In-situ Spectroscopic Reflectometry for Polycrystalline Silicon Thin Film Etch Rate Determination During Reactive Ion Etching

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Abstract

Accurate film thickness monitors are important for the development of real-time feedback control of dry etch processes and are very useful for run-to-run process control and process diagnostics. Technologically important films such as polycrystalline Si, which can have process-dependent refractive indices and/or surface roughness, pose significant challenges for low-cost, high-speed film thickness measurement systems. We have used spectroscopic reflectometry (SR) to make accurate *in-situ*, high-speed film thickness measurements during plasma etching of polycrystalline Si. The SR system determines the film thickness using a least squares regression algorithm that fits the theoretical reflectance to the experimental reflectance versus wavelength data. We have included physically-based models for the variation of the polycrystalline Si bulk refractive indices and surface roughness in the fitting procedure. The parameters of the refractive index models are adjusted at the beginning of each run to account for wafer-to-wafer variations *without the use of additional ex-situ measurements*. We have used *ex-situ* spectroscopic ellipsometry to validate the models used and to check the accuracy of our SR measurements. Currently, our SR system can acquire data in 40 ms and the software can calculate the polycrystalline Si thickness in less than 55 ms per measurement, so that a new film thickness and etch rate estimate can be obtained in less than 100 ms. The methods used for analysis of polycrystalline Si are also directly useful for improving the accuracy of microscope-based spectral reflection measurement systems commonly used for in-line measurements. Using similar optical modeling concepts, the SR technique can also be used to accurately measure film thicknesses and etch rates of other thin films with process-dependent optical constants, such as deposited dielectrics and compound semiconductors.

Key words: reflectometry, polysilicon, *in-situ* thin film metrology, reactive ion etching

INTRODUCTION

Reactive ion etching (RIE) is widely used for the definition of critical features in the fabrication process of microelectronic devices and circuitry. As the integrated circuits industry continues its progress toward higher performance circuitry, circuit designers are pushing the minimum device feature sizes to smaller values. This has resulted in the placement of strict demands on the fabrication industry to successfully manufacture circuits with smaller line widths and thinner films[1]. Because of its widespread use for feature definition, control of reactive ion etching is of particular importance to this effort[2–6].

We are applying real-time feedback control (RTC) theory to reactive ion etch processes in an attempt to make them more robust[4, 7–9]. Our control strategy (discussed in the previous references) is based on the measurement and feedback control of plasma process parameters (plasma species concentrations and self induced DC bias voltage), rather than wafer parameters (remaining film thicknesses and surface morphology), both to allow faster feedback system response and to circumvent the very difficult problem of obtaining accurate, real-time wafer state data from patterned VLSI wafers. However, measurement of the effectiveness of this control scheme and the possible eventual implementation of feedback from wafer measurements requires that high-speed wafer measurements be available from test wafers. Also, data acquired from high-speed, *in-situ* measurements can be very useful for process diagnostics, process optimization, and run-to-run control[10]. Controlling the amount of material etched is critical to most dry etch applications; therefore, our initial feedback control work has concentrated on etch rate stabilization. Our model etch problem is the etching of polycrystalline silicon (used for most modern VLSI MOSFET gates) over thin SiO_2 layers on Si. To measure the effect of the real-time feedback controllers on etch rate, we have

investigated *in-situ*, high-speed measurements of polycrystalline silicon (poly Si) film thicknesses.

Reflection-based measurement techniques using wavelengths in the near infrared-visible-near ultraviolet range have been employed for *in-situ* process monitoring of film thicknesses and etch or deposition rates. These techniques will be discussed below. Films such as poly Si, however, pose a significant challenge for these techniques due to the variation in the refractive index with grain size (and thus with deposition and annealing conditions) and to the presence of surface roughness[11]. In order to obtain accurate poly Si thicknesses and etch rates from optical data, it is critical to have a model which accounts for the variations in the bulk poly Si and surface roughness refractive indices, and to employ a measurement technique that obtains sufficient information to determine (or preferably over-determine) the parameters in this model.

A number of optical reflection-based systems have been used as *in-situ* thin film thickness monitors. These include single wavelength reflectometers (SWR), single wavelength ellipsometers (SWE), spectroscopic ellipsometers (SE), spectroscopic reflectometers (SR), and optical emission interferometers (OEI). The SWR and SWE systems have been employed by Stefani and Butler[3] and Marcoux and Foo[12]. These systems provide both excellent S/N and the capability of acquiring data quickly when lasers are employed as sources of incident light. However, these systems do not provide enough information in a single time step to determine the thicknesses of the films in a multi-film stack with high confidence. This hinders these systems from being employed in many of the areas in which RTC is needed. OEI has also been used to determine the wafer state[13], and has been employed in an imaging mode to obtain real-time uniformity information[6]. OEI uses light from the plasma as a source of incident radiation, thereby reducing the cost and complexity of the wafer state monitor system. However, most plasmas used for microelectronics processing do not emit radia-

tion at sufficiently high intensities compared to the noise in the photodetection and data acquisition systems. Although the low S/N ratio that follows from such a small signal could be improved by time-averaging the total measured reflected intensity, this is not practical for real-time applications where data must be acquired as quickly as possible. Furthermore, current practical implementations of OEI are quasi-monochromatic and suffer from the same accuracy problems on multi-film stacks as SWE and SWR. SE systems have been used[2, 3, 5, 14–16] because of the wealth of information and TEM-level accuracy[17] that they are capable of providing. However, although they have been demonstrated to be very accurate for *in-situ* applications, SEs are relatively expensive, somewhat slow (requiring sampling times of about 0.5 seconds and data analysis times on the same order), and require highly specialized vacuum ports which are not practical on some systems.

Spectroscopic reflectometry provides many of the advantages of SE and offers the possibility of increased measurement speed. In SR, the sample reflectance is measured over a broad wavelength range. The interference structure in the reflectance versus wavelength curves provides information on the thicknesses of films in a multi-film stack down to roughly one optical penetration length. In practical applications, up to four layers (depending on film absorption) can be characterized with SR. Changes in the refractive index dispersion provide sensitivity to changes in film composition, density, crystallinity, and other physical parameters. SR does have reduced accuracy compared with SE, but the increased speed is important in many process control applications. *Ex-situ*, microscope-based SRs (such as Nanospecs, Tencor/Prometrics TF systems, Leitz MPV-SP, and others) are commonly used in the semiconductor industry for in-line film thickness measurements.

SR has been previously applied to real-time process monitoring using relatively expensive spectroscopic array detectors for high-speed measurements[18]. Fortunately, the recent availability of

low cost, broad-band CCD spectrometers provides the opportunity to determine the real-time effect of the plasma on the wafer using high-speed spectroscopic reflectometry in many systems without the chamber modifications required for SE. The system that we used in these experiments was purchased commercially. It can collect a set of data every 40 milliseconds and can provide enough information to confidently determine the thicknesses of films under observation with a single data set. This particular system, also, allows access to its software. This enables modification of the optical models to make them more suitable for application to the thin films of interest and allows more effective integration of the measurement system with the RIE control computer.

In this paper we will report on both the development of this SR system and on the physically-based approximations used to measure poly Si thicknesses and etch rates. *In-situ* measurements are compared to *ex-situ* microscope-based SR, *in-situ* SWR, and *ex-situ* SE. Finally, we will show examples of the advantages of using this system in the real-time monitoring of poly Si etching in an Applied 8300 RIE.

