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Wavelength Dependence of Wafer Film Thickness Measurement by Ellipsometer

Khan Salman[1], Musarrat Islam[1], Erteza Tawsif Efaz[1], MD. Muntasir Rafi[1]

Department of Electrical and Electronic Engineering (EEE)
Ahsanullah University of Science and Technology (AUST)
Dhaka, Bangladesh

Abstract - This paper mainly represents how wavelength affects wafer thickness which has been measured by ellipsometry method. The thickness of a semiconductor wafer can desperately repercussion mechanical and electronic yield of the devices fabricated on it. As such for this particular research, the work is carried out by specific equations, correlations and compiled by MATLAB simulations. We worked for different hypothetical sample wafer and defined a range of wavelengths at which the measured thickness error will be minimum. In future this study will be useful for improving the performance of different wafer characterization techniques which will increase the usage of these circuits in electronic devices.

Keywords - reflection coefficient; film thickness; ellipsometer; wavelength; wafer.

I. INTRODUCTION

Semiconductor has revolutionized the modern civilization. Semiconductors are fundamental materials in all neoteric electrical devices. A semiconductor is a solid with a variable electrical conductivity that can be controlled over a wide range. This nature of semiconductor leads to the fabrication of integrated circuits. The use of Integrated Circuit (IC) is being increased day by day and are developed from wafer.

In the earlier period of device fabrication, the purity was not maintained strictly due to larger feature width, specially which were far greater than ten micrometers. But now-a-days devices become smaller and integrated, as a result purity has become a tremendous issue. Today, even the air is being filtered to remove the smallest particles, which could contribute to defects on the wafers. Normally a wafer is made out of extremely pure Silicon (Si) which is grown into a mono-crystalline cylindrical ingots using the Czochralski process. These ingots are then sliced into wafer with a specific thickness. Though silicon is one of the most important building block of modern electronic devices; due to its very low occurrence of defect, other semiconductors are getting more importance in nanotechnology [1]. Many of the researchers are searching for the materials light absorbing capability over a wide range of solar wavelengths and that must be in a cost effective way. The thickness is one of the most important parameters of a semiconductor which critically control the electro-mechanical properties of devices fabricated on it [2].

The thickness of a wafer is important for maximum microelectronic devices mainly for mechanical properties - to control and provide stability of devices by reducing the stresses from various device fabrication process. However, for precious thickness measurement of microelectronic device fabrication, there should be a noncontact method. Again, for minority-carrier devices such as solar cells, the entire thickness of the wafer participates in the optical and electronic performance of the device. In this paper, our work is based on thickness measurement of a silicon wafer in noncontact method by Ellipsometry system.

II. THEORITICAL BACKGROUND

Ellipsometry is a metrology for thin-film characterization which is noncontact and nondestructive technique. A spectral ellipsometer reflects the light beam from the surface of a sample and measures the change in polarization that occur [3].

This technique primarily used for investigation of the complex refractive index or thickness, which gives access to fundamental physical parameters and is related to a variety of sample properties, including morphology, glass quality, chemical composition, electrical conductivity film thickness and optical constant measurement. The mechanism of ellipsometry is based on exploiting polarization transformation when beam of polarized light is reflected/transmitted from interface/film after that acquires relative phase distinction between S-P polarization components [4][5].

Our work is carried out by some equations which is being used in 'Ellipsometry' project [4] and we formulated different formula to measure wafer thickness. A wide range of application fields such as biotechnology, optoelectronics, semiconductors, functional coatings and photovoltaic materials for which Spectroscopic ellipsometry is indispensable. When ellipsometric measurements are performed on a three phase optical system consisting of an ambient-film-substrate structure, it is possible to determine the thickness of the film, if the refractive indexes for the three media are known.

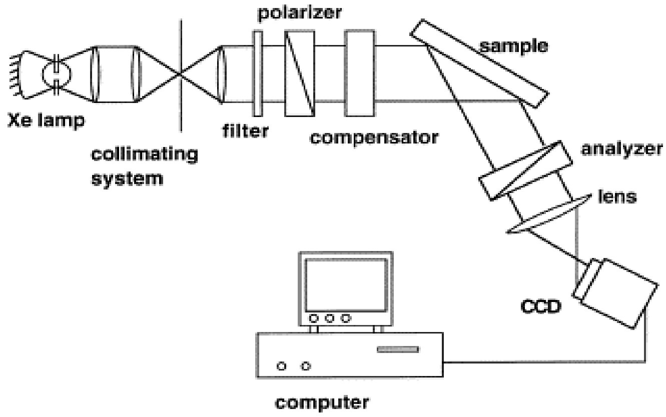

Figure 1. Experimental setup of photometric ellipsometer [2]

This section concerns relating the film thickness to the ellipsometric parameters ψ and Δ. An ambient-film-substrate optical system is depicted in Figure 2. From the below figure it can be seen that, the incident wave is partially reflected and partially transmitted.

