Recent Developments in Real-Time Thickness Control Of Plasma Deposited Thin Film Dielectrics Using Optical Emission Interferometry

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Keywords: PECVD, silicon nitride, optical emission interferometry, endpoint, manufacturing

Abstract

In this paper, we report on new developments in *in-situ* optical emission interferometry to extend the capability of real-time thickness monitoring and control to ultra-thin PECVD films of thicknesses between about 300 and 800Å. It is shown that by utilizing a multi-wavelength approach, control of thickness can be achieved. The multi-wavelength technique is relevant to device applications where performance is critically and directly dependent on the incorporated thin film PECVD layer thickness. One such example is the metal-insulator-capacitor that utilizes a thin silicon nitride layer (~500Å) as the dielectric.

INTRODUCTION

A key technical goal in III-V and III-N compound semiconductor manufacturing is to achieve and maintain consistent product device performance. Control of not only the composition of the many constituent layers in these devices but also the thicknesses of the individual layers is one of several critical requirements necessary to meet this goal. This also applies to the Si-based dielectric films such as silicon nitride (SiN_x), silicon dioxide (SiO_2), and silicon oxynitride (SiO_yN_x) prepared by plasma-enhanced chemical vapor deposition (PECVD) that are incorporated into many of these device structures. [1] For both control purposes and device design rules, repeatable wafer-to-wafer film thickness within ±1 % of the target is often desired.

A robust PECVD process terminated at fixed time combined with monitoring and actively controlling the main process parameters such as rf power, reactor pressure, gas flows, and temperatures are important steps towards achieving acceptable film thickness repeatability. However, due to small but significant variations in the deposition rate caused by short and long term fluctuations in process conditions, the fixed time deposition approach is not sufficient to reliably maintain tight control. Most notable are fluctuations in the wafer-to-wafer deposition rate influenced by parameters that cannot be easily monitored such as the effect of overall PECVD reactor condition or cleanliness. In order to achieve repeatable wafer-to-wafer film thickness, it is therefore necessary to go one step further and monitor and control in real-time the *actual* film deposition on the wafer.

To overcome the limitations of the fixed time approach, we presented in a previous publication [2] a non-invasive and non-disruptive automated technique to monitor in real-time the thickness of the depositing film and terminate, or endpoint, the process when the target thickness had been achieved. This technique is based on optical emission interferometry (OEI). The plasma emission reflected from the wafer is monitored through one of the gas introduction holes in the upper electrode of the PECVD reactor. As illustrated by the example for SiN_x shown in Figure 1, as the film thickness increases, the reflected intensity undergoes a cyclical variation due to interference effects. Using knowledge of the SiN_x refractive index combined with the determination in real-time of the location of the indicated maxima and minima, the film thickness can be immediately calculated as the film is deposited. The full optical interference cycle thickness, d_c is defined as

$$d_c = \frac{\lambda}{2n_f} \qquad (1)$$

where λ is the emission wavelength and n_f is the film refractive index at this wavelength. For improved thickness resolution, a short (UV) wavelength such as the N_2 emission band at 337.1nm is optimum.

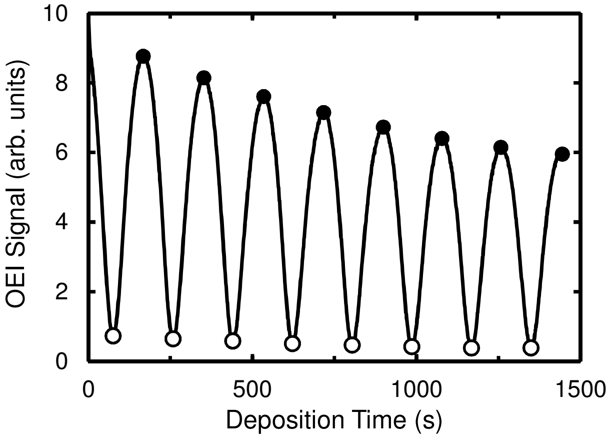

Figure 1. Example of cyclic variation in monitored OEI reflectance signal at 337.1nm for PECVD SiN_x film deposited on Si.

Aided by software, by simply counting full and fractional reflectance interference cycles, the film thickness can be determined at any time during the deposition process. This technique is capable of reliable and repeatable control within about ±1% down to about the minimum thickness that corresponds to the first full optical interference cycle. From Eq. (1) at 337.1nm, this corresponds to minimum thicknesses of approximately 800Å and 1100Å for SiN_x and SiO_2 films, respectively. However, for many compound semiconductor applications, there are requirements for films with thicknesses lower than these values. As an example, the SiN_x dielectric in metal-insulator-metal (MIM) capacitors is typically very thin and on the order of 500Å to achieve the necessary high capacitance.[3] As defined by Eq. (2), the MIM capacitance, C and the film thickness, d_f are strongly interrelated.

