Analysis of flow field characteristics in IC equipment chamber based on orthogonal design

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Abstract. This paper aims to study the influence of the configuration of processing chamber as a part of IC equipment on flow field characteristics. Four parameters, including chamber height, chamber diameter, inlet mass flow rate and outlet area, are arranged using orthogonally design method to study their influence on flow distribution in the processing chamber with the commercial software-Fluent. The velocity, pressure and temperature distribution above the holder were analysed respectively. The velocity difference value of the gas flow above the holder is defined as the evaluation criteria to evaluate the uniformity of the gas flow. The quantitative relationship between key parameters and the uniformity of gas flow was found through analysis of experimental results. According to our study, the chamber height is the most significant factor, and then follows the outlet area, chamber diameter and inlet mass flow rate. This research can provide insights into the study and design of configuration of etcher, plasma enhanced chemical vapor deposition (PECVD) equipment, and other systems with similar configuration and processing condition.

1. Introduction

The vigorous development of electronic information industry depends on the improvement of IC (integrated circuit) equipment design and manufacturing technology. The processing chamber, a quite common part of IC equipment, has not attracted enough attention to be optimized during the equipment research process. Meanwhile, more emphasises were put on single structure parameter during the research process. Furthermore, the distribution of temperature and flow among the processing chamber are the most important factors determining the process homogeneity. Consequently, it is of great significance to research the influence of structure characteristics and processing parameters on the uniformity of temperature and flow distribution in the chamber. Actually, researchers have laid a solid foundation of research jobs regarding the temperature and flow distribution through experiment [1-3] and numerical simulation [4-7].

As the influence of inlet location and mass flow rate on etcher process were analysed. Moreover, the impact of inlet location and mass flow, vacuum pump outlet area and location were also the key parameters should be optimized to improve the uniformity of flow filed[8,10].The influence of showerhead structure on RF-PECVD chamber were researched through finite volume method(FVM) and SIMPLE algorithm[5]. Moreover, using a 12 inch PECVD device, the simulation of flow velocity, pressure and temperature distribution based on four types of steady flow chambers were studied [11].During the past few years, investigations concerned with the flow field or other parameters also have been mentioned. However, most experiments focused on the influence of only a single parameter.
on flow distribution inside processing chamber, while analysis of the overall impact of the relationship among various parameters was absence.

This present study informs a variable structure plasma chamber and builds the 3-D symmetrical simulation models of the chamber. Besides, the parameters of the chamber, such as chamber height, chamber diameter, inlet flow mass rate and outlet area were arranged by using orthogonal design method. In addition, every simulation corresponding to the orthogonal design was computed by a numerical code-Fluent. After the simulation results of velocity, pressure and temperature above the holder of chamber were analyzed respectively, the velocity difference value between the maximum and minimum velocity value was selected as the evaluation criteria to analyze the influence of these parameters on the uniformity of the gas flow distribution in chamber. Finally, the quantitative effect of these parameters to gas flow distribution were obtained.

2. Modeling and Orthogonal Experimental Design

2.1. Chamber model

There are various kinds of processing chambers used in integrated circuit manufacturing processing technology, and as the process and application are different, so are the structure of chambers. However, those parameters affecting the flow distribution are similar, and which also are the important factors of chamber system, such as inlet system, gas distribution system, chamber height, chamber diameter and outlet system. This paper presents a chamber structure, whose gas flows into the chamber from the inlet employed at the center of top cover of the chamber. And next, the gas flow through two-stage showerhead following, by which makes the gas distributes more evenly. The gas flow out of chamber through the outlet, which area could be changed, arranged around the bottom of chamber radially. The schematic of the chamber structure is shown in Figure 1. As figure 1 shows, the distance between the second showerhead and holder is H, the diameter of chamber is D, and the outlet section is a rectangular section (not shown in figure 1) with which area is $S (a \times b)$. Due to the processing chamber with symmetrical structure, about one-eighth of the three-dimensional structure was taken to model and mesh. The one-eighth 3-D grid model is shown in figure 2.

