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Honey I Shrunk The World

Research and development in nanotechnology at the University of Illinois

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IMAGINE THIS: JANE FALLS ILL. BEING A DIABETIC, HER glucose levels are measured around the clock through a nanoscale glucose sensor implanted in her thumb. Her readings are communicated to her physician's patient monitoring system, and her sudden drop in glucose alerts her physician's office. The nurse at the physician's clinic responds to the alert and sends the glucose sensor an electronic command to release insulin. This scenario may sound like science fiction, but it is among the future possibilities that nanotechnologies hold.

The 21st century will be the time when nanoscience and healthcare become nearly synonymous. Every seven seconds another baby boomer turns 50; by 2030, about 72 million baby boomers will have reached their golden years. The corresponding rise in healthcare costs will drive the development of novel technologies to treat the health issues facing this population, from bone injuries to cancer, from diabetes to neurological disorders.

Engineers generally have built materials and devices using a top-down approach. By contrast, nanotechnology starts at the bottom, with the most fundamental structures of matter, and offers unique possibilities of engineering unimaginably small devices and systems. This makes it possible to totally rethink how we can create faster, lighter, and stronger materials and devices. These will be ultrasmall devices with extraordinary energy-saving features such as multifunctionality, portability, and interoperability.

As with many new technologies, the hype is that nanotechnology will solve many more of the major problems facing the world—

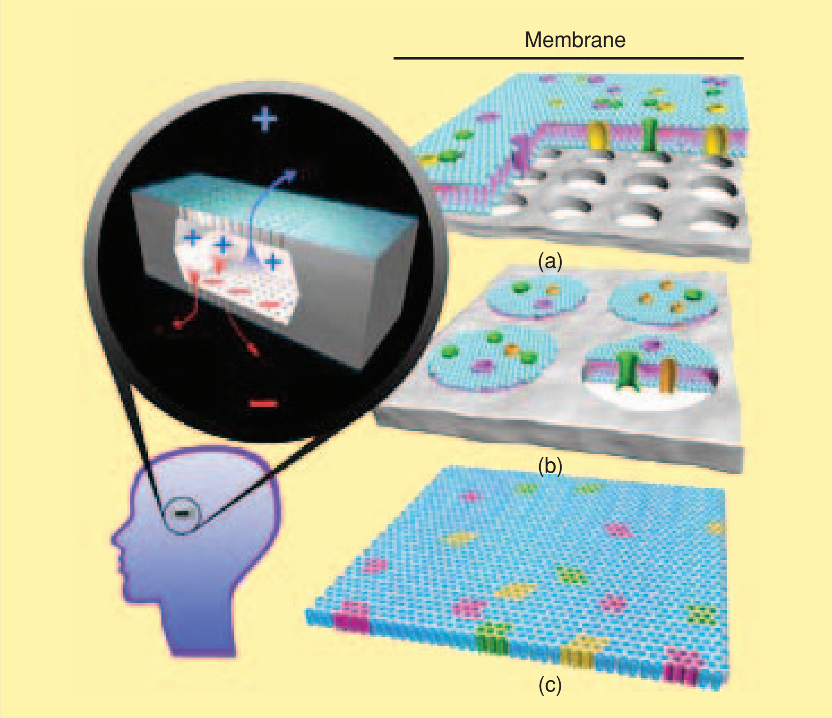

FIGURE 1 Conceptual framework of a "biobattery" for retinal implants. (Image courtesy of CDBN, 2006.)

poverty, disease, hunger, scarcity of clean drinking water—than is reasonably possible. These claims are not helpful for public understanding of the technology, and they tend to raise unrealistic expectations and anxieties. Is nanotechnology something that should induce alarm over self-replicating nanorobots taking over the world? Is it a panacea we should embrace blindly? As usual, the answer is somewhere in between. We observe that many of the United Nations Millennium Development Goals potentially can be achieved by leveraging nanotechnology.

