Modeling and Simulation of a Vacuum System Used in Semiconductor Manufacturing

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Abstract. The etching process is always carried out in an extremely high vacuum system. When performing batch operations such as transferring wafers, the vacuum degree will fluctuate violently if we don't control it, and the case is prohibitive. The simulation models of the vacuum and the essential valve are established, and calculation results are shown. The conductance of the valve is analyzed with opening of the valve plate.

Keywords: Vacuum System, Valve Plate, Conductance, Modeling, Simulation

1 Introduction

Etching is one of the most critical techniques in integrated circuit manufacturing for pattern transfer, second only to photolithography[1]. It determines the dimensional accuracy, actual performance, and integrability of devices[2]. Etching reactions typically occur in a high-vacuum environment, making the design and control of the vacuum system crucial. The vacuum system must quickly achieve the required low-pressure state and maintain a stable vacuum during the etching process to ensure uniform and repeatable etching reactions.

In vacuum system design, calculating the conductance of pipeline components and certain sections of the vacuum system is essential[3]. The Monte Carlo simulation is a commonly used method for vacuum system conductance calculations[4], providing less deviation compared to traditional theoretical methods. Early proponents of calculation formulas include Knudsen, Dusham, and Clausing[5]. Guo Wanshi[6] suggested that although these formulas are precise and theoretically significant, they are complex and inconvenient in practical use. Thus, deriving conductance probabilities from different forms of the Clausing equation results in simpler and more applicable formulas. Huang Si[7] simplified medium and low vacuum systems into systems comprising a vacuum chamber, vacuum pipeline, and vacuum pump for studying vacuum flow states. Gong Wei[8] analyzed correction factors for small-hole conductance in ultra-high vacuum calibration systems and dynamic flow calibration systems. Peng Nan[9] calculated the conductance of louvered and herringbone baffles. Qi Weihong[10] calculated the conductance of vacuum angle valves in molecular flow. Yuan Shuaiyang[11] studied the flow characteristics of high vacuum gate valves. Peng Chuantao[12] researched the conductance of metal sealing rings in high vacuum valves. However, valve plate, commonly used in etching processes, have relatively sparse conductance studies, thus this paper aims to theoretically and simulate the conductance of valve plate to provide reference for related personnel.

This study aims to establish a simulation model of the vacuum system in semiconductor etching using simulation software to deeply analyze the conductance characteristics of the vacuum system. It studies the conductance variation with valve opening changes, achieving precise control of the vacuum degree during the etching process, and providing guidance for optimizing actual equipment.

2 Function and Structure of Vacuum System

The main function of the vacuum system is to evacuate the air and other gases from the reaction chamber, creating and maintaining a low-pressure environment. When gas flow is in the free molecular flow region, collisions between molecules can be ignored, and only collisions between molecules and walls need to be considered. In rectangular microchannels, only geometric factors of airflow are considered, while other non-geometric factors like gas temperature and pressure are included in the inlet conductance. This allows separating the study of non-geometric and geometric factors[13]. A typical vacuum system includes components such as vacuum pumps, vacuum chambers, vacuum valves, pressure sensors, and control systems[14]. Its basic principle is shown in Figure 1. The reaction gas enters the reaction chamber through the intake pipeline and is then evacuated by the vacuum pump through the vacuum valve. The pressure sensor continuously monitors the pressure in the reaction chamber and transmits the pressure data to the control system. The control system adjusts the valve plate based on the current pressure readings, thus reasonably and quickly controlling the vacuum degree in the reaction chamber.

