Polishing silicon modification layer on silicon carbide surface by ion beam figuring

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Silicon (Si) modification layer on silicon carbide (SiC) surface is widely used in space optical systems. To achieve high-quality optical surface, the technology of ion beam figuring (IBF) is studied. The radio frequency ion beam source is introduced briefly. Then the removal function experiment is studied. The volume removal stability of the IBF reached 97% in 10 h continuous working testing. The parameters of the IBF removal function are calculated by Gaussian fitting including the removal rate and the full-width half-maximum. Then the removal function results are used in practical fabrication. The workpiece is a plane with Si modification layer on SiC surface. After 148 min processing IBF, the final surface error reaches 1.2 nm RMS.

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The silicon (Si) modification layer on silicon carbide (SiC) is very popular in space optical systems nowadays. SiC is very suitable for space environment because of its low density, high-specific stiffness, and good thermal conductivity[1]. But the SiC surface has too much scattering and cannot be used in optical system directly. The surface modification was required to produce Si layer on SiC surface. Then the Si layer was polished to achieve the optical performance such as roughness and surface error. The polishing of Si layer is more challenging than the manufacturing of standard glass materials. The required surface form accuracy cannot be achieved by conventional polishing methods because of the unpredictable behavior of the polishing tools, which leads to an unstable removal rate.

Here, the ion beam figuring (IBF)[2,3] method is used to manufacture Si modification layer on SiC surface with nano-scale accuracies. The IBF uses a beam of high-energy ions directed toward a target substrate in a controllable way and removes material from an optical surface by physical bombardment of surface. Ions sputter the substrate on impact and break surface bonds removing material in molecular units. IBF enables the removal of various materials because the removal is based on physical mechanism. Because of noncontact figuring, IBF avoids the problems just like edge effects and load press. The Gaussian type removal function is very beneficial to make the surface error converge coherently.

Similar to the typical computer controlled optical surfacing method, the material removal by an IBF can be found as the convolution between an ion-beam removal function and fabrication dwell-time function. The IBF removal function is tested by experiments. The results are analyzed by the Gaussian function fitting method to obtain the parameters. The dwell-time function is computed by deconvolution calculation. A matrix-based algorithm has been developed to solve the dwell-time function. The removal function experiment was studied. The volume removal stability of the IBF reached 97% in 10 h continuous working testing. Then the practical fabrications were done as a proof of our research of the IBF Si modification layer using SiC method. After 148 min of processing IBF, the final surface error reached 1.2 nm RMS.

Two types of ion beam sources are commonly used in IBF, Kaufman source and radio frequency (RF) source[4,5]. The oldest plasma source is the Kaufman source. It consists of grounded or isolated cylindrical walls and a glowing wire which emits electrons thermally (cathode). Adjacent to the reactor wall, the cylindrical anode is installed which is set to the topmost potential within the discharge. The discharge voltage is defined as the difference between cathode potential and anode potential. By this configuration, the ions are accelerated toward the grid optics, whereas the electrons remain confined in the plasma source. Its main advantages are the ease of use and simplicity; however, it suffers from a limited cathode lifetime (cathode wear by evaporation processes), which is further reduced when reactive gases are applied. Hence, a good performance with ever-increasing demands for radial uniformities becomes more and more difficult to meet.

In contrast to the Kaufman source, with the newly developed RF sources, almost no contamination is detectable. So the RF source has much better performance in optical polishing. The simple structure of the RF source is shown in Fig. 1. The ion was generated by collisional impact in the beam source, then extracted and subsequently accelerated by the grid systems in order to generate a collimated beam. The ion beam should have high intensity and high beam uniformity at the same time.

Our laboratory cooperated with NTG Neue Technologien GmbH & Co. KG of Germany from 2012.

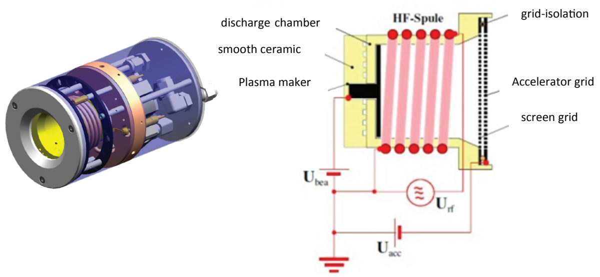


Fig. 1. Diagrammatic sketch of the RF ion beam source.

We finished the IBF machine named IBF1500, which meaned the maximum workpiece diameter is 1500 mm. The device has three movement axes (X–Y–Z) which means the ion beam source just has the ability of linear motion without rotation. It can be used in nano-scale polishing of flat, sphere, and asphere optics. The compensation of the removal function changing was calculated by dwell-time computation software in asphere and off-axis asphere optics figuring. As can be seen in Fig. 2, the ion beam source is horizontally placed opposite to workpiece which stands vertically. The internal structure of the IBF machine is different from that of normal IBF plants because of the consideration of saving vacuum space and the convenience mounting of big optics workpiece.

