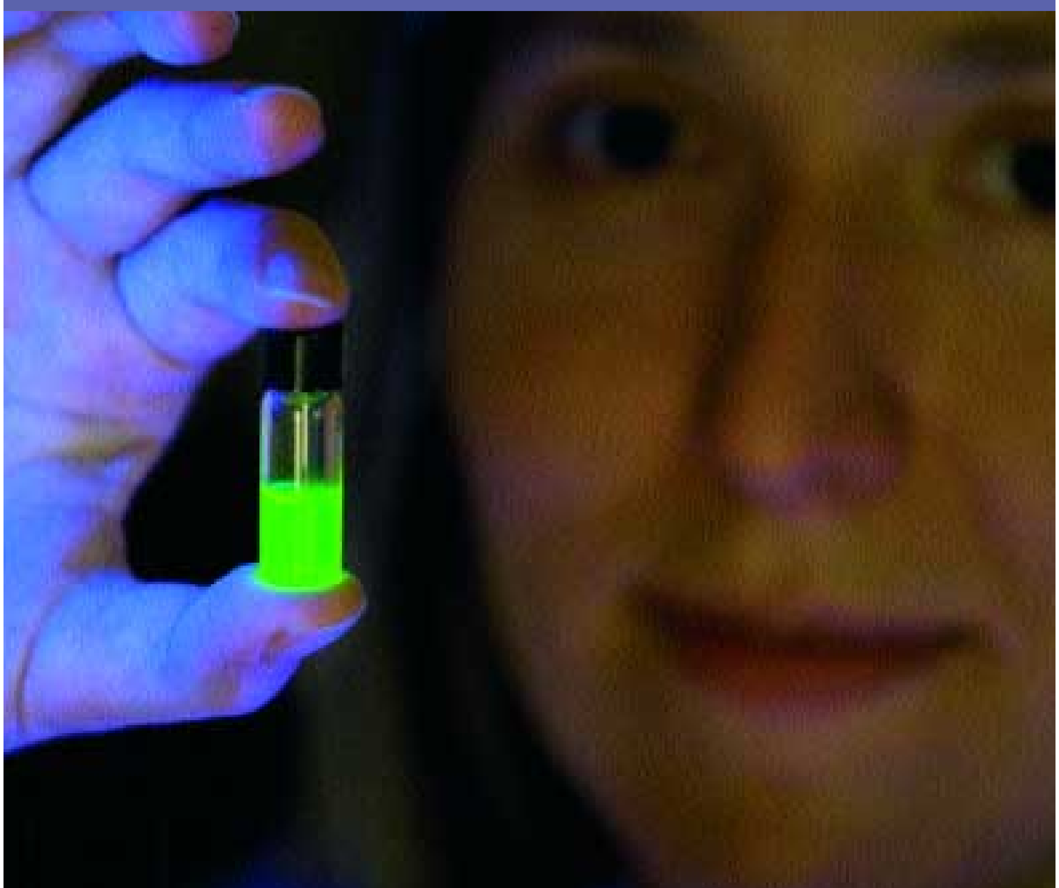
EXPLORING THE TINIEST OF SCIENCE FRONTIERS

Physicist Sculpts with Atoms to Build Electronic Devices

BY PATRICIA MCADAMS • PHOTOS BY LISA GODFREY



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Blinking pixels on Marija Drndic's computer screen twinkle like stars from a distant galaxy. The computerized flashing represents the activity of nanocrystals, minuscule specks of matter that pulse with energy on the outskirts of scientific inquiry. Understanding this blinking effect, tracking the intensity of the specks over time and regulating the fluorescence of a single particle are among the goals of Drndic and her laboratory team.

"We want to know how to control this blinking, because it is an obstacle for many applications where nanocrystals could be used as fluorescent markers," says Drndic, an assistant professor in the Department of Physics and Astronomy. A single nanocrystal, for example, could be used to tag DNA molecules or proteins.

