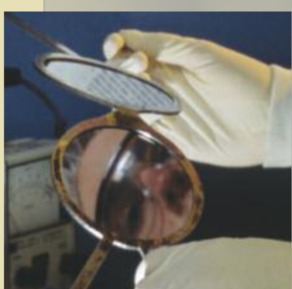
amplitude

Engineering Advances at the University of Notre Dame
Spring 2009 • Volume 1, Number 1

FOCUS ON NANOTECHNOLOGY

- Next-generation Transistors
- Rainbow Solar Cells
- Nano-sized Labs-on-a-Chip
- Beyond Conventional Electronic Technology



Contents

Scheduled to be completed in January 2010, the Stinson-Remick Hall of Engineering will house the McCourtney Engineering Learning Center, a unique undergraduate facility; the Notre Dame Nanofabrication Facility; the Notre Dame Energy Center; and several labs of the Midwest Institute for Nanoelectronics Discovery. Watch the building's progress at *http://www.nd.edu/campus-and-community/sights-sounds/webcams/met.*

A LETTER FROM THE DEAN

Dear Friends and Colleagues,

I am very pleased to share with you the inaugural issue of *Amplitude,* a new research publication of the College of Engineering here at the University of Notre Dame. Founded in 1842, the University is committed to the three goals of research preeminence, a distinctive Catholic character, and an unsurpassed commitment to graduate and undergraduate education. In this publication, we are pleased to apprise you of some of our most significant recent accomplishments in research.

Our focus in this initial issue is nanotechnology, and one of our lead stories focuses on our college's pursuit of the next generation of logic devices for integrated circuits and computers in the 21st century. Some of the contenders in this pursuit were invented here at Notre Dame: magnetic cellular automata and graphene nanoribbon tunnel transistors. Our research teams, headed by Alan Seabaugh, Debdeep Jena, Patrick Fay, Michael Niemier, and Wolfgang Porod, are pursuing device demonstrations of these materials by mid-summer 2009. These projects are all part of the Midwest Institute for Nanoelectronics Discovery (MIND), a new Semiconductor Research Corporation-Nanoelectronics Research Initiative (SRC-NRI) national center awarded in March 2008. Led by Seabaugh, this center involves a number of universities and national laboratories, including Purdue University, the University of Michigan, the University of Illinois, Pennsylvania State University, and the National Institute of Standards and Technology, with the University of Notre Dame serving as the lead institution. MIND's funding for its first three years is approximately $20 million, with funds coming from the SRC-NRI, the City of South Bend, the State of Indiana, and internal University funds.

I am also pleased to announce the awarding of a new Energy Frontier Research Center (EFRC) on Actinide Materials to a group headed by Peter Burns, the Henry J. Massman Professor of Civil Engineering and Geological Sciences. The group — which includes researchers from the University of California at Davis, the University of Michigan, George Washington University, and Rensselaer Polytechnic Institute, as well as from Sandia, Savannah River, and Pacific Northwest national laboratories — will develop new states of matter based on nanostructured forms of actinides and actinide complexes as potential fuel and waste forms for next-generation nuclear energy generation. The EFRCs are the signature basic research programs recently announced by the Department of Energy.

We describe in *Amplitude* a variety of other significant recent accomplishments and recognitions, including the election of Ahsan Kareem, the Robert M. Moran Professor of Civil Engineering and Geological Sciences, to the National Academy of Engineering. I hope you will enjoy learning about our research programs, and we look forward to interacting fruitfully with your faculty and colleagues.

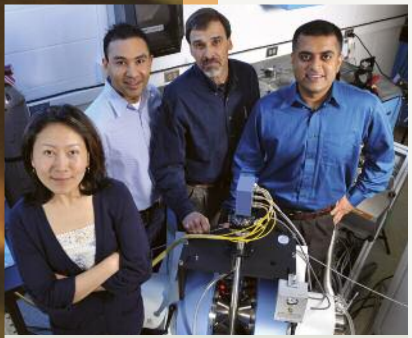
Sincerely,

Peter Kilpatrick

Peter Kilpatrick
Matthew H. McCloskey Dean of Engineering

Tunnel Vision: The Path to a New Kind of Transistor

The metal-oxide-semiconductor field-effect transistor (MOSFET) is the most common device used today in digital and analog applications, such as watches, cell phones, computers, automobiles, and satellites. A MOSFET amplifies or switches electronic signals. The smaller it becomes, as has been the norm for the last 40 years, the more challenges arise. Notre Dame researchers have taken a fundamental physical limit in the conventional transistor and turned it into the primary control mechanism for a new switch. Since a College of Engineering study discussing this process, "Graphene Nanoribbon Tunnel Transistors," was published in IEEE Electron Device Letters *in late 2008, it has been one of the top ten most highly accessed papers. By embracing the phenomenon of quantum mechanical tunneling instead of trying to avoid it, a new transistor has been born.*



Huili Xing
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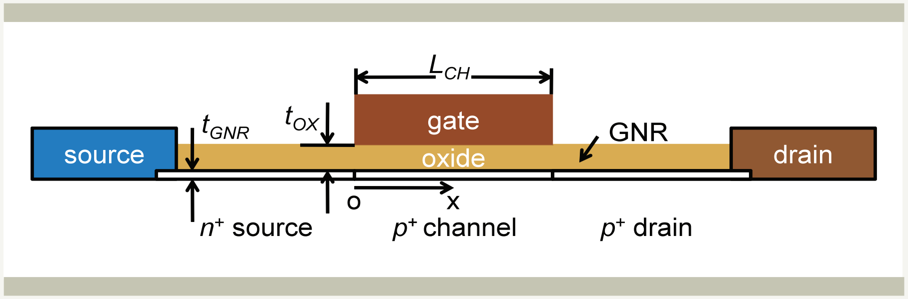
In today's transistors, electrons move from place to place by raising and lowering energy barriers ... much like barriers are raised and lowered to control water flow over a dam. Quantum tunneling comes into play when the thickness of these barriers becomes comparable to the wavelength of the electron (an electron has both wave and particle properties). Traditionally, tunneling has been an unwanted effect in transistor switching research. "We turned the problem on its head," said Associate Professor **Debdeep Jena**. "If the thing you are fighting dominates all the desirable effects, perhaps it's time to befriend it and see how you can use it."



In 2008, Jena, **Alan C. Seabaugh**, and then graduate student **Qin Zhang** began to explore the idea that electrons could be electronically induced to tunnel or not to tunnel in graphene nanoribbons (GNRs) in order to form tunneling field-effect transistors (TFETs). Graphene, a single plane of hexagonally-bonded carbon atoms that is one atom thick, is currently a hot topic in

	Current MOSFET	GNR TFET	unit
Equivalent oxide thickness *EOT*	0.75	1	nm
Supply voltage V_{DD}	1	0.1	V
Drive current I_D	1639	800	µA/µm
Off-state leakage current I_{OFF}	0.70	0.000025	µA/µm
Intrinsic speed ~ $I_D / C_{ox} V_{DD}$	1961	11000	GHz
Off-leakage power ~ $I_{OFF} V_{DD}$	0.70	0.0000025	µW/µm
Dynamic power ~ 1/2 $I_D V_{DD}$	820	40	µW/µm
	ITRS 2007 Edition		

nanoelectronics research. It is strong (200 times stronger than steel), but its primary attraction for electronics applications comes from its excellent transport properties — very high electron and hole mobilities and near ideal electrostatics.

