# Design and Fabrication of MEMS-Based Micropropulsion Devices at JPL

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## ABSTRACT

The development and fabrication of microfabricated propulsion components at the Jet Propulsion Laboratory (JPL) is reviewed. These include a vaporizing liquid micro-thruster (VLM), which vaporizes propellant to produce thrust. Thrust performances of 32  $\mu$ N for an input power of 0.8 W were measured. Miniature solenoid and latch valves are being developed by Moog, Inc. in collaboration with JPL. Although metal-based, these valves employ batch fabrication approaches in their design. A valve prototype 1 cm<sup>3</sup> in size and weighing 7 gram was recently manufactured by Moog. This valve has a power requirement (holding power) of 0.7 W, a 5-V operating voltage, and response times of 1.5 ms (open) and 0.5 ms (close). In a lifetest at Moog this valve reached 1,000,000 cycles. A piezoelectrically actuated microvalve is being developed at JPL. The device is still in early development, however, initial testing showed leak rates as low as 0.001 sccm N<sub>2</sub> at pressures between 10-100 psig. A micro-isolation valve being developed at JPL is aimed at isolating propulsion systems prior to their use. This one-time opening valve can be actuated with 0.01 J within 0.1 ms. This valve, fabricated entirely from silicon and Pyrex, reaches burst pressures as high as 3,000 psia.

Keywords: Micropropulsion, Microvalves, Microfabrication, Microspacecraft

## **1. INTRODUCTION**

## Background

Spacecraft propulsion is being pushed to significantly reduced component sizes and masses, as well as performances into the sub-milli-Newton to micro-Newton thrust range. Required minimum impulses to be delivered by the propulsion device may be as low as micro-Newton-seconds or less. Such developments are the consequence of novel mission concepts currently being studied within the National Aeronautics and Space Administration (NASA) and the Department of defense (DoD)<sup>1.2</sup>.

Interferometry missions, for example, being considered by NASA may consist of several spacecraft flying in precise formation, allowing optical signals received by each spacecraft to be analyzed via interferometry to study planets orbiting distant stars, or seeking to detect gravity wave effects. The formation flying requirements may translate into required thruster minimum impulse bit performances into the 10s of micro-Newton seconds or below and thrust control accuracies of 0.1 micro-Newton or less.

Large inflatable spacecraft will have a need to offset solar pressure disturbance torques acting on the large inflatable portions of the spacecraft. Very small propulsion devices integrated with the inflatable structure, thus taking advantage of the usually large moment arm provided by this structure, may effectively offset disturbance torques. Larger moment arms translate into lower required thrust values, possibly as low as in the milli-Newton range even for quite large (multi-100-kg class) spacecraft, and consequently result in less required propellant.

However, one of the most exciting mission scenarios being studied recently by both NASA and DoD involve microspacecraft. Such spacecraft, generally understood as spacecraft of a few tens of kilograms in mass or less, may be flown in large constellations, for example, consisting of dozens or even hundreds of such craft. Such constellations may be used for scientific applications, exploring regions of space simultaneously, mapping magnetic field tensors or particle distributions. Other constellation missions may have defense applications, simulating large radar apertures in space by operating individual antennas on multiple, widely distributed microspacecraft in unison, resulting in high-resolution

imagery of Earth. Microspacecraft may also be used as probes to be released by lager craft for particularly dangerous portions of a mission, such as a Saturn ring explorer, or passage through a comet tail, for example. Here the risk to a larger, single spacecraft may prove too great given the potentially significant investments made in such a mission. However, if multiple micro-probes where available on a larger mother-craft, they could be expendable.

Micorspacecraft have particularly stringent propulsion requirements. In addition to low thrust and impulse requirements as a result of the low spacecraft masses, severe component mass, size, and power limitations must also be adhered to. In particular attitude control, typically requiring a set of a dozen thrusters or so for three-axis spacecraft stabilization, requires the mass and size of individual thruster modules to be pushed beyond the current state-of-the-art in propulsion hardware, in particular for very small microspacecraft in the sub-10-kg range or so. The lack of applicable hardware for such applications is especially notable for liquid propulsion systems, which may be required in such cases due to denser propellant storage over otherwise used cold gas propulsion systems. In addition, power levels on microspacecraft will be severely limited. Power densities of about 1 W/kg per spacecraft mass are currently being anticipated, meaning that a 1 kg spacecraft may have a total power budget of possibly no more than 1 W. Propulsion systems, as well as all other spacecraft subsystems, will be required to operate within such power limits.

