In-situ monitoring of etch uniformity using plasma emission interferometry

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(Received 5 February 2015; accepted 27 March 2015; published 9 April 2015)

A method for *in-situ* real-time monitoring of the etch uniformity of a dielectric film during plasma etching in a restricted geometry is reported. The method is based on interferometry using the natural plasma emission as the light source. Interference patterns are created by light reflections at the Brewster angle between the electrodes of parallel-plate capacitively coupled plasma reactors with small interelectrode gap. The method can be useful as a monitor for statistical process control. © *2015 American Vacuum Society*. [http://dx.doi.org/10.1116/1.4917168]

I. INTRODUCTION

Optical emission spectroscopy (OES) is a very common *in-situ* diagnostic in plasma processing. It is a noninvasive, inexpensive method that provides real time information. OES is often used for end-point detection, based on the enhancement of emission from etchant species, or reduction of emission from etching products, or change of surface reflectivity at end-point.[1–3] OES is sometimes used for chamber state monitoring, since certain peaks may reflect the presence of specific chamber walls coatings.

The thickness of a film before and after etching (and therefrom the etching rate) is usually measured *ex-situ* by, for example, ellipsometry. There are cases of incorporating an ellipsometer in a plasma chamber for *in-situ* film thickness (and etch rate) measurement,[4,5] but this is difficult to implement in industrial etchers.

Another technique for *in-situ* etch rate measurement is interferometry. Interference (Fig. 1) occurs when a light beam (1) is partially reflected (2) from the top of a transparent dielectric film (photoresist, PR, shown in Fig. 1) and partially refracted (3) through the film toward the substrate. Refracted light is reflected at the wafer–film interface, only to be refracted once more at the top surface of the film (3). The superposition of light beams (2) and (3) forms an interference pattern due to the difference of the optical paths of the two beams. When the difference of the optical paths ($\Delta s = 2nb - a$) is equal to an integer number of wavelengths ($\Delta s = N\lambda$), constructive interference and a maximum in intensity is observed. On the other hand, when $\Delta s = [N + (1/2)]\lambda$, destructive interference and a minimum in intensity is observed. The optical path difference for incidence angle (Θ), film thickness d, and refractive index n, is (assuming air or vacuum with $n = 1$ for the adjacent material)

$$\Delta s = 2d\sqrt{n^2 - \sin^2\Theta}\,. \quad (1)$$

Hence, if the refractive index of the film and the incidence angle are known, it is possible to calculate the film thickness, given an observed interference pattern. Because plasma emits light in all directions, an external light source (e.g., a low power He-Ne laser) is most often used to define angle Θ.[6] Alternatively, one can use simple optical arrangements to limit the light collection angle,[7] or use a CCD camera to monitor the whole wafer simultaneously.[8,9] An advantage of the latter is the possibility of obtaining the spatial distribution of film thickness across the wafer, i.e., uniformity. However, use of a CCD requires a relatively large window, and is impractical for industrial parallel-plate capacitively coupled plasma (CCP) reactors with small interelectrode spacing.

This work reports an *in-situ* real-time technique to monitor etch rate uniformity of a transparent film based on interferometry, using the natural plasma emission as the light

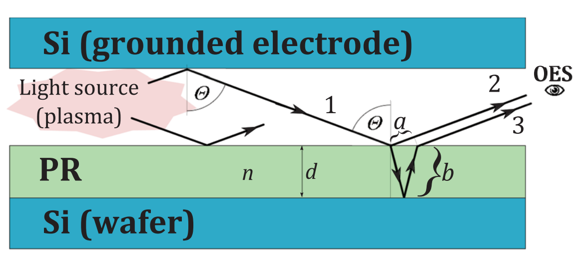

FIG. 1. (Color online) Schematic of interelectrode space (not to scale). Superposition of light beams (2) and (3) can form an interference pattern. The interference is more intense for light rays reflecting off the Si plate at the Brewster angle Θ.

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source. This technique requires only one view port on the chamber sidewall, and it is particularly suited for CCPs with small interelectrode gap.

II. EXPERIMENTAL SETUP

Measurements were performed in a Lam Research Flex E 300 mm capacitively coupled plasma etcher, shown schematically in Fig. 2. The upper grounded electrode was made of silicon. The wafer was held by an electrostatic chuck (ESC) on the lower powered electrode.

