Investigation and Control of Spatial Characteristics of Chamber-Cleaning Plasmas

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Abstract. Planar laser-induced fluorescence (PLIF) measurements were made to determine 2-D spatial maps of CF_2 density as a chemical marker of plasma uniformity in 9% O_2/91% CF_4 chamber-cleaning plasmas. Measurements were made in the capacitively-coupled Gaseous Electronics Conference (GEC) RF Reference Cell as pressure was varied from 13.3 Pa (100 mTorr) to 133.3 Pa (1000 mTorr) and electrode gap was varied from 2.25 cm to 0.5 cm. Discharge current and voltage measurements were also made and compared to the optical measurements. Smaller gaps resulted in increased radial uniformity and extended the pressure range over which CF_2 density and electrical properties remain constant. These results provide insight into the optimization of chamber-cleaning processes and reactors as well as provide necessary data for validation of plasma simulations.

INTRODUCTION

Fluorocarbon plasmas are widely used by the semiconductor industry for in situ cleaning of deposition chambers as well as etching. To reduce operating costs and environmentally harmful emissions, these plasmas must be optimized for efficient gas utilization, fast cleaning or etch rates, and desired spatial characteristics. Spatial variations in cleaning rates on different reactor surfaces are likely related to spatial variations in reactive gas phase species in the plasma. Understanding the effect of factors such as pressure, plasma current, and electrode gap size on the reactive species spatial characteristics would aid in the optimization of these plasmas.

To investigate the behavior of the spatial distribution of reactive species in the plasma, a series of experiments was initiated in which O_2/CF_4 and O_2/C_2F_6 chamber-cleaning plasmas were investigated in the capacitively-coupled Gaseous Electronics Conference (GEC) RF Reference Cell. Planar laser-induced fluorescence (PLIF) was used to measure the 2-D density distribution of the CF_2 radical as a chemical marker of plasma uniformity. CF_2 is an important reactive species in fluorocarbon etching plasmas, because it is believed to be a major participant in the formation of the polymer layer which is necessary for selective etching of oxide and nitride layers on silicon. In PLIF, the entire 2-D map of the CF_2 density is collected simultaneously, eliminating the need for multiple point measurements.

In an initial set of experiments,[1] the pressure-dependence of PLIF data was studied and found to be correlated to optical emission and electrical measurements. These results led to an investigation[2] of whether the spatial distribution of CF_2 could be changed by controlling the flow of current through the plasma by means of a variable impedance load connected between the non-powered electrode and ground. In some commercial reactors, however, the electrode gap is significantly smaller than the gap in the GEC cell used in previous work. To study how a reduction of the electrode gap affects plasma spatial and electrical properties, we performed the experiments presented here, in which we measured PLIF of CF_2 and electrical properties in O_2/CF_4 discharges with varying electrode gaps.

EXPERIMENTAL

Experiments were conducted in 9% O_2/91% CF_4 chamber-cleaning plasmas at pressures varying from 13.3 Pa to 133.3 Pa (100 mTorr to 1000 mTorr) and total gas flow rate of 8.8 standard cubic centimeters

per minute (sccm) in a GEC reference cell.[3] It is a stainless steel, parallel-plate, capacitively-coupled, radio-frequency (rf) discharge reactor with quartz windows and 10.2 cm diameter, water-cooled, aluminum electrodes separated by a gap of 2.25 cm. Each electrode is surrounded by an aluminum oxide insulator and a stainless steel ground shield. The electrodes are not movable, so the electrode gap was varied by placing anodized aluminum disks of various heights on the lower electrode, as shown in Fig. 1. Because the anodized disks lack a ground shield, we grounded the lower electrode and powered the upper electrode, unlike in previous studies where the lower electrode was powered.[1, 2] The upper electrode was powered by a 13.56 MHz power supply, coupled through a matching network. A current probe and a voltage probe were attached to the input power lead. Probes were also mounted on the copper wire that grounded the lower electrode to the exterior of the cell. Using procedures described previously,[4] the stray impedance of the cell was characterized. This characterization allows us to determine the current and voltage at the electrodes, the plasma impedance, and the plasma power, i.e., the power delivered to the discharge itself, excluding all external power losses. Measurements were made at 30 W of plasma power, which corresponds to a power density which is comparable to industrial reactors operated at hundreds of watts, because of the larger size of industrial reactors and the fact that external losses are usually not taken into account.

