Effect of capacitive coupling on inductively coupled fluorocarbon plasma processing

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This article describes results obtained using various plasma and surface diagnostics in a study of inductively coupled fluorocarbon plasmas in which the amount of capacitive coupling was systematically varied. It is found that the plasma density decreases while the electron temperature increases as the amount of capacitive coupling is increased at a constant source power level. The rate at which the dielectric coupling window is eroded is found to scale with both the peak-to-peak rf voltage and the ion current density, and the dielectric window erosion is found to influence the resulting plasma gas-phase chemistry. The changes in plasma electrical and chemical characteristics have a large impact on the surface processes occurring in inductively coupled fluorocarbon plasmas such as fluorocarbon deposition, fluorocarbon etching, SiO2 etching and Si etching. Further, we show how the selective SiO2-to-Si etch process changes with varying capacitive coupling. © 1999 American Vacuum Society. [S0734-2101(99)01806-0]

I. INTRODUCTION

In inductively coupled plasmas (ICP), the plasma generation is always to some extent due to capacitive coupling of rf power from the induction coil to the plasma. Capacitive coupling has been reported to result in the erosion of the dielectric window and several hardware optimizations, such as the introduction of a Faraday shield, the alteration of dielectric window shape, or the application of an axial magnetic field, have been suggested to minimize the capacitive coupling component. This article summarizes experimental results obtained in a study of inductively coupled fluorocarbon plasmas in which the amount of capacitive coupling was systematically controlled by varying the settings in the rf matching network, source power and operating pressure. We show how various plasma and surface diagnostics can be used to evaluate the effects of capacitive coupling. It is found that capacitive coupling influences the plasma electrical characteristics and plasma gas-phase chemistry, which affects the resulting etch rates. In particular, we show how the selective SiO2-to-Si etch process changes with varying capacitive coupling.

II. EXPERIMENTAL SETUP

The experiments summarized in this work were mainly performed in CHF3 and C2F6 inductively coupled discharges in the process window of 6–20 mTorr operating pressure, 10–40 sccm total gas flow, and 600–1400 W source power. The first part of the experimental results is shown for CHF3 only, while C2F6 discharges essentially showed the same trends. Where CHF3 and C2F6 show some variation results from both gases are presented.

For details on the inductively coupled plasma source employed in this study, we refer to earlier publications. A description of the rf matching network, which is used to control the capacitive to inductive coupling ratio, is provided. The various diagnostics used to monitor the plasma gas phase characteristics or the substrate conditions are also briefly discussed.

A. Network

Figure 1 schematically shows the induction coil and the matching network, which consists of three tunable capacitors (7–1000 pF) and an inductor with a fixed impedance (4 μH). This matching network configuration is different from the typical configuration where the coil terminating capacitor B in Fig. 1(a) is absent. In this work, we use the coil terminating capacitor to systematically vary the reactance between the center of the induction coil and ground potential. If the coil terminating reactance is increased for a given rf power level, it is found that the peak-to-peak rf voltage V2 measured at the center of the coil increases, while the peak-to-peak rf voltage V1 at the outer side of the coil decreases, see Fig. 1(b). Part of these rf voltages on the coil is not standing over the dielectric window and will be coupled to the plasma in a capacitive fashion. Since the plasma density is larger in the center part of the reactor than at the edge, the rf power (product of current and voltage) dissipated in capacitive fashion increases as the coil terminating reactance is increased. As the total rf power is kept at a constant level, the rf power used for inductive coupling decreases as the power consumed by capacitive coupling increases. The setting of the coil terminating capacitor can thus be used to control the ratio of capacitive to inductive power coupling from the coil to the plasma.