Power was supplied at two frequencies: 27 MHz to control mainly the plasma density, and 2 MHz to control the ion bombardment energy. The gap between the two electrodes could be varied between 17 and 34 mm. The interelectrode gap was typically set to 20 mm in the present work. The plasma was surrounded by quartz confinement rings. Plasma emission was observed through a fused quartz window on the chamber sidewall. An optical fiber was used to channel light to a spectrometer equipped with a linear CCD detector (Ocean Optics) with a wavelength range from 200 to 866 nm over 1023 pixels. In some experiments, a polarization filter was placed between the window and the optical fiber. Wafers of 300 mm-diameter with a 2000 nm-thick photoresist or a 600-nm thick silicon dioxide film were used. Etching of photoresist was performed under the following conditions: 120 mTorr, 750 W power at 27 MHz, 100 W power at 2 MHz, and 400 sccm N_2 + 400 sccm H_2 gas flow.

III. RESULTS

Oscillations observed in the plasma emission spectra (Fig. 3), while etching a 2000 nm-thick photoresist film, were initially attributed to plasma instabilities. The oscillations had a peak-to-peak amplitude of up to 2% of the average intensity. Further experiments showed that the oscillation period depended on the wavelength. Thus, modulation of the emission was not due to plasma instabilities.

The dependence of the oscillation period on wavelength is even more noticeable in Fig. 4, where intensity is normalized to the [−1, 1] interval, and plotted as a 2D graph with the wavelength on the y-axis, and etching time on the x-axis. By assuming that the etching rate is uniform and measuring the film thickness by ellipsometry at different times, it is possible to add a film thickness horizontal axis (see top of Fig. 4). Figures 3 and 4 also show that multiple wavelengths may be used to obtain interference patterns, provided that the film is transparent to these wavelengths.

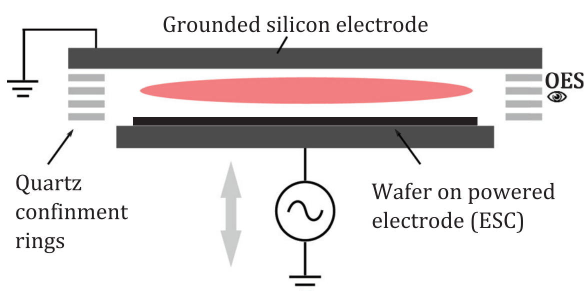

FIG. 2. (Color online) Schematic of the CCP chamber used for experimental work. Light was collected from a window on the side of the reactor. ESC, electrostatic chuck.

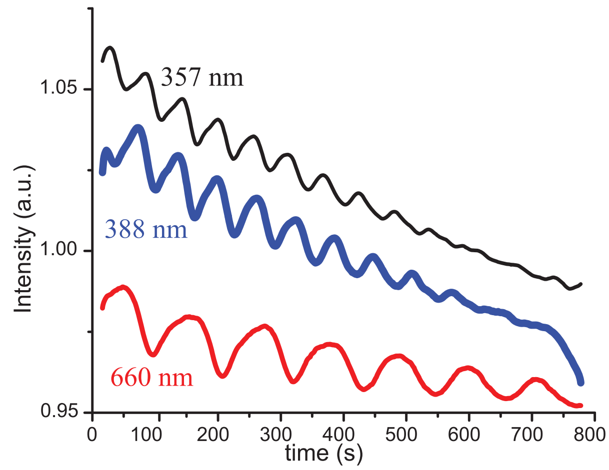

FIG. 3. (Color online) Oscillations in plasma emission during etching of photoresist. The oscillation period depends on the wavelength. The period is ~56 s for 357 nm, ~62 s for 388 nm, and ~110 s for 660 nm.

Similar interference patterns were observed when etching a 600 nm-thick oxide layer in the reactor shown in Fig. 2, as well as in a different CCP tool (TEL Vigus). However, no interference pattern was observed in a transformer coupled plasma (TCP) reactor in which the wafer was 10 cm away from the quartz window separating the radio frequency inductive coil from the plasma. Lastly, the interference pattern did not change significantly when varying the gap between the electrodes (up to 34 mm) of the CCP reactor of Fig. 2.

