

Optical Emission Spectroscopy for Plasma Etch Endpoint Detection

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Abstract- Optical Emission Spectroscopy was implemented for determining the endpoint of film removal through detecting shifts in plasma emission intensity during an etch process. A preliminary procedure has been developed for detecting endpoint with the factory nitride and oxide etch processes at RIT. In conjunction with the development of an endpoint process, the minimum sensitivity for the OES endpoint system was investigated. A minimum of 0.5% exposed nitride versus resist area is required for accurately detecting endpoint on Nitride, while 5% open area is necessary for Oxide.

1. INTRODUCTION

Through real time recording of plasma intensity over the full spectrum of optical emission, slight shifts in reacted chemistry can be detected [1]. Singling out specific peaks can indicate the completed etch through a desired film [2]. OES endpoint involves analysis of the light spectrum emitted from a plasma during an etch process. Plasma reactions result in discrete emission peaks dependent on the reactant chemistry in the chamber. Isolating emission peaks and recording the intensity over time allows for detection of a change of state in the process chamber. This change of state corresponds to the completion of an etch process.

Typical OES systems involve two main components, a CCD array for recording emission intensity and a computer system for recording the data and computing an endpoint signal. A fiber optic probe is used to gather light at the window of a plasma chamber, and transmit that light to a CCD array calibrated to record light intensity over the full spectrum of optical emission. Data is acquired through specialized computer software that enables real time statistical analysis and feedback, and archival for statistical modeling.

The sensitivity of OES for EP detection relies on detecting changes in the etch chemistry. Finding the minimum sensitivity is crucial as every new generation of semiconductor design involves geometry shrinks [7],[8]. As the geometry shrinks, the total amount of open area on

a wafer is reduced, and thus the amount of reactant chemistry in the plasma etch chamber is reduced. EP signals rely on separating the reactant chemistry from background noise for determining when the etch is completed. Current systems are detecting shifts on the order of 2% of the background signal. A portion of this experiment will involve determining if there is a limit to OES sensitivity. By varying the amount of open area on a wafer from a full 100% exposed film down to 0.1% open area, the sensitivity of OES will be investigated. Data will be collected based on a fixed etch time for purpose of analysis. Based on the recorded data, a best-fit model will be generated for determining EP. This model will then be tested, and successful EP detection will be determined through verification of etch completion.

Material requirements for the experiment were limited to available equipment. The challenge is to implement an endpoint system at RIT using the available tools consisting of an OES probe capable of detecting wavelengths between 200-1050 nm, and software from Ocean Optics for data acquisition. The computer system was a basic PC running Windows operating system, with an 800 mhz processor.

2. SUMMARY OF PROJECT OBJECTIVES

A. Implement plasma etch endpoint at RIT

Available equipment was utilized to implement a data acquisition system for detecting endpoint during a plasma etch process.

B. Develop operating procedure for using OES system

In order for the system to be utilized beyond this project, an operating procedure must be developed. This will include determining the simplest approach for implementing endpoint detection using real time OES measurements and developing a user manual for future operation.

C. Investigate OES sensitivity

Determine the minimum amount of etch area that can be exposed, and still detect endpoint. This will be accomplished by varying the percentage of exposed film that is to be etched.

D. Develop statistical model for analyzing endpoint signal

The final goal of the project is to develop a new model for endpoint detection. Current endpoint processes involve complex statistical models for sorting through the enormous amount of recorded data to determine endpoint. For use at RIT, the simplest functional model would be ideal.

3. OES SETUP

The basic OES system is comprised of three main components. First is the computer, which is a basic PC that is fast enough to calculate and store the enormous amount of data generated by the OES systems. The heart of the OES system is comprised of a fiber optic probe for transferring the optical signal to the CCD array, which measures the emission intensity. An Ocean Optics OES system was used with a spectral sensitivity from 190nm to 1050 nm. The final component of the OES system is the software itself. Ocean Optics OOIBase32 program was used for data acquisition. Once data was recorded, it was transferred to Excel for analysis.

