Dwelling time calculation for film uniformity correction
by ion beam sputtering process on larger optical
materials

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Abstract: It is difficult to obtain film with uniform thickness and constant
performance for optical components with larger diameter. It is a critical technology to
improve the film uniformity during the deposition process. The ion beam sputtering
system was used to prepare the film on the surface of large-aperture optical elements.
The performance of film including thickness and roughness were measured by step
profiler and optical profilometer instrument. The film thickness correction model was
proposed in this paper. The optimized dwell time ratio was obtained by the film
thickness data obtained from former experiments, and the dwell time distribution was
calculated, after several iteration with the model, uniform film can be achieved on
optical elements over 300mm in diameter. Taking the Si film on the surface of fused
silica as an example. The research results show that, different film thickness between
100nm and 400nm can be obtained, when the film thickness is more than 200nm, the
film uniformity from more than 13% to less than 0.5%. The surface roughness
variation of optical material before and after film deposition were studied, which
provide stable process for obtaining high performance film on larger optical
components.

1. Introduction
Optical films have been widely used in optical systems, and the film quality has a significant
influence on their application. Higher energy of the particles can be obtained by the ion
beam sputter deposition process [1]. Compared with other film deposition technologies,
ion beam sputtering has the advantages of higher purity, lower substrate temperature, better repeatability, and different kind of films, because it's slower deposition rate, it is easy to monitor the entire deposition process.

Interference optical film by ion beam sputtering deposition has been carried out since the 1970s, but the film quality was not very good in the early days. The wide beam ion source made a breakthrough in ion beam sputtering in 1975, and the interference optical thin film with very low loss was prepared successfully [2]. At present, with the development of science and technology, this technology has gradually improved. It can not only produce ultra-low-loss reflective mirrors with high reflectivity, but also can be used to prepare the planarization layer films, which is necessary in the ion beam deposition correction polishing technology [3].

Ion beam sputtering and deposition is a new film formation technology developed on the basis of ion beam technology. The ion beam is composed of the ions of the inert gas. The high energy ion beam impacts on the target of the material that needs to be deposited. It causes the sputtering of the target atoms, and then the film is deposited on the surface of the optical element.

Nowadays, large-aperture optical elements are often used in high-quality optical systems. The film thickness uniformity is difficult to control during deposition process. The factors affecting the uniformity of the film are closely related to the process used and the deposition method [4]. The film thickness correction experiments were carried out by using ion beam figuring system, and then we can effectively solve the problem of film thickness uniformity by optimizing the center /edge dwell time ratio and other parameters. Due to the stability of the deposition rate, the time monitoring method for film thickness correction makes the whole process easier to automate. The RF ion source was adopted, due to the single-charged ion in the plasma generated by RF induction, small amount of ion sputtering on the screen grid, which increases the uniformity of the beam [5]. In addition, it also has the advantages of simple structure and electrodeless discharge, which make it provide better quality film. Furthermore, the film can be applied widely in the aviation and aerospace fields.

The research mainly focuses on the sputtering process in this paper, the ion beam sputtering (IBS) system was used, and the uniformity of deposited films on large-aperture optical elements by controlling ion beam stability and optimizing the center/edge dwell time ratio, the film with different thickness were obtained on the surface of larger optical components. Uniform film can be achieved on optical elements over 300mm in diameter.

2. Ion beam sputtering (IBS) process

In this experiment, the ion beam sputtering and polishing system was used for film deposition and OTFP ST50 film thickness device was used to measure the thickness of the deposited silicon film.

The parameters of the RF ion source used in the experiment are the following, frequency is 13.56MHz, power is 120W, ion beam is 20mmFWHM.

After ensuring that the power supply and the water-cooling device can work normally, the experimental research started. Argon was selected as the working gas; the silicon film was deposited on the fused silica with the diameter of 300mm. Figure 1 shows a schematic diagram of the experimental process. The optical element is fixed by a clamping structure located the top of the vacuum chamber. It is rotated at a constant speed at the horizontal
position to ensure that the film is evenly plated on the optical element. The angle between the surface of the silicon target, ion source, and the optical element are kept the same value 45°C, and the distance from the target center to optical elements is 25mm. The ion source together with the target material keep reciprocating motion with the snake curve, which moving from one edge of the element to the other, as shown in figure 2, and the moving speed is 2mm/s.