EXPERIMENTAL HARDWARE

A block diagram of the SR system on our Applied 8300 Hexode RIE is shown in Figure 1. The main components of this reflectometry system, including the source lamp, optical fibers, and light detector, were purchased from Ocean Optics, Inc. The source lamp is a tungsten halogen lamp that provides continuous spectral output from roughly 250 to 2700 nm. The light is focused onto a 400 μm single core silica fiber and is collimated using an Oriel glass compound lens. Once collimated, the light is passed through an Oriel inconel beamsplitter, and reflected light is collected onto a 100 μm silica fiber using a second compound collimating lens. This arrangement allows us to perform near normal reflectometry, which reduces the complexity of the equations used in the

analysis process. This reduction in the complexity of the equations decreases the amount of time necessary to determine the thin film properties and will be discussed later in this paper. Also, the normal incidence geometry is the most easily implemented case for our reactor.

The intensity of the light reflected from the sample is detected with a fixed grating (600 lines/mm, 500 nm blaze) Ebert geometry spectrometer using a Hitachi 1100-element, linear CCD array, which connects to a standard PC using an EISA-compatible data acquisition card. The usable wavelength range is 360-850 nm at a spectral resolution of 5 nm with this arrangement. This resolution is more than adequate for thickness determination in most semiconductor thin film measurements. Improved resolution can be obtained at the expense of the signal to noise ratio. The wavelength versus pixel position calibration was performed using a Hg lamp and a quadratic fitting procedure. For etch monitoring, we log the data from all 1100 pixels but select between 25 and 200 wavelengths evenly spaced between 400 and 800 nm for analysis. This range is chosen so that most of the visible spectrum is observed, which allows a more unambiguous determination of the film thickness. The number of wavelengths at which data is analyzed is selected to minimize the amount of time necessary to accurately determine the thin film properties. The process used to determine this number will be discussed later in this paper.

A Computer Boards CIO-CTR05 timer board with the AMD 9513 system timer controller has been incorporated into this system to provide a clock accurate to 1 microsecond. The clock is used to mark the time at which the reflected intensity is recorded. This ”time stamping” is a requirement for accurate determination of the real-time etch rate by numeric differentiation of the thickness versus time data.

The reflected intensity from a Si reference wafer is collected shortly before each run. The sys-

tem is calibrated using this reflected intensity to map the reflected intensity from a sample to the theoretical reflectance for that sample on a wavelength by wavelength basis using:

$$R_{sample}\,(\lambda) \;=\; [I_{meas}\,(\lambda)/I_{Si,ref}\,(\lambda)] \times R_{Si,theory}\,(\lambda), \tag{1}$$

where R_{sample} is the theoretical sample reflectance, I_{meas} is the measured reflected intensity from the sample, $I_{Si,ref}$ is the measured reflected intensity from a silicon reference sample, and $R_{Si,theory}$ is the theoretical reflectance from a silicon sample. This equation takes into account the wavelength dependent response of the optical system including the current state of the optical port on the RIE. Coating or etching of the optical port during the run can lead to time dependent error, but we have found no significant changes on a run-to-run basis. After a large number of runs (≈ 100) the window transmission drops and the window must be replaced. We can include a second spectrometer to measure and correct for the real-time changes in the lamp intensity versus wavelength in a double beam mode, but have not yet found this to be necessary.

Another complication that arises from the *in-situ* nature of this work is the effect of the plasma emission on our detected SR signal. Plasma emission lines pose a possible problem as they are collected along with the light reflected from the wafer by our detection system. For instance, in our CF_4 plasma there is a strong emission at 703.7 nm due to the excitation of fluorine in the plasma. Furthermore, the intensity of this emission line may change with changes in the processing conditions (such as input power, pressure, gas flows, and process gases). Fortunately, we have observed that these emission lines cause no noticeable effect on the detected SR signal in the experiments described in this work. Two factors prevent this from becoming a problem for our system. Firstly, the incident beam that we use for the measurements is collimated and the reflected light is focused

onto the receiving fiber. This allows most of the reflected signal to be guided to our detector by the fiber. The plasma, however, is a diffuse source which emits only a small fraction of its total intensity into the acceptance angle of our collecting optics. Secondly, it should be noted that describing the intensity of the emission line at 703.7 nm as being ”strong” means that it is strong relative to the background emissions originating from the plasma. Fortunately, the brightness of the ”strong” emission lines from plasmas used in microelectronics device fabrication are generally small compared to that of the light emitted from our collimated source lamp (and in our case the detected emissions from the plasma are even small relative to the noise inherent to our detection system). Therefore, only a small percentage of the total detected intensity originates from the plasma itself.

In systems where the emissions from the plasma cannot be ignored, they can be removed from the detected SR signal by making a separate measurement of the relevant plasma emissions and subtracting the emission intensities from their respective intensities in the detected SR signal. In our case, we could use our system in a double beam mode and simply perform a subtraction of the intensity of the plasma emissions from the detected SR signal. This additional step would remove the affects of plasma emissions from our SR data.

DATA ANALYSIS

Background theory on using reflectometry for the determination of thin film thickness can be found in many sources[19–21]. Only a few comments on the theory are offered here. The basic principle behind reflectometry is that the reflectance from the sample of thin films is a function of the optical constants associated with the films and the film thicknesses. Film thicknesses can be found by least squares fitting of the theoretical reflectance to the experimental reflectance using assumed values for the refractive indices versus wavelength. For nondispersive transparent films, only the

”optical” thickness (the product of the refractive index and the physical thickness) can be found uniquely. However, for dispersive films and weakly absorbing films, the reflectance curves can be used to uniquely determine the film thickness(es). If an accurate model is available to describe the variation of the film refractive index curve versus its deposition process conditions, then these variations can be accounted for to obtain more accurate film thicknesses.

A typical set of reflectance versus wavelength data is shown in Figure 2. To determine the film thickness, we need only to provide the regression algorithm with the raw reflectance data and appropriate optical models for the thin films of interest. We use a non-linear least squares regression algorithm that is based on the Levenberg-Marquardt method[22]. Generally, the optical model used is one which assumes quasi-ideal thin films. Such films are isotropic with optically smooth, parallel interfaces[19]. With quasi-ideal thin films, only the film thickness and optical constants (refractive index) affect the magnitude of the reflected intensity. And although the equations are non-linear with respect to the film thickness, the regression routines are efficient in determination of the thin film thicknesses.

In practice, however, some of the films of interest do not fall into the category of quasi-ideal thin films. In such cases, properties other than the thin film thickness and refractive index may affect the magnitude of the intensity reflected from the sample. This is the case with poly Si. As a consequence, much work has been done on determination of poly Si film thickness via interferometry[3, 6, 14, 16, 17]. It has been shown that the optical properties of the poly Si necessary for the film thickness determination are quite sensitive to the processing conditions during the poly Si deposition[11, 23].

