UPPSALA
UNIVERSITET

Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1003

Development of Micro-components for Attitude and Communication Systems on Small Vehicles in Space and Extreme Environments

KRISTOFFER PALMER

ACTA
UNIVERSITATIS
UPSALIENSIS
UPPSALA
2013

ISSN 1651-6214
ISBN 978-91-554-8555-9
urn:nbn:se:uu:diva-186862

Dissertation presented at Uppsala University to be publicly examined in Polhelmsalen, Lägerhyddsvägen 1, Uppsala, Friday, January 11, 2013 at 10:00 for the degree of Doctor of Philosophy. The examination will be conducted in English.

Abstract

Palmer, K. 2013. Development of Microcomponents for Attitude and Communication Systems on Small Vehicles in Space and Extreme Environments. Acta Universitatis Upsaliensis. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1003. 43 pp. Uppsala. ISBN 978-91-554-8555-9.

In this thesis, components intended for vehicles in space and other extreme environments have been realized using microsystems technology to facilitate miniaturized, yet high-performing systems beneficial for small spacecraft and other vehicles with limited size and power.

Cold gas thrusters commonly used on spacecraft basically accelerate a gaseous propellant stored under high pressure. When miniaturized, their performance is reduced because of viscous forces. Here, with a special masking and etching scheme, making silicon micronozzles close to rotationally symmetric, this shortcoming was mitigated as indicated by schlieren imaging of the rocket exhaust and a comparison with conventionally manufactured micronozzles with rectangular cross-sections. Schlieren imaging was also used to detect leakage, quantify thrust vector deviation, and measure shock cell periods in the exhaust. Correlation was made to operational conditions.

Similarly operating zirconia thrusters with integrated heaters and flow sensors were developed to allow for higher operating temperature. Successful testing at 1000°C, suggests that the propellant efficiency could be increased by 7.5%, and also makes them candidates for chemical propulsion.

A silicon thruster operating in rarefied gas regimes was also developed. Being suspended in a silicon dioxide frame reducing heat losses, a total efficiency of 17% was reached.

Relating to the integrated micropropulsion systems, two types of flow sensors were developed. Through finite element modeling, the insertion of sensor fingers in the fluid was shown to be an interesting concept for high-pressure applications.

Utilizing the same principle, a velocity sensor for a miniaturized submersible was developed. With a power consumption below 15 mW, it was able to measure directions with an accuracy of ±8º, and speed with an error less than 22%.

To enable high-speed optical communication between spacecraft, a Free Space Optics communication system, and particularly its dual-axis beam-steering actuator, was developed. Through thermal actuation, optical angles larger than 40º were obtained. A lumped thermal model was used to study design changes, vacuum operation and feedback control.

Understanding and mastering heat transfer in microsystems have been vital in many of the studies conducted. Throughout, advanced micromachining and modeling have been used as a step towards high-performance systems for space and other extreme environments.

Kristoffer Palmer, Uppsala University, Ångström Space Technology Centre (ÅSTC), 516, SE-751 20 Uppsala, Sweden.

ISSN 1651-6214
ISBN 978-91-554-8555-9
urn:nbn:se:uu:diva-186862 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-186862)

Till min familj

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Lekholm, V., Palmer, K., and Thornell, G. (2012) Schlieren Imaging of Microthruster Exhausts for Qualitative and Quantitative Analysis. *Measurement science and technology*, 23(8):085403-

II Palmer, K., Vargas Catalan, E., Lekholm, V., and Thornell, G. (2012) Investigation of exhausts from fabricated silicon micronozzles with rectangular and close to rotationally symmetric cross sections. Submitted to *Journal of Micromechanics and Microengineering*

III Lekholm, V., Persson, A., Palmer, K., Ericson, F., and Thornell, G. (2012) High-temperature zirconia microthruster with integrated flow sensor. Submitted to *Journal of Micromechanics and Microengineering*

IV Palmer, K., Nguyen, H., and Thornell, G. (2012) Fabrication and Evaluation of a Free Molecule Micro-Resistojet with a Thick Silicon Dioxide Insulation and Suspension. Submitted to *Journal of Micromechanics and Microengineering*

V Palmer, K., Kratz, H., Nguyen, H., and Thornell, G. (2012) A highly integratable silicon thermal gas flow sensor. *Journal of Micromechanics and Microengineering*, 22(6):065015-

VI Palmer, K., Nguyen, H., and Thornell, G. (2012) Finite Element Analysis of the Effect on Employing Thermal Through Vias and Heat Fingers to Increase Heat Transfer to Fluid in Calorimetric Flow Sensors. Submitted to *Sensors and Actuators A*

VII Palmer, K., Jonsson, J., Nguyen, H., and Thornell, G. (2012) Two-Dimensional Thermal Velocity Sensor for Submersible navigation and Minute Flow Measurements. *IEEE Sensors Journal*, In press, Digitally published, DOI: 10.1109/JSEN.2012.2216866

VIII Palmer, K., Lotfi, S., Berglund, M., Thornell, G., and Kratz, H. (2010) A micromachined dual-axis beam steering actuator for use in a miniaturized optical space communication system. *Journal of Micromechanics and Microengineering*, 20(10):105007-

IX Berglund, M., Palmer, K., Lotfi, S., Kratz, H., and Thornell, G. (2012) Dynamic characterization and modelling of a dual-axis beam steering device for performance understanding, optimization, and control design. Submitted to *Journal of Micromechanics and Microengineering*

Author's contributions to the Publications

I Minor parts of concept, planning and experimental work, major part of analysis.

II All concept, most of planning and experimental work and of analysis.

III Minor parts of concept, planning and experimental work, major of analysis.

IV All concept, planning, experimental work and analysis.

V Minor part of concept, most of planning, experimental work and analysis.

VI All concept, experimental work and analysis, most of planning.

VII Minor part of concept, most of planning, experimental work and analysis.

VIII Minor part of concept, major part of planning, most part of experimental work and analysis.

IX Minor part of concept, planning and experimental work, major part of analysis.

Contents

Abbreviations

MST	Microsystems technology
MEMS	Microelectromechanical systems
IC	Integrated circuits
DADU	Deeper Access Deeper Understanding
DRIE	Deep Reactive Ion Etching
RIE	Reactive Ion Etching
UV	Ultraviolet
LTCC	Low temperature co-fired ceramics
HTCC	High temperature co-fired ceramics
FMMR	Free molecule Microresistojet
FEA	Finite Element Analysis
FSO	Free Space Optics

Introduction

In October 1957, now more than 55 years ago, the Soviet Union placed the first man-made object in orbit around Earth. The spacecraft, *Sputnik 1*, was the first substantial result of the recently declared Space Race, which twelve years later would reach its climax when Neil Armstrong put his moon boots on the lunar surface. Since then, thousands of spacecraft have been launched, and today, we rely on satellites for communication, television, navigation, weather reports, etc in our every-day life. Governments and organizations use satellites for purposes such as surveillance and agricultural observation while scientists utilize satellites for further Earth and climate observation, increased understanding of the Earth's magnetic fields and atmosphere and their interaction with the solar wind. Scientific spacecraft are also part of our exploration of the universe. Spacecraft have been used to explore planets and moons in our solar system, and recently, it was reported that the spacecraft Voyager 1 may be on the verge of leaving our solar system.

A significant part of the cost of a spacecraft mission is the launch cost. An estimation is that the launch cost per kilogram is between 5 000 and 50 000 USD [1]. This has driven the development of smaller, more cost-effective spacecraft, and has enabled relatively small companies, low-income countries and universities to be a larger part of the space community.

However, to maintain functionality when decreasing the size of a spacecraft, subsystems and their respective components must be reduced in size but still perform well. Some components may be scaled down in size using conventional machining, whereas other may need a drastic change of fabrication technology to be realized.

Microsystems technology (MST), or Microelectromechanical systems (MEMS), has emerged from the integrated circuits (IC) industry, where the rapid advancements more or less has formed our modern society. It was the possibilities of using the semiconductor material silicon, the basis of the IC industry, as a mechanical substrate and an electrical material that initially formed the concept, but today MEMS is rather defined as fabrication of devices with at least some of their dimensions in the micrometer range, that is, measured in millionths of a meter [2, 3]. Many of the materials and processing techniques, where the batch fabrication possibilities from the IC industry is a key, are ideal for fabricating low-cost devices, which is one of the commercial driving forces in MEMS fabrication. Furthermore, microtechnology may also provide more than just smaller systems. It may also enable new types of device functions and, in some aspects, such as sensor resolution, even increase device performance.

While most people have a fairly good idea of what space is, the term *extreme environments* might be more unacquainted to many. In [4], it is described as environments that are hostile to human beings with regards to, for instance, temperature, pressure, radioactivity, acidity, oxygen level, vibration, shocks, etc. From this, it can be concluded that also space is an extreme environment.

Nevertheless, we have the desire to explore these dangerous places, and this desire does not seem to go away. More than 50 years after Gagarin's journey to outer space, Virgin Galactic are on the brink of bringing ordinary people to space, and more than 50 years after the first descent to the Mariana Trench, James Cameron showed that others want to go there as well. Most exploration, and utilization, of these environments are, however, conducted unmanned, and, doing so with small vehicles may be very beneficial.

This thesis focuses on development of microcomponents for attitude control (propulsion included) and communication subsystems for small vehicles in space and other extreme environments. The need for microcomponents and microsystems development is described, and so are a number of possible solutions to the challenges of future exploration of space and extreme environments. The components have been developed with the state of current technology and its limits in mind. Starting from an idea, the different components have been designed, modeled, manufactured and evaluated. Following evaluation, redesign and remodeling have, in some cases, also been conducted. In the development work, choosing of materials and processing techniques is a key factor in realizing the devices and their functions. Both standard processing as well as less conventional methods have been incorporated in the development of the devices.

This summary aims at putting the thesis's papers into context and to provide an understanding to a reader who might not have a background it the fields they cover. After reading, the reader should have an idea of the challenging tasks of developing systems for small, yet highly functional, vehicles, and of what the future in the explorations of extreme environments might hold.

Microsystems Technology

Just as we rely on satellites on daily basis, microtechnology is today a vital part of our life. The sensors for triggering the airbags in our cars, the ink-jet heads in printers, and some microphones, camera-focusing motors and motion-detecting sensors in mobile phones are just a few examples of today's commercial MEMS devices. With the high maturity levels of MEMS technology reached, it is today a serious approach of fabricating miniature components and systems for space technologies.

