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Characteristics of pulsed dual frequency inductively coupled plasma

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To control the plasma characteristics more efficiently, a dual antenna inductively coupled plasma (DF-ICP) source composed of a 12-turn inner antenna operated at 2 MHz and a 3-turn outer antenna at 13.56 MHz was pulsed. The effects of pulsing to each antenna on the change of plasma characteristics and SiO_2 etch characteristics using Ar/C_4F_8 gas mixtures were investigated. When the duty percentage was decreased from continuous wave (CW) mode to 30% for the inner or outer ICP antenna, decrease of the average electron temperature was observed for the pulsing of each antenna. Increase of the CF_2/F ratio was also observed with decreasing duty percentage of each antenna, indicating decreased dissociation of the C_4F_8 gas due to the decreased average electron temperature. When SiO_2 etching was investigated as a function of pulse duty percentage, increase of the etch selectivity of SiO_2 over amorphous carbon layer (ACL) was observed while decreasing the SiO_2 etch rate. The increase of etch selectivity was related to the change of gas dissociation characteristics, as observed by the decrease of average electron temperature and consequent increase of the CF_2/F ratio. The decrease of the SiO_2 etch rate could be compensated for by using the rf power compensated mode, that is, by maintaining the same time-average rf power during pulsing, instead of using the conventional pulsing mode. Through use of the power compensated mode, increased etch selectivity of SiO_2/ACL similar to the conventional pulsing mode could be observed without significant decrease of the SiO_2 etch rate. Finally, by using the rf power compensated mode while pulsing rf powers to both antennas, the plasma uniformity over the 300 mm diameter substrate could be improved from 7% for the CW conditions to about around 3.3% with the duty percentage of 30%.

1. Introduction

Controlling the dissociation characteristics of the reactive gases and the distribution of the dissociated gases over the substrate surface is one of the important factors in the etching of nanoscale semiconductor materials. For control of the plasma characteristics as required for nanoscale semiconductor device processing, various plasma sources including capacitively coupled plasma (CCP) sources and inductively coupled plasma (ICP) sources have been widely investigated.[1–6] CCP sources are known to have excellent plasma uniformity while having low plasma density of about a few $10^{10}/cm^3$, in addition to low gas dissociation characteristics. In contrast, ICP sources are known to have less plasma uniformity while having high plasma density, which is above $10^{11}/cm^3$, along with high gas dissociation characteristics. Even though ICP sources tend to show high processing rates due to their high plasma density and high dissociation rates, the low etch selectivity over a mask material as well as low plasma uniformity have limited the application of ICP sources to semiconductor material processing.[7,8]

To control the dissociation characteristics without significantly decreasing the plasma density, ICP sources partially mixed with a CCP component have been investigated by some researchers for improvement of the etch selectivity of the ICP source without significantly decrease of the processing rates. Dual antenna ICP sources operated by a dual frequency composed of two significantly different rf frequencies have been also investigated for control of the electron energy distribution in the plasma to change the dissociation characteristics of the reactive gases; therefore, by using two different rf frequencies instead of a single one, it is possible to vary the plasma characteristics by changing the power ratio of the two frequencies.[9–16]

Regarding CCP sources, various pulsed plasma techniques have been widely investigated to allow control of the gas dissociation characteristics by controlling the electron distribution in the plasma, to decrease the damage induced by the plasma process, and to improve the plasma uniformity over the substrate surface.[17–19] Pulsed ICP sources were also investigated by a few researchers, who showed that the plasma characteristics such as electron temperature and plasma potential, in addition to the mode change from E-mode to H-mode, can be controlled by the pulse technique.[20,21]

In this study, a dual antenna ICP source operated using a dual frequency composed of 2 and 13.56 MHz was used and the rf power to each antenna was pulsed. The effect of rf pulsing of each ICP antenna on the plasma characteristics and SiO_2 etching characteristics was then investigated for possible application to various next generation semiconductor materials processing. The results showed that plasma uniformity is related to the power ratio provided to the dual antenna and the pulse duty percentage. The plasma and etch characteristics were also related to the rf duty percentage, in addition to the rf power frequency applied to the antenna. The pulse duty frequency did not significantly change the plasma and etch properties.