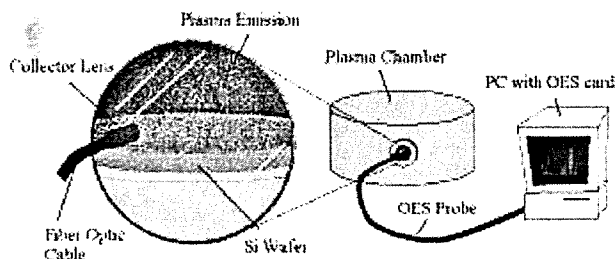


Fig.1. Diagram of OES process elements

The process for acquiring an emission spectrum as was done in this experiment is illustrated in figure 1. A fiber optic probe was temporarily mounted at the viewing window on the side of the plasma chamber. The probe was positioned to record emission near the center of the chamber, about an inch above the wafer. A collector lens at the end of the probe helped to boost the strength of the signal, as well as to average the emission signal for better data consistency. The gathered light is then sent to the CCD array via the fiber optic probe, which then measures the relative light intensity over the full spectrum of optical emission in fraction of nanometer increments. The software then sums the intensity data over a user defined

time interval. The integrated data is available for real time viewing over the full spectrum. Details of the data acquisition options for the OOIBase32 software package are available in the operating manual for the system.

After initial test measurements were made with the system, it was evident that the wavelength measurements were not accurate. The systems data acquisition was checked with the Ocean Optics Hg-1, mercury lamp emission calibration sample. It was discovered that the system had been improperly calibrated. The problem was that the software records data as pixel information and then applies a linear regression to label the wavelength axis on the plot. Changing the spectrometer channel settings back to the factory default calibration corrected the issue. Rechecking the Mercury sample indicated the wavelength was accurately displayed within ± 0.1 nm accuracy.

4. SENSITIVITY INVESTIGATION

Endpoint detection simply involves the detection of shifts in plasma emission intensity over time. Plasma emission is however a complex function of the reaction between etchant species and the film to be etched. In addition there is emission from uncontrolled processes in the chamber such as the resist on the wafer. As less film is exposed to the chamber versus the amount of resist covering the wafer, the signal to noise ratio is greatly reduced. The minimum sensitivity for EP detection can then be described by the smallest percentage of the wafer with exposed film to be etched versus resist that yields a detectable EP signal.

A. Preparation

Before the experiment could begin, a process had to be developed for creating a resist pattern with an exact percentage of open area. The goal was to develop a resist coat, expose, and develop process for creating open areas on the wafer totaling 5%, 1%, 0.5%, and 0.1%. First the actual dimensions of the wafer were measured to determine the total wafer surface area. The total wafer surface area was calculated to be 77.82 cm^2 , or $7.78\text{E}9 \text{ } \mu\text{m}^2$.

The next step was to pick an existing mask to use. The CMOS test mask via and metal2 layers were chosen due to the uniformity of features present on the mask. The features on the mask were equal sized squares with similar spacing between features. The total open area generated at the wafer surface was calculated as $716,000 \text{ } \mu\text{m}^2$ for the via mask and $846,000 \text{ } \mu\text{m}^2$ for the metal2 mask. Using these numbers, the total amount of repeated exposures necessary to generate the desired percentage open area was calculated as follows.

% Open Area	Mask	# Repeated Exp
0.10%	Via	11
0.50%	Metal 2	46
1%	Metal 2	92
5%	Open	13

Table 1. Mask used for percent area

Once the desired film was deposited on each wafer, the standard RIT resist process was used for patterning. Wafers were coated with positive resist using the 4" Wafertac. A program had to be written for exposing each desired percent open area using the GCA g-line stepper. Once exposed, wafers were developed using the standard process and then each wafer was carefully inspected for accurate pattern generation and desired film thickness. Wafers at this point were ready for the etch experiment.

B. Oxide Etch Experiment

Preparation for the oxide etch involved growing a thermal SiO₂ layer, and patterning the wafers with the appropriate percent open area. 18 cleaned wafers labeled EP-01 thru EP-18 were loaded into the automated oxide furnace, using recipe 350 for 5000Å of oxide growth. Following is a plot of the resulting oxide thickness for each wafer.

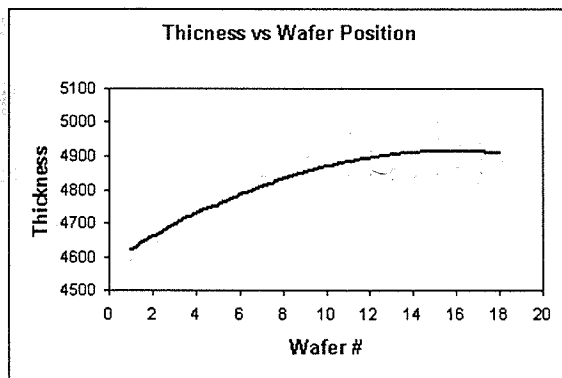


Fig. 2. Oxide thickness variation by wafer

Next, resist was deposited and patterned for each wafer with the following open area parameters.