As mentioned in the introduction, the technology originates from the IC industry, but has grown from the area of small electronics to more or less the whole physics area. *Silicon*, the single-crystal substrate material inherited from the IC industry, has many interesting and beneficial physical properties apart from the purely electrical [3]. It is, for instance, very pure, experiences no fatigue, and it can withstand many aggressive chemicals. These properties, and more, together with the processing techniques available, have made it a corner stone in MEMS, and the batch manufacturing of reliable and rather inexpensive components. Of course, the electrical properties are still important, and utilized also in MEMS components. Today, other materials, both more and less expensive ones, are also used in the microfabrication world. For instance, *quartz* and *diamond* are used in some applications, where the end products will be rather expensive but capable of, for instance, high temperature, whereas different *polymers* are used in low-cost applications. Silicon processing is, much due to its maturity, often used, for instance, to create moulds for subsequent low-cost polymer production.

Silicon micromachining is a repetitive process where materials are added or removed in different procedures. The silicon substrate itself, is a thin (about 300-500 μm) wafer with a typical diameter of 10 cm (but generally larger in the industry).Typically, thin (about a few nanometers to a few micrometers) layers are deposited or grown on the silicon substrate. Selected parts of the layers, or the silicon itself can then be removed in different *etch* processes. Processes regarding the thin layers are generally referred to as surface micromachining, whereas etching tens or hundreds of micrometers deep trenches in the silicon wafer is referred to as bulk micromachining.

With a well thought-out design, and careful planning of the process scheme, the different materials used will have different impacts on the properties of final device. Material properties made use of, can for instance, be mechanical, electrical and thermal conductivities (including isolating), optical, porosity, catalyzing or chemical, magnetic, hydrophility, etc.

The selection of what material to remove is usually made through *photolithography*. It is a process where a polymer, often sensitive to UV light, is deposited on the silicon wafer and UV-exposed through a glass mask on which a pattern with feature sizes as small as about a micrometer has been printed using a laser. The pattern is transferred to the polymer, which after some treatment, can be used as a mask in an etch process where the pattern is transferred to the layer beneath. By using a set of masks, specifically designed for a process procedure, and repeating this, components are created.

The technique allows for several components (depending on their size) to be manufactured next to each other on the wafer, and at the same time, i.e. in parallel. In many processes, several wafers can even be processed simultaneously, for instance when being submerged into an etching acid. This so-called *batch fabrication* is the main explanation of the low-cost capabilities of MEMS and IC components. Furthermore, since all components in a batch experience (almost) the exact same conditions, they will be very similar to each other, provided of course that the laboratory process and environment control is acceptable. Since the feature sizes are so small, it is of great importance that the environment is particle free. Because of this, all fabrication takes place in a cleanroom with filtered air supply where the staff wears full-body overalls to reduce risks of contamination, *Figure 1*.

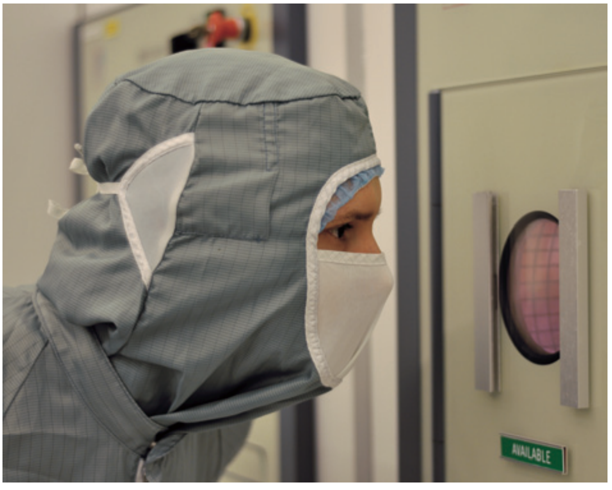

Figure 1. The author dressed in cleanroom garment and looking at a plasma.

With MEMS comes the ability to integrate different components with each other directly on the same chip. It can be done by bonding several wafers to each other, or by processing more than one kind of components on the wafer.

Besides chemical and physical etching processes in, for instance, acid baths or plasma chambers, there are less traditional micromachining (from an IC point of view) where techniques such as powder blasting and laser machining are used. For the principles of micromachining and examples of components, the reader is referred to [2, 3, 5, 6].

Figure 2 shows two common and partly substrate materials, silicon and borosilicate (Pyrex).

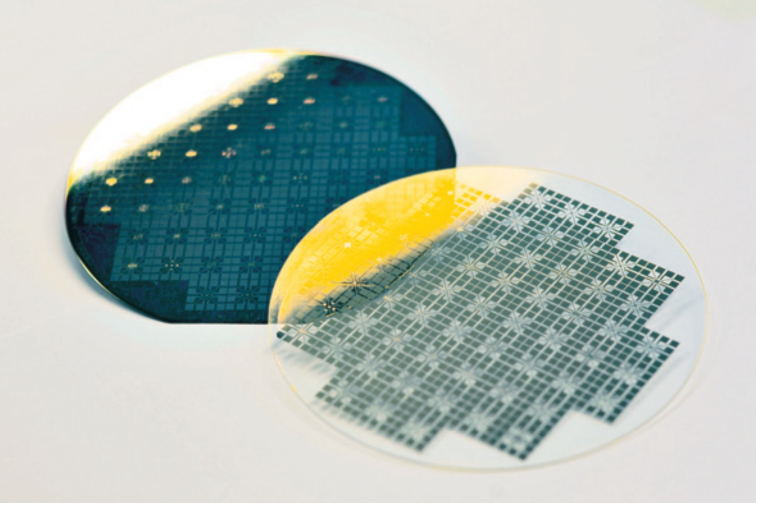

Figure 2. Ten-centimeter diameter silicon wafer (left) and a borosilicate glass wafer (right) patterned with similar patterns from the development work for **Paper VII**. Each wafer contains 61 components.

An important phenomenon when decreasing the size of an object is scaling. Different properties depend on the length (L), area (L^2) or volume (L^3) or combinations thereof. For instance, the heat generated by an object is proportional to its volume, whereas the heat lost to its surroundings is proportional to its surface, so the ratio of heat lost to generated is proportional to L^2/L^3, or $1/L$. Consequently, a small object must, relatively, generate more heat than a large one to maintain a certain temperature. An often used example from nature is the comparison of a shrew-mouse with an elephant, where the mouse must eat almost its own weight every day to survive.

Small Spacecraft

As mentioned in the introduction, the driving force of manufacturing smaller spacecraft is the possibility of reducing cost. Three often mentioned groups of small-size spacecraft are micro, nano and picospacecraft which often, but not always, are defined as spacecraft with masses less than 100, 10 and 1 kg, respectively [7]. Note that “micro” etc. in this context say nothing about the technology used. Instead they are pure size references with respect to large spacecraft. Fully functioning spacecraft with masses over several tens of kg are indeed possible to manufacture using conventional technology, but with smaller sizes, functionality and performance would then have to be sacrificed. Cubesats, a standard picospacecraft type often used by, for instance, universities, are cubical spacecraft with a side of 10 cm and a mass of about 1.3 kg or less. These typically carry a quite simple payload like a camera or some minor measuring devices. Some have attitude control in form of gyros or magnetorquers, or very simple cold gas systems. More advanced systems are hard to fit in with conventional technology.

This is where MEMS technology is a promising solution, and why many MEMS scientist have directed their interest towards nano and picospacecraft. Also, the low cost of a cubesat mission means that the mission team might be prepared to risk more by testing a new technology. Besides small size and low mass, MEMS components often offer performance advantages that may qualify them as candidates for operation on large spacecraft [8].

The integration aspects of MEMS mean that even more mass and volume can be saved by for instance integrating filters, valves, transducers and heaters in a single thruster chip or unit. Thus, there is no need for single-component housing or cables and piping between the components [9-12] **PaperIII**. As an example, *Figure 3* shows a picospacecraft together with a commercial off-the-shelf (COTS) flow sensor and a bare-chip sensor from **Paper V**. Surely, the piping can be reduced, and there might be smaller packaged sensors, but it is evident that a number of such packages quickly fills a small spacecraft. By integrating several systems by for instance stacking chips like the one in the figure, much is gained.

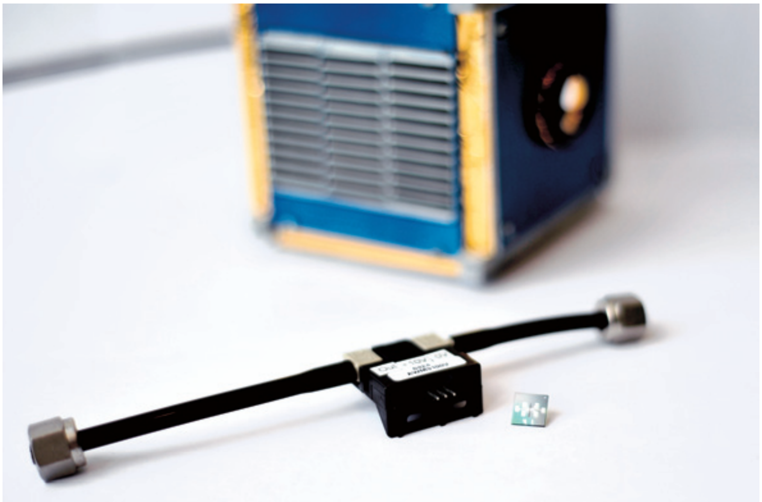

Figure 3. A COTS flow sensor together with a flow sensor from **Paper V**, and a cubesat spacecraft model (10 cm in width, height and depth).

Propulsion and attitude control microcomponents

A spacecraft should preferably know its position, velocity and orientation, and be able to control them. For this the *Guidance and Navigation*, *Attitude Determination and Control* and *Propulsion* subsystems are used. To rotate a spacecraft, components such as reaction wheels, gyros and magnetorquers can be used without consuming any propellant (fuel) [13]. However, thrusters, which expel a propellant, may also be used, and to actually change the spacecraft's orbit, thrusters are needed. Given a mission, the requirements on the attitude control and propulsion system will determine what types of thrusters are usable. A critical issue is the amount of propellant that is estimated to be consumed during the entire mission (spacecraft cannot stop and refill fuel at a gas station). This propellant, and all other parts of the system, must fit into the spacecraft, and it is obvious that a propellant efficient, compact system is preferable.

