A VAPORIZING WATER MICRO-THRUSTER

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ABSTRACT

Vaporizing water micro-thrusters are fabricated and tested. A single micro-thruster we developed, fabricated by MEMS technologies, consists of a micro-resistor, a vaporizing chamber, a nozzle, a propellant inlet and a micro channel. The water propellant is fed into the thruster from a propellant tank by capillary force and pressure. The micro-thruster works in a pulse mode. During each period, an electric pulse is applied on the micro-resistor to heat the water in the chamber to vaporize it into high-pressure gas. A thrust is then produced as the gas exits through the nozzle. Test results show that for a single micro-thruster with pulse power of 48W, the total impulse produced in a second is more than 0.2×10^{-6}N • s.

INTRODUCTION

A micro-propulsion system can be used in micro satellites for orbit lifting, speed adjusting, gravitation compensation, station keeping, attitude control and so on. It mainly consists of micro-thruster, micro-valve, micro-pump, micro-plumbing, sensors and control circuit, etc. The focal point of current researches on micro-propulsion system is to develop small high performance chemical system and low power-consuming electric system. JPL exhibited prototypes of two kinds of micro-resistojet fabricated using MEMS technology in 1997. One is a subliming solid micro-thruster, the other a vaporizing liquid micro-thruster. Each of them weights only a few grams with the size of 1cm^2. Their performance goals include Isp up to 50sec ~ 125sec, thrust up to 0.5mN, and power less than 5W. TRW, the aerospace corporation and CIT have fabricated and tested a arrays of "Digital Propulsion"[1]. A three-layer sandwich is fabricated, containing micro-resistors, thrust chambers, and rupture diaphragms. Initial tests have produced 10^{-4} N • s of impulsion and about 100 Watt of power. A work is currently underway to study a micro-bipropellant rocket engine in MIT. The engine is composed of five or six silicon wafers piled up and interconnected using microfabrication technologies. A combustion chamber, a nozzle, two micro-pumps, two micro-valves and a cooling plumbing will be fabricated on silicon wafers. It is anticipated to produce 15N of thrust while consuming liquid oxygen and methanol propellants[2].

In this paper, a kind of vaporizing water micro-thrusters with a heating resistor is proposed. The fabrication results and testing characteristics of this micro-thruster are shown..

OPERATION PRINCIPLE

The micro-thruster we developed is mainly composed of a heating resistor, a vaporizing chamber, a nozzle, a propellant inlet and a micro channel. In the micro-thruster, electric power is supplied to vaporize the liquid propellant into gas, which exits through nozzle to produce thrust. The working principle of the micro-thruster is similar to that of a thermal-bubble inkjet. The difference between the bubble inkjet and our micro-thruster is that, for inkjet, only a little part of ink should be vaporized to form a bubble, for micro-thruster, however, all the propellant in the chamber is needed to be vaporized. Obviously, the driving power consumption of micro-thruster is much larger than that of inkjet.

As shown in Fig.1, the micro resistojet propulsion system[3] consists of a power source, a control circuit, a propellant control system and a single or arrayed vaporizing water micro-thruster(s). The propellant is fed into the chamber by capillary force and pressure from a propellant storing tank. The micro-thruster works in pulse mode. A pulsed electric current with pulse width of the order of micro-second is applied on the heating resistor, thereby the propellant in the chamber is vaporized into gas with high temperature and high pressure in a very short time. The gas exits through the specially shaped nozzle rapidly to produce thrust.

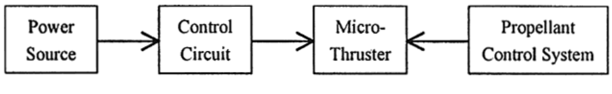


Fig.1 Micro resistojet propulsion system construction

CONFIGURATION AND FABRICATION

The micro-thruster chip, fabricated by MEMS technologies, consists of two silicon wafers as shown in Fig.2. The nozzle and the holes for wire bonding are fabricated on the top wafer by bulk silicon etching. A shallow slot is bulk-etched to form the vaporizing chamber and the micro channel on the front side of the bottom wafer. The heating resistor, internal wire and bonding pad are all formed by metal Ti at the bottom of the chamber to simplify the fabrication process. In order to concentrate the heat produced at the center of the chamber and consequently reduce the heat loss on the internal wire, we make the width of the internal wire much larger than that of the heating resistor to reduce the resistance of the wire, as shown in Fig5(b). The propellant inlet and a cavity are bulk-etched from the back side of the bottom wafer. The cavity formed under the heating resistor is aimed to reduce heat capacitance of the bottom silicon layer, which also decrease the heat loss. The vaporizing chamber is connected with a propellant tank through a micro channel and an inlet. External wires go through the holes in the top wafer for wire bonding with the pads. Three types of nozzles are designed: convergent nozzle, de laval nozzle, and divergent nozzle, which are shown in Fig.3.

