, the team developed a new experimental method which can now be used to make similar measurements of other two-dimensional superconducting materials.

"There's a whole family of 2D superconductors that is waiting to be probed, and we are really just scratching the surface," says study co-lead author Joel Wang, a research scientist in MIT's Research Laboratory of Electronics (RLE).

The study's co-authors from MIT's main campus and Lincoln Laboratory include co-lead author and former RLE postdoc Miuko Tanaka, Pablo Jarillo-Herrero, William D. Oliver and others.

Magic resonance

Since its discovery in 2004, graphene has proven to be a wonder substance of sorts. The material is effectively a single, atom-thin sheet of graphite consisting of a precise, chicken-wire lattice of carbon atoms. This simple configuration can exhibit a host of superlative qualities in terms of graphene's strength, durability, and ability to conduct electricity and heat.

In 2018, Jarillo-Herrero discovered that when two graphene sheets are stacked on top of each other, at a precise, "magic" angle, the twisted structure—known as magic-angle twisted bilayer graphene, or MATBG—exhibits entirely new properties, including superconductivity, in which electrons pair up, rather than repelling each other as they do in everyday materials.

These so-called Cooper pairs can form a superfluid, with the potential to superconduct, meaning they could move through a material as an effortless, friction-free current.

"But even though Cooper pairs have no resistance, you have to apply some push, in the form of an electric field, to get the current to move," Wang explains.

"Superfluid stiffness refers to how easy it is to get these particles to move, in order to drive superconductivity."

Today, scientists can measure superfluid stiffness in superconducting materials through methods that generally involve placing a material in a microwave resonator—a device which has a characteristic resonance frequency at which an electrical signal will oscillate, at microwave frequencies, much like a vibrating violin string.

If a superconducting material is placed within a microwave resonator, it can change the device's resonance frequency, and in particular, its "kinetic inductance," by an amount that scientists can directly relate to the material's superfluid stiffness.

However, to date, such approaches have only been compatible with large, thick material samples. The MIT team realized that to measure superfluid stiffness in atomically thin materials like MATBG would require a new approach.

"Compared to MATBG, the typical superconductor that is probed using resonators is 10 to 100 times thicker and larger in area," Wang says. "We weren't sure if such a tiny material would generate any measurable inductance at all."

A captured signal

The challenge to measuring superfluid stiffness in MATBG has to do with attaching the supremely delicate material to the surface of the microwave resonator as seamlessly as possible.

"To make this work, you want to make an ideally lossless—i.e., superconducting—contact between the two materials," Wang explains. "Otherwise, the microwave signal you send in will be degraded or even just bounce back instead of going into your target material."

Will Oliver's group at MIT has been developing techniques to precisely connect extremely delicate, two-dimensional materials, with the goal of building new types of quantum bits for future quantum-computing devices.

For their new study, Tanaka, Wang, and their colleagues applied these techniques to seamlessly connect a tiny sample of MATBG to the end of an aluminum microwave resonator. To do so, the group first used conventional methods to assemble MATBG, then sandwiched the structure between two insulating layers of hexagonal boron nitride, to help maintain MATBG's atomic structure and properties.

"Aluminum is a material we use regularly in our superconducting quantum computing research, for example, aluminum resonators to read out aluminum quantum bits (qubits)," Oliver explains.

"So, we thought, why not make the most of the resonator from aluminum, which is relatively straightforward for us, and then add a little MATBG to the end of it? It turned out to be a good idea."

"To contact the MATBG, we etch it very sharply, like cutting through layers of a cake with a very sharp knife," Wang says. "We expose a side of the freshly-cut MATBG, onto which we then deposit aluminum—the same material as the resonator—to make a good contact and form an aluminum lead."

The researchers then connected the aluminum leads of the MATBG structure to the larger aluminum microwave resonator. They sent a microwave signal through the resonator and measured the resulting shift in its resonance frequency, from which they could infer the kinetic inductance of the MATBG.

When they converted the measured inductance to a value of superfluid stiffness, however, the researchers found that it was much larger than what conventional theories of superconductivity would have predicted. They had a hunch that the surplus had to do with MATBG's quantum geometry—the way the quantum states of electrons correlate to one another.

"We saw a tenfold increase in superfluid stiffness compared to conventional expectations, with a temperature dependence consistent with what the theory of quantum geometry predicts," Tanaka says. "This was a 'smoking gun' that

pointed to the role of quantum geometry in governing superfluid stiffness in this two-dimensional material."

"This work represents a great example of how one can use sophisticated quantum technology currently used in quantum circuits to investigate condensed matter systems consisting of strongly interacting particles," adds Jarillo-Herrero.

A complementary study on magic-angle twisted trilayer graphene (MATTG), conducted by a collaboration between Philip Kim's group at Harvard University and Jarillo-Herrero's group at MIT, appears in the same issue of *Nature*.

More information: Joel Wang et al, Superfluid stiffness of magic-angle twisted bilayer graphene, *Nature* (2025). DOI: [10.1038/s41586-024-08494-7](https://doi.org/10.1038/s41586-024-08494-7). www.nature.com/articles/s41586-024-08494-7

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Provided by Massachusetts Institute of Technology

Scientists use waste CO₂ and microwaves to produce high-energy plasma in seconds

A group of scientists has developed special CO₂-derived carbon nanotubes that can generate sustained plasma almost instantly when exposed to microwaves from a standard microwave oven.

Plasma is the stuff that makes lightning flash, stars shine, and neon signs glow. It is a special state of matter, like a supercharged gas. It happens when atoms lose some of their electrons, creating a mix of free-moving charged particles.

This makes plasma highly energetic and a good conductor of electricity. It has a wide range of applications across various fields. For instance, it can play an important [role in fusion energy research](#), and enable the development of advanced water and air purification technologies.

Moreover, its unique properties can also contribute to the creation of the next generation of medical sterilization, cancer treatments, and even space propulsion systems.

However, producing high-energy plasma for industrial applications requires specialized equipment and a controlled environment with extremely high temperatures. This is where the [CO₂-derived carbon nanotubes](#) can make a huge difference. They promise an easy and more accessible method to produce plasma.

A ninja technique to produce plasma

In their new study, the researchers reveal a method that only uses carbon nanotubes and a microwave oven to produce plasma with temperatures between [820 °C and 925 °C](#).

Unlike conventional methods, this approach requires no vacuum chambers, no controlled gas environment, and no hi-tech equipment. The researchers claim that this is made possible due to the unique molecular structure of their CO₂-derived [carbon nanotubes](#).

These tubes were produced using the molten carbonate electrolysis of carbon dioxide — a method that converts carbon dioxide (CO₂) into carbon or carbon-based materials using electricity and a high-temperature molten salt.

The process starts with heating a carbonate salt, such as lithium carbonate, until it melts, forming a conductive liquid. The [CO₂ gas captured from greenhouse](#) emissions is introduced into this molten mixture. When an electric current is applied, chemical reactions take place at the electrodes.

At the anode, carbonate ions lose electrons, producing oxygen gas. At the cathode, CO₂ is broken down, resulting in solid carbon. The carbon nanotubes developed using this carbon showed exceptional electrical and magnetic properties.

When these nanotubes were placed inside a microwave, within seconds yellow-white colored plasma emerged with a temperature exceeding 800 °C. “An

unexpected and high-powered plasma is induced by carbon nanotubes in air under microwave irradiation," the study authors [note](#).

CO₂-derived nanotubes are probably the best

The researchers also tried to produce plasma with commercially available carbon nanotubes (CNT), graphene, and other materials, but none of them could generate [sustained high-energy plasma](#) like their CO₂-derived nanotubes.

The nanotubes are also special because they are made from waste greenhouse CO₂. "The sole reactant preparing these carbon nanotubes is the greenhouse gas CO₂," the researchers note.

So while some conventional plasma-production methods contribute to carbon emissions, the CO₂-derived nanotubes offer a more environmentally friendly approach by utilizing waste carbon dioxide as a raw material to generate plasma.

The study also authors tested the quality of the plasma produced through their method. They used it to purify some [carbon nanotube](#) samples, and the results of the test were impressive.

"It decreased their impurity level and increased their resistance to combustion," the study authors said. They further claim their CNT-induced microwave-driven plasma takes "100-fold less time, consumes 10× less power, and produces higher purity CNTs than purification in a conventional plasma cleaning treatment chamber."

These findings suggest that CO₂-derived nanotubes are likely to play an important role in industrial-scale plasma production. However, high-energy plasma could be just one of their many interesting applications.

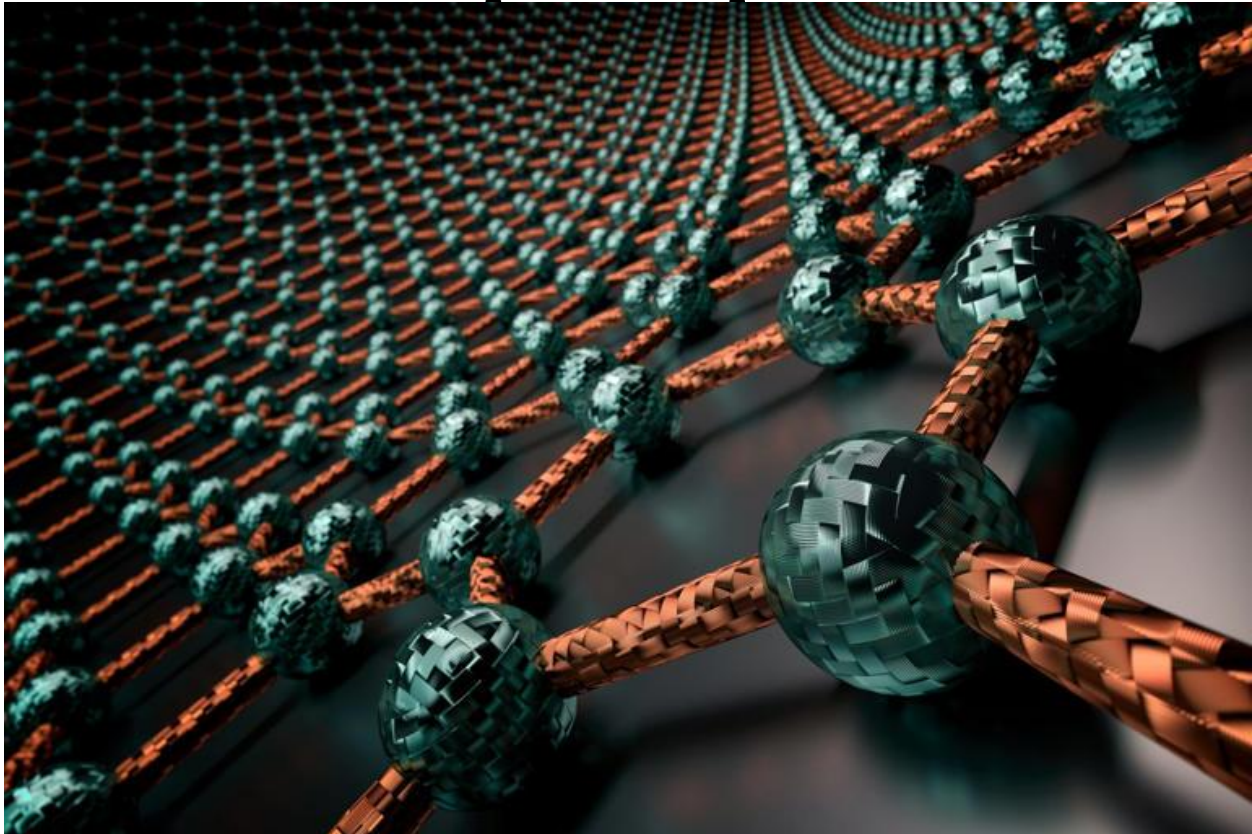
The [study](#) is published in the journal *Nanoscale*

Graphene concrete: Recent advances in production methods, performance properties, environmental impact and economic viability

Ali H. AlateahCite

<https://doi.org/10.1016/j.cscm.2023.e02653>Get rights and contentConcrete, foundational in modern construction, grapples with environmental concerns and performance limitations. Responding to this, this review unravels the potential of graphene-infused concrete. The techniques of integrating graphene into concrete, targeting the discovery of groundbreaking construction materials were systematically probe. Some studies highlight remarkable improvements: adding 0.03% [graphene oxide](#) (GO) bolstered concrete's [flexural strength](#) by over 40%, and a concentration of 0.05% GO optimized flexural strength by roughly 35%. Impressively, some studies showcased an elevation of up to 79.5% in flexural strength. Notably, incorporating just 0.01–0.1% graphene by weight can amplify [compressive strength](#), flexural strength, and [elastic modulus](#) by over 100%. Parallely, the environmental footprints of graphene's synthesis and its fusion into concrete, illuminating prospects for significant carbon emission curtailments and enhanced sustainability were scrutinized. On the economic front, while graphene concrete currently costs 5–10 times more than its conventional counterpart, its superior attributes suggest promising long-term cost benefits. Conclusively, this review findings spotlight graphene-augmented concrete as pivotal for a sustainable, economically sound, and high-caliber construction future.

What Factors Impact Graphene Cost?



What Factors Impact Graphene Cost? ©Forance / Shutterstock© Investing News Network

Graphene has the potential to spur advances in a variety of sectors, from transport to medicine to electronics. Unfortunately, the high cost of graphene production has slowed commercialization.

Graphene prices have come down substantially from its early days, when it reportedly cost tens of thousands of dollars to make a piece of high-quality graphene the size of a postage stamp.

However, the 21st century wonder material remains expensive. Specific graphene pricing data is hard to come by, but relatively recent estimates peg the commercial [cost of graphene](#) in a range of US\$100 to US\$10,000 per kilogram. The wide variance is mainly because the price of graphene is determined by a number of factors, such as production method, form, quality and quantity.

