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Use of In-Situ Optical Emission Spectroscopy for Leak Fault Detection and Classification in Plasma Etching

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***Abstract*—*In-situ* optical emission spectroscopy (OES) is employed for leak detection in plasma etching system. A misprocessing is reported for significantly reduced silicon etch rate with chlorine gas, and OES is used as a supplementary sensor to analyze the gas phase species that reside in the process chamber. Potential cause of misprocessing reaches to chamber O-ring wear out, MFC leaks, and/or leak at gas delivery line, and experiments are performed to funnel down the potential of the cause. While monitoring the plasma chemistry of the process chamber using OES, the emission trace for nitrogen species is observed at the chlorine gas supply. No trace of nitrogen species is found in other than chlorine gas supply, and we found that the amount of chlorine gas is slightly fluctuating. We successfully found the root cause of the reported misprocessing which may jeopardize the quality of thin film processing. Based on a quantitative analysis of the amount of nitrogen observed in the chamber, we conclude that the source of the leak is the fitting of the chlorine mass flow controller with the amount of around 2-5 sccm.**

***Index Terms*—Leak detection, fault detection and classification, optical emission spectroscopy**

I. INTRODUCTION

Dry etching that uses low temperature plasmas in low pressure regime (< 50 mTorr) process is one of the most crucial processes in semiconductor geometry patterning, and high density plasma in much lower pressure regime (< 10 mTorr) is recommended for improved etch result and higher throughput [1]. Lower pressure can provide increased mean free path that yields a more anisotropic etch response. However, even a small chamber leak will introduce undesired gas species to form either a non-volatile product with dissociated gas on the etch surface, or additional material on wafer surface to act as an etch stop. In other words, the leak degrades the gas purity and perturbs the plasma process. Therefore, the detection of leak on its onset, not only increases the process throughput, but also decreases the time required for finding the source of a process fault.

One of the early inventions for leak detection was based on a procedural method by comparing the etch rates of two layered materials of spin-on-glass (SOG) and a consecutive Plasma Enhanced Chemical Vapor Deposition (PECVD) oxide in plasma etching [2]. Li and Yen reported enhanced airborne particle contaminant control with gas leaking detection system (GLDS), which consists of two open-path Fourier transform infrared (OP-FTIR) spectrometers [3]. Recently, a similar technique for gas leak detection with optical emission spectroscopy (OES) was proposed by comparing OES with other diagnostic tools; a voltage meter and add-on pressure gauge [4]. The result showed that OES was more sensitive to detect gas leakage during plasma discharge operation than the other diagnostic tools.

However, it is generally understood that changes in chamber pressure caused by chamber/gas leak vary ion and radical concentrations. Thus, the observed optical emission intensity may not be quantitatively meaningful. When additional gas molecules from a leak are

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introduced to the process chamber, they affect the magnitude of the existing optical emission spectrum. For this reason, quantitative modeling and analysis of OES data needs to be carefully considered. More recently, in-situ chamber leak detection using OES data was presented [5]. Neural network modeling that normalizes the OES data alleviates the concerns of quantitative modeling, and a Cumulative Sum (CUSUM) control chart increased sensitivity of the detected leak.

In this paper, OES is employed for in-situ chamber chemistry monitoring to detect anomalies during etching. Based on the analysis of plasma chemistry in silicon etching with chlorine, three experimental runs (with each injecting one type of gas at a time) were performed to check for undesirable gas species residing in the process chamber. Another set of three experimental runs followed to quantify the amount of gas additionally introduced to the chamber by the leak. Chemical actinometry by *Ar* was applied to quantify the observed optical emission intensity of plasma [6]. In the first experiment, we observed additional nitrogen gas species when only chlorine was introduced, and no trace of nitrogen was found in the case of argon. The second set of experiments revealed additionally introduced argon from the chlorine line leak. This actinometric evaluation was done by the observation of optical emission intensities at 584.5 nm and 643.5 nm that correspond to nitrogen. From the results, we inferred that the observed nitrogen originated from air caused by a leak in the chlorine line. Section 2 provides problem definition and describes the experimental setup. Experimental results and the analysis are presented in Section 3, followed by conclusions in Section 4.

