John Woollam's Career in Ellipsometry

by Jennifer Ouellette

A pioneering physicist builds a business measuring optical properties

John Woollam, standing in front of a display of patent certificates at the J. A. Woollam Co. headquarters in Lincoln, Nebraska, examines a silicon wafer, which can be measured with spectroscopic ellipsometry to reveal overcoat film thickness and composition.

Photography by Ben Weddle and Associates (www.benweddle.com)

Once, the academic researcher-turned-businessman was a rarity. Today, physics entrepreneurs start their own companies at the drop of an investment dollar, spinning university research into commercially viable products and applications. One of the first but little heralded pioneers to do so was John Woollam, a physics and electrical engineering professor at the University of Nebraska–Lincoln (UNL), who turned his expertise in ellipsometry into a viable commercial business. Founded in Lincoln in 1987, J. A. Woollam Co., Inc., has grown into a worldwide leader in spectroscopic ellipsometry. It holds more than 40 patents and employs 35-plus people, more than half of whom have engineering or science degrees.

Woollam came by his interest in science, business, and engineering naturally, thanks to the influence of his father, who owned a company in Kalamazoo, Michigan, selling water pumps. Arthur Woollam left school after the 9th grade to support his mother following his own father's death, but he became a registered engineer through correspondence courses. He routinely took his son to the job with him, demonstrating the principles of how water pumps worked and the use of water in manufacturing. The younger Woollam spent hours building creations in his father's shop. Nonetheless, he admits, he was less than a stellar student in junior high, mostly because school did not interest him.

That attitude had changed by his sophomore year of high school, after a history teacher convinced him that although grades are not everything, they do provide a benchmark for achievement. That same year, Woollam joined the high school swim team, which forced him to learn to budget his time effectively, a skill that has served him well throughout his career. Another strong influence was his high school physics teacher, Roy Mesic, who ran a rigorous class and encouraged the teenager to tackle problem solving on his own if he wanted to succeed in physics. "You learn enormously by solving physics problems, because you are applying mathematics to what happens in the real world," says Woollam, who encourages his own students to do the same. "I don't just get up and lecture; I make sure they work problems so they can use their minds."

Electromagnetics and optics captured Woollam's interest early on and formed the basis of his high school physics project. "I have always been fascinated by the sheer elegance of Maxwell's equations, their symmetry, and the beauty of the solutions," he says. So at Kenyon College (Gambier, Ohio), he opted to major in physics instead of electrical engineering, encouraged by his advisor, Franklin Miller, Jr., author of the widely used textbook *Col-*

lege Physics. For graduate school, Woollam attended Michigan State University (MSU). He earned a master's in physics in 1963, but he flunked the Ph.D. qualifying examination the first time he took it. Undaunted, he went back to his high school solution: problem solving. "My reaction to a lack of success is to fight back even harder," he says. "So I took every problem on every exam for the previous 10 years and solved every one of them during the next year." This time, he passed the test—topping his class—and earned his Ph.D. from MSU in 1967.

Career start

After graduate school, Woollam worked in cryophysics and superconductivity for 13 years as an employee of the National Aeronautics and Space Administration (NASA), where his assignments included developing advanced power and propulsion systems, among other projects. In his spare time, he earned a master's degree in electrical engineering from the Case Institute of Technology at Case Western Reserve University (Cleveland, Ohio) in 1978 to supplement his physics background.

When NASA began scaling back its investment in superconductivity research, Woollam became interested in exploring other employment. Instead of accepting a position offered to him at Wright-Patterson Air Force Base, he moved to UNL—then as now, one of the country's leading centers of ellipsometry. When he was asked by the dean to take over the ellipsometry program, Woollam agreed. "I was still doing cryophysics at the time, toting liquid nitrogen and helium across campus in the middle of a Nebraska winter, so I welcomed the change," he jokes.

