Platform for nano-discovery

Nanomaterials expert and materials scientist **Professor Qing Chen** discusses with *International Innovation* the finer points of her work with carbon nanotubes, the developments the field has seen in recent years and her own contribution to experimental methods in this area.

**Why did you first become interested in materials science and later in carbon nanotube (CNT) engineering? As a materials scientist with over 20 years’ experience, how would you say the landscape has evolved in this time?**

I have been deeply attracted to materials science since I was an undergraduate student in physics about 30 years ago. Materials science is a very broad research field, and it is closely related to physics, as well as chemistry, electronic science and technology, biology and other disciplines.

I believe that the observation of CNTs is one of the most important scientific breakthroughs seen in recent decades. The realisation of single-layer graphene and the increasingly popular study of its properties has been another very important step, which has stimulated intense research into various 2D nanomaterials. In the last 20 years, many new nanomaterials have been synthesised, characterised and modified. Along with these achievements has come the discovery of new properties and functions, new physical and chemical phenomena and, ultimately, new technologies. The field of nanoscience has grown with unprecedented speed, and is now fueling progress in more traditional areas of study.

**Who makes up your research group and what skills and experiences make them particularly well suited to cutting-edge CNT research?**

My research group includes three faculty members and around 15 PhD students. The faculty members have expertise in nanofabrication, nanomanipulation and nanocharacterisation, as applied in both electronics and physics. The background of the students includes materials science, physics and microelectronics. Having people with different experiences working together ensures that they stimulate and help one another, and is very important for our research.

We also work very closely with other groups in our Key Laboratory, especially those focusing on nanodevices and device physics. We have a number of ongoing collaborations with people in other universities and the Chinese Academy of Sciences as well. The importance of collaboration with other experts cannot be overstated.

**Scanning electron microscopy (SEM) is central to many of your investigations. Why is this technique so apt for nanomaterial characterisation and manipulation?**

SEM allows for imaging with a spatial resolution of a couple of nanometres. Although a worse resolution than that facilitated by transmission electron microscope, the scanning electron microscope has a much larger sample chamber that can tolerate multi-detectors and multi-nanomanipulators. This opens up the possibility of conducting multiple characterisation, measurement and manipulation operations on the same nano-object. For example, we simultaneously have four nanomanipulators as well as electrical, mechanical and optical probes in the chamber of our microscope, enabling us to perform at most four-terminal multi-physics measurements on individual nanomaterials under the visualisation of SEM.

**Could you describe how, in a recent publication, you used SEM to approach the fundamental scientific problems involved in lithium-air (Li-O2) batteries?**

We built an all-solid-state Li-O2 battery by using a CNT as the cathode, LiO2, as solid-state electrolyte and metallic Li as the anode. Our entire experiment was then performed in situ within the SEM chamber without air exposure, so that the possibility of contamination – which has plagued previous reports – could be avoided. Using this setup, we were able for the first time to directly observe the charge and discharge processes – identifying in particular varying morphologies among discharge products.

**Why are current and next-generation silicon complementary metal-oxide-semiconductor (CMOS) devices becoming increasingly more difficult to scale down? What makes CNTs promising alternatives?**

Quantum mechanics tells us that electrons can tunnel through a very thin dielectric layer. With the scaling down of planar silicon CMOS devices, it becomes more and more difficult to reduce the equivalent gate oxide thickness to achieve higher performance without increasing the leakage current tunneling through the gate.

High-mobility channel materials may be suitable candidates to replace silicon channels in CMOS devices, simultaneously reducing power consumption and enhancing performance. CNTs can have very high mobility (larger than 100,000 cm²/V s) for both electrons and holes, while the mobility of electrons and holes in silicon is much lower, at just 1,600 cm²/V s for electrons and 500 cm²/V s for holes.

**SOME CARBON NANOTUBE FUTURE APPLICATIONS**

- Battery anodes and cathodes
- Fuel cells
- CMOS devices
- Dental implants
- Artificial muscles
- Health and environmental sensors
- Cancer diagnosis and treatment
- Oil spill cleanup
- Morphing aircraft wings
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**Material benefit**

A team at **Peking University** based at the Key Laboratory for the Physics and Chemistry of Nanodevices, Ministry of Education of the People’s Republic of China, has recently developed a new platform for manipulating nanomaterials under a microscope. A number of novel discoveries have already proceeded from this innovative approach.

**AS INTEREST IN** nanomaterials has exploded in recent years, the favourite subject of scientists in this field – graphene – has become a household name. And as evermore attention is devoted to this promising material, more tantalising properties and applications for it seem to come to light. Although isolated graphene was only successfully measured in 2004, the intervening decade has seen countless revelations concerning the optical, electrical and mechanical possibilities of a sheet of carbon that is only one atom thick. Because graphene is a material structured on a scale so far-removed from human proportions, it behaves very differently to its bulk counterpart – graphite.

When it comes to answering the question of how these surprising properties are achieved, this factor of proportion is a crucial consideration. In graphene and most other nanomaterials, the small scale of the subject means that minute alterations to structure can radically alter function. It is partly for this reason that many materials scientists working with graphene concentrate on specific shapes the sheet can make; for example, nanotubes, spherical fullerenes or even carbon nanohorns. It is also important to consider the number of graphene layers that will go into one of these arrangements, since a single-walled nanotube will behave differently to a two-walled or multi-walled one.