The PLIF technique has been discussed in detail previously.[1, 5] The 266 nm laser beam from a quadrupled Nd:YAG laser was expanded using cylindrical optics into a vertical laser sheet approximately 2.5 cm tall and 0.5 cm thick. The laser sheet passes through the plasma, exciting the CF_2 radicals from the X (0, 1, 0) ground electronic state to the A(0, 2, 0) excited electronic state. The laser-excited CF_2 fluoresces primarily to the X(0, 0-20, 0) states,[6] emitting light between 250 nm and 400 nm. The fluorescence between 300 nm and 400 nm was imaged normal to the laser sheet, using an intensified charge-coupled device (ICCD) camera with a 105 mm, f/4.5 ultraviolet lens. Colored glass filters reduced broadband plasma emission and block the scattered laser light. For each image, up to 1050 laser shots were averaged. In PLIF, the image is not line-of-sight integrated, because only the CF_2 in the plane of the laser sheet is excited and detected. The spatial resolution was determined by the 5.0 mm laser sheet thickness and the 0.2 mm x 0.2 mm imaged dimensions of the camera pixels.

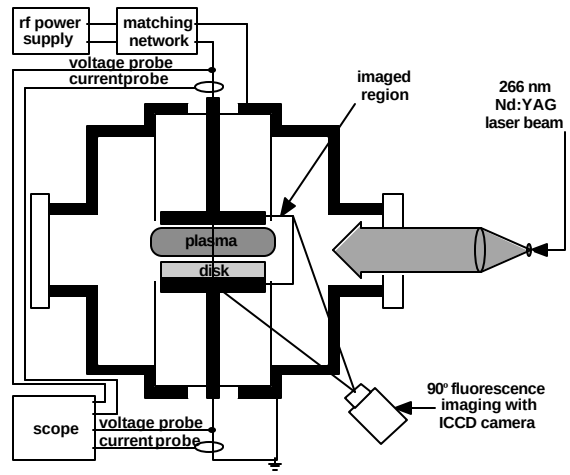

FIGURE 1. Experimental schematic of GEC reactor, including spacer disk, electrical probes and PLIF apparatus.

Broadband, spontaneous plasma emission from multiple species between 300 nm and 400 nm, measured with the laser blocked, was subtracted from each PLIF image. The PLIF images were normalized for spatial variations and drift in the laser intensity, as described previously.[1] In addition, a uniform field correction[5] was applied to the images to normalize for any slight variations in collection efficiency across the ICCD. The optical detection for the PLIF is arranged so that with the full electrode gap of 2.25 cm, there is no vignetting of the fluorescence optical collection volume. However, when the aluminum disks are used to reduce the gap, some optical paths between the plane of the laser sheet and the ICCD lens are obscured. To determine how this affects the CF_2 PLIF images, PLIF was performed on acetone gas, which was seeded at 1.7 % by volume in air and flowed through the cell at 350 Torr total cell pressure, with no plasma ignited. The acetone was excited with the 266 nm laser sheet, and detected via the ICCD camera between 350 nm and 400 nm. For the case of the smallest gap (0.5 cm), the acetone PLIF images indicated that corrections to the CF_2 fluorescence intensity of up to 25 % were necessary. Thus, the images for the 0.5 cm gap were divided by the normalized acetone images. For other gaps, fluorescence collection problems were minor; the CF_2 density within 1 mm or 2 mm of the electrode surfaces may be reduced due to shadowing of the electrodes. Because errors were so small and dividing by the acetone images introduces noise, the CF_2 PLIF images for gaps other than 0.5 cm were not corrected. Care was taken to operate under conditions where the CF_2 PLIF intensity is proportional to the ground electronic state CF_2 density, as discussed previously.[1] We verified that collisional quenching does not affect the

fluorescence intensity yield, and we used low laser intensities to keep the CF_2 PLIF signal in the linear regime. Temperature variations which could cause changes in PLIF intensity due to changes in ground state rotational and vibrational population distribution are believed to be small especially under these constant power conditions.