Ellipsometry is not a new technique, having been around since the early 20th century. But not until the computer advances that began in the late 1970s did it become useful for both basic and applied research. "There is a tremendous amount of calculation involved because the physical quantity that scientists are interested in is not contained in the raw data that the instrument creates," says Ping He, one of Woollam's former students and an employee of J. A. Woollam Co. since 1993. "Those quantities must be calculated based on physics first principles, which is nearly impossible without a computer." Ellipsometers measure the elliptical states of polarized light reflected from or transmitted through a material surface. By studying interface-induced changes—specifically, the phase differences in the interaction between the material and polarized light—one can measure fundamental optical properties of physical systems, including the refractive index, absorption coefficient, surface roughness, alloy concentrations, and thickness.

Woollam used ellipsometry at UNL to study new semiconductor materials for high-frequency electronic devices, such as gallium arsenide and aluminum gallium arsenide. However, he became frustrated by the time it took to acquire data using the ellipsometers and creaky computers of the time: roughly 20 minutes for a single wavelength and several hours or a day for a full spectrum. "I was interested in using ellipsometry in materials and surface science, so I needed the answers much faster," he says. "So we decided to automate the process." The innovative instrument proved so much faster at collecting data on material properties that Samuel Alterovitz,

Outside company headquarters are engineers and physicists (left to right) Thomas Tiwald, Jeff Hale, John Woollam, Martin Liphardt, and Ping He.

a former NASA colleague who had worked in Woollam's lab for a year as a visiting scientist, wanted to have a similar capability. The company won a competitive bidding process, and an improved version of the instrument was completed in 1988.

Alterovitz's enthusiasm for the new instrument encouraged Woollam to set up a fledgling enterprise through contracts from the Small Business Innovation Research program of the Defense Advanced Research Projects Agency, while NASA grants continued to partly fund Woollam's UNL research. It was a daring step for

Woollam watches while James Hilfiker loads a sample into a spectroscopic ellipsometer that covers the vacuum ultraviolet to the near infrared.

the time. "For a university professor to start his own company in the mid-1980s was not a common thing," says Alterovitz, although 10 years later the practice would be almost commonplace. "This was 5 to 10 years before the advent of the Internet, when the fastest personal computer available was a 286 processor. But John has always been an independent person, and he didn't want to just sell his ideas to a big company."

Woollam hired two students who had recently graduated to develop a commercial prototype of the instrument, completing a second ellipsometer for the Army Research Laboratory–Watertown (MA) in June 1989. By then, the instrument's data-gathering and processing speeds had improved so much that Woollam felt confident exhibiting his instruments at trade shows, where he signed up his first commercial customers. "Those instruments were a significant advance in the technology, and they made us globally competitive in the ellipsometer market," says Woollam. The early sales helped get the company off the ground, although Woollam had to dip into his personal finances to keep the firm financially sound in those early years.

Business success

Since then, J. A. Woollam Co. has flourished, largely because of its diversified market, in which the fiscal ups and downs of several cyclical industries tend to balance each other out. For example, the telecommunications industry—particularly manufacturers of WDM (wavelength division multiplexing) filters—needs ellipsometers. Other application areas include solid-state lasers, light-emitting diodes, and optical detectors based on compound semiconductor materials, as well as organic light-emitting diodes (OLEDs). Many involved in the widespread efforts to develop OLEDs envision them one day replacing incandescent lightbulbs as low-cost light sources.

The semiconductor industry is another major application area for ellipsometry because of the large number of thin-film processes it employs. For example, applied in situ, spectroscopic ellipsometry could potentially lead to large cost savings in the semiconductor industry by controlling thin-film properties in silicon integrated circuits at an earlier stage in the manufacturing process. Current procedures locate problems when it is too late to take corrective action. The semiconductor industry also uses ellipsometers to develop new photoresists for lithography, for use in building thin-film devices for the next generation of silicon integrated circuits.

