Multi-wavelength angle-resolved reflectometer for thickness and refractive index measurement of thin-film structures

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Abstract

Reflectometry has long been used to measure the optical property of thin films by observing the wavelength-dependent intensity variation of the reflected light from the specimen. In this paper, we describe a new way of implementing reflectometry that enables optical property measurements of single- and multi-layered thin-film structures for in-line inspection. For the purpose, the scheme of angle-resolved reflectometry is realized using a high-NA objective. The specimen is illuminated using a broadband light source providing multiple wavelengths in sequence through a series of spectral filters. Compared to traditional ways of reflectometry, the new method enables accumulating abundant reflectance information with different wavelengths, incidence angles, and polarization states with no need of any mechanical moving part. The measured reflectance data is then fitted into the theoretical model of multi-reflection, which allows both the thickness and refractive index of thin-film structures are accurately identified. This method turns out to be fast and also immune to vibration, thereby being very well suited for the in-line inspection in diverse industrial fields.

Keywords: Thin-film metrology, thickness measurement, refractive-index measurement, multi-wavelength reflectometry, angle-resolved reflectometry

1. Introduction

Thin-film metrology has shown significant importance for past several decades as a major part of thin-film manipulations; and its inspection has been highly needed in diverse forefront industrial fields. Contemporary manufacturing processes have required novel measurement techniques for optical properties of complicated thin-film structures such as densely patterned thin-film samples as well as multi-layered structures.

Both ellipsometry and reflectometry have long been developed as the representative metrological tools for non-destructive thin-film inspection, so that these techniques have been diversified to handle more complex targets with higher accuracy [1]. Employment of further methods such as the spectroscopic methods and the variable-incidence angle methods can increase the amount of accessible data [2, 3]. Generally, the more plentiful data is obtained, the better chance we may take to measure diverse types of samples. As combining several schemes into one system, however, the compound system gets more complicated and possibly becomes in need of mechanically moving parts so that they confront limitations for being applied to the industrial field where high speed and robust measurement is required. Several attempts have been tried to complement these problems such as the embodiment of angle-resolved reflectance measurement with a high numerical aperture objective lens [4].

In this paper, we present multi-wavelength angle-resolved reflectometry that can measure thin-film structures with high speed and accuracy so that it will be suitable for in-line measurements in various industrial fields. The multi-wavelength angle-resolved reflectometer can gather rich amount of reflectance data of a point with varying incidence angle, polarization state and wavelength by means of the simultaneous adoption of both an optical
filters and a high numerical aperture objective lens; this enables fast and accurate measurement of the film thickness and refractive index of multi layered thin-films as well as single layered ones.

2. Optical configurations

Reflectometry yields the targeted optical properties by the analysis of the absolute reflectance $R_{abs}$, the ratio of the intensity of the reflected beam $I_{ref}$ to that of the incident beam $I_{inc}$; it varies with respect to wavelengths $\lambda$, polarization directions $\vec{P}$, the angles of incidence $\theta$, and the properties of the thin-film sample such as the thickness $d$ and the refractive index $n$ (eqn. 1).

$$R_{abs}(\lambda, \vec{P}, \theta; n, d) = \frac{I_{ref}}{I_{inc}}$$  \hspace{1cm} (1)

In practice, the absolute reflectance of the sample $R_{sam.abs}$ is able to be figured out in use of the standard specimen whose absolute reflectance variation $R_{std.abs}$ had already been well established.

$$R_{sam.abs}(\lambda, \vec{P}, \theta; n, d) = \frac{I_{ref,sam}}{I_{ref, std}} \times R_{std.abs}$$ \hspace{1cm} (2)

Fig. 1. Optical configurations of the multi-wavelength angle-resolved reflectometer. The upper left inset shows the simulated reflectance variation with respect to wavelength, angle of incidence, and polarization direction of the incident beam. The upper right one depicts the actual image of the back focal plane of the objective lens for the multi-layered thin-film sample. (L: lens, I: iris, F: optical filter, P: polarizer, BS: beam splitter, TL: tube lens, OL: objective lens, BFP: back focal plane of the objective lens, CCD: charge-coupled device).
The optical setup is based on the simplest form of a normal-incidence reflectometer (Fig. 1). The broadband light source such as Tungsten-Halogen lamp or Xenon arc lamp with optical filters produces beam of desired center wavelengths with a narrow bandwidth. In place of the optical filters, an acousto-optic tunable filter can reduce the measurement time within few tens of millisecond per a single point; this has the whole system more suitable to the in-line measurement applications.

