MICROPROPULSION SYSTEMS RESEARCH AND MANUFACTURE IN SWEDEN

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Abstract: Micropropulsion for spacecraft is an enabling technology for many future missions, and may increase the performance and drastically reduce the mass required for advanced propulsion systems. The Swedish activities in micropropulsion at The Angstrom Space Technology Centre (ASTC) are outlined. The research targets two major issues: the development of system parts, and the research into integration techniques and strategies. This paper collects a multitude of devices relevant to the micropropulsion system design, together with representative functional demonstrations.

The items are mainly intended for chemical micropropulsion systems or fuel-feed systems for electric propulsion. In particular, gas handling devices, sensors, and actuators are presented. These include silicon nozzles, thin film heaters, suspended microcoil heaters, proportional piezoelectric valves, proportional and isolation valves using phase-change material, thermal throttle flow-regulators, high-pressure regulators, 3D-particle filters, and sensors for strain, pressure, flow, and thrust. Moreover, integration techniques and interface structures are presented, for example low-temperature plasma-assisted silicon wafer bonding, multiwafer bonding, thin film soldering, hermetic electric through-wafer via connections, and multiconnector through-wafer vias.

Emphasis is on how these items are designed to allow for system integration in a multiwafer silicon stack, comprising a complete micropropulsion system. In this manner, all items form a parts collection available to the system design. This strategy is exemplified by three micropropulsion systems researched at the ASTC.

First, the cold/hot gas micropropulsion system is suitable for small spacecraft or when the demands on stability and pointing precision are extreme. The system performance depends strongly on the use of gas flow control. The complete gas handling system of four independent thrusters is integrated in the assembly of four structured silicon wafers. Each independent thruster contains a proportional valve, sensors for pressure, temperature, and thrust feedback, a converging-diverging micronozzle, and a suspended microcoil heater. The mass of the system is below 60 g. In total, this will provide the spacecraft with a safe, clean, low-powered, redundant, and flexible system for three-axis stabilization and attitude control.

Second, a Xenon feed system for ion propulsion is heavily miniaturized using microsystems technology. Basically, a micromachined high-pressure regulator receives the gas from the storage, and the flow is further modulated by a thermally controlled flow restrictor. The flow restrictor microsystem comprises narrow ducts, thin film heaters, suspended parts for heat management, and flow sensors. Hereby, the amount of xenon required by the electric propulsion systems can be promptly delivered. The complete system mass is estimated to 150g.

Third, within the EU IST program, the ASTC participates in the development of a micro-pyrotechnic actuator system (Micropyros), suitable for short-duration space propulsion. The Micropyros integrate a full matrix of minute solid combustion rocket engines into panels situated on the spacecraft hull. The thrusters can be individually ignited, and each deliver thrust in the millinewton range. The ASTC focuses on the integration of the propulsion part by low-temperature bonding, and the characterization of the complete system.

Introduction

Propulsion systems designed to provide small thrust of some newtons down to micronewtons range have been appointed as a constraint for achievement of extreme stabilisation, pointing precision for many space missions under development. Miniaturisation using conventional technology does not produce sufficiently small systems to be applicable to nanosatellites and smaller spacecrafts. Micropropulsion systems made by Micro System Technology (MST, or MEMS) are the natural solution for very small spacecrafts, as the same time they are applicable for even lager spacecrafts. Such systems are believed to be the technological solution of vital importance for several decades to come. The ASTC in Sweden develops nanosatellites for various purposes, therefore research and manufacture of micropropulsion systems is one of the main activities. Cold/hot gas micropropulsion, micropyros, microsystem for xenon feed are three of the ongoing projects at ASTC.

The characteristic feature of almost all the projects is that the systems are heavily miniaturized into integrated silicon wafer stacks. MST reduces the systems mass drastically, at the same time the system efficiency increases, and the power needed for operation is lowered dramatically [1, 2]. The small MST-based Xenon feed system developed at ASTC, which includes gas handling system, sensors, electronic control system, and housing, weights barely about 150 gram [3]. The MST-based microthruster pod contains everything necessary for autonomous operation, except fuel, yet it weights below 60 gram. However, high level of integration implies that the system design has to be considered carefully before the design work starts, since such a system cannot be modified, nor repaired [4].

In this paper the items mainly intended for cold/hot gas micropropulsion systems, Xenon feed systems for electric propulsion, in particular, gas handling devices, sensors, and actuators are presented. Furthermore, design of system part enabling system integration and the integration methods will be emphasized.

