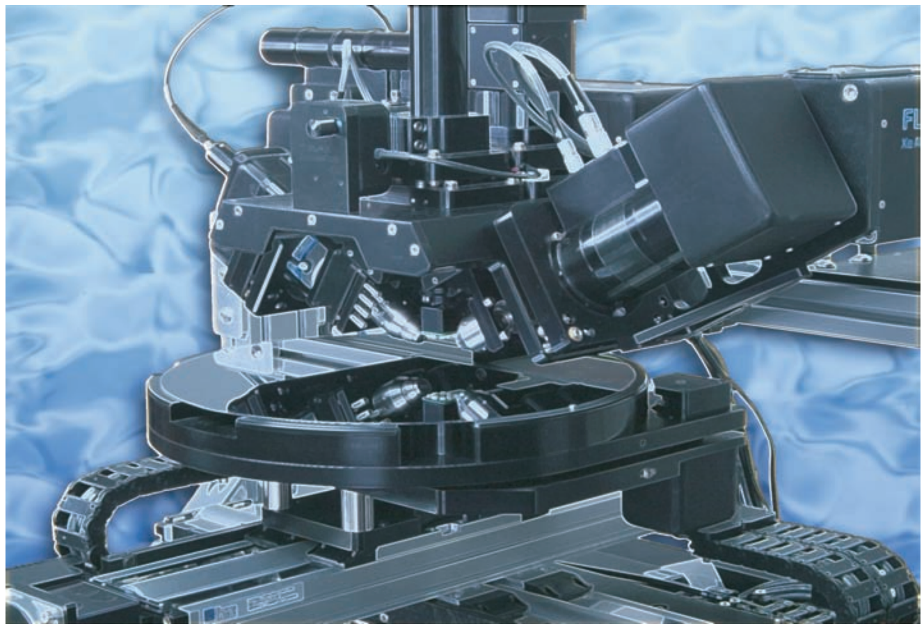
J. A. WOOLLAM CO., INC.

Issue 7
January 2006

Woollam Co. News

Short Course Schedules:

- Orlando, Florida
  Standard Course
  February 20 - 23
- Lincoln, Nebraska
  Advanced Course
  June 12 - 16
- To Be Announced
  Standard Course
  (October)



In this issue, we look at a few of the latest advances in ellipsometry: anisotropic characterization, integration in industrial environments, and the PSEMI oscillator model. These topics brings to mind a quote from Bertrand Russell:

"Even if the open windows of science at first make us shiver... in the end, the fresh air brings vigor, and the great spaces have a splendor of their own"

Although the advanced topics discussed in this Newsletter may send a "shiver", it is exciting to see the progress that defines today's state-of-the-art. In that regard, we celebrate Mathias Schubert as our featured researcher. He has opened new "windows" with regard to generalized ellipsometry for anisotropic material characterization, and infrared ellipsometry for studying compound semiconductors. We hope you will enjoy the "fresh air" throughout these pages. May your own research lead to new splendor.

Inside this issue:

Featured Employees

We are proud to introduce two new employees that have joined the Woollam team in 2005: Marge Knight and Neha Singh. We would also like to introduce our new Korean representative, WizOptics. We are very happy to have these individuals on board and feel they greatly enhance the Woollam Company.

Marge Knight

Marge Knight joined the J. A. Woollam Co (JAWCo) July 18, 2005 as the new "Controller". She is in charge of the financial group at the company. This is an extremely important role as she oversees inventory tracking, accounts receivable, accounts payable, and most importantly payroll ☺.

Marge graduated from the University of Nebraska with a BS in business administration. She worked for 25 years as a CPA for Hanigan Bjorkman Ecklund CPA's in Lincoln.

She says working at JAWCo so far has proven to be both exciting and enjoyable. Learning international banking and foreign trade regulations has presented entirely new, but very interesting challenges. After 25 years of working with other CPAs, Marge is having to adjust to conversations with nerdy engineers. So far she has been a good sport and shown interest!

Marge and her husband, Jeff, feel blessed to be raising their 2-year-old grandson, Tommy. Having a 2-year old running about the house does not leave them with much free time, but they enjoy spending time with friends and family.

Neha Singh

Neha Singh recently joined JAWCo as an applications engineer. She started as a student intern while finishing her masters degree in Electrical Engineering. Most of her duties involve sample measurements, instrument installations, and customer training. However, a recent tour to India has helped expand her expertise in marketing and sales.

Neha received her Bachelors Degree from Jawaharlal Nehru Technological University in India. As a graduate student at the University of Nebraska, her research involved femtosecond laser ablation of metal surfaces.

When she came to Lincoln from a big Indian city, she didn't imagine staying here much beyond her education but now she thinks she is addicted to the Midwestern people. She enjoys water sports and anything in the rivers and the oceans.

So there is no confusion, the picture of Neha was taken in New York not Lincoln!

New Korean Representative: WizOptics

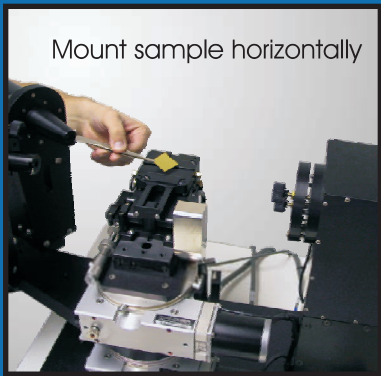
JAWCo is proud to announce WizOptics as our new representative in South Korea. They are a small company with three partners joined by an accountant: Mr. Kang, Mr. Park, Mr. Kim, and Ms. An (left to right). All three partners are well trained in optical measurement technology with years of ellipsometry and other optical metrology experience. We look to have improved customer support and training in South Korea.

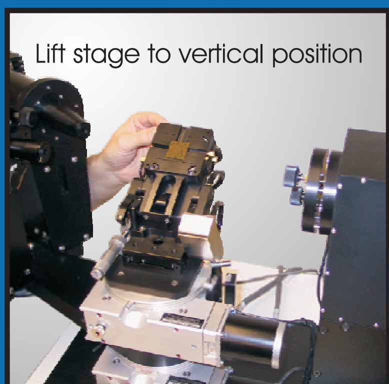
www.wizoptics.com

Contact JAWCo to find out if these options will work with your system.