"Nanotechnology is a still-emerging field of science aimed at studying and manipulating objects on a very small scale," she says. "We are working with particles as small as a nanometer in size, which is 10,000 times smaller than the diameter of a human hair."

Drndic investigates the optical and electrical properties of these nanocrystals as well as nanowires and biomaterials. While much of this work is in its infancy, some early discoveries have earned her the highest honor a young scientist can achieve. In June 2005, she traveled to the White House to receive the Presidential Early Career Award for Scientists and Engineers (PECASE).

She reaches under the hood in her lab and lifts a tray of vials filled with substances in a dazzling array of color. Inside the vials, about half the size of her index finger, are nanocrystals of exquisitely ordered atoms. "Nanocrystals exist in a rainbow of colors," she explains. "For example, 2-nanometer cadmium selenide nanocrystals emit a blue light, while 8-nanometer particles emit red. The sizes in between are green, yellow and orange. The color shifts depend on size. This is because electrons occupy a well-defined energy ladder, and the spacing of levels in this ladder increases as the nanocrystal size decreases."

Because nanocrystals are so small, they are governed by the laws of quantum mechanics, rather than classical physics. The latter describes the motion of objects that range in size from planets to molecules. Drndic is taking an atom's-eye view, where different laws hold sway. Here, where electrons overlap and interact, collective and complex properties appear, and novel results are possible. Among these unusual effects are the differing splashes of color that her nanocrystals exhibit at room temperature.

"This is important because in the past, people have mostly studied quantum effects in nanostructures that were bigger than this," she explains. "You had to cool down the structures to very low temperatures, however, to see these effects."

According to Drndic, research at room temperature is significant for new applications such as transistors and memory or logic devices. Her work may one day have application, too, in the area of sensors. The properties of nanocrystals depend on their environment. By studying the light emitted from particles, researchers might be able to detect the kinds of molecules that are around them.

"Another possible application is quantum computation, which is probably far in the future, if at all," she adds. "Theoretically, if you do computations quicker, you could solve a variety of currently unsolvable problems related to encryption or cryptography."

Nanoelectronics program officer Chagaan Baatar in the Department of Defense, Office of Naval Research, who recommended Drndic for the PECASE Award, says the nomination is a two-step process. The candidate first must win the Navy's Young Investigator Program (YIP) Award, another highly competitive honor. "In 2004, Dr. Drndic emerged as the top YIP candidate in the electronics division and went on to become one of only two PECASE nominees by the Navy in that year. Her research in nanocrystal-based electronics holds great potential for future Department of Defense applications requiring ultra-low power, high density electronic components."

Drndic was born and raised in Belgrade in the former Yugoslavia (now Serbia), although she spent years of her childhood living and traveling throughout Africa with her grandparents. "At a very early age, I became interested in big questions like, Why are we here? and What is the meaning of life? Also, my paternal grandfather had a physics degree in celestial mechanics, and he would explain why the sky is blue and reasons for other everyday phenomena." Stories of the stars and sun sparked her imagination, and she was drawn to reading books about scientists and science.

She started college at the University of Belgrade but transferred to Harvard in her junior year, in part because of the civil war, which had just begun. Most of her family had left the country and were urging her to leave as well. She earned a Ph.D. from Harvard in 2000 and then spent three years working as a Pappalardo Fellow at MIT before coming to Penn in 2003.

For her thesis research, Drndic developed microelectromagnets, minute wires engineered into circles and lines or combinations of these.

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"Our first experiment was to make a magnetic mirror for atoms," she says, sketching the microelectromagnet she designed. The line depicting the nanowire snaked back and forth across the paper, creating a dense fabric of parallel lines. "If you connect this device to a big power supply and put a voltage across, you get an electrical current. And when you have an electrical current, you have a magnetic field. It is the geometry here that is important."

The magnetic field produced by this configuration allows atoms to bounce off the magnet just as light reflects off a mirror. If the atoms come toward the magnet perpendicularly to the surface, they bounce back on a perpendicular line. If they come in at an angle, they will go out at an equal reflection angle.