Cold/hot gas micropropulsion system

The technical data of the Cold/hot gas micropropulsion system are summarized shortly in the following:

- Thruster pod dimension: diameter 42.5 mm
- Overall length 54,5 mm
- Weight: below 60 gram
- Expected specific impulse: 120 s (with Nitrogen and internal heater at the nozzle outlet)
- Max thrust: 0.5-10 mN (dependent on design)
- Subsystems included: 3D-particle filter, electronic control, gas handling

The tiny autonomous thruster pod, figure 1, with four independent nozzles for X- and Z-axis, as mentioned above, is suitable not only for nanosatellites, but also for larger space vehicles, which need high resolution of stabilization and attitude control. A possible configuration uses two pairs of thruster pods with their shafts mounted symmetrically to the spacecraft in right angles. This configuration provides redundancy of function for all six degrees of freedom, since it entails two thrusters in each direction of the X- and Y-axis (for both positive and negative direction) and four thrusters in each direction of the Z-axis.

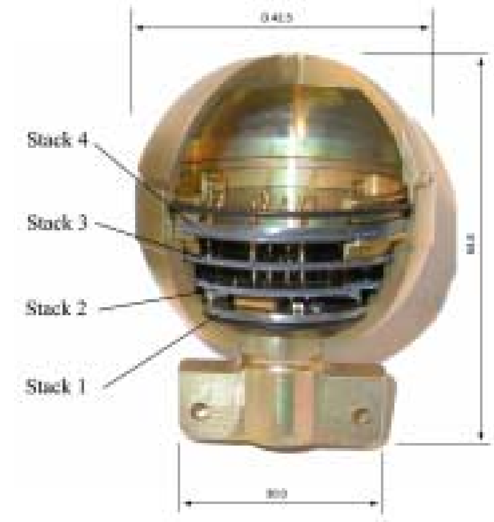

Figure 1: Thruster pod dimensions and the whole micropropulsion system inside

The thruster pod contains four silicon wafer stacks. One is the three-dimensional particle filter with an electronic subsystem. Two of them contain only electronics and one is the gas handling system. The design is made for any non-corrosive cold gas propellant. Figure 2 shows the block diagram of one microsthruster. The electronic control system is allocated among all four wafer stacks by reasons of required space and signal quality.

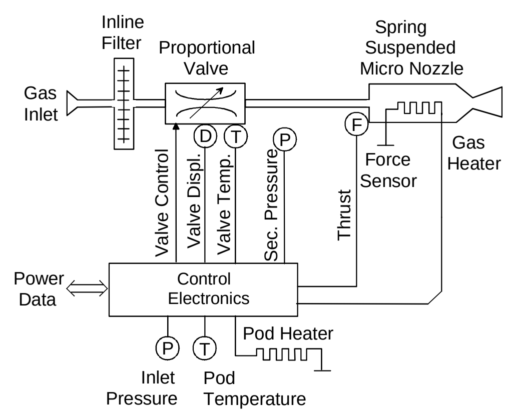

Figure 2: Micro thruster block diagram.

The first silicon wafer stack at the gas inlet to the thruster pod is a two-stage particle filter. It shall protect the pod from contaminating particles generated in the supply system tubing, shut-off valves, etc. The three wafers in this stack constitute the slot filter and V-groove filter (also called 3D-particle filter, and occasionally the fishbone filter). By definition, 1D-filter cannot stop thin flakes, 2D-filter miss fibres, but 3D-filter stops all of them.

The slot filter performs the coarse filtering, where the low channel height works as a one-dimensional filter. Figure 3 shows the design in principle, and the magnified top-view of the manufactured slot filter. The main advantage with the design is the outstanding mechanical robustness. The simple manufacturing with only two anisotropic wet etch steps is also a good advantage. The application area for the filter is as a pre-filter and as a mechanical shield against pressure shock waves.

