PEMs IN ELLIPSOMETRY

Ellipsometry is a method for determining the properties of a material from the polarization characteristics of elliptically polarized incident light reflected from its surface. Thin film and material properties measurements have become primary applications of ellipsometric techniques. In PEM-based ellipsometry the ellipsometric parameters Ψ and Δ are obtained by modulating the polarization state of the transmitted beam to produce a time-dependent intensity. Ψ and Δ can be determined using analog and digital techniques to resolve the polarization state that occurs on reflection. Analog signals can be demodulated using lock-in amplifiers, as shown in Figure 1.

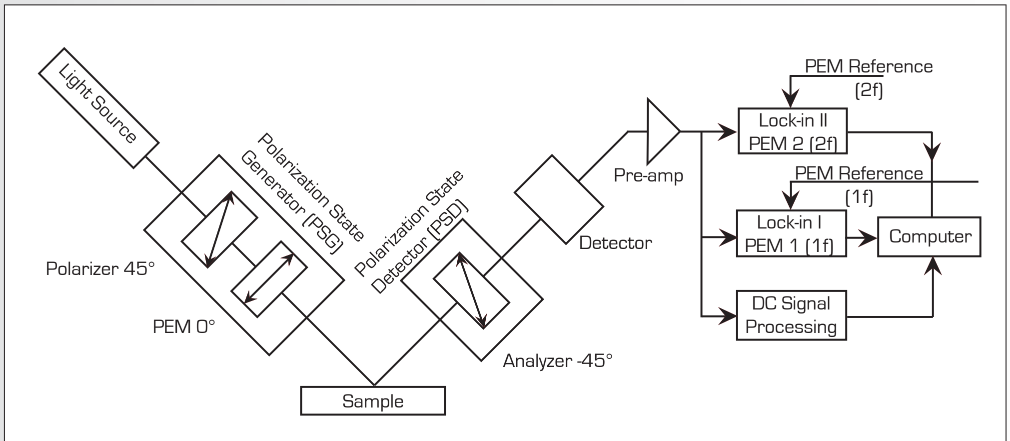

FIGURE 1. BLOCK DIAGRAM OF LOCK-IN AMPLIFIER DEMODULATION

The ellipsometric angles Ψ and Δ are related to three components of the detected signal: the dc component, a component at the PEM frequency (1f), and a component at twice the PEM frequency (2f). When using a PEM for ellipsometric measurements, it is helpful to use the N, S, and C notations that were originated by Jasperson and Schnatterly[1].

N, S, and C are defined as

$$N = \cos(2\Psi)$$

$$S = \sin(2\Psi)\sin(\Delta)$$

$$C = \sin(2\Psi)\cos(\Delta)$$

and are also elements of the Mueller matrix. Figure 2 is the Mueller matrix for isotropic materials in terms of N, S, and C[1,3].

$$M = \begin{pmatrix} 1 & -N & 0 & 0 \\ -N & 1 & 0 & 0 \\ 0 & 0 & C & S \\ 0 & 0 & -S & C \end{pmatrix}$$

FIGURE 2. MUELLER MATRIX FOR AN ISOTROPIC SAMPLE

PEM THEORY

The phenomenon of photoelasticity is the basis for operation of the PEM. If a transparent optical element is connected to a piezoelectric transducer in a resonant circuit and allowed to oscillate, the compression and stretching during oscillation induces birefringence. Birefringence is an optical property of material where light travels at different speeds depending on the polarization direction as it enters the material. When two light waves with perpendicular polarization components enter a birefringent optical element in phase they experience a phase shift along the beam path. The total phase difference when they emerge is known as retardation and can be expressed in distance (nm), waves (quarter wave, half wave, etc.) or phase angle (degrees, radians). The peak retardation is the amplitude of the sinusoidal retardation as a function of time.

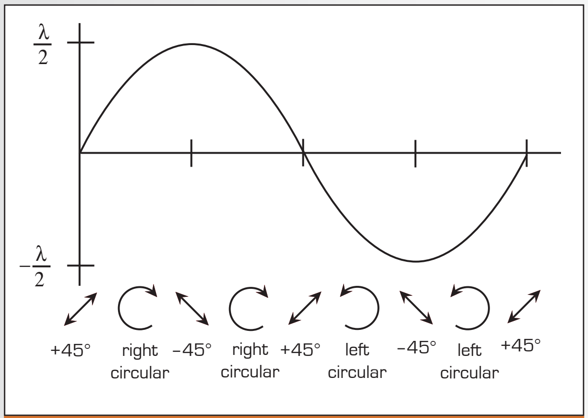

FIGURE 3. HALF-WAVE RETARDATION

A photoelastic modulator induces modulated phase shifts $\delta(t)$ between the fast and slow axes of the optical element. This modulated phase shift $\delta(t)$ is given by[2]:

$$\delta(t) = \frac{2\pi}{\lambda}(n_x - n_y)\sin(\omega t) = P(\lambda)\sin(\omega t)$$

The voltage that is applied to the modulator to control the retardation amplitude will depend on the wavelength of light, l. P(l) is the amplitude of modulation and ω represents the frequency of modulation of the PEM. When data is generated as a result of ellipsometric measurements the modulation signal of the PEM (which is the sine or cosine of the retardation value $\delta(t)$) may be expanded and expressed in terms of Bessel functions.

