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# Sense, Actuate and Survive

*Ceramic Microsystems for High-Temperature  
Aerospace Applications*

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### **Abstract**

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In aerospace applications, but also in manufacturing, mining, energy industry and natural hazards, high temperature, corrosion, erosion and radiation, challenge the performance and being of hardware.

In this work, high-temperature co-fired ceramic (HTCC) alumina and platinum have been used for a range of devices intended for aerospace applications at up to 1000°C.

The thermomechanics of a pressure sensor was investigated, and the interfacing was attained by wireless powering and reading. However, read range was limited and sensitivity decreased with temperature. Silver, electroplated after sintering, was found to remedy this until it eventually alloyed with platinum.

Copper was electroplated and oxidized for oxygen storage in a microcombustor, intended for sample preparation for optogalvanic spectroscopy (OGS) to indicate extraterrestrial life. Despite delamination, caused by residual stresses, the device operated successfully.

Conversely, pre-firing metallization by integration of platinum wires was studied. Freely suspended, and despite heat-induced shape irregularities, these were found advantageous over screen printed elements for gas heating, and temperature and pressure sensing. By fusing off the wires, spherical tips, allowing for impedance monitoring of microplasma sources in, e.g., OGS, were formed.

Microplasma sources can also be used for gas heating. This, together with screen printed and suspended resistive heaters, was evaluated in a microthruster, showing that plasma heating is the most effective, implying fuel consumption reduction in satellite propulsion.

In conclusion, HTCC alumina microdevices are thermally stable and could benefit several aerospace applications, especially with the complementary metallization schemes devised here.

Future developments are expected to include both processing and design, all with the intention of sensing, actuating and surviving in high-temperature environments.

*Keywords:* High temperature, ceramics, microsystems, aerospace, sensors, thrusters

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*To my family. Always loved, never forgotten.*



# List of Papers

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

- I     *Thermomechanical Properties and Performance of Ceramic Resonators for Wireless Reading at High Temperatures*  
**Sturesson, P.**, Khaji, Z., Knaust, S., Klintberg, L., and Thornell, G.  
Journal of Micromechanics and Microengineering, 25(9):5016 (2015)
- II    *Ceramic Pressure Sensor for High Temperatures. Investigation of the Effect of Metallization on Read Range*  
**Sturesson, P.**, Khaji, Z., Klintberg, L., and Thornell, G.  
IEEE Sensors Journal, 17(8):2411-2421 (2017)
- III   *Manufacturing and Characterization of a Ceramic Microcombustor with Integrated Oxygen Storage and Release Element*  
Khaji, Z., **Sturesson, P.**, Klintberg, L., and Thornell, G.  
Journal of Micromechanics and Microengineering, 25(10):4006 (2015)
- IV   *Pirani Microgauge Fabricated of High-Temperature Co-fired Ceramics with Integrated Platinum Wires*  
**Sturesson, P.**, Klintberg, L., and Thornell, G.  
Sensors and Actuators A: Physical, Submitted
- V    *Manufacturing Miniature Langmuir Probes by Fusing Bond Wires*  
Berglund, M., **Sturesson, P.**, Thornell, G., and Persson, A.  
Journal of Micromechanics and Microengineering, 25(10):5012 (2015)
- VI   *Effect of Resistive and Plasma Heating on the Specific Impulse of a Ceramic Cold-Gas Thruster*  
**Sturesson, P.**, Seton, R., Klintberg, L., Thornell, G., and Persson, A.  
IEEE Journal of Microelectromechanical Systems, Submitted

In addition, the following paper is included to give a detailed analysis of the applicability of HTCC pressure sensors in military jet engines.

- A     *On the Applicability and Utility of Microsystems in Military Jet Engines.*  
         **Sturesson, P.**, and Bull, P.  
         In Manuscript

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## Author's contribution to the publications

- I       Minor part of concept, major part of planning, most of experimentals and analysis.
- II      Major part of concept, most of planning and experimentals, and major part of analysis.
- III     Minor part of concept, major part of planning, experimentals and analysis.
- IV     Major part of concept, most of planning, all experimentals and most of analysis.
- V       Minor part of concept, planning, experimentals and analysis.
- VI     Major part of concept, most of planning, and major part of experimentals and analysis.

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# Abbreviations

MST	Microsystems Technology
ÅSTC	Ångström Space Technology Centre
SEDU	Swedish Defence University
NASA	National Aeronautics and Space Administration
JPL	Jet Propulsion Laboratory
GPS	Global Positioning System
CTE	Coefficient of Thermal Expansion
SiC	Silicon Carbide
GaN	Gallium Nitride
LTCC	Low-Temperature Co-fired Ceramics
HTCC	High-Temperature Co-fired Ceramics
PCB	Printed Circuit Board
OGS	Optogalvanic Spectroscopy
OGE	Optogalvanic Effect
MSSS	Malin Space Science Systems
LoC	Lab on a Chip
CR	Constant Resistance



# Introduction

Throughout history, there has always been those among mankind that have admired and strived to reach higher altitudes. In Greek mythology, Daedalus, being a tremendous engineer and a formidable athlete, managed to design and fabricate wings from wax and feathers for himself and his son, Icarus, to escape from the island of Crete. Impressively, both could actuate their wings enough to fly. Unfortunately, Icarus was unequipped with a good understanding of harsh environments. Thus, he flew too high and the wax failed to sustain the heat from the sun.

In a more modern historical and also military context, taking advantage of high ground has been a key tactical element for the commander in planning a battle on the ground [1] and mastering the airspace is the pinnacle of this idea. Even if much of the framework that dominates current military theory discourse was written before aircraft were available, airspace dominance is paramount for conventional warfare [2].

Air and space vehicles are still vital parts of strategic military assets but their development is more and more governed by requirements from civil society. The aircraft is the main vehicle for transporting people around the globe, but due to the expulsion of greenhouse gases, there is a need for energy consumption reductions. Beyond that, substituting jet fuel will require changes in both aerodynamics and propulsion technology [3]. For military aircraft, there is a constant requirement to develop more fuel-efficient engines in order to increase the endurance in air and the operational range, but also to reduce maintenance [4]. This requires accurate engine control and system health monitoring [5]-[6]. Moreover, as a protection measure radar and thermal signatures are constantly reduced, which implies suitable construction materials and a general size reduction.

Leaving the atmosphere of Earth to explore others planets, the required vehicles are quite different. These rather large spacecraft are packed with instruments, all with designated tasks [7]. Once landed, exploring another planet demands the capability to sustain and remotely sense this new environment and to collect, prepare and analyse sample material [8]. In 2012, the remotely operated vehicle Curiosity landed on Mars and has since collected large amounts of sample from the surface layers of the planet. Recently, organic material were again discovered, [9], and sparked the ever-lasting question: is there life on Mars?

Returning to Earth, but still remaining in orbit around it, satellite activities are intense. Military satellites commonly operate at about 500-700 km altitude in polar orbits, as this allows global coverage over time. Farther out, communications satellites are positioned in geostationary orbit at about 35 580 km altitude in the equatorial plane. Traditionally, military satellites are large in order to carry sensors and communication apertures that fulfil operational requirements. This requires large launch rockets for the satellites to access space and the required fuel amount is a significant cost driver. With a typical launcher-to-satellite ratio of 99:1, a small change in satellite mass will result in a highly reduced need for propellant and, hence reduce the cost [10].

Microsystems technology (MST) entails the research, development and fabrication of sensors and actuators with designed features between one micrometre and one millimetre [11]. Such devices can be fitted into other, larger systems without compromising their functionality, or enable miniaturization of complete systems, such as cell phones. Having its origins from semiconductor and microelectronics technology, MST has for a long time benefitted from the advantages of silicon as a nearly defect-free substrate material and silicon processing technology with its well-developed methods.

Cube satellites are attempts to establish a small-satellite community [12]. They are designed and manufactured from standardised 10 x 10 x 10 cm cubic units and quad satellites are comprised of 25 x 25 x 5 cm quadratic units [13]. This size constraints dictate subsystem development and enables universities and industry to develop and batch-produce satellites on standardized platforms. This increases the affordability for end users and today many countries, institutions and companies can afford their own satellite. As with aircraft and outer space vehicles, cube satellites are, in spite of their size, rarely built from or includes MST devices.

