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An Investigation into the Effect of Design Parameters on Plasma Density in DBD (Dielectric Barrier Discharges)

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Abstract. DBD (Dielectric Barrier Discharges) plasma is often used to clean the surface of semiconductors. The cleaning performance is affected by many process parameters such as electric voltage, the gas composition, gas speed, thickness of the dielectric wall, gap distance, and plasma duration time. In this study, the plasma density is predicted by a coupled simulation of gas flow, chemistry mixing and reaction, plasma generation, and electric field. A 13.56 MHz RF source is used to generate plasma. The effect of the dielectric thickness, the gap distance, the gas flow velocity, and electric voltage on the plasma density is investigated. It is shown that the plasma density increases as the dielectric thickness decreases, the gap distance increases, the gas velocity increases, and electric voltage increases, respectively. Finally, experiments are carried out to verify the analysis results.

Introduction

Plasma has been used in semiconductor processes such as chemical vapor decomposition [1,2], surface coating, etching, and surface cleaning. Among many processes for semi-conductor wafer, etching is one of the key technologies. With increased demand for small sized semiconductors-thus necessitating high aspect ratio and fine critical dimensions-dry etching processes are mainly employed at present [3]. Plasma processes are also frequently employed in surface cleaning prior to joining process [4-6]. If the surface is not clean, the joining quality drops remarkably. Therefore, the surface of the wafer should be cleaned before joining.

Numerous studies on plasma generation and cleaning performance have been conducted. Most of these studies have been carried out by experiments as it is very difficult to model the plasma behavior [4-8]. There has been relatively little analytical investigation of the plasma processes owing to inherent difficulties and inaccuracy. The analysis of plasma generation consists of a flow analysis for gas, an electromagnetic field analysis for the ionized plasma and electrode, a plasma transportation analysis, and a chemical reaction analysis at the electrode and dielectric wall. Analysis of plasma requires knowledge of wide subjects such as fluid dynamics, chemistry, electricity, and physics. Furthermore, these analyses may contain considerable error with the exception of the electromagnetic field analysis. For these reasons, few analyses of the plasma process have been carried out. Recently, however, advances in this area have been made with the development of dynamic analyses for electrons and ions and chemical reaction analyses [9-12]. Jiang et al. [9] studied the thermal mechanism and flow of ion particles for various values of RF voltage in capacitively coupled plasma.

In this study, the plasma generation in DBD was analysed and the plasma density was predicted. The authors investigated the effect of DBD process parameters such as the dielectric wall thickness, the gap distance between electrode and dielectric wall, the gas inlet velocity, and the RF voltage on the plasma density. The analyses were carried out using commercial software CFD-ACE [11], and analysis modules for fluid dynamics, chemical reaction and mixing, electromagnetic field, and plasma transportation were included. From the analysis results, it was found that the plasma density increases as the dielectric thickness decreases, the gap distance increases, the gas velocity increases, and electric RF voltage increases, respectively.

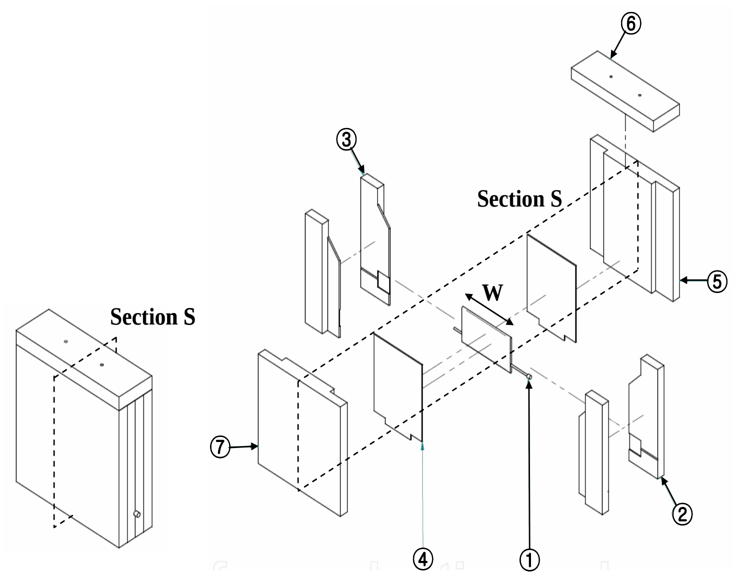
Description of 2Dimensional Analysis Model for DBD