B. Diagnostics

The plasma gas phase is diagnosed using optical emission spectroscopy (OES) in the visible light range (250–850 nm)
using an EG&G Princeton Research Optical Emission setup. Mass spectrometry is employed to measure fluxes of species impacting on the surfaces exposed to the plasma. Two mass spectrometers were used in this work, namely a Leybold In-ficon Aggressive Gas Monitor (AGM) and a Balzers Plasma Process Monitor (PPM 422). A detailed description of these mass spectrometers is given by Li et al. Briefly, the AGM is a mass spectrometer that is operated in a mode where 70 eV electrons ionize neutral species entering the ionization chamber. The PPM 422, on the other hand, was operated in a non-post-ionization mode. In this mode, no dissociation of species occurs inside the mass spectrometer, which allows to directly measure positive ion fluxes from the plasma. Since the PPM 422 is equipped with an energy analyzer, one can also measure the energy of the ions entering the mass spectrometer. For certain experiments we used the PPM 422 in a mode where the ionization is switched on, but the ionization energy is varied between 10 and 30 eV. This mode allows to perform appearance mass spectrometry, which yields information on radical densities in the plasma gas phase.

Surface modifications due to plasma exposure and the rates at which etch and deposition processes take place on the surfaces of substrates placed in the center of a 125 mm silicon wafer, are monitored in real time using in situ He–Ne ellipsometry. The wafer is electrostatically clamped to a cooled chuck. The chuck is rf biased independently from the plasma generation.

III. RESULTS AND DISCUSSION

A. Plasma electrical characteristics

Figure 2 shows the ion current densities measured as a function of the coil terminating reactance measured in 40 sccm CHF₃ discharge at 1400 W source power and 6 mTorr operating pressure measured using Langmuir probe measurements.

![Fig. 1](image1.png)

**Fig. 1.** (a) Schematic of the matching network, and (b) peak-to-peak voltages V₁ and V₂ measured with a high voltage probe at network positions indicated in (a) for a 40 sccm CHF₃ plasma at 200 W rf power and 6 mTorr operating pressure.

![Fig. 2](image2.png)

**Fig. 2.** Ion current densities as a function of the coil terminating reactance measured in 40 sccm CHF₃ discharge at 1400 W source power and 6 mTorr operating pressure measured using Langmuir probe measurements.

Figure 2 shows the ion current densities measured (at 2 cm above the wafer surface in the center of the reactor) with a Langmuir probe in 40 sccm CHF₃ discharges at 1400 W source power and 6.5 mTorr operating pressure as a function of coil terminating reactance. It shows that the ion current density decreases as the coil terminating reactance increases, i.e., as the capacitive to inductive coupling ratio increases. The same trend is observed in discharges fed with C₂F₆, O₂, or Ar. Similar to the ion current density, the optical emission intensity integrated over the visible light range decreases in these gases as the coil terminating reactance increases.

The above results indicate that capacitive coupling is less efficient in terms of plasma generation than inductive coupling. This can be explained by the fact that the power coupled in a capacitive fashion is absorbed by ions that are accelerated across the high voltage plasma sheath at the coupling window, and does not contribute to plasma generation. At a constant source power, the plasma generation is thus reduced as the capacitive coupling increases. In fact, the amount of source power that is dissipated in a capacitive fashion can be estimated from Fig. 2, by assuming that at around 20 Ω coil terminating reactance all power delivered to the plasma is dissipated in an inductive fashion and used for plasma production. The reduction in the ion current density with increasing coil terminating reactance is then a measure for the power dissipated in a capacitive fashion. For example, at 40 Ω coil terminating reactance, the ion current density is reduced to around 75% of the value measured at 20 Ω, indicating that at this setting 25% of the delivered power is dissipated in a capacitive fashion.