This article provides a brief snapshot of some of the agricultural, biological, electronics, medical, and manufacturing applications currently under active research and development at the University of Illinois Center for Nanoscale Science and Technology (CNST) collaboratory. The trend has been to prefix the word *nano* to any application (such as nanoagriculture, nanoelectronics, nanomedicine, etc.) that leverages features at the nanoscale to design and develop materials, processes, sensors, devices, and systems.

ABOUT THE CNST

Some may see the University of Illinois at Urbana-Champaign (UIUC) as a geographically challenged location, while others view it as an intellectual power house that thrives on innovation, with such worldwide impacting discoveries as transistors, light-emitting diodes, magnetic resonance imaging, plasma display, the Web browser, and thousands more.

The University of Illinois CNST is one of the premier research and education centers in the country, known worldwide for its multidisciplinary projects. In 2007, the University of Illinois was ranked among the top three academic institutions in nanotechnology research, education, and facilities by *Small Times* magazine.

The CNST was established in 2001 at the College of Engineering, UIUC, to bring together various researchers and groups who were working on nanotechnology or were interested in leveraging the potential of the evolving technology. Currently at UIUC, there are more than 150 nanotechnology researchers and several hundred graduate students, with 75 courses offered, covering a range of nanotechnology topics. In addition, specialized training courses for academia and industry on nanofabrication, nanocharacterization, mechanosensitivity, and nanocomputation are also offered.

With more than US$200 million invested in nanotechnology infrastructure, the CNST works as a collaboratory, working with several laboratories and centers engaged in nanotechnology research. The main laboratories are user facilities open to academia and industry. Reflecting the multidisciplinary nature of the technology, the CNST works with researchers from ten colleges and more than 30 departments across the campus. There are more than ten startup companies located at the University Research Park and other locations in Illinois which have emanated from nanotechnology research conducted at the University of Illinois nanotechnology laboratories.

There are several areas in which the University of Illinois is conducting cutting-edge research. These include bionanotechnology, computational nanotechnology, nanocharacterization, nanoelectronics, nanofabrication, nanoelectromechanical systems, nanoenvironment, nanoscale energy, nanomaterials, nanomanufacturing, nanomedicine, and nanophotonics.

NANOMEDICINE

According to the United Nations Population Fund, population aging represents one of the most significant demographic shifts in history. The health consequences associated with this shift will present major challenges for a growing segment of the U.S. population, with considerable economic implications. Current advances in nanotechnology are going to positively affect living environments and improve the health and quality of life for this rapidly growing elderly population.

CANCER RESEARCH

A National Cancer Institute (NCI)-funded project is among eight such projects funded nationally by the NCI in 2005. The Siteman Center of Cancer Nanotechnology Excellence (SCCNE) is based at Washington University in Saint Louis, with researchers at its medical school providing the core leadership in clinical applications, while the CNST is providing nanomaterials and nanofabrication expertise. The SCCNE-UIUC has funded several seed projects to help develop technologies for cancer therapeutics. Multifunctional nanoparticles prepared through controlled chemistry and molecular self-assembly are being developed to allow targeted delivery of chemotherapeutics for cancer treatment. The U.S. Agency for International Development-funded cancer nanomedicine project involving international collaborators is investigating plant-extract-induced cancer cell apoptosis using biosensors.

> Nanotechnology starts at the bottom, with the most fundamental structures of matter, and offers the possibility of engineering unimaginably tiny devices and systems.

IMAGING

The application of nanotechnology for the detection, diagnosis, and treatment of cancer relies on the fundamental understanding of the dynamics associated with nanoparticle and probe biodistribution in in vivo tumors. In this project, a novel class of targeted nanoparticles and probes with distinct optical signatures is being developed to enable high-resolution in vivo imaging via spectroscopic optical coherence tomography (SOCT). SOCT will be used to track the in vivo dynamics of nanomaterials, an area of increasing importance as researchers look toward the translation of such materials as contrast and therapeutic agents in clinical trials.

