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Q&A Tomás Palacios

Taking charge

Nature Outlook *talks to the first director of the MIT's Centre for Graphene Devices and Systems, which was created in July 2011 to foster collaboration among academic, industrial and government groups studying this form of carbon.*

What is the appeal of graphene?

Graphene is an extreme material. There is nothing thinner or with better transport properties than this one-atom-thick layer of carbon atoms. These and other properties offer tremendous opportunities in electronics, materials science and chemical engineering. In addition, the initial work on graphene has motivated research in many other layered materials, such as boron nitride and tungsten disulphide. All these materials offer the ultimate nanotechnology dream: atomic control at the macroscale.

What's the big deal about single layer?

High-frequency transistors require the charge carriers to be as close as possible to the gate electrode that controls the flow of current. In conventional materials, like the silicon used in ordinary transistors, the electrons spread in the vertical direction by at least 5 to 10 nanometres. This reduces the gate electrode's control of these electrons, which in turn limits how small and fast the transistors are. Confining the carriers to one layer of atoms preserves that control. In semi-transparent electrodes for flat panel displays, graphene's single-atom-thickness minimizes light absorption and makes for almost transparent layers.

How well characterized are graphene's properties?

We understand its low-energy transport properties quite well. However, we still need a lot more work to develop devices and systems that can benefit from these properties. One example is the very long mean free path of charge carriers in graphene. In many cases, charges can travel across graphene for more than one micrometre without bumping into anything. That is orders of magnitude farther than in other materials. This reduced scattering could enable a new generation of devices inspired by the old vacuum-tube electronics, where the electrons are controlled not only by electric fields but also by magnetic fields. Somewhat related is the possibility of measuring the quantum Hall effect at room temperature in this device — a phenomenon resulting from the interaction between an electric current and a magnetic field. That could be useful when you need a precise measure of resistance or voltage — such as those needed in metrology or high-speed communications.

How widespread are the potential applications of graphene in electronics?

The first commercial application will probably be as a semi-transparent electrode in solar cells, light-emitting diodes (LEDs) or touch screens. The metal used in transparent conducting films is expensive; graphene could be much cheaper, and much more flexible and robust. Several companies, including South Korea's Samsung and Spain's Graphenea Nanomaterials, either already have some initial products or plan to have prototypes and products on the market soon.

Another interesting application is in microprocessors. As transistors get smaller and smaller, the diameter of the wires connecting them also needs to shrink. With conventional metallic conductors, defects and grain boundaries in the structure of crystalline metals can cause electrical resistivity to increase quickly at scales smaller than 50 nm. Because graphene is a single crystal, there are no grain boundaries, and its resistivity should stay roughly constant with diameter. That makes it ideal for low-resistance interconnections in sub-20-nm transistors.

Once some of these initial applications are successful, many others will follow. Look at optics, for example. Graphene absorbs light uniformly across the entire spectrum, from the infrared to the ultraviolet — that's true of very few other materials. We are taking advantage of this to develop a new generation of night-vision devices, which will be cheaper and able to cover larger fields of view. We hope to build an advanced prototype in 2012.

Those are improvements on known technology. What about things that would be possible only with graphene?

The development of a room-temperature quantum Hall effect device could enable a new generation of electronic circuits based on the precise voltage and resistance references that it would enable. The high performance of graphene devices over very large areas would also allow low-cost electronics in novel forms; think of a coffee cup that displays today's news headlines, windows that display the outside temperature, and clothing that acts as antennae to extend the range of phones. Researchers are also investigating the use of graphene devices to steer electron beams in a way similar to what we do today in optics with light. This could revolutionize optical communications and enable new approaches for quantum computation and reconfigurable computers.

Where is graphene on the development continuum from research to manufacturing?

Devices involving semi-transparent electronics are very close to the market. Other applications, such as the use of graphene in computation or in very-large-area electronics, will take quite a bit longer. This is, among other reasons, due to the highly interdisciplinary work required for these applications. Methods to grow high-quality, large-area graphene films need to be developed; the fabrication technologies have to be modified to prevent the degradation of this one-atom-thick material during device fabrication; and, finally, new ways to integrate graphene devices and systems with more conventional electronics need to be invented.