2. Experimental methods

The experimental setup of the dual frequency (DF) ICP source used in this study is shown Fig. 1. The processing chamber was made of anodized aluminum with an inner diameter of 630 mm, and a 35-mm-thick quartz window was covered on the top side of the processing chamber. The substrate holder (>300 mm diameter) was cooled by a chiller to be maintained at room temperature. The spiral ICP antenna on the top of the processing chamber was separated into two parts. One was a 12-turn inner antenna operated at 2 MHz, and the other was a 3-turn outer antenna operated at 13.56 MHz.[22] During the CW conditions, 300 W of 2 MHz rf power was applied to the inner antenna while 800 W of 13.56 MHz rf power was applied to the outer antenna. Ar 10 mTorr was used for characterization using the probes, and an Ar/C_4F_8 (10 : 2) gas mixture at 10 mTorr was used for plasma characterization and etching. The 2 MHz rf power or 13.56 MHz rf power was pulsed with the duty percentage from 100% (continuous wave, CW) to 30%, and the pulse

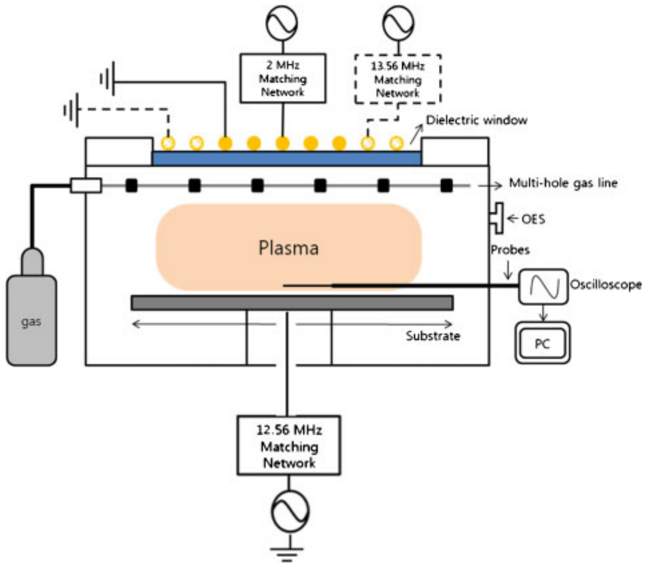


Fig. 1. (Color online) Schematic diagram of the DF-ICP system used in this experiment.

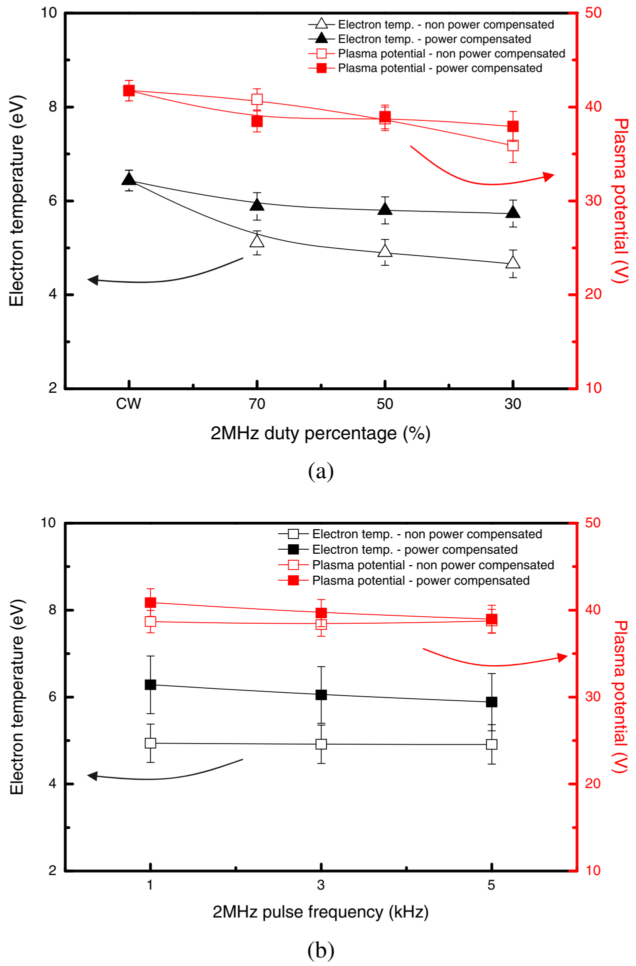


Fig. 2. (Color online) Plasma potential and electron temperature estimated using a homemade emissive probe as a function of (a) pulse duty percentage at the pulse frequency of 5 kHz and (b) pulse frequency at the duty percentage of 50% for the rf power compensated and non-compensated modes. 80 sccm Ar at 10 mTorr was used. The 2 MHz rf power was pulsed from CW conditions (300 W) to 30% while keeping the 13.56 MHz rf power provided to the outer antenna at CW conditions (800 W).

frequency was varied from 1 to 5 kHz. When the 13.56 MHz rf power was on pulse mode, the 2 MHz rf power was maintained in CW mode, and vice versa.