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d_f} \qquad (2)$$

where ε_r is the SiN_x dielectric constant, A is MIM capacitor electrode area, and ε_0 is the permittivity of free space.

From Figure 2, a SiN_x film thickness of 500Å would be between the half and full cycle thicknesses of about 400Å and 800Å, respectively. Therefore, in real-time, the actual film thickness by single wavelength OEI can only be determined once during the deposition process, at or just after the half-cycle thickness at the first reflectance minima. Establishment of this point is critically dependent on accurate determination of the time at which the first reflectance minima occurs, and termination of the process is then based on extrapolation from this point, assuming a linear increase in film thickness with time. However, as is shown in Figure 3, the deposition rate in the early stages of film growth can be highly non-linear as the plasma conditions stabilize. A linear extrapolation leads to a significant error in the predicted process endpoint time, and hence error in the final film thickness.

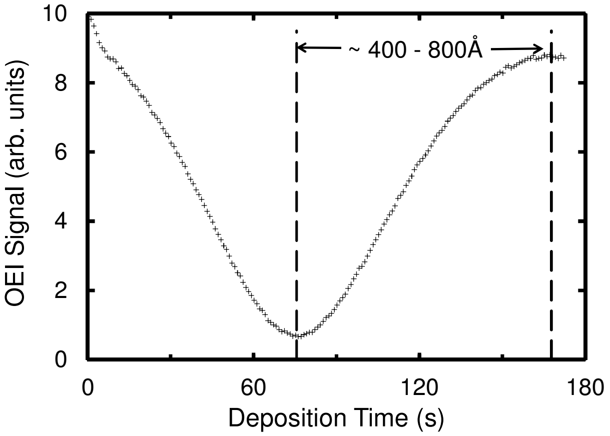

Figure 2. Cyclic variation in monitored OEI reflectance signal at 337.1nm for a thin PECVD SiN_x film deposited on Si.

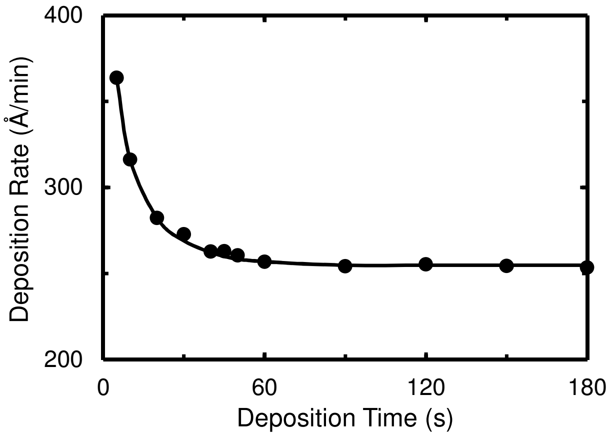

Figure 3. Measured PECVD SiN_x deposition rate *versus* deposition time.

In this paper, to address the issue of real-time control in this important thickness regime, we describe an extension of the OEI technique that involves a multi-wavelength approach exploiting the presence of several N_2 plasma emission bands in the UV common to all Si-based dielectric deposition plasmas. Figure 4 shows a representative plasma emission spectrum for PECVD SiN_x showing the presence of multiple discrete and predominately N_2 related spectral bands in the UV regime between about 300 – 400nm.

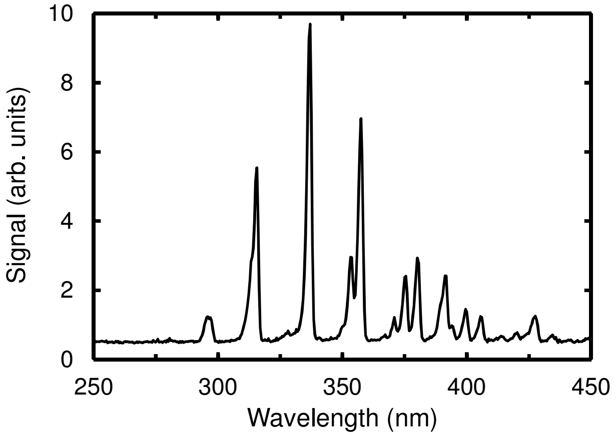

Figure 4. Typical UV plasma emission spectrum for PECVD SiN_x.

THEORY

To highlight the advantage of the multi-wavelength approach, it is necessary to consider results from theoretical modeling. Figure 5 shows the calculated SiN_x reflectance on Si as a function of film thickness at 6 different UV N_2 plasma emission wavelengths selected from Figure 4. The reflectance was calculated based on optical thin film reflectance theory[4,5] and uses accepted values for the optical constants for SiN_x and Si.[6] The model is rigorous and includes the optical dispersion for both SiN_x and Si.