#### Scope of this Paper

In the following chapters, micropropulsion development efforts currently underway at NASA's Jet Propulsion Laboratory (JPL) will be reviewed. Although JPL has a broad micropropulsion development program, covering all mission aspects discussed above, microfabricated, or MEMS (Microelectromechanical Systems), propulsion systems and in particular their methods of fabrication will be high-lighted in this paper given the focus of this conference. Such systems, due to their achievable small size and mass, may be particularly important for microspacecraft attitude control, yet could potentially be adapted to other mission scenarios discussed above as well. References found at the end of this paper provide a broader overview of the micropropulsion field, including non-MEMS propulsion and the significant development efforts currently underway at many other institutions in the US and abroad as well<sup>2</sup>.

## 2. MICROPROPULSION DEVELOPMENTS AT JPL

JPL currently manages a broad micropropulsion program consisting of many individual micropropulsion development projects. Focus in this paper, however, will be on microfabricated, or MEMS, propulsion devices and their fabrication. Currently under development in the MEMS propulsion category is a silicon-chip-based Vaporizing Liquid Micro-Thruster (VLM), vaporizing a suitable liquid propellant on demand to produce thrust. Valve developments, anticipated to be crucial in the realization of MEMS-based propulsion modules, involve the development of micro-solenoid valves by Moog Space Products Division in collaboration with JPL, a micro-piezo-valve developed in-house at JPL's Micro Devices Laboratory, and a Micro-Isolation Valve (MIV). The MIV is a single-shot, one-time opening valve designed to isolate propulsion systems prior to their use and providing zero-leak rates. Both the VLM and the MIV are developed by JPL's Advanced Propulsion Group in close collaboration with JPL's MDL.

As mentioned, other micropropulsion development efforts are under way at JPL as well. These include a micro-ion engine development project<sup>3</sup>, aimed at producing ion engines in the 3-cm diameter range or less, about one order of magnitude below the size of current ion engine technology. These devices still employ conventional fabrication technologies in their construction, however, will be integrated with microfabricated devices, such as Field Emitter Arrays for cathodes and neutralizers, and micromachined ion engine grids. Developments are also underway on a so called Vacuum Arc Ion Thruster with Alameda Sciences Inc. In this design, a metal cathode is ablated by spark erosion to produce very small impulse bits and low thrust levels<sup>4</sup>. Studies of laser-ablation thrusters, which use laser beams to ablate propellant off a solid fuel bar, have been conducted. Efficiencies of such thruster concepts may be low, however, very small impulse bits may be achieved. Finally, in collaboration with the Austrian Research Centre Seibersdorf (ARCS) in Austria, a field emission electric propulsion (FEEP) device using indium fuel was recently tested jointly at JPL. Such devices accelerate indium ions, generated via field emission near a sharp needle tip, in an electrostatic field.

None of the latter devices employ MEMS technologies exclusively in their fabrication, and a review of these thruster technologies thus extents beyond the scope of this paper. The following chapters will focus on JPL's MEMS propulsion developments.

## 3. MEMS PROPULSION DESIGN PHILOSOPHY

MEMS propulsion represents a considerable deviation from more traditional propulsion technologies, requiring a substantial amount of research and development into the fabrication and integration of such devices that is unique to them. The resulting research and development investments need to be justified in terms of any unique advantages of MEMS propulsion devices over more conventional technologies. One area, where MEMS propulsion may have such unique advantages over other systems, is microspacecraft attitude control, requiring multiple, very small and lightweight thruster modules to be integrated with a microspacecraft buses that may range in mass anywhere from a few tens of kilograms to 1 kg or less<sup>2</sup>. Here MEMS propulsion systems offer the obvious benefits of very small size (chip sizes may be on the order of 1 cm<sup>2</sup> or less and weigh but a few gram), as well as performance. Since nozzle throat sizes only a few microns in diameter may be machined, and thrust generated by a chemical or electrothermal device is directly proportional to nozzle throat area, very small thrust levels may be achieved. For example, the VLM thruster discussed below has generated thrust levels on the order of 32 micro-N in recent tests. Furthermore, if such thruster are combined with fast acting microvalves (in need of much future development) very small thruster impulse bits in the micro-Newton second range or below may indeed be achieved, as may be required depending on microspacecraft pointing accuracies.