RESULTS AND DISCUSSION

CF_2 PLIF results at selected pressures are shown in Figs. 2, 3, 4 and 5 for electrode gaps of 2.25 cm, 1.5 cm, 1.0 cm and 0.5 cm, respectively. Each image shows the right half of the plasma with the electrodes in black and the relative CF_2 density on a scale of eight grays. Although within a figure, the images have been normalized to the same intensity grayscale, each figure is shown in a different intensity grayscale, optimized to best illustrate the density changes for each gap. The grayscale intensity bar shown at the bottom of each figure also gives numerical values which can be used to compare intensities between figures.

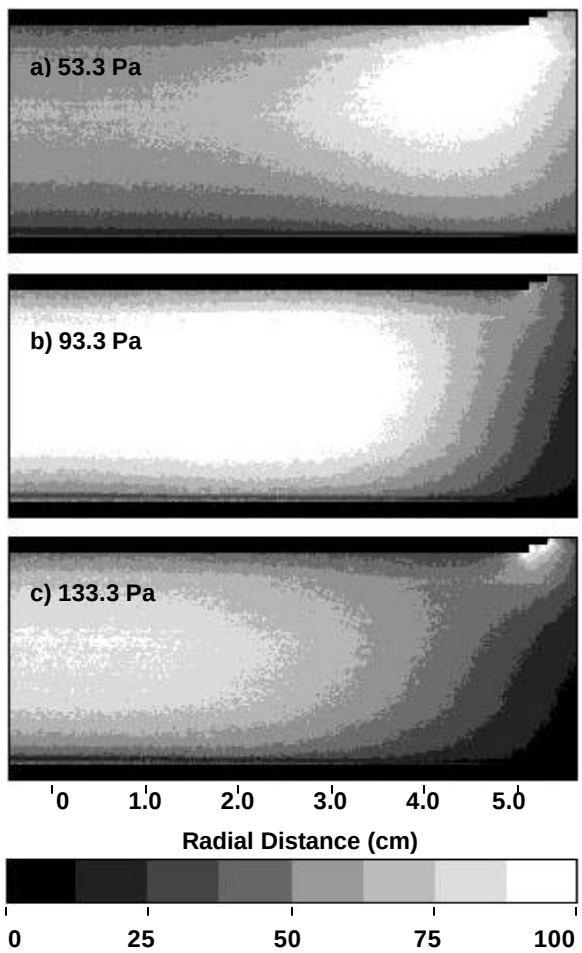

FIGURE 2. CF_2 PLIF images in a 30 W, 9% O_2/91% CF_4 plasma with a gap of 2.25 cm at pressures of a) 53.3 Pa, b) 93.3 Pa, and c) 133.3 Pa. In each image, the right half of the plasma is shown. Electrodes are shown in black.

In Fig. 2, the full electrode gap of 2.25 cm is shown for 53.3 Pa (400 mTorr), 93.3 Pa (700 mTorr), and 133.3 Pa (1000 mTorr). In this case no disks were necessary to narrow the gap, and the only difference between these images and previously published data[1] is that the upper electrode is powered instead of the lower electrode. As discussed previously,[1] three types of behavior are observed. At low pressures (53.3 Pa, 400 mTorr), the CF_2 density has a broad peak near the edge of the powered electrode. At intermediate pressures (93.3 Pa, 700 mTorr), the plasma is more confined to the region between the electrodes and is more radially uniform. At high pressures (133.3 Pa, 1000 mTorr), a very sharp maximum in CF_2 appears near the edge of the powered electrode. As discussed previously,[1] one expects reactive species to be generated in regions of high current density due to the increased number of hot electrons in these regions. The shift in location of maximum CF_2 density with increasing pressure can be explained by examining I_{ge}/I_{pe}, the ratio of the fundamental (13.56 MHz) amplitudes of the current at the ground electrode and the powered electrode. As shown in Fig. 6a, at low pressures I_{ge}/I_{pe} is low, because a large fraction of the rf current flows to the ground shields and/or reactor walls. At intermediate pressure, most of the current flows directly across the gap, producing a maximum in I_{ge}/I_{pe}. At high pressure I_{ge}/I_{pe} falls as an increasing fraction of the current takes the very short path from the powered electrode directly to its ground shield. In each case, the region of maximum CF_2 density occurs in the region of high current density. Images of broadband spontaneous optical emission (not shown), which indicate where reactive species are generated, support this interpretation.

