

## Conference Paper

# Microelectromechanical Sensors and Microstructures in Aerospace Applications

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## Abstract

The solutions in the sphere of MEMS technologies in space are overviewed in this article. The main emphasis is on micro-thrusters, which have the potential to enable missions that require micro-propulsive maneuvers for formation flying and precision pointing of micro-, nano-, or pico-sized satellites. The possible use of MEMS sensors and technologies of production are shown.

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## 1. Introduction

To piece together a note on microelectromechanical systems (MEMS) and microstructures for aerospace applications is perhaps foolhardy as we are still in the infancy of micron-scale machines in space flight [1]. To move from the infancy of a technology to maturity takes years and many awkward periods. For example, we did not truly attain the age of flight until the late 1940s, when flying became accessible to many individuals. The insertion or adoption period, from the infancy of flight, began with the Wright Brothers in 1903 and took more than 50 years until it was popularized [2]. Similarly, the birth of MEMS began in 1969 with a resonant gate field-effect transistor designed by Westinghouse. During the next decade, manufacturers began using bulk etched silicon wafers to produce pressure sensors, and experimentation continued into the early 1980s to create surface-micromachined polysilicon actuators that were used in disc drive heads.

By the late 1980s, the potential of MEMS devices was increased, and widespread design and implementation grew in the microelectronics and biomedical industries. In 30 years, MEMS moved from the technical curiosity realm to the commercial potential world. In the 1990s, the U.S. Government and relevant agencies had large-scale MEMS support and projects underway. The Air Force Office of Scientific Research (AFOSR) was supporting basic research in materials, while the Defense Advanced Research Projects Agency (DARPA) initiated its foundry service in 1993. Additionally, the National


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Institute of Standards and Technology (NIST) began supporting commercial foundries. In the late 1990s, early demonstrations of MEMS in aerospace applications began to be presented.

## 2. Implications of MEMS and Microsystems in Aerospace

The starting point for microengineering could be set, depending on the standards, sometime in the 15th century, when the first watchmakers started to make pocket watches, devices micromachined after their macroscopic counterparts. With the introduction of quartz for timekeeping purposes around 1960, watches became the first true MEMS device [3].

When we think of MEMS or micromachining, wrist and pocket watches do not necessarily come to mind. While these devices often are a watchmaker's piece of art, they are a piece of their own, handcrafted in single numbers, none like the other. Today, one of the major aspects of MEMS and micromachining is batch processing, producing large numbers of devices with identical properties, at the same time assembled parallel in automatic processes. The introduction of microelectronics into watches has resulted in better watches costing a few dollars instead of a few thousand dollars, and similarly the introduction of silicon surface micromachining on the wafer level has reduced, for example, the price of an accelerometer, the integral part of any car's airbag, to a few dimes.

Spacecraft application of micromachined systems is different in the sense that batch production is not a requirement in the first place – many spacecraft and the applications are unique and only produced in a small number. Also, the price tag is often not based on the product, but more or less determined by the space qualification and integration into the spacecraft. Key driving influences of miniaturization of microelectronics are the reduced cost and mass production. These drivers combine with the current significant trend to integrate more and more components and subsystems into fewer and fewer chips, enabling increased functionality in ever-smaller packages. MEMS and other sensors and actuator technologies allow for the possibility of miniaturizing and integrating entire systems and platforms. This combination of reduced size, weight, and cost per unit with increased functionality has significant implications for Air Force missions, from global reach to situational awareness and to corollary civilian scientific and commercial based missions. Examples include the rapid low-cost global deployment of sensors, launch-on-demand tactical satellites [4], distributed Microelectromechanical Systems and Microstructures in Aerospace Applications sensor networks, and

affordable unmanned aerial vehicles (UAVs). Collective arrays of satellites that function in a synchronized fashion promise significant new opportunities in capabilities and robustness of satellite systems. For example, the weight and size reduction in inertial measurement units (IMUs) composed of MEMS accelerometers and rate gyros, global positioning system (GPS) receivers for navigation and attitude determination, and MEMS-based micro-thruster systems are enablers for small spacecraft, probes, space robotics, nanosatellites, and small planetary landers [5-9].

