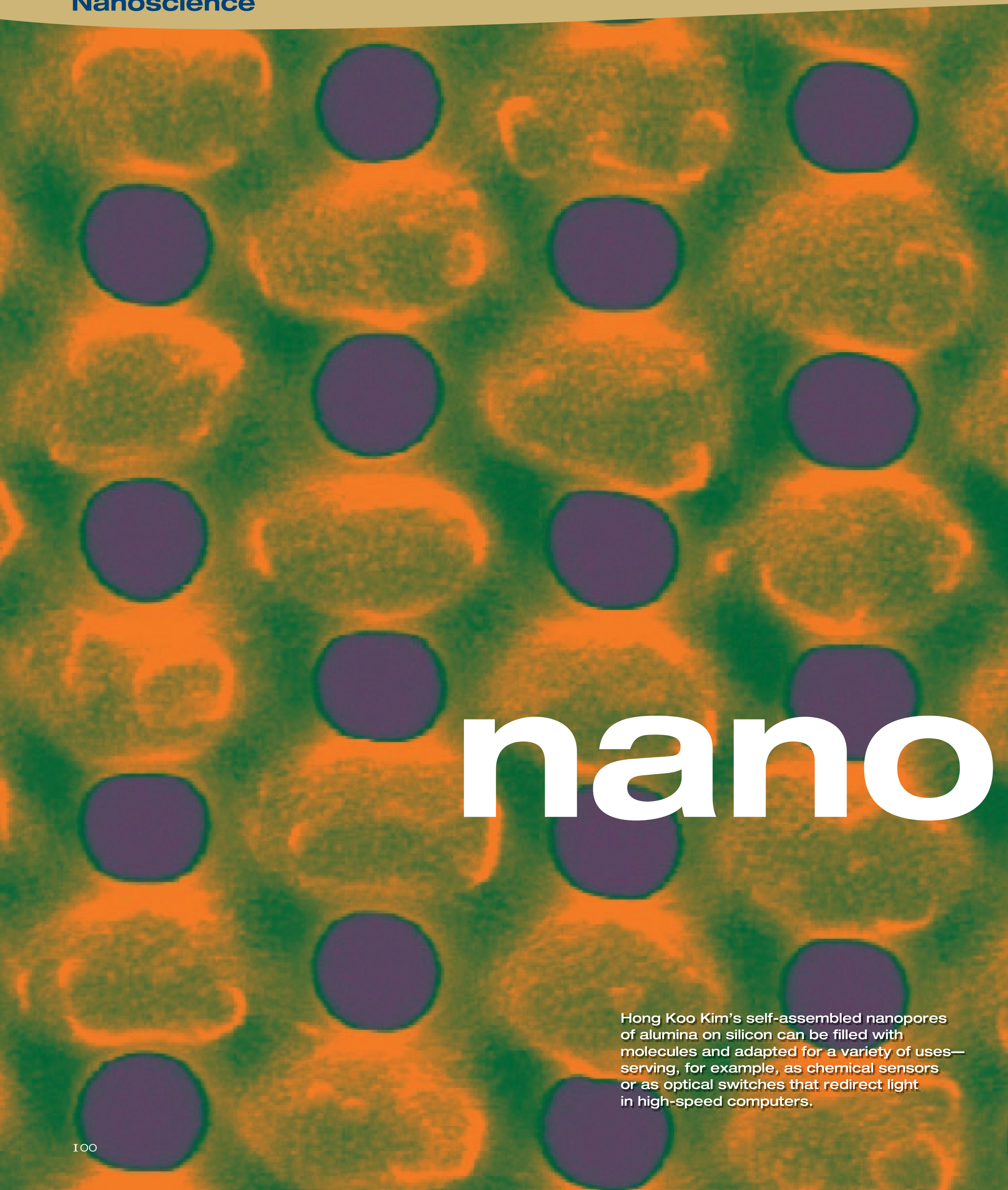
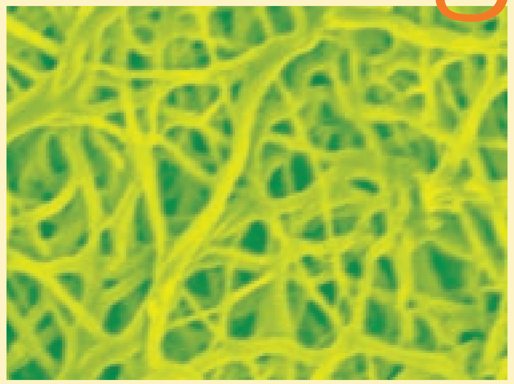


