One-dimensional Spectroscopic Measurement of Patterned Structures Using a Custom-built Spectral Imaging Ellipsometer

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Abstract. A novel spectral imaging ellipsometer based on a mono-axial power spectrograph has been developed for one-dimensional spectroscopic measurement of patterned structures. To obtain the imaging data of a patterned sample using ellipsometry can be realized by conventional ellipsometers with 2-dimesional (2D) scanning sample stage or 2D imaging ellipsometers with imaging optics. The former has major advantage of high precision, but it has disadvantage in the measurement speed due to mechanical scanning. The latter uses a 2D imaging detector to extract 3D spatial information. So it must be the type of a single-wavelength ellipsometer. Analyzing the spatial structure of a multi-layered sample needs the spectroscopic measurement at each spatial point. Therefore we have developed a real-time spectral imaging ellipsometer base on a mono-axial spectrograph which can give not only 1D spatial information but also 1D spectroscopic information. The mono-axial spectrograph is simply composed of entrance slit, holographic transmission grating, and cylindrical doublet as shown in Figure. The custom-built spectral imaging ellipsometer has the spectral resolution of 10 nm and the spatial resolution of 200 μm. In the near future the spatial resolution will be enhanced by adopting a focusing optics.

INTRODUCTION

Optical methods for measuring thickness of transparent films are widely used in the semiconductor fabrication industry. These methods have superior advantages over conventional destructive and ex-situ measurement methods such as Scanning Electron Microscopy (SEM), Tunneling Electron Microscopy (TEM), and etc. Among them the ellipsometry has very high resolution down to sub-angstroms because it is based on the polarimetric measurement, which is very sensitive to thin film thickness changes [1]. Ellipsometry measures two parameters, Ψ and Δ defined as the ratio of the relative amplitude and phase difference for p- and s-polarized light before and after reflecting on sample surfaces [2]. The optical and geometrical properties of thin film layers are extracted under the model fitting procedure using these measured ellipsometric parameters. So, natively spectroscopic ellipsometric parameters suggest more flexibility for analyzing multi-layered and complex film structures relative to those of single wavelength. Intrinsically ellipsometry is a point measurement method. So conventional single wavelength and spectroscopic ellipsometers (SE) measure the averaged values of those ellipsometric parameters in the region of interest. However, it becomes more important to efficiently measure multi-point and spatial structures of thin film layer in semiconductor and emerging biomedical industry [3]. To overcome such a shortcoming in the conventional ellipsometry, Ralph F. Cohh et al. ('99) presented dynamic imaging ellipsometer which employing a two-dimensional CCD sensor as a detector [4]. Bruce M. Law ('96), A. Albersdörfer ('98) and Danny van Noort (2000) suggested similar types of imaging ellipsometers [3,5-6]. However, all these types are based on simple substitution of the detector to two-dimensional sensors with the basic structures of conventional point measuring ellipsometers unchanged. Also, conventional SE uses a mechanical scanning monochromator to get spectroscopic data for the analysis of more complicated and ambiguous film structures. But, it takes too much time to apply it for the semiconductor industry. In order to enhance this disadvantage, Eiki Adachi and Tanooka ('95) demonstrated the first color imaging ellipsometer with a color CCD camera as the detector. For this, only three color-filtered spectroscopic information has been used to get ellispsometric parameters [7]. So, the lack of spectroscopic information gives limits for analyzing the accurate optical and geometrical structure of thin films. To solve such shortcomings, we have developed a novel spectral imaging ellipsometers employing a specially fabricated mono-axial power spectrograph. The developed spectral imaging ellipsometer can measure spectroscopic ellipsometric parameters along the line of entrance slit of the spectrograph. It has superiority in the sense that it improves the measurement time for getting spatial and spectroscopic data set simultaneously.

SPECTRAL IMAGING ELLIPSOMETER

Fig. 1 shows the proposed spectral imaging ellipsometer employing a mono-axial power spectrograph. It consists of white light source part, polarization state generation part, and polarization state resolving part. The white light is generated by Quartz Tungsten Halogen lamp (QTH lamp) with collimating lens of focal length of 300 mm.