Graphene has many exciting applications. Notably, its properties have been applied to graphene-polymer composites. Together, these carbon-based materials are effective in energy, biomedicine, aerospace, and electronics

applications. In addition, graphene can be used for water purification due to its naturally occurring water-repellent properties.

Other key applications of graphene include graphene-conductive inks, which can be used for printed electronics in applications like logic circuits, inkjet printing, environmental sensors, and smart clothing.

Here's a look at how graphene is made, and why the production process plays a key role in graphene cost.

In this article

What is the origin of graphene?

[Graphene's origin story](#) is by now well known. The 2D material was first produced in 2004, when two professors at the University of Manchester used Scotch tape to peel flakes of it off a chunk of graphite.

The story gives the impression that it's easy to make graphene, but that's not entirely true. The Scotch tape method, while a fun party trick, can only produce a very small amount of graphene — certainly not enough to use commercially.

How is graphene made?

The Scotch tape method of making graphene is known as exfoliation, and there are other ways to create graphene via exfoliated graphite as well. For instance, a diamond wedge can cleave graphene layers.

But what are some other ways of making graphene? Currently, the most popular method is [chemical vapor deposition](#) (CVD). The deposition process involves a mix of gases reacting with a surface to create a graphene layer. The process creates high-quality graphene, but the graphene is often damaged when it comes time to detach it from its substrate.

Looking at the process in greater depth, [Graphenea states](#) that another problem with CVD is that it's difficult to create a totally uniform layer of graphene on a substrate. Graphenea also notes that much work is being put into reducing problems with CVD. For example, scientists are experimenting with treating the substrate before the reaction that creates graphene takes place. Even so, it's expected to take a long time for the wrinkles to be smoothed out.

The [Graphene Flagship identifies](#) a number of other ways of making graphene, including direct chemical synthesis; the material can also be made by putting natural graphite in a solution.

Some of the latest innovations in graphene creation don't involve the use of chemicals and can be conducted in the open air, as opposed to in vacuums. One method that was patented in 2017 is able to [create larger quantities of graphene](#) using acetylene, oxygen and a spark plug. Unfortunately, this process creates unrefined chunks of material and not sheets, meaning more money must be spent to make the graphene chunks useable.

In 2021, the Indian Institute of Technology Patna developed a way to produce graphene [using a plasma gun](#); it's possible it will prove to be a cheaper, yet scalable route to producing high-quality graphene material. The method has been shown to produce single-layer graphene 85 percent of the time without hazardous chemicals or expensive solvents, and estimates show that doing so only costs about US\$1.12 per gram of graphene.

In mid-2022, chemical manufacturing company [CleanGraph announced](#) its proprietary process for transforming graphite into graphene, saying it had been developed over the past four years with the help of partnerships with market leaders in the construction industry and prominent universities. This method of producing graphene reportedly reduces the environmental impact by 99 percent compared to traditional graphene production.

"Expanded graphite is a layered nanocarbon material, which is produced at industrial scale by oxidative intercalation and high-temperature expansion of natural graphite. CleanGraph is a novel proprietary process to chemically modify graphite into various forms of graphene in a faster, more productive and ecologically friendly way," as per the company.

Along with construction materials, the graphene produced by this method can also be used for heating, battery technology and as a sorbent.

More recently, in late 2023 [NanoXplore \(TSX:GRA,OTCQX:NNXPF\)](#) unveiled a new [proprietary large-scale dry process](#) for manufacturing graphene based on advanced exfoliation technology. It has a lower CAPEX compared to liquid-based exfoliation methods.

"The technology finds potential applications in batteries and lightweight composites, enhancing its appeal in cutting-edge industries," states the company. "This new manufacturing process also opens doors to a myriad of applications, including plastic pipes, geosynthetics, recycled plastics, concrete, drilling fluids, and insulation foams, among others."

What factors impact graphene cost?

Getting an understanding of how graphene is produced is crucial to understanding graphene cost. That's because the way in which graphene is made has a major impact on how much it ultimately costs.

Echo Zhang, founder of China-based graphene technology company GrapheneRich, [explains](#) that CVD and liquid-phase exfoliation are the most expensive methods due to the "advanced equipment and high energy consumption required." Meanwhile, the chemical reduction of graphene oxide is cheaper but may produce lower quality material.

Graphene oxide, which has advanced composite, biotechnology and water filtration applications, can cost between US\$100 and US\$500 per kilogram. "The price can vary depending on the oxidation level, production method, and supplier," Zhang states.

Graphenea [also highlights](#) that while graphene oxide is relatively inexpensive to produce, its lower quality means it can't be used in batteries, flexible touch screens and "other advanced opto-electronic applications."

In contrast, CVD graphene, which Zhang calls "top-tier graphene" resulting in a "high-performance material with excellent properties," fetches upwards of

US\$10,000 or more per kilogram. Its often used in advanced electronics and energy-storage systems.

"Methods like CVD, which produce high-quality, high-purity graphene, are generally more expensive than liquid-phase exfoliation or reduction of graphene oxide," Zhang explains. "The production method affects both the quality and the cost of the final product."

Commercial-grade graphene can be produced in larger quantities, resulting in a price range of US\$100 to US\$1,000 per kilogram. This grade of graphene is used in energy storage, sensors and composites. "These prices depend on the production scale and the quality of the graphene being produced," Zhang states.

The issue, of course, is that with few commercial applications for graphene yet available, few end-users are looking to buy the material in large quantities.

What is the future of graphene research?

Those involved in graphene research hope that ultimately more commercial applications for the material will be developed, spurring advances that will make cost-effective mass production of the material a reality.

Graphene products are making their way into next-generation electronics such as flexible and foldable screens, enhanced batteries and "lightning-speed" computers.

Graphene can also be used to create more fuel-efficient cars, faster and lighter aircraft and paint that could end deterioration of ships and cars. Overall, there's no shortage of applications for graphene products.

Graphene's impressive properties and the fact that it's made from carbon, much like human bodies, makes it well suited to [biotechnologies](#), including tools that can help healthcare professionals scan a patient's biosignals quickly, accurately and safely.

"Graphene is a single layer of carbon molecules," explained Dr. Kiana Aran, chief scientific officer at Cardea Bio, and Keck Graduate Institute associate professor of bioengineering. "Everything in our body is made of carbon. It's the most

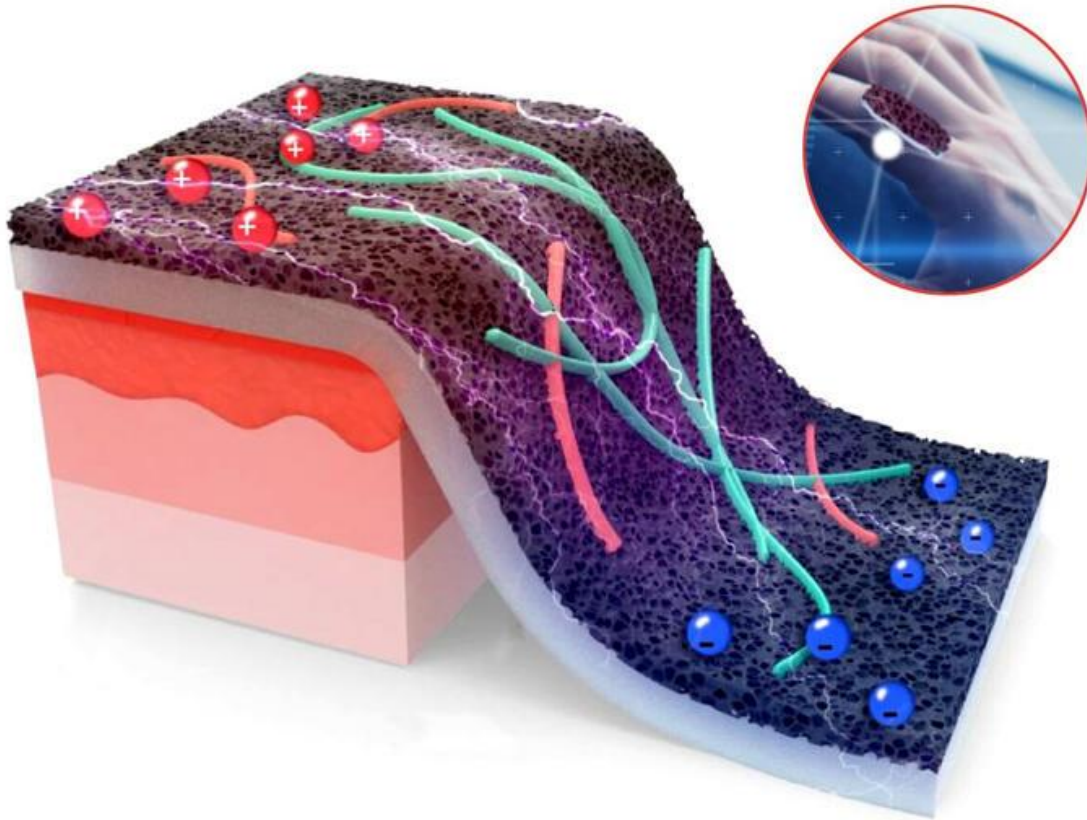
compatible material we can find that has amazing electronic properties. You can build electronics and conjugate with biology, without impacting ... biology and without biology impacting it."

Researchers at the Georgia Institute of Technology have [created the first functional semiconductor](#) made from graphene. As an alternative to silicon, the breakthrough has the potential to allow for smaller and faster electronic devices, which may have applications for quantum computing.

In terms of market growth, [Grand View Research notes](#), "Market growth stage is high, and pace of the market growth is accelerating. Graphene market is characterized by a high degree of innovation owing to rising advancements driven by factors including research and development. Subsequently, innovative applications are constantly emerging, disrupting existing industries and creating new ones."

The market research firm projects that the graphene market will see revenues grow at a compound annual growth rate of 35.1 percent between 2024 and 2030 to reach US\$1.61 billion. The automotive, aerospace and medical industries are the core drivers of demand for the material. Graphene's role as a powerful catalyst in the chemical industry is also expected to contribute to increased demand for the wonder material on a global scale.

Self-powered graphene smart sensor takes the pain out of wound monitoring



The flexible sensor, ideal for use in the human body, uses laser-induced graphene to simultaneously but separately measure temperature and strain, potentially enabling better wound healing monitoring by providing clearer insights into inflammation and recovery. Credit: Jennifer M. McCann

A major challenge in self-powered wearable sensors for health care monitoring is distinguishing different signals when they occur at the same time. Researchers from Penn State and China's Hebei University of Technology have addressed this issue by uncovering a new property of a sensor material, enabling the team to develop a new type of flexible sensor that can accurately measure both temperature and physical strain simultaneously but separately to more precisely pinpoint various signals.

"This unique sensor material we've developed has potentially important applications in health care monitoring," said Huanyu "Larry" Cheng, James L. Henderson, Jr. Memorial Associate Professor of Engineering Science and

Mechanics (ESM) at Penn State and co-corresponding author of the study [published](#) in *Nature Communications*.

"By accurately measuring both temperature changes and physical deformation or strain created by a healing wound and measure that by separating the two signals, it could revolutionize the tracking of wound healing. Doctors could get a much clearer picture of the healing process, identifying issues like inflammation early on."

The researchers aimed to accurately measure temperature and strain signals without cross talk by using laser-induced graphene, a two-dimensional (2D) material. Like all 2D materials including regular graphene, laser-induced graphene is one to a few atoms thick with unique properties, but with a twist. Laser-induced graphene (LIG) forms when a laser heats certain carbon-rich materials—like plastic or wood—in a way that converts their surface into a graphene structure. The laser essentially "writes" the graphene directly onto the material, making it a simple and scalable way to produce graphene patterns for electronics, sensors and energy devices.

LIG has been used before in various applications. Previously, Cheng and his team have used LIG for gas sensors, electrochemical detectors for sweat analysis, supercapacitors, and more. However, the researchers said they believe they discovered a new property of LIG for the first time that makes it ideal for a multi-purpose and accurate sensor.

"In this particular study, we kind of stumbled upon the fact that this material also has thermoelectric properties," Cheng said. "We believe this is the first time anyone has reported laser-induced graphene having thermoelectric capabilities. And that's really important for what we're trying to do here, which is to separately measure both temperature changes and physical strain or deformation."

Thermoelectric properties in a material refer to the ability to convert temperature differences into electrical voltage and vice versa, enabling such materials to be used for applications like energy harvesting and temperature sensing. According to Cheng, this newly identified thermoelectric property of LIG makes it easy to separate the two sensor measurements and ideal for health care applications such as a sensor embedded in a bandage.

"When you have materials that are sensitive to both temperature and strain, it can be tricky to tell which signal is causing changes in the material," Cheng said. "But by using this thermoelectric effect in the laser-induced graphene, we can essentially decouple those two measurements. We can look at the electrical resistance to get information about the strain, while also measuring the thermal voltage to determine the temperature. This is why doctors could use it to track both temperature fluctuations and physical changes in the wound site and give a much clearer picture of how the healing is progressing."

He also noted that the sensor is highly sensitive, detecting temperature changes as small as 0.5 degrees Celsius. The material's design takes advantage of the way porous graphene and thermoelectric components work together, making it nearly four times better at converting heat into electricity. The sensor can also stretch up to 45%, as well as conform to different shapes and surfaces, without losing function.

"The porous structure of this material creates a lot of tiny spaces and channels that allow it to interact with its surroundings in a very sensitive way," Cheng said. "This makes it well-suited for interfacing with human soft tissues, in contrast to more rigid thermoelectric materials, such as ceramic-based ones."

