A PIEZOELECTRIC LIQUID-COMPATIBLE MICROVALVE FOR INTERGRAED MICROPROPULSION

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

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

ABSTRACT

A leak-tight, low-power, liquid-compatible, piezoelectric microvalve has been designed, fabricated, and fully characterized. The measured leak rate of the microvalve using Helium gas is 3 x 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 provides the 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 nearly exponential savings in launch costs as well as significant increases in mission duration. In order to enable the construction of such 'microspacecraft', each subsystem will 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 small propellant flow rates. Microvalves are needed to control these propellant flows.

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, which can provide precisely controlled, small propellant flow from a liquid propellant tank. Due to the limited resources of propellant and power, the microvalve must exhibit leak-tight and low power operation (See Table 1). Previously reported liquid-compatible microvalves using electromagnetic and thermal actuators show high power consumption and/or slow actuation [3, 4], which are unacceptable for micropropulsion applications. Other liquid-compatible microvalves using electrostatic and piezoelectric actuators do not meet the requirements of low leak rate or pressure range [5, 6]. Therefore, in this paper, we present a leak-tight, low-power, fast-actuation microvalve for proportional flow control of liquid propellant.

DESIGN OF MICROVALVE

The microvalve controls the flow of propellant from the pressurized propellant tank. The microvalve is actuated by a custom-designed piezoelectric stack actuator, which is bonded onto silicon microvalve components consisting of a seat, a lower-boss, and an upper-boss, as shown in Figure 1. The piezoelectric actuator consists of two active zones and an inactive zone. Active zones only expand vertically as a voltage is applied to the piezoelectric actuator. Unlike our previous microvalve for high-pressure Xenon Electric Propulsion [2], the microvalve reported in this paper has a silicon membrane called upper-boss, isolating the piezoelectric actuator from the liquid propellant. Because the liquid propellant remains inside the silicon chamber, so it doesn't cause the electrical short in the piezoelectric actuator. The upper-boss is compression bonded to the lower boss using Au metal layers. The bonded boss wafer is subsequently bonded to the seat wafer. The custom-designed piezoelectric actuator is bonded on top of the upper boss wafer using an epoxy.

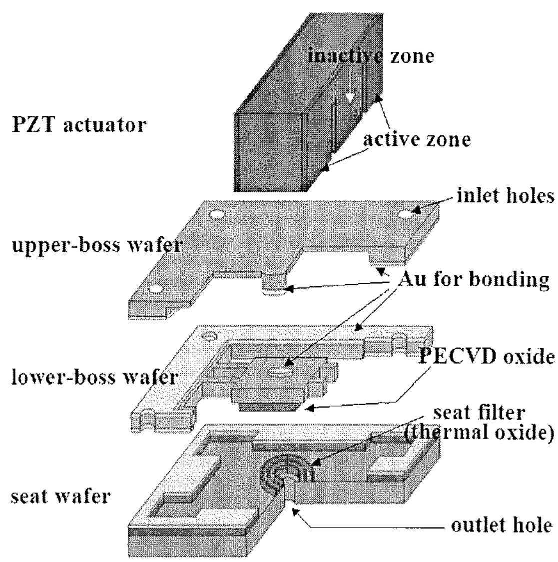

Figure 1. *Structure of the liquid-microvalve. All silicon components are metal-to-metal compression bonded and the custom-designed piezoelectric stack is bonded on top of the upper-boss wafer.*

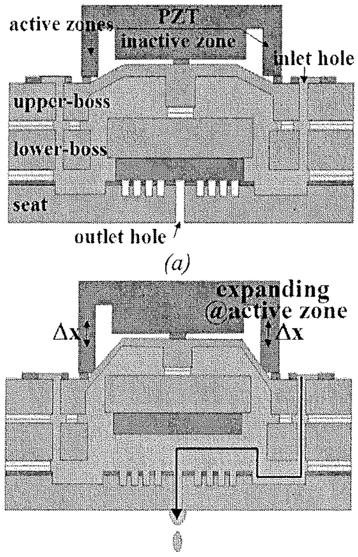

Figure 2. Operating principle of the microvalve. (a) normally-closed "off" state (b) "on" state:

Figure 2 shows the microvalve operation principle. The microvalve is the normally closed ("off" state), as shown in Figure 2 (a), because the initial pressure is applied from the pre-stressed silicon tethers and the piezoelectric actuator to the seat wafer [2]. Application of a voltage to the piezoelectric actuator makes the active zones of the piezoelectric actuator vertically expand, lifting up the lower-boss center plate from the seat plate, as shown in Figure2 (b). This action creates flow path between the inlet and outlet holes. Changing the upward movement distance using the voltage in the piezoelectric actuator can control the propellant flow rate.

FABRICATION

In the seat wafer, the seat rings are formed by etching the oxide film using 10:1 Buffered Oxide Etchant (BOE). Then, the wafer is etched using a deep reactive ion etcher (DRIE). It has lift-off Cr/Pt/Au film on the oxide film for Au-Au compression bonding. Then, it has been etched through using DRIE in order to make outlet hole in the center. In the lower boss wafer, 2 μm Plasma Enhanced Chemical Vapor Deposition (PECVD) silicon dioxide has been deposited and patterned on the center plate. Au-Au compression bonding metal layers such as Cr/Pt/Au has been patterned on the both side the wafer. A final DRIE process has been done for defining tether, and center plate. In the upper boss wafer, thin membrane has been defined using DRIE. Cr/Pt/Au layer has been patterned for the bonding process. Four inlet holes in each corner have been made by through etching with DRIE. The SEM images of the fabricated silicon components are shown in Figure 3. In Figure 3, seat wafer has outlet hole, seat filters, Au film for bonding. In the upper boss wafer, there are 4 inlet holes, thin membrane, and Au film for bonding. In the lower boss wafer, there are tether, center plate, inlet holes, Au film for bonding.

Figure 4 shows the packaged microvalve. Inlet gas tube is connected to inlet hole in the upper wafer. There are +/- electrode lines for applying the voltages in the piezoelectric actuator and outlet hole in the seat wafer. Outlet hole diameter is about 200 μm.

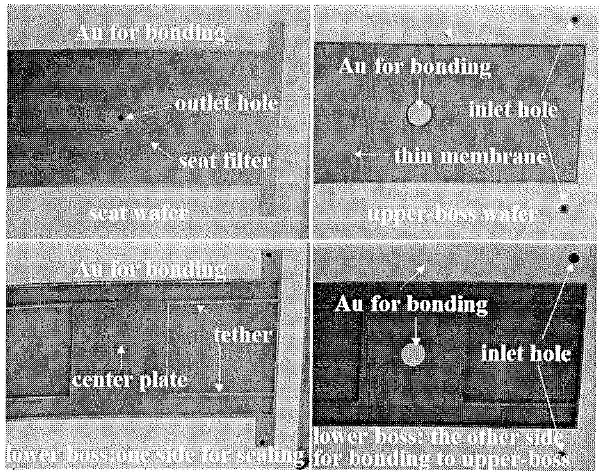

Figure 3. SEM images of seat, upper boss, and lower boss.

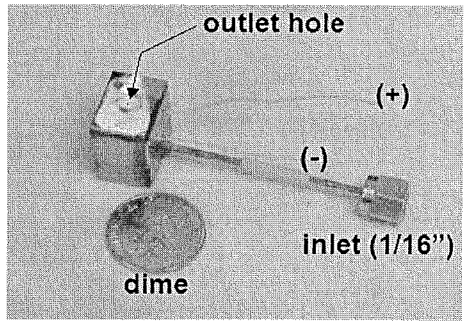

Figure 4. Packaged microvalve.

MEASUREMENTS

We measured stroke of the piezoelectric actuator before and after bonding to silicon components. Those are almost identical, as shown in Figure 5. It means that the piezoelectric actuator exerts a very high seating force that can provide robust on-off operation for the microvalve. The blocking force of the stacked multi-layer piezoelectric actuator used in the microvalve is about 1000 N. And the deflection in the piezoelectric actuator is about 4 μm and $-1 \mu m$ at the applications of 50 V and – 10 V, respectively.