In the recent paper, the Notre Dame team computed the electrical properties that could be expected in these transistors with ribbon widths between 3 and 10 nanometers, corresponding to energy bandgaps in the range of 0.46 to 0.14eV. The study proved that the widths of the graphene nanoribbons controlled the heights of the energy barriers presented to the electrons. It also identified an optimum nanoribbon width that would maximize the tunneling when the switch was on and the blocking ability of the energy barrier when the switch was off. In fact, the graphene based TFET switches worked five times faster and used 20 times less power than transistors on the market today.

With those results the Notre Dame nanoelectronics researchers are justifiably enthusiastic about a graphene nanoribbon tunnel transistor and the potential for faster and more energy-efficient electronics.

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Prashant V. Kamat
Professor
Chemistry and Biochemistry

Concurrent Professor
Chemical and Biomolecular Engineering

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Laying the Foundation for an Efficient Solar Cell

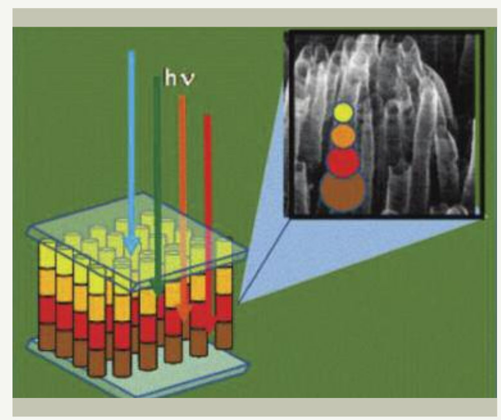
By varying the size of quantum dots in a solar cell array, researchers at the University of Notre Dame may have found the key to the next generation of solar cells. They have already shown that these nanoparticles can more efficiently harvest the full spectrum of solar energy. To get a sense of scale, a nanometer can be defined as the length a beard grows in the amount of time it takes to raise a razor to the face.[1] *And the magnitude of the sun's power? A recent global climate and energy report estimates that in one year the sun delivers almost twice as much energy to the Earth as will ever be gathered from all of the non-renewable energy resources — oil, coal, natural gas, and uranium — combined.*[2]

Quantum dots are semiconductor nanostructures recognized for their ability to generate free electrons and create an electrical current when exposed to light, and they have been getting a lot of attention as light-harvesting materials. The size-dependent optical and electrical properties of quantum dots are known in the research community. The potential usefulness of the size effects for applications in solar cells, however, is what Professor **Prashant V. Kamat** wanted to explore.

He knew that to be efficient in a solar cell array, quantum dots must collect light from many wavelengths. "Our approach was to demonstrate the size effect in solar cells and then maximize the photoresponse of the quantum dot cells," said Kamat. In fact, his was the first study to directly compare how different-sized quantum dots, capable of absorbing different wavelengths of light, would perform when incorporated into solar cells.

Kamat and his team combined spectroscopic and photoelectrochemical techniques as they assembled cadmium selenide (CdSe) quantum dots of four sizes between 2.3 and 3.7 nanometers in a single layer on the surface of titanium dioxide (TiO_2) nano films and nanotubes. After exposure to light, the quantum dots injected electrons into the TiO_2 structures, which were then collected on a conducting electrode that generated an electric current.

The researchers observed a trade-off in performance corresponding with quantum dot size. The smaller quantum dots (absorbing the shortest wavelengths of the spectrum) injected electrons into TiO_2 at a faster rate than larger dots, but the larger dots (absorbing the longest wavelengths) gathered a greater percentage of incoming photons.



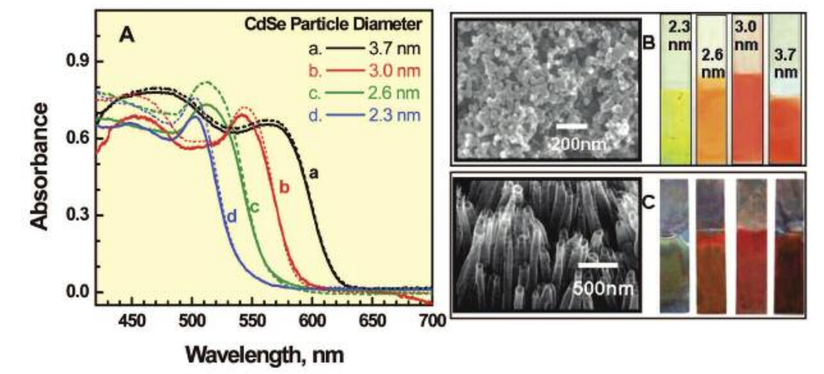
While these findings followed Kamat's basic expectations, the degree of the increased efficiency with decreasing particle size demonstrated that the importance of size effect was even more significant than he had thought. The Notre Dame group proved that by using the size-dependent property of quantum dots, researchers can tune a solar cell's ability to more efficiently use the sun's wavelengths.

The study is the groundwork for a solar cell that consists of different-sized quantum dots arranged in an orderly fashion. Such a cell would combine the faster electron injection rate of the small quantum dots with the greater absorption range of larger ones for a highly efficient solar cell.

Named the "rainbow solar cell," this next-generation solar cell is the focus of continuing research at the University. To construct the most efficient solar cell possible, Kamat says that a solar cell must accomplish three things:

- It must collect as much of the solar spectrum as possible.
- Once absorbed, light must be converted into moving electrons.
- After the electrons are created, they need the ability to freely move throughout the cell, creating electrical current.

He and his team have accomplished all three: They have proven that different-sized quantum dots can be tuned to take advantage of more of the solar spectrum. As important, they have achieved a photon-to-electron conversion efficiency at a specific wavelength of up to 70 percent.



However, the total power conversion efficiency of these cells is in the range of 1-2 percent. Thus, the team is working to further optimize the cell design and will reach a value of 4-5 percent efficiency. The ultimate goal is a next-generation solar cell that can convert 30-40 percent of the sun's incident light into electricity. (Commercially available solar technology only converts 15-20 percent into usable electricity.) Lastly, his choice of a TiO_2 nanotube structure provided a direct pathway to help the electrons travel faster and more freely.

Working with structures so small could make one lose sight of a bigger picture. The Notre Dame team appreciates the scientific and social promise offered by quantum dots and are proud to be working toward a safe, affordable renewable energy solution.

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[1]Kahn, J., "Welcome to the World of Nanotechnology," *National Geographic Magazine*, June 2008.

[2]Global Climate and Energy Project at Stanford University.

Paul W. Bohn
Arthur J. Schmitt Professor
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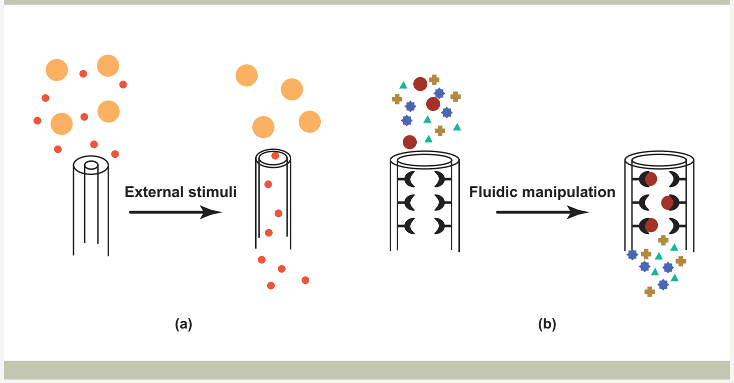
Nanofluidic Networks Expand Diagnostic Technology

Imagine a handheld device that could identify a bacterial contaminant in a food source while it was still in a processing plant, detect a pollutant in water at the source in real-time, or isolate a virus or infectious disease in a country with limited medical and diagnostic resources. These are actual scenarios where current lab-on-a-chip technology provides fast and accurate diagnostics when time and information are critical. But even these micro labs cannot process exceedingly small (mass limited) samples effectively. The incorporation of nanofluidic elements into lab-on-a-chip technology as demonstrated by Notre Dame researchers expands this technology and its functionality.