Combustion environments, other planets and space in general force technological systems into operating in harsh and challenging environments with, e.g., high temperatures, erosion, corrosion and radiation. Microsystems working under these conditions must survive and sustain their functionality. However, high temperatures challenges silicon as structure material as it becomes conductive and softens when heated above 400 °C [14]. Therefore, alternatives must be considered.

This thesis presents studies on microsystems with sensing and actuating functionality and, to some extent, survivability under extraordinary conditions. By, contrary to Daidalos, choosing materials with mechanically, electrically and chemically stable properties, microdevices has been designed, fabricated and evaluated in harsh laboratory environments and their applicability has been discussed. Most studies featured in this thesis are based on a common set of manufacturing processes, some of which have been refined and developed. The results from these can be employed not only in their designated applications but also in many other fields with demanding conditions, such as natural catastrophe operations, volcanic research and manufacturing industry.

This research was performed at the Ångström Space Technology Centre (ÅSTC) as a collaboration between Uppsala University and The Swedish Defence University (SEDU).

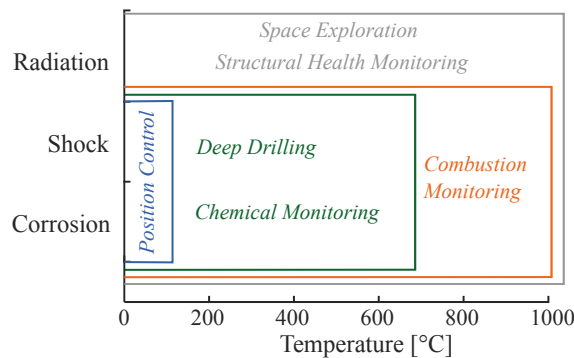
ÅSTC is a research group, hosted by the Microsystems Technology Division at Uppsala University. Since its inauguration in 2000, its research has focused on small satellites, their subsystems and other related vehicles and instruments.

SEDU is responsible for all higher military education programs and its research covers a broad palette of disciplines, from technology to strategy and general military theory.

# Harsh Environments

High-temperature environments, a focus in this thesis, is part of and closely related to the research field of harsh environments. This term is today established for applications of devices and systems under conditions which, in reference to normal every-day conditions, challenges the integration, functionality, performance and even survival of the device [15]. Sometimes the terms “Extreme” or “Hostile” substitutes “Harsh”, [16]–[19], but this may confuse the context with that of other research fields. Typically, “Extreme Environments” refer to conditions for microbe life-forms, [20]–[21], and “Hostile Environments” can either refer to psychological issues, e.g. social mechanisms in group dynamics, [22], or to military tactical concerns where hostility primarily refers to the objectivities of an adversary or situations with high psychological pressure [23]. Military electronics are required to sustain temperatures between  $-40\text{ }^{\circ}\text{C}$  and  $125\text{ }^{\circ}\text{C}$  and harsh environments, in terms of temperature, often takes off from this range [24].

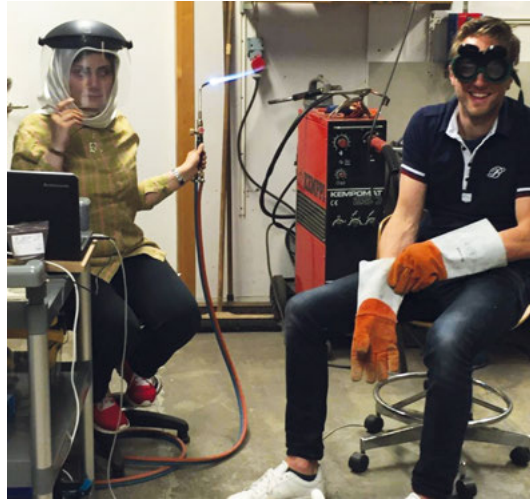
Regardless of appearing inside and outside a system, harsh environments are described from physical conditions and mechanisms, such as temperature, erosion, corrosion, radiation, chemical reactivity, shock and vibration [15]. Many of these aspects are relevant in aerospace applications, but also in other applications such as deep drilling and chemical manufacturing, figure 1.



*Figure 1.* Examples of applications and their harsh environmental conditions as a function of temperature, compiled from [15], [25].

A major challenge with evaluating devices in harsh environments is to facilitate a suitable laboratory setup, as it needs to sustain similar conditions as the device. High-temperature setups induce heat-effects on both mechanical and

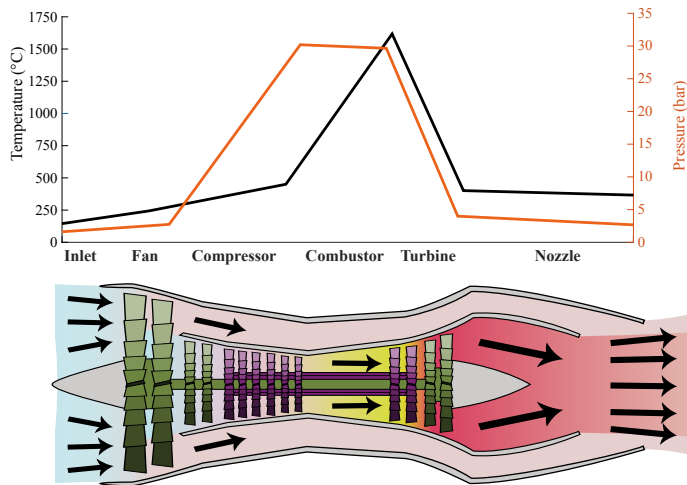
electrical interfaces. This requires a balance between isolating heat-dependent parameters in the setup and in the device under test. During the work presented here, it has been clear that despite the size of the Ångström Laboratory, there is a sheer absence of high-temperature equipment for device evaluation. This has required unconventional use of available equipment, figure 2.



*Figure 2.* Laboratory session in the Ångström workshop forge. The author prepares for sample heating with an oxyacetylene flame.

## Jet Engine

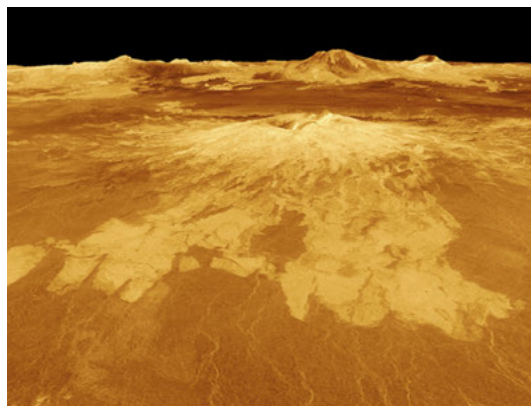
Modern military jet engines exhibit temperatures up to about 1500 °C, figure 3. In future jet engines, described in more detail in **Paper A**, the maximum temperatures from combustion are expected to reach up to 1700 °C with pressure ranges of 15-70:1, with respect to normal atmospheric pressure. The resulting flow of hot gas may in its turn cause erosion and corrosion on the engine surface materials [26]. Also, future high-speed aircraft will generate temperatures of at least 2000 °C on the fuselage skin due to the aerodynamic drag. This will of course require materials that can sustain those temperatures in order to avoid active cooling measures [27].



*Figure 3.* Harsh internal environment. Cross-section of a turbofan jet engine with approximate temperature and pressure, compiled from [26], variations along the gas flow, indicated by the black arrows. Jet engine courtesy of K. Ainsqatsi.

## Planetary Exploration

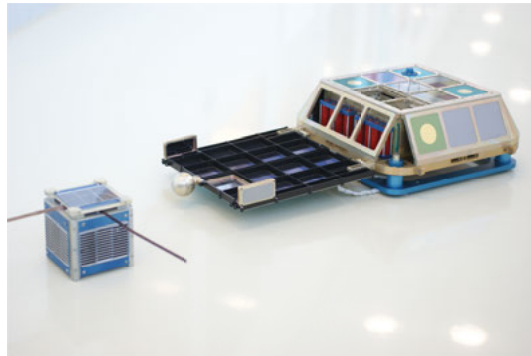
On most other planets, far far away, the ambient environment can be suspected to be harsh. A conventional launch causes vibrations and loads from the ignition of the launch rocket engines [28]. Then, leaving the atmosphere, and also Earth's magnetic field, will expose satellites to massive radiation. Once landed on a planet, the surface conditions may be harsh in general, as on Venus, figure 4, where the temperature can reach about 450 °C and the atmospheric pressure is almost 90 times that on Earth [29]-[30].