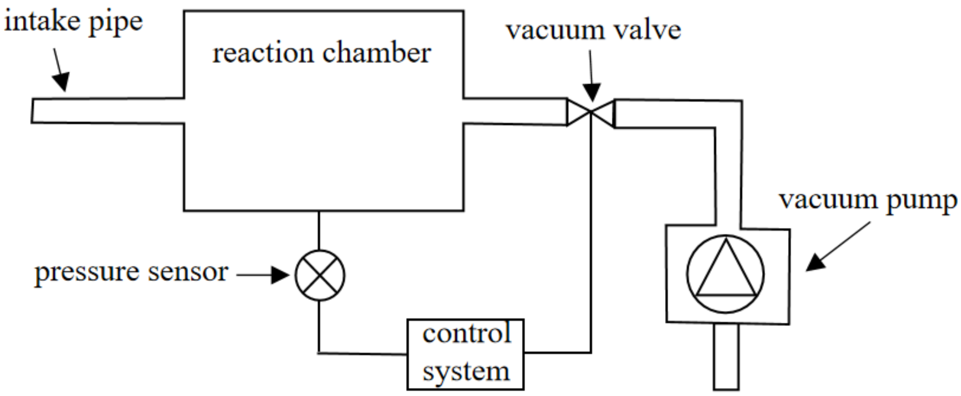

Fig. 1. Schematic diagram of the vacuum system operation

3 System Modeling

Vacuum degree control involves the interaction of multiple factors, including the performance of vacuum pumps, system conductance characteristics, and precise adjustment of valve plate. Traditional control methods often rely on experience and trial-and-error, which are inefficient and inaccurate for complex semiconductor etching equipment. Therefore, using simulation technology to optimize vacuum system design and control strategies has become an efficient and reliable solution.

3.1 Reaction Chamber

For a vacuum system, assuming the internal gas is ideal, with no intermolecular interactions and negligible molecular volume, it satisfies the ideal gas law:

$$PV = nRT \tag{1}$$

where P is the gas pressure in Pa, V is the gas volume in L, n is the amount of gas in mol, R is the ideal gas constant in J/(mol·K), and T is the absolute temperature of the gas in K.

During the evacuation process, the gas continuously flows, and the flow rate Q at the entrance is calculated as:

$$Q = \frac{d(PV)}{dt} \tag{2}$$

where t is time in s. Q is a parameter that describes gas flow in sccm, considering the invariability under different gas states, similar to how mass flow rate remains constant under different states.

3.2 Valve Plate

Due to the continuous change of the valve plate opening during the operation of the valve plate, the valve plate can be equivalent to a circular hole with a continuously changing gas flow area. The conductance of the valve plate in molecular flow is approximated using the conductance formula for a circular tube.For a vacuum component, its conductance calculation formula is:

$$C = \frac{Q}{\Delta P} \tag{3}$$

Since the valve plate will continuously change its opening when the vacuum valve is working, the vacuum valve can be equivalent to a circular hole with a continuously changing gas flow area. According to the conductance formula of the circular tube, the approximate conductance of the valve plate in molecular flow can be derived.The flow rate of gas through the circular hole in molecular flow is:

$$Q_{mk} = \sqrt{\frac{RT}{2\pi M}}(P_1 - P_2)A_0 = 1.15\sqrt{\frac{T}{M}}(P_1 - P_2)A_0 = 0.9\sqrt{\frac{T}{M}}(P_1 - P_2)D^2 \tag{4}$$

where Q_{mk} is the gas flow through the circular hole in Pa·m^3/s, A_0 is the area of the circular hole in m^2, P_1 and P_2 are the pressures at the inlet and outlet of the pipeline in Pa, D is the diameter of the circular hole in m, and M is the molar mass of the gas in kg/mol.The conductance C of the circular hole is calculated as:

$$C = 0.9\sqrt{\frac{T}{M}}D^2 \tag{5}$$

By combining (3) and (5), we can obtain the relationship between the pressure at the valve and the flow area of the valve when the inlet flow rate in a vacuum system is known:

$$P = \frac{Q}{0.9D^2}\sqrt{\frac{M}{T}} \tag{6}$$

3.3 Vacuum Bump

Under high vacuum conditions, gas molecule motion is constrained by the mean free path, and molecular flow theory is applicable. The specific flow rate equation can be described by combining the basic formula of molecular flow:

$$Q = \frac{1}{4} nvA \tag{7}$$

where n is the number density of gas molecules in m^{-3}; v is the average speed of gas molecules in $m \cdot s^{-1}$; A is the effective cross-sectional area of the pump in m^2.