Hong Koo Kim's self-assembled nanopores of alumina on silicon can be filled with molecules and adapted for a variety of uses—serving, for example, as chemical sensors or as optical switches that redirect light in high-speed computers.

# thinking small



# nano science

It's been said that small opportunities are often the beginning of great enterprises. Perhaps nowhere are such possibilities more advantageous than at the University of Pittsburgh, where thinking small has led to big plans.

With potential creations ranging from scaffolding to help heal damaged hearts to sensors to detect glucose levels in the body to circuits to lead to smaller and faster computers, Pitt's new Institute of NanoScience and Engineering represents the University's commitment to dozens of projects within the emerging field of nanoscience. Hong Koo Kim, professor of electrical engineering and the Whiteford Faculty Fellow, and David Snoke, an associate professor of physics and astronomy, codirect the new institute, whose formation was announced during a conference in December 2002.

The prefix nano signifies a billionth: A billionth of a second is a nanosecond; a billionth of a meter is a nanometer. So, nanoscience is the study of the world around us at one of the smallest of levels. Similarly, nanoengineering and nanotechnology use atoms and molecules as basic blocks to build minute machines, create new materials, and perform molecular tasks.

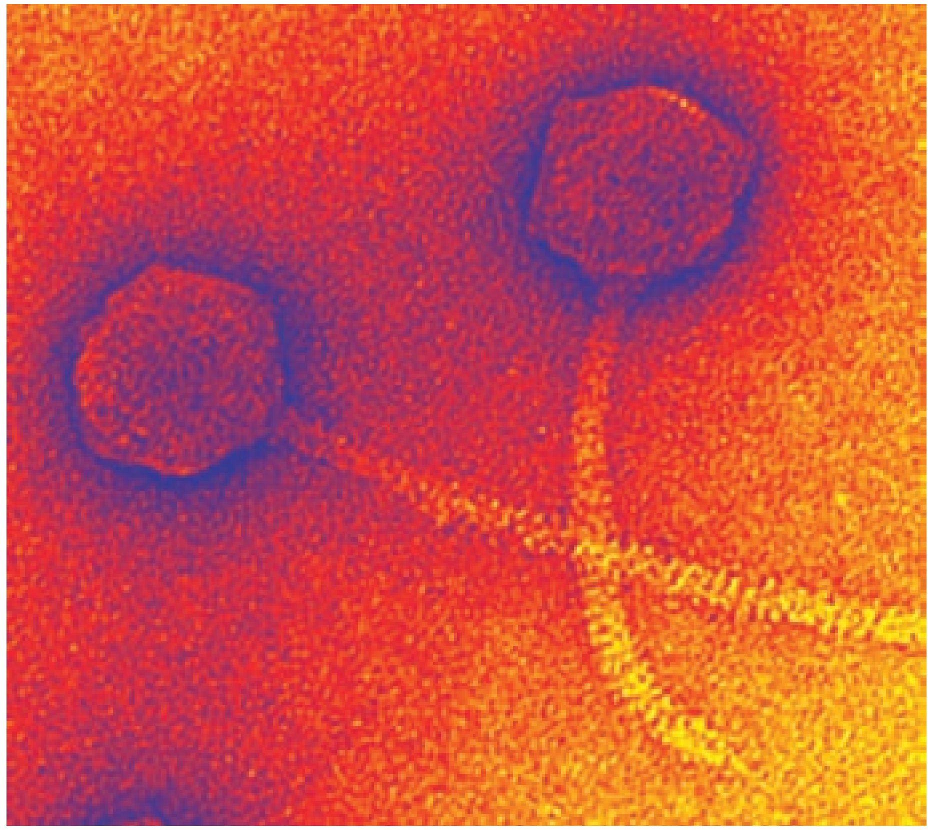
In 1999, the federal government's National Science and Technology Council (NTSC), in a report on nanoscience, engineering, and technology, offered the scientific world a challenge: "What if we could build things the way nature does—atom by atom and molecule by molecule? Scientists are already finding answers to these questions. The more they learn, the more they suspect nanoscience and nanoengineering will become as socially transforming as the development of running water, electricity, antibiotics, and microelectronics."

