Design and Development of Plasma Window Using Microhollow Cathode Discharge

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A plasma window is an atmosphere-vacuum interface, formed by the interaction of the ideal gas pressure effect and dynamic viscosity effect of plasma. The application of a plasma window is the generation of a pressure difference between 1 and 7×10^3 Pa without a large exhaust system. In this study, we designed an apparatus with a microhollow cathode discharge for plasma window generation. A resulting pressure difference between 0.889 and 8×10^3 Pa and a pressure ratio of approximately 10^4 were obtained.

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The plasma window, proposed by Hershcovitch, at the Brookhaven National Laboratory in 1995, is an atmosphere-vacuum interface, obtained by the interaction of the ideal gas pressure effect and dynamic viscosity effect of plasma [1, 2]. The plasma window is used for electron beam melting [1, 3], in X-ray transmission [4], proton beam transmission [5], low-Z gas charge strippers for heavy-ion accelerators [6, 7], and accelerator-driven subcritical nuclear energy systems [8]. When individual membranes are used for the creation of high-energy ion beams, they experience deposition and radiation damage, similar to conventional ion beams. Plasma windows can potentially overcome these limitations [9]. Plasma windows have also been used as valves for stopping gas flow [10,11].

Conventional plasma windows use plasma generated by cascade arc discharge—a technique proposed by Maecker [12] and improved by Sumaker [13]. In this technique, a high-temperature and high-density plasma under atmospheric pressure is generated by installing multiple intermediate electrodes between the anode and cathode [14]. Plasma, as the primary element in plasma windows, creates a pressure difference [15]. The plasma window is desirable due to its ability to generate a pressure difference between 1 and 7×10^3 Pa, without requiring a large exhaust system, that can be divided into multiple compartments [16]. Therefore, the generation of high-temperature, high-density plasmas and the measurement of their parameters are of significant interest [14–19].

To develop a plasma window that can generate the desired pressure difference, we designed and devised a plasma window that uses a microhollow cathode discharge [20] instead of a cascade arc discharge. A microhollow cathode discharge forms a hollow cathode glow discharge under atmospheric pressure by reducing the diameter of the hollow cathode [21, 22] to approximately 10^{-6} m [23]. The hollow cathode glow discharge is primarily characterized by the pendular motion of high-energy electrons and efficient collection of ions, which can produce high-density plasma [24–27]. In steady-state microhollow cathodes, the electron temperature and electron density were confirmed to be 1 eV, and 10^{15} cm^{-3}, respectively [28]. Owing to the small diameter of the microhollow cathode, the gas flow rate is low, and the flow path in the microhollow cathode is filled with dense plasma [27, 29].

This study aims to develop a plasma window with almost no gas passage using a microhollow cathode discharge. However, a distinct disadvantage is the small diameter of the proposed plasma window relative that of conventional windows, which is attributable to the small diameter of the microhollow cathode and an electromagnetically unavailable sheath region, which is affected by charged particles and X-rays.

The geometry of the electrode is shown in Fig. 1. The electrode structure comprises a 1 mm thick polytetrafluoroethylene (PTFE; Teflon) insulator sandwiched between two 1 mm thick stainless-steel plates and bored with 300 μm holes.

The electrodes were placed in a vacuum vessel to form a high- and low-side area.

The experiment was initiated with the stop valve at open position. A vacuum pump was used to evacuate both the high- and low-side areas. The stop valve was then closed to stop the evacuation of the high-side area. A constant voltage was applied through a 20 kΩ ballast resistor between the electrodes.

Gas (air) was injected into the high-side area using a

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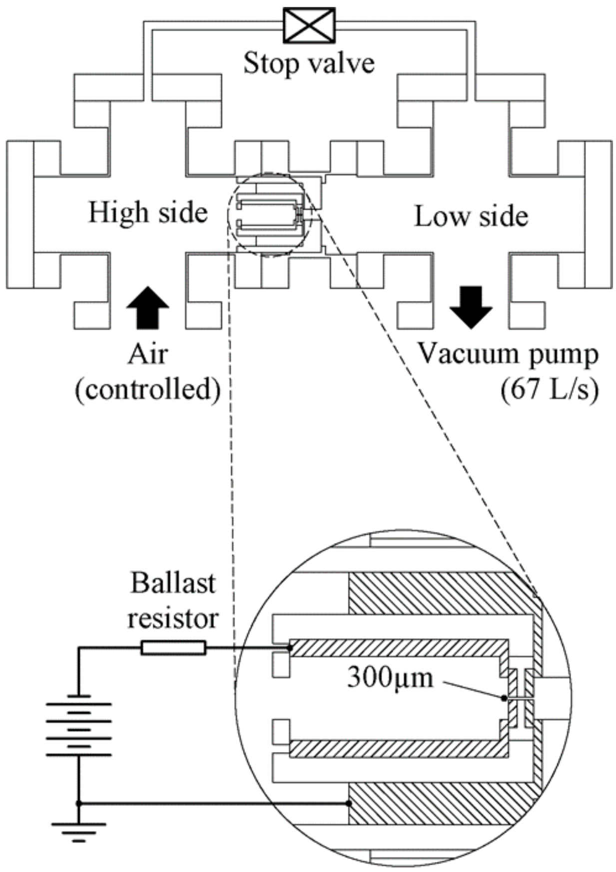

Fig. 1 Schematics of experimental equipment.