Figure 5 shows the impact of etching nonuniformity on the interference pattern. Photoresist (starting thickness 2000 nm) was etched using a N_2-H_2 based process, which was modified so as to generate three types of etching outcomes: uniform, center-fast, and edge-fast. This was achieved by using uniformity tuning features of the etching reactor, such as flowing additional gases (e.g., O_2 and/or

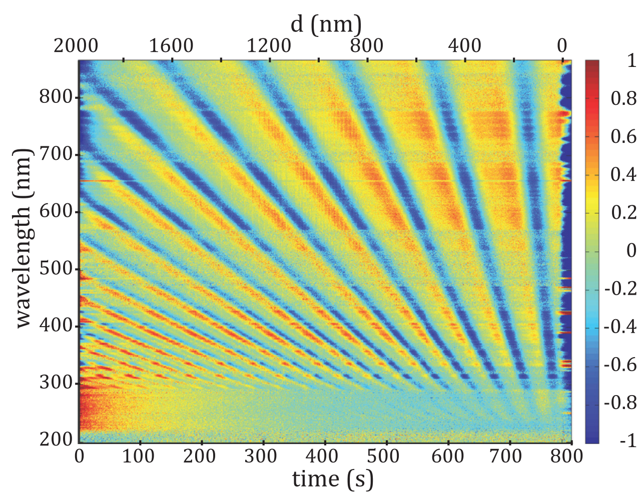

FIG. 4. (Color online) Variation of the OES intensity during etching of photoresist rescaled to the [−1, 1] interval for each wavelength. The thickness of the film, measured by ellipsometry, is shown on the upper horizontal axis.

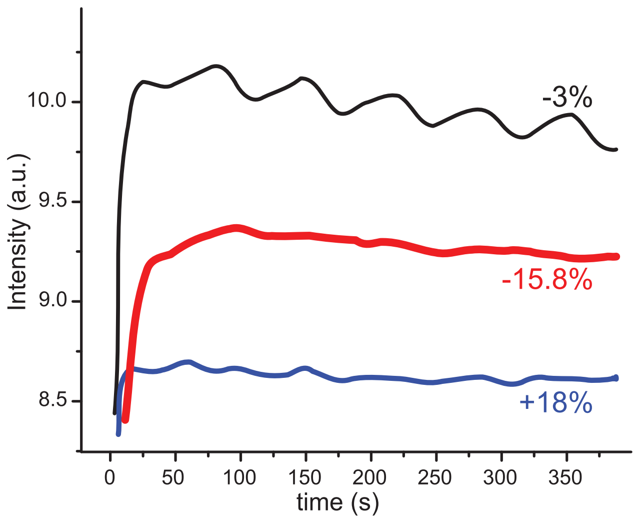

FIG. 5. (Color online) OES signals (387.6 nm) illustrating the impact of nonuniform etching (see Table I) on the interference pattern; (top line): −3.0% 3σ uniformity (center fast); (middle line): −15.8% 3σ uniformity (center fast), and (bottom line): +18% 3σ uniformity (edge fast). For high enough etching nonuniformity oscillations due to interference are suppressed.

CF_4) in the edge zone of the showerhead electrode, or adjusting the center-to-edge temperature difference of the dual-zone electrostatic chuck. For small etching nonuniformity (3%), oscillations are present from the start and persist until the end of etching (−3% line); such oscillations are suppressed almost from the start for rather large etching nonuniformity (−15.8% and +18% lines). Uniformity is defined as the standard deviation (3σ) from the average film thickness, with negative values when the wafer center etches faster, and positive values when the wafer edge etches faster. Table I shows the thickness difference Δd (center-edge) at the start and after 150 s of etching, for each of three recipes considered. For the 3% uniformity case, Δd remains within 15 nm until the end of etching. This is low enough for interference to occur and persist for the whole period. It takes a Δd of ≈50 nm (only 2.5% of the starting film thickness) to suppress the interference. Thus, for both the −15.8% and +18% uniformity cases, the oscillations are comparable to the noise level from the start of the process. This provides a new way to sense the presence of etching nonuniformity *in-situ*, by monitoring the oscillations of the interference pattern in real time. Although this method provides spatially averaged information, it can still be useful for statistical process control.

Light reflected from the wafer and the top electrode is mostly s-polarized, in contrast to that emitted by the plasma, which is mostly nonpolarized. Using polarization filters, the intensity of s- and p-polarized light was measured and is shown in Fig. 6. Only s-polarized light yields clear oscillations due to interference. Using polarization filters, the emission intensity oscillations could be enhanced or diminished. Polarization filters could also help separate light coming directly from the plasma (mostly non-polarized) and light reflected from the wafer and the top electrode (s-polarized). S-polarized light could be used for the proposed method and p-polarized signal could be used for more sensitive end-point detection.

TABLE I. Photoresist film thickness difference (center–edge) at the start and after 150 s etching. Three different recipes were implemented to vary the etch nonuniformity.