RETINAL PROSTHESIS

The long-term vision of the National Institutes of Health (NIH)-funded National Center for Design of Biomimetic Nanoconductors (CDBN) is to conduct interdisciplinary research for advancing medical nanotechnology. The Center plans to develop nanoscale technologies for diagnosis and treatment of disease and for the creation of tiny implants. The short-term goal is to power a new device that promises to return vision to those blinded by eye disease. The first project of the new center is the design of a "biobattery" or power source for retinal prosthesis (Figure 1).

NANOELECTRONICS AND NANOPHOTONICS

A Pentium IV chip carries 42 million transistors. Based on nanofabrication techniques such as nanolithography, the next generation of chips is likely to see a five-fold increase to 220 million transistors. Researchers are working on a range of topics including nanotubes, quantum dots, vertical cavity surface emitting lasers, colloidal assembly of materials, thin films, processing of semiconductors and other materials at the nanometer level, and application of these techniques to the realization of ultra-high-speed optoelectronic devices, circuits, and switching devices.

CARBON NANOTUBES

Carbon nanotubes are tiny, cylindrical tubes made up of pure carbon, a few nanometers in diameter. Nanotubes can conduct electricity and may be useful as wires. They are also being explored for potential postsilicon chip technologies. Nearer term, hybrid technologies that combine the two are more likely and could directly leverage the vast silicon infrastructure already in place. Investigators have been studying the interaction between nanotubes and silicon at the atomic level, for which the ultra-clean dry contact process was developed to maximize useful information (Figure 2). Atomistic-level information is becoming increasingly important as chip technology shrinks.

TRANSISTOR LASER

The transistor laser has now been found to possess fundamental nonlinear characteristics that are new to a transistor and permit its use as a dual-input, dual-output, high-frequency signal processor. By modifying the base region with quantum wells and resonator configurations, researchers at the Micro and Nanotechnology Laboratory have shifted the transistor operation from spontaneous emission to stimulated emission. The transistor laser also raises the possibility of replacing wiring between components at the chip or board level with optical interconnects, thus offering a wealth of flexibility and capability in electronic-photonic integrated circuits.

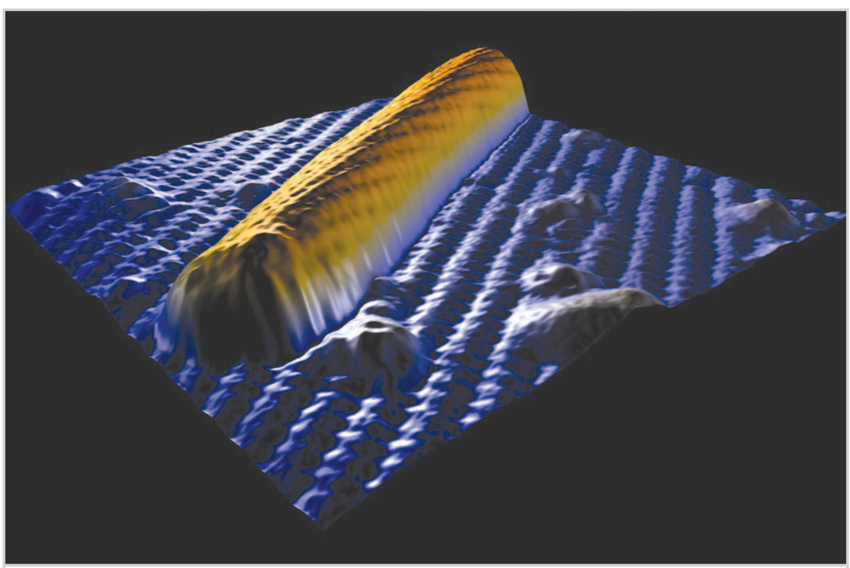

FIGURE 2 A new dry contact transfer method developed at the UIUC for ultraclean deposition of nanostructures such as nanotubes. (Image courtesy of P. Albrecht and J. Lyding, 2003.)