*Figure 4.* Harsh planet. 3-D mosaic rendition from Magellan radar imagery of the volcano Sapas Mons on Venus. Courtesy of NASA/JPL.

## Small Satellite Control

Small satellites, figure 5, are favourable for the monetary minded, but reduced size often reduces performance for e.g. optical and radar satellites. One way to mitigate this is to operate satellites at lower altitudes and another is formation flying of several satellites to form a large aperture. This is, however, not trivial and requires adequate communication and manoeuvre control and also orbit maintenance.



*Figure 5.* Small satellites manufactured at ÅSTC. A 1U cube satellite (left) and Nanospace-1, with one solar panel, featuring a small spherical thruster pod on its remote side.

One major future paradigm shift in space operations is the pending launch of large satellite swarms that aim to provide a global internet coverage. In 2010, about 1000 satellites were active in orbit [31]. In March 2018, the number was about 1740 [32]. Several concepts for non-geostationary satellite constellations for global internet provision are presented, which may imply about 15000 satellites [33]. This will also require traffic control and, again, manoeuvre control to reduce the risk of collision. For this, on-board thrusters will be a critical asset.

Onboard a satellite, propellant fuel is limited, but electrical energy is renewable. Therefore, thrusters should produce as much total thrust as possible from the fuel available. The common figure of merit for this is the fuels specific impulse.

Cold gas microthrusters expel pressurized gas to generate thrust. The exhaust speed is increased by expelling the gas through a nozzle, which increases the thrust generated from a given amount of fuel, and thereby increases the specific impulse. This can be further increased by also heating the gas before it is expelled. Increased heating requires temperature tolerant structure materials, the fuel efficiency is therefore directly dependent on these.

# Microsystems Technology

As more and more complex components and systems can be realised, more functionality seems to be required in products. Early mobile phone generations were large and mainly intended for phone-calls only. Modern followers contain at least two cameras, sometimes also a thermal camera, Global Positioning System (GPS) and Wireless internet radios, gyro accelerators, multi-core data processors, gigabyte size memory, an operative system, and a battery that may provide week-long operation before re-charging is required. This is feasible because all sub-systems in the phone have been, in part, manufactured with microelectronics and MST.

Common mechanical and electrical manufacturing tools may not be sufficient when a reduction, from what is regarded as a conventional mass and volume of a system, is required. Other means are then required and this is where MST enables further size reductions.

MST stems from the microelectronics manufacturing toolbox, and silicon processing and silicon-based microsystems has long been the core of the research field. The possibility of fabricating single crystalline substrates from silicon and control its semiconducting properties, has led to a large contribution to society from silicon-based research and industry.

Microdevices are set to sense changes in ambient physical conditions or to actuate a phenomenon. Typically, they work via a mechanism, table 1, designed into the device, causing the desired effect.

Table 1. *Typical physical causes, used in microsystems, and their effects.*

<i>Cause</i>	Pressure	Chemical reactions	Temperature	Erosion
<i>Effect</i>	Deformation	Corrosion	Strain/Stress	Wear

Materials used for exploiting these mechanisms, must have suitable properties. For harsh environments, and high temperatures in particular, material properties must be stable or at least change with temperature in a predictable way. One material property in high-temperature applications is the melting point, which can be regarded as the temperature limit for survival for ceramics and metals. From a mechanical point of view, the coefficient of thermal expansion (CTE), hardness and Young's modulus are important properties as they affect both functionality and integrability of a device. These properties'



temperature dependency is different for different materials, which may affect the feasibility of integrating devices fabricated from different materials.

Silicon, the core MST material, reaches semiconducting limitations when the temperature reaches 300 °C, [34], and at above 400 °C, it becomes soft and its ability to sustain mechanical load will degrade rapidly [14].

Currently, structure materials, considered for temperature applications above 400 °C, can be divided into three main classes: semiconductors, metal alloys and ceramics. Silicon carbide (SiC) has a wide bandgap and retains its semiconducting properties up to at least 400 °C and can be processed with a similar toolbox as silicon. It is also mechanically and chemically stable up to 600 °C [15]. Recently, SiC pressure sensors, based on piezoresistivity, have been reported to work at 800 °C [35]. However, SiC begins to suffer from oxidation at temperatures above 900 °C, in some cases already at 600 °C [15].

Gallium nitride (GaN) has an even wider band-gap than SiC and is regarded to have a high potential in power electronics and high-frequency radio applications. So far, it has been used in applications at around 600 °C [15]-[16]. It is however, together with SiC, temperature-limited with respect to its bandgap and is reported to partly decompose already at 750 °C [25].

Nickel and titanium-based metal alloys are well-known for their temperature tolerance and are commonly used in e.g. jet engines as surface materials, [36]-[37]. Lately, also binary and ternary ceramics have, based on their mechanical stability up to 1700 °C, been considered as substitutes for metal alloys in future jet engines [38]. There are, however, still challenges balancing internal stress and, consequently, reducing the risk of cracking phenomena. And moreover, these materials are not yet explored for MST devices and applications.

## Co-fired Ceramics – Rocks with Electrical and Mechanical Infrastructure

Common ceramic substrate materials, typically aluminium oxide (alumina) and zirconium oxide (zirconia), have several properties that make them suitable for harsh environments. They are chemically stable, their melting points exceed 2000 °C, [39]-[40] and their mechanical properties are stable, at least up to 1000 °C [41].

Zirconia has good fracture toughness but if used as a substrate for circuits, its ion conduction at high temperatures, [42], may cause problems. Ion conduction has been exploited in high-temperature gas flow sensors, [43]-[44], but will in other cases limit the use of electrical circuitry.

The hardness and poor heat conductivity make alumina vulnerable to cracking, thermal shock and unnecessary heat accumulation. In contrast to silicon, that can be processed to be almost completely free from defects, alumina and

zirconia often feature structural errors, from which mechanical failure can be initiated. This makes interfacing of ceramic materials and devices difficult. However, this has been a long issue of consideration and recent achievements, particularly addressing thermal gradients and interfacing, have been reported [45].

Neither alumina nor zirconia are semiconductors and their chemical stability makes them unsuitable for the fabrication processes of silicon, SiC and GaN.

One alternative for fabricating temperature tolerant microsystems is co-fired ceramics. These are developed for and extensively used as carrier substrates for semiconductor devices and circuits [46]. The application of co-fired ceramics for microdevices was early adopted by [47] and [48] and has increased during the last two decades.

Co-fired ceramics are suitable for MST as they can be processed in a green-body state. In this, ceramic grains with a diameter of a few micrometers are mixed into an organic binder and processed into tape sheets with a typical thickness between 50 and 200  $\mu\text{m}$ . Green body sheets have the nominal flexibility of the organic binder and can be both mechanically structured and metallized. They can further be bonded into stacks, contoured and finally fired, in order to remove the binder and to sinter the ceramic grains, into a monolithic structure.

There are two main categories of co-fired ceramics, Low-Temperature Co-Fired Ceramics (LTCC) and High-Temperature Co-fired Ceramics (HTCC). Both categories are based around the same ceramic materials, mainly alumina, but LTCC has a glass phase in the binder material that allows it to be sintered at about 850-900  $^{\circ}\text{C}$  [46]. Here silver, with its low electrical resistivity, can be used for metallization of conductors and also fired together with the ceramic substrate as the firing temperature is below the melting point of silver (about 960  $^{\circ}\text{C}$ ) [48]. For HTCC, the glass phase is removed in the binder which requires firing temperature in the range of 1500-1600  $^{\circ}\text{C}$ . This limits the metal alternatives to tungsten and platinum, and for non-embedded conductors that come in contact with oxygen, the latter is the only alternative available.