The coatings industry often uses coatings with a low-refractive-index material combined with a high-refractive-index material to make optical filters or reflectors. On the horizon are so-called active optical coatings based on electrochromic materials, which change color when a voltage is applied, as well as Cermet coatings, which are made using nanoparticles embedded in dielectric materials to build systems that convert solar energy into an efficient heat source for space missions.

Woollam still maintains an active research program at UNL, which fre-

HOW IT WORKS **Spectroscopic ellipsometry uses the change in polarization of light incident at an oblique angle to a sample surface to determine nanoscale information about the material. The polarization of the input light is known, and analysis of the polarization of a transmitted or reflected beam can be used to yield properties of the material, including index of refraction, extinction coefficient, thickness, roughness, void fraction, uniformity, and anisotropy. The mathematical analysis is based on the "ellipse of polarization," which uses the *p-s* coordinate system, and this gives ellipsometry its name (see also http://www.uta.edu/optics/research/ellipsometry/ellipsometry.htm). The technique is used on bulk materials, liquids, surfaces of solids, and multilayered thin films. Information learned is greatly enhanced by using wavelengths over a wide spectral range, from vacuum ultraviolet to mid-infrared, and two or more angles of incidence of the light beam to the surface. The technique does not require standard materials for calibration, because light intensity ratios are measured rather than absolute intensity. Ellipsometry is useful in any ambient medium through which light can travel, including air, vacuum, inert gases, water, and oils. Spectroscopic ellipsometers are used ex situ in an open laboratory environment and in situ, for example, on vacuum- or gas-reaction process chambers.**

See also Automated Spectroscopic Ellipsometry. *The Industrial Physicist*, March 1996, pp. 30–34. (http://www.aip.org/tip/INPHFA/vol-2/iss-1/p30.pdf)

quently feeds back into his company, and vice versa. Recently, he has turned to studying biomaterials interfaces, especially protein attachment to different types of surfaces. Using spectroscopic ellipsometry, he studies and characterizes molecular layers as thin as a single molecule with dimensional scales of a few nanometers. “It is one of the greatest technical challenges I have ever encountered,” says Woollam. “I had grown accustomed to working with inorganic materials, but even ones as complex as titanium dioxide are simple compared to most biomaterials.”

Among the basic problems he is studying at UNL is how proteins attach to the surface of common implant materials, such as those used in heart valves and stents, which are meshed tubes used to keep arteries open. In this research, his group is testing a prototype instrument developed by his company for infrared (IR) ellipsometry. A protein’s IR signature can indicate which molecules are present, a capability with potential applications in medical biosensing and possible new markets for the company’s ellipsometers in biology, biochemistry, and medicine. “We are constantly working to improve our instruments and discover new markets and applications,” says Woollam. “You want to stay ahead of your competitors, not get stuck trying to catch up.”

