The Research of ZnSe Aspheric Vacuum Plasma Sputtering Polishing Surface Roughness

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ABSTRACT

In this paper, ZnSe aspheric optical element in the vacuum plasma polishing technology was studied, the paper mainly discusses the principle of plasma sputtering polishing and the effects of process parameters on ZnSe aspheric surface roughness. Firstly, the relationship between sputtering yield and ion energy and the relationship between density of the beam and the incident angle were gained by simulation research with the use of the SRIM software. And the relationship between polishing efficiency and process parameters was studied. Secondly, the relationship between polishing result and polishing rate under different process parameters was studied by the vacuum plasma polishing removal experiment with the use of the vacuum plasma equipment. The effects of rf power, ion beam energy and beam density on the polishing result were studied. The relationship between plasma characteristics and substrate surface roughness after polishing and polishing efficiency were established. Finally, with the mechanism of plasma polishing gained by simulation and experimental, the vacuum plasma polishing process parameters were obtained.

KEYWORDS: ZnSe aspheric; vacuum plasma sputtering; SRIM; polishing experiments

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INTRODUCTION

With the development of science and technology, fine processing is working gradually in submicron and nanometer direction. The quality requirements, whether on civilian or military devices, is higher and higher. However, the traditional processing mode or special processing would damage the surface and sub-surface of the workpiece more or less. Low energy ion beam etching [1] is a processing method based on sputtering removal, the method can reduce the damage on the surface relative to the traditional large area contact processing, but when the iron beam is bombarding the sample surface, the atoms would leave from the matrix because of collision, or large matrix atoms delocalize, resulting in the phenomenon such as internal vacancy, displacement, once they reach to a certain, the amorphous layer will be generated inside. As result, this will produce the change of the surface morphology and surface damage. The atom in the crystal has a fixed position stable, there is a threshold energy of Edisp, making atoms bound together. When the threshold energy of motion energy of atoms more than Edisp, the atoms are separated from the original position, causing such defects as the matrix lattice vacancy, gap and dislocations etc.

ZnSe aspheric optical element plasma polishing is in a vacuum chamber, removing material by physical sputtering and chemical reaction in order to realize the optical mirror machining method. Plasma, which consists of positive and negative ions and electrons, as well as neutral species, is commonly called as the fourth state of matter. The method is a high-resolution, non-intrusive optical technique for full-field super smooth mirror, the biggest advantage of PCVM is its capability of atomic removing. The density of plasma can be controlled, and beam density distribution is stable, Plasma processing can obtain stable function, beam processing uncertainty is high, the surface shape of convergence is fast, there is no refined grinding head wear problems in the processing method. Plasma polishing exist no edge effect, suitable for aspheric surface, ultra-light mirror and mirror processing.

Japan Osaka university is the earliest engaged in the research unit, they developed a called Plasma Chemical Vaporization Machining, PCVM for short. The experiment used electrode with different rotation speed to stimulate plasma, according to different processing purposes and workpiece shape, different types of electrode used. Osaka university in the semiconductor wafer machining to achieve 0.4 nm surface roughness, The Lawrence Livermore national laboratory of Plasma processing Technology in recent years also showed a great interest, they developed reaction atomic Plasma processing Technology, applying the Technology of RAPT in some materials has achieved less than 3Å surface roughness. British Cranfield university professor Paul Shore with RAPT company jointly developed the HELIOS 1200-3, to machining large diameter optical lens.

This article introduces the principle of vacuum plasma polishing, and through the simulation, to obtain the relationship between the sputtering yield and process parameters, and by using the method of single factor experiment, has carried on the preliminary process experiment, obtain higher ZnSe aspheric surface roughness.
THEORETICAL ANALYSIS

The basic principle of ion beam processing is based on the effect of ion sputtering to achieve removing and implanting of surface material. Based on the Sigmund sputtering theory\cite{1,2}, the sputtering yield, \( Y \), is relative to the incident energy of ion beam and the incident angle of ion beam. The formula is as follows:

\[
Y = \frac{v_0 N}{J \cos\left(\arctan\left(\sqrt{(\nabla_x h)^2 + \nabla_y h^2}\right)\right)}
\]  

(1)

Among them, \( v_0 \) is etching rate of the normal direction, \( N \) is density of the target atom, \( J \) is the uniform beam density.