However, it has been pointed out - and rightfully so<sup>2</sup> - that while MEMS thruster and valve chip sizes may indeed be machined to quite small sizes, packaging and subsequent integration of individually packaged MEMS-devices via microtubing may considerable add to the mass and particularly the volume of the final assembled propulsion system. As Fig. 1 (center) indicates, currently already existing are very small, yet entirely conventionally machined cold gas propulsion devices that rival in size individually packaged silicon-based microvalves. However, a quantum-leap in overall propulsion system size reduction may be achieved if microfabricated propulsion system components are assembled at the chip-level instead, and then packaged as a complete unit. Fig. 1 (right) shows this currently envisioned MEMS propulsion design philosophy. Here, the integration of thrusters, valves, and the necessary driver electronics is envisioned via chip-to-chip bonding or other applicable integration technologies. In the example shown in Fig. 1, JPL developed components are shown, however, this vision could apply to other MEMS-based propulsion components as well. The assembled propulsion modules would feature minimal external interfaces, consisting of few wire leads to provide power and control, and a propellant inlet line. The realization of such microfabricated, highly integrated micropropulsion modules not only will allow for significant mass and volume savings over existing propulsion technologies, possibly enabling propulsive capability for very small microspacecraft, but also reduce cost and complexity of integration of propulsion systems into microspacecraft due to its modular character.

Although the benefits of such a MEMS propulsion design approach may be of particular importance for future microspacecraft, it may also be applied to other spacecraft and missions featuring larger spacecraft buses, but having



#### Fig. 1: Vision of Highly Integrated MEMS Micropropulsion Modules

small thrust and impulse bit requirements, as discussed in the Introduction. Here the small size and modular character of such systems may not be mandatory, but beneficial and allow mass and cost savings to be realized over more conventional systems.

Note that many technical problems still remain to be addressed in the realization of such a MEMS propulsion design philosophy. These include the development of suitable bonding and integration technologies, some of which are now being studied at JPL and are discussed further below. Others include thermal control of such ultra-compact devices, and 3-D electronic interfacing. At present, progress is being made at JPL and other insitutions<sup>2</sup> in the component level development. In the remainder of this paper, the design and fabrication of these JPL MEMS propulsion devices is reviewed, and initial test data are briefly reported upon. Further details may be found in the references listed throughout the next chapters.

## 4. VAPORIZING LIQUID MICRO-THRUSTER (VLM)

#### Concept

The Vaporizing Liquid Micro-Thruster (VLM) vaporizes a liquid propellant upon demand to produce thrust<sup>5</sup>. Its use is aimed towards microspacecraft attitude control, requiring multiple, very small thruster modules located around the spacecraft bus. The chip consists of a three-laminate set of chips (Fig. 2). The outer two chips feature thin film deposited gold heater elements, separated by a center spacer wafer. The heater surfaces and the center spacer form the walls of a flow channel, through which liquid propellant, such as water, for example, is fed, and heated to vaporization by the heater elements. The heater elements are heated by passing an electric current through them. The propellant vapor is then expanded through a nozzle to produce thrust. Water is being used as propellant in initial laboratory tests due to its safety and ease of use. Later, other propellants, such as ammonia, having about half the heat of vaporization as water, may be used, reducing the required power input to the thruster for a given flow rate.

## Fabrication

Fabrication of the VLM relies heavily on silicon bulk micro-machining. This family of processes, which has descended from the very mature field of integrated circuit micro-fabrication, is very powerful and able to produce precise structures. When combined with wafer and die bonding, bulk micro-machining can be used to create complex mechanical systems with exceptional tolerances and capabilities. It is entirely possible to fabricate the many components that are required for a micro-propulsion system with this technology. In particular, the native precision and versatility of bulk micro-machining easily molds itself to the requirements of the VLM.

The VLM has three components that define its performance: the vaporization channel, the heaters, and the outlet nozzle. The channel is created by bonding the three dies together, the middle of which has a long cavity that has been etched through. The outer dies hold the metal heaters that lie above or below the channel, as well as the electrical vias that are necessary to provide power to the device. The inlet is also on one of the outer die. The position of the vapor outlet nozzle has historically also been in the other of these outer die. However it has been moved in the latest version of the VLM.



Fig. 2: Schematic of the VLM Concept

The earliest implementations of the VLMs (termed 1st Generation) featured nozzles made using wet anisotropic silicon etching. Single crystal silicon in its natural state is a "diamond-lattice" structure, where certain planes, such as the <111> plane, contain more silicon atoms than others. Anisotropic etchants take advantage of this fact to selectively etch some planes faster than others. In the case of silicon, anisotropic etchants attack the <100> plane much faster than the <111> plane, and can therefore be used to create very regular, rectangular, beveled features, with at bevel angle of 54.7 ° to the etch plane, as shown in Fig.3. By exposing a silicon wafer to the etchant from both the front and the backside, it is possible to fabricate converging-diverging nozzle structures. While the angle is not optimal for a propulsion nozzle, it was adequate for a proof of concept. For convenience, the vaporizing channel was also made using bulk micromachining.

