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Characteristic of a dielectric barrier discharges using capillary dielectric and its application to photoresist etching

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Abstract

In this study, atmospheric pressure plasmas were generated using a dielectric barrier discharge equipment using capillary dielectric materials and the characteristics of the plasmas and the surface cleaning rate were studied as a function of He/O_2 gas mixture and electrode material. The use of capillary dielectric instead of blank dielectric increased the plasma density by effectively using the voltage sustained in the dielectric for accelerating electrons at the capillary holes, therefore, by forming ion beam-like plasmas at the holes in addition to typical dielectric barrier discharges. The addition and increase of oxygen into He decreased the plasma density monotonically due to the increased charge neutralization; however, oxygen atoms increased initially and showed a maximum with the increase of oxygen. The etch trend of photoresist, therefore the cleaning rate of organic materials, was related to that of oxygen atoms in the plasma. As capillary dielectric materials, the use of ceramics instead of Teflon showed higher photoresist etch rate with higher radical and plasma densities due to the higher sustaining voltage at the air gap between the electrodes.

Keywords: Dielectric barrier discharge; Capillary dielectric materials; Plasma density

1. Introduction

Currently, electronic industries including semiconductor industry and flat panel display industry are using low pressure plasmas or wet chemicals for surface cleaning of the substrates. However, low pressure processing is very costly due to the use of vacuum and wet processing is environmentally undesirable due to the use of large amount of chemicals. If stable atmospheric plasmas could be realized, not only the decrease of processing cost by not using expensive vacuum equipment but also the increase of productivity due to the large amount of reaction species at the atmospheric pressure may be obtained in addition to the environmentally desirable characteristics [1–4]. Due to these potential benefits, many different types of atmospheric pressure plasmas such as dielectric barrier discharges [4–7], pulsed corona discharges, microwave plasma discharge, atmospheric pressure touch, etc. are currently under investigation and are applied to the cleaning of various substrates in addition to etching and thin film deposition [8–12].

Recently, capillary electrode discharge, a different type of dielectric barrier discharge having a number of parallel holes in the dielectric of the electrode, has been also used to generate atmospheric pressure plasmas and its characteristics have been investigated for the application to the removal of organic materials from the substrates. The high-aspect-ratio parallel holes, that is, capillaries in the dielectric of the electrode act as the current limiting resistor during the glow-to-arc transition, and also increase plasma density by accelerating electrons in the capillary through the electric field formed in the dielectric material during the AC voltage application to the electrode.

In this study, the effects of input AC voltage, helium flow rate, oxygen flow rate, and the dielectric material of the electrode on the He/O_2 discharges were investigated to obtain high etch rates of organic materials by optimizing these process parameters. Also, the mecha-

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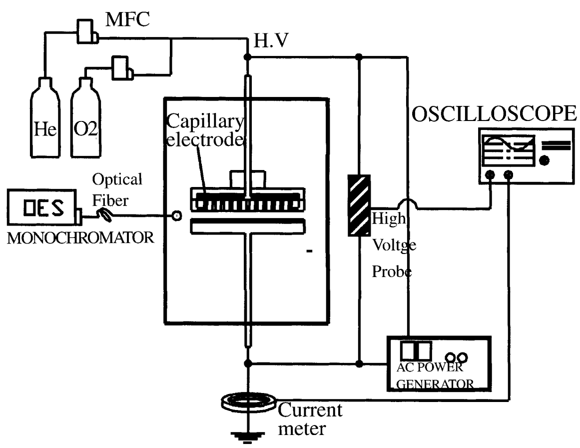

Fig. 1. Schematic diagram of capillary electrode discharge system used in the experiment.

nism obtaining high etch rate of organic materials in the He/O_2 atmospheric capillary electrode discharges were investigated using a current probe and an optical emission spectroscope.

2. Experiment

The experimental system used in this experiment is shown in Fig. 1. AC voltages with sine wave (20–30 kHz, 0–15 kV) were applied between the two electrodes of 150-mm diameter. The power electrode was covered with 8-mm-thick dielectric material with 700 parallel holes (the aspect ratio of the holes: 8) in it and the ground electrode was covered with 3-mm-thick blank quartz. The air gap between the two electrodes was maintained at 4 mm. To investigate the influence of dielectric material itself, two different dielectric materials such as Teflon and ceramic were used to the power electrode.

Different He/O_2 gas mixtures were used in this experiment and the flow rates of He and O_2 were varied independently. The flow rate of He was varied in the range from 4 to 14 slm and that of oxygen was from 0 to 80 sccm. The gas mixtures were fed through the capillary holes of the power electrode using 0.6-mm diameter stainless tubing which is also used for power feeding. As the samples, 1.2-μm-thick photoresist covered glass substrates were used and the photoresist etch rates were used as a measure of surface cleaning rate.

