Profile of Peidong Yang

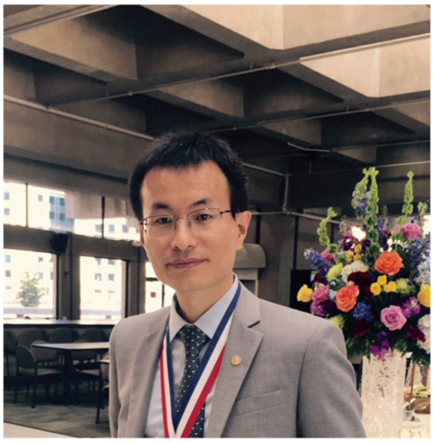
Paul Gabrielsen, *Science Writer*

In the fall of 2015, Peidong Yang, professor of chemistry at the University of California, Berkeley, received a phone call from the MacArthur Foundation. The caller asked if Yang was alone. Having just finished his lunch, Yang hurried to his office. The caller identified himself as the director of the Foundation, and told Yang of his selection for a MacArthur fellowship.

The grant recognized Yang's pioneering work in developing semiconductor nanowires, which are small filaments with tunable optical and physical properties. By the time of the MacArthur grant, Yang, who was elected to the National Academy of Sciences in 2016, had already made advances in nanowire photonics, including nanoscale lasers. Shortly thereafter, he and his group showed how nanowires could contribute to a zero-carbon energy future by mimicking one of biology's basic processes: photosynthesis.

Education in China

Yang was born in 1971 in Suzhou, China, a city called "the Venice of the East" because of its many canals. The child of a doctor and a teacher, Yang and his two older siblings were raised in a culture that placed high value on education. In a secondary education system that Yang describes as examination-heavy, he excelled in chemistry and mathematics. Praised by his teachers for his scores, Yang chose chemistry as a major when, in 1988, he entered the University of Science and Technology of China in Hefei, 200 miles from Suzhou.



Peidong Yang. Image courtesy of Peidong Yang.

As a second-year undergraduate, Yang joined the laboratory of Yitai Qian, who studied high-temperature superconductors. "I was fascinated with the solid-state materials chemistry of these high-T superconductors," Yang says. "You can mix compounds and make new crystals and new compositions and get a higher transition temperature for the superconductor state." His years in Qian's laboratory set the course for Yang's own research program in solid-state chemistry and materials engineering that continues today.

Opening a New Field at Harvard

Yang applied to dozens of graduate schools in the United States. Ironically, the first to reject his application was the University of California, Berkeley, although six schools eventually offered him admission. Yang chose Harvard University, in part because Charles Lieber, a chemist who would become Yang's graduate advisor, was a member of the faculty. At the time, in 1993, Lieber was studying high-temperature superconductors, but that line of research was winding down in favor of the emerging field of nanochemistry. Many of Lieber's students were working on buckminsterfullerene (60-carbon spheres) and carbon nanotubes, both structures made from one-atom-thick sheets of carbon.

Lieber and Yang chose a different tack. If carbon atoms can form such structures, they mused, what about other elements on the periodic table? Their experiments led to the development of semiconductor nanowires. "The moment you make the semiconductor into this filament," Yang says, "their chemical properties and physical properties change. That's what we were chasing after."

Yang and Lieber's work helped launch a new field of nanoscience as other groups also experimented with nanowires, nanorods, and nanowhiskers. Nanowires are typically between 1 and 100 nanometers in diameter, 1,000 times smaller than a human hair. In electron microscope images, nanowires made from various materials, including silicon, oxides, and nitrides, look variously like needles, strands of hair, or shag carpets.

Yang and Lieber began by growing nanowires of magnesium oxide inside copper oxide superconductors (1) to enhance the critical current densities of the superconductors. The pair was granted a patent for metal oxide nanorods in 1999 (2), and by the time Yang graduated from Harvard, he and Lieber had successfully grown junctions between silicon nanowires and carbon nanotubes (3).

Inspired by Lieber's creativity and drive to pursue new ideas, Yang chose to pause his nanowire research for his postdoctoral fellowship and spend some time in a completely unrelated field. Yang joined the laboratory

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of Galen Stucky at the University of California, Santa Barbara, where Stucky was working on self-assembly of porous materials in solution. With fellow postdoctoral scholar Dongyuan Zhao, Yang developed high surface area materials SBA-15 and SBA-16, which are now classified as mesoporous materials, or silica structures with pores between 2 and 50 nanometers in diameter. Although Yang's postdoctoral fellowship only lasted 16 months, he and his colleagues published several papers in *Nature* (4) and *Science* (5) on their new materials. "It's quite amazing," Yang says of his research output in a relatively brief time. "It's partially because at that time the topic was very exciting."

