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Using imaging ellipsometry to determine angular distribution of ellipsometric parameters without scanning mechanism

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ABSTRACT

This work presents a focused beam approach using a polarizer-sample-analyzer (PSA) imaging ellipsometer to deduce multiple sets of ellipsometric parameters with the information of multiple incident angles in one measurement. Using a three-intensity measurement technique, an additional parameter α can be obtained to locate the ideal incident plane of a focused beam. Meanwhile, the ellipsometric parameters on the ideal incident plane are also analyzed. Based on α and the ellipsometric parameters, the variation in the intensity and phase response with a range of incident angles are examined without using a mechanical scanning apparatus. Measurements made of two zones on a reference wafer with different film thicknesses demonstrate results that are almost consistent with those predicted by the theoretical model.

1. Introduction

Ellipsometry is an optical technique based on exploiting the polarization transformation for the characterization of films or interfaces. In recent decades, it has been proven particularly advantageous because of its capability for fast non-contact measurement and remarkable sensitivity to sub-monolayer region, (e.g., atoms or molecules) [1]. Multi-wavelength measurement with a spectrometer or determination of multi-incident angles with scanning devices are desirable approaches in modern ellipsometric measurement to obtain more information at various wavelengths or angles that allow additional accuracy or more detailed sample characteristics [2]. However, in the conventional ellipsometric apparatus, the incident beam usually has to be nearly collimated, developing a compact spot on the sample that has almost the same incident angle with respect to the sample. The mechanical apparatus normally installed in the ellipsometer system for the purpose of multiple angle measurement has made the system bulky and cumbersome. One improvement method to enable the feature of multi-incident angle measurement has been to use a focused beam substantially normal to the sample surface [3–7]. In this approach, a polarized beam forms a cone with a wide range of incident angles generated through a high numerical aperture lens, but the highest incident angle is reliant on the numerical aperture (N.A.) of the lens. If using an objective lens with N.A. = 0.65, the maximum angle of incidence would be 40.54°, still far from the conventional incident angle of 65° or 70°, which are the most sensitive incident angles for films on silicon substrates found in the semiconductor industry. Another approach used is similar to the conventional ellipsometric configuration and with a lens employed before the sample to focus the incident light beam to provide a range of different incident angles [8–10]. The incoming beam strokes the sample in an oblique direction and the reflected light is collimated in a linear multi-element detector array located on the calibrated incident plane. As a result, each element of the detector located a specific incident angle of reflected rays from the sample and the ellipsometric parameters with a range of incidences can be deduced without any scanning equipment. Calibration of the incident plane is the principle issue in this approach; thus, a blocking element is set as a reference sign in the incident beam to correct the incident angles and the incident plane. However, this approach is usually based on visual observation during the calibration process which makes the calibration procedure complicated and rough.

We have developed an analytical solution approach that not only can determine the ellipsometric parameters but also analyze the surface orientation of the sample. The predominant feature of this approach is the ability to examine the normal direction of a reflected surface and obtain corrected ellipsometric parameters even in non-ideal measurement conditions, i.e., a tilted or curved surface. This technique has been applied in the measurement of film thickness on curved substrates and used to examine the surface orientation and characteristics of an SPR sensor chip [11–14]. In this work, this technique is further employed in a focused beam configuration to determine multiple sets of ellipsometric parameters with the information of multiple incident angles in one

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measurement. The incident beam was focused by means of insertion of a spherical lens before the sample to introduce a substantial range of incident angles, after which the amplitude change and phase shift of the TE and TM waves were evaluated by using the imaging ellipsometric measurement technique. This development allows one to distinguish whether the rays of a focused beam are on the incident plane. Meanwhile, ellipsometric parameters on the incident plane with the information of multiple incident angles can also be examined. We demonstrated the results of the calibration process and two oxide films with different thicknesses in this study.

2. Theory

The most common technique for the measurement of refraction refractive indices or layer thickness is ellipsometry, which measures the change of polarization states of light reflected from the sample surface. A polarizer-sample-analyzer (PSA) imaging ellipsometer is illustrated in Fig. 1, where the light beam is reflected from a test surface and the intensity distribution is detected through use of a charged-coupled device (CCD). Reflection causes separate changes in the amplitude and phase of the p and s components of the reflected light field due to local changes in film thickness or refractive index. The changes are usually characterized by the ratio of the complex Fresnel reflection coefficient ρ, which can be expressed in terms of the ellipsometric parameters Ψ and Δ as:

$$\rho=\frac{r_p}{r_s}=\tan\Psi e^{i\Delta}, \quad (1)$$

where r_p and r_s are the reflection coefficients of linearly polarized light parallel or perpendicular to the incident plane, respectively. The measured intensity can be written as

$$I=I_o(\sin^2P\sin^2A+\tan^2\Psi\cos^2P\cos^2A +0.5\tan\Psi\cos\Delta\sin 2P\sin 2A), \quad (2)$$

where the azimuths P and A are the transmission axes of the polarizer and analyzer, respectively. If the azimuth of the polarizer was set at $\pm 45^\circ$ with respect to the incident plane and deviated by a small angle α, Eq. (2) could be rewritten as

$$I=I_o\{\sin^2A+\tan^2\Psi\cos^2A\pm[(\sin^2A-\tan^2\Psi\cos^2A)\sin(2\alpha) + \tan\Psi\cos\Delta\sin(2A)\cos(2\alpha)]\}, \quad (3)$$