MEMS thrusters and propulsion systems (see, for instance [9-12, 14-25]) have the capability of delivering low thrust levels and reducing the size and mass of the propulsion system which may enable both orbit and three-axis control of micro and nanospacecraft. In this thesis, microthrusters utilizing gaseous propellants have been developed and evaluated (**Paper II, III, IV**) or just studied (**Paper I**). The thrusters fabricated are all designed to improve the efficiency of existing systems in different ways. In **Paper II**, it is done by controlling the shape of the nozzle, in **Paper III** by enabling higher chip propellant temperature and in **Paper IV** by reducing the heat loss. Schlieren imaging, a technique for visualizing the thruster jets, has been used in **Papers I-III**, and has proven to be a promising quality control method for microthrusters.

Micro flow sensors have been developed with the goal of being integratable in silicon-based systems such as the thrusters (**Paper V and VI**), and, based on the same measuring principle of calorimetric flow sensing, a velocity sensor for a miniaturized submersible has been developed (**Paper VII**).

Paper I

The working principle of cold gas thrusters is that gas stored under high pressure is fed through a converging-diverging nozzle, in which it is accelerated to supersonic velocities and expands to provide thrust. An often used method to increase the efficiency of the thruster, is to heat the gas, since the exit velocity is proportional to the square root of the gas temperature [13]. When doing so, the thruster can also be referred to as a heated cold gas thruster, or resistojet. These types of thrusters are well studied in microscale [9, 10, 14, 24] and have even been space qualified [11]. The objective with the study was to study micronozzles exhaust characteristics during operation. At microscale, effects from viscous forces at the boundaries might decrease the performance [26] compared with larger rockets.

The jet exhausts from DRIE etched thrusters were studied under atmospheric and vacuum conditions using schlieren imaging. Schlieren imaging [27] is a technique that enables visualization of inhomogeneities in transparent media, such as gases. The principle behind it is that differences in pressure and temperature lead to differences in the media's refractive index. Using a so called schlieren setup this can be imaged.

The results showed that shock cells were present in the jet, *Figure 4*. Shock cells appear in a supersonic jet exhaust that is mismatched, which means that the pressure in the exhaust is different from that of the ambient [28, 29]. This may decrease the thruster performance [29]. The shock cell separation distance was observed to increase with increasing feed pressure, which is expected since it changes the exhaust exit pressure. It was also observed that the separation distance increased when the integrated propellant heaters were activated in order to increase the propellant efficiency. Furthermore, leaks in a nozzle were detected, *Figure 5*.

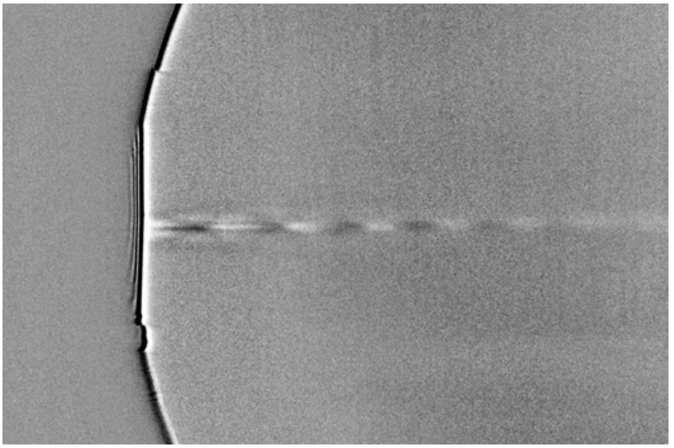

Figure 4. Supersonic exhaust from a microrocket (located in the left side of the image) operating in vacuum. The periodic pattern shows that there are shock cells in the exhaust jet because of pressure differences. The field of view is about 6.5×4 mm. (Figure from **Paper II**, © 2012 IOP).

The imaging confirmed that the thrusters' exhausts were supersonic The results showed that schlieren imaging is a useful tool for quality control of microthrusters, since leaks that otherwise might pass unnoticed can be detected. By measuring the shock cell separation distance from a thruster, flow conditions can be estimated.

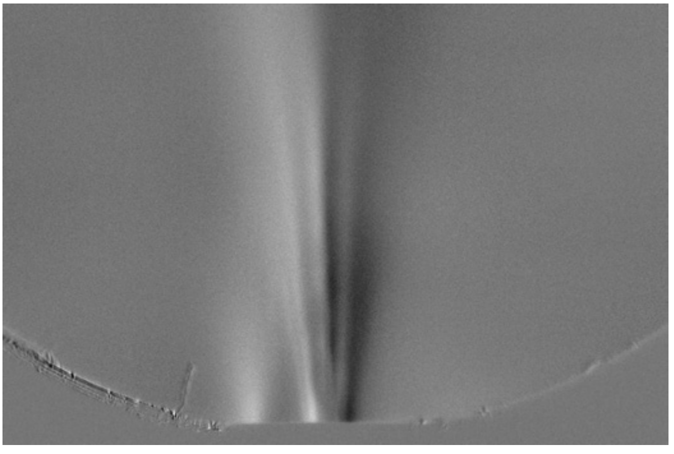

Figure 5. Supersonic exhaust and leak from a microrocket (located in the image bottom) operating in vacuum. The leak is visible as a white disturbance on the left side of the exhaust. The field of view is about 7×4.5 mm. (Figure from **Paper II**, © 2012 IOP).

Paper II

As mentioned above, with small channels, the viscous losses increase. However, it is not only the size of the channel that needs to be taken into account, but also shape of it. A flow through a channel or pipe with a circular cross section exhibits lower losses than one through a rectangular channel of the same cross-section area. Conventional cold gas microrockets, such as the ones studied in **Paper I,** typically have rectangular cross sections. This is a result of limitations in the conventional DRIE process where the side walls typically are vertical. Therefore, these rockets suffer from reduced performance, not only because of the small scale, i.e. the nozzle cross section area, but also because of the rectangular shape of it.

In **Paper II**, cold gas microrockets with close to rotationally symmetric cross sections were developed and studied using schlieren imaging. The rockets were fabricated by using a technique that employs a less directionally-dependent etch technique through an etch mask of differently sized and spaced holes [30, 31]. During the etching, the etched grooves from the small holes grow together to form a large nozzle-shaped groove of varying width and depth, *Figure 6*. For comparison, rockets with rectangular cross sections were also imaged. The symmetries and the directions of the exhaust jets were compared for different feed pressures during vacuum operation.

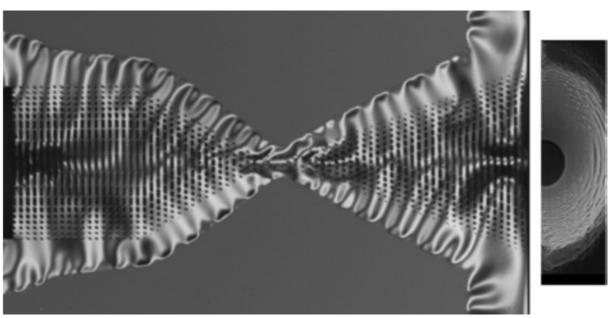

Figure 6. Microscope top-view image of a half-nozzle (with etch mask still present) after etching (left), and a scanning electron microscope image viewing a half-nozzle from the exit direction (right). To complete a nozzle, two such half-nozzles are bonded to each other after removing the etch masks. The length of the nozzle is about 600 µm.

Schlieren imaging showed that the exhaust from the close to rotationally symmetric and the rectangular nozzles had quite similar exhausts, although the exhaust of the former was somewhat more symmetric. It was, however, not easy to perform direct and objective comparisons due to differences in dimensions. Additionally, the jet exhausts from the nozzles with rectangular cross sections were found to deviate from the direction of the microrocket's symmetry axis, *Figure 7*. The deviation also depended on the feed pressure. It was believed that this was due to small side-wall inclinations observed from DRIE etching. A deviating jet may result in errors in spacecraft attitude control since the resulting thrust vector may be difficult to predict.

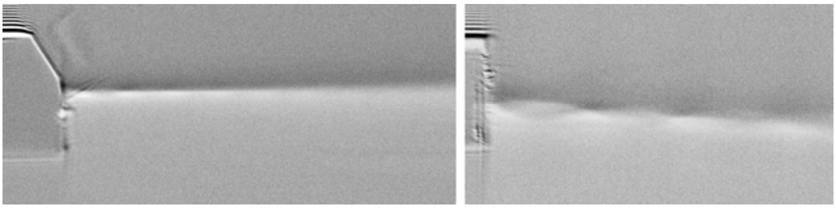

Figure 7. Schlieren images of exhaust jets from nozzles with close to rotationally symmetric cross section (left), and rectangular cross section (right). The thickness of the visible rocket chip in the right image is about 1 mm.

From the results it was concluded that close to rotationally symmetric micronozzles are possible to fabricate in silicon, and that these may enable more propellant efficient cold gas systems. Moreover, it was found that the wall inclination angle in DRIE etched nozzles may be an important factor. This further adds to the usefulness of schlieren imaging for microthruster quality control.

Paper III

It is not only the shape of the channel, **Paper II**, that can be used to affect the propellant efficiency in microrockets, but also, as described **Paper I**, the temperature of the gas just before entering the converging-diverging nozzle. The increase in propellant efficiency is theoretically proportional to the square root of the temperature increase [13]. What limits the temperature that the gas can be heated to, is, apart from the heating efficiency, the maximum operation temperature of the thruster material and, of course, the available electric power. Silicon suffers from (thermal) softening at a few hundred degrees Celsius. Thus it is not a suitable high-temperature thruster material. Thrusters fabricated of ceramic materials show better potential for high temperature operation [32, 33]. **In Paper III**, microthrusters with integrated heaters and flow sensors (with principle of operation similar to those in **Papers V-VII**) were fabricated using zirconia, a High Temperature Cofired Ceramic (HTCC) sintered at 1400-1600ºC.

During the fabrication, etched silicon tools were used to punch and emboss fluidic structures in zirconia-based tapes which also contain a polymeric binder making them easy to shape and join. To complete the components, platinum heating and sensing elements were screen printed, and the tapes were laminated and sintered. During sintering, the binder material in the tape vanishes and a hard ceramic structure is obtained.

