Polarization on the Prairie: The History of Ellipsometry in Nebraska

By Ron Synowicki

A common question we receive is "What's a high-tech optics company doing in Lincoln, Nebraska?" Granted, Nebraska is better known for football and steaks than optics. However, ellipsometry has a very rich and interesting tradition at the University of Nebraska-Lincoln (UNL) and the J.A. Woollam Company.

1961-1981: The First 20 Years

In 1956 Professor Nick Bashara founded the Electrical Materials Laboratory in the basement of Ferguson Hall on the University of Nebraska-Lincoln campus. His primary research interest was studying the effects of undesired porosity in thin films.

Pores lowered the density of the material, which also lowered the dielectric constant of the films, causing semiconductor devices to fail. The lower dielectric constant appeared as a lower refractive index at optical wavelengths. Thus, it was possible to determine the quality of a deposited film by monitoring the refractive index. Correctly determining that index required precise knowledge of the film thickness, however. Bashara recognized that ellipsometry was perfectly suited for simultaneously measuring the refractive index and thickness of thin films. In 1961, ellipsometry work began in the Electrical Materials Laboratory. Bashara's ellipsometers were primarily home-built, often by heavily modifying commercial Gaertner and Rudolph ellipsometer systems.

Throughout the 1960s and 1970s professor Bashara and his students published 85 papers in major scientific journals, with 15 Ph.D. or M.S. Degrees granted by the University of Nebraska. In addition to their studies of dielectric films, Bashara and his students used ellipsometry to study how sputter cleaning or ion-implantation caused surface damage to silicon wafers, and how even small amounts of absorption in films could lead to experimental errors if the absorption was neglected in the data analysis.

In 1967 Rasheed Azzam came to the University of Nebraska, where he soon became Professor Bashara's graduate student, earning his Ph.D. under Bashara. His dissertation research concentrated on developing the theory of generalized ellipsometry, but he also pursued interest in new instrumentation and analysis techniques. The collaboration between Azzam and Bashara in the 1960s and 1970s led to the renowned book *Ellipsometry and Polarized Light*, which was first published in 1977. It is the first English language monograph on the subject of ellipsometry, and has stood the test of time. Researchers still turn to this text today as the "bible" of ellipsometry. In addition to their book, Azzam and Bashara hosted the second and third international conferences on ellipsometry in 1968 and 1975.

1981-2001: The Next 20 Years

The year 1981 marked a "changing of the guard" in the University of Nebraska ellipsometry labs. Professor Azzam left Lincoln for the University of New Orleans, where he remains a professor today. Nick Bashara retired in 1981, leaving the university with a long history of ellipsometry, lots of ellipsometry hardware, and in need of a new ellipsometry leader.

John Woollam arrived at the University in 1979 after thirteen years of work at NASA-Lewis Research Center in Cleveland, Ohio. The timing was perfect as in 1981 Woollam agreed to continue Azzam and Bashara's ellipsometry work in the laboratories.

The new era of ellipsometry at UNL saw amazing advances at the hands of many key researchers. George Bu-Abbud finished a Ph.D. that started under Bashara by automating the ellipsometer hardware-making research more convenient. This hardware advance was complemented by improvements in the software for data analysis. Marty Rost took the old McCrackin code and developed software to run on the first DEC computer that UNL received. His software advances led to some of the earliest 3D sensitivity graphs. On the applications side, Dr. Samuel Alterovitz came to UNL in the early 80's to work on semiconductor applications. He is currently at NASA, where he continues to advance applications of SE.

Paul Snyder arrived at UNL in 1985; first as a postdoc and later as a professor. He also has focused on semiconductor applications and his alloy-shifing algorithm is still invaluable to ellipsometry analysis.

New researchers brought different interests to the University. Bashara had concentrated primarily on dielectric films, whereas, the electronic properties of semiconductor materials were now of interest. This necessitated additional developments in both ellipsometer hardware and experimental technique.

Bashara's experimental philosophy was to acquire data at one wavelength and at many angles of incidence. His approach was well suited for the study of dielectrics because the refractive index of a dielectric material varies slowly and smoothly. However, for semiconductors the opposite is true. The refractive index of crystalline materials show sharp spectral features due to electronic transitions in the material. The position and shape of these features are of great interest because they are key to understanding the electronic properties of the material. So, when studying crystalline semiconductors, well-resolved spectroscopic data over a wide spectral range are desired, and fewer angles of incidence are generally needed.