Wafer #	% Open Area
1-3, 18	0.10%
4-6	0.50%
7-9, 17	1%
10-12, 16	5%
13-15	100%

Table 2. Percent open area by wafer

Before running an experimental wafer, a blanket resist test wafer was run to determine the effectiveness of the OES system for detecting an EP signal. The default resist etch recipe was used with no modifications. Data acquisition was set to integrate over 500 msec intervals with a 50 msec delay. Observing the full spectrum 4 min 19 sec into the etch, there were 4 major peaks that dropped significantly. The etch was manually stopped and the wafer was analyzed for residual resist. With the wafer cleared, it was determined that EP was detected for the resist process.

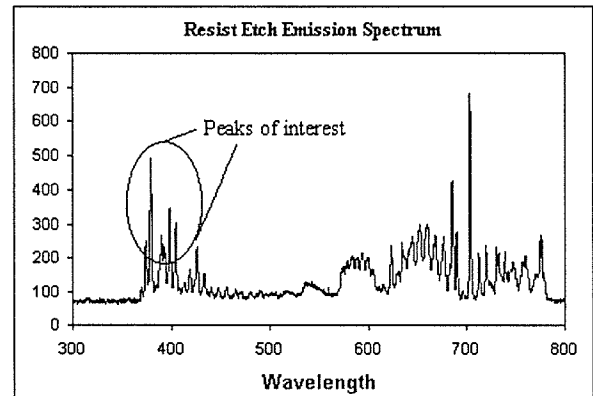


Fig. 3. Resist sample emission spectrum

Chamber 3 on the DryTek Quad RIE etch tool was used for the oxide etch. Prior to running the etch, the chamber was seasoned for 10 minutes. Seasoning the DryTek involves running the chamber in the chemistry to be used for the etch process in order to purge the chamber and gas lines of any impurities. The OES system was run during the seasoning to acquire data for the emission of the etch chemistry alone. The main etch parameters for the factory oxide etch are as follows.

Chemistry: 30 sccm CF₄, 60 sccm CHF₃, 60 sccm Ar
 Pressure: 200 mT
 Power: 300 watts

The initial power was only 100 watts yielding an etch rate of only 200Å/min. Increasing the power to 300 watts achieved an etch rate of about 550Å/min.

The final preparation before running the experiment was to determine the effectiveness of the etch process for the varied experimental parameters. The etch rate of the resist in the oxide etch chemistry was determined to be 200

A/min. This was checked to be sure that the increased power did not cause the resist to be removed completely during the etch. After correcting calibration issues that arose during the preliminary work, and adding a larger hard drive to the OES computer to account for the massive data files being generated, it was time for the full processing run.

Preliminary etch work with test wafers EP-16 and EP-17 demonstrated that the smaller open area wafers required a longer etch to fully clear the oxide film. This was an interesting effect, considering the wafers with smaller percent open areas also had a thinner oxide film from deposition. The etch time was compensated accordingly and all wafers were run sequentially in the etch chamber.

Wafer	Open Area	Etch Time
13-15	100%	10 min
10-12	5%	12 min
7-9	1%	12 min
4-6	0.5%	12:50 min
1-3	0.1%	13:20 min

Table 3

During the etch process, there were four major peaks from 400 nm to 500 nm that were most noticeably affected by the change in open area. Upon completion of data acquisition, a CD was burned with all information for later analysis.

C. Nitride Etch Experiment

After completion of the oxide etch process, all wafers were stripped of resist. The remaining oxide film was removed in buffered HF, and the bare Si wafers were cleaned using the RCA clean. With the cleaned wafers, a pad oxide was grown prior to nitride deposition for the purpose of stress relief and as an etch stop layer. An average of 650Å of oxide was grown on each wafer using the Kooi recipe in the automated furnace.

Next was the deposition of nitride in the LPCVD furnace. The RIT standard 2.5:1 nitride recipe was used with a deposition rate of approximately 40 Å/min. Following deposition the nitride thickness was measured across every wafer. The resulting thickness was an average of 1000Å of nitride with good wafer-to-wafer uniformity.