Figure 3 shows additional results on the effect of capacitive coupling on the plasma electrical characteristics. Figure 3(a) shows the plasma potential $V_{pl}$ as a function of the coil terminating reactance measured in 40 sccm CHF₃ discharge at 1400 W source power and 6 mTorr operating pressure using the PPM 422. It is found that in the case of a high capacitive-to-inductive coupling ratio, the plasma potential is
higher than in a more inductive mode. Also included in Fig. 3(a) are the corresponding floating potentials $V_f$ measured at the extraction hood of the PPM 422. From the difference between the plasma and floating potential, one can calculate the electron temperature using the relation:

$$T_e = \frac{\left(V_{pl} - V_f\right)}{\frac{1}{2} \ln\left[m_i/(2\pi m_e)\right]},$$

(1)

that follows from equating the electron current and ion current Langmuir equations at floating potential. In Eq. (1), $m_e$ is the electron mass and $m_i$ is the average ion mass. The electron temperatures calculated using values for the average ion mass obtained from positive ion mass spectrometry at the corresponding conditions are plotted in Fig. 3(b). It shows that the electron temperature is higher in a high capacitive-to-inductive coupling ratio mode than in a more inductive mode.

### B. Erosion of quartz coupling window

As mentioned above, due to the capacitive coupling a negative self-bias potential with respect to the plasma develops on this window. The values of the self-bias potential will depend on the capacitive-to-inductive coupling ratio, but can easily be in the range between 10 and 100 V. $^5$

Rueger et al. $^5$ showed for the current ICP tool that if SiO$_2$ is exposed to bombardment of fluorocarbon ions with energies above a certain threshold energy chemical sputtering of the SiO$_2$ material occurs, and that below the threshold fluorocarbon deposition occurs. It is clear from this that dependent on the capacitive-to-inductive coupling ratio, fluorocarbon deposition (at a highly inductive mode, i.e., low ion energies) or chemical sputtering (at a high capacitive-to-inductive mode, i.e., high ion energies) is expected to occur at the quartz window. Indeed, in fluorocarbon discharges with a relatively high threshold bias, e.g., CHF$_3$, and at conditions where capacitive coupling is limited, fluorocarbon deposition on the quartz window can be observed. In discharges with a lower threshold bias, e.g., C$_2$F$_6$, we did not observe fluorocarbon deposition on the window even in the most inductive mode. This is explained by the fact that the quartz window is not cooled and will heat up significantly. Since the fluorocarbon deposition rate decreases as the temperature of the surface that it deposits on increases, $^7$ no net fluorocarbon deposition can occur on the quartz coupling window even in the most inductive mode used in this work. The quartz window sputter rate, however, is significantly reduced in a more inductive mode, as we will show below by presenting various experimental results.

Figure 4 shows positive ion spectra, i.e., ion energy distributions, of the most dominant ionic species measured using the Balzers plasma sampling tool PPM 422 in a 40 sccm CHF$_3$ discharge at 1400 W source power, 6 mTorr operating pressure at the 40 $\Omega$ coil terminating reactance settings. The ion energy distributions were measured while the extraction hood of the plasma-sampling tool was at floating potential. The ion energy, i.e., potential in Fig. 4, is measured with respect to ground potential. The ion spectrum obtained for this condition shows that a significant part of the ion flux is related to species originating from quartz window erosion, such as mass 28 (CO$^+$, Si$^+$), mass 47 (COF$^+$, SiF$^+$), and mass 85 (SiF$_3^+$). Due to the flux coming from the quartz window, the partial pressure of fluorocarbon ions will be reduced. Figure 5(a) shows the variation of the relative amount of fluorocarbon species as a function of process conditions at a coil terminating reactance of 40 $\Omega$ in CHF$_3$ discharges. It can be seen that the relative amount of window...
erosion related species increases with increasing source power, decreasing gas flow, and decreasing pressure. The percentage of fluorocarbon ions can for certain conditions be lower than 50% of the total ion flux. Interestingly, the average composition/average ion mass of the fluorocarbon ions seems only to be determined by the source power and pressure, while being independent of the flow, see Figs. 5(a) and 5(c), respectively. Even though the partial pressure of fluorocarbon species varies significantly with flow, it appears that the dissociation and ionization of the fluorocarbon parent molecule is not significantly altered. Similar trends were observed for C$_2$F$_6$ plasmas.