Small fluid samples need careful handling to preserve sample integrity. Some samples, like pheromones or neurotransmitters, are available only in limited quantities, and they can be destroyed during multi-step procedures. Others are small due to an aspect of the substance itself. For example, toxins must be handled in minute quantities to minimize potential harm to the diagnostician.

A team of University of Notre Dame researchers, led by **Paul W. Bohn**, the Arthur J. Schmitt Professor of Chemical and Biomolecular Engineering and concurrent professor of chemistry and biochemistry, has successfully addressed this challenge. They have developed platforms to capture individual molecules of interest in mass-limited quantities and created intelligent chemical reaction chambers in the space of a nanopore. Information can now be extracted from samples consisting of a few hundred-thousand molecules and manipulated as needed.

The team accomplished this by designing hybrid microfluidic/nanofluidic networks with nanoporous membranes in layered (3D) architectures. In previous studies at other research universities, devices had been limited to two microfluidic layers using a single layer of nanofluidic interconnects. Bohn's hybrid networks with 3D architecture combine the advantages of traditional microfluidic devices with integrated-circuit-like capabilities, such as the ability to maintain separate, chemically unique environments within a single



interconnected device, as well as the ability to transfer fluid between these two environments at will.

Each nanopore of a nanocapillary array membrane (NCAM) in the 3D hybrid microfluidic/nanofluidic system works as an intelligent chemical reaction chamber where substances can be loaded or unloaded externally via fluidic manipulation. The ability to confine mass-limited reactants within a nanopore also significantly increases the probability of a desired reaction. The use of chemical reaction chambers speeds up the reaction rate in cases where the kinetics is transport limited.

Notre Dame researchers' success offers several possibilities for future lab-on-a-chip devices. For instance, a gated injection could be performed from a microchannel filled with a complex sample mixture into another channel where a preparative electrophoretic separation would be carried out. A specific component band could then be collected from this separation, transferred to yet another spatial plane and into a channel filled with a chiral separator where, after an additional separation, a specific enantiomer could be transferred to a final microchannel interface and a mass spectrometer for detection. Another possibility is an antibody-modified NCAM capturing a specific property from a complex sample mixture, thus performing a combined preparatory separation and *de facto* preconcentration, prior to an on-demand release by fluidic manipulation for further analytic steps.

Molar Concentration of a Single Molecule in a Single Nanopore

Pore Diameter (nm)	Single Pore Volume[a] (L)	Single Molecule Concentration (M)
200	3.14×10^{-17}	5.29×10^{-9}
100	7.85×10^{-18}	2.11×10^{-8}
30	7.07×10^{-19}	2.35×10^{-7}
10	7.85×10^{-20}	2.11×10^{-6}

[a] *Thickness of the NCAM is generally 6-10 µm depending on the pore size; 10 µm thickness was used to calculate the volume of a single pore.*

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Michael Niemier
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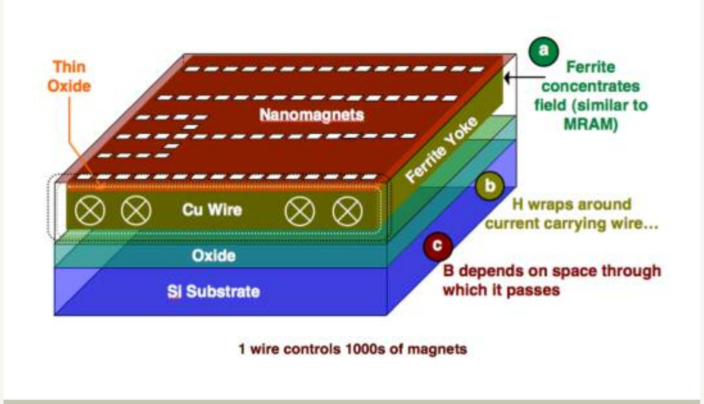
Nanomagnetic Devices Present an Attractive Solution

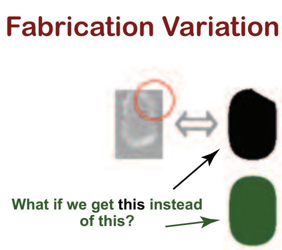
For the last 40 years conventional electronic technology (CMOS) has relied on shrinking transistors to produce smaller, faster, and cheaper devices (cell phones, laptop computers, iPods, and more). The laws of physics prevent these devices from working below a certain size. Because of this, researchers across the country have been searching for a new logic device to either replace or augment CMOS technology. University of Notre Dame researchers have achieved a series of firsts, including their most recent accomplishment, that may well prove to be a giant leap toward achieving a new type of processing system, one driven by nanomagnets and their interactions rather than electric current flow.

In 1997, Notre Dame researchers were the first to physically demonstrate Quantum-dot Cellular Automata (QCA), a transistorless approach to computing that moves and processes information via nearest-neighbor interactions rather than electric current. Less than ten years later, researchers at Notre Dame were the first to demonstrate logic gates with a magnetic implementation of this device architecture. This was an important first step toward showing that nanoscale magnets could ultimately perform more complex computations, computations that would require much less energy than equivalent CMOS circuits.

Assistant Professor **Michael Niemier** and a team from the departments of computer science and engineering and electrical engineering have been pursuing the design of circuit elements constructed with nanoscale magnets and using the QCA device architecture. In magnetic QCA (MQCA), logical operations and data flow are accomplished by manipulating the polarizations of nanoscale magnets. Niemier and his team are moving toward another "first"; they have designed MQCA structures that should facilitate more complex, circuit-level tasks. They have also demonstrated how these structures interact with the on-chip drive circuitry currently envisioned for MQCA-based systems through simulations and are proceeding to prototype testing.

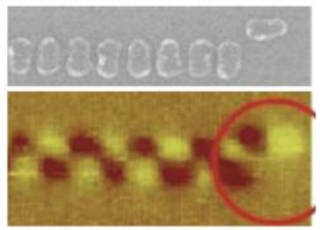


Previous efforts of this nature had suggested the components required for a functionally complete logic set, but there was still a large gap between basic MQCA devices and computationally interesting MQCA systems. The Notre Dame team narrowed this gap by designing unique circuit structures essential for building MQCA systems. They used physical level simulation to demonstrate how external stimuli affect the logic state of individual magnets of various sizes and shapes. Within this study, they (a) ensured that all of the structures required to build a circuit could be controlled with implementable, on-chip drive circuitry, (b) designed structures that allowed data to flow orthogonally in the direction of the external stimuli, and (c) have proposed designs for crossing two logical signals with nanomagnets.



Niemier, DFTS, 2008

These studies revealed a number of physical and external design parameters, such as nanomagnetic shapes and sizes and clocking field (the external stimuli) strengths and shapes, which are key to circuit-level behavior. Careful selection of these parameters helps not only to facilitate computationally interesting circuits but can also improve circuit performance.


