feature

Back to the future

Peter Rodgers

The first issue of *Nature Nanotechnology*, published five years ago, contained seven research papers. We catch up with the authors of those papers and ask how nanotechnology has changed since then.

Tzahi Cohen-Karni was an MSc student at the Weizmann Institute of Science in Israel when he did the work that resulted in him being the first author on the first paper published in *Nature Nanotechnology*. Working with Ernesto Joselevich and three other colleagues, he studied how the electronic conductance of a carbon nanotube changed as it was twisted. Five years later he has received a PhD from Harvard for work on nanobioelectronics[1] and has just started as a postdoctoral associate in bioengineering at Massachusetts Institute of Technology (MIT).

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> Yang Yang

Cohen-Karni was one of seven first authors in that first issue of *Nature Nanotechnology*, and his story is fairly typical. All seven are still active in science and engineering, with six of them currently based in a university or academic environment: the exception is Ricky Tseng, who has moved from the University of California, Los Angeles (UCLA) — where he worked on novel forms of electronic memory — to become an engineer at Intel. And six of the seven are now based in the United States, compared with four back in 2006. The seven last authors, on the other hand, are all still based in the same institutions as five years ago, although their research interests have evolved since then, and continue to do so.

What next

"Energy, energy, energy," replies Yang Yang, Tseng's PhD supervisor at UCLA, when I ask him what he would like to be working on in five years. "I would like to solve the energy problem, from generation to storage to improved efficiency. There are so many things that need to be done, and there is so little time left."

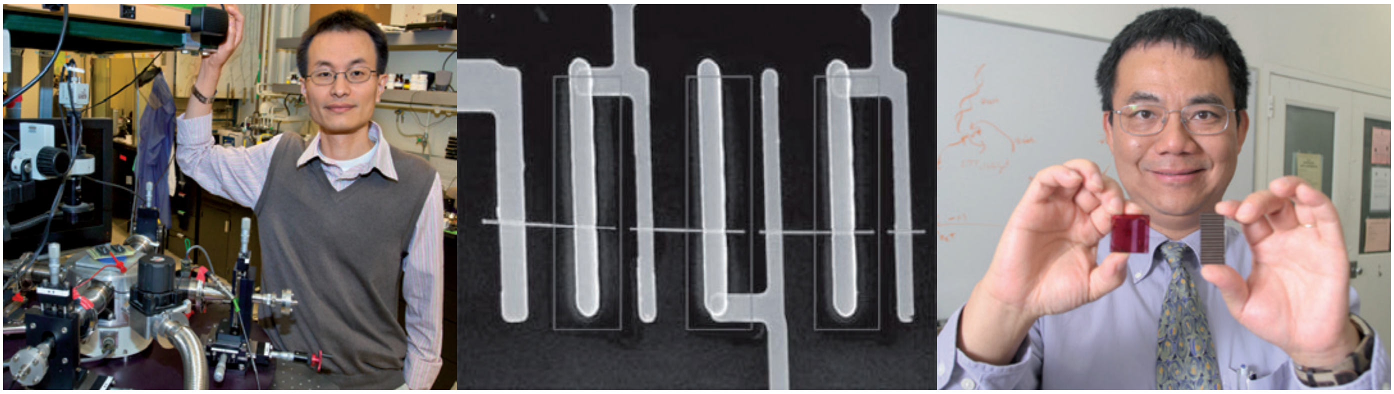
Peidong Yang of Berkeley, last author of a paper on silicon nanowires, is also increasingly interested in applying nanotechnology to energy problems. "I will devote most of my efforts towards artificial photosynthesis," he says, "and the high surface areas available with semiconductor nanowires will play a significant role in this work." The biggest challenge in this area, says Yang, is controlling the transfer of energy and electric charge across interfaces within complex nanostructures.

Another theme to emerge in e-mail interviews with the authors is the need to address the problem of manufacturability. "There seems to be a big gap between research into nanoscale science and technology, and its application in industry," says Tseng, who stresses the need to consider if any proposed device can be produced in high volumes and at low cost. Yang Yang agrees: "Manufacture is the biggest challenge — it is hard to do in a systematic manner."

However, Joselevich stresses that a detailed understanding of nanoscale structures and phenomena is needed to underpin applications. "There is a lot of fundamental science yet to be learned about how nanostructures form, how they organize themselves, and how their properties are related to their structure," he says. "I believe that it is investment in fundamental nanoscience that will eventually lead to new technology. There will not be a real technological advance if we only promote applied research." This is particularly true for nanotubes and nanowires, says Joselevich. "These structures are terribly hard to control and manipulate, and this is what is holding back their most promising applications."

Nanotubes and beyond

'Welcome to the nanoSQUID', trumpeted the cover of the first issue of *Nature Nanotechnology*, referring to the carbon nanotube superconducting quantum interference device developed by a



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Peidong Yang of Berkeley (left) and Yang Yang of UCLA (right) are two of a growing number of nanoscientists working on energy-related research. The scanning electron micrograph from Yang's lab at Berkeley shows three solar cells in series on a single nanowire[8].