II. EXPERIMENTAL APPARATUS

The engineering problem addressed in this study was lower silicon etch rate in an inductively coupled plasma (ICP) etcher that is located in Pettit Microelectronics Research at the Georgia Institute of Technology. A schematic diagram of the employed system is presented in Fig. 1. The system consists of 10 gas lines and silicon etching uses Cl_2 while the back side of wafer is cooled with *He*. In this etcher, materials allowed in the process chamber are III/V materials, SiO_2, and Si_3N_4. No anomaly in material processing was reported, except in shallow

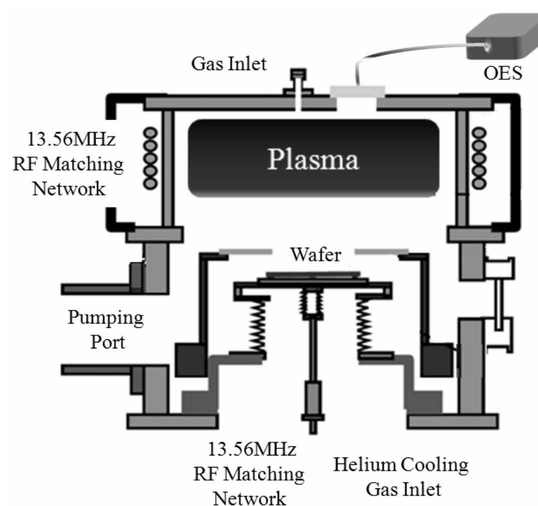

Fig. 1. A schematic diagram of the employed ICP-RIE system with OES sensor setup.

trench isolation (STI) using chlorine. A significantly reduced silicon etch rate (from 250 nm/min to 10 nm/min) with unusual wafer color was reported by users, and the fault was caused by the introduction of nitrogen in the chamber during etching. The unexpected introduction of nitrogen forms a silicon nitride non-volatile by-product, and this material may act as an etch stop or etch inhibitor during the process. However, finding the source of nitrogen introduction is a challenge as the many possibilities include a chamber leak from O-rings, mass flow controller (MFC) mis-calibration, gas delivery line leaks, and etc [7].

If proper process and/or equipment models are available, classification of the detected fault can be accomplished by employing equipment engineering data. However, the availability of such data in a research environment is limited [8]. To assist in identifying the root cause of the fault in this case, we employed optical emission spectroscopy (OES) as an in-situ sensor for plasma process monitoring. OES is the most well-known noninvasive plasma monitoring technique, and it has been utilized for a diverse set of practical applications, including endpoint detection, process monitoring, process modeling, and equipment malfunction diagnosis [9]. The Sensor Cluster Manager (SCM) OES data acquisition software was used in this study to enhance the real-time data acquisition and off-line data analysis.

When chamber pressure is lower than a few tens of mTorr, the potential across the discharge increases and

Table 1. A list of experimental set for qualitative and quantitative analysis

Run #	Gas Flow (sccm)			Description
	N_2	Cl_2	Ar	
1	5	0	0	Reference for N_2
2	0	20	0	Reference for Cl_2
3	0	0	5	Reference for Ar
4	5	0	5	Normalized analysis of N_2
5	0	20	5	Normalized analysis of Cl_2
6	5	20	5	Normalized analysis of N_2

the sheath potential becomes larger. At very low pressure of a few mTorr, low reactant density increases the mean free path of reactant particles and ion energy increases, allowing the chemical sputtering of chlorine. Dissociated chlorine radicals form $SiCl_x$, and this substance is absorbed into the silicon wafer and subsequently desorbed as a volatile product by acquiring thermal energy from plasma reaction. In this study, *N*, *Cl*, and *Ar* related OES peaks were monitored.

