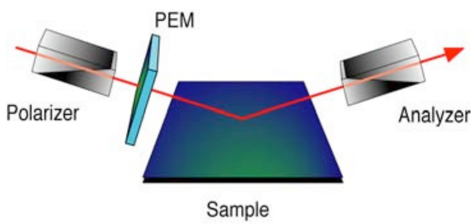
What is Ellipsometry ?

Ellipsometry is a non-destructive, light optical analysis technique that requires neither sample preparation nor special measurement environment. Samples of almost any size and shape can be examined “as-is” and are unaffected by the process. The non-contact nature of the technique lends itself to measuring materials like semiconductor wafers, optical components like mirrors, coatings, and LCD displays.

Ellipsometry uses the fact that light undergoes some change in polarization when it is reflected off the surface of a material. The polarization change is characteristic of the surface structure of the sample and so we can obtain various information about the material simply by analyzing the reflected light beam.

Although most commercial ellipsometers are designed for operation only in reflection geometry, JASCO instruments can also be configured for transmission work. So, any transparent material can be studied and in this case, for example the bulk materials properties can be analyzed. In the case of a LCD display, both the reflective (surface layer) and transmission (bulk, LC part) information are required. With a semiconductor wafer, only reflection data is required and so simpler instruments can be used.



Measure Ψ and Δ

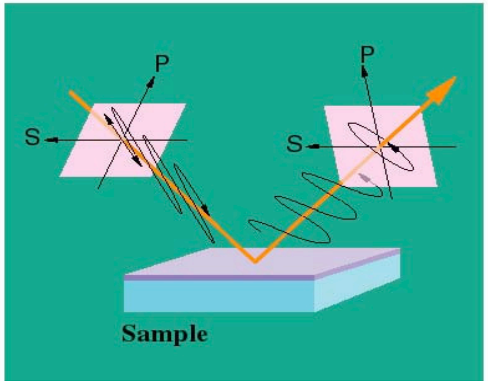
Model based analysis

Film thickness
Refractive Index (n)
Extinction Coefficient (k)
Surface Roughness
Anisotropy
Retardation
Phase Difference
Birefringence

Ellipsometry

Ellipsometry does not directly measure thickness or optical constants, It measures change in light polarization expressed as Ψ and Δ. Ψ and Δ determine the differential changes in amplitude and phase, respectively, experienced upon reflection by the components of the electric vector parallel and perpendicular to the plane of incidence.

Relation between Polarization Change and Ellipsometric Parameters (Δ, Ψ)



$$\Delta = \Delta_p - \Delta_s$$

$$\tan\Psi = \frac{(E_p/E_s)_{\mathrm{Reflected}}}{(E_p/E_s)_{\mathrm{Incident}}}$$

$$\frac{r_p}{r_s} = \tan\Psi\, e^{i\Delta}$$

Δ: relative phase change

Ψ: relative amplitude change

In the ellipsometry it is usual to describe the polarization states in a system of two orthogonal basis vectors (p,s). The s-direction stands thereby perpendicularly to the plane of incidence. The measured variables are the two ellipsometric angles Δ (DELTA) and Ψ (PSI). Whereby Δ (DELTA) is the phase difference between p- and s-direction of the complex Fresnel reflection coefficient (Rs, Rp) with given wavelength and angle of incidence. However tan(Ψ (PSI)) is a measure for the change of the absolute value of Rs and Rp. Because the ellipsometry measures the ratio of these two values (Rs, Rp), it is a very exact and reproducible measuring method.

What does Ellipsometry tell us about samples ?

Variable angle spectroscopic ellipsometry tells us:

1. Material optical constant n, k directly
2. How these constants vary with wavelength
3. Variation with incidence angle

By computer modeling:

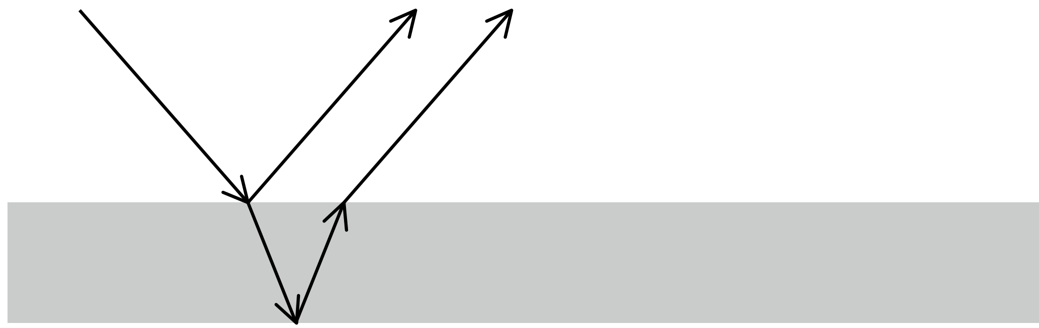
Thickness of single or multiple layers

By processing the data from many points on the sample:

Generate 2-D or 3-D “maps” of the sample surface

Ellipsometry is very sensitive to ultra-thin films of 1 Å up to about 1 μm.