Once measured, the wafers were prepared with the appropriate open area, using the same procedure as the oxide etch experiment. After development, all wafers were checked and prepared for the etch process.

The factory nitride etch recipe was verified prior to running the experiment. The following etch parameters were used.

Chemistry: SF₆
Pressure: 300 mT

Power: 280 watts

The etch rate of nitride was tested for a blanket film and was determined to be 660 Å/min. Checking the etch rate of the smaller percentage open area verified that the etch rate was slower, therefore the etch time was compensated for each subsequent level of open area. The etch times that were chosen are shown in table 4.

Wafer	Open Area	Etch Time
13-15	100%	2:20 min
10-12	5%	2:30 min
7-9	1%	2:30 min
4-6	0.5%	2:45 min
1-3	0.1%	2:45 min

Table 4

After verifying that the etch parameters would work for all experimental settings, the process was started. The etch was run in chamber 2 of the DryTek Quad. Prior to beginning the experimental wafers, the chamber was seasoned with the nitride etch chemistry for the required ten minutes. Data was recording with the OES system for comparison of the raw etch chemistry with the actual etch run data. All wafers were sequentially etched with the data being archived to a CD upon completion of the experiment.

5. DATA ANALYSIS

Gathering all of the experimental data illustrated one of the complications associated with using OES for EP detection. The total amount of data recorded from etching 36 wafers combined with all the preliminary data exceeded 2 GB. To make matters worse, the Ocean Optics software package stores the data in individual text files for each time interval. For the oxide data, this exceeds 1300 text files per wafer etched. In order to analyze the data, there was a definite need to compress the information into a single file.

A. Extracting the data

Using Excel, a macro was written for extracting the data from the individual text files and importing them into a single Excel workbook. All text files for a single wafer run were placed in a temporary folder. From here each text file is opened and the emission intensity data is cut and pasted into a single workbook. Each column in the new workbook contains the emission data for a specific time increment. After writing and debugging the macro, all of the data was sorted and extracted into separate Excel files for each wafer run. The extracted data was then archived to 5 zip disks and analysis could begin.

B. Determining a basic EP model

From previous experience with industrial EP systems, the simplest model was chosen and implemented to verify the data. First, two peaks are chosen to ratio over the full etch time. The goal is to find a ratio of peaks that yields a consistent wafer-to-wafer signal indicating EP. It is important to note that when looking at the peaks, the data is given in fraction of a nm increments. Singling out a single fraction may result in poor results, as there are many slight variations in the signal over time and across wafers. Instead a band pass of 30 data points is summed in order to get a more consistent signal. In essence the data is integrated over a short interval to enhance the uniformity of the EP signal.

Choosing individual wavelengths is a combination of known chemistry and visible changes in the spectrum. Observing data collected during the etch process, significant peaks can be pinpointed. The nitride etch data was the first set looked at due to the relatively simpler emission profile.

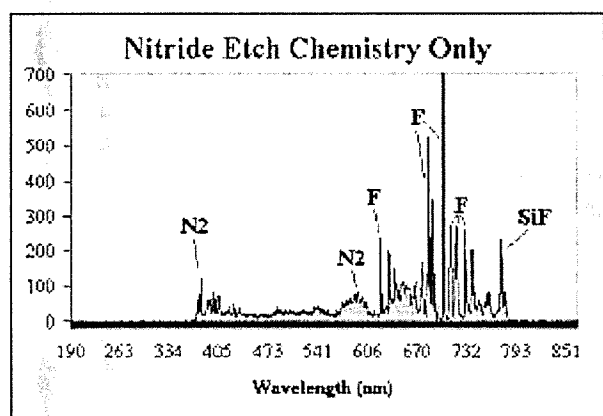


Fig. 4. Spectral emission during nitride seasoning

Figure 4 illustrates the basic nitride etch chemistry while seasoning the chamber. The wafer with blanket nitride was then compared with the data for seasoning the chamber.