"The fabrication of this device was challenging because when you put a lot of electrical current through the wires to get a strong magnetic field, the wires get too hot and burn, so you destroy your device." When she first proposed her goal in a paper, her professor — a famous atomic physicist — declared that it could not be done.

Unruffled, Drndic moved forward, solving one technical problem after another until she succeeded.

"Eventually I put micron-size gold wires on sapphire, because sapphire is a good heat conductor, and it worked. It's funny because this device is a very simple idea, but it became a pretty big hit." Because microelectromagnets allow physicists to manipulate atoms in ways impossible in the past, the magnets have had far-reaching effects in only a few years.

"One of the things we are excited about now," Drndic says, "is the synthesis of a variety of nanocrystal shapes." She replaces the vials under the hood in her lab and moves to a computer nearby. The computer is connected to the lab's atomic force microscope, which uses a sharp tip to probe minuscule surfaces with great accuracy. By moving the tip around, an image of the surface can be made and transferred to the computer screen.

Drndic points to colorful images of dumbbells, tetrapods and other shapes. These structures, what nanoscientists call "devices" — a mere 20 nanometers in diameter — have been fashioned from nanocrystals, which often self-assemble because of forces between the particles. Drndic and her team are studying this self-assembly as well as what properties the devices may have.

"When you put a voltage across these devices, the current can behave differently depending on the configuration of the nanocrystals in your device."

Drndic also is looking at possible biomaterial mergers in chemistry, wherein she and her colleagues will interface nanocrystals with proteins, DNA and polymers. "One reason would be to make metallic wires out of DNA," she says, referring to the double-stranded molecule of life. DNA's two strands unravel and separate during replication, and each strand serves as a template to grow a new one. This precise and predictable copying of genetic information onto new complementary strands of DNA is the basis for inheritance. "DNA has nice properties of recognition and could possibly be used to create circuitry," Drndic says. "For now, this research is 'out there' too. It's difficult to pinpoint where the impact is going to be."

She hopes to make tiny nanocrystal devices with only one, two or three particles. Ultimately, she wants to electronically control the individual nanocrystals in these devices. Achieving this could one day result in applications from quantum electronics to biology and medicine.

A sign on the blue door leading into her lab reads: "Erasmus Darwin held that every so often, you should try a damn fool experiment. He played his trombone to his tulips. This particular result was in fact negative."

Drndic may not be serenading tulips, but she has been seduced by the intricacies of science at the edge and loves grappling with solutions to baffling problems.

"Taking nanocrystals that are unexplored, exploring them more, then discovering and building applications are all important," she says. "History typically shows that something insightful and useful comes out of adventures in research." ■

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Undergrad Energy

MARIJA DRNDIC IS FASCINATED BY HER RESEARCH, YET CONFESSES THAT MENTORING STUDENTS IS ONE OF THE BEST PARTS OF HER DAILY LIFE. Particularly energized by beginning students whose enthusiasm she finds contagious, the nanoscientist welcomes about six undergraduates to work in her lab throughout the year. The budding scientists are effusive about what this opportunity has meant to them. Greg Calusine, who is attempting to build nanocrystal-based solar cells, says that working in the lab has allowed him to become more sure of what he wants to do. "This experience will undoubtedly help me get into grad school and continue on as an experimental physicist," he says.

Arif Shiliwala, who is modeling nanocrystal transport systems, says that Drndic has her students perform real research leading to great papers. "All my projects have had a direct impact on frontline research," Shiliwala says. "Dr. Drndic is a phenomenal professor too. She is extremely funny and always has great stories to share."

Drndic, a luminous personality with an easygoing nature, says the pleasure is mutual. "I've been in this field for a long time, so my brain thinks in clichés. But when you have beginning students, they look at physics from scratch. Often, they ask very important questions that I failed to think about."

—PATRICIA MCADAMS