Adaptation of this theory can be done for other PECVD films and wafer types.

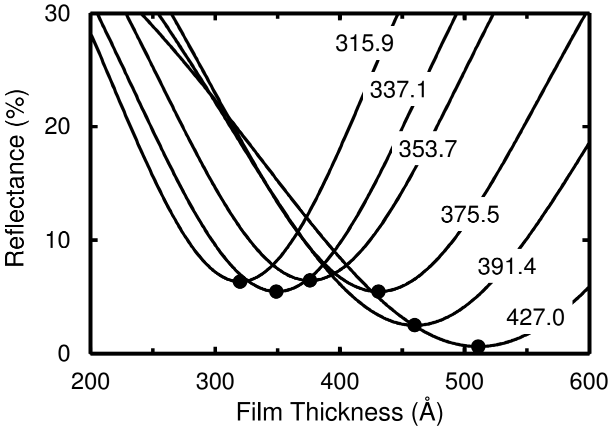

Figure 5. Calculated reflectance of a SiN_x film deposited on Si as function of film thickness at the indicated UV N_2 plasma emission wavelengths expressed in nanometers. The symbols, (●) denote the unique film thickness at each first reflectance minima.

The key result from Figure 5 is that at each of the UV wavelengths, there is a well-defined unique film thickness that occurs for each first reflectance minima. Therefore, as suggested from Figure 6 that by monitoring the reflected signal at these wavelengths during the deposition process, it is possible to determine precisely the thickness-time dependence for films from about 300Å and upwards, without assuming a linear growth in film thickness.

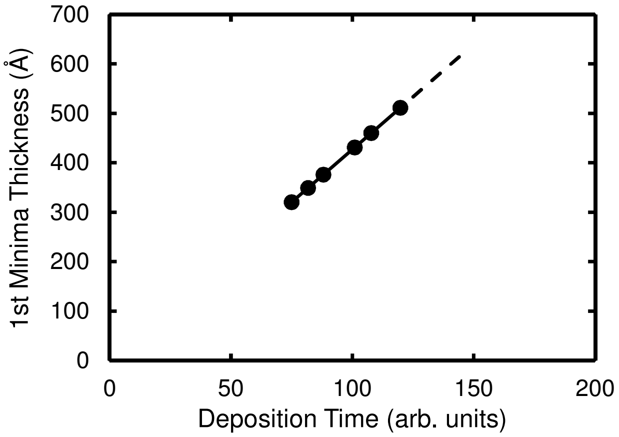

Figure 6. Calculated PECVD SiN_x film thickness *versus* deposition time dependence derived from the location of the first reflectance minima (●), from the calculated data in Figure 5.

EXPERIMENTAL

All the SiN_x deposition work was conducted on a Plasma-Therm, LLC Versaline™ PECVD parallel-plate production reactor with a 13.56 MHz rf excitation source. The system was configured with Plasma-Therm, LLC EndpointWorks™ to monitor the OEI signals and terminate the deposition process when the target thickness has been achieved. A more detailed description of the reactor has been given in a previous publication.[1]

The reactor was configured for single 150 mm Si wafer handling. A well-established and fully characterized process suitable for thin film applications was used to deposit all the films used in this study. These films were produced at a deposition rate of about 250Å/min from a plasma chemistry of SiH_4, NH_3, N_2, and He at a fixed deposition temperature of 300°C. The typical thickness non-uniformity was approximately ±1% or better for a 6mm edge exclusion. The non-uniformity is defined from a 25 site measurement as the thickness range divided by twice the mean thickness expressed as a percentage.

For post deposition thin film thickness and refractive index verification, a Sentech model SE 500 ellipsometer operating at 633nm was used. All films had a refractive index of 2.0 at this measurement wavelength.

RESULTS AND DISCUSSION

A) Refractive Index: Wavelength Dependence

As with many reflectance techniques, the film thickness measured is strictly the optical thickness which is the product of refractive index and the physical film thickness. Therefore, in order to determine the physical film thickness by the multi-wavelength technique, it is necessary to determine the refractive index of the SiN_x film at each emission band in the UV regime. It should be noted that a precise determination of the refractive index is necessary, since any error in this value will result directly in an error in the estimation of physical film thickness. The refractive indices can be found precisely by growing a thick SiN_x film and monitoring the reflectance signals at all the UV N_2 emission wavelengths. Measuring the film thickness following deposition, the refractive index at each wavelength can then be deduced by counting the large number of interference cycles, such as shown in Figure 1, and applying the following equation:

$$n_\lambda = N_\lambda \left(\frac{\lambda}{2d_f}\right) \tag{3}$$

where n_λ is the film refractive index and N_λ is the number of interference cycles at the emission wavelength λ, respectively. The physical thickness is d_f.