FIGURE 3 Concept drawing of macroscale flexible electronic system for living environments. The system will enable the occupant to tailor the appearance of the living environment and interact with one's physician or a loved one. (Image courtesy of J. Rogers, University of Illinois, and O. Ataman, University of Colorado, Boulder, 2006.)

MACROSCALE FLEXIBLE ELECTRONIC SYSTEMS

Forced sedentary living, and the health consequences associated with it, pose major problems for a growing segment of the U.S. population and, in turn, for an economy that must support this population. Some of these significant challenges can be addressed by macroscale flexible electronic systems (MFESs) that integrate visual information display, in the form of wall-scale digital environments, and health-monitoring technology, in the form of home-aware nanosensors, seamlessly into the private home environment (Figure 3). A high-bandwidth version of this type of system will provide a real-time immersion environment for communicating with physicians, relatives, or loved ones. The capabilities offered by such a system will have real and positive impacts on the well-being, state of mind, and physical health of the occupant. The MFES may provide the next generation of architectural framework to assist with both healthcare and security needs.

NANOSCALE ENERGY

The energy demand is anticipated to double from 14 TW to 28 TW by 2050. Couple this with the rising oil prices—currently hovering around US$90 a barrel and likely to rise—and the interest in finding alternate sources of energy, including effectively harnessing solar energy, will continue to take the front stage if we are to maintain our quality of life. Silicon nanoparticles developed at the University of Illinois, when coated onto a silicon solar cell, can boost power, reduce heat, and prolong the cell's life. A 60% performance enhancement in the ultraviolet range has been shown in the solar cells with the application of 1 nm-sized silicon nanoparticles. The process of coating solar cells with silicon nanoparticles could be integrated fairly easily into the manufacturing process with minimal additional cost.

NANOWIRES

As the size of sensor networks and mobile devices shrinks toward the microscale, and even nanoscale, there is a growing need for suitable power sources. Because even the tiniest battery is too big to be used in nanoscale devices, scientists are exploring nanosize systems that can salvage energy from the environment. Now, researchers at UIUC have shown that a single nanowire can produce power by harvesting mechanical energy. Made of piezoelectric material, the nanowire generates a voltage when mechanically deformed. To measure the voltage produced by such a tiny wire, however, the researchers first had to build an extremely sensitive and precise mechanical testing stage.

BIOMEMS AND BIONANOTECHNOLOGY

Working at the confluence of biotechnology and nanotechnology, researchers are addressing overarching biological questions by exploring engineering solutions. For example, research is also being conducted on nanofluidic devices, pathogenesis of fungi, biosecurity, neural prosthetics, temperature-sensitive capsules for on-demand drug delivery, use of bacteria for delivery of nanoparticles loaded with drug cargo, design and development of biomicroelectricamechanical (BioMEMS)-integrated biochips for detection of cells, DNA, proteins, and small molecules from fluids for food safety, environmental, and clinical applications.

PHOTONIC CRYSTAL BIOSENSORS

The Nano Sensors Group at the Micro and Nanotechnology Laboratory focuses on the design, fabrication, and application of photonic crystals for drug discovery research, diagnostic testing, and environmental monitoring. The photonic crystal biosensors are manufactured using nanoreplica molding, leading to inexpensive production of continuous sheets of plastic film, which are incorporated into disposable plastic labware. New applications for photonic crystal biosensors have included screening of small-molecule drug compounds for treatment of Parkinson's disease, detection and identification of soybean rust spores, and detection of viral contaminants in ground water.

MECHANOBIOLOGY

Working at the confluence of biology and engineering has led to experimental evidence suggesting that extracellular and intracellular mechanical forces have a profound influence on a wide range of cell behavior such as growth, differentiation, apoptosis, gene expression, adhesion, and signal transduction. The study of cell mechanics has drawn considerable attention from diverse fields. The Center for Cellular Mechanics at the University of Illinois is making advances in micro-nano technology, offering unique opportunities for probing biological phenomena at a cellular and subcellular scale, which may profoundly impact the study of cell mechanics.

> Reflecting the multidisciplinary nature of the technology, the CNST works with researchers from ten colleges and more than 30 departments across the campus.