## Standard Processing

The standard HTCC processing involves screen printing of metal pastes on, and mechanical structuring of, green-body sheets. The sheets are then stacked and laminated and single devices are contoured and fired.

Screen printing metal pastes contain metal grains, solvents and organic binders. They are printed on the green-body tape through a fine-meshed screen. The pattern, and the thickness of monolayers of the printed paste, here 25  $\mu\text{m}$ , is determined by openings in a polymer emulsion covering the mesh. The minimum width of screen printed metal paste is limited by the edge quality of the emulsion openings and by the screen mesh line resolution. Screen

meshes with 500 lines per inch and 40  $\mu\text{m}$  openings have been reported in [49] and [50], here a screen mesh of 325 lines per inch has been available, allowing a lateral printing resolution of about 150  $\mu\text{m}$  with retained quality.

Screen printing of platinum is the standard method for metallization in **Papers I-IV and VI**. Usually, only one layer is printed, but in **Paper II**, a planar coil pattern was screen-printed with double-layers of platinum paste.

As etching is not an available option for removing material from an HTCC substrate, mechanical methods are required. In carrier substrate fabrication, through-hole vias are being punched through each layer. Embossing with pattern tools from silicon has been reported as a method for fabricating gas channels and 2.5-D De Laval nozzles [51]. For the studies presented in **Paper I, III and IV-VI**, micromachining with a Printed Circuit Board (PCB) plotter has been the main method for structuring cavities and channels. In **Paper II**, graphite patterns were screen-printed and used as embossing tools.

The complexity of a ceramic microdevice can be increased by aligning and stacking a multitude of sheets and thus creating three-dimensional structures. To form bonds between the sheets, they are laminated at high pressure (200 bar), and at 70 °C. As the mechanical structures will be mechanically loaded during the lamination, mechanical support is required to avoid deformation or collapse. This is solved by inserting sacrificial materials, here graphite, into all mechanical voids. These materials can be micromachined from tape sheets or, as mentioned above, screen-printed as pastes.

A laminated stack usually comprises of a batch, containing several devices. These can be contoured with a cutting blade, if the stack is thin, or with a contour routing tool for thicker stacks. The discrete devices are finally fired in a high-temperature furnace. This follows a scheme with temperature and time levels set to remove the organic binders and the sacrificial inserts and to sinter the ceramic and metal grains. The size of a single component, and of all its features, is reduced with 17-20 % in each direction during lamination and firing. This implies a resulting lateral resolution of 120-125  $\mu\text{m}$  for screen printing.

## Wire Integration

One fabrication novelty in this thesis is the integration of platinum wires with standard HTCC processing. This has its origins from a problem observed during the work presented in **Paper I**, where a mismatch between lateral and vertical shrinkage of platinum caused a low manufacturing yield for through-hole vias. Bond wires as metal elements in vias had previously been reported from other MST applications [52]. Here, contrary to the HTCC stack, metal wires were not expected to shrink during the firing process, but rather to curve as they retain their original length while the stacks they are attached to shrink. This was observed, together with irregularities along the wires, figure 6a.

Scanning Electron Microscope analysis, figure 6b, indicates that these irregularities are displacements along grain boundaries in the wire, caused by the thermomechanical load on the wires during sintering.

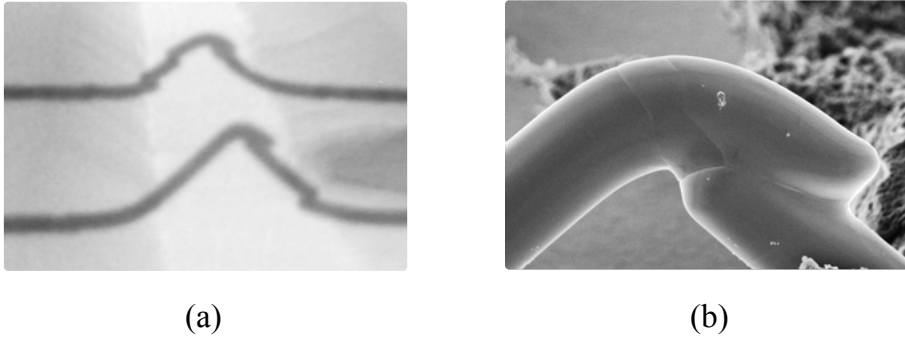


Figure 6. X-ray image of platinum wires, suspended across a HTCC alumina channel (a), and a close-up view of the front wire from scanning electron microscopy (b).

## Electroplating

After sintering, further processing of devices made from HTCC is difficult. The conducting properties of platinum is relatively poor compared to silver and copper and may sometimes limit the performance of microdevices. For devices with non-embedded conductors, *in situ*-electroplating after sintering was attempted. To the current knowledge, this was presented for the first time for HTCC microdevices in **Papers II** and **III**.

The main principle of the process is to electrically connect a conductor and place the entire device in an ion-bearing liquid solution. By running a current through the solution between two electrodes, with the conductor attached to the negative electrode, ions will recombine on the device conductor. The thickness of the deposited layer is controlled with current and time and the surface structure can be controlled with e.g. temperature and agitation.

# High-Temperature Aerospace Applications Studied in this Thesis

The studies in this thesis have had different approaches to both applications and environments. They are here organised from their intended applications and described by their functionality. Table 2 illustrates how the papers are related to application, functionality, fabrication and environment.

Table 2. The papers in this thesis organised after application, fabrication remarks and high-temperature environment.

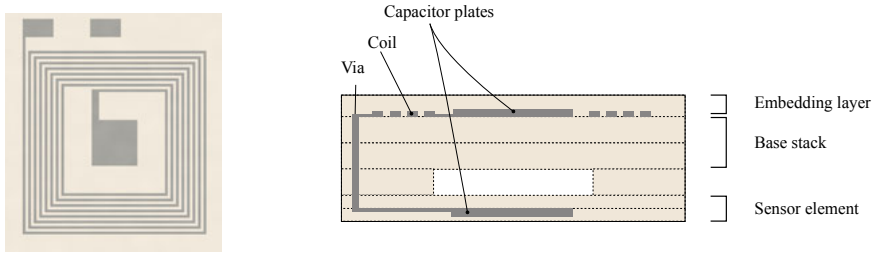
<i>Application</i>	Combustion Environment		Planetary Exploration		Satellite Control	
<i>Paper</i>	<b>I</b>	<b>II</b>	<b>III</b>	<b>IV</b>	<b>V</b>	<b>VI</b>
<i>Functionality</i>	Sensor	Sensor	Sensor/actuator	Sensor	Sensor	Sensor/actuator
<i>Metallization</i>	Screen printing	Screen printing /Electroplating	Screen printing /Electroplating /Oxidation	Screen printing /Wires	Wires	Screen printing /Wires
<i>Structuring</i>	Milled Cavity	Internal Embossing	Milled Cavity	Milled cavity	Milled Cavity	Drilled Cavity
<i>External</i>	1000 °C, 2.5 bar	900 °C, 2.5 bar				
<i>Internal</i>			1000 °C	830/1500 °C	>1760 °C	N/A

## Sensors in High-Temperature Environments

For accurate and efficient regulation of e.g. jet engines, sensors measuring pressure, temperature and gas mass flow are preferably placed at all critical positions, and in all sections of the engine, including the combustion chamber and the afterburner, **Paper A**. Due to the temperature and pressure levels, sensing, as well as both mechanical and electrical interfacing and device survival, is challenging.

In **Paper I** and **II**, wireless powering and reading of pressure sensors, based on LC resonator circuitry, in temperatures up to 1000 °C were studied. A LC resonator is a closed circuit consisting of a plate capacitor and a coil, figure 7. When it is exposed to an alternating field, an electric current will flow through the coil and charge the capacitor. As the capacitor discharges, a current in reverse direction will charge the capacitor with an opposite field direction. This phenomenon acts like an electrical pendulum and has a specific resonance frequency depending on the geometrical and dielectric features of the device. Temperature and pressure induced changes in capacitance, either by

change in the relative permittivity or the geometry of the circuit will cause the resonance frequency to shift.



*Figure 7.* Top view (left) and side view (right) of the pressure sensor device design in Paper I.

