

Development of micro-solid propellant thruster array with improved repeatability

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Abstract: This paper presents the structure design, fabrication, and thrust measurement of a 5×5 micro-solid propellant thruster array. The micro-igniter developed in our previous study was used to verify the concept and improve the repeatability of the thruster array. The measured average thrust of each unit thruster was 0.238 N, and the calculated standard deviation was 0.031. All unit thrusters were successfully ignited; therefore, ignition was 100% successful. The standard deviation value obtained in this study indicated an improvement in the repeatability of the micro-thruster array. An ignition control system was developed and finally integrated with the thruster array.

Keywords: microthruster, microigniter, solid propellant, repeatability

INTRODUCTION

The development of MEMS technology has made it possible to produce micro-systems in the aerospace field; these include micro aerial vehicles (MAV), micro-missiles, and micro/nano-satellites. These systems can be used in more varied missions than conventional systems due to their low mass and very small size. In addition, the production cost of these systems can be greatly reduced, and hence, mass production is possible.

In many missions, a micro-propulsion system is needed for attitude control to effectively operate the micro-systems [1-2]. Many kinds of micro-propulsion systems have been developed, but the micro-solid propellant thruster is regarded as the most suitable system because it has a very simple structure and does not need moving parts. Its one-shot characteristic, which is the main disadvantage, can be compensated for by the array form. In this array form, repeatability—more simply, relatively low thruster variation in each thruster unit—is an important factor to realizing a successful thruster. Many research teams have developed micro-solid propellant thruster arrays [3-7], but there have been no studies on improving the repeatability so far.

In our previous study, we developed a new type of glass-based micro-igniter to improve the uniformity of the ignition characteristics in each igniter [8]. The main feature of this igniter is that a heater is in direct contact with the propellant for certain adhesion between the propellant and heater. Another feature is the fabrication method of its glass membrane. The membrane is fabricated by a polishing process instead of the wet etching process for a uniform membrane surface. These features were expected to improve the repeatability of the thruster array because the heater on the upper surface of membrane and non-uniform surface of the membrane were the main limitations of the previous glass-based micro-solid propellant thruster [7].

In this study, a 5×5 micro-solid propellant thruster array, including the igniter developed in the

previous study, was developed to verify the improvement in the repeatability. A fixture was fabricated in order to apply input voltage for firing test due to the electrodes which faced downward. The repeatability of the thruster array was evaluated using the firing test. A thruster array control system, including the PC program, was developed and finally integrated with the thruster array.

THRUSTER ARRAY STRUCTURE

The schematic of the micro-solid propellant thruster is shown in Fig. 1. All parts of the thruster array were fabricated using photosensitive glass wafer due to its low thermal conductivity and low fabrication cost. In addition, the thick membrane fabricated from the glass wafer helps protect the propellant from outside elements. This point is very important to thrusters in micro/nano-satellites because they operate in harsh space environments.

The thruster array consists of five layers: the seal layer, chamber layer, igniter layer, intermediary layer, and nozzle layer. The seal layer is located at the bottom of the thruster array to seal the propellant. The chamber diameter is 1 mm, as it was in our previous study [7-8]. The intermediary layer is inserted between the igniter layer and nozzle layer to structurally support the electrodes. The igniter layer consists of the heater (and electrodes) and membrane. The heater is patterned onto the membrane, and the

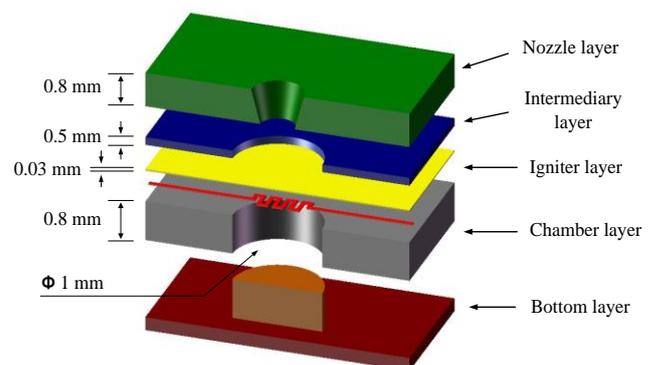


Figure 1. Schematic of micro-solid propellant thruster

membrane is formed by the polishing process, as it was in the previous study [8]. The nozzle layer is located at the top of the thruster array to accelerate the gas flow.

