Compensators

Most newer Woollam spectroscopic ellipsometers; such as the VASE, M-2000, IR-VASE and VUV-VASE; include an optical compensator (retarder) element. In this article we will address advantages and methods of incorporating a compensator element into the ellipsometer optical design. This review of compensator technology is important to help understand the operation of your ellipsometer and unlock its full potential for your application.

- **What is a Retarder (Compensator) ?**

A retarder is an optical element that changes the phase of an incident wave, delaying one of the two orthogonal light constituents. This delay occurs because of optical anisotropy ($n_o \neq n_e$) in the retarder. Each of the two orthogonal electric fields see a different index which produces a different phase velocity for each.

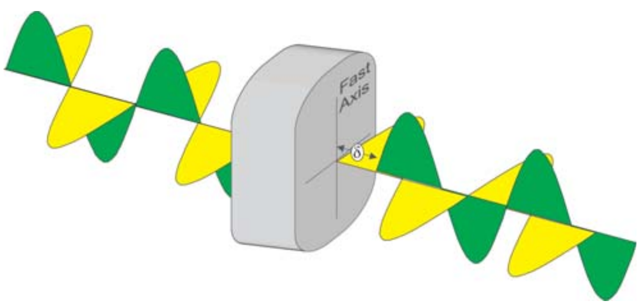


Figure 1. Retarder element introducing a phase shift between the two light constituents.

A compensator is a retarder element that introduces a 90° phase change. Therefore, if linearly polarized light is input, it will exit the compensator with circularly polarized light.

- **Why use a Compensator in an Ellipsometer**

Compensators are used in ellipsometry enhance measurement accuracy . Rotating Analalyzer/Polarizer ellipsometers (RAE and RPE) are very simple to construct and can be highly accurate over a wide spectral range. However, they have the following limitations:

1. Cannot determine the "handedness" of the phase term D. In other words, they measure Δ from 0° to 180° when in reality D varies from 0° to 360°.
2. precision and accuracy is poor when Δ is near 0° or 180°.

These limitations are inconsequential for many applications. However, accurate Δ near 0° and 180° can be helpful if measurements are not possible near the Brewster condition. For instance, in-situ ellipsometry is often limited to a fixed angle. This does not allow for movement of angle to put D in the optimized measurement region. For other samples, Δ does not stay in an optimal region except for a very narrow ranges of angles. Examples include thin layers or index matched layers on transparent substrates.

<u>Null ellipsometers</u> measure Ψ and Δ with high precision and accuracy over the entire range. However, the null configuration is not generally employed in spectroscopic systems as it is slower.

<u>Phase modulation ellipsometers</u> (PME) measure Δ accurately over the full 0 360° range, but suffer from Ψ accuracy problems when Ψ is near 0° or 45°, depending on the particular instrument configuration[3] (this limitation can be overcome by the additional complexity of a dual channel detection system[4]). The photoelastic modulator used in PME ellipsometer systems are inherently chromatic optical elements, and the drive voltage must be accurately adjusted at each wavelength during a spectroscopic scan. Furthermore, due to the high modulation frequency, it is not possible to construct a PME system which simultaneously acquires spectroscopic ellipsometric data (implementing true parallel signal acquisition and readout) with existing diode array spectrometer technology.

<u>Compensator ellipsometers</u> measure both Ψ and Δ accurately over their full ranges.

Δ values near 0° or 180° corresponds to linearly polarized light. Δ has its highest sensitivity when the light is circular polarized (Δ=90°). Placing a compensator in the light path converts the polarization state to circularly polarized (or an elliptical state nearly circular) ensuring the measurement is always acquired in a region of highest sensitivity .

At the Woollam Company two different compensator designs are used: 1) RAE with adjustable retarder [VASE and VUV-VASE] and 2) Rotating compensator ellipsometer (RCE) [M-2000 and IR-VASE].

