Nanotechnology is a world where materials that behave one way at one size, begin to do their own thing when they get really small. It’s where something as hard as a diamond can also be flexible. It’s where even Einstein didn’t believe his own theory suggesting quantum entanglement – because surely no process that “spooky” could exist in the physical world.

Yet because some particles act differently in the nanoworld, they open up seemingly miraculous improvements in systems that might otherwise be reaching the wall in terms of overall performance. Sometimes just being smaller opens possibilities for new materials and devices.

In this brief overview of nanotechnology research in ECE, we’ll look at how research at the nanoscale is impacting lighting, medicine, displays, electronics, information security and the far-out world of quantum computing. Our faculty are also looking into how to manufacture these devices.

Nanotechnology is science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nanometers.

[National Nanotechnology Initiative]
It Starts With a Dot, a Quantum Dot

Quantum dots are the cornerstone of a broad spectrum of research at the nanoscale. A quantum dot is a 2-10 nanometer particle made of some semiconductor material. Like many nanoscale particles, they display characteristics distinct from the same material in bulk – which make them a fascinating source for new technologies, including lighting sources, lasers, solar cells, medical imaging, and quantum computing.

Quantum dots were first discovered in the early 1980’s. Just a few years later, a team of researchers that included Pallab Bhattacharya, Charles M. Vest Distinguished University Professor, and Prof. Jasprit Singh, showed that under certain circumstances, quantum dots organized themselves into unique three-dimensional structures. The scientific community didn’t pay much attention when they published their findings in 1988 – the results seemed too far-fetched.

This changed in 1996 when Bhattacharya came out with the world’s first room temperature Indium Gallium Arsenide (InGaAs)/GaAs quantum dot laser based on self-organized quantum dots. Contributing to this groundbreaking device were Ted Norris, Gérard A. Mourou Professor of EECS, who used ultrafast spectroscopy to better understand the material as well as anticipate its performance in lasers and photodetectors, and Prof. Jamie Phillips, who was involved with the experimental work as a graduate student. Prof. Bhattacharya has continued to be a worldwide leader exploring the capabilities of quantum dots for new devices.

Are Plasmons the Key to Entirely New Devices?

We may know the answer to that question once Prof. Norris is done investigating their properties. “Plasmons may be the route to very sensitive biosensors, improved solar cells, photodetectors, light emitters, and even optical communications in a chip,” stated Prof. Norris, who has been using a process called Electron Energy Loss Spectroscopy (EELS) to understand plasmons.

Plasmons are tiny quasiparticles that correspond to the oscillation of electrons in a metal. Plasmons in individual metallic nanoparticles are difficult to study optically, since nanoscale particles are many times smaller than the wavelength of light. EELS opens up the possibility of mapping out the plasmons in nanostructures directly, although it’s important to be careful in relating the EELS measurement to the optical properties of the material. The ultra-high resolution of EELS may enable the study of objects smaller than 10 nanometers.

Prof. Norris is working with Prof. Bhattacharya to use EELS to study nanostructures made of semiconductors, relatively unexplored territory. They started with simple structures such as gold and silver nanowires, and are now moving to more complicated systems. Prof. Norris says the research has been extremely promising.

Polaritons Enable Groundbreaking Lasers

Polaritons are manmade quantum phenomena that come about under specific conditions involving photons and excitons (electron-hole pairs). These part light and part matter particles, once created, take on unique properties of their own.

Stephen Forrest, William Gould Dow Professor of Electrical Engineering and U-M Vice President for Research, and his group were the first to demonstrate room-temperature polariton lasing in an organic semiconductor material in 2010. By doing so, they achieved a long sought-after optics phenomenon that could lead to more efficient and flexible lasers for telecommunications and quantum computing applications, among other uses. The next step is to use polaritons to do electrical rather than optical pumping of organic semiconductors.

Using inorganic material, Prof. Bhattacharya developed the first electrically injected polariton laser in 2012, a feat that researchers around the world had been trying to demonstrate since it was first proposed in 1996. The experimental results were published in 2013, in Physical Review Letters. A typical laser generates light through Light Amplification by Stimulated Emission of Radiation, hence its name. This new device generates light through Light Amplification by Stimulated Scattering of Polaritons – thereby creating an entirely new laser paradigm.