"Flip-down" stage (vertical stage)

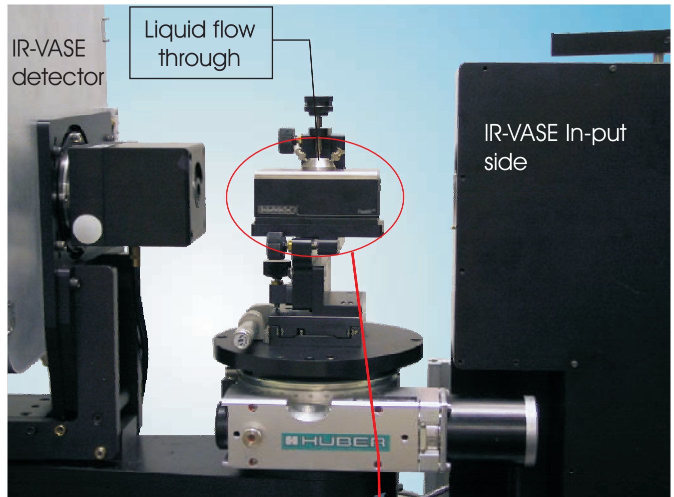
Flip-down stage makes mounting fragile samples easier and safer.

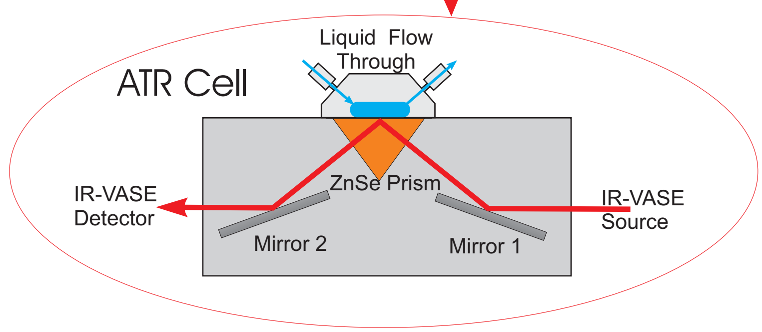


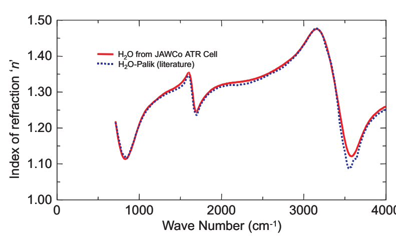


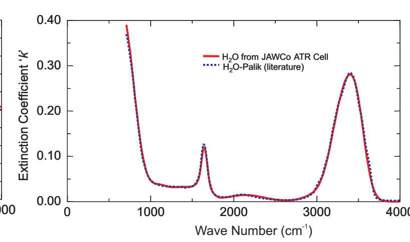
ATR cell for IR-VASE

JAWCo now offers an ATR cell for measuring the refractive index of liquids.



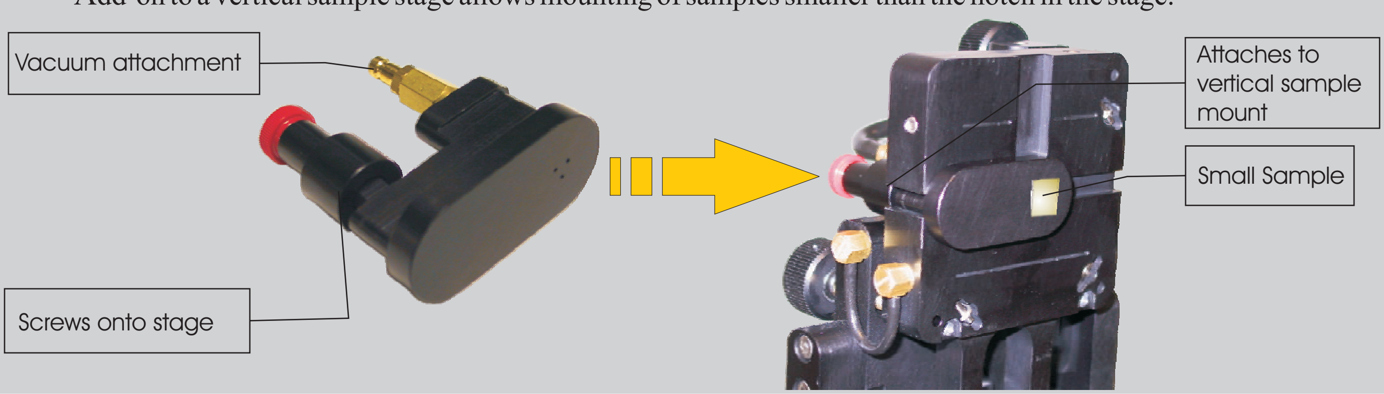






Small sample holder (vertical stage)

Add-on to a vertical sample stage allows mounting of samples smaller than the notch in the stage.



Moving beyond the lab– Industrial Integration by: Corey Bungay

Spectroscopic ellipsometry (SE) is commonly used for thin film characterization of coatings on semiconductor and glass substrates. The smooth surfaces of these substrates provide a specular reflection which is ideal for ellipsometry. However, not all industries use such ideal substrates. Thin film technologies are also applied to metals (stainless steel, copper, aluminum, etc.), plastics, and poly-crystalline semiconductors. These coated substrates are used for food packaging, automotive industry, reflectors, tools, and solar cells, to name a few. These industries have recently looked to SE as a tool for in-line or *in situ* monitoring and control.

Here we will discuss integration of SE for monitoring and characterization of thin films on non-ideal substrates in industrial-scale settings. Discussions include applications using rolls of large metal sheets, metal gears, and solar cells. We will look at some specific cases and address the challenges and solutions the J. A. Woollam Company (JAWCo) has provided.

