A PIEZOELECTRIC LIQUID-COMPATIBLE MICROVALVE FOR INTEGRATED MICROPROPULSION

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ABSTRACT

A leak-tight, low-power, liquid-compatible, piezoelectric microvalve has been designed, fabricated, and fully characterized. The measured leak rate of the microvalve for Helium gas is 3×10^{-6} scc/sec. The measured forward flow rate using deionized (DI) water is approximately 64 mg/min at 20 psi with the applied voltage of 50V. The resonance frequency of the microvalve is about 11.1 kHz. The measured dynamic power consumption of the microvalve is approximately 60 mW at 50Hz. The measured static power consumption is approximately 2.5 mW at 20V. The microvalve is designed for proportional flow control of liquid propellant for integrated micropropulsion.

INTRODUCTION

Micro/nano spacecraft concepts are of great interest in the aerospace community [1]. Reduction in the mass and size of a space instrument or subsystem results in a nearly exponential savings in launch costs as well as a significant increase in mission duration. In order to enable the construction of such 'microspacecraft', each subsystem will also have to be reduced in size and adapted in function to fit within the spacecraft size and mass envelope, and thereby require extensive miniaturization. Furthermore, thrust levels and impulse bits will have to be reduced in magnitude. The reduction in thrust levels and impulse bits requires fine control of very low propellant flow rates. Microvalves are therefore needed to control such propellant flow.

The authors' group has already demonstrated gas-compatible microvalves for Xenon Electric Propulsion [2]. Recently, JPL has initiated the development of 1-kg-class microspacecraft test-beds, requiring leak-tight, liquid-compatible microvalves, capable of providing precisely controlled, low propellant flow from a liquid propellant tank. Due to the limited resources of propellant and power, such a microvalve must exhibit leak-tight and low power operation (See Table 1). Previously reported liquid-compatible microvalves using electromagnetic and thermal actuators have high power consumption and/or slow actuation [3, 4], both of which are unacceptable for micropropulsion applications. Other liquid-compatible microvalves using either electrostatic or piezoelectric actuators do not meet the demanding requirements of

Table 1. Microvalve specifications for controlling NASA's 1-kg-class microspacecraft propulsion.

	Generic microvalve requirements
Propellant type	Liquid
Inlet Pressure	~ 50 psi
Leak Rate	$< 5 \times 10^{-5}$ scc/sec (helium)
Response Time	< 0.1 msec
Power consumption	< 4 mW

low leak rate or large pressure ranges [5, 6]. Therefore, in this paper, we present the results of development of our leak-tight, low-power, fast-actuation microvalve for proportional flow control of liquid propellant.

DESIGN OF MICROVALVE

Our microvalve is actuated using a custom-designed piezoelectric stack actuator, which is bonded onto silicon-based components consisting of a valve seat, a lower boss, and an upper boss, as shown in Figure 1. The piezoelectric actuator consists of two active zones surrounding a central inactive zone. Active zones expand vertically as a voltage is applied to the piezoelectric stack. Unlike in our previous microvalve design for high-pressure Xenon Electric Propulsion [2], the microvalve reported in this paper has a silicon membrane called the upper-boss, for isolating the piezoelectric actuator from the liquid propellant. Because the liquid propellant remains inside the silicon chamber, it does not cause electrical shorting within the piezoelectric actuator. The upper boss layer is compression bonded to the lower boss using Au bonding metallization. The bonded boss stack is subsequently bonded to the valve seat. Finally, the custom-designed piezoelectric actuator is epoxy bonded to the top of the upper boss layer.

Figure 1. Structure of the liquid microvalve. All silicon components are metal-to-metal compression bonded and the custom-designed piezoelectric stack is bonded on top of the upper-boss wafer.

Figure 2. Operating principle of the microvalve. (a) normally-closed “off” state (b) actuated “on” state:

Figure 2 shows the microvalve operation principle. The microvalve is the normally closed (“off” state), as shown in Figure 2 (a). The normally closed condition is achieved by applying an initial seating pressure on the valve seat during the bonding of the piezoelectric actuator to the silicon assembly [2]. Application of a voltage to the piezoelectric actuator makes the active zones of the piezoelectric actuator expand vertically, lifting up the lower-boss center plate from the valve seat, as shown in Figure 2(b). This raising action opens up a flow path between the inlet and outlet holes. Proportional flow control of the fluid is achieved by controlling the upward displacement of the piezoelectric actuator by changing the applied voltage.