FABRICATION PROCESS

Intermediary layer, chamber layer, and bottom layer

The intermediary layer, chamber layer, and bottom layer were fabricated by anisotropic etching of photosensitive glass. The fabrication process is shown on the left-hand side of Fig. 2. The photosensitive glass wafer was diced into $30 \times 30 \times 1$ mm parts (Fig. 2(a)). The wafer was then selectively exposed to ultraviolet (UV) light with a wavelength of approximately 310 nm (Fig. 2(b)). The exposed wafer was then inserted into a programmable furnace for heat treatment. During the heat treatment, only the properties of the glass on the exposed area changed due to recrystallization (Fig. 2(c)). The wafer was wet-etched by a 10% hydrofluoric acid (HF) solution. The recrystallized area was etched 20 times faster than the unexposed area (Fig. 2(d)). After the etching process, the wafer was polished because the unexposed area roughened during the etching process.

Nozzle layer

A nozzle layer was fabricated with anisotropic etching on one side [7]. The fabrication process is shown in Fig. 2. The exposure of the photosensitive glass wafer and heat treatment of the wafer were the same for the examples shown in Figs. 2(a–c). The backside was protected by attaching Kapton tape to avoid etching (Fig. 2(c-1)). The wafer was then etched on one side by the 10% HF solution (Fig. 2(d-1)).

Igniter layer

The fabrication process of the igniter layer was divided into two parts: patterning of the heater and electrodes and fabrication of the membrane. The heater and electrodes were patterned onto the glass wafer first, and the membrane had to be fabricated after the wafer was integrated with the chamber layer because of a structural problem. The heater and electrode patterning process is shown in Fig. 2, and the membrane fabrication process is shown in Fig. 3. A $30 \times 30 \times 1$ mm glass wafer was prepared (Fig. 2(e)). To form the heater and electrodes, a 300 \AA thick layer of Cr and 4000 \AA thick layer of Ni were sputter-deposited onto the glass wafer (Fig. 2(f)). The Cr layer was used as the seal layer to improve Ni adhesion to the glass wafer. Ni was selected as the material of the heater and electrodes due to its low oxidation property. A photoresist was deposited and patterned to protect the heater and electrode region from the etchant (Figs. 2(g, h)). The Ni layer was etched first by using piranha solution. Then, the Cr layer was etched by using CR-7 solution (Fig. 2(i)). After the photoresist was removed, the heater and electrodes were patterned onto the glass

wafer (Fig. 2(j)).

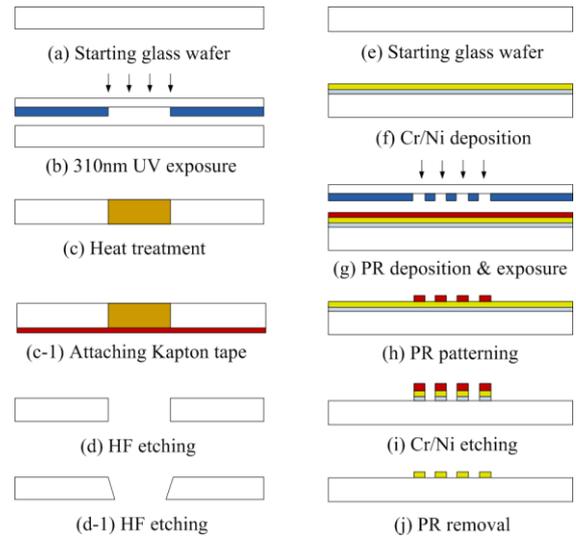


Figure 2. Fabrication process of each layer

Assembly of layers

The first step of the assembly process was the fabrication of the igniter and chamber layer. This process was a key process in the fabrication of the thruster array because an imperfect bond between these two layers can result in propellant leakage and breaking of the membrane during the polishing process. In the previous study, we developed a new UV-bonding process to ensure a certain bond [8]. This process is shown in the left-hand side of Fig. 3. UV-curable glue was spin-coated onto the igniter layer (Fig. 3(a)). Before deposition, the UV-curable glue was mixed with acetone to decrease its viscosity. The viscosity of the UV-curable glue had to be decreased to enable it to be spin-coated thinly for perfect removal, which is shown in Fig. 3(d). When UV-curable glue and acetone were mixed at a 5:3 ratio, the optimal bonding result was obtained [8]. The igniter and chamber layers were carefully aligned and exposed to UV light (Figs. 3(b, c)). The two layers were then soaked in acetone to remove the glue that had been exposed to the outside within the chamber (Fig. 3(d)).

