Angstrom Advanced Inc.

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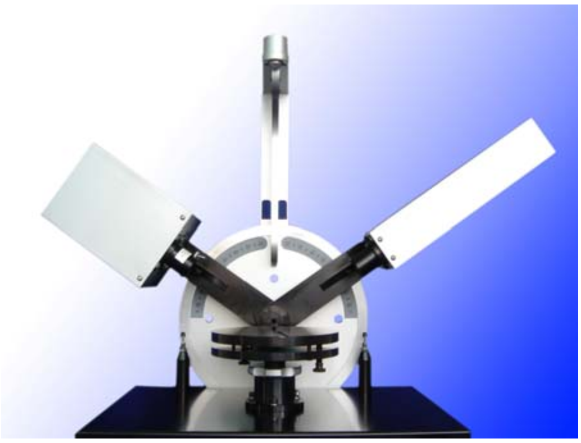
World Class Ellipsometer

Thin film thickness and optical thickness characterization

Angstrom Advanced is the leading supplier for ellipsometers. We offer full range of ellipsometers for thin film thickness measurement and optical characterization for refractive index and extinction coefficient (n & k). The Angstrom Advanced ellipsometer family includes discrete wavelength ellipsometers (single wavelength ellipsometers and multi-wavelength ellipsometers), deep UV, UV, VIS, NIR and IR spectroscopic ellipsometers. Our ellipsometers have been delivered to many renowned universities, research institutes and companies worldwide. Angstrom Advanced's goal is to supply the most accurate and repeatable ellipsometers with the highest standard of customer satisfaction. Many upgrade accessories are available for different applications.



Introduction to Ellipsometer

1. A brief definition of Ellipsometry and Ellipsomter

Ellipsometry is an optical technique for the investigation of optical properties of materials. An ellipsometer is an optical instrument which carries out the ellipsometry measurement. It measures the change of polarization state of light. The analyses are based on the physical theorems -- mainly the Fresnel's Reflection Equations. Generally, polarization of lights is illustrated by an ellipse, this is how the word "ellipsometry" and "ellipsometer" comes from.

The technique has been known for a century, yet it became widely used as standard instrument only several decades. Even though both refraction and reflection (and many other physical phenomena) can cause the polarization state change, most ellipsometry applications only concern the reflection, more specified, the reflection from a stack of films. Through the data analysis, many properties and parameter about the film can be abstracted, including optical constant (refractive index *n* and extinction coefficient *k*), film thickness, composition, roughness, gradience and many more. It is commonly used to characterize film thickness for single layers or complex multilayer stacks.

Ellipsometry is a precise measurement in nature. The measurement principle automatically cancels the changes of absolute intensity of light, which is a normal error source in optical measurement. In its standard measurement of film thickness, its accuracy can reach angstrom or sub-angstrom.

Measurement of optical thick film is not the advantage of ellipsometer because the polarization state change theoritically is a period function of the thickness. The problem can be overcome by multiple incident angle measurement or even by using spectro-ellipsometer, however, the most precision range of the ellipsometer is under about 2000-3000Å.

2. Light and Polarization

Light can be imagined as electromagnetic waves, and can be expressed using its electrical field by following equations:

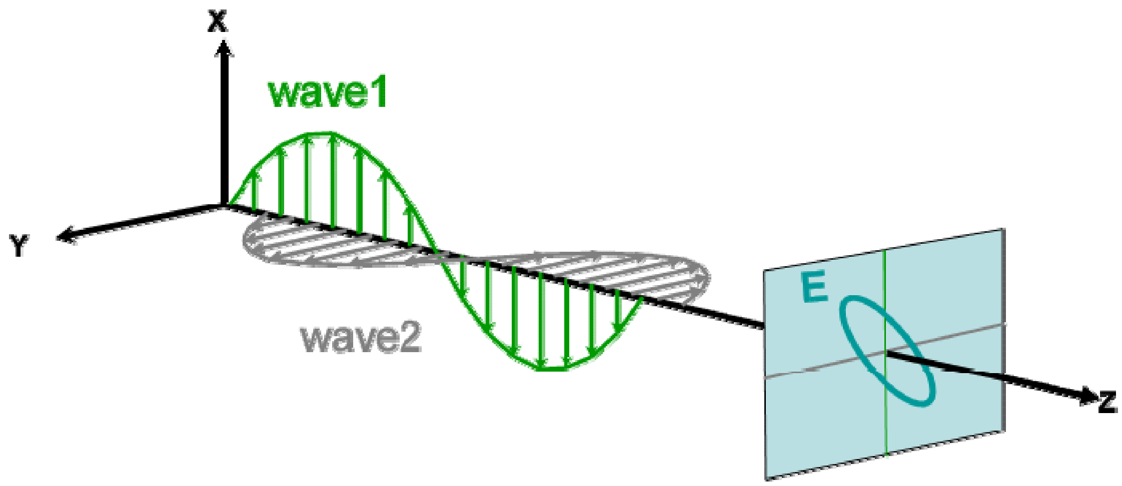
$$\vec{E}(s,t) = A_1 \cos[\omega t - \mathbf{k}\cdot s + \delta_1]\mathbf{u}_1 + A_2 \cos[\omega t - \mathbf{k}\cdot s + \delta_2]\mathbf{u}_2$$