Then-President Bill Clinton, recognizing the growing importance of nanoscale science and technology, established the National Nanotechnology Initiative (NNI) in 2000. "Imagine the possibilities: materials with 10 times the strength of steel and only a fraction of the weight, shrinking all the information housed in the Library of Congress into a device the size of a sugar cube, detecting cancerous tumors when they are only a few cells in size," he said at the time.

Miniaturization has long captured the imagination of science fiction writers, who created tiny protagonists in literature and film to explore and battle in worlds invisible to the naked eye.

Throughout history, technology has followed a trend for making products smaller. In turn, miniaturization often has led to greater convenience and portability and reduced manufacturing costs. Moreover, miniaturization has been indispensable in creating storage and processing speed in computers: Computers that occupied entire building floors during the 1950s and 1960s are a child's toys compared with today's handheld PDAs.

But the reality is that nanotechnology is about far more than just miniaturization. Materials on the nanoscale can take on remarkably different properties than they do on the macroscale. As a 2000 NTSC report on nanoscience made clear: "Compared to the physical properties and behavior of isolated molecules or bulk materials, materials with structural features in the ranges of one to 100 nanometers—100 to 10,000 times smaller than the diameter of a human hair—exhibit important changes which traditional models and theories cannot explain."



*Roger Hendrix calls bacteriophages "the original nanoengineers." Researchers are studying the organisms' structure, locomotion, and reproduction methods for hints about nanoscale self-assembly and as a possible means of delivering drugs inside the body.*

Says Pitt's Kim: "On the nanoscale, the materials' properties are usually dominated by quantum and surface effects." While quantum theory is not new—its predictions for the behavior of individual atoms and for large crystals were verified prior to World War II—some of its predictions for small arrays of atoms, although strongly challenged by Albert Einstein, were verified only in the past 10 years, leading to exotic and as yet unexplored phenomena at the nanoscale for many materials.

In some of these phenomena, many events appear to happen by chance, with information seemingly moving faster than the speed of light (once thought impossible). If a researcher can see these events, his or her act of observation can change the outcome of an experiment. As such, nanoscience is turning much of classical science on its head.

## Timing Is Everything

The federal government's support for nanoscale science has climbed rapidly in the three years since Clinton's speech, reaching nearly $750 million to date.

The National Science Foundation, moreover, predicts that the market for nanotech products and services will reach $1 trillion by the year 2015.

Pitt, under the leadership of Provost James V. Maher, created the Institute of NanoScience and Engineering to take advantage of those factors. Its existence also helps Pitt researchers working in related fields have easy access to one another's work. Previously, researchers working in their respective areas might have been unaware of a colleague's related research.

"As a top-tier research university, we have outstanding strengths in many fields that are central to the study and application of nanoscience and nanotechnology," says Craig Wilcox, a professor of chemistry who was a pivotal figure in getting nanoscience recognized as a campus priority. "We have a responsibility to our students and to the broader community to continue that tradition of excellence and to use our resources to contribute to this national initiative."