**FORM AND FUNCTION**

Due to the many arrangements possible, scientists hoping to turn the properties of nanomaterials like graphene to practical benefit have a number of options in terms of altering the nanoscale structure of these materials in order to optimise their functions for use in novel devices. However, as with other fields of materials science, practitioners are often forced to rely on numerical modelling in order to predict optimal configurations and develop suitable subjects. Although some tools already exist for manipulating nanomaterial samples in situ, small variations between samples make a big difference in this field, and manipulating the same sample in situ in different ways, and therefore gathering more accurate data, is not an option with traditional methods.

One research laboratory based at Peking University in the Chinese capital Beijing has recently developed a novel platform allowing them to overcome this issue. The Key Laboratory for the Physics and Chemistry of Nanodevices is headed by Professor Lian-Mao Peng and, as its name suggests, focuses on revealing the physical and chemical properties of nanomaterials, as well as developing novel nanodevices for a range of applications. Towards these goals, one of two Vice-Directors of the Lab Professor Qing Chen and her colleagues pursue four main research directions: nanomaterial fabrication; the theoretical study of nanomaterials; individual nanomaterial and device investigation; and the development and integration of nanodevices. Their new experimental platform has aided them in all of these aims – and could help other investigators as well.

**MAXIMISING MICROSCOPY**

Although she contributes to most of the branches of the Laboratory’s work, Chen’s specialism lies in the study of specific nanomaterials and devices. In this area, the most important goals are to discern the relationship between the structure of a nanomaterial and its properties, and to develop novel characterisation and measurement platforms as well as nanomanipulation, fabrication and modification methods to alter the material and achieve desired properties. The Beijing scientists focus most often on accomplishing these objectives for carbon nanotubes (CNTs), but they have also applied their methods to nanowires and nanosheets in the past.

For the purpose of characterising nanoobjects, electron microscopy techniques are often favoured on the basis that they can directly image even tiny subjects like
nanotubes with high (nanometre to atomic level) spatial resolution. There are two basic methods: scanning (SEM) and transmission electron microscopy (TEM). Whereas TEM produces a 2D projected image of the sample by transmitting electrons through it, SEM produces a 3D image by bouncing electrons off the sample’s surface. Each method has its own advantages. The easy sample preparation and large sample chamber which can host multi-detectors make SEM as important as TEM, although SEM has a lower resolution.

A PROMISING PLATFORM
The platform developed by Chen and her collaborators is based on an environmental scanning electron microscope but adds four nanomanipulators, a tensile tester, both DC and high-frequency electrical measurement systems, an optical measurement system with laser and spectrometer, and a system for mechanical measurement. It is therefore suitable for gathering multi-terminal electrical, optical and mechanical measurements on single nanomaterial samples at a range of temperatures and in a variety of gaseous environments. “Even though the platform is based on SEM, we can actually transfer the tested nanomaterials into a transmission electron microscope for further atomic structure characterisation,” Chen notes.

It is easy to see the utility of this platform in determining the structure of a nanomaterial – a central determinant of its behaviour together with its performance – in measuring strain. Using Chen’s SEM platform, it is possible to quantitatively study the impact of strain on most of the material’s essential properties; determining, for example, at what tensile strain CNTs exhibit the best electrical transport properties. All properties measured can also be directly correlated with the atomic structure of the material, offering a potential insight into the mechanisms of nanomaterial properties at the most fundamental level.

NEW POSSIBILITIES
Finalised in 2012, Chen’s new approach to characterising nanomaterials in detail, along with a portfolio of novel methods designed to optimise such experiments, is the culmination of 18 years’ work. During that time, the partly-built platform was used to achieve some interesting results. Among other accomplishments, they have developed doping-free CNT FETs, an important advance in CNT-based complementary metal-oxide-semiconductor devices; demonstrated light coupling and modulation in a coupled nanowire ring-Fabry-Pérot cavity, and successfully created a solid-state lithium-oxygen (Li-O₂) battery. Using the platform, they also observed phonon-assisted electron emission from individual CNTs. Their recent study also demonstrates superlubricity in double-walled CNTs.

In addition to these practical achievements, there have been concomitant advances in scientific understanding of the relationship between structure and properties in nanomaterials. A 2008 paper, for example, documented the team’s discovery that the natural frequency of the multi-walled CNT as a function of its length fits with the Timoshenko beam model when the nanotube is short, but not with the Euler-Bernoulli beam model, which is more widely used. Similarly, the work of Chen and her colleagues on the resonance frequency of CNTs yielded positive results in 2009, when they showed that the structure’s behaviour under tension fits well with continuum beam theory. A final study in 2014 has demonstrated the capacity of axial strain to tune a CNT resonator. All of these results will contribute to the enhanced development of such resonators.

THE FUTURE
Nanomaterials will undoubtedly play a prominent role in future technologies, and it is research groups like Chen’s, which bring novel platforms and experimental methods into play, that will lead the way. As she herself predicts: “In the next five years, we will learn more about how strain changes the electronic and optoelectronic properties of nanomaterials,” and her team hopes to apply this knowledge to the development of devices with advanced functions within the next decade.