

Advanced Plasma Polishing Process: Principle, Recent Applications, Challenges, and Future Scope



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Abstract In current years, optical components are the most important and necessary components of making electronic chips, semiconductors, lenses, and mirrors. In those fields, the quality of the surface is very important. Micro-cracks, lattice disturbances, and other flaws are always present on the final surfaces of components manufactured in traditional contact machining methods. In order to satisfy all those drawbacks, an advanced plasma polishing process, named medium-pressure plasma polishing (MPPP) process, has been developed. It removes surface and subsurface damage while polishing of optical components. The present article focused on a comprehensive literature review of the proposed process, with principles and applications. Moreover, this article addresses the investigation of surface roughness, morphology, and chemical composition before and after the MPPP process using 3D optical profiler, FESEM, and EDX analysis, respectively. The surface roughness of fused silica has been slightly increased from initial surface roughness (R_a) 0.35 to final R_a 0.37 μm after plasma processing. Further, the result shows the morphology has been improved after processing. EDX result shows the presence of fluorine on the surface of fused silica, and it shows the reaction has been involved during processing. Moreover, the research challenges and future scope have also been discussed.

Keywords Plasma polishing · Material removal · Surface roughness · FESEM · EDX · Optical material

Nomenclature

MPPP	Medium-pressure plasma process
PAP	Plasma-assisted polishing
APPP	Atmospheric pressure plasma process

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SF ₆	Sulfur hexafluoride
RF	Radio-frequency
MFM	Mass flow meters
EDX	Energy-dispersive X-ray
FESEM	Field-emission scanning electron microscopy
MRR	Material removal rate
sccm	Standard cubic centimeter per minute
APPJ	Atmospheric pressure plasma jet
AFM	Atomic force microscopy
XPS	X-ray photoelectron spectroscopy

1 Introduction

In recent years, the demand for optical components has been increasing due to the development of electronics-related manufacturing industries. Also, the usage of optical components is increasing due to the rapid growth of science and the evolution of modern technologies. So, considering these factors, the surface finishing of optical components must be in the range of nanofinish and ultra-smooth surfaces [1]. The optical components play an important role in producing electronic chips and semiconductor-correlated products. The commonly used optical components like lenses, telecommunication lasers, and mirrors [2]. Due to its properties, the optical components are majorly used in aeronautical navigation, aerostatic and electronic components. The main reason for using optical components in those fields is because of their individual physical properties [1]. Numerous optical materials are used in various applications like precision lenses, synchrotrons, optics windows, wave plates, optical domes, infrared optics, and precision mirrors. In addition to optical fields, fused silica is commonly used in laser-related components, aeronautical components, electronics chips, etc. These optical materials' outstanding finishing quality is crucial since these parts are utilized in extremely precise equipment such as space telescopes, metrology, machine inspection, surveillance, projection, and thermal imaging, among other things. The components of optical are categorized into many categories; materials mentioned below are very much used in the fields of aeronautical, surveillance metrology, electronics, manufacturing section, etc. The subsequent classifications are the substance which is crystalline, like calcium fluoride, and glasses, like fused silica. The substance has a low thermal expansion, like zerodur, and metals like copper and aluminum. The reason behind using fused silica is because of its unique physical properties. The properties, like more resistance and withstanding high temperature [3], will not be chemically reactive and also transparent to visible light. Nanofinishing through unconventional techniques has emerged as a novel technology for optical material processing [4]. Material surface quality is critical for science and industry. In addition to this, high processing efficiency is necessary to process the components. The atmospheric pressure plasma

process (APPP) technique can easily polish complex interior shapes, freeform, and targeted areas. The potential for using these sophisticated finishing procedures to polish various complicated freeform components constructed of diverse materials is examined.