Since the thermoelectric aspect of LIG also means it can generate electrical power when there is a temperature difference, LIG sensors are self-powered. According to Cheng, this could be particularly useful for continuous monitoring in clinical settings and for other applications, such as helping detecting fires in remote locations.

In addition to refining the sensor, the team is developing a wireless system that will allow people to monitor the data from the sensor remotely. This will make it possible to track important information, such as temperature or strain, in real time using smartphones or other devices.

"For example, a doctor could monitor a patient's condition from a distance, or emergency responders could receive alerts about dangerous temperature changes," Cheng said. "These advancements aim to make the technology more accessible and effective, helping to improve health monitoring and safety in everyday situations."

Along with Cheng, other paper authors include Ankan Dutta, graduate student in engineering science and mechanics at Penn State; and Li Yang, Xue Chen, Hui Zhang, Zihan Wang, Mingyang Zin, Shuaijie Du and Guizhi Xu, all from Hebei University of Technology.

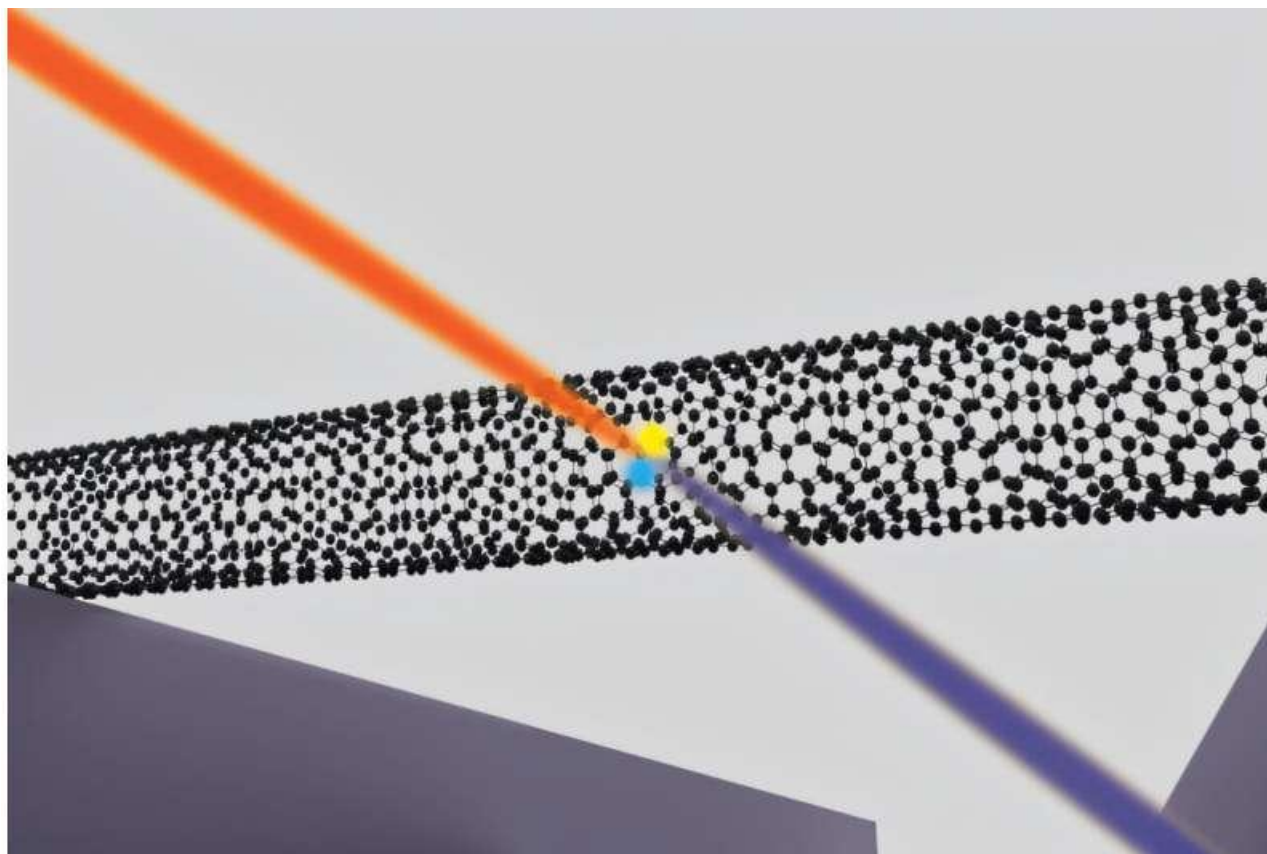
More information: Li Yang et al, Thermoelectric porous laser-induced graphene-based strain-temperature decoupling and self-powered sensing, *Nature Communications* (2025). DOI: [10.1038/s41467-024-55790-x](https://doi.org/10.1038/s41467-024-55790-x)

Provided by Pennsylvania State University

FEBRUARY 20, 2025

How carbon nanotubes give out more than they receive

by [RIKEN](#)



When infrared light (orange ray) hits a carbon nanotube suspended over a trench in a silicon substrate, the nanotube emits light with a higher energy (purple ray). Three RIKEN researchers have determined how this occurs. Credit: RIKEN Center for Advanced Photonics

Three RIKEN physicists have discovered how tiny tubes of carbon spit out light that is more energetic than the light shone on them. This finding could help to exploit the process in applications such as solar power and biological imaging.

Some special paints glow when you shine ultraviolet light on them. They are classical examples of conventional photoluminescence: when illuminated by high-energy light ([ultraviolet light](#)), they emit lower energy light ([visible light](#)).

But surprisingly, certain materials exhibit the opposite effect—shine light on them and they emit higher energy light. This curious phenomenon is called up-conversion

photoluminescence (UCPL). It could boost the efficiency of solar cells, for example, by converting low-energy light into higher-energy wavelengths suitable for generating electricity.

In regular photoluminescence, light hits a material and kicks an electron into a higher energy level, leaving behind a positively charged "hole."

Initially, the electron–hole pair sticks together in a state known as an exciton. But eventually, the electron and hole recombine, emitting light in the process.

In normal photoluminescence, the exciton loses energy to the material, and hence the emitted light carries away less energy than the incoming light brought in. In UCPL, however, the exciton receives an energy boost from the material by interacting with vibrations in it known as phonons.

Now, Yuichiro Kato and two colleagues, all at the RIKEN Center for Advanced Photonics, have pinned down exactly how UCPL works in single-walled carbon nanotubes—drinking-straw-like cylinders of carbon just a few billionths of a meter wide. The study is [published](#) in the journal *Physical Review B*.

Previous theories had suggested that UCPL could only happen in single-walled carbon nanotubes if [excitons](#) were temporarily trapped by defects in the nanotube's structure. But the researchers found that UCPL occurred with [high efficiency](#) even in defect-free nanotubes, suggesting that an alternative mechanism was at work.

The trio discovered that when an electron is excited by light, it gets a simultaneous energy boost from a phonon to form a "dark exciton" state. After losing a little energy, the exciton finally emits light with more energy than the incoming laser.

Raising the temperature produced a stronger UCPL effect, confirming predictions made by their model. "Phonons are more abundant at higher temperatures, enhancing the likelihood of phonon-mediated transitions," says Kato.

The researchers plan to study the possibility of cooling a nanotube using laser illumination to remove [thermal energy](#) by UCPL and explore energy-harvesting opportunities to create a nanotube-based device.

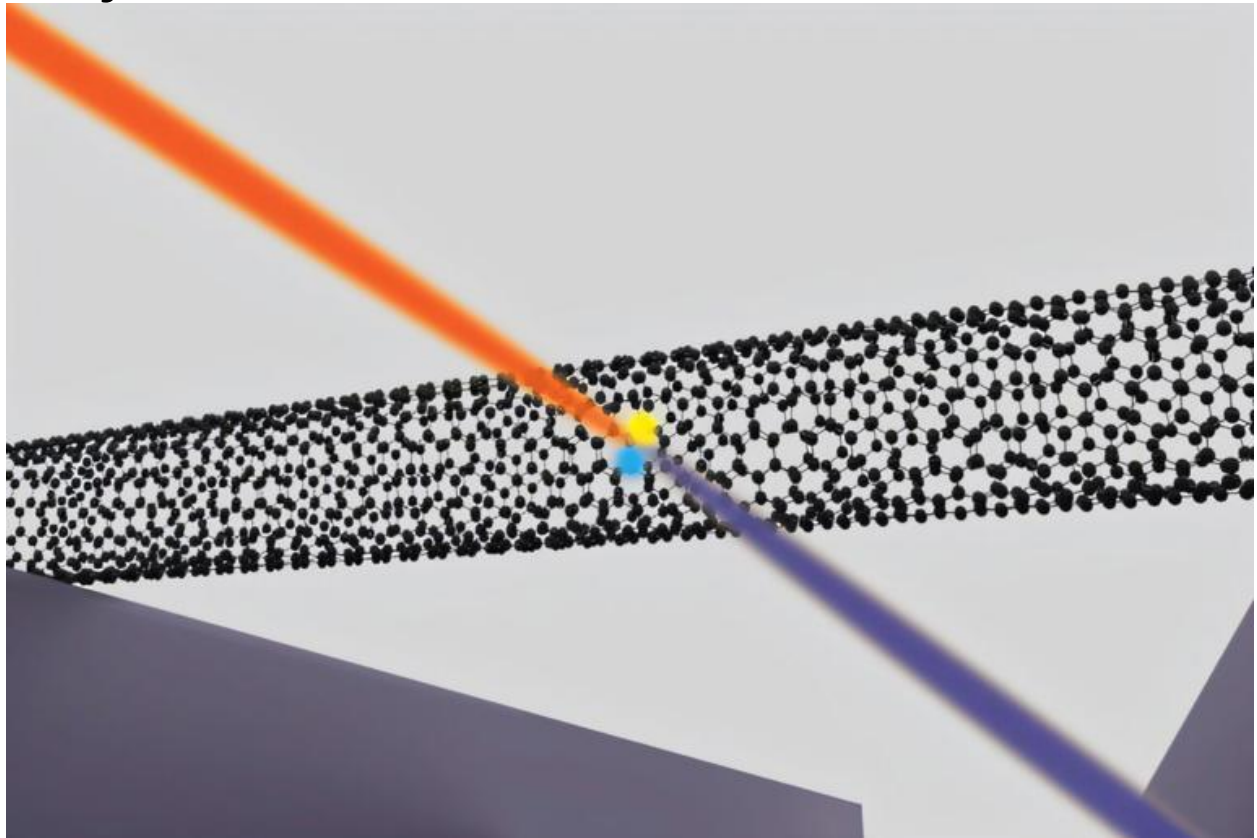
"By establishing an intrinsic model of UCPL in [single-walled carbon nanotubes](#), we hope to open up new possibilities for designing advanced optoelectronic and photonic devices," says Kato.

More information: Daichi Kozawa et al, Intrinsic process for upconversion photoluminescence via K -momentum–phonon coupling in carbon nanotubes, *Physical Review B* (2024). DOI: [10.1103/PhysRevB.110.155418](https://doi.org/10.1103/PhysRevB.110.155418)

Journal information: [Physical Review B](#)

Provided by [RIKEN](#)

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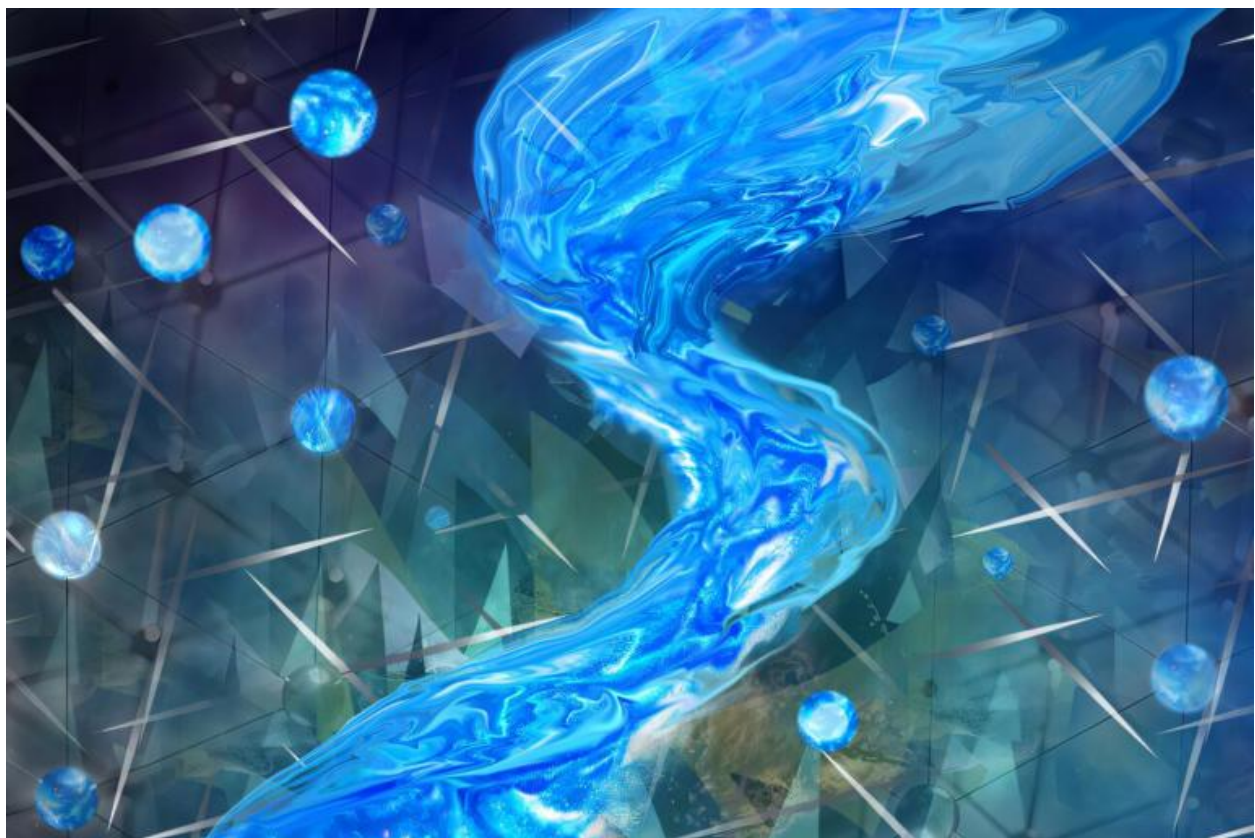
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Provided by RIKEN