In **Paper I**, the issue of interfacing was addressed by studying the thermomechanical properties of devices with different substrate thicknesses. The resonance frequency was logged as the devices were mechanically deformed and then the curvature of the devices, as a result of bimorphic behaviour, was measured during heating to 400 °C. Further on, wireless pressure sensing was studied with a device with a pressure sensitive membrane suspended over a milled cavity. The pressure sensitivity was evaluated at room temperature, 500 °C and 1000 °C before the membrane was perforated in order to separate the main temperature-dependent influence on the resonance frequency.

It was found that the devices were thermomechanically stable at least up to 400 °C. The pressure sensitivity was reduced with increasing temperature, which also was expected. However, wireless pressure sensing at 1000 °C was at that time unprecedented.

In **Paper II**, the issues of wireless powering and reading and pressure-sensitive membranes were further studied. First, a simplified fabrication of membranes was investigated. Instead of suspending membranes over milled cavities, a membrane was draped over screen-printed graphite paste. It was assumed that by decreasing the capacitor plate distance, a pressure-induced change would cause a large proportional shift of the resonance frequency. By screen printing a sacrificial insert to define the cavity, the plate capacitor distance could be reduced with about 10 %.

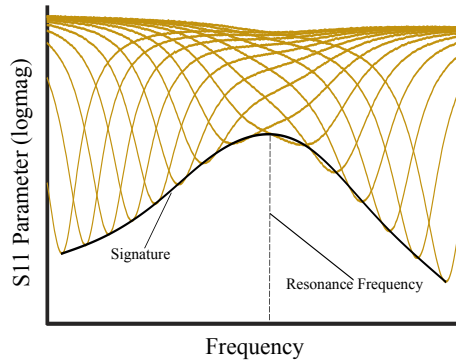
The production yield of the membranes proved successful but the shape and inside of the membranes became irregular, which affected the pressure-induced change of resonance frequency at different temperatures. Typically, the devices exhibited a very large pressure-sensitivity at 500 °C but not at 900 °C.

The wireless reading performed in **Paper I** indicated very short read ranges. This led to the main investigation of **Paper II**, to reduce the resistivity of the LC resonator devices in order to increase the read range between reader

antenna and device. Here, two methods were compared: double-layer screen-printing of low-resistive platinum and silver electroplating on a single-layer of high-resistive platinum. The challenge was to study the temperature stability of these two metallization alternatives. A time-dependent read-range was observed and it was shown that silver, when heated, initially reduced the resistivity and increased the read range. Then silver and platinum alloyed which increased the overall resistivity and reduced the read range.

## Wireless Communication

In both **Paper I** and **II**, an antenna, transmitting an alternating magnetic field, was used for powering and reading the pressure sensor devices. The general principal of this method is to place the pressure device in the harsh environment while keeping the reader antenna outside in a more benign environment. As the resistivity of metal conductors increases with temperature, the signal from the devices will weaken. This was mitigated by sweeping the resonance frequency of the reader antenna around the assumed resonance frequency of the pressure sensor device while continuously logging its signal response, figure 8. From this, a frequency dependent signature, including the resonance frequency, of the sensor devices could be extracted, even at very weak signal responses.



*Figure 8.* Frequency sweep of the reader antenna, placed over a passive LC resonator device. The signature is defined by the minimum of the voltage return loss coefficient,  $S_{11}$ , at each frequency and the resonance frequency is found at the signature maximum.

In practice, wireless powering and reading by magnetic field-coupling has limitations. The read range is limited because of the decay of the magnetic fields against distance, and the presence of metal inside the coupled fields will distort the signal. On the other hand, the coupled fields are very local and will not interact with metal outside their perimeter. The ultimate performance of devices employing this method is yet to be observed.

## Metallization for Carbon Isotope Analysis

The search for past and present life-forms is a never-ending quest for exploration on other celestial bodies than our own planet earth. One principle of searching for life is to look for features typical for life on earth. One such feature, for carbon based lifeforms, is the ratio of carbon-12 and carbon-13 isotopes, as these are characteristic for e.g. size, location of habitat and ecosystem [53]. This ratio can be analysed with optogalvanic spectroscopy (OGS) by analysing the optogalvanic effect (OGE) on a carbon dioxide-plasma containing carbon from samples that are collected from a planet surface, e.g. by a rover, figure 9.



*Figure 9.* The mars rover Curiosity taking a self-portrait at the Buckskin drilling site on lower Mount Sharp, Mars. Courtesy of NASA/JPL-Caltech/MSSS.

The optogalvanic effect exploits a change of the impedance of an oscillating gas discharge when it is exposed by light [54]. By perturbation of a carbon dioxide plasma with laser pulses, resonant with each carbon isotope, the ratio between the isotopes can be determined. In [55], Berglund *et al.* demonstrated the transfer of microplasma-source technology from PCB to HTCC which initiated the work at ÅSTC towards a complete ceramic lab on a chip (LoC) instrument employing OGS for planetary exploration.

The first sub-system to be included in the instrument regarded the preparation of collected samples. For organic material, i.e. carbon-based compounds, combustion in an oxygen environment will generate carbon dioxide. However, as the instrument is intended to work in vacuum, or in a very low-pressure atmosphere, sufficient concentrations of oxygen may not be available.

**Paper III** entails the development, fabrication and characterization of a microcombustor with an integrated heater, temperature sensor and oxygen storage. The concept was based on principles from HTCC microthruster technology, [51], and reworked for this purpose. Copper was electroplated on a resistive heater and oxidized for oxygen storage. Resistive heating to about 900 °C was then used for releasing the oxygen and combusting samples of organic material, placed in the devices combustion chamber.

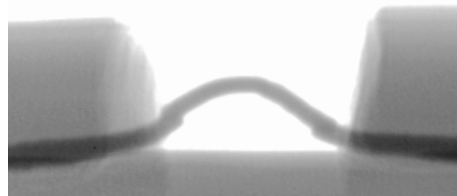


This device, being the smallest in the world to date, is favourable for very small samples, something that can be expected for planetary exploration, as well as on Earth, e.g. in archaeology and forensic studies. The use of copper oxide for oxygen storage in microsystems was novel and successful and the device could be demonstrated in operation. However, the change in crystalline structure from copper to copper oxide caused stress, and sometimes detachment, in the boundary between the oxide and the platinum heater, something that the production yield suffered from and also making it, so far, suitable for one-time use.

As platinum has a near-linear and very stable temperature-dependent resistivity, resistive platinum elements are well-suited as temperature sensors. The one featured in the combustor exhibits a linear temperature signal and although thermography shows a temperature gradient along both heater and temperature sensor, the sensing signal provides good control over the temperature condition in the combustor.

For monitoring gas pressure in general, and in the instrument in particular, the integration of platinum wires into HTCC was exploited. Here, the potential advantages of freely suspended sensor elements were investigated.

In [56], the first design of a HTCC micropirani gauge, with a freely suspended platinum wire as sensor element, was fabricated and evaluated. This concept was refined in **Paper IV**, figure 10. With the previously observed effect of wire curving, wire elements were more thoroughly investigated and compared with reference samples with screen-printed sensor elements.



*Figure 10.* Wire element of a Pirani gauge with an open cavity.

The performance of the devices, both with open and closed cavities around the sensor element, were compared in constant-resistance (CR) mode, at an element temperature of 100 °C, and in dynamic mode with rapid heating from a constant feed current. Further on, the performance of wire elements with different lengths were studied and the upper limit of wire element length, with a retained curvature, was briefly evaluated. Finally, one device was operated in a high-temperature mode, with a glowing sensor element.

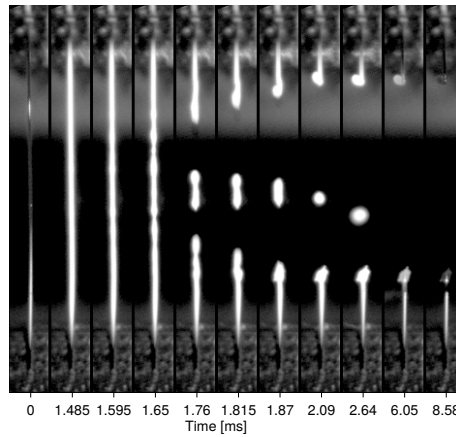
It was found that when operated in CR mode, wire elements exhibited longer dynamic ranges with covered cavities than screen-printed elements. No significant difference was observed with open cavities. In dynamic mode, the wire elements were more sensitive, and the pressure-dependent signals of the

printed elements were surprisingly unstable over the pressure range they were evaluated for.