The number density of molecules n:

$$n = \frac{P}{k_B T} \tag{8}$$

where k_B is the boltzmann constant in $J \cdot K^{-1}$; P is gas pressure.

The average speed v:

$$v = \sqrt{\frac{8 k_B T}{\pi m}} \tag{9}$$

where m is the the mass of gas molecules in kg.

Substituting equations (8) and (9) into equation (7),the specific flow rate expression for a vacuum pump under molecular flow conditions is:

$$Q = PA \sqrt{\frac{1}{2\pi m k_B T}} \tag{10}$$

4 Simulation

4.1 Simulation of Valve Flow Area

A typical vacuum system can be simplified into the model shown in Figure 2. The entire model includes a reaction chamber, an L-shaped circular tube at the entrance, and a pathway below the reaction chamber, which contains a valve plate body and its movement space. The valve body of the valve plate is modeled according to its characteristics. The pressure value at the yellow point on the outer side of the reaction chamber is calculated using simulation software to analyze the conductance variation with valve opening changes.

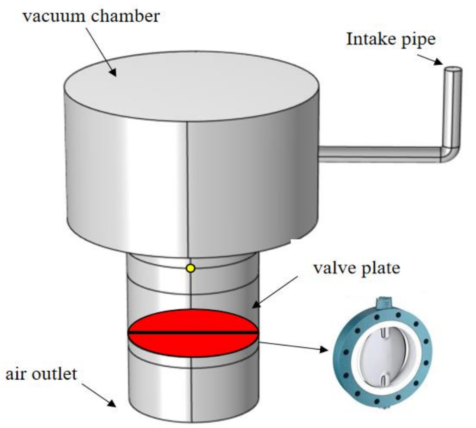

Fig. 2. Schematic diagram of the simulation model

The change in flow area of the valve during opening and closing is analyzed. Assuming the flow area is a cross-section, a 1.5mm space is added between the upper cross-section and the top of the valve plate to ensure that the pressure inside the chamber does not increase indefinitely when the valve is closed. By rotating the valve plate 0.5° each time from fully open to closed, the relationship between valve opening and flow area can be obtained, as shown in Figure 3.

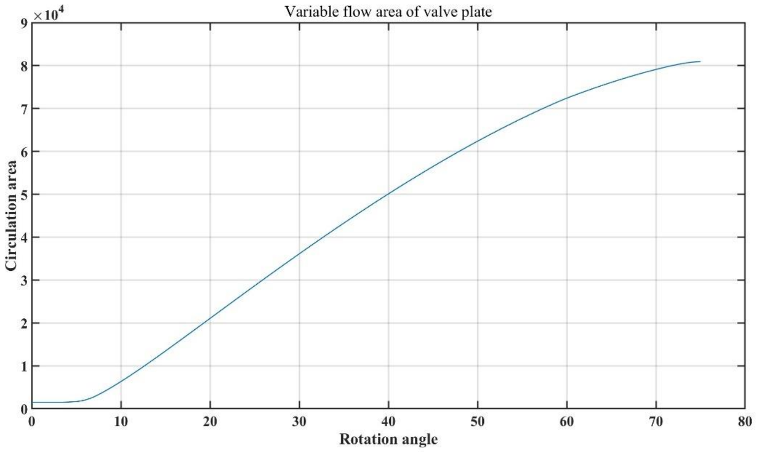

Fig. 3. Flow area variation

Firstly, within a small angle range (0° to 30°), the flow area exhibits high sensitivity to changes in the angle. In this range, the reduction in flow area is relatively rapid, indicating that the flow rate is highly responsive to changes in valve opening. Therefore, in practical system control, it is recommended to adopt more precise control methods when the valve opening is small. For example, a high-resolution angle controller and a highly sensitive pressure sensor can be introduced to achieve finer control over flow rate changes during small-angle adjustments. This meticulous adjustment approach helps to avoid excessive flow fluctuations, ensuring that system pressure remains within the desired range, thereby improving system stability and control accuracy.