		Δd (center-edge) (nm)		
Wafer	3σ (%)	$t = 0$ s	$t = 150$ s	Average etch rate (nm/min)
1	3	15.1	4.7	159
2	−15.8	19.6	−121.8	138
3	+18	10.0	+284	216

IV. DISCUSSION

Based on the results shown above, it is safe to conclude that the observed oscillations in the OES signal are caused by interference of the plasma emitted light, and not by plasma oscillations. It appears that the (upper) electrode, in close proximity to the wafer, plays a pivotal role in the formation of the interference pattern.

In thin film interferometry, it is common to use a laser beam incident on the film at a desired angle. This configuration provides information about the film at the location where the laser beam interrogates the substrate. In CCD interferometry, each pixel of the camera images a certain region of the wafer, and provides information on the film averaged over that region. In the present method, the optical fiber collects light from the whole wafer, thus only average information across the wafer can be obtained. In fact, the optical fiber collects light coming directly from the plasma as well as light reflected by the film. The former light carries no information about the film; therefore, it contributes a constant background level (neglecting slow reactor/plasma drifts). The latter light may be (at least partially) polarized with a reflection coefficient dependent on the angle of incidence. When using the natural plasma emission as the light source, interference due to light reflected at a particular angle is canceled from interference at other angles. However, among all possible angles and polarizations, the s-

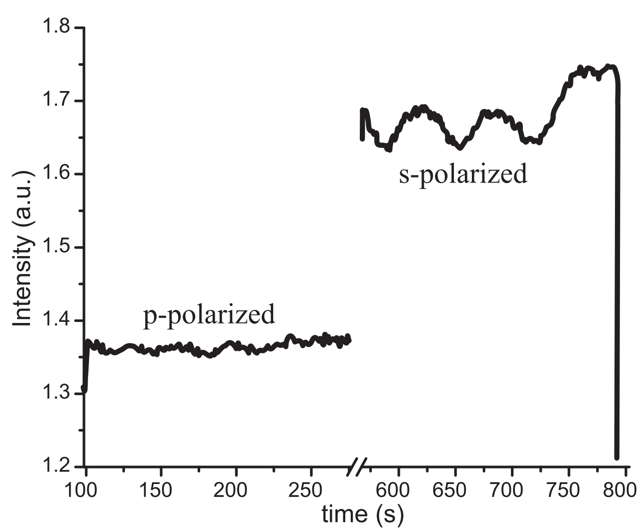

FIG. 6. OES signal for p- and s-polarized light (750 nm). Intensity oscillations are clearly visible only for the s-polarized light.

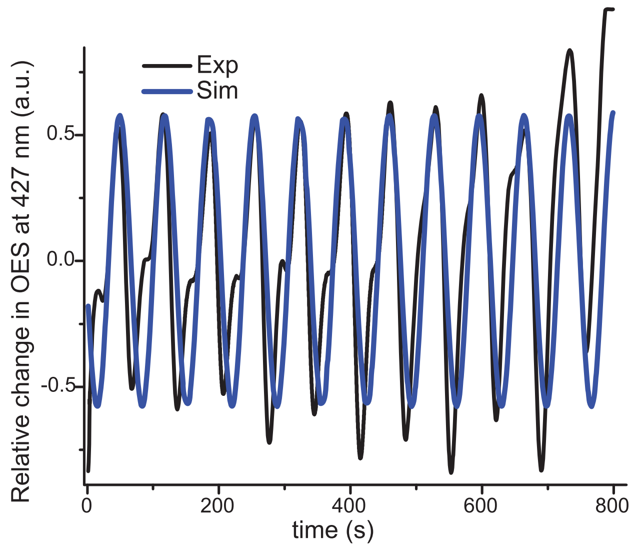

FIG. 7. (Color online) Comparison between simulation (thicker line) and experimental data (thinner line) of the interference at 427 nm during etching of a 2000-nm thick photoresist film.

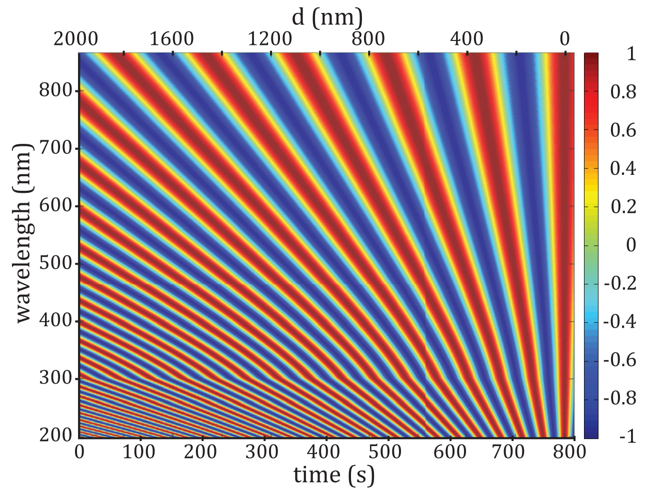

FIG. 8. (Color online) Simulation of interference pattern during etching of a 2000-nm thick photoresist film.

