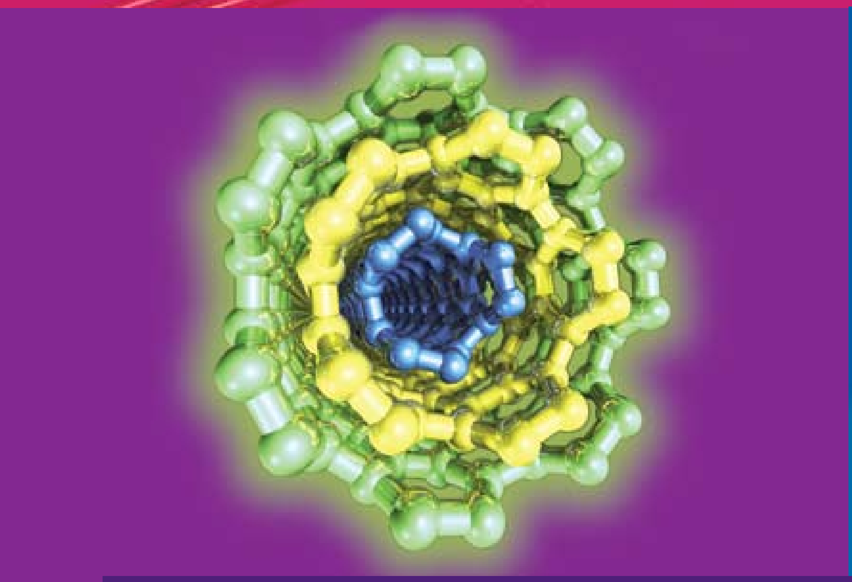
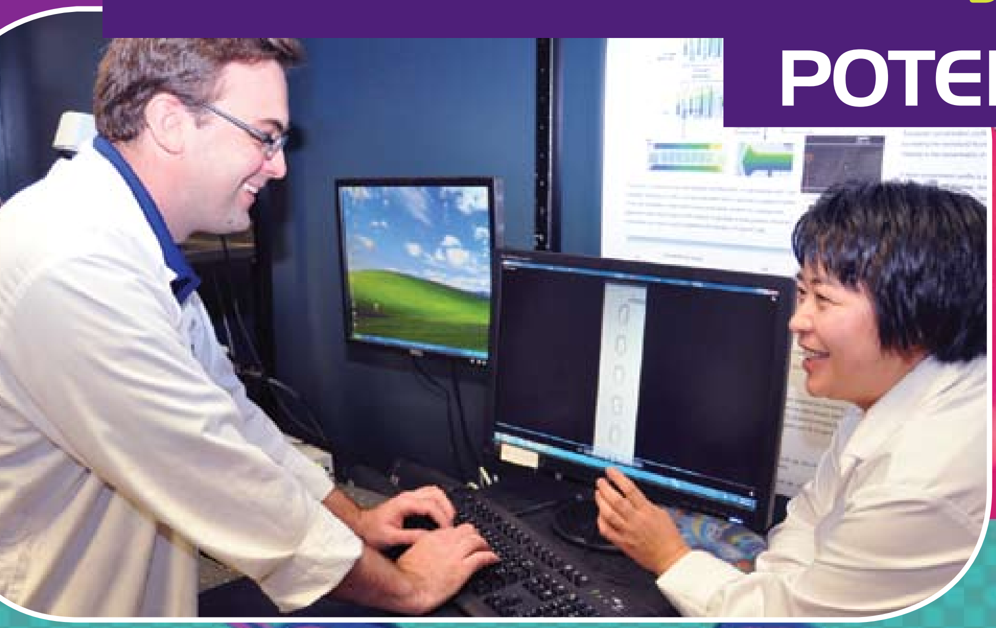
THINKING SMALL



What is nanotechnology's POTENTIAL ?



By Nicole Axworthy and Jennifer Coombes

Over the next 50 years or so, it's likely solutions to some of the world's most difficult challenges will come via nanotechnology–the design and fabrication of tiny structures and devices with novel properties and functions.

Nanotechnology is intrinsically multi-disciplinary, reliant on the basic science, analytical techniques and methodologies of such disciplines as chemistry, physics, engineering, materials science and molecular biology.