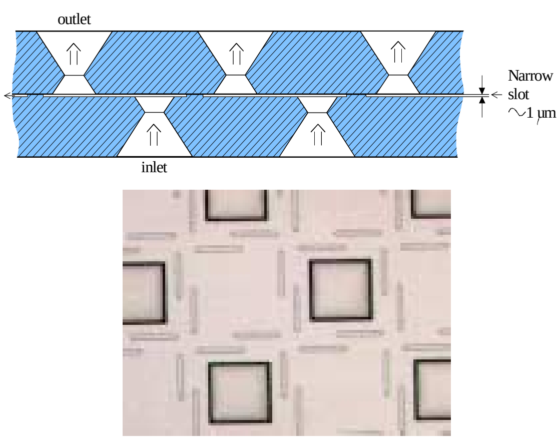

Figure 3: Slot filter design concept, cross-section (above) and magnified top-view of the manufactured filter (below)

The 3D-particle filter is the step after the coarse filtering, realized by bonding two silicon wafers with etched V-grooves to form a fishbone pattern, featuring several sharp bends of 90 degree [5]. Figure 4 shows the design concept, and the SEM of one wafer manufactured for V-groove filter. The filter is capable to stop all particles with diameter larger than one micron.

The upper surface of the filter stack is used for mounting an electronic subsystem. The one that was selected to be placed here is the input EMI-filter, and the double redundant system for conversion of the input voltage between 8 and 40 V to 5 V output for operation in the rest of the thruster electronic system, figure 5.

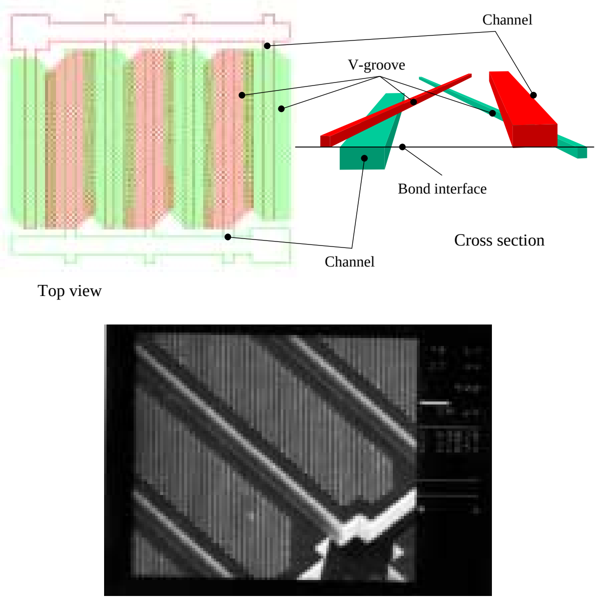

Figure 4: Design concept of the 3D-particle filter (above) and the SEM picture of the etched silicon wafer before bonding (below)

The second silicon wafer stack, figure 1, composed of two wafers contains only digital electronics, such as the dual CAN-bus interface.

The third silicon wafer stack, also composed of two wafers, contains only analogue electronics for management of signals to and from the sensors in the thruster pod, mainly those in the next wafer stack.

Figure 5: The particle filter stack with the input EMI-filter and double electronic system for conversion of the input voltage to operation voltage for the thruster pod. The ¼ part of this pod half is cut out for visibility.

The fourth silicon wafer stack is the gas handling system. Figure 6 depicts the Final Edition [1] of the gas handling system in the thruster pod. In this design a Phase Change Material (PCM) proportional valves replace the Piezoelectric valves in the earlier design, eliminating two silicon wafers in the gas handling stack and saving an immensely number of costly works. As the valves are integrated in the existing silicon wafer the number of clean room processes for the whole system is remarkably reduced.

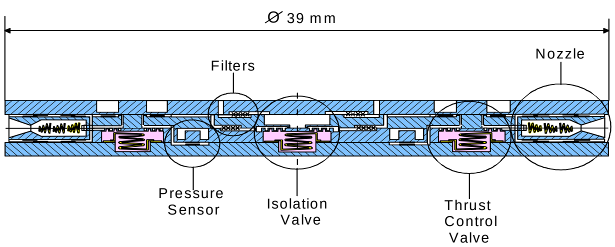

Figure 6: Cross-section of the gas handling stack composed of four silicon wafers with integrated PCM valves

The gas handling stack also contains 3D-particle filters, which protect the thrust control valves from damage by debris, that can be generated in the gas feed system.

The electronic components allocated on the surface of this wafer stack are those for sampling of signals, mainly from temperature sensors, pressure sensors, and thrust sensors. The closeness to the sensors is necessary to achieve the best possible signal quality.