This laser takes about 1,000 times less energy to operate than a conventional laser, and can be potentially used in any application where a laser is used today, such as consumer electronics, optical communications and the Internet, laser surgery and other medical applications, and displays. First however, the laser needs to operate closer to room temperature, which means raising its operating temperature from 30K to at least 200K. Proving the viability of this laser at room temperature is the next holy grail for Prof. Bhattacharya, and now for many other researchers worldwide.
Quantum Research for Quantum Computing

One of the most mysterious nanoscale phenomena is quantum entanglement. Even Albert Einstein, who alluded to this effect in a 1935 paper, called it “spooky” and refused to believe it was scientifically accurate. At the risk of oversimplification – quantum entanglement happens when the smallest of particles (such as photons, electrons, or molecules) interact and separate – yet somehow remain linked such that when the state of one of the particles changes, the other particle will change in exactly the same way – no matter their distance apart.

50 years after Einstein’s spooky theory, quantum entanglement was proven to be a real phenomenon – and became the subject of intense exploration as a means to achieve quantum computing. Because of their ability to represent multiple states simultaneously, quantum computers could theoretically factor numbers dramatically faster and with smaller computers than conventional computers. Factoring numbers is the basis for encryption schemes used to protect computer data.

Duncan Steel, Robert J. Hiller Professor, and a group of collaborators from the Naval Research Laboratory and UC-San Diego recently demonstrated quantum entanglement between an electron spin state and a photon polarization state, both resulting from their association with a quantum dot. A quantum dot acts like a transistor in a conventional computer. Lasers are used to excite the quantum dot, which then emits the photon, while the electron spin state remains with the quantum dot. Because the electron and photon were quantum entangled, the researchers were able to transfer information between the two. “Now we can send that photon to another device and transfer the information back into another electron,” explained Prof. Steel. This was a major accomplishment that was mirrored by two unrelated groups working on the same problem. Though the processes used were slightly different, the results were similar and corroborative.

This was simply the latest of several quantum research milestones accomplished by Prof. Steel. In 1998, his group was the first to demonstrate coherent optical control of a single quantum dot. This work led to the idea that quantum dots could be used to build quantum computers. In 2000, Duncan’s group made the first demonstration of optically-induced quantum entanglement in a single quantum dot, and used this to make the first universal quantum gate in a solid-state device.

In 2008, Prof. Steel and his group took yet another important step toward practical quantum computing when they became the first to control the inherent duality of a qubit, or quantum bit. A quantum bit is analogous to a regular bit in that it is a unit of information. However, a qubit differs dramatically from its classical counterpart in being able to simultaneously hold two states. A bit is either 0 or 1 whereas a qubit can simultaneously hold two states correlating to the 0 and 1 of classical computing. A qubit could be defined by the spin of an electron or other atomic particle. In this groundbreaking work, lasers were used to trap the spin of one electron that was confined in a single self-assembled quantum dot. But they could only trap it for the briefest of time.

In 2009, Prof. Steel and colleagues succeeded in lengthening the stable existence of the qubit by more than 1,000 times. Accomplished with the help of a laser, Prof Steel called this unexpected result “a remarkable piece of physics in nature.” It broke down yet another tall barrier to realizing a quantum computer.

A key aspect of Prof. Steel’s most recent demonstration of quantum entanglement is that it is scalable, which is critical to realizing a scalable quantum dot quantum computer architecture.

Quantum Research for Classical Computing

Prof. Steel is also looking to use the quantum properties that emerge in nanoscale materials and devices for classical computing. “Moore’s Law dictates an end to CMOS,” says Prof. Steel. “As we transition from the classical to the quantum world, can we still make these classic computer systems work in the way we want using quantum technologies?” If so, the payoff will be exponentially smaller, faster machines running on a fraction of the power that can solve problems virtually unsolvable with today’s computers.