Ion sputtering process is composed of a large number of concurrent collision, which can be described from the angle of Statistics. Because the energy exchange plays a major role, which was produced by the nuclear collision, so the nuclear collision problem in ion etching can be regarded as two elastic scattering problems. For the elastic collision, when the incident ion energy is low, it is suitable for shielding Coulomb potential function\cite{3} to characterize the interaction between the two bodies, the Thomas-Fermi potential function of power series approximate form:

\[
V(r) \propto r^{-\frac{1}{m}}
\]

Potential function based on this form, the approximate form of the differential scattering cross section is given by the Lind-hard:

\[
d\sigma(E,T) \approx C_m E^{-n} T^{-1-n} dT
\]  

(2)

Where \( C_m \) represents as follows:

\[
C_m = \frac{\pi}{2} \lambda_m a_1^2 \left(\frac{M_1}{M_2}\right)^n \left(\frac{2Z_i Z_a e^2}{a_1}\right)^{2m}
\]  

(3)

\( M \) is a constant related with the energy of incident ion, when energy of the incident ion is 500eV~1000eV, \( m = 0.25 \). \( \lambda_m \) is the dimensionless function of \( m \). \( Z_i \) and \( Z_a \) are the number of the protons of incident ions and the atomic of the work. \( a_1 \) is shielding radius given by Lind-hard.

There are two parts of the iron energy incident to workpiece: 1) nuclear stopping power \( S_n(\varepsilon) \) ----- the ion energy transfers to the nucleus of the target in the collision, generating large angle offset, and the wasted energy make the substrate lattice atoms produce defects such as vacancies, interstitial atoms, dislocations and so on. Consequently, the defects and metastable structures, the main factor for the subsurface damage, will be formed in the solid surface; 2) Electronic stopping power \( S_e(\varepsilon) \) ----- Excitation and ionizing the energy of the electronic outside nuclei in the workpiece, The moving ions stimulate electrons in atoms, or make atoms capture electrons, the energy of collision loss is small, the smaller of Ions deflection and lattice damage can be negligible.

The workpiece measurement of incident ions in stopping power of the incident Ions energy loss of unit distance statistical average should be defined as follow:

\[
\frac{dE}{dx} = -NS(\varepsilon) = -N(S_n(\varepsilon) + S_e(\varepsilon))
\]  

(4)

\( N \)----- The atomic density of the workpiece material
the nuclear stopping power is defined as statistical average of the incident ions in the workpiece during the movement by the elastic collision energy loss

\[ S_n(\varepsilon) = \int_0^\varepsilon Td\sigma(\varepsilon, T) \quad (5) \]

(2) into equation (5), we can get nuclear stopping power of low energy ion incident

\[ S_n(\varepsilon) = \frac{1}{1-m} C_m \gamma^{1-m} \varepsilon^{1-2m} \]

(6)

The nuclear stopping power is the major factor in low energy ions beam incident, (6) into equation (4), Solving invasion depth of the incident ions in the workpiece ignoring the electronic stopping power

\[ R(\varepsilon) \approx \int_0^\varepsilon S_n(\varepsilon) Td\varepsilon = \frac{1-m}{2m} \gamma^{m-1} \frac{\varepsilon^{2m}}{NC_m} \]

(7)

The constant associated with the incident ions and the atomic mass of workpiece

The above is the description of the sputtering process. When the incident ions bombard the workpiece, the momentum and energy transformation in atomic collisions with the workpiece material which will be damaged to the workpiece surface.

**SIMULATION AND ANALYSIS OF SRIM**

SRIM[^4] is a software, which is used for simulation of the stopping power and range distribution about the particles got in solid. It follows Cascade collision theory to model, regarding target as disordered structure. The ion and target atom collision uses two-body collision approximation, the ion hops randomly between two collisions, and the hop distance is determined by the mean free path. Potential energy of interaction between ion and atom applies Screened Coulomb potential, and the ion charge state in solid adopts Effective charge approximation. SRIM includes several parts. While simulating the process of sputtering, the incident ions can be not only in same energy, angle and location, but also in different.

SRIM was used to simulate the silica structure, and one hundred thousand particles were adopted to ensure the small enough error. In simulation, we mainly consider the vacancy density and the extent of damage of the silica matrix caused by different incident angle and energy under the premise of the biggest materials sputtering yield. Thus, one can got a certain value of energy and angle of ions beam which damage the surface least.

![Figure 1](image1.png)  ![Figure 2](image2.png)

**Figure 1.** The relationship between ion beam sputtering yield and incident angle.  **Figure 2.** The relationship between ion beam sputtering yield and energy change.
Sputtering yield is one of the most important physical parameters to describe the sputtering characteristics. In Fig.1, it describes the relationship between different incident angle and sputtering yield under the energy of 500ev, 1000ev, 1500ev, 2000ev. Fig.2 shows the relationship between ion beam sputtering yield and energy.

