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MEMS Micropropulsion Components for Small Spacecraft

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ABSTRACT

This paper presents a number of MEMS-based micropropulsion components for small spacecraft. First a description of four components, all integral parts of the cold gas micropropulsion system custom designed for the Prisma satellites (launched June 2010). One of the most complex miniaturised micropropulsion components on board Prisma is the MEMS thruster chip, comprising four microthrusters integrated in a six-silicon-wafer package weighing only 4 grams. Proportional MEMS thruster valves and internal gas heaters are key integral parts of the thruster chip, providing µN-to-mN thrust in four orthogonal directions. Other MEMS components on Prisma are: a MEMS isolation valve, a MEMS pressure relief valve, and a MEMS pressure sensor. Hereafter, further developments of the MEMS components are presented, e.g. implementation of closed-loop thrust control on the MEMS thruster chip and proportional valves for ion engines to regulate xenon in the 5-50 µg/s regime with a 0.2 µg/s resolution. Finally, a concept of a completely miniaturised propulsion system intended for CubeSat applications is shown. All components are good examples of how extreme mass savings can be achieved by using MEMS technology, and by integrating several components and functionalities into one common chip or housing, which is of special interest for small spacecraft missions.

INTRODUCTION

Micro Electro Mechanical Systems (MEMS) technology provides the necessary tools for the desirable and crucial miniaturization in space applications. MEMS technology can not only save orders of magnitude in mass and volume of individual components, it can also allow increased redundancy, and enable novel spacecraft designs and mission scenarios. Although MEMS has changed the landscape in many areas such as biotech, automotive, and telecom it is just being introduced to the space sector in terms of development and qualification on component level. In a longer term perspective, MEMS-based space application areas will climb the ladder from components to subsystem and possibly even to complete systems.

Introducing MEMS technology offers a mass reduction from several hundred grams per sensor using conventional technology to tens of grams for a MEMS sensor packaged as a stand-alone sensor. Given the opportunity to integrate the same sensor in any other mechanical housing, the additional weight by adding a MEMS-based sensing element, the added mass is in the order of a few grams only. The inherently low mass, volume and power consumption does add value to the system in terms of reduced costs, but does also in many cases allow increased redundancy, performance, and functionality.

Another aspect of MEMS technology for space applications is as an enabling technology for new applications or missions. One such example is the miniaturized propulsion system described in this paper. Such a system opens for formation flying or precision control of small and medium sized satellites with limited resources in terms of mass- and power budgets.[1,2]

Miniaturized satellite propulsion system

Micropropulsion is one of the space applications where MEMS can play a significant role, both in terms of miniaturization and unique performance.[3,4] Hereafter follows a description of four MEMS components for space applications. All of the described components are part of the cold gas micro-propulsion system onboard the Prisma satellite and was launched for their first in-space flight demonstration in June 2010. The mission is still ongoing at the time of writing, but is briefly described towards the end of this paper.[5,6] The key component in a micropropulsion system is the thruster and this paper presents a complex microsystem, which comprises four complete thrusters integrated into a six-wafer-stack thruster module. Three out of the four MEMS components has been manufactured by NanoSpace personnel in the Ångström Laboratory, Uppsala University, and key process steps e.g. dry etching were performed in dedicated equipment procured by the company in order to achieve strict process control.

Regardless whether the main objective is to reduce size and cost or to enable mission scenarios e.g. precision formation flying, the concept of MEMS-based micropropulsion needs to be demonstrated in space before this new technology will be accepted on a broader base. First after this has been achieved, MEMS components and systems will be more widely used in space applications. Small spacecraft missions, requiring low thrust, is a natural platform for MEMS to start from.

MICROPROPULSION SYSTEM DESIGN

The developed MEMS-based micropropulsion system for Prisma is in principle similar to any conventional cold gas system – though with the functional difference that the thrust can be modulated proportionally in the sub milli-Newton range instead of the commonly used on/off modulation. The cold gas micropropulsion system is shown schematically in Figure 1. It consists of the following major components/subassemblies:

- a high pressure-type propellant tank,
- two MEMS thruster pod assemblies (4 thrusters each),
- a pressure regulator,
- a MEMS isolation valve with integrated filter,
- two pressure transducers (whereof one MEMS),
- a pressurant fill/vent valve
- a MEMS pressure relief valve.

The propulsion system also consists of tubing to connect all components, mounting structure, heaters and thermostats, electrical connectors and wiring required for conducting power to the components and heaters as well as telemetry to the spacecraft.

The driver electronics, called remote terminal unit, to monitor and control the micropropulsion system and handle the interfaces with the spacecraft data- and power bus, was also developed under the Prisma program.

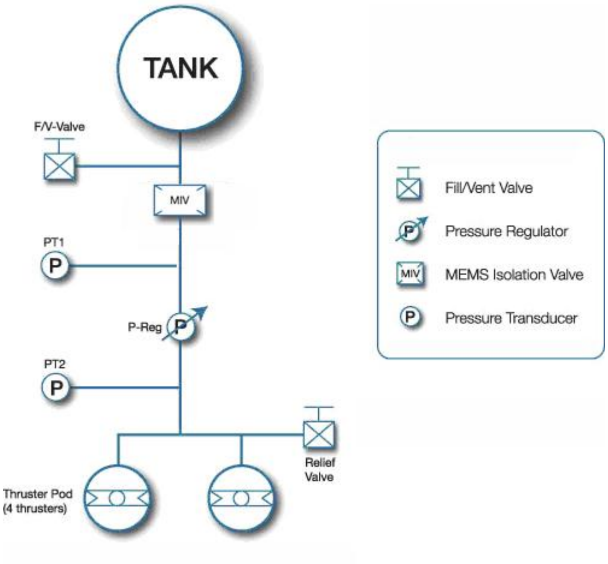


Figure 1: Schematic system layout of the Prisma micropropulsion system.