DNA SEQUENCING

In recent years, the cost of DNA sequencing has gone down 50-fold; however, it still costs about US$10 million to sequence 3 billion base pairs, the amount of DNA found in the genomes of humans and other mammals. The project explores the feasibility of sequencing a DNA molecule using a type of silicon integrated circuit. The circuit incorporates a nanopore mechanism with a molecular trap that forces the DNA molecule to oscillate back and forth between electrodes, measuring the electrical signal associated with each specific base. The efforts are aimed at speeding the rate at which the next generation of sequencing technologies becomes available in the scientific laboratory and the medical clinic.

CLEAN WATER

Ensuring the availability of clean, abundant fresh water for human use is among the most critical issues facing the United States and the world. More than 1 billion people in the world lack access to clean water, and things are not getting any better. Water is pivotal to the United States in terms of economy, health, food, and energy. In 1993 in Milwaukee, Wisconsin, the outbreak of *Cryptosporidium parvum* (4–8 µ in size), a protozoan parasite that causes gastrointestinal illness, resulted in thousands of people getting sick and costing US$96 million in healthcare and associated costs.

There is a dire need to not only conserve water but also to develop novel and affordable technologies for supplying clean drinking water. The National Science Foundation-funded Center of Advanced Materials for Purification of Water with Systems (CAMPWS) is engaged in developing nanofilteration devices, which are among the possible solutions to prevent future such outbreaks.

NANOAGRICULTURE

BIOSENSORS

The United States is at risk of being attacked by soybean rust spore, and the risk has become even higher due to the recent increase in the number and ferocity of the hurricanes hitting the United States' coasts. Due to the "threat" of soybean rust, knowing whether to apply fungicides is a perplexing question. There are two different fungal species, *Phakopsora pachyrhizi* and *Phakopsora meibomiae*, that cause soybean rust. It is a serious foliage disease, which has the potential to decimate soybean crop, causing huge economic losses to U.S. agriculture estimated at US$640 million to US$1.3 billion. Therefore, timely detection of soybean rust spore is critical. Collaborative work is underway involving the Colleges of Engineering, Agriculture, and the United States Department of Agriculture in developing field-deployable biosensors for early detection of the spores (Figure 4).

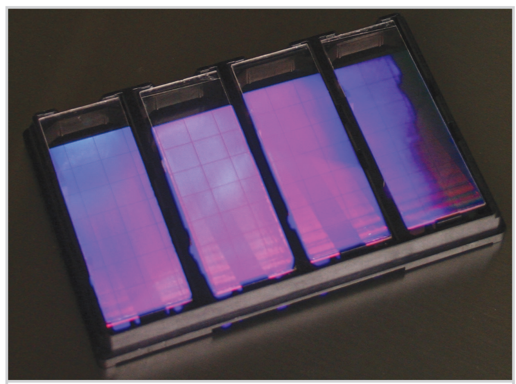

FIGURE 4 Photonic crystal optical biosensors fabricated from plastic sheets and attached to standard microscope slides for enhancement of fluorescent dye output and label-free detection of cancer cells, soybean rust spores, and virus particles. (Image courtesy of B. Cunningham, 2007.)

HARNESSING CORN WASTE

Zein is a waste product in the corn-to-ethanol process. This corn byproduct would not be such a waste anymore, as researchers in the Food Science Department, intrigued by the bricklike shape of the corn zein molecule, see its potential as a building block for tiny structures small enough to be measured in nanometers—cages, for example, that could carry biocompounds to targeted sites in the human body or scaffolds on which to grow neat sheets of skin cells instead of bulky clumps of tissue. A physician may want a specific drug to attach itself to a particular part of the body or affect only a certain kind of tissue, say for treating cancer. Potentially, corn zein also can function as a transport mechanism for growing single neurons for studying neurological disorders.

NANOMANUFACTURING

The National Science Foundation-funded Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems (Nano-CEMMS), a collaboratory of the University of Illinois CNST, addresses a pivotal problem in the development of nanotechnology: how to assemble structures at sizes smaller than can be seen (or transduced) and manipulated (or transcribed).