The leak and flow rates of the fabricated microvalves have been tested using Helium-gas and DI water. The flow test block diagram is shown in Figure 6. First of all, we measured the Helium leak rate using Mass Flow Meter (MFM) of which resolution is about 1.0×10^{-2} scc/s. If the leak rate is undetectable with MFM, then we measured the Helium leak rate using Helium leak detector. The measured leak rates are ranged from 3×10^{-6} scc/sec to 4×10^{-5} scc/sec at 50 psi, as shown in Figure 7. We believe that the low leak rates are attributable to the combination of the smooth hard-seating surfaces (RMS surface roughness is 0.3 nm) and the pre-stressed seating configuration [2].

The measured forward flow rate at the various inlet pressures using deionized (DI) water is shown in Figure 8. As the voltage at the piezoelectric actuator increases, the deflection in the piezoelectric actuator increases. That means the larger flow path in the outlet hole at the microvalve. Thus, the DI water flow rate increases. DI water flow rate is approximately 60 mg/min at 20 psi (at an applied voltage of 40V).

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

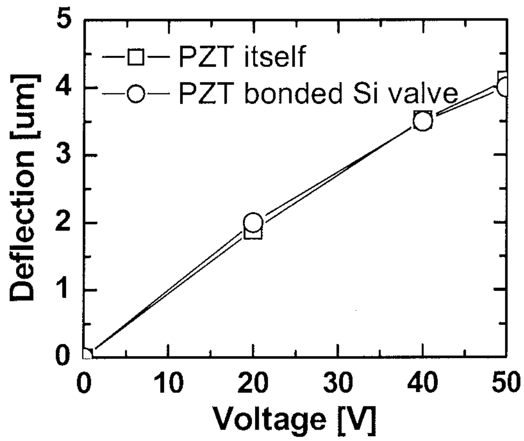

Figure 5. *PZT actuator displacements vs. voltages.*

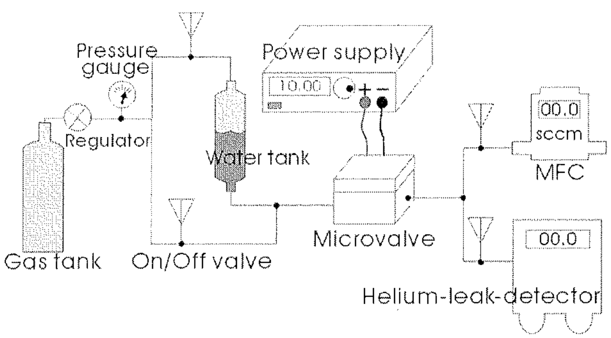

Figure 6. *Flow test diagram*

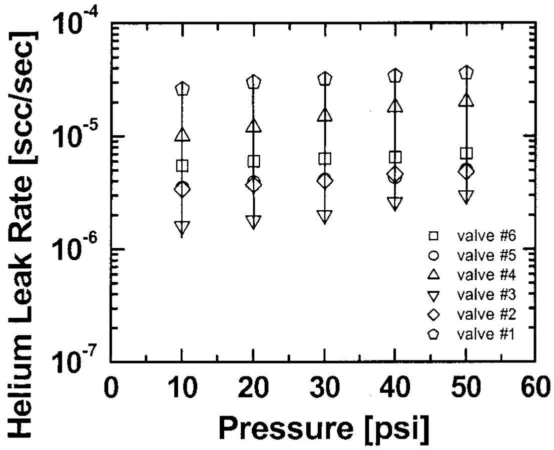

Figure 7. *Internal leak rate of normally-closed (non-actuated) 6 microvalves.*

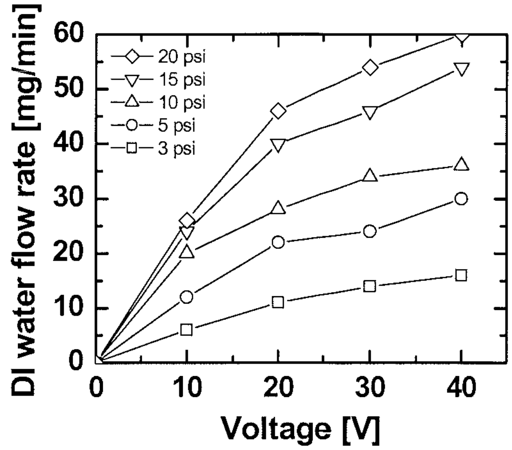

