Novel wide-angle ellipsometric arrangement for thin film thickness measurement

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Keywords: parabolic mirror, rotating analyzer ellipsometry, wide angle of incidence, Si-SiO\textsubscript{2} system, null ellipsometry

Abstract

A parabolic mirror is used for the first time in a wide-angle ellipsometric system to determine the parameters \(\psi\) and \(\Delta\) and the thickness of SiO\textsubscript{2} layer naturally grown on Si crystal substrate. Collimated illuminating beam of diameter 20 mm incident on a parabolic mirror is reflected on the Si-SiO\textsubscript{2} system to provide wide angle of incidence. The polarization states of points in the illuminated area are determined and the data is analyzed for real-time thickness maps over the measured area of the surface. The thickness of SiO\textsubscript{2} layer is found as 3.02 nm with Standard deviation \(\pm 0.12\) nm. Null ellipsometer is also used at different angles of incidence to check our result and nearly the same thickness value was obtained.

1. Introduction

Ellipsometry is an accurate, contactless and non-destructive technique for thin film characterization. Measurements are usually carried with a beam of very small diameter so that results are obtained for a single spot. To measure the lateral distribution of optical properties of the surface, measurements can be carried out point by point by mechanical scanning techniques \cite{1} which are time-consuming work particularly if the surface is of large area. Methods for wide angle of incidence ellipsometry were presented using non-collimated beam \cite{2, 3} or extended source for illumination \cite{4}. In this work, a new imaging ellipsometric system is used to determine the thickness of SiO\textsubscript{2} film grown on Si substrate. The surface is illuminated by collimated beam reflected from parabolic mirror providing wide angle of incidence. In this way, different points on the surface are studied at different incidence angles. Measurements are performed at wavelength 632.8 nm with He-Ne laser at three orientations of the analyzer. Results are then analyzed to find the thickness of the SiO\textsubscript{2} layer. A null ellipsometer is also used to determine the ellipsometric parameters \(\psi\) and \(\Delta\) to determine the thickness of SiO\textsubscript{2} layer. It was intended to use the air-Si-SiO\textsubscript{2} system in our work which was extensively studied by different authors to compare our results with previous studies.

2. Experimental

The optical system used for wide angle measurement is a photometric rotating analyzer ellipsometer RAE, figure 1. Light emitted from He-Ne laser source (\(\lambda = 632.8\) nm) falls on a polarizing prism \(P\) oriented at azimuth 45° followed by lens \(L_1\) and beam expander. The expanded beam with diameter \(\sim 20\) mm falls on the parabolic mirror and is reflected on the Si-SiO\textsubscript{2} system at different incidence angles ranging from 44° to 72°. The beam is reflected again to the parabolic mirror and then to the other arm of the ellipsometer. The two lenses \(L_2\) and \(L_3\) reduce the beam size to be fully accepted by the analyzer \(A\) and the sensing area of CCD camera (CMOS EO-1312M monochrome, computer controlled digital camera).

Ellipsometry measures the change in the polarization state of reflected light. Properties of the reflecting surface are obtained by analysis of polarization changes. The measured parameters are \(\psi\) and \(\Delta\) where \(\tan\psi\) is the change in amplitude ratio and \(\Delta\) is the change in phase. The general equation of ellipsometry relates the
complex reflectance ratio $\rho$ to the parameters $\psi$ and $\Delta$ by [5]

$$\rho = \frac{r_p}{r_s} = \tan \psi e^{i\Delta}$$  \hspace{1cm} (1)

Three measurements with the analyzer A set at $0^\circ$, $45^\circ$ and $90^\circ$ are sufficient to determine the parameters $\psi$ and $\Delta$ with $P$ fixed at azimuth $45^\circ$ [6]. The intensity at the detector is given as [7]

$$I = 0.5[s_0 + s_1 \cos 2\alpha_2 + s_2 \sin 2\alpha_2]$$

$$= 0.5s_0[1 + (s_1/s_0) \cos 2\alpha_2 + (s_2/s_0) \sin 2\alpha_2]$$  \hspace{1cm} (2)

Where $\alpha_2$ is the analyzer orientation and $s_0$, $s_1$ and $s_2$ are the Stokes parameters defined as [5]

$$s_0 = E_P E_P^* + E_S E_S^*$$  \hspace{1cm} (3a)

$$s_1 = E_P E_P^* - E_S E_S^*$$  \hspace{1cm} (3b)

$$s_2 = E_P E_S^* + E_S E_P^*$$  \hspace{1cm} (3c)