![Figure 1](image1.png)

**Figure 1.** Schematic diagram of the sputtering process.

![Figure 2](image2.png)

**Figure 2.** The movement path of target.

In order to save the time of vacuum pumping and to ensure the cleanliness of the working environment, the vacuum chamber is mainly composed of two parts, which are the secondary vacuum chamber and the main vacuum chamber of the working experiment. The main vacuum chamber is pumped first. When the vacuum chamber pressure reaches 5.0×10⁻¹ Pa, the vacuum of the auxiliary vacuum chamber is pumped again. When the pressure of the sub-vacuum chamber reaches 2.5×10⁻¹ Pa, the optical components are transferred to the main vacuum chamber for the experiment. When the vacuum degree is about 1×10⁻³Pa, the ion source was ignited, and then the parameters such as voltage and current of the ion source are adjusted accordingly.

The sputtering deposition film program can be carried out after the ion source is stabilized for half an hour, and then the experiment can be performed. In order to ensure the uniformity of the large-aperture optical element film, it is necessary to use a film thickness detector to measure and analyze the film thickness after experiment. The experiment is carried out again after optimizing the dwell time of the center/edge of the ion beam at the rotating base plate, until it meet the technical indicator.
3. Results and analysis

3.1. Film thickness by IBS

The IBS process was carried out with different deposition time, thickness were measured by Surface profilerASTQ1002295, different film thickness between 100nm and 400nm can be obtained when the deposition time were increased, the results are shown separately in figures 3-6.

The sample number is #824, as shown in figure 3, at different position, three testing point were chosen, and thickness is 164.2 nm, 144.7 nm, 124.3 nm and the average value is 144.4 nm. It can be seen that the thickness of film is not very uniform.

![Figure 3. The Si film thickness is more than 100nm.](image)

For the sample number is #766, as shown in figure 4, its thickness is 222.8 nm, 227.9 nm, 220.6 nm, and the average value is 223.8 nm.

![Figure 4. The Si film thickness is more than 200nm.](image)

The sample number is #850, as shown in figure 5, film thickness is 365.6 nm, 372.5 nm, 369.8 nm, and the average value is 369.3.4 nm.
The sample number is #820, as shown in figure 6, film thickness is 404.1 nm, 392.1 nm, 402.7 nm, and the average is 399.6 nm.

It can be seen that from above research results, different film thicknesses ranging from 100 nm to 400 nm can be obtained.

3.2. Dwelling time calculation for film uniformity correction

The former experimental research results show that the parameters such as the beam voltage, gas flow and working distance have a certain influence on the thickness of the thin film deposited by sputtering, and it will also affect the uniformity of the films. When the beam voltage is gradually increased, the energy and sputtering efficiency of the ion beam will increase after the acceleration of the ion beam. So the film thickness will gradually increase. In addition, the amount of argon flow determines the ion beam obtained by ionization, and therefore has an effect on the sputtering efficiency and the film thickness and its uniformity [6-9]. For our research in this paper, in view of the five-axis system specificity of the ion beam deposition correction polishing system, the dwell time of the ion beam at the center or edge of the rotating sample has a greater influence on the overall film thickness uniformity of the large aperture optical elements. After analyzing and determining the optimal remaining parameters, the dwell time ratio of the ion beam at the center edge of the rotating base plate is tested to improve the uniformity of the ion beam sputter deposited thin film on the surface of the large aperture optical element. The parameters of the ion source are shown in table 1.
Table 1. The experimental parameters of ion beam sputtering deposition.

| Beam of neutralizer | Beam Voltage | ACC Voltage | Gas Current | Working distance |
|---------------------|--------------|-------------|-------------|------------------|
| 22mA                | 1000v        | 19mA        | 300v        | 6mA              |
|                     | 10sccm       | 25mm        |             |                  |

The film deposition rate by ion beam sputtering is stable. Therefore, controlling the dwell time at each position of the optical element determines the uniformity of film thickness on the surface of the element. The uniformity of film thickness $U$ is calculated as equation (1),

$$U = \frac{MAX - MIN}{W_{AVG}} \times 100\%$$ (1)

Silicon target with a diameter of 100mm was used for sputtering film. The sputtering time is set to 6 hours. The film thickness of the optical element is measured by using OTFP ST50 film thickness device. The test position is shown in figure 2. According to the experimental data analysis, the film thickness gradually increases from the center to the edge of the optical element. The optimization experiment was carried out by adjusting the dwell time ratio of the ion source at the center and edge. Center Dwelltime Diff. $I$ is calculated as equation (2),

$$I = \left(1 - \frac{Cd_n}{Ed_n} \cdot \frac{Cd_1}{Ed_1}\right) \times 100\%$$ (2)

Here, $n$ represents the number of experiments, $n=1, 2, 3...$

The film thickness on the optical element measured by step profiler. The schematic diagram of the test position of a coated optical element with a diameter of 300mm. In order to obtain the information of the film thickness uniformity, at least five regions (C, X+, Y+, X-, Y) was tested, and 3 points at one region, the average value was calculated.