The benefits include decreased parts count per spacecraft, increased functionality per unit spacecraft mass, and the ability to mass produce micro-, nano-, and picosatellites for launch-on-demand tactical applications (e.g., inspector spacecraft) and distributed space systems. Microlaunch vehicles enabled by micromachined subsystems and components such as MEMS liquid rocket engines, valves, gyros, and accelerometers could deliver 1 or 2 kg to low-Earth orbit. Thus, it will be possible to place a payload (albeit a small one) as well as fully functional microsattellites into orbit for \$10,000 to \$50,000, rather than the \$10 million to \$50 million required today [10].

In fact, researchers at the South West Research Institute have performed extensive tests and determined that the vacuum of space produces an ideal environment for some applications using MEMS devices. MEMS devices processed in a vacuum for 1010 cycles had improved motion with decreased voltage.

### 3. Materials and Methods

Over the past several years, MEMS catalytic monopropellant micro-thruster research and development has been conducted at NASA's GSFC. Eleven MEMS-based propulsion systems have the potential to enable missions that require micro-propulsive maneuvers for formation flying and precision pointing of robots [15], micro-, nano-, or pico-sized satellites [13, 16]. Current propulsion technology cannot meet the minimum thrust requirements (10-1000 mN) or impulse-bit requirements (1-1000 mN\_sec), or satisfy the severely limited system mass (< 0.1 kg), volume (< 1 cm<sup>3</sup>), and power constraints (< 1 W) [11, 12]. When compared to other proposed micro-propulsion concepts, MEMS catalytic monopropellant thrusters show the promise of the combined advantages of high specific density, low system power and volume, large range of thrust levels, repeatable thrust vectors, and simplicity of integration. Overall, this approach offers an attractive technology solution to provide scalable micro-Newton-level micro-thrusters. This particular MEMS micro-thruster design utilizes hydrogen peroxide as the propellant and the targeted thrust level range is between 10 and 500 mN with impulse

bits between 1 and 1000 mN<sub>sec</sub> and a specific impulse (Isp) greater than 110 sec. Individual MEMS fabricated reaction chambers are approximately 3.0 × 2.5 × 2.0 mm. Thrust chambers are etched in a 0.5 mm silicon substrate and the vapor is deposited with silver using a catalyst mask.

## 4. Results and Discussion

The evaluation of a fabrication process for an application requires the assessment of a number of factors:

- the process-critical dimension (i.e., the smallest dimension that can be fabricated);
- the process precision (i.e., dimensional accuracy or nominal device dimension);
- materials available for fabrication;
- assembly requirements to produce a functioning device;
- process scalability (i.e., Can large quantities of devices be produced?); and
- integrability with other fabrication processes (e.g., microelectronics).

A large assortment of MEMS fabrication processes have been developed, but they may be grouped into three broad categories, which are discussed in further detail in subsequent sections.

- lithographie, Galvanoformung, Abformung (LIGA);
- bulk micromachining; and
- sacrificial surface micromachining;

Figure 1 shows the basic concepts of each fabrication category. Bulk micromachining and sacrificial surface micromachining are frequently silicon based and are generally very synergistic to the microelectronics industry since they tend to use common tool sets.