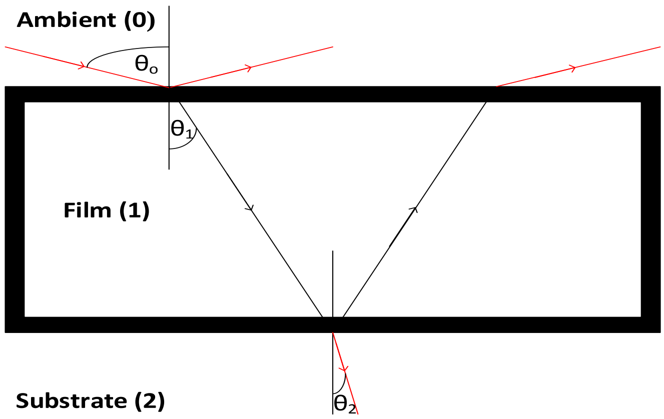

Figure 2. Illustration of ambient-film-substrate optical system [3]

The incident light wave from the ellipsometer strikes the surface boundary between ambient and film at an angle of θ_o, which will also be the angle of the reflected wave due to Snell's law.

III. MATHEMATICAL EQUATION

Reflection and transmission of a polarized wave due to surface boundaries in a three phase optical system, where total reflection coefficients of σ and π polarized light are [6],

$$P_\sigma = \frac{\rho_{01,\sigma} + \rho_{12,\sigma} e^{-j2\beta}}{1 + \rho_{01,\sigma}\rho_{12,\sigma} e^{-j2\beta}} \quad (1)$$

$$P_\pi = \frac{\rho_{01,\pi} + \rho_{12,\pi} e^{-j2\beta}}{1 + \rho_{01,\pi}\rho_{12,\pi} e^{-j2\beta}} \quad (2)$$

An expression for β is given by,

$$\beta = \frac{2\pi}{\lambda}\left(\widetilde{n}_1 . \frac{1}{\cos(\theta_1)} - \frac{\widetilde{n}_1 . \sin(\theta_1)}{\sin(\theta_0)} . \frac{d \sin(\theta_1) \sin(\theta_0)}{\cos(\theta_1)}\right) \quad (3)$$

$$\beta = \frac{2\pi \, \widetilde{n}_1 \, d}{\lambda}\left(\frac{1 - \sin^2(\theta_1)}{\cos(\theta_1)}\right) \quad (4)$$

$$\beta = \frac{2\pi d}{\lambda} \widetilde{n}_1 \cos(\theta_1) \quad (5)$$

$$\boldsymbol{\beta} = 2\pi \frac{d}{\lambda}\sqrt{\widetilde{n_1}^2 - \widetilde{n_0}^2 \sin^2(\theta_0)} \tag{6}$$

(1) and (2) can be related to the ellipsometric parameters, where the reflection coefficients in a two-phase optical system ρ_π and ρ_σ are replaced by the reflection coefficients of a three-phase optical system P_π and P_σ,

$$\mathbf{P} = \frac{P_\pi}{P_\sigma} = \tan(\psi)e^{j\Delta} \tag{7}$$

Where the parameter P is introduced as the complex reflection ratio. By inserting the expressions for P_π and P_σ the following is given,

$$\mathbf{P} = \mathbf{P}_\pi \times \frac{1}{P_\sigma} = \frac{\rho_{01,\pi}+\rho_{12,\pi}e^{-j2\beta}}{1+\rho_{01,\pi}\rho_{12,\pi}e^{-j2\beta}} \times \frac{1+\rho_{01,\sigma}\rho_{12,\sigma}e^{-j2\beta}}{\rho_{01,\sigma}+\rho_{12,\sigma}e^{-j2\beta}} \tag{8}$$

$$= \frac{\rho_{12,\pi}\rho_{01,\sigma}\rho_{12,\sigma}e^{-j4\beta} + (\rho_{01,\pi}\rho_{01,\sigma}\rho_{12,\sigma}+\rho_{12,\pi})e^{-j2\beta}+\rho_{01,\pi}}{\rho_{01,\pi}\rho_{01,\pi}\rho_{12,\pi}e^{-j4\beta}+(\rho_{01,\pi}\rho_{12,\pi}\rho_{01,\sigma}+\rho_{12,\sigma})e^{-j2\beta}+\rho_{01,\sigma}} \tag{9}$$