Figure 3 shows retardation vs. time for a modulator cycle and indicates polarization states at several different times during a cycle. In this figure the PEM acts as a half-wave plate at the instant of maximum retardation and rotates the plane of polarization by 90°.[2]

CALCULATION OF Ψ AND Δ

The basis functions for the polarizer - PEM pair in Figure 1 are:

$$X(t) = \sin(A\sin(\omega t)) = 2J_1(A)\sin(\omega t) + 2J_3(A)\sin(3\omega t) + \ldots$$
$$Y(t) = \cos(A\sin(\omega t)) = J_0(A) + 2J_2(A)\sin(2\omega t) + 2J_4(A)\sin(4\omega t) + \ldots$$

The quantity A is the Bessel angle of the PEM modulation and is proportional to the angle of modulation (typically this is set to 2.4048 radians, where $J_0(A)= 0$). The frequency, f, of the PEM is typically a nominal 50 kHz[4]. The intensity waveform of the detected light is related to these basis functions by the following equation[3]:

$$I(t) = I_0[I_{DC} + (I_X - \delta_0 I_Y)\, X(t) + (I_Y + \delta_0 I_X)\, Y(t)]$$

where d_0 is the static retardation of the PEM measured during calibration and I_0 equals the nominal dc intensity. This assumes that the phase difference between the PEM and the PEM reference signal is negligible.

The intensity equation shows that intensity is dependent upon the two time dependent basis functions X(t) and Y(t) and the three parameters I_X, I_Y and I_{dc}. If we set the azimuthal angle of the analyzer to 45°, then:

$$I_{DC} = 1$$
$$I_X = S$$
$$I_Y = -N\cdot\sin(2\theta_m) - C\cdot\cos(2\theta_m)$$

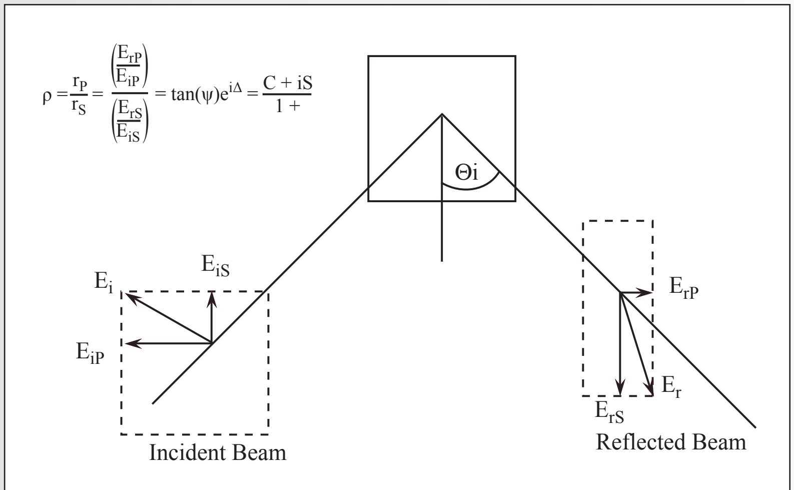

FIGURE 4. RELECTANCE GEOMETRY AND Ψ AND Δ AS RELATED TO THE RATIO OF THE REFLECTION COEFFICIENTS OF R_P AND R_S

The quantity θ_m is the azimuthal angle of the PSG polarizer - PEM pair. N, S, and C are related to the fundamental ellipsometry equation as shown in Figure 4. As can be seen, I_X measures S while I_Y measures a linear combination of N and S depending on the azimuthal angle θ_m.