The LIGA process is capable of making complex structures of electroplatable metals with very high aspect ratios and thicknesses of several hundred microns. The LIGA process utilizes x-ray lithography, thick resist layers, and electroplated metals to form complex structures. Since x-ray synchrotron radiation is used as the exposure source for LIGA, the mask substrate is made of materials transparent to x-rays (e.g., silicon nitride, polysilicon). An appropriate mask-patterned layer would be a high atomic

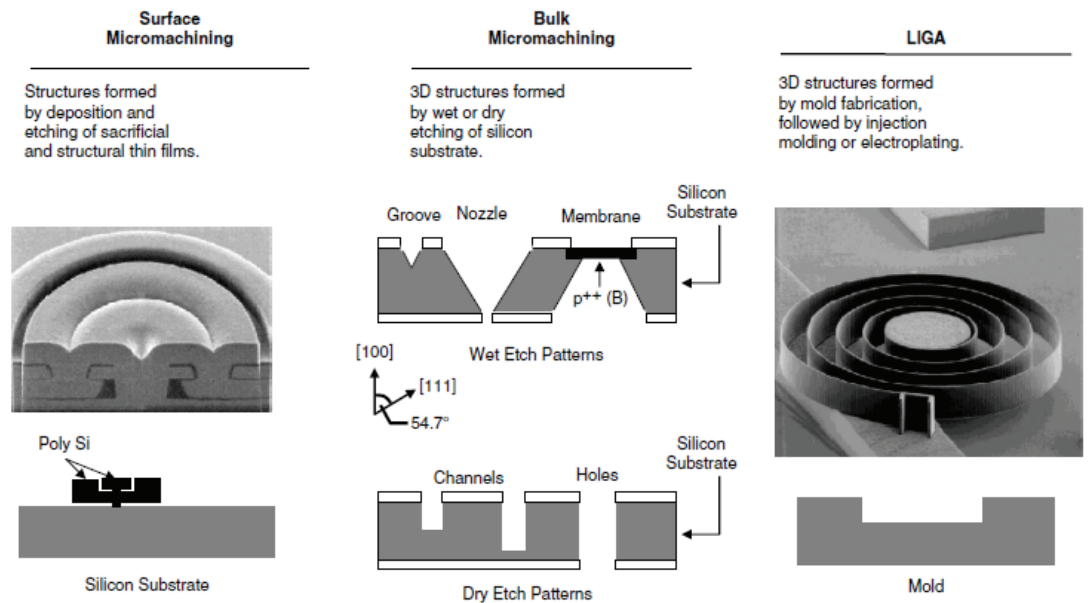


Figure 1: MEMS fabrication technology categories.

weight material (e.g., gold). The LIGA fabrication sequence shown schematically in Figure 2 starts with the deposition of a sacrificial material such as polyimide, which is used for separating the LIGA part from the substrate after fabrication. The sacrificial material should have good adhesion to the substrate yet be readily removed when desired. A thin seed layer of material is then deposited, which will enable the electroplating of the LIGA base material. A frequently used seed material would be a sputter-deposited alloy of titanium and nickel. Then a thick layer of the resist material, polymethylmethacrylate (PMMA), is applied.

The synchrotron provides a source of high-energy collimated x-ray radiation needed to expose the thick layer of resist material. The exposure system of the mask and x-ray synchrotron radiation can produce vertical sidewalls in the developed PMMA layer. The next step is the electroplating of the base material (e.g., nickel) and polishing of the top layer of the deposited base material. Then the PMMA and sacrificial material are removed to produce a complete LIGA part. Since LIGA can produce metal parts, magnetic actuation is feasible [14].

Assembly of LIGA devices for large-scale manufacturing is a challenging issue.

## 5. Conclusions

Three categories of MEMS fabrication technologies were presented: bulk micromachining, LIGA, and sacrificial surface micromachining. Bulk micromachining is primarily

