MEMS micro-valve for space applications

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Abstract

We report on the development of a micro-electro-mechanical systems (MEMS) valve that is designed to meet the rigorous performance requirements for a variety of space applications, such as micro-propulsion, in situ chemical analysis of other planets, or microbiology. These systems often require very small yet reliable silicon valves with extremely low leak rates and long shelf lives. Also, they must survive the perils of space travel, which include unstoppable radiation, monumental shock and vibration forces, as well as extreme variations in temperature. Currently, no commercial MEMS valve meets these requirements. At JPL, we are developing a piezoelectric MEMS valve that attempts to address the unique problem of space. We begin with proven configurations that may seem familiar. However, we have implemented some major design innovations that should produce a superior valve. The JPL micro-valve is expected to have an extremely low leak rate, limited susceptibility to particulates, vibration or radiation, as well as a wide operational temperature range. Published by Elsevier Science S.A. All rights reserved.

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1. Introduction

Micro-electro-mechanical systems (MEMS) have always had huge potential applications for space. Any reduction in mass or power required for a space instrument or subsystem results in an exponential savings for launch cost as well as a significant increase in mission lifetime. It is a cry for MEMS if ever there was one. Unfortunately, no NASA project engineer will embrace a smaller subsystem if it means a sacrifice of performance, and certain aspects of MEMS have yet to rise to the occasion.

MEMS fluidics and sensors have come a long way. Unfortunately, MEMS control actuators have not kept up. For example, very complicated yet precise analysis for life can be done on a silicon chip. However, we have yet to find a silicon valve that can keep the chamber sealed and the reagents from subliming away during the journey to Mars. We can implement the entire propulsion system for a small spacecraft in silicon, yet have no way of controlling the flow of the propellants [1]. Indeed, NASA has identified a low-leak space qualified regulator valve as a key technology for enabling micro-instruments, micro-spacecraft, and the future of space exploration.

Valve requirements for a typical micro-spacecraft mission are given in Table 1 [2]. These numbers are very general, since no two missions are exactly alike. However, these data points can serve as a baseline to determine whether or not a valve could have potential applications in space.

Unfortunately, no commercial MEMS valves appear to be able meet both the performance and reliability requirements usually set out by NASA. Because of their low masses, most MEMS designs will fare well against shock, vibration. However, either the lifetime, temperature or the leak rate requirements knock these devices out of the running. Therefore, JPL has undertaken the development of a micro-valve that will have a low leak rate, be impervious to particulates, and survive the punishments of both launch and space travel, yet still perform upon reaching its final destination [3].

2. Design

Larger, commercially available diaphragm valves provided the baseline for the design of this valve. Fig. 1
Table 1
Typical requirements for NASA deep space micro spacecraft propulsion

<table>
<thead>
<tr>
<th>Valve</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Leak rate</td>
<td>$&lt; 0.3$ scc/h Helium</td>
</tr>
<tr>
<td>Actuation speed</td>
<td>$&lt; 10$ ms</td>
</tr>
<tr>
<td>Inlet pressure</td>
<td>$0–400$ psia</td>
</tr>
<tr>
<td>Shock</td>
<td>$3000$ G at $10$ kHz</td>
</tr>
<tr>
<td>Vibration</td>
<td>$31.5$ G for $3$ min</td>
</tr>
<tr>
<td>Temperature</td>
<td>$-120^\circ$C to $200^\circ$C</td>
</tr>
<tr>
<td>Radiation</td>
<td>$50$ krad/year</td>
</tr>
<tr>
<td>Particulates</td>
<td>$1.0$ μm</td>
</tr>
</tbody>
</table>

shows examples of some actual diaphragm and seat parts. Schematic cross-sectional views are given in Fig. 2. The stand-alone device has a square footprint of 1.6 cm on a side, and should have a height of less than three millimeters. This may seem large for a MEMS device. However, since a valve’s leak rate is partly dependent on its sealing area, we feel that it makes sense to build a larger than typical micro-valve to satisfy the requirements for space applications.

The valve begins as three separate parts: the seat, the diaphragm, and the actuator. The base of the valve is known as the seat. This is the part that will interface with the rest of the micro-fluidic system. The seat contains the inlet and the outlet, as well as a set of seal rings around each opening inside the device. The center section of the valve is known as the diaphragm wafer. It has a circular corrugated diaphragm, with a circular boss in the center, covering both openings in the seat. The boss is either fully suspended by the diaphragm, or is also supported by four silicon bridges. Finally, the actuator consists of a piezoelectric disk in a rigid housing. All three parts are bonded together using a gold-to-gold thermo-compression bond.

2.1. Operation

The valve is normally closed. The piezoelectric stack is forced into a slightly contracted position during the bonding process, to apply a large sealing force on the two openings. A simple Young’s Modulus calculation can be used to determine the initial sealing force. Application of a voltage across the stack will cause it to contract even further, lifting the diaphragm away from the seat, as shown in Fig. 2 (not to scale). This creates a channel between the two openings, allowing for the passage of fluids. Because of the diaphragm, dead space is minimal.