Physicists find unexpected crystals of electrons in new ultrathin material



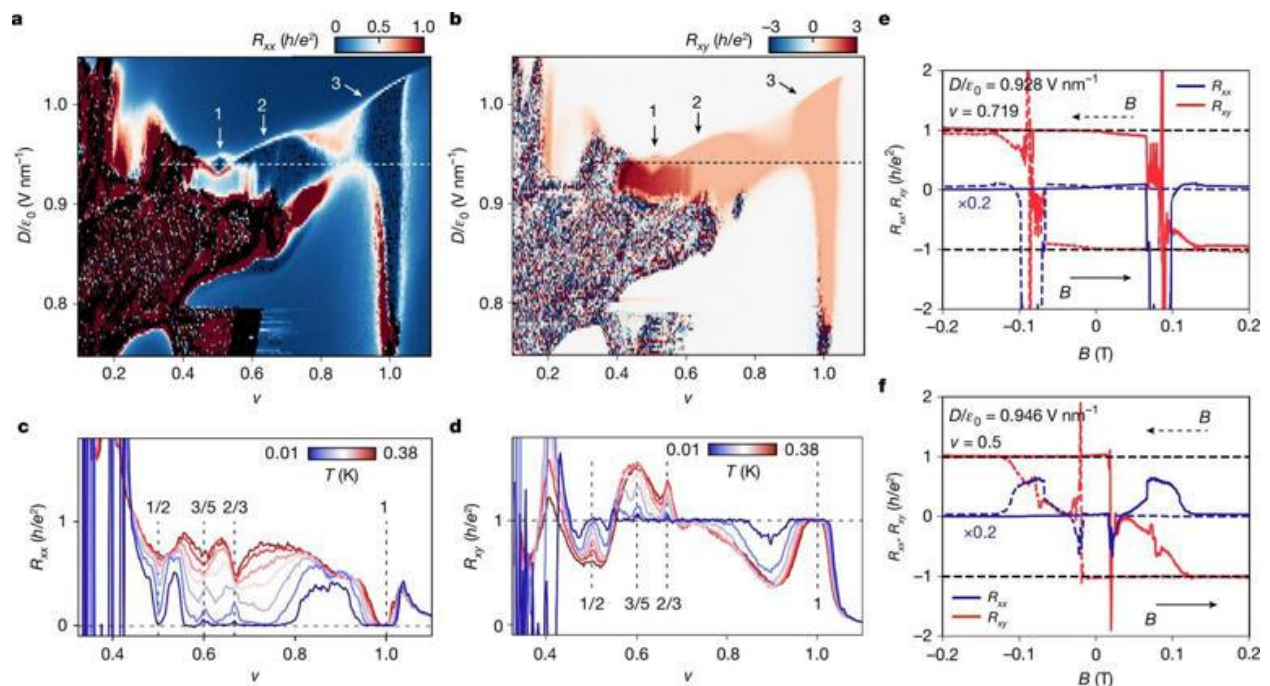
This graphic visualizes how electrons can behave as a solid (left, glacier-like structure) or liquid (river-like structure) depending on the voltage applied to a new material cooled to an ultra-low temperature akin to that of outer space. Credit: Michael Hurley and Sampson Wilcox/Research Laboratory of Electronics

MIT physicists report the unexpected discovery of electrons forming crystalline structures in a material only billionths of a meter thick. The work adds to a gold mine of discoveries originating from the material, which the same team discovered only about three years ago.

In a paper [published](#) Jan. 22 in *Nature*, the team describes how electrons in devices made, in part, of the new material can become solid, or form crystals, by changing the voltage applied to the devices when they are kept at a temperature similar to that of outer space. Under the same conditions, they also showed the emergence of two new electronic states that add to [work they reported last year](#) showing that electrons can split into fractions of themselves.

The physicists were able to make the discoveries thanks to new custom-made filters for better insulation of the equipment involved in the work. These allowed them to cool their devices to a temperature an order of magnitude colder than they achieved for the earlier results.

The team also observed all of these phenomena using two slightly different "versions" of the new material, one composed of five layers of atomically thin carbon; the other composed of four layers. This indicates "that there's a family of materials where you can get this kind of behavior, which is exciting," says Long Ju, an assistant professor in the MIT Department of Physics who led the work. Ju is also affiliated with MIT's Materials Research Laboratory and Research Lab of Electronics.



EQAH states in device 1, the pentalayer device. Credit: Nature (2025). DOI: 10.1038/s41586-024-08470-1

Referring to the new material, known as rhombohedral pentalayer graphene, Ju says, "We found a gold mine, and every scoop is revealing something new."

New material

Rhombohedral pentalayer graphene is essentially a special form of pencil lead. Pencil lead, or graphite, is composed of graphene, a single layer of carbon atoms arranged in hexagons resembling a honeycomb structure. Rhombohedral pentalayer graphene is composed of five layers of graphene stacked in a specific overlapping order.

Since Ju and colleagues discovered the material, they have tinkered with it by adding layers of another material they thought might accentuate the graphene's properties, or even produce new phenomena. For example, in 2023 they created a sandwich of rhombohedral pentalayer graphene with "buns" made of hexagonal boron nitride. By applying different voltages, or amounts of electricity, to the sandwich, they discovered three important properties never before seen in natural graphite.

Last year, Ju and colleagues reported yet another important and even more surprising phenomenon: Electrons became fractions of themselves upon applying a current to a new device composed of rhombohedral pentalayer graphene and hexagonal boron nitride.

This is important because this "fractional quantum Hall effect" has only been seen in a few systems, usually under very high magnetic fields. The Ju work showed that the phenomenon could occur in a fairly simple material without a magnetic field. As a result, it is called the "fractional quantum anomalous Hall effect" (anomalous indicates that no magnetic field is necessary).

New results

In the current work, the Ju team reports yet more unexpected phenomena from the general rhombohedral graphene/boron nitride system when it is cooled to 30 millikelvins (1 millikelvin is equivalent to -459.668 degrees Fahrenheit). In last year's paper, Ju and colleagues reported six fractional states of electrons. In the current work, they report discovering two more of these fractional states.

They also found another unusual electronic phenomenon: the integer quantum anomalous Hall effect in a wide range of electron densities. The fractional quantum anomalous Hall effect was understood to emerge in an electron "liquid" phase, analogous to water. In contrast, the new state that the team has now observed can be interpreted as an electron "solid" phase—resembling the formation of electronic "ice"—that can also coexist with the fractional quantum anomalous Hall states when the system's voltage is carefully tuned at ultra-low temperatures.

One way to think about the relation between the integer and fractional states is to imagine a map created by tuning electric voltages: By tuning the system with different voltages, you can create a "landscape" similar to a river (which represents the liquid-like fractional states) cutting through glaciers (which represent the solid-like integer effect), Ju explains.

Ju notes that his team observed all of these phenomena not only in pentalayer rhombohedral graphene, but also in rhombohedral graphene composed of four layers. This creates a family of materials, and indicates that other "relatives" may exist.

"This work shows how rich this material is in exhibiting exotic phenomena. We've just added more flavor to this already very interesting material," says Zhengguang Lu, a co-first author of the paper. Lu, who conducted the work as a postdoc at MIT, is now on the faculty at Florida State University.

More information: Zhengguang Lu et al, Extended quantum anomalous Hall states in graphene/hBN moiré superlattices, *Nature* (2025). DOI: [10.1038/s41586-024-08470-1](https://doi.org/10.1038/s41586-024-08470-1)

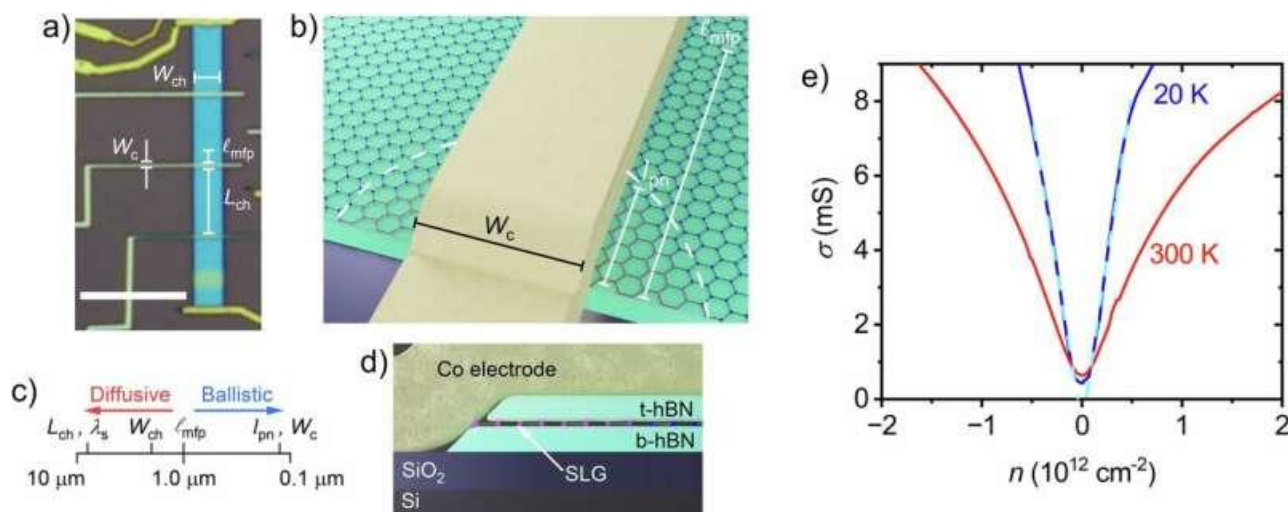
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Provided by Massachusetts Institute of Technology

FEBRUARY 26, 2025

Graphene's quantum spin injection promises energy-efficient spintronics

by [University of Manchester](#)



Device and 1D contact architecture. Credit: *Communications Materials* (2025). DOI: 10.1038/s43246-025-00744-z

Researchers at the National Graphene Institute at the University of Manchester have achieved a significant milestone in the field of quantum electronics with their latest study on spin injection in graphene. The paper, [published](#) recently in *Communications Materials*, outlines advancements in spintronics and quantum transport.

Spin [transport](#) electronics, or spintronics, represents a revolutionary alternative to traditional electronics by utilizing the spin of electrons rather than their charge to transfer and store information. This method promises energy-efficient and high-speed solutions that exceed the limitations of classical computation, for next generation classical and quantum computation.

The Manchester team, led by Dr. Ivan Vera-Marun, has fully encapsulated [monolayer graphene](#) in [hexagonal boron nitride](#), an insulating and atomically flat 2D material, to protect its high quality. By engineering the 2D material stack to expose only the edges of [graphene](#), and laying magnetic nanowire electrodes over the stack, they successfully form one-dimensional (1D) contacts.

Quantum behavior and ballistic transport

The study explores the injection process via these 1D contacts at low temperatures (20 K), revealing that electron transport across the interface is quantum in nature. The contacts act

as quantum point contacts (QPCs), commonly used in quantum nanotechnology and metrology.

First author of the paper, Dr. Daniel Burrow, said, "This quantum behavior is evidenced by the measurement of quantized conductance through the contacts, indicating that the energy spectrum of electrons transforms into discrete energy subbands upon injection. By adjusting the [electron density](#) in the graphene and applying a [magnetic field](#), we visualized these subbands and explored their connection with spin transport."

These QPCs, formed by using magnetic nanowires, avoid the need to engineer a physical constriction within the graphene channel, which makes their implementation more practical than previous approaches.

Implications for quantum nanotechnology

The state-of-the-art device architecture developed by the Manchester team offers a straightforward method for creating tunable QPCs in graphene, overcoming fabrication challenges associated with other methods. The magnetic nature of the nanoscale contacts enables quantized [spin injection](#), paving the way for energy-efficient devices in spin-based quantum nanotechnology.

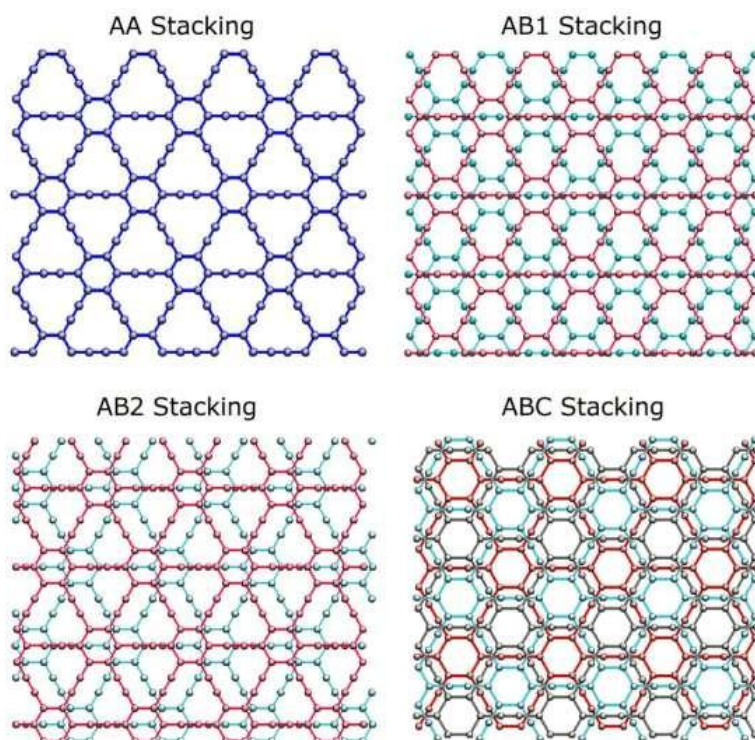
Furthermore, the demonstration of ballistic spin injection presents an encouraging step towards the development of low-power ballistic spintronics. Future research efforts will focus on enhancing spin transport in graphene by leveraging the quantum nature of injection via the QPCs.

