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Full Length Article

Using a fast dual-wavelength imaging ellipsometric system to measure the flow thickness profile of an oil thin film

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ABSTRACT

Dual-wavelength light sources with stroboscopic illumination technique were applied in a process of photoelastic modulated ellipsometry to retrieve two-dimensional ellipsometric parameters of thin films on a silicon substrate. Two laser diodes were alternately switched on and modulated by a programmable pulse generator to generate four short pulses at specific temporal phase angles in a modulation cycle, and short pulses were used to freeze the intensity variation of the PEM modulated signal that allows ellipsometric images to be captured by a charge-coupled device. Although the phase retardation of a photoelastic modulator is related to the light wavelength, we employed an equivalent phase retardation technique to avoid any setting from the photoelastic modulator. As a result, the ellipsometric parameters of different wavelengths may be rapidly obtained using this dual-wavelength ellipsometric system every 4 s. Both static and dynamic experiments are demonstrated in this work.

1. Introduction

Among other optical techniques, ellipsometry is one of the most powerful tools for characterizing optical properties, including determining film thicknesses and refractive indices with a high degree of accuracy. Currently, common applications of ellipsometry include measuring thin films for solar cells, optical coatings, microelectronics, and biosensing applications [1–4]. However, currently most ellipsometric measurements are based on a single point and use a single-wavelength or spectroscopic approach [5]. As the size of many electronic devices become smaller, the uniformity of the thin-film thickness, a high degree of resolution, and a large field of view have become more desirable for industrial applications. Therefore, ellipsometry with a spatially-resolved capability to assess two-dimensional morphologies of a surface are a natural evolution of ellipsometric measurement techniques [6]. Thus far, the commercial imaging ellipsometer has been operated on the principle of the classical null technique; instruments used are typically equipped with stepping motors to change the azimuth angle of the polarizer, compensator, or analyzer, and they use Charge-coupled Device (CCD) or Complementary Metal-Oxide-Semiconductor (CMOS) detectors to take a sequence of images in order to gather enough information to calculate all null positions [7,8]. This approach is relatively slow, is limited by the mechanical rotation speed, and the modulation frequency usually falls within a noise range of other mechanical devices; this impedes data acquisition and, eventually, system stability. In addition, for a sample with inhomogeneous surface characteristics, the measurement process may need to collect many more images to determine the null positions of each measurement point; this makes the measurements relatively cumbersome and impractical for industrial applications [9].

The ellipsometer based on the use of a PEM modulator is the most prevalent configuration for real-time measurement; it has a typical modulation frequency of 50 kHz with no moving parts [10,11]. For single spot measurement, one employed either lock-in amplifiers or the Fourier analysis technique to obtain the ellipsometric parameters in near real-time, but this approach is not applicable for a two-dimensional measurement, because the modulation frequency of the photoelastic modulator (PEM) is too high to compare it with the exposure times of the CCD camera. This deficiency was overcome by replacing the light source with an ultra-stable short pulse, known as the stroboscopic illumination technique, which was synchronized with the PEM modulation to freeze the intensity signal at specific times in the modulation cycles [12,13]. In this work, we demonstrate that this approach can yield a set of two-dimensional ellipsometric parameters in the order of a few seconds. Since the retardation of the PEM has to be kept con-

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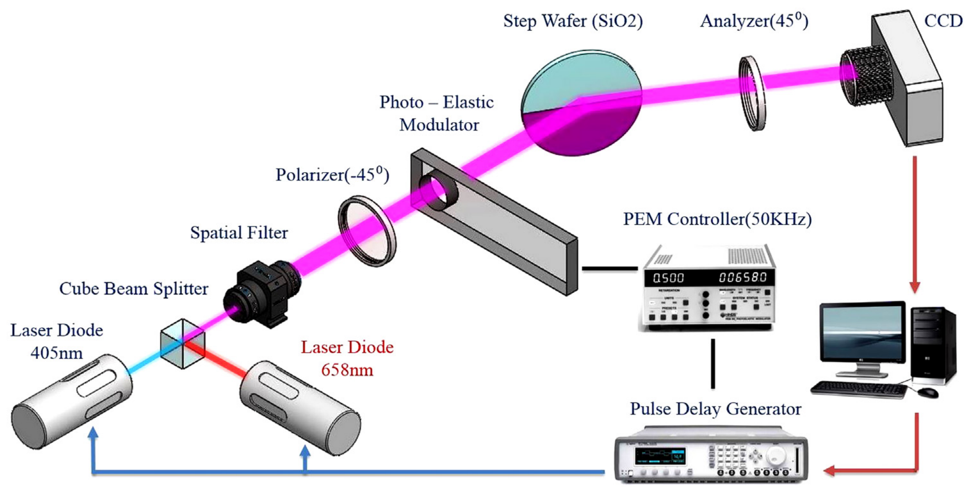

Fig. 1. Fast dual-wavelength imaging ellipsometric system.

stant over different wavelengths, the applied voltage of the PEM controller is adjusted followed by the wavelength change. After the adjustment process, time was required to allow the equipment to again reach a stable resonant condition; this limited this approach to single wavelength measurement.