As a member of the Center for Photonic and Multiscale Nanomaterials, Prof. Steel is investigating new materials that could make it easier to incorporate quantum features into classical computing systems. For example, some quantum dot materials, such as indium nitride, must be kept at extremely cold temperatures, whereas others, such as gallium nitride, could be kept at room temperature.
His approach is to control quantum devices optically, which does away with the need to bond wires to the devices. It also means it’s possible to reconfigure a device simply by changing the laser. About 15 years ago, Prof. Steel and his group built the first solid-state device for quantum information; it was a NOT gate. “It takes a lot of physics to figure out how to build quantum devices,” said Duncan, “But solving these kinds of problems will lead to technological breakthroughs that aren’t even on anyone’s radar.”

**Photons for Quantum Cryptography**

In today’s computers, private information, such as a credit card number, is encrypted digitally before entering cyberspace. If the information is somehow decrypted and stolen, which happens with alarming regularity, no one would know until bank accounts start to be emptied or secrets leaked. However, if each bit of information sent was equipped with its own nanosized quantum-based photon, it would always be possible to know if a third party was trying to intercept the message. That’s because a quantum message being sent as photons will instantaneously change if it’s being observed (this is called the wave function collapse) as a byproduct of quantum entanglement.

Prof. Steel’s group demonstrated the key quantum requirement (entanglement), and is now demonstrating the link. In related work, faculty are perfecting devices that can generate the photons needed for quantum computing and cryptography.

Prof. Bhattacharya and his team combined quantum dots, GaN nanowires, and electrical injection to create a device that is capable of producing a single photon at a time, while controlling the polarization of the photon. Both attributes are key to accomplishing certain types of quantum cryptography, which require each photon to possess the same degree of linear polarization.

The simplicity of its design and the materials used make it a very attractive improvement over existing technology. It uses the same semiconducting materials commonly used in LEDs and solar cells, and the nanowires are grown on silicon, which is cheap and scalable.

In addition to its applicability to quantum cryptography, this single photon emitter is also useful for quantum information processing and metrology applications. Prof. Bhattacharya is currently working on a device that operates closer to room temperature.

Prof. Ku and his group developed a system for generating a “site-controlled” single photon from quantum dots that is based on semiconductor lithography. His system operates at 90 degrees K, which is the highest temperature on record for a single photon source that can generate millions of photons on demand.

“Room-temperature operation is important,” said Prof. Ku. “But equally critical for practical applications is the ability to arbitrarily control the output polarization and the ability for the photons to be easily coupled to other optical components such as an optical cavity. The lithographic approach is very promising to these ends.” A “deterministic” single photon emitter translates into a marketable product for banks and other institutions that will pay heavily for security.

The NSF Center for Photonic and Multiscale Nanomaterials (C-PHOM) was established at Michigan in 2011. Directed by Prof. Ted Norris, research in the Center is focused on controlling how light interacts with matter on all length scales, from nano up to the scale of the wavelength. C-PHOM has two primary research focuses as well as a third area devoted to financially supporting new research directions.

Prof. Bhattacharya leads the area concentrating on wide-bandgap nanostructured materials for quantum light emitters. The research is similar to work he and Prof. Norris accomplished more than a decade ago with the InGaAs/GaAs quantum dot laser, but with an important difference. They are now working with the material Indium Gallium Nitride (InGaN), a completely different animal.

These materials can be used to generate blue, green, and possibly even red light emitters – and contain the promise of new and highly efficient devices. “The material challenges that come with nitrides are enormous,” said Prof. Norris, adding that Prof. Bhattacharya’s work with nanowires may be a real breakthrough technology for gallium nitride. Also involved in this research from ECE are Rachel Goldman (Materials Science and ECE), P.C. Ku, Jamie Phillips, and Duncan Steel. Roberto Merlin, Peter A. Franken Professor of Physics and EECS, leads the second research area, which is focused on advanced electromagnetic metamaterials and near-field tools. A metamaterial is an artificial material made up of nano-sized particles that are engineered to take on properties not possible with natural materials. Part of this research involves studying the nonlinear optical properties of the nano building blocks that will create the materials. This research thrust also involves ECE faculty Tony Grbic, who is the Ernest and Betty Kuh Distinguished Faculty Scholar, Jay Guo, and John Schotland (Math and ECE).
Renewable Energy From the Sun

Nanotechnology offers the possibility of new materials built from quantum dot or other nanostructures to convert solar energy into electricity with greater overall efficiency than is possible with silicon. Silicon is the current material of choice for solar cells due to its low cost, but these solar cells are highly inefficient. The solar cell industry doesn’t need the thousand-fold improvements that nanotechnology has offered other fields. But it does need further improvements to make solar energy economically competitive with fossil fuel.