We model our poly Si films by using a two layer approximation with the first layer being a bulk

poly Si layer and the second being a thin surface roughness layer. The refractive index versus wavelength for each layer is estimated using Bruggeman's effective medium approximation (BEMA):

$$0 = \sum_i [\Big((\varepsilon_i - \varepsilon_h)/(\varepsilon_i + \kappa\varepsilon_h)\Big) \times \nu_i] \quad (2)$$

where, ε_h is the dielectric constant of the effective medium, κ is the screening parameter, ε_i is the dielectric constant of material *i*, and ν_i is the volume fraction of material *i* in the effective medium. This approximation is a self-consistent model of the dielectric response arising from mixtures of chemically separate materials and has been used widely in ellipsometry[5, 14, 16, 17]. For the bulk poly Si, we assume a binary mixture of amorphous and single crystalline Si (a-Si and c-Si, respectively). A screening factor of 1 was assumed, which corresponds to a mixture of columns of a-Si and c-Si, since LPCVD poly Si tends to grow in columnar grains. For the surface roughness layer, a BEMA was used which included a-Si, c-Si, and voids (air), also using a screening factor of 1 to approximate the behavior of vertically oriented surface asperities. This model was tested using *ex-situ* spectroscopic ellipsometry at multiple angles of incidence. SE data was collected over the 230-850 nm range using a Sopra GESP-5 system. Simultaneous fits of this model to 3 angles of incidence (65, 70, and 75°) yielded very good agreement between theory and experiment over the 350-850 nm range. Some deviations were noted in the 230-350 nm range. These errors could be due to failure of the BEMA to describe the surface roughness effects in the UV or to crystallite size dependent refractive indices. A three component BEMA (a-Si, c-Si, voids) for the bulk poly Si was also used in fitting the SE data, but no statistically significant void fractions were found and, therefore, a binary BEMA was used in all subsequent analysis.

EXPERIMENTAL RESULTS

To demonstrate that using this system does not result in a loss in the quality of the acquired data or a loss in the accuracy of the calculated film thickness (as compared to presently used *ex-situ* methods), we performed two experiments. In the first experiment, we studied the application of the SR system to determine the thickness of an oxide film. In the second experiment we studied the determination of the thickness of more complex thin films, such as poly Si.

In order for the *in-situ* wafer state monitor to be acceptable, the raw data acquired by the system must be indicative of the real-time reflectance from the sample and the regression routines must provide accurate values of the film thicknesses. In Figure 2 we compare the normalized reflectance data collected using the *in-situ* SR and data collected using an *ex-situ* SR. As can be seen from the comparison, the two sets of data are almost identical. This demonstrates that moving from *ex-situ* metrology to *in-situ* metrology does not result in a loss in the quality of the acquired data. We also point out here that the data collected by the *in-situ* SR was collected in 40 ms. Even at this data acquisition rate, the quality of the acquired data is comparable to that acquired by using the *ex-situ* microscope-based SR which takes more time to acquire its data.

The next step in the system validation process is to determine the probable oxide film thickness by using models that describe the interaction of the light with the oxide film. Here wet oxide was a good film to examine because it is a quasi-ideal film. Figure 3 shows the experimental reflectance data plotted with the theoretical reflectance which was found by the least squares regression routine. From the theoretical fit, the oxide thickness was found to be approximately 615.5 nm. This compares well to the result found by making the measurement on an *ex-situ* microscope-based SR (616.5 nm). This experiment indicates that when using data that is representative of the reflectance

from the sample along with the correct optical models for the films of interest, this system determines thin film thicknesses that are comparable to those determined by *ex-situ* systems.

Moving on to a more interesting case, we used the *in-situ* SR to determine the thickness of a poly Si film on oxide on silicon substrate. We initially modeled this structure as quasi-ideal films of poly Si on oxide on silicon substrate (the PO model). As can be noted from Figure 4, there was a significant difference in the theoretical fit and the experimental data, especially at the shorter wavelengths. Therefore, the accuracy of the poly Si thickness determined by the routine was questionable. Because we are confident in the accuracy of the *in-situ* SR data, we deduce that the model used for the structure was probably not accounting for all significant interactions that the light had with the structure. The poly Si used in these experiments was thick and absorptive enough so that the reflected intensity at shorter wavelengths was only due to surface reflections. In a case such as this, a poor fit of the reflected intensity at shorter wavelengths is indicative of poor modeling of the poly Si surface. In an attempt to address this issue, we added an oxide overlayer onto the surface of the poly Si (the OPO model). Existence of an oxide overlayer is quite possible because the measurements are taken in the ambient of a cleanroom where native oxide layers naturally form on the poly Si. However, significant differences in the fitted theoretical curve and the measured data were still observed.

For our poly Si deposition conditions, the post deposition surface of the poly Si is not optically smooth, as assumed by the thin film models used in the aforementioned experiments. In fact AFM results shown in Figure 5a indicate that the pre-etch poly Si surface is rough with an rms roughness of 154 Å. This prompted the inclusion of a surface roughness layer as described in the previous section. Figure 6 shows the pre-etch theoretical reflectance using the BEMA to model the poly Si

plotted along with the experimental reflectance from the poly Si / oxide / silicon substrate structure. As can be seen, this method provides a much better fit than did the simple PO or the OPO model.

By using the effective medium theory in the complete scattering matrix problem for the poly Si / oxide / silicon substrate sample, we are able to determine the thicknesses and the refractive indices (by including the material volume fractions in the regression) of the bulk and surface roughness layers without the need to make *ex-situ* measurements. Figure 5a shows the pre-etch thicknesses and compositional estimates for both the surface roughness layer and the poly Si bulk layer that were found using BEMA. This takes approximately 10 seconds. Once the etch begins, we fix the model's compositional parameters and oxide thickness, then determine the values of the bulk poly Si and surface roughness thicknesses as the sample is etched. The post-etch AFM and BEMA results shown in Figure 5b indicate that although the regression routines using BEMA do not return an rms magnitude of the surface roughness thickness that is equal to that determined by AFM results, they do predict the correct trends.

As a demonstration of the system's applicability with films of different thicknesses, we performed an etch of poly Si, stopping intermittently to compare *in-situ* measurements from the SR to *ex-situ* measurements performed on a SE (using a wavelength range from 300 to 800 nm and an incident angle of 75°). The results from this experiment are presented in Table 1. As can be seen, the *in-situ* SR and the *ex-situ* SE method show good agreement, where the *in-situ* SR provides results accurate to within 4% of the values found from SE for films of various thicknesses. There are noticeable differences between the SR and SE data in the extracted film compositional parameters, particularly for the roughness layer. We have observed that a number of different regression solutions for the roughness layer are possible from the SR data with only minor variations in the total

mean square error of the fit, demonstrating that for thin roughness layers, the absolute accuracy of SR is not good; however, agreement between the bulk poly Si results is much better and, again, the total film thickness results agree very well. While SE provides inherent advantages over SR in analyzing thin surface layers, such as our roughness layers, the SE measurements here have the added advantage of more UV information. The compositional estimates for the surface roughness layer are dominated by the UV data in both cases. If the SR instrumentation was modified to include data to 300 nm (or less), the surface roughness estimates should be improved.

Also, it is possible that diffuse scattering from the surface roughness layer is affecting the SR results. In using the BEMA, we are assuming that diffuse scattering is insignificant. The Rayleigh criterion states that this approximation is valid if

$$\sigma < \Big(\lambda/(8cos\theta_i)\Big), \tag{3}$$

where σ is the rms surface roughness and θ_i is the angle of incidence. At 400 nm and normal incidence, this corresponds to an rms surface roughness limit of 500 Å. For the as-deposited films, we are close to this limit. For our SE measurements we are well away from Rayleigh limits.

Furthermore, comparison of the SR and SE results with AFM show that both optical techniques over-estimate σ, suggesting that the single layer BEMA is not an accurate approximation for the surface roughness layer. We will examine those issues further in future work.