or

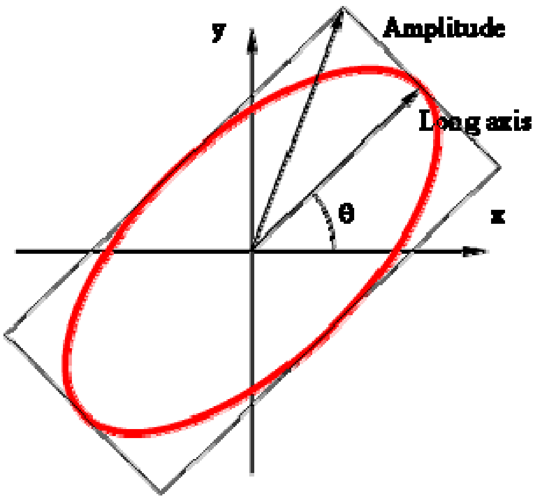
$$\vec{E}(s,t) = real\left(A_1 e^{-j(\omega t - \mathbf{k}\cdot s + \delta_1)}\mathbf{u}_1 + A_2 e^{-j(\omega t - \mathbf{k}\cdot s + \delta_2)}\mathbf{u}_2 \right)$$

where **u**1 and **u**2 are two unit vectors to indicated the direction of two orthogonal components, w is the angular frequency of the wave; **k** is the wave number whose absolute value is 2p/l (l is the wavelength of light in medium), and the directional part indicate the propagating direction of the light; **s** is the directional distance for study the amplitude of electrical field; A1 and A2 are amplitude and d1 and d2 are phases.

The trace of the end of electrical field is normally used to describe the polarization state. As we can see from following graph, ellipse is the general case of polarization.



To specify polarized wave, *q* (azimuth angle, the direction of long axis of the ellipse), e (ellipticity - the ratio the short to the long axis), A (amplitude, the half of the diagonal of the most tighten rectangle box), directional wave number **k**, handness and the exact phase. Normally, A, wave number and the exact phase are not concerned in the study. The parameters under interest can be converted to amplitude ratio and phase difference between the two components, and vice versa.

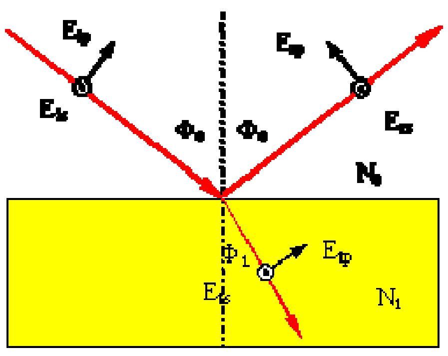


When the two components of the electrical field are exactly in phase to each other, the ellipticity will be 0 and the light is linearly polarized. Another special case is circular polarization, where the ellipticity is 1 and the phase difference is 90 or 270 degree.

The equations above supposed a single wavelength, which indicates a strict monochromatic light. Commonly, light is superposition of many waves, each of which can be expressed by the equation in the part of their lifetime. They might differ in the frequency (color), and amplitudes and phases (polarization). Polarization is an indication of how the light spirally propagates in the space. If all the waves followed the same rule of polarization (same ratio of amplitude and phase difference), the light is said to be polarized. Sunlight, which is composed of light wave with different wavelength and polarization style, can be polarized after reflected from surface of water. Photographer normally need an analyzer to get rid of the strong reflection from the surface and catch the fishes in the water.