For the measurement of plasma uniformity, both rf power sources were also pulsed together. In some cases, in addition to the conventional pulse mode, the rf power compensated pulse mode was used to compensate for decrease of the SiO_2 etch rate induced by the pulsing, wherein the time average rf power to the ICP antenna was maintained at the same rate by increasing the rf power during the pulse on time (for example, for 50% duty percentage, two times higher rf power was applied during the pulse on time to compensate).

To investigate the plasma characteristics, a homemade emissive probe was installed 20 mm below the antenna and at the center of the chamber. For Ar plasmas, plasma potentials and floating potentials were measured by the emissive probe, and the electron temperatures were estimated from the differences between the two, as shown below:[23]

$$V_p - V_f = \frac{kT_e}{2e} \ln\left(\frac{\pi m}{2M}\right),$$

where V_p and V_f are the plasma potential and floating potential, respectively, k is the Boltzmann constant, T_e is electron temperature, m is electron mass, and M is the atomic mass of the Ar plasma. An optical emission spectroscope (OES; Andor SR-303i-A) was used for measurement of the dissociation characteristics of the reactive gas mixture used in the experiment. The OES was placed at the quartz window port located at the center of the vacuum chamber to collect the light emitted by the plasma. To measure the non-uniformity of the plasma, a homemade electrostatic probe was employed, and the ion saturation current of the probe biased at −30 V was measured over the substrate from 0 mm (center) to 150 mm (edge).

To correlate the plasma characteristics of the dual frequency-dual antenna pulsed ICP with the material processing characteristics, amorphous carbon layer (ACL) and SiO_2 were etched with the gas mixture of Ar/C_4F_8 (10 : 2) at 10 mTorr. While etching the samples using the pulsed dual frequency mode, the substrate was biased at −100 V with a separate 12.56 MHz (not 13.56 MHz) rf power (RFPP 20S) source located at the bottom of the chamber. The etch rates and resulting selectivities were measured using a step profilometer (Alpha-Step 500).

3. Results and discussion

3.1 Electron temperature and plasma potential

Using an emissive probe, variation of the plasma potential and floating potentials was measured and used to calculate the electron temperature for the pulsed DF-ICPs using 80 sccm Ar at 10 mTorr. 300 W of 2 MHz rf power and 800 W of 13.56 MHz rf power were applied to the inner and outer antenna during the CW conditions, respectively, and either the 2 MHz rf power or 13.56 MHz rf power was selectively pulsed from 100% (CW) to 30% while the other rf power was maintained in CW mode. Figure 2(a) shows the measured plasma potential and the calculated electron temperature as a function of the 2 MHz duty percentage while keeping the pulse frequency at 5 kHz. As shown in the figure, when the 2 MHz rf power duty percentage was decreased from CW to 30%, decreases of both the time average plasma potential and the time average electron temperature from 41.7 to 35.8 V and from 6.4 to 4.6 eV, respectively, could be observed. During conventional rf pulsing (non rf power compensated mode), decrease of the duty percentage caused a decrease in the time average rf power to the plasma; therefore, to maintain the time average rf power to the plasma at the same level as provided for the CW conditions for the pulsed plasmas, the rf power pulsed to the antenna was compensated. Variation of the plasma potential and the electron temperature was also investigated for the rf power under compensated mode, the results of which are also shown in Fig. 2(a). As can be seen in the figure, the plasma potentials and electron temperatures were also decreased with the decrease of duty percentage, similar to those observed for the non rf compensated mode. However, the plasma potential and the electron temperature appeared to be a little lower at the same duty percentage for the non rf power compensated mode.

Figure 2(b) shows the effect of pulse frequency on the plasma potential and the electron temperature when 2 MHz rf power was pulsed with the duty percentage of 50% for the conditions in Fig. 2(a). As shown in the figure, the plasma potentials and electron temperatures did not vary significantly with the pulse frequency for both the compensated non-compensated rf power modes.