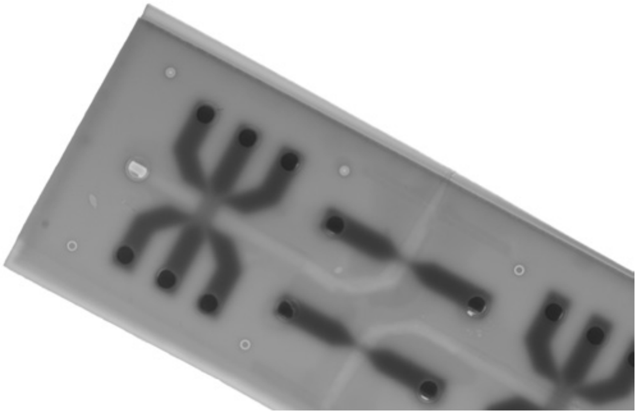

Figure 8. Zirconia thrusters with integrated calorimetric flow sensors. Two opposing thrusters are located on the chip's long sides with the heater upstream. The flow sensor is located close to the inlet (bright dot to the left). The width of the device is about 10 mm.

Operating temperatures exceeding 1000ºC were reached, and, like in **Paper I**, the propellant consumption was observed to decrease with heating. The effect was lower than expected, though. The flow sensor showed an increasing signal throughout the feed pressure interval tested. Schlieren imaging was also used to confirm the supersonic exhaust.

It is believed that a reason that the effect of the heating was lower than expected, is that the thrusters have a fairly small heater-fluid interface area.

HTCC thrusters are also a promising approach to monopropellant [17, 32] or bipropellant [23, 33, 34] chemical thrusters, due both to the high-temperature capabilities and because ceramics are generally chemically inert.

Paper IV

Here, a propulsion concept [18] very different from the thrusters in **Papers I-III**, was investigated. In a Free Molecule Micro-resistojet (FMMR), instead of expelling the propellant using high pressure, the thruster is operated at very low pressure. It is so low that the propellant molecules collide more with walls in narrow straight channels forming so-called expansion slots than with other gas molecules. By heating the walls, more energy is added to the molecules which accelerate out of the nozzle, *Figure 9*. This is a concept where, instead of having to cope with the viscous losses of high-pressure microthrusters, it uses the microscale to its advantage. Using a gaseous propellant, the propellant efficiency is still lower than for a cold gas thuster, but since no high pressure is needed, the propellant can actually be stored in liquid [21] or solid form, which may reduce the total system size and mass.

In **Paper IV**, it was investigated if the heat loss, which is rather high, could be reduced to increase the thruster efficiency.

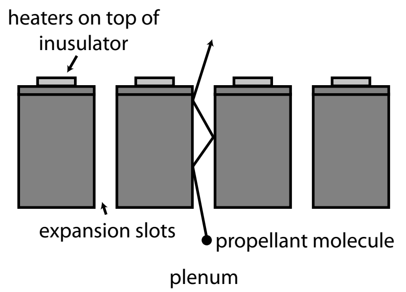

Figure 9. Working principle of an FMMR seen in a cross section. The propellant molecules gain kinetic energy from the heated walls and accelerate out from the thruster to provide thrust.

The developed silicon-based thruster had a heating island in which the gas expelling channels were etched, *Figure 10*. Surrounding the island, a suspending frame of thick silicon dioxide, basically glass, acted as a thermal barrier since its thermal conductivity is much lower than that of silicon. It was fabricated by thermal oxidation of narrow trenches etched in silicon.

The thruster was evaluated in vacuum during operation, and its thermal properties were imaged with an IR camera in atmospheric pressure.

Figure 10. Microscope image of the fabricated FMMR. The central openings are seen as bright lines and are surrounded by the insulating silicon dioxide frame. A metal heater line is located between the openings. The chip is about 10×10 mm.

The frame showed to be an effective heat barrier capable of keeping the island at a much higher temperature than the rest of the chip (at least with a difference of 150ºC). During vacuum operation, the thruster total efficiency was calculated to be higher than for a thruster of the same type [18]. The thrust obtained varied from about 10 to 1000 µN, *Figure 11*.

A further developed system with liquid propellant storage is a promising concept for nanospacecraft. It may also be monolithically integrated with a flow sensor as in **Paper VI** and [35], since they are based on the same building concept, and also with the sensor in **Paper V**, which consumes less power, has higher sensitivity and works well at low pressures.

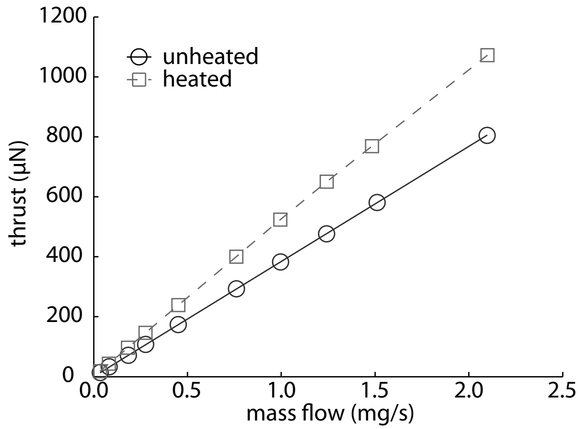

Figure 11. The FMMR's calculated thrust vs. mass flow both with the heater at about 300ºC and the heater switched off.

Paper V

As mentioned, and studied in **Paper III**, integrating components such as flow sensors is a key factor in developing propulsion systems suitable for very small spacecraft. In **Paper V**, a flow sensor intended for being integrated in silicon-based systems was investigated. The principle it works by is that of convective heat transfer [36-38]. On both sides (upstream and downstream) of a heater, temperature sensing elements are placed. If there is no flow across the elements, both sensing elements read the same temperature. When a flow is introduced, the upstream element will be cooled, and the downstream elements heated since it receives more heat from the heater by convective heat transfer. The difference in the temperatures read, constitutes the sensor signal which is dependent on the flow rate.

In the sensor developed, the integrated flow channel is separated from the metal heating and sensing elements by an about 3 µm thin membrane consisting of silicon dioxide and silicon nitride (selected due to their low thermal conductivity). During the development, unconventional processing was used in order to pattern the heating and sensing elements on a thin transparent membrane, and to protect a surface that was to be used as a bond surface. An interfacer concept for the micro-macro connections of the characterization system was also developed and later used also in **Papers II, IV, and VI**, *Figure 12*.

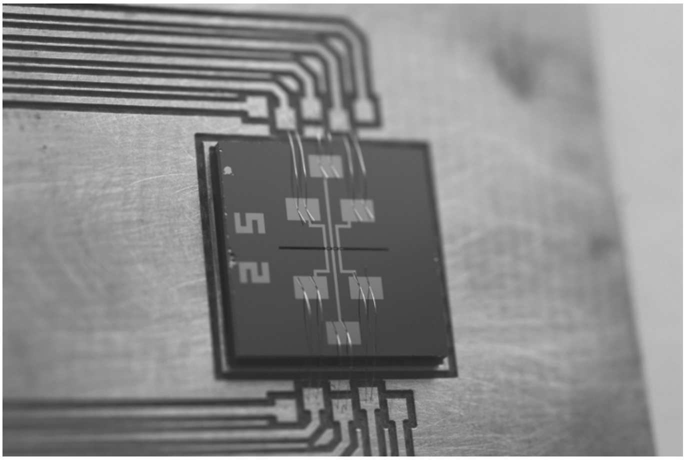

Figure 12. Fabricated flow sensor mounted on a printed circuit board interfacer and wire bonded to it for electrical connections. The channel and thin membrane are seen as a thin horizontal line along the center of the chip. The chip is about 10×10 mm. (Image from **Paper V**, © 2012 IOP)

The sensor signal for different heating voltages (i.e. temperatures) is seen in *Figure 13*. Measurements during pulsed heating gave a sensor response time in the millisecond range. The power consumption was less than 40 mW at a heater temperature of about 300ºC.

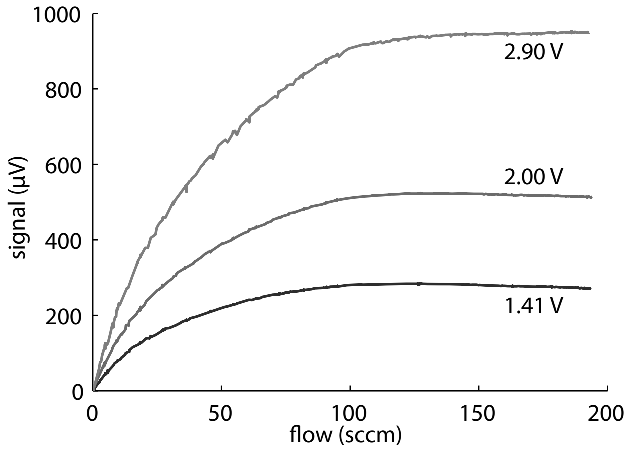

Figure 13. Measured calorimetric sensor signal vs. flow rate for different heating voltages. (Image from **Paper V**, © 2012 IOP).

This type of sensor might not be suitable in a high-pressure gas system since the thin membrane might crack at high pressures. But in systems with lower pressures, such as that in **Paper IV**, or an electric propulsion system with, for instance, gas fed to an ion thruster, it might be used.

Paper VI

With the experiences from **Paper V**, further studies on calorimetric flow sensors were conduced. In **Paper V**, the thin membrane kept heat losses along the membrane low and heat, i.e. the signal carrier, could quickly transfer through the thin membrane. The new sensor was designed to be able to withstand higher pressures. For this,a thicker membrane was created with the same method as in **Paper IV**. To be able to conduct heat through the membrane, silicon islands were selectively saved as heat conductors between the sensing elements and the gas. The fabricated sensor had a low signal [35]. Therfore, a Finite Element Analysis (FEA) study was performed in order to confirm explanations of the weak signal, understand the sensors behavior, and, finally, to find improved designs.

The solution to obtain stronger signal was to extend the silicon vias down into the fluid. The effect of extension and different designs of the heating and sensing elements were studied.