What more futuristic applications do you imagine?

We are working on high-frequency graphene electronics — on clothes, paper and other items — to communicate with smartphones. We are collaborating with industrial partners on graphene-based patches to monitor glucose levels in the blood of people with diabetes. Every object would just need a graphene-based sticker to connect to the Internet. In collaboration with the International Iberian Nanotechnology Laboratory in Braga, Portugal, we are developing a graphene sensor to detect *E. coli* in food.

Another promising area is the use of graphene in supercapacitors. The key here is to increase the surface-to-volume ratio of the electrodes that form the capacitor. To do this, researchers have recently used forests of carbon nanotubes, but only half of the nanotube's surface is exposed to the electrolyte; the other half is shielded by shape of the nanotube. With graphene, the entire surface — both sides of the layer of carbon — is available. This greater exposure enables higher energy storage. Something similar happens with conductive fibres. Carbon nanotubes are now used to make polymer fibres conductive, but the nanotubes only touch at a single point. When two graphene flakes touch, on the other hand, they do so over a much larger area. This more intimate contact increases the electrical and thermal conductivity.

Does any particular electronics stand to benefit from graphene?

Terahertz electronics presents a good opportunity. Most of the digital electronics in our computers work at a frequency of a few gigahertz (GHz). The analogue electronics used for wireless communications operates in the 2–40 GHz range, and a few radar and imaging systems work at 100–200 GHz. However, we have limited options today if we want electronics operating at frequencies in the 300 GHz to 3 terahertz (THz) range

What does graphene offer to terahertz electronics?

Graphene's high charge mobility, in combination with its one-atom thickness, makes it attractive for filling the 'terahertz gap'. Devices operating at this range would work in advanced imaging systems, secure communications and chemical sensors based on terahertz spectroscopy. We need to find, however, a solution to graphene's lack of bandgap — a range of energies that the electrons are unable to occupy.

What specific areas of technology will the centre focus on?

We will soon see a pipeline of graphene applications beginning to emerge, and our centre will be an integral part of that. For that, we pursue a multidisciplinary approach where we are bringing together physicists, materials scientists, and chemical and electronic engineers to help move graphene from being a really amazing material to being an engineering reality that opens new industries. That requires collaboration between academia, industry and government.

What kind of support is the centre receiving from industry?

If we want graphene to be successful beyond basic science it is important that industry adopts it and develops products with it. In the centre, we have industrial members who provide highly complementary expertise and are helping to create a 'graphene ecosystem'. The Santa Clara, California, company Applied Materials, for example, a leader in processing equipment for the semiconductor industry, is excited about adapting its technologies to graphene. Another one of our member companies, STMicroelectronics, is working with us in the development of the next generation of graphene chemical and biological sensors, while the Dutch company DSM is contributing its expertise in chemistry and advanced materials.

Where does the government enter the centre's planning?

Agencies such as the Office of Naval Research and NASA have been supporting graphene research for many years through several programmes. We are currently working with them to develop detailed roadmaps for device and system insertion.

Does your centre plan to study and develop any two-dimensional materials other than graphene?

Graphene is an amazing material but it isn't necessarily the best material for every application. We have extensive work on 2D materials such as boron nitride or tungsten disulphide, materials that could be very interesting in high-power, high-temperature applications, among others.

Every technology faces hurdles in going from lab to market. What particular challenges does graphene face?

We face several. First, the commercialization of graphene at affordable prices requires the development of mass production techniques. Second, many applications, most notably digital electronics, require a material that has a bandgap — a demand that would seem to rule graphene out. Finally, we need to create an ecosystem for graphene in which companies interested in developing growth and processing equipment talk to companies interested in devices and materials.

What do you hope the centre will have achieved in its first five years?

Our ultimate goal is to transform graphene from a wonder material to an engineering reality. By 2016, I hope we will have generated commercial applications in electronics, chemistry and materials that take advantage of graphene's unique properties. I am certain that it will transform many fields. At the MIT Centre for Graphene Devices and Systems we are trying to speed up this process. ■

Interview by **Peter Gwynne***, a freelance science writer based in Sandwich, Massachusetts.*