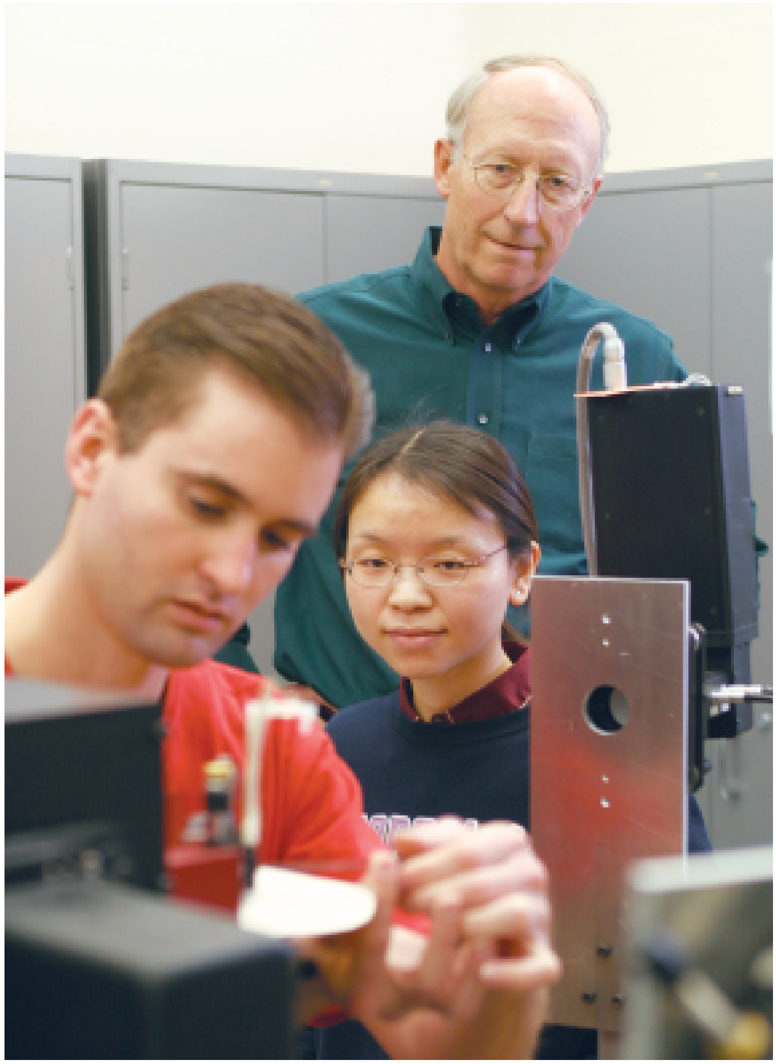
Committed teacher

As if juggling his company and conducting academic research were not enough, Woollam remains deeply committed to teaching, which he views as having a synergistic relationship with his industrial career. He tailors many of his courses to mesh with industrial applications, such as a class on magnetism in which he covers its applications in magnetic memories in addition to the fundamental physics. This approach helps students understand current issues in high-tech industries and helps Woollam understand the needs of future customers. And as an advisor, he can steer students into particularly promising career areas. “Large numbers of physics students go into industrial jobs these days, so knowing about physics in industry is vitally important,” he says.

Teaching also gives him a constant source of fresh talent for J. A. Woollam Co. All of the scientists he employs are former students less than age 40 who, like Ping He, opted to remain in Lincoln to work with their former professor. “John will let his students try their own ideas,” rather than dictating what they do, says Ping He. Woollam has adopted the same approach with his employees, which is part of what attracts former students to his company.

Woollam Co.’s employees have made a favorable impression over the years on Harland Tompkins, among others. Tompkins, a world-renowned expert on ellipsometry and the author of two books on the topic, worked for several years with Woollam’s instruments while employed by Motorola. As with many other company customers, his feedback and suggestions over the years have helped improve the company’s products. “They listen to all their customers. I firmly believe their equipment is the finest in the world, and that is part of the reason why,” says Tompkins. Since his retirement, he has continued to advise the company as a technical consultant.

Even those students who do not end up working for Woollam’s company find their lives imprinted by his influence. Hass Machlab earned his master’s degree under Woollam, working on photothermal deflection spectroscopy, and stayed for another two years as a research associate before joining Rockwell. Like Woollam, Machlab has an entrepreneurial bent and left Rockwell to start his own company, Innovative Software Engineering (Iowa City, IA), which provides software-development and consulting services. Although he maintains that entrepreneurs are born, not made, Machlab nonetheless credits Woollam with being a valuable role model. “He is an incredibly driven and positive person, an excellent teacher, yet he runs his own company as well as a Center for Microelectronic and Optical Materials Research, without sacrificing quality [in any arena],” says Machlab, who learned a great deal about the business environment from watching his former mentor. “Even now, with my own company, I still find myself doing things the way John does them.” Ω



Students Leon Castro (left) and Li Yan load a biological sample into an infrared spectroscopic ellipsometer for Woollam’s class in optical properties of materials at the department of electrical engineering at the University of Nebraska–Lincoln.