Proof of Concept

First, what are the challenges when dealing with non-ideal substrates? Metal and poly-crystalline silicon solar cells often have rough and scattering surfaces. Metal and plastic rolls are in constant motion as they travel through the deposition process chamber. Also, these rolls can be found in harsh industrial environments (high heat and humidity, contamination, etc.) and the operators have very little, if any, optics background.

JAWCo has dealt with various coatings on non-ideal substrates including organic and silicone films, SiO_2, diamond-like-carbon (DLC), metal carbide, and TiO_2. In all cases, the first step to process integration involved determining whether sufficient results could be obtained from such surfaces. In collaboration with Rollin Lakis of the Nuclear Materials Science Group at Los Alamos National Laboratory, we studied a series of silicon oxide (SiO_2) films on machined nickel.

Machined nickel coupons of various surface finishes were glued to silicon wafers. SiO_2 films were sputter deposited on the nickel/silicon surfaces. The samples provided reference locations (silicon substrate) which should have comparable SiO_2 film thickness but an ideal surface. Figure 1 shows a nickel on silicon test sample. Four different samples were made, each with differing SiO_2 thickness (nominally 30nm, 60nm, 90nm, and 120nm).

Ellipsometric data were acquired at locations on the nickel coupons as well as on the silicon, as close as possible to the coupons. For the nickel samples, SiO_2 layer thickness was fit to Δ data only. This is because Δ is more sensitive to the film index-thickness product and less sensitive to the substrate and interface properties. The thickness linearly correlated to the reference thicknesses. As one would expect, the more specular the surface finish the better the results. Figure 2 is a plot comparing SiO_2 thickness from one machined nickel surface and silicon.

Figure 1. Test sample: Machined Ni coupons glued to silicon wafer. SiO_2 films deposited on Ni and Si at the same time.

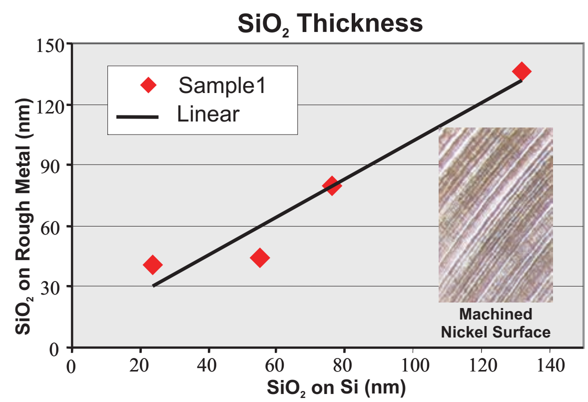


Figure 2. Comparison of SiO_2 thickness measured on Si and rough machined Ni substrates.

Hardware Integration

Once it is shown that SE can be used to quantify film thickness, hardware must be integrated to the deposition process equipment.

In-line monitoring of substrates in constant motion requires rapid data acquisition. The ability of the M-2000 to acquire a full spectrum in less than a second makes it ideal for this application.

JAWCo has developed the M-2000 "RP" (Return Path) for SE monitoring of roll-to-roll web coating in relatively harsh industrial environments. All optical elements are contained in a single environmentally protected housing. A double bounce reflection technique allows all ellipsometer parts to be housed as a single unit. The light path is such that it exits the unit, reflects off the substrate band, then reflects off a mirror positioned at an oblique angle from band. The mirror reflects the light back onto the band and to the detector positioned approximately parallel to the light source. Figure 3 is an illustration of the M-2000 RP optical path.

Industrial Integration Cont.

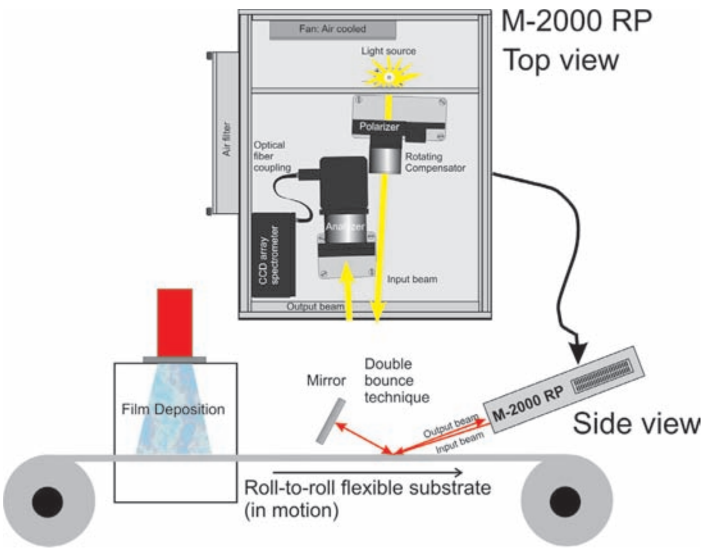


Figure 3. M-2000 RP optical layout and double bounce reflection technique.

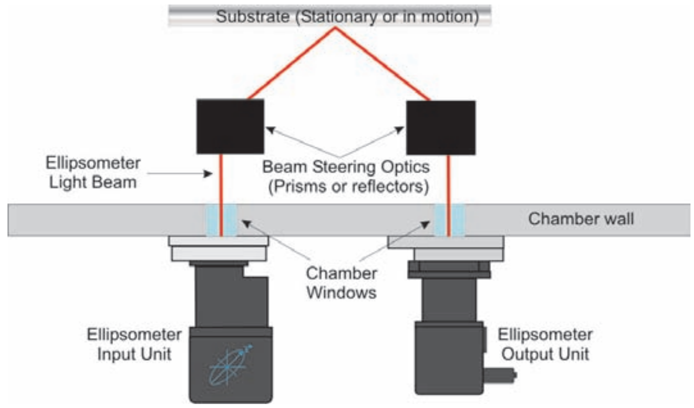


Figure 4. *In situ* or in-line M-2000 mounted parallel with beam steering optics for optimum reflection angle.