After these experiments, we used the system for real-time data acquisition. Having demonstrated the ability of this system to determine accurate values of film thickness for both oxide and poly Si, we performed experiments to determine how quickly we could get these values. When doing the initial experiments, we used the reflectance at 200 evenly spaced wavelengths in the range

from 400 to 800 nm as the input data to our regression routines. By doing this, the routines could determine the film thickness of the two films in the poly Si model in approximately 350 ms. For real-time applications we wanted to reduce this time significantly. The most obvious way to do this, while using the same hardware and software, was to reduce the number of wavelengths used in the regression routines. In Table 2, we present typical results of using 200, 100, 50, and 25 data points in the regression routines. As can be seen from the table, the total amount of time needed to calculate the two thicknesses, the bulk poly Si and the roughness overlayer, is reduced substantially by moving from 200 data points to 25 data points. As important is the result that the thicknesses determined by the regression routines change only slightly from those computed using 200 data points (which is used for comparison because it should have the highest associated confidence). With these results we are able to reduce the computation time to 55 ms with minimal loss of accuracy in the results of the computation. Without this outcome, we would have been limited to performing the thickness determination at $\geq$ 350 ms intervals. This would have limited the use of the SR system in RTC of etch rate.

Next we compared the real-time, *in-situ* poly Si etch rates determined by the SR system to those determined by an *in-situ* SWR system. The etch rate determined by the SR system was computed by taking a time derivative of the calculated thickness data. The etch rate for the SWR system was computed using the method discussed by Marcoux and Foo[12] and Wu, et. al.[24]. (We refer to this method as the peak-valley (P-V) subtraction method.) The results are shown in Figure 7. As can be seen from the plot, the two methods agree well. However, the SR system provides a great deal more detail about the etch rate than does the SWR, especially with regards to the initial etch rate transient and sudden changes in the etch rate that may occur. The advantages of having the

capability to determine the *in-situ* etch rate are further demonstrated in the final experiment.

It should be noted that the etch rate determined by the P-V subtraction method is inversely proportional to the refractive index of the material being etched. Because the poly Si refractive index is sensitive to processing conditions during poly Si deposition, best poly Si etch rate results are obtained from the P-V subtraction method when an accurate refractive index for the bulk poly Si under observation is found. In our case, the bulk poly Si refractive index was found from the SR data using a regression routine that employed BEMA. In any case, this information cannot be found from single wavelength systems, and therefore must be found using some sort of *in-situ* or *ex-situ* multi-wavelength system.

Before proceeding to the final experiment, it should also be noted that we used general least squares smoothing on the etch rates presented in this paper. We smoothed[25] the data by fitting a second order polynomial to a sliding window of 7 1/2 seconds of data. This method of smoothing has a significant effect on the point-by-point etch rate through averaging away some of the etch rate ”noise”. As the window is increased to include more data the etch rate appears more smooth. However, this smoothing should have no effect on the average etch rate for the run. As can be seen from the plot in Figure 7, the etch rate is still not ideally smooth or ”noiseless”. We attribute this noise to error terms that arise from noise in our data acquisition system, imperfect models for our thin films, and imperfect regression algorithms for quickly determining the film thicknesses. The consequence of these error terms is a calculated thickness with an associated thickness noise. When the thickness is differentiated these errors are propagated through to the etch rate. More work is being done on quantifying the etch rate noise and on determining the bandwidths for filters that can be used to attenuate this noise[26].

Finally, we present results of an experiment that demonstrates one of the potential benefits of having a real-time wafer state monitor. Research is being done at the University of Michigan on reducing variance in the etch rate of poly Si during reactive ion etching[27]. The rationale is that if the individual processes that collectively dominate the etching can be controlled, then the variance in the etch rate itself can also be controlled. This experiment uses a CF_4-based etch chemistry. For the etch conditions, the two main etch processes have been identified as a physically driven process and a chemically driven process. Furthermore, the chemically driven etch process has been linked to the concentration of the fluorine radicals ($[F]$) in the plasma and the physically driven etch process has been linked to the energy of the ions that bombard the surface of the wafer being etched. (Note: The energy of the ions is related to the self induced dc bias voltage, V_{bias}, built up across the powered electrode sheath.) Therefore, if the $[F]$ in the plasma and the V_{bias} are controlled, then the etch rate variance could be brought under control. A real-time feedback controller has been constructed to do just this. By changing the rf power coupled into the plasma and the throttle position of the pumping system, the controller attempts to keep $[F]$ and V_{bias} constant. Given the assumptions the model makes, the resulting etch rate will be more constant than it would be in systems without the real-time feedback control.

In order to measure the effectiveness of the controllers under development, our *in-situ* wafer state monitor must detect changes in the etch rate that may occur over small time scales. To demonstrate how quickly our *in-situ* SR monitor responds to such changes in the etch rate, we intentionally introduced an oxygen leak into the reactive ion etch chamber during the second half of an etch. As can be seen from the results presented in Figure 8, the *in-situ* SR system detected the increased etch rate in fewer than 5 seconds. Also seen in Figure 8 is the trend showing the decrease in the surface

roughness layer as the etch progresses. This was discussed in previous sections. Using this system, we are able to observe the real-time etch rates of the bulk poly Si and the surface roughness layer. This ability has provided great insight into how our controllers could be modified for improved performance in real-time feedback control systems. This is just one demonstration of the applicability of *in-situ* SR.

CONCLUSIONS

We have designed and implemented a prototype film thickness monitor based on the principles of spectroscopic reflectometry for use in real-time feedback control of dry etch processes. The film thickness monitor is inexpensive, fast, and accurate. Data can be acquired in as little as 40 ms and the analysis can be done in 55 ms. Not only have we demonstrated the use of this thickness monitor on quasi-ideal thin films, such as SiO_2, but we have also shown that the monitor provides accurate results for non-ideal films such as poly Si, which have process-dependent refractive indices and surface roughness.

The thicknesses provided by the *in-situ* SR monitor were within $\approx$ 2% of those provided by *ex-situ* SR for simple SiO_2 films. We demonstrated the capability of the system to determine to the thicknesses of poly Si films that varied from $\approx$ 155 nm to $\approx$ 590 nm in thickness. The thicknesses determined here were within $\approx$ 4% of those determined using a system based on *ex-situ* SE. Finally, we showed that the *in-situ* thickness monitor not only provided the same quality of information given by SWR, but also offered detailed information about initial etch rate transients and sudden changes in the etch rate that was not available from SWR.

The results of this research indicate that this system is beneficial for both off-line and on-line analysis. Off-line, the system can be used to provide film thickness and etch rate information for

run-to-run control of reactive ion etch processes. This was demonstrated using poly Si. Such information can be used to eliminate some of the measurements that are presently made *ex-situ*. This information can also be used as a diagnostic for the average and instantaneous etch rate for input to run-to-run controllers. The results of the experiments also indicate possibilities for on-line uses for the system as well. Many of the methods used to determine etch rate are not capable of providing predictive endpoint detection. However, this system determines the film etch rate from the real-time remaining film thickness. This remaining film thickness can be used for predictive endpoint detection. Furthermore, the system can be used on-line to provide real-time etch rates for use as input to systems for RTC of plasma etching.

Future research is directed at providing on-line use of the system. This work will entail providing remaining film thickness and etch rate during the etch. We must find adequate methods by which we can communicate the computed thicknesses and/or etch rates to the control platform. Work is on-going in this area. We will also demonstrate the utility of the system in on-line applications by using the information provided for process development, for monitoring the etch of patterned wafers, for providing input data for RTC etch rate controllers, and to aid in the development of optical models that better quantify surface roughness.

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LIST OF FIGURES

Figure 1: Block diagram of the SR system on our Applied 8300 Hexode RIE.