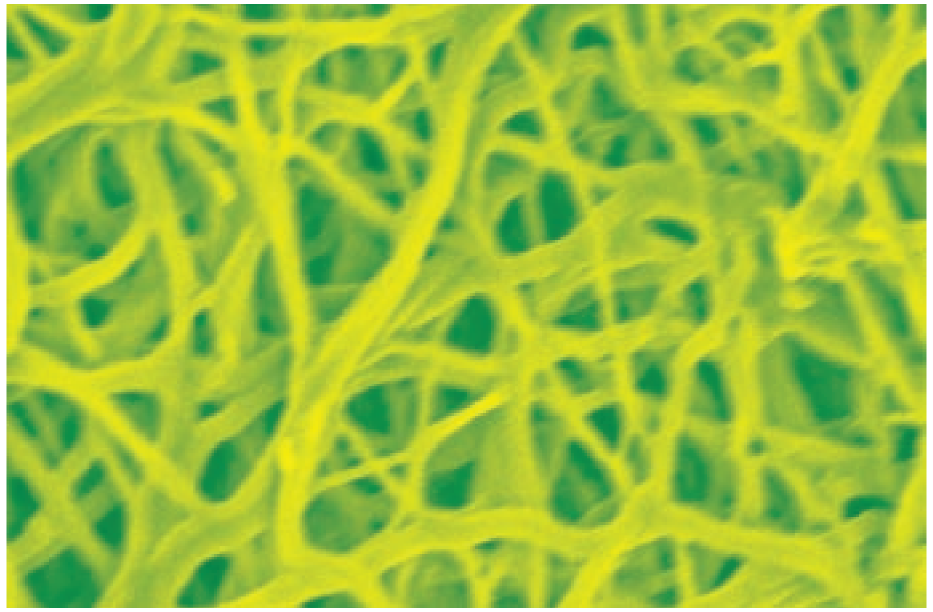
"I see the institute as making fundamental, rather than incremental, changes in nanotechnology," says Kim. "The institute combines all of the University's strengths in the basic sciences, in chemistry, physics, and biology; in the School of Engineering, which has quite a good track record in connecting research to application; and in the health sciences, where the applications are closest to completion."

With the institute's natural encouragement of interconnectivity among departments, Pitt should be poised to usher in rapid development in the nano fields, Kim says.

## Human Factor

Such revolutionary technology as a sensor that detects cancerous tumors when they are only a few cells in size may not be as far off as it would seem, particularly since work of this nature is ongoing at Pitt.

Sanford Asher, professor of chemistry in the School of Arts and Sciences, is creating sensors to detect chemicals inside and outside of the body. By suspending different particles in gels, he creates what are called colloidal arrays, which, depending on the particles, can react to the presence of, and therefore detect the presence of, other chemicals.



*William Wagner's research group is developing biodegradable flexible polymer scaffolds that have nanoscale features and that can be combined with cells to create soft tissue structures.*

One of the more promising applications of Asher's work involves chemical sensing in the body. He has developed a material that can be embedded into a contact lens to measure the glucose levels in the tear fluid of diabetics: If the patient's glucose level is too high or low, the lens changes color.

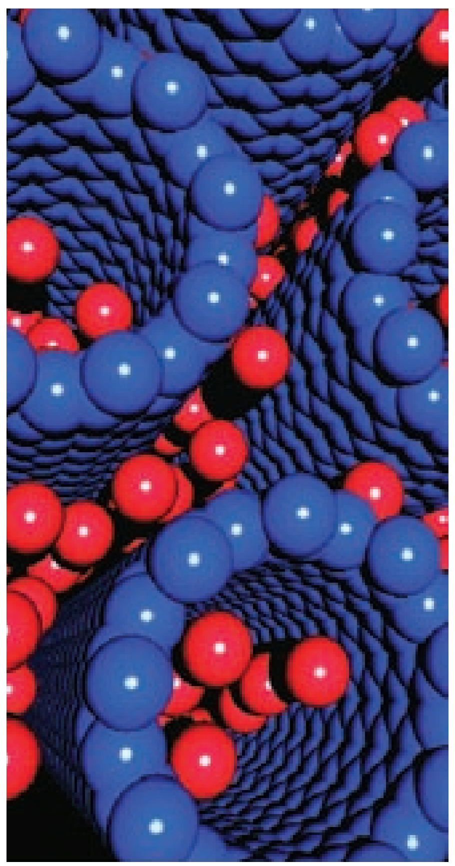
"A diabetic patient could carry around a color wheel, in a case similar to a compact makeup mirror, and compare the colors on the wheel to the color of the lens to determine his or her glucose level," says Asher.