The gas handling system contains a large number of innovative MST-solutions in order to make a very compact and reliable system. One example is the suspended nozzles with position sensors for direct measurement of thrust, which is formed by the two mid-wafers, figure 6 and 7. The measurement problem for such a small thrust force is solved by letting the upper electrode of the capacitive sensor move along with the nozzle in a clever way, in which the right hand side electrode increases its capacitance, while the left hand side electrode decreases the same. When the capacitors are coupled in an AC excited bridge a stable and sensitive signal can be extracted. Temperature drift will be minimized as all bridge components consist of the same material and experience the same temperature. Direct measurement of thrust in this way is reliable and simple, without relying on derivations from secondary data [1].

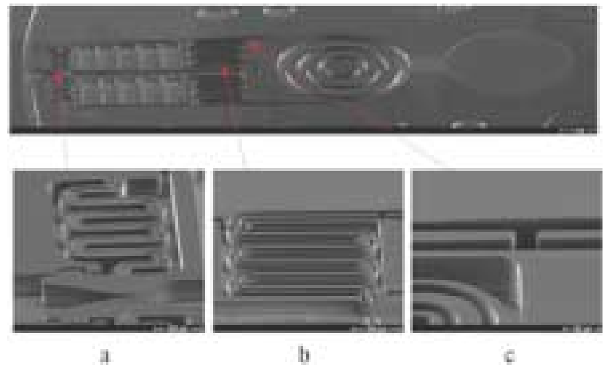

Figure 7: SEM-pictures of one wafer shows spring suspended nozzle with capacitive thrust sensors on its both sides (above). The close-ups shows: a) the front spring with a groove for the conductor to the heater coils, b) the rear spring with two parallel gas channels, c) details of a cross-connection between the gas channels for redundancy.

In order to improve the specific impulse for the cold gas miropropulsion system a heater was needed to allow the system to operate in a hot gas mode. A suspended microcoil heater in the heat exchange chamber for the gas was the solution, figure 8. It is an advanced art of engineering in MST, since the microcoil has to be made separately in a special Lasser-assisted Chemical Vapour Deposition (LCVD) process, and then added by laser welding into the heat exchange chamber just before the nozzle intlet. Different designs with single, double and triple heater filaments in form of conical and cylindrical microcoil has been considered.

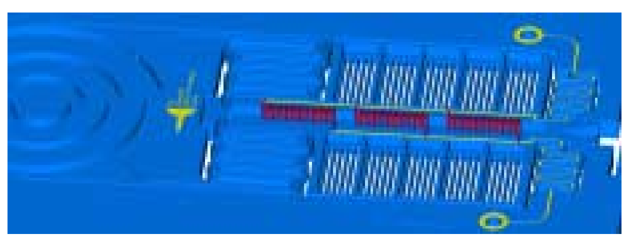

Figure 8: Cross section rendering of the Laval nozzle with triple microcoil heater set-up

The most promising filament (or microcoil) material seems to be Diamond Like Carbon (DLC), figure 9. The LCVD-process turns carbon from ethane into DLC at a temperature between 2000 and 3000 K [6, 7]. The smallest outer diameter of microcoil made at ASTC up to the present is 200 micron, and the wire diameter is 20 micron. The pitch and outer diameter of the coil can be varied along the length of the coil. In the further experiment the DLC coil will be coated with tungsten thin film in a separate CVD process at temperatures between 760 and 1050 K [8].

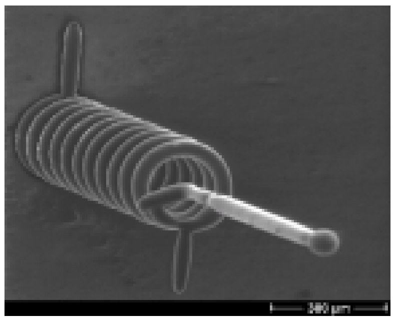

Figure 9: Microcoil filaments of DLC. The smallest outer diameter is 300 micron. The wire diameter is 50 micron. The pitch and outer diameter can be varied along the length.

The demand on high degree of integration requires repeatedly iteration of design. Knowledge in MST-processes, material science, and a good deal of engineering skill is a must in order to success in producing a tiny but high performance system. One example of design change is mentioned above – the FCM-valves instead of PZT-valves. Another example is the added microcoil heater. Many other key parts of the gas handling system, which is the core of the micropropulsion system, have been repeatedly redesigned to make this "final edition" of the system.