We initially investigated three types of potential faults: (1) a chamber leak induced by O-ring wear out; (2) a N_2 MFC malfunction; and (3) a gas delivery line leak. Our assumption was that the first scenario would result in consistent detection of nitrogen despite of the injection of no argon containing gas. The second scenario could be explained by either an inconsistent or non-scalable level of argon intensity with/without *Ar* injection. Any suspicious result other than these first two may be related to the fitting of an MFC or corrosion of a gas delivery line. More complex fault classification and propagation scenarios can be considered, but this study focused on the gas chemistry. The two sets of split experiments listed in Table 1 were considered to test various hypotheses for fault classification. The first three runs were for performed for testing the first hypothesis by comparing Run #2 and Run #3. On the other hand, a comparison of Run #1 and Run #2 and Run #4 and Run #5 will provide evidence regarding the second hypothesis. While the experiments were performed, the remaining process parameters were set to be at nominal values (Top RF power 300 W, Bottom RF Power 70 W, and Pressure 3 mTorr) of the baseline process for two minutes of etch time.

III. Result and Discussion

Experimental runs of Run #1 ~ #3 were performed to test the hypothesis of chamber leak due to O-ring wear out. The underlying assumption is that such event allows nitrogen to be detected regardless of the choice of process gas injected because nitrogen is more than 78 % of air. In Run #1, OES data was collected when 5 sccm of nitrogen was injected into the chamber. The result showed very similar OES data pattern as previously experienced with nitrogen plasma, but it is difficult to say with certainty that the observed OES spectrum stems solely from the injected nitrogen. Run #2 was performed with 20 sccm of chlorine, and the acquired OES data showed some nitrogen related peaks along with high intensity levels for chlorine peaks. However, the next experiment with 5 sccm of *Ar* injection did not show any nitrogen in the chamber in Run #3. Based on an intuitive analysis of this first set of experiments, it cannot be concluded that the chamber leak resulted from broken vacuum seal. Fig. 2 shows the acquired spectra from the runs of Run #1-3.

Fig. 3(a) shows the OES spectrum for Run #4 with 5 sccm of N_2 and *Ar*. The wavelengths for peaks that

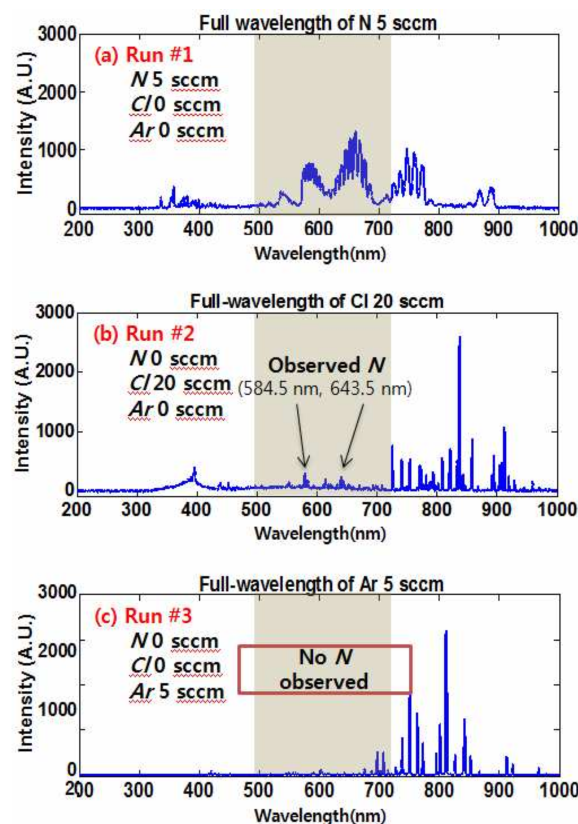

Fig. 2. OES data acquired from the runs of Run #1 to Run #3 (Single gas injection).