The surface and substrate properties significantly impact the life and efficiency of the optical device [5]. The final surfaces of components created by the contact machining process are constantly subject to flaws such as micro-cracks, pits, adhered material, and lattice disturbances. In order to satisfy and overcome all those drawbacks, researchers put more effect into developing advanced technology to make ultra-smooth surface finishing. A non-contact medium-pressure plasma process (MPPP) has been developed [6]. It is one of the very important methods for surface finishing of optical components, i.e., lenses, mirrors, prism, etc. [7]. Using chemical and physical actions, it can remove the material atom by atom level. This newly developing technique gives us a very good surface finish without any surface contamination and zero sub-surface defect on optical components [8]. Arnold et al. [9] proposed a plasma jet-based process, and it could be applied for surface figures or shaping error modification on an optical substrate. Moreover, it also discussed outlooks of the surface with plasma interaction. Paetzelt et al. [10] reported plasma jet polishing applies to the highly localized working area, i.e., plane, spherical, aspheric, and micro-structured substrates. Jin et al. [11] reported plasma finishing processes on a fused silica substrate. Also, an investigation is conducted into the surface characterizations of fused silica using Ar/CF₄ plasma at atmospheric pressure. Moreover, atomic force microscopy (AFM) and X-ray photoelectron spectroscopy (XPS) are employed to examine the morphology and chemical development of fused silica surfaces. Gerhard et al. [12] reported the polishing of fused silica and investigated the surface and near-surface effects at atmospheric pressure. The plasma process significantly reduces the transmission of the investigated glass samples. Additionally, ellipsometry shows a reduction in the superficial index of refraction of around 3.66% at a wavelength of 636.7 nm. A reduction in surface polarity of 30.23% is found using surface energy measurements. Cui et al. [13] reported a combined theoretical and experimental investigation into the influence of packing surface structure and plasma discharge on SF₆ degradation in γ -Al₂O₃ packing DBD system. Experiment results reveal that the hydration impact of the surface (due to moisture) and the presence of reactive gases in the plasma can considerably reduce SF₆ degradation, but they have little influence on discharge behavior. Graves [14] observed that non-equilibrium, low-pressure, weakly to partly ionized gas discharge plasmas are employed for a variety of surface processing applications. Deng et al. [15] proposed the optimization of plasma oxidation and abrasive polishing to increase the material removal rate (MRR) applied on substrate 4H-SiC using the plasma-assisted polishing (PAP) process. It showed that the plasma oxidation rate was significantly enhanced with a low water vapor content in He gas. Plasma process removes the material from the workpiece by creating low-temperature plasma inside the plasma chamber. Yadav et al. [3] investigated the atomistic material removal rate using a medium-pressure plasma process (MPPP) on a fused silica surface, and further material

removal mechanism is discussed. Plasma polishing parameters, i.e., gas composition, pressure ratio, total pressure, and RF power, affecting the material removal rate of fused silica, have been presented. Field-emission scanning electron microscopy (FESEM) is an advanced imaging technique used to visualize the surface structure and topography of a sample at high resolution [16, 17]. Yadav et al. [18] investigated plasma-processed fused silica substrate, and it is characterized using FESEM and EDX, which depict the presence of silicon, oxygen, and fluorine on the processed substrate. This technique overcame all the drawbacks using traditional methods and gave a high-quality surface finish on optical parts [19]. The finishing of optical components using the traditional polishing method, more surface damage occurs, and it also produces some micro-cracks in the surface [20]. All those factors affect the performance of the optical components. These drawbacks happen while using traditional polishing methods due to physical contact between the workpiece and the tool [21]. To satisfy all those requirements, research in the field of optical polishing with soft material surfaces, a novel non-contact MPPP, has been developed for the finishing of optical components. It removes the sub-surface damage from the surface of optical component.

The present study conducts experiments to find the surface roughness of optical components. The novelty of the process arises from the fact that the current medium-pressure plasma polishing process is capable of polishing complex 3D profiles with cavities where neither a tool nor a beam can reach and can remove the material from the surface without any contamination deposition during processing. Ionized atoms in the plasma chamber help remove material from the fused silica surface. This paper presents the schematic diagram, an actual photograph of the developed experimental setup, and the principle of the plasma polishing process. Moreover, the surface roughness, morphology, and chemical composition of the processed surface before and after the plasma process using a 3D optical profiler, FESEM, and EDX, respectively. The research challenges and future scope have also been discussed.

2 Materials and Methods

The following section presents the plasma process principle, the plasma processing flow chart, and the schematic and actual photograph of the developed experimental setup.