Photoresist etch rates were measured using a step profilometer (Alpha-step 500). The applied voltage and current were measured using a high voltage probe (Tektronix P6015A) located on the power electrode and current probe (Pearson electronics: 6600 Current probe) located on the ground electrode, respectively. The optical emission from the excited species such as O* and He* were observed using optical emission spectroscopy (SC Tech. PCM402).

3. Results and discussion

To generate plasmas at the atmospheric pressure, a voltage higher than breakdown voltage is required, however, due to the excessive current flow at the high voltage, glow-to-arc transition is easily occurred. To prevent the glow-to-arc transition and to obtain stable glow discharges, a resistor limiting the excessive current flow is required and in general, a dielectric barrier located between the electrodes is used to limit the excessive current by charging the dielectric. However, the use of the dielectric between the electrodes increases the operating voltage between the electrodes and the discharge itself is not efficient because quite a portion of the applied voltage developed in the dielectric is lost without using for generating plasmas. Therefore, discharge current and plasma density are very low. However, by drilling a number of small and parallel high-aspect-ratio holes (i.e. capillaries) in the dielectrics, the voltage developed in the dielectric can be used for generating plasmas by accelerating electrons in the holes. Previous study [13] showed that, at the same input power, higher current with lower sustaining voltage could be obtained by using the capillary electrodes (holes in the dielectric) instead of using conventional dielectric barrier electrodes (no holes in the dielectric). Ion beam-like bright and dense plasmas could be observed at the holes by using capillary electrode plasmas. Also, by using He/O_2 gas mixtures, organic materials such as photoresist could be etched uniformly. In this study, the effect of operational parameters such as input voltage, He flow rate, and oxygen flow rate and the effect of capillary dielectric materials on the surface cleaning and its cleaning mechanism were investigated.

Fig. 2 shows the effect of input voltage on the photoresist etch rate and measured root-mean-square (rms) current. The dielectric material used in the experiment was ceramic. Pure He, 4.5 slm and 30 sccm of O_2 were used in the experiment. As shown in the figure, the increase of input voltage increased the photoresist etch rate almost linearly. The increase of photoresist etch rate with the increase of input power shown in this experiment is possibly related to the increase of oxygen atoms or ions in the plasma. The monotonic increase of discharge current with the increase of input voltage appears to support the increase of plasma density. The maximum voltage that can be applied with stable plasmas was 9 kV (rms) and unstable plasmas such as filamentary discharges were obtained at the voltage higher than 9 kV.

Fig. 3 shows the effect He flow rate on the photoresist etch rate and measured current when 8 kV of input voltage and 20 sccm of O_2 were used. The increase of He flow rate up to 6 slm increased photoresist etch rates slightly, however, the further increase of He flow rate decreased the etch rate rapidly. In the case of measured

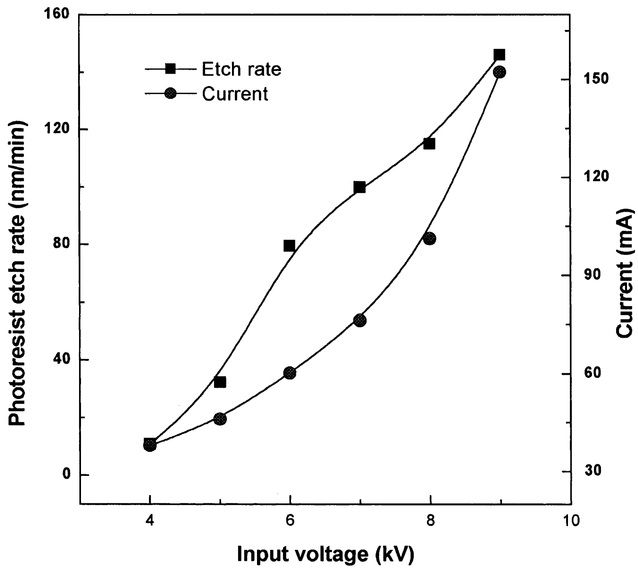

Fig. 2. Effect of applied voltage of the photoresist etch rate and rms current (4.5 slm He, 30 sccm O_2, air gap of 4 mm and ceramic as the dielectric to power electrode).

current, the current was saturated at above 8 slm of He flow after initial increase of the current with the increase of He flow rate. The saturation of current appears to be from the loss of charged particles by excessive gas flow to outside of the reactor without conducting. The initial increase of the photoresist etch rate with the increase of He flow rate appears to be from the increased transport of oxygen atoms or ions to the photoresist by the increased gas flow, however, the rapid decrease of photoresist etch rate with the further increase of He flow