A. Imre, et. al., "Majority Logic Gate for Magnetic Quantum-dot Cellular Automata," *Science*, 2006, 311, 5758, 205-208.

According to Niemier, the next step is fabricating MQCA-based systems, which should be fairly straightforward. "Nanomagnets can be made using conventional lithography or by leveraging electron beam lithography and liftoff to form specific patterns of magnetic material." Researchers could also employ imprint lithography where the imprint is used to make molds, and then the molds can be used to make the nanomagnet shapes. Niemier and his team believe that these methods should be compatible with, and can take advantage of, advances in current CMOS fabrication techniques.

Another advantage to nanomagnetic technology is that the magnets are inherently resistant to radiation. Thus, any type of MQCA system placed in space would be immune to the effects of radiation, which eventually destroy traditional CMOS chips.

Still in the fundamental stages of research, Notre Dame is on the road to another first: developing an all-magnetic system that offers more complex computations and uses less energy.

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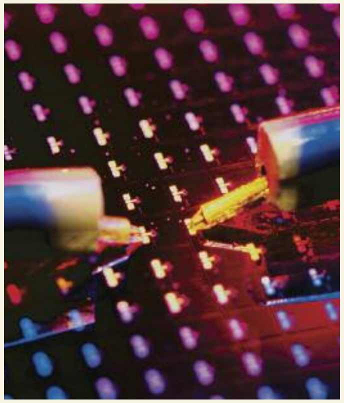
The University of Notre Dame is home to the Midwest Institute for Nanoelectronics Discovery (MIND), one of only four nanoelectronics research centers funded by the Semiconductor Research Corporation's Nanoelectronics Research Initiative (SRC-NRI). Each of the others is also located on a university campus. And, each is pursuing the same goal: to enable future breakthroughs in semiconductor technology via nanoelectronics by developing advanced devices, circuits, and nanosystems with performance capabilities beyond conventional devices.



Notre Dame Lands Key Nanoelectronics Research Center

According to **Jeff Welser**, the director of the NRI, "The challenge for nanoelectronics is to ensure that society's expectations for electronic applications can continue to be met. ... Semiconductor technology is the underpinning to everything from the cell phones in our pockets to the supercomputers in our research labs, so nanoelectronics progress is crucial to innovation not only in all areas of science and technology but also to our nation's continued economic growth."

The three other centers — at the University of Texas, the University of California at Los Angeles, and the State University of New York at Albany — have already led to economic growth in their communities, particularly in expanded technology investment and job creation. For example, the development of the center in Albany, N.Y., brought more than 2,000 new jobs and new business development to the area. According to Indiana Governor Mitch Daniels, "For Indiana, this means national leadership in a central technology of the future, and we'd be excited to welcome it anywhere in our state. But it's a special thrill to see it come to Notre Dame, which now enters new dimensions of research prominence and contributions to its home state through the partnership with Purdue."

MIND, while led by Notre Dame researchers, is a consortium that includes Cornell University, the Georgia Institute of Technology, Purdue University, the University of Illinois, Pennsylvania State University, the University of Michigan, the University of Texas at Dallas, Argonne National Laboratory, the National Institute of Standards and Technology, and the National High Magnetic Field Laboratory.

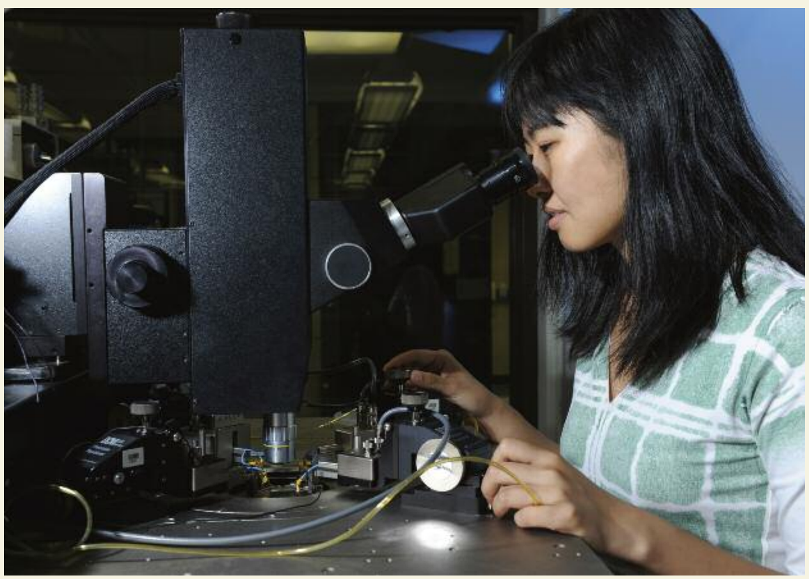
Over the next three years MIND will spend approximately $20 million on consortium projects. The state of Indiana has promised $12 million, the SRC-NRI $3 million, and the city of South Bend $1 million. In addition, IBM is providing $2 million in equipment, and the five universities in the consortium are contributing matching funds totalling close to $3 million. MIND organizers anticipate supplemental funding via federal grant applications through the National Nanotechnology Initiative.

Because central themes of the consortium encompass energy-efficient devices and systems, all MIND researchers will focus on topics not covered by the other SRC-NRI centers. Specific projects include lateral field-effect tunnel transistors, extremely scaled gated tunnel transistors, energy dissipation in nonequilibrium systems, nanomagnet logic devices, and circuit design and architectures for emerging devices.

With its history in nanotechnology, particularly in nanoelectronics, Notre Dame is confident in its pursuit of these directions. "Five years ago, some of the ideas we had for switching electrons with quantum mechanical tunneling effects were considered too novel," says **Alan C. Seabaugh**, MIND director and professor of electrical engineering. "Today, we know it's possible. We know how to deal with electronics and move charge. And, we're looking forward to exploring the possibilities and shaping the development of nanoelectronics right here in the Midwest."

MIND also closely ties Notre Dame to the economic development initiatives of Indiana and South Bend. It is anticipated that related commercialization activities will occur in the new Innovation Park at Notre Dame and that nanoelectronics commercialization and manufacturing facilities will spring up in the research facility the city is developing to support new jobs and investment associated with MIND and other advances made at the University.

For more information about MIND, visit http://mind.nd.edu.

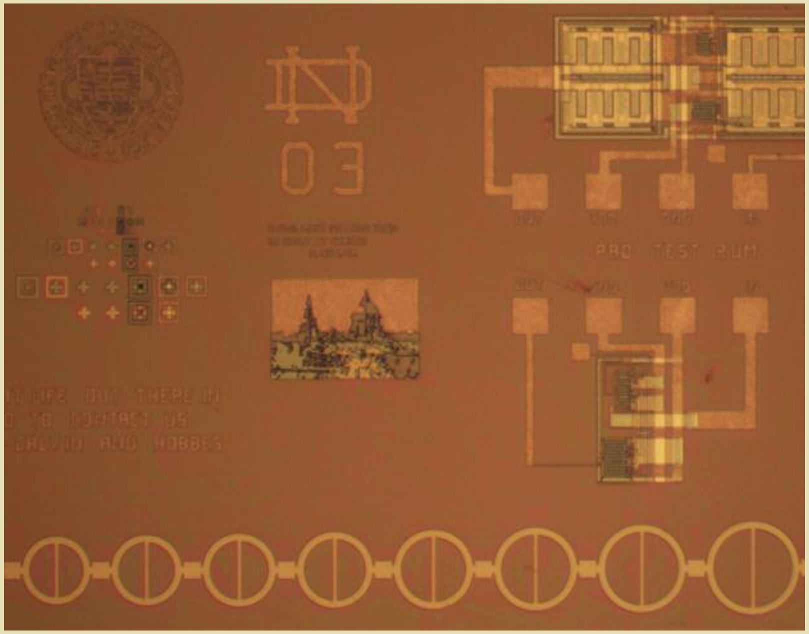


Notre Dame's Innovation Park

Currently under construction is Innovation Park at Notre Dame, a business incubator that will facilitate the migration of research and new venture ideas into the marketplace. When complete, the 12-acre park is expected to include up to five buildings and house clients that range from start-up companies to Fortune 100 corporations.