For millions of diabetics, this noninvasive procedure could eliminate the need to prick their fingers to test their blood sugar several times a day.

Colloidal arrays could lead to the creation of sensors to detect the presence of a bladder cancer protein or a prostate-specific antigen. Among Asher's collaborators in the School of Medicine are Mohamed A. Virji, director of the Division of Clinical Pathology; David Finegold, a professor in the Department of Pediatrics; Robert Getzenberg, associate professor of urology; and Juan Puyana, associate professor of surgery and critical care medicine.

As Asher and colleagues create chemical sensors to detect the presence of physiological change or disease, William Wagner is taking advantage of the human body's ability to heal itself. Wagner, a professor of surgery and chemical and petroleum engineering and bioengineering, is developing biodegradable scaffolding for soft tissue engineering. His challenge is to create a substance that could be placed in a patient's body to support and enhance tissue growth in a diseased or injured body part, such as a myocardial patch to help heal the heart of a victim of cardiac arrest. Once the heart grows new tissue, the scaffolding on which the cells grow should dissolve with no adverse effects to the body.

By applying an electrical charge to nanosized polymer fibers, a process called electrospinning, Wagner has been able to create porous structures that promote tissue cells to grow around and inside pores. Wagner and Bruce Doll, chair of the Department of Periodontics in the School of Dental



*This snapshot from a molecular simulation shows hydrogen (red spheres) sticking to a bundle of carbon nanotubes (shown in blue). It was generated by J. Karl Johnson and was featured on the cover of the July 2004 report "Science for the 21st Century," published by the National Science and Technology Council.*

Medicine—who is working on ways to regenerate bone tissue—conduct much of their research through the McGowan Institute for Regenerative Medicine.

Nanoscience also can take advantage of the most abundant form of life on earth—bacteriophages, viruses that affect bacteria. To that end, Pitt's Graham Hatfull and Roger Hendrix, codirectors of the Pittsburgh Bacteriophage Institute, are studying the strength of the protein shell that protects the bacteriophages' DNA, how bacteriophages reproduce, and how the organisms move. The investigators aim to create applications that adapt the structure of a bacteriophage's protein shell to protect chemicals or drugs in the human body. They also hope to use the organisms as "molecular railroads," as Hatfull refers to them—or transport mechanisms for drug delivery. "Bacteriophages are the original nanoengineers, and the better we understand them, the more we'll be able to accomplish ourselves," says Hendrix.

## Creative Touch

Researchers have noticed that placing certain particles into organic and inorganic materials causes the particles to arrange themselves into patterns—a creative touch some Pitt researchers believe they can make use of in building blocks, superstrong coatings, and miniature circuits.

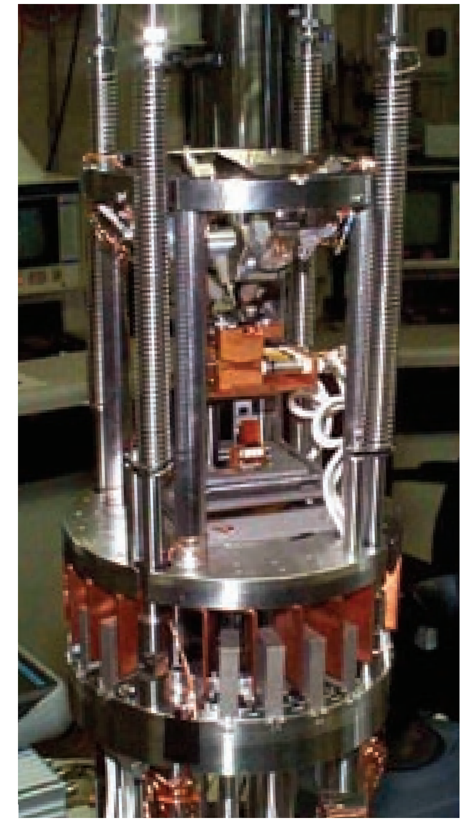
"The issue of how to assemble composites on a nanoscale is one of the biggest problems facing researchers in nanotechnology," says Anna Balazs, Robert Von der Luft Professor in the Department of Chemical and Petroleum Engineering, "and self-assembly is the most efficient means."

