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Characterization of a Complex Multilayer Structure on a Silicon-On-Insulator Wafer Using Spectroscopic Ellipsometry

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Spectroscopic ellipsometry (SE) is used to characterize a complex multilayer structures of oxide/nitride/oxide layers on bonded silicon-on-insulator (SOI) wafers. Results are discussed upon three main points of view including the effects of the beam size on evaluating the SOI substrate, the beam divergence and the effect of applying different data fitting parameters to get reliable structure. Optimum results for a wavelength range of 250 to 850 nm have been obtained by using a combination of a lens and nearly 1 mm slit width. One interesting result is that because of the observed slight vertical error, and the measured tan Ψ parameter greater than one, we have to avoid making fitting on tan Ψ and cos Δ to obtain best calculated data close to the nominal values.

1. INTRODUCTION

Bonded SOI wafers have been paid much attention for ULSI devices[1]. Recently, These SOI wafers had been successfully evaluated using spectroscopic ellipsometry (SE) by the authors[2]. In this paper, multilayer structures of bonded SOI wafers with oxide/nitride/oxide layers prepared by wet oxidation and chemical vapor deposition process were investigated by SE. Nominal values for the ONO-films were 1, 6, and 13.5 nm, respectively. Results are discussed upon three main points of view including first the effect of the beam size, the beam divergence and finally, the effect of applying different data fitting parameters to get reliable structure of thickness data very close to the nominal values.

2. EXPERIMENTAL DETAILS

The ellipsometric measurements were carried out using MOSS ES-4G model developed by SOPRA at an angle of incidence $\phi = 75.22°$ using a microspot lens of 3mm diameter and 150mm focal length that allows to focus the beam on a very small area. Further measurements were done by attaching slits of different widths to the microspot lens to get rid of the light beam divergence. A measurement wavelength range from 250 to 850 nm for a total of 241 different wavelengths was used.

In fact, in any spectroscopic ellipsometry experiment, the object is to measure the complex ratio of Fresnel reflection coefficients[3], which is given by

$$\rho = \frac{r_p}{r_s} = \tan\psi\, e^{i\Delta},$$

where r_p and r_s are the complex Fresnel reflection coefficients for light polarized parallel and perpendicular to the plane of incidence respectively. In the data analysis, Bruggeman effective medium approximation (BEMA) was used[4]. The best fit was determined using Marquardt regression analysis by the least value for the estimator σ given by

$$\sigma = \sqrt{\frac{1}{2*N-P}\sum_{i=1}^{N}\left[(\alpha_i^m - \alpha_i^c)^2 + (\beta_i^m - \beta_i^c)^2\right]},$$

where N is the number of measured wavelengths, P is the number of the fitting parameters, and c, m are referred to calculated and measured data respectively. And the the two quantities α and β are the second-order Fourier coefficients of the signal measured by the photo multiplier tube (PMT). These two quantities α and β are related to the ellipsometric parameters of tan ψ and cos Δ through the following expressions

$$\alpha = \frac{\tan^2\psi - \tan^2 A}{\tan^2\psi + \tan^2 A},$$

$$\beta = 2\cos\Delta\,\frac{\tan\psi\,\tan A}{\tan^2\psi + \tan^2 A},$$

where A is the analyzer azimuth angle. And the values of α and β are confined between -1 and +1, however the values of tan Ψ could reach large values greater than one. It is the reason why we always must fit on α and β parameters when, the values of tan Ψ spectrum reaches values greater than 1.

Jellison's complex dielectric constants for crystalline silicon were the most appropriate to simulate reliable ONO multilayer structure on bonded SOI wafers[5].

3. RESULTS AND DISCUSSION

3.1 The effect of the beam size on evaluating the SOI substrate of the structure

Measurements were performed using only a conventional setup of beam diameter 3 mm at normal incidence. It was reported by the authors[2] that good regression results were not obtained because of the non-uniform, silicon layer of the SOI substrate.

In this case, we obtained a measured curve with low-peak-amplitude oscillations that didn't coincide in peak-amplitudes with that of the regression curve. The measured curve started to oscillate nearly from 450nm, because the incident beam can penetrate into non-uniform silicon layers. So, starting from this limit many interference patterns occurred and appeared in the form of low-peak-amplitude oscillations. As a matter of fact, to get good fitting between conventional measurements and corresponding regression curve a lens should be used to minimize the beam size.