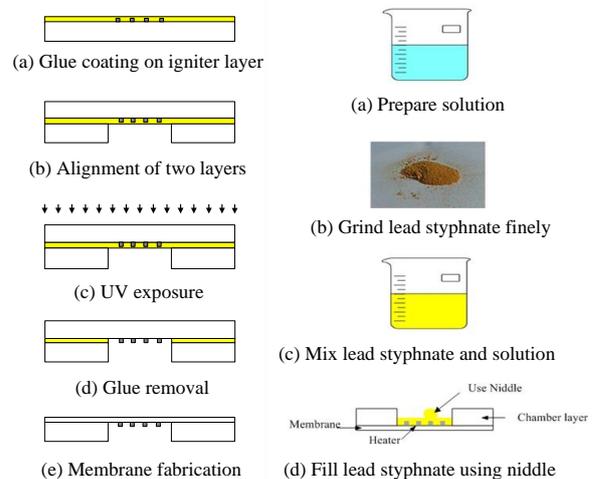


Figure 3. Integration of igniter and chamber layer and propellant loading process

Finally, the igniter layer was polished to form the membrane (Fig. 3(e)). The thickness of the membrane was 30 μm .

The second step of the assembly process was to load the chamber with the propellant. Lead styphnate was used as the propellant due to its high explosiveness. The loading process was the same as that in our previous studies [7-8]. This process is shown on the right-hand side of Fig. 3.

The third step of the assembly process was to integrate other layers with the igniter and chamber layers. This integration process is shown in Fig. 4. All layers were integrated using the UV-bonding process. This bonding process consisted of attaching Kapton tape to prevent a hole from being plugged and the propellant from being wetted by the glue, spin coating of the glue, alignment, and UV exposure. Fig. 5 shows the fabrication of each layer of the thruster array, and Fig. 6 shows the fabricated thruster array.

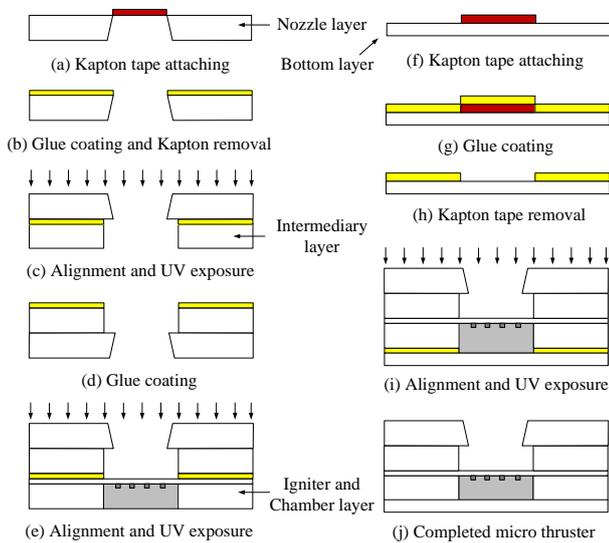


Figure 4. Integration process of nozzle, intermediary and bottom layer

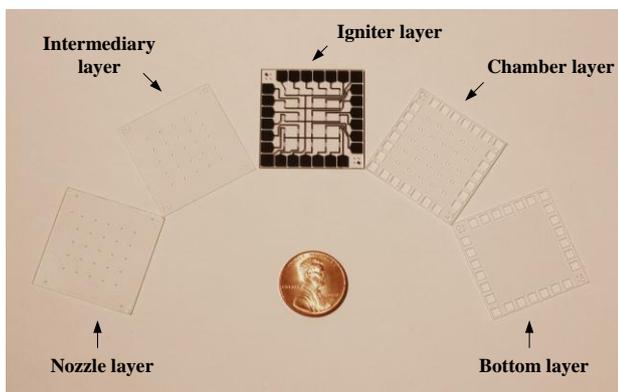


Figure 5. Fabricated each layer of thruster array

THRUST MEASUREMENT

Experimental setup

The experimental setup for the thrust measurement of the micro-thruster array is shown in Fig. 7. The input voltage was applied to the thruster array by a power supply. A quartz force sensor was used to

measure the thrust. The sensor converted the thrust into an electric charge, and the charge meter converted the electric charge into voltage.