Balazs has developed a computer model that predicts the patterns into which nanoparticles and nanorods self-assemble in organic and inorganic composite materials. These models, then, can help Balazs and other researchers to develop new photonic and electronic materials, or even biomimetic matter—a substance that reacts as if it were part of a living organism. Her work could benefit such superstrong products as bulletproof vests. It also could be used in nanoelectronic circuits, to create faster computers, and in magnetic storage, to give computers greater storage capacity.

Kim sees the process of self-assembly on a nanoscale as a potential gold mine.

Using oxidized aluminum to create what amounts to a checkerboard array of "nanopores," Kim is developing self-organized nanostructures on such technologically important wafers as silicon or glass. His nanopores, arranged in a perfect crystalline order, can be filled with materials to create chemical or optical sensors that can detect the presence of pathogens in the blood or biochemical agents in the air. They also have the potential to be used in computing applications that could allow for a great deal of memory in a small space. The pores could even be used as nanomembranes to separate chemicals in drug development or to sequester such hazardous pollutants as nitric oxide from the air in an environmental cleanup.

Kim also is creating arrays that can be used in electronics and in optics, the science of the origin and propagation of light and vision. Optics, as a field, is faced with several problems tied uniquely to the ever-increasing need for miniaturized components. Among them, light cannot make a 90-degree turn, something it would be required to do many times in a photon circuit. Kim's material, however, can be used to solve this problem: He fills the pores in a selected area of his array with dielectric or metallic materials. These



*The nanoworkbench developed by John T. Yates, Jr., and coworkers is used by nanoscale investigators. Its four-probe scanning tunneling microscope (STM) moves a tiny metal probe across a specimen's surface.*

engineered, nanostructured materials—so-called photonic crystal waveguides—allow sharp bending of light within photon circuits. The process will shrink a photon circuit to 10,000 times smaller than what the current photonics technology offers, enabling the development of photonic chips about the same size as state-of-the-art electronic chips, with much faster speed and bandwidth at least 1,000 times greater. Kim's research is a step toward the creation of new chips for the fastest and most powerful computing and communication applications.

Anyone familiar with wood knows the secret behind the strength of plywood: Alternating layers of wood enhance the strength beyond the sturdiness of a single plank of similar thickness. Scott Xinjuan Mao, a professor in the Department of Mechanical Engineering, is using that same principle with nanolayered composites consisting of hundreds of alternating layers of different metals and ceramics. Unlike plywood, however, each layer of Mao's material is only a molecule thick.

"These composites hold promise as ultra-hard coatings because of their hardness and wear resistance," says Mao. The coatings could have commercial application in any setting that requires strength and endurance, such as the fender of an automobile.

Another promising area of materials being studied at Pitt in relation to nanoscience is carbon nanotubes. These hollow cylinders of carbon have a myriad of potential applications in producing nanometer-sized electronic devices of the future.

"One of the other things you can do with nanotubes that makes them interesting to chemists is to use them as test tubes and fill them with molecules," says John T. Yates Jr., the R.K. Mellon Professor of Chemistry and Physics and director of Pitt's Surface Science Center. That process lets nanoscientists perform experiments on a nanoscale, in order to discover whether or not a chemical has different properties on a molecular level as opposed to a macroscale level.

While Yates also explores the use of nanotubes as containers for toxic chemicals to aid in environmental cleanup, J. Karl Johnson has been investigating single-walled carbon nanotubes as nanosieves. Johnson, associate professor of chemical and petroleum engineering and codirector of the Center for Molecular and Materials Simulations, is taking advantage of the porous structure of carbon nanotubes to separate molecules. He and John T. Yates, Jr., and coworkers have discovered that heating nanotubes to 1,000 degrees Kelvin opens the ends and sides of the nanotube, allowing gases to enter. Their studies should be valuable in determining the usefulness of carbon nanotubes in membranes for gas separations (such as separating an active ingredient from a reagent in drug discovery), as well as in environmental cleanup to separate toxic gases from benign ones.