Making three-dimensional nanoscale devices and systems from millions to trillions of different types of molecules is extremely challenging. The Center is developing a reliable, robust, and cost-effective

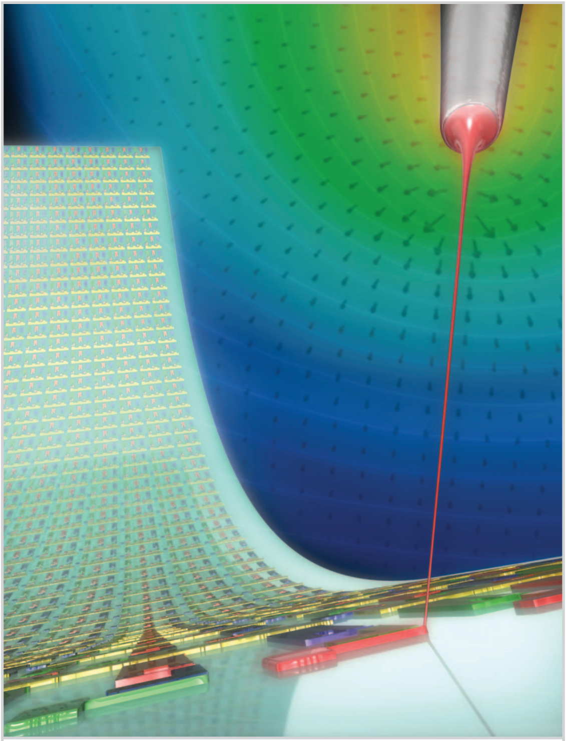

FIGURE 5 E-jet printing uses electric fields to pull the fluid out, and consists of a gold-coated microcapillary nozzle (300 nm diameter) mounted on a computer-controlled mechanical support. (Image courtesy of J. Rogers, et al., 2007.)

nanomanufacturing system to make nanostructures from multiple materials. This technology will allow advancements and discoveries in nanoscience to move from the laboratory to production. Manufacturing at the nanoscale is a challenge in itself; however, the other challenge is to develop a diverse U.S. workforce of educators, scientists, engineers, and practitioners to advance nanomanufacturing technology in the United States and beyond.

PATTERNING OF NANOSTRUCTURES

Creating high-resolution metallic interconnects is an essential part of the fabrication of microchips and other nanoscale devices. Researchers at the University of Illinois have developed a simple and robust electrochemical process for the direct patterning of metallic interconnects and other nanostructures. An electrohydrodynamic jet (e-jet) printing process has been invented by researchers at Nano-CEMMS that produces patterns and functional devices, thus establishing new resolution benchmarks for liquid printing, significantly exceeding those of established ink-jet technologies (Figure 5). This type of e-jet printing could be used for large-area circuits, displays, photovoltaic modules, and related devices, and has other wide-ranging application possibilities in security, biotechnology, and photonics.

SOCIETAL IMPLICATIONS

Nanotechnology, which transcends several scientific fields, provides tremendous opportunities. At the same time, it raises important issues for our environment—for health-care and for society at large. We have a unique opportunity to guide this nascent industry now, and nanotechnology's societal implications must be part of the discourse from the very conception of research and development activities. It is imperative, then, that individual researchers, academic institutions, funding agencies, and governments include the public in the discourse on nanotechnology advances.

CONCLUSIONS

The convergence of biotechnologies, infotechnologies, and nanotechnologies provides us with immense opportunities and pathways to address major issues confronting humankind. The basic research continues at the University of Illinois with recent focus on conducting translational research in order to make a tangible difference in how we live and interact with our environment. The ongoing efforts are harbinger to paradigm-shifting novel products; however, it will be at least a decade or more before any of these products hit the market. Yet we can confidently say that positive change is inevitable, and the University of Illinois is at the forefront in bringing that change.

READ MORE ABOUT IT

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