Instead of using a regression technique, we have developed an analytical solution approach to obtain the ellipsometric parameters Ψ and Δ which are free from the deviation of the polarizer and analyzer by measuring the intensities at both the positive and negative polarizing angle at $A=0^\circ$, 60°, and 120°. Three specific analyzer angles were set, because the numerical calculations show that azimuthal angles of the analyzer differing from each other by 60° in this configuration have about three times less experimental random noise than those differing from each other by 45° (i.e., 0°, 45°, and 90°), and the deviation α also can be determined by taking the same measurements. In brief, the measurement was performed while the polarizer with its azimuth set at $\pm 45^\circ$ and the analyzer with its azimuths at 0°, 60° and 120° that six intensities form two sets of three-intensity measurements were fulfilled to deduce the ellipsometric parameters and α accurately [14]. After calibrating the azimuth angle of the polarizer and analyzer using a flat surface such as water, the value of α is confirmed to be equal to characterize the tilt angle of the surface normal [11,13]. In this focused beam configuration, α is indicated to be a perpendicular component of the incident ray to the incident plane, as shown in Fig. 2. The measured map of ellipsometric parameters from a focused beam configuration contained both information about light reflected from the ideal incident plane and that reflected from elsewhere. One method to distinguish between them is to examine whether the ellipsometric parameters are associated with zero points of α. In summary, with this technique we are able to determine the ideal incident plane by α while it equals zero, and the ellipsometric parameters on the ideal incident plane along with the information about the angular distributions can be obtained from a focused beam configuration. All parameters are determined analytically, which means that specialized equipment or elaborate alignment processes are not required during the measurement process.

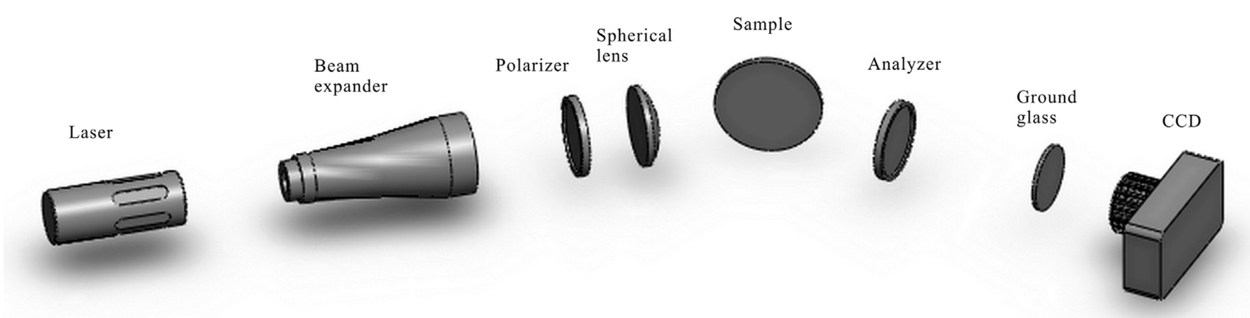

Fig. 1. Experimental setup of the focused beam ellipsometer.

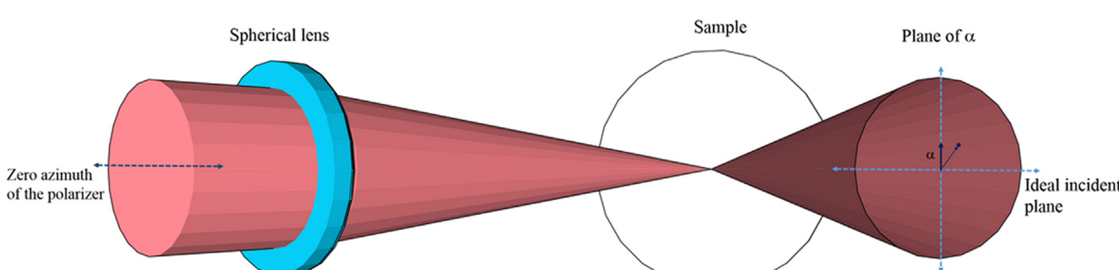

Fig. 2. Trajectory of a beam in the focusing ellipsometer as it is reflected from a flat sample: solid circle shows a light spot of the reflected beam on the image plane; α, perpendicular component of the incident ray to the incident plane.