Next, while maintaining 2 MHz rf power to the inner antenna at the CW conditions of 300 W, the 13.56 MHz rf power provided to the outer antenna was pulsed, and the effect of pulse duty percentage and duty frequency on variation of the plasma potentials and electron temperatures was measured, for both the compensated non-compensated rf power modes. The results are shown in Figs. 3(a) and 3(b), respectively, in which the other operating conditions were the same as those in Figs. 2(a) and 2(b). As shown in Fig. 3(a), similar to the 2 MHz pulsing, decrease of pulse duty percentage from CW to 30% caused a decrease of the plasma potential and the electron temperature from 41.7 to 25.5 V and from 6.4 to 3.0 eV, respectively, for the non rf power compensated mode. In the case of the rf power compensated mode, the plasma potential and the electron temperature were also decreased to 37.1 V and 5 eV, respectively, with decrease of duty percentage to 30%, although the differences were not as high as those of the non rf power compensated mode. Although the differences appear not to be significant, the 13.56 MHz pulsing showed more change of the plasma potential and electron temperature when the duty percentage was varied from CW to 30% than did variation of the 2 MHz pulsing for both the rf power compensated mode and the non-compensated mode.

When the rf pulse frequency to the 13.56 MHz rf power was varied, no significant change of plasma potentials and electron temperatures with variation of rf pulse frequency was observed, as shown in Fig. 3(b), which was generally similar to the variation of rf pulse frequency to the 2 MHz rf power shown in Fig. 2(b), although the plasma potential appeared to be decreased with the rf pulse frequency for the rf compensated mode. Decrease of the duty percentage of ICP power to the antenna without rf power compensation decreased the pulse-on time of the antenna operating in ICP mode; therefore, not only the plasma potential, but also the electron temperature was decreased for both 2 and

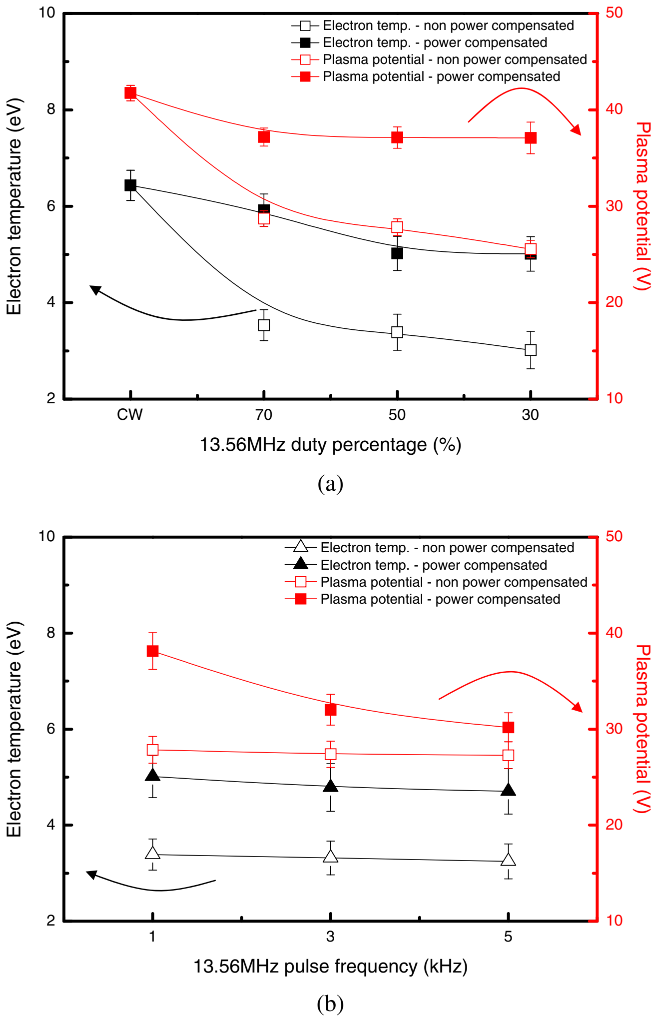


Fig. 3. (Color online) Plasma potential and electron temperature as a function of (a) pulse duty percentage at the pulse frequency of 5 kHz and (b) pulse frequency at the duty percentage of 50% for the rf power compensated and non-compensated modes. The 13.56 MHz rf power was pulsed from CW conditions (800 W) to 30% while keeping the 2 MHz rf power provided to the inner antenna at CW conditions (300 W). The other operating conditions were the same as those in Fig. 2.