- **Rotating Analyzer Ellipsometer (RAE) with Adjustable Retarder (AutoRetarder™)**

In theory, the RAE and RPE 'Δ' measurement limitations can be eliminated by simply adding a compensator to the beam path (either before or after the sample). However, this is more challenging than it sounds, for several reasons: 1) a perfectly ideal spectroscopic compensator element does not exist, 2) compensator elements which can be used spectroscopically (such as Fresnel Rhombs) are only pseudo-achromatic, bulky, and difficult to align, and 3) if the retardance of the compensator is not meticulously calibrated (throughout the entire spectral range), or if the compensator is not properly aligned, the accuracy of the ellipsometric data will be degraded (instead of enhanced) by the introduction of the compensator element.

In spite of these challenges, our VASE and VUV-VASE do successfully integrate a compensating element with a high accuracy RAE. In this system, a computer controlled MgF_2 Berek waveplate is used to accurately introduce retardance into the beam path[5]. Since the retarder is under computer control, it is possible to generate appropriate retardance values (0 - 90°) over a broad (150- 1700 nm) spectral range. Figures 2 & 3 show examples of a variable angle and spectroscopic ellipsometric data which were acquired with such a system. In these examples, it is the accurate measurement of the ellipsometric Δ parameter near 0° and 180° which enables a determination of the thickness and index of a dielectric film deposited on a polycarbonate substrate, and the optical constants and surface roughness layer on a glass microscope slide.

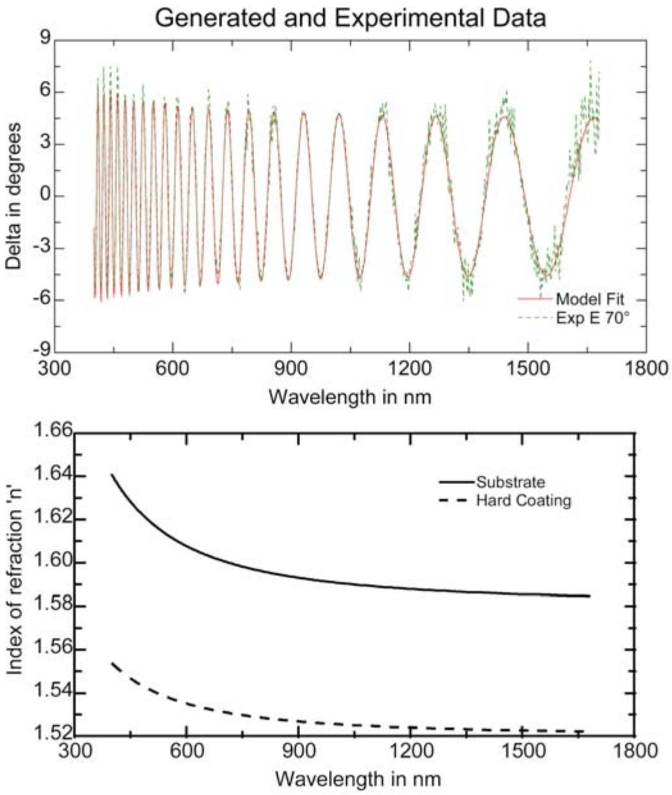
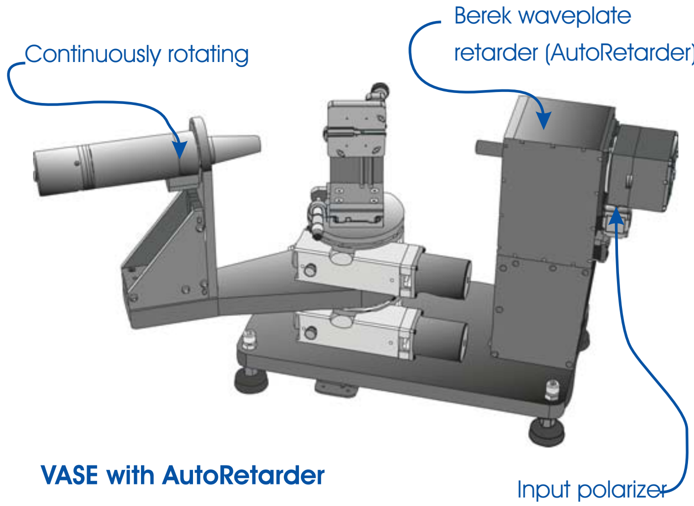


Figure 2a and 2b. Ellipsometric Ψ (not shown) and Δ (a) data acquired with a retarder-equipped RAE system[5] on a polycarbonate lens with a thick (4.35mm) hard coating. Accurate measurement of the period and amplitude of oscillations in both Ψ and Δ (notice it is very close to zero) enabled accurate determination of the film thickness and optical constants (b).