In this study, a curtain type DBD plasma generator has been subjected to the analysis. Fig. 1 shows the curtain type DBD plasma generator in assembled and disassembled states. The part marked ′①′ is the electrode and that marked ′④′ is the dielectric wall. The names and materials used for the parts are listed in Table 1. Gas flows into the chamber through holes on the top cover and flows out at the bottom of the chamber. While gas flows downward from the top to the bottom of the chamber, it is excited by RF voltage and plasma is generated. The gap between the electrode and the dielectric wall is very small compared to the width 'W'. Therefore, it can be assumed that the results are uniform along the width direction at the central region marked by a dotted line. With this assumption, a 2-dimensional analysis is carried out for the section delineated in Fig. 1 by a dotted line.

The section that is subjected to the analysis is shown in Fig. 2 along with the boundary conditions. The electrode is treated by a boundary condition and the dielectric wall is modeled as a solid. A ground condition, i.e., an electric voltage of 0, is imposed on the left side of the dielectric wall. A constant velocity condition is imposed on the inlet boundary and a constant pressure condition is imposed on the outlet boundary. The gas pressure and surrounding pressure are both 100 Pa and a 13.56 MHz RF source is imposed on the electrode. The analysis is carried out using commercial software 'CFD-ACE'. Time integration for the RF plasma analysis is carried out independently upon time integration for the flow analysis. Time integration for the plasma analysis is carried out 300 times in 1 Hz and time integration for the flow and electromagnetic field analysis is carried every 10^{-5} second. The time integration interval has a major effect on the convergence and accuracy of the solution. With the time integration interval mentioned above, the solution converged well and a reliable solution could be obtained.

Table 1 Materials used for each part in Fig. 1

NO	Title	Material
1	Electrode	
2	Insulator(1)	Teflon
3	Insulator(2)	Teflon
4	Insulator	Ceramic
5	Right Side Wall	A 6061-T6
6	Top Cover	A 6061-T6
7	Left Side Wall	A 6061-T6



(a) (b)

Fig. 1 Curtain type DBD in (a) assembled and (b) disassembled states.

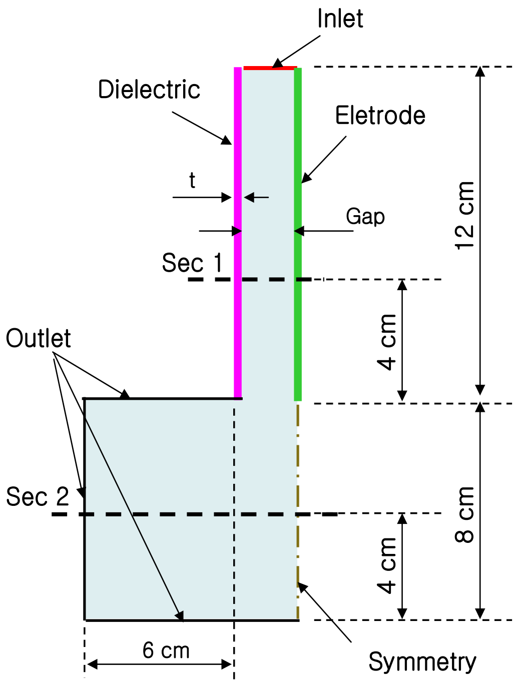


Fig. 2 Two dimensional analysis model and boundary conditions.

Results and Discussions

In order to investigate the effect of the thickness of the dielectric wall, the gap between the electrode and dielectric wall, the RF electric voltage, and the inlet gas velocity on the plasma density, analyses were carried out as follows:

i) The thickness of the dielectric wall is varied from 0.1 cm to 0.5 cm.
ii) The gap between the electrode and dielectric wall is varied from 0.5 cm to 2.0 cm.
iii) The gas inlet velocity is varied from 1.0 m/s to 15 m/s.
iv) RF electric voltage is varied from 200V to 800 V.