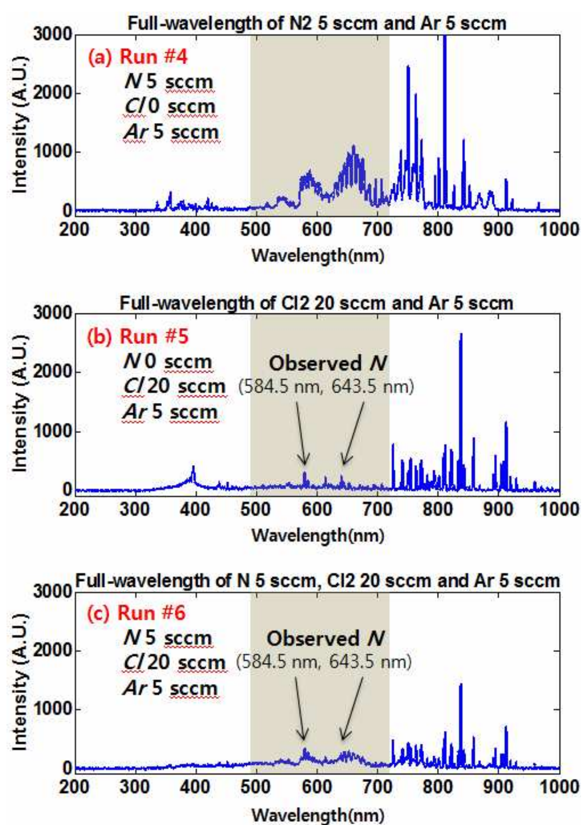

Fig. 3. OES data acquired from Run #4 and Run #5 (with 5 sccm of *Ar*).

correspond to the gas species in the chamber were expected to be the linear combination of Run #1 and Run #3 in Fig. 2, but the observed optical emission intensities are not such a simple combination. The intensities of nitrogen presented in Fig. 2(a) and Fig. 3(a) remained in comparable the magnitude of the scale, but the intensity of argon in Fig. 3(a) is about 5 times lower than that in Fig. 2(c). It appears that nitrogen was detected when chlorine was injected, and it is suspected that the primary cause was either an MFC or gas line leak. However, no definitive conclusions can be drawn with regard to an MFC malfunction (or unstable MFC operation) from these results.

Comparing Fig. 3(a) and (b), some amount of nitrogen is observed in Run #5, which had no nitrogen introduced. This is also observed in Fig. 2(a) and (b) for Run #1 and Run #2. The lower optical emission intensity is not because of decreased photon emission, but because of the total photon count at the CCD photo detector. Therefore, directly intensity amount comparison of OES data in each run is not reliable. For this reason, a direct

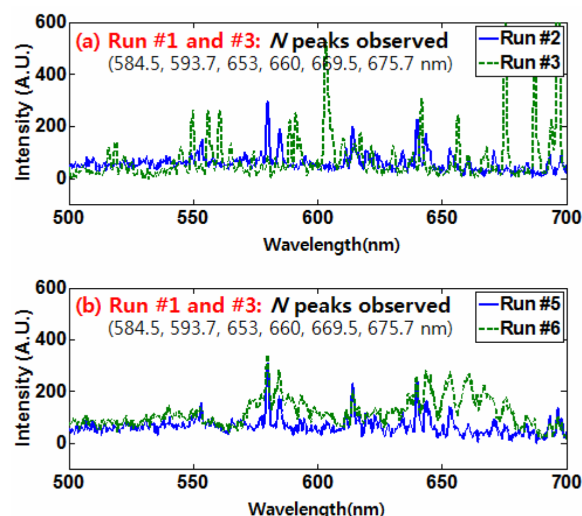

Fig. 4. Expanded Scope of nitrogen detected region of 500 nm ~ 700 nm.

comparison of OES data in its way should be cautiously considered, and actinometric analysis using a non-volatile gas species is recommended for further quantitative analysis [6]. Before employing chemical actinometry, we magnified the wavelength regions where nitrogen was detected by a simultaneous comparison of Run #2 and Run #3 and Run #5 and Run #6, respectively as shown in Fig. 4(a) and (b). It is noteworthy that the optical emission intensity corresponding to argon does not change much with augmented process gases because argon is gas whose reaction with other gases is extremely limited. Since the amount of *Ar* is strictly controlled, the observed *Ar* intensity can serve as a measure of the intensity of other gas species.