MEMS components

The cold gas micropropulsion system includes a number of novel MEMS components custom designed by NanoSpace; the thruster pod assemblies, the isolation valve with an integrated filter, and the pressure relief valve.[7,8] In addition to these components one of the pressure sensors are based on innovative MEMS technology, it is developed by the Norwegian company Presens AS.[9,10]

THRUSTER POD ASSEMBLY

The mechanical design of the thruster pod assembly consists of a spherical housing, acting as a pressurized plenum. It is a conventionally made fine-mechanical aluminum housing with a diameter of 44 mm (1.73”). Each thruster pod assembly comprises a MEMS thruster chip, mechanical and electrical interface components between the MEMS chip and the pod and to the rest of the spacecraft. The pod has a mass of 115 grams and is designed for a max expected operating pressure (MEOP) of 6 bars (87 psia) of non-corrosive gases. The thruster pod assembly interfaces a conventional gas storage and feed system with a screwed fitting to the feed system tubing. See Figure 2.

Figure 2: Images of the thruster pod assembly. In the picture to the right is with upper hemisphere removed. The thruster pod assembly is 44 mm (1.73”) in diameter and 51 mm (22”) in height.

MEMS THRUSTER CHIP

Design and Requirements

The MEMS thruster chip (Fig. 3) contains four individual rocket engines capable of delivering thrust in the micro- to milli-Newton range. Each individual thruster has a nozzle, proportional flow control valve, filter, and internal gas heaters inside the stagnation chamber to improve the specific impulse. All four thrusters are integrated in the same silicon-stack, which is located in the equatorial plane of the thruster pod assembly. The direction of thrust is in-plane with 90° between each thruster. Figure 2 and Figure 3 shows the MEMS thruster chip inside the pod assembly.

A summary of the design requirements for the micropropulsion thruster is given in Table 1.

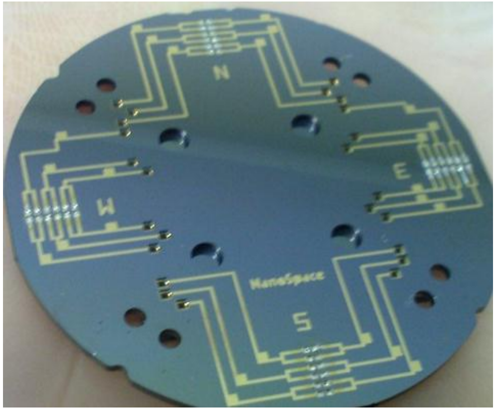


Figure 3: The six-wafer-stack thruster chip, manufactured using six fusion-bonded silicon wafers. The diameter is 40 mm (1.57”).

Table 1: Design requirement for the micropropulsion thruster.

Requirement	Parameter	Comment
Thrust	10µN – 1mN	Each thruster
Isp	50 -100 sec	Higher w heated N_2
Power	<3 W/thruster	Average
Feed pressure	4 bar (58 psia)	Nominal
MEOP	6 bar (87 psia)	Max Exp. Op. Pressure
Proof	9 bar(87 psia)	
Burst	12 bar (174 psia)	
Temperatures	0 to 50°C (32 to 122F)	Operating
	-10 to 60°C (14 to 140 F)	Non-operating
Mass	115 g	
Dimension	44 mm (1.73”) 51 mm (2”)	Diameter Height

The primary fabrication processes are deep reactive ion etching (DRIE) of photolithographically defined geometries and fusion bonding of multiple silicon wafers and wafer chips. Metallization, filling and sealing of actuator materials are part of the post-processing due to the high temperatures used for the bond anneal.

The fabrication sequence of the six-wafer-thick stack is split into two branches, a circular two-wafer nozzle package and a four-wafer valve package as can be seen from Fig. 4.

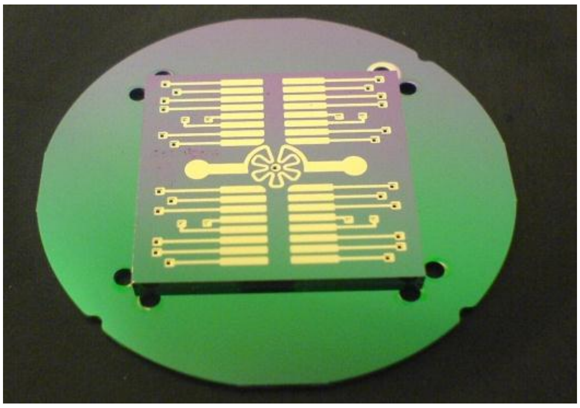


Figure 4: The MEMS thruster chip seen up-side down, manufactured using six fusion-bonded silicon chips. The metallic thin film pattern on the backside of the square four-wafer-stack valve package is the electrical interface to the connectors in the pod assembly. The square part is 22 by 22 mm (0.87”x0.87”) and the diameter is 40 mm (1.57”).