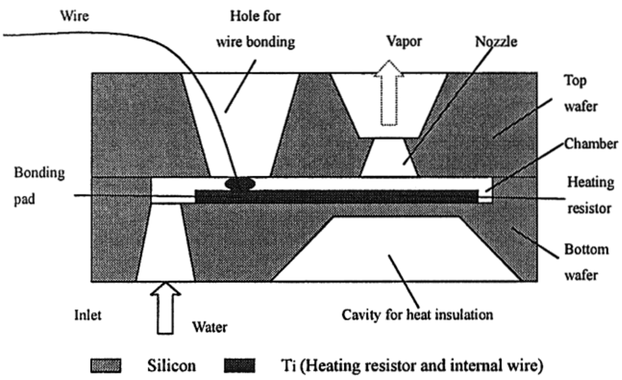
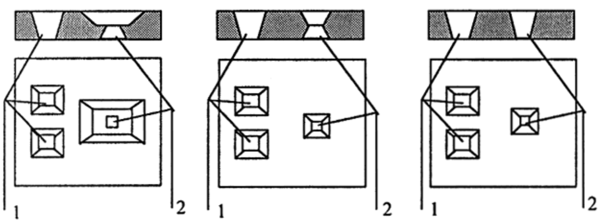


Fig.2 Configuration of the micro-thruster chip

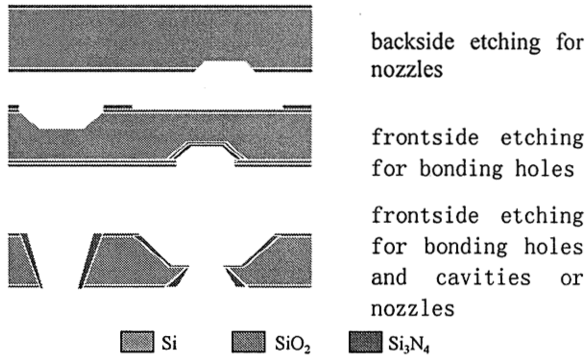


1.Holes for bonding 2. Nozzle
(a) convergent nozzle (b) de laval nozzle (c) divergent nozzle

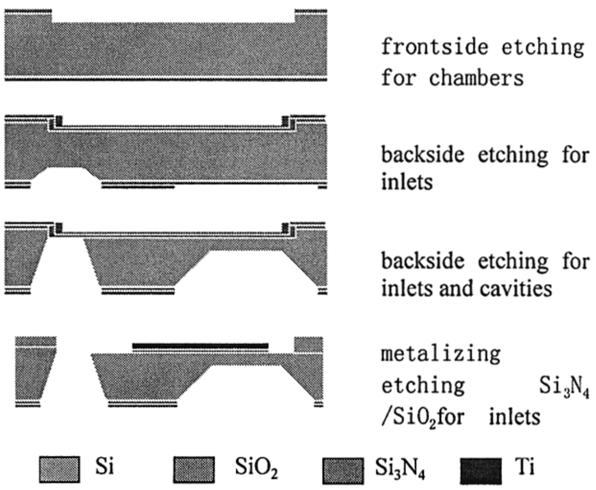
Fig.3 Schematic of the three types of the nozzles

The fabrication process of a micro-thruster chip is shown in Fig.4, in which (a) is the process of the top wafer and (b) the bottom wafer. After the process, the two wafers are bonded together.

In some micro-thrusters, the inside surface of the nozzle is specially treated to be hydrophobic to prevent water propellant from entering the nozzle to reduce the water drop ejection in operation, which wastes the propellant and decreases the performance of the micro-thruster significantly.