Several ECE faculty are working on different aspects of solar cell technology, including Prof. Stephen Forrest, Prof. Jay Guo, Prof. P.C. Ku, Prof. Jamie Phillips, and Prof. Zhaohui Zhong.

Prof. Forrest is a world leader in organic photovoltaics, which is the study of organic materials to create solar cells. In 2010, along with researchers at Argonne National Laboratory and Northwestern University, he came up with a general theory for organics that was a theoretical corollary to Shockley’s well-known diode equation for semiconductors. “Organics have always evaded clear scientific definition,” said Prof. Forrest. “This new ideal diode equation will hopefully serve as the theoretical foundation of organic electronics in the future.”

In recent work, Prof. Forrest and his team put this theory to the test, and it worked. His group achieved better than a 50% improvement in energy-conversion efficiency by developing techniques to control nanocrystalline order at the active interface in organic photovoltaics. This critical advance provides a fundamental understanding of the process of solar-to-electrical energy conversion in organic thin film solar cells, and the linkage of efficiency to molecular and crystal structure.

Prof. Forrest also discovered a way to build flexible solar cells made from the inorganic material gallium arsenide (GaAs) in a way that opens the door to mass production, which would dramatically lower their cost. He has shown 22% overall efficiency in these solar cells, and is investigating ways to increase that efficiency to 30%. This would put solar cells made from GaAs on a par economically with those made from silicon.

Prof. Jamie Phillips investigates new optoelectronic materials for next-generation solar cells (as well as for infrared detectors and thin film electronics). He has been studying quantum dot intermediate-band solar cells (IBSCs) to see if his group can realize the improved efficiency that researchers believe are inherent in these devices. Working with inorganic materials, he demonstrated the first ZnTe:O IBSC, and more recently has turned his attention to GaSb/GaAs type-II quantum dots. By analyzing what happens in the individual quantum dots, he demonstrated that this form of quantum dot should be a good candidate for efficient IBSCs.

Prof. Norris has been involved with solar cell research from the perspective of defining the fundamental aspects of new materials. Using ultrafast laser technology, he is able to explore the most basic properties of the proposed materials to gauge how effective they will be converting solar energy to electrical power.

Energy-efficient Lighting

Lighting accounts for as much as 25% of all the energy expended in the United States. The U.S. Department of Energy believes that widespread use of white light LEDs could cut the energy expended on lighting in half by 2030.

Light emitting diodes (LEDs) are dramatically more efficient than their incandescent and fluorescent counterparts. There is already a huge consumer market for these devices, including: electronic devices; automotive, household, industrial, and aviation lighting; advertising; traffic lights; and more.

An LED is illuminated by the movement of electronics in a semiconductor material. Researchers continuously investigate different semiconductor materials for making LEDs in search of the combination that will give the best color with the lowest threshold current density, meaning the lowest amount of energy needed to generate light. LEDs can generate red, green, blue, or white light.
Quantum Dots and Nanowires for Better Green and Red LEDs and Lasers

In 2011, Prof. Bhattacharya demonstrated the world’s first quantum dot Indium Gallium Nitride (InGaN) laser that could emit the color green. The quantum dot lasers have a threshold current density that is 10 times lower than lasers of other materials used to generate green. Solid-state green lasers are required for full-color mobile projectors, optical data storage, and for medical and military applications; they will eventually find applications in solid-state lighting. Bhattacharya’s group also demonstrated blue quantum dot lasers in their stride.

The green InGaN laser was a significant achievement, but not as big as what he’s done now, which is to demonstrate red emission from an InGaN-GaN quantum dot laser, a feat considered virtually impossible. This result has also been recently published. A potential major application of such red emitting lasers is heads-up displays in automobile windshields.

Both achievements (red and green emission) were also made possible with InGaN-GaN nanowires. A nanowire is a nanostructure that measures 10s of nanometers in diameter and can be of any length. Quantum mechanical effects come into play with nanowires, making their properties unique from their bulk counterparts.