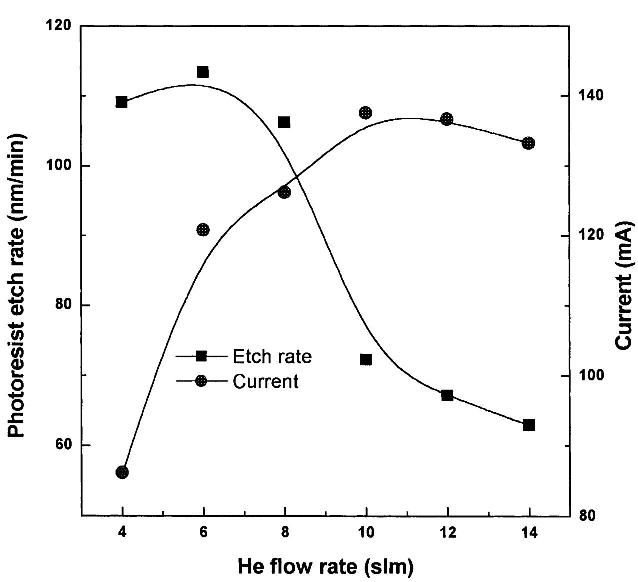

Fig. 3. Effect of He flow rate on photoresist etch rate and rms current (20 sccm of O_2, 8 kV of rms applied voltage, 4 mm of air gap and ceramic as the dielectric to power electrode).

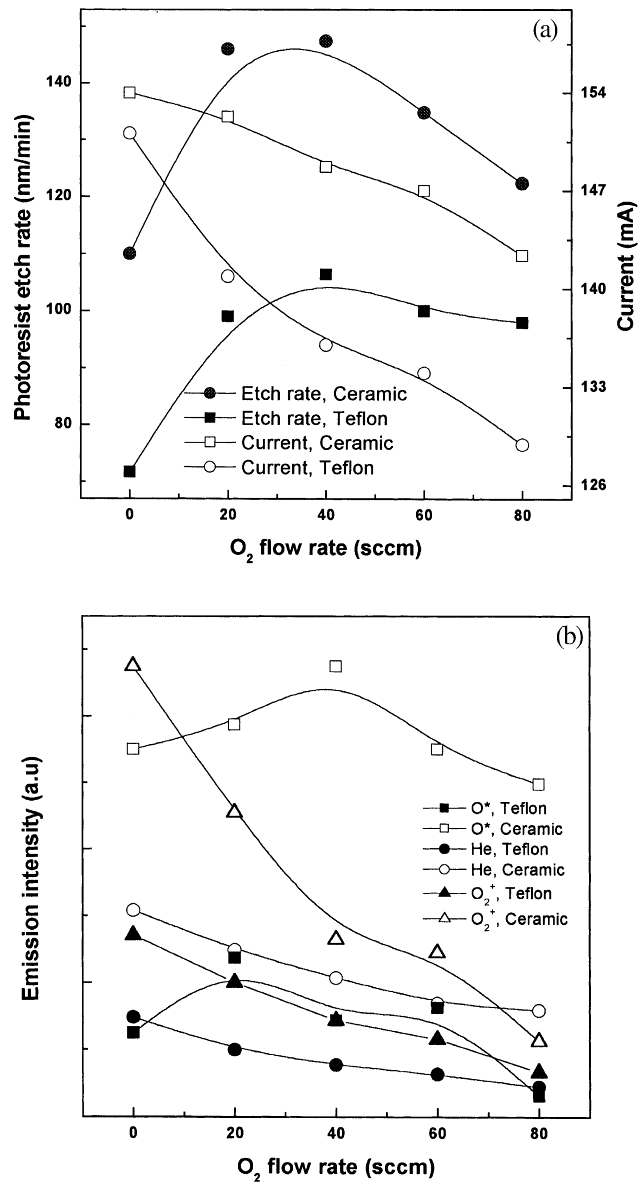

Fig. 4. Effect of O_2 flow rate and different capillary dielectric materials on (a) the photoresist etch rate and rms current and (b) the measured optical emission intensities of He*, O_2^+ and O* by optical emission spectroscopy. (6 slm of He, 9 kV of rms applied voltage and as dielectric materials ceramic and Teflon were used.)

rate appears to be more related to the decrease of oxygen atoms or ions due to the decreased oxygen percentage in the chamber by the increased He gas flow to the chamber.

