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Spatially phase-retarded spectroscopic ellipsometry

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Abstract
In this investigation, we propose a novel type of spectroscopic ellipsometer, named as spatially phase-retarded spectroscopic ellipsometry (SPARSE) based on the spatial polarization distribution opposed to the temporal polarization changes. SPARSE can collect all information, necessary to characterize film structures, with a single image acquisition and it has the benefit of real-time measurements. For the verification, feasible experiments with single film layered Certificated Reference Materials (CRMs) and multi-layered film specimens were carried out.

Keywords: Spatial phase retardation, spectroscopic ellipsometry, multi-layered thin film

1. Introduction

Recently, film structures have played an important role in semiconductor and display industries for high performance and multi-functionalities of the products. In the manufacturing process of film structures, the inspection or measurement procedure is essential for the confirmation of their desired functions and the uniformity. Ellipsometry has become a standard tool for characterizing film structures to typically extract film thicknesses and refractive indices [1]. Based on the polarization changes of the reflected light on a specimen, an ellipsometer detects intensity variations corresponding to initial polarizations and wavelengths in order to calculate so-called ellipsometric angles, ψ and Δ. A spectroscopic ellipsometer (SE) can collect more information about a specimen compared to a monochromatic ellipsometer and it is typically more robust to determine the film thicknesses and refractive indices of the film layers [2]. However, SE needs various polarization states of the incident light and it leads to the use of rotating polarizing components such as a polarizer, an analyzer [3] and a compensator independent of the type of optical configurations of SE. Therefore, these types of SE fundamentally consume long acquisition time because of mechanical rotations.

In order to overcome this limitation of SE in real-time applications, SE based on a photo elastic modulator (PEM), which induces mechanical stress in a specific birefringent crystal in a moment, with lock-in techniques was developed and the acquisition time was reduced as an order of a few tens of ms according to the response time of the PEM [4]. However, PEM-SE still relies on the temporal polarization scanning and it fundamentally needs sequential acquisition time.

In this investigation, we propose another novel type of SE based on the spatial polarization distribution opposed to the temporal polarization changes. The proposed ellipsometer is named as spatially phase-retarded spectroscopic ellipsometry (SPARSE) and it can collect all information, necessary to characterize film structures, with a single image acquisition. Instead of using temporal phase retardation devices, a spatial phase retardation plate is used and an imaging spectrometer can obtain the intensity variations by polarization states and wavelengths.

2. Principle of SPARSE

Figure 1 shows the optical configuration of SPARSE. As an optical source, a broadband light is used and the light with a small beam size is linearly polarized by a linear polarizer (P). Then, the light is incident to a film specimen and reflected off with the polarization changes caused by the ratio of *p*-pol and *s*-pol waves. The reflected light passes through a beam expander and the large size of the light goes through spatial phase retardations by a spatial phase retardation plate (SPR), designed to provide the periodic phase retardation along a horizontal axis. The spatially phase retarded light passes through an analyzer (A) and detected in an imaging spectrometer (IS). Then, the imaging spectrometer only images one of the horizontal lines of SPR at the center and spectrally resolve this line as an image as seen in Fig. 2.

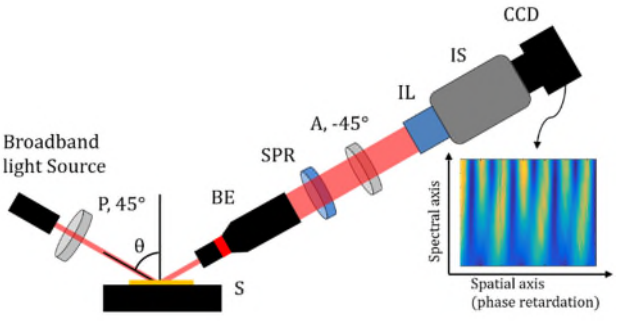

Figure 1. Optical configuration of SPARSE. P, polarizer; S, specimen; BE, beam expander; SPR, spatial phase retardation plate; A, analyzer; IL, imaging lens; IS, imaging spectrometer.

In Fig. 2, the horizontal axis of the image indicates the polarization changes caused by the periodic phase retardations while the vertical axis means the spectral axis. As known in Fig. 2, the intensity variations by various polarization states and wavelengths can be obtained at once in a single acquisition of the image in SPARSE and it can be a good alternative to analyze film structures in real-time. By the nonlinear optimization to minimize least squared values of differences between the measured and theoretical images, SPARSE can determine film

thicknesses. In this case, the optical and geometrical properties in the measured point are assumed as uniform because SPARSE regards the large size of the beam as a point.

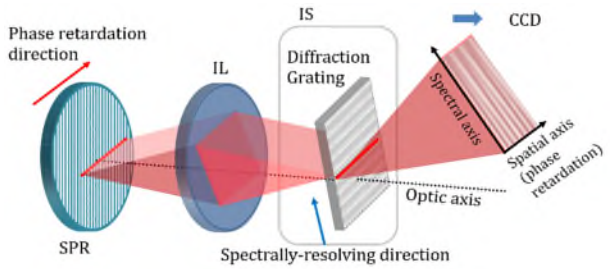

Figure 2. Acquisition of the single image containing intensity variations corresponding to polarization changes and wavelengths in SPARSE.