FABRICATION

The “knife-edge” seat rings are formed on the valve seat by patterning and etching a thermal oxide film using 10:1 Buffered Oxide Etchant (BOE). Subsequently, the wafer is etched using a deep reactive ion etcher (DRIE). Following DRIE, a Cr/Pt/Au film is deposited on the oxide film and patterned using a lift-off process. This metallization is used for the Au-Au compression bonding. Following the metallization step, a central outlet hole is formed using DRIE. On the lower boss plate, a 2- μm -thick Plasma Enhanced Chemical Vapor Deposition (PECVD) silicon dioxide is deposited and patterned. As in the previous case a Au-Au compression bonding metallization consisting of Cr/Pt/Au sandwiched layers are formed on both sides of the wafer. A final DRIE process is performed for defining the tether and the center plate. On the upper boss plate, the thin membrane is defined using DRIE, followed by the deposition and patterning of the Cr/Pt/Au bonding layer. Four inlet holes are formed subsequently in each corner of the boss plate using DRIE. Scanning Electron Microscope (SEM) images of the microfabricated silicon components are shown in Figure 3. In Figure 3, the valve seat has an outlet hole, concentric “knife-edge” rings (which also act as a particle filter) and the Au bonding metallization. On the upper boss plate, there are 4 inlet holes, a thin membrane, and the Au

bonding metallization. On the lower boss plate, the tether, center plate, inlet holes, and the Au bonding metallization are seen.

Figure 4 shows the fully assembled and packaged microvalve. The inlet gas tube is connected to the inlet hole in the upper boss plate. Also seen are the wires for applying voltage to the piezoelectric actuator and the outlet hole in the seat wafer. The outlet hole diameter is about 200 μm .

Figure 3. SEM images of the (a) valve seat, (b) upper boss plate, and (c) valve sealing surface of the lower boss plate and (d) upper boss bonding side of the lower boss plate.

Figure 4. Fully assembled and packaged microvalve.

MEASUREMENTS

We measured the stroke of the piezoelectric actuator before and after bonding to silicon components. As shown in Figure 5, there is negligible difference in stroke between the two conditions. This implies that the piezoelectric actuator essentially exerts a very high seating force and can provide robust on-off operation for the microvalve. The blocking force of the stacked multi-layer piezoelectric actuator used in the microvalve is estimated at approximately 1000 N. The measured deflection of the piezoelectric actuator is about 4 μm and $-1 \mu\text{m}$ respectively at the applied voltages of 50 V and -10 V.

Leak rate (off state) and flow rate (on state) testing of the packaged microvalves were conducted using both Helium-gas and DI water. The flow test block diagram is shown in Figure 6. Flow rate was measured using an external Mass Flow Meter (MFM) with a measurement resolution of approximately 1.0×10^{-2} scc/s.

Helium leak rates were measured using a Helium leak detector. The measured leak rates ranged from 3×10^{-6} scc/sec to 4×10^{-5} scc/sec at an inlet pressure of 50 psi, as shown in Figure 7. We believe that the low leak rates are attributable to the combination of the smooth hard-seat surfaces (RMS surface roughness is 0.3 nm) and the pre-loaded seating configuration [2].

The measured forward flow rates at various inlet pressures for deionized (DI) water are shown in Figure 8. As the voltage applied to the piezoelectric actuator increases, the vertical deflection increases, increasing the flow of the DI water. The measured flow rate is approximately 60 mg/min at an inlet pressure of 20 psi (for an applied voltage of 40V).

As shown in Figure 9, we measured the DI water flow rate versus the various duty ratios of the pulsed voltage signal for different inlet pressures. The measured dynamic flow rate is 30 mg/min at 90% pulse width for a 15 psi inlet pressure.

Figure 5. PZT actuator vertical displacement vs. applied voltage in the unbonded and bonded states.

Figure 6. Schematic diagram showing the microvalve test setup.

Figure 7. Measured leak rates for six normally-closed (non-actuated) microvalves.

Figure 8. Measured flow rates for an actuated microvalve at various inlet pressures.

Figure 9. Measured flow rates for a microvalve actuated with voltage pulses with varying duty ratios for various inlet pressures. (An 18 V square pulse was applied)

Figure 10. Power consumption versus operating frequency for a microvalve operated with 10 V_{p-p} sinusoidal signals.

Figure 11. Measured frequency response of the microvalve. The estimated transient response time is about 30 μ s.

The measured static power consumption is primarily due to the leakage current in the piezoelectric actuator and was measured at 2.5 mW at 20 V. The dynamic power consumption was measured by taking the phase delay into account. Figure 10 shows the dynamic power consumption measurement results. For instance, the dynamic power consumption is about 60 mW for 10 V_{p-p} , 50 Hz actuation. This value is very low compared to the power consumed by either thermally-actuated or magnetically-actuated microvalves. This power consumption is further reduced to a few milli watts when the microvalve is operated in a static proportional flow control mode.

We have also measured the resonance frequency of the piezoelectric actuator bonded to silicon microvalve using a laser doppler vibrometer, as shown in Figure 11. The measured valve is about 11.1 kHz, which shows that the microvalve is capable of fast transient response.

CONCLUSIONS

We have successfully demonstrated piezoelectrically-actuated liquid-compatible silicon microvalves. The measured leak rate of

a microvalve using Helium gas is 3×10^{-6} scc/sec. The measured static power consumption is approximately 2.5 mW at 20V. The measured dynamic power consumption of the microvalve is approximately 60 mW at 50Hz. The microvalve is capable of proportional flow control of liquid propellant for integrated micropropulsion applications.

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