According to **David Brenner**, the park's president and chief executive officer, in addition to spin-off projects developed from the Midwest Institute for Nanoelectronics Discovery, several young Notre Dame-based ventures are being considered for the first phase of development. Three of these — EmNet, a company that provides wireless solutions for distributed control and sensing; MedXCycle, a medical supply company; and RFWare, a student-faculty project resulting in software for first responders in emergency situations — will be housed in the first structure, a 54,000-sq.-ft. building that will feature wet and dry laboratories, green house incubation facilities, conference rooms, and administrative and collaborative areas.

For more information about Innovation Park, visit http://www.innovationparknd.com.



Nanofabrication Facility to Expand and Open to Off-campus Users

High-resolution Imaging

Electronic and Optical Characterization

Plasma and Reactive Ion Etching

Photolithography

Photomask Fabrication

Thin Film Deposition

Rapid Thermal Processing

Nanolithography

Packaging

Metrology

"A key element of nanotechnology research at Notre Dame is that we have a comprehensive facility for fabricating nano- and micro-electronic devices," says **Patrick J. Fay**, professor of electrical engineering and director of the Notre Dame Nanofabrication Facility (NDNF). Each year NDNF serves approximately 150 users across the University — faculty, postdoctoral researchers, graduate students, and undergraduates.

Even though much of the NDNF equipment is comparable to that found in high-profile industrial and government labs, the fundamental difference between research facilities in industry and the NDNF involves the scope of materials and processes explored. "Having a complete nanofabrication lab on campus means we can study a wide range of problems in nano- and microelectronics. It benefits everyone and gives Notre Dame a real research advantage."

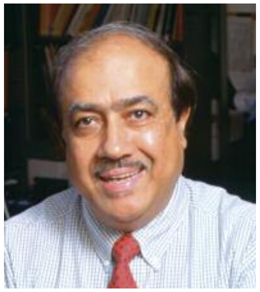
The NDNF offers researchers the ability to investigate a wide range of materials, using a diverse array of processing techniques, without many of the restrictions that are typical of mainstream industrial R&D labs. For example, the NDNF supports researchers working on silicon and silicon-related electronic devices, as well as faculty and students exploring other materials. It's not unusual to find some researchers working with gallium arsenide and indium phosphide, while others are focusing on less conventional materials with interesting electrical properties, such as zinc selenide nanowires, carbon nanotubes, graphene, and organic polymer-based materials. In addition, devices for solar energy conversion, computation, telecommunications, environmental sensing, and many other applications are being pursued using the NDNF's resources.

Research in the NDNF is not restricted to electronics. It includes the study of microfluidic devices for medical applications and micron-scale mechanical device fabrication.

The flexibility and diversity of the research fostered in the NDNF is vital to continue advancing the functionality and performance of electronic and non-electronic devices alike for applications in industries such as communications, computing, consumer electronics, health care, energy harvesting and conversion, and transportation.

One of the most recent developments involves a new facility, which will be located in the Stinson-Remick Hall of Engineering. "It's a very exciting time," says Fay. "We will almost double our space, allowing us to purchase more equipment, augment our capabilities, and accommodate more users from across campus ... as well as from institutions that do not have this type of facility."

For more information about the full suite of equipment in NDNF or using the NDNF facilities, visit http://www.nd.edu/~ndnf.



Kareem Named to National Academy of Engineering

Ahsan Kareem, the Robert M. Moran Professor of Civil Engineering and Geological Sciences and Director of the NatHaz Modeling Laboratory, has been elected a member of the National Academy of Engineering (NAE) for contributions to "analyses and designs to account for wind effects on tall buildings, long-span bridges, and other structures."

A faculty member at Notre Dame since 1990, Kareem specializes in probabilistic structural dynamics, fluid-structure interactions, structural safety, and the mitigation of natural hazards. To better understand and predict the impact of natural hazards on the constructed environment, he uses computer models and laboratory and full-scale experiments to study the dynamic effects of environmental loads under winds, waves, and earth-quakes on structures and to develop mitigative strategies to enhance the performance and safety of structures.

Kareem has served in the administration, management, and organization of numerous professional societies, including the American Society of Civil Engineers (ASCE), as well as committees of the National Research Council, NAE, and the American Association for Wind Engineering. In addition, he has served as a senior consultant to several major oil, insurance, and consulting engineering companies and the United Nations.

He was also recently named the lead U.S. collaborator for a project titled "New Frontiers of Education and Research in Wind Engineering" at Tokyo Polytechnic University's Global Center for Excellence. Founded by the Japanese Ministry of Education, Culture, Sports, Science and Technology, the center was established to build a sustainable urban environment that is resilient to extreme wind events and is in harmony with regional and local environments.

Among his other recent honors are the ASCE's State-of-the-Art award for scholarly contributions to full-scale monitoring of tall buildings, an appointment as an advisory professor at Tongji University in Shanghai, and selection as the inaugural recipient of the Alan G. Davenport Medal, presented by the International Association for Wind Engineering in recognition of his distinguished achievement in the dynamic wind effects on structures. He has also received the Robert H. Scanlan Medal for outstanding original contributions to the study of wind-load effects on structural design and the Jack E. Cermak Medal in recognition of his contributions to the study of wind effects on structures. His receipt of the Davenport, Scanlan, and Cermak medals is an unmatched recognition in his field.

IAS Appoints Porod Hans Fischer Senior Fellow

The Institute for Advanced Study (IAS) at the Technische Universität München (TUM) has selected **Wolfgang Porod**, the Frank M. Freimann Professor of Electrical Engineering, as a Hans Fischer Senior Fellow. The fellowship is named in honor of a TUM professor (Hans Fischer) who was awarded the 1930 Nobel Prize in chemistry for his pioneering efforts in hemoglobin.

Porod, like the other senior fellows, will pursue research activities following the motto "High Risk, High Reward," as the IAS is concerned with impact on advanced research fields in the long run, supporting top-level research without the burden of bureaucratic requirements. An expert in the area of nanoelectronics and quantum devices, he will continue to exploit new physical phenomena at the nanoscale for novel information processing devices and systems while at IAS.

A faculty member since 1986, Porod's research focuses on solid state physics and its application to electronics; device reliability, degradation, and breakdown; quantum devices and architectures for nanoelectronics; and the limits imposed by the laws of physics on computation. He is the co-inventor of Quantum-dot Cellular Automata, a transistorless approach to computing, and serves as director of the Center for Nano Science and Technology.

Porod is also a fellow of IEEE and has authored more than 300 publications and presentations. He serves on the advisory and program committees of several international meetings and is a reviewer of proposals to the National Science Foundation, NASA, and several technical journals. In addition, he is active in many professional societies and serves as a speaker in IEEE Distinguished Lecturer programs.

Energy Frontier Research Center Established at Notre Dame

On April 27, 2009, at the annual meeting of the National Academy of Sciences, the White House announced that the University of Notre Dame will be home to one of the 46 new multi-million-dollar Energy Frontier Research Centers (EFRC) being established by the U.S. Department of Energy (DOE). The new University center, which will be titled "Materials Science of Actinides," will pursue advanced scientific research on energy. Specifically, it will focus on elements that are the basis of nuclear energy — uranium, plutonium, and other actinides. Research conducted in the center will seek to understand and control materials that contain actinides at the nanoscale and is intended to lay the scientific foundation for advanced nuclear energy systems that may provide much more energy while creating less nuclear waste.