- **Rotating Compensator Ellipsometers (RCE)**

Another approach to introduce a compensator into the ellipsometer beam path is to implement the Rotating Compensator Ellipsometer (RCE) configuration. There are many advantages to the RCE configuration, including[6]: accurate measurement of the ellipsometric Y and Δ parameters over the complete measurement range (Ψ=0-90°, Δ=0-360°), no residual input or output polarization sensitivity (due to a fixed polarizer on input, and a fixed analyzer on the output), and the capability to directly measure depolarization effects. However, only recently have Spectroscopic RCE systems been



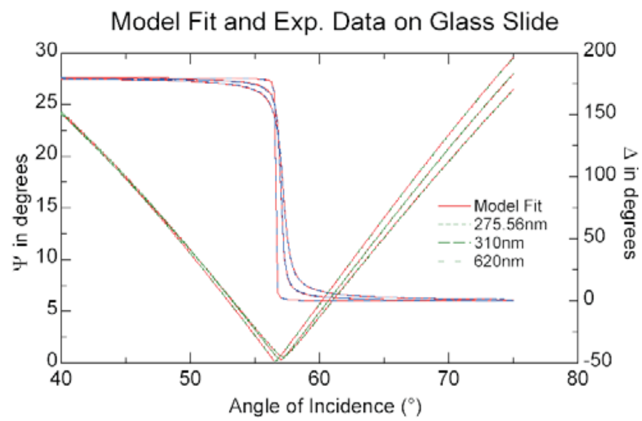


Figure 3. Accurate measurement of variable angle ellipsometric data near the Brewster angle on a glass microscope slide, using VASE with AutoRetarder. This very accurate measurement of Δ would not be possible with a standard RAE or RPE system.

constructed[7-9]. The prior lack of spectroscopic RCE systems, in spite of the well known advantages to this configuration, was mainly due to the perceived difficulty of constructing a mechanically rotatable compensator element which behaves ideally (retardance »90°) over a wide spectral range. Recently, this challenge has been successfully addressed in a number of ways: 1) a special rhomb-like prism retarder has been used to implement a Fourier Transform Infrared (FTIR) RCE system [IR-VASE] 2) a realization that ellipsometric data can still be acquired (albeit with reduced Δ measurement capability) even as the retardance of the compensator passes through 180° in part of the spectrum (which is inevitable when using standard waveplates for compensator elements, as their retardance exhibits a 1/l dependence), and 3) development of multi-element, pseudo-achromatic compensators coupled with a rigorous calibration methodology[10] [M-2000]. The M-2000 also employs a CCD array detector, making simultaneous acquisition of spectroscopic ellipsometric data possible[11]. In addition, by switching the light source and/or diode array detector, it is possible to cover a variety of spectral ranges, from the DUV (190 nm) to the NIR (1700 nm).

- **Advanced Measurement Capabilities**

The VASE + AutoRetarder™ and RCE ellipsometer designs also allows advanced measurement capabilities such as depolarization, G-VASE™ (anisotropic) and Mueller-matrix sample scans.

Depolarization can occur from patterned samples, non-uniform film thickness, and more. Including depolarization data in a regression fit to the optical model helps to quantify the non-idealities. Figure 4b shows the depolarization due to bandwidth and thickness non-uniformity in a micron thick film. Correct modeling allowed the best fit of Figure 4a.

Anisotropic samples; including plastics, liquid crystals, and non-cubic crystals; are best characterized using G-VASE™ (anisotropic) measurements. For an anisotropic measurement the ellipsometer measures the standard Y and D as well as ratios of cross polarized light. This results in acquisition of three Ψ and three Δ parameters at every wavelength (Ψ, Ψ_{ps}, Ψ_{sp}, Δ, Δ_{ps}, Δ_{sp}). This additional information helps to sort out the complexity of an anisotropic material.