Berkeley at Last

Both Lieber and Stucky encouraged Yang to begin applying for faculty positions after a year at the University of California, Santa Barbara. The research proposal he included in his application marked a return to semiconductor nanowires. Yang's proposal explored the interactions of nanowires with both light and heat and ways to convert those interactions into electricity. With his nanowire experience and his strong publication record, Yang garnered several job offers. He accepted an offer in 1999 from the University of California, Berkeley.

In his initial years at Berkeley, Yang explored the optical properties of nanowires. Because the composition, length, diameter, and density of nanowires are highly tunable, nanowires can perform a staggering range of optical functions. As light absorbers, nanowires could serve as photodetectors, chemical sensors, and solar cells. As light emitters, they could function as light-emitting diodes, photon waveguides, and lasers (6).

Converting Energy with Nanowires

With his experience studying the interactions of light with nanowire semiconductors, Yang was well-positioned to take on the challenge of artificial photosynthesis when Steven Chu, then laboratory director of Lawrence Berkeley National Laboratory and later Secretary of Energy, launched the Helios Solar Energy Research Center to spur research into synthetic photosynthesis. Natural photosynthesis is essentially the conversion of light energy, carbon dioxide, and water into organic compounds, with oxygen as a byproduct. An artificial photosynthesis system could generate not only power but also useful chemical byproducts while consuming, rather than emitting, carbon dioxide.

Yang's initial design used high surface area nanowire arrays as the light absorption medium, which would pass electrons to a catalyst that would expedite the splitting of water molecules and the reduction of carbon dioxide molecules. The design was completed shortly after the Helios program was announced (7). But fully developing the system and its materials would take more than a decade.

Meanwhile, Yang's group also explored nanowires' thermoelectric applications. Thermoelectric generators require no moving parts to produce electricity, only a strong temperature difference between hot and cold plates, coupled together with the right thermoelectric materials. At the right scale, such generators could recycle waste heat from many industrial processes into electricity.

The practically 1D nature of nanowires can control the transport of heat and electricity within a material, and in the hands of Yang's laboratory members nanowires achieved improved efficiency over previous bismuth telluride thermoelectric generators. In 2009 Yang and former thermoelectric project team member Matt Scullin launched Alphabet Energy to market nanowire-based thermoelectric generators. Scullin is the CEO of the company, which now sells several thermoelectric products that can recover up to 2.5% of the electricity available from waste heat. The generators are connected to exhaust flows in factories, oil fields, and other industrial processes and use the heat from the exhaust to produce electricity. This zero-emissions energy offsets the power required by the process, reducing electricity use and carbon emissions.

An Artificial Leaf

In 2015, Yang's group published the design of their fully integrated artificial photosynthesis system (8). By Yang's own description, the system is "cyborgian," fusing biology and nanochemistry. Nanowire semiconductors absorb light energy and convert it into electricity, then feed those electrons to bacterial catalysts that combine water and carbon dioxide into organic compounds. Initially, the system produced acetate as a product, and the acetate can then be converted into other chemicals, such as butanol and polymers. The cyborgian system, Yang says, might someday aid human space exploration by efficiently converting waste products back into useful materials, conserving limited resources (9).

Yang's integrated system has developed in parallel with the artificial leaf system developed by Daniel Nocera at Harvard University. Both groups have designed systems that use light energy to split water molecules and synthesize new organic compounds. Nocera's research is more focused on catalysts than semiconductor nanostructures, however. Light-energy harvesting is achieved through conventional photovoltaic technology.

Yang continues to investigate additional materials and formulations to expand his nanowire photonics portfolio. In his Inaugural Article (10), Yang describes a class of semiconductor nanowires that use halide elements, such as chlorine, bromine, and iodine to link atoms together through ionic bonding rather than traditional covalent bonding. The properties of the nanowires, called inorganic halide perovskites, are highly tunable depending on the halides included. "We show that you can have lots of flexibility to reconfigure the crystal lattice to use the desired optical properties or desired electronic structure," he says.

Artificial photosynthesis is Yang's primary research focus for the next several years as he looks forward to not only reducing, or fixing, carbon dioxide in synthetic processes, but fixing nitrogen as well.

Yang is also returning to his homeland to help further the culture of education that drew him to science in the first place. Working with officials at the recently opened ShanghaiTech University, Yang is assisting in recruiting and vetting faculty at the first completely tenure-track university in China (11). In a system new to China, tenure-track professors begin their career as independent researchers instead of ascending through the previous hierarchical system. The goal, Yang says, is to encourage more original and basic research in a country with thousands of universities and millions of students. "It's an experiment," he says.

"Long-term, we are trying to offer a carbon-neutral solution for energy," Yang says of his laboratory's primary research focus. "Imagine if one day this synthetic technology is implemented at a large scale. Then we are recycling carbon. I'm quite confident that storing solar energy into chemical bonds is the ultimate solution."

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