The advances this field will bring will be equally broad-ranging. Already, nanotechnology is changing health care, medicine, security, electronics, communications and computing.

Here are the stories of four nanotechnology projects representative of the work happening right now under the direction of Ontario engineers. Some projects are top-down, which refers to making nano-scale structures by machining, templating and lithographic techniques. Others are bottom-up, involving building organic and inorganic materials into defined structures, atom by atom, or molecule by molecule.

All will change life as we know it.

GREEN-TECH ANSWERS TO GLOBAL ISSUES

A bright research lab, concealed within a large office suite in a mixed residential/commercial high-rise in downtown Toronto, is a hub for green-tech research of a very small kind. Here, several eager, full-time scientists are using a novel, eco-friendly process to design and create nanotechnology-based materials and products.

This is the home of Vive Nano, a growing firm founded in 2006 by PhD chemists Jordan Dinglasan and Darren Anderson in a chemistry lab at the University of Toronto. The firm is zeroing in on products for the crop protection industry. Nanotechnology makes it possible to reformulate pesticides by encapsulating their active ingredient inside a tiny ball so it is more effective. This means farmers can use less, saving money and decreasing chemical run-off.

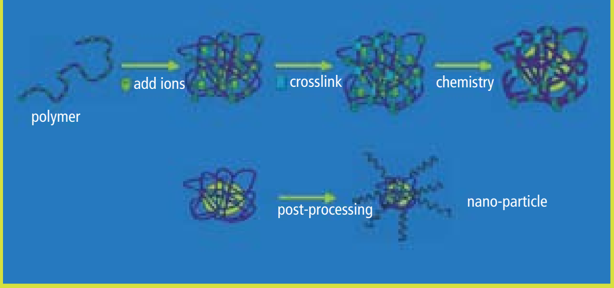
Flavio Campagnaro, P.Eng., Vive Nano's vice president of manufacturing, was brought on board to help commercialize and develop the firm's core technology. He says the technology is well suited to commercial production because its green, scalable and inexpensive.

Vive Nano's encapsulation technology to synthesize nano-particles employs a flexible process based on the principle of polymer collapse, using basic, benign, water-based inputs.

"We start with a polyelectrolyte. Every repeating unit has a charge, so it repels itself," explains Flavio Campagnaro, P.Eng., vice president of manufacturing. "We add the opposite charge all along the polymer, which neutralizes the charge so it doesn't have to repel itself and it kind of collapses into a ball…We do a bit of chemistry to it so it stays locked in place and then we have a nano-particle. Now we have a little core of polymer with the nano-particle inside it and we can do some more chemistry to that to turn it into the end product we want." He says the process is green, scalable and inexpensive–critical characteristics for addressing big challenges in global issues like food, water and energy efficiency.

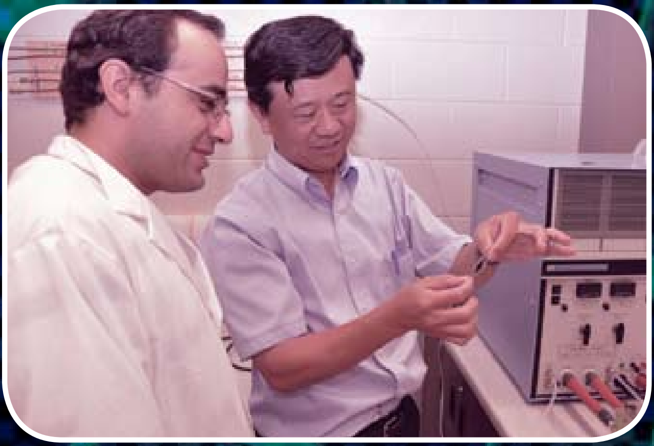
The technology is also being applied to make ultra-small, nano-particle-based supported catalysts, which give Vive Nano's customers the ability to carry out reactions with decreased energy, and increased quality and selectivity. New products in this area are expected to have an impact on biofuel and fuel cell development, as well as water treatment and environmental remediation.