It was found that with fingers extending deep into the channel, the signal strength increases, *Figure 14*. This is because of improved convective heat transfer in the solid-fluid interface, and hence a consequence of higher power dissipation. A figure of merit is the ratio of signal strength to power dissipation, which can be seen as a sort of efficiency. Depending on the flow rate, the designs with highest such ratio differs. An example of the temperature distribution is seen in *Figure 15*.

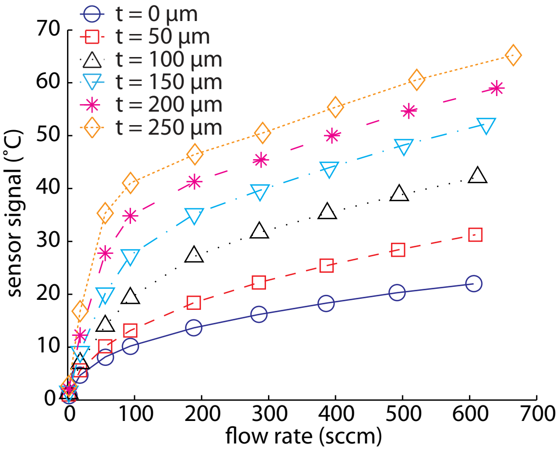

Figure 14. Sensor signal vs. flow rate for different lengths of the heating and sensing fingers. The channel height was 500 µm.

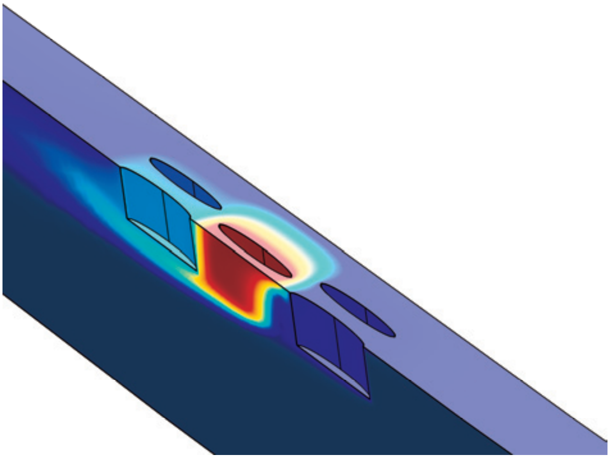

Figure 15. Image from the simulation cut along the center line of the channel. Here, only the fluid and its temperature (indicated by the color) are visible, no structural parts. (Note the holes where the heating and sensing fingers are.) Dark blue is room temperature and dark red 320ºC, the heater temperature. The flow direction is towards the top-left corner. The height of the channel is 470 µm.

It was concluded that extending fingers is an interesting concept in cases where a thick membrane must be used because of high pressures or of requirements on robustness.

Paper VII

The miniaturized submersible Deeper Access, Deeper Understanding (DADU), was developed with the goal of making a submersible small enough to be able to explore otherwise inaccessible underwater environments such as subglacial lakes, underwater caves etc. It is an about 20 cm long cylindrical vehicle with a diameter of 5 cm. Several of its instruments have been developed. In many respects, the system architecture and requirements of such a vehicle is similar to a microspacecraft. And in a similar way, MEMS components provide the capability of high functionality in a small mass with limited power. For full description, the reader is referred to [39, 40].

A sensor utilizing the same principle as in **Papers V and VI**, but capable of measuring in two perpendicular directions, hence the velocity in a plane, was developed. It was designed to be able to measure both the submersible velocity of a few centimeters per second, and very small underwater currents of velocities less than 1 mm/s. Since it would be placed on the hull of a submersible, it also had to be robust, and the electronics had to be compatible with subsurface conditions. (By placing more than one sensor on the hull, a three-dimensional flow can be detected.)

Prior to the manufacturing, the sensor was modeled using FEA to find suitable designs. Furthermore, the effects of soft biofouling, i.e. growth of algae, on the sensor surface were modeled.

To make the senor as robust as possible, it was fabricated on a borosilicate glass wafer, which, in comparison with silicon, has considerably lower thermal conductivity, so that heat losses could be kept low.

Measurements were conducted in a water tank in which the sensor was moved around using a robot arm. With a power consumption lower than 15 mW, the chip velocity could be measured with an directional error less than ±8º and a speed error less than 25% when moving at 10 mm/s. An example of the sensor signal is seen in *Figure 16*.

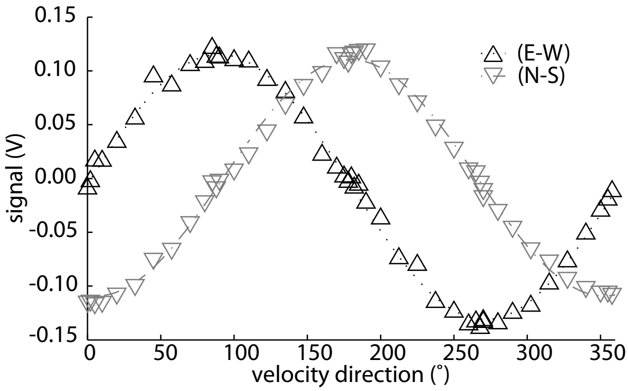

Figure 16. Sensor signal in the two perpendicular sensing directions when moving wit a speed of 10 mm/s.

Communication microcomponents

In future small spacecraft mission utilizing fractionized spacecraft architecture or cooperative flying, there might be huge data volumes that need to be transferred at a few hundred Mbps. This, if using conventional RF and microwave communication, could require heavy and bulky systems, which simply would be too heavy for small spacecraft.

Free Space Optics (FSO) communication is a promising solution where a compact communication system offers a data rate of tens of Gbps.

Paper VIII and **IX** regard the development of a critical component in an FSO system intended for inter-spacecraft communication in kilometer-sized formations. For an agile and dynamic system, the laser beams should be able to be pointed to other spacecraft. For this, a micromirror actuator, which can scan the beam in two directions, has been developed.

Paper VIII

Paper VIII describes the design, fabrication and testing of the thermally actuated micromirror capable of steering the beam using two perpendicular joints. Thermal actuators are popular due to their large stroke and high force, but have here two disadvantages: high power consumption and some thermal crosstalk. The working principle in thermal actuators is usually a mismatch between two materials' thermal expansion. In this work, the design was based on v-grooves filled with a polymer where curing shrinkage and thermal expansion together with the geometry of the grooves result in movements when the temperature changes [41].

In this component, the required actuating-angle ranges were different from those in [41]. Therefore, the actuating material was changed from polyimide to SU-8 which is a photopatternable epoxy.

The mirror here two joints for steering the beam in two dimensions. The largest optical rotational angle range tested was larger than 40º in both directions. However, the mirrors suffered from thermal cross talk meaning that the entire ranges could not be covered independently by the two joints. Furthermore, it was found that the best working actuators had a silicon backbone structure beneath the actuating material, *Figure 17*. It is believed that this silicon also served as thermal protection in a plasma etching step during the fabrication otherwise damaging the polymer somewhat.

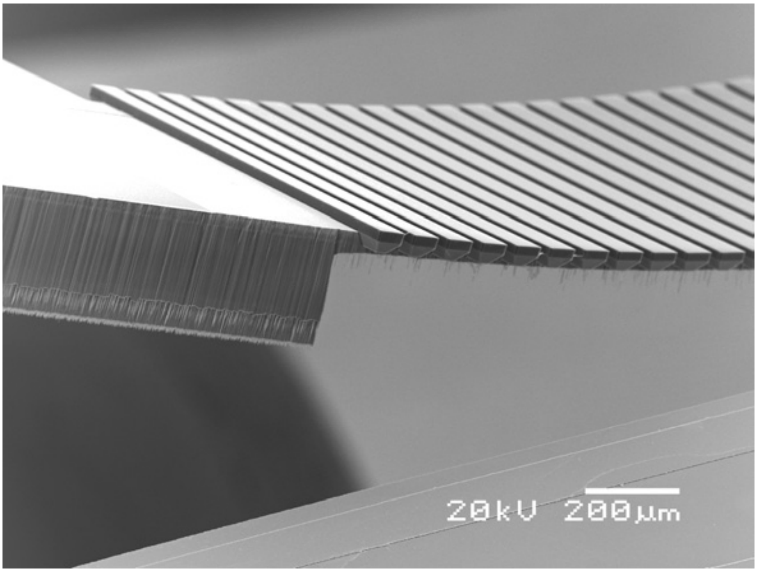

Figure 17. A micromirror joint where the trapezoid-shape of the actuating SU-8 confined in grooves is visible. The backbone silicon under the grooves is also visible.

Paper IX

Here, a model of one of the actuators, *Figure 18*, in **Paper VIII**, was created. It was a so called lumped thermal model where the thermal properties and other parameters are translated into an equivalent electric circuit model.

The model was created by assuming values for physical properties, and was then adjusted using measurement results. In this way, a model describing the device was created. From this, different cases such as operation in vacuum and the effects of manufacturing parts of the device in thermally insulating silicon dioxide as in **Paper IV and VI** can be studied.

It was found that changing parts of the device into silicon dioxide reduced the thermal cross talk significantly, and made a larger scan range possible. It also improved the operation in vacuum. A feedback control was also simulated. It was shown that by implementing such a control, a desired tracking path could be followed.

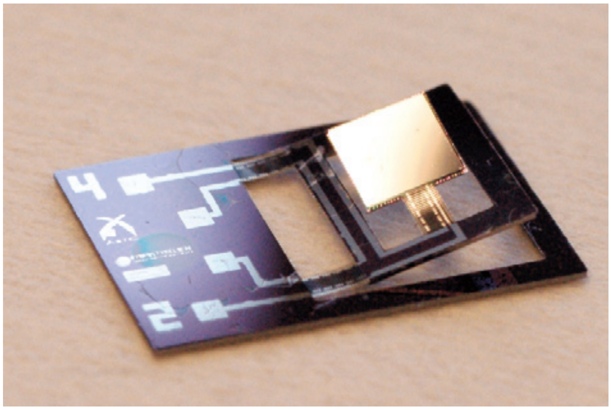

Figure 18. The physical device modeled. The mirror is covered in reflective aluminium, which also is used for the integrated heaters. The size of the mirror is 3.5×3.5 mm.

Discussion and Conclusions

In this work, components for miniaturized attitude, propulsion and communication subsystems have been developed. Different kinds of microthrusters have been developed, where the shape of the nozzle (**Paper II**), the material of the whole device (**Paper III**), or selected parts of the component (**Paper IV**) may enable increased system efficiencies.