Figure 7 shows the refractive index wavelength dependence in the UV determined from a 6200Å thick SiN_x

film prepared under identical process conditions to the thin films.

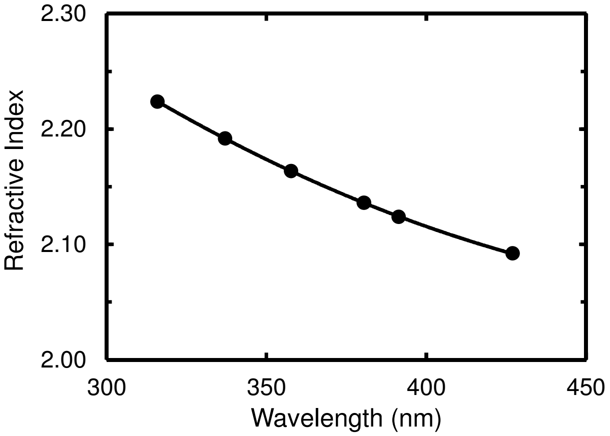

Figure 7. PECVD SiN_x refractive index *versus* wavelength determined in the UV regime from a 6200Å thick film.

B) Comparison between Theory and Experiment

To validate the multi-wavelength approach, it is necessary to compare experimental results for thicknesses at the first reflectance minima for each of the six UV N_2 emission bands selected from the spectra against predictions from the theoretical model. Figure 8 shows the correlation of the measured film thickness from six SiN_x deposition runs terminated at the first reflectance minima for each of the emission band wavelengths plotted against the results from the model using the refractive index values for SiN_x determined from Figure 7. The experimental results are in excellent agreement with the theoretical model.

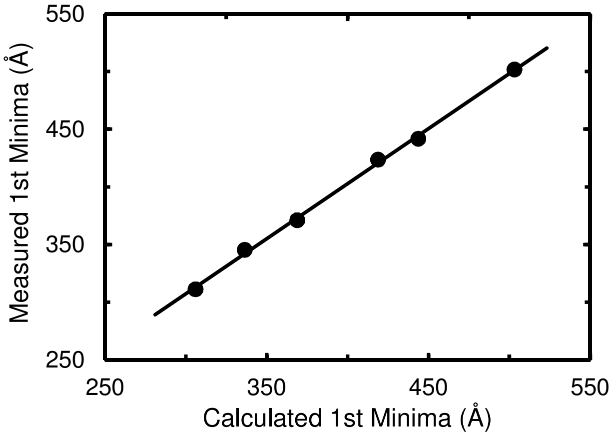

Figure 8. Measured PECVD SiN_x thickness at the first reflectance minima for the selected 6 N_2 emission bands *versus* the calculated results from the model.

C) Testing of Multi-Wavelength Technique

A series of 10 fixed time deposition runs were completed targeting 600Å while recording all the OEI data at the 6 selected UV wavelengths. In Figure 9, representative results of this series taken from one run are shown. The location of the measured first reflectance minima extrapolate by simple linear fit to the final thickness measured post deposition by ellipsometry.

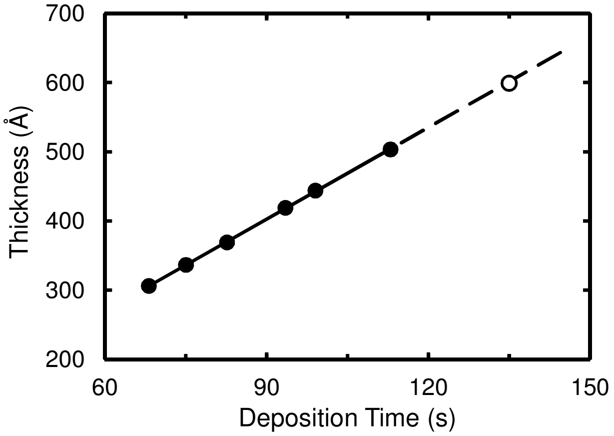

Figure 9. Measured PECVD SiN_x film thickness *versus* deposition time. The symbols, (●) denote the unique film thickness at each measured first reflectance minima collected at each UV wavelength. The open symbol denotes the final thickness by ellipsometry.

CONCLUSIONS

Demonstrated the viability of the multi-wavelength OEI technique for real-time thickness control of PECVD SiN_x films in the thickness range 300 to 800Å

Future work will focus on evaluating the technique for different material systems and also higher deposition rates processes.

ACKNOWLEDGEMENTS

The authors wish to recognize Michael Moore, John Nolan, Joe Barraco, Mike Teixeira, and Jason Plumhoff for their technical support during the course of this project.

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ACRONYMS

PECVD: plasma enhanced chemical vapor deposition
SiN_x: silicon nitride
SiO_yN_x : silicon oxynitride
MIM: Metal-Insulator-Metal
OEI: Optical Emission Interferometry