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Short Note

A New Spectral Imaging Ellipsometer for Measuring the Thickness of Patterned Thin Films

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We proposed spectral imaging ellipsometry that uniquely combines one-dimensional imaging and spectroscopic ellipsometry. This type of ellipsometry enables the measurement of the optical parameters and dimensional structures of patterned or multilayered thin films. We demonstrated the result of the measurement of the thickness of patterned SiO_2 layers with 3 nm accuracy and 200 µm spatial resolution. [DOI: 10.1143/JJAP.43.6475]

KEYWORDS: spectral imaging, imaging ellipsometer, thin film, thickness, ellipsometry

Thin-film processing techniques are widely used in many types of manufacturing. Clearly, they are central to fabrication in microelectronics, an area that has grown tremendously in recent decades. Optical-based diagnostics probably affect thin-film processing more than any other diagnostic techniques. Of the various types of optical diagnostics, ellipsometry is currently being used extensively in the industry to measure the thickness and other properties of the thin layers of dielectrics and semiconductors and, to a small extent, conductors because it can measure very thin layers.1)

Ellipsometric theory is based on Fresnel reflection or transmission equations for the polarized light that encounters boundaries in planar multilayered materials.2,3) The ellipsometric measurement is normally expressed in terms of Psi (ψ) and Delta (Δ) as

$$\rho = \tan(\psi)\exp(i\Delta) = \frac{r_\mathrm{p}}{r_\mathrm{s}}, \tag{1}$$

where r_p and r_s are the complex Fresnel reflection coefficients of the sample for p- (in the plane of incidence) and s- (perpendicular to the plane of incidence) polarized lights, respectively. Fast ellipsometry methods with single or multiple wavelengths have been adopted for monitoring film growth *in situ*, allowing for the precise control of film deposition processes.4) However, traditional ellipsometry remains a technique of macroanalysis, that is, the size of the sample cannot be smaller than one or two millimeters. The development of imaging ellipsometry, which combines ellipsometry with microscopy, has overcome this limitation.5–8)

In ellipsometry, to extract useful information on a material structure, one needs to perform a model-dependent analysis of the ellipsometric data. Specifically, for complex multilayer coatings, we need the spectroscopic data of ellipsometry to analyze optical parameters such as refractive index, extinction coefficient, film thickness, and roughness anisotropy.2) However, conventional 2-D imaging ellipsometers are limited to one set of 2-D data points of ψ and Δ at a single wavelength or at two or three wavelengths.8) From this data set, we cannot simultaneously determine the multiple optical parameters of a sample. We therefore suggest spectral imaging ellipsometry that overcomes the limitation by combining spectroscopic ellipsometry and one-dimensional imaging.

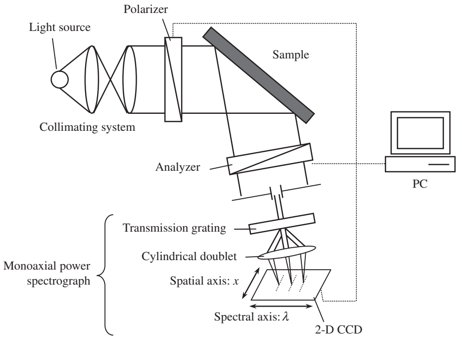

Fig. 1. Schematic diagram of proposed spectral imaging ellipsometer with monoaxial power spectrograph.

Figure 1 shows the schematic of a spectral imaging ellipsometer that includes a custom-built, monoaxial power spectrograph with a spectral range of 450 nm to 670 nm and a conventional rotating analyzer ellipsometer with an angle of incidence of 70°. A quartz-tungsten-halogen lamp generates white light, which is then collimated by a collimating system that uses an achromatic lens with a focal length of 300 mm. The collimated beam is linearly polarized after it passes through a polarizer. The linearly polarized beam is then reflected off the sample into an analyzer and imaged onto a 2-D CCD camera in the monaxial power spectrograph. The Glan–Thompson prisms in the polarizer can be rotated by stepping, while those in the analyzer can be rotated by DC motors. The spectrograph is composed of an entrance slit, a holographic transmission grating, a focusing cylindrical doublet, and a 2-D CCD camera.9)

Using the spectral imaging ellipsometer, we acquired the ellipsometric parameters $\psi(x,\lambda)$ and $\Delta(x,\lambda)$ for a uniformly deposited SiO_2 film on a silicon substrate as functions of the spatial coordinate x and light wavelength λ, as shown in Fig. 2. To calculate the thickness profile of SiO_2 film, we performed a model-dependent fitting procedure of adjusting film thickness d using the Marquardt–Levenberg algorithm. To aid in this fitting, the mean-squared-error (MSE) function is defined in eq. (2), where sums of differences between theoretically calculated spectroscopic ellipsometric parameters, Ψ_mod and Δ_mod, and those acquired experimentally, denoted Ψ_exp and Δ_exp. The thin-film model used in this study is a three-phase model (ambient/film/substrate).