Internal gas heaters

The nozzles are designed converging and diverging nozzles in microscale with a throat area of about 7500 µm^2. In order to improve the specific impulse the stagnation chamber is filled with gas heaters (see Fig. 5). These heaters are capable of increasing the gas temperature with several hundred degrees Kelvin in the stagnation chamber. In addition to the fundamental nozzle structures, connection channels and holes for different purposes are also etched through the nozzle package e.g. four circular gas inlet holes to feed gas to each of the four valves, square holes for electrical vias, and guide pin holes for the bond alignment.

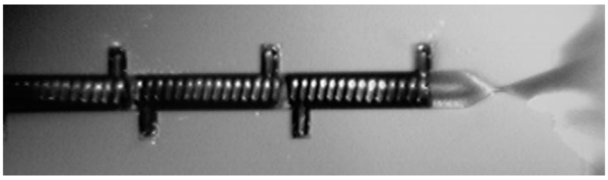


Figure 5: Photograph of three gas heaters in the stagnation chamber and the nozzle to the right.

Flow Control Valves

As an integral part of the MEMS thruster chip, a novel concept for proportional flow control valves has been developed and demonstrated. The valve requirements are found in table 2. Each thruster module has four orthogonal thrusters that can be fired alone or simultaneously using the four valves to individually and proportionally regulate the gas flow to each of the four nozzles.

The valve concept is based on a Phase Change Material (PCM) actuation principle. An enclosed cavity is filled with PCM which increases in volume when it goes from solid to liquid phase. The phase change is achieved by resistive heating and the melting point can be chosen to fit the thermal requirements of the system. The flow is modulated proportionally by adjusting the applied power to heaters in a PCM-cavity, which actuates on the valve seat due to the expansion. The valves are fabricated using four fusion bonded silicon chips and each valve stack has four integrated PCM-actuated normally-closed valves.

Valve interfaces are designed for bonding towards the nozzle package and electrical connection to the pod assembly connector.

Table 2: Proportional MEMS valve requirements.

Requirement	Parameter
Type	2-way, Normally-closed
Configuration	4 valves/chip
Flow range	0-2 mg/s @ 4bar GN2
MEOP:	6 Bar (87 psia)
Internal leakage	<10^{-4} scc/sec gaseousN_2
Operating temp:	0 to 50ºC
Chip mass	<2 gram
Dimensions:	22x22 mm 1.2 mm thick
Power	<3W

The valve seat package is two fusion bonded square chips with the purpose to interface the nozzle package and also act as a normally-closed valve seat. The valve seat chips also include via holes and channels to lead gas from the valves to the nozzles. The inlet and outlets on the valve seat package is shown in Fig. 6.

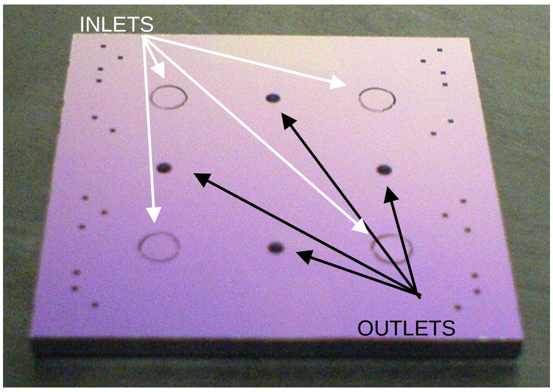


Fig. 6: The valve seat package, 22 mm (0.87") in side, seen from the nozzle side.

Individual proportional flow control valves for other applications

The MEMS valve concept developed for the MEMS thruster chip has also been utilized in another application, namely a flow control device to feed ion thrusters with Xenon. The specific requirement on such a device is on extremely low and accurate flow rate demanded by the Ion engine. The required flow rate can be as low as 5 – 50 µg/s with a required resolution in the sub micro-grams per second. This kind of flow rate control requirements is difficult to meet using conventional valve technologies. On the contrary, MEMS technology is ideally suited to handle micro-fluidics in this regime. This is an example where MEMS technology can offer improved, or even unique, functionality to space applications. Images of the Xenon flow control module and the chip is shown in Fig. 7 and Fig. 8, and some of the essential requirements of the same is shown in Table 3. Note that these requirements are tailored to a specific Ion thruster, and that even other flow ranges can be achieved with this concept.

Table 3: Design requirement for the Xenon flow control valve for a mini-Ion engine

Requirement	Parameter
Type	2-way, Normally-open
Configuration	1 valves/chip
Flow range	5-50 µg/s @ 2bar Xe
Flow rate resolution	± 0.5 µg/s
MEOP:	2 Bar
External leakage	<10^{-6} scc/sec GHe@MEOP
Operating temp:	17 to 50ºC (63 to 122 F)
Chip mass	<1 gram
Dimensions:	8x20 mm (0.31x0.79 inches)
Power	<1W

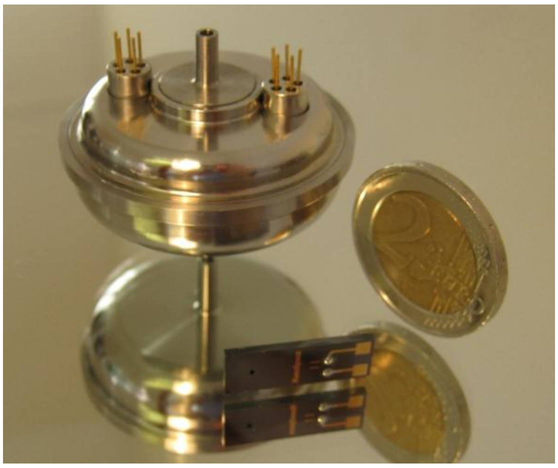


Fig. 7: Photographs of the Xenon flow control module assembly (a) and the flow control chip (b).