A 3500  $\mu\text{m}$  long wire element was easily heated beyond the Draper point at about 525  $^{\circ}\text{C}$ , where metals start to glow from their black-body radiation [57]. Thermography and resistance analysis showed that the wire element had a mean temperature of 830  $^{\circ}\text{C}$  and, at hot spots, a maximum temperature around 1500  $^{\circ}\text{C}$  without failure. At this temperature, the wire device exhibited a similar pressure sensitivity as when it was operated at 100  $^{\circ}\text{C}$  but it had increased its upper limit of the dynamic range from 25 Torr to about 700 Torr.

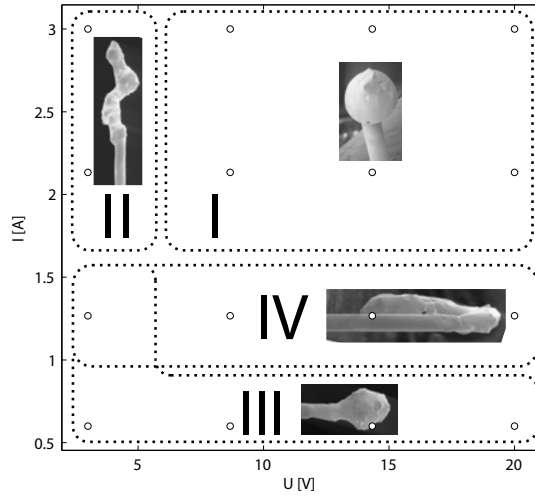
Operation with high sensor element temperature makes pressure sensing in high-temperature environments feasible, but the exact sensitivity and dynamic range in this application is yet to be experimentally investigated.

The impedance in the plasma source during operation can be effectively measured with Langmuir probes, placed in the plasma gap and biased with a voltage. In **Paper V**, the feasibility of fabricating spherical microscale Langmuir probes from wires was investigated. Platinum bond wires, with and without parylene coating for electrical isolation, were fused off at different voltages and currents. High-speed imagery was used for studying melting and material transport along the wire tips, figure 11.



*Figure 11.* High-speed imagery mosaic of a fusing event. The central, free-flying platinum is omitted in forming the probe tips. Courtesy of Martin Berglund.

The resulting shape of the probe tips were then evaluated, categorized and mapped against the voltage and current settings for fusing, figure 12.

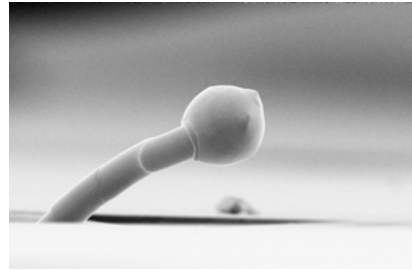


*Figure 12.* Map of probe tip shape categories against fusing voltage and current. Note that some powers can be found at different positions on the map, but with different resulting probe tip shapes. Courtesy of Martin Berglund.

With this method, electrically isolated spherical probes were successfully fabricated with good repeatability and demonstrated in a PCB microplasma source. Following this study, the results could be transferred from PCB to HTCC, figure 13.



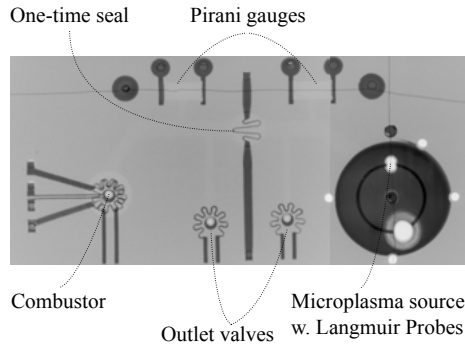
(a)



(b)

*Figure 13.* Langmuir probe tips, fused off with 20 V and 3 A on a PCB substrate (a) and on a HTCC substrate (b).

In [58], the complete lab-on-a-chip OGS-instrument, fabricated from HTCC was reported, figure 14. The instrument comprises the sub-systems described above and can combust organic material into carbon dioxide gas, feed it to a microplasma source for OGS analysis with fused off microscale Langmuir probes. Micropirani gauges are monitoring the gas pressure and a ceramic seal, [59], is controlling the gas flow.



*Figure 14. X-ray mosaic of a complete LoC instrument for OGS. Note the embedded gas channels in the alumina substrate. Courtesy of Martin Berglund.*

Although a complete lab-on-a-chip, this device is still dependent on support systems that are yet to be miniaturized and the future applications of this instrument are yet to come.

## Small Satellite Control

The feasibility of fabricating microplasma sources and freely suspended and temperature tolerant wire elements led to the interest of comparing methods for gas heating in a cold gas thruster. Gas heating aims at increasing the propellant efficiency, i.e. the specific impulse of the propellant.

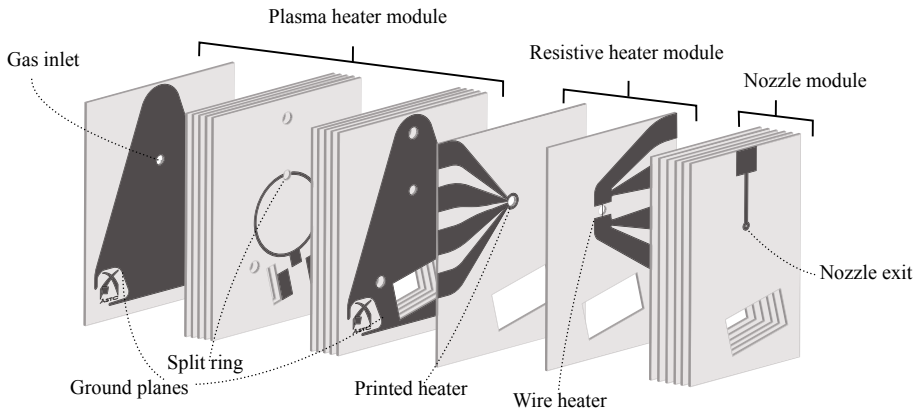
Resistive heating in cold gas thrusters are traditionally performed with surface-printed heaters [60]–[61]. It was here assumed that with laminar flow, a suspended heater would transfer heat to the eventually expelled gas more efficient, and some evaluations have been reported, [62]–[65]. Plasma heating is also reported for relatively small systems, [66]–[72], where a large volume of the gas in the thruster’s stagnation chamber is ionized and functions as a jet engine afterburner.

With all methods reported in separate studies, they have, however, not been compared in one device, which was the objective for the work presented in **Paper VI**, where the development and initial characterization of a ceramic microthruster with two resistive and one plasma heater is presented.

The device was developed from the idea of using an integrated platinum wire as a heater and compare its gas heating efficiency to more conventional resistive heating from a surface-printed thick-film heater. Later on, the microplasma source was added to the concept.

The design of the device could benefit from many previous studies at ÅSTC. In practice, many of the design-rules and sub-system elements featured in [58], [73] and **Paper V** are reused in this microthruster, albeit in a rearranged order, position and functionality.

As the heating methods are independent from each other, the entire device could be fabricated in modules, figure 15.



*Figure 15.* Exploded view of heater and nozzle modules, each featuring the corresponding amount of sheet layers. Note the shaft for connection to the plasma heater module.

One design issue for microthrusters is the often resulting square cross-section of the nozzle and the lack of a converging-diverging (De Laval) nozzle out from the plane of the thruster, something that was considered in [74]. Here, a drilled nozzle was used. From [75], it was found that ionized xenon gas exhibited a relatively long recombination time and in, [68], a visible exhaust plume from ionized gas was observed, including shock cells, which was also observed in [76]. These occur when the expelled gas is supersonic and there is a small pressure difference between the exhaust plume and the ambient space it is expelled in, figure 16.



*Figure 16.* Shock cells from the microthruster exhaust plume in **Paper VI** (left), and from the space shuttle Atlantis during launch (right). Courtesy of NASA.