3.2 The effect of the beam divergence and the measured intensity limitations for evaluating the ONO film

Using an experimental setup with a lens the measured peak-amplitude oscillations became higher but, as shown in Fig.1 another problem happened beyond 450 nm coming from ONO films. This effect happened due to light beam divergence. In order to minimize this divergence problem, a slit with suitable width should be used. The used slit width was around 1.5 mm. As we expected, the part of the measured curve including the information of the ONO film shifts down and becomes closer to that one measured with only the conventional setup as shown in Fig. 1. Using 1mm slit width nearly best coincidence beyond 450 nm occurred as shown in Fig. 2.

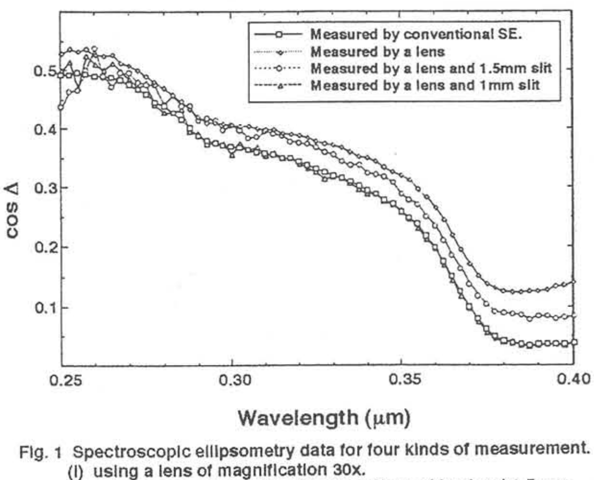

Fig. 1 Spectroscopic ellipsometry data for four kinds of measurement.
(I) using a lens of magnification 30x.
(II) using a lens of magnification 30x attached to about 1.5 mm slit width.
(III) using a lens of magnification 30x attached to about 1 mm slit width.
(vI) using a conventional setup with a normal spot size of 3 mm.

Table I shows a comparison between layer thicknesses of the ONO films on bonded SOI in case of using wide and narrow slits both for weighted data on α and β parameters. From which many interesting conclusions can easily be noticed as following

Using the wide slit width, it was obvious that the thickness of each layer and the total layer thickness of the ONO films were greatly deviated from their nominal thickness values of 1, 6, 13.5, and 20.5 nm respectively, while by the use of the narrow slit width they were very close to them except the uppermost very thin thermal SiO_2 layer which still shows a big discrepancy with its corresponding nominal ones due to the SE limitations. Also, the least value of σ was obtained by the using of the narrower slit.

Table I Comparison between layer thicknesses of the ONO films on bonded SOI in case of using wide and narrow slits both for weighted data on α and β parameters.

	Thickness (nm)		
Layer	Wide Slit	Narrow Slit	Nominal Values
SiO_2	7.0	2.7	1
Si_3N_4	7.1	6.1	6
SiO_2	9.4	13.8	13.5
Si	716.7	739.9	—
SiO_2	523.0	524.9	520
ONO thickness (nm)	23.5	22.6	20.5
σ *	0.02302	0.02116	—

* weighted on α and β.

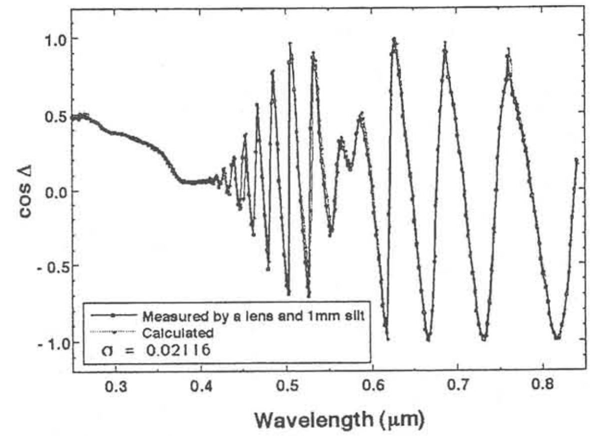

Fig. 2 Best fitting between calculated and measured spectroscopic ellipsometry data for an investigated ONO film on SOI substrate.