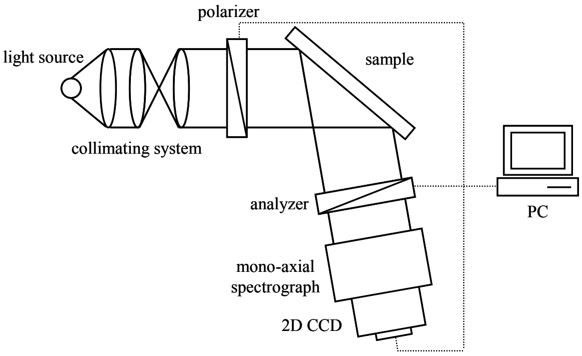


FIGURE 1. Schematic diagram of a custom-built spectral imaging ellipsometer. It consists of light source, polarizer, sample holder, and mono-axial power spectrograph. Specially fabricated mono-axial power spectrograph is attached before CCD sensor for getting spatial and spectroscopic information.

And polarization generation and resolving parts are composed with rotating Glan-Thompson prisms driven by rotating step motor and DC motor. Each motor guarantees angular precision less than 0.01°. Unpolarized collimated white light is emitted by QTH lamp and then it becomes to linearly polarized light after passing the polarization state generation part. Reflecting on sample surface changes to it elliptically polarized light and the polarization resolving part analyzes its exact polarization state. Finally, the light enters to spectrograph and it disperses with its wavelength. And CCD camera captures two-dimensional images, one axis along the spatial line on the sample surface and the other for spectroscopic information of the light. To achieve this we have developed a mono-axial power spectrograph compatible with optical structures of conventional ellipsometers. That is, in general ellipsometry, uniform incident angle on sample surface is inevitable. For that reasons it is required to use a high performance collimating system. Consequently the light used in the ellipsometry is based on plane waves. And in order to expand spectral imaging capabilities with structures of conventional ellipsometer, the monochromator is substituted by two-dimensional imaging spectrograph. However, in this situation the input field on the spectrograph is collimated so it loses one of the spatial or spectroscopic information in focal plane of spectrograph due to collimating or focusing lenses in the conventional spectrograph. To solve this problem, using the mono-axial power spectrograph the input beam passes through the dispersing element, such as gratings and finally the dispersed beam is focused before the CCD camera using cylindrical doublet. In this way, it is measured 3-dimensional data cube, that is, ellipsometric parameters corresponding to given wavelength at specific spatial line. Fig. 2 shows the proposed mono-axial power spectrograph for spectral imaging ellipsometer.

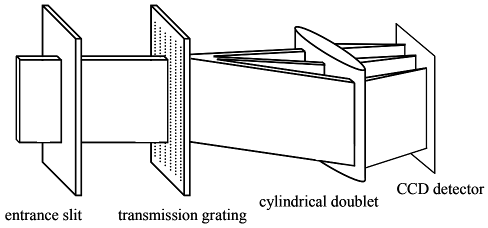
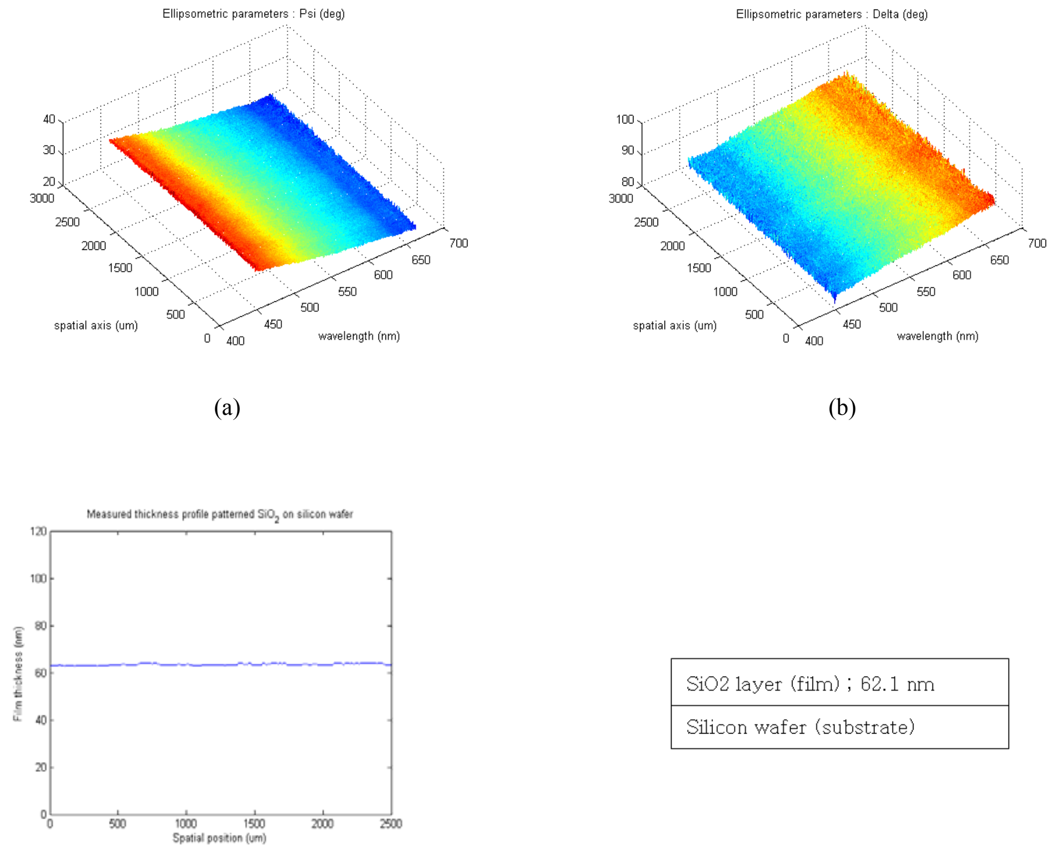