2.2. Seat design

Several design considerations have been implemented to try and satisfy the requirements for space applications as well as achieve a low leak rate. The first step towards that goal is the larger sealing area between the inlet and the outlet. Also, we apply the sealing force to both the inlet and the outlet of the valve. Finally, there is a large sealing area around both openings, preventing leakage to the environment. This seal is implemented through a large area gold-to-gold thermo-compression bond.

This MEMS valve is currently a hard seat design. This means that both sealing surfaces have high elastic moduli and will not deform. The surfaces must be extremely flat to prevent leaks, and the actuation force must be enough to crush any particles that become trapped on the seal. In the future, we will investigate the use of soft materials that will deform slightly when the valve is closed, thereby accommodating any stubborn imperfections that may exist.

Further immunity to particulates will be realized through the unique geometry of the sealing area. Instead of a flat sealing surface, we have implemented a series of closely spaced 20-μm high rings, expanding outward from both the inlet and the outlet. Because these rings are so many and so dense, they still provide a large sealing area. However, this configuration has the added benefit of being able to withstand small particles that may be in the flow. Most particles will be trapped in the valleys between the rings. Some, however, will become embedded into the sealing surface. Therefore, it will be vital that the surface
of the rings be coated with a hard, wear resistant material, such as silicon nitride or diamond, which can crush any offending impurities. Finally, any single scratch that may occur will likely not create an open path from the inlet to the outlet, since it will only affect a limited number of rings.

2.3. Actuator design

Finally, this device moves away from the thermal actuation found in most commercial-off-the-shelf (COTS) valves [4] and instead uses a piezoelectric disk. Piezoelectric actuation has not been utilized very often in miniature valves since it requires very high voltages in order to produce a substantial deflection. However, recent advances in laminated piezo stacks may mitigate this concern. The laminated piezo stack is one where electrodes are interlaced with thin (100 μm) layers of piezoelectric material. In this configuration, a small voltage can be applied in parallel to many layers to achieve the same electric field and therefore the same deflection as a large voltage applied across one thicker piezoelectric layer.

Typically, a piezoelectric material such as lead zirconate titanate (PZT) can provide a maximum strain (δ) of 0.001. Given a Young’s modulus (E) for this material of ~63 GPa, the maximum possible pressure (σ) that will be developed is $E \times \delta = 63$ MPa. Over a 10-mm disk, this a force of approximately 5000 N, (or the equivalent of a 500-kg or 227-lb weight), distributed over the seal rings. Due to mechanical pre-loading, not all of this force would be available to actuate the valve. However, this is still several orders of magnitude larger than the force produced by typical bimetalic designs [5], and should lead to more robust valves with better leak rates. Finally, in comparison with thermally actuated schemes, the ambient temperatures seen by this valve will not have to be so tightly controlled. This is especially important for space applications.

3. Processing

Figs. 3 and 4 shows some examples of finished parts for the JPL micro-valve. The dimensions of both the diaphragm and seat are 16 mm by 16 mm by 0.4 mm. The fabrication process relies heavily on a Deep-Trench Reactive Ion Etch (DRIE) to machine circular features into silicon. Presently, only seats and diaphragms have been fabricated and assembled. We feel it necessary to thoroughly test the seat-diaphragm structures before embarking on the design and implementation of the actuator.

Both pieces are bulk micro-machined from n-type (100) silicon wafers. In order to create circular shapes, we use a novel DRIE technique. This involves a series of alternating etching/passivation steps to achieve straight side-walls in silicon irrespective of the crystal plane. The etching is...
done by a combination of SF₆ and O₂ gasses, and the passivation by a combination of C₄F₈ and O₂ gasses. We also use a low-pressure chemical vapor deposition (LPCVD) system to passivate the surfaces and fabricate the diaphragm. Finally, we use metal-to-metal diffusion bonding technique to assemble the parts. Bonding surfaces are metalized with a Ti/Pt/Au layer (0.26 μm total thickness), and then held under high temperature (350–400°C) and pressure (1–20 MPa or 10–200 bar) to create a single diffused layer, thereby bonding the two pieces.

The process for fabricating the seat-diaphragm assembly is outlined below.

1. First, seal rings and corrugations are etched into the seat and diaphragm wafers, respectively.
2. Patterning and DRIE etching through from the backside to fabricate the inlet and the outlet.
3. A low-stress 1um thick silicon nitride membrane is grown over all surfaces of both wafers.
4. Boss is released using DRIE etching from top of diaphragm wafer.
5. Next, metal is evaporated onto the bonding surfaces and patterned to create bonding areas.
6. The backside of the diaphragm wafer is patterned and etched to release the boss.
7. The wafers are bonded.

