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TECHNICAL NOTE

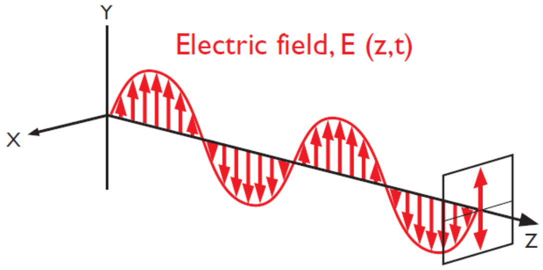
Spectroscopic Ellipsometry

Ellipsometry is a powerful analytical tool in the characterization of thin films in many applications, including semiconductors, dielectrics, metals and polymers. It is a non-contact, non-destructive optical technique, that measures the polarization change as light reflects from a material structure. This change in polarization is related to properties like thin film thickness and refractive index.

Theory

Light can be described as a travelling electromagnetic wave. The electric field of this transverse wave is always orthogonal to the propagation direction. Therefore, the electric field of a wave traveling along the z-direction can be described by its x- and y- components. In ellipsometry, we are interested in the polarization state of the light. The polarization state is defined by the shape that the electric field (resulting from combination of x- and y-components) traces out at any point along the z-direction.

Several different types of polarization can be distinguished. When the x- and y-components are perpendicular and in phase with each other, a linearly polarized wave results. In Fig. 1, a linearly polarized wave with the electric field oscillating in the y-direction is shown.



Elliptically polarized light is illustrated in Fig. 2. In this polarization state, the x- and y-components can take on any arbitrary phase and amplitude. The result is an ellipse propagating along the z-direction.

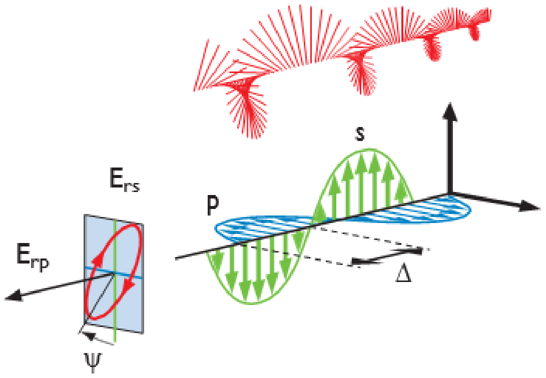


Fig. 2.: Visualization of propagating elliptically polarized light. For an elliptically polarized wave both components have arbitrary amplitude and phase

In a reflection configuration, it makes sense to define the directions of the x- and y components of the electric field relative to the plane of incidence. The plane of incidence is the plane perpendicular to the surface of the sample that contains the incident and reflected light rays (see Fig.3).

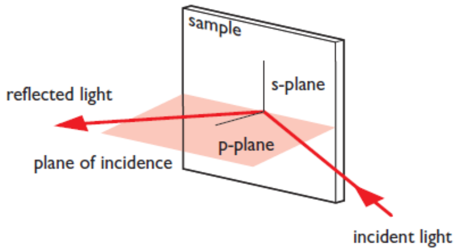


Fig. 3: The plane of incidence

The two components of the electric field are now defined as one parallel (p) to the plane of incidence and the other perpendicular (s) to that plane. It follows from the continuity conditions of electric and magnetic fields across optical interfaces that the p and s components reflect differently. The so-called Fresnel equations that describe the reflectance of the p and s components contain the optical properties of the material(s) and hence lie at the heart of the ellipsometric measurement.

The angular dependence of p and s reflectance is illustrated in the silicon example of Fig.4. The Rs reflectance increases steadily, while the Rp reflectance goes through a minimum. The angle corresponding to the minimum is called the Brewster angle. Ellipsometry measurements are most sensitive to film characteristics around this Brewster angle.

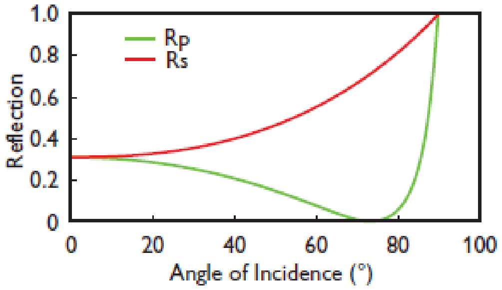


Fig. 4: The reflectance as a function of angle of incidence for the parallel (Rp) and perpendicular (Rs) components of polarized light.

Ellipsometry

The term ellipsometry stems from measuring elliptically polarized light. The incident light interacts with the sample and reflects from it (see Fig. 3). The interaction of the light with the sample causes a polarization change in the light, from linear to elliptical polarization. This change is measured by analyzing the light reflected from the sample.

The polarization change is represented as an amplitude ratio, Ψ (Psi), and a phase difference, Δ (Delta). In Fig. 5, the behavior of Psi and Delta as function of incidence angle is depicted. Because ellipsometry measures a ratio instead of pure intensities, it is not affected by intensity instabilities of the light source or atmospheric absorption.