Fig. 3 shows the plasma (Ar^+) density at 95 seconds after the imposition of RF voltage. The sheath between the electrode and the dielectric wall is well described. The plasma density on the central region is high and plasma flows out from the chamber at the outlet. In the process, the plasma takes place in the chamber within a couple of seconds. In the analysis, however, the plasma generation is retarded and the plasma density does reach a steady state until 10 seconds. This is attributed to the time integration for plasma generation not reflecting the abrupt generation of plasma. Therefore, the absolute values of plasma density with time do not have any physical meaning and only the relative values have meaning. In the analysis, it was very difficult to obtain a steady state solution due to the very long computation time. It took approximately a week to simulate until 95 seconds (see Fig. 3). Therefore, for the initial study on the plasma cleaning process, the effects of process parameters on the plasma density are investigated in relative measure.

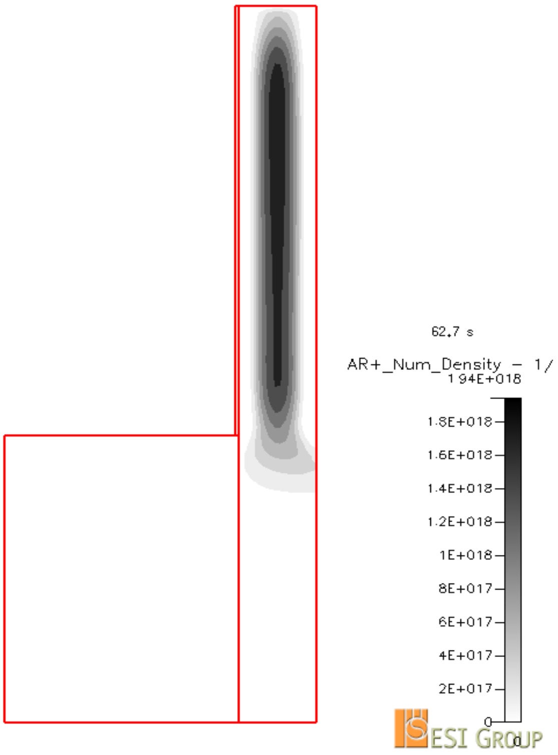
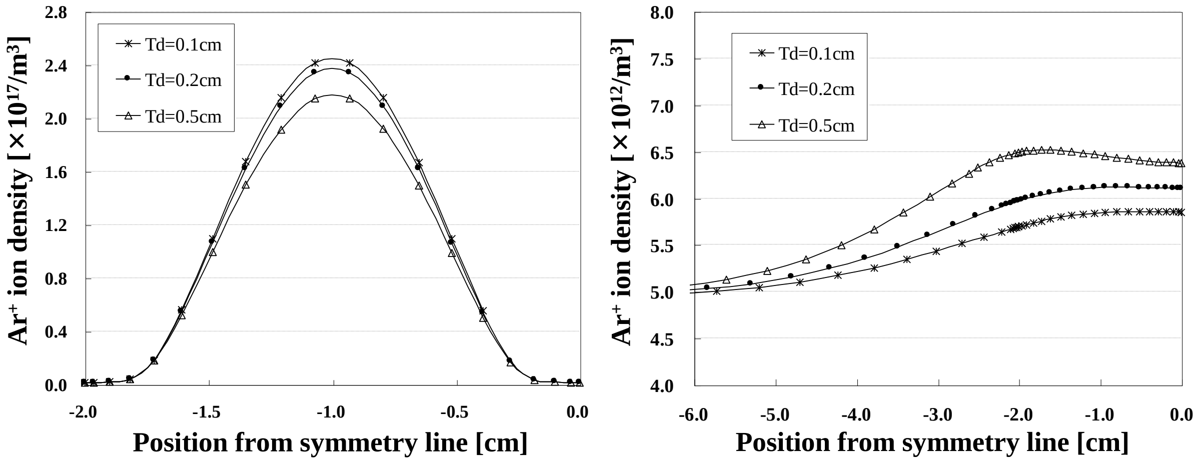