Micropyros system

Research on micropyros systems is an ongoing project at ASTC in collaboration with LAAS-CNRS and Lacroix in Toulouse, France; IMT, University of Neuchâtel, Switzerland; Instrumentation & Communication System (SIC) in Barcelona, Spain; and IMTEK, Freiburg University, Germany [9, 10]. The ASTC part in this collaboration is to perform low temperature direct bonding, thin film soldering, and charaterization of the thrust vector.

The micropyros system with its solid propellant exhibits the simplicity in design and very low system mass. Ignition energy is very low, barely few up to tens of milli Joule depending on the ignition material. The expected thrust force is a few mN, and the thrust force is almost digital. As the solid propellant is known for its one blast/reservoir the thrust impulse is to be designed by selection of propellant and the reservoir dimension.

The micropyros system can be used for station keeping of nanosatellites and larger spacecrafts that require limited duration propulsion and thrust, e.g. deployment mechanisms or orbit operations [10].

The design concept is shown in figure 10, in which the propellant is loaded into reservoirs by screen printing technique before the bonding process. It is simple and reliable propellant filling, thus the repetitive thrust force can be secured.

The presence of the solid propellant implies that bonding of the distance part and the igniter part with the reservoir part has to be performed at low temperature. Also for that same reason, liquids or media used in the bonding process have to be non-aggressive to the propellant and the rest of the MST-system. A low temperature plasma activated bonding process, at room temperature up to 200 ^{0}C, has been selected for this specific system.

The plasma activation step is performed before the bonding step, where the wafer in the plasma experiences a maximum temperature of 121 ^{0}C. The plasma does not attack the propellant, or other parts of the MST-system. So far the test bond shows good strength according to the requirements.

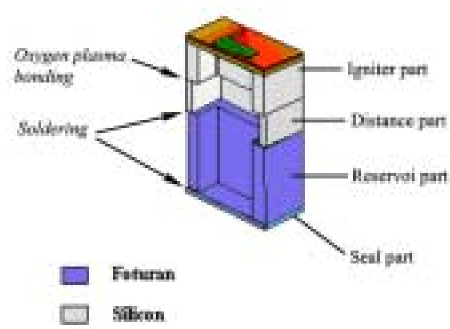

Figure 10: Design concept of a microelement from a micropyros array

Because combustion of the energetic propellant generates high temperature in the reservoir, there is an obvious risk that the propellant in reservoirs nearby can ignite themselves. Silicon is a good thermal conductor, why Foturan-glass has been considered to be used as the reservoir part. The Foturan surface roughness does not admit the direct bonding procedure, therefore thin film soldering is chosen as a viable option. Thin film soldering can be used even between the nozzle part (not shown in the figure above) and the igniter part for the case that the surfaces to be bonded do not allow direct bonding.

For characterization of the thrust vector a measurement equipment, also MST-based, has been developed. The design of the key component for thrust vector measurement is shown in figure 11. The test thrusters array is fixed on the platform suspended by four springs etched out from a silicon wafer. Twelve piezo-resistive sensors, which are strategically placed on the springs, give stress signals that by use of modal analysis can be used to determinate the size and direction of the thrust vector.

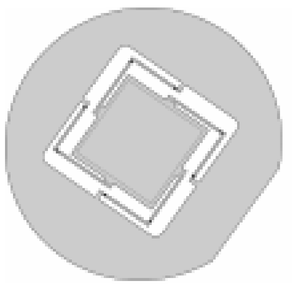

Figure 11: MST-based key component for thrust vector measurement

Xenon feed system

The Xenon feed system developed at ASTC is to be used as the only component between the Xenon storage tank and the ion thruster(s), figure 12 (left). Input to the system is gas from the Xenon storage tank and spacecraft power and data. Output is a well defined gas flow to the ion thruster(s). The only component not included in the Xenon feed system is the fill and drain valve, which should be easily accessible from the outside.