The three dies are bonded together using a gold thermal-compression bond. Two gold layers, when brought into contact at high pressure and temperature, will tend to diffuse into one another, creating a single layer. This bonding process has been experimentally shown to be very sound. For the VLM, the process is especially synergistic, since the device already uses gold metallic layers to create the heaters. High quality seals are achieved by simply adding a ring of gold around the outside of the device.

Later implementations of the VLM (2<sup>nd</sup> Generation) began to take advantage of a novel process known as Deep Reactive Ion Etching (DRIE). Reactive ion etching, which uses an energized plasma to etch two-dimensional patterns into various materials, has long been a popular micro-machining tool. DRIE uses alternate cycles of etching and passivation to create relatively tall (greater than 500 um) structures with almost perpendicular sidewalls. This technology gives the micro-machinist new freedoms when it comes to the design of MEMS devices. Initially, DRIE was used to create longer "meandering" channels in the VLM, which lead to improved thermal efficiency. Figure 4 shows a cross section of such as device. The inlet and the outlet nozzles were still made using anisotropic etching. However, the snake-like vaporization channel in the center die was made with the DRIE process.



Water Before Etching, Top and Side Views

Fig. 3: Anisotropic Etching of VLM Components



Fig. 4: Cross-Section of the VLM (2<sup>nd</sup> Generation). Channel is outlined in black.

Recently, the outlet nozzle fabrication has also been altered to take advantage of the DRIE process. In fact, the entire shape of the device is now carved out by DRIE. The outlet is etched into the end of the channel, and the thrust vector points out of the side of the device. Figure 5 shows a schematic of this concept. The nozzle is now essentially two-dimensional, nominally 200 um tall. The 50 um wide throat, as well as a wide range of convergence and divergence angles are all very easily achieved using the DRIE techniques. Figure 6 shows a photograph of such a VLM. The nozzle has a divergence angle of 30 degrees. Note the T-shape of the thruster chip. The narrow section of the T-chip features the heater. The thruster chip is bonded to a support structure, facilitating the plumbing of the propellant inlet, only over the wide section of the T, featuring the electrical contacts, leaving the heater section cantilevered and not in touch with the substrate. Heat generated by the heater elements now has to conduct along the length of the narrow T-section in order to reach the support structure. This provides a torturous conductive path that reduces heat losses from the VLM T-chip over earlier designs.







Fig. 6: SEM Micrographs of a VLM T-Thruster (3rd generation) showing Channel Etch with Nozzle

#### **Initial Test Results:**

A thruster of the T-type shown in Fig. 6 has recently been tested on a thrust stand at JPL. This thrust stand is of a torsional spring design, and based on earlier versions developed at Princeton University<sup>6</sup>. Thrust data of 32  $\mu$ N at power levels of 0.8 W were measured. The thrust was determined within an accuracy of about 0.5  $\mu$ N. To date, no specific impulse data are available yet and data post processing continues. However, in previous tests mass flow rates through the thruster ranged around tenths of grams per hour under conditions were the thruster successfully vaporized the injected flow rates completely without liquid droplet ejection.

## 4. MOOG MICRO-VALVES (MMV)

#### Background

A comprehensive family of microvalves is key to the reality of micro-thruster modules such as shown in Fig.1, and ultimately totally integrated and compact micro-propulsion feed systems. A recent survey has shown that although many commercial, chip-based micro-valve designs exist, none appear suited for space propulsion applications due to reasons of leakage, slow response, propellant incompatibility, inadequate pressure and temperature ranges, among others<sup>7</sup>. Moreover, no latching type valve exists, which would be welcomed to very substantially mitigate power consumption in micropropulsion systems.

Fast valve actuation and long cycle life are key attributes of normally-closed (NC) thruster valves in order to generate tiny MIB (minimum impulse bit) from the microthruster. Propellant leakage is a major concern for all propulsion systems, but particularly for microspacecraft systems due to the severely limited size of the propellant supply. Even a very small valve leakage could potentially deplete a significant fraction of the loaded propellant, especially when gaseous propellant is used. Other general attributes needed in the microvalve family include compact modular packaging capability, and the ability to robustly package with other MEMS devices

Moog, Inc., in partnership with JPL, is investigating and developing new valving design concepts that can employ MEMS and MEMS-like batch fabrication processes to enable the economical manufacture of a complete family of precision and high performance microvalves. The development status of the Moog micro valves is summarized in the reminder of this section.