For multiple layers, the materials must be transparent or semi-transparent.



What does Ellipsometry tell us about samples ?

Optical constants

By reflecting a light beam off the surface of our sample, the polarization of the beam is altered. In the simplest ellipsometer, we illuminate the sample with a linearly polarized light beam and after reflection, the beam is circularly or elliptically polarized, to some degree. We use a polarization-sensitive analyzer to measure the degree of elliptical polarization. By doing this, we obtain the refractive index, n, and extinction coefficient, k, of the sample surface.

Refractive index (n): Propagation speed of the wave through the sample and direction of propagation

Extinction coefficient (k): relates how much of the energy of the wave is absorbed in a material

Both vary with wavelength and temperature.

Thickness

However, ellipsometry can also provide more, detailed information. For example, many new materials, including semiconductor wafers, are made with single or multiple thin layers of different materials, deposited or “grown” on a substrate layer. Three examples of this are:

SiO_2 on Si (semiconductor wafer processing)

SiO_2 on glass (optical coating on glass)

ITO (indium tin oxide) on glass (LCD manufacture)

In this case, we already know the refractive index of the materials (SiO_2, Si, ITO) from reference work, but we want to know the thickness of the layers: even a few Å thick “thin films” can be measrued extremely accurately.

What does Ellipsometry tell us about samples ?

Variable angle

Most commercial ellipsometers are “variable angle” instruments. We can measure the sample using a range of incidence angles (typically, from 40º to 90º) in order to study the sample at or near to the “Brewster” angle, for optimum sensitivity. When measuring thin film properties, data are collected at a range of angle in small steps of a degree or more.

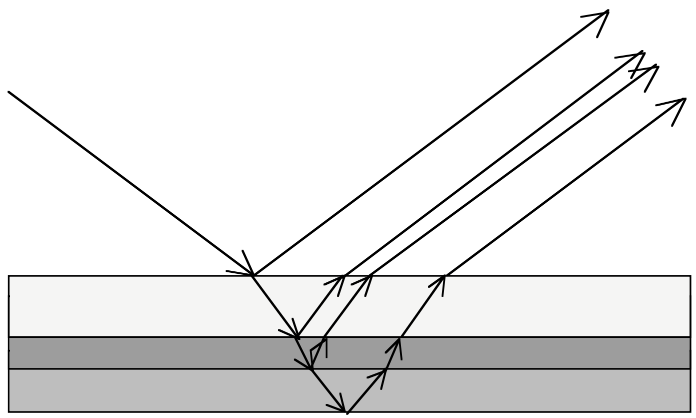
Variable wavelength

Materials reflect or transmit light differently according to the wavelength of the light, and so a comprehensive ellipsometer is equipped with a spectrometer to enable variable-wavelength light to be used. In some cases, data can be obtained at a single wavelength and here a small He-Ne or solid-state laser is used for its intense light and small beam size.

What does Ellipsometry tell us about samples ?

Multiple layers

By obtaining ellipsometry data over a range of angles and wavelengths and using the known optical parameters of the sample layer materials, computer processing allows us to “model” not only single but multiple layer samples. By comparison of the observed data with a computer-generated “model” of the ellipsometer results, we can deduce the thickness of up to 20 multiple, overlaying layers of different materials. Although the ellipsometer cannot tell us the layer thickness directly, the data obtained are sufficiently accurate to enable us to fit a proposed model structure to the data with good confidence. Compared with this non-destructive ellipsometry approach, alternatives such as transmission electron microscopy require enormously time-consuming and of course sample-consuming preparative work. The ellipsometer obtains the data in minutes rather than hours or days, and it is therefore ideally suited to applications requiring fast results.



How do Ellipsometers work?

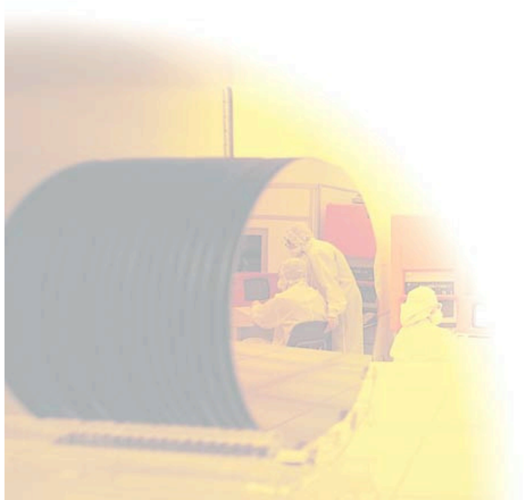
Basics

There are three basic designs of ellipsometer in general use but all three are doing approximately the same work. We illuminate the sample with a narrow, parallel beam of monochromatic light of known polarisation, at a known angle of incidence. Using a polarisation-sensitive analyser, we measure the change in polarisation after reflection from the sample's surface. From this polarisation change we calculate optical parameters for the sample. The differences between the various instruments are mostly due to the choice of polarizer and analyser systems, and light sources.

