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Catalyst Microsystem Design and Manufacture for a Monopropellant Microrocket Engine

J. Bejhed[1], R. Lindegren[1], R Thorslund[1] , J.R. Wallbank[2], , A. M. Baker[3], L. Stenmark[1], J. Köhler[1]
[1]ÅSTC, Dep. Engineering Sciences, Uppsala University, Box 534, SE-751 21 Uppsala, Sweden
[2] Chemistry Division, Surrey University, Guildford, United Kingdom
[3]Surrey Satellite Technology Ltd, Guildford, United Kingdom

Abstract

The catalyst bed in the proposed Micro Electro Mechanical Systems (MEMS) monopropellant micro rocket engine is one of the key components under development. A honeycomb structure, with deposited Silver or Manganese Oxide, will serve as the catalyst bed for Hydrogen Peroxide decomposition. Included in the catalyst bed are heaters integrated, to facilitate ignition of the engine. Critical design parameters, such as heat generation and through put has been investigated. Some single catalyst bed chip where manufactured to find an appropriate process. The manufactured chips where evaluated in terms of through-put and deposition of catalyst material. Resulting in a feasible manufacturing description of the catalyst bed has been developed.

Keywords: MEMS, catalyst, monopropellant, hydrogen peroxide, rocket, silicon

1. INTRODUCTION

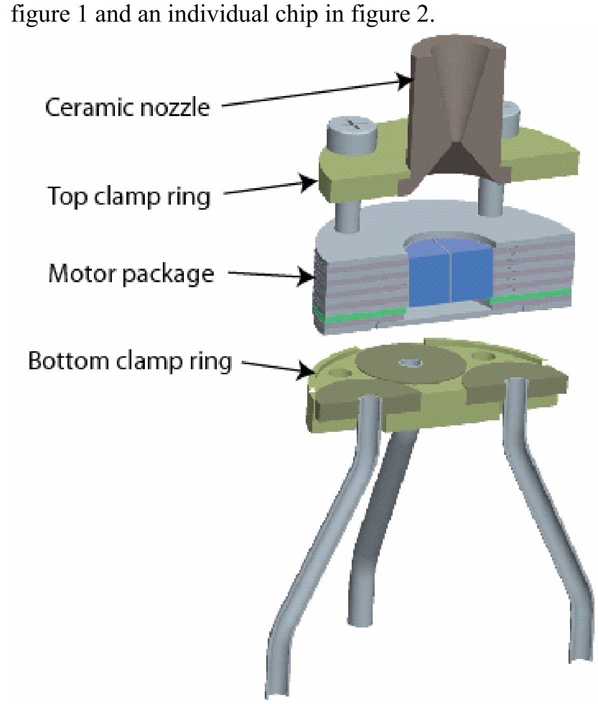
Many low-cost space missions suffer from problems associated with securing a precise orbit injection from the launch vehicle, often as a result of a shared or secondary launch, leading to a compromised orbit. Furthermore, requirements for constellation forming, LEO drag compensation, maneuverings for satellite inspection, formation flying, and end of life deorbiting indicate a need for significant ΔV capability in small spacecraft, ideally coupled with high thrust levels (up to 1N) to minimise energy losses. Conventionally engineered propulsion systems can deliver performances in the 100m/s ΔV range [1], but these are typically expensive solutions, using toxic propellants, and, in many case, do not scale favorably to the smaller sizes demanded.
The current study team have identified a near-term performance gap in the market for small satellites, defined by the lack of proposed systems which could provide an Isp in the range 100-300s. A candidate technology, with the potential to fill the identified performance gap for micropropulsion systems in the near future, is that of a high-thrust MEMS-based monopropellant microrocket engine. It is such a concept which is being pursued by this study team.

Earlier studies suggested Hydrogen Peroxide as the preferred propellant, from a detailed trade-off [2.]

The microengineered catalyst bed was identified as critical component and chosen for device demonstration. Thus, the ongoing development of a monopropellant microrocket engine has made a dedicated effort to realize a catalyst microsystem for decomposition of hydrogen peroxide. The bulk material is silicon, and the current baseline catalyst material is silver. An option to replace the catalyst material with manganese oxide is under development. Previous work on catalytic combustion microrockets includes the NASA Goddard Centre of Space Flight [3].

2. CATALYST DESIGN AND MANUFACTURE

The catalyst bed comprises eight small catalyst chip, bonded together forming a 4.2 mm high stack. Liquid hydrogen peroxide are inserted through the fluid handling wafer and decomposed in the catalyst bed, streaming up towards the nozzle. In between every second wafer a heater is incorporated, rising the temperature to facilitate ignition of the engine. The whole stack can be seen in figure 1 and an individual chip in figure 2.