In **Paper II**, the full three-dimensional geometry of the thruster with close to rotationally-symmetric shape should, according to theory, make the component suffer less from viscous losses, and hence make it more propellant effective. Furthermore, it was also found that the more easily-fabricated, DRIE-etched thrusters may suffer from diverging thrust vectors.

The thruster in **Paper III** is capable of being operated at significantly higher temperatures than a silicon-based thruster. By raising the temperature of the propellant, the propellant efficiency is increased. A high-temperature capable thruster is also beneficial when utilizing chemical reaction thrusters, which are both more propellant effective, and may store propellant as liquids for a more compact system.

The thruster in **Paper IV**, which also may use propellant stored in liquid form, does not improve the propellant efficiency over similar thrusters, but may increase the thruster efficiency by reducing the power consumption compared with similar thrusters presented.

Paper V and **VI** describe the development of flow sensors designed for being integratable with silicon-based microfluidic components such as in **Paper I, II, and IV**. In **Paper III**, a working flow sensor is integrated on the thruster chip. With increased integration, the system efficiency may be increased, and the reduced system volume is of great importance on nano- and picospacecraft, which then might be able to carry more payload, for instance.

With a more advanced payload and an increase in data rate requirements, an optical inter-spacecraft communication system might be needed. **Paper VIII** demonstrated a beam steering device capable of optical scan angles of more than 40º, but with severe thermal cross talk. In **Paper IX**, it was shown that design and process changes could improve the performance. In addition, a feedback controlled system free and accurate beam steering was devised.

The velocity sensor in **Paper VII** proved to be a well performing and power efficient device, which could be an effective approach to miniaturized submersible attitude systems where it could help to improve the total system both for navigation and scientific purposes.

Apart from the components, schlieren imaging, **Paper I-III**, has also proven to be an efficient evaluation and quality control tool.

Throughout the thesis, advanced silicon processing to form, for instance, thick silicon dioxide and three-dimensional shapes using silicon trench oxidation and semi-isotropic etching utilizing microloading and RIE lag, has been used in new research areas. Other processes, such as patterning transparent membranes and protecting bond surfaces with aluminium (**Paper V**) have, to the author's knowledge, not been reported elsewhere.

Outlook

These days are exciting days for the space and MEMS community. With the constant maturation of MEMS, we are approaching the days of effective and capable nano- and picospacecraft. With increased performance of attitude control and propulsion systems, the usability of these spacecraft might really match larger spacecraft. Small picospacecraft may, for instance, be used as rapidly deployable surveillance spacecraft during catastrophes, or be used in high-risk missions where loss of a small, relatively inexpensive spacecraft might be acceptable. In such cases, more than one spacecraft might also be used to increase redundancy. Furthermore, fleets of formation flying spacecraft could increase scientific or commercial gain in missions.

There are many propulsion systems under development, and some available, both relatively simple and more advanced ones. Hopefully, these systems will be given plenty of flight opportunities and serve well.

The components developed in this thesis are not yet ready to be launched into space, or submerged under water, on real missions. I believe, though, that given time, some might be part of future exploration of space, or used for terrestrial applications. With some further development and thrust measurements that could confirm the performance, the thruster in **Paper II** could possibly replace current DRIE-etched thrusters. For more compact systems with liquid propellant storage, both the ceramic thruster in **Paper III**, and the FMMR in **Paper IV** are exciting solutions that both here have suggestions of process compatible integrated flow sensors.

As it is now, they are merely small steps in the development of integrated high-performance microsystems. But sometimes, even a small step is a giant leap.

Svensk sammanfattning

Få ting skapade av människan, om ens något, är lika tekniskt komplext som en modern satellit. Och inget är nog lika utlämnat och hjälplöst när det väl tagits i drift. Satelliter är inte bara obemannade utan i praktiken onåbara när det gått så långt. Man tar emot data och lägesrapporter från dem och skickar tillbaka styrkommandon, men man tar aldrig in en uppskjuten satellit i depå för reparation, service eller tankning. Kommer en aldrig så liten satellit närmare en annan än flera kilometer, ljuder troligen varningsklockorna och undanmanövrar förbereds om det är möjligt. För trots att det finns tusentals mer eller mindre tjänliga satelliter i omloppsbana kring jorden och man därför kan frestas att tro att det är enkelt att skicka upp ytterligare en, är nämligen verksamheten normalt oerhört kostsam och en krockad eller på annat sätt förlorad satellit något ytterst beklämmande. Tekniken är alltså på alla vis fantastiskt utmanande, men tillåter inga brister. Den måste fungera när den tagits i bruk, helt enkelt.

Samtidigt är satelliternas användningsområden många och viktiga för oss. Man behöver inte vara forskare med variationer i solvinden som största intresse, inte heller militär med uppdrag att bevaka trupptransporter eller militära förläggningar, eller statistiker som vill veta hur skogs- och jordbruksarealer minskar eller ökar i storlek. Det räcker med att man vill veta hur morgondagens väder ska bli, att man tittar på TV, eller låter bilresan underlättas av GPS-navigatorn. Det kan till och med räcka att man talar i telefon för att man ska vara satellitanvändare. Och det finns inget som tyder på annat än att användningen ökar, och gör så snabbt.

Världen vill inte bara ha fler satelliter, man vill ha dem billigare och snabbare, och man är inte beredd att göra avkall på funktionalitet och driftsäkerhet. Så långt är instruktionerna till satellitingenjörerna klara: Tekniken ska vara både bättre och billigare. Samtidigt kraxar de erfarna att man ju inte kan skicka upp ny teknik i rymden innan den har varit där och bevisat sin duglighet. Detta är branschens stora Moment 22.

Sedan ett drygt decennium eller så, finns emellertid stora förespråkare för användningen av en smått revolutionerande teknik som kan uppfylla de satellitberoendes krav och samtidigt kanske nästan smygas in i den konservativa rymdbranschen i form av intressanta men inledningsvis oförargliga påhäng: Mikrosystemtekniken. *Mikrosystemteknik*, eller *mikroteknik* eller rent av det, från engelskan, direktöversatta: *mikroelektromekaniska system*, handlar nämligen om kraftigt miniatyriserad, mångsidig och potentiellt billig teknik – åtminstone om den får avsättning stor nog för att motivera lite storskaligare tillverkning.

Tekniken har sitt ursprung i den mikroelektronik eller halvledarteknik som bland annat gjort att räknemaskiner, som för 50 år sedan fyllde stora salar, i dag ryms – med mångfaldigad prestanda – i ett armbandsur. Men där mikroelektroniken är specialiserad och faktiskt endast flyttar elektriska laddningar, spänner mikrosystemtekniken över fysikens alla domäner. Till exempel kan mekaniskt arbete uträttas, flöden av gas och vätskor strypas och snabbas på, ljus- och ljudvågor fokuseras och riktas om, och magnetiska och termiska effekter genereras och detekteras. Och allt detta görs, på gott och ont, i system som typiskt är mindre än en sockerbit och som har detaljer som lättast mäts i enheten mikrometer, det vill säga en miljondels meter. Liksom halvledartekniken, fast inte i riktigt samma omfattning, har mikrosystemtekniken sedan länge infiltrerat till och med vår vardag. Redan i en modern bil finns flera tiotals så kallade mikrosensorer, som ska ge oss besked om allt från motorns förbränning och bränslets åtgång till däcktryck och kupétemperatur. (Att hitta exempel på teknikområdets andra stora komponentklass, mikroaktuatorerna, som är ställdon, eller ”muskler” och motorer, om man så vill, på samma skala, är än så länge lite svårare. Det ligger i teknikens natur att det är lättare för något litet att påverkas av något stort, än vice versa.)

Nämnda förespråkare menar nu i korthet att den här tekniken skulle kunna användas för att krympa satelliter och annan sammansatt rymdteknik avsevärt, men utan att väsentligt förlora funktionalitet eller prestanda. I vissa avseenden, till exempel när det handlar om ett instruments upplösning, känslighet och snabbhet, skulle man till och med kunna få bättre presterande teknik. Dessutom blir miniatyriserad teknik energisnålare, för att nämna ytterligare en fördel. Tyngst vägande är ändå den mindre massan. Där ser man omedelbart möjligheten att spara pengar och tid i uppskjutningen, där varje kilo kostar ca 100 000 kr att få i omloppsbana för konventionella satelliter, medan en riktigt liten farkost kanske till och med kan få åka snålskjuts på en större eftersom den kan vara i det närmaste försvinnande liten i jämförelse.

Här bör ett möjligt missförstånd redas ut: En satellit är långt från så liten som den allra första: Sputnik 1 från 1957. I själva verket är, till exempel, en modern kommunikationssatellit en pjäs stor som en mindre buss, medan branschens småttingar, som utan att ha något med mikro- eller nanoteknik att göra, sorteras i klasserna *mikro*, *nano* och *piko* med sina respektive viktklasser på 10-100, 1-10 och 0-1 kg. Dessvärre är de riktigt små satelliterna än så länge inte bara lätta till kroppen utan också till förmågan. De allra minsta klarar bara precis av att försörja sig med solenergi och att driva en liten pingande radiosändare, som blott meddelar att satelliten lever medan den obevekligen dalar i sin bana tills den brinner upp i atmosfären. Ytterst sällan härbärgerar de någon nyttolast – det vill säga det som normalt är huvudsyftet med varje rymdfarkost. Istället arbetar de vanligtvis i marknadsföringens eller pedagogikens tjänst.

Syftet med den här doktorsavhandlingen handlar inte om att miniatyrisera vetenskapliga instrument, som skulle kunna utgöra nyttolasten på små satelliter, även om flera av resultaten och slutsatserna är tillräckligt generella för att tillämpas även där. Den ägnas istället åt minatyriseringsfrågor som rör de kanske svåraste delsystemen att krympa på en rymdfarkost, det för *kommunikation* och det för *attitydkontroll & framdrivning*. Båda innehåller komponenter som väger mycket, och båda är energislukande. Annars är det svårt att hitta gemensamma drag som inte dessutom delas av flera andra delsystem.