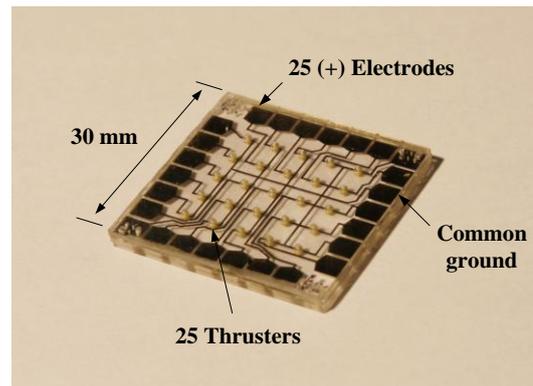


Figure 6. Fabricated micro thruster array

All voltages were acquired by an oscilloscope and a PC. A high-speed camera was used to capture the combustion of the thruster array. Electrodes for applying the input voltage faced downward in this thruster design. Hence, a fixture was used to ignite the thruster array.

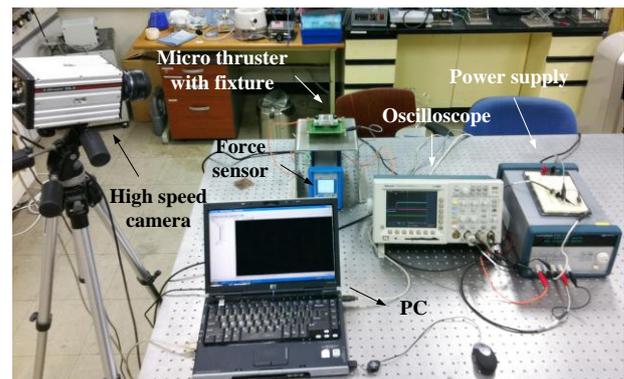


Figure 7. Experimental setup

Measurement results

All unit thrusters in the thruster array were ignited to measure their thrust. Fig. 8 shows the combustion of the thruster array, and Fig. 9 shows the measured thrust of each unit thruster. All unit thrusters successfully ignited and produced thrust, and hence, the ignition success rate was 100%. The measured average thrust was 0.238 N, and the calculated standard deviation of the thrust was 0.031.

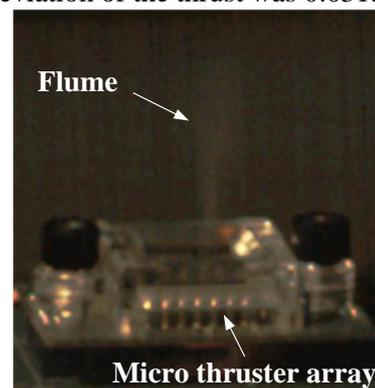


Figure 8. Combustion of thruster array

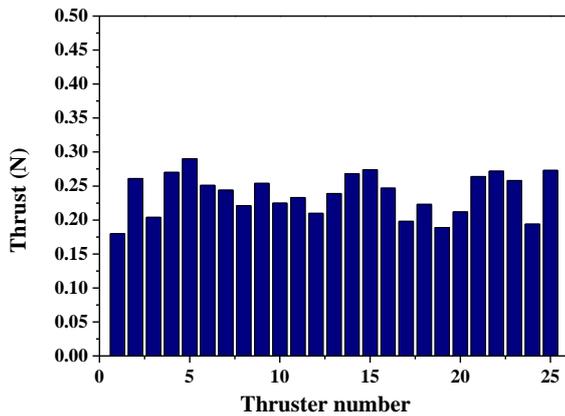


Figure 9. Measured thrust of unit thrusters

IGNITION CONTROL SYSTEM

An ignition control system was developed in order to ignite the desired unit thruster in the thruster array. Figure 10 shows the developed ignition control system. An electric circuit was built on a board including a micro-control processor and relays. This circuit was connected to a PC, and the control system was controlled by a PC program. An input voltage was applied to the control system by the power supply. The micro-thruster array was integrated with the fixture first, and then, the fixture was integrated with the control system.