In this work, we adopted an equivalent phase retardation technique that used dual wavelength ellipsometric measurement to extend the imaging ellipsometry technique without any adjustment of the photoelastic modulator or of the optical configuration. The phase response of the photoelastic modulator with different wavelengths was corrected by changing the initiating time of the pulse light; in this manner, output polarization states for both wavelengths generated from the PEM were the same. During the measurement, the shift of the wavelength was alternatively operated electrically and automatically; therefore, the image acquisition time for one set of ellipsometric parameters remained virtually unchanged. The thickness profile of a two-step thickness reference wafer with dual wavelengths was demonstrated as the standard test, and we also measured the drainage behavior of matching oil on a silicon wafer using this dual wavelength imaging ellipsometry.

2. Theory

Ellipsometry measures the changes of polarization in light that is reflected from the sample surface; such changes can be used to deduce the optical parameters of the sample. The ellipsometric parameters, Ψ and Δ, are defined as:

$$\tan\Psi e^{i\Delta} = \frac{r_P}{r_S} \quad (1)$$

Where r_p and r_s are the complex Fresnel reflection coefficients for polarized light that is parallel and perpendicular to the plane of incidence, respectively. We replaced the compensator with a PEM in the polarizer-compensator-sample-analyze setup, as shown in Fig. 1. The final polarization state can be expressed by the operation of their corresponding Mueller matrices; i.e., the polarization state can be expressed as:

$$S_f = M_A(A) M_S(\Psi, \Delta) M_{PEM}(\Delta_P) S_P \quad (2)$$

where the Stokes vectors S_f and S_P are the final polarization state and the incident linearly polarized light at the azimuth angle of P. Moreover, $M_{PEM}(\Delta_P)$, $M_S(\Psi, \Delta)$, and $M_A(A)$ represent the Mueller matrix of the PEM, the sample and the analyzer respectively. In this configuration, the optic axis of the PEM is at zero with respect to the incident plane. When $P = -45°$ and $A = 45°$, the reflected intensity can be found to be:

$$I(\omega t) = \frac{I_0}{2}\left[1 - \sin 2\Psi \cos(\Delta\text{-}\Delta_p)\right] \quad (3)$$

where I_0 is the normalized intensity of the system, and Δ_P is the dynamic retardation of the PEM, which is modulated as $\delta_0 \sin\omega t$. If the modulation amplitude δ_0 is 0.5 waves, one can formulate the temporal intensity as:

$$I(\omega t) = \frac{I_0}{2}\left[1 - \sin 2\Psi \cos(\Delta - \pi \sin\omega t)\right] \quad (4)$$

where ωt indicates the temporal phase angle in a modulated cycle. In practice, we found there is an initial phase shift x between the modulated signal $I(\omega t)$ and the reference signal from the PEM driver, and the temporal intensity can be modified as [14]:

$$I'(\omega t) = \frac{I_0}{2}\left\{1 - \sin 2\Psi \cos\left[\Delta - \pi \sin(\omega t + x)\right]\right\} \quad (5)$$

Since there are three unknowns in Eq. (5), namely, Ψ, Δ, and x, we deduce them by means of five specific phase angles $\omega t = [0°, 30°, 90°, 180°, \text{and } 210°]$. When the phase angles are 0°, 30°, 180°, and 210°, the initial phase shift x can be obtained through the following:

$$\frac{I'(210°) - I'(30°)}{I'(180°) - I'(0°)} = \frac{\sin\left[\pi \sin(x)\right]}{\sin\left[\pi \sin\left(x + \frac{\pi}{6}\right)\right]} \quad (6)$$

After solving the initial phase shift x from Eq. (6), one can extract the ellipsometric parameter Δ by the intensity measurements at $\omega t = 0°, 30°, 90°$, and 210° from the following:

$$\frac{I'(90°) - I'(0°)}{I'(210°) - I'(30°)} = \frac{-\sin\frac{\pi[\cos(x) - \sin(x)]}{2} \sin\left\{\Delta - \frac{\pi[\cos(x) + \sin(x)]}{2}\right\}}{\sin(\Delta)\sin\left[\pi \sin\left(x + \frac{\pi}{6}\right)\right]} \quad (7)$$

Moreover, the value of Ψ can be obtained by substituting the Δ and x into

$$\frac{I'(90°) - I'(0°)}{I'(90°) + I'(0°)} = \frac{-\sin(2\Psi)\sin\left\{\Delta - \frac{\pi[\sin(x) + \cos(x)]}{2}\right\}\sin\left\{\frac{\pi[\sin(x) - \cos(x)]}{2}\right\}}{1 - \sin(2\Psi)\cos\left\{\Delta - \frac{\pi[\sin(x) + \cos(x)]}{2}\right\}\sin\left\{\frac{\pi[\sin(x) - \cos(x)]}{2}\right\}} \quad (8)$$

In sum, three unknowns x, Δ, and Ψ in Eq. (5) can be directly deduced from Eq. (6)–(8) by means of five specific phase angles at