> "On the nanoscale, the materials' properties are usually dominated by quantum and surface effects. While the quantum theory is not new, some of its predictions are leading to exotic and as yet unexplored phenomena on the nanoscale for many materials."
>
> — Hong Koo Kim

Chemistry Professor Rob Coalson, meanwhile, is developing ways to use carbon nanotubes as molecular wires to transport electrons in such devices as quantum computers. Even the thinnest conventional wires are thousands of times too thick to use in quantum computing circuitry, so Coalson developed a way to substitute nanotubes, using a laser to successfully "prod" electrons through the nanotubes from one point in the circuit to another.

## The Nanotech Toolbox

Centuries ago, artisans marveled at the ability of Swiss watchmakers to craft, assemble, and repair the delicate workings of their watches. The cogs and wheels in those watches might as well be blocks in the Great Pyramid of Cheops, in comparison to the atoms and molecules in nanotechnology.

It's important for scientists and engineers to be able to see what they are doing on the macroscale, and it is no different on the nanoscale. But "seeing" nanoscale materials and devices presents a particular set of problems, since nanoparticles are too small for conventional microscopes to magnify. Gilbert Walker, associate professor of chemistry, and his team of researchers are developing a new, high-resolution imaging method, called apertureless nearfield scanning infrared microscopy (ANSIM), to determine the chemical characteristics of nanoscale materials under ambient, or natural, conditions. ANSIM can identify chemical components at a resolution of less than 100 nanometers under ambient conditions. Other current ways of imaging molecules are not as precise.

"Right now, there is no powerful technique for chemical imaging under ambient conditions," says Walker. "With far-range spectroscopy, you can't image anything smaller than about half the wavelength of the light you use. One of the solutions has been to use shortwave radiation, but that works best under vacuum conditions. And there are very often limits to using light in the invisible and infrared ranges.

"If you shine a light at a particle, you'll see a scattering of light, with a very intense distribution of light, called the near-field, nearest to the particle. We use the scattering of the light in this area for imaging purposes."

While Walker scatters light, Hrvoje Petek, professor of physics and astronomy, manipulates lasers in his important breakthrough in imaging nanotechnology. Petek and his colleagues were the first researchers ever to observe photo-energized reactions on metal surfaces in real time, using time-resolved photoemission spectroscopy. "This is the first step in using lasers to observe and control the dynamics of atoms and molecules at the solid vacuum interface," Petek says. "This could be the seed for technology where single atoms are used as electronic switches or for

*The optical nanoscope is used by researchers to see nanomaterials.*

processes where lasers are used in the synthesis and actuation of nanoelectronic devices."

While Balazs and Kim tout the benefits of using nanomaterials that build themselves, nanoscientists and nanoengineers in many cases still need—and will continue to need—to manipulate their raw, unseen materials. For this basic necessity, Yates, director of Pitt's Surface Science Center, offers nanoresearchers a new tool.

Yates is in the final stages of developing a device called the nanoworkbench, which will be among the world's most powerful instruments for nanoscale investigations. The nanoworkbench consists of a four-probe scanning tunneling microscope (STM), which moves a tiny pointed metal probe across the surface of a specimen. This causes electrons in the specimen to "jump," or tunnel, across the gap between the probe and the specimen. By measuring the jump, researchers can detect the surface of the specimen, allowing them to "see" what they're working on.

## Quantum Leaps

The promise of quantum computing—which could increase the speed and power of computers to levels that will make today's fastest units appear to be as slow and cramped as the 1950s ENIAC seems today—depends on breakthroughs made in the nanoscale.

At the Center for Oxide Semiconductor Quantum Computing, Jeremy Levy, center director, and his team are developing the materials and the processes needed to make quantum computers a reality.