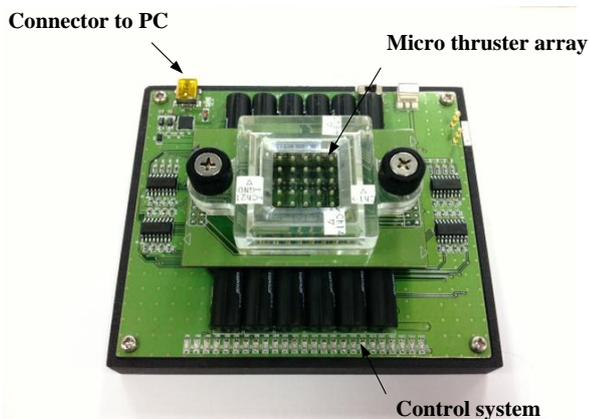


Figure 10. Developed ignition control system

CONCLUSION

The fabrication and performance evaluation of a 5×5 micro-solid propellant thruster array for improved repeatability is described here. In this micro-thruster array, the micro-igniter developed in our previous study was used because this igniter was ultimately developed in order to improve the repeatability of the thruster array. The fabrication process of each layer of the thruster array was established by using a photosensitive glass wafer. After the fabrication of each layer, the fabrication of the micro-thruster array was completed through the assembly process. The size of the fabricated thruster array was 30×30 mm, and each thruster unit had a chamber diameter of 1 mm. The membrane thickness was 30 μm . The thrust of

each unit thruster in the thruster array was evaluated through a firing test. The measured average thrust was 0.238 N, and the calculated standard deviation was 0.031. The ignition success rate was 100% because all unit thrusters successfully ignited. The standard deviation values showed that the repeatability of the micro-thruster array was improved. One reason that a standard deviation value occurred was the non-uniform amounts of the propellant, which was filled by hand. The standard deviation can be minimized if the amount of the propellant is made uniform by machine filling. To control the micro-thruster array, an ignition control system was developed. The control system consists of a control circuit, thruster jig, and PC program. This study demonstrated that improving the repeatability of a micro-thruster array for real applications is possible and verified the concept of the new micro-igniter proposed in our previous study.

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REFERENCES

- [1] J.Muller, I.Chakraborty, S.Vargo, C.Marrese, V.White, D.Bame 2000 Towards micropropulsion system on-a-chip: initial results of component feasibility studies *Proceedings of Aerospace Conference IEEE* 149-168
- [2] S.Cass 2001 MEMS in space *IEEE Spectrum* **38** 56-61
- [3] D.H.Lewis, S.W.Janson, R.B.Cohen, E.K.Antonsson 2000 Digital micropropulsion *Sensors and Actuators A* **80** 143-154
- [4] K.L.Zhang, S.K.Chou, S.S.Ang 2004 Development of solid propellant microthruster with chamber and nozzle etched on a wafer surface *Journal of Micromechanics and Microengineering* **14** 785-792
- [5] C.Rossi, B.Larangot, D.Lagrange, A.Chaalane 2005 Final characterization of MEMS-based pyrotechnical microthrusters *Sensors and Actuators A* **121** 508-514
- [6] S.Tanaka, K.Kondo, H.Habu, A.Itoh, M.Watanabe, K.Hori, M.Esashi 2008 B/Ti multilayer reactive igniters for a micro solid propellant array thruster *Sensor and Actuators A* **144** 361-366
- [7] Jongkwang Lee, Kyunghwan Kim, Sejin Kwon 2010 Design, fabrication, and testing of MEMS solid propellant thruster array chip on glass wafer *Sensor and Actuators A* **157** 126-134
- [8] Daeban Seo, Jongkwang Lee, Sejin Kwon 2010 Improvement of uniformity and ignition characteristics of micro igniter on glass wafer for micro solid propellant thruster *Proceedings of PowerMEMS 2010* 35-38