For the actuator, we intend to use a silicon housing with a piezoelectric disk. Metalized vias will be etched through the housing to make electrical contacts. This piece will also be bonded to the seat-diaphragm assembly through a metal-to-metal diffusion process.

4. Testing

Currently, only the seat and the diaphragm parts have been fabricated. However, these two bonded together complete the entire fluidic path, and were tested to demonstrate operation as a regulator. Fig. 5 shows the preliminary testing apparatus. The valve is mounted onto a metal plate from which the inlet and outlet holes could easily be accessed. Air pressure at the inlet can be accurately varied using a series of gauges and regulators. The total volume of flow can be measured at the output. This and a precision timer are used to determine flow rate. Preliminary tests include measuring the open flow rate vs. inlet pressure, and the force necessary to stop flow verses inlet pressure. Typical results are shown in Table 2.
Mating MEMS systems to testing apparatus has unexpectedly proven to be one of the larger challenges to this project. Traditional methods of plumbing gasses to a valve and measuring flows are too bulky to work here. New couplings and measurement techniques needed to be developed to interface the micro and macro worlds. The next step with this apparatus will be to use a piezoelectric stack to apply sealing force, and improve the flow rate measurement scheme to determine the leak rates for given inlet pressures.

5. Future challenges

The JPL micro-valve is still in its infancy. Upon completing further flow rate and leak tests on diaphragm and seat assemblies, we will build actuated valves. Considering that the piezoelectric disks will produce at most 10 mN of deflection for a 10-mm high disk, the fabrication tolerances must be tightly controlled to produce exactly the right sealing pre-load, yet still be able to open the valve. Also, we intend to devote a significant effort into perfecting the hard seat, which will include experimentation with seat coatings capable of withstanding high sealing forces and particulates.

6. Conclusion

Micro and miniature fluidic systems have a broad range of applications both in research and in industry. NASA has a keen interest in reducing the size and mass of its fluidic systems, both in science instruments and in spacecraft subsystems such as propulsion. Quality MEMS valves will be vital to micro-fluidics. They are also the most difficult problem to solve.

The space environment is very unique, as are the kinds of tasks that people actually wish to accomplish in space. Mass is at a premium, and cost efficiency takes a back seat to performance. MEMS is tailor-made for the space industry. At JPL, we are attempting to blend simple innovations with proven configurations in order to produce the best possible valve for space applications.

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References


Biographies

Indrani Chakraborty received her combined Bachelor’s/Master’s Degree in Mechanical Engineering from MIT in 1996. Since 1992, she has been working as an intern at the Jet Propulsion Laboratory. Her projects include design, fabrication and programming of autonomous mobile robots and robotic manipulators. Upon graduation, she joined JPL as a member of the technical staff at the Micro Devices Laboratory Sec. 346, where she has also worked on several different projects, including the JPL/UCLA micro gyroscope, the free flying magnetometer, micro propulsion, micro valves, and reliability and space qualification of MEMS.

Dr. William C. Tang received his PhD in Electrical Engineering and Computer Sciences from the University of California at Berkeley in 1990, after authoring a landmark doctoral thesis on the electrostatic comb drive. In 1990, he joined Ford Research Laboratory in Dearborn, Michigan, and in 1993 became the Sensor Research Manager at Ford Microelectronics, Inc., in Colorado Springs, CO, where he was instrumental to the airbag accelerometers program. In 1996, he joined JPL as supervisor of the MEMS Technology Group. Dr. Tang holds three US patents, and is the author and co-author for over thirty conference and refereed papers in the MEMS field. Dr. Tang is currently serving on the Editorial Board for the Institute of Physics Publishing, contributing to the Journal of Micromechanics and Microengineering.
David P. Bame has spent the last 25 years in aerospace hardware development. His resume includes Northrop Aircraft and National Technical Systems. At JPL since 1990, he has developed extensive experience in environmental testing of flight hardware. This includes the design, build-up and testing of flight spacecraft systems, including work for the NASA's Wide Field Camera 2, LPX, MSTI 1 and 2, Cassini, Mars Pathfinder, Mars Observer, Mars Global Surveyor, and Topex. Most recently, he has been involved in the development of micro-spacecraft as well as packaging and testing of MEMS.

Dr. Tony K. Tang received his PhD in Electrical Engineering from the University of Illinois in 1991. His doctoral thesis dealt with the integration of passive and active III–V semiconductor photonic devices. As a senior research scientist at Raytheon Research Division from 1991 to 1993, he worked on micro-machined Si bolometers, infrared detectors, micro-optics and waveguides, and 3D imaging systems. Presently Dr. Tang is a Member of Senior Technical Staff at JPL. He is the task leader of the micro-gyro and micro inertial reference system projects. His other research topics include silicon micromachining, micro-valves and pumps, micro-accelerometers, sun sensors, pressure sensors, and diamond micro-machining.