Where $E_P$ and $E_S$ are the parallel and perpendicular components of the electric vector and the asterisks denote complex conjugates. The intensity at different analyzer orientations are given from (2) as

$$I(0^\circ) = 0.5(s_0 + s_1)$$  \hspace{1cm} (4a)

$$I(45^\circ) = 0.5(s_0 + s_2)$$  \hspace{1cm} (4b)

$$I(90^\circ) = 0.5(s_0 - s_1)$$  \hspace{1cm} (4c)

Also, the intensity at the detector is related to the ellipsometric parameters $\psi$ and $\Delta$ by the relation [7]

$$I = 0.5\, s_0 \left[ 1 - \cos 2\psi \cos 2\alpha_2 + \sin 2\psi \cos \Delta \sin 2\alpha_2 \right]$$  \hspace{1cm} (5)

Comparing equations (2) and (5) we get

$$\cos 2\psi = -(s_1/s_0) = [I(90^\circ) - I(0^\circ)]/[I(90^\circ) + I(0^\circ)]$$  \hspace{1cm} (6a)

$$\sin 2\psi \cos \Delta = (s_2/s_0) = [2I(45^\circ)]/[I(90^\circ) + I(0^\circ)]$$  \hspace{1cm} (6b)
Replacing \( r_p \) and \( r_s \) in equation (1) by the reflection coefficients of the three-phase optical system, figure 2, we get

\[
\rho = \frac{r_p}{r_s} = \frac{[r_{01,\rho} + r_{12,\rho}e^{-i2\beta}] \cdot [1 + r_{01,\rho}r_{12,\rho}e^{-i2\beta}]}{[1 + r_{01,\rho}r_{12,\rho}e^{-i2\beta}] \cdot [r_{01,\rho} + r_{12,\rho}e^{-i2\beta}]} \tag{7}
\]

Where \( \beta \) is the phase change due to light propagation through medium 1 and

\[
\begin{align*}
r_{01,\rho} &= (n_1 \cos \theta_0 - n_0 \cos \theta_1)/(n_1 \cos \theta_0 - n_0 \cos \theta_1), \tag{8a} \\
r_{12,\rho} &= (n_2 \cos \theta_1 - n_1 \cos \theta_2)/(n_2 \cos \theta_1 - n_1 \cos \theta_2), \tag{8b} \\
r_{01,\sigma} &= (n_0 \cos \theta_0 - n_1 \cos \theta_1)/(n_0 \cos \theta_0 + n_1 \cos \theta_1), \tag{8c} \\
r_{12,\sigma} &= (n_1 \cos \theta_1 - n_2 \cos \theta_2)/(n_1 \cos \theta_1 + n_2 \cos \theta_2). \tag{8d}
\end{align*}
\]

Substituting with the values of \( n_0 \) (= 1) and \( n_1 \) (= 1.4570) and \( n_2 \) (3.8827 – i 0.0196), the angles \( \theta_0, \theta_1 \) and \( \theta_2 \) are calculated using Snell’s law

\[
n_0 \sin \theta_0 = n_1 \sin \theta_1 = n_2 \sin \theta_2 \tag{9}
\]

with \( \theta_0 \) ranging between 44° and 72°.

We used the value \( n_1 = 1.457 \) for the refractive index of SiO₂ since ellipsometry cannot determine both the refractive index and thickness for ultrathin films, nor can it effectively separate the quantities. Noting that in [8] it is stated that: ‘errors in the fixed SiO₂ index values translate into errors in film thickness, but these thickness errors are usually only a fraction of a monolayer for native oxides. This level of error traditionally has been acceptable in semiconductor manufacturing’.

Equation (5) could be written in the form

\[
\rho = (AX^2 + BX + C)/(DX^2 + EX + F) \tag{10}
\]

where \( A = \rho_{12,\sigma}\rho_{01,\sigma}\rho_{12,\sigma}, B = \rho_{01,\sigma}\rho_{01,\rho}\rho_{12,\sigma} + \rho_{12,\sigma}C = \rho_{01,\sigma}D = \rho_{01,\sigma}\rho_{12,\sigma}\rho_{01,\sigma} + \rho_{12,\sigma}F = \rho_{01,\sigma} \) and \( X = \exp(-i2\beta) \).

Solving for \( X \) and substituting in the expression

\[
d = i \ln(X) \lambda/4 \pi n_1 \cos \theta_1 \tag{11}
\]

we get the required film thickness \( d \).