At conditions where the coil terminating reactance is only 10 $\Omega$, the percentage of quartz window erosion related species are orders of magnitude lower. At this setting the ion flux consists almost completely of fluorocarbon related ions in the whole process window (10–40 sccm C$_2$F$_6$ or CHF$_3$ gas flow, 6–20 mTorr operating pressure, and 600–1400 W source power). Figure 6 shows the intensities of the most dominant ionic species as a function of coil terminating reactance measured using the PPM 422 in 40 sccm CHF$_3$ discharges at 1400 W source power and 6 mTorr operating pressure.

Neutral mass spectra using the AGM can also be used to monitor changes in plasma chemistry. Figure 7 compares results from neutral mass spectrometry performed in 40 sccm CHF$_3$ discharges at 1400 W source power and 6 mTorr operating pressure at a 40 and 10 $\Omega$ coil terminating reactance setting. Figure 7 shows the difference spectra obtained by subtracting the plasma off spectrum from the plasma on spectrum both measured at 70 eV ionization energy. The pressure was kept at 6 mTorr for both plasma off and on conditions. In the 40 $\Omega$ case, where capacitive coupling is more significant, there is a large contribution of species originating from the quartz window erosion. These contributions are significantly reduced when running the same plasma at a more inductively coupled setting.
Optical emission spectroscopy also yields information on the partial pressure of quartz window related species, e.g., CO and SiF. Figure 8 compares the optical emission spectra obtained in 40 sccm CHF$_3$ discharges at 1400 W source power and 6 mTorr operating pressure at the coil terminating reactance settings of 40 and 10 $\Omega$. In the spectrum corresponding to a more capacitively coupled plasma, significant peaks that can be contributed to SiF species are present, while these peaks are much lower in the inductively coupled case. Further, species originating from the feedgas CHF$_3$, such as carbon, fluorine, and hydrogen are more dominant at the inductive setting. Again, it is clear from these results that quartz window erosion decreases as the coupling mode shifts from a higher to lower capacitive-to-inductive coupling ratio.

A fourth method for observing the erosion of the quartz window is to monitor the minimum pressure that can be achieved in the reactor, with the throttle valve completely opened as a function of coil terminating reactance. In a highly inductive mode, i.e., 10 $\Omega$ reactance, the minimum pressure achievable in a 40 sccm CHF$_3$ discharge at 1400 W source power is around 4.2 mTorr. The pressure increase between the plasma on and off condition is around 0.1–0.2 mTorr, and is mainly ascribed to dissociation of the parent CHF$_3$ molecules (which is typically less than 10%). In a more capacitive mode, i.e., 40 $\Omega$ reactance, the minimum pressure achievable is around 5.2 mTorr. The pressure increase at this condition corresponds to a flow increase of about 10 sccm, indicating that the flow from the quartz window can be quite significant. This observation is consistent with PPM 422 results obtained in a 10 sccm CHF$_3$ discharge at 1400 W and 6 mTorr, where the partial pressure of quartz window related species can be as high as 50% of the total pressure.

The last experimental result for quartz window erosion comes from physically measuring the amount of quartz removed from a window that was used for approximately one year in our ICP reactor. The ICP was used on average 3 h per day for 365 days and typically operated at a source power level between 600 and 1400 W at pressures between 6 and 20 mTorr and a coil terminating reactance of 40 $\Omega$, i.e., a significantly high capacitive-to-inductive coupling ratio. Figure 9(a) shows the profile of the eroded quartz window. Interestingly, the erosion is most significant in a donut shape area around the center of the quartz window. This result is in excellent agreement with electric field measurements by Hopwood et al. in a planar Ar ICP that indicated that the maximum inductive plasma generation occurs in a donut shaped area close to the quartz window. Simulations by Ventzek et al. of planar ICPs also indicate that the ion density is highest in this donut shape area. When inspecting the cross-sectional window profile more carefully, see Fig. 9(b), one notices that the erosion occurred faster at the positions where the coil was located and a high peak-to-peak voltage was present on the coil. The observations on the window profile are consistent with the idea that the quartz window erosion will scale with both the ion flux and the ion
energy. The resulting erosion rate is therefore highest at the locations where both the ion current density peaks, i.e., the donut, and the self-bias voltage peaks, i.e., under the coil. Further, from the total amount of quartz material removed during the period of one year, one can calculate the average atomic flux from the window. When taking a density of quartz of 2.6 g/cm², one finds an average flow from the 23 cm diameter window of around 5 sccm. Realizing that the reactor has not been run at the maximum source power setting, which has been observed to correspond to a maximum window erosion, one finds that the calculated and experimentally determined flow are in good agreement.

