Can graphene keep its promise?

Over the past decade, the carbon material known as graphene has been hailed as a ‘wonder material’, which might revolutionize everything from microelectronic circuitry to ultra-strong composite engineering. Graphene displays several striking properties: it conducts electricity, it is transparent, and exceedingly strong and lightweight. But will it live up to its promise?

Graphene—sheets of carbon atoms joined into a one-atom-thick mesh of hexagonal rings—hit the headlines in 2004 when researchers at the University of Manchester in England found a way to make this material from common graphite. Familiar metallic-grey graphite consists of many graphene sheets stacked on top of one another, and Andre Geim, Konstantin Novoselov and their collaborators at Manchester showed that by repeatedly stripping Scotch tape from top of little islands of graphite, they could gradually remove layers until the islands were just a few sheets, or even a single sheet, of the carbon honeycomb structure.

Contrary to common belief, this wasn’t the first report of graphene. It had been talked about since at least the 1940s, and had been previously made by depositing individual carbon atoms or molecules from a gas into thin films on metal surface (chemical vapour deposition, CVD) or by chemically exfoliating the layers of natural graphite. However, Geim and Novoselov were the first to isolate graphene crystals large enough for all sorts of measurements, and their method made graphene much more accessible for study in the lab. Their subsequent research on the unusual electronic properties of graphene—unusual largely because they involve electrons moving in just the two dimensions of the atomic layers—won the pair the 2010 Nobel Prize in physics. That award seemed to set the seal on graphene as one of the most compelling new arenas for research in physics, chemistry, and materials science, and now many groups and companies are racing to find the first major industrial application of graphene. For example, electronics companies such as Samsung are investigating its use as a tough, transparent electrically conducting layer for smart-phone screens, as well as developing graphene transistors for the circuitry of these and other handheld devices.

NSR spoke to leading graphene researchers Hui-Ming Cheng and Wencai Ren of the Shenyang National Laboratory for Materials Science at the Institute of Metal Research, Chinese Academy of Sciences, in Shenyang about the current state of play in graphene science.

Q: Please could you say something about your own research on graphene?

A: Graphene research in my group started in 2007, and mainly focuses on the synthesis of graphene materials and their applications such as energy storage, functional coatings, composites, and flexible optoelectronics. We have developed a novel method to produce high-quality graphene materials in large quantity and at low cost. And using CVD we have made millimetre-size graphene single crystals, large-area transparent conductive films, and highly conductive three-dimensional interconnected graphene networks. We’re exploring the applications of these materials in transparent conducting films, lithium-ion and lithium–sulphur batteries, supercapacitors (energy-storage devices), thermal management, conductive inks, anticorrosion coatings, composites, and so on. We’re also trying to commercialize graphene materials in collaboration with companies.

Q: Was research on graphene helped by earlier studies of carbon nanostructures such as fullerences and nanotubes?

A: The earlier studies of carbon nanotubes (tubes of pure carbon a few angstroms to tens of nanometres across, discovered in 1991) strongly stimulated graphene research. Many ideas about the applications of graphene come from carbon nanotube studies, because graphene and carbon nanotubes have similar properties such as very high mobility, good electrical and...
thermal conductivity, high tensile strength, excellent flexibility, and chemical stability. In addition, many researchers who previously worked on carbon nanotubes have switched to graphene research in the past several years. Nevertheless, I believe that graphene would have emerged even without the prior work on carbon nanotubes, because it has been predicted to have a wide range of interesting physical phenomena and been widely used for describing properties of various carbon-based materials since the 1940s.

Q: Graphene has several fascinating properties. Which do you consider to be the most interesting from a purely scientific point of view?

A: Because of the unique one-atom-thick, two-dimensional structure, and exceptionally high crystal quality, graphene has many fascinating properties such as linear electronic spectrum (the electrons’ energy is proportional to their wave vector), giant electron mobility, extremely high current density, high mechanical strength and elasticity, record thermal conductivity, high optical transparency as well as complete impermeability to gases. From the fundamental point of view, perhaps the most interesting property of graphene is that electrons propagating through the honeycomb lattice completely lose their effective mass, and behave as if they are ‘quasi-particles’ of zero mass moving at relativistic speeds. So this two-dimensional system allows one to study the subtle and rich physics of quantum electrodynamics in bench-top experiments, which previously was thought to be observable only in black holes and high-energy particle accelerators.

Q: As an electronic material, graphene seems to have some very attractive properties (such as very fast transport), as well as some significant drawbacks, in particular the lack of an energy gap between the band of conduction electrons and the empty energy band above it. This band gap is what makes silicon a semiconductor that can be switched between conducting and non-conducting states with an electric field, so that transistors can be turned on and off. How do you think these properties will limit the electronic applications of graphene?