2.2. The Flow Field Numerical Model

The flow field of processing chamber is proceeded by a commercial software-Fluent, which uses finite-volume method (FVM) to discrete the control equation of module. And the control equation in terms of the gas flow field in chamber should follow continuity equation, momentum and energy conservation equation.
The boundary conditions are defined as follows: 1. Inlet: the inlet sets as a mass-flow inlet; 2. Outlet: to make the outlet flow divergent completely, the model outlets are extended than their actual length which would not affect the simulation results. The outlet sets as a pressure outlet; 3. Symmetry Wall: as the simulation model is one eighth of the whole model, the two sides are set as symmetry wall; 4. Cylinder Wall: besides the symmetry wall, the cylinder walls set as no-slip wall; 5. Holder Surface: as the holder is the heat source of the chamber space, the holder surface temperature is set as constant as 473.16k.

2.3. Orthogonal Experimental Design

The inlet mass rate $Q$, holder height (instead of chamber height) $H$, chamber diameter $D$, outlet section area $S$ are taken as variable factors, the orthogonal experimental design methods is adopted and $L_9(3^4)$ table is chosen for the experiment. And every variable factor has three levels, such as the inlet mass rate is 90sccm (outlet pressure is 0.5Pa), 325sccm (outlet pressure is 30 Pa) and 625sccm (outlet pressure is 50Pa); holder height is 65mm, 125mm and 185mm; chamber diameter is 360mm, 470mm and 560mm; outlet section area is $5 \text{mm} \times 25 \text{mm}$, $15 \text{mm} \times 25 \text{mm}$ and $30 \text{mm} \times 25 \text{mm}$. The orthogonal experimental table is shown in Table 1.

| No. | Column No. | Factor | Inlet Mass Rate sccm | Holder Height mm | Chamber Diameter mm | Outlet Section Area mm $\times$ mm |
|-----|------------|--------|----------------------|------------------|---------------------|-----------------------------------|
| 1   | 1          | Symbol | $Q_1$                | $H_1$            | $H_1$               | $(a_1 \times b)$                  |
| 2   | 2          |        | $Q_1$                | $H_2$            | $H_2$               | $(a_2 \times b)$                  |
| 3   | 3          |        | $Q_1$                | $H_3$            | $H_3$               | $(a_3 \times b)$                  |
| 4   | 4          |        | $Q_2$                | $H_1$            | $H_1$               | $(a_1 \times b)$                  |
| 5   | 5          |        | $Q_2$                | $H_2$            | $H_2$               | $(a_2 \times b)$                  |
| 6   | 6          |        | $Q_2$                | $H_3$            | $H_3$               | $(a_3 \times b)$                  |
| 7   | 7          |        | $Q_3$                | $H_1$            | $H_1$               | $(a_1 \times b)$                  |
| 8   | 8          |        | $Q_3$                | $H_2$            | $H_2$               | $(a_2 \times b)$                  |
| 9   | 9          |        | $Q_3$                | $H_3$            | $H_3$               | $(a_3 \times b)$                  |

3. Simulation results and discussion

Every experiment from No.1 to No.9 in Table 1 is simulated, and the distribution of flow velocity, pressure and temperature in the area above 10mm [14] of the holder are analyzed respectively.

3.1. Velocity Distribution

The velocity distribution lines in the chamber of every experiment are shown in figure 3 as follow:
Figure 3. Flow Velocity Distribution