13.56 MHz after time-averaging, as shown in Figs. 2(a) and 3(a), respectively. This was due to the increased pulse-off time with zero plasma potential and zero electron temperature in a duty cycle. On the other hand, when the rf power to the ICP antenna was compensated to make the time average power equal for the different duty percentages, the instant power to the ICP antenna during the pulse-on time was increased with decreasing duty percentage. In general, it was observed that the electron temperature and plasma potential did not increase linearly with increase of the rf power to the ICP antenna. That is, they increased slower with the increase of rf power (data not shown). Therefore, the time average electron temperature and plasma potential appeared to decrease with decreasing duty percentage, even though the time average rf power to the antenna was constant, as shown in Figs. 2(a) and 3(a). However, when the pulse frequency was varied at a fixed duty percentage, due to lack of change in the plasma potential and electron temperature during the pulse-on time while maintaining the ratio of pulse-on time/pulse-off time, no significant changes in the time-averaged plasma potential and electron temperature were observed for both 2 and 13.56 MHz, as shown in Figs. 2(b) and 3(b), respectively, both with and without rf power compensation.

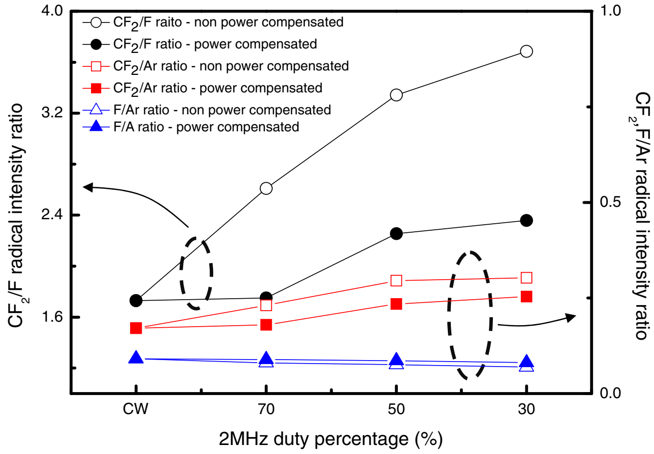
3.2 OES analysis

The variation of gas dissociation characteristics was measured using OES as a function of the pulse duty percentage of 2 MHz rf power or 13.56 MHz rf power. Similar to experiments shown in Figs. 2 and 3, 300 W of 2 MHz rf power was applied to the inner antenna while 800 W of 13.56 MHz rf power was applied to the outer antenna for CW conditions. As the gas mixture, Ar/C_4F_8 (10 : 2) at 10 mTorr was used. The optical emission peak intensity of F (703.7 nm) was measured as the etching precursor for both SiO_2 and ACL, and that of CF_2 (275.4 nm) was measured as the polymerizing precursor for ACL.[24,25] These peaks were measured to investigate the characteristics of gas dissociation and recombination in the plasma during pulsing. In addition, intensity of the optical emission peak of Ar (750.4 nm) was also measured for estimation of the radical densities using Ar actinometry, which takes the ratio of the optical emission peak intensities of radicals to the optical emission peak intensity of Ar.[26] Figure 4(a) shows the optical emission intensity ratio of F/Ar, CF_2/Ar, and CF_2/F, measured as a function of pulse duty percentage of 2 MHz rf power to the inner antenna. The optical emission intensity ratios were measured for both the rf power compensated and non-compensated modes. As shown in Fig. 4(a), decrease of the 2 MHz duty percentage resulted in decrease of the ratio of F/Ar while increasing the ratio of CF_2/Ar, which indicated decreased gas dissociation or increased amounts of radical recombination with decreasing duty percentage. This was observed for both the rf power compensated and non-compensated modes, due to the increased time without plasma with the decreasing duty percentage. The decrease of F/Ar, increase of CF_2/Ar, and increase of CF_2/F were higher for the non rf power compensated mode.