2.1 Principle of Plasma Process

In the polishing process, the process and reactive gas with the optimal ratio are properly mixed and then admitted into the process chamber. The reaction gas is then ionized by radio-frequency (RF) power in the plasma chamber to generate high-density energy reactive radicals [22]. The plasma generates the radicals and ion

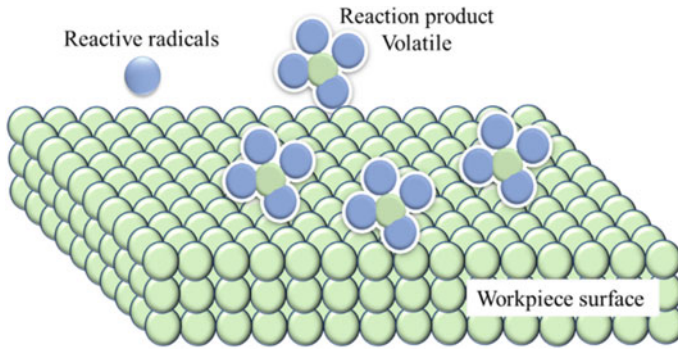
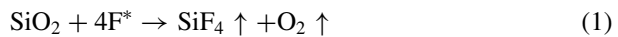


Fig. 1 Principle of plasma process

species which react with the surface of the workpiece as energetic radicals, ions, and electrons. The reactive radicals then interact chemically with the workpiece's surface atoms. These radicals make surface reactions with the fused silica, which makes effective atomic-scale material removal. Further, the volatile product, i.e., SiF_4 , generated and removed the material from the surface, as shown in Fig. 1. This process eliminates the material from the surface of the workpiece by the radical and ion species. The probable reaction is illustrated in Eqs. (1) and (2) [3].

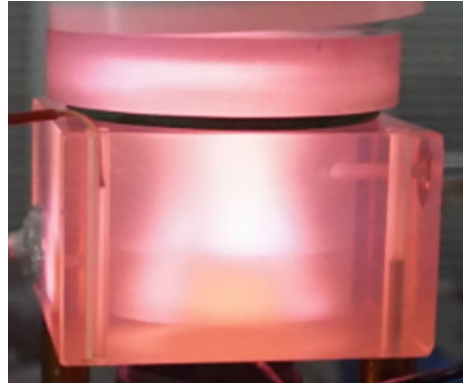


2.2 Experimental Setup

The medium-pressure plasma polishing setup consists of gas cylinders (He, O_2 , and sulfur hexafluoride (SF_6)), mass flow meters (MFM, sccm: standard cubic centimeter per minute), a plasma chamber, a pump, and RF power. The gasses flow into the mass flow meter from the gas cylinder, and a separate controller is used to control the flow rate of the gasses and admitted into the plasma chamber. The gasses are allowed to enter into the chamber, and RF power is used to ionize the gasses inside the chamber, leading to the production of plasma inside the chamber. The generation of plasma inside the process chamber during polishing is shown in Fig. 2.

The schematic diagram and actual photograph of the developed experimental setup of the medium-pressure plasma process are illustrated in Fig. 3a and b, respectively. The method achieved an ultra-smooth finish with a high material removal rate and good surface finish [18]. The gasses are coming out from gas cylinders, and a mass flow meter is used to control the flow of gases. Further, the gases are filled in the

Fig. 2 Generation of plasma inside the chamber



plasma chamber with optimum ratio and ionized using RF power. The pump is used to create the vacuum inside the chamber just before the filling of gases, and also, it helps to exhaust generated gases during processing.

2.3 Flow Chart of Medium-Pressure Plasma Polishing Process

The machining stages in the medium-pressure plasma polishing process are organized in circular diagrams in a flow chart, as shown in Fig. 4. Initially, the process gases come from different gas cylinders and pass through mass flow meters. It controls the flow rate of the gases. The gases are then admitted into the plasma chamber at a particular partial pressure controlled by the flow rates of mass flow meters. RF power ionizes the gases into radicals, ions, atoms, and molecules. The radicals react with fused silica substrate and generate volatile silicon tetrafluoride (SiF_4) compounds.

3 Results and Discussion

The following section provides fused silica's surface roughness, morphology, and elemental composition before and after processing using a 3D optical profiler, FESEM, and EDX.