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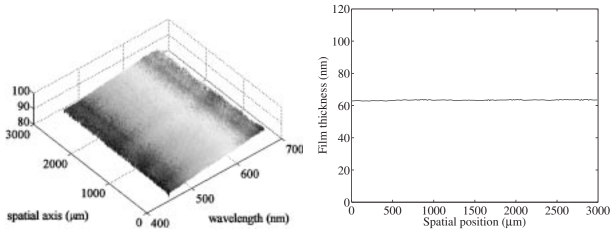
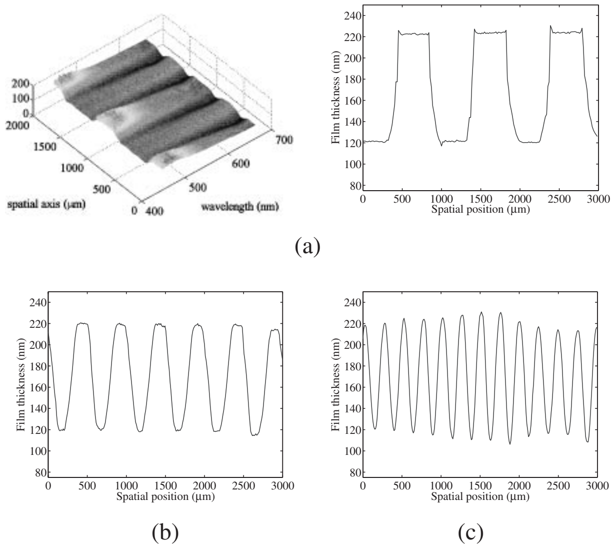
$$MSE = \sqrt{\frac{1}{2N} \sum_{i=\lambda_i,\lambda_2,\ldots,\lambda_N} [\{\psi^i_{\mathrm{mod}}(d) - \psi^i_{\mathrm{exp}}(d)\}^2 + \{\Delta^i_{\mathrm{mod}}(d) - \Delta^i_{\mathrm{exp}}(d)\}^2]} \quad (2)$$

Figure 2(b) shows the obtained one-dimensional thickness profile of the SiO_2 film for the sample. The mean fitted film thicknesses along the x-coordinate is 63.4 nm ± 0.2 nm where the small standard deviation implies that each pixel point in the CDD camera works reliably. By comparison, the thickness of this sample is measured using a commercial ellipsometer (VUV-VASE; vacuum ultraviolet variable angle spectroscopic ellipsometer, J. A. Woollam Co., Inc.). The thickness measured by VUV-VASE is 62.14 nm. Thus, the measurement error for the manufactured spectral imaging ellipsometer is found to be less than 3 nm. To test the spectral imaging ellipsometer, we fabricated three 100-nm-deep SiO_2 gratings on top of a 124-nm-thick SiO_2 layer with a silicon wafer as a substrate. The nominal values of their barrier and valley widths were almost the same; namely 500 µm, 250 µm, and 125 µm, respectively. The experimental data of Δ for 500-µm-width sample is shown in Fig. 3. The results clearly show the existence of distinct polarization effects for different regions and different wavelengths. Using the three-phase model, we obtained a line image of the film thickness. For the 500-µm-width sample, the film thickness of the flat top was 122.0 nm and that of the trench area was 222.9 nm. We also obtained a SEM image of the thickness profile of the same sample: the thickness of the thinner layer was 124.7 nm and that of the thicker layer was 225.0 nm. The difference in film thicknesses determined by the two different measurement techniques was approximately 3 nm. As the patterned width of the grating became smaller, the thickness profile was severely distorted. Finally, for the 125-µm-width sample, the profile was smoothened as shown in Fig. 3(c).



(a) (b)

Fig. 2. Results of spatial and spectroscopic ellipsometric parameter measurement for uniformly deposited SiO_2 film on silicon substrate. (a) Ellipsometric parameters Δ, (b) Fitted thickness profile.



(a)

(b) (c)

Fig. 3. Measurements of spatial and spectroscopic ellipsometric parameters and the fitted thickness profile of patterned SiO_2 film on silicon substrate. Pattern widths for (a) 500 µm, (b) 250 µm, and (c) 125 µm.

The result shows that the spatial resolution of the spectral imaging ellipsometer is limited to approximately 200 µm. This limitation is a general problem for imaging ellipsometry. And it is caused by the diffraction at the unclear boundary between the mesa and trench of the sample. However, this limitation can be ameliorated by adopting an objective lens in front of the spectrograph. Other possible causes of the deviation of experimental data are the inherent dark signal of the CCD camera, the unstable intensity of the white light source, and the inaccurate angle of incidence.

In conclusion, we developed a new spectral imaging ellipsometer with a custom-built, monaxial power spectrograph whose spatial and spectroscopic data can be measured simultaneously using a 2-D CCD camera. The spectral imaging ellipsometer is a unique combination of one-dimensional imaging and spectroscopic ellipsometry. It is a novel tool for real-time measurement of the optical parameters and dimensional structures of patterned or multilayered coatings. Although the spectral imaging ellipsometer can only measure one-dimensional spatial information, it measures much faster than conventional spectroscopic ellipsometers with a mechanically scanning monochromator. Even though a fast measurement time is achieved, the spectral imaging ellipsometer loses accuracy compared with conventional ellipsometers.

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