Fig. 4 shows the effect of oxygen flow rate and dielectric materials on (a) the photoresist etch rate and rms current and (b) the measured optical emission intensities of He*, O_2^+ and O* by optical emission spectroscopy. He, 6 slm and, as the dielectric material, ceramic and Teflon were used. The oxygen flow rate was varied from 0 to 80 sccm. As shown in Fig. 4a, the addition and increase of O_2 up to approximately 40 sccm increased photoresist etch rate and the further increase of oxygen decreased the photoresist etch rate. In the case of the measured current, the addition and increase of oxygen decreased the current monotonically. The decrease of current with the increase of oxygen in He/O_2 appears to be related to the removal of electrons by the formation of oxygen negative ions because atoms or molecules with high electronegativity such as F and O tend to form electronegative ions by the recombination of electrons and the radicals at low energies. However, the formation of O^- has not been confirmed yet, therefore, more study is required.

Also, due to the high collision probability between molecules at the atmospheric pressure, charge neutralization probability between electropositive ions such as He^+ and O_2^+ and electronegative ions such as O^- will be also very high. Therefore, the decrease of measured current with the increase of oxygen appears to be related to the decrease of plasma density due to the increase of charge neutralization in the plasma. Even though, plasma density is decreased with the increase of oxygen, radicals such as oxygen atom can increase with increase of oxygen percentage in He/O_2.

Fig. 4b shows the measured optical emission intensities of O, O_2^+ and He with the increase of oxygen in He. He optical emission lines were observed at 447.1, 501.6, 587.6, 667.8, 706.5 and 728.3 nm while the emission lines from oxygen atom were observed at 436.8, 533.1, 615.8, 645.6, 777.2, 794.8, 822.2 and 844.6 nm. Optical emissions from molecular oxygen ion (O_2^+) were also observed in the range from 580 to 640 nm. As shown in the figure, the increase of oxygen in He/O_2 increased optical emission intensities from oxygen atom until 40 sccm of O_2 was reached similar to the change of photoresist etch rate with oxygen. In the case of He and O_2^+, the increase of oxygen decreased the optical emission intensities from He and O_2^+ monotonically similar to the change of current with oxygen. Therefore, the photoresist etch rate in our atmospheric He/O_2 plasmas is believed to be dependent on the density of oxygen atoms in the plasmas. Ozone generated by the addition and increase of oxygen may also affect the photoresist etch rate, however, the effect of ozone was not investigated and currently under study using an ozone detector.

Fig. 4 also shows the effect of dielectric materials of the same thickness to power electrode on photoresist etch rate, the measured current and optical emission intensities from O, He and O_2^+ as a function of oxygen flow rate in He/O_2. As shown in Fig. 4a, the use of ceramic showed higher photoresist etch rate and higher measured current compared to that of Teflon. Also, optical emission intensities from O*, O_2^+ and He were generally higher for ceramic. Therefore, the use of ceramic appears to increase the photoresist etch rate due to the increase of oxygen atoms by the increase of plasma density. When applied voltage between the two electrodes is kept same, higher voltage is sustained at the air gap between the electrodes when the dielectric constant of the dielectric is higher. Therefore, the increase of plasma density by using ceramic instead of Teflon appears to be related to the increased voltage at the air gap due to the higher dielectric constant of ceramic. The difference of secondary electron emission from the dielectric surface might be also important, however, when the effect of different coatings on the same dielectric material was investigated, no significant differences were observed (not shown). Therefore, the effect of different dielectric material in our experimental conditions was mostly related to the difference of voltage sustained at the air gap between the electrodes.

4. Conclusions

In this study, the effect of input voltage, He/O_2 gas mixture and the capillary dielectric materials of the power electrode on the photoresist etch rate was studied as a measure of organic material cleaning rate using capillary electrode atmospheric discharges and its etch mechanism was investigated using a current probe and optical emission spectroscopy.

The use of capillary dielectric instead of blank dielectric to power electrode in dielectric barrier discharge increased the plasma density by effectively using the voltage sustained in the dielectric for accelerating electrons at the capillary holes, therefore, increasing plasma density. The addition and increase of oxygen into He decreased the plasma density monotonically by the increased charge neutralization, however, in the case of oxygen atoms, there was initial increase of oxygen atoms with the increase of oxygen. The amount of oxygen atoms in the plasma appears to be related to the photoresist etch rate, therefore, the cleaning rate of organic materials. The uses of ceramics as the capillary dielectric material instead of Teflon showed higher photoresist etch rates with the increase of radical and plasma densities. The increase of photoresist etch rates with ceramic instead of Teflon appears to be related to the increase of oxygen atoms by the increased sustaining voltage at the air gap between the electrodes due to the higher dielectric constant of ceramics compared to Teflon for our experimental conditions.

Acknowledgments

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