Study on temperature field and flow field of doped oxidized silicon wafer prepared by vertical furnace

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Abstract. In this paper, the temperature field and flow field of the doped oxidized silicon wafer are studied by finite element simulation. The preparation parameters are optimized. The simulation results are verified by experiments. Experiment and simulation results show that the heater on the wafer surface temperature significantly affect the homogeneity. The temperature uniformity of the wafer surface at the bottom of the reaction chamber is significantly affected by the pedestal. By using the vertical diffusion furnace to prepare the doped oxidized silicon wafer, the uniformity of the film thickness is guaranteed. Finally, high quality silicon wafers are prepared in batches.

1. Introduction
Semiconductor industry is a high technology industry. The industry continues to reduce the size of the chip while expanding the size of the wafer to improve chip production and reduce chip costs[1]. Technology of semiconductor manufacturing equipment is higher required by The continuous and rapid development of semiconductor manufacturing process[2]. 300mm semiconductor diffusion equipment has become the mainstream equipment in the international semiconductor industry. The level of semiconductor process equipment in China lags behind the international level. At present, the stage of 300mm semiconductor diffusion equipment is still researched and developed in China. In recent years, The preferential policies are formulated[3]. Integrated circuit manufacturing factories have been set up in line with international standards. The independent research and industrialization indicate rapid development of Semiconductor integrated circuit in China. As the key technology of semiconductor diffusion equipment, the reaction chamber is in urgent need of research and analysis.

300mm wafer fabrication process demands the equipment. It is of great significance to study the reaction chamber of the key components of semiconductor diffusion equipment. At a given temperature, the process gas reaction generates the appropriate film. In the process, the stable temperature in the thermal reaction chamber must be ensured, and the temperature required by the process can be achieved. The instability of the airflow in the reaction chamber will also lead to poor technical results. In this paper, SiO₂ thin films are prepared by vertical diffusion furnace. C₂H₂Cl₂ as reactant is using for the growth of the oxide film. The influence of reaction chamber parameters on the temperature field and flow field is studied by finite element simulation method, and the process parameters of suitable for doping oxidation are obtained. A method for preparing oxide film with good uniformity of batch silicon wafer is explored.
2. Finite element model

The reaction chamber is the key component of the semiconductor diffusion equipment. It is mainly composed of process tube, boat, pedestal, thermocouple, heater and process tube fixing assembly. The reaction chamber is modeled by Solidworks 3D modeling software. As shown in Figure 1, the process tube used in this experiment is a cylindrical single layer tube. The reaction chamber can process 125 wafers simultaneously. Silicon wafer is the standard size wafer of 300mm in diameter.

The process tube makes the silicon wafer separate from the outside to form a sealed chamber. The process tube fixing assembly fixed the process tube on the equipment. The sealing ring is isolated from outside pollutants into equipment. The boat loads multiple silicon wafers in a stacked manner. The pedestal below the boat is used to keep the reaction chamber constant temperature. The pedestal is also used for heat insulation to protect the parts below the pedestal. The boat and the pedestal enter the process tube, and the constant temperature of the reaction chamber is controlled by the thermocouple, and the process gas is injected into the process. As the process is carried out at higher temperatures, the components in the reaction chamber are required to withstand high temperatures, and parts of the material under high temperature can not pollute the reaction chamber.

![Figure 1. Structure diagram of reaction chamber.](image)

1- process tube; 2- boat; 3- pedestal; 4- process tube fixing assembly; 5- thermocouple

The finite element software FLUENT was used to simulate the reaction chamber. the model is meshed by software. Because the wafer thickness is too small in comparison with the size of the reaction chamber, in this case, simple and unified mesh partition is not suitable for the experiment. The general processing method is to block the model and encrypt the key parts of the grid.
After completing the design of the reaction chamber structure, the uniformity of the temperature field and the airflow field in the process tube are simulated and analyzed, which is an important index for the design to meet the process requirements. The simulation conditions are set according to the actual process requirements. The exhaust pressure is -40 Pa. The temperature boundary condition is set to 800 °C. Considering the cooling water circulation in the reaction chamber, according to the experimental data, the temperature of the cooling water of the heater is generally about 30 °C. Therefore, the wall of the heater is set at constant temperature which is 30 °C. Table 1 lists the physical properties of quartz and silicon wafers.