Vive Nano's process

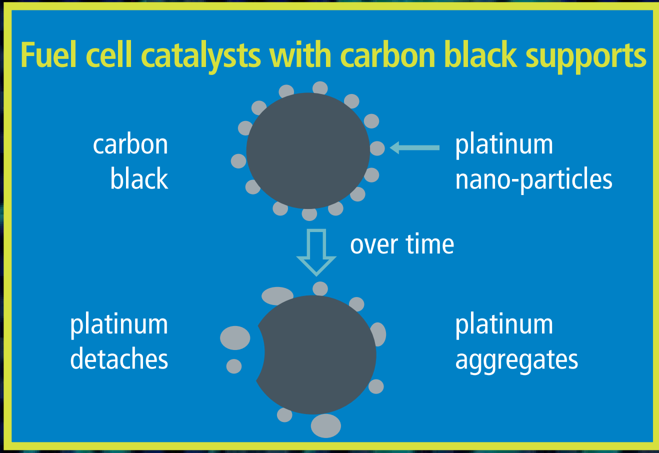


Other applications include coating glass and concrete in a photocatalytic film, which breaks down harmful organic material when exposed to sunlight, allowing buildings to clean themselves.

"Once you see it, it's a very clever technology," says Campagnaro, who was brought on board to help the company bridge the gap between lab research and commercializing the technology for mass production. "The nice thing about our technology from an environmental point of view is that the polymers we use are common



PhD student Mohammad Norouzi Banis (left), helps Andy Sun, PhD, test a sheet of nano-tubes at the lab's fuel cell test station. Growing nano-tubes and nano-wires seems deceptively simple. Sun's lab mostly uses the chemical vapour deposition method, which requires just three ingredients: a carbon-containing gas such as methane, a catalyst (e.g. iron) and high heat–about 800 C. The nano-tubes are grown on a substrate to which they form strong bonds, so there are none of the possible safety concerns of nano-particles becoming airborne.



Catalysts in fuel cells are currently made of a core of carbon black with platinum nano-particles attached to the surface. Carbon black is prone to corrosion, however, which can cause platinum particles to aggregate or detach. This causes an uneven distribution and, in turn, inefficient fuel cell performance.

ones–they're used in all kinds of applications that we're already exposed to, and so they've been demonstrated to be safe for decades. Virtually all our chemistry is done in water, so we're not using any nasty solvents or high-temperature processes."

Vive Nano has earned kudos for its pioneering technology and clean-tech approach with awards like the Deloitte Technology Green 15, Frost & Sullivan's 2010 North American Technology Innovation of the Year award, the *Canadian Business* Clean 15 competition and Corporate Knights' Canada's Clean-tech Next 10 Emerging Leaders list.

It didn't take long for investors to realize the technology's potential. "What really kicked us into gear was very strong support from government," Campagnaro says about the company's creation and growth. Initially, Vive Nano received early-stage funding from the Ontario Centres of Excellence and was also supported with resources from MaRS, a not-for-profit corporation that helps entrepreneurs commercialize publicly funded research, as well as several local angel investors. Since then, the company has attracted millions more in funding, from the Ontario Ministry of Research and Innovation's Innovation Development Fund, and from the federal government's Sustainable Development Technology Canada Fund. Although much of the company's work has yet to move beyond the lab, the government investment made it possible for Vive Nano to build a pilot plant, expand research and development, and demonstrate its processes and products to industrial partners–it's working on several different products with major international companies. "These materials will, of course, have to go through a regulated suite of environmental safety tests prior to being introduced to the market," says Campagnaro.

Because nanotechnology is a new and quickly developing field, the company is participating in a large environmental toxicity study, led by the University of Alberta and National Research Council Canada. Samples of Vive Nano's materials are sent to the university, where a network of researchers tests various aspects of the ecotoxicology of the nano-materials and documents how the materials behave over the course of the three-year study. The study data will help regulators understand the interaction of new molecules with the ecosystem and provide an important foundation for a science-based policy on environmental risk assessment of nano-particles.