3. Experiment

In order to verify the principle of SPARSE, feasible experiments to measure film thicknesses were performed. As an optical source, a super continuum light was used due to high spatial coherence and broad spectrum. In this case, the original beam spot size was 1 mm and it was extended up to 30 mm by 30x beam expander. The light was incident to the specimen with 70 °, typically used in ellipsometry. As a polarizer and an analyzer, linear film polarizers were used and the rotation angles were set as 45˚ and -45˚ with respect to the incident plane. As an imaging spectrometer, a commercial product (V8, Specim) was used and a CCD camera obtained the image. As a SPR, we used a pseudo depolarizer which consists of rotating liquid crystal (LC) periodic array. This depolarizer is commercially available and the manufacturer provides the specification of 2˚ of fast axis rotation of LC per every 25 μm. Because the rotation angles of the fast axes are horizontally changed and periodic, the phase retardations between *p*-pol and *s*-pol waves can be also defined as horizontally periodic.

Before the film thickness measurements, the calibration of several parameters such as the rotation angles of the polarizing components, spectral variation of phase retardation and the incident angle of the light was carried out. After the calibration of SPARSE, we used certificated reference materials (CRMs) provided by the national metrology institute of Korea (KRISS), which consists of Si substrate and single film layer of SiO_2 to verify the capability of measuring film thickness. We prepared 4 CRMs with the film thicknesses of 14.3 nm, 55.8 nm, 110.1 nm and 507.3 nm and measured the film thicknesses. The measured image for each CRM has the tendency of the similar pattern and shape with its counterpart of the theoretical image and the film thickness was also calculated nearby the nominal value. The measured thicknesses of CRMs were 14.1 nm, 54.6 nm, 110.4 nm and 506.2 nm, respectively and each repeatability defined as the standard deviation of 15 consecutive measurement results was less than 1 nm.

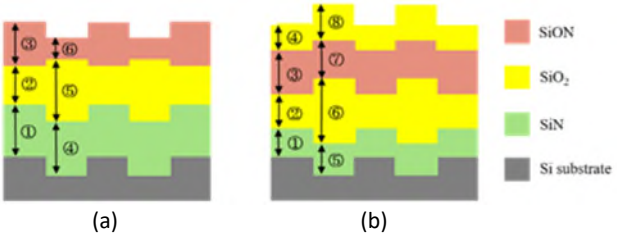

Figure 3. Structures of (a) a 3-layered film specimen and (b) a 4-layered film specimen.

To extend the capability of SPARSE, film thicknesses of a 3-layered film specimen, which consists of SiON-SiO_2-SiN film layers on Si substrate and a 4-layered film specimen, which consists of SiO_2-SiON-SiO_2-SiN film layers on Si substrate as shown in Fig. 3, were measured at two distinct locations. As the result, it was confirmed that the measured images were similar to the theoretical values and the measured thicknesses were close to the provided values by the manufacturer as known in Table 1. For the comparison, the same specimen was also measured with the well calibrated PC_RSA (polarizer-rotating compensator-sample-analyzer) type ellipsometer and there are slight deviations between two measurement results.

Table 1 Sumary of measurement result for 3- and 4- layered film specimen

	Provided (nm)	PC_RSA (nm)	SPARSE (nm)
3-layered film specimen			
①	125	123.5	121.6
②	125	113.6	114.0
③	135	124.6	127.0
④	135	124.9	116.9
⑤	160	159.6	153.0
⑥	46	64.4	57.5
4-layered film specimen			
①	61	57	58.6
②	89	83.7	84.2
③	123	116.5	122.0
④	60	54.9	56.4
⑤	76	82.4	83.5
⑥	150	159.9	152.3
⑦	78	75.0	63.1
⑧	123	120.1	131.2

The uniformity and stability of the spatial intensity distribution and the spectral distribution of the light source are important issues in SPARSE. In the image obtained by SPARSE, as aforementioned, the horizontal axis represents the phase retardation caused by the fast axis rotation of LC but the spatial intensity fluctuation deteriorate the phase retardation relationship between the horizontal pixels of the image, which leads to measurement errors. In addition, the indefinite spectral distribution disturbs the minimization of the difference between the measured and theoretical images in the optimization process. In this investigation, the spectral distribution was previously measured and it was applied to the measured image by the simple operation of division. However, in general, the spectral distribution of the light can be temporally changed and the instability lowers the measurement accuracy.

4. Conclusion

We proposed and experimentally verified the new type of spectroscopic ellipsometry, SPARSE, which uses spatial phase retardations instead of using temporal ones. In a single acquisition of the image in SPARSE, all information to extract the ellipsometric angles was contained and the film thicknesses of specimens were able to be measured. We expect that SPARSE can be a good alternative to analyze film structures in real-time.

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