Conversely, in the large-angle range (30° to 75°), changes in the flow area tend to flatten, showing lower sensitivity. Thus, in this angle range, the opening and closing process of the valve has a relatively minor impact on the flow rate and pressure. In practical control, a rougher adjustment method can be employed, reducing the need for precise control over valve angles. This not only simplifies the design of the control system but also improves the efficiency of valve operation and reduces response time while maintaining the performance of the vacuum system.

Finally, based on the variation of the flow area during the valve's opening and closing process, a dynamic control strategy can be introduced into the actual control system. Given the nonlinear relationship between flow area and opening angle, the control system should have adaptive adjustment capabilities. In the range of smaller valve openings, the control system should operate at a slower opening and closing speed to ensure precise control of flow rate and pressure. However, in the range of larger openings, the system can increase the speed of opening and closing to improve overall operational efficiency. Moreover, by combining real-time feedback during the opening and closing process with the simulated results of the conductance change, the control system can dynamically adjust the valve opening to achieve optimal control of the target vacuum level and flow rate.

4.2 Simulation of Valve Plate Flow Characteristics

To simplify the complex gas dynamics process, thermal radiation effects and surface chemical reactions are ignored[15]. Using numerical simulation software, the gas transmission process is simulated. By using the Navier-Stokes method and traditional computational fluid dynamics, the pressure model after simulation is obtained, giving the pressure value at a certain point in the reaction chamber.

Initial conditions for the simulation include: boundary material as aluminum alloy, simulated gas as nitrogen, environmental temperature at 293.15K, initial pressure at 10^5Pa, inlet flow rate at 100sccm, and pump speed at 3000L/s for the vacuum pump at the outlet. Under these conditions, the simulation is conducted by rotating the valve plate 0.75° each time and simulating multiple times, converting the pressure values at the red point to conductance. The relationship between valve opening from 0-100 and conductance is obtained, as shown in Figure 4.

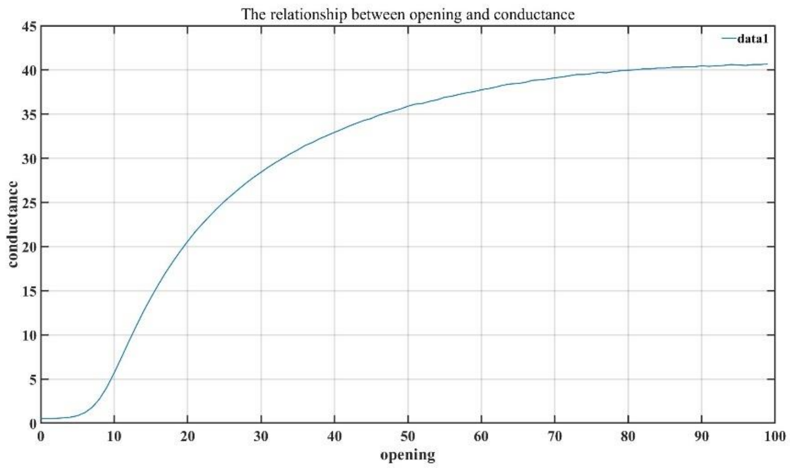

Fig. 4. Relationship between valve opening and conductance

According to the simulation results, in the range of 0° to 20°, the conductance is highly sensitive to changes in valve opening, especially between 0° and 10°, where conductance increases rapidly. In the actual system, when the valve operates within this small opening range, a more precise control strategy is required. For instance, high-resolution controllers and sensitive pressure sensors should be employed to finely adjust the valve opening and better manage flow rate and system pressure. This fine-tuned control will help avoid significant fluctuations in flow rate and pressure, which could destabilize the system. Such precise control is particularly important during the system start-up phase or when small flow adjustments are needed.