Visible shock cells made it possible to evaluate the relative specific impulse of the device from recording the exhaust plume and measuring the distance from the nozzle exit to the first shock cell.

The resistive elements could also alter their functionality between actuating heat and sensing temperature. In this way, each resistive element could also be evaluated as temperature sensors while the other heated the gas.

Plasma heating increased the specific impulse of non-heated gas expulsion with 25 %, followed by the wire element with 18 % and the surface-printed heater with about 1.5 %. The design of the device was unfavourable for the surface-printed heater and a higher impact on the specific impulse has been reported [61]. The comparison still shows the advantage of freely suspended wire heaters and above all, the potential of plasma heating. Not all details were optimized in the design of the device and further improvements can be made.

Finally, following this study, the wire heater was fused off, again from the settings in **Paper V**, and the resulting probe tips were used for measuring the plasma impedance, by measuring the current between the probes against voltage, figure 17. From this, electron temperature and density as well as ion density can be determined, [78], which points out the direction for the future studies of plasma heating.

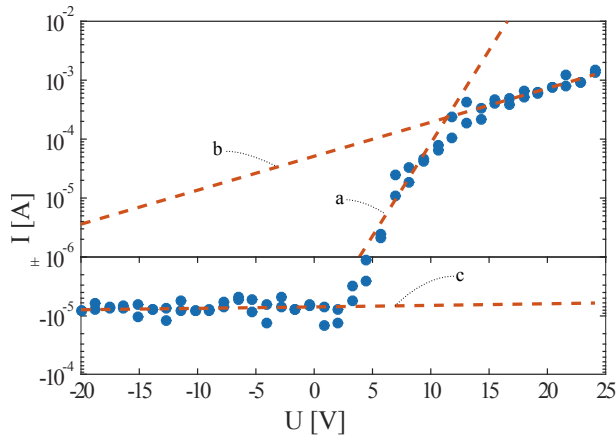


Figure 17. I-V curve from the Langmuir probes inside the stagnation chamber of the microthruster. The dashed asymptotic lines mark out the electron temperature (a), electron density (b) and ion density (c).

# Concluding Remarks

This thesis presents a variety of devices and applications, manufactured from HTCC. The knowledge gained from this work rests upon the results, presented in the scientific reports. Here, facts about magnitudes and boundaries, for mechanisms that sensing or actuating relies upon, are revealed and to some extent quantified. The feasibility of wireless powering and pressure sensing at 1000 °C was demonstrated, to the authors knowledge for the first time, in Paper I. Also, combustion of carbon-based material from internal heating and oxygen release was conceptually proven in Paper III. For microthrusters, plasma heating was compared with conventional and novel resistive heating and, although assumed for a long time, the advantage was shown in one single device.

Many devices have, in all studies, once successfully fabricated, been surprisingly stable in their performance, which also implies their survivability.

Apart from the results from the studies, much knowledge about manufacturing with HTCC has been gained. The common fabrication toolbox has been used and extended to include *in-situ* electroplating and integration of thin wires. This has been feasible because of the high-temperature applications. Electroplating and oxidizing of copper was made possible because it was compatible with platinum but also since HTCC could sustain the temperature required for releasing the oxygen from the copper oxide. The integration of wires was initiated by design issues that could not be solved with conventional HTCC processing. Moreover, curving of wires could be taken advantage of for both pressure sensing, electrical connections and gas heating.

What can also be concluded is that the knowledge, gained in early studies, could successfully be invested in later studies. The microthruster in Paper VI was in many ways the result from many years of accumulated manufacturing tricks and design rules for performance.

In a historical context, this thesis has used pre-Neolithic structure materials (ceramics) and applied 19<sup>th</sup> and 20<sup>th</sup> century physics in devices with circuits, manufactured with a 2000-year-old technology. The novelty, if only brief in time, in the work lies in the combination of new knowledge and technologies discovered by past giants. It is a personal wish that the work presented in this thesis can provide a small contribution to the common knowledge and to push MST forward to the benefit of future peers. Good luck to you all.

Finally, would Daedalus and Icarus have benefitted from this thesis? Maybe he could have had temperature sensors attached to his sons wings that

could have warned him not to fly too high. It is questionable if he would have cared anyway. The most sensible course of action would have been to *sense* the heat, actuate away from the sun and enjoy the sensation that he could actually fly. Above all, he would have survived. But that would perhaps have been less of a story.



# Svensk sammanfattning

Människans strävan efter att flyga är gammal. I den klassiska grekiska mytologin kan man läsa om Daidalos, som under fångenskap tillverkade vingar av vax och fjädrar åt sig och sin son, Ikaros. Medveten om vingmaterialens begränsningar i krävande miljöer, rådde han sin son att varken flyga för högt eller lågt. Ikaros däremot, saknade denna insikt och rusig av sin nyvunna förmåga flög han upp i skyn och kom för nära solen. Vaxet smälte och han dödsstörtade ned i havet.

I modern tid har förmågan att flyga haft en viktig del för samhällsutvecklingen, så även för utvecklingen av krigföring, där flyg- och rymdsystem ofta har varit föremål för nationell prestige, inte minst under det kalla kriget.

Typiskt för flyg- och rymdsystem är att de genererar eller uppehåller sig i miljöer som är mycket krävande jämfört med de som vi upplever till vardags. Krävande miljöer innebär höga temperaturer, aggressiva kemiska förhållanden, erosion och strålning och kräver material som kan både överleva och fungera i sådana förhållanden.

Idag är flygplanet det huvudsakliga transportmedlet för global transport av människor, men utsläppen av växthusgaser från flygplansmotorer har lett till ett behov av att utveckla mer energieffektiva flygplan. En sådan utveckling är omfattande och berör inte bara motorer utan även flygplanskropparnas aerodynamik. En utveckling av mer energieffektiva flygplansmotorer är viktig inom militär luftfart eftersom detta leder till ökad dragkraft, aktionsradie, uthållighet i luften och en minskad logistisk belastning. Men utvecklad prestanda utsätter flygplan för större påfrestningar, vilket i sin tur ställer högre krav på konstruktion och material. I en framtida modern jetmotor kan man förvänta sig temperaturer på upp till 1700 °C och tryck som motsvarar upp till 70 atmosfärer. För att tåla detta och t.ex. förbränna bränslet idealt, behöver jetmotorerna drift och hälsa övervakas på ett direkt och icke-störande sätt.

I rymden, ovan atmosfären, används inte flygplan utan satelliter och rymdsonder med destinationer i andra delar av och utanför vårt solsystem. Likt flygande laboratorier är de fullproppade med instrument, alla med tydliga syften och uppgifter. Vål nere på en annan planet behöver dessa farkoster kunna känna av och överleva den rådande miljön för att kunna lösa sina uppgifter. År 2012 landade Curiosity, en fjärrstyrd hjulfarkost, på Mars för att samla prover från planetens yta. Den har sedan dess funnit både organiska

molekyler och fossila spår som liknar mikroorganismer, vilket har pånyttfött den eviga och oundvikliga frågan: Finns det liv på Mars?

Återigen till Jorden, eller i alla fall till en omloppsbana runt den. Här finns många civila och militära satellitsystem som bistår samhället med allt fler tjänster. Traditionellt har militära spanings- och övervakningssystem stora sensoraperturer för att kunna ha tillräckligt hög upplösning i sitt data och därmed vara operativt relevanta. Detta har krävt stora satelliter och bärarketer vilket generat höga kostnader.

Satelliter med reducerad storlek har varit ett växande område sedan slutet på 1990-talet. Kubsatelliter är uppbyggda utifrån en form- och storleksmodul på 10 x 10 x 10 cm. Dessa har gett en grogrund för universitet, små bolag och myndigheter att utforska både rymdteknik och rymdbaserade tjänster. För att små satelliter ska kunna vara militärt intressanta för traditionella uppgifter behöver de bl. a. kunna flyga lågt och i grupp för att t. ex. tillsammans generera stora syntetiska sensoraperturer, vilket ställer krav på manövrerbarhet och förmåga att kompensera för inbromsning av atmosfären.