This is an equation of 11 parameters, where the two ellipsometric parameters ψ and Δ are related to nine real parameters. These parameters are the real and imaginary parts of the complex refractive indexes $\widetilde{n_0}$, $\widetilde{n_1}$, $\widetilde{n_2}$, the angle of incidence θ_0, the free-space wavelength of the incident light wave λ and the film thickness d. If a set of ellipsometric parameters are measured at a given angle of incidence and a given wavelength the thickness of the film is the only unknown, assuming that the refractive indexes of the ambient, film and substrate are known.

Thus by solving for d, the film thickness of a sample can be determined from equation (9) as,

$$\mathbf{P} = \frac{AX^2+BX+C}{DX^2+EX+F} \tag{10}$$

Where, $\mathbf{A} = \rho_{12,\pi}\rho_{01,\sigma}\rho_{12,\sigma}$

$\mathbf{B} = \rho_{01,\pi}\rho_{01,\sigma}\rho_{12,\sigma} + \rho_{12,\pi}$

$\mathbf{C} = \rho_{01,\pi}$

$\mathbf{D} = \rho_{01,\pi}\rho_{01,\pi}\rho_{12,\pi}$

$\mathbf{F} = \rho_{01,\sigma}$

$\mathbf{X} = e^{-j2\beta}$

And $\mathbf{E} = \rho_{01,\pi}\rho_{12,\pi}\rho_{01,\sigma} + \rho_{12,\sigma}$

Rearrangement of equation 10 yields,

$$\mathbf{(PD-A)X^2+(PE-B)X+(PF-C) = 0} \tag{11}$$

Which is a complex quadratic equation with the solution,

$$\mathbf{X} = \frac{-(PE-B)\pm\sqrt{(PE-B)^2-4(PA-D)(PF-C)}}{2(PA-D)} \tag{12}$$

If the refractive index for the film is known, two analytical solutions to this equation exist, namely X_1 and X_2. If the refractive index for the film is not known, but is assumed real i.e. $\widetilde{n_1} = n_1$, solutions to (12) can be found by iteration. In this iteration procedure n_1 is varied until the condition |X| = 1 is satisfied. As $X = e^{-j2\beta}$ where β is given by (6) it is given that |X| must equal 1. With the determined value of n_1 a value for X is also given. X determined from either of the methods, it is possible to calculate the film thickness due to,

$$\mathbf{X} = e^{-j2\beta} \tag{13}$$

$$\ln(X) = -j4\pi\frac{d}{\lambda}\widetilde{n_1}\cos(\theta_1) \qquad (14)$$

$$d = \frac{j\ln(X)\lambda}{4\pi\widetilde{n_1}\cos(\theta_1)} \qquad (15)$$

Our study is mainly based on (12), (13) and (15). We got the effect of wavelength when we substitute (13) on the place of 'X' in (15). Further we again measure the effect of reflection coefficient ($\rho_{\pi}, \rho_{\sigma}$) on film thickness by substituting (12) on the place of 'X' in (15).

Here d is the required thickness and only one solution for the film thickness is valid, which should be real and positive. In the presence of errors, the calculated thickness may be complex. In this case the solution with the smaller imaginary part should be chosen.

IV. SIMULATION RESULT

In this study we used above equations for MATLAB simulation and compared our simulated wafer thickness with different sample wafers. The wave length varied from 50-1300nm where the sample wafer thickness variation was 300, 500 and 700µm for three different cases. And thus we have found the following simulated results.