Beam steering optics have been developed for use on deposition chambers both *in situ* and in-line. The beam steering optics allow the ellipsometer input and output to be mounted parallel to each other but still provide optimum oblique reflection angles off the sample. This often makes it much easier to retro-fit to existing chambers. Figure 4 shows the general concept. This type of configuration has been used on many process chambers such as sputter, e-beam evaporation, MBE, MOCVD, CVD/PECVD, and more.

Finally, JAWCo has worked with VON ARDENNE to develop a measurement system for in-line monitoring of multi-layer dielectrics on metal bands. Multiple M-2000 ellipsometers positioned after each layer deposition provide accurate measurement of all layer thicknesses. Each ellipsometer communicates the model to the next ellipsometer in the process so the only unknown is the current top layer. This ensures unique, accurate results for the entire structure. Figure 5 shows a typical VON ARDENNE system with multiple ellipsometers mounted after each layer deposition.

Software

For SE to be a viable tool for industrial applications the system must be automated. Most operators have little to no optics background so the system must be push button with obvious results reporting. JAWCo has developed custom software packages based on the EASE platform (Woollam Newsletter, Issue 5). The software is designed for simple push-button operation. The operator chooses the corresponding sample type and the software automatically acquires data and fits it to a predetermined model. The thickness is displayed in either green or red depending if it is in-spec or out-of-spec, respectively. The software can be used in a "monitoring mode" or can communicate with the process chamber for control.

Conclusion

Industrial-scale applications introduce a large set of complications (sample non-idealities, full automation, etc.). However, JAWCo continues to develop SE to meet the demands of new applications. Please contact a JAWCo applications engineer to discuss how SE can enhance and improve your process.

Further Reading:

1. U. Seyfert, E. Reinhold, J. Richter, "Industrial PVD solutions for metal strip coating," Proc. of Autumn Congress of European Coil Coating Ass., Brussels, (2004).
2. E. Reinhold, J. Richter, U. Seyfert, C. Steuer, "Large area metal strip coatings by EB-PVD - current aims and physical limitations," Proceedings of 46th annual SVC, San Francisco, CA, May 2003.
3. Dale E. Morton, Blaine Johs, and Jeff Hale, "Optical monitoring of thin-films using spectroscopic ellipsometry," 45th Ann. Tech. Conf. Proc. of the SVC, (2002).

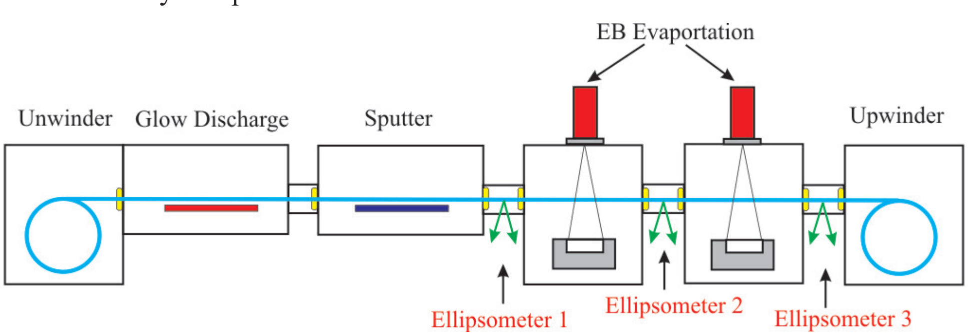


Figure 5. Multiple ellipsometers used in multi-layer deposition chamber. Each ellipsometer "communicates" its model to the next ellipsometer ensuring accurate results for entire sample structure.

“PSEMI” Oscillator Model

by Tom Tiwald

In Newsletter 6 we began a new series to focus on different dispersion models. We began with the Tauc-Lorentz oscillator, which is used for amorphous materials both above and below the bandgap. In this feature, we will introduce the PSEMI™ oscillator, which originated in 1995 but is more accessible today through the GENOSC™ layer.

Applications

The PSEMI oscillator combines a highly flexible functional shape with Kramers-Kronig consistent properties. Unlike classical oscillators, its flexibility allows description of crystalline semiconductors.

What are the differences between amorphous and crystalline semiconductors? Primarily, a crystalline material has long-range order that leads to sharp features in the optical spectra. If the long-range crystal periodicity breaks down, the material becomes amorphous and absorption features broaden. The PSEMI oscillator model is perfect for modeling the sharper absorption spectra of crystalline semiconductors. In addition, the PSEMI absorption goes to zero at low and high energy endpoints, which permit use of this oscillator across the spectrum for direct and indirect semiconductors (see Advanced insert).

The potential applications for the PSEMI include a wide variety of semiconductors:

- Si, Ge, SiGe
- III-V Binaries: GaAs, AlAs, InP, GaP, InAs, InSb, AlSb, GaSb, GaN, AlN
- III-V Alloys: AlGaAs, InGaAs, AlInAs, InGaAsP, AlGaN, InGaN
- II-VIs: ZnO, ZnS, ZnSe, CdS, CdSe, CdTe, HgCdTe

Most crystalline semiconductors are well-established optically. However, a dispersion-relation for these materials has significant importance when studying optical changes due to composition, temperature, strain, …

Advanced

The UV-Visible optical properties of semiconductors are dominated by electronic transition absorption features. This absorption occurs when the incoming light provides enough energy to an electron to allow a “jump” to elevated state.

The amount of absorption depends on the number of full and empty states in the material at equal energy difference (JDOS-joint density of states). In addition, the absorption shape will depend on whether the transition is “direct” or “indirect”. If full and empty states are at the same momentum, the electron makes a “direct” jump (Figure 1). However, if the full and empty states are not located at the same momentum, the transition also requires some momentum to make the “indirect” transition occur. The probability of an indirect transition is much lower than a direct transition. Comparing the bandgap absorption between Silicon (indirect at 1.1eV) and GaAs (direct at 1.4eV), it is easy to see the quick onset of absorption only occurs for the direct transition.