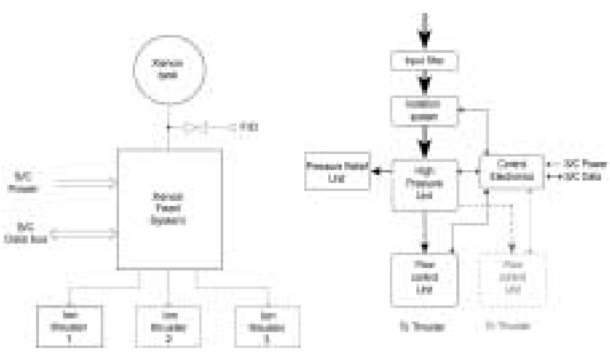

Figure 12: Top level block diagram (left) and block diagram of micromechanical modules in the system (right)

The system will have overall dimension of 52x52x42.4 mm and an estimated weight of 150g. The exploded view of the system is shown in figure 13. Some of the technical data of the system are:

- Supply pressure MEOP: 200 bar
- Mass flow rate: 40mg/s
- Mass flow regulation: From 0-40 mg/s in 40µg/s increment
- Stability: ±1%
- Mass: 150 g
- Power: < 8W
- Operating temperature: -50°/+90°
- Operation life time: 15 years

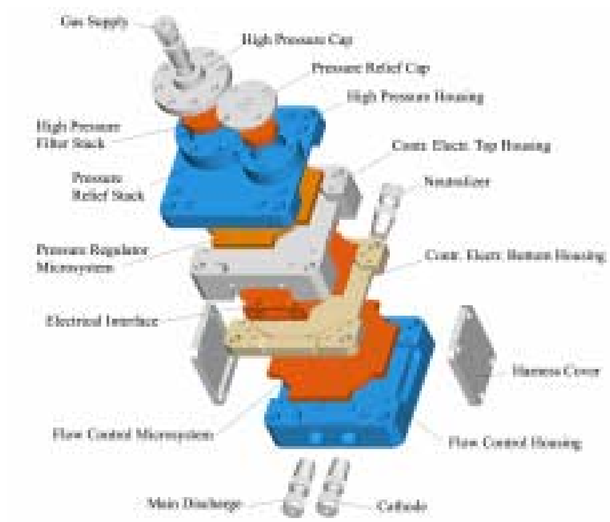

Figure 13: Exploded view of the Xenon feed system

In detail, the Xenon feed system comprises six silicon modules, some passive and other active, figure 13. The block diagram of the system is shown in figure 12 (right*)*. High pressurized gas from the storage tank enters the system through a passive filter stack to the isolation module, which contains a redundant "pyro-valve" set, and integrated high pressure sensors. The high pressure unit in the next step reduces the gas pressure to 2-3 bars. It is composed of two parallel proportional valves in a small closed loop with pressure sensors at the low pressure side. The temperature sensors and heaters are integrated within the module. The passive pressure relief unit is connected to the secondary side of the high pressure unit in order to protect the flow control unit(s) further down the line.

The key component in the Xenon feed system is the flow control unit, which divides the gas into three branches, one branch for each outlet, namely the cathode, the neutralizer, and the main discharge. Each branch is individually controlled, via a closed loop between a flow sensor and a flow regulating device. Each branch also has its own heaters, temperature sensors, pressure sensors, and fine particles filters.

Two different flow regulating methods are under development. They are performed by means of either the PCM-valve or the thermal throttle.

The PCM-valve is a paraffin phase transition actuator, where paraffin is sealed within a closed cavity formed by corrugated membranes, as shown in figure 14. As paraffin melts, the volume increases and will buckle the corrugated membranes, which in turn will seal the valve lid disc against the valve seat.

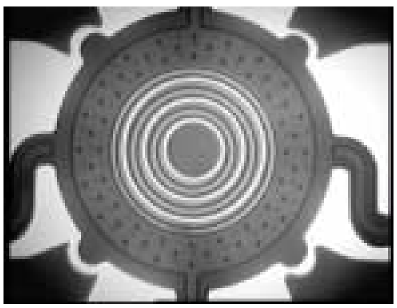

Figure 14: The PCM-valve. The corrugated membranes enclosing the paraffin.

In the thermal throttle heat is applied to the gas, which passes through a narrow heat exchanger, figure 15. As the temperature increases, the Xenon gas viscosity will increase, and thus the mass flow through the device will be reduced. The ducts act both as flow restrictors and thermal radiators transfering the heat into the gas from thin film platinum resistors on the outside of the heat exchanger.

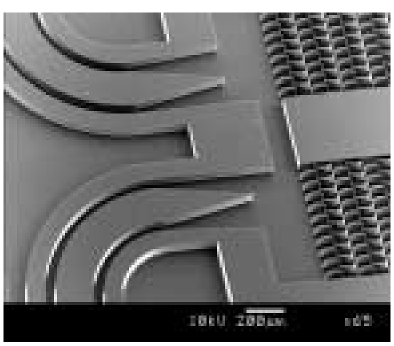

Figure 15: The inlet to the heat exchanger chamber with the narrow ducts.