Figure 2: Comparison of experimental sample reflectance data from *in-situ* SR system to experimental sample reflectance data from *ex-situ* SR system. The sample was $\approx$ 600 nm thermally grown, wet oxide / Si substrate.

Figure 3: Comparison of experimental sample reflectance data from *in-situ* SR system to theoretical sample reflectance determined using a least squares regression routine. The sample was $\approx$ 600 nm thermally grown, wet oxide / Si substrate.

Figure 4: Comparison of experimental sample reflectance data from *in-situ* SR system to the sets of theoretical sample reflectance determined using the PO and the OPO models in the least squares regression routine. The PO model assumes quasi-ideal films of poly Si / SiO_2 / Si substrate. The OPO model assumes quasi-ideal films of SiO_2 overlayer / poly Si / SiO_2 / Si substrate.

Figure 5: AFM and BEMA results showing a) a pre-etch poly Si sample where the AFM indicates an rms roughness of 15.4 nm and b) a post-etch poly Si sample where the AFM indicates an rms roughness of 10.4 nm.

Figure 6: Comparison of experimental sample reflectance data from *in-situ* SR system to the theoretical sample reflectance determined using BEMA in the least squares regression routine.

Figure 7: Comparison of etch rate determined using data from the SR system to etch rate determined from HeNe (at a wavelength of 632.8 nm) SWR data using the P-V subtraction method.

Figure 8: Plot of real-time, *in-situ* poly Si film thickness and etch rate. Plot shows an etch with an intentional oxygen leak injected over the second half of the etch (500 to 1000 sec etch).

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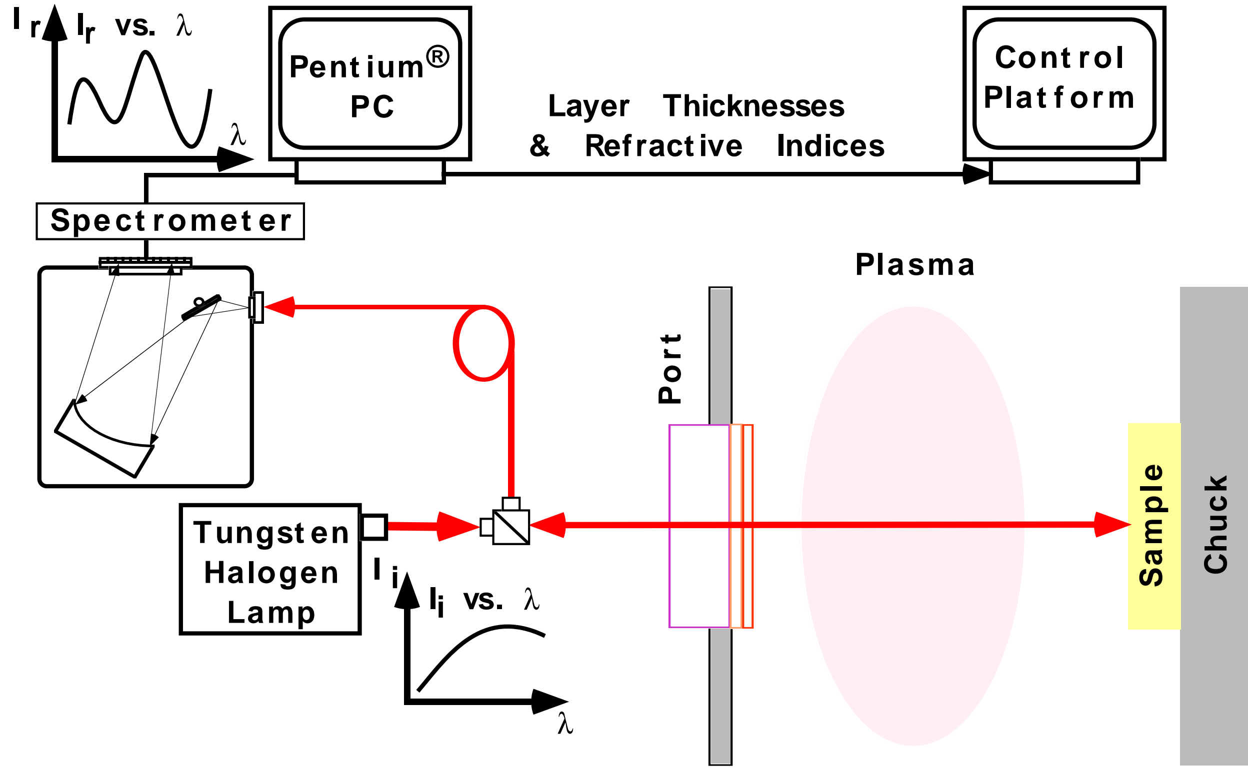
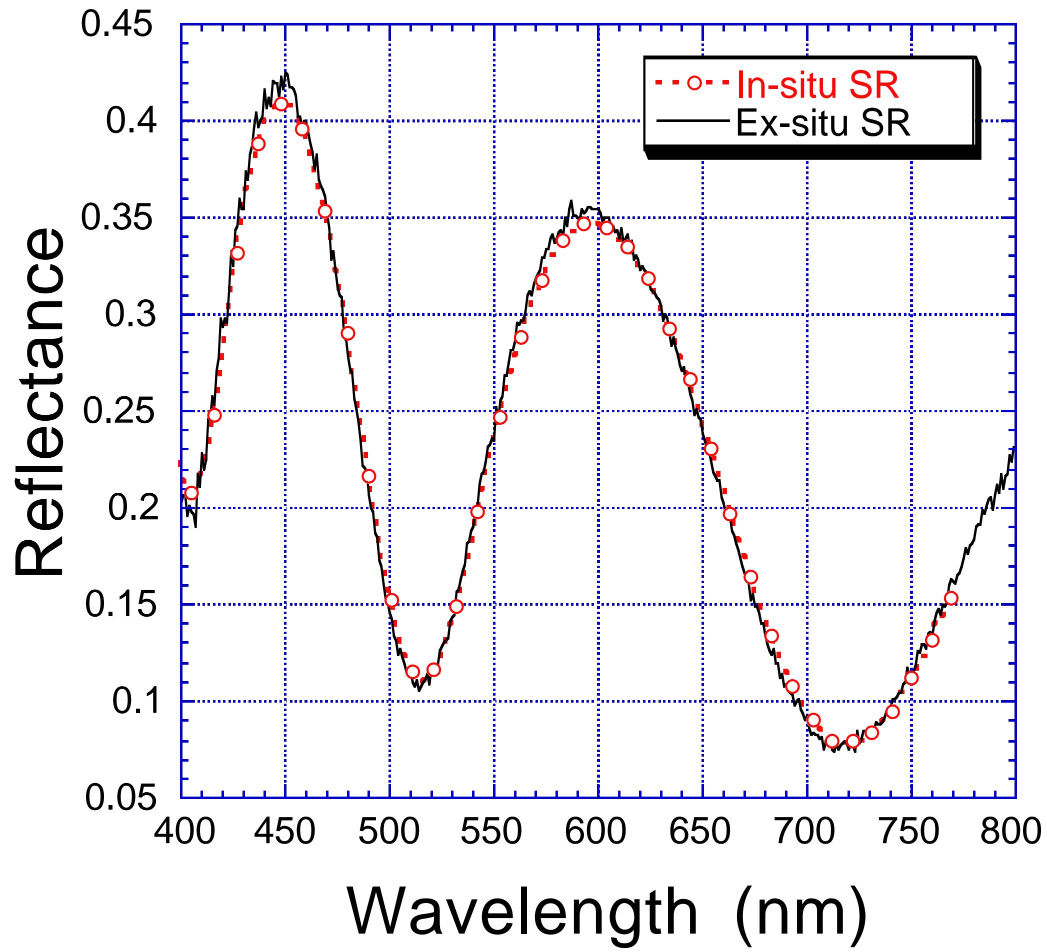
Table 1: Comparison of poly Si film thicknesses and compositions found using both *in-situ* SR and *ex-situ* SE. The sample started as $\approx$ 600 nm poly Si / $\approx$ 30 nm SiO_2 / Si substrate. To get these results, the poly Si was etched with intermittent stops to allow characterization of the film with *ex-situ* SE measurements.