(a) Fabrication process of the top wafer



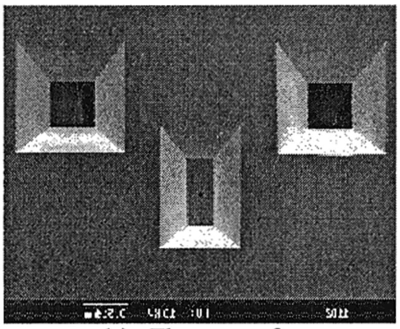
(b) Fabrication process of the bottom wafer

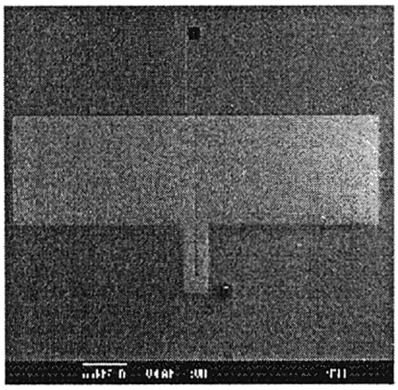
Fig.4 Fabrication process of the micro-thruster chip

We fabricated individual micro-thrusters and 2 × 2 arrayed micro-thruster of different structure and size. The arrayed one can be able to work with only one thruster or with several thrusters at the same time. Fig.5(a) shows a SEM graph of the top silicon wafer of a single micro-thruster. There is a nozzle with a throat size of 30μm × 30μm on the bottom of the center rectangle slot. The two square holes are for wire bonding. Fig.5(b) shows the front side of the bottom silicon wafer. The shape of the heating resistor using metal Ti, the internal wires and the bonding pads, which are positioned on the bottom of a 2μm shallow chamber, is discernible. And the inlet and the micro channel for propellant input are shown too. Fig.5(c) shows the back side of the bottom silicon wafer. The rectangle cavity is used to reduce heat capacitance, and the square hole above is the inlet.

80 units are fabricated on a pair of 4-inch silicon wafers. The size of the silicon chip of the individual micro-thruster is $7 \times 7 \times 1mm^3$, and the packaged chip $18 \times 13 \times 5mm^3$. The size of the silicon chip of the 2×2 arrayed micro-thruster is $10 \times 10 \times 1mm^3$, and the

packaged chip 28 × 20 × 5mm³. The mass of the packaged chips of the both micro-thrusters ranges from 0.9g to 2.1g.


(a) The top wafer


(b) Front side of the bottom wafer

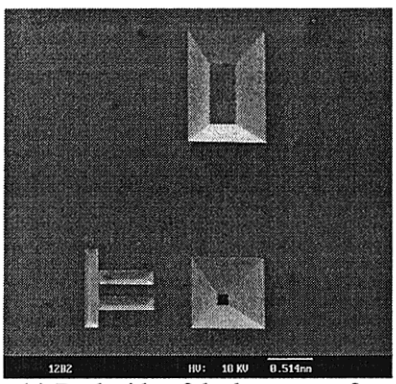
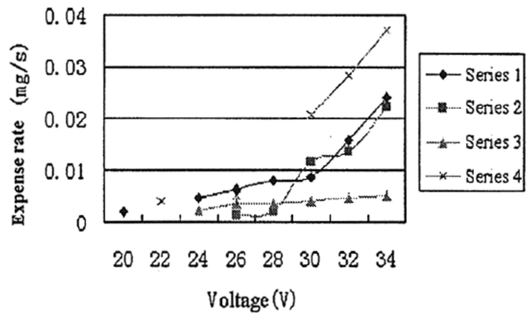

(c) Back side of the bottom wafer

Fig.5 The SEM graphs of a single micro-thruster chip

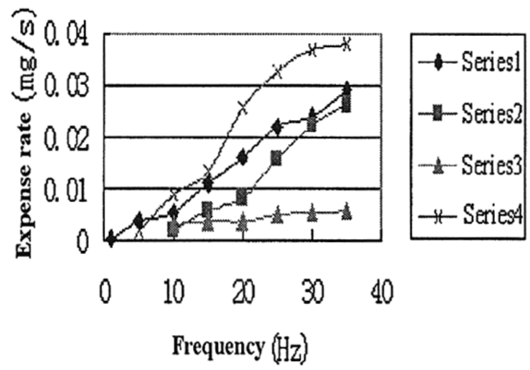
TESING

The performances of the micro-thrusters have been tested. Four types of micro-thrusters used for testing are as following. Series1: valid chamber area 300μm × 750μm, convergent nozzle, heating resistor 39 Ω. Series2: valid chamber area 600μm × 1500μm, convergent nozzle, heating resistor 36 Ω. Series3: valid chamber area 300μm × 750μm, convergent nozzle with hydrophobic surface, heating resistor 39 Ω. Series4: valid chamber area 600μm × 1500μm, divergent nozzle, heating resistor 36 Ω.