Peter C. Burns, the Henry J. Massman Chair of the Department of Civil Engineering and Geological Sciences, will serve as the director of the new center. According to Burns, "This is a unique and important opportunity for scholars at Notre Dame and partner institutions to impact energy challenges facing the nation and the world."

EFRC researchers will take advantage of new capabilities in nanotechnology, high-intensity light sources, neutron scattering sources, supercomputing, and other advanced instrumentation in its efforts to develop the groundwork for new fundamental advances in solar energy, biofuels, transportation, energy efficiency, electricity storage and transmission, clean coal and carbon capture and sequestration, and nuclear energy.

Of the 46 EFRCs selected, 31 are led by universities, 12 by DOE national laboratories, two by nonprofit organizations, and one by a corporate research laboratory. The DOE plans to fund each center at $2.5 million per year for an initial five-year period. The locations were selected from a pool of approximately 260 applicants, who responded to a solicitation issued by the DOE Office of Science in 2008.

Notre Dame's EFRC is one of 16 to be funded by President Obama's American Recovery and Reinvestment Act. The criterion for providing an EFRC with Recovery Act funding was job creation. The EFRCs chosen to receive this funding provided the most employment for postdoctoral associates, graduate students, undergraduates and technical staff, in keeping with the Recovery Act's objective to preserve and create jobs and promote economic recovery.

The new center builds upon Notre Dame's expertise in actinides research. For more information, visit http://www.nd.edu/~cegeos/people/faculty/burns.htm.

Kogge Leads DARPA ExaScale Computing Study

"Does the current course of mainstream computing technology allow for a 1,000X increase in the computational capabilities of computing systems by 2015?" That was the question members of the ExaScale Computing Study: Technology Challenges in Achieving Exascale Systems committee were asked to consider. The follow-up question was: "If current trends are not capable of permitting such an increase, what are the major challenges, and how might they be best addressed?" "The committee's goal," says study lead **Peter M. Kogge**, the Ted H. McCourtney Professor of Computer Science and Engineering, "was not to provide solutions or specific designs for computers in 2015. It was to develop a deep understanding of the technological challenges that could prohibit such a large increase in computing capabilities for data center-sized systems [supercomputers], departmental-sized systems, and embedded systems." All study members agreed on two things: If a 1,000X increase were to be achieved, it would be in a way that does not currently exist and that any such achievement would come through an interdisciplinary approach.

Chosen by the Defense Advanced Research Projects Agency to lead the study, Kogge also selected the study participants and served as its editor. He discussed the study results with *IEEE Spectrum;* the radio interview is available at *http://www.ieee.org/netstorage/spectrum/radio/mp3/1208kogge.mp3*.

An expert in advanced computer architectures, Kogge is the author of two books and the holder of 20 patents. He is also an IBM fellow, as well as a fellow of the Institute of Electrical and Electronics Engineers. Kogge graduated from Notre Dame in 1968 with a bachelor's degree in electrical engineering; he returned as a faculty member in 1994.

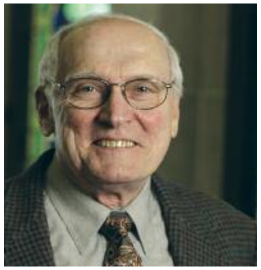
ACS Taps Brennecke as Stieglitz Lecturer

As the 2008 Julius Stieglitz Lecturer, **Joan F. Brennecke** joined a list of honorees that includes 13 Nobel Laureates and more than 35 members of the National Academy of Sciences. Presented annually by the Chicago section of the American Chemical Society (ACS) and the University of Chicago, this is the highest ACS section award given.

Brennecke, the first chemical engineer to be honored, is the Keating-Crawford Professor of Chemical and Biomolecular Engineering and Director of the Notre Dame Energy Center. A faculty member since 1989, she is internationally known for her research in the development of supercritical fluids and ionic liquids. Her research interests include supercritical fluid technology, ionic liquids, thermodynamics, environmentally benign chemical processing, and carbon dioxide separation, storage, and usage.

A member of the ACS, the American Institute of Chemical Engineers (AIChE), and the American Society of Engineering Education, Brennecke is also the recipient of the 2007 John M. Prausnitz Award, the 2006 Professional Progress Award (AIChE), the 2001 Ipatieff Prize, and a 1991 Presidential Young Investigator Award.

Merz Named MRS Fellow



James L. Merz, the Frank M. Freimann Professor of Electrical Engineering, has been named a fellow of the Materials Research Society.

An internationally recognized scholar in the field of optoelectronic materials and devices, Merz was cited for his "outstanding achievements in electronic materials, particularly compound semiconductors ... and for intellectual leadership in advancing materials research in the U.S. and internationally."

He most recently served the University as interim dean of the College of Engineering and vice president for graduate studies and research. A Notre Dame alumnus, Merz returned to the University in 1994 to direct a team of researchers investigating Quantum-dot Cellular Automata, sometimes called Notre Dame logic.

Prior to his return, he served as professor of electrical engineering, professor of materials, and director of the Center for Quantized Electronic Structures (QUEST) at the University of California at Santa Barbara. In addition to directing QUEST, a National Science Foundation (NSF) science and technology center, Merz chaired the national council of directors of the NSF science and technology centers. He has published more than 400 papers and holds five patents.

Merz is a fellow of the American Association for the Advancement of Science, the American Physical Society and the Institute of Electrical and Electronic Engineers; and he is a member of the Society for Values in Higher Education. He also is the recipient of an Alexander von Humboldt Research Award in recognition of lifetime achievements in science and engineering and an honorary doctorate from Linköping University in Sweden.

Gates Grant Funds Malaria Vector Research

In July 2007, the Bill & Melinda Gates Foundation awarded a grant in excess of $20 million to the University of Notre Dame, to be used over a five-year period in support of multidisciplinary efforts to develop and evaluate improved methods for controlling malaria.

The goal of the team — assembled by **Frank Collins**, the George and Winifred Clark Professor of Biological Sciences and concurrent professor of computer science and engineering, and **Gregory R. Madey**, research professor in computer science and engineering — is to gather evidence of how malaria vectors (mosquitoes) behave, how the disease is transmitted, and how control methods work in specific sites, each with a different rate of transmission, from low to moderate to holoendemic.

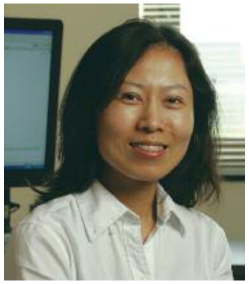
According to Collins and Madey, it is not enough to simply impose malaria controls — insecticide-treated bed nets, indoor residual spray, or medical treatment — without understanding more about locale-specific rates of transmission and the impact of individual control techniques in those areas. In fact, a single method of intervention cannot provide lasting control. For this reason, the consortium project includes partners from the Swiss Tropical Institute, the U.S. Centers for Disease Control, and the London School of Tropical Medicine and Hygiene, as well as researchers from each of the test sites in Indonesia, Tanzania, Kenya, and Zambia.

In addition to identifying the types of mosquitoes in a particular area, the team is tracking when the mosquitoes bite, morning or night; where they take their meals, indoors or outdoors; and how often they feed. They are also monitoring the human population, tracking everyone (infected or not) to determine how frequently mosquitoes infect people in an area.