Kommunikationen handlar om att skicka eller ta emot information, antingen mellan två farkoster eller mellan en farkost och en rymd- eller jordbaserad station. Attitydkontroll & framdrivning handlar dels om att kunna rikta farkosten (justera dess attityd) mot intressanta platser på jorden eller i rymden, eller mot en annan farkost, dels om att, till exempel, skjuta på den fortfarande oundvikliga kremeringen i jordens atmosfär genom att korrigera satellitens banhöjd.

Det finns flera sätt att tillgodose båda funktionerna på även om kommunikationen är den minst artrika. Nästan alltid baseras den på radiovågor. I sig behöver inte den formen vara mycket otympligare än andra, men ofta är den mindre urskillningslös och strålar sitt budskap även för döva öron, så att säga, vilket gör den mindre resurssnål och i behov av tunga kraftaggregat. Dessutom kan radiokommunikation i vissa fall vara otillräckligt snabb. Till exempel finns det långt gångna planer på att låta formationsflygande nanosatelliter samverka för att göra mätningar som kräver utbyta av stora mängder data på kort tid. För det ändamålet är så kallad optisk trådlös kommunikation ett intressant alternativ. Man kan likna det vid övergången från Internet genom kopparledning till Internet genom optisk fiber, fast i det här fallet avstår man fibern eftersom sikten är både klar och rak i rymden och lyser istället fritt med sin laser. För att det ska fungera måste man klara av att hålla ihop strålen – forma den – men gärna också kunna rikta den för att hitta, eller till och med följa, mottagaren. Båda kräver noggrannhet eftersom avstånden mäts i mil och minsta vinkelavvikelse ger stora fel i slutänden. I avhandlingen föreslås, tillverkas och undersöks för det första en så kallad Fresnel-lins liten nog att kunna rymmas på tvärsnittet av ett tjockt hårstrå, men sedan, och framförallt, en spegel som kan vinklas i olika riktningar eftersom den hängts upp i tunna ramar och leder. Nästan allt är gjort av kisel, som för övrigt är det vanligaste materialet för mikroelektronik, men delar av lederna består av plast. Genom att värma upp plasten, som expanderar mer med temperaturen än kislet, med elektriska värmare av mikroskopiska mått, får man lederna att böja sig på ett mjukt och välkontrollerat sätt. När det sker, vinklas spegeln och därmed ljusstrålen, som kommer från en fluglortsstor ljuskälla och passerar linsen, om. Två uppsatser i avhandlingen handlar om hur detta kommunikationssystem, som är åtminstone mindre än tusendelen så tungt som motsvarigheten på jorden, ska utformas och tillverkas, och hur det uppför sig. Av särskild betydelse för det senare, är värmefördelningen i spegelupphängningen och hur den så kallade termiska överhörningen, det vill säga läckaget av värme från en led till en annan, påverkar styrning och prestanda.

Beträffande attitydkontroll och framdrivning, finns en desto rikare flora av tekniker. Många av dessa så kallade rakettekniker låter sig dessutom miniatyriseras åtminstone till någon grad. Eftersom även stora farkoster kan ha behov av svaga, men inte nödvändigtvis riktigt små, raketmotorer för att kunna finjustera sin attityd eller göra mindre manövrar, och dessa sägs stå för mikroframdrivning (eng. micropropulsion) råder viss begreppsförvirring, men också ett överlapp. Ty medan stora motorer, hur svaga de än är, inte kan tjänstgöra på små farkoster, kan små motorer står för finmotoriken på stora farkoster. Två raketprinciper har undersökts i avhandlingsarbetet. Den ena, som berörs av fem delarbeten, förkroppsligas i så kallade kallgasraketer. I dessa har man bränsle i form av en komprimerad gas som man puffar ut lite i taget av genom ett litet munstycke. I grundutförandet motsvarar den tillgängliga mängden raketenergi av graden av kompression i bränsletanken, något som alltså bestäms redan på marken och före uppskjutningen. (Det är en sorts elastisk energi som i lagring och frisättning kan liknas vid det som händer i ett gummisnoddsdrivet modellplan, även om den inte portioneras i det fallet.) Med insikten att bränslets och bränsletankens massa lätt blir en betydande del av en liten rymdfarkosts hela massa, värmer man, i en vidareutveckling, gasen precis innan den släpps ut genom raketmunstycket, den så kallade dysan. Eftersom värmningen gör att energin hos gasen ökar, krävs en mindre mängd gas för en bestämd manöver, och eftersom värmningen kan göras med elektricitet från de solceller som så gott som alla satelliter har, kan bränsle- och alltså massbesparingar göras. Drivs bara motorn tillräckligt sällan, kan man även utan extra solcellsbestyckning komma långt med den outsinliga solenergin så länge man inte går för långt ut i solsystemet. Problemet blir snarare hur man kan tillföra så mycket värme som möjligt till sin gas.

I avhandlingens ”varma kallgasraketer”, som alla har gaskanaler och dysor smalare än hårstrån, och förträngningar som mäts i enstaka miljondels meter, har flera saker studerats. Bland annat har bränsleåtgången relaterats till graden av värmning. En särskild teknik för avbildning av den annars osynliga plymen har utvecklats och det har, till exempel, kunnat visas att hastigheten hos gasen verkligen ökar med temperaturen och hur den gör det på den här skalan. Ett i sammanhanget nytt material, nämligen keramen zirkoniumoxid, som klarar långt högre temperaturer än kisel, som har använts för arbetets andra raketer, har prövats med lovande resultat. Och just kislet, som med de vanliga och ibland lite kompromisslösa mikrotillverkningsteknikerna, som ofta baseras på närmast fotografiska metoder och etsning, lättast låter sig formas till dysor med rektangulära tvärsnitt, har här kuvats till att medge rotationssymmetriska munstycken som ger ett bättre definierat raketutblås och troligen också ökad bränsleeffektivitet, enligt det delarbetets rön.

Bränsleåtgången, som således är av stor betydelse, övervakas med en särskild flödesmätare som är tillräckligt liten för att kunna integreras, det vill säga införlivas sömlöst, i de små raketmotorerna. Två uppsatser rör hur dessa flödessensorer fungerar och kan förbättras. Eftersom just den princip som undersökts här, baseras på att mängden värme som förs mellan två punkter i kontakt med den förbiströmmande gasen beror av hur starkt flödet är, kommer insikterna om hur värme breder ut sig och kan kontrolleras i mikroskala till användning även i dessa fall. Som i några andra delarbeten, har datorbaserade simuleringsverktyg varit värdefulla komplement till det som mödosamts tillverkats och karaktäriserats fysiskt.

En spännande avknoppning på arbetena med flödesgivare, blev arbetet med att använda samma princip fast för att bestämma både styrka och riktning hos ett vätskeflöde över en yta i syfte att kunna registrera hur en undervattensfarkost, ungefär lika stor som två läskburkar, rör sig i vätska. Även här handlar det om en påfrestande miljö som ställer höga krav på komponenten. Emellertid blev det här det enda delarbetet i vilket effekten av biologisk påväxt behövde undersökas.

Slutligen studerades ännu en raketprincip i avhandlingen. Den utnyttjar en företeelse som knappast har någon makroskopisk motsvarighet, men som kan fylla en viktig funktion i raketbranschen: riktigt, riktigt svag dragkraft för finjustering av små, små satelliter. Precis som i kallgasraketerna, används här en gas, men trycket är så lågt att det inte går att tala om regelrätta flöden. Det är faktiskt så lågt och raketen så liten att gasmolekylerna, som normalt kolliderar med varandra så oerhört mycket oftare än de kolliderar med väggarna till det kärl de vistas i och därmed skapar intern oreda i leden, här kan få energi från kollisionen med utvalda och uppvärmda väggpartier och sedan ta sig ut i rymdens omgivande tomhet utan att på vägen dit dela med sig till andra gasmolekyler. På så sätt fås en ytterst svag men likväl ganska effektiv rekyl i farkosten, åtminstone om man kan se till att värma raketen, och därmed gasen, med måtta och utan att elda för mycket för kråkorna. Naturligtvis har även den här delen av forskningen haft god nytta av insikten i hur värme kan styras i mikroskala. Särskilt viktigt har det varit att skapa en robust, det vill säga tjockväggig, struktur som ändå minimerar värmeförlusterna. För detta användes en särskild teknik som rostar kisel, som är en mycket god värmeledare, till den goda värmeisolatorn kiseldioxid, men skenbart i en omfattning som inte borde vara möjlig.

Sammanfattningsvis, har forskargärningen handlat om att förstå hur värme kan dirigeras på en storleksskala där man normalt kanske knappt förväntar sig annat än en och samma temperatur. Denna förståelse har utnyttjats för att realisera komponenter av betydelse för framdrivning, attitydkontroll och kommunikation av och med rymdfarkoster alldeles för små för att kunna utnyttja konventionella tekniker.

Acknowledgements

Ett enormt stort tack till Greger, Henrik och Hugo för att ni valde att satsa på mig och för allt det ni gjort för att det här arbetet skulle kunna bli av.

Tack till Anders för alla år vi spenderat på det här bygget (och på andra), för allt du bidragit med till mitt arbete här.

Tack till Johan för all hjälp, som ofta har behövts på allt för kort sikt, och svar på alla halvkorkade frågor.

Tack till Ville som från dagarna som paraffinpumpslaborant har gått via exjobbare till väldigt uppskattad kollega.

Tack till Martin, Jonas och Sara för roliga samarbeten i korta och evighetslånga projekt.

Tack till Ernesto och Ulrika som med entusiasm och hårt arbete bidragit till mina projekt.

Tack till alla er ovanstående för allt roligt vi haft under mina år här och rådjur, joppar, bookbusters, kick-offer, resor och allt annat jag minns med glädje.

Tack till er på MSL som ställt upp och hjälpt till alla de gånger det behövts i renummet (det har varit några gånger). Tack också till Örjan som tagit sig mycket tid att hjälpa till med renrumsrelaterade saker.

Tack till alla på NanoSpace som ställt upp med hjälp både i och utanför renrummet och lånat ut välbehövlig utrustning.

Tack till alla MSTare, speciellt Sam, Lena och Sven och hjälpt till med mycket genom åren.

Tack till alla tribologer och MIMare som varit en stor del av att jag alltid trivts på jobbet.

Tack också till inom administrationen.

Ett jättetack till min familj och mina vänner för allt ni gjort för mig och för all förståelse för att vi ses allt för sällan och för att jag aldrig orkar prata om vad jag jobbar med. Hoppas ni vet nu.