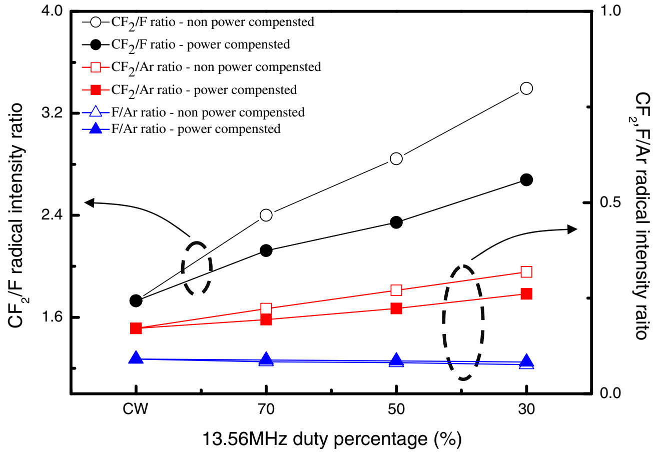
Figure 4(b) shows the optical emission intensity ratios of F/Ar, CF_2/Ar, and CF_2/F measured as a function of the pulse duty percentage of 13.56 MHz rf power provided to the outer antenna. When 13.56 MHz rf power was pulsed, similar results were obtained as for 2 MHz rf power shown in Fig. 4(a). The decrease of pulse duty percentage caused decrease of the F/Ar with increase of the CF_2/Ar; therefore, the CF_2/F was also increased with decrease of the duty percentage. As was observed for variation of the 2 MHz rf power, the non rf power compensated mode also showed larger changes than the compensated mode.

3.3 SiO_2 etch rate and etch selectivity

Using the Ar/C_4F_8 (10 : 2) gas mixture at 10 mTorr employed for investigation of the gas dissociation in Fig. 4, the etch rates of SiO_2 and the etch selectivity over ACL were investigated for the pulsing of 2 MHz rf power or 13.56 MHz rf power. For the etching of SiO_2 and ACL, the substrate was biased at −100 V using a separate 12.56 MHz rf power source. Figure 5(a) shows the etch rates of SiO_2 and the etch selectivities of SiO_2 over ACL, measured as a function of 2 MHz rf power duty percentage for the rf power compensated and non-compensated modes. For the non-compensated mode, the SiO_2 etch rate was decreased from 2450 Å/min at the CW condition to about 1030 Å/min at 30% duty percentage due to the decrease of plasma on time with decreasing duty percentage. However, decrease of duty percentage increased the etch selectivity of SiO_2 over ACL from 3.2 at the CW condition to 4.8 at the 30% duty percentage. In the case of the rf power compensated mode, the SiO_2 etch rates did not vary significantly with decreasing duty percentage due to the power compensation. However, the etch selectivity of SiO_2 over ACL was still increased with decreasing duty percentage, although the increase was not as significant as that for the non rf power compensated mode.



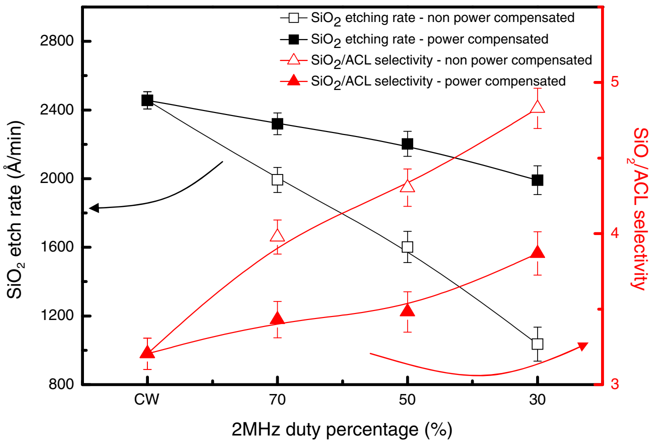
(a)



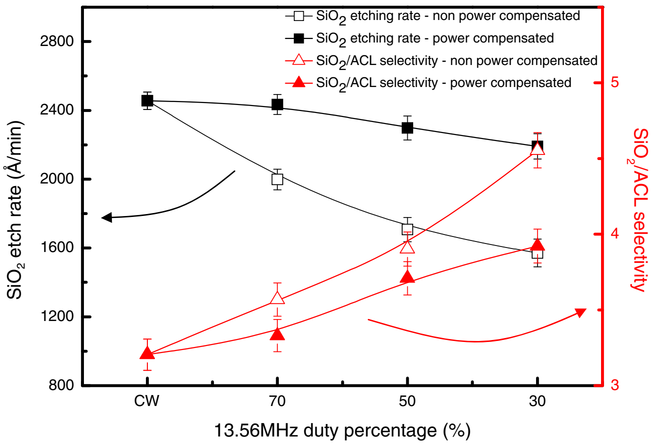
(b)