We measured expense rates of water propellant of the micro-thrusters using an electric balance, whose precision is up to 0.1mg, to record the mass variation of the micro-thrusters and the water tank after a period of operation. According to the test results, series3 has the smallest expense rate. This means that the hydrophobic surface reduces propellant wasting. Fig.6 shows the relationship of the expense rate to voltage and to frequency for the four micro-thrusters. From the Fig.6, we can see that the expense rate increases as voltage and frequency is increased. The maximum expense rate of propellant is 0.038mg/s.



(a)



(b)

Fig.6 Relationship of flow rate to voltage (a) and to frequency (b)

Fig.7 shows the velocity and the diameter distribution of the ejected water vapor particles of the series1 micro-thruster, which are measured by a laser Doppler velocity measurement system. According to Fig.7, the maximum velocity of the ejected water vapor particles is 20m/s, average velocity is 8.9095m/s, velocity variance is 4.81105m/s, and the average diameter of the ejected water vapor particles is 19.5μm, with the driving pulse width 900μs, voltage 34V, frequency 30Hz. The total impulse of the micro-thruster produced in a second, calculated from the expense rate and the average velocity of the ejected vapor, is more than 0.2×10^{-6}N • s[4].

Pulse width (μs)	Series1		Series2		Series3		Series4	
	velocity (m/s)	diameter (μm)	velocity (m/s)	diameter (μm)	velocity (m/s)	diameter (μm)	velocity (m/s)	diameter (μm)
600	9.22	19.9						
700	9.57	17.6			6.68	25.7		
800	8.95	18.4			5.68	26.8		
900	8.91	19.5			4.47	31		
1000					5.04	26.5		
1100					4.23	15		
1200							3.77	19.1
1300			3.44	18.5			4.96	13.2
1400			3.55	15.2			4.61	22.4
1500			3.05	17.1			4.03	14.2

Table 1 Average velocities and diameters versus driving pulse width for four types of the micro thrusters
Driving frequency: 30Hz, Voltage: 34V

Voltage (V)	Series1		Series2		Series3		Series4	
	velocity (m/s)	diameter (μm)	velocity (m/s)	diameter (μm)	velocity (m/s)	diameter (μm)	velocity (m/s)	diameter (μm)
32	6.43	21.2	3.57	17.2			2.1637	34.4
34	8.95	18.4	3.05	17.1	5.68	26.8	4.0318	14.2
36	8.58	14.8			5.65	19.7		
38					4.52	17.5		

Table 2 Average velocities and diameters versus driving voltages for four types of the micro thrusters
Series1, Series3: Frequency: 30Hz, Pulse width: 800μs
Series2, Series4: Frequency: 30Hz, Pulse width: 1500μs

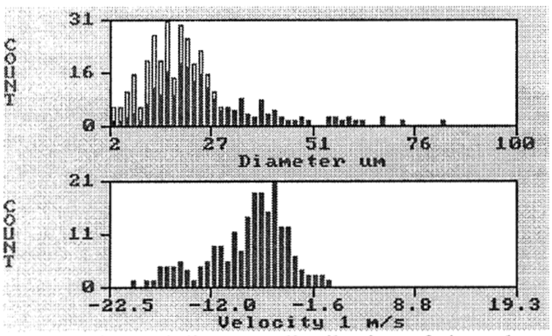


Fig.7 Velocity and diameter distribution of ejected water vapor particles
Pulse width: 900μs, Voltage: 34V,
Frequency: 30Hz

Table 1 shows the average velocities and the average diameter of ejected water vapor particles for the four types of the micro-thrusters versus the driving pulse width, and Table 2 shows these versus the driving voltage. The micro-thruster of Series1 has a maximum velocity and that of Series3 has a maximum diameter. The velocity of Series2 and Series4 are lower than that of the Series1 and Series2, maybe because the chamber volume of Series2 and Series4 is four times of that of Series1 and Series3, but the driving power is only about two times. There are not clearly changes the average diameter of ejected water vapor particles when the driving pulse width and voltage change little. The maximum velocity of ejected water vapor particle is up to 28m/s.