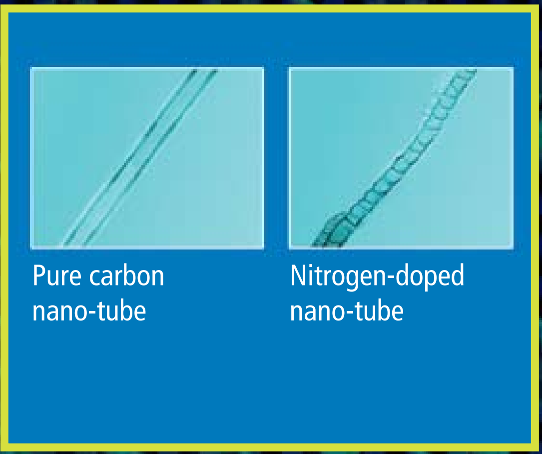
"It's important to approach new technology with an open mind and be aware of the consequences," Campagnaro explains. "We [as a society] have learned a lot from our mistakes in the past and how to approach new technologies and I think, as a society, we can approach this new technology responsibly. As a company we're trying to approach it responsibly."

CLEAN ENERGY FROM CARBON NANO-TUBES

For many years, the dream of powering cars with clean, quiet, environmentally friendly fuel cells has been just that–a dream. Until now, concerns about cost and durability have always been barriers to their full-on commercial viability.

But fuel cell vehicles may be popping up on driveways sooner rather than later thanks to the exciting nanotechnology research of Xueliang (Andy) Sun, PhD, Canada research chair in the development of nano-materials for energy, and associate professor, department of mechanical and materials engineering, University of Western Ontario.

In collaboration with British Columbia-based Ballard Power Systems and Natural Sciences and Engineering Research Council of Canada (NSERC), Sun is designing and synthesizing novel nano-materials to address the two main problems of using fuel cells to power cars–the high cost and low durability of the catalysts in polymer electrolyte membrane (PEM) fuel cells.



A better support for a fuel cell catalyst consists of nitrogen-doped nano-tubes. Unlike carbon nano-tubes, they provide active binding sites that allow platinum nano-particles to attach more evenly.

Doug Perovic, PhD, P.Eng., professor, materials science and engineering department, and Celestica chair of materials for microelectronics, University of Toronto, led a team to create a new class of nano-materials.

Materials chemistry PhD student Wendong Wang (left), and engineering technologist Dan Grozea, PhD, are important members of the PMO research team. Their PMO thin films and vapour delivery technique could satisfy the immediate and long-term needs of the semiconductor industry.

"Currently, the catalysts in these fuel cells are made of a core of carbon black with platinum nano-particles attached to the surface. But carbon black is prone to corrosion, which can cause the platinum particles to clump or detach, resulting in an uneven distribution of the precious metal. This results in inefficient performance of the fuel cell and a shortened life span," explains Sun.

Sun's group is working to eliminate the corrosion problem and minimize the amount of platinum needed for the catalysts by replacing the traditional carbon black core supports with carbon nano-tubes.

But these are not just any carbon nano-tubes. The perfect electronic structure of a regular carbon nano-tube doesn't allow platinum particles to bind easily to its surface. So, Sun and his team are the first to have developed a way to add nitrogen to carbon nano-tubes to provide active binding sites for platinum particles to attach, and to do so more evenly.

Under a transmission electron microscope, these so-called nitrogen-doped carbon nano-tubes resemble the structure of bamboo. "Unlike the long, straight carbon nano-tubes people may have seen, these nano-tubes look like they have defects–but for our purposes, these are good defects to have," says Sun. "When there is a uniform deposit of platinum, you can use less. With nitrogen-doped nano-tubes, the performance of a fuel cell is greatly increased and the cost is dramatically reduced. It's win-win."

These catalysts are also more durable due to the stronger interaction with nitrogen-doped nano-tubes, which will allow for a longer operational life of the next generation of fuel cells.

Sun is working on a similar project with GM Canada. But instead of replacing the carbon black cores with nano-tubes, he is experimenting with using metal oxide nano-wires as the platinum support. Sun feels this may ultimately be a better solution because the nano-wires also partially replace the platinum, which reduces the need for the costly metal altogether. However, this area of research, though promising, is still a couple of years away from commercialization.

There is no doubt that nanotechnology will have a profound impact on power generation. And, if Sun has anything to say about it, fuel cell technology for the automotive industry will be shifting from a technology that's promising to one that we'll see on the streets before we know it.