Största tack av alla till Suvi (och Simba) som stöttat mig och som alltid får mig på bättre humör när det behövs som mest.

Tack också till alla andra.

References

[1] F. Corporation, "Space Transportation Costs: Trends in Price Per Pound to Orbit," 2002.

[2] M. J. Madou, *Fundametnals of Microfabrication*, 2 ed. USA: CRC Press LLC, 2002.

[3] W. S. Trimmer, *Micromechanics and MEMS: Classic and Seminal papers to 1990*. USA: IEEE, 1997.

[4] J. Jonsson, "Microsystems Technology for Underwater Vehicle Applications," in *Uppsala University, Ångström Space Technology Centre (ÅSTC)*. vol. PhD Uppsala: Uppsala University, 2012, p. 88.

[5] T.-R. Hsu, *MEMS and microsystems: design, manufacture and nanoscale engineering*, 2 ed. USA: wiley, 2008.

[6] S. Franssila, *Introduction to Microfabrication*, 1 ed. Chippenham, Wiltshire, UK: Wiley, 2004.

[7] M. M. Micci and A. D. Ketsdever, *Micropropulsion for Small Spacecraft* vol. 187. Reston, VA, United States of America: American Institute of Aeronautics and Astronautics, 2000.

[8] J. K. Ziemer and S. M. Merkowitz, "Microthrust propulsion of the LISA mission," in *40th AIAA Joint Propulsion Conference* Fort Lauderdale, Florida: Pasadena, CA : Jet Propulsion Laboratory, National Aeronautics and Space Administration, 2004, 2004.

[9] J. Köhler, J. Bejhed, H. Kratz, F. Bruhn, U. Lindberg, K. Hjort, and L. Stenmark, "A hybrid cold gas microthruster system for spacecraft," *Sensors and Actuators A: Physical,* vol. 97-98, pp. 587-598, 2002.

[10] M. Louwerse, H. Jansen, and M. Elwenspoek, "A modular assembly method of a feed and thruster system for Cubesats," *Journal of Micromechanics and Microengineering,* vol. 20, p. 115011, 2010.

[11] P. Rangsten, J. Bejhed, H. Johansson, M. Bendixen, K. Jonsson, and T.-A. Grönland, "Advanced MEMS components in closed-loop micro propulsion applications," in *26th Annual AIAA/USU Conference on Small Satellites*, Logan, UT, USA, 2012, pp. Advanced Technologies II, SSC12-X-2.

[12] P. Rangsten, M. Bendixen, J. Bejhed, H. Johansson, K. Jonsson, and T.-A. Grönland, "Six-Wafer-Stack MEMS Thrusters in Space," in *The 10th International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications*, Leuven, Belgium, 2010.

[13] W. J. Larson and J. R. Wertz, *Space Mission Analysis and Design*, 3 ed. United States of America: Kluwer Academic Publishers, Microcosm Press, 1999.

[14] R. L. Bayt and K. S. Breuer, "Analysis and testing of a silicon intrinsic-point heater in a micropropulsion application," *Sensors and Actuators A: Physical,* vol. 91, pp. 249-255, 2001.
[15] L. Giulio, B. Marco, F. Aldo, T. P. Domenico, and M. Mario, "Microthrusters in silicon for aerospace application," *Aerospace and Electronic Systems Magazine, IEEE,* vol. 17, pp. 22-27, 2002.
[16] R. Hebden, R. Bielby, A. Baker, S. Mistry, J. Köhler, L. Stenmark, B. Sanders, J.-L. Moerel, W. Halswijk, C. Rops, F. Breussin, and M. Lang, "The development and test of a hydrogen peroxide monopropellant micro-rocket engine using MEMS technology," in *ESA 5th Roundtable discussion on Micro/Nano Technologies for Space* Noordwijk, The Netherlands, 2005.
[17] D. L. Hitt, C. M. Zakrzwski, and M. A. Thomas, "MEMS-based satellite micropropulsion via catalyzed hydrogen peroxide decomposition," *Smart Materials and Structures,* vol. 10, pp. 1163-75, 2001.
[18] A. D. Ketsdever, R. H. Lee, and T. C. Lilly, "Performance testing of a microfabricated propulsion system for nanosatellite applications," *Journal of Micromechanics and Microengineering,* vol. 15, pp. 2254-2263, 2005.
[19] R. Krpoun, M. Rdber, and H. R. Shea, "Microfabrication and test of an integrated colloid thruster," in *Micro Electro Mechanical Systems, 2008. MEMS 2008. IEEE 21st International Conference on*, 2008, pp. 964-967.
[20] R. Krpoun and H. R. Shea, "Integrated out-of-plane nanoelectrospray thruster arrays for spacecraft propulsion," *Journal of Micromechanics and Microengineering,* vol. 19, p. 045019, 2009.
[21] R. H. Lee, A. M. Bauer, K. M. D., T. C. Lilly, J. A. Duncan, and A. D. Ketsdever, "Performance Characterization of the Free Molecule Micro-Resistojet Utilizing Water Propellant," in *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Cincinnati, OH, USA, 2007.
[22] D. H. Lewis, S. W. Janson, R. B. Cohen, and E. K. Antonsson, "Digital micropropulsion," *Sensors and Actuators A: Physical,* vol. 80, pp. 143-154, 2000.
[23] A. P. London, A. A. Ayón, A. H. Epstein, S. M. Spearing, T. Harrison, Y. Peles, and J. L. Kerrebrock, "Microfabrication of a high pressure bipropellant rocket engine," *Sensors and Actuators A: Physical,* vol. 92, pp. 351-357, 2001.
[24] M. Mihailovic, T. V. Mathew, J. F. Creemer, B. T. C. Zandbergen, and P. M. Sarro, "MEMS silicon-based resistojet micro-thruster for attitude control of nano-satellites," in *Solid-State Sensors, Actuators and Microsystems Conference (TRANSDUCERS), 2011 16th International*, pp. 262-265.
[25] C. Rossi, D. Briand, M. Dumonteuil, T. Camps, P. Q. Pham, and N. F. d. Rooij, "Matrix of 10 × 10 addressed solid propellant microthrusters: Review of the technologies," *Sensors and Actuators A: Physical,* vol. 126, pp. 241-252, 2006.
[26] J. A. Morinigo and J. Hermida-Quesada, "Solid-gas surface effect on the performance of a MEMS-class nozzle for micropropulsion," *Sensors and Actuators A: Physical,* vol. 162, pp. 61-71, 2010.
[27] G. S. Settles, *Schlieren and Shadowgraph Techniques*, 1st, 2nd printing ed. Germany: Springer, 2001.

[28] D. Munday, E. Gutmark, J. Liu, and K. Kailasanath, "Flow structure and acoustics of supersonic jets from conical convergent-divergent nozzles," *Physics of Fluids,* vol. 23, pp. 116102-13, 2011.

[29] G. P. Sutton and O. Biblarz, *Rocket propulsion elements*, 7 ed. New York, NY, USA: Wiley, 2001.

[30] K. Gantz, L. Renaghan, and M. Agah, "Development of a comprehensive model for RIE-lag-based three-dimensional microchannel fabrication," *Journal of Micromechanics and Microengineering,* vol. 18, p. 025003, 2008.

[31] P. Zellner, L. Renaghan, Z. Hasnain, and M. Agah, "A fabrication technology for three-dimensional micro total analysis systems," *Journal of Micromechanics and Microengineering,* vol. 20, p. 045013, 2010.

[32] K. H. Cheah, P. S. Khiew, and J. K. Chin, "Fabrication of a zirconia MEMS-based microthruster by gel casting on PDMS soft molds," *Journal of Micromechanics and Microengineering,* vol. 22, p. 095013, 2012.

[33] W. Ming-Hsun and L. Po-Shen, "Design, fabrication and characterization of a low-temperature co-fired ceramic gaseous bi-propellant microthruster," *Journal of Micromechanics and Microengineering,* vol. 20, p. 085026, 2010.

[34] A. P. London, A. H. Epstein, and J. L. Kerrebrock, "High-pressure bipropellant microrocket engine," *Journal of Propulsion and Power,* vol. 17, pp. 780-787, 2001.

[35] K. Palmer, H. Kratz, H. Nguyen, and G. Thornell, "Infrared imaging of an integratable, robust thermal flow sensor with a thick silicon dioxide membrane and through-going silicon heat conductors," in *Thermal Investigations of ICs and Systems (THERMINIC), 2011 17th International Workshop on*, 2011, pp. 1-4.

[36] N. T. Nguyen, "Micromachined flow sensors--a review," *Flow Measurement and Instrumentation,* vol. 8, pp. 7-16, 1997.

[37] B. W. v. Oudheusden, "Silicon flow sensors," *IEE Proceedings,* vol. 135, p. Pt. D, 1988.

[38] Y.-H. Wang, C.-P. Chen, C.-M. Chang, C.-P. Lin, C.-H. Lin, L.-M. Fu, and C.-Y. Lee, "MEMS-based gas flow sensors," *Microfluidics and Nanofluidics,* vol. 6, pp. 333-346, 2009.

[39] J. Jonsson, J. Sundqvist, H. Nguyen, H. Kratz, M. Berglund, S. Ogden, K. Palmer, K. Smedfors, S. Wagner, and G. Thornell, "Miniaturized submersible for exploration of small aqueous environments," in *IEEE Oceans' 11* Waikoloa, HI, USA, 2011.

[40] J. Jonsson, J. Sundqvist, H. Nguyen, M. Berglund, S. Ogden, K. Palmer, K. Smedfors, Johansson, K. Hjort, and G. Thornell, "Instrumentation and vehicle platform of a miniaturized submersible for exploration of terrestrial and extraterrestrial aqueous environments," *Acta Astronautica,* vol. 79, pp. 203-211, 2012.

[41] T. Ebefors, E. Kälvesten, and G. Stemme, "Dynamic actuation of polyimide V-groove joints by electrical heating," *Sensors and Actuators A: Physical,* vol. 67, pp. 199-204, 1998.

Acta Universitatis Upsaliensis

Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1003

Editor: The Dean of the Faculty of Science and Technology

A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology.

ACTA
UNIVERSITATIS
UPSALIENSIS
UPPSALA
2013

Distribution: publications.uu.se
urn:nbn:se:uu:diva-186862