As we know, the removal function distribution of the IBF is a perfect Gaussian function, which is very good for the convergence of the surface error. In our removal experiments, we first made several removal spots with definite ion beam parameters. Then we tested the surface changing and obtained the removal function distribution maps. In order to analyze the removal stability, we fitted the removal distribution with Gaussian function.

The removal ability of the IBF depends on the removal target materials, so we should use the same Si modification layer on SiC for experiments. The workpiece diameter was 95 mm, the surface was polished by traditional method and the error reached RMS 1/20 λ ($\lambda = 632.8$ nm). The surface porosity layer was removed totally and ensured material uniformity. The dwell time of the surface of the ion beam source was set to 100 s to make removal spots serially, the interval of each spot was 1 h. In this long-time process, the vacuum of the chamber should be kept constant at 4×10^{-3} Pa. The gas used was argon and the flow was 4 sccm. The power of the RF generator was 50 W. The beam voltage was 1000 V and the acceleration voltage was 100 V. The work distance of the source head to the workpiece surface was 30 mm.

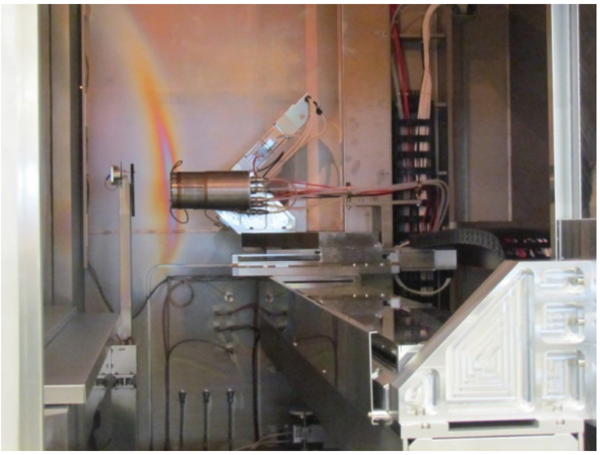


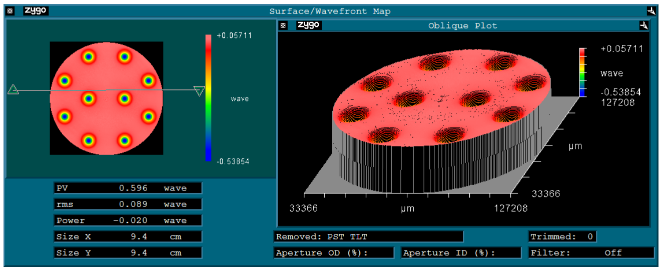
Fig. 2. Internal structure of the ion beam machine.

The removal function results were tested by Zygo interferometer. The testing position of the workpiece after removal should be in the same position before removal. As shown in Fig. 3, the data are treated by interferometer software automatically and the results are the removal function distributions.

The individual removal function distribution is shown in Fig. 4. The shape of the removal function is similar to the ideal Gaussian function distribution. The conclusion is in agreement with the theoretical physics. In order to analyze the stability of the removal quantitatively, the distribution is fitted by ideal Gaussian function as

$$R(x,y) = \text{Rate} * e^{-(x/\sigma_x)^2-(y/\sigma_y)^2}, \tag{1}$$

where $R(x, y)$ is the distribution of the removal function, and σ_x, σ_y are the Gaussian functions standard deviation. Full-width at half-maximum (FWHM) is also a widely used parameter to describe the size of the removal function. In order to reduce the fit residual error, we use two Gaussian functions as fit base. The results of the removal function are shown in Table 1. The most important volume rate stability is about 97.1% in 10 h, which is quite good for deterministic fabrication.



PV 0.596 wave
rms 0.089 wave
Power -0.020 wave
Size X 9.4 cm
Size Y 9.4 cm
Removed: PST TLT
Trimmed: 0
Aperture OD (%):
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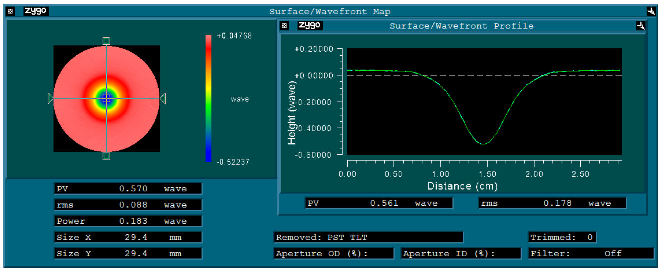
Fig. 3. Interference measure of the removal function experiments.



PV 0.570 wave
rms 0.088 wave
Power 0.183 wave
Size X 29.4 mm
Size Y 29.4 mm
PV 0.561 wave
rms 0.178 wave
Removed: PST TLT
Trimmed: 0
Aperture OD (%):
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Fig. 4. Individual removal function distribution.