Using PDAs, team members have already gathered the history of every person in each test area. They are also monitoring the malaria controls being used in those areas to determine the impact interventions are having and at what point the insects either become genetically resistant to a particular intervention or change their behavior because of the intervention.

Madey and graduate students in the Department of Computer Science and Engineering will develop databases from the huge amount of information being collected. They will then supervise the data analysis and management methods, geographical information systems, data quality assessment, and modeling and simulations that will help standardize the information. Results will be made available to malaria control program managers around the world, who will be able to access the data based on the mosquito species, population and location, rate of transmission, and intervention methods used. These efforts will not eradicate malaria, but they may dramatically reduce the prevalence and death rate of the disease.

Electrical Engineers Receive NSF CAREER Awards



Vijay Gupta and **Huili (Grace) Xing**, assistant professors in the Department of Electrical Engineering at the University of Notre Dame, have been named 2009 National Science Foundation (NSF) Early Career Development (CAREER) Award recipients. The award is one of the highest honors given by the U.S. government to young faculty in engineering and science.

A faculty member since 2008, Gupta's research focuses on the systematic and verifiably correct design of cyber-physical systems, such as cooperative multi-agent systems, networked control systems and sensor networks.

His CAREER project, titled "Scalable and Optimal Co-design of Control and Communication Protocols in Cyber-physical Systems," explores the next generation of engineering systems composed of multiple complex dynamical systems interacting across communication networks. The project proposes a scalable and efficient approach for designing the communication and control algorithms for such systems. It also includes the development of a new interdisciplinary graduate course, new projects for the department's senior thesis project course and a high school outreach program to motivate students, particularly minorities and women, to pursue engineering as a career.

Xing's expertise is in the design, fabrication, and characterization of semiconductors, nanostructures, and devices for applications, including high-speed high-power electronics, energy-efficient electronics, and IR/THz photodetectors.

Her CAREER project, titled "Graphene and Graphene Nanoribbon Optoelectronic Properties and Devices," focuses on developing and demonstrating a series of optoelectronic device concepts (primarily photodetectors) based on graphene and graphene nanoribbons (GNRs) and then using those devices as vehicles to extract the optoelectronic properties of graphene and GNRs. This research will deepen the understanding of electron excitation-relaxation dynamics, minority carrier lifetime, external electrostatic gating and wave guiding, and dielectric effects, all of which are important for graphene-enabled applications, such as tunable photodetectors, THz emitters, biosensors, and other devices yet to be invented. The educational component of Xing's project involves undergraduate students and middle school teachers and students — especially young girls — via the University's "Expanding Your Horizons" workshops, the participation of female students from Saint Mary's College in the dual-degree program in engineering, and a summer research opportunities program for women faculty from the college.

A member of the Materials Research Society, Institute of Electrical and Electronics Engineers, Electrochemical Society and American Society for Engineering Education, Xing joined the Notre Dame faculty in 2004.

Batill Named Fulbright Scholar

Stephen M. Batill, professor of aerospace and mechanical engineering, was named a 2008-09 Fulbright Scholar. During his appointment, which runs from January through August 2009, he will be lecturing and conducting research on monitoring and enhancing the product design process in the Product Innovation Management Department at Delft University of Technology in the Netherlands. Immediately preceding his Fulbright term, he served a semester as a scholar-in-residence at IDEO design consultancy in Palo Alto, Calif.

Batill's research interests are in aerospace and mechanical systems design, methodology and education, and multidisciplinary design optimization. An associate fellow of the American Institute of Aeronautics and Astronautics, he is also a member of the American Society for Engineering Education and of the American Society of Mechanical Engineers.

Batill has served on the faculty since 1978. Prior to that he served on the faculty at the U.S. Air Force Academy and was an aeronautical engineer at the Air Force Flight Dynamics Laboratory at Wright-Patterson Air Force Base. He is also a Triple Domer, receiving his bachelor's degree in 1969, his master's in 1970, and his doctorate (all in aerospace engineering) in 1972.

Actuators Improve Wind Turbine Performance

Denmark, Germany, and Spain are each close to meeting their goal of generating 30 percent of their respective electric power needs from wind energy. In contrast, the United States generates about 1.5 percent of its electricity from wind energy, a far cry from maximizing the resources that could be exploited for America.

While few are proposing that wind is the sole answer to the energy challenge, it is one of the renewable tools at society's disposal, one that is becoming more popular, more cost efficient, and soon more effective.

Researchers in the Center for Flow Physics and Control — Clark Equipment Professor **Thomas C. Corke**, director of the center (right), and Professor **Robert C. Nelson** — are investigating distributed active flow control as a way to improve wind turbine performance. Innovative Plasma Aerodynamic Control Effectors (PACE) developed at Notre Dame are being used to enhance energy capture from a turbine and to reduce aerodynamic loads and noise produced by the turbine.

PACE actuators modify the flow around each blade in real-time, steady and unsteady conditions alike. In addition to reducing maintenance costs, the PACE increase operational hours of a turbine, making the machine more cost competitive. (The cost of power from wind farms has dropped from 38¢ to 4¢ per kWh since 1980, but factors still include the cost of the system itself, lease or purchase of land on which the turbines are located, transmission requirements to connect to the power grid, maintenance, and the amount of time the wind conditions are within the operational range of the turbine.)

PACE extend the operational range of a turbine in a variety of wind conditions for maximum energy conversion. Experiments in a subsonic wind tunnel at the University demonstrate separation control, lift enhancement, and improved power extraction. Other benefits of the PACE include that they are fully electronic with no moving parts, can withstand high-force loading, and can be laminated onto the blade surface.

PATENT INFORMATION

U.S. Patent No. 7,380,756
Single Dielecric Barrier Aerodynamic Plasma Actuation
Developed jointly with the U.S. Air Force Academy, Notre Dame has obtained exclusive licensing rights. Issued on June 3, 2008.

An additional patent, filed in October 2007 with Orbital Research, Inc., ***Wind Turbine with Improved Performance and Method***, is pending as are multiple follow-on applications for a number of industrial uses.

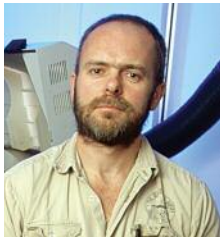
Hybrid Cellular Automata Improves Vehicle Safety

Steel armor, while it increases soldier survivability, adds thousands of pounds to a military vehicle. The added weight reduces speed (critical in a war zone) and overtaxes the engine. The solution, according to **John E. Renaud**, chair and professor of the Department of Aerospace and Mechanical Engineering, may be found in innovative structural and materials designs. He and a team of faculty and students in the Design Automation Laboratory, in collaboration with researchers at nearby AM General (Mishawaka, Ind.), are working to improve soldier survivability in vehicles, whether from a blast or a crash.

Part of a $1.3 million grant from the U.S. Army Tank Automotive Research Development and Engineering Center, the Notre Dame team is pioneering design and manufacturing methods that include rapid up-armor structural synthesis, topologically controlled lightweight ceramic armor design, and nonlinear transient vehicle crashworthiness design. Their efforts will not only benefit soldiers on battlefields around the world, but they will also impact the local economy.

The team is applying Hybrid Cellular Automata, a computer-aided design and manufacturing framework developed at Notre Dame, to simulate advanced materials and model their behavior in a variety of crash events, from roadside bombs and mines to rocket-propelled grenades.