Lowering the Cost of White Light LEDs

White light LED products are becoming increasingly prevalent on the market as an alternative to incandescent and fluorescent lighting, yet their quality and energy efficiency widely varies, and they are relatively expensive.

Prof. P.C. Ku is investigating an approach to white light LED development that could substantially lower the cost of fabricating the devices. He is growing his own materials, including nanowires, through gallium nitride epitaxy in order to perfect a nonpolar LED substrate. LEDs are typically fabricated on polar substrates because they are far less expensive and simpler to deal with than nonpolar material. However, polar substrates generate an electric field, which make them highly inefficient.

Prof. Ku has achieved good results with his nonpolar substrate, and now is in the process of fabricating LED devices on top of it. “We are trying to bridge the gap between a very expensive non silicon LED lightbulb, and a cheap one,” said Prof. Ku.

More Like Real Sunlight

“I want to walk into a room and get the best kind of light – so you’ll be healthy, alert, and able to work,” says Prof. Ku. That means a light source that provides some of the same benefits as real sunlight. There is scientific evidence that sunlight provides us not only the ability to see, but to feel well and more alert. This effect seems to be related to a receptor in the eye that’s linked to our circadian rhythm, or our daily clock. This receptor in the eye senses the blue light from the sun, which in turn regulates how much melatonin is produced by the body; melatonin is directly related to sleep patterns.

Prof. Ku’s ideal office light will combine the blue light of the sun with bright, attractive, energy-efficient lighting. To achieve this goal, he’s working with Prof. Mojtaba Nawab (Architecture & Urban Planning) and Prof. Kwoon Wong (Ophthalmology & Visual Sciences) to find the right combination of lighting to satisfy both our conscious and subconscious vision.

Prof. Ku formed a company with Prof. Max Shtein (Materials Science and Engineering) called Arborlight, which specializes in LED lighting for retail and office settings.

OLEDs for Displays and Lighting

An organic light emitting diode (OLED) is an LED that contains an organic semiconductor, such as carbon. Unlike LED’s, they can be molded into any shape. The first modern OLED was developed by researchers at Eastman Kodak in 1987, but it was highly inefficient. The OLED industry began to really take off when Prof. Forrest built the first phosphorescent OLED with Prof. Mark E. Thompson (Dept. of Chemistry, USC) in 1998. “We used a simple quantum mechanics trick to develop materials that could make them 100% efficient,” said Prof. Forrest. Soon after, they were considered the hot new material for displays.

When Samsung developed their super-sharp OLED displays for use in their Galaxy 3 and 4 smart phones, they used many of the same materials and device structures first developed in Prof. Forrest’s lab.

OLEDs may one day be used for general lighting. Proponents believe the quality of white light produced by an OLED is superior to an LED, but they lag in overall performance in terms of efficiency, longevity, and cost. Prof. Forrest and his group are working to overcome these deficiencies. For example, they developed a low-index grid (LIG) embedded in the organic layer to redirect the light; when combined with additional methods to extract light, a LIG can lead to a threefold increase in overall efficiency. Improved manufacturing may also lower the cost of white light OLEDs.
Ultrasound Becomes “Nanosound”

Ultrasound deals with pressurized sound waves at frequencies higher than audible sound. As the frequency of the sound waves is increased from KHz to MHz levels, they become useful for medical imaging and even non-invasive therapy. For example, highly focused ultrasound has been used to fragment large kidney stones and prostate tumors, without invasive surgery. Being able to focus the ultrasound beam even smaller would open the door to treating tiny cancerous tumors, artery-clogging plaques or even targeting single cells for targeted drug delivery.

Our faculty were able to accomplish an extremely focused sound beam through the use of an optoacoustic lens that embeds carbon nanotubes in a polymeric film. In experiments, the researchers detached a single ovarian cancer cell from healthy surrounding tissue, and blasted a hole less than 150 micrometers in an artificial kidney stone. With this new technique, doctors could target tumors as small as 75 µm in diameter, much smaller than the 2 mm threshold that is currently possible. This work was accomplished by a team of researchers led by Prof. Jay Guo, Prof. Euisik Yoon, Prof. John Hart (Mechanical Engineering), and Prof. Zhen Xu (Biomedical Engineering).