Working parameters such as the ion source beam size, acceleration voltage, gas flow rate and working distance were kept the same value, but the ion beam dwell time ratio was changed, that is to say, the action time of the ion beam on the center and edge position of fused silica materials is different. The efficiency of the ion beam sputtering deposition film was directly improved and resulted in the best uniformity of film. In order to study the parameter Center Dwelltime Diff. $I$, the dwell time ratio of the ion source at the center and edge. The effects of $I$ on the film thickness uniformity $U$ were studied, the testing results of film thickness at different regions (C, X+, Y+, X-, Y) were tested, when the $I$ from 0, -13.8%, -22% to -26.6% and the film thickness uniformity $U$ have been improved greatly, which is from 13.4%, 7.2%, 4.4% to 0.42%, which are shown in figures 7-10.
Figure 7. Film uniformity U=13.4%.

Figure 8. Film uniformity U=7.2%.

Figure 9. Film uniformity U=4.4%.
The trend of film thickness uniformity on the fused silica surface can be seen clearly, which is from the initial 13.4% to the final 0.42%. It achieves the purpose of experiment and meets the requirements of subsequent experiments. At the same time, it solved the problem of uniformity of film thickness by ion beam sputter deposition on the surface of large-aperture optical elements.

The film thickness meter is detected by the interference principle of light. Figure 11 shows the film thickness after correction in the center, figure 11(a), is 212.7nm, and in the edge region, figure 11(b), is 212.0nm. The red line represents the actual reflectivity on the surface of the optical element, and the blue line represents the reflectivity of the silicon film thickness required when the software simulation calculates the closest to the measured value. The blue line represents the reflectivity of the silicon film thickness that is closest to the actual value, which is calculated by software simulation. According to the curve fitting, the surface film thickness on the optical element is obtained, the display value can be seen on the upper blue rectangular box.

Figure 10. Film uniformity U=0.42%.

Figure 11. The film thickness in (a) center and (b) edge region after correction.
The deposition rate has a certain influence on the growth process of the thin film, which will change the micro-morphology of the surface and affect the surface roughness. Research of different deposition rates on the surface roughness was carried out to find the ideal deposition rate and improve the surface roughness of the optical materials.

Thin films of different thicknesses at different deposition rates were obtained, and then the surface roughness is tested. ZYGO's NewView™ 9000 3D optical profilometer is used to measure surface roughness. Three points were selected for the average value during the test to avoid accidental errors, table 2 below shows the data calculated and analyzed.

| deposition rate(nm/min) | 1.82 | 2.61 | 3.56 | 4.25 | 5.72 |
|-------------------------|------|------|------|------|------|
| film thickness(nm)      | 162  | 234  | 285  | 340  | 460  |
| roughness before IBS (nm)| 2.12 | 2.35 | 1.5  | 0.74 | 1.6  |
| roughness after IBS (nm)| 2.57 | 2.67 | 1.16 | 1.0  | 2.1  |
| roughness variation(nm) | 0.45 | 0.32 | -0.34| 0.26 | 0.5  |

With the increase of deposition rate, the thickness of the film increases, and the roughness change value increases first and then decreases. From figure 12, it can be seen that the film roughness changes before and after IBS; before IBS the film roughness Sa is 1.089nm (figure 12(a)), after IBS the Sa is 0.892nm (figure 12(b)), the optical components surface roughness has been improved after film deposition.

4. Conclusion
The dwell time ratio of the ion beam at the center and edge on the optical element is calculated based on the difference of the film thickness between the center area and the edge area of the sputtering coating. The results show that the film thickness uniformity can reach...
less than 0.5%, which solves the problem of film thickness uniformity of large-aperture optical elements which more than 300mm in diameter by ion beam sputtering deposition process. The optical components surface roughness has been improved after film deposition. This can not only fully optimize the design of optical films and improve the control precision of film thickness, but also can be applied to the preparation of various high-performance optical films. It is important to improve the film quality on the surface of optical elements and increase the performance of the optical element. Under the premise of ensuring the uniformity of film thickness, the focus of further research is how to optimize the experimental parameters of ion source and improve the surface roughness of large aperture optical elements.

5. References

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