All system control and data handling are supervised from the control electronic module, which has a direct connection to the spacecraft. The control electronic module also distributes power to the other modules in the system.

One major advantage with the modular concept of the xenon feed system is the possibility to control several ion thrusters from one feed system By connecting several flow control units to the same high pressure unit several ion engines can be simultaneously supplied with gas. The control electronic module must be designed to fit the number of thrusters.

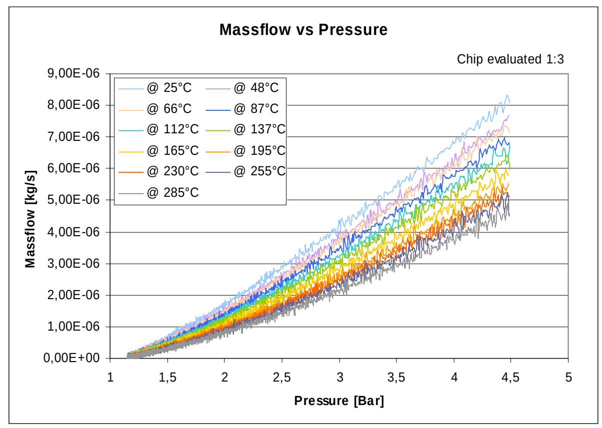

Figure 16: Mass low as function of pressure at different temperatures

Some performance evaluations of one of the flow regulating devices have been performed. The graph in figure 16 is the results from the first test, which indicates that the thermal throttle device does modulate the flow. A higher temperature results in lower mass flow. However, even with an unheated gas the device does not yet meet the specifications of 40mg/s.

Different levels of integration

In order to provide very small micropropulsion systems with high system specific impulse, one has to heavily miniaturize and integrate all the parts and subsystems into one unit. The question here is how to do it with respect to the limited mass and volume of the system. MST can elegantly solve this major miniaturization problem. However, integration is not only a technology issue, but also a course of action.

The integration issue can be divided into five levels:

- Wafer integration
- Wafer-to-wafer integration
- Device integration
- MST-modules-to-housing integration
- MST-system to spacecraft integration

1. Wafer integration

Wafer integration is simply about how to put a suitable selection of system parts on one silicon wafer. At this level the integration method starts from a plain silicon wafer and processes through various MST-processes, such as pattern transfer, etching, deposition, implantation. The result obtained is a processed wafer, in which entire subsystem or a number of parts of a subsystem are made. The material of choice is the silicon. Etching is the most frequent micromachining process in MST using silicon as the bulk material and therefore shapes are limited. Focused Ion Beam (FIB), laser assisted machining and deposition methods are more exotic and expensive, but they can achieve more demanding 3D-shapes, like channels or nozzles with truly rotation-symmetric cross section, or conical microcoil heater.

At the planning stage of the system parts requirements, shapes and sizes have to be sorted out, matched to fabrication processes. The system design has to be iterated; reconsidered again and again. Once the masks for pattern transfer are drawn and the manufacture process started, it will be expensive to make any change, since change often means restarting the mask design.

2. Wafer-to-wafer integration – bonding

An advanced MST-system, especially when it contains parts and sensors in layers, and cavities or channels with closed cross section, requires bonding of processed silicon wafers. In addition, by bonding them together many mechanical and electrical connections can be made simple and reliable. Furthermore, the wafer stacks provide much better mechanical strain and higher vibration resistance than a single silicon wafer.

By bonding wafers together a number of parts with channels up and down inside the stack, without connection and sealing can be formed. Even zero-level packaging is not needed. Often the wafer on top and bottom of the stack have they own structures on one side, but the top and bottom side can be plain, and serves as the protection layers for the stack. Thus, no further packaging is needed.

High temperature direct bonding [11], above 800 ^{0}C, that requires about 3 hours annealing, normally is employed unless the thermal budget of parts on the wafers disallows this. In this case plasma activated low temperature direct bonding [12], with annealing at room temperature and slightly higher, for up to 100 hours, is the right process. Bonding of multi wafer stack put a higher requirement on bond alignment apparatus because of the double side alignment and the variable thickness of the stack.