Employing *Ar* actinometry, a quantitative investigation of the amount of nitrogen in the chamber during this series of experiments was performed. The nitrogen peak intensities at 584.5 and 643.5 nm were divided by that of *Ar* peak wavelength at 750 nm. The time traces for the nitrogen peaks for Run #4 (*Ar*: 5 sccm and N_2: 5 sccm) that appear in Fig. 5(a) and (b) show very stable and consistent levels, and no evidence of a N_2 MFC malfunction is observed. However, the selected nitrogen peaks in both Run #5 and Run #6, with 20 sccm of chlorine injected, showed noticeable fluctuations. This confirms that additional nitrogen was introduced when the chlorine was injected. A primary suspect for the fluctuation of the nitrogen peaks is an undesired and uncontrolled amount of nitrogen injection from the gas

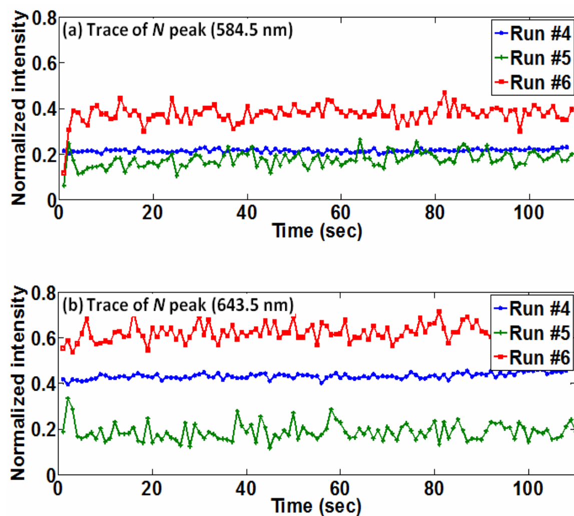

Fig. 5. *Ar* actinometry applied time trace of nitrogen peaks at 584.5 nm and 643.5 nm.

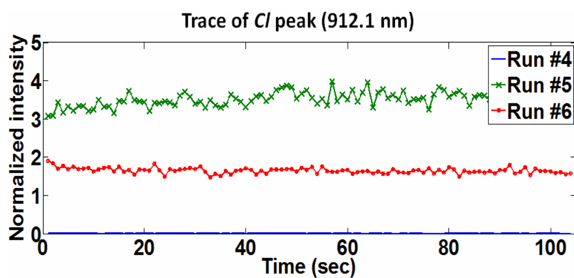

Fig. 6. Trace of the chlorine peak at 912 nm in Run #5 and Run #6.

line/fitting. A Cl_2 MFC malfunction that caused plasma perturbation with uncontrolled amount of gas injection could be another possibility.

To evaluate this possibility of a Cl_2 MFC malfunction, the optical emission intensity of chlorine observed at 912.1 nm from Run #4 and Run #5 was investigated. Run #5 in Fig. 6 shows some fluctuation in the peak for chlorine, and this may be interpreted as unstable MFC operation. However, when there is a leak at the fitting between MFC and gas cylinder, the actual amount of chlorine might also vary with the magnitude of the air leak at the fitting. In other words, the actual amount of chlorine injected into the chamber is smaller than what it is supposed to be because the Cl_2 MFC generates Cl_2 and air at 20 sccm. The amount of air is uncontrolled and dependent on the vacuum conditions. It is clearly possible that the fluctuation of nitrogen in Run #5 and Run #6 was mainly due to the uncontrolled of nitrogen injection from the gas line fitting, and this caused faulty silicon trench etching with chlorine. Thus, the second and third hypotheses were partially accepted, and replacement of the Cl_2 MFC solved the problem.

IV. CONCLUSIONS

This paper presented a method for leak detection in plasma etching using optical emission spectroscopy. A process fault with significantly reduced etch rate was reported for silicon etching with chlorine gas, and OES was as a tool for the leak detection and fault classification. During a series of experiments, an undesired nitrogen presence was identified from the OES data. Three hypotheses for the cause of the nitrogen - chamber O-ring wear out, MFC leaks, and gas delivery line leaks - were evaluated. It was concluded that the source of the leak was a fitting for the chlorine mass flow controller. This approach contributes to not only leak fault detection and classification with OES, but also suggests the general applicability of OES for real time plasma process monitoring for reliable and defect-free fabrication.

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