| Name  | Density (kg · m⁻³) | Thermal coefficient (W · (m · K)⁻¹) | Specific heat capacity (J · (kg · °C)⁻¹) |
|-------|-------------------|---------------------------------|-------------------------------------|
| GE214 | 2210              | 1.38                            | 968                                 |
| OP3   | 2000              | 1.24                            | 926                                 |
| Silicon | 2330          | 124                             | 702                                 |

3. Temperature field and flow field  
After setting the simulation parameters, according to the existing experimental data, the process gas inlet flow is set to 20L/min, 30L/min, 40L/min, the other conditions are consistent with the airflow field simulation. It is found that with the increase of gas flow, the thickness of SiO2 film is thicker. Figure 3 is the flow velocity simulation of the process gas inlet flow rate of 30L/min. As shown in Figure 3a, the velocity streamlines show uniform spiral distribution, which indicates that the overall airflow field of the reaction chamber is uniform. The maximum speed difference is 0.28m/s. As shown in Figure 3b, the velocity distribution at the bottom 500mm of the process tube is concentric circle. The velocity appears uniform gradient variation along the radial direction. It shows that the velocity of the same diameter of the process tube is basically the same, and the maximum speed difference is 0.03m/s. The simulation results show that the speed of the process tube is concentric circle at different heights. For single wafer surface uniformity, it is found from the cross section that the gas distribution in the same diameter position is uniform, which is beneficial to the uniformity of the radial film thickness of silicon wafer. As the diameter becomes larger, the velocity of process gas increases and the amount of reaction gas increases in the same time. The thickness of silicon wafer is annular, outer
thickness and inner thin. The maximum speed difference is 0.26m/s. As shown in Figure 3c, the velocity variation on the longitudinal section of the process tube is not obvious, and the maximum speed difference is 0.07m/s. For the uniformity of the surface of different silicon wafers, from the longitudinal section analysis, it is found that the velocity change is not obvious and the uniformity between the surfaces is good.

The inlet air volume is too small, the air velocity difference becomes smaller, the uniformity becomes better, and the film thickness is thinner. When the inlet air volume is too large, the air velocity difference becomes larger and the uniformity becomes worse, which leads to the thickness of the film being thicker. According to the above simulation analysis and experimental data available. The intake flow is set to 30L/min, different wafer uniformity is good. The outer layer of the same silicon wafer is slightly thicker than the inside.

According to the simulation analysis, with the increase of temperature, the SiO$_2$ film formed by doping oxidation becomes thicker. When the heater is 800℃, the temperature distribution on the cross section of the process tube is concentric circle and varies uniformly along the radial direction. The temperature of the same diameter in the cross section of the reaction chamber is the same, and the simulation results show that the temperature at different heights is concentric. For single wafer surface uniformity, it is found from the cross section that the temperature distribution in the same diameter position is uniform, which is beneficial to the uniformity of the radial film thickness of silicon wafer. As the diameter increases, the temperature variation is not obvious, and the maximum temperature difference at the bottom of the reaction chamber is 1.7℃. From the longitudinal section analysis, it is found that the temperature change in the middle and upper part of the reaction chamber is not obvious, which is beneficial to the uniformity of the surface. The reaction chamber through the upper and middle part of the heater temperature field can effectively control the uniformity of film thickness, but the temperature at the bottom of the reaction chamber by heating wire and pedestal. The pedestal
belongs to the passive endothermic and exothermic structure, and does not produce heat itself. With the increase of weight, the heat capacity of the pedestal increases, and the endothermic and exothermic rate decreases. The temperature rising and cooling rate simulation of the heat preservation barrel is shown in figure 4.

![Temperature variation curve of pedestal.](image1)

In summary, when the heater is 800°C, the surface uniformity is good. The outer surface of the doped oxide film is slightly thinner than the inside, but it can counteract the difference of the thickness of the inner surface under the action of the airflow field. The temperature at the bottom of the reaction chamber is caused by the heating wire and the pedestal. The thickness of the outer silicon wafer is thicker than that of the inner silicon wafer.