The detailed analysis of the beam divergence effect in both cases of using only microspot lens and using microspot lens attached by 1 mm slit could be illustrated as following. In both cases, one can easily notice that the obtained information was not represented only by a 75° incident Brewster angle Φ_1 but also by all the informations coming across inclination angles of θ_1 and θ_2 respectively for beam divergence along the 75° beam angle. In the first case the divergence angle θ_1 can easily be calculated to be 1.72°. Therefore, actual information didn't come through the incident Brewster angle Φ_1, but through the range of the beam divergence around that angle. This means that the real incident angle in this case can be quantitatively given by Φ_1 Real = 75° ± 1.72°. And the average information at any time will be always observed at the 75° beam. Similarly for the second case, the divergence angle θ_2 could be easily given by 0.57°. Again, this means that the real incident angle in this case is now minimized by Φ_2 Real = 75° ± 0.57°.

3.3 The effect of applying different data fitting parameters

The effect of applying different data fitting parameters was also investigated. An interesting result was that, by applying the latter measurement setup still slight vertical error existed. So, it is not recommended to use tan Ψ and cos Δ parameters as a fitting technique on the calculated data in order to obtain thickness accuracy. Beyond 450 nm of the measured curve which includes the information of the ONO films, a big error occurred vertically between the lens and narrow slit measurement data and that of the conventional ones. This means that we have to avoid regression analysis by fitting on tan Ψ and cos Δ parameters. Because they mainly affect the fitting upside-down, instead, we used a curve fitting of α, β parameters by the use of σ eq. to get accurate thicknesses of the ONO films. On the other hand, since the values of α and β parameters are always confined between -1 and +1 however the values of tan Ψ could reach large values greater than one as in our case. So, this is the other reason that why one always must fit on α and β parameters when, the values of tan Ψ spectrum reaches values greater than one.

Many interesting conclusions were indicated in Table II which shows a comparison between layer thicknesses of the ONO films on bonded SOI in case of applying different data fitting parameters, at two different measured positions using a narrow slit attached to the lens. From the comparison one can notice the following.

Always at any position on the investigated sample, data fitting on α and β was much more better than that on tan Ψ and cos Δ i.e.,the obtained thickness values were very close to their corresponding nominal values except the uppermost oxide layer that may be attributed to the limitation of the S.E. for such thin oxide layer (1 nm). Besides, at any position on the investigated sample the confidence limits for either the thickness of each layer or the total layer thicknesses of the ONO films were of the least values in case of applying data fitting on α and β parameters excluded from this shown table for simplicity. Also, at any position on the investigated sample the value of σ is smaller in case of data fitting on α and β parameters than that of fitting on tan Ψ and cos Δ parameters. Finally at best fitting, the thicknesses at a minimum σ value of 0.02116 were obtained with the least values of thickness errors in buried SiO_2 layer, the silicon and SiO_2 layers of the SOI substrate, not shown also here for table simplicity.

Table II Comparison between layer thicknesses of the ONO films on bonded SOI in case of applying different data fitting parameters, at two different measured positions using narrow slit attached to the lens.

Layer	Thickness (nm)			
	Position A		Position B	
	α,β	tanΨ, cos Δ	α,β	tan Ψ, cos Δ
SiO_2	2.7	3.2	2.9	3.9
Si_3N_4	6.1	5.7	6.0	4.7
SiO_2	13.8	14.2	13.8	14.9
Si	739.9	739.8	963.7	963.5
SiO_2	524.9	523.0	529.1	529.0
ONO Thickness (nm)	22.6	23.1	22.8	23.6
σ	0.021	0.037	0.027	0.038

4. CONCLUSION

Bonded SOI structures with ONO layers were investigated using SE. By the essential use of a lens and narrow slit in order to minimize the light beam divergence, optimum thicknesses nearly close to the nominal values were obtained. Due to the observed vertical error, and the large values (greater than 1) in tan Ψ spectrum, data fitting on α and β parameters was recommended to obtain best calculated data close to the nominal thickness values.

5. ACKNOWLEDGMENT

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6. REFERENCES

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