More information: Daniel Burrow et al, Spin polarised quantised transport via one-dimensional nanowire-graphene contacts, *Communications Materials* (2025). DOI: [10.1038/s43246-025-00744-z](https://doi.org/10.1038/s43246-025-00744-z)

Journal information: [Communications Materials](#)
Provided by [University of Manchester](#)

Graphyne's transformation: A new carbon form with potential for electronics

by [Case Western Reserve University](#)



Orthogonal to sheet plane views of AA, AB1, AB2, and ABC stacking arrangements for graphyne. Only the AA and AB1 packing modes are consistent with the interplanar reaction of triple bonds to form polyacetylene chains in reacted graphyne. Credit: *Proceedings of the National Academy of Sciences* (2025). DOI: 10.1073/pnas.2413194122

Graphyne is a crystalline form of carbon that is distinct from both diamond and graphite. Unlike diamond, where each atom possesses four immediate neighbors, or graphite, where each atom has three, graphyne's structure combines two-coordinate and three-coordinate carbons.

Computational models suggest that graphyne has highly compelling electronic, mechanical and [optical properties](#). It is predicted to be a semiconductor with a band gap appropriate for electronic devices, ultra-high charge carrier mobility far surpassing that of silicon, and ultimate strength comparable to that of graphene.

Applications of graphyne in [carbon](#) electronics, energy harvesting and storage, gas separations and catalysis have been proposed. While graphyne was first theoretically predicted more than three decades ago, its [synthesis](#) remained elusive.

The Rodionov group at CWRU developed the first practical synthesis of graphyne in 2022, and [their work](#) was published in the *Journal of the American Chemical Society*.

Now, in a [new paper](#) published in the *Proceedings of the National Academy of Sciences*, the Rodionov group and an international team of collaborators from the University of Texas at Dallas, Georgia Institute of Technology, Deakin University (Australia), and Campinas University (Brazil) describe a transformation of graphyne in an entirely different form of carbon.

This transformation completely eliminates all the two-coordinate acetylenic carbons from graphyne, yet it preserves the layered structure. The transformation also modifies the band gap of the material. This finding may enable future techniques for fabricating all-carbon electronic chips with performance unattainable by the current silicon technology.

More information: Ali E. Aliev et al, A planar-sheet nongraphitic zero-bandgap sp^2 carbon phase made by the low-temperature reaction of γ -graphyne, *Proceedings of the National Academy of Sciences* (2025). DOI: [10.1073/pnas.2413194122](https://doi.org/10.1073/pnas.2413194122)

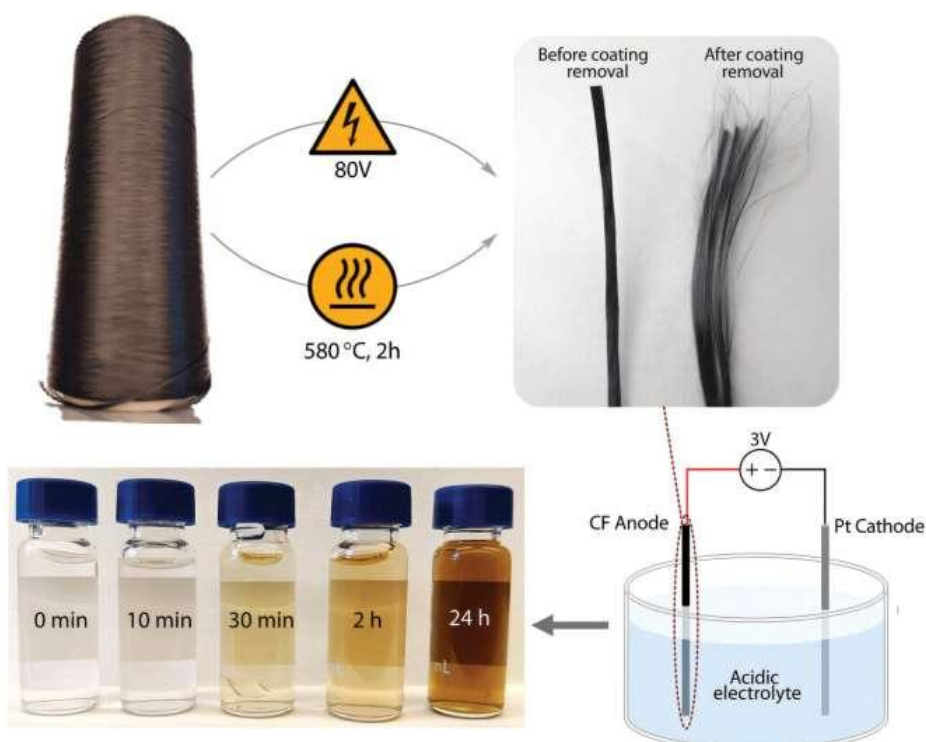
Journal information: [Journal of the American Chemical Society](#) , [Proceedings of the National Academy of Sciences](#)

Provided by [Case Western Reserve University](#)

MARCH 3, 2025

Graphene production technique offers green alternative to graphite mining

by [KTH Royal Institute of Technology](#)



From carbon fibers to graphene oxide. Credit: KTH Royal Institute of Technology
Researchers in Sweden report a green alternative to reduce reliance on mining graphite, the raw source behind the "wonder material" graphene. In the journal [Small](#), researchers at KTH Royal Institute of Technology say they have developed a reproducible and scalable method for producing graphene oxide (GO) nanosheets from commercial carbon fibers, marking a breakthrough in sustainable nanomaterial synthesis.

The process involves exfoliating carbon fibers with [nitric acid](#), which provides high yields of one-atom-thick sheets of graphene oxide with characteristics comparable to commercial GO sourced from mined [graphite](#).

Graphene oxide is a widely studied nanomaterial that can be used in [car batteries](#) when its thin sheets stack together, forming layers similar to graphite. It is also useful in high-performance composites, [water purification](#) and electronic devices. However, synthesis from mined graphite requires harsh chemicals and often results in material inconsistencies due to variations in graphite purity.

Richard Olsson, professor of polymeric materials at KTH, says the proof of concept was carried out with carbon fibers derived from polyacrylonitrile (PAN), a widely available polymer that undergoes high-temperature oxidation and graphitization. He says the method could be duplicated with other raw sources, such as raw sources such as biomass or forest industry sidestreams.

Olsson points to the electric vehicle battery market as one that can benefit from the new technology. "The core of graphite battery functionality can be found in the layered graphene inside, which can be harvested from commercial carbon fibers using this method," he says.

"The future of auto manufacturing will build on battery-based power, and the question is where the graphite will be sourced? They are going to need alternatives."



Richard Olsson, professor in polymeric materials at KTH Royal Institute of Technology, displays two sources of valuable graphene oxide, a spool of ordinary commercial carbon fiber and a piece of mined graphite. Credit: KTH Royal Institute of Technology

The method consists of transforming the carbon fibers using the process of electrochemical oxidation in a bath of water and nitric acid.

The bath acts as a conductor and when an [electric current](#) is sent through carbon fiber, the material begins to lose electrons, which transforms the surface in much the same way that oxidization appears as rust on a car. In this case, the transformation causes layers of nanoscale [graphene oxide](#) to peel off from the carbon fibers' surface.

The study discovered a window in which just 5% nitric acid was perfect for creating these tiny nanosheets, ranging from 0.1 to 1 micrometer in size, with a uniform thickness of about 0.9 nanometers. Notably, the GO nanosheets synthesized this way emerged in circular and elliptical shapes, in contrast to the polygonal shapes typical of GO synthesized from natural, mined graphite.

Compared to existing synthetic methods, the new approach delivers a [high yield](#) of 200 milligrams of GO per gram of carbon fiber. This efficient conversion rate makes it viable for large-scale production, addressing a key challenge in nanomaterial synthesis, he says.

To ensure the nanosheets met quality standards, the researchers examined and measured the properties and structure of the material with a number of advanced techniques.

The study also explored methods to remove protective polymer coatings from commercial carbon fibers before oxidation, heating at 580°C for two hours and shock-heating to 1,200°C for three seconds—both proving effective. The research demonstrated that the nature of electrical conduction within the fibers plays a crucial role in the electrochemical exfoliation process.

Olsson says the next steps for the researchers include investigating biobased sources for [carbon fibers](#), delving deeper into how the process works.

More information: Alba Español et al, Making Synthetic 2D Graphene Oxide Nanosheets by Electrochemical Oxidation of Commercial Carbon Fibres, *Small* (2025). DOI: [10.1002/sml.202408972](https://doi.org/10.1002/sml.202408972)

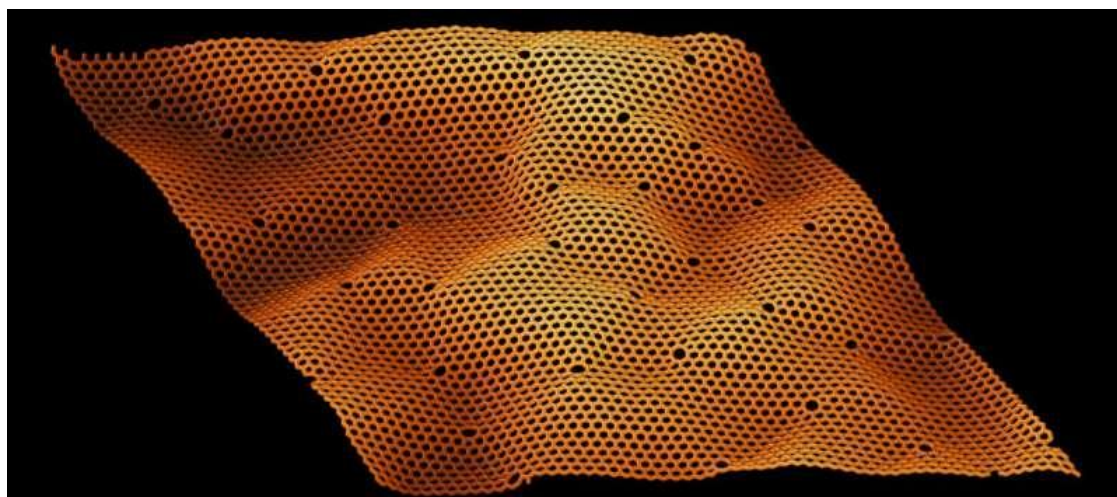
Journal information: [Small](#)

Provided by [KTH Royal Institute of Technology](#)

MARCH 3, 2025

Breaking the surface: How damage reshapes ripples in graphene

by [University of Cambridge](#)



Defects in a flexible sheet. Credit: Dr. Camille Scalliet

Defects in two-dimensional materials (such as an atom-thick sheet of graphene) can dramatically alter the way that the surface ripples, even stopping the sheet in place like a freeze frame.

Rippling is a crucial property of 2D materials and influences strength, conductivity, chemical activity and fluid interactions. Understanding the relationship between rippling and defects is essential for key technologies such as flexible electronics, energy storage, catalysis and nanofluidics. New research on this topic is [published](#) in *PNAS*.

Dr. Fabian Thiemann, the first author of the paper, started this research during his Ph.D. between UCL, the University of Cambridge and Imperial College London, and is now a Research Scientist at IBM.

He said, "While experiments can capture the overall shape of rippled membranes, they struggle to resolve how these structures evolve at the atomic scale over time. Our simulations bridge this gap, allowing us to track the rippling dynamics in detail and uncover the role of microscopic defects in shaping the material's morphology."

Frozen ripples

Two-dimensional materials are at the forefront of technological research, such as in ultra-thin flexible screens, faster electronics, and water filtration. What may seem like a flat surface, though, is never truly flat at the atomic level. Like a pond, these 2D surfaces have tiny ripples that affect their properties.

The researchers used machine learning-based computer models that represent 2D sheets of graphene and other materials. With these models, they can observe the rippling behavior of different materials with and without defects. They found that defects in the sheet affect the way that ripples move, and most crucially, that above a certain concentration, the defects freeze the membrane and it loses its flexibility.

Professor Angelos Michaelides in the ICE group at the Yusuf Hamied Department of Chemistry at the University of Cambridge commented, "The wholesale impact such a small proportion of defects can have on the dynamics of graphene is remarkable. The prospects for exploiting these new fundamental insights are exciting and numerous, particularly in nanofluidics."

Designing around defects

Dr. Camille Scalliet worked on this project when she was a Herchel Smith Postdoctoral Fellow at the University of Cambridge, and is now a permanent researcher at the Laboratoire de Physique de l'École Normale Supérieure in Paris.

She remarked, "By understanding how defects influence these ripples, our work helps engineers control the physical behavior of these materials by using [defects](#)—something traditionally considered undesirable—as a design tool."

Erich A. Müller, Professor of Thermodynamics at the Department of Chemical Engineering, Imperial College London, added, "This work is a premier example of how machine learning potentials (a sub-discipline of artificial intelligence) are transforming the field of materials science by enabling more accurate, efficient, and data-driven predictions of material properties. This is accelerating materials discovery and design, leading to the development of novel materials with desired functionalities for various applications."