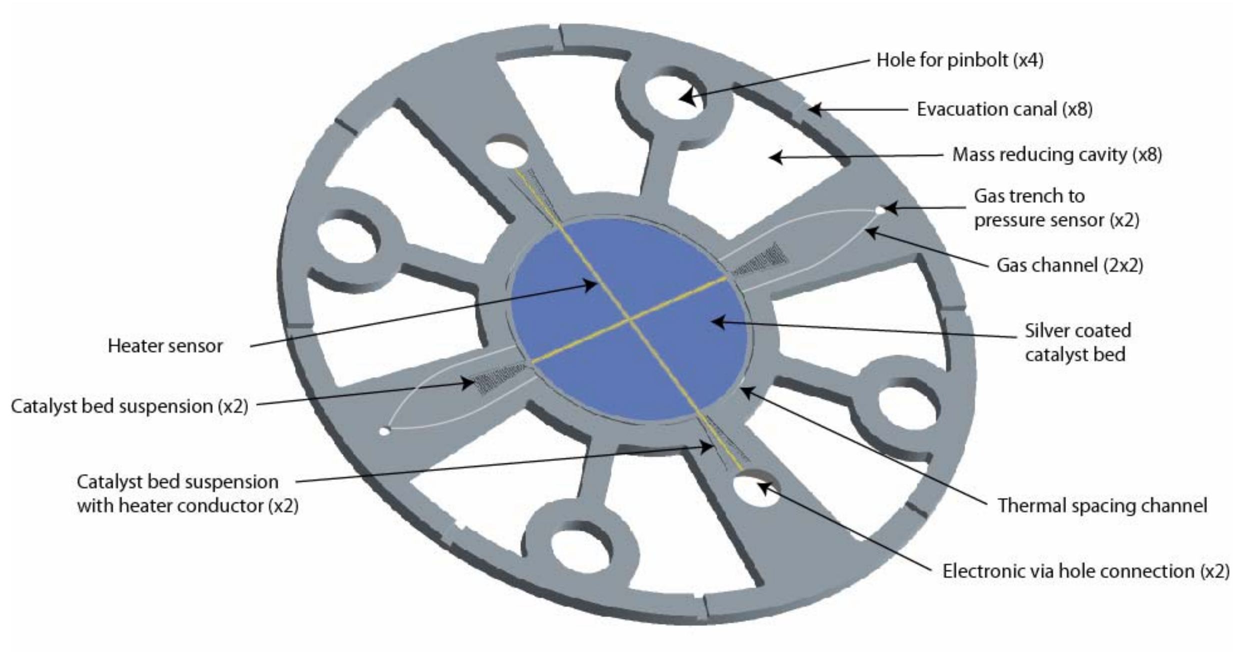


Figure 2: Catalyst wafer overview. All different functional parts are indicated. Eight similar small wafers are laminated in order to form a catalyst pack. The darker circular area in the middle contains the honeycomb structure, carrier of the catalyst coating. The honeycomb structure is suspended by four struts from the surrounding bulk silicon structure, enabling reduced thermal conductance from the device.