Fig. 3 Plasma(Ar+) density after 95 seconds

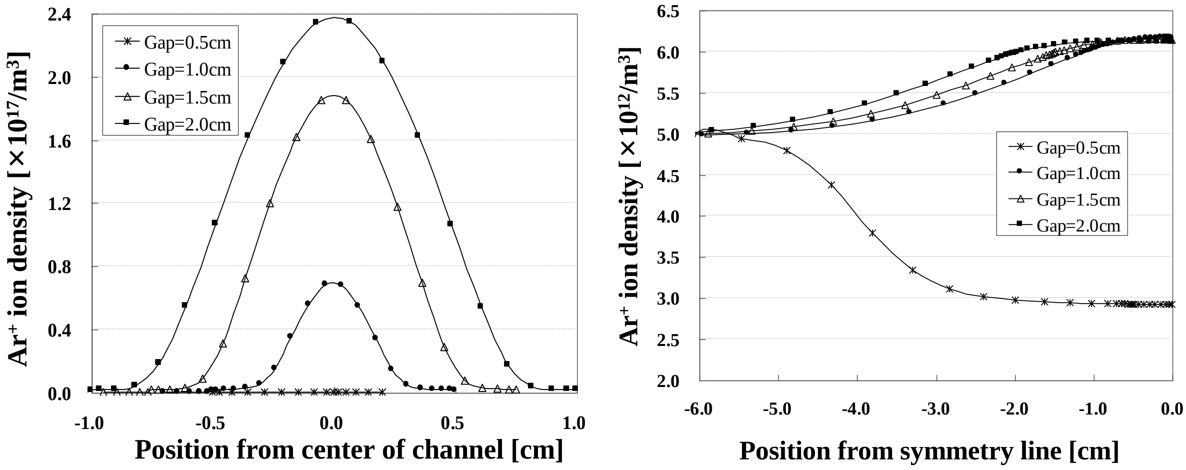
Figs. 4~7 show the effect of four process parameters on plasma density. The plasma density distributions are shown along section 1 and section 2. Sections 1 and 2 are shown in Fig. 2 and marked as ‘Sec 1’ and ‘Sec 2’, respectively. Fig. 4 shows the change of the plasma density distribution for various dielectric wall thickness values. The sheath near the electrode or the dielectric wall is not affected by the dielectric wall thickness. The plasma density at the central region of section 1, however, increases slightly as the dielectric thickness decreases. On the contrary to the results along the section 1, the maximum plasma density on the central region of the section 2 increases the dielectric thickness increases. The effect of gap distance is shown in Fig. 5. It is shown that the plasma density increases as the gap thickness increases in the both sections 1 and 2. The reason is considered that the amount of gas in the chamber is not sufficient to produce plasma when the gap distance is small. Another reason is that the thickness of the sheath band is large compared to the gap distance, and therefore the space where the plasma is generated is not sufficient. If the gas pressure or the gas density increases, the width of the sheath band width may decrease and the plasma density distribution is expected to show a different tendency.

Fig. 6 shows the plasma density for various gas inlet velocities. The plasma density increases with the inlet gas velocity. It is considered that high kinematic energy activated the phase change to plasma. Fig. 7 shows the plasma density distribution for various RF voltages. As expected, the plasma density increases as the RF voltage increases. It is shown that high RF voltage provides more energy to the gas and further activates the phase change to plasma.