polarized light coming after reflection at the Brewster angle (~74° for silicon for the wavelengths of interest[10]) has higher coefficient of reflection than that of p-polarized light. Due to the small interelectrode spacing of the CCP reactor, light can bounce up to five times between the top (Si) electrode and the wafer. Multiple reflections serve to enhance the intensity of the s-polarized relative to the p-polarized light, resulting in a net interference pattern.

This explanation is corroborated by the fact that the interference pattern was found to depend only on the preferential angle, which in this case is determined by the material of the top electrode (the Brewster angle of silicon), and not by the interelectrode gap or the axial position of the optical fiber. The lack of interference pattern in the case of the TCP reactor is attributed to the large spacing between the wafer and the quartz window, preventing reflections of the light between these two plates, which would amplify the interference at the Brewster angle of quartz.

To test the Brewster angle enhancement hypothesis, results of a simulation were compared with experimental data (Figs. 7 and 8; the simulated results of Fig. 8 are to be compared to the experimental data of Fig. 4). In the simulation, the interference pattern was calculated using Eq. (1). The incidence angle used was 74° (the Brewster angle for Si). The wavelength dependent refractive index of the photoresist was obtained by independent spectroscopic ellipsometry measurements. The agreement between simulation and experimental data is reasonably good. The noticeable discrepancy in Fig. 7 may be due to the fact that the experimental interference signal was integrated over the whole wafer, with nonuniform photoresist thickness, while the simulation employed a uniform film thickness.

V. CONCLUSION

Optical emission from parallel plate capacitively coupled plasmas, with small interelectrode gap, during etching of dielectric films (photoresist, oxide), can yield periodic patterns due to interference. Multiple reflections at the Brewster angle between the top electrode and the wafer play a major role in forming the interference patterns. Such patterns can be used to monitor *in-situ* and in real-time the thickness of dielectric films and thus the etch rate and its uniformity. However, only a spatially averaged (over the whole wafer) measure can be obtained. A simple indicator of etching uniformity is the amplitude of light intensity oscillations. For otherwise identical conditions, the better the film thickness uniformity, the larger the amplitude of oscillations. Such monitoring of etch uniformity may be of interest in statistical process control.[11] The proposed method appears to be particularly suited for CCPs with small interelectrode gap. An additional advantage of the method is that no hardware modification is needed, provided a port exists on the reactor sidewall with optical access to the plasma.

ACKNOWLEDGMENTS

The authors would like to thank Shigeru Tahara and Laurent Souriau for help with the data acquisition. D.J.E. is grateful to NSF Grant No. IIP-1343387 for financial support.

[1]I. P. Herman, *Optical Diagnostics for Thin Film Processing* (Academic, San Diego, CA, 1996), p. 783.
[2]H. H. Yue, S. J. Qin, J. Wiseman, and A. Toprac, J. Vac. Sci. Technol., A **19**, 66 (2001).
[3]I. H. Hutchinson, *Principles of Plasma Diagnostics*, 2nd ed. (Cambridge University, New York, 2005), p. 460.
[4]H. L. Maynard, J. Vac. Sci. Technol., B **15**, 109 (1997).
[5]P. A. Heimann, J. Electrochem. Soc. **132**, 2003 (1985).
[6]D. Economou, E. Aydil, and G. Barna, Solid State Technol. **34**, 107 (1991).
[7]C. Johnson and D. Johnson, ECS Trans. **34**, 421 (2011).
[8]K. Wong, J. Vac. Sci. Technol., A **15**, 1403 (1997).
[9]S. V. Pendharkar, D. J. Resnick, W. J. Dauksher, K. D. Cummings, I. Tepermeister, and W. T. Conner, J. Vac. Sci. Technol., A **15**, 816 (1997).
[10]J. S. Wong and Y.-S. Yen, Appl. Spectrosc. **42**, 598 (1988).
[11]G. S. May and C. J. Spanos, *Fundamentals of Semiconductor Manufacturing and Process Control* (John Wiley & Sons, New York, 2006), p. 428.