3. Reflection and Fresnel's Equations

Polarization state of light will be changed after reflection and refraction. To describe the change, light is decomposed into two linearly polarized components: one along the direction normal to the incident plane (called the transverse electrical field and denoted by TE, E_s or $E_\perp$ and the other in the incident plane (called the transverse magnetic field and denoted by TM, E_p or $E_{//}$). Subscripts i,r,t is used to indicate incident, reflected, transmitted light. They are illustrated in the graph below, as light reflected and refracted when entering medium N_1 from medium N_0



The Fresnel's reflection equations specify the change of each components in the reflected and refracted light by *r* and *t*.

$$\frac{E_{rp}}{E_{ip}} = r_p = \frac{N_1 \cos\Phi_0 - N_0 \cos\Phi_1}{N_1 \cos\Phi_0 + N_0 \cos\Phi_1} = \frac{\tan(\Phi_0 - \Phi_1)}{\tan(\Phi_0 + \Phi_1)}$$

$$\frac{E_{rs}}{E_{is}} = r_s = \frac{N_0 \cos\Phi_0 - N_1 \cos\Phi_1}{N_0 \cos\Phi_0 + N_1 \cos\Phi_1} = \frac{-\sin(\Phi_0 - \Phi_1)}{\sin(\Phi_0 + \Phi_1)}$$

$$\frac{E_{tp}}{E_{ip}} = t_p = \frac{2N_0 \cos\Phi_0}{N_1 \cos\Phi_0 + N_0 \cos\Phi_1} = \frac{2\sin\Phi_1 \cos\Phi_0}{\sin(\Phi_0 + \Phi_1)\cos(\Phi_0 - \Phi_1)}$$

$$\frac{E_{ts}}{E_{is}} = t_s = \frac{2N_0 \cos\Phi_0}{N_0 \cos\Phi_0 + N_1 \cos\Phi_1} = \frac{2\sin\Phi_1 \cos\Phi_0}{\sin(\Phi_0 + \Phi_1)}$$

Most of symbols in the above equations are self explained in the graph, except the complex refractive index $\mathbf{N} = n + jk$, where n = c/v (the ratio of light speed in vacuum to in medium, specifies the effect of medium on wave number **k**) is the refractive index and k is extinction coefficient, which is related to the absorption constant a by:

$$\alpha = \frac{2\omega k}{c} = \frac{4\pi k}{\lambda}$$

In addition, Φ_0 and Φ_1 follows the rule of refraction:

$$N_0 \sin\Phi_0 = N_1 \sin\Phi_1$$

The measurement of both *r* and *p* involves the measurement of two lights' intensity. This is not an easy thing in reality because of small difference in the response of individual detectors and time variation of intensity of light source. Ellipsometry bypasses the difficulty beautifully by measuring the ratio between r_s and r_p (or t_s and t_p).

$$\rho = \frac{r_p}{r_s} = \tan\psi \exp(j\Delta)$$

Take a close look we find that

$$\Delta = \angle\rho = \angle r_p - \angle r_s = (\angle E_{rp} - \angle E_{rs}) - (\angle E_{ip} - \angle E_{is})$$

describes the change (from incident to reflected light) in phase difference between the two components.

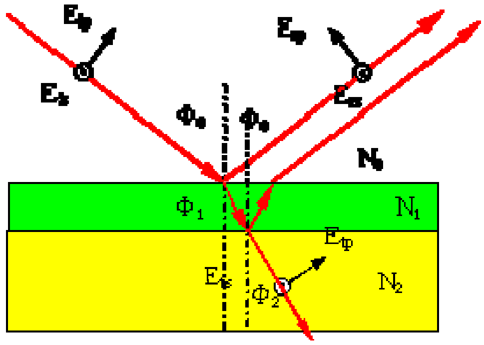
$$\tan\psi = |\rho| = \frac{|r_p|}{|r_s|} = \frac{|E_{rp}|}{|E_{ip}|} \cdot \frac{|E_{is}|}{|E_{rs}|} = \frac{|E_{rp}|}{|E_{rs}|} \div \frac{|E_{ip}|}{|E_{is}|}$$

describes the change (from incident to reflected light) in the amplitude ratio between the two components.

As discussed in last section, we need only to know the polarization state (determine the ellipse) of incident and reflected light respectively. The polarization state of incident light is totally controllable by orientation of the polarizer and phase plate, therefore only the polarization state of reflected light need to be measured.

4. Drude's Equations

Ellipsomtry was first used by Drude to measurement very thin film in 1889. Drude's equation is a counterpart of Fresnel's equation for the film structure. It is the basic of the ellipsometry.