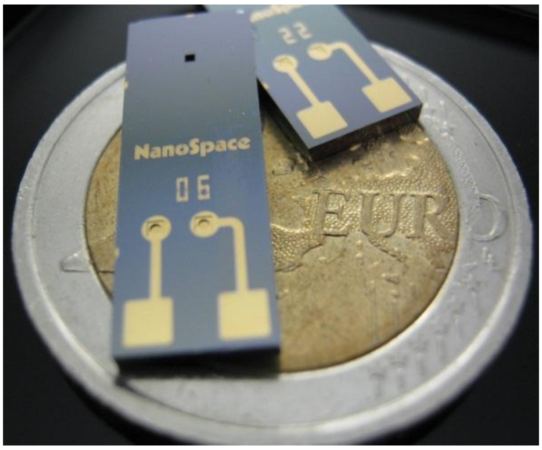


Fig. 8: Photographs of the Xenon flow control chip. The size of the chip is 8 by 20 mm (0.31x0.79").

An example of successfully operating a Xenon flow control unit in closed-loop mode is shown in figure 9. In this case a moderately high mass flow change, around 0.8µg/s, was commanded to the module. The mass flow rate is rather rapidly adjusted to the new flow. This was repeated for several flow rates in the low flow regime, 7 to 14µg/s.

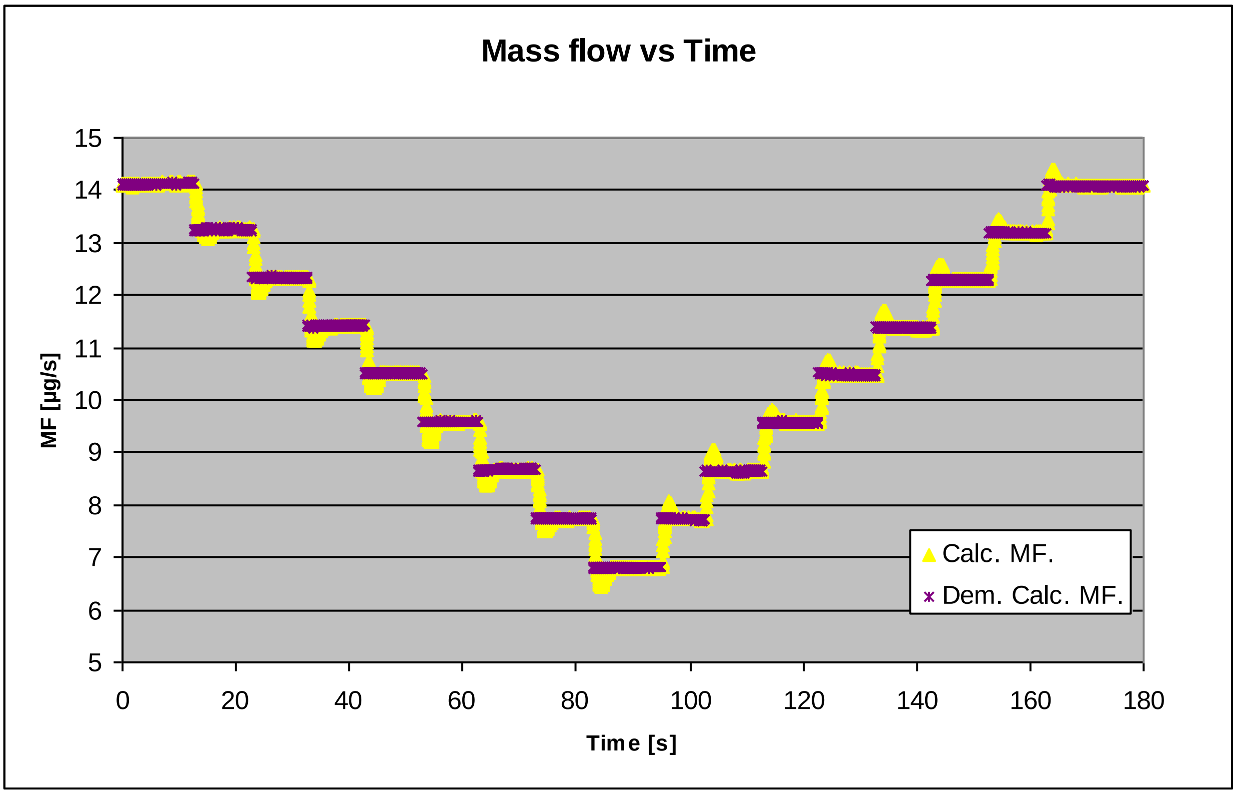


Figure 9. Closed-loop test result of the Xenon flow control module, demonstrating 0.8µg/s step changes in the 7 to 14µg/s flow range.