Looking ahead, the researchers are eager to build on these findings. Reflecting on the future of their research, Fabian Thiemann and Camille Scalliet stated, "There are great ways to continue this work. Our next steps are to study more complicated situations at the nanoscale, such as membranes in contact with water or other materials. This is just the beginning for this collaboration."

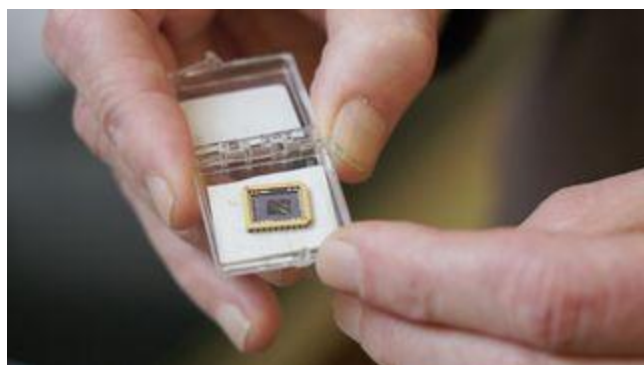
More information: Fabian L. Thiemann et al, Defects induce phase transition from dynamic to static rippling in graphene, *Proceedings of the National Academy of Sciences* (2025). DOI: [10.1073/pnas.2416932122](https://doi.org/10.1073/pnas.2416932122)

Journal information: [Proceedings of the National Academy of Sciences](#)
Provided by [University of Cambridge](#)

World's 1st graphene semiconductor could power future quantum computers

published January 8, 2024

Scientists overcame a limitation in graphene to harness the material as a working semiconductor at terahertz frequencies with 10 times the mobility of silicon.



Like light, electrons in graphene have quantum mechanical wave-like properties that can be accessed in devices, making such a semiconductor a good choice for use in future quantum computers. (Image credit: Christopher McKenney/Georgia Tech)

Scientists have created the world's first working graphene-based semiconductor, which could pave the way for chips that power much faster PCs and quantum computers in the future.

The new semiconducting material, made from epitaxial graphene (a particular crystal structure of carbon chemically bonded to silicon carbide), allows for more mobility than [silicon](#), meaning electrons move with less resistance. Transistors made in this way can operate at terahertz frequencies — 10 times faster than the silicon-based transistors used in chips used today — the researchers wrote in a study published Jan. 3 in the journal [Nature](#).

Semiconductors have properties of both conductors and insulators. At the right temperature range, electrons move through the semiconductor material — but only if a certain amount of energy is applied.

Almost every chip uses a semiconductor made from silicon, but the material is reaching its limits, lead researcher [Walt de Heer](#), a professor at the Georgia Institute of Technology, told Live Science in an email. These limits include the maximum speed at which transistors can "switch" between their on-off positions, the heat they generate through resistance and the smallest size people can make them.

This means the rapid advancements we've seen throughout the [history of computing](#) are beginning to slow.

Rare magnetism found in the world's strongest material [Graphene](#), meanwhile, is made from a single layer of carbon atoms tightly bound in a hexagonal lattice, and is a better conductor than silicon, meaning electrons move with less resistance through the material. Despite its favorable properties, graphene has never been harnessed in electronics because of the lack of a "band gap" — a minimum amount of energy needed to move electrons when an electric field is applied to it. Band gaps are what enable transistors to switch on and off.

To function as a working transistor, the graphene must be treated in some way, but in the past, this has damaged its properties, de Heer said. But the researchers worked around this challenge by fusing graphene onto silicon carbide using special furnaces and a special heating and cooling process. By putting atoms on the graphene that "donate" electrons to the system, which is known as "doping", they created a functional graphene semiconductor with a band gap.

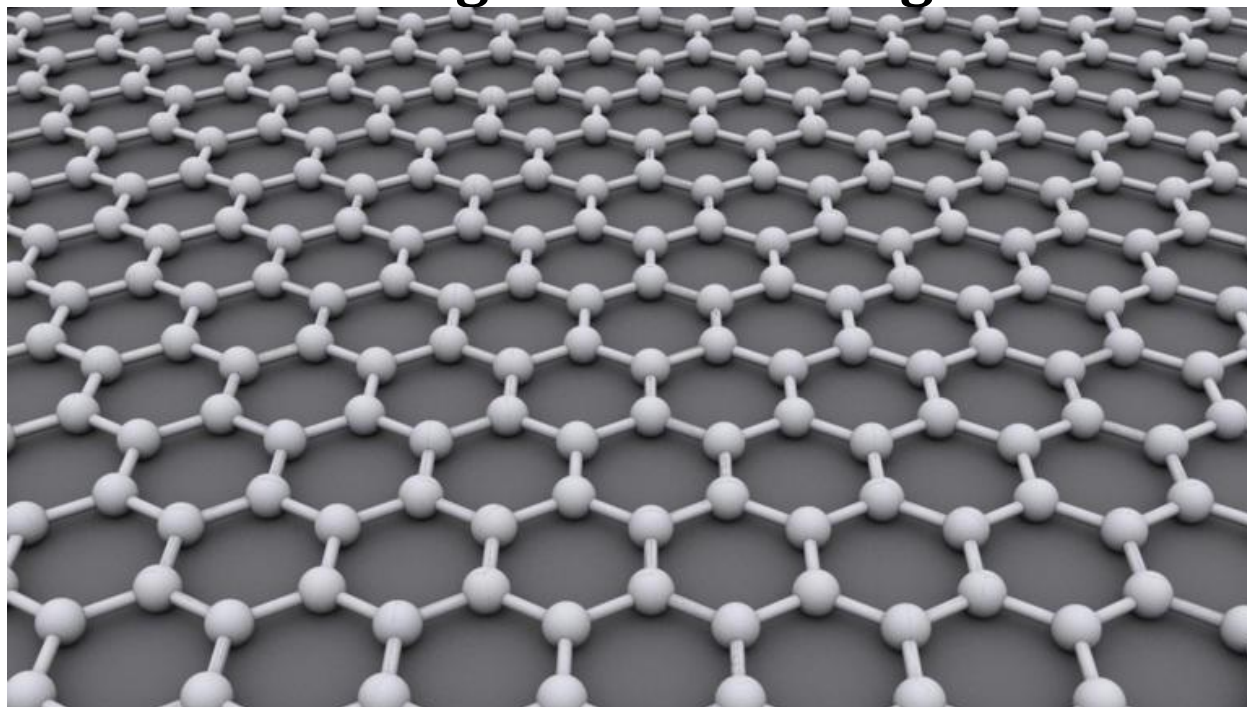
Not only is this the first graphene-based semiconductor to work, but it can also be integrated into existing manufacturing processes. The transition from making silicon wafers to the silicon carbide wafers used in epitaxial graphene is "quite feasible," de Heer said.

Graphene-based semiconductors also have a potential future use in quantum computing, the researchers wrote in the study.

"Like light, electrons in graphene have quantum mechanical wave-like properties that can be accessed in devices, particularly at very low temperatures," de Heer said.

This is an area the scientists hope to explore in subsequent research, but de Heer said it remains to be seen whether graphene-based semiconductors can work better than the current [superconducting](#) technology, which is used in the most advanced quantum computers.

Chinese scientists 'squeeze' metals to atomic scale in groundbreaking method



Chinese scientists 'squeeze' metals to atomic scale in groundbreaking method

Material science research into 2D materials has accelerated since the discovery of graphene in 2004. Graphene is a 2D sheet of carbon atoms, arranged in a way that each carbon atom is bonded to three other carbon atoms.

Today, several 2D materials are being studied for various purposes, like MXenes for energy storage.

Most existing 2D materials exist in a layered structural form known as van der Waals (vdW) layered crystal structures. While these materials hold many interesting properties, scientists have long wanted to probe thin 2D metals.

Now, researchers from the Institute of Physics (IOP) of the Chinese Academy of Sciences have developed a new manufacturing technique for developing 2D metals.

This method, known as vdW squeezing, is a convenient and universal manufacturing technique that allows researchers to make the metal layer in the Angstrom thickness limit, i.e., the atomic scale.

Challenges with thin 2D metals

The vdW structure seen most commonly when dealing with [2D materials](#) refers to sheets of a material like graphene stacked together. The interaction between the atoms is strong within layers but much weaker across layers, relying on the vdW force, which is a weak force.

This arrangement makes it possible to separate these materials into extremely thin layers or sheets, similar to peeling apart sheets from a stack of sticky notes.

However, in the case of metals, the interaction is equally strong across the layers, meaning it is much more challenging to separate the layers. Additionally, metal atoms naturally prefer clustering, which is why single layers of metal atoms are unstable and reactive.

Due to these challenges, traditional methods like those used on graphite—to obtain thin [2D sheets of materials](#) (graphene)—cannot be used for metals.

This hindrance hides a whole class of materials waiting to be studied and used for various scientific and technological applications.

The solution

The vdW squeezing method developed by the Chinese researchers involves melting pure metals and then compressing them between two incredibly rigid, atomically flat surfaces.

These surfaces act as high-precision anvils, ensuring the metal forms uniformly, while their hardness allows for the application of high pressure required to reach the minimal thickness.

After metal formation, the anvils serve as protective layers, encapsulating the 2D metal and preventing it from oxidizing or degrading when exposed to the environment.

The researchers used their technique to successfully produce 2D thin sheets of various metals, including bismuth, tin, lead, indium, and gallium. These metal sheets measured between six and nine Angstroms in thickness or two to three atoms in height.

In particular, the bismuth sheet revealed excellent physical properties compared to its natural bulkier form, including significantly enhanced electrical conductivity.

In a [press release](#), the study's co-author, Prof. Zhang Guangyu from IOP, mentioned that their method could also be used for amorphous (those that don't have a crystal structure) and other 2D non-vdW compounds.

Versatile and highly precise

The method stands out due to its versatile approach. By controlling the squeezing precision, the thickness of the 2D metals can be controlled with atomic precision, which is to say the materials can be monolayer, bilayer, or trilayer.

Another feature that makes the method stand out is the stability. The researchers found that by fully encapsulating the 2D metals between protective layers (the anvils), they remain stable in normal environmental conditions.

This has been a significant challenge with [2D thin materials](#) as they degrade quickly when exposed to air and moisture.

While we can't say with certainty what kind of advancements this brings, the vdW squeezing method does offer an opportunity to study the layer-dependent properties of thin 2D metals, something we didn't have access to before.

The study is published in [Nature](#) Journal.

APRIL 29, 2025

Sponge-like carbon nanotube thermoelectric generator easily molds to complex shapes and powers sensors

by [National Research Council of Science and Technology](#)



Schematic illustration showing the fabrication process of the CNT/BST foam with various shapes. Effects of the BST content and annealing temperature on TE properties of the CNT/BST foams. Highly improved zT value of CNT/BST foam compared to pristine CNT foam. Credit: Korea Research Institute of Chemical Technology (KRICT)

A Korean research team has developed a novel thermoelectric material and generator (TEG) that leverages sponge-like carbon nanotube (CNT) structures, improving the limitations of organic thermoelectric materials while retaining flexibility. The resulting device

is expected to be useful in powering small-scale wearable sensors through thermal energy harvesting.

The research is [published](#) in the journal *Carbon Energy*.

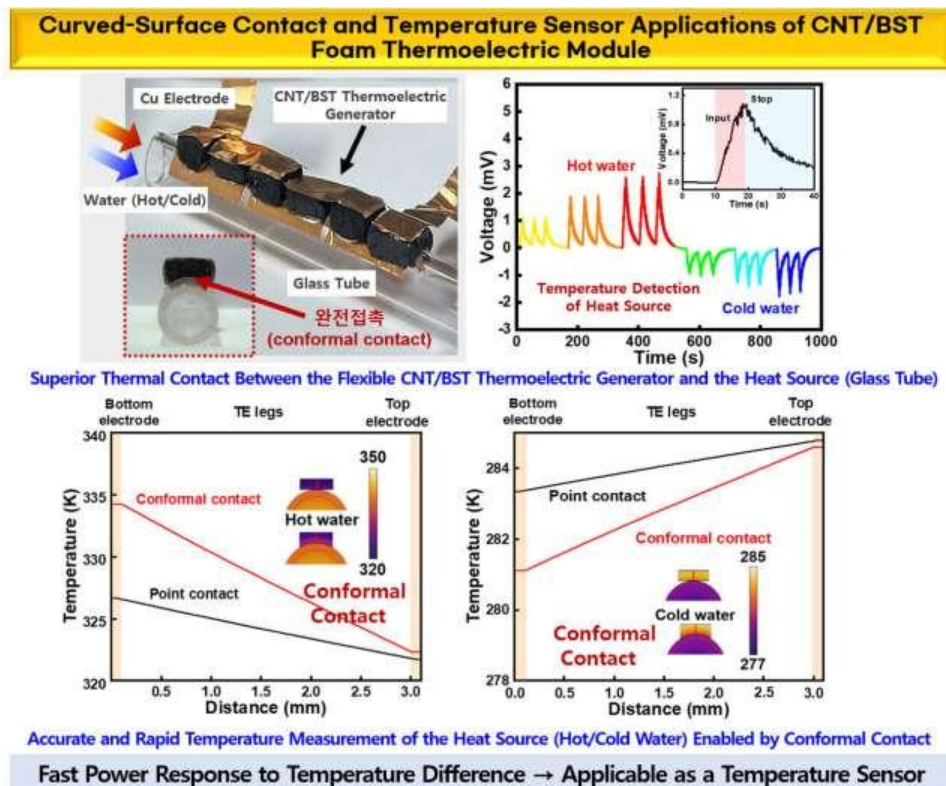
Led by Drs. Mijeong Han and Young Hun Kang at the Korea Research Institute of Chemical Technology (KRICT), the team combined carbon nanotubes with $\text{Bi}_{0.45}\text{Sb}_{1.55}\text{Te}_3$ (BST) in a porous foam structure to maximize thermoelectric performance.