The CF_2 PLIF images shown in Fig. 3 for an electrode gap of 1.5 cm are very similar to those for the 2.25 cm gap; however, the peak in CF_2 density at the plasma center and the maximum radial uniformity occur at a slightly higher pressure of 106.7 Pa (800 mTorr). At 133.3 Pa (1000 mTorr), the CF_2 density in the center of the plasma decreases slightly, but no collapse of the CF_2 density toward the edge of the powered electrode is observed. In Fig. 4, the CF_2 density maps for the 1.0 cm gap show a similar trend; the peak in CF_2 density at the center of the plasma and the maximum radial uniformity occur at a higher pressure of 120.0 Pa (900 mTorr). In this series, there is very little change between 106.7 Pa (800 mTorr) and 133.3 Pa (1000 mTorr). Thus, narrower electrode

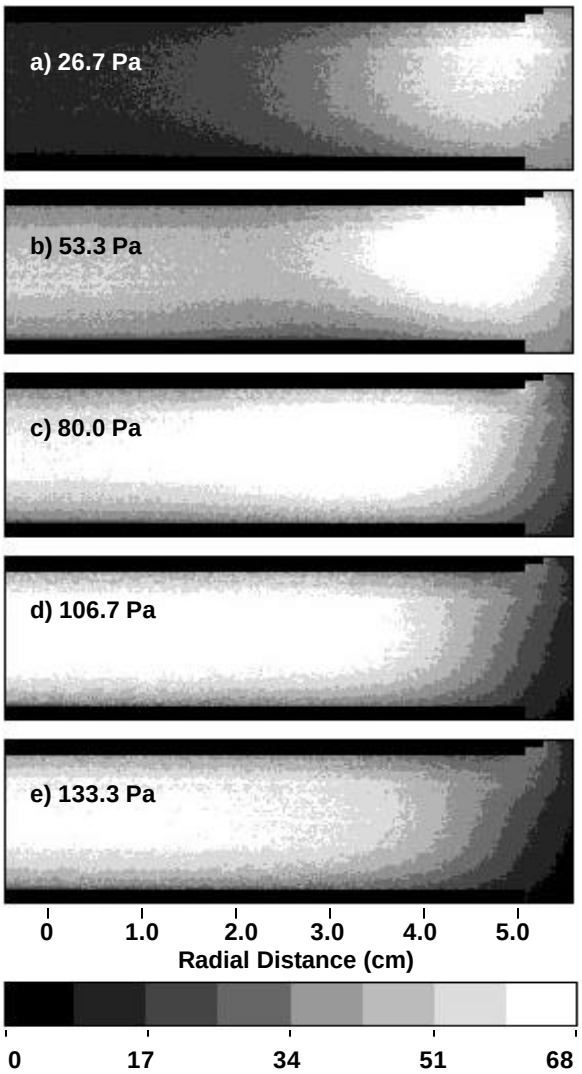

FIGURE 3. CF_2 PLIF images in a 30 W, 9 % O_2/CF_4 plasma with a gap of 1.5 cm at pressures of a) 26.7 Pa, b) 53.3 Pa, c) 80.0 Pa, d) 106.7 Pa, and e) 133.3 Pa.

gaps cause the plasma to be less sensitive to changes in pressure in the region of higher pressure. The CF_2 PLIF images for the 0.5 cm electrode gap, shown in Fig. 5, display somewhat different behavior than the data for previous gaps. The CF_2 density is fairly radially uniform at all pressures above 26.7 Pa (200 mTorr), and drops off in intensity between 53.3 Pa (400 mTorr) and 133.3 Pa (1000 mTorr) while remaining radially uniform. In all of the images, we observe a decreasing gradient of CF_2 density as it nears the electrode surfaces, which indicates that the electrode surfaces act as a sink for CF_2.

