

# MEMS-BASED SOLID PROPELLANT MICROTHRUSTER DESIGN FOR CUBESAT APPLICATION

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**Abstract:** This paper presents some of the considerations developers of a MEMS-fabricated solid propellant microthruster should consider when designing it for the space environment. Space is a harsh environment in terms of the vacuum, vibrations and shock during launch, temperature extremes, and radiation. These aspects must be considered during the design phase in order to ensure the reliability of the device in orbit. These aspects are investigated by the team at York University and Defence Research and Development Canada-Valcartier when moving from a prototype solid propellant microthruster constructed using conventional materials and standard micromachining to a MEMS-fabricated microthruster.

**Keywords:** solid propellant microthruster, space environment, reliability, vacuum, radiation

## INTRODUCTION

A recent trend in the spacecraft community is a move towards smaller satellites, and therefore, miniaturized systems are becoming increasingly more important. An enabling technology that facilitates this miniaturization is microelectromechanical systems (MEMS). One area in particular that MEMS has played a large role is micropropulsion. The various elements of the microthruster such as nozzles and chambers are fabricated using etchable materials such as silicon as opposed to traditional aluminum. While this presents significant savings in mass and volume, the lack of a long space heritage results in the reliability of these systems in the harsh environment of space to be relatively unknown. Moreover, due to the novel aspect of this technology, design standards are not yet in place. In addition, the behavior and associated failure mechanisms are dependent on fabrication processes and specific mission scenarios. In this paper, the most applicable failure mechanisms for the microthruster structure are discussed.

## SOLID PROPELLANT MICROTHRUSTER

A solid propellant microthruster (SPM) prototype has been developed at York University Space Engineering Nanosatellite Demonstration (YUsend) Laboratory using standard micromachining and conventional materials such as titanium, nichrome wire, and a printed circuit board. Its design, fabrication, and testing are described in [1] and is shown in Fig. 1. The microthruster firing is shown in Fig. 2.

As described in [2], a typical SPM design consists of several layers bonded together in a sandwich configuration. The layers include a nozzle layer, an igniter layer, a chamber layer and a sealing layer. Typically, the nozzle layer is fabricated using silicon, in which the nozzle is etched. The igniter layer

consists of a polysilicon resistor on a thin dielectric membrane/diaphragm (silicon dioxide and silicon nitride). The polysilicon resistor heats up to the ignition temperature of the propellant, which is stored in the chamber layer. The chamber layer is typically made of silicon, ceramic, or glass-ceramic. Finally, the sealing layer, usually made of Pyrex, closes the bottom of the microthruster. The layers are bonded together using anodic bonding, a UV sensitive polymer, and a thermal epoxy. This microthruster configuration etched in a two-dimensional array forms the complete SPM concept. The goal of the YUsend team in constructing the SPM prototype was to understand the SPM concept in preparation for a flight-ready MEMS version for the YUsend-1 CubeSat shown in Fig. 3.

A CubeSat is a standardized nanosatellite design and to date, over 50 CubeSats have been launched or are under development around the world. In its smallest form factor, a CubeSat measures  $10 \times 10 \times 10 \text{ cm}^3$  and weights approximately 1 kg. Due to its size and mass restrictions, MEMS technology has been the enabling factor in its sudden growth and expansion. In recent years, CubeSats have been recognized as cost-effective means for not only training, but also for technology demonstration and Earth observation missions. MEMS-based components for CubeSats include both sensors (rate sensors, magnetometers, gyroscopes, and sun sensors) and attitude actuators (torque coils and thrusters). Several research groups have developed MEMS-based SPMs; however, there has been limited effort in preparing this technology for in orbit demonstration. This involves the appropriate selection of materials capable of surviving the demanding launch conditions and the harsh space environment. The microthruster presents unique challenges in comparison to other space-based MEMS devices in that it will operate on the outside of the spacecraft. Therefore it is not protected by a hermetic seal nor shielded by the

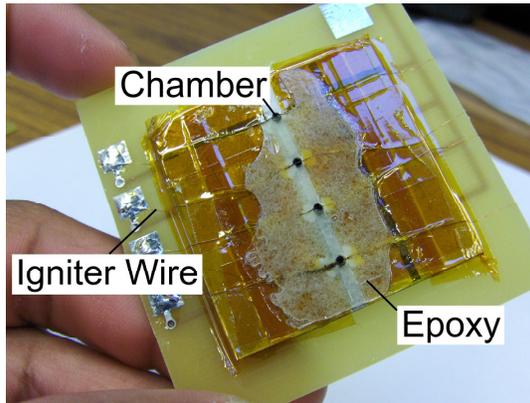


Fig. 1: YUsend prototype SPM

spacecraft. As we proceed from the prototype's low cost materials to MEMS fabrication, it is necessary to investigate if the space environment will pose significant problems for the elements of the microthruster. In general, because of the lack of moving parts and relative simplicity of the design, it is assumed that not many issues will arise. However, there are still a number of concerns that have been found within the literature.