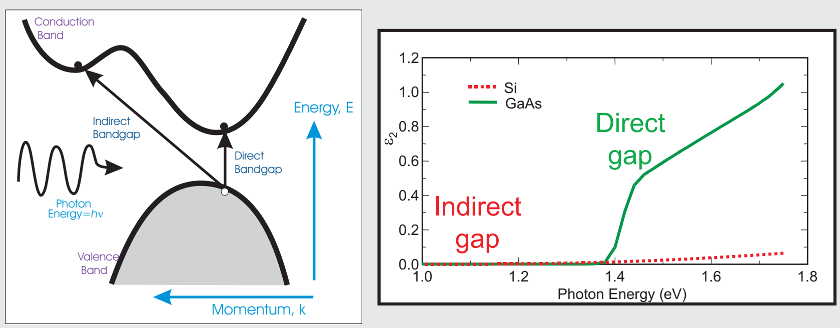


Figure 1. a) Band diagram showing a direct and indirect electronic transitions. b) ε_2 of Si and GaAs. The direct bandgap of GaAs has an abrupt onset of absorption whereas the indirect bandgap of Si has a slow increase towards higher energies.

Strong variation in the JDOS at a specific frequency is referred to as a Critical Point. There are 4 types of 3-dimensional Critical Points (M0, M1, M2, and M3). These are represented by 4 different PSEMI oscillators within the GENOSC™ layer (Figure 2). Absorption in a real material may be a combination of multiple different critical points. The M0 absorption is witnessed at the bandgap of a direct transition, where no absorption occurs at lower energies and the absorption quickly rises (like a step-function) at the bandgap energy.

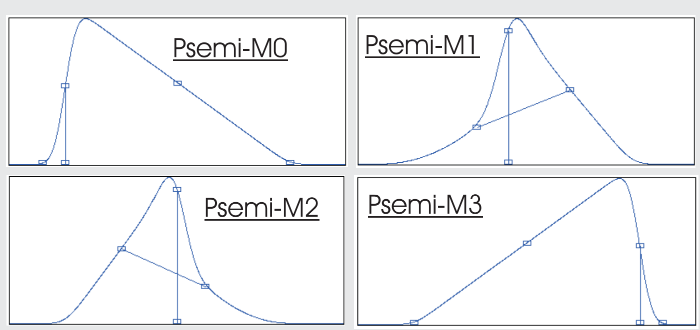


Figure 2. . Genosc™ dielectric function display showing the *PSEMI-M0*, *PSEMI-M1*, *PSEMI-M2*, and *PSEMI-M3*. The *PSEMI-Tri* oscillator is shown in Figure 3.

Practical use

There are five types of "Psemi" oscillators: Psemi-M0, Psemi-M1, Psemi-M2, Psemi-M3 and Psemi-Tri. All five are variations of the more general Herzinger-Johs® Parameterized Semiconductor Oscillator function originally introduced in the WVASE32® "psemi.mat" layer. The fifth oscillator, Psemi-Tri, is intended for general use.

Each PSEMI oscillator consists of four polynomial spline functions (labeled F_I, F_{II}, F_{III} & F_{IV} in Figure 3) connected end-to-end. The overall shape of a PSEMI function can be altered by changing the control points, endpoints, center energy and amplitude. The bottom graph of Figure 3 demonstrates the flexibility of these functions, showing how various combinations of left and right control point amplitudes can produce different asymmetrical ε_2 curves in the PSEMI-Tri oscillator.

The Genosc™ PSEMI oscillators allow the user to vary and fit 7 free parameters. The more general Herzinger-Johs® function allows for independent adjustment of all 12 parameters. PSEMI Oscillator shapes can be altered graphically by manipulating the blue boxes with the mouse, or by manually changing the values of the seven free variables.

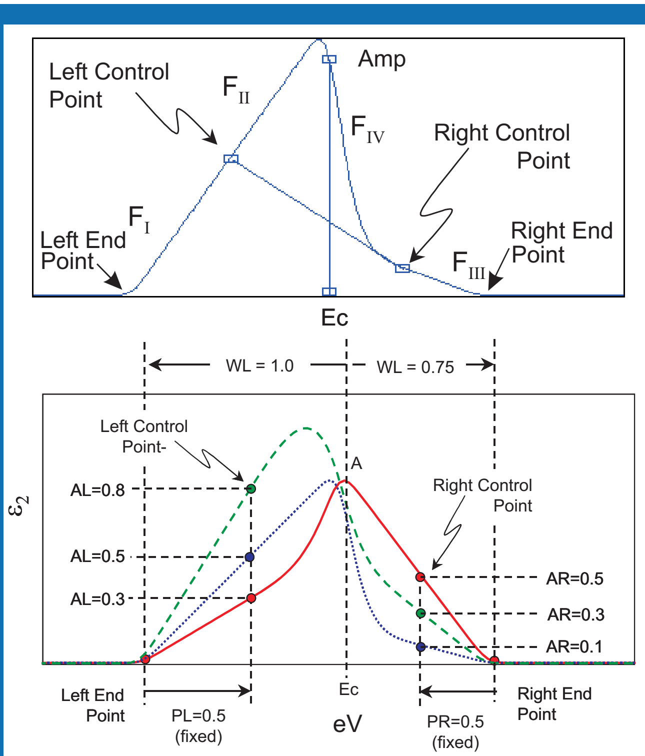


Figure 3. Two views of *PSEMI-Tri* oscillator. The Genosc™ dielectric function display shows polynomial spline functions F_I, F_{II}, F_{III} & F_{IV}, as well as the endpoints and control-points. Bottom figure shows *PSEMI-Tri* shape for several combinations of AL & AR.

Examples

Figure 4 shows an ensemble of six PSEMI oscillators used to model the dielectric function of InP. One can see that all critical points in the ε_2 spectra can be described accurately with these advanced oscillators.