Mikrosystemteknik (MST) är ett forsknings- och industrifält med ursprung ur halvledarindustrin som innebär utveckling och tillverkning av mikrosystem, t. ex. sensorer och aktuatorer, med strukturdetaljer i storleksordningar mellan 1 och 100 mikrometer ( $1\ \mu\text{m} = 0.000001\ \text{m}$ ). Sådana komponenter och system kan integreras i större system för att möjliggöra ökad funktionalitet. De kan också användas för att reducera storleken av t.ex. mobiltelefoner.

Mikrosystem är traditionellt baserade på kisel, vilket är ett mycket fördelaktigt material eftersom det har halvledande egenskaper som kan kontrolleras och utnyttjas. Det kan dessutom mönstras och struktureras med kemiska processer som tillåter mycket små detaljer. Däremot, vid temperaturer över 600 °C och i kemiskt aggressiva miljöer krävs andra material. Många vanliga keramiska material, såsom aluminiumoxid och zirkoniumoxid, är kemiskt stabila och har stabila mekaniska egenskaper väl över 1000 °C. Däremot är de inte halvledande och den kemiska stabiliteten gör att de inte kan struktureras med samma metoder som t. ex. kisel.

Samsintrade keramer (eng. co-fired ceramics) består, inledningsvis, av keramiska korn, blandade med ett polymert bindemedel, s. k. grönkroppstillstånd och kan produceras i form av tunna tejper. Dessa har mekaniska egenskaper som övergripande bestäms av bindemedlet, vilket gör att de upplevs som mjuka och kan struktureras genom prägling, fräsning eller laserbaserad bearbetning. Därtill kan elektriska ledare mönstras på varje lager genom screentryckning av metallpasta. Mikrosystem kan tillverkas av samsintrade keramer genom strukturering av flera lager som sedan lamineras ihop till en tredimensionell stack. En sådan färdigställs sedan i en högttemperaturugn där det organiska bindemedlet avgår och de kvarvarande keramiska kornen sintrar ihop till en monolit – en sten med hålrum och elektriska ledare.

Detta avhandlingsarbete har utförts vid Ångström rymdtekniskt centrum (ÅSTC) i samarbete med Försvarshögskolan och presenterar mikrosystem för tillämpningar inom jetmotorövervakning, planetär utforskning och satellitkontroll. Samtliga mikrosystem är utvecklade och tillverkade av samsintrad aluminiumoxid och platina vid Ångströmlaboratoriet i Uppsala.

I den första studien har sensorer med tryckkänsliga membran för tryckavkänning i högtemperaturmiljöer utforskats. Två utmaningar med att placera mikrosystem i högtemperaturmiljöer är att de är svåra att både ansluta elektriskt och integrera mekaniskt. Här har dessa utmaningar angripits med trådlös kraftförsörjning och avläsning av sensorn samt en utvärdering av dess termomekaniska egenskaper. Trådlös tryckavkänning har demonstrerats i temperaturer upp till 1000 °C, men med ett begränsat läsavstånd. Detta har behandlats i nästa studie där elektroplätning av silver på sensorns kommunikationsdel, har utvärderats för reducerad resistans och ökat läsavstånd. Denna metod visade sig fungera, men bara temporärt, varaktiga lösningar på denna utmaning kvarstår.

Tillverkningsmetoder som utvecklats för de första studierna, bland annat elektroplätning, har senare kunnat tillämpas i utvecklingen av ett system för analys av kol-isotoper. Livsformer, såsom vi känner dem på Jorden, har, genom sin ämnesomsättning, en karaktäristisk sammansättning av vanligt och tungt kol. Sammansättningen kan bestämmas, bland annat genom optogalvanisk spektroskopi (OGS). Denna, något tungvrickande, metod bygger på att jonisera gas, d. v. s. generera ett plasma, innehållandes kol i detta fall. Genom att påverka plasmat med laserpulser och samtidigt mäta dess elektriska motstånd, impedans, kan man bestämma den efterfrågade kolsammansättningen.

Vid ÅSTC har ett litet instrument för denna metod utvecklats. Insamlade organiska fynd kan där förbrännas i en miniatyriserad reaktor, presenterad i denna avhandlings tredje studie. Reaktorn har en värmare av platina, som elektropläterats med koppar som sedan oxiderats, för lagring av syre. När kopparoxiden värms till ca 850 °C kan syret frigöras och det organiska materialet kan förbrännas till koldioxid. Denna funktion är påvisad och demonstrerad. Den kan dock påverkas av interna spänningar och hittills ska denna reaktor betraktas som en engångsartikel.

Den genererade gasen från reaktorn övervakas sedan med en trycksensor. I den finns en tunn platinatråd integrerad, inspänd och frilagd från sin omgivning. Genom att använda detta sensorelement enligt den drygt hundraåriga Piraniprincipen, kan den bestämma gasens densitet och därmed tryck.

Integration av trådar i en teknologi som annars tillämpar yttryckta elektriska ledare är en intrikat utmaning som har studerats i avhandlingens fjärde studie. Samsintrade keramer krymper under själva sintringen, vilket integrerade trådar inte göra. De kröks i stället till bågar som reser sig över substrats ytor. På detta sätt kan de både påverka och påverkas av omgivande

gaser på ett mer effektivt sätt än yttryckta ledare kan. Detta kunde visas för Pirani-trycksensorer och sedan även för gasvärmning i en senare studie. Trådarna kan dessutom avbrännas kontrollerat för att forma sfäriska ändar, s.k. Langmuirprober, för impedansmätning i ett plasma. I avhandlingens femte studie undersöks denna process genom en kartläggning av trådändarnas form som en funktion av elektrisk spänning och ström. De nyvunna rönen har sedan framgångsrikt tillämpats i en mikroplasmakälla, avsedd att generera plasma för OGS.

Design av mikroplasmakällor har tidigare studerats noggrant och även anpassats för samsintrade keramer. Tillsammans med studierna i denna avhandling har de kunnat integreras i instrumentet, vars tillämpning och användning väntar i en spännande framtid.

En annan tillämpning av mikroplasmakällor är gasvärmning, vilket är användbart i mikroraketer för manövrering och bankontroll av små satelliter. Mikroraketer, små inkarnationer av de vittkända bärraketsystemen, utgörs i sin enklaste form av en trycksatt gastank, en ventil och ett munstycke. Genom att öppna ventilen och accelerera gasen genom munstycket uppstår dragkraft. Väl i omloppsbana är gasen en ändlig resurs, medan elektrisk energi är förnyelsebar. Genom att värma upp gasen innan den passerar munstycket, ökar man tryckskillnaden mellan munstycket och dess omgivning. Det leder till en ökad specifik impuls, d. v. s. högre dragkraft från den förbrukade gasen.

I avhandlingens sjätte och sista studie har tre olika principer för uppvärmning av xenon-gas jämförts. Två av dessa bygger på resistiv uppvärmning, den ena med en yttryckt värmare och den andra med en integrerad trådvärmare. Den tredje principen bygger på plasmavärmning, vilket liknar tillämpningen av en efterbrännkammare i en militär jetmotor. När gasmolekyler passerar genom plasmat värms de upp av kollisioner med joner och elektroner, innan det passerar munstycket. Dessa principer är var och en för sig kända sedan tidigare men tillämpningen av alla tre i ett mikroraketsystem är unik.

Utvärderingen baserades på mätning av dragkraft och utvärdering av chockceller i den joniserade och ljusavgivande gasplymen vid användning av plasmavärmaren. Metoderna kunde också överbryggas för jämförelse av de olika resultaten. Dessa visade en tydlig fördel med plasmavärmning framför trådvärmaren och den yttryckta värmaren.

Avslutningsvis kan det konstateras att denna avhandling visar på en flora av tillämpningar av en teknologi som bygger på en av världens äldsta materialtyper, keramer. Det kan faktiskt vidare konstateras att utöver uråldriga strukturmateriell har principer från arton- och nittonhundratalsfysik tillämpats på tillverkningsmetoder och tillämpningar vars ursprung och idéer återfinns i nittonhundratalets mitt. Originaliteten och nyheten i arbetet återfinns i mikrostrukturteknikens kärna: de små detaljerna och den okonventionella användningen av känd kunskap, utövad av miniatyrer från jättars axlar.

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