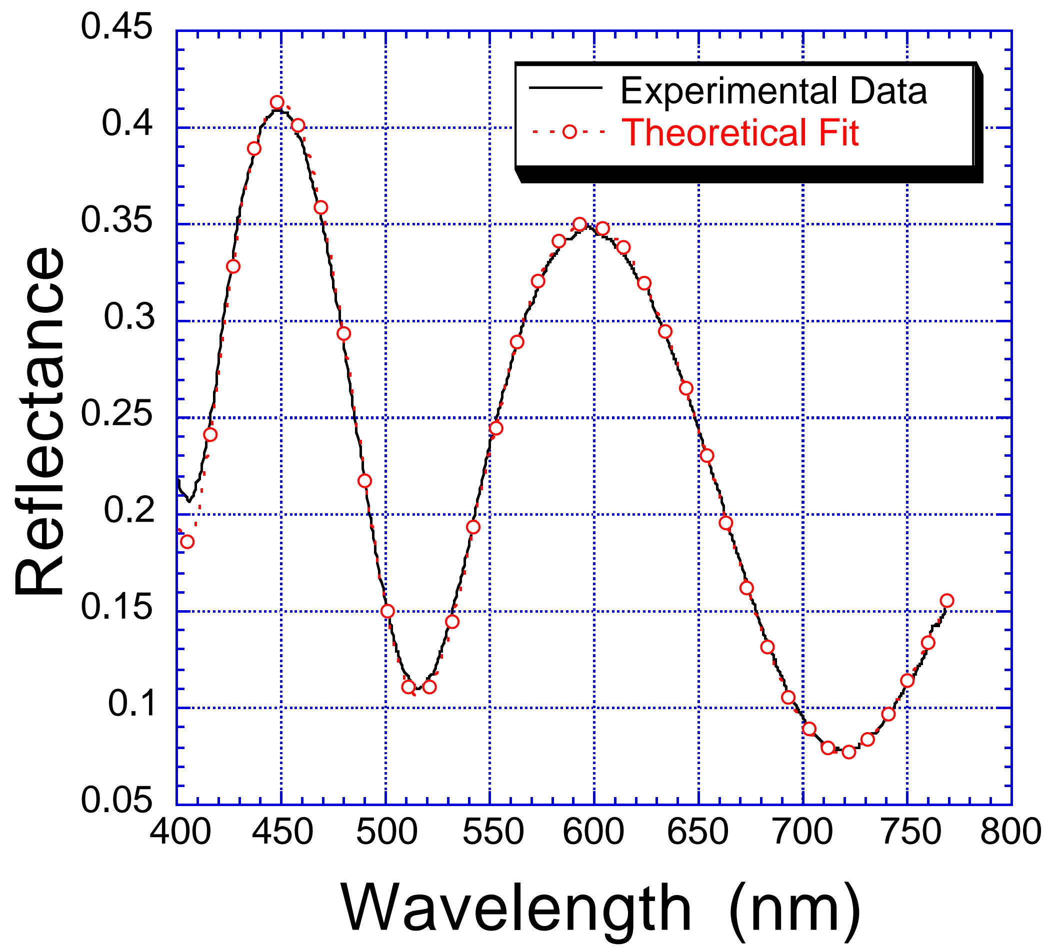
Table 2: Comparison of the accuracy and computation times associated with using fewer data points in the regression routine employed.

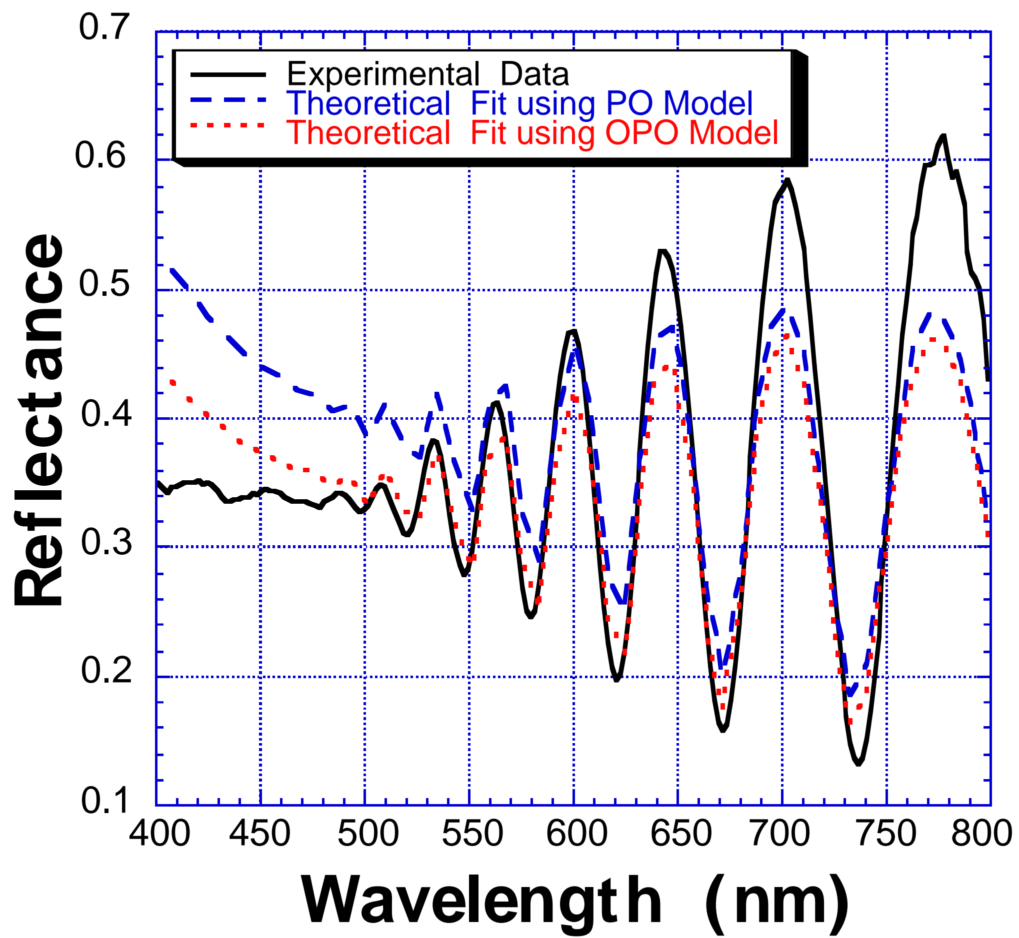


I r
Ir vs. λ
λ
Pentium®
PC
Layer Thicknesses
& Refractive Indices
Control
Platform
Spectrometer
Plasma
Port
Sample
Chuck
Tungsten
Halogen
Lamp
I i
Ii vs. λ
λ