Nulling ellipsometer

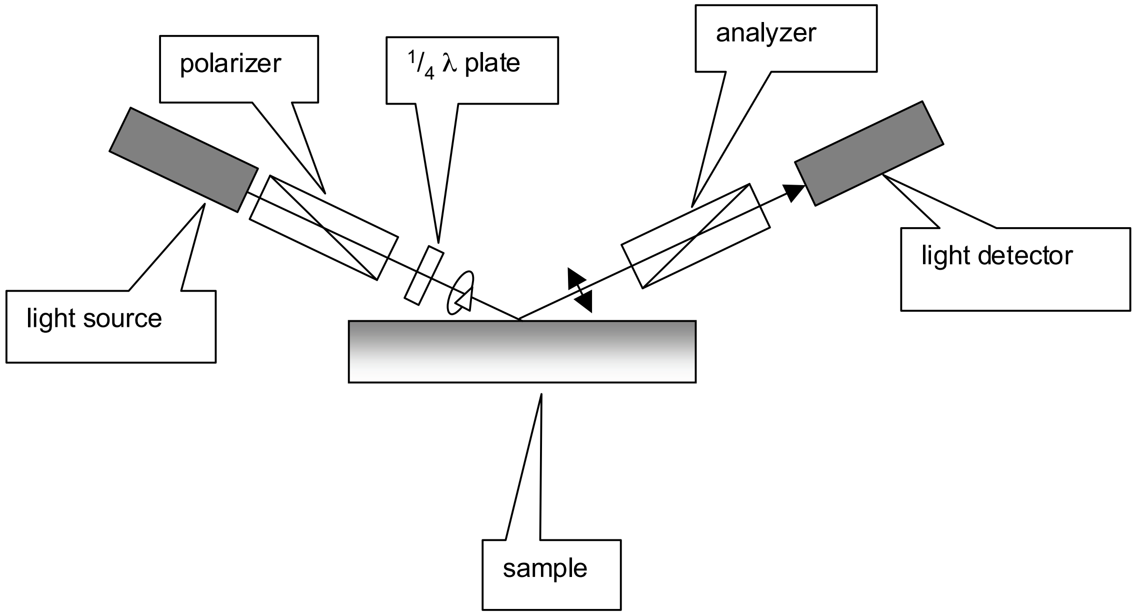
Rotating analyser

Photo elastic modulator ellipsometers



Nulling ellipsometer

The simplest ellipsometer utilises a “nulling” principle. A beam of elliptically polarised light illuminates the sample. A polarizing analyser is rotated to find the minimum for light entering the detector. The disadvantages of this system are, the optical components are wavelength-specific, and real-time measurements of millisecond scale phenomena cannot be made.