Improved POC Medical Testing With Nanoelectronics

Point-of-care (POC) medical testing is any diagnostic test done outside a hospital setting. It offers immediate diagnosis and treatment for a variety of medical issues ranging from diabetes and heart problems to pregnancy diagnosis. The U.S. is the leader in POC testing products, recently valued at $3.68B in 2012.

Nanoelectronic sensors are ideally suited to POC devices. Current nanoelectronic sensors are capable of detecting a wide array of molecules in certain solutions. However, they fail in solutions that contain a high percentage of salt due to the bioscreening effect. Many desirable applications have salt, including testing human blood. Prof. Zhong has developed a technique for operating a carbon-based nanoelectronic sensing platform at frequencies high enough to help mitigate the bioscreening effect. He is now developing a graphene-based biosensor to further improve the efficiency of these devices.

Graphene is a material that could bring on a revolution in the electronics world by competing with or even replacing silicon in high-performance computers and electronics. Graphene is comprised of a single layer of carbon atoms arranged in a hexagonal pattern. It is highly conductive (conducting electricity 30 times faster than silicon and heat 10 times faster than copper), flexible yet harder than a diamond, and absorbs only 2.3% of the light it encounters. It is also inexpensive and easily manufactured.

Discovering What Graphene Can Do — Researchers around the world have been hot on the trail for ways to exploit graphene. At Michigan, Prof. Ted Norris has been studying the ultrafast electron dynamics in this material for about six years to lay the groundwork for its use in practical devices. He’s been particularly successful at unlocking the secrets of graphene through a coherent control experiment, where short laser pulses were used to inject electrical currents into this material. “Normally when you shine light on a material it’ll create electrons and holes,” explained Prof. Norris. “But they aren’t going anywhere. We can do it in such a way that we can create an electron current, and measure it by the terahertz radiation it emits. We’ve been able to learn a lot about the material that way.”

World’s First Room Temperature Infrared Photodetector — Building on this information, Prof. Zhaohui Zhong and his team recently succeeded in building the first known room temperature broadband infrared (IR) photodetector. IR detectors are used in a wide array of applications, including optical fiber communications and lasers; imaging in industry, medicine, and science; remote sensing; and detection of humans and animals during the day and night. IR photodetectors offer increased sensitivity and response time compared to their thermal counterparts, but a conventional IR photodetector must operate below 100 K to work at the mid to far infrared region. Prof. Zhong’s new IR photodetector changes all that. A paper detailing the device will be published soon.
Move Over Flash – Memristor Technology is the New Boss

Memristors offer the promise of transforming the semiconductor industry by enabling smaller, faster, cheaper chips and computers. In some areas, such as memory, the improvement over existing technology will be exponential. A memristor is a nanoscale computer component that offers both memory and logic functions in one simple package. More specifically, it is a two-terminal resistive switching device with inherent memory.

Prof. Wei Lu and his team built a specific type of memristor device called resistive random access memory (RRAM), which has fabulous inherent properties for computing. RRAM is capable of extremely high density because it is not made from silicon and can therefore be stacked vertically, yet is still cost effective and scalable. With RRAM it is possible to randomly write and erase bits, and it has very low switching energy.

Prof. Wei Lu and his team are among the leaders in developing this technology to the point where it can be commercialized. “Every major semiconductor company has significant effort in these devices because it is considered the future of next-generation memory,” said Prof. Lu. His company, Crossbar, Inc., developed an RRAM prototype and is promising vast improvements in memory capabilities. For example, a smartphone using this technology could store 250 hours of HD video and carry a charge for a week. RRAM has the potential of replacing the flash memory used in tablets, digital cameras, and solid-state drives.

Memristor Brainiacs – Memristors for Super-charged Computing and Image Processing

Because memristors combine high density with actions based on past behavior, Prof. Lu has been investigating whether they could work together in ways resembling human neurons. There are about 85 billion neurons in the human brain, each interacting with their neighbors through synapses. Synapses are the gaps between neurons; they are the means by which neurons pass on chemical or electrical signals to neighboring neurons.