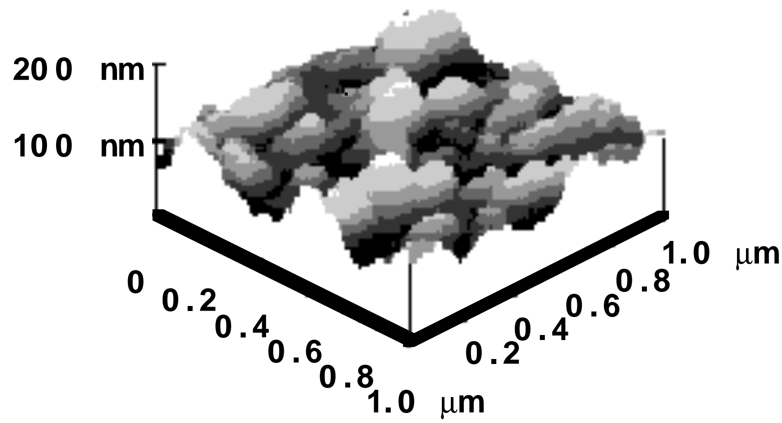
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Reflectance
400
450
500
550
600
650
700
750
800
Wavelength (nm)
In-situ SR
Ex-situ SR


0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Reflectance
400
450
500
550
600
650
700
750
800
Wavelength (nm)
Experimental Data
Theoretical Fit



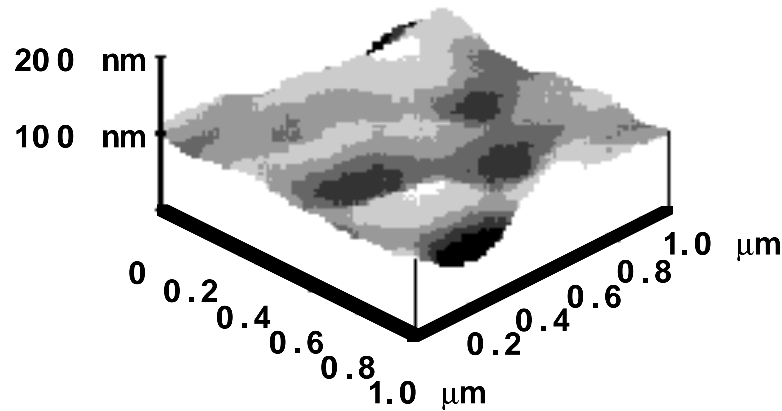
Experimental Data
Theoretical Fit using PO Model
Theoretical Fit using OPO Model
Reflectance
Wavelength (nm)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
400
450
500
550
600
650
700
750
800

a) Pre - Etch

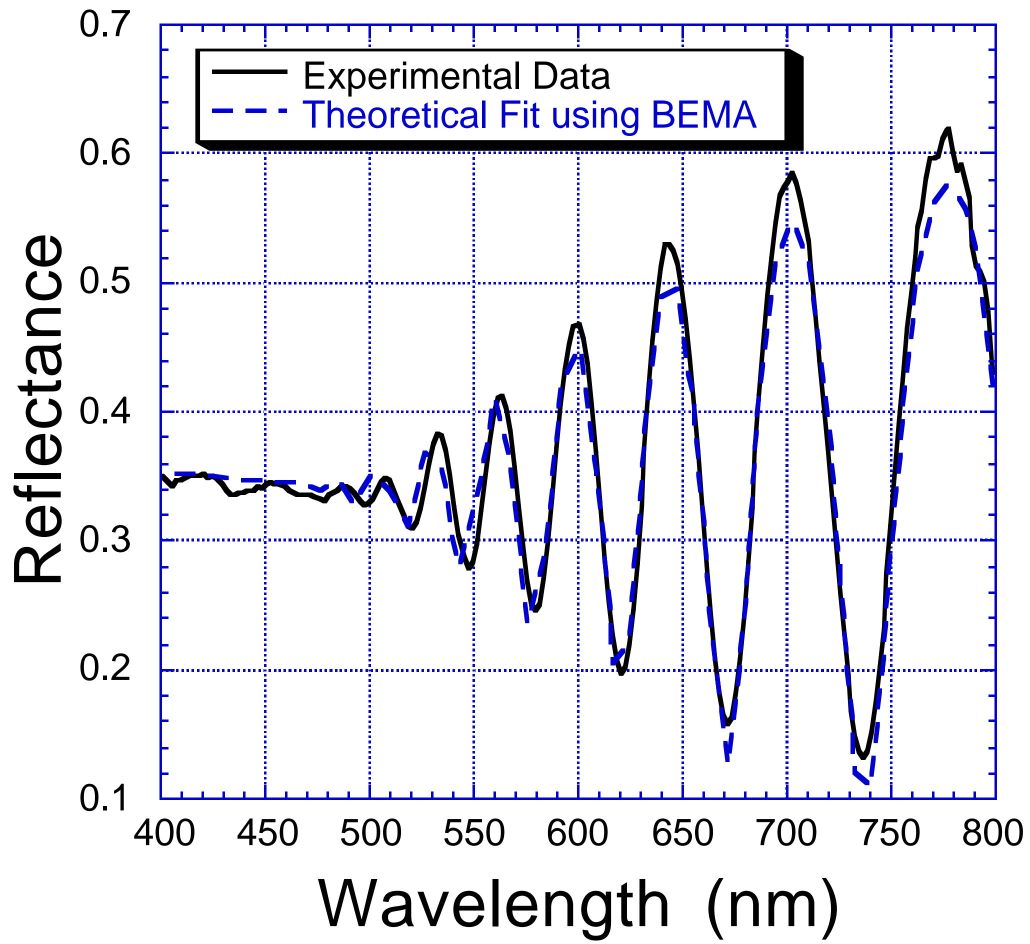


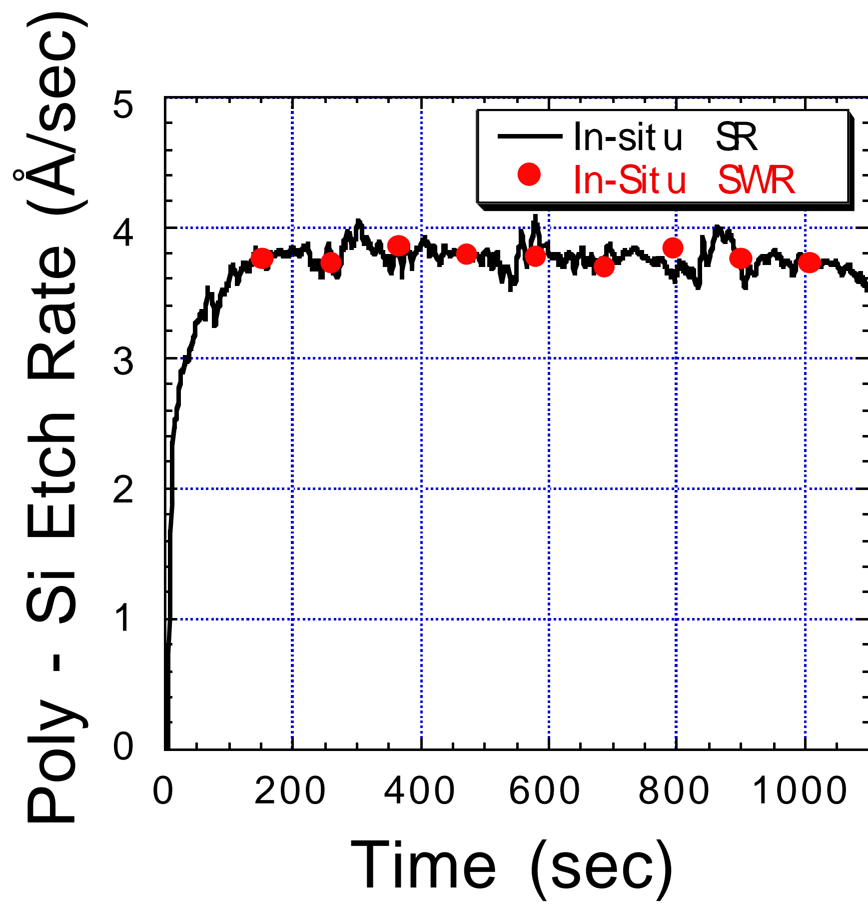
Surface Roughness 47.3% c:Si, 3.9% a:Si, 48.8% Void 17.1 nm
Bulk Poly Si Layer 91.1% c:Si, 8.9% a:Si 793.58 nm
Oxide 40.0 nm
Si Substrate Semi - Infinite