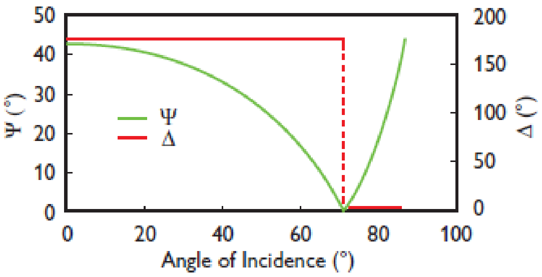


Fig. 5: Behavior of Psi (Ψ) and Delta(Δ), which describe the polarization state of reflected light after interaction with a sample. Ψ is the ratio of the reflected intensities Rp and Rs and Δ is their relative phase change.

Generally, measurements are performed at different angles of incidence and in a wavelength range of interest (Variable Angle Spectroscopic Ellipsometry, VASE). This procedure helps to ensure collection of sufficient data to allow determination of multiple unknown parameters in difficult, multi-layer samples.

Data Analysis

Ellipsometry does not actually measure sample properties directly, but Psi and Delta are functions of these properties. To extract useful information about thin films, a model is constructed that describes the optical parameters of the sample. Then, the unknown parameters and the thickness are fit to obtain a best match between the theoretical response and the experimental Psi and Delta data.

Refractive index and extinction coefficient

Ellipsometry is primarily used to measure film thickness, the refractive index (n) and the extinction coefficient (k). These properties describe the optical behavior of materials and are not constant but vary with wavelength and temperature. Furthermore, they can also depend on direction in case of optically anisotropic materials (birefringence). Often n and k can be related to other material properties, like composition, porosity or electrical properties.

Layer thickness

When light is incident on a thin film it is reflected by both the top and bottom interfaces. Each reflected wave will have its own phase and amplitude, which causes interference of the reflected light. Thicker films will show more interference fringes (Figure 6).

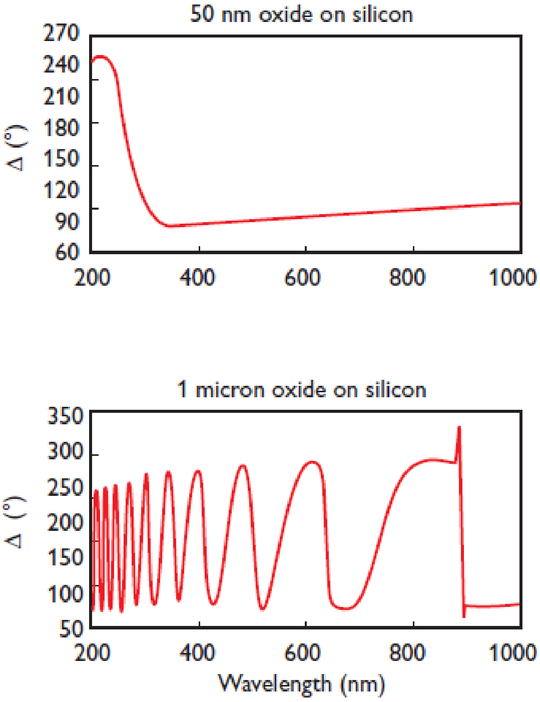


Fig. 6: Layer thickness studies: the number of interference fringes is characteristic for the film thickness.

Because of the occurrence of interference fringes, layer thicknesses can be determined very accurately, both for single layer thin films (see Figure 7) as well as for multilayer stacks.

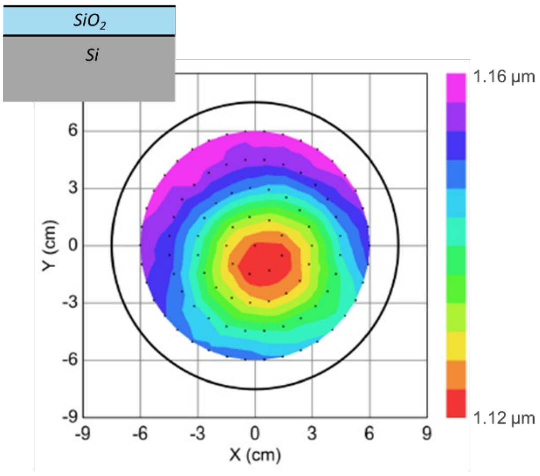


Fig. 7: Example of thickness mapping of a silicon oxide layer on a silicon wafer.

Applications

- Thickness, optical constants of organic and inorganic thin films on flat substrates.
- Individual layer thicknesses of complex multi-stack samples.
- Thermal expansion of organic and inorganic thin layers.
- Optical anisotropy of polymer films.

Technical specifications

Acquired data:

- Reflection and transmission ellipsometric data, polarized transmission and reflection intensity (wavelength range 192 – 1689 nm).
- Lateral information: 200 µm or 2 mm depending on selected spot size.
- Automated sample translation stage (150 x 150 mm) available for mapping procedures.

Accuracy (thickness, optical constants):

- Mainly determined by how well the optical model describes the real sample.
- Precision (repeatability) can be better than 0.1 nm for thickness and better than 0.001 for n and k.

Sample type & requirements:

- Solids, thin layers and multilayers with optically flat substrates.
- Thickness from sub-monolayer coverage to µm range.

Heating experiments:

- Temperature (max. 300°C) dependent measurements are possible, also in different atmospheres.

Spot size:

- 200 µm or 2 mm.

Strengths

- Non-contact, non-destructive.
- Not affected by intensity instabilities of the light source or atmospheric absorption.
- Fast.
- Precise thin film thickness and optical constants measurements.

Limitations

- No direct measurement of material properties; an optical model of the sample must be fitted to the data.
- Requires optically flat sample surfaces.