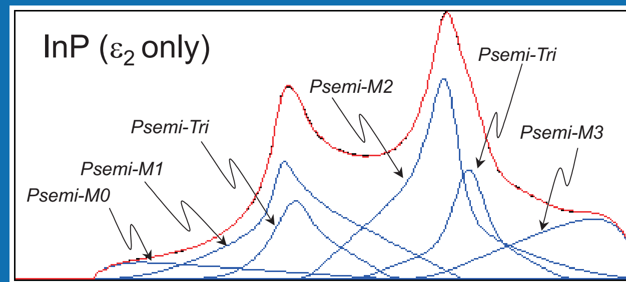


Figure 4. Genosc™ dielectric function display showing *Psemi* oscillator fit for InP ε_2. Blue line = individual oscillator, Black line = dispersion model, Red line = reference ε_2

Two PSEMI oscillators were used to fit the GaN dielectric function shown in Figure 5. Note how efficiently the PSEMI-M0 oscillator fits the direct bandgap region. The direct bandgap shape would be difficult to do with other oscillator types. However, many alternatives could be used in place of the PSEMI-M2 oscillator to describe the increasing absorption towards higher energy.

Because each PSEMI oscillator is defined by seven free parameters, correlation must be considered. Users can minimize correlation by restricting the number of fit parameters, and use no more than the minimum number of oscillators required for a good fit.

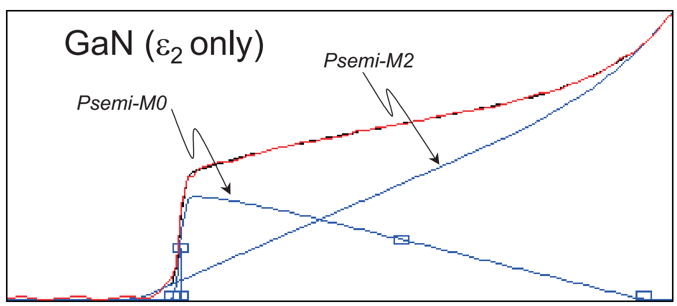


Figure 5. Genosc™ dielectric function display showing *Psemi* oscillator fit for GaN (ε_2 only).

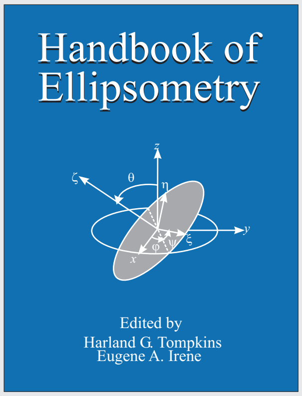
References

1. US Patent #5,796,983 "Dielectric function parametric model, and method of use".

2. B. Johs, C.M. Herzinger, J.H. Dinan, A. Cornfeld, and J.D. Benson "Development of a parametric optical constant model for $Hg_{1-x}Cd_xTe$ for control of composition by spectroscopic ellipsometry during MBE growth" *Thin Solid Films* **313-314** (1998) 137.

3. B. Johs et al. "Overview of Variable Angle Spectroscopic Ellipsometry (VASE), Part II: Advanced Applications" *SPIE Proc.* **CR72** (1999) 29.

Two new books on spectroscopic ellipsometry have recently been published. The first, *Handbook of Ellipsometry*, is a compilation of various topics in ellipsometry. Each chapter is written by a world expert in ellipsometry. James Hilfiker, an applications engineer with JAWCo, wrote a chapter on VUV ellipsometry. The second book, *Infrared Ellipsometry on Semiconductor Structures*, is written by Dr. Mathias Schubert. Dr. Schubert is our featured researcher presented on the next page.



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Editors:
Harland G. Tompkins and Eugene A. Irene

Chapters

1. Polarized Light and Ellipsometry
2. Optical Physics of Materials
3. Data Analysis for Spectroscopic Ellipsometry
4. Optical Components and Simple PCSA (Polarizer, Compensator, Sample, Analyzer) Ellipsometer
5. Rotating Polarizer and Analyzer Ellipsometry
6. Polarization Modulation Ellipsometry
7. Multichannel Ellipsometry
8. SiO_2 Films
9. Theory and Application of Generalized Ellipsometry
10. VUV Ellipsometry
11. Spectroscopic Infrared Ellipsometry
12. Ellipsometry in Life Sciences

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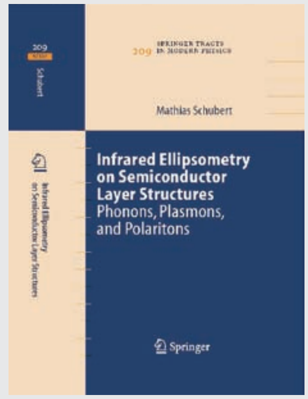

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Springer Tracts in Modern Physics
Volume: 209

Title: ***Infrared Ellipsometry on Semiconductor Layer Structures: Phonons, Plasmons, and Polaritons***
Author: Mathias Schubert

The study of semiconductor-layer structures using infrared ellipsometry is a rapidly growing field within optical spectroscopy. This book offers basic insights into the concepts of phonons, plasmons, and polaritons, and the infrared dielectric function of semiconductors in layered structures. It describes how strain, composition, and the state of the atomic order within the complex layer structures of multinary alloys can be determined from an infrared ellipsometry examination. Special emphasis is given to free-charge-carrier properties, and magneto-optical effects. A broad range of experimental examples are described, including multinary alloys of zincblende and wurtzite structure semiconductor materials, and applications to organic layer structures are explored.

4th International Conference on Spectroscopic Ellipsometry

Stockholm Sweden June 11-17, 2007

IC4SE
Stockholm 2007

Prof. Mathias Schubert

Mathias Schubert has accomplished more with ellipsometry in the past 10 years than most of us can hope to achieve. He has expanded the theory, understanding, and application of ellipsometry to many diverse areas of interest to both industry and general science. His work in anisotropy and infrared ellipsometry has put him at the forefront of worldwide research. In the process, he has become one of the most prolific ellipsometry authors and all before his 40th birthday.

Mathias started using ellipsometry while still a graduate student at Leipzig University, where he was studying $GaInP_2$. During these early years, he developed the technique of generalized ellipsometry (g-SE) into a practical method for characterizing anisotropic materials. With a clear understanding of g-SE, the research world was his oyster. He has since applied this method to many difficult anisotropic samples including chiral liquid crystals, mixed-phase Boron Nitride, non-cubic single crystals like sapphire and rutile, and even superlattice-type order-birefringence. His wealth of knowledge in this area is summarized in various references and book chapters, including Chapter 9 of the new Handbook of Ellipsometry (page 8).