#### Moog Micro Thruster Valve (MMV) - Concept and Fabrication

A joint development activity between Moog Inc., Systems Group, and JPL is addressing the need for a fast-acting, leaktight, long-life, NC microvalve for microthruster operation and other critical microspacecraft applications. This valve, termed the Moog Micro Valve (MMV), is a solenoid-type of hybrid metal/MEMS construction, approximately 1 cm<sup>3</sup> size (see Fig. 7). The valve features no-sliding-fit (NSF) operation and uses metal construction to provide long term compatibility with both gas and liquid propellants. The valve body is made using low cost MEMS-like metal batch fabrication techniques, and a MEMS-fabricated coil is being developed. MMV performance is characterized by much faster actuation times, higher sealing forces, and much broader thermal and pressure operating ranges than available in silicon material MEMS microvalves<sup>7</sup>.



Fig. 7: Prototype Moog Micro Thruster Valve (MMV)

The valve is designed to be interfaced directly through special Kovar-to-Pyrex bonding with other MEMS devices, such as the above described VLM thruster, or other silicon-based MEMS propulsion components<sup>8</sup>. It is anticipated that through the use of MEMS-like wafer batch-fabrication processes in both the metal parts and by MEMS coil fabrication, these microvalves will be produced more cost-effectively and would be scalable to even smaller sizes.

An internally funded Moog and JPL R&D activity pioneered MEMS coil fabrication, and led to the assembly and test of a valve prototype with several batch fabrication features. The MEMS coil will consist of a stack of spiral coil wafers, produced through copper electroplating onto a silicon substrate using a thick photoresist mold. One such wafer is shown in Fig. 8. Stacking several of such wafers on top of each other and bonding them on a wafer-level is intended to allow coils to be more economically manufactured, and to be made in even smaller sizes.

MEMS coil fabrication begins with lithographically defining a polymer mold, electroplating of copper into it to form the actual coil, and then free the coil from the substrate and mount it inside the valve's casing. The photoresist chosen for the MEMS coil was the photosensitive epoxy SU8 from the Microlithography Chemical Corporation. SU8 has extremely good capabilities for thick, high aspect ratio optical lithography. SU8 could repeatably define a pattern 100-200 microns thick, but has the property that once exposed it cannot be removed. This property was harnessed by using the SU8 as both an insulator between coil windings, and as a method to bind the copper windings together so that they do not unspool. Thus, by use of the SU8 and a sacrificial layer on the substrate, a free standing high aspect ratio disc containing the coil and insulator could be made.

In order to keep the resistance of the coil down to acceptable levels, a coil thickness of 125 microns height by 90 microns width and a 40 micron insulating layer of SU8 between windings was chosen. Given the size constraints of the valve, only 14-16 turns per wafer could thus be produced,, vastly short of the total number of turns of approximately 250 required for the valve. Thus, it was concluded that a technique of stacking these free standing coils was needed. Thus, a "washer" technique was explored. Individual coil layers would have to be stacked, aligned, so that bonding pads between layers could bond the copper from layer to layer, and bonded. To avoid electrical shorting between layers, a thin insulating layer of SU8 was deposited onto the washers with openings for the bonding pads before the release from the silicon wafer substrate. In initial feasibility type-testing of this design approach, a conductive epoxy was chosen to glue the washers together.

MEMS coil development requires additional study. The initial development activity was cut short due to lack of followon funding. Future work will focus on further process refinement of the copper electroplating, and improved joining techniques between individual washers, ideally eliminating epoxy from the final assembly.



Fig. 8: Single Spiral MEMS Coil Chip

## Moog Microvalve (MMV) - Test Results

Using a conventional wire-wound coil as a placeholder, Moog tested prototype MMVs at the wafer level to characterize general operation and performance – with special emphasis on leak tightness of the design approach. Nominal performance characteristics obtained during the testing of 5 MMVs are summarized in Table 1. No internal leakage was detectable (i.e.  $<10^{-4}$  sccs GN<sub>2</sub>) even after performing 1 million opening and closing cycles. This demonstrates that long-life, gas leak-tight microvalves are feasible. Continuous power levels are very low (0.7 W) at a holding voltage of only 2 Vdc. These values are very compatible with anticipated microspacecraft design constraints. MMV volume is  $\sim 1$  cm<sup>3</sup>, (corresponding to about 2/3 of the linear dimensions of a sugar-cube) and the valve weighs about 7 gram.