Table 1. Results of Removal Function Experiments

Number	**Rate (summed)**	**Rate**	**FWHM** *X*	**FWHM** *Y*	**Volume Rate**	**Sigma** *X*	**Sigma** *Y*	**Residual Fit Sigma**
	(nm/s)	**(nm/s)**	**(mm)**	**(mm)**	**(mm^3/min)**	**(mm)**	**(mm)**	**(nm)**
1	3.681	1.879 1.802	5.722	5.73	0.009482	4.443 2.727	4.405 2.752	1.137521
2	3.694	1.813 1.881	5.674	5.687	0.00942	4.461 2.726	4.437 2.748	0.986307
3	3.677	1.787 1.89	5.674	5.675	0.009333	4.446 2.744	4.435 2.75	1.07677
4	3.652	1.915 1.737	5.694	5.7	0.009315	4.391 2.693	4.37 2.709	1.048713
5	3.629	1.968 1.661	5.728	5.723	0.009379	4.393 2.676	4.379 2.678	0.914112
6	3,634	1.996 1.638	5.724	5.715	0.009378	4.379 2.66	4.364 2.661	0.941787
7	3.613	2.1 1,513	5.716	5.708	0,009253	4.309 2.605	4.288 2.61	1.004337
8	3.648	2.047 1.601	5.692	5.682	0.009275	4.327 2.629	4.303 2.634	1.041529
9	3.58	1.913 1.667	5.702	5.703	0.009258	4.429 2.654	4.401 2.67	1.265011
10	3.652	2.077 1.575	5.683	5.675	0.009212	4.289 2.622	4.268 2.628	1.132238
Mean Values	3.646		5.701	5.700	0.009331			
Standard Deviation	0.032		0.020	0.019	0.000080			
Standard Deviation (%)	0.886		0.344	0.327	0.859			
Peak-to-valley Value Error (%)	3.127		0.947	0.965	2.894			

The removal function parameters are achieved by removal function experiments, the results can be used in the surface error remove polishing. In this part, a Si layer on SiC surface workpiece was polished by IBF to prove its feasibility and effects. The IBF was not in contact with the surface, so the dwell path range could be larger than the measure data to avoid edge effects. The matrix-based algorithm was used to solve the dwell function. As shown in Eq. (1), the removal function has a value in the total workpiece area, which is not convenient to calculate. We make a region cutting-off with semi-diameter equal to 3*max (σx, σy) according to statistics methods. In our case, the removal in 3*max (σx, σy) is about 0.012% of maximum removal of center. So the cutting would not influence the fabrication.

The diameter of the workpiece is 118 mm. The same parameter as removal function experiments was used in this fabrication processing as shown in Fig. 5. The initial surface error is 27 nm RMS before IBF processing. As shown in Fig. 6, the surface error reaches 1.2 nm RMS after 148 min processing.

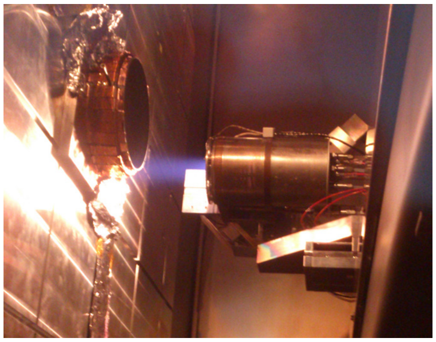

Fig. 5. IBF processing exhibition.

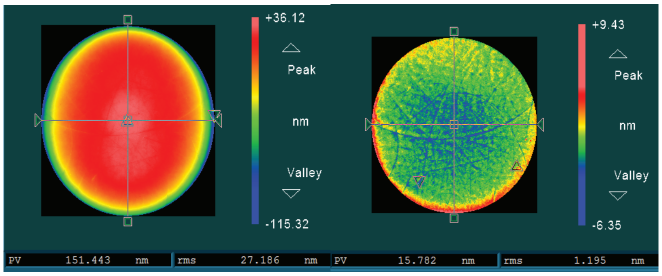

Fig. 6. Initial surface error and the processing results.

From the results, it looks like that the IBF makes the removal rate a little more, maybe because the vacuum has changed and the removal rate increased slightly. The result is good enough because it is almost close to the limit of our interferometer.

In conclusion, IBF is widely used for nano-scale accuracies optics manufacturing. Here, the processing of Si modification layer on SiC with IBF is studied. The removal function experiment is also studied. The volume removal stability of the IBF reaches 97% in 10 h continuous working testing. Then the practical fabrications are done. After 148 min of processing, the final surface error reaches 1.2 nm RMS from 27 nm RMS. It means the IBF can be used in Si modification layer on SiC mirrors final polishing.

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