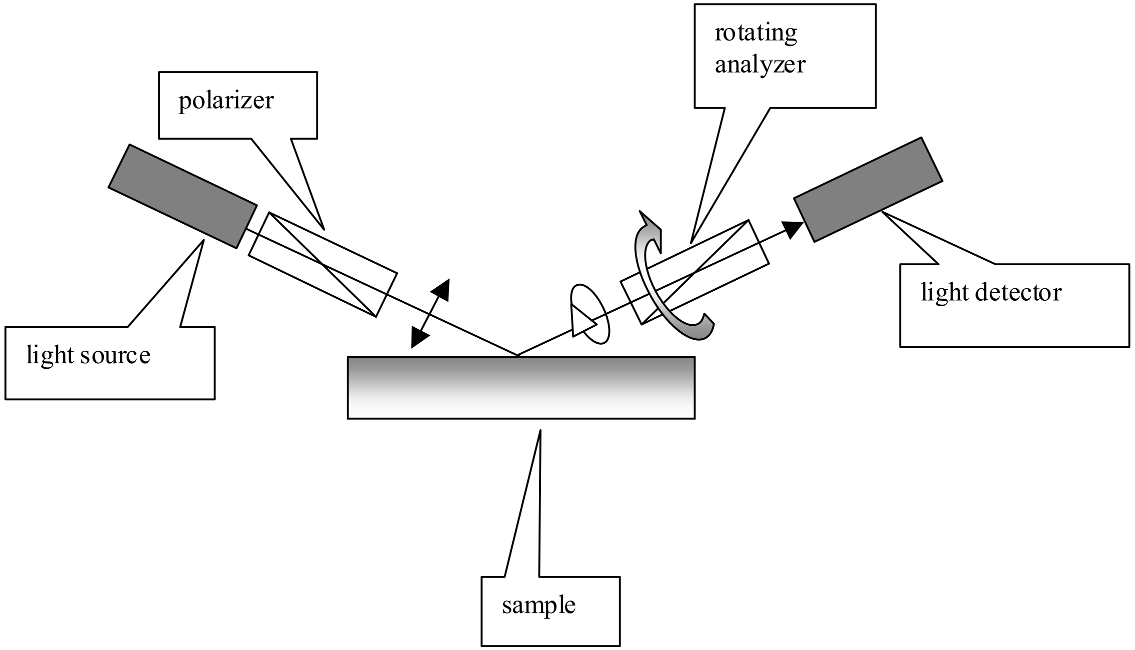


Nulling ellipsometer schematic

Rotating analyser

Most older commercial ellipsometers use a continuously rotating analyser method. This method uses linearly polarized incident light that is elliptically polarized by reflection from the sample. The rotating analyser then produces a detector output intensity as a function of polarization angle.

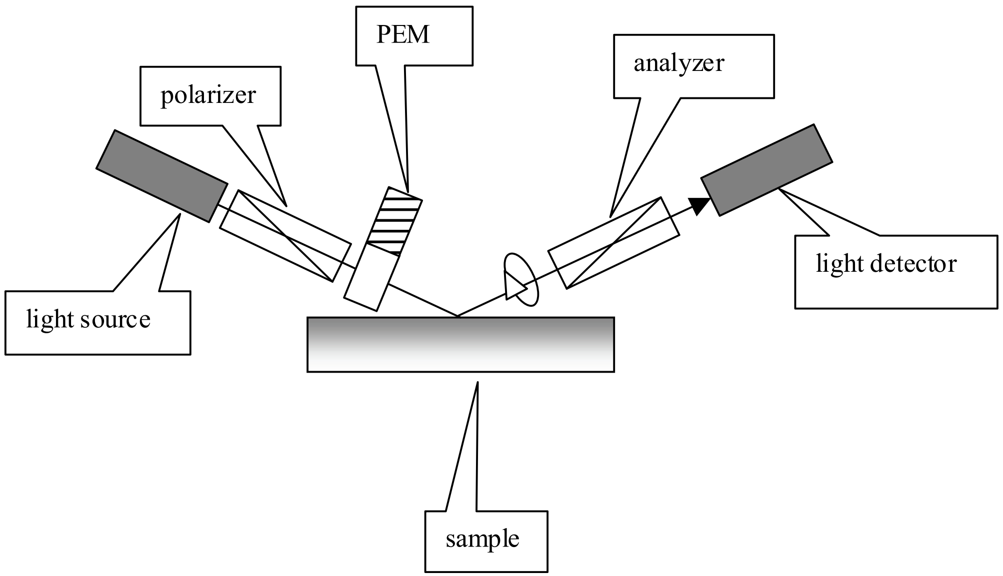
These systems have the advantage of compatibility with spectrometer illumination systems, and a reasonably fast acquisition speed compared with the nulling method. Also, the control electronics are relatively simple.



Rotating analyser ellipsometer schematic

Photo elastic modulator ellipsometers

Photo elastic modulator (PEM) optics is used in the “latest generation” ellipsometers. These instruments are also referred to as “solid state” ellipsometers, because there are no moving parts required for acquiring data. Essentially, the quarter wave (λ/4) plate in Figure 2, is replaced by the PEM which comprises a quartz window element and a piezo-electric transducer. The PEM, driven by the computer and control electronics, modulates the light beam polarization at 50 kHz and a fixed analyser element allows the detector to generate a corresponding signal after the beam is reflected from the sample. Theoretically, time resolution of 20μs can be achieved but in practice longer (~1 ms) sampling intervals are used.



The PEM system, whilst fast and accurate, requires various kinds of control electronics in order to operate and stabilise the measurements. In particular, the PEM itself is very sensitive to changes in temperature and requires different applied voltages for different wavelengths. The technology for doing this is the subject of three Japanese patents held by JASCO. Currently only JASCO and two other manufacturers produce PEM ellipsometers: the majority of competitor’s products employ rotating analysers.

The PEM geometry is the most sensitive to thin layers because the measured property Δ, the phase difference, is given as a $\sin^{-1}$ function whereas the rotating analyser Δ is a $\cos^{-1}$ function. Advantages of PEM spectroscopic ellipsometry (PEMSE) are:

- Faster measurement speed
- Higher measurement stability
- Higher sensitivity at small retardations
- Very sensitive to ultra-thin films