FIGURE 2. Mono-axial power spectrograph for spectral imaging ellipsometer. Spectrograph consists of entrance slit, transmission grating, cylindrical doublet, and CCD detector. Two-dimensional images are captured by detector, one-dimensional for spectroscopic and the other for spatial.

The spectrograph consists of an entrance slit, a transmission grating and a focusing cylindrical doublet. The output beam of the ellipsomter is directed into the entrance slit of spectrograph, so the beam is cut off by the narrow rectangle shape of slit. The long line of rectangle slit is parallel to spatial axis and the other to spectral axis. For adaptability and compactness of the spectrograph, it is chosen to 25.4 mm for the focal length and its overall size has been designed to be less than 120 mm(L) × 100 mm(W) × 100 mm(H).

EXPERIMENTS

In our works, two samples are measured using the manufactured spectral imaging ellipsometer. The first measured sample is uniformly deposited SiO_2 film on whole silicon wafer. It is the CRM(Certified Reference Material) certified by KRISS(Korea Research Institute of Standards). Generally this material is used for calibrating conventional ellispometers. So, it is good reference sample for newly developed ellipsomters. Measured spectroscopic ellipsometric parameters along one-dimensional spatial line on the sample surface is shown in Fig. 3. Uniform values of ellipsometric parameters along the spatial axis shows that the manufactured spectral imaging ellipsometers works reliably at each CCD pixel points. The result of the fitting shows that the SiO_2 film is about 63.4 nm and that of certified value is 62.1 nm. It shows that the manufactured ellipsometer is accurate with less than 2 nm measurement errors.



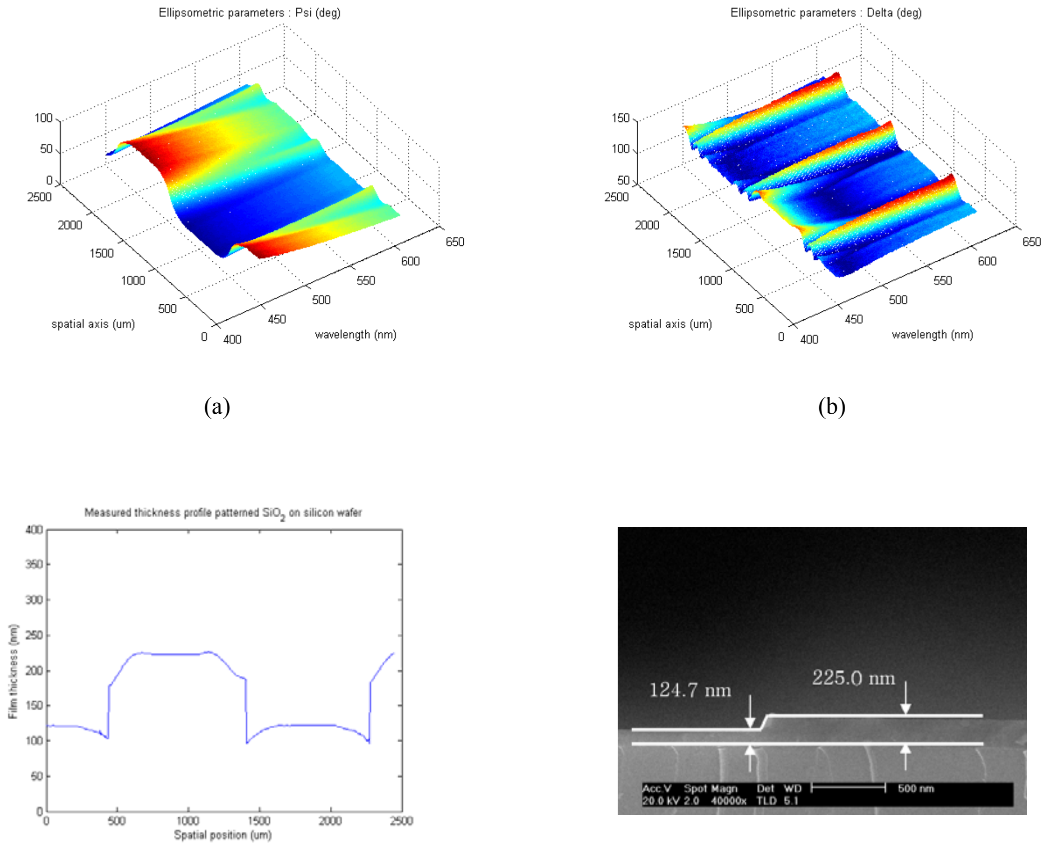
(a) (b)