In a groundbreaking 2010 paper, Prof. Lu described how 2 terminal memristor devices can interact with CMOS transistors in a manner very similar to the synapses and neurons in the human brain. He envisions building a computer in which the memristors will act as artificial synapses between conventional circuits, which will act as the artificial neurons.

One specific application of this device is image processing. “With the proliferation of sensors, videos, and images in today’s world, we increasingly run into the problem of having much more data than we can process in a timely fashion,” said Prof. Lu. “Our approach aims to change that.”

He plans to build a system that uses memristors as memory nodes along traditional wired connections between circuits to improve the efficiency of the machine’s learning process. “Most data in images or videos are essentially noise,” Lu said. “Instead of processing all of it or transmitting it fully and wasting precious bandwidth, adaptive neural networks can extract key features and reconstruct the images with a much smaller amount of data.”

Communicating With Flexible Electronics

Compared to traditional printed circuit boards, flexible printed circuits offer unparalleled design flexibility in addition to increased performance in many areas. They are used in most any industry, including biomedical (devices that rest on the skin for health monitoring, as well as medical implants), energy (flexible solar cells), automotive systems, electronics (cell phones, displays, wearable electronics), and telecommunications.

In terms of advancing the field of flexible circuits, a key concern is to improve the method for receiving and transmitting collected data. “One of the most important elements in communications is modulating the signal,” explains Prof. Zhong. “If you want to broadcast music on a radio station, or send information electronically, you have to modulate and encode information into a carrier wave, and that’s done by modulators.”

Prof. Zhaohui Zhong and his group have developed the first all-graphene flexible, transparent digital modulator for high-speed communications. It is the first time anyone has shown quaternary modulation with a graphene circuit, which doubles the speed of existing binary modulation schemes. It is also bipolar, which enables a drastic reduction in circuit complexity compared to conventional silicon-based modulators. This technique can be applied to today’s multimedia and communication devices for increased performance. His group is also pushing the circuitry to higher frequencies which will expand the range of applications that can benefit from graphene circuitry.
Nanotechnology for Sharper Displays and Disappearing Ink

A carbon nanotube is a cylindrical structure made from carbon sheets that are one atom thick. Quantum effects come into play because of their size, resulting in unusual electrical and mechanical properties.

Nanostructured Color for Sharp, Efficient, Displays

While investigating a way to build more efficient, smaller, and higher-definition display screens, Prof. Guo and his group discovered that nano-thin sheets of metal with precisely spaced gratings could be used to generate different colors. “Amazingly, we found that even a few slits can already produce well-defined color, which shows its potential for extremely high-resolution display and spectral imaging,” Guo said. This includes projection displays as well as wearable, bendable, and extremely compact displays.

This new technique makes use of optical resonance rather than absorption as in traditional color pigments, and the reflected light can be recycled to improve the display efficiency. His team used this technique to make what they believe is the smallest color U-M logo. At about 12-by-9 microns, it’s about 1/6 the width of a human hair. Such color filters can also be integrated into color imaging devices.

In related work, Prof. Guo has taken a lesson from the beautiful colors we see on peacock feathers. The feathers themselves are brown in pigment, but take on their iridescent color due to light interference from the fine structures on the surface of the feathers.

However, for display applications, the fact that the color changed with the viewing angle was problematic.

Prof. Jay Guo and his team discovered that nano-sized cavities etched in glass and covered with a thin metal can be used to generate colors that stay true up to an angle of ±80 degrees. “With this reflective color,” said Guo, “you could view the display in direct sunlight. It’s very similar to color print.”

Surprising Disappearing Nano-ink

Prof. Guo would say the most exciting kind of discoveries are accidental. He and a postdoctoral researcher were investigating cloaking with optical metamaterials, and getting nowhere. Then, a material was dropped onto a dense carbon nanotube “forest” (when carbon nanotubes are closely aligned the individual tubes will stand straight up – creating an effect like a forest of trees) and couldn’t be found. It seemed to have just disappeared.

Seeing what was possible, they created a coating made of carbon nanotubes that when “painted” onto a raised 3-D image, made it appear as a 2 dimensional black sheet. The key was to position the carbon nanotubes, which absorb light across a broad band of wavelengths, just right to absorb virtually all the light. When placed on a black background, the image disappears from sight.