The authors of the first paper to be published in *Nature Nanotechnology* were based at the Weizmann Institute of Science in Israel. Ernesto Joselevich (sitting with laptop) and Sidney Cohen (right) are still at the Weizmann. Lior Segev (left) is now a physicist at Applied Materials Israel, Onit Srur-Lavi (standing) is a chemist at Tadiran Batteries, and Tzahi Cohen-Karni (on screen) is a postdoc at MIT.

group led by Wolfgang Wernsdorfer of the Laboratoire Louis Néel in Grenoble. Wernsdorfer and the first author on the paper, Jean-Pierre Cleuziou, are still working together in Grenoble, where efforts to use the nanoSQUID to study the properties of single-molecule magnets are part of a wider research programme in molecular quantum spintronics[2] — a field that combines three rapidly evolving areas of research: molecular electronics, quantum computing and spintronics.

"The aim is to manipulate spins and charges in electronic devices containing one or more molecules," says Wernsdorfer. "The weak spin-orbit and hyperfine interactions in organic molecules suggest that spin coherence may be preserved over much longer times and distances than in conventional metals or semiconductors." There is also scope to integrate functions — such as the use of light or electric fields for switching — directly into the molecule. "The main targets for the next five years are in fundamental science," says Wernsdorfer, "but applications in quantum electronics are expected in the long run."

Carbon nanotubes featured in four of the seven papers in the first issue, and one of them — about a technique called density gradient ultracentrifugation (DGU) developed at Northwestern University to sort nanotubes by electronic structure — had been cited 566 times at the time of writing, making it the journal's second most-cited paper. (The most cited, 'Processable aqueous dispersions of graphene nanosheets', has received 844 citations since it was published in February 2008).

Nanotubes are generally manufactured as a mixture of metallic and semiconducting nanotubes, and finding a reliable method for separating out just the semiconducting nanotubes for applications in electronics had long been a challenge. "Five years ago, I would have said that the isolation of significant quantities of high-quality monodisperse nanomaterials was the primary challenge," says Mark Hersam, who was the last author on the Northwestern paper. "However, I believe that DGU and related separation methods have essentially solved this problem over the past five years. Now the principal challenge is assembly and integration. In the vast majority of applications, nanomaterials will need to be precisely positioned or patterned and interfaced with other materials."

Hersam has used monodisperse nanotubes obtained with DGU to make a variety of devices, including transistors and sensors, and is exploring new applications such as batteries, solar cells, drug delivery and biomedical imaging. He has also applied DGU to other materials, including graphene[3] and metallic nanoparticles[4], and co-founded a company called Nanointegris to commercialize the technology.

Mike Arnold, first author on the DGU paper, is also working on applications of highly pure nanotubes in his new position as an assistant professor at the University of Wisconsin. "My group is especially interested in using purified semiconducting nanotubes as photoabsorbers in photovoltaic and photodetector devices," he says, "because nanotubes are strong optical absorbers with tunable near-infrared bandgaps and excellent chemical stability. Five years from now, I hope to be publishing on a 20% efficient carbon solar cell."

When nano meets bio

Seunghun Hong of Seoul National University was the last author on a paper that reported how conventional microfabrication facilities could be used for the large-scale assembly of devices based on nanotubes or nanowires. Since then Hong and his co-workers have published more than 40 papers on devices and structures assembled with this method, including an artificial nose based on nanotubes[5] and surfaces that can control the differentiation of stem cells[6].

Hong's work at Seoul is now centred on hybrid systems comprised of solid-state devices and organic materials. The biggest challenge in this area, he says, is to develop new methods for the control and measurement of single biomolecules. However, he stresses that there has been significant progress in recent years, citing an approach to real-time DNA sequencing based on photonic nanostructures that has been developed at Pacific Biosciences[7]. One of Hong's ambitions is to integrate taste receptors with nanotube-based transistors to make an artificial tongue.

> "Five years from now, I hope to be publishing on a 20% efficient carbon solar cell."
> Mike Arnold

Another researcher working on biological applications of nanoscale devices is Gang Logan Liu, who was a graduate student at Berkeley when he was first author on a paper that demonstrated that a nanoplasmonic molecule can measure nuclease activity and protein–DNA binding. Now an assistant professor at the University of Illinois in Urbana-Champaign, Liu plans to develop new nanophotonic and nanoelectronic sensors for applications in health care and environmental protection.

Back at MIT, Cohen-Karni is also keen to explore the "fascinating" interface between the physical and biological worlds. "Having a background in materials science," he says, "I feel that there is so much that you can do by incorporating nanoscale materials into biological systems, either to create new hybrids of nanomaterials and biological materials such as tissue, or to use nanodevices to investigate biological systems."

With so many possibilities, at the bio–nano frontier and elsewhere, the next five years look set to be just as interesting and unpredictable as the past five. ❒

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