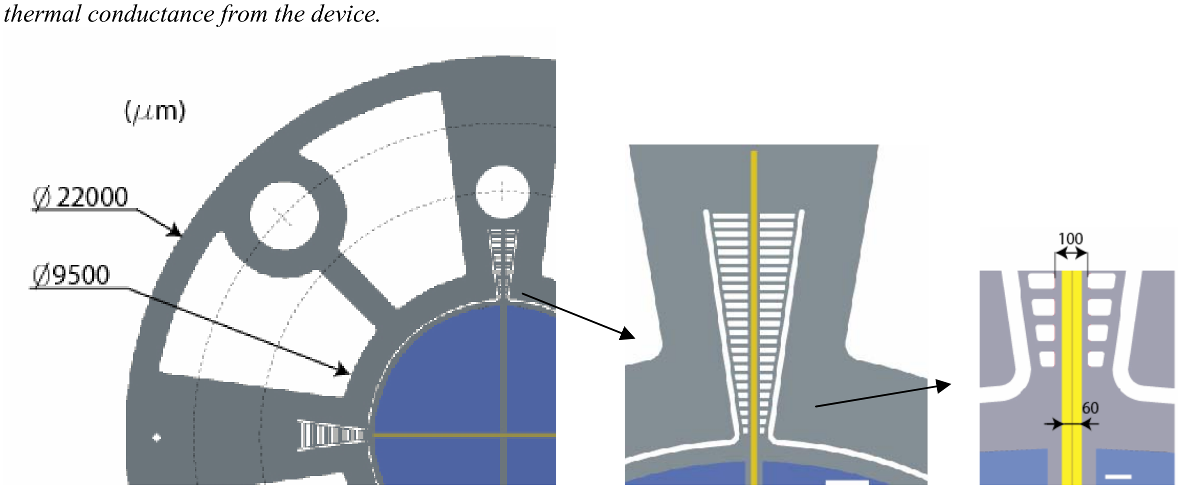


Figure 3: Detailed design of the catalyst wafer. All dimensions are in micrometers. Each wafer is 525 micrometers thick.. From left to right: 1. The overall dimensions of the catalyst bed. 2. The details of a suspension strut containing a heater path. One pair of struts has this feature, whilst the other pair has not. 3. Fine details of the strut interface to the catalyst bed structure.

2.1. Suspended silicon catalyst bed

The catalyst bed is suspended on very thin, perforated arms, etched in the silicon wafer, in order to minimise conductive losses between the catalyst bed and the bulk of the microrocket engine [4] . Moreover, the heat sink of the bulk material around the decomposition chamber was reduced by removal of unnecessary material.

The inner structure has through-etched holes in a honeycomb structure. The dimensions of the honeycomb structure are selected to give a large contact area of the catalyst bed, but still avoid large flow resistance. To serve as a catalyst, the inside of the holes is coated with a thin-film catalytic material. There are a total of eight bonded wafers in the catalyst bed design where every other contains Cr-Pt heaters. These four heaters are connected in a parallel circuit by through-etched via holes. Initially, a voltage is applied, raising the temperature to facilitate ignition of the engine. Once ignited, the heat generated from the decomposition will be sufficient to maintain the process.

The honeycomb structure suspension consists of four perforated beams. This perforation is reducing the thermal flow from the inner structure. The wafers are direct-bonded in pairs to seal the heaters from the propellant. Four pairs are then bonded to form the complete catalyst microsystem.

2.2. Catalyst deposition

Silver or manganese oxide will be used as catalyst to accomplish the hydrogen peroxide (HTP) decomposition.

A) Electroless Silver catalyst (from Ploykomposit AB) has been successfully deposited in the honeycomb structure, showing excellent conformal coating and deposition selectivity. The electroless silver process is selective and will only adhere to silicon. This makes the pre-patterning of the silver straightforward, using standard lithography. The electroless deposition is autocatalytic, with a deposition rate of about two microns per hour. The surface roughness increase with increasing thickness, but below ten microns the surface more or less mirrors the substrate surface. Up to two microns thick silver coatings has been tested in this present experiment. The adhesion of the film -as deposited- was tested with the common tape-test. This yielded 100% positive results, i.e. no part of the silver coating could be removed by scotch tape. The adhesion will increase further by a thermal treatment at 900°C. Hereby, a strong eutectic Si/Ag interface is formed.

B) Manganese oxide catalyst As an alternative to electroless Silver, initial progress has been made on different Manganese Oxide CVD coatings. Due to the high temperature, combined with the rapid diffusion of silver in silicon, an alternative to silver might be required. Also, Mn-oxide has a very suitable thermal expansion coefficient. Development of a CVD process compatible with the required micro machining processes is addressed.

2.3. Thermal issues

For the decomposing hydrogen peroxide monopropellant microrocket engine concept, silicon can safely be used without concerns over issues such as creep in the high temperature environment. Detailed thermal analyses have been performed for both transient and steady-state heat flows within the system, in order to confirm this.

From a MEMS fabrication point of view, silicon is a well-understood material with a mature status in terms of developed micromachining processes (e.g. masking, etching, diffusion bonding etc). Silicon offers good potential for the monopropellant microrocket engine concept. However, silicon is known to suffer from reduced strength at elevated temperatures, why the temperature in the catalyst bed should not exceed about 675°C.

3. RESULTS

One wafer containing many individual catalyst beds has been manufactured. The chip where manufactured without the Cr-Pt heater. A picture of a catalyst bed can be seen in figure 4, and more in detail in figure 5.