Parameter	MMV Performance
Mass (gram)	7
Size (cm <sup>3</sup> )	1 (approx. 1 x 1 x 1 cm)
Leakage (sccs GN <sub>2</sub> )	< $10^{-4}$ (in all tests, during/after $10^{6}$ cycles, 0 to 70°C)
Effective Flow Area (in.)	0.010 ESEOD (equivalent sharp edge orifice diameter)
Power, holding (W)	0.7 (continuous)
Bus Voltage (vdc)	5
Response, GN <sub>2</sub> (ms)	1.5 (open), 0.5 (close)
Pressure (psi)	300 (nom), 1000 (max)
Operating Temp (°C)	0-70**
Life	1,000,000 cycles*

Table1: Nominal Performance of 5 Prototype MMVs

\*1 MMV tested. Test terminated voluntarily

\*\* 1 MMV tested

## Moog Latching Micro Valve (LMV) - Concept and Fabrication

Another important member of the Moog Microvalve family is being developed, termed the Moog LMV (latching micro valve). The LMV slashes the electrical energy needed, since it is electrically actuated to the open or closed position by an electrical signal for only a very brief period of time (a few milliseconds). The electrical signal is then removed while the valve remains "latched" in its new position, without consuming any electrical power. Another momentary electrical pulse is applied to return the valve back to its original position. The low-power LMV is ideally suited for applications where the valve can be both closed and open for extended periods of time during a microspacecraft mission.

A micro (only 7 mm outside diameter) permanent magnet is used to provide the valve end position latching forces. The magnet is molded to its final shape by using a thermoplastic material to bind magnetic powder (usually neodymium, iron and boron). Like injection-molded plastic parts, this permanent magnet can be precisely and inexpensively produced. The LMV employs a flexure, as used in the MMV, to enable reliable frictionless, no-sliding-fit operation. The thin sheet metal flexure is precisely and inexpensively batch produced by a photolithography etching process. Other design features, including the solenoid coil, are the same as used in the MMV. Therefore, the MEMS coil development (see previous MMV discussion) is also applicable to the LMV. Also like the MMV, the LMV solenoid and body subassemblies can be batch fabricated on metal wafers. The LMV has the same external size and shape (1 cm<sup>3</sup> cube) as the MMV, as well as identical manifold fluid port and feedthrough pin type electrical interfaces.

## Moog Latching Microvalve (LMV) - Test Results

Two prototype LMVs have been subject to performance characterization tests, and their performance is quite satisfactory, as summarized in Table 2.

Parameter	LMV Performance
Mass (gram)	7
Size (cm <sup>3</sup> )	1 (approx. 1 x 1 x 1 cm)
Leakage (sccs GN <sub>2</sub> )	< 10 <sup>-4</sup>
Effective Flow Area (in.)	0.010 ESEOD (equivalent sharp edge orifice diameter)
Power, holding (W)	Not Applicable
Bus Voltage (vdc)	5
Response, GN <sub>2</sub> (ms)	0.8 (open), 0.5 (close)
Pressure (psi)	300 (nom), 1000 (max)

Table 2: Nominal Performance Characteristics of 2 Prototype LMVs

#### **Other Microvalve Applications**

The MMV and LMV microvalves may be used in any number of applications, extending well beyond the field of spacecraft micropropulsion. The Moog microvalves may, for example, be used in experiments that need low-flow rate fluid management, and in certain macroscopic rocket propulsion such as xenon feed systems found in electric (Hall and ion) propulsion systems. Upon full implementation of the economies of batch fabrication and testing, there also exists a substantial commercial, non-space market for such microvalves, covering such varied areas as laboratory and industrial instruments, micro-fluidics, drug delivery, biomedical applications, and micro robotics.

## **5. MICRO-PIEZO VALVE**

#### Concept

The JPL developed micro-piezo valve uses a piezo-stack to actuate the valve in place of the solenoid used in the MMV family of valves. The valve consists of three separate parts: the seat, the boss, and the actuator. The recent micro-piezo valve designs features several novelties over earlier versions, including a normally closed enhanced sealing feature, a localized actuation of the piezo stack, and a new valve seat filter design.

The seat is the part that interfaces with the rest of the fluidic systems. The seat contains the inlet and the outlet, as well as a set of seal rings around the outlet opening inside the device (see Fig. 9). The center section of the valve has a rectangular boss in the center bonded to the center part of piezo stack actuator, covering the outlet opening of the seat. The actuator part consists of a custom designed piezoelectric stack bonded over the boss structure in a rigid housing. The valve is normally closed. This structure makes it possible to provide a high sealing force, since the inlet flow and pressure contribute to sealing and thus to the desired normally closed mode of operation. Application of a voltage across the stack will cause the leg portions of the piezoelectric stack actuator to expand, lifting the diaphragm away from the seat, as shown in Fig. 9. This creates a channel between the two openings, allowing for the passage of fluids. A large sealing force may be capable of embedding or crushing any particulates that could damage the integrity of the sealing surface. The piezo stack produces 50Mpa of pressure over a 3 mm<sup>2</sup> area, corresponding to 15 GPa over the sealing ring top surface area, which meets the seating pressure requirement of a hard seat. Immunity to particulates will be realized through the unique geometry of the sealing area. Instead of a flat sealing surface, a series of 10  $\mu$ m high, 1  $\mu$ m wide rings is implemented. Most particles will be trapped in the valleys between the rings. 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.