While conventional thermoelectric materials are typically metal-based and rigid, the use of CNTs allows for light weight and mechanical flexibility—although previous attempts have resulted in low thermoelectric performance and poor durability.

To overcome these challenges, the team developed a proprietary fabrication technique that transforms CNTs into bulk foams rather than thin films. This was achieved by heating and solidifying a powder-filled mold to create a sponge-like structure.

A method was also developed to uniformly distribute the thermoelectric BST particles within the foam's pores, improving both mechanical stability and thermoelectric performance.

As a result, the CNT/BST foam achieved a zT of 7.8×10^{-3} —5.7 times higher than that of pristine CNT foam. When applied to a flexible thermoelectric generator and tested on a [glass tube](#) at a temperature difference of 21.8 K, the device generated output power of 15.7 μW —enough to operate wearable sensors.



The concave TEG conforming to a cylindrical glass tube. Output voltage of the concave

TEG with different water temperatures in the glass tube. The water flowed for 10 s and stopped for 20 s. Simulated temperature distributions inside the TE legs with hot-water and cold-water flows. Credit: Korea Research Institute of Chemical Technology (KRICT) Durability was confirmed through 10,000-cycle bending tests, with minimal performance loss. Moreover, the entire fabrication process takes just four hours, compared to over three days for traditional CNT-based TEGs, highlighting the material's excellent scalability.

The team plans to further enhance thermoelectric efficiency through doping strategies and aims for commercialization by 2030. Future applications include integration into thermal management systems for batteries and AI data centers, as well as wearable and autonomous electronic devices.

"This study represents a significant step forward in developing flexible, self-powered devices," said the researchers, adding that the material's moldability and durability open new frontiers in energy harvesting.

More information: Myeong Hoon Jeong et al, High-performance and flexible thermoelectric generator based on a robust carbon nanotube/BiSbTe foam, *Carbon Energy* (2024). DOI: [10.1002/cey2.650](https://doi.org/10.1002/cey2.650)

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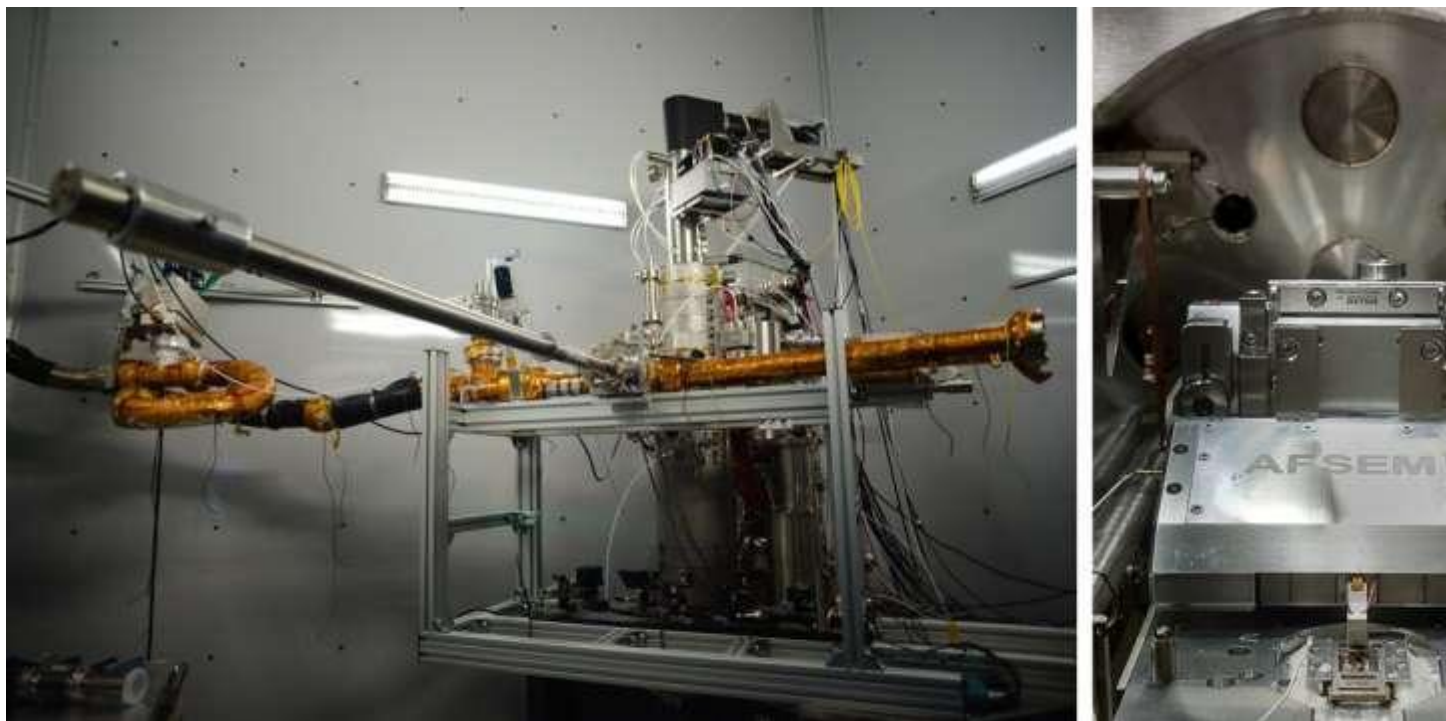
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MAY 6, 2025

[The GIST](#)
[Editors' notes](#)

Physicists create ultra-stretchable graphene via an accordion-like rippling effect

by [University of Vienna](#)



Photographs of the utilized microscopes. Left: The 3 meters high, scanning transmission electron microscope Nion Ultra STEM 100 by Bruker Corporation. Right: View into the airless chamber containing the microscope AFSEM by Quantum Design GmbH. Credit: Wael Joudi, Jani Kotakoski

Graphene is a "miracle material": mechanically extremely strong and electrically highly conductive, ideal for related applications. Using a unique method, physicists at the University of Vienna led by Jani Kotakoski have for the first time made graphene drastically more stretchable by rippling it like an accordion. This paves the way for new applications in which certain stretchability is required (e.g. wearable electronics).

In a collaboration with the Vienna University of Technology, the exact mechanism of this phenomenon has been revealed and [published](#) in the journal *Physical Review Letters*.

The first experimental evidence of graphene in 2004 established a completely new class of materials, the so-called two-dimensional (2D) solids. Their name stems from the fact that they are only a single layer of atoms thick, giving rise to exotic material properties that could benefit various areas of application.

Graphene, for example, stands out with its enormous electrical conductivity, but it is also very stiff. This extreme stiffness is a result of the honeycomb-shaped arrangement of the atoms in the material. Intuitively, the removal of some atoms from the material alongside their bonds should lead to a reduction in stiffness. However, scientific studies have reported both a slight reduction as well as a significant increase.

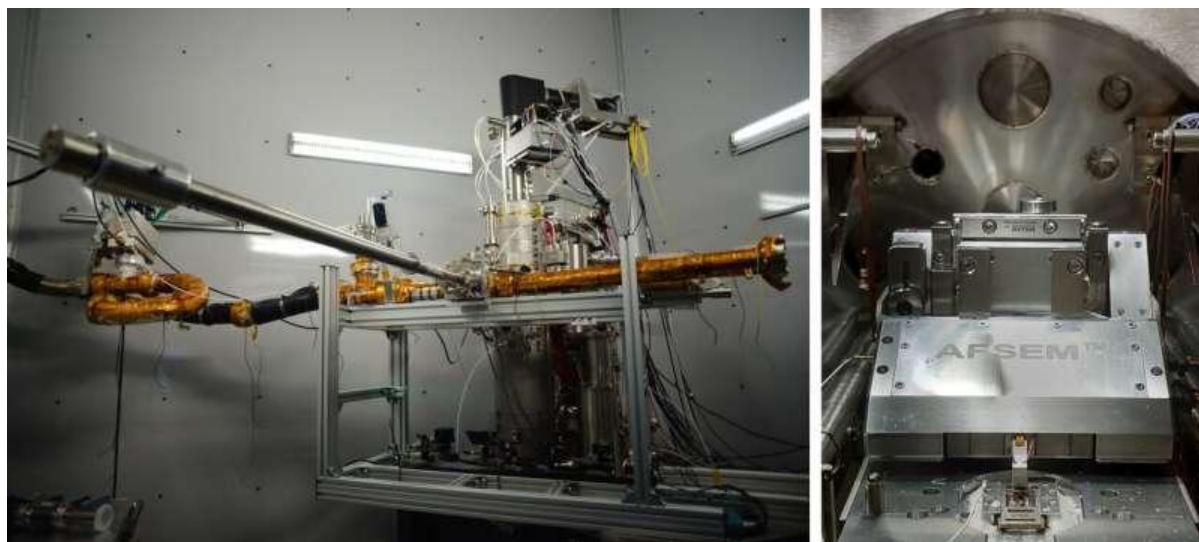
These contradictions have now been clarified through new measurements conducted by researchers of the group led by Jani Kotakoski at the University of Vienna. The experiments were carried out with state-of-the-art devices all sharing the same ultra-clean airless

environment. This allows transporting samples between the different devices without ever being exposed to ambient air.

MAY 6, 2025

Physicists create ultra-stretchable graphene via an accordion-like rippling effect

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Photographs of the utilized microscopes. Left: The 3 meters high, scanning transmission electron microscope Nion Ultra STEM 100 by Bruker Corporation. Right: View into the airless chamber containing the microscope AFSEM by Quantum Design GmbH. Credit: Wael Joudi, Jani Kotakoski

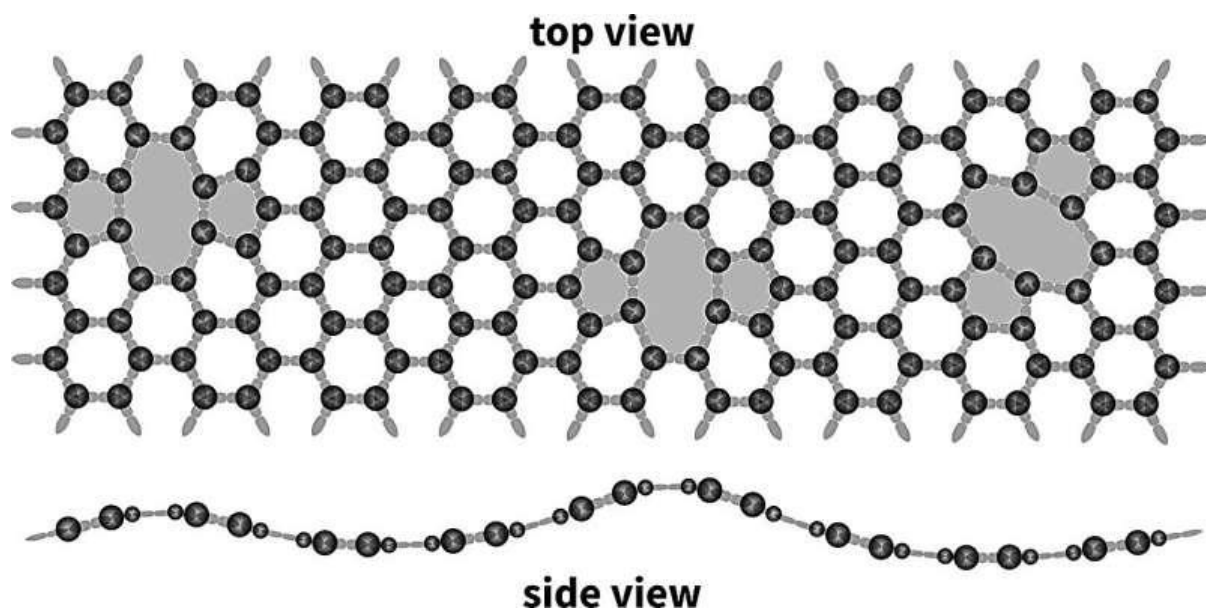
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Schematic representation of the atomic structure of graphene. The black spheres represent carbon atoms, the gray rods illustrate bonds between them. The gray-marked areas represent vacancies, which cause the corrugation visible in the side view. Credit: Wael Joudi

"This unique system we have developed in the University of Vienna allows us to examine 2D materials without interference," explains Jani Kotakoski.

Wael Joudi, first author of the study, adds, "For the first time, this kind of experiment has been carried out with the graphene fully isolated from ambient air and the foreign particles it contains. Without this separation, these particles would quickly settle on the surface, affecting the experiment procedure and measurements."

In fact, the focus on meticulous cleanliness of the material surface led to the discovery of the so-called accordion effect with regard to the stiffness of graphene: already the removal of two neighboring atoms leads to discernible bulging of the initially flat material.

Several bulges together result in a corrugation of the material: "You can imagine it like an accordion. When pulled apart, the waved material now gets flattened, which requires much

less force than stretching the flat material and therefore it becomes more stretchable," explains Joudi.