**C. Fluorocarbon deposition, fluorocarbon etching and selective SiO₂-to-Si etching**

The above results demonstrate that capacitive coupling strongly affects both plasma electrical characteristics and the plasma chemistry. In this section, we will investigate how surface processes such as fluorocarbon deposition, fluorocarbon etching, and selective SiO₂-to-Si etching are influenced by these capacitive coupling effects.

As described in earlier publications on inductively coupled fluorocarbon plasmas, fluorocarbon deposition occurs on unbiased substrates, while net etching of the substrate occurs when a sufficiently high rf bias power is applied. Figure 10 shows the rates at which fluorocarbon deposition takes place as a function of coil terminating reactance in 40 sccm CHF₃ discharges at 1400 W source power and 6 mTorr operating pressure. If rf bias power is applied to the substrates on which fluorocarbon material was deposited, the deposited material can be etched back. The rates at which the fluorocarbon material is removed is shown in Fig. 11 as a function of coil terminating reactance in 40 sccm CHF₃ discharges at 1400 W source power and 6 mTorr operating pressure. The rf bias power level was adjusted in these experiments such that the self-bias voltage that developed on the wafer was −100 V.

Figure 12(a) shows the SiO₂ and Si etch rates as a function of coil terminating reactance, measured in 40 sccm CHF₃ plasmas at 1400 W source power and 6 mTorr operating pressure. The rf bias power level was adjusted in these experiments such that the self-bias voltage that developed on the wafer was −100 V. Similar to the ion current density and the integrated optical emission intensity, both the SiO₂ and Si etch rates decrease as the coil terminating reactance increases. Figure 12(b) shows the SiO₂-to-Si etch rate ratio, i.e., SiO₂-to-Si etch selectivity, at the corresponding conditions.
tions. A maximum in the SiO₂-to-Si selectivity is found to occur at a condition where the coil terminating reactance is around 40 V, i.e., the condition where the partial pressure of species created in the quartz window erosion process is maximum, see Fig. 6.

In order to investigate in greater detail how the contribution of the quartz window erosion affects the SiO₂-to-Si selectivity, we measured the SiO₂ and Si etch rates as a function of source power, operating pressure and gas flow in both C₂F₆ and CHF₃ at a coil terminating reactance of 40 V. These conditions are similar to the ones where positive ion mass spectrometry was performed, see Fig. 5. The etch rates were determined at self-bias voltages of 2100 V.

Figure 13 shows the SiO₂ etch yields, i.e., atoms removed per ion calculated by assuming a SiO₂ density of 2.3 g/cm³, measured at the various conditions as a function of the relative amount of fluorocarbon ions in the total ion flux. The only nonfluorocarbon ions detected in the ion flux are ions related to erosion of the quartz window. The relative amount of fluorocarbon ions in the total ion flux is therefore a good monitor for the quartz window erosion contribution to the plasma chemistry. Figures 13(a) and 13(b) clearly show that the SiO₂ etch yield strongly decreases as the percentage of fluorocarbon ions in the total ion flux decreases, in both C₂F₆ and CHF₃, respectively. This behavior is consistent with the chemical sputtering mechanism of SiO₂ in inductively coupled fluorocarbon plasma as described by Rueger et al. The SiO₂ chemical sputter yield is expected to decrease as the relative amount of fluorine in the total ion flux decreases. The difference in the SiO₂ yield in C₂F₆ and CHF₃ discharges is small. However, the SiO₂ yield in CHF₃ is consistently lower than in C₂F₆. This difference can be ascribed to the fact that the average stoichiometry of fluorocarbon ions in C₂F₆ is roughly CF₃, while it is CF₂ in CHF₃. In low energy ion beam studies, the yield of CF₃ ions has been found to be higher than the yield of CF₂ ions.