MEMS ISOLATION VALVE (MIV)

The MEMS Isolation Valve (MIV) is a simple, reliable, robust and high pressure compatible micro isolation valve. The MIV is a normally-closed one-shot valve, sealed with metal to be leakage proof. The electro-thermal activation ensures a slow shock-free opening of the gas path. The MIV also includes a filter that that takes care of debris caused by the activation of the one shot valve, that acts as a passive flow restrictor reducing the shock wave downstream, and that acts as a gas filter during normal operation. Narrow v-grooves are formed in the surfaces of the wafers together with wider distribution channels and through-wafer holes. When the two wafers are bonded together the v-grooves overlap and thus forms a so called fish bone filter.The MIV is redundant in the respect that it has two gas inlet holes, individually activated, and nine connected gas outlet holes.The concept is novel and patented. The gas inlet hole is sealed with a metal alloy. Surrounding the inlet hole is a metallic heater element positioned. Upon activation, a voltage is applied to the heater element. The generated heat is localized around the metal plug. As the temperature increases the plug will melt. The high gas pressure in the tank will force the melted metal into the chip, and the gas path is opened, as shown in Fig. 10.

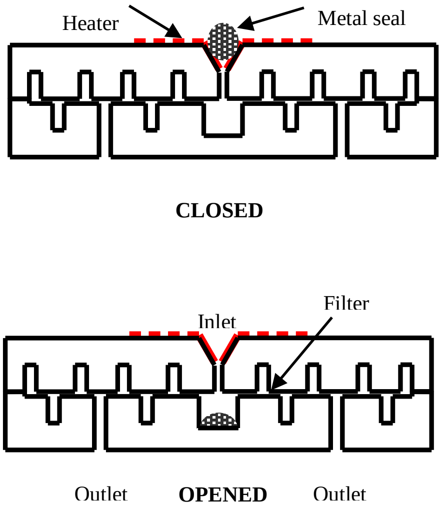
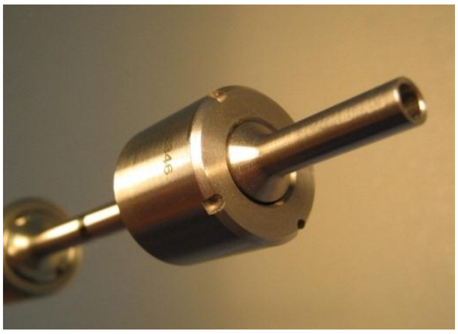


Fig. 10: Schematic of the (top) sealed isolation valve and (bottom) the activated valve with a free path for the gas through the filter region to the multiple outlets.

The MIV chip is two-wafer stack and has a weight less than one gram and is 12 mm (0.47") in diameter and 1.2 mm (0.047") thick. Starting material is 625µm, 6" wafers and both wet and dry etching is used. The fusion bonding is performed on wafer level. The MIV is a high pressure device (Fig. 11.) and has been proof tested up to 500 bars (7250 psia). Other technical data is presented in Table 4 below.

Table 4: Design requirement for the MEMS isolation valve (MIV).

Requirement	Parameter
Filtration Rating	2 micron (abs)
Max flow	>10 mg/sGN2
Pressure drop	<1 bar
MEOP Burst pressure	200 Bar (2900 psia) 500 Bar (7250 psia)
Mass	<1 gram chip 86 gram housing (SS)
Dimensions	Ø=Chip 12 mm (0.47") Ø=Housing 25 mm (0.98")



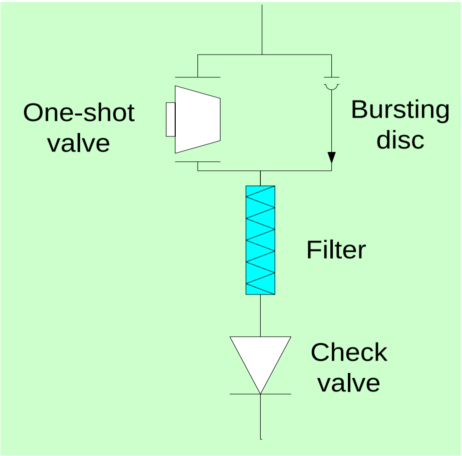
(a)

(b)

Fig. 11: Photograph of a MEMS isolation valve housing (a) and separate MIV-chips (b).

MEMS PRESSURE RELIEF VALVE

The MEMS Pressure Relief Valve (MPRV) is designed to safely relief pressure in a system in case of an unexpected pressure increase. This functionality is commonly required in pressurized systems onboard satellites. The MPRV can be opened either actively by an electrical signal, or passively, by a burst membrane. Moreover, the MPRV has a check valve functionality which closes again when the pressure returns to the nominal value. The MPRV is redundant with two active and two passive inlets and does also contain a filter. A functional schematic and picture of some MPRV chips are shown in Fig. 12. The specification is similar to the MIV with the addition of membrane burst at 10 bar (145 psia) and check valve crack open at 6 bar (87 psia). Three wafers are needed for a MPRV.



(a)

(b)

Fig.12: Schematics of the four functions within the MEMS pressure relief valve (a) and examples of the MEMS pressure relief chips (b).