### SPACE ENVIRONMENT

The space environment includes a very high vacuum, launch vibrations and shock, thermal extremes and cycling, radiation, and atomic oxygen. One additional consideration is humidity during various stages of development such as spacecraft integration with the launch vehicle.

#### Vacuum

Outer space has a vacuum of less than  $10^{-6}$  Torr, which is a very high vacuum. The vacuum environment induces outgassing of materials. One area of concern is the outgassing of the solid propellant that can damage the thin dielectric diaphragm and/or contaminate spacecraft surfaces. Especially since many groups modify the formulation of the propellant for greater performance capability or for ease of filling the chambers, the exact nature of the propellant under vacuum needs consideration. As stated in [2], the main cause of their ignition failure is the early rupture of the membrane. This occurs when the propellant touching the igniter element begins to heat, even below its ignition temperature, and releases gases [2]. Therefore as evident, any release of gas, either through thermal stimuli or through outgassing, presents a failure mechanism for the diaphragm.

#### Launch Vibrations and Shock

The main concerns for the microthruster under this environment are fracture, fatigue, and stiction. Stiction is inadvertent adhesion of several structures when they come in contact. This mode is less likely to be observed in the microthruster due to the lack of bending structures.



Fig. 2: YUsend prototype SPM test firing

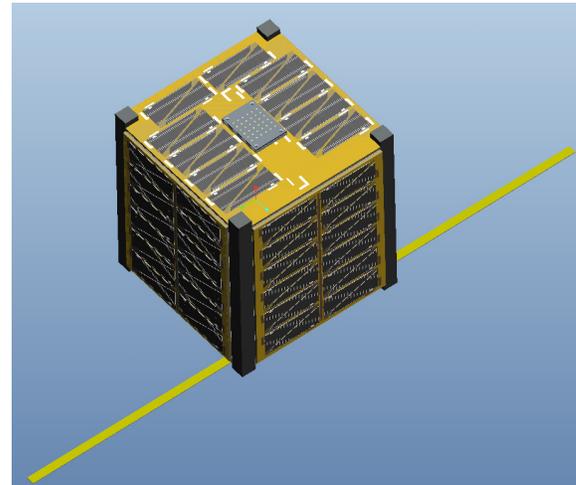


Fig. 3: YUsend-1 CubeSat and integrated MEMS-based solid propellant microthruster

However the diaphragm layer is typically separated from the nozzle by a short distance. If these two surfaces are not adequately separated, stiction may occur possibly as a result of diaphragm deformations caused by vibrations.

Fracture is possible with chamber layer materials such as silicon and Foturan (glass ceramic), which are brittle materials. A representative value of the vibration level experienced during launch is 3–20g and a shock value of 500g at stage and fairing separation [3]. Typically, a MEMS device experiences only millinewtons of force even at 1000g and most commercial devices can withstand this level [3]. However, a microthruster diaphragm is usually designed to rupture easily, and therefore poses some concerns about its survivability. Another important element to consider is the coupling between the frequency of the applied vibration and the natural frequency of the MEMS structure [3].

A key element to avoiding fracture-related problems will be the method of microthruster attachment to the spacecraft. The attachment mechanism should avoid creating stresses in the substrate or creating micro-fractures that may propagate under vibration and lead to a complete fracture of the device.

A significant concern in developing solid propellant microthrusters for orbit is the risk involved with the solid propellant, which is a large concern for the launch provider and for the other satellites involved with the launch vehicle. In order to address the launch provider's concerns, extensive tests need to be performed to demonstrate the safety of the device.