At the same conditions that we measured the SiO₂ etch yields also the Si etch yields were determined. The Si etch yields are also plotted in Figs. 13(a) and 13(b) as a function of the percentage of fluorocarbon ions in the total ion flux, in both C₂F₆ and CHF₃, respectively. Si etching has previously been shown to occur through a mechanism where the etch precursor fluorine diffuses through a fluorocarbon film that is present on the Si surface during steady-state conditions. The thickness of this fluorocarbon film, which determines the Si etch yield ultimately, was found to be directly related to the fluorocarbon deposition and fluorocarbon etching per incident ion. In order to explain the trends in the Si etch yield as a function of process parameters, we therefore also measured the fluorocarbon deposition and fluorocarbon etching per ion at the same conditions.

Figure 14 shows the fluorocarbon deposition per ion, i.e., sticking, in both C₂F₆ and CHF₃ plasmas as a function of the percentage of fluorocarbon ions in the total ion flux. In the cases that a large percentage of the total ion flux is due to window erosion related species, i.e., low percentage of fluorocarbon ions, the amount of fluorocarbon material deposited per ion is similar for both C₂F₆ and CHF₃. As the percentage of fluorocarbon ions increases, one expects that the difference between a C₂F₆ and a CHF₃ chemistry becomes more pronounced. Indeed, a significant difference between the fluorocarbon deposition characteristics of C₂F₆ and CHF₃ is observed, i.e., the deposition per ion is much lower in C₂F₆ than in CHF₃. A possible explanation for the difference in deposition behavior is the presence of hydrogen in a CHF₃ discharge that scavenges F, which is widely accepted as being an etchant for many materials, from the discharge and the fluorocarbon surface. The reduction in F may result in a reduction of the “spontaneous” etching of fluorocarbon material during fluorocarbon deposition processes.
deposition per ion is plotted as a function of fluorocarbon percentage in the ion flux, a similar trend can be expected in the neutral/radical flux, i.e., the fluorocarbon percentage in the ion flux can be used as an indicator of the overall fluorocarbon percentage in the plasma. This is supported by appearance mass spectrometry results that showed increased intensities of the radicals related to window erosion at conditions where also increased ion intensities related to the window erosion was observed.

The composition of fluorocarbon material deposited in CHF$_3$ was investigated using x-ray photoelectron spectroscopy both at a condition where the fluorocarbon percentage of the plasma is relatively low (25%) and a condition with a higher (50%) fluorocarbon percentage. The results are summarized in Fig. 15. It is clear from these results that if the fluorocarbon percentage in the plasma is relatively low, a significant amount of window erosion related material is being incorporated in the deposited material.

The fluorocarbon etching per ion, i.e., yield, at $\sim$100 V self-bias in both C$_2$F$_6$ and CHF$_3$ plasmas is plotted in Fig. 16 as a function of the percentage of fluorocarbon ions in the total ion flux. First of all, it can be observed that for both C$_2$F$_6$ and CHF$_3$, the fluorocarbon etch yield increases as the percentage of fluorocarbon in the plasma increases. Further, it shows that the fluorocarbon etch yield is much higher in C$_2$F$_6$ than in CHF$_3$ over the whole parameter range. These trends can be explained by the fact that the fluorocarbon etch yield is determined both by (1) the plasma gas phase chemical composition, and (2) the composition of the deposited fluorocarbon material. The role of the latter was investigated in an experiment in which we sputtered the fluorocarbon films from Fig. 15 in an Ar discharge. It was found that the Ar sputter rate of the fluorocarbon film with the largest amount of species related to the quartz erosion was significantly lower than the sputter rate of the other fluorocarbon film.