Figure 8. *Flow rates of an actuated microvalve.*

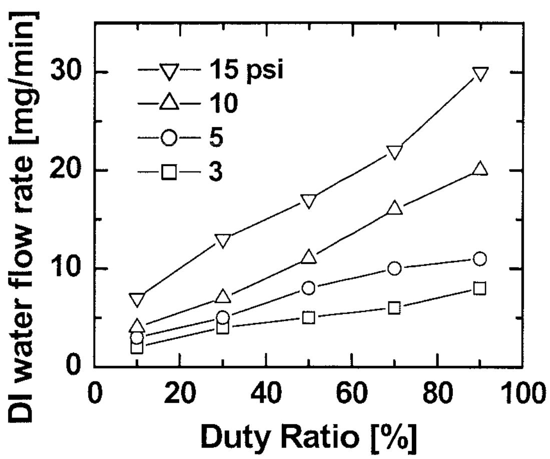

Figure 9. *Flow rates of a microvalve actuated with pulse width modulation at 100 psi. (Applied 18 V square pulse)*

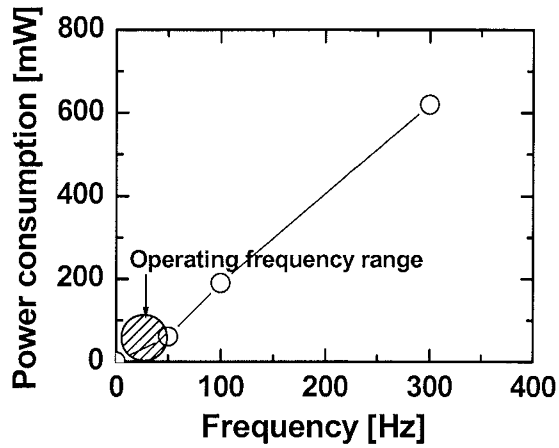

Figure 10. Power consumption in the microvalve at 10 $V_{p\text{-}p}$ sinusoidal signals.

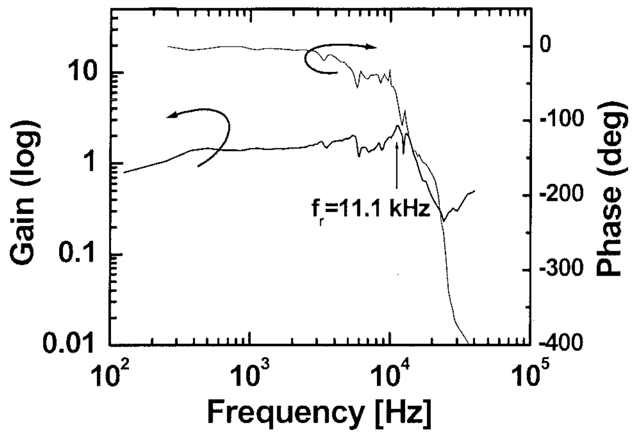

***Figure 11.** The measured frequency response of PZT-bonded silicon microvalve. The estimated transient response time is about 30 μsec.*

The measured static power consumption caused by the leakage current in the piezoelectric actuator is 2.5 mW at 20 V. The dynamic power consumption is measured using the phase delay. Figure 10 shows the measurement results of dynamic power consumption. For example, the dynamic power consumptions are about 60 mW at 10 $V_{p\text{-}p}$, 50 Hz operations, which is very low compared to other thermal or magnetic actuation microvalves. However, it only consumes a few mill watts when the microvalve is operated for proportional control mode (static power consumption).

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

CONCLUSIONS

We have successfully demonstrated the piezoelectric actuation liquid-compatible silicon microvalves. The measured leak rate of the microvalve using Helium gas is 3 x 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 provides the proportional flow control of liquid propellant for integrated micropropulsion.

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