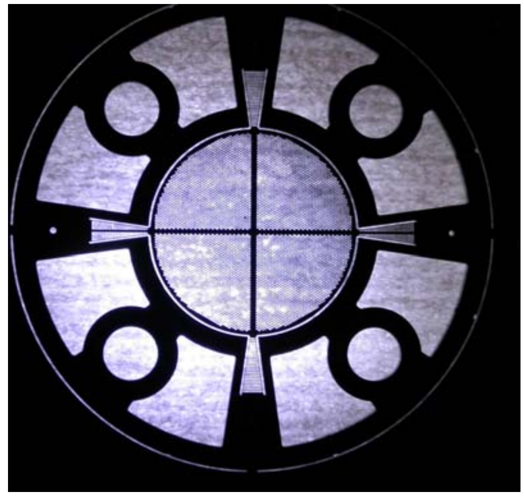


Figure 4 – A top picture of the catalyst bed wafer which is illuminated from below. It can be seen that the vertical suspending beams, in difference to the horizontal, lack heater conductor beams. Outside the horizontal suspending beams the electrical via hols can be seen.

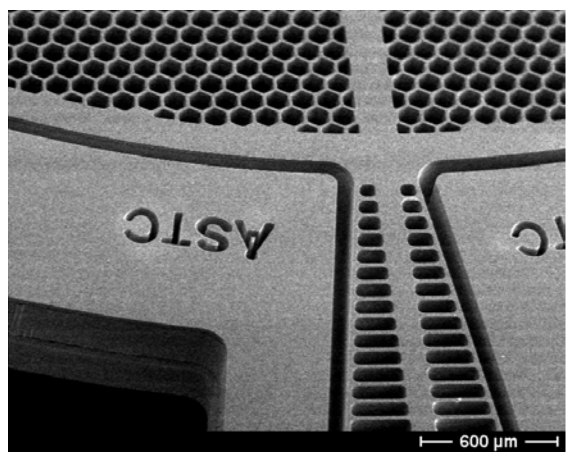


Figure 5 – A SEM picture of the honeycomb suspending beam. The conductor pattern is clearly visible, but not metallized. The thermal spacing surrounding the honeycomb structure is 50µm wide.

The mass flow for nitrogen through a single catalyst chip, at room temperature and inlet pressure 4 bars, has been tested to be at least 2.5g/s as an average value. This is sufficient for the current micro engine design, and may even be too high flow capacity, due to low residence time of the propellant in the catalyst channels. However, the design leaves ample room for tuning the flow resistance to order by decreasing the dimensions of the hexagonal cells. The mass flow will reduce significantly with increased length of the catalyst cells, raised temperature of the structure and the gas, and with higher viscosity of the product gases.

Some test chips where used to investigate the electroless silver plating. The initial result from silver plating is very promising. One catalyst bed was diced opened and the silver coverage inside the honeycomb structure was investigated, as shown in figure 6 and 7. It revealed a uniform coverage despite minimal process optimization However, this process was evaluated on a single chip with a thickness of 525µm. This must be scaled up to a thickness of 4.2 mm.

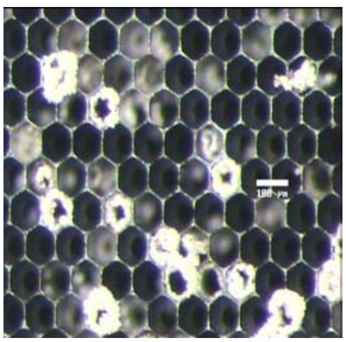


Figure 6: Granular deposits at the pipe orifices. These are normally removed using a pumped electroless plating setup.

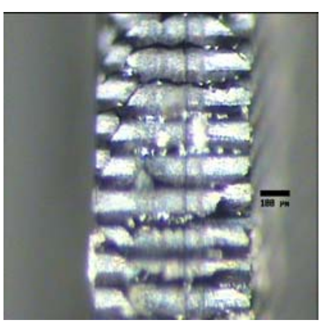


Figure 7: Cross-sections of the catalyst bed structure, showing the conformal silver coating achieved by non-pumped electroless plating. The cross section is made by cleaving, which leaves a very rough section. The bright, reflecting surfaces are silver.

4. CONCLUSIONS

The critical item of the catalyst in a monopropellant microrocket engine has been described in detail. Overall, a feasible manufacturing description has been developed.

Some of the manufacturing processes has been evaluated with success. Further investigation to enable silver coating through 4.2 mm long, thin, channels requires some process optimization.

Due to the difficulties to verify the flow rates through the catalyst bed, at these temperatures, it is reasonable to ensure a large enough mass flow through the device. The catalyst bed is therefore over-dimensioned. The flow are limited in the injector in the fluid handling wafer.

ACKNOWLEDGEMENT

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