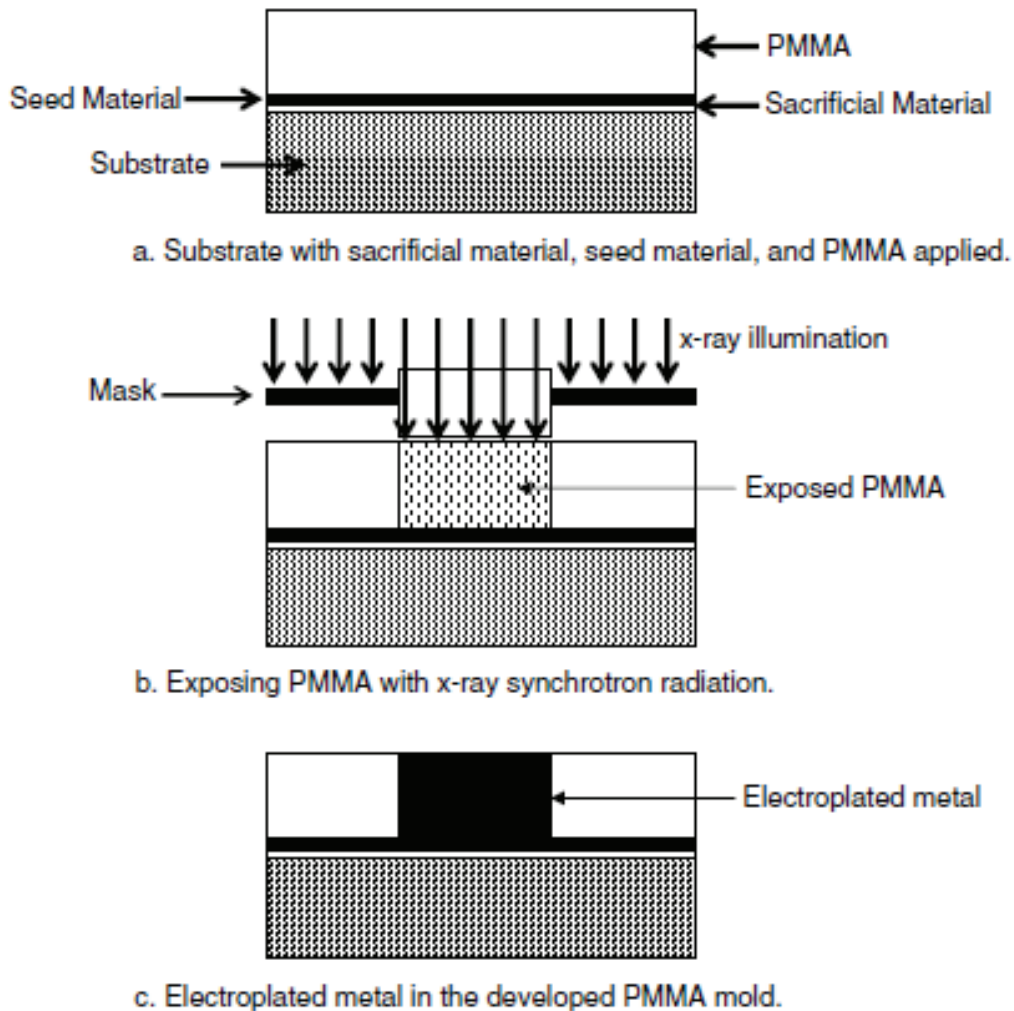


Figure 2: LIGA fabrication sequence.

a silicon-based technology that employs wet chemical etches and reactive ion etches to fabricate devices with a high aspect ratio. Control of the bulk micromachining etches with techniques such as etch stops material selectivity is necessary to make useful devices. Commercial applications utilizing bulk micromachining are available such as accelerometers and ink-jet nozzles. LIGA is a fabrication technology that utilizes x-ray synchrotron radiation, a thick resist material and electroplating technology to produce high aspect ratio metallic devices. Surface micromachining is a technology that uses thick films and processes from the microelectronic industry to produce devices. Surface micromachining employs two types of materials, a sacrificial material and a structural material, in alternating layers. A release process removes the sacrificial material in the last step in the process, which produces free function structural devices. Surface micromachining enables large arrays of devices since no assembly is required. Surface micromachining can also be integrated with microelectronic for sensing and control.

New materials are being developed to enhance MEMS applications. For example, silicon carbide is a hard, high-temperature material, which can withstand harsh environments. Silicon-germanium and diamond are materials that can be deposited at low temperatures, which enable increased MEMS process flexibility.

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