(c) (d)

FIGURE 3. The measurement results of uniformly deposited SiO_2 on silicon wafer. (a)Spectroscopic ellipsometric parameters, Ψ and (b)spectroscopic ellipsometric parameters, Δ along one-dimensional spatial line on the sample. (c) One-dimensional thickness profile of SiO_2 film is calculated with least square fitting. (d) Certified thickness value of SiO_2 film using reference spectroscopic ellipsometer in KRISS.

The second measured sample is one-dimensional patterned SiO_2 film on silicon wafer. The pattern width is 1 mm. Measured spectroscopic ellipsometric parameters along one-dimensional spatial line on the sample is shown in Fig. 4(a), (b), and the one-dimensional patterned ellipsometric parameters can be found in these figures. It shows complex pattern on the abrupt change of film thickness, so we can guess that it possesses erroneous ellipsometric parameters. Fig. 4(c) and (d) shows results of fitted thickness and the SEM image of the patterned sample. In the results we can find the guessed erroneous thickness region is in the edge of thickness changes. The result of the fitting shows the thinner pattern to be 122.0 nm and the thicker pattern to be 222.9 nm. And the thickness measured by reference Spectroscopic Ellipsometer in KRISS has shown the thinner to be 124.7 nm and the thicker to be 225.0 nm. Analogous to results for first sample, the manufactured ellipsometer measures the thickness about 2 nm errors.

As shown in Fig. 4(c), the transition region for film thickness changes from thinner pattern to thicker one, it shows that the spatial resolution for manufactured ellipsometer and the value is about 200 μm. Its value is limited to this value, because the diffraction effect occurs strongly in collimated white light source in manufactured spectral imaging ellipsometer. And it can be improved by adopting focusing optic before reflecting on the sample.



(a) (b)

(c) (d)

FIGURE 4. The measurement results of patterned SiO_2 film on silicon wafer. (a)Spectroscopic ellipsometric parameters, Ψ and (b)spectroscopic ellipsometric parameters, Δ along one-dimensional spatial line on the sample. (c) One-dimensional thickness profile of SiO_2 film is calculated with least square fitting. (d) SEM image of patterned SiO_2 film sample.

CONCLUSION

A novel spectral imaging ellipsometer employing a mono-axial power spectrograph has been developed. The developed system has the capability of obtaining one-dimensional spectroscopic ellipsometric parameters to extract thin film thickness profile along the sample surface. Most of all it has superior advantages in measurement speed compared with conventional single point measuring ellipsometers. To realize spectral imaging ellipsometer we have proposed plug-in type mono-axial power spectrograph which is compatible with optical structures of conventional ellipsometer. With this we have manufactured prototype system, and measured various thin film samples. The manufactured system shows 2 nm accuracy in measurement of thin film and 200 μm in spatial resolution. In the near future focusing optics will be applied to the system for improving the spatial resolution. In conclusion, it is expected that the spectral imaging ellipsometer can be applied for thin film thickness measurement for various patterned samples such as dielectric materials in semiconductors.

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