Fig. 4. (Color online) Optical emission intensity ratio of F/Ar, CF_2/Ar, and CF_2/F measured as a function of pulse duty percentage of (a) 2 MHz rf power or (b) 13.56 MHz rf power for both the rf power compensated and non-compensated modes. An Ar/C_4F_8 (10 : 2) gas mixture at 10 mTorr was utilized in this experiment. The other operating conditions were the same as those in Figs. 2(a) and 3(a), respectively.

Figure 5(b) shows the etch rates of SiO_2 and the etch selectivities of SiO_2 over ACL, measured as a function of 13.56 MHz rf power duty percentage. The process conditions are the same as those in Fig. 4(b). Similar to Fig. 5(a), the SiO_2 etch rate was decreased from 2450 Å/min at the CW condition to about 1570 Å/min at 30% duty percentage for the non-compensated mode; however, decrease of the duty percentage increased the etch selectivity of SiO_2 over ACL from 3.2 at the CW conditions to 4.5 at the duty percentage of 30%. Similar to Fig. 5(a), the rf power compensated mode



(a)



(b)

Fig. 5. (Color online) Etch rates of SiO_2 and the etch selectivities of SiO_2 over ACL measured as a function of (a) 2 MHz rf power duty percentage and (b) 13.56 MHz rf power duty percentage for the rf power compensated and non-compensated modes. The substrate was biased at −100 V using a separate 12.56 MHz rf power source while maintaining the substrate at room temperature. The other operating conditions were the same as those in Fig. 4.

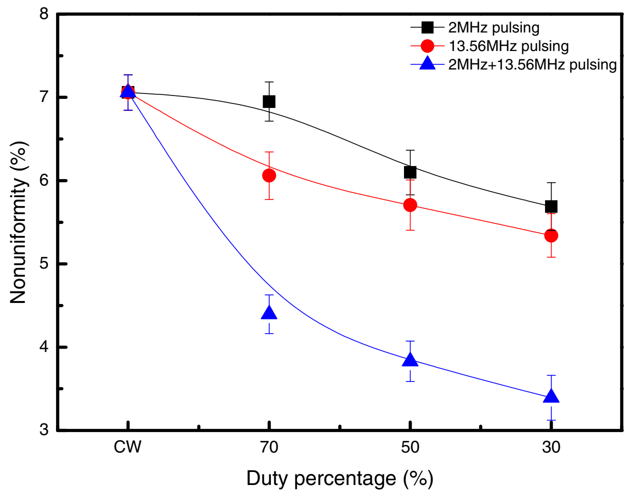


Fig. 6. (Color online) Plasma uniformity of the DF-ICP source measured using an electrostatic probe for the rf power compensated mode as a function of 2 MHz rf power duty percentage and 13.56 MHz rf power duty percentage. In addition, the plasma uniformity measured by pulsing both the 2 MHz rf power and 13.56 MHz rf power together is also shown. Ar at 80 sccm and 10 mTorr was used, and the ion saturation current biased at −30 V, which was located 20 mm above the substrate holder, was used to estimate the plasma uniformity from the center (0 mm) of the wafer to the edge of the wafer (150 mm).

also resulted in increased etch selectivity of SiO_2 over ACL with decrease of the duty percentage, while not significantly decreasing the SiO_2 etch rates.

The observed increase of the etch selectivity of SiO_2/ACL with decrease of the duty percentage is believed to be related to the change of gas dissociation characteristics observed in Fig. 4. Decrease of the duty percentage increases CF_x radical density while decreasing F density, due to increased re-combination of dissociated radicals from C_4F_8 with increasing pulse off time in a pulse cycle. F is the etchant for the etching of both ACL and SiO_2; however, CF_x ($x = 1, 2$) is a polymerizing precursor for ACL, while it is still an etchant for SiO_2. Due to the increased CF_2/F ratio in the plasma resulting from decrease of the duty percentage for both the 2 and 13.56 MHz rf power pulsing, the etch selectivity was believed to be increased with decreasing duty percentage, as shown in Figs. 5(a) and 5(b). The lower etch selectivity of SiO_2/ACL for the rf power compensated mode compared to that observed for the non-compensated mode shown in Figs. 5(a) and 5(b) appears to be also related to the lower CF_2/F ratios obtained for the rf power compensated mode, as shown in Figs. 4(a) and 4(b), respectively.