Chip diameter is 12 mm (0.47").

MEMS PRESSURE SENSOR

There are two pressure sensors in the micropropulsion system, where the high pressure sensor is MEMS-based and developed by the Norwegian company Presens AS. It is a piezoresistive silicon MEMS pressure sensor developed for full-scale measurement ranges up to 1000 bar for high-precision oil & gas, aerospace and space applications. The measurement principle exploited includes the incorporation of a piezoresistive resistor bridge externally on a tubular silicon structure. More details about the pressure sensor can be found through Presens AS.

Table 5: Key requirements of Presens MEMS pressure sensor

Requirement	Parameter
Pressure range (FS)	Up to 1000 bar (14500 psia)
Sensitivity	0 - 200 µV/V/bar
Accuracy	0.05% of Full Scale
Mass (media protected)	< 75 gram
Mass (clean gas)	< 40 gram
Temperature range	-10 to +130 deg C (14 to 266F)

PRISMA SATELLITES

Prisma is an ongoing satellite mission comprising two satellites, one highly maneuverable Mango satellite (150kg) and one Tango satellite (40kg) without orbit control. See Fig. 13. The project constitutes an in-orbit test bed for Guidance, Navigation and Control (GNC) algorithms and sensors for advanced formation flying and rendezvous operations. Several experiments regarding maneuvering and sensor demonstrations will be performed during the mission time. The project is carried out by Swedish Space Corporation (SSC) in close cooperation with the German Aerospace Centre (DLR), CNES and the Danish Technical University.

The Prisma satellites were successfully launched from Yasny, Russia, on 15 June 2010, clamped together on a Dnepr launcher. Prisma has a low, sun-synchronous, dawn/dusk orbit at 600 km altitude. Apart from the MEMS-based micropropulsion system, the project will also demonstrate another new propulsion technology, the High Performance Green Propellant system developed by ECAPS.[11]

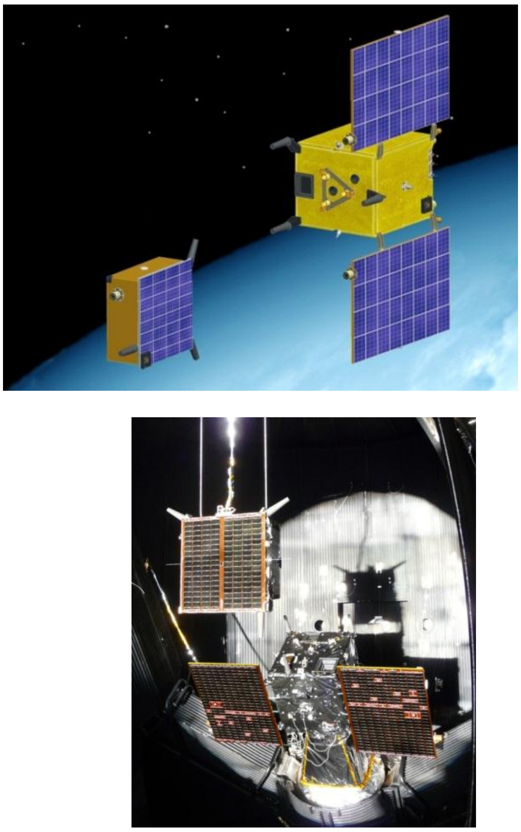


Fig. 13: The PRISMA spacecraft.

MICROTHRUSTER WITH THRUST CONTROL

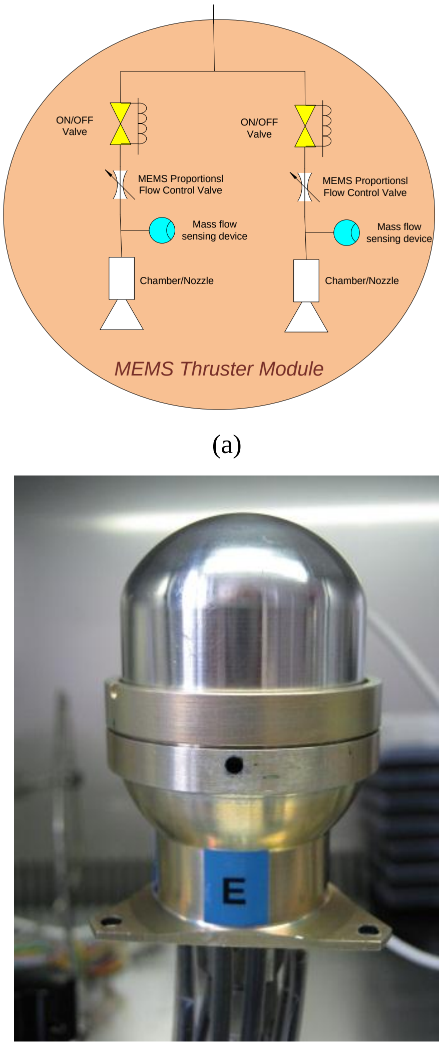
Although the MEMS thrusters on Prisma can provide proportional thrust, there is no closed-loop control implemented. Instead thrust for different input commands is predicted based upon calibration tests on ground. A feature to measure delivered thrust in real time, and implemented in the control loop of the thruster, would indeed improve the functionality of a micropropulsion system. This is an essential feature for satellite mission requiring “drag free flight”. NanoSpace is currently working on implementing such a closed-loop thrust control capability under an ongoing ESA contract. The mentioned Xenon flow control module already has a similar closed loop flow control.