NANO-MATERIALS INSPIRED BY NATURE

Back in 1965, *Electronics* magazine asked Gordon Moore, then research director of electronics pioneer Fairchild Semiconductor, to predict the future of the microchip industry. At the time, the industry was in its infancy; Intel, now the world's biggest chip-maker, would not be founded (by Moore, coincidentally) for another three years. Nonetheless, he confidently argued that engineers would be able to cram an ever-increasing number of transistors onto microchips, and he guessed that the number would double about every two years.

Moore's law, ironically, is an insight into the dynamics of the rapid technological change that still holds true today. As the semiconductors that power the chips and lasers responsible for computing information shrink down to the nano-scale, they produce higher levels of electrical resistance and capacitance that ultimately slow performance. For the last several years, a research team led by University of Toronto professors Doug Perovic, PhD, P.Eng., of materials science and engineering, and Geoffrey Ozin, of chemistry, has been seeking to solve this problem by creating a new class of materials.

The material, known as periodic mesoporous organosilica (PMO), is a thin nano-porous film. It was created by mixing an organosilica precursor containing organic groups with a surfactant in an aqueous solution–similar to a soap that mixes oil and water–which causes the organosilica to self-assemble into a nano-structure. When the surfactant was washed away, it left a nano-porous material. When the researchers examined the thin film that remained, they discovered it made an excellent dielectric material that could be used to significantly improve the speed and reduce crosstalk of information transferred between the tiny wires inside microelectronic devices. Conventionally, computer chip manufacturers have insulated their wire interconnections with silica glass, preventing them from coming into contact and interfering with each other. The PMO acts as a better dielectric, allowing transistor components to shrink even further.

"Imagine a sponge," Perovic describes. "Nature makes this random labyrinth of holes within this sponge material. We want to design an exact architecture of holes, maybe circular or rod-like, a certain size, a certain spacing, a certain type of material in the walls between the holes. That can give you very different types of materials for electronic means, for drug delivery, for catalysis, chemical reactions, for separating chemicals, for making detectors…the range of possibilities there is quite phenomenal. Nature makes a lot of porous stuff, and chemists have learned from that and taken it further."

PMO thin films are usually fabricated by spin coating and dip coating, both liquid-phase delivery techniques. After several different approaches, the team realized this technique–"where we basically spray this stuff down and spin it onto a platter, like making crepes, essentially," says Perovic–was not conducive to common, large-scale electronics industry techniques.

Under Perovic's and Ozin's supervision, materials chemistry PhD student Wendong Wang came up with a new technique. "We recently developed a vapour phase delivery technique, called vacuum assisted aerosol deposition (VAAD), and have investigated the properties most related to low-k [low dielectric constant] applications," Wang says. Essentially, for a dielectric to be successfully integrated into existing semiconductor manufacturing processes, it has to satisfy certain criteria: most importantly, it must have a low dielectric constant, sufficient mechanical strength and humidity resistance. Wang says the PMO thin films used in the VAAD technique possess a combination of properties that satisfy the immediate and long-term needs of the semiconductor industry.

According to Perovic, creating this new form of nano-scale technology is all about collaboration. "What's really the future and likely the ultimate approach is a combination of both physics and chemistry," says Perovic. "I joined with some fundamental scientists–physicists and more recently chemists–and they make some great stuff in a beaker, so to speak. Our job in engineering, I think, is to see if we can take these materials to the next level and to ask, 'Is this something that can be integrated and commercialized?'"

Lab-on-a-chip technology scales multiple laboratory processes down to a miniaturized chip format. Microscopic volumes of liquids move through a system of micro- and nano-sized channels to perform complex biomedical processes.

Perovic and his team seem to have hit the mark. In April, student Wang presented their research findings at the Materials Research Society's spring meeting in San Francisco, and there was overwhelming interest from industry. "Intel started calling us right away," says Perovic.

"If we get this material into every computer chip, I mean, that's massive," he continues. "It may only last for a year and a half, because that industry is very progressive and they can change things in a one-year timeline. But if we could hit that niche and show that it's a material that isn't just going to do its job for the next level of production but maybe for the next 10 years, then that's fantastic. So we're quite excited about that."

THE INCREDIBLE SHRINKING LABORATORY

Imagine being able to analyze tiny amounts of blood and recommend therapy within moments, instantly test for contaminants in water, or help speed new drugs to market–all with a device that fits in the palm of your hand.