b) Post - Etch

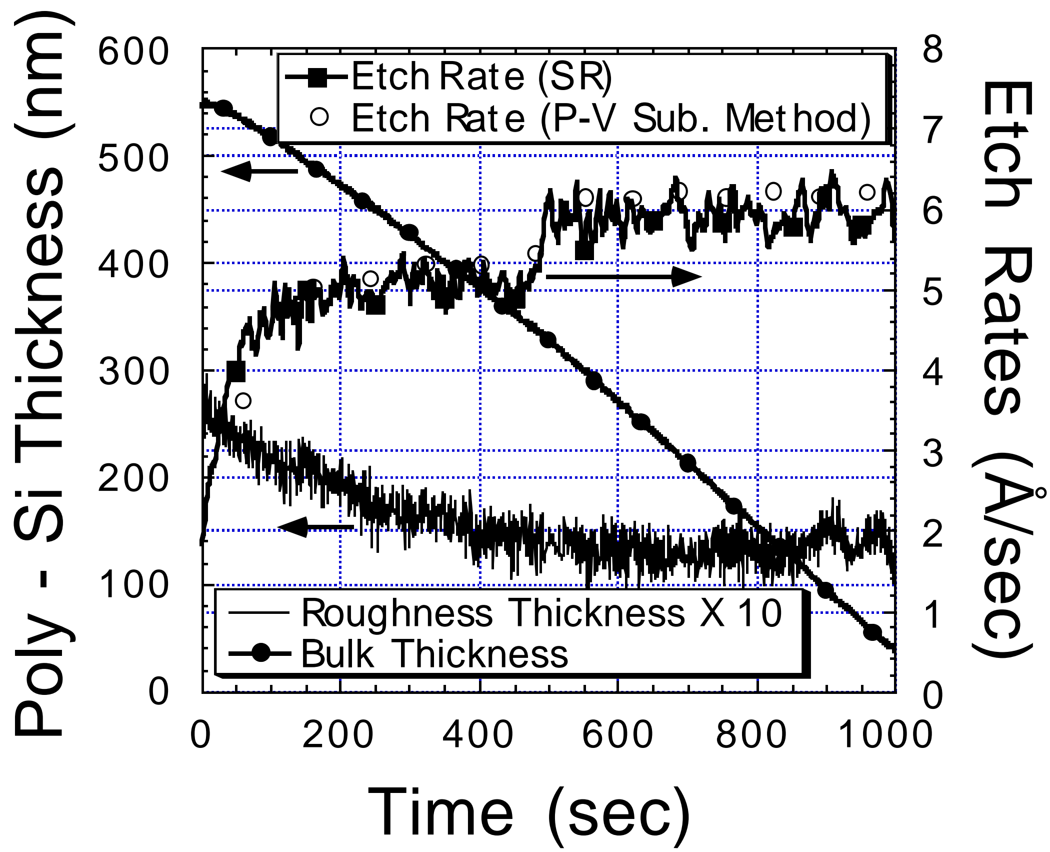


Surface Roughness 47.3% c:Si, 3.9% a:Si, 48.8% Void 14.4 nm
Bulk Poly Si Layer 91.1% c:Si, 8.9% a:Si 351.12 nm
Oxide 40.0 nm
Si Substrate Semi - Infinite


0.7
0.6
0.5
0.4
0.3
0.2
0.1
Reflectance
400
450
500
550
600
650
700
750
800
Wavelength (nm)
Experimental Data
Theoretical Fit using BEMA



Poly - Si Etch Rate (Å/sec)
Time (sec)
In-situ SR
In-Situ SWR
0
1
2
3
4
5
0
200
400
600
800
1000



Etch Rate (SR)
Etch Rate (P-V Sub. Method)
Roughness Thickness X 10
Bulk Thickness
Poly - Si Thickness (nm)
Etch Rates (Å/sec)
Time (sec)
600
500
400
300
200
100
0
8
7
6
5
4
3
2
1
0
0
200
400
600
800
1000

Meas #	Material	SR	SE	| SR - SE |
1	Poly Roughness	408 +/- 3 Å 83% a-Si, 15% c-Si, 2% Void	374 +/- 2 Å 65% a-Si, 23% c-Si, 12% Void	
	Poly Bulk	5518 +/- 4 Å 7% a-Si, 93% c-Si	5597 +/- 2 Å 9% a-Si, 91% c-Si	
	Poly Total	5926 +/- 7 Å	5971 +/- 4 Å	45 Å
2	Poly Roughness	127 +/- 2 Å 61% a-Si, 36% c-Si, 3% Void	170 +/- 2 Å 33% a-Si, 55% c-Si, 12% Void	
	Poly Bulk	4488 +/- 1 Å 10% a-Si, 90% c-Si	4477 +/- 3 Å 9% a-Si, 91% c-Si	
	Poly Total	4615 +/- 3 Å	4647 +/- 5 Å	32 Å
3	Poly Roughness	206 +/- 2 Å 22% a-Si, 75% c-Si, 3% Void	163 +/- 17 Å 30% a-Si, 63% c-Si, 7% Void	
	Poly Bulk	3251 +/- 3 Å 21% a-Si, 79% c-Si	3344 +/- 16 Å 18% a-Si, 82% c-Si	
	Poly Total	3457 +/- 5 Å	3507 +/- 33 Å	50 Å
4	Poly Roughness	127 +/- 2 Å 11% a-Si, 87% c-Si, 2% Void	147 +/- 1 Å 31% a-Si, 62% c-Si, 7% Void	
	Poly Bulk	2357 +/- 3 Å 13% a-Si, 87% c-Si	2395 +/- 1 Å 12% a-Si, 82% c-Si	
	Poly Total	2484 +/- 5 Å	2542 +/- 2 Å	58 Å
5	Poly Roughness	125 +/- 2 Å 29% a-Si, 69% c-Si, 2% Void	115 +/- 1 Å 34% a-Si, 61% c-Si, 5% Void	
	Poly Bulk	1428 +/- 3 Å 33% a-Si, 67% c-Si	1378 +/- 1 Å 16% a-Si, 84% c-Si	
	Poly Total	1553 +/- 5 Å	1493 +/- 2 Å	60 Å

Number of Points used in fit	Average time for analysis (ms)	Bulk Polysilicon Thickness (Å)	Roughness Thickness (Å)	Combined Thickness (Å)	% Change (compared to 200 Point fit)
200	351	7926.00	170.50	8096.50	0.00 %
100	165	7921.60	151.60	8073.20	- 0.288 %
50	93	7923.30	165.20	8088.50	- 0.099 %
25	55	7930.00	164.00	8094.00	- 0.031 %