As the gap is decreased, the current path to the grounded electrode becomes more favorable than paths to the chamber walls or the ground shields, so that the current ratio I_{ge}/I_{pe}, shown in Fig. 6a,

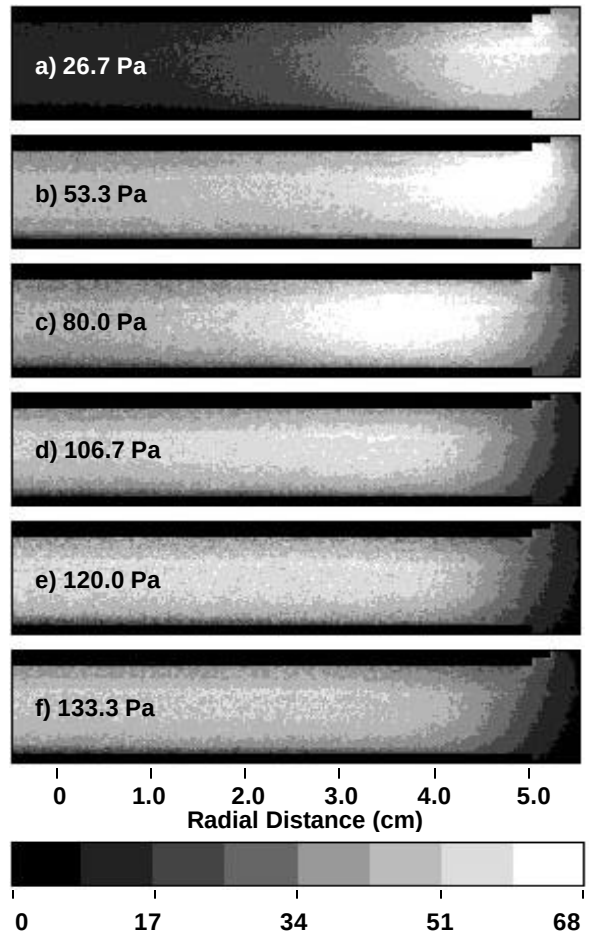

FIGURE 4. CF_2 PLIF images in a 30 W, 9 % O_2/CF_4 plasma with a gap of 1.0 cm at pressures of a) 26.7 Pa, b) 53.3 Pa, c) 80.0 Pa, d) 106.7 Pa, e) 120.0 Pa, and f) 133.3 Pa.

increases. High values of I_{ge}/I_{pe} are correlated with radially uniform CF_2 distributions. At low pressures, all gaps show a decrease in I_{ge}/I_{pe} with decreasing pressure that coincides with a decrease in radial uniformity. The decline in I_{ge}/I_{pe} at high pressures for the 2.25 cm gap and the simultaneous collapse in CF_2 towards the rim of the powered electrode are not observed for the smaller gaps.

In Fig. 6b, CF_2 PLIF at the radial center of the plasma has been integrated axially for each image and is shown plotted versus pressure. At low pressures, the CF_2 density at the radial center increases with pressure. This is probably due to an increase in the generation of CF_2 at the radial center, which accompanies the increase in I_{ge}/I_{pe}. In general, CF_2 density decreases with decreasing electrode gap. This decrease is consistent with the electrode surfaces acting as a sink for CF_2; as the gap decreases from 2.25 cm to 0.5 cm, the ratio of the area of the electrodes to the volume of the gap increases by a