We can see from Fig 1, the sputtering yield has nonlinear correlation with the angle. In the 500ev can make the sputtering yield a maximum angle is 73.211°, when 1000ev can make the sputtering yield a maximum angle is 73.623°, 1500ev can make the sputtering yield a maximum angle is 74.137°, 2000ev can make the sputtering yield a maximum angle is 74.923°. As can be seen from Figure 1, the incident angle is increased monotonically from 0 to about 74° with the increasing of the sputtering yield, and reached a maximum in 74.923°. This is because collision cascade diffuses longitudinally to the target when the incident angle is very small; while the incident angle becomes larger, the collision cascade diffuses gradually along parallel target surface transverse, the sputtering yield increases with the increasing number of cascade collision, near the target surface within a certain depth. However, the sputtering yield decreases sharply, when the incident angle increases more than 74.923°, this can be explained a collision cascade caused sputtering was concentrated upon very near to the surface range in the large incident angle, within this range, the back scattering of incident particles can not make the collision cascade fully expand, which prompts low enough energy collision recoil atoms to decrease sharply, resulting in the rapid decline of sputtering yield.

The figure 2 shows the relationship between the sputtering yield and the energy. We can draw different energy on the sputtering yield of trends from Figure 2, and it can be observed that the sputtering yield shows a approximately positive linear correlation with the energy. Therefore, in the permit conditions of low energy ion beam etching, the ion beam etching energy as large can be choused to increase the sputtering yield.

During the low energy ion beam etching processing, the phenomenon such as vacancy, displacement, etc. is the major cause of crystal changing and subsurface damage. Analyzing the data obtained by the simulation, one can get the variation curve of vacancy and the angle, the energy as well. Figure 3 describes the vacancy number rises slightly with the angle changing, maximums in 68°, and then produces a sharp decline. The shift trend is being aggravated, there is a large number of ions
in the matrix, the performance will change if the number reaches a certain level. As shown in Fig4, in the maximum sputtering yield angle (74.923°), the relationship between the quantity of different energies corresponding to the vacancy, it can be observed that the number of vacancies caused by ion sputtering increases with the increase of the energy.

**SPUTTERING POLISHING EXPERIMENTS**

(1) The influence of ion beam energy on surface roughness

During tests of ion beam energy, ion beam other parameters are set to: ion beam density is 35 mA, oxygen is 6 SCCM, argon gas quantity is 7.2 SCCM, sputtering time is 1 hour. Using ion beam energy, respectively 400 eV, 500 eV, 600 eV, 700 eV, 800 eV on the etching experiments. Figure 3.4 shows different of the relationship between ion beam energy and the surface roughness variation.

Figure 5. The surface roughness variation with the change of the relation between ion beam energy.

Figure 5 shows: With the increase of ion beam energy, the plate surface roughness increases slightly, this is because the surface flow physical sputtering, and the two phenomena of physical function and oxygen reactive ion beam etching effect of basic offset. When the surface is collision atomic energy is greater than the binding energy on the surface, will be out of the workpiece surface. Physical sputtering can increase the plate surface roughness, the surface atoms flow can reduce the surface roughness; Working gas in the experiment of adding oxygen, oxygen reactive ion beam etching will bring influence on the variation of surface roughness.

(2) The influence of oxygen content on the surface roughness

The working gas of experiments is argon and oxygen, the total gas flow rate is 13.2 SCCM. In reaction process, different species have their own functions. Free radicals cause surface modification reaction and electron, ion mainly cause etching reaction. Inspection work oxygen gas, Other parameters setting of ion beam, ion beam energy is 400 ev, ion beam density is 25 ma, etching time is 1 hour. With different content of oxygen in polishing of ZnSe. The content of oxygen is respectively 2sccm, 4sccm, 6sccm, 8sccm, 10sccm.
CONCLUSIONS

By analyzing, the SRIM simulation data, we show here the nonlinear dependence of the ion beam etching sputtering yield on the incident angle with a maximum value in about 74.923°. The sputtering yield increases with the increase of ion beam energy. Projection depth, which represents the particles into the substrate, shows increasing trend with the increasing energy. This can clearly demonstrate the direct proportion between the damage depth of ion beam processing and the energy increasing of the injury, but the layer thickness has a negative correlation with the increasing incident angle. In certain energy, proper increasing of ion incident angle can increase the sputtering yield and reduce the surface damage layer thickness. This can give priority to increasing angle in ion beam etching under the premise of suitable energy. Study on the ion beam etching in the hope of improving the etching removal rate, and ensure the uniformity of etching with high anisotropy and low radiation damage at the same time. The simulation can get the process parameters at the maximum etch removal rate, probe into the injury and make more accurate predictions. It is expected that the study can provides reference for the next step of research.

The last, through theoretical analysis, simulation and experimental verification, it is concluded that when the ion beam density of 25 ma, anode voltage is 400 v, 6 SCCM oxygen flow rate, argon gas flow rate of 7.2 SCCM, polishing the surface of the best quality.

REFERENCES