## Fabrication

The process sequence for the micro-piezo valve is as follows: Seal rings are etched into the seat wafer. Metal is evaporated onto the bonding surfaces and patterned to create bonding areas. The wafers are patterned and DRIE etched to fabricate the inlet and the outlet and boss structure. Metal is evaporated onto the boss and seat surface and patterned to create electric connection for piezoelectric actuators. The seat and boss wafers are bonded with the piezoelectric stack. Figure 10 shows the fabricated silicon components of the valve structure.

#### **Test Results**

The valve was mounted onto a metal plate from which the inlet and outlet holes could easily be accessed. Air pressure at the inlet is accurately varied using a series of gauges and regulators. The flow rate was measured at the inlet pressure range of 0 - 1000 psig. Recent leak testing showed a promising result with an extremely low leak rate (< 0.001 sccm N<sub>2</sub> @  $100 \sim 1000$  psig). Incorporation of piezo stack actuator will reduce the leak rate at lower inlet pressure (0 ~ 100 psig).







Fig.10: Micro-Piezo Valve Chip

## 6. MICRO-ISOLATION VALVE (MIV)

#### Concept

Isolation valves, such as the commonly used pyro-valves used in conventional feed systems, are one-time opening valves (normally closed type) or one-time closing valves (normally open type). Thus, they cannot replace the function of a valve allowing for repeated actuation, but serve critical functions in a propulsion system nonetheless. Isolation valves serve to seal the propulsion system during launch, for example, where valves designed for repeated actuation may shutter, leading to leakage, or seal a propulsion system during long, inactive interplanetary cruises, providing zero leak rates. The latter point is of particular importance for microspacecraft applications. Unlike conventional spacecraft, microspacecraft dormant for large portions of the mission, during which the limited microspacecraft propellant supply will need to be conserved. All valves designed for repeated actuation will leak to some degree across valve seats. In the case of microspacecraft, the limited propellant supply, combined with possibly long dormant spacecraft periods, may cause even the smallest leak rates to have a potentially disastrous impact on the mission, leading to the loss of all or a significant portion of the propellant. Zero-leak rate isolation valves may therefore play a much greater role in microspacecraft than in conventional spacecraft.

A MEMS version of such an isolation valve is currently being developed at JPL<sup>9-11</sup>. This valve is silicon-based and fits on a chip 1x1x0.05 cm<sup>3</sup> in size. The valve concept is shown in Fig. 11. In this valve concept, flow is prevented from exiting the valve prior to actuation by a doped silicon barrier blocking the flow. This barrier ("plug" - see Fig. 11) is an integral part of the valve structure, machined by etching it into place and does not feature any seals that may be compromised through contamination or vibrations experienced by the valve. To actuate the valve, an electric current is passed through the narrow barrier (10 - 50  $\mu$ m thick). As a result of the heat dissipation by the current passing through the barrier, causing it to melt, and the upstream propellant pressure the barrier is blown away, opening the valve. Operational valves will be required to provide adequate filtration to prevent plug debris from exiting the chip, potentially contaminating downstream flow components. In its current design, the silicon flow passages are sealed via an anodically bonded Pyrex cover, allowing for viewing of the flow passages in this stage of the experimental program.

#### Fabrication

The MIV devices are fabricated from doped silicon wafers using standard MEMS (Microelectromechanical Systems) processing techniques (Fig. 12). The selective removal (etching of channels) or addition of materials (metal leads) is used to define the structure of the device. Chrome plated glass masks are used to define the features on the wafer. A set of three masks (aligned to each other using alignment marks) is needed to completely define the structures of the micro-isolation valve. The masks are for the metallization (high-current path), the device features (channel, plug and filter), and the inlet/outlet (gas flow path). The processing begins with the deposition of the metal leads onto the surface of the wafer. The metal leads provide the current path needed to melt the plug in the flow channel. The metal consists of three



Fig.11: Perspective view of the micro-isolation valve showing the metal leads, channel and plug, and the inlet/outlet holes.