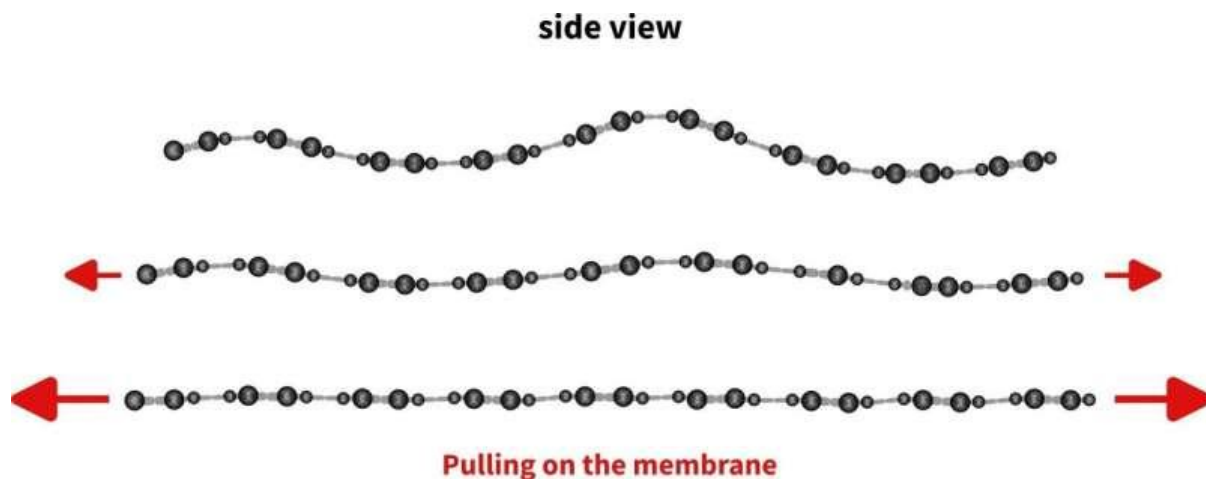


Illustration of the accordion effect. The material with corrugation caused by vacancies is flattened by mechanical stretching. The lower amount of force required results in the measurable softening of the graphene. Credit: Wael Joudi
Simulations carried out by the theoretical physicists Rika Saskia Windisch and Florian Libisch from the Vienna University of Technology confirm both the formation of waves and the resulting stretchability.

The experiments also showed that foreign particles on the material surface not only suppress this effect, but lead to the opposite result. Specifically, their influence makes the material appear stiffer, which also explains contradictions of the past.

"This shows the importance of the measurement environment when dealing with 2D materials. The results open up a way to regulate the stiffness of [graphene](#) and thus pave the way for potential applications," concludes Joudi.

More information: Wael Joudi et al, Corrugation-Dominated Mechanical Softening of Defect-Engineered Graphene, *Physical Review Letters* (2025). DOI: [10.1103/PhysRevLett.134.166102](https://doi.org/10.1103/PhysRevLett.134.166102)

Journal information: [Physical Review Letters](#)
Provided by [University of Vienna](#)

(Image Source: ScienceBrush, Talieh Ghiasi, TU Delft)

SCIENTISTS ACHIEVE THE “IMPOSSIBLE,” UNLOCKING QUANTUM CIRCUITS USING MAGNETIC GRAPHENE

TIM MCMILLAN · JUNE 27, 2025

Scientists have just taken a significant step toward a long-awaited dream by creating ultra-thin, magnetically-

controlled [quantum](#) devices that don't need bulky magnets to function.

In a groundbreaking study, a research team led by physicists at Delft University of Technology in the Netherlands has experimentally confirmed the elusive quantum spin Hall effect (QSH) in magnetic [graphene](#), eliminating the need for an external magnetic field. This study represents a significant advancement in our understanding of quantum physics, opening up new possibilities for future technologies.

This first-of-its-kind achievement means future quantum circuitry could be smaller, faster, and far more practical than ever imagined.

“Spin is a quantum mechanical property of electrons, which is like a tiny magnet carried by the electrons, pointing up or down,” lead author and researcher at TU Delft and Harvard University, Dr. Talieh S. Ghiasi, explained in a [statement](#). “We can leverage the spin of electrons to transfer and process information in so-called spintronics devices.”

“Such circuits hold promise for next-generation technologies, including faster and more energy-efficient electronics, quantum computing, and advanced memory devices.” This breakthrough not only validates theoretical predictions but also propels us into a future of advanced and efficient technologies.

The findings, published in [Nature Communications](#), detail how the team successfully induced a quantum spin Hall state in graphene by layering it on top of a van der Waals antiferromagnetic material called CrPS₄.

This layered structure fundamentally alters the band structure of graphene, introducing spin-orbit and exchange interactions that are strong enough to give rise to exotic, topologically protected edge states. These special states allow electrons to move along the edges of the material without resistance and with their spins locked in opposite directions—a hallmark of QSH behavior.

For years, scientists have sought to harness spin—an intrinsic property of electrons—in place of charge to create next-generation “spintronic” devices. However, achieving long-distance, coherent spin transport—a state in which the spins of electrons remain in a fixed relationship over a long distance—has been notoriously difficult. Conventional methods required strong magnetic fields to split electron spins and create the necessary quantum edge states.

This study demonstrates that magnetism can originate from within. By carefully choosing a [magnetic partner material](#) for graphene—specifically, CrPS₄—the researchers induced both magnetism and spin-orbit coupling within the graphene itself. As a result, they achieved spin-polarized, helical edge states.

“The detection of the QSH states at zero external magnetic fields, together with the AH [anomalous Hall] signal that persists up to room temperature, opens the route for practical applications of magnetic graphene in quantum spintronic circuitries,” the researchers wrote in the study. This breakthrough paves the way for a new era of practical and efficient quantum technologies.

The experimental setup involved layering monolayer graphene on a flake of CrPS₄ and encapsulating it with hexagonal boron nitride (hBN). CrPS₄ is an air-stable magnetic semiconductor with a Néel temperature of around 38 K and strong interlayer antiferromagnetic coupling.

Using advanced electrical transport measurements, the team demonstrated that this configuration induces staggered potential and spin-orbit interactions within the graphene. These alterations open a topological gap in the graphene’s bulk, allowing gapless “helical” edge states to form—essentially creating a quantum spin Hall insulator.

Key evidence was obtained by measuring the conductance of the device near the charge neutrality point at zero magnetic fields. The conductance plateaued at precisely $2e^2/h$ —matching theoretical predictions for QSH states where two spin-polarized channels

counter-propagate along opposite edges of the device without dissipation.

The researchers confirmed these observations across various device geometries and probing configurations, ruling out conventional transport mechanisms. They also observed a large anomalous Hall (AH) effect—a separate spin-related phenomenon—which persisted even at room temperature, further validating the presence of induced magnetic and spin-orbit interactions in the system.

The coexistence of QSH and AH effects in a single graphene-based structure is a powerful demonstration of what's possible when spintronic principles meet topological physics. Most crucially, this work sidesteps one of the biggest hurdles to practical implementation: the need for external magnetic fields or cryogenic environments.

Because the observed quantum effects arise solely from the material's proximity-engineered properties, devices can be scaled down dramatically—ideal for integration into low-power quantum circuits, logic gates, and even fault-tolerant quantum memory architectures.

The researchers conclude that their system not only deepens our understanding of quantum edge states in graphene but also demonstrates a practical pathway toward developing more applicable [two-dimensional topological devices](#).

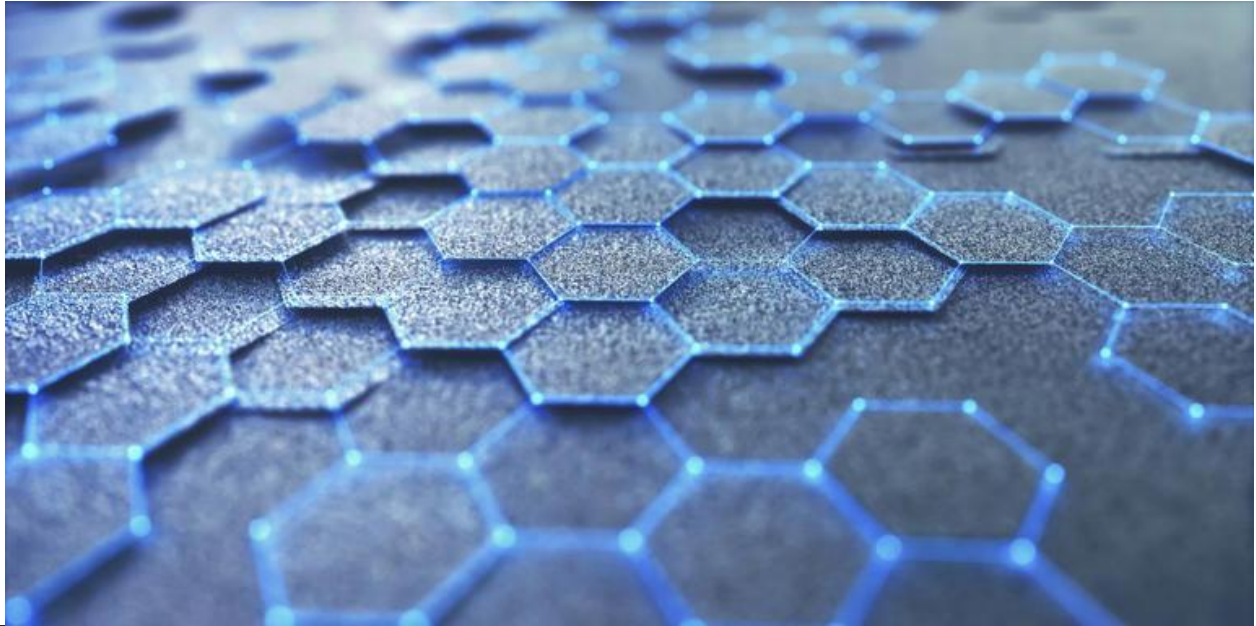
While the experiments mark a significant milestone, the researchers remain cautious about the challenges that still lie ahead. For instance, fine-tuning the strength of spin-orbit interactions and minimizing disorder in the graphene channel will be essential to improving device performance.

Nonetheless, the achievement validates theoretical predictions made nearly two decades ago that graphene, when appropriately modified, could host robust quantum spin Hall states. As Dr. Ghiasi and colleagues continue to refine these devices, their research may herald a new generation of room-temperature spintronic and [quantum logic technologies](#).

“The detection of quantum spin currents in graphene has always required large magnetic fields that are practically impossible to integrate on-chip.” Dr. Ghiasi said. “Thus, the fact that we are now achieving the quantum spin currents without the need for external magnetic fields opens the path for the future applications of these quantum spintronic devices.”

Correction and Editor’s Note: An earlier version of this article incorrectly indicated that researchers had observed quantum spin Hall effect phenomena at room temperature. In a clarifying message to The Debrief, lead study author Dr. Talieh S. Ghiasi explained, “The main message of the paper is the observation of the quantum spin transport (namely, quantum spin Hall effect) at zero external magnetic fields. This quantum phenomenon is observed at cryogenic temperatures (far below room temperature). The room temperature effect that is referred to in our study is only about the anomalous Hall effect (AHE), which is not a quantum phenomenon.”

A Miracle Material Just Defied a Law of Physics



- Graphene is stronger than steel and a better conductor than copper, making the two-dimensional material of particular interest to scientists.
- In a new paper, scientists found that when tuned to its Dirac point—the moment when a material is neither a metal nor an insulator—graphene flouts the Wiedemann–Franz law, which states that the ratio of the thermal and electrical conductivity of a metal is proportional to temperature.
- This makes graphene a potentially low-cost platform for studying questions plaguing high-energy physics and astrophysics.

First produced in 2004 by scientists Andre Geim and Konstantin Novoselov (who won the Nobel Prize in Physics for their efforts in 2010), **graphene**—a two-dimensional material made of carbon atoms—has since been described as “**magic**” and a “**wonder material**” for being both stronger than steel *and* a better conductor than copper. Two decades on, graphene is finally finding its way into a variety of industries, and will likely play a central role in future technologies.

Now, a new paper from scientists at the Indian Institute of Science (IISc) in Bengaluru, India, and the National Institute for Materials Science in Japan show that the wonders of

graphene have never ceased. They discovered that when graphene's electron composition is tuned to its [Dirac](#) point—the moment when a material is neither a metal nor an insulator—the subatomic structure behaves like a quantum fluid.

In fact, it even approached the properties of a “[perfect fluid](#),” which is when a material exhibits no viscosity. This is closely similar to [a quark-gluon plasma](#), the subatomic primordial soup of the universe that formed a fraction of a second after the [Big Bang](#) (and also forms within the bowels of the Large Hadron Collider at CERN).

Perhaps even more surprising is that graphene appeared to flout a well-established rule of physics known as the Wiedemann–Franz law, which states that the ratio of the thermal and electrical conductivity of a [metal](#) is proportional to temperature. Instead, they found an *inverse* relationship that formed a *200-fold deviation* from this law. In other words, thermal conductivity increased as electrical conductivity decreased (and vice versa). The results of the study were published in the journal [Nature Physics](#).

“It is amazing that there is so much to do on just a single layer of graphene even after 20 years of discovery,” Arindam Ghosh, one of the co-authors of the study from IISc, said in [a press statement](#).

Despite its dramatic nature, this breakdown in the Wiedemann–Franz law wasn't totally unexpected. A 2016 study [published in the journal Science](#) noted that graphene exhibited this behavior at the Dirac point. This, however, study takes things a bit further, stating that this is the first time that the universally-applicable experimental evaluation of electric [conductivity](#) was possible.

“Our experiment addresses the missing piece in the potential of high-quality graphene as a testing bed for some of the unifying concepts in [physics](#),” the authors wrote.

The researchers now see graphene as a potentially low-cost platform for exploring concepts in high-energy physics and [astrophysics](#), including black-hole thermodynamics and entanglement entropy scaling. Graphene could also become a particularly powerful quantum sensor, as it's capable of detecting extremely weak magnetic fields.

In other words, some 20 years after its [discovery](#), graphene's full potential still has yet to be fully realized.