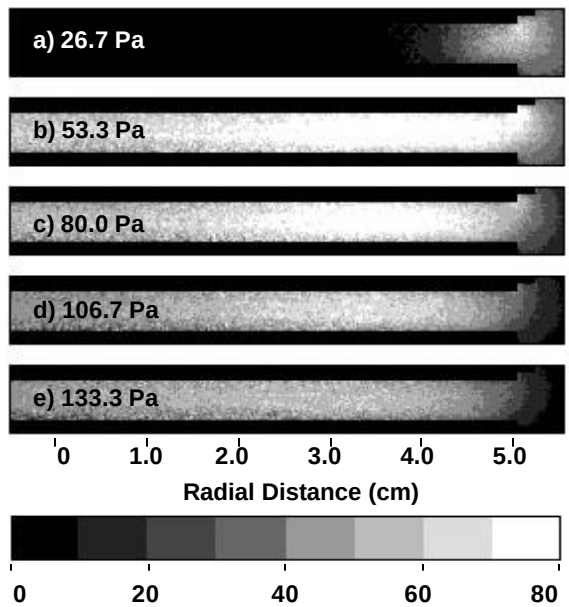

FIGURE 5. CF_2 PLIF images in a 30 W, 9 % O_2/CF_4 plasma with a gap of 0.5 cm at pressures of a) 26.7 Pa, b) 53.3 Pa, c) 80.0 Pa, d) 106.7 Pa, and e) 133.3 Pa.

factor of 4.5, which should greatly increase the importance of surface losses. Both the CF_2 PLIF at the axial center in Fig. 6b and I_{ge}/I_{pe} in Fig. 6a become less sensitive to pressure as the electrode gap decreases. This could indicate that the parameter space for operation is increased for smaller gaps.

CONCLUSIONS

In this study, PLIF has been utilized to measure the spatial distribution of CF_2 as a function of electrode gap in 30 W, 9% O_2/91% CF_4 chamber-cleaning plasmas. Together with plasma current and voltage measurements, these data provide valuable insight into these plasmas. When electrode gap was decreased, CF_2 density at the radial center decreased, suggesting that the surface loss of CF_2 increases with increasing surface to volume ratio. In addition, smaller gaps resulted in increased radial uniformity over a wider pressure range, as the current path from the powered to the grounded electrode became more favorable. Decreasing the gap also extended the pressure range over which CF_2 density and electrical properties remain roughly constant. The insight into the properties of fluorocarbon plasmas provided by these measurements could aid in the optimization of chamber-cleaning processes and reactors. These results also provide necessary data for input and validation of plasma simulations.

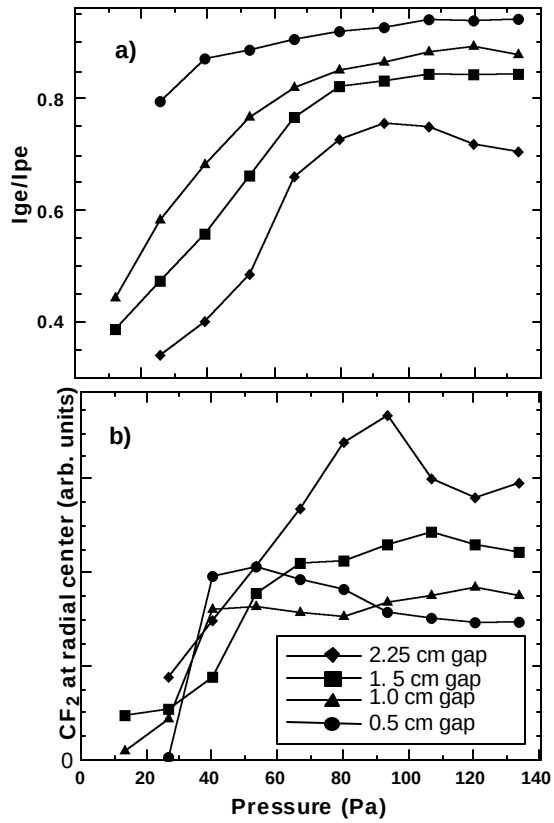

FIGURE 6. Plots versus pressure for various gaps. a) I_{ge}/I_{pe}, the ratio of the fundamental (13.56 MHz) amplitudes of the current at the ground electrode and the powered electrode. I_{ge}/I_{pe} has an uncertainty of $\pm$ 5%, dominated by systematic errors in the oscillosope and probes. b) CF_2 PLIF, axially averaged along the radial centerline. The baseline represents a density of zero.

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