When going through the propulsion requirements for a number of future missions it was found that the ones related to accurate control of the actual thrust generated was the most important and challenging requirements. Issues like thrust range, force measurement, resolution, response times, accuracy is critical in the design and testing of a micropropulsion system. In addition to these parameters, the issue of how to implement a thrust control loop is essential. The best (and most difficult) concept is to have a closed loop control using the delivered thrust as the controlling parameter.

Re-design of microthruster pod assembly

The micropropulsion system on Prisma had an open-loop thrust control and careful calibration on ground was necessary. NanoSpace has developed such a thrust control by integrating a mass flow sensor on the thruster chip together with some control electronics and miniature solenoid valves. See figure 14a.

The new MEMS thruster module contains two individual thrusters each with a mass flow sensor and control electronics. Furthermore an in-line normally-closed solenoid valve has been introduced in order to improve the minimum impulse bit. The integrated miniature solenoid valve is also acting as a main shut-off valve for respective microthruster.



(a)

(b)

Figure 14. Schematic of the manufactured MEMS thruster module (a) and a photo of the thruster pod assembly (b) with the height 65 mm (2.52”).

Testing

Development testing confirmed the manufacturability and testability. Following this initial development testing more standardized tests, including environmental testing was performed.

Environmental tests, i.e. vibration, shock and thermal cycling were performed at different test facilities and confirmed the design in terms of robustness and gives confidence to survive future qualifications. See figure 15.

Functional and performance testing confirmed the design of the chosen closed-loop concept. Thrust range in the region 0-1mN, with a thrust control resolution better than 1 µN was achieved using the new closed-loop microthruster (Fig. 16). More testing and optimisation of regulation software can improve the performance even further.

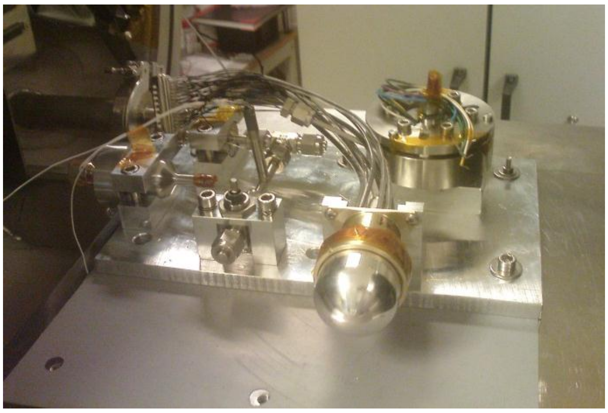


Figure 15. Test object mounted on temperature controlled table in vacuum chamber (still open)

Results of closed-loop thrust control

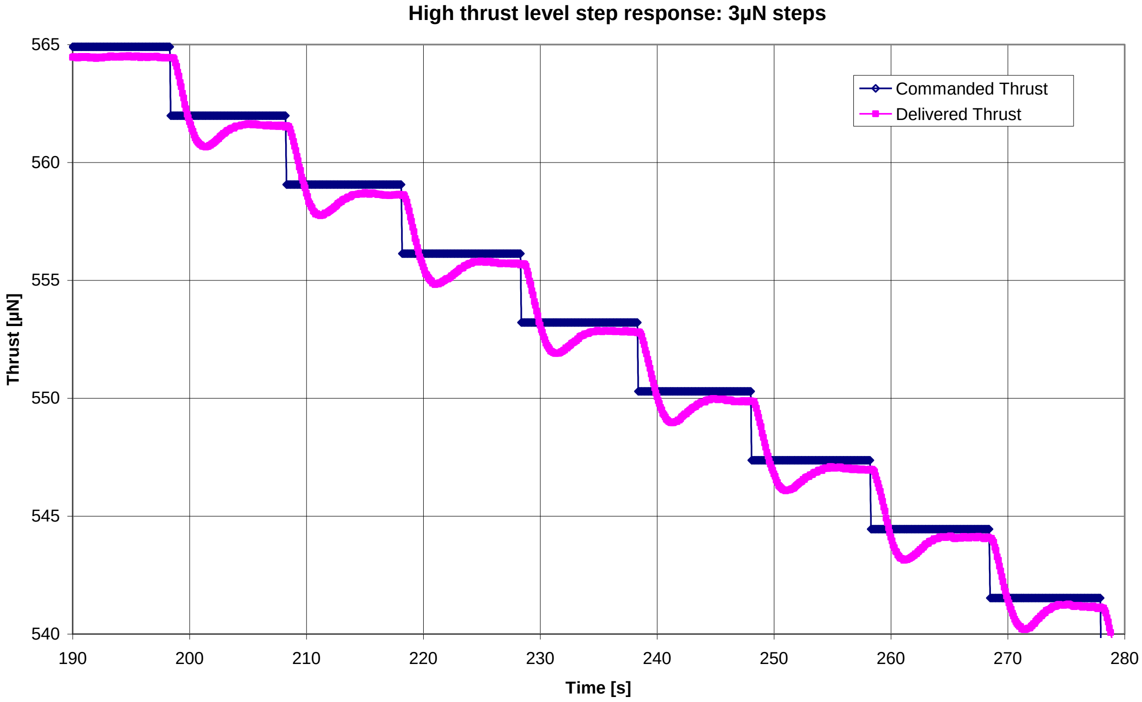


Figure 16. Test result of a single microthruster operating in closed-loop control mode using the integrated MEMS valve to respond to the commanded steps of 3 µN. Thrust is calculated from the measured flow rate and assuming an Isp of 60 sec.