The thrust force of a micro thruster is roughly determined using an initially measurement system shown in Fig.8. The micro-thruster is mounted to the foundation of a micro translation stage, and a cantilever beam is fixed on the moving part of the stage which adjust the free end of the cantilever beam to aim at the nozzle. When the micro-thruster is operating, the gas which dashes out through the nozzle hits the free end of the beam and make it deflect.

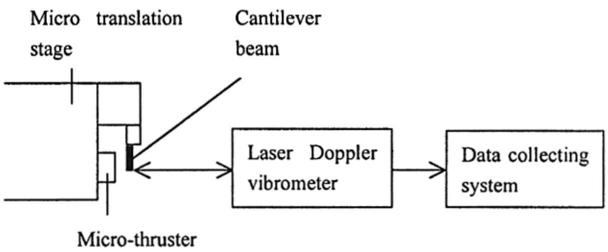


Fig.8 Schematic of micro-thruster measurement system

By measuring the displacement of the free end of a cantilever beam, the approximate thrust of the micro-thruster can be calculated from the following formula.

$$F = \frac{3EI}{l^3} d \qquad (1)$$

where E is the Young's modulus of the cantilever beam, 120GPa with metal Cu beam, l the length of the beam, 5mm and I is the cross section moment of inertia of the beam, and can be expressed as

$$I = \frac{bh^3}{12} \qquad (2)$$

where b is the width of the beam, 2mm, and h the thickness, 30μm.

Fig.9 shows the displacement curve of the Series1 micro-thruster measured by a laser Doppler vibrometer. The maximum thrust is about 2.9μN based on the curve. Table 3 and table 4 show the thrust forces versus driving frequencies and voltages respectively for Series1 and Series3 of micro-thrusters. The thrust force increases along with the increasing of the driving pulse width and voltage.

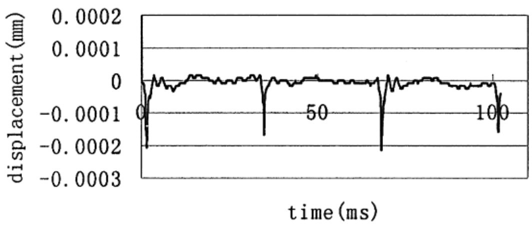


Fig.9 Displacement of the free end of a cantilever
Pulse width: 900μs Voltage: 34V
Frequency: 30Hz

Pulse width (Hz)	Thrust force (μN)	
	Series1	Series3
500	0.82	1.44
600	1.13	1.65
700	1.74	1.84
800	2.15	2.26
900	2.86	2.77

Table 3 Thrust forces versus driving frequencies for two types of micro-thrusters.
Driving frequency: 30Hz, Voltage 34V

Voltage (V)	Thrust force (μN)	
	Series1	Series3
32	0.71	1.02
34	2.15	2.26
36	2.57	2.57
38		2.77

Table 4 Thrust forces versus driving voltages for two types of micro-thrusters
Driving frequency: 30Hz, Pulse width: 800μs

DISCUSSION

We temporarily selected water as the propellant because of its cheapness and safety, and suitability for study in a university. Result of the water propellant micro-thruster is significant for further investigation though its performance is not so good. In practical applications, N_2H_4, NH_3, etc. can be selected as propellant for better performance.

The measured results of the velocity of ejected vapor are lower comparing with that on the real application case, because when the hot vapor dash out to the environment with normal temperature and atmospheric pressure, the vapor will coagulate reducing but increasing the diameters of particles. The invacuum measurement condition as well as the gap between the outlet of the nozzle and the free end of the beam cause the measured value of the thrust less than the real one. In addition, though the actual action of the thrust is an impulse in a very short time, we calculated the thrust force as a static force, which can make to evaluate the thrust lower too.

CONCLUSION

In this paper, the design and configuration of initial prototypes of vaporizing water micro-thrusters have been described, and the primary test data have been reported. The application of the micro-thrusters aims at the position control of micro-satellites. The micro-thruster chip consists of a micro-resistor, a vaporizing chamber, a nozzle, an inlet and a micro channel, with two silicon wafers bonded together. In the test condition, The maximum average velocity of ejected vapor particles is 8.5m/s, and the maximum velocity is 28m/s, The maximum thrust is 2.9μN and the total impulse produced in a second is more than 0.2×10^{-6}N • s. The maximum expense rate of propellant is 0.038mg/s. The characters of the four types of the micro thrusters must be investigated more detailedly in future.

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