Analog Demodulation

A common way to analyze the intensity waveform is to examine the detector signal using a lock-in amplifier. The I_X component is derived from the 1f signal (where the modulation frequency of the PEM is nominally 50 kHz), and the I_Y component from the 2f signal. Since the waveform is normalized to the dc intensity, the signals from the lock-in amplifiers are given by:[3]

$$\frac{I_{1f}}{I_{DC}} = 2J_1(A)\cdot(I_X - \delta_0 \cdot I_Y) \qquad \frac{I_{2f}}{I_{DC}} = 2J_2(A)\cdot(I_Y + \delta_0 \cdot I_X)$$

Digital Demodulation

It is also possible to obtain the basis function coefficients from the intensity waveform using digital techniques. The digital analysis approach can determine many more parameters, which can then be used to increase the information content and/or the accuracy of the measurements. One method that can give very accurate values of the amplitudes is to perform an integration of the waveforms over n periods with a time duration T as shown in the following equations:[3]

$$I_{DC} = \frac{1}{2\pi\cdot n} \cdot \int_0^{nT} I(t)dt$$

$$I_X - \delta_0 I_Y = \frac{1}{2\pi\cdot n\cdot J_1(A)} \cdot \int_0^{nT} \sin(\omega t)\cdot I(t)dt$$

$$I_Y - \delta_0 I_X = \frac{1}{2\pi\cdot n\cdot J_2(A)} \cdot \int_0^{nT} \cos(2\omega t)\cdot I(t)dt$$

MEASUREMENT PARAMETERS

In a single PEM ellipsometer as illustrated in Figure 1, it is possible to obtain the parameter S and either N or C. If the polarizer in the PSD is replaced with a Wollaston prism polarizer and both channels are detected, it is possible to measure N, S, and C for isotropic materials. All three parameters, N, S, and C, can also be determined if a second measurement is taken with the modulator azimuth angle changed from 0° to 45°. Ψ and Δ can then be calculated using the following relations:

$$\frac{S}{C} = \tan(\Delta)$$

$$S^2 + C^2 = \sin^2(2\Psi)$$

$$N = \cos(2\Psi)$$

When a second PEM is placed in the PSD arm of the ellipsometer, many more parameters may be measured. The 2-PEM ellipsometer, as shown in Figure 5, is capable of measuring 8 of the 15 elements of the reduced sample Mueller matrix in a single spectroscopic scan. For normal isotropic samples, N, S, and C can be determined from a single measurement. For anisotropic samples, all the cross-polarization terms can also be determined from a single scan. By changing the azimuthal angles of the PEMs, 13 of the 15 elements of the reduced sample Mueller matrix are available after two scans and the entire Mueller matrix can be obtained after 4 scans. Hinds Instruments offers the hardware as well as the data collection and analysis software for this system.

REFERENCES

For a more complete discussion of topics such as phase difference, anisotropic measurements and dual PEM systems, please see the listed references.

1. S. N. Jasperson and S. E. Schnatterly, "*An Improved Method for High Reflectivity Ellipsometry Based on a New Polarization Modulation Technique*," Rev. Sci. Instrum., 40, 761-767 (1969); Errata, 41, 152 (1970).
2. PEM-90 Brochure, Hinds Instruments, Inc.
3. G. E. Jellison, Jr. and F. A. Modine, "*Polarization Modulation Ellipsometry*," Chapter 6 in Handbook of Spectroscopic Ellipsometry (H. G. Tompkins and E. Irene, eds. Noyes, 2003). in press.
4. G. E. Jellison, Jr. and F. A. Modine, "*Two-modulator Generalized Ellipsometry: Experiment and Calibration*," Appl. Opt. 36, 8184-8189, (1997).
5. G. E. Jellison, Jr. and F. A. Modine, "*Two-modulator Generalized Ellipsometry: Theory*," Appl. Opt. 36, 8190-8198, (1997).

SUGGESTED READING

1. G. E. Jellison, Jr. "*Data Analysis for Spectroscopic Ellipsometry*," Chapter 3 in Handbook of Spectroscopic Ellipsometry (H. G. Tompkins and E. Irene, eds. Noyes, 2003). in press.
2. R. M. A. Azzam and N. M. Bashara, Ellipsometry and Polarized Light , (North-Holland, Amsterdam, 1987), pp 260-262, 415-416.
3. G. E. Jellison Jr. and F. A. Modine, "*Accurate Calibration of a Photoelastic Modulator in a Polarization Modulation Ellipsometry Experiment*," Pro. Soc. PhotoOpt. Instrum. Eng., 1166, pp. 231-241, (1990).
4. G. E. Jellison Jr., "*Data analysis for spectroscopic ellipsometry*," Thin Solid Films, 234, pp. 416-422, (1993).
5. G. E. Jellison Jr., "*Spectroscopic Ellipsometry Data Analysis: Measured versus Calculated Quantities,*" Thin Solid Films, 313-314, pp. 33-39, (1998).
6. G. E. Jellison Jr. and F. A. Modine, "*Two-modulator generalized ellipsometer for complete Mueller matrix measurement*," U. S. Patent No. 5956147, (1999).

Hinds Instruments, Inc / 7245 NW Evergreen Pkwy / Hillsboro, OR 97124 / USA
T: 503.690.2000 / F: 503.690.3000 / sales@hindsinstruments.com / www.hindsinstruments.com