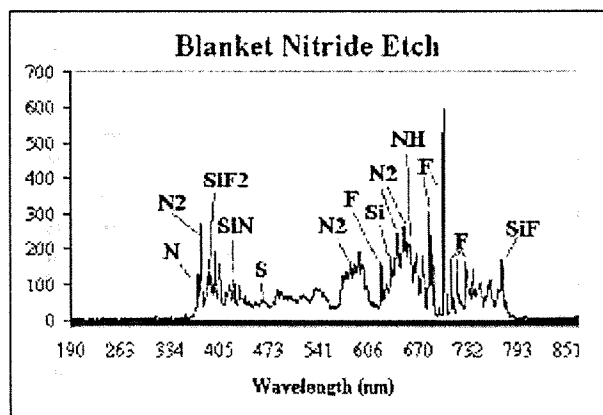


Fig. 5. Spectral emission during nitride etch

Observing the significant differences between the blanket nitride etch and the seasoning data, a few areas of interest were looked at in detail. Segregating these portions of the data out, peaks were compared during the full length of the etch process to determine which peaks showed the most significant variation, indicating EP. Analysis demonstrated the most significant ratio between the N₂ peak at 385 nm versus the fluorine peak at 685 nm.

The process was repeated for the oxide data.

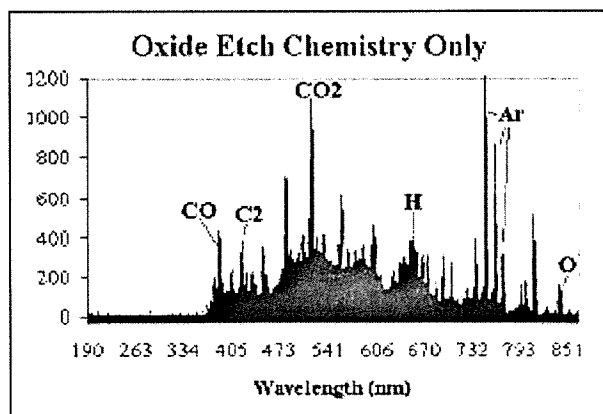


Fig. 6. Spectral emission during oxide seasoning

The oxide seasoning data shown in figure 6 illustrates the complexity of the emission profile relative to the nitride data.

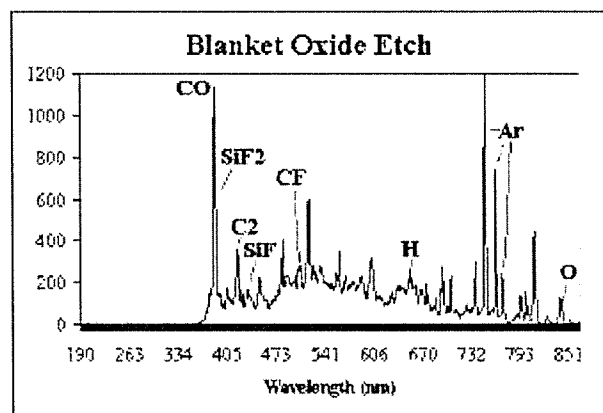


Fig. 7. Spectral emission during oxide etch

Comparing the seasoning data with the blanket oxide etch data demonstrates a significant difference at 380 nm. The peak at this location is a combination of CO and SiF₂ emissions. Examining all the data was complicated by the amount of noise that was present in the signal. The best results that were obtainable were with a ratio of the CO peak at 380 nm with an argon peak at 750 nm.

6. RESULTS

The major accomplishment was successful implementation of endpoint detection at RIT. The result is a functioning OES system for post processing endpoint detection. The available software package has the capability of displaying peak ratios in real time, however, true real time endpoint detection will require additional software. In addition a series of Excel macros were written for analyzing the precise time of etch completion, which will allow feedback for etch rate, and amount of over etch. Use of the system will provide students with a valuable introduction to endpoint detection as used in industry today.

Results for the sensitivity investigation were obtained through use of the peak ratios that were determined in the full analysis of the data. EP traces were then plotted for each wafer in the investigation and were comprised of only the ratio between peaks. For determining the actual EP time, the slope of the plot was analyzed versus time in order to generate a more sensitive model. The time was chosen as the point where the rate of change in the slope was reduced to a set value.

