Nanoscience: *The New High Frontier*

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Abstract

Exploring the properties of matter at the atomic and molecular scale is opening a new era for science and technology. The article presents research areas that are of particular interest to scientists today and discusses the potential technology applications that may be implemented based on the discoveries. Application areas include polymer composites, advanced coatings and catalysts, molecular computing, and biological systems. There is a tremendous opportunity for Canadians to benefit from nanotechnology but seizing the opportunity requires that we develop a national strategy and make co-ordinated investments in niche areas that exploit particular Canadian strengths.

Sommaire

L'exploration des propriétés de la matière à l'échelle atomique et moléculaire marque une nouvelle ère pour la science et la technologie. Cet article souligne les domaines de recherche qui sont les plus intéressants pour les scientifiques et discute des applications technologiques possibles provenant des découvertes dans ce domaine. Les domaines d'application comprennent les polymères composites, les matériaux et catalyseurs avancés, l'informatique moléculaire, et les systèmes biologiques moléculaires. Il existe présentement une immense opportunité pour le Canada dans le domaine de la nanotechnologie. Cependant, pour pouvoir en faire partie il est impératif qu'une stratégie nationale soit développée et que le pays se prépare à investir dans les crénaux concernés pour bénéficier des compétences canadiennes.

1.0 Introduction

Canadians have grown used to amazing progress in such established fields as computers and biotechnology. Now "nanoscience", a new kid on the block, may revolutionize many other sciences, technologies and industries.

Nanotechnology's subject is the extremely small. It gets its name from a unit of measurement, the nanometre-a billionth of a metre, the size of a molecule and only ten times bigger than a hydrogen atom. But the new science doesn't stop with understanding nature on these scales. Its spinning off an engineering arm called "nanotechnology", which can manufacture structures and devices on the atomic scale.

Interesting enough, sure. But how could this matter to anyone not directly involved with it? Here is Dr. Neal Lane, Chief Advisor on Science and Technology to the former US President: "If I was asked for an area of science and engineering that would produce the breakthroughs of tomorrow, I would point to nanoscale science. It is the high frontier of the 21st century R&D [1]."

Nanoscience deciphers, and nanotechnology applies, the amazing properties that materials exhibit at the tiny scales of the molecule or atom. At that level, materials can display odd and counter-intuitive behavior. Its a world where the impossible is suddenly routine.

In a sense, all modern science is nanoscience. According to Dr. Tom Jackman, Director of the National Research Council's Institute for Microstructural Sciences, a scientist always wants to know more about nature. "Deepening our understanding", he says, "means getting down to smaller and smaller scales. And once we understand, we can also implement." Nanoscience leads directly to nanotechnology - which is nothing less than engineering on the atomic scale.

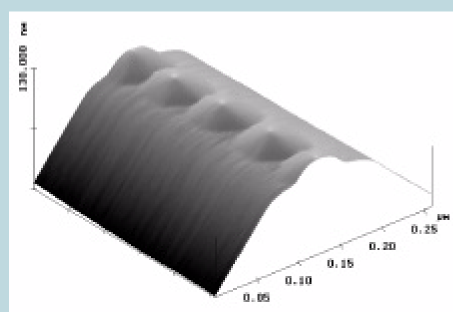
Scientists permanent quest for higher, faster, farther and especially smaller has led to modern nanoscience through the convergence of three factors:

- First, technology has supplied new instruments, such as the scanning tunnelling microscope, that let researchers track and manipulate things as small as single atoms.
- Second, recent advances in information technology let scientists construct computer-based models to visualize things too small to see directly, that otherwise are too strange to understand. One big multinational firm has developed technology that lets a systems designer "walk through" structures smaller than a microchip, seeing them as if the scientist were a few nanometres tall.
- The third enabling field of nanoscience is metrology, the science of measurement. Size, shape, mass, voltage, current and other attributes must be found in every experiment. Nanoscience poses a special challenge to metrology, for all its quantities are vanishingly small.

International or SI standards, whether of length, mass, time, or other basic properties, are administered by *Le bureau international des poids et mesures* in Paris, France. Each nation that uses SI units maintains a national laboratory that conducts R&D in ultra-fine measurement. The NR's Institute for National Measurement Standards in Ottawa has this role in Canada (Figure 1).

Consider length. The metre was defined in 1799 as one ten-millionth of the great-circle distance from the North Pole to the Earth's equator. It was redefined in 1889 as the length of a rod of precious-metal alloy, measurable to a micrometre (0.000 001 m) and kept in a Parisian vault. As metrology achieved sub-micrometre measurements, the metre was again redefined in 1960 as a certain number of wavelengths of visible light from energetic krypton atoms. Today, with the advent of lasers as more stable light sources, the metre's definition is based on Einstein's absolute: the speed of light in a vacuum. Now length metrology to tens of nanometres is routine at most national labs, and nanometre measurement is common.

Figure 1: Atomic force micrograph showing 20 nm high self-assembled quantum dots of InAs on an InP template (NRC Institute for Microstructural Sciences).



An especially hot area within nanoscience is the emerging field of molecular computing. Today's C-MOS computer chips are based on silicon. Experts believe this type of chip will reach its functional limits very soon. To replace it, researchers are experimenting with nanoscale devices that require only a few electrons' difference to "flop" - the basic action by which computers processes data. If quantum-computing devices [2] can be made to flop in reliable ways and can also be mass produced, they will process data at rates that make today's 1-GHz clock-speeds seem like a crawl. Commercial prototypes of a quantum computer, says Dr. Stan Williams of Hewlett-Packard Corporation, may be available within five years. Conveniently, this will be just as today's conventional micro-circuits hit the end of their capacity.