Using the data from Figs. 14 and 16, we can predict what will happen to the thickness of the fluorocarbon film that covers the Si surface during steady-state etching. First of all, we know that C$_2$F$_6$ typically yields a lower fluorocarbon deposition per ion and a higher fluorocarbon etch yield than CHF$_3$. The steady-state fluorocarbon film thickness is therefore expected to be lower in C$_2$F$_6$ discharges. Further, for C$_2$F$_6$, the deposition per ion increases and the fluorocarbon etch yield decreases as the percentage of fluorocarbon in the discharge decreases. The steady-state fluorocarbon film thickness is therefore expected to increase as the fluorocarbon percentage in the C$_2$F$_6$ plasma decreases. For CHF$_3$, both the deposition per ion and the fluorocarbon etch yield decrease as the percentage of fluorocarbon in the discharge decreases. The decrease in etch yield, however, is more pronounced than the decrease in deposition per ion. The steady-state fluorocarbon film thickness is therefore also expected to increase as the fluorocarbon percentage in the CHF$_3$ plasma decreases. Figure 17 shows the thicknesses of the steady-state fluorocarbon films measured at the various conditions using ellipsometry. The trends are indeed consistent with the data from Figs. 14 and 16.

Finally, Fig. 13(c) shows the ratio of the SiO$_2$-to-Si etch yields, i.e., SiO$_2$-to-Si selectivity, as a function of the fluorocarbon percentage in the discharge. First, it shows that due to the relatively high Si etch yields in C$_2$F$_6$, which is a result of the reduced steady-state fluorocarbon film thickness, the SiO$_2$-to-Si selectivity is much higher in CHF$_3$ than C$_2$F$_6$. Further, it can be seen that the SiO$_2$-to-Si selectivity strongly increases as the fluorocarbon percentage in the plasma decreases. In other words, the amount of window erosion related material in the plasma has a strong effect on the
SiO<sub>2</sub>-to-Si selectivity. The parameter that controls the amount of window erosion related material in the plasma, i.e., the amount of capacitive-to-inductive coupling ratio, is therefore an important control knob for optimizing selective SiO<sub>2</sub>-to-Si etch processes.

The above observations of increased selectivity with increased amounts of window erosion related material in the plasma is consistent with observations from Bell et al., who find that the SiO<sub>2</sub>-to-Si<sub>3</sub>N<sub>4</sub> selectivity increases as CO is added to their fluorocarbon discharge. Since the SiO<sub>2</sub>-to-Si selectivity is increased as CO is added to the C<sub>2</sub>F<sub>6</sub> and CHF<sub>3</sub> discharges due to window erosion, the mechanism of the selectivity enhancement may also be related.

**IV. SUMMARY AND CONCLUSIONS**

In this work, it has been shown how various plasma and surface diagnostics can be used to study the effect of capacitive coupling on plasma electrical and chemical characteristics. It is found that the plasma density decreases while the electron temperature increases as the amount of capacitive coupling is increased at a constant source power level. Further, it is found that capacitive coupling is responsible for the erosion of the dielectric coupling window. The rate at which the dielectric coupling window is eroded is found to scale with both the peak-to-peak rf voltage and the ion current density. The dielectric window erosion is found to influence the resulting plasma gas-phase chemistry. The changes in plasma electrical and chemical characteristics have a large impact on the surface processes occurring in inductively coupled fluorocarbon plasmas. At a given rf power, the fluorocarbon deposition rate and the fluorocarbon, SiO<sub>2</sub> and Si etch rates decrease in various fashions as capacitive coupling is increased. It is shown how the selective SiO<sub>2</sub>-to-Si etch process (which results from a complex mechanism in which the ion flux to the surface, fluorocarbon deposition and fluorocarbon etching at the surface are balanced) varies with capacitive coupling. Based on this it is concluded that capacitive coupling control is an important parameter that should not be ignored when optimizing plasma processes.

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