CERAMIC COLD GAS MICROTHRUSTER WITH INTEGRATED FLOW SENSOR

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Abstract: For aggressive environments, the material properties of silicon become a limitation. Macroscopically, ceramics are as common for high-temperature applications as is silicon in miniaturized systems, but this group of materials has been little exploited for MEMS components. This paper describes the design, manufacturing and characterization of a ceramic, heated cold-gas microthruster with integrated flow sensor, using HTCC processing and silicon tools. The calorimetric flow sensor is integrated in the structure, and heaters are embedded in the stagnation chamber of the nozzle. The heater was shown to improve the efficiency of the thruster, as confirmed by measurements of the flow rate. Flow rate changes were seen as changes in resistance of the fabricated flow sensor.
The choice of yttria stabilized zirconia as material for the components make them robust and capable of withstanding very high temperatures. Samples have been shown capable of achieving temperatures locally exceeding 1000ºC.

Keywords: Zirconium dioxide, YSZ, HTCC, high-temperature MEMS, microfluidics, microthrusters

INTRODUCTION

Silicon MEMS components are used in a wide variety of applications in almost all areas: commercial, industrial, military, scientific, etc. However, for hot or otherwise aggressive environments, e.g., fuel cells, combustion engines, aerospace and processing industry, silicon cannot be used. The material properties of silicon can also reduce the functionality of the component.

For example, higher temperature in the stagnation chamber of heated cold gas microthrusters will increase the specific impulse, i.e. the efficiency of the thruster [1]. This reduces the fuel consumption of the spacecraft, and can be used to decrease its launch weight or increase its operational lifetime, or both.

Calorimetric flow sensors [2] measure heat transferred from a central heater to adjacent resistive thermal sensors by gas flowing by. The transferred heat is related to gas composition, flow rate and direction. Here, too, higher temperatures of the central heater can improve performance of the device.

Macroscopically, ceramics are frequently employed for high-temperature applications, but, largely due to the lack of means for high-resolution structuring, this group of materials hasn't been widely exploited for MEMS components. Previous work [3] has shown how silicon tools can be used for microstructuring and microfabrication of yttria-stabilized zirconium dioxide (YSZ), which, combined with standard HTCC processing [4], can be used to fabricate complex microcomponents, suitable for high-temperature applications.

This paper details the application of silicon-based manufacture processes in the fabrication of ceramic microthrusters, figure 1, with embedded heaters, and integrated calorimetric flow sensor. The functionality of the thruster is demonstrated, and the influence of the heaters with respect to flow rate is studied. Measurements from the calorimetric flow sensor is compared with those from a commercial device.

MATERIALS AND METHODS

For this study, YSZ8 tape from Electroscience Laboratories (ESL) was used in thicknesses of 15 and 125 µm (ESL 42400 and 42401 respectively). This tape was chosen for its very small grain size, which allowed for high-resolution patterning. Silicon tools for punching and embossing were fabricated using photolithography of aluminum-coated silicon followed by deep reactive ion etching (DRIE) [3].

The tools were designed for punching of channels, interfaces, vias for electrical connections, and embossing of a microthruster. Metallization was accomplished by screen printing of platinum paste (ESL 5542).

Microthrusters were manufactured from four tape layers, figure 2, with a bottom, unpatterned, layer for increased stability, a layer with printed heaters (3 patterning steps), the channel layer (6 patterning steps), and a top, sealing, layer (3 patterning steps). The channels were then filled with fugitive material (ESL 49000), and the layers aligned and laminated, using a multilayer press (Bungard, Belgium). The resulting stacks were sintered at 1450ºC for 90 minutes.

Gas was fed to the thruster through tubes glued to the components with epoxy to ensure mechanical and pneumatic integrity. A pressure transducer (Swagelok, USA) followed by a mass flow sensor (Honeywell International Inc., USA) monitored flow to the thruster. Electrical connections were accomplished by probing.