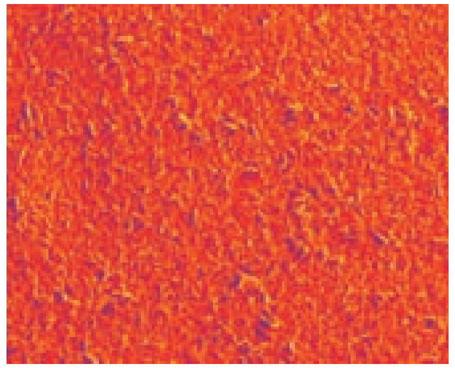
In 2003, Levy, an associate professor of physics and astronomy, and his colleagues made a major breakthrough when they were able to control the spin of an electron using electrical, rather than magnetic, force. The breakthrough is important in that it demonstrates that spin-based technologies, or spintronics, are compatible with technologies used in today's electronics.

Electrons, the basic elements of electricity, are negatively charged particles that encircle the nuclei of all atoms. Electrons can move to produce electrical currents, but they also spin about their own axes, which can point either up or down. This spin creates a small magnetic field that other magnetic fields can affect.

Levy's advance demonstrates the possibility of using the spin orientation of electrons to store information, much in the same way that the open and closed states of electrical switches store information in computers.

> "We have some tremendous challenges to meet. We need new antibiotics and other therapeutic agents. We need lighter materials, reduced energy consumption, cleaner manufacturing methods, faster diagnostic tools, and more. Of course we want all of this at a lower cost, too."
>
> — Craig Wilcox





*Dental medicine research includes studying the use of nanoscale polymer scaffolds for bone tissue engineering.*

Scientists have been able to manipulate electron and nuclear spin with magnetic fields, but magnetic fields are more difficult to generate and control on a smaller scale.

"Most researchers using the spin-based model for spintronics and quantum computing have assumed that the behavior of spins must be controlled by magnetic fields," says Levy. "The prospect of controlling 100 million magnets, each independently on the equivalent of [the size of] a chip, has boggled the imagination of researchers. However, with electrical gates, we already control 100 million devices in modern computers."

Another potential breakthrough in quantum computing involves small bits of optical energy called "excitons." Snoke, Kim's partner in directing the institute, discovered a way to create and move excitons over relatively long distances, a development that could lead to the creation of semiconductors in which excitons are shuttled and controlled to form "excitonic circuits."

In conventional semiconductors, electrons or their absence (so-called holes) move in circuits to perform functions such as computation and storage of information. In his research, Snoke used laser light to separate an electron from an atom. The "excited" electron plus the hole remaining on the atom compose an exciton, which moves like an energy particle, a particle that could potentially carry information.

In most cases, excitons exist for only a few nanoseconds (billionths of a second) and travel only a few microns (millionths of a meter) before the electron and hole reunite and re-emit the light.

Using quantum "wells"—nanoholes, essentially, in the compound gallium arsenide—Snoke and his team were able to extend the amount of time the electron and hole were apart and, consequently, the distance the exciton traveled.

"A millimeter may not seem like a long distance, but with circuits now being designed on micron scales—that is, thousandths of a millimeter—a distance of a millimeter is tremendously long compared to typical circuit dimensions," says Snoke. "Therefore, the exciton particles can easily travel over the distances needed for computer circuits."

In turn, the computational power of quantum computing, once realized, could open up opportunities not yet imaginable, across countless fields of science.

## The Road Ahead

The NNI, the federal government's National Nanotechnology Initiative, has instituted a series of challenges to researchers to develop potential breakthroughs that, if one day realized, could provide major, broad-based economic benefits to the United States, as well as dramatically improve the quality of life for its citizens.

Pitt investigators, accepting those challenges, already are hard at work solving them through a variety of research projects, only a sampling of them described here.

"Good research has specific goals," says Wilcox, one of nanoscience's greatest advocates at Pitt. "Often the goal is to answer an important question, improve an existing technology, or create transforming technologies to replace existing technologies. The importance of these goals is in proportion to their capacity to help improve the quality of our lives, reduce suffering, and raise the human spirit.

"We have some tremendous challenges to meet. We need new antibiotics and other therapeutic agents. We need lighter materials, reduced energy consumption, cleaner manufacturing methods, faster diagnostic tools, and more. Of course we want all of this at a lower cost, too. The needs are complex, and by bringing together teams of experts, we can make faster progress." ■

*Sanford Asher's group develops new photonic crystal materials for optical switching, optical memories, and chemical detection devices.*