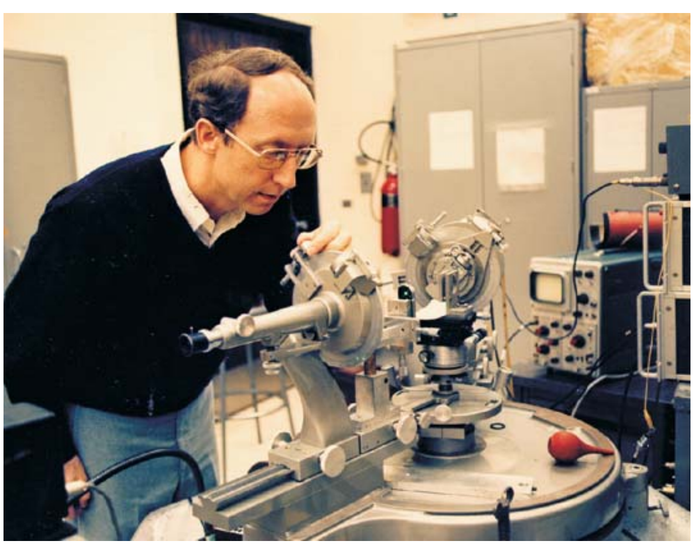
Throughout the 1980's Bashara's ellipsometers were upgraded by replacing the discrete wavelength sources with white light-driven monochromators. This resulted in continuous spectral coverage from the ultraviolet to the near infrared. This was perfect for studying semiconductor materials. Thus, the University's first spectroscopic ellipsometer was born.

While going spectroscopic, the systems retained Bashara's multiple angle capability, resulting in a complete ellipsometer package that was both variable angle and fully spectroscopic at the same time. Combining both capabilities in one instrument provided the ultimate in research flexibility - suited for studying dielectrics, semiconductors, metals, or any of these in combination. The term "VASE®" was coined to describe the Variable Angle Spectroscopic Ellipsometer system built by this group.

The new flexibility of the VASE® technique greatly expanded the scope of ellipsometry research into many new areas. These included compound semiconductor materials such as GaAs, InP and their complicated alloys, which are the basis for light emitting diodes and laser diodes so commonly used today. Solar cell materials were investigated, along with magneto-optic materials for the data storage industry. Other new research areas investigated transparent conducting oxides for flat-panel displays, "Diamondlike" carbon hard coatings, oxidation-resistant coatings for spacecraft, as well as all types of films used in the silicon microchip industry. Recent additions to the university research program include electrochromic and photochromic layers and devices, and thin films for biological and medical applications.

Spectroscopic ellipsometry was also applied to monitoring and control of thin film deposition and etching Since in-situ ellipsometry requires the ellipsometer to literally be bolted on a vacuum chamber, only one fixed angle of incidence is available. In-situ processing is one application where spectroscopic data can still provide more information through multiple wavelength data points despite the constraints of one angle of incidence.

Spectroscopic data sets at multiple angles brought about one major new problem. Namely, many data points can be acquired and need to be analyzed simultaneously. Therefore, automation was needed for data acquisition of literally hundreds of data points, and serious number crunching was required for the data analysis. Fortunately, the 1980s were the decade that introduced the personal computer (PC) for both control of instrumentation and desktop number crunching.



John Woollam working on an early UNL ellipsometer.

Notable research at the University continued into the 90's with many students including Craig Herzinger, Bill McGahan, Ping He, Tom Tiwald, and Dan Thompson (to name just a few). Mathias Schubert also arrived, first as a student and later as a visitor, from Leipzig University. Schubert advanced generalized ellipsometry. He and fellow collaborators conducted research on compound semiconductors, emphasizing infrared.

Active use of ellipsometry for materials research continues today at full speed in the UNL college of engineering, involving UNL researchers from physics, chemistry, electrical engineering, and mechanical engineering.

1987: The J.A. Woollam Company.

Integrating the personal computer into the hardware and software of ellipsometry made the VASE® ellipsometer an incredibly flexible research tool and viable commercial product. Visitors to the UNL ellipsometry labs began to express interest in acquiring VASE® ellipsometers for their own labs. With the university focused on educational and research goals, a separate company was needed to serve the commercial marketplace. Thus, the J.A. Woollam Company (JAWCo™) was founded in 1987 to provide the research community with the most powerful and flexible research ellipsometers in the world.

Making a commercial product requires developing a one-of-a-kind laboratory instrument into a robust, reliable, field-survivable tool. This is a huge engineering task, even for an instrument like the VASE® with a well established record in research. Graduates from UNL were hired to develop a new ellipsometer that was commercially viable. Blaine Johs came to the company late in 1989 and wrote the software for data acquisition and analysis (WVASE32) from the ground up. This software continues to evolve with the rapid pace of new instrumentation and applications to lead the world in features and power. At the same time, the orginal VASE® technology was constantly improved. Fast diode array instruments were also developed, originally due to in situ SE needs.

An old saying says that there is no stopping an idea whose time has come. The VASE® ellipsometer proves this statement to be true. The Woollam company was originally established as a small, independent vehicle to supply ellipsometers to researchers on a one-by-one, very small volume basis. By the early 1990s, however, the time was right for SE technology to find itself in the unique position to characterize the ever shrinking films found in commercial electronic devices and many other applications.

The J.A. Woollam Company is now in its 14th year and has grown to 44 employees with a worldwide sales and support network. Over 600 spectroscopic ellipsometers have been installed worldwide.

A Bright Future

This year celebrates twenty years of ellipsometry for John Woollam and exactly finishes the second half of ellipsometry history in Nebraska. With such a strong history behind us and a bright future ahead the next 20 years of ellipsometry in Nebraska will certainly be just as exciting.