3.4 Plasma uniformity

The plasma uniformity is increasingly important for next generation plasma processing due to the increase of wafer size. The pulsing of rf power can improve the plasma uniformity due to increase of plasma diffusion during the pulse off time.[27] The plasma uniformity during rf power pulsing of the DF-ICP source was measured for the rf power compensated mode while pulsing 2 MHz rf power to the inner antenna or 13.56 MHz rf power to the outer antenna. In addition, the plasma uniformity was also measured when pulsing both 2 MHz rf power and 13.56 MHz rf power together. Ar at 80 sccm and 10 mTorr was utilized in this experiment, and the ion saturation current of an electrostatic probe biased at −30 V and located 20 mm above the substrate holder was used for estimation of the plasma uniformity from the center (0 mm) of the wafer to the edge of the wafer (150 mm). As shown in Fig. 6, decrease of the duty percentage from the CW conditions to 30% improved the plasma uniformity from about 7% to about 5.6% for the 30% 2 MHz rf power pulsing, and to about 5.3% for the 30% 13.56 MHz rf power pulsing. Therefore, by pulsing the DF-ICP source, improvement of the plasma uniformity in addition to improvement of the etch selectivity of SiO_2/ACL is believed to have been obtained without significant change of the SiO_2 etch rate. In addition, by pulsing both the 2 MHz rf power provided to the inner antenna and the 13.56 MHz rf power to the outer antenna together, further improvement of the plasma uniformity to about 3.3% could be obtained at the duty percentage of 30%.

The improvement of plasma uniformity observed in Fig. 6 is related to plasma diffusion during the pulse-off time, as the plasma is given time to diffuse in the chamber at that time. Therefore, the plasma uniformity is improved with decrease in the duty percentage. In addition, because the ICP antenna used was composed of two antennas, as shown in Fig. 1, the best plasma uniformity was obtained when optimized rf powers were applied to both antennas (in this case, about 800 W to the inner antenna and about 300 W to the outer antenna for the CW rf power conditions). At the optimized CW rf powers for both antennas, when one of the rf powers (2 MHz or 13.56 MHz rf power) was pulsed, resulting in a lower rf power being applied to one of the ICP antennas; therefore, improvement of the plasma uniformity was less even, although the uniformity was improved due to the increased plasma diffusion. However, when both antennas were pulsed together at the optimized CW rf power conditions, the best improvement of plasma uniformity was obtained due to increased diffusion during the pulse-off time, in addition to the optimized uniformity of the plasma density during the pulse-on time.

4. Conclusions

In this study, a DF-ICP source composed of an inner spiral ICP antenna operated at 2 MHz rf power and an outer spiral ICP antenna operated at 13.56 MHz rf power was utilized for pulsing of either the 2 MHz rf power or the 13.56 MHz rf power to examine of the effects on the plasma characteristics and SiO_2 etch characteristics using Ar or Ar/C_4F_8 gas. By pulsing the rf power to the inner antenna or to the outer antenna while etching SiO_2 with ACL as the etch mask using Ar/C_4F_8, increase of the SiO_2 etch selectivity over ACL could be obtained for the conventional rf pulsing (non rf power compensated mode). The increase of the etch selectivity observed with decrease of the duty percentage was related to the increased recombination of dissociated gases due to the increase of pulse off time, as observed by the increase of the CF_2/F ratio with decrease of the duty percentage. When the rf power compensated mode was used instead of the conventional non-compensated mode, the improvement of SiO_2 etch selectivity over ACL was also observed without significant change of the SiO_2 etch rate, although the improvement of SiO_2 etch selectivity was not as high as that obtained using the non rf power compensated mode. In addition, by pulsing the rf power, significant improvement of the plasma uniformity was obtained. Especially, improvement of the plasma uniformity from 7.0% at the CW conditions to about 3.3% at the 30% pulse duty percentage could be obtained by pulsing both the 2 MHz rf power and 13.56 MHz rf power together, without significantly changing the SiO_2 etch rate.

Acknowledgments

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