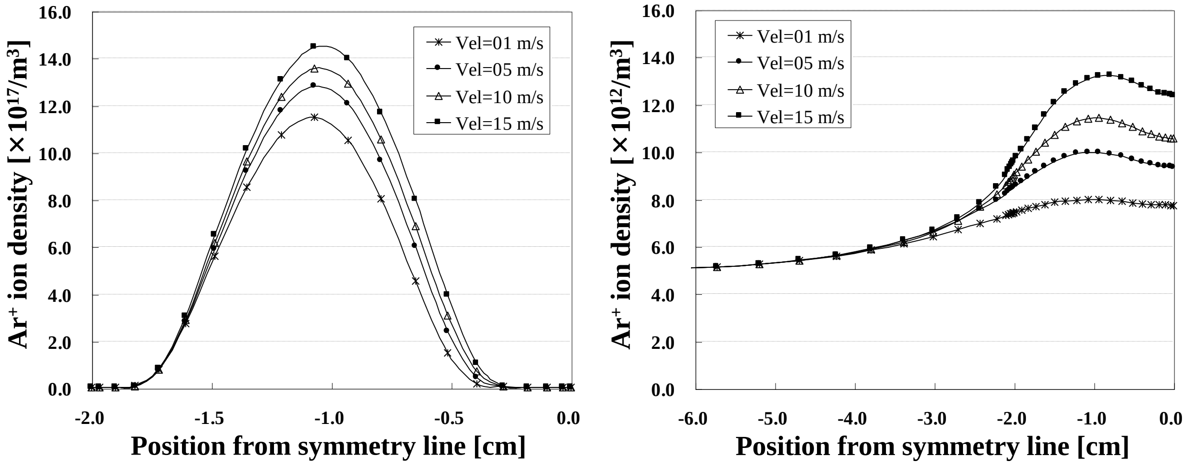
(a) Section 1 (b) Section 2

Fig. 4 Plasma(Ar$^+$) density distribution for different dielectric thicknesses.



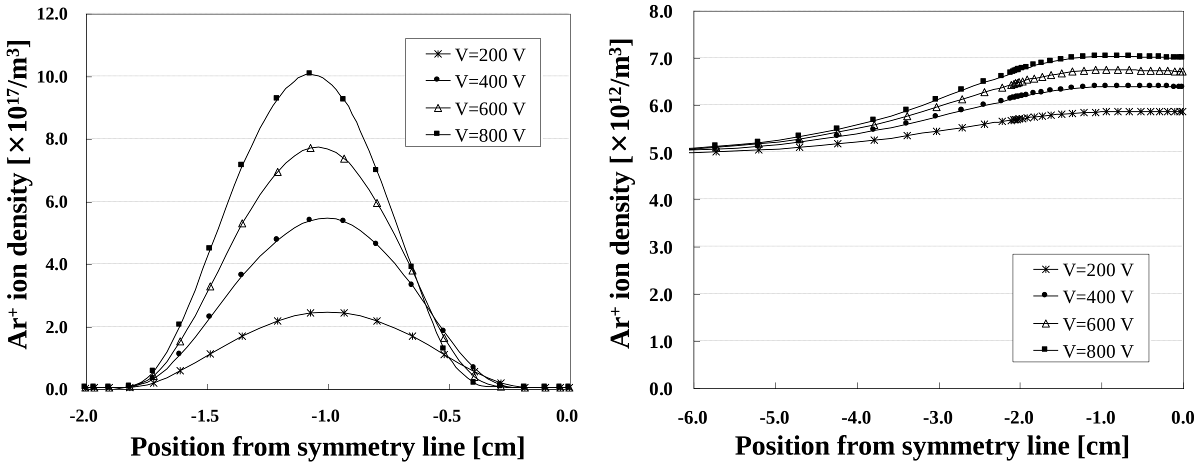
(a) Section 1 (b) Section 2

Fig. 5 Plasma(Ar$^+$) density distribution for different gap distances.



(a) Section 1 (b) Section 2

Fig. 6 Plasma(Ar$^+$) density distribution for different inlet velocities.



(a) Section 1 (b) Section 2

Fig. 7 Plasma(Ar$^+$) density distribution for different RF voltages.

To verify the analysis results, experiments are carried out. In the experiments, the contact angle after plasma treatment is measured instead of measuring the plasma density. Polyamide film is subjected to the plasma treatment. Fig. 8 shows the photo of water droplet on Polyamide film before and after plasma treatment. Measured contact angle and calculated plasma density for gas velocity and electric power are shown in Fig. 9. The contact angle decreases as the gas velocity and electric power increase. This means that cleaning quality increases as the gas velocity and electric power increase. The plasma ion density increases as the gas velocity and electric power increase. This result is qualitatively consistent with that of measured contact angle. Therefore, it is shown that better cleaning quality can be obtained with higher plasma density.