MEMS-BASED PROPULSION MODULE FOR CUBESATS

As CubeSats attain more and more interest from industry and other players who want more than a low-cost platform to access space, propulsion capability is becoming more and more crucial. To date, more than 50 CubeSats have been launched but only very few with propulsion technology on-board. The natural starting point when miniaturizing a propulsion system is of course the thruster itself, then the other components such as valves, pressure regulators, filters etc will follow. In the end, the rest of the feed system and the tank will be of interest. At least, that is the case in many companies, including Nanospace.

Although a cold gas micropropulsion system offer a great degree of simplicity, the large propellant mass fraction in combination with the mass penalty of the tank due to usage of high pressure vessels, disqualifies it as propulsion technology for CubeSats. The natural step is to look at liquefied gas thrusters, such as butane or ammonia, where a low pressure tank could be used.[12]

In figure 17 below an initial design of a MEMS-based propulsion module intended for CubeSats is visualized. There are a MEMS thruster chip in each corner together with a miniature solenoid valve and some front end electronics. The size is 10x10 cm and 3 cm thick.

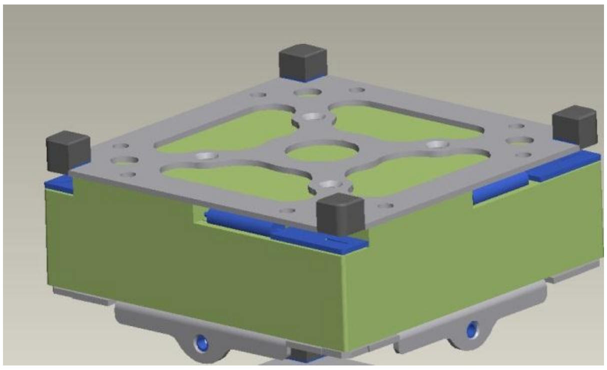


Figure 17. Schematic design of a micropropulsion module for CubeSat application, comprising four individual MEMS thruster (in blue) at the respectively corner.

The first Prisma cold gas micropropulsion system presented above was not designed with a pico- or nanosatellite application in mind and hence no optimization of power consumption for the valves were made. This is one of the remaining challenges to solve before the suggested module fully meets the requirements of a CubeSat mission.

DISCUSSION

Integration and Interfaces

Although the separate parts or components, e.g. micro heaters, fulfill their individual requirements in terms of performance, life time, temperature etc, their mutual integration require specially developed manufacturing procedures and quality control steps. Also the interface between the micro- and the macro-world is a critical system level aspect. For example, novel electrical vias through a six wafer stack, were invented and manufactured for the MEMS thruster chip on Prisma. Also the mechanical clamping of the brittle silicon chips needed special attention. Mechanical and electrical interfaces are major challenges that not only has to be solved, but also demonstrated in space several times before this kind of MEMS-products will be accepted by the space community.

Space validation

The space market puts severe requirements on product assurance and manufacturing quality control since failure of a part or a component in space can be extremely expensive. Therefore, all components or systems must be space qualified before they are accepted. This means extensive qualification testing to verify compliance to all requirements such as performance, vacuum, shock, vibration, radiation hardness, life time, etc.

The nature of MEMS production is not from structure via component to system as in conventional manufacturing. For these complex microsystems a new technical approach is used to assure reliability. Functional testing can typically not be done until the component is finalized. Therefore process control and process verification become very critical. For this reason a dedicated DRIE was procured by NanoSpace to achieve strict process control.

Future work

Although the MEMS thrusters on Prisma can provide proportional thrust, there is no closed loop control implemented. Instead thrust for different input commands is predicted based upon calibration tests on ground. A feature to measure delivered thrust in real time, and implemented in the control loop of the thruster, would indeed improve the functionality of a micropropulsion system. This is an essential feature for satellite mission requiring “drag free flight”. NanoSpace is currently working on implementing such a closed loop thrust control capability under an ongoing ESA contract. The mentioned Xenon flow control module already has a similar closed loop flow control.

CONCLUDING REMARK

NanoSpace is one of very few European companies devoted to development of MEMS products for space applications and has flown a number of new MEMS components in space for the first time on the Prisma mission 2010. The presented MEMS micropropulsion components are an example of how size and mass can be decreased, and still allow redundancy and fulfill the requirements. The main achievement of the custom designed micropropulsion system is that several critical components such as the isolation valve, the pressure relief valve, and the complex thruster module, with all its novel integral parts, have been invented, designed, manufactured, tested, functionally verified, and launched within five years.

The next generation MEMS based microthrusters will benefit from the closed-loop control capability that already has been demonstrated and the same technology will be used in flow control of Xenon for small ion engines. Since the inherent batch processing in MEMS manufacturing also have the potential of saving cost, these and other MEMS components will hopefully make their way into the CubeSat market too - eventually.

ACKNOWLEDGEMENTS

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