Along the path of exploration, Mathias soon discovered the challenges and potential rewards of using ellipsometry in the infrared. He has since become a pioneer of this nearly untapped research area. By combining generalized ellipsometry with IR ellipsometry, he was able to study topics of worldwide interest; including group III-Nitrides for LED and laser diode applications, ordered III-V semiconductors for optoelectronic applications, and electrochromic films. Instead of relying on conventional techniques, Mathias was quick to expand the latest methods to target his characterization requirements. This has led to his pursuit of far-infrared ellipsometry, infrared magneto-optic studies, and even Terahertz ellipsometry.

In recent years, Mathias has also helped expand optical techniques into industrial applications, such as in-line and *in situ* process control with ellipsometry and Raman (see Page 4 for related article on Industrial Integration). His work on functional optical coatings and solar cells has enabled the characterization of new, exciting materials in each area. His current research interest is focused on artificial nanostructure and complex medium electromagnetism, and characterization using g-SE from the Terahertz to the Deep ultraviolet spectral region.

All of his research has combined into a wealth of publications that include over 120 journal articles, 4 book chapters, and a new book on IR ellipsometry (Page 8). He has traveled the world to collaborate with fellow researchers and present his research in over 150 conference talks, including 17 invited lectures.

Mathias generously acknowledges that he couldn't have done all this great work alone and he is fortunate to be surrounded by a great group of ellipsometry researchers. Mathias is pictured (far left) with the Ellipsometry Workgroup at the University of Leipzig. This year sees his career moving forward, as he has accepted an Associate Professor position at the University of Nebraska-Lincoln. UNL has a rich history of ellipsometry-related research that dates back to the early 1960s (before he was born), including their role as host to the early International Conferences on Ellipsometry. Mathias completes the "changing of the guard" with his role as joint-organizer in the next International Conference on Spectroscopic Ellipsometry to be held in Stockholm in 2007 (page 8).

Mathias is busy setting up his new labs with the help of Tino Hofmann, a postdoc also from Leipzig. He will soon be joined in Lincoln by his family. His wife Eva has her Ph.D. in Crystallography and is currently researching three-dimensional nanostructure preparation by glancing-angle deposition. Mathias has three beautiful daughters; Sophie-Luise, Annemarie, and Johanna; between ages 12 and 5. We wish them the best of luck and hope they will be happy to call Nebraska home.

For more information on Mathias and his research, please see the following websites:
Ellipsometry.unl.edu
www.unl.edu/cmra/faculty/schubert.htm

Common Questions about Anisotropy

by James Hilfiker

Anisotropic samples provide exciting new challenges to ellipsometry researchers. Advanced measurements and data analysis techniques are now available to enable anisotropic characterization. However, these techniques are seldom 'push-button' and require an understanding of the primary issues. Hopefully, the following discussions will move you toward that understanding.

Q: What is anisotropy?

A: In a normal "isotropic" sample, the optical properties are the same in all directions. Anisotropy refers to the directional-dependent optical properties of a material. In other words, the *n,k* values may be different for electric fields (light) traveling through the material in different directions. Figure 1 show the ordinary and extraordinary optical constants of 4H silicon carbide.

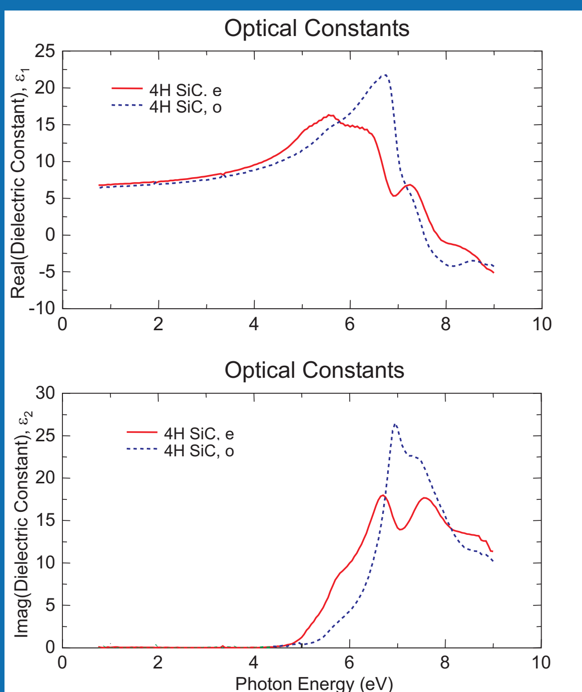

Figure 1. Anisotropic crystalline SiC optical constants.

Q: What do Uniaxial and Biaxial refer to?

A: A uniaxial material has 2 different optical properties ($n_x = n_y \neq n_z$). A biaxial material has 3 different optical constants ($n_x \neq n_y \neq N_z$).

Q: Why is a material anisotropic?

A: The optical properties of a material depend on the underlying atomic or molecular structure. If this basic building block has a non-symmetric 'shape' and a long-range order throughout the material, then the material can be anisotropic. For example, an electronic transition may occur at different resonant energies depending on the spacing between atoms in a non-cubic crystal. This would lead to different *n,k* values across the spectrum.

Q: What are common anisotropic materials?

A: Due to the need for both non-symmetric "shape" and long-range order, anisotropic materials tend to be of a couple types: non-cubic crystals and ordered organics. Included in the first type are such materials as rutile (with tetragonal symmetry) and sapphire with its hexagonal crystal structure. A few anisotropic organics include liquid crystal films and PET.

Q: ***What special methods can be applied when measuring anisotropic materials?***

A: This is a very open question, as it depends on the type of anisotropy (uniaxial, biaxial), the type of sample (substrate only, thin film, transparent or opaque substrate,…), and the orientation of the anisotropic material. For many simple samples, the anisotropic orientation is aligned with the sample normal ($n_x = n_y \neq n_z$). For this case, it is best to measure a wide range of incident angles to change the path length the light travels through the film (experiencing different optical properties in different directions as it goes). This type of anisotropy can be handled without resorting to *Generalized Ellipsometry*.