This technology is already a reality and called lab-on-a-chip (LOC), a nano-scale lab that shrinks multiple laboratory processes down to a miniaturized chip format.

LOC and microfluidics, the study of fluids in tiny channels, is the focus of Carolyn Ren, PhD, P.Eng., Canada research chair in lab-on-a-chip technology, and director, Waterloo Microfluidics Lab, department of mechanical and mechatronics engineering, University of Waterloo.

A typical LOC consists of a small piece of glass or polymer, or a combination of these materials, that works by moving microscopic volumes of liquids through a system of micro- and nano-sized channels. Together with embedded sensors and electrodes, the chips perform sensitive and complex chemical and biomedical processes.

LOC devices require only extremely small amounts of biological samples and reagents–on the order of nano-litres to pico-litres–and integrate parallel processes to analyze samples faster and more cheaply than traditional benchtop labs. As a platform, LOCs can be used for unlimited purposes, including

Carolyn Ren, PhD, P.Eng., adjusts the fluid flow through a lab-on-a-chip she manufactured in her lab. This technology significantly advances protein separation technology and could revolutionize protein- and biomarker-based disease diagnosis.

Ren and PhD student Tomasz Glawdel monitor microdroplets in real time that are traveling in a lab-on-a-chip. Instead of a continuous stream, aqueous droplets are dispersed in a carrier oil, each droplet acting as a single "microreactor" that can be controlled independently. This technology may soon allow pharmaceutical companies to test individual concentrations of drugs at a rate of 1000 per second and help get drugs to market faster.

chemical analysis, environmental monitoring, medical diagnostics and forensic science.

With funding from NSERC, International Science and Technology Partnerships Canada Inc. and the Ontario Centres of Excellence, Ren's group has been working with Toronto-based Convergent Bioscience since 2006 to develop a chip-based, multi-dimensional protein-separation platform for rapid disease diagnosis.

This research significantly advances protein-separation technology, replacing older, unidimensional capillary-based separations, and could revolutionize protein- and biomarker-based disease diagnosis, and accelerate the identification of potential drug candidates for treating disease.

Ren's group manufactures its own LOC designs in the lab. First, a pattern of channels is transferred to a silicon wafer using photolithography to create a master. PDMS, a polymer, is then poured onto the master and either baked or cured at room temperature. Next, a layer of glass, PDMS or quartz is added and may or may not be permanently bonded to the chip, depending on what it will be used for.

"This [making the master] is the most difficult part because of the precision needed to create the tiny channels. But once they're finished, the masters can be used hundreds of times, which cuts down on the cost of fabricating each chip," says Ren.

Although observation of the processes running on LOCs can be done using a variety of techniques, including fluorescent visualization and UV absorbance, Ren's chips use built-in capacitance sensors. "This makes the chips extremely portable. You just need the chip, an electrical source and a computer, which means that even poorly equipped clinics can perform diagnostic tests with no lab support," explains Ren.

Ren is particularly excited about droplet-based LOC, a new area of her team's research that enables high-throughput screening. With droplet-based LOC, fluids are handled in a microdroplet form rather than continuous streams in the microchannels. Independent aqueous droplets are dispersed in a carrier oil, each droplet acting as a single "microreactor" that can be controlled independently.

This system allows hundreds of tests not only to be done at the same time, but also at different concentrations, or other varying parameters.

"This has tremendous value, especially for the pharmaceutical industry. Evaluating dosages of drugs is a daunting process requiring hundreds of tests and a great deal of time, which contributes to the high cost of many drugs. The droplet-based system will allow the simultaneous testing of individual concentrations of drugs at a rate of 1000 per second, an order of magnitude higher throughput than the current rate of testing. With shorter test times, drugs get to market faster," says Ren.

Ren estimates her team is within a year of releasing this flexible new platform, which will be completely customizable for pharmaceutical and other companies that require high-throughput testing.

"As engineers, we want to make things work faster, better and a lot cheaper. It's really exciting to be designing something that is so directly applicable to many industries and has the potential to revolutionize them. But right now," she says, "we're working on controlling droplet size, transport and trafficking, and getting the whole system to work reliably." Σ