It can be concluded from figure 3 that while changing the chamber characteristic parameters, the velocity distribution shows regularity. The velocity value has been increasing from the center of holder to a certain position at which the value reaches maximum. Then, from the certain position to the chamber wall, the velocity value decrease monotonously. That is because when the gas flows through the second showerhead into chamber, then flows out of chamber from the outlets radial arranged around the bottom part of chamber. At the center position of holder, as the movement of gas in all directions is same, the velocity is zero. In every experiment model, the diameter of holder is 300mm (radius is 150mm). In No.1, No.6 and No.8 experiments, the climax velocity values are at the edge of holder, at which the position is 150mm and all of them have the same parameter of chamber diameter. Likewise, in No.3, No.6 and No.9 experiments, all of which have same holder height, the maximum velocity values also emerge at the edge of holder and all velocity lines have a similar trend on the left side. Although No.2, No.4 and No.9 experiments have same chamber diameter, the holder height of No.9 experiment is too high to make the holder closer to the second showerhead, which makes the right-side of velocity line of No.9 experiment different from No.2 and No.4 experiments. As the holder height of No.3 experiment is higher than the others, the velocity line of No.3 experiment is not similar to No.5 and No.7 experiments, despite of their same chamber diameter. Nevertheless, the velocity lines of No.5 and No.7 experiments have the same trend. From the lines of No.1, No.2 and No.3 experiments, we can obtain that the peak values of velocity shift left gradually, and end up with the middle of the lines.

3.2. Pressure Distribution
The pressure distribution lines in the chamber of every experiment are shown in figure 4 as follow:
It can be concluded from figure 4 (a) that while changing the chamber characteristic parameters, the pressure distribution shows regularity. The pressure above the holder almost unchanged. During every experiment, all the pressure values in the area above 10mm of the holder decrease slowly, from the center of holder to the chamber wall. The figure 4 (b) shows the pressure distribution of No.3 experiment. In addition, it shows that the pressure value is invariable fundamentally at the beginning, and then decreases from the position of 50mm to 175mm, then trends to a stable value. Similarly, other experiments also have a stable distribution segment at the initial stage, after then the pressure value decrease slowly to a certain value (the other experiments' results not show as figures). Though pressure values in every experiment have a decreasing trend, the change of every pressure value is subtle. Consequently, the process and structure parameter have negligible effect on the pressure distribution.

3.3. Temperature Distribution

The temperature distribution lines in the chamber of every experiment are shown in figure 5 as follow:

![Figure 5. Gas Flow Temperature Distribution](image)

It can be concluded from figure 5 that while changing the chamber characteristic parameters, the pressure distribution show regularity. As the position value increases, the temperatures above 10mm of holder area keep a constant temperature at a segment. When reaching at a certain position, the temperatures decrease rapidly. Moreover, the reason lays in the fact that the holder is the main heat source that distribute uniformly, so the temperature distribution above holder area has uniform distribution. However, on the edge of holder, along with the gas flow and heat source disappearing, the
temperatures at this position change acutely. As every experiment from No.1 to No.9 has the same holder diameter. Therefore, every experiment has the same temperature distribution. While the chamber diameter varies, the temperature decreases until it equals to the temperature of wall. It is thus clear that when the holder is the main heat source, change of process and structure parameters barely affect the temperature.

3.4. Data Analysis
Through above analyses, it can be concluded that when the process and structure parameters changed, they had little influence on pressure and temperature distribution uniformity. However, the velocity distribution varied observably while the process and structure parameters changed. Therefore, the velocity difference value between the maximum and minimum velocity in the area above 10mm of holder could be used as the analytical factor. In addition, the velocity difference value can show the gas distribution uniformity above the holder. The fewer of the velocity difference value, the more uniformity of the gas distribution. The analysis of velocity difference value $\Delta V$ between the maximum and minimum velocity is shown in Table 2.