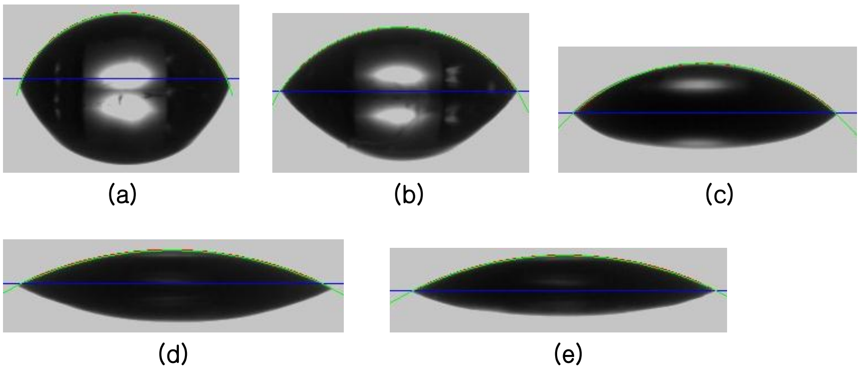


Fig. 8 Photos of water droplet on the Polyamide film (a)before plasma treatment and after plasma treatment with electric power of (b)150 W, (c)180 W, (d)210 W, and (e)240 W

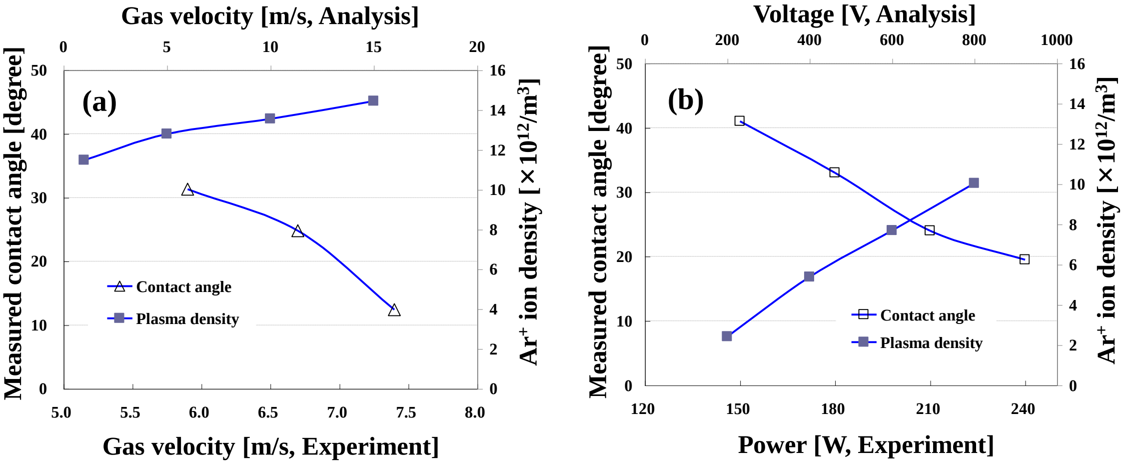


Fig. 9 Measured contact angle and calculated ion density for (a) gas velocity and (b) electric power

Summary

A curtain type DBD plasma generator, which is often used for the surface cleaning of semiconductors, has been subjected to analyses using the commercial code 'CFD-ACE'. In the first step of the plasma analysis, the effect of process parameters on plasma density was investigated. Analyses were carried out for various values of the dielectric thickness, the gap distance between the electrode and the dielectric wall, the gas inlet velocity, and RF electric voltage. The analysis results show that the plasma density increases as the dielectric thickness increases or the gap distance increases. The plasma density also increases as the gas inlet velocity increases or RF electric voltage increases. To verify the analysis, contact angle is measured after plasma treatment. The experimental results of contact angle show that the analysis results are qualitatively consistent with the experiment. A correlation between plasma density and cleaning performance is investigated. As a result, it is shown that the analysis results can be used in the design of a DBD plasma generator.

Acknowledgements

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