A: The very high mobility and ballistic transport (electrons move without being scattered by the atomic lattice) over distances of almost a micrometre make graphene a very attractive electronic material. However, graphene does intrinsically lack a band gap. Although many methods have been developed to open it up, the gap that can be obtained so far is usually very small, and the mobility is greatly reduced. Therefore, it will be very difficult to use graphene as a channel material in high-performance integrated logic circuits.

High-frequency electronics is another intriguing application of graphene, because of its extremely high carrier mobility, but there are still many problems that need to be addressed.

As Novoselov has said, graphene will probably be used here only after 2021, when even mature technologies such as III–V semiconducting materials (such as gallium arsenide) will no longer be able to sustain high-frequency applications because the devices will be so small [see K. S. Novoselov et al., Nature 490, 192 (2012)].

Q: What do you think will be the first important commercial applications of graphene? And how do you think these applications might change in the longer term?

A: For applications, it is very difficult to say which properties are the most useful. It is really the combination of excellent properties that makes graphene very different from other materials. For example, flexible transparent conductive films have been widely considered to be one of the promising applications of graphene in electronic devices, not only because of the high electrical conductivity but also the high optical transparency, good flexibility and elasticity, and chemical durability. In contrast, the commonly used transparent conductor indium tin oxide cannot deliver the combination of properties required for flexible transparent conductive films.

Utilizing both the ultra-light and ultra-strong properties, the tennis-racquet company Head has integrated graphene into the shafts so that weight can be redistributed to more functionally relevant areas of the handle and tip. This gives the player more power for less effort.

Energy storage has become more important for economic development, and will be even more so in the future—just think that in 2013 consumers bought five billion lithium-ion cells to supply laptops, cameras, mobile phones, and electric cars. There’s a lot of interest in using graphene in energy storage. Graphene-based electrodes can greatly improve the performance of batteries and supercapacitors, and as large-scale graphene production develops, this use of graphene will probably become one of the first industrial applications. In January 2014, Changzhou Cubic Energy Technology Company announced that China’s first graphene-based supercapacitor production line started production. In contrast, electronic applications may take several decades to develop.

We think applications of graphene depend on the development of large-scale synthesis methods. Recently, the chemical...
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exfoliation method (where sheets of graphite are separated with the aid of chemicals) has developed very fast. In 2012, we built a pilot production line for high-quality graphene sheets, in which the particles have fewer than 10 layers, with a capacity of 1.5 tonnes per year. Based on this technology, a production line with a capacity of 100 tonnes per year is under design and construction. In 2013, Ningbo Morsh Technology in Zhejiang Province announced the operation of a graphene production line with a capacity of 300 tonnes per year. Because of such advances, the cost of graphene materials has been greatly reduced.

Q: What do you think will become the most important method of fabricating graphene for commercial purposes? It is better to mass-produce the material in ways that might incur imperfections, or to use more expensive techniques to produce very high quality graphene?
A: Different applications need different graphene materials. For example, large-area high-quality graphene transparent conductive films are highly desirable for flexible electronics, but mass production of graphene powders or suspensions is a prerequisite for applications in energy storage, coatings and composites, and so on. Defects and functional chemical groups in graphene sheets can in fact be helpful for some applications, like energy storage and catalysis. CVD has great potential for growing large-area high-quality graphene films, and chemical exfoliation is good for large-scale production of graphene powders or suspensions.

Q: What are the primary areas of graphene research in China? Is there any kind of centralized organization for coordinating graphene research, for example, along the lines of the European Union’s Graphene Flagship?
A: Graphene research in China is very active. It focuses on areas including CVD growth of high-quality graphene, large-scale synthesis of graphene powders and suspensions by chemical exfoliation, chemical assembly of graphene materials, and their applications in transparent conducting films, lithium-ion batteries, supercapacitors, composites, electrochemical sensing, solar cells, and so on. But there’s no centralized organization yet for coordinating Chinese graphene research.

Besides fundamental research, the industrialization and commercialization of graphene in China are very active too. An innovation alliance of graphene industries was established in 2013, which mainly focuses on coordinating the development of graphene industry in China.

Q: What would be your advice to new researchers/teams wanting to enter the graphene field? It is already quite crowded, so is it better to go after the ‘big goals’ or to find one’s own niche?
A: Graphene has been extensively studied for about 10 years, and a lot has been achieved. But it usually takes at least tens of years to realize real applications for any new material. There are still many open challenges that needed to be addressed before the applications of graphene appear in the market, such as how to produce materials with on-demand or application-oriented structure and properties, how to further reduce the production costs, and how to realize continuous production cleanly. And there are still new physical phenomena being observed in graphene. Yes, the field is really crowded now, so newcomers should think carefully what they can do before jumping in. The direction they choose should look for unsolved challenges based on their background and interests, and it’s better to find one’s own niche, of course.

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