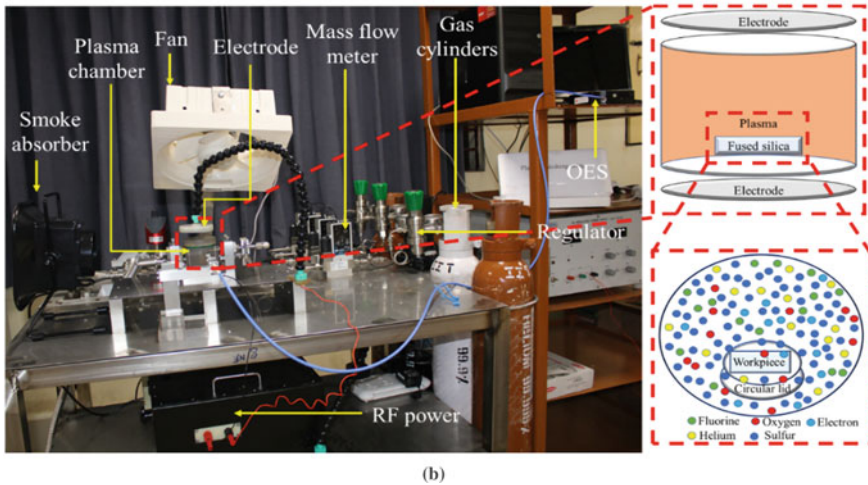
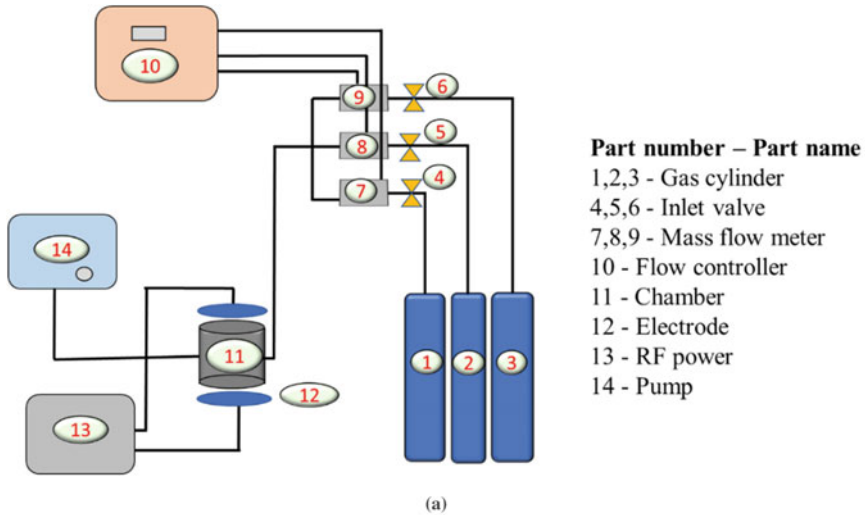


Fig. 3 Experimental setup of medium-pressure plasma polishing **a** schematic diagram and **b** actual photograph

3.1 Surface Finishing of Fused Silica Substrate

The experiments are carried out using He, O₂, and SF₆ plasma to investigate the surface roughness of fused silica. The process parameters, i.e., gas composition, pressure ratio, total pressure of plasma chamber, and RF power, have been chosen based on the previous literature survey and preliminary experiments. Higher discharge directly affects the surface profile in the plasma polishing process. Complete plasma discharge

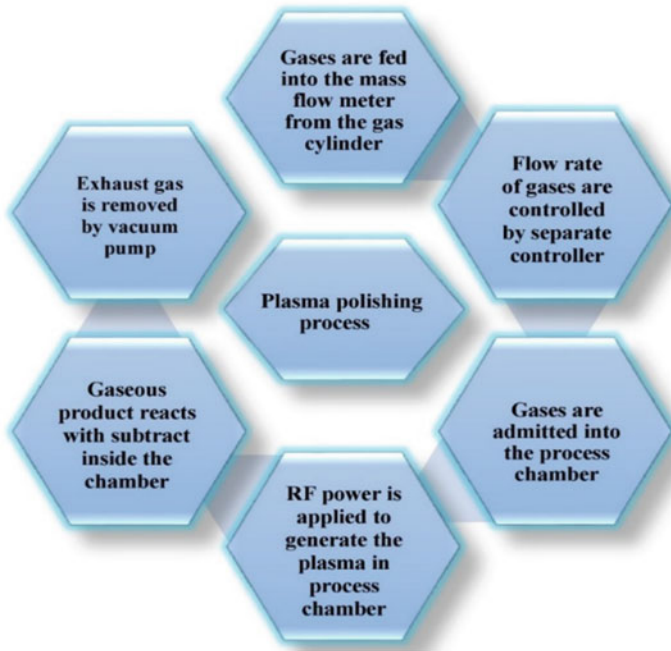


Fig. 4 Flow chart of the plasma polishing process

leads to uniform material removal from the substrate. The processing parameters of the plasma process are illustrated in Table 1.