Potential applications include ultra-crisp display screens, solar heating, and even camouflage for stealth aircraft. A Belgium artist interested in the project sent Prof. Guo a work made of titanium to use as a test piece.

How the LNF and NNIN Can Help You With Your Research at the Nanoscale

The Lurie Nanofabrication Facility ensures Michigan’s future as a major player in future micro and nanotechnology. The LNF was a founding member of the National Nanotechnology Infrastructure Network (NNIN), an NSF-funded program initiated in 2004 to make the promise of Nanotechnology accessible to all. The NNIN is an integrated network of premier user facilities across the nation offering 24/7 affordable access to production-level fabrication tools supported by specially trained experts. In addition to fabrication tools, the NNIN also provides expert-supported free computation resources that can help optimize processing and reduce fabrication iterations. With capabilities that would otherwise be cost-prohibitive for smaller organizations or research groups, the LNF and NNIN can enable a wide range of research projects.

For more information and/or to schedule a tour of the LNF, please contact Dr. Khaled Mnaymneh, LNF/NNIN Outreach Coordinator (kmnay@lnf.umich.edu; 734-545-4507).
Research in nanotechnology caught fire in the early 1980’s thanks in large part to the commercialization of Molecular Beam Epitaxy (MBE) systems and scanning tunneling microscopes. These devices allowed researchers to grow and view molecular and atomic scale structures for the first time.

Some areas of manufacturing, such as the modern computer chip with its nanoscale transistors, has kept pace reasonably well with nanotechnology. One reason for this is the extreme adaptability of silicon to manufacturing processes and different semiconductor materials. However, the semiconductor industry is not currently capable of manufacturing many other forms of technology based on nano-sized components.

Major governmental programs have been initiated to assist in new forms of nanomanufacturing, including the Presidential call for a $1B investment to create a National Network for Manufacturing Innovation (NNMI). Part of this investment will focus on micro and nanoscale manufacturing.

Here at Michigan, the Center for Wireless Integrated Micro-Sensing & Systems (WIMS²) held a Nano and Micro Manufacturing Workshop to bring together interdisciplinary researchers and manufacturers of nanotechnology (see pg. 35 for more info). Just a few weeks later, NSF held the NSF Workshop on Future Research Needs in Advanced Manufacturing from Industrial Perspective. Both workshops involved leaders from industry and academia discussing how to bring more nanotechnology research to market.

Profs. Guo and Zhong, in collaboration with Prof. Steven Yalisove (MSE) and Prof. John Hart (MIT), have their own program in scalable nanomanufacturing. They are using ultrafast femtosecond lasers to build and scale up carbon-based nanostructures, such as carbon nanotubes and graphene.

Prof. Lu’s company, Crossbar, Inc., will manufacture a new class of computer memory based on his work with nanoscale memristors.

Prof. Becky Peterson uses solution-based nanomanufacturing techniques to create nanoscale features via ink-jet printing. By selective surface energy patterning, she can scale down the gate length of printed thin film transistors for high-performance, flexible, large-area, and printable electronics.

During the past decade, Prof. Guo and his group have been perfecting a technique for roll-to-roll nanolithography. Nano-imprint lithography enables large area, low cost fabrication of nanoscale structures. Among the many applications for these structures are transparent electrodes for use in organic photovoltaic devices, liquid crystal displays (LCDs), touch panels, and organic light emitting diodes (OLEDs).

Prof. Guo’s group built a prototype device for high-throughput and high-resolution nanoscale patterning. This technique allows for large area printing with a variety of substrates, and includes a method for producing metal mesh patterns as a transparent electrode. His method is being used by major companies in Japan and Korea for commercial applications, and once perfected, could be used to print components for displays and solar cells.

Research in nanotechnology is the key to future transformative advances in electronics, medicine, computing, and energy. The research described in this article points to applications that may be on the marketplace in a year, or perhaps 10–20 years. It’s an exciting area filled with discovery as the research continues to reveal important and even startling results.

If this is a world you’d like to explore further, come visit our labs or contact us. We’ll try to respond within a nanosecond.