Fig. 12: Summary of the main steps that are completed to fabricate a micro-isolation valve. A.) Patterning of the metals. B.) Evaporation of the metal leads onto the doped silicon wafer. C.) Liftoff. D.) Patterning of the device features and DRIE etching.

layers that provide adhesion to the silicon (Ti), a diffusion barrier (Pt), and a current carrying layer (Au). The device features and the inlet/outlets are then etched into the silicon using a deep reactive ion etching system (DRIE). This deep RIE system, which is manufactured by Surface Technology Systems, Inc. (STS), provides highly anisotropic etching parameters in silicon. The fabrication of these structures results from the utilization of an alternating inductively coupled plasma of SF<sub>6</sub> and  $C_4F_8$  gases<sup>12</sup>. Etching of exposed silicon areas occurs during the SF<sub>6</sub> plasma step where a fluorine-rich environment chemically reacts with and removes silicon from the wafer. The  $C_4F_8$  step is used to control the anisotropy by passivating the sidewalls of the etched features throughout the process. This step helps to prevent lateral etching (i.e. undercutting) of the silicon features as well as the mask layer during the next etch step. This STS system can provide silicon etching rates of about 4.5 µm/min, aspect ratios of 30:1 and sidewall angles of 90±<0.25°.

The next step is to anodically bond a Pyrex cover plate on the wafer. Anodic bonding allows for a hermetic seal between the silicon and Pyrex and still allows for visualization in the channel for diagnostic purposes. Results from burst tests of the plug<sup>11</sup> showed a relatively large amount of debris in the flow channel (Fig. 13). The current design therefore incorporates a filter system to trap any debris before it reaches the outlet (Fig. 14). Various filtration schemes have been fabricated and detailed evaluations of these designs are in progress.

#### **Test Results**

Detailed experimental results are given elsewhere<sup>9-11</sup>. To summarize briefly, the MIV was subjected to burst pressure testing by internally pressurizing it via the inlet port. The valve reached burst pressures up to 3,000 pisg. Two burst failure modes where observed: MIV chips with plug thicknesses of 20 micron or less failed due to plug breakage. Valve chips featuring thicker plugs (up to 50 micron tested) failed due to Pyrex breakage over the inlet port<sup>9,10</sup>. It is anticipated, that thicker Pyrex, or silicon covers will further increase burst pressure values if they can be successfully bonded. Current Pyrex thickness was 0.5 mm.

Further tests revealed that the plugs could be opened with minimal energies, as little as 0.01J in the case of the thinnest plugs (25 micron) tested. The plug opening process involved both melting near the top edges of the plug where the current was confined due to skin effects, as well as breakage further below<sup>11</sup>. This breakage is likely due to thermal shock: it was noticed that the valve opens very rapidly within as little as 0.1 ms. During this short time, thermal stresses may develop between the hot top portion of the plug, where the resistive current is flowing, and the relatively cooler



Fig. 13: SEM showing post-burst debris in the flow channel.



Fig. 14: SEM of newest MIV design that incorporates a filter to stop debris.

lower portions of the plug, causing the plug to fracture. Especially the fracture process results in multiple small shards of silicon material that may be injected into the downstream flow path. These shards will need to be filtered before exiting the chip to avoid contamination of downstream components. Initially, plug melting was assumed to be the dominant process in the plug opening process. Molten material can be condensed on cool wall surfaces (see Fig. 13), and hence relatively simple and effective debris trapping schemes might have been devised. The solid, sub-micron shards generated by fracture will be more difficult to trap and is the subject of ongoing research (see Fig. 14).

## 7. CONCLUSIONS

Micromachined propulsion systems will likely be required, or at least highly beneficial, for attitude control purposes on very small future microspacecraft in the <10 kg mass category. Such microspacecraft are envisioned to be used in large constellations of spacecraft, initially for scientific and military purposes. At JPL, several different micropropulsion components are being studied, in part together with Moog, Inc.. These include a vaporizing liquid micro-thruster for attitude control applications, micro-solenoid valves explored jointly with Moog, a micro-piezo valve, and a micro-isolation valve. The conceptual approaches, fabrication, and initial results obtained where reviewed. If these, or other MEMS-based propulsion components can be successfully developed, one might envision them to be integrated via chip-to-chip bonding or some other system-on-a-chip approach to be packaged into highly integrated, ultra-compact thruster modules featuring minimal external interfaces. Many technology challenges, in particular in the bonding/integration area and thermal control, still remain to be resolved in such an approach. However, if realizable, these micromachined propulsion modules may enable the realization of propulsive capability on even the smallest microspacecraft contemplated, greatly increasing their scientific, military, or commercial value. In addition, such modules may be used on larger spacecraft as well, where the associated weight and volume savings are beneficial, even though they may not

be mandatory. Here, the very small thrust and impulse capability of MEMS propulsion devices, due to the ability to machine extremely small nozzle sizes, may prove highly desirable for some ultra-precise formation flying missions.

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