### **Thermal Extremes and Cycling**

For a CubeSat in low Earth orbit, it can experience temperature ranges of  $-80^{\circ}\text{C}$  to  $+100^{\circ}\text{C}$  about 16 times per day [3]. The largest issue of the thermal environment arises due to the mismatch of material coefficients of thermal expansion (CTE) [3]. This can result in cracking and/or delamination of the layers. This is especially applicable to the sandwich-layer approach to microthruster fabrication that involves multiple layers of different materials. Fortunately, Pyrex, which is used as the sealing layer in many designs, has a CTE similar to silicon, which is used as the chamber layer. However, silicon nitride and silicon dioxide of the dielectric membrane/diaphragm have different CTEs [4]. With this mismatch of CTEs, under thermal cycling, delamination of layers could occur due to material fatigue [4]. Moreover, because the microthruster will operate in the vacuum of space, heat gain from solar radiation and other radiation sources or from the igniter can only be dissipated through conduction and radiation. However to prevent runaway ignition between chambers and to promote combustion within a single chamber, chamber layer conductivity is low. This may be a concern due to the possible developments of hot spots. An effective thermal management system addressing these concerns will be necessary.

### **Radiation**

Particles encountered in the radiation environment are high-energy electrons and protons [5]. These particles affect the device materials by causing ionization [5]. A positive aspect of MEMS is that even under large radiation doses, the mechanical properties of silicon and metals are mostly unchanged [3]. Silicon is intrinsically radiation hard [3]. The most susceptible layer on the microthruster to radiation is the igniter layer. The dielectric layer is susceptible to charge buildup that is drained away by the polysilicon resistor and may contribute to varying levels of current required for ignition.

A key aspect of the microthruster susceptible to radiation is the addressing circuitry. The addressing technology described in [6] involves Zener polysilicon diodes that sit on a dielectric membrane. It contains several areas of p-doped and n-doped areas sitting on top of a dielectric layer. The main failure mode at high radiation doses for MEMS devices is the build-up of charge in dielectric layers [3],[7]. The type of radiation damage experienced by the addressing circuitry is from a total dose effect. In semiconductor devices,

these effects can affect threshold voltages, which can negatively affect current gain, increase leakage current, and possibly affect device functionality [5]. Since the microthruster cannot be shielded, the addressing circuitry needs to be built using a radiation hard design.

### **Atomic Oxygen**

Atomic oxygen (AO) exists in large amounts at low Earth orbit and is highly reactive [5]. In designs that use Foturan as the chamber-layer material, silver atoms form due to exposure to UV light [2]. Typically, this is performed to create a faster etching process. However silver is not a desirable material in space due to AO. The silver will oxidize until the oxide layer flakes off due to mechanical or thermal stresses within this layer [8]. As a result, AO will slowly degrade the material significantly compromising its structural integrity.

### **Humidity**

Since the microthruster is not hermetically sealed, it is susceptible to the humidity at all stages of device development. Good handling and storage procedures can help reduce humidity-related concerns. One microthruster aspect especially susceptible to humidity is the propellant. For example, glycidyl azide polymer, is hygroscopic, and will absorb moisture over time leading to performance degradation. Similarly, surface micromachined devices, such as the igniter element, are extremely hydrophilic as a result of the processing methods involved [4]. Water will condense into small cracks and cavities on the surface of these structures [4]. Therefore, care must be taken to control the humidity level at each stage, if possible.

## **DISCUSSION**

From the applicable concerns derived from the literature, the vast majority apply to the igniter layer. This is because the thin membrane/diaphragm is intrinsically a weak structure to allow easy rupture during ignition. Moreover, it is also where the circuitry is integrated with the rest of the mechanical MEMS structures, and typically, electronics are very susceptible to radiation damage. The situation is worsened by the fact that the circuitry is not shielded, which exposes it to even greater levels of radiation. In addition, due to the microthruster being attached to the outside of the spacecraft, special attention must be given to the attachment mechanism. While the microthruster must be attached securely, it must also be damped from the large vibrations the spacecraft structure encounters. Normally, a MEMS device within the spacecraft sits on a circuit board, which is flexible to some degree. However, the spacecraft structure is very rigid. As a result, this may result in fracturing problems. A final aspect of concern is the propellant. Newly formulated propellants must be extensively characterized. Its safety must also be demonstrated to the launch provider. Overall, lack of

moving parts and simplicity has resulted in a highly reliable device.

## CONCLUSION

This paper has reported on some of the main failure mechanisms expected to be observed for a MEMS-fabricated solid propellant microthruster. MEMS offers many advantages in terms of mass and volume savings but presents a level of uncertainty in terms of reliability in the space environment. Although the literature has revealed several areas of consideration, each MEMS device will behave differently based on the fabrication process and mission scenario. This is especially true for the microthruster that must operate in a harsher environment than some of the other MEMS devices in the literature that are shielded or hermetically sealed. As a result, it is very critical that validation tests be performed. It is also important that microthruster test firings be performed in these harsh environments.

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