Drude's equations can be derived from Fresnel's equation with combination of the interference between the layers. The reflected light is a superposition of beams , $E_i r_{01}$ $E_i t_{01} r_{12} t_{10} e^{-j2\beta}$..., $E_i t_{01} r_{12}^{N+1} r_{10}^{N} t_{10} e^{-j2N\beta}$... where the subscript 01 means light enter medium 1 from medium 0 and β is the phase delay the beam experiences during propagating from the top surface of the film to the bottom surface of the film. The subscripts s and p are ignored here for both components, following this rule. From last section we know that $r_{ab} = -r_{ba}$ and $t_{ba} t_{ab} + r_{ab}^2 = 1$. These lead us to the Drude's equations:

$$R = \frac{r_{01} + r_{12} e^{-j2\beta}}{1 + r_{01} r_{12} e^{-j2\beta}}$$

$$T = \frac{t_{01} t_{12} e^{-j\beta}}{1 + r_{01} r_{12} e^{-j2\beta}}$$

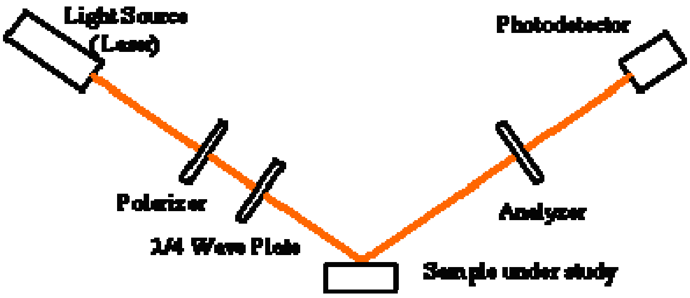
$$\beta = 2\pi\left(\frac{d_1}{\lambda}\right) N_1 \cos\phi_1 = 2\pi\left(\frac{d_1}{\lambda}\right)\left(N_1^2 - N_0^2 \sin\phi_0\right)^{\frac{1}{2}}$$

For a stack of multiple layers, the Drude's equations can be used recursively from the bottom to the top layer. Frensel's reflection and transmission amplitude coefficient of each surface are first calculated; an effective coefficient of the bottom film is calculated by substituting the amplitude coefficient into Drude's equations; then by using this effective coefficient as an amplitude coefficient, an effective coefficient of next-to-the-bottom layer is calculated by the Drude's equations, …., until the top layer is reached.

For transparent films, will be periodic as the thickness of film increases, causing the periodicity of vector (Ψ,Δ) as functions of film thickness. This non-uniqueness is a main limitation of ellipsometer.

5. Ellipsometer and Data Processing Software

Ellipsometer measures the Ψ and Δ at different incident angle (or even at different wavelength). A general configuration of ellipsometer is illustrated as:

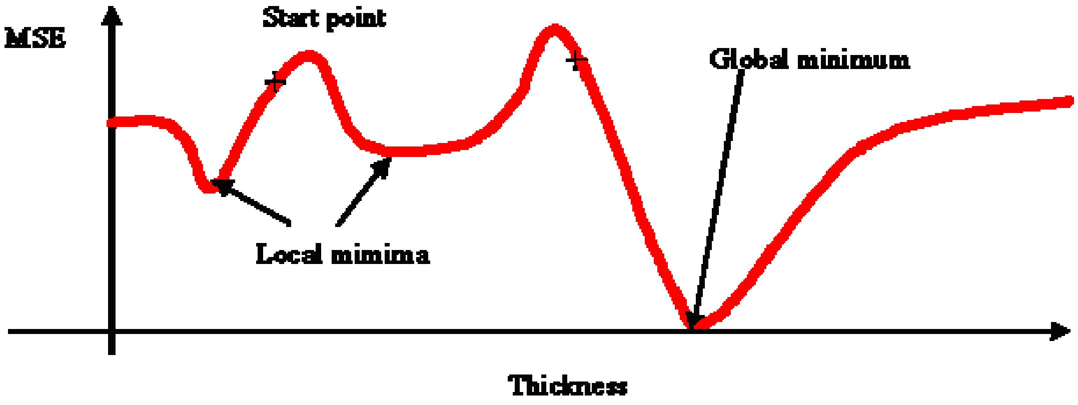


According to the operation mode, ellipsometer can be classified into rotate elements, polarization modulation and null ellipsometer. Polarization modulation is, in fact, only a way to avoid the rotate components by using polarization modulation devices (it offers the benefit of fast operation and less mechanical vibration). A null ellipsometer normally need human being to interact to find a condition in which the reflected light is nulled at the detector. This needs to be implemented by adjusting the azimuth angle of polarizer, wave plate and analyzer. Even though very accurate, null ellipsometer needs patience and experience to find the nulling condition. Rotating elements ellipsometer has several variants, including rotate polarizer or analyzer (in both case, the wave plate might be absent) and rotating wave plate. The intensity at the detector side is measured as a function of rotating angle, and be analyzed by Fourier analysis to determine the polarization state change. They are normally called photonic ellipsomter because the way to measure optical energy. Because the fast operation, photonic ellipsometer normally can take tens or hundreads of measurements to average off the random error.