Figure 5a and b shows 2D roughness profiles before and after plasma processing, respectively. The experiments have been performed on the process parameters, i.e., gas composition (He:(SF₆ + O₂)) of 92:8, pressure ratio (SF₆/O₂) of 1:1, RF power of 80 W, and machining time of 55 min. The surface roughness is marginally increased from 0.35 μm to 0.37 μm after plasma processing. Before and after plasma processing, the surface finish of fused silica is measured by a 3D profiler. It is evident

Table 1 Processing parameters of plasma experiment

Parameters	Values
Gas composition (He: (SF ₆ + O ₂))	92:8
RF power	80 W
Pressure ratio (SF ₆ /O ₂)	1:1
Flow rate of He	58 sccm
Flow rate of O ₂	0.90 sccm
Flow rate of SF ₆	1.40 sccm
Total pressure of plasma chamber	20 mbar
Machining time	55 min

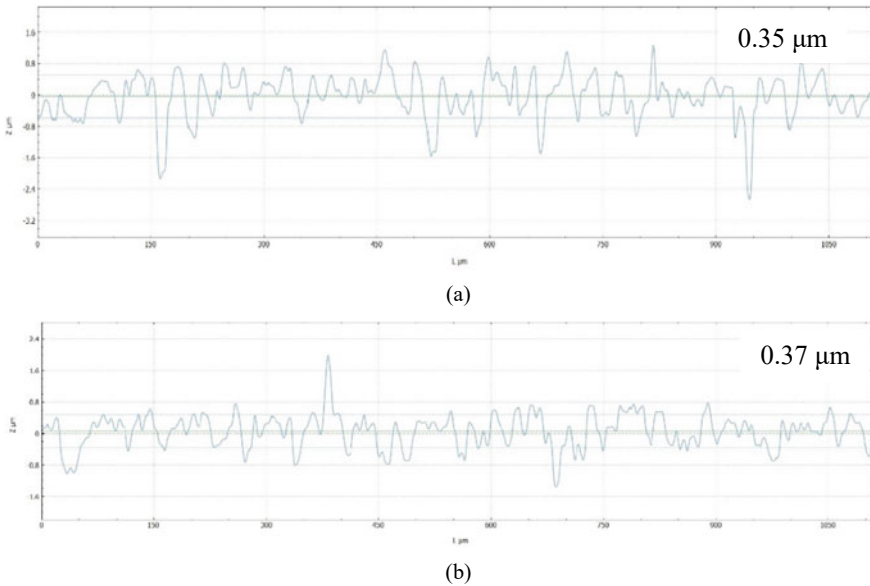


Fig. 5 Surface roughness of fused silica **a** before and **b** after medium-pressure plasma process

by the workpiece contrast that the substrate surface, after plasma processing, achieved a good surface finish without any surface defects and surface contamination. Three surface profiles are used to measure each sample's initial and final surface roughness values. After that, an average value of surface roughness is calculated.

3.2 *Microstructure and Chemical Composition Analysis*

FESEM provides the morphology of the substrate's surface. The surface morphology of fused silica before and after processing is illustrated in Fig. 6a and b, respectively. The micro-cracks and adhered materials have been detected on the original surface, as illustrated in Fig. 6a. The results showed that the cracks, etched pit, and deposition had been removed after the plasma process, as shown in Fig. 6b. EDX is used to analyze the elemental composition on the substrate surface. The EDX findings of fused silica before and after the plasma process are presented in Fig. 7a and b, respectively. It is obvious that before processing Si, O, and after the process, it consists of four elements such as Si, F, O, and C, detected on the surface of fused silica, where the majority of the oxygen and carbon elements come from atmospheric air. The presence of fluorine elements shows that the reaction occurred during processing.

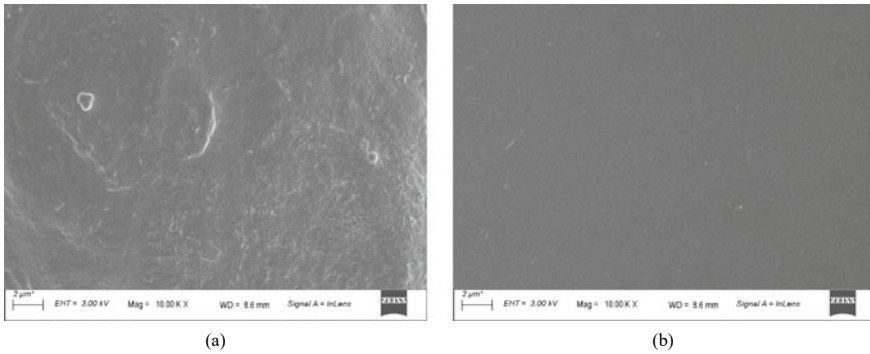


Fig. 6 FESEM image of fused silica **a** before and **b** after medium-pressure plasma process