The beam passing through collimation lenses and a polarizer in turn is steered to the sample via an objective lens. The objective lens with high numerical aperture makes the reflectance data attainable with varying angles of incidence for both polarization states at once (Fig. 2). Figure 2(a) displays the image of the back focal plane of the objective lens. When the polarization direction of the incident beam is assumed to be parallel to the x-axis, the pixels on the horizontal diametric line capture the intensity data of TM polarization, and those on the vertical diametric line do the intensity data of TM polarization. Moreover, we can collect the beams of the angle of incidence from 0° to θ_{max} as shown in Fig. 2(c). The maximum angle θ_{max} is determined as the following equation:

$$\theta_{\text{max}} = \arcsin(NA),$$

where NA indicates the numerical aperture of the objective lens.

The light reflected from the sample reaches two individual CCD cameras; one captures the image of the back focal plane of the objective lens, and the other checks the focusing state of the objective lens upon the sample. The system originally aims a single point measurement at a time; however, the translational stage where the sample is mounted makes it feasible to measure the optical property variation in either linear or planar scale.

3. Analysis methods

After the acquisition of the reflectance data from experiments, the optical property of a sample can be analyzed with the estimated model which has been assumed in advance. The
generalized mathematical expression of the theoretical reflectance is decided by using 2 by 2 matrices approach with Fresnel reflection coefficients [5]; and Cauchy equations can be adopted as well when the refractive index of the film ought to be analyzed. As the last part of the analysis, the theoretical reflectance distribution is going to be fitted into the measured one by means of the minimization of the merit function using Levenberg-Marquardt nonlinear least square method (Fig. 3).

As mentioned above, the reflectometer can gather the large number of reflectance data which are dependent to the three major parameters: wavelength, angle of incidence, and polarization direction. This helps to widen the range of sample to be handled using the fitting algorithm, and to lessen the possibility for the variables to converge into inappropriate local minima during the fitting step.

4. Experimental results and its analysis

The experiments are executed on diverse samples with different target parameters. As noted in the Table 1, samples are not only the single oxide film layered one of changed film thickness from 30 nm to 3.4 μm, but the multi-layered one whose thin-film structure comprises oxide, nitride, and oxide consecutively on silicon substrate.

<table>
<thead>
<tr>
<th>Film (on Silicon substrate)</th>
<th>Target variables</th>
<th>Reference values*</th>
<th>Measured values</th>
<th>Repeatability**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxide</td>
<td>d1</td>
<td>d1=28.4 nm</td>
<td>d1=29.8 nm</td>
<td>-</td>
</tr>
<tr>
<td>Oxide</td>
<td>d1</td>
<td>d1=513.2 nm</td>
<td>d1=514.3 nm</td>
<td>σ1=0.3</td>
</tr>
<tr>
<td>Oxide</td>
<td>d1, n(λ)</td>
<td>d1=513.2 nm, n(λ)**</td>
<td>d1= 515.2 nm, Δnavg=0.0045</td>
<td>-</td>
</tr>
<tr>
<td>Oxide</td>
<td>d1</td>
<td>d1=3403 nm</td>
<td>d1=3422 nm</td>
<td>-</td>
</tr>
<tr>
<td>Oxide / Nitride / Oxide</td>
<td>d1, d2, d3</td>
<td>d1=16.8 nm, d2=194.9 nm, d3=762.6 nm</td>
<td>d1=20.9 nm, d2=194.6 nm, d3=760.5 nm</td>
<td>σ1=0.08, σ2=0.09, σ3=0.14</td>
</tr>
</tbody>
</table>

* 1σ value for 30 consecutive measurements
** Values from spectroscopic ellipsometer
*** Refractive index value within the visible wavelength range(400 nm to 700 nm)

For an either type of sample, thickness measurement results show the accuracy less than 1 percent and repeatability of less than 1 nm. The simultaneous measurement of the thickness and refractive index for the single layered sample also gives reasonable accuracy. This high
repeatability indicates the system is robust enough for the in-line measurements of thin-films to the external disturbances such as vibration or air flow.

Compared to the results shown in the Table 1, the measurement in linear scale has been executed as well in use of a translational stage. The thickness variation of an ONO three-layered sample has been measured at 10 nm intervals, so the thickness profile can be reconstructed if the unevenness of the top surface profile of the silicon substrate had been assumed beforehand (Fig. 4).

![Fig. 4. Reconstructed linear profile of the patterned thin-film sample. It is assumed that the height of the top surface of the substrate in the multi-layered region would be 400 nm higher than that in the single layered region.](image)

5. Conclusion

In this paper, the improved reflectometer has been proposed for optical property measurements of thin-film specimens. The acquisition of the plentiful reflectance data with varying wavelengths, angles of incidence, and polarization directions make the system possible to analyze optical properties not only of single layered samples but also of multi-layered ones. This multi-wavelength angle-resolved reflectometry can be a potent candidate for the in-line thin-film measurements because of the simplicity of the optical configurations and the fast measurement speed.

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References