A. Sample wafer thickness of 300µm

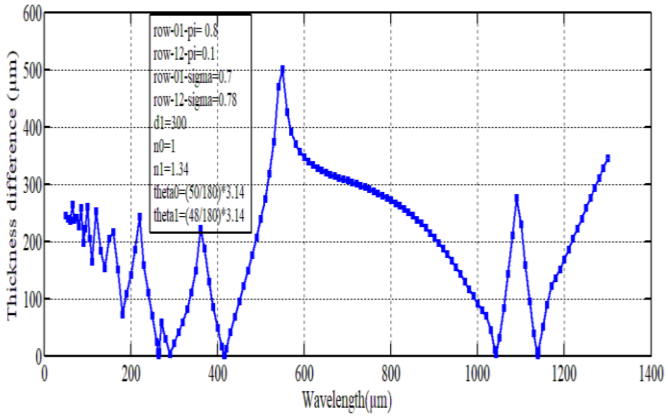

Figure 3. Thickness difference/wavelength for 300µm wafer

From figure 3 it can be seen that, at a range of 50-420nm wavelength, the thickness difference between sample wafer and experimental wafer varied from 0.33-270µm. Minimum thickness difference was found 0.33µm at 264nm wavelength. As the wavelength was varied form 421-1040nm, thickness difference varied from 1.22-500µm. For wavelength of 550nm, maximum thickness difference was found 500µm.

B. Sample wafer thickness of 500µm

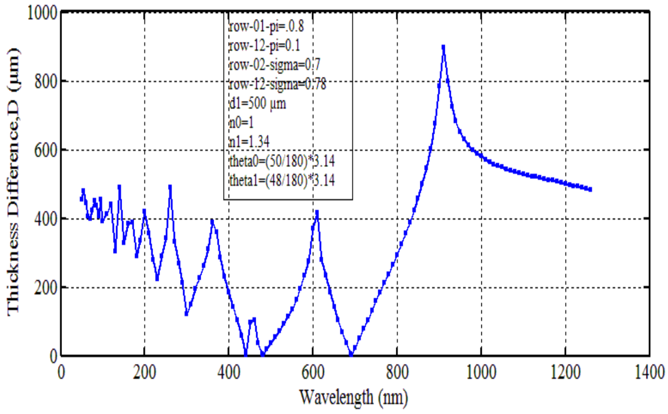

Figure 4. Thickness difference/wavelength for 500µm wafer

From figure 4 it can be seen that, at a range of 50-440nm wavelength, the thickness difference between sample wafer and experimental wafer varied from 0.57-500µm. Minimum thickness difference was found 0.57µm at 440nm wavelength. As the wavelength was varied form 441-692nm, thickness difference varied from 0.91-416µm. For wavelength of 910nm, maximum thickness difference was found 897µm.

C. Sample wafer thickness of 700µm

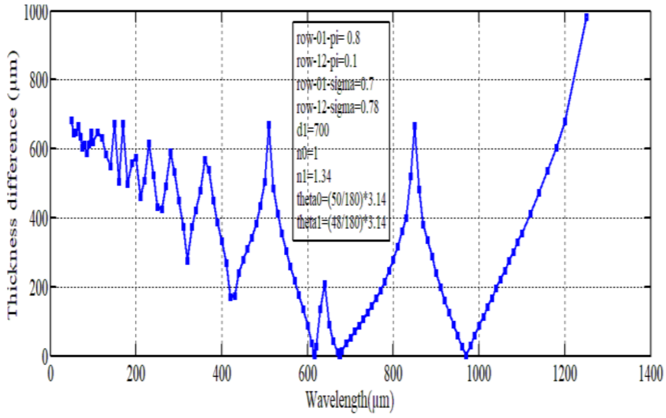

Figure 5. Thickness difference/wavelength for 700µm wafer

From figure 5 it can be seen that, at a range of 50-674nm wavelength, the thickness difference between sample wafer and experimental wafer varied from 0.26-685µm. Minimum thickness difference was found 0.26µm at 674nm wavelength. As the wavelength was varied form 675-970nm, thickness difference varied from 0.75-675µm. For wavelength of 1250nm, maximum thickness difference was found 1000µm.

V. CONCLUSION

Wafer thickness measurement is a useful parameter for evaluating the overall performance of a semiconductor device and ellipsometry is more authentic method for thickness measurement in nanotechnology. There are ten parameters for thickness measurement in ellipsometry system. In this paper, nature of thickness difference is being determined due to variation of different parameters. Results showed that in some cases, the thickness difference is near to zero. According to their wavelength, it is the perfect match for the measurement though this is not a convincing one but still effective.

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