Mueller-matrix measurements are useful when the sample is both depolarizing and anisotropic.\

*Excerpts from B. Johs et al., “Overview of Variable Angle Spectroscopic Ellipsometry (VASE), Part II: Advanced Applications.” SPIE Proc. Vol. CR72, (1999), p. 29-58

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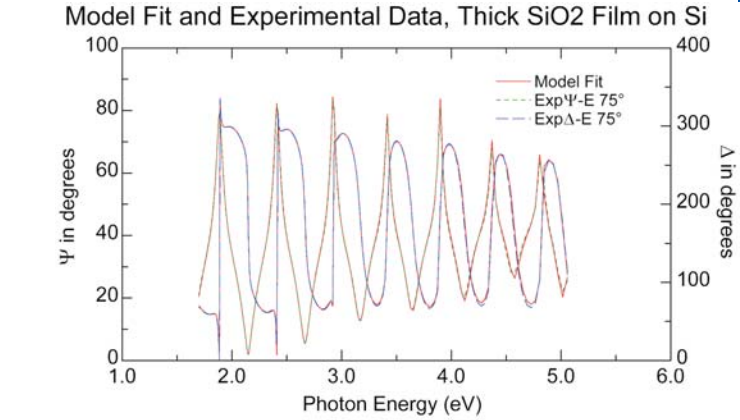

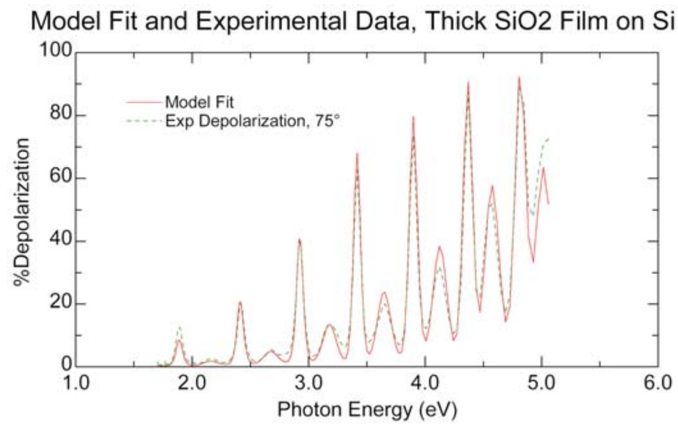

Figure 4a and 4b. Spectroscopic ellipsometric (a) and depolarization (b) data acquired on a 10540Å SiO_2 film on Si by a M-2000. To fit the depolarization data, a spectrometer bandwidth of 7nm (assuming a Gaussian profile) and a film thickness non-uniformity of 0.44% were included in the optical model

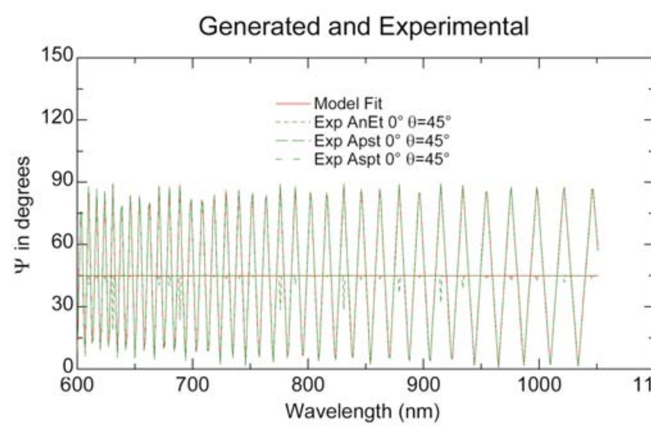

Figure 5: G-VASE™ data acquired on LiNb substrate. The oscillations in the data are due to a conversion of p-polarized light to s-polarized and vice versa. Six data points are acquired at each wavelength when performing a G-VASE™ measurement .