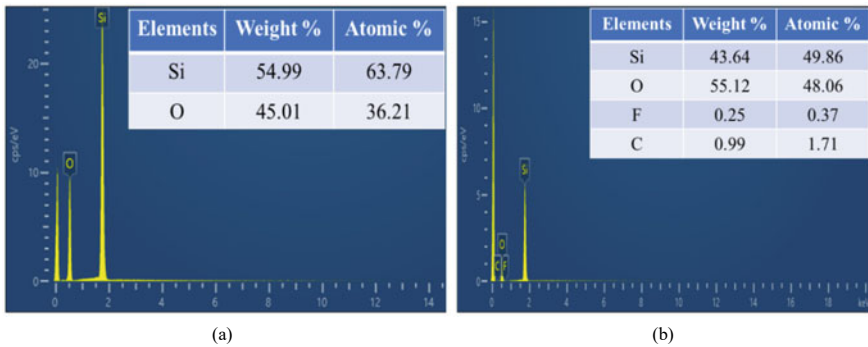


Fig. 7 EDX image of fused silica **a** before and **b** after medium-pressure plasma process

4 Research Challenges

The current development of optics-related industries requires the extremely severe quality of the surface with less damage. This type of requirement is the present challenge of optic polishing technology. Using traditional processes always creates damage, such as micro-cracks and lattice disturbances, on the surface of the work-piece. The conventional polishing method is not suitable for functional brittle, hard materials like glass, ceramics, and crystal due to the individual characteristics of those materials. For the finishing of optical materials, most of the researchers used non-conventional plasma processes and utilized some common gases like sulfur hexafluoride (SF_6), helium (He), argon (Ar), and carbon tetrafluoride (CF_4) to polish optical materials such as fused silica, silicon, ceramics, and zeredur materials. Very few researchers have discussed polishing the critical complex and freeform optical surfaces. Several researchers have reported that the material removal rate of optical material is $5\text{--}32 \text{ mm}^3/\text{min}$ using a plasma process. However, the efficiency of this process is low, and improvements in the surface roughness are not so much good.

During processing, it requires periodically cleaning the process chamber to make the finishing process more efficient. The plasma process is mainly utilized to improve the sub-surface defect of optical material.

5 Future Scope

The plasma process has a promising future and is expected to have several significant applications across various fields. The process parameters can explore in some higher range to get the optimum MRR and better surface finish. There are some potential areas where the plasma process can make a significant impact:

- **Surface modification and coating:** Medium-pressure plasma processes can be used for surface modification and deposition of functional coatings. With medium-pressure plasmas, treating a wide range of materials, including polymers, ceramics, metals, and composites, is possible. These processes can improve surface adhesion, enhance wear resistance, provide corrosion protection, and introduce specific functionalities like hydrophobicity or antibacterial properties.
- **Electronics manufacturing:** Medium-pressure plasma processes find extensive applications in the electronics manufacturing industry. They can be used for cleaning and activating surfaces prior to bonding or soldering processes, improving the adhesion and reliability of electronic components. Medium-pressure plasma can also be employed for the surface treatment of printed circuit boards (PCBs), enhancing their performance and ensuring better solderability.
- **Semiconductor industry:** The medium-pressure plasma process is well-suited for various semiconductor manufacturing steps. It can be utilized for precise etching of semiconductor materials, such as silicon, gallium arsenide, and other compound semiconductors. Medium-pressure plasma processes can also facilitate the deposition of thin films and patterned coatings used in integrated circuits and other electronic devices.

6 Conclusion

This article briefly discusses the optical substrates, application of optical materials, schematic and actual photograph of the experimental setup, and principle of the plasma polishing process. 3D optical profilometer, FESEM, and EDX are used to find out the surface roughness, morphology, and chemical composition of the processed surface are included. The following conclusion can be drawn:

- The surface roughness of fused silica has slightly increased from 0.35 μm to 0.37 μm after the treatment of the plasma process.
- FESEM results show that fused silica morphology has improved, such as cracks, etched pits, and holes after the plasma process.

- EDX results show that the elements Si and O are presented on the initial surface, and F, C, Si, and O are observed on the processed surface after the plasma process. The presence of fluorine elements shows the reaction on the fused silica's surface.

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