In a separate effort, the team is working with Honda to protect the occupants of passenger vehicles. Even though the most recent statistics indicate that 2008 automotive fatalities dropped below 38,000 (the lowest since 1961), the issue that continues to elude manufacturers is vehicle crash-worthiness design. It is one of the most difficult problems to address because of the complex challenges of modeling, the development of new materials, and the cost of manufacturing. The methods that Renaud and his team — **Andres Tovar**, research assistant professor; **Lianshui Guo**, visiting scholar from Beijing University of Aeronautics and Astronautics; **Byung Soo Kang**, postdoctoral research associate from Hanyang University in Seoul; and graduate students **Neal Patel**, **Chandan Mozumder**, **Punit Bandi**, **Charlie Penninger**, **Huade Tan**, and **Jack Goetz** — have been developing, which simulate the way bone remodels itself and the varying loads placed on the body, also employs a cellular automata computing paradigm. The Notre Dame topology optimization software synthesizes structures that will be subjected to nonlinear dynamic transient loading in a crash event. The team has successfully applied this methodology to synthesize bumper systems, door beams, and knee bolster designs. The final objective is to design structural components that absorb energy during a crash, while retaining stiffness nearest to passengers. Notre Dame and Honda are currently working to license the software for commercial use.



Neal Named to Lunar Science Institute

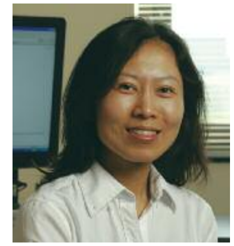
Clive R. Neal, professor of civil engineering and geological sciences, has been named to a select team of scientists tasked with growing the nation's technical capabilities in lunar science and developing educational opportunities in space science. Initial members of the National Aeronautics and Space Administration newly formed Lunar Science Institute (LSI) represent Notre Dame; the Lunar & Planetary Institute; the universities of Arizona, Houston, and Maryland; Rice University; Southwest Research Institute; and National Institute of Polar Research. They will investigate if the Earth and moon were resurfaced by asteroids and comets billions of years ago and how such heavy bombardment influenced the evolution of life on earth.

In his role in the LSI, Neal will be studying rocks collected at all of the Apollo landing sites via optical and electron microscopy to determine their age and the veracity of the lunar cataclysm hypothesis.

In addition to studying the origin and evolution of the moon, Neal research focuses on the geochemical and environmental consequences of plate interactions and petrogenesis of Large Igneous Provinces, as well as the environmental effects of heavy pollution. A faculty member since 1990, he is a member of the Mineralogical Society of America, Geological Society of America, American Geophysical Union, American Association for the Advancement of Science, and National Association of Geoscience Teachers.

Young Investigators Honored by AFSOR

Vikas Tomar, assistant professor of aerospace and mechanical engineering, and **Huili (Grace) Xing**, assistant professor of electrical engineering, were selected by the Air Force Office of Scientific Research (AFSOR) as part of the 2008 Young Investigator Program (YIP). The program is open only to engineers and scientists at U.S. research institutions who have received a doctoral degree within the last five years and show "exceptional ability and promise for conducting basic research." YIP honorees for 2008 will share



approximately $12.1 million for their research efforts as outlined in their winning proposals. Competition for the award was intense; the AFSOR received 210 proposals encompassing a broad range of areas, including aerospace, chemical and materials sciences, physics and electronics, mathematics, information technologies, and life sciences.

Tomar, who joined the University in 2006, is investigating nanoscale thermal conduction and mechanical strength correlation in high-temperature ceramics as part of his efforts in the YIP. It coincides well with his work in Notre Dame's Multiphysics Laboratory, where he is studying advanced ceramic matrix composites for use in energy plants.

Xing's YIP focuses on the quantum limits of nitride RF high-electron mobility transistors. Through experimental and theoretical approaches, she is investigating the physical origins of the upper limit of speed and power-handling capabilities in gallium-nitride based semiconductor transistors.

IEEE Recognizes Costello's Paper as Most Outstanding

The Institute of Electrical and Electronics Engineers (IEEE) has named **Daniel J. Costello Jr.**, the Leonard Bettex Professor of Electrical Engineering, the recipient of the 2009 IEEE Donald G. Fink Prize Paper Award. The annual award honors the most outstanding survey, review, or tutorial paper published among all of the organization's 144 transactions, journals, and magazines.

Costello's paper, titled "Channel Coding: The Road to Channel Capacity," appeared in the June 2007 issue of the *Proceedings of the IEEE*. Co-authored with **G. David Forney** of the Massachusetts Institute of Technology, the paper describes the 60-year trajectory of research into making digital communications more robust and efficient through the controlled introduction of redundancy. Channel coding is used in virtually every existing digital communication system, including cell phones, cable modems, DSL lines, and satellite systems. Costello has made sustained and profound contributions to the research described in this article.

A fellow of the IEEE, Costello received his master's (1966) and doctoral degrees (1969) from the University and returned to Notre Dame in 1985 as a member of the Department of Electrical Engineering faculty. He has received the Alexander von Humboldt Foundation Research Prize, the IEEE Third Millennium Medal, and the Seattle University (his undergraduate institution) Centennial Alumni Award. He has also served as a member of the IEEE Information Theory Society Board of Governors and as associate editor for the *IEEE Transactions on Communications* and the *IEEE Transactions on Information Theory*.

Other Significant College of Engineering Headlines ...

2007

TWO PECASE WINNERS
J. Nicholas Laneman and James P. Schmeideler Receive PECASE Award

TWO NSF CAREER HONOREES
Debdeep Jena and Douglas Thain Named Early Career Award Recipients

TOP 10 MOST CITED
Peter C. Burns Named among Top 10 Most Cited Geosciences Authors

NEW AAAS FELLOW
James L. Merz Named AAAS Fellow

PRAUZNITZ AWARD
Joan F. Brennecke Receives Prauznitz Award

INAUGURAL DAVENPORT MEDAL
Ahsan Kareem Receives Inaugural Davenport Medal

FULBRIGHT SCHOLAR
Yih-Fang Huang Named Fulbright Scholar

IEEE MAC VAN VALKENBURG AWARD
Ruey-Wen Liu Named Recipient of Van Valkenburg Award

MAX JAKOB MEMORIAL AWARD
ASME Honors Kwang-Tzu Yang with Max Jakob Memorial Award

SPECIAL APPOINTMENT
Ahsan Kareem Appointed Advisory Professor to Tongji University of Shanghai

ARMY CIVILIAN SERVICE AWARD
Joannes Westerink Awarded U.S. Department of the Army Outstanding Civilian Service Award

2006

TWO NSF CAREER HONOREES
J. Nicholas Laneman and Christian Poellabauer Named Early CAREER Award Winners

NEW APS FELLOW
Thomas C. Corke Named APS Fellow

NEW ASME FELLOW
Timothy Ovaert Named ASME Fellow

FIRST IAPR FELLOW AT NOTRE DAME
Patrick Flynn First Faculty Member Named IAPR Fellow

INAUGURAL EARLY CAREER FACULTY FELLOW AWARD
Ryan K. Roeder Named First Recipient of the Minerals, Metals, & Materials Society Early Career Faculty Fellow Award

PROFESSIONAL PROGRESS AWARD
Joan F. Brennecke Receives AIChE Professional Progress Award

ASEE GLOBAL EDUCATOR AWARD
Stephen E. Silliman Honored with American Society for Engineering Education's Global Engineering and Engineering Technology Educator Award

For information on these headlines, as well as the latest news from the College of Engineering, visit *http://www.nd.edu/~engineer/publications.*

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