Another widely used method to classify the ellipsometer is by the light source. The abbreviation SWE means single wavelength ellipsometer, which means a "monochromatic" light source -- normally a laser -- is used as light source; while SE is the short name for Spectroscopic Ellipsometer, which means the light source covers a spectrum range. There are also Discrete Wavelength Ellipsometers which applied several discrete wavelength.

For a bulk material, a measurement at single incident angle is enough to determine the refractive index and extinction coefficient. For films with known refractive index and extinction coefficient, it can be used to determine the thickness. However, in reality the measurement itself is not as simple as measuring a bulk material. Refractive index and extinction coefficient of a film might differ greatly from the bulk materials due to the effect of the substrate on which it grows as well as the growth condition. Things get more complex with multiple layer stacks. These changes make the refractive index and extinction coefficient an unknown variable, and makes manual solution of the equations almost impossible. Therefore, modern ellipsometers need to be equiped with powerful software, not only for the hardware control and data acquisition, but also the data analysis.

The processing of the experiment data (which normally only the records of incident angle, wavelength, Y and D) starts from make a model to describe the film stack. With a correct model, the software then carries out a minimum searching based on an elevation function (which normally the MSE- mean square error) according to the variable specified. Because the minimum search algorithm is normally ended up with a local minimal point, the starting point plays an important role in the result, with The modeling process is very important to the correctness of the result.


MSE
Start point
Global minimum
Local mimima
Thickness

PHE 102 Spectroscopic Ellipsometer

Features

• Very fast measurement in the UV/VIS range 250 - 1100 nm with diode array detector or motor spectrometer (monochromator)
• Optional extension of spectral range into the NIR (700 - 1700 nm) or (700 - 2100 nm)
• Optional extension of UV-VIS range (190 - 1100 nm)
• Rotating polarizer provides accurate measurement of any polarization state \
• Step scan analyzer for high speed low noise acquisition
• Variable angle from 20-90° automated angle with 20-90° is available
• Fast determination of thickness and refractive index of single or multi-layer samples
• Broad range Psi and Delta data are measured automatically and fitted through the PHE-102 software
• Includes PHE-102 software, the most comprehensive program available for data acquisition and analysis. It combines state-of-the-art mathematical fitting algorithms with a large selection of modeling options for fast, accurate data analysis. an advanced spectroscopic ellipsometry software
• Built in library of materials properties, includes several hundreds materials models
• Mixture of new materials by use of know material properties

Introduction

The PHE-102 series are variable angle spectroscopic ellipsometers operating in the spectral range 250 - 1100 nm or 250-1700nm or 250-2100nm. In the PHE-102 a broad band white light source is used to illuminate the sample spot. The layer stack imparts a change in state of polarization to the light and is reflected back through the analyzer and into the detector which are measured as the ellipsometric parameters of Psi and Delta. The spectral dependence of the refractive index and dielectric constants of the materials and much more are determined by fitting the measured data to a theoretical model which describes the layer structure in detail.

Two technical concepts are available for the PHE-102 spectroscopic ellipsometer. The first concept uses a photodiode array(or CCD) as detector. In this case the measurement in the UV/VIS NIR region is based on the Step Scan Analyzer principle where no parts are moving during a measurement and a multi element fast diode array detection is used: The reflected light is analyzed at discrete analyzer positions with an optical multichannel analyzer, consisting of a grating and high performance photodiode array detector providing high spectral resolution. This concept allows fast measurements. The second concept uses instead of the photodiode array a monochromator for wavelength selection. This concept is slower but has better precision.

Software

Our truly user friendly PHE Spectroscopic software allows the user to measure and analyze multiple material layers and complex thin film structures with mixed layers, interface layers and much more.The state-of-art software has several hundreds materials models. The PHE-102 includes all the hardware and software needed for acquiring and analyzing this kind sample data.

Materials Library

Speed	Typical measurement including data analysis 1 ~ 2.0 minutes
Thickness range of transparent films measurement	0 - 30000 nm
Thickness range of absorptive films measurement	0 - 30000 nm
Refractive index	± 0.0001
Thickness accuracy	± 0.01nm
Range of angle of incidence	20 - 90°, automated angle with 20-90 ° available
Reflection angle steps	5° ± 0.01°
Spot size	Ellipse ~ 1 mm × 3mm
Stability	Long term (months) ± 0.01° in Δ
Measurement time	1 s ~ 2.0 minutes
Sample stage	Wafer chuck up to 200mm diameter
Sample stage adjustments	Tilt and height
Sample alignment	automated
Standard wavelength	250-1100nm, 250-1700nm, 250-2100nm

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