The benefits of nanoscience and nanotechnology extend beyond computing materials, to materials in general. Scientists at NRC's Industrial Materials Institute in Quebec have improved the structural properties of plastics by 50% through the addition of nano-sized particles of clay. Worldwide market estimates for these polymeric nanocomposites by 2009 are in the region of four to five billion dollars per year. This nano-R&D is part of an NRC program to change the properties of materials by introducing tiny particles into various substrates [3]. Ultimately, scientists think, we may be able to create nanocomposites entirely novel substances or "designer materials". Want perfect elasticity in a transparent solid? Strong magnetic properties in an inert, low-cost, sprayable fluid? In ten years you might simply be able to call in your local nanomaterials firm and tell them what you need. They will make your material to order.

However, this is mostly long-term stuff: you won't see much nanoscience in your daily life for a few years yet. Dr. Dennis Salahub, Director General of NRC's Steacie Institute for Molecular Sciences, believes the real benefits of nanotechnology are yet to come yet come they will. "Projects in nanotechnology research may start out as intellectual curiosities," he says. "But eventually, they will have huge economic value".

As an example, Dr. Salahub cites carbon nano-structures called fullerenes and buckyballs, discovered 20 years ago and named for the visionary US engineer Buckminster Fuller. To visualize a buckyball, look at the geodesic dome from the US Pavilion at Expo'67 in Montreal. Then imagine it smaller by a hundred billion times in length, and a million billion billion billion times in volume. Yet despite their tiny size, or perhaps because of it, fullerene structures called nanotubes are already being explored for commercial video displays.

The engineering in nanotechnology is of a radically different type. From time immemorial, humans have made things; with nanotechnology, we let things make themselves. If this seems like science fiction, consider that Canada's most widely used construction material puts itself together using natural nanotechnology. It's called wood. Trees make wood by combining carbon from the air, hydrogen and oxygen from ground water, and sunlight. There's no reason we can't copy these natural nano-processes ourselves.

In some areas, we already have. One young NRC researcher, Dr. Bob Wolkow, recently startled scientists around the world by persuading a nanotech wire to assemble itself on a silicon substrate. The wire was the thickness of a single atom. Dr. Wolkow (Figure 2) is one member of a seven-person team at NRC that won a 2001 Outstanding Achievement Award for its work in molecular interfaces. The citation was full of phrases such as:

- international recognition,
- new developments in physics, chemistry and biology,
- tools for creating & understanding molecular structures on surfaces,
- the next revolution in microchip fabrication,
- tiny devices that sense, analyze and respond to information in their environment.

Nanotechnology has many potential applications in medicine and health, says NRC's Salahub. Some of Canada's most advanced work along these lines is done in Edmonton. Scientists from the University of Alberta are developing portable "laboratory-on-a-chip" sensors that are so sensitive and rugged that they can detect individual molecules in a fluid sample right at a patient's bedside. Soon waiting for medical-test results may shrink from days or weeks to mere minutes. One Canadian company has already established a market for hand-held blood chemistry analyzers based on nanotechnology. Its markets could grow to several billion dollars per year worldwide. Similar nanotechnology-based devices may revolutionize detection and treatment of cancer, AIDS, diabetes and other scourges.

Figure 2: Dr. Wolkow is one member of a seven-person team at NRC that won a 2001 Outstanding Achievement Award for its work in molecular interfaces. Dr. Wolkow uses the scanning tunnelling microscope to manipulate individual molecules.

Nanotechnology has cautions as well as promises. While Canada participates in a lot of nanotechnology R&D, by world standards its work is insufficient in many fields. "No national strategy has been developed to concentrate the separate pockets of expertise in nanotechnology and nanoscience across Canada," says Dr. Peter Hackett, NRC Vice-President, Research. "Nor has a federal network of Centres of Excellence in nanotechnology yet been created. Yet Taiwan and Korea both have centres for nanoelectronics, China has a 10-years nanotech program for materials and probes, and the US nanotech budget for 2002 alone exceeds half a billion dollars."

Dr. Hackett would like to see Canada take on niche projects that build on our proven national strengths such as electronics, aerospace, biomaterials and pharmaceuticals. That strategy, he says, will let Canada develop nanotech-based businesses that convert new knowledge into jobs and profits.

Admittedly, that process may prove a long haul. Despite its promise, nanoscience is still a high-risk venture that demands massive up-front investment. Many of its new products may take 10 or 20 years to reach consumers, and not all private companies are prepared to invest in such long shots. But despite such cautions, NRC believes nanotechnology is worth the investment in dollars and time.

"I am convinced that within the next few years, the number of Canadian companies commercializing products based on some nanotechnology will increase significantly," says Dr. Yves Deslandes, Chemical Process Director at NRC. Applications could include new types of coating, energy storage, catalysts, and biological devices such as sensors with very tiny pores.

"In the long term, nobody can predict what will happen," Dr. Deslandes concludes. "We simply have to be ready to use our new discoveries."

2.0 References For Further Reading

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About the Editor

Dr. Peter Hackett obtained a Ph.D. in 1972 in physical chemistry from the University of Southampton, England.

He joined the Division of Chemistry of the National Research Council (NRC) as a post-doctorate fellow in 1972. Dr. Hackett is an internationally recognised chemical physicist who pioneered many applications of lasers in chemistry. In July 1995, he was appointed Director General of NRC Steacie Institute for Molecular Sciences. Since January 1998, Dr. Hackett is NRC's Vice-President of Research.

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