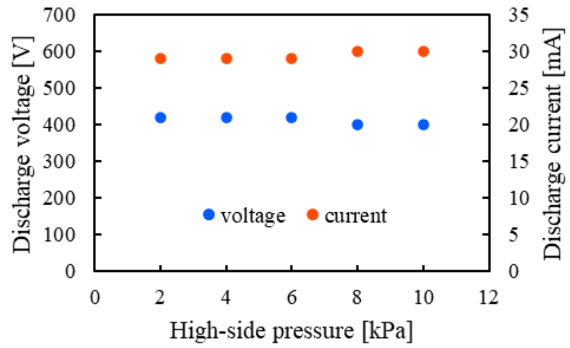

Fig. 2 Correlation of discharge data with high-side pressure.

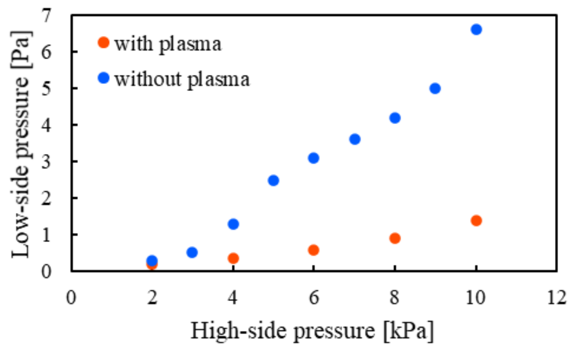

Fig. 3 Correlation of low-side area pressure with high-side pressure.

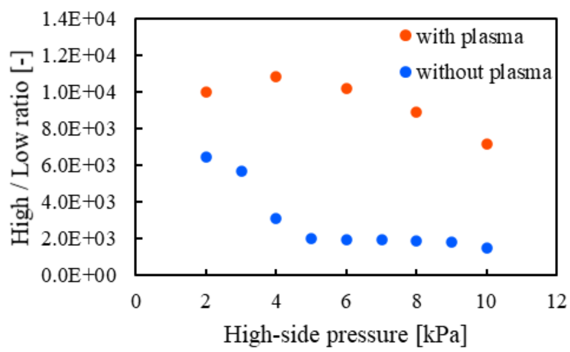

Fig. 4 Correlation of pressure ratio with high-side pressure.

piezo valve until the target pressure was reached to obtain steady discharge, and the pressure and discharge values of both regions were measured.

Similarly, the pressure values were measured in the absence of plasma and using the same procedure without applying a voltage.

The results of the experiment are presented as the relationship between the high-side pressure and the discharge data in Fig. 2, relationship between the high-side and low-side pressure in Fig. 3, and the relationship between the high-side pressure and pressure ratio in Fig. 4.

The stable discharge was formed in the microhollow cathode at 2 - 10 kPa, beyond which, including atmospheric pressure, no discharge could be formed. It has been previously reported that a microhollow cathode diameter of less than 100 μm is required to form an electrical discharge at atmospheric pressure [27, 30]. Therefore, the diameter of the experimental apparatus used in this study (300 μm) may have prevented discharge beyond the specified range. In addition, the use of air may have contributed to the prevention of discharge under atmospheric pressure. Further, the discharge formed at 400 V suggested the presence of a sheath region approximately 100 μm thick [30, 31], which is one-third of the microhollow cathode diameter.

The pressure difference was confirmed to have increased under all pressure conditions in the presence of plasma. This indicates that the plasma functioned as a plasma window. The pressure difference between the child and the plasma became more pronounced with increasing pressure on the high-pressure side. This may have been caused by the sheath becoming thinner as the pressure increased, increasing the area of plasma present [31]. An increase of pressure ratio of up to one order of magnitude, from 10^3 - 10^4, was achieved in the presence of plasma. In this experiment, a pressure difference of 0.889 - 8×10^3 Pa was obtained, which satisfies requirement of 1 - 7×10^3 Pa. However, for the transmission of charged particles and X-rays, the generated plasma window is smaller than required owing to the presence of a sheath region. Therefore, the diameter of the microhollow cathode should be increased while maintaining the pressure difference.

A plasma window based on a micro-hollow cathode discharge was designed to generate a pressure difference of $1 - 7 \times 10^3$ Pa—without using a large exhaust system—for practical application. A $0.889 - 8 \times 10^3$ Pa pressure difference or a pressure ratio of approximately 10^4 was achieved, which satisfies the functional requirements of a plasma window. However, for practical applicability, the diameter of the microhollow cathode should be increased while maintaining the desired pressure difference.

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