Between 20° and 40°, the rate of increase in conductance begins to slow down, acting as a transition zone between small and large openings. In this range, the control system can use a more moderate approach, without requiring the same level of precision as in the small opening range. However, the system should still maintain flexibility to ensure a smooth increase in conductance. This range is typically used during steady-state operation when the system requires a stable flow to maintain vacuum conditions inside the chamber.

When the valve opening exceeds 40°, the increase in conductance flattens, and from 60° to 100°, it tends to stabilize. In this range, the conductance is less sensitive to valve opening changes, allowing for a more coarse control strategy. For instance, when operating the valve in a large opening range, the opening and closing process can be sped up without precise adjustments. This operation phase is most suitable when the system is in a high vacuum state, and fast adjustments to gas flow are needed. Since pressure changes are relatively stable in this range, the system can focus more on efficiency than on fine-tuned control.

Incorporating a dynamic adjustment mechanism based on real-time feedback of pressure and flow rate can optimize the control strategy further. The control system should have adaptive capabilities to adjust the valve opening based on the conductance changes in different opening ranges. Particularly during the transition from small to medium openings, the system should dynamically adjust its control logic to maintain stable conductance.

5. application

In the vacuum system, only the pressure magnitude is monitored. Additionally, the container size of the reaction chamber need to be estimated. To estimate the volume V, the PV flow equation of the gas is:

$$\frac{d(PV)}{dt} = Q - CP \tag{10}$$

Now, assuming the volume V is constant (the volume of the container does not change over time). Considering P is the pressure of the gas and V is constant, the above equation can be rewritten and arranged:

$$\frac{dP}{dt} = \frac{Q}{V} - P\frac{C}{V} \tag{11}$$

This is a first-order linear differential equation with constant coefficients, which describes how the pressure P changes over time t. To solve this equation, assume that at t=0, the pressure is P_0, and as $t\to\infty$, the pressure approaches the steady pressure P_∞.

By separating the variables in equation (7), we get:

$$\frac{dP}{P_\infty - P} = -C\frac{dt}{V} \tag{12}$$

Integrating both sides simultaneously from $t = 0$ to $t = t$ and from $P = P_0$ to $P = P(t)$:

$$\int_{P0}^{P(t)} \frac{dP}{P_\infty - P} = -\int_0^t C\frac{dt}{V} \tag{13}$$

The integral on the left side results in the negative natural logarithm function, while the right side integral is linear function with respect to t. Combining and solving:

$$P(t) = P_\infty + (P_0 - P_\infty)e^{-\frac{C}{V}t} \tag{14}$$

This equation describes how the pressure P changes over time t, where P_∞ is the steady pressure after a long time and P_0 is the initial pressure. The term $e^{-\frac{C}{V}t}$ is a decay factor that describes how the pressure grows from its initial value to its steady value. Based on the above formula, during the volume estimation process, the pressure must be in the rising phase.

Thus, it is only necessary to select any two points during the dynamic process for calculation, without waiting for the pressure to reach a steady state. Taking the natural logarithm:

$$ln(P(t) - P_\infty) = ln(P_0 - P_\infty) - \frac{Ct}{V} \tag{15}$$

Given Q/C=P_∞, the volume V can be obtained as:

$$V = \frac{Ct}{ln\left(\frac{P_0 - \frac{Q}{C}}{P(t) - \frac{Q}{C}}\right)} \tag{16}$$

The above formula can be used to calculate the size of a reaction chamber. When a vacuum valve moves its valve plate from fully open to fully closed, the pressure value recorded over a period of time is shown in the figure 5. Any two points can be selected for calculation during the dynamic process, and the volume of the vacuum chamber can be calculated to be 78.4L by taking the average value of multiple calculations.