4. Experiment

In order to verify the simulation results, a new type of oxidation furnace equipment is developed. In the experiment, the heater temperature is 800°C, and the reaction chamber pressure is -40 Pa. In the experiment, the temperature distribution of different silicon wafers is measured by R thermocouple, and the temperature distribution in the surface of single silicon wafer is measured by TC-Wafer sensor. Figure 5 shows the difference of temperature between different silicon wafers in the reaction chamber. It can be seen from the data that the temperature of different silicon wafers is within the range of
800°C ± 1°C. This is consistent with the changing trend of the simulation results. In contrast, the change rate of temperature distribution at the two ends of the reaction chamber is much higher than that of the simulation results. The reason for this problem may be the insufficient consideration of convection heat transfer in simulation.

Figure 5. Temperature distribution curves of different silicon wafers.

According to the simulation results, the temperature uniformity of the wafer surface in the bottom of the reaction chamber is the worst. The bottom position was selected for testing. Table 2 shows the temperature distribution at the different positions of the bottom of the reaction chamber. $X_1$, $X_2$, $X_3$, and $X_4$ are the temperature measurement points at the edge of silicon wafer. $Y_1$ and $Y_2$ are the temperature measuring points at the center of silicon wafer. $\bar{X}$ is the average value of the edge. $\bar{Y}$ is the average value of the center. In the three repeated test, the maximum difference of temperature in different positions was 1.3°C. The intermediate temperature is lower than the external temperature, which is different from the simulation results. The temperature distribution of the silicon wafer is affected by the large amount of heat absorbed by the pedestal.

Table 2. Temperature distribution at different positions of a single wafer.

| Number | $X_1$/°C | $X_2$/°C | $X_3$/°C | $X_4$/°C | $Y_1$/°C | $Y_2$/°C | $\bar{X}$/°C | $\bar{Y}$/°C | $\bar{X}-\bar{Y}$/°C |
|--------|-----------|-----------|-----------|-----------|-----------|-----------|-------------|-------------|-----------------|
| 1      | 820.2     | 818.6     | 821.2     | 822.5     | 819.5     | 819.8     | 820.6       | 819.7       | 0.9             |
| 2      | 820.1     | 818.7     | 819.9     | 821.7     | 818.8     | 819.1     | 820.1       | 819.0       | 1.1             |
| 3      | 820.4     | 818.8     | 820.9     | 822.4     | 819.1     | 819.5     | 820.6       | 819.3       | 1.3             |

The SiO$_2$ film is doped and oxidized by DCE process. The thickness of silicon wafer is measured after the experiment. The influence of temperature field and flow field on the structure and quality of SiO$_2$ wafers doped with oxide is analyzed. The simulation results are verified. The thickness distribution of the silicon wafer is analyzed. The thickness of the outer silicon wafer is thicker than that of the inner silicon wafer. It is positively correlated with the temperature distribution in Table 2. It is proved that the temperature has great influence on the growth of oxide film. Figure 6 is the thickness curve of silicon wafer. STD is the standard deviation of the thickness of silicon wafer in different positions. CL is control line. The thickness uniformity of all silicon wafers is less than 0.39. This is to meet the requirements of the process. Therefore, The silicon wafer has a uniform temperature distribution and a good uniformity of film thickness. The growth of doped oxide film can be satisfied. High quality silicon wafers are prepared.
Figure 6. Film thickness curve of silicon wafer.

5. Conclusion
In the process of preparation of SiO$_2$ film doped oxide silicon wafer, the uniformity of temperature field and flow field near the silicon wafer will determine the film thickness uniformity. The controlled effective change of temperature field and flow field is the focus of research in preparation of doped silicon oxide film. In this paper, the main factors that affect the temperature field and flow field are analyzed by the finite element simulation method. The experimental parameters for the uniform flow field and temperature field near the silicon wafer are obtained, and the simulation is verified by experiments. The temperature uniformity of the wafer surface at the bottom of the reaction chamber is significantly affected by the pedestal. By using the vertical diffusion furnace to prepare the doped oxidized silicon wafer, the uniformity of the film thickness is guaranteed. Finally, high quality silicon wafers are prepared in batches.

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