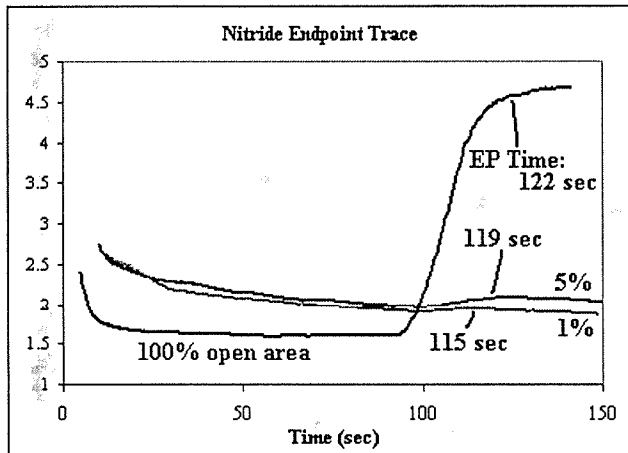


Fig. 8. Nitride EP trace for 100% to 1% open area

Figure 8 illustrates the incredible signal that was generated by the full nitride wafer reaching endpoint. Further analysis of the data provides insight into details of the process chamber, including etch uniformity.

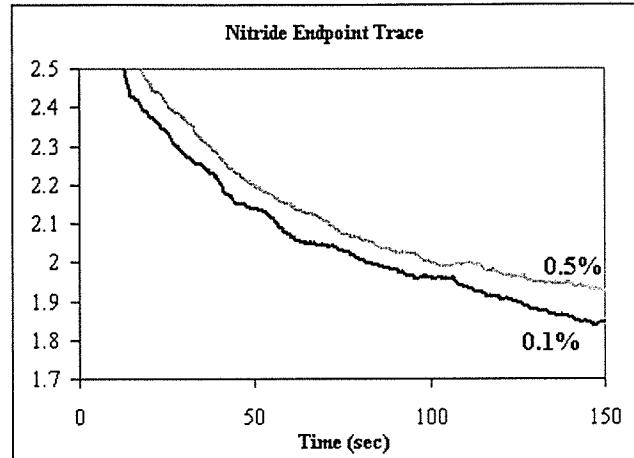


Fig. 9. Nitride EP trace for 0.5% and 0.1% open area

Comparing the EP signals in figure 8 with those of the 0.5% and 0.1% open area wafers demonstrates the diminished sensitivity of the OES system as the open area is reduced. The height of the EP transition is directly related to the amount of open area. From this knowledge, the minimum sensitivity can be determined if the level of background noise is known. A minimum signal to noise ratio of 2:1 is recommended for consistent EP detection.

The oxide etch signal had a much greater amount of background noise. The result was an EP trace as follows in figure 10.

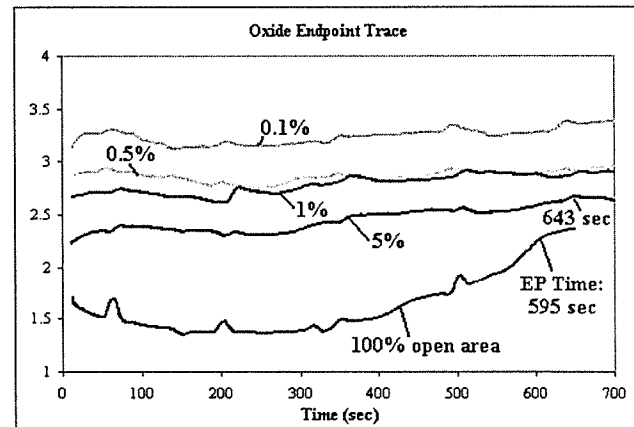


Fig. 10. Oxide EP trace for 100% to 0.1% open area

Analyzing the trace indicated an accurate signal with a minimum of 5% open area. The complexity of the etch chemistry contributed to the degradation of the signal. It is also possible that what was detected as noise could have been due to a fault in one of the gas lines that feeds the oxide etch chemistry, or in the plasma chamber itself. However, constraints surrounding this experiment eliminated the option of investigating these possibilities. Further analysis of the oxide data could indicate a better set of peak ratios.

7. CONCLUSION

Post processing etch endpoint has been successfully implemented at RIT. In addition, experimental data illustrated the difficulty in detecting EP with small amounts of open area on the wafer. Nitride etch endpoint has been demonstrated with a maximum sensitivity of 0.5% exposed nitride. Oxide endpoint capabilities have so far been proven down to 5% open area. Real time EP detection is possible with the current setup through careful manual operation of the OES system. Automated EP will only be possible with the addition of new OES software and system upgrades to the plasma etch chamber.

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Keith R. Miller was born in small town north of Los Angels, California January 11, 1977. At the end of this paragraph, he will have completed his Bachelor of Science degree in Microelectronic Engineering from RIT. His career will be starting with Advanced Micro Devices in Sunnyvale, California, working as a rotational engineer in the Submicron Development Center.