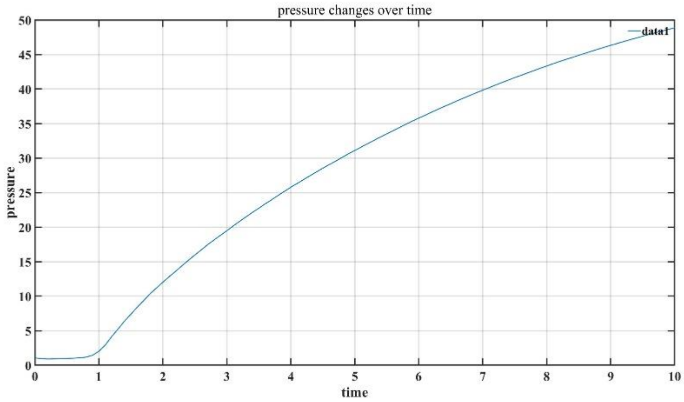

Fig. 5. Pressure change diagram of valve from fully open to fully closed

6 Conclusion

This study investigated the vacuum system in the etching process, conducting a theoretical analysis of a vacuum system with valve plate under molecular flow conditions. A simulation model was established using simulation software to analyze the variation in flow area during the opening and closing of the valve plate. It was found that the flow area is less sensitive to changes in larger angle ranges. The relationship between the valve opening and conductance was also simulated and calculated. The change in conductance is not linear; it decreases more rapidly with increasing opening, and the rate of decrease slows and becomes more stable at larger openings. This relationship allows for basic control of the valve plate, enabling the current vacuum system to achieve the required vacuum degree. Finally, A method has been proposed to estimate the volume of the reaction chamber.

References

1. Wu, B., Kumar, A., Pamarthy, S. "High aspect ratio silicon etch: A review." Journal of Applied Physics, 2010, 108: 051101.
2. Vakkada Ramachandran, A., Nazarious, M.I., Mathanlal, T., Zorzano, M-P., et al. "Space Environmental Chamber for Planetary Studies." Sensors, 2020; 20(14): 3996.
3. Hucknall, D. J. "Vacuum Technology and Applications." [M]. 1991.
4. Bello, Igor. "Vacuum and Ultravacuum: Physics and Technology." [M]. CRC Press, 2017-11-02.
5. Loeb, L. B. "The Kinetic Theory of Gases." [M]. Courier Dover Publications.
6. Guo, Wantu. "Calculation of Molecular Flow Conductance Probability through Circular Ducts." [J]. Vacuum Science and Technology, 1982(06): 366-37.
7. Huang, Si, Guo, Jiawei, Yi, Tiankun, et al. "Study on the Calculation Method for Pumping Process in a Vacuum System." [J]. Journal of Physics: Conference Series, 2021.
8. Gong, Wei, Zhang, Dixin, Cheng, Yongjun, Feng, Yan, Lu, Yaowen. "Theoretical Calculation and Monte Carlo Calculation of Small Hole Conductance." [J]. Vacuum and Cryogenics, 2009, 15(04): 215-221.

9. Peng, Nan, Xiong, Lianyou, Liu, Liqiang, Zhang, Liang. "Calculation of Conductance Probability for Cryopump Radiation Baffles." [J]. Cryogenic Engineering, 2006(06): 21-24+34.
10. Qi, Weihong, Bao, Gang, Zhu, Dong, Xu, Kai. "Study on Conductance of High Vacuum Valves in Molecular Flow." [J]. Machine Tool & Hydraulics, 2013, 41(09): 35-38.
11. Yuan, Shuaiyang. "Research and Analysis of Detection Mechanism of Low Particle High Vacuum Gate Valve." [D]. University of Electronic Science and Technology of China.
12. Peng, Chuantao. "Performance Analysis and Structural Optimization of Metal Sealing Rings for Ultra-High Vacuum Valves." [D]. Sichuan University.
13. Zhang, Yichen, Chen, Rongfa, Li, Canlun. "Vacuum System Design." [M]. Beijing: Metallurgical Industry Press, 2013.
14. Shi, Yu. "Fault Analysis and Troubleshooting of QSN750 Direct Reading Spectrometer Vacuum System." [J]. Analytical Instrumentation, 2010(4): 72-73.
15. Yu, H. Q., Zou, R. "Design and Numerical Simulation of Vertical Spray Atomic Layer Deposition Reactor." [J]. Science Technology and Engineering, 2011, 30: 7433-06.