3. Device integration – adding obtainable subsystems to your system.

Since different microcontrollers and available electronic parts in form of naked chips are used in the electronic control systems, the natural way is to add them by soldering on a separate control stack or into the processed stack. Here the silicon wafer has superceded the printed circuit board. The line width on the silicon wafer can be adapted to connection pads on the naked chips much easier and the thermal expansion of those hybrids and the carrying wafer is perfectly matched as they all are made from the same material. Figure 17 gives an idea about an MST-based system in comparison to an equivalent conventional system.

Another example on device integration is the suspended microcoil heaters in the hot gas micropropulsion system. The DLC microcoils are manufactured in a high temperature LCVD process (2000 - 3000 K). At this temperature the wafer would be seriously degraded. One preferable integration method is laser welding the coils in the heat exchange chamber in one silicon wafer, just before the outlet of the de Laval nozzles [1].

Figure 17: Left: CON Unit of SMART-1, State of the Art design. Total of ~ 200 ICs, mass: 9.2 kg, dimensions: 259x286x208 mm. Right: 3 MMS Modules includes all components of the CON unit and also discrete components, resistors, capacitors, etc. Total weight: ~120g, size: 74x74x22 mm. Reduction: 70 times in weight, 120 times in volume.

4. MST-modules-to-housing integration

The next integration level after obtaining a MST-system in a silicon wafer or wafer stack is to put them in a protective housing or supporting framework. A single silicon wafer is too fragile to be used as a building stone, particularly when it contains deep etched structures. When it is properly assembled in the protection frame they can act as a main wall or a supporting framework in the spacecraft.

Silicon multi-wafer stacks are mechanically strong enough to be used as a construction material, but its brittleness also requires a special mechanical protection. It has to be fixed firmly in its housing or framework without direct contact with the metal. (The most frequently metal used is Aluminium AA7075.) The stack can be supported on both sides by o-rings or by mould curing directly in the housing, figure 18. Occasionally screw joint reinforcement is used with rubber tube insulation or o-ring insulation.

A thin rubber support is a main type of interface between the silicon wafer stack made by MST and the aluminium housing made by conventional technology with very narrow tolerance. Both curing and screw reinforcement call for special assembly fixtures in order to avoid bending when tightening. The most important feature in mechanical assembly of silicon wafers or wafer stacks is that only symmetrical pressing force is applied on them from both sides. Assembly methods which result in bending of silicon wafer are devastating for this brittle material.

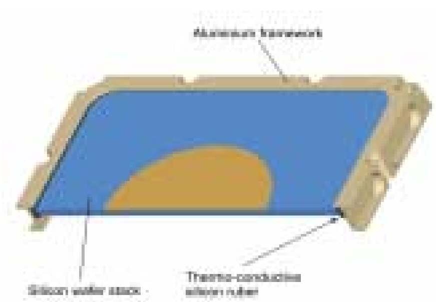

Figure 18: Cut view: The assembly of silicon wafer stack can be made by mould curing directly in the supporting framework

5. MST-system to spacecraft integration

The last integration level is rather straightforward. This is how to attach the MST-system to the spacecraft with its conventional interfaces for power, gas supply, and interface for signal exchange. The most preferable method is to use standard conventional but space certified joint elements, such as screws, screw plugs for tubing connection, instantaneous coupling, etc. Two objectives, which can be achieved by using conventional joint elements, are easy handling and space-proven technology.

Summary

The presented microsystems for space application are still under research and development (R&D). There many parts of the systems have been manufactured and tested. Nevertheless, the systems exhibit high potential for use on nanosatellites and larger spacecrafts, which require small thrust and short thrust duration. Some reflections from R&D of miniaturization of the micropropulsion systems are:

- When working on Nano- and smaller satellites we have no choice to avoid MST-systems.
- MST-systems are applicable even for larger spacecrafts.

And some reflections regarding integration are:

- When using MST-modules, packing and connectors inside the modules becomes obsolete.
- The MST-modules need special solution for assembling in macro components (housing)
- Standard joints should be used to attach the module housing to the spacecraft

As the trend of space activities worldwide points to the smaller missions, the cost of the spacecrafts, the launch, etc. has to be kept tight. Manufacture of MST-based spacecrafts needs neither a huge industry site, nor a giant launcher to put them on orbit. It is believed that it is only a matter of time before this high-tech will be proven in space. The technology itself is not a sensation today, but the implementation in the space technology needs a paradigm shift, both in belief and in design. Faster-better-cheaper missions [13] need MST – the next step that we have to take.

References

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