Q: What is Generalized Ellipsometry?

A: This refers to an advanced ellipsometry measurement that involves the complete 2X2 Jones matrix description of the sample. Normal ellipsometry ignores the off-diagonal elements of this matrix, as they are zero for isotropic materials. Equation 1 below is the Jones matrix for an isotropic sample. Anisotropic materials can cross-couple the p- and s- polarized light, leading to non-zero off diagonal elements. To get the full details of the 2X2 Jones matrix, requires 6 values (3 Psi and 3 Delta) instead of the standard 2 terms (Psi and Delta) of a normal ellipsometry measurement. Equation 2a gives the Jones matrix representation for an anisotropic sample. Equations 2b-2d are our definitions of the measured generalized ellipsometry parameters.

$$\begin{pmatrix} E_p^{out} \\ E_s^{out} \end{pmatrix} = \mathbf{J} \begin{pmatrix} E_p^{in} \\ E_s^{in} \end{pmatrix} = \begin{pmatrix} r_{pp} & 0 \\ 0 & r_{ss} \end{pmatrix} \begin{pmatrix} E_p^{in} \\ E_s^{in} \end{pmatrix} \qquad (1)$$

$$\begin{pmatrix} E_p^{out} \\ E_s^{out} \end{pmatrix} = \begin{pmatrix} r_{pp} & r_{sp} \\ r_{ps} & r_{ss} \end{pmatrix} \cdot \begin{pmatrix} E_p^{in} \\ E_s^{in} \end{pmatrix} \qquad (2a)$$

$$AnE = \tan(\Psi) \cdot e^{i\Delta} = \frac{r_{pp}}{r_{ss}} \qquad \text{(2b)}$$

$$Aps = \tan(\Psi_{ps}) \cdot e^{i\Delta_{ps}} = \frac{r_{ps}}{r_{pp}} \qquad \text{(2c)}$$

$$Asp = \tan(\Psi_{sp}) \cdot e^{i\Delta_{sp}} = \frac{r_{sp}}{r_{ss}} \qquad \text{(2d)}$$

Q: If I don't use Generalized Ellipsometry, am I ignoring the sample anisotropy?
A: No, the standard Psi and Delta data will be affected by the anisotropy, but there won't be enough information to determine how they were affected. The off-diagonal elements are needed to help distinguish how the standard data were affected by anisotropy.

Q: How do I handle anisotropic substrates?
A: This question depends on the information you are searching to find. Are you interested in (i) the substrate material properties? Or (ii) measuring films on this anisotropic substrate?
(i) If you are interested in the substrate material properties, which will be directional dependent, you are best served by a series of *generalized ellipsometry* measurements at different incident angles and possibly at different sample orientations. It is probably best to discuss your application with a Woollam Applications engineer as they can provide great input into the best approach for each type of substrate.
(ii) If you don't care about the substrate, but need to measure thin films on this surface, you have a couple of options. First, you can roughen the back of transparent substrates. The anisotropy effects are strongest after traveling through a substrate and returning to the surface. If this “backside” reflection can be avoided (by scattering the light of the back surface or spatially separating this secondary beam), the substrate anisotropy effects will be minimal. Second, you can work through the full characterization of a bare substrate and then use this in your model for the coated samples. However, this is much more time consuming.

Q: How do I model anisotropic materials?
A: The Woollam analysis software uses a layer called “biaxial.mat” to describe up to 3 orthogonal optical properties. The orientation of these three values can be adjusted via three Euler angles. These three angles rotate and tilt the optical axes to correct for the true position of the material properties relative to the ellipsometer sample position.

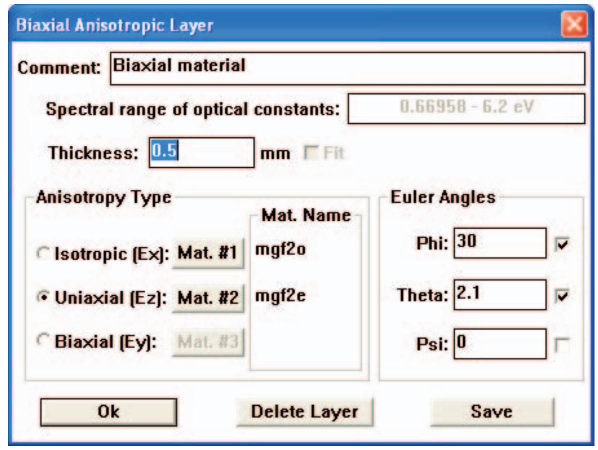

Figure 2. Biaxial.mat layer for describing the optical properties of an anisotropic material.

Q: How do I adjust the Euler angles?
A: There is a nice description of the Euler angles in the WVASE32 addendum. However, it is best to get started with a few simple facts. First, it unlikely you will need all three angles. For simplicity, try to describe the material with the first 2 Euler angles (Phi and Theta). Phi rotates the in-plane orientation around the sample normal. Theta will tip the Z-direction away from the sample normal. There are examples using different Euler angles in the WVASE32 addendum.

Q: How sensitive is ellipsometry to the anisotropy in a material?
A: This question depends on the path length in the material. For substrates, transmission ellipsometry can be sensitive to Δn of 0.00001 or smaller. However, a 10nm thick film will show sensitivity to Δn about 0.1.

Q: Where can I find out more about anisotropy?
A: Most of the software-related information is handled by the WVASE32 addendum, with sections describing “anisotropic” data acquisition, the biaxial layer, Euler angles, and general anisotropic sample procedures.

An excellent resource for generalized ellipsometry comes from Mathias Schubert's chapter in the Handbook of Ellipsometry, features on Page 10. Dr. Schubert has published dozens of papers on the theory and application of generalized ellipsometry and this chapter is a nice review from the world-expert.

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