| No. | Column No. | Factor | Symbol | Inlet Mass Rate scrm | Holder Height mm | Chamber Diameter mm | Outlet Section Area $mm \times mm$ | Velocity Difference Value $\Delta V$ m/s |
|-----|------------|--------|--------|----------------------|------------------|---------------------|-----------------------------------|----------------------------------------|
| 1   | 1          | 1      | 1$(Q_1)$ | 1$(H_1)$ | 1$(D_1)$ | 1$(a_1 \times b)$ | 1.5                               |
| 2   | 2          | 2      | 1$(Q_1)$ | 2$(H_2)$ | 2$(D_2)$ | 2$(a_2 \times b)$ | 0.55                              |
| 3   | 3          | 3      | 1$(Q_1)$ | 3$(H_3)$ | 3$(D_3)$ | 3$(a_3 \times b)$ | 6.7                               |
| 4   | 4          | 4      | 2$(Q_2)$ | 1$(H_1)$ | 2$(D_2)$ | 3$(a_3 \times b)$ | 0.36                              |
| 5   | 5          | 5      | 2$(Q_2)$ | 2$(H_2)$ | 3$(D_3)$ | 1$(a_1 \times b)$ | 0.26                              |
| 6   | 6          | 6      | 2$(Q_2)$ | 3$(H_3)$ | 1$(D_1)$ | 2$(a_2 \times b)$ | 4.2                               |
| 7   | 7          | 7      | 3$(Q_3)$ | 1$(H_1)$ | 3$(D_3)$ | 2$(a_2 \times b)$ | 0.35                              |
| 8   | 8          | 8      | 3$(Q_3)$ | 2$(H_2)$ | 1$(D_1)$ | 3$(a_3 \times b)$ | 4.4                               |
| 9   | 9          | 9      | 3$(Q_3)$ | 3$(H_3)$ | 2$(D_2)$ | 1$(a_1 \times b)$ | 2                                 |

Table 3. Results Analysis

|       | 1     | 2     | 3     | 4     |
|-------|-------|-------|-------|-------|
| K1    | 8.75  | 2.21  | 7.7   | 3.76  |
| K2    | 4.82  | 5.21  | 2.91  | 5.1   |
| K3    | 6.75  | 12.9  | 7.31  | 11.46 |
| k1    | 2.19  | 0.55  | 1.93  | 0.94  |
| k2    | 1.20  | 1.30  | 0.73  | 1.28  |
| k3    | 1.69  | 3.23  | 1.20  | 2.87  |
| Range | 0.99  | 2.68  | 1.20  | 1.93  |

Important Order $H=S>d>Q$

The velocity difference value between the maximum and minimum values reflects velocity changes of the airflow above holder. Moreover, the velocity distribution also plays a pivotal role in the process of practical devices, such as thin film deposition or etching. Uniform gas flow means a uniform distribution process gas, whose velocity distribution affects the practical process substantially. From the results of orthogonally designed experiment in Table 3, the sequence of factors affecting the gas distribution is holder height, outlet section area, chamber height and inlet mass. In addition, the holder
height, corresponding to chamber height or the distance between up and down electrode, is the most significant factor affecting the uniformity of gas distribution in practical devices. In conclusion, at the initial stage of device design, the chamber height and electrode distance should be confirmed firstly. Furthermore, various outlet section areas still affect the gas distribution. Since the outlet section area is different, the outlet gas flow under a certain vacuum pumping speed also differs. In other words, the changes in outlet gas flow affect gas distribution above the holder area in chamber. Hence, under circumstances of satisfying structure performance and cost control requirements with similar cases, install valves can adjust sizes of outlet section, so as to suffice various process requirements. In actual process devices, we can increase chamber diameter under cost control limitations, enhancing the capability of handling chips simultaneously and process efficiency as well.

Conclusion
The parameters of processing chamber such as inlet mass rate $Q$, holder height (instead of chamber height) $H$, chamber diameter $D$, outlet section area $S$, all of which have three levels, have been modelled and analysed by the orthogonal experimental design. Firstly, the orthogonal experiment design table was built with numbers of factors and levels of every factor. After analysing the velocity, pressure and temperature distribution in the area of 10mm above the holder, the velocity difference value between the maximum and minimum velocity is chosen as the analytical index. Furthermore, from the results of orthogonally designed experiment, the sequence of indexes affecting the gas distribution uniformity is holder height, outlet section area, chamber height and inlet mass. Finally, it comes to the conclusion that the experiment results could be a reference for IC processing chamber design and manufacture.

As the IC process is a complicated physical chemical process, under the coupling of physical field and multiphase, further works and theoretical study are needed to simulate the comprehensive process by considering the coupling of flow field, thermal field, electromagnetic field, and plasma and chemistry reaction simultaneously. Meanwhile, the simulation results also should be verified with experimental data. The research in this paper is a guide for development and application of chamber structure design. Hence further research about the uniformity of plasma distribution is needed, which will be our main research work in future.

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