To check the result obtained by the photometric wide-angle ellipsometer, the same three-phase system was investigated by null ellipsometry at angles of incidence ranging between 45° and 70° in steps of 5°, figure 3. Light from the same He-Ne source falls on the polarizer \( P \) followed by a quarterwave phase plate \( C \) oriented with its fast axis at 45°. The beam is then incident on the three-phase sample \( S \) at the selected angles of incidence. The beam reflected from the sample passes through the analyzer \( A \) and is detected by the detecting system \( D \) (photomultiplier, power supply and millivolt-meter). \( P \) and \( A \) are simultaneously adjusted for extinction and the ellipsometric parameters \( \psi \) and \( \Delta \) are calculated from the relations

\[
\psi = A_0 = -A_0', \tag{12}
\]

\[
\Delta = 2P_0 - 90° = 2P_0' - 270° \tag{13}
\]

where \( (P_0, A_0) \) and \( (P_0', A_0') \) are the two extinction pairs and

\[
P_0' = P_0 \pm 90°, \tag{14a}
\]

\[
A_0' = A_0 \pm 90°. \tag{14b}
\]

With \( \psi \) and \( \Delta \) obtained, the thickness is obtained with the same procedure used in photometric ellipsometry.

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**Figure 3.** Null ellipsometer, \( P \): polarizer, \( A \): analyzer, \( C \): compensator.
3. Results and discussion

Figure 4 represents the reflectances $R_p$ and $R_s$ of SiO$_2$ showing Brewster angle at $\sim 56^\circ$ in agreement with published data. Intensity distributions at the three analyzer settings ($0^\circ$, $45^\circ$ and $90^\circ$) are presented in figures 5(a)–(c).

![Figure 4](image1)

**Figure 4.** Reflectances $R_p$ and $R_s$ versus angles of incidence.

![Figure 5](image2)

**Figure 5.** Intensity distribution for the three analyzer orientations (a) $0^\circ$, (b) $45^\circ$ and (c) $90^\circ$. 
The ellipsometric parameters $\psi$ and $\Delta$ for different angles of incidence using the wide angle of incidence system shown in figure 1 are presented in figures 6(a), (b). Results were obtained using MATLAB software. The thickness of SiO$_2$ film as calculated at different angles of incidence is shown in figures 7(a), (b) and is found to range between 2.54 nm and 3.16 nm with a mean value of 3.02 nm and we concluded that

$$d = 3.02 \pm 0.12 \text{ nm}$$

where the value 0.12 nm is the standard deviation of the mean.

Measurements are also performed using null ellipsometer at the same wavelength $\lambda = 632.8$ nm and at angles of incidence ranging between 45° and 70° in steps of 5°. The quarterwave plate C is set with its fast axis oriented at 45° and the two polarizing prisms $P$ and $A$ are simultaneously rotated for extinction. Results for the calculated parameters $\psi$ and $\Delta$ are presented in figures 6(a), (b) with continuous lines. The thickness of the film as calculated from null ellipsometric measurements is

$$d = 2.95 \pm 0.08 \text{ nm}$$

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**Figure 6.** The ellipsometric parameters $\psi$ and $\Delta$ (a), (b) at different angles of incidence obtained from wide-angle of incidence ellipsometry. The continuous lines are results from null ellipsometric measurements.
and is shown in figure 7(a) by the continuous line which is in high agreement with value obtained by wide angle ellipsometry. The value 0.08 is the standard deviation of the mean.

Our results for $\psi$, $\Delta$ and thickness values obtained from both methods and from previous work [8] show high agreement confirming the success of our method for wide angle ellipsometry using parabolic mirror which provides wide range of angles of incidence. Small differences between results in equations (15) and (16) arise probably from alignment errors or local non-uniformity of the film. In comparison with mechanical scanning methods where measurements are performed at each angles separately, our method is time-saving and allows for measurements in a wide range of angles. Also, using parabolic mirror instead of a lens in wide-angle ellipsometry is advantageous in that a parabolic mirror eliminates spherical aberration providing a sharp and clear image which is not the case with spherical lens. Besides, a single-shot measurement reduces $1/f$ noise (shot noise) to a large extent and makes it negligible in comparison with mechanical scanning methods [9].

Perturbation of polarization from angle-dependent reflection from the parabolic mirror is of negligible effect on the results. This is concluded on the basis of agreement between the results of the parameters $\psi$ and $\Delta$ (figure 6) with those obtained from null ellipsometry and also results for the thickness of SiO$_2$ layer from both methods (figure 7). A final note is that it is true that the parabolic mirror introduces phase shift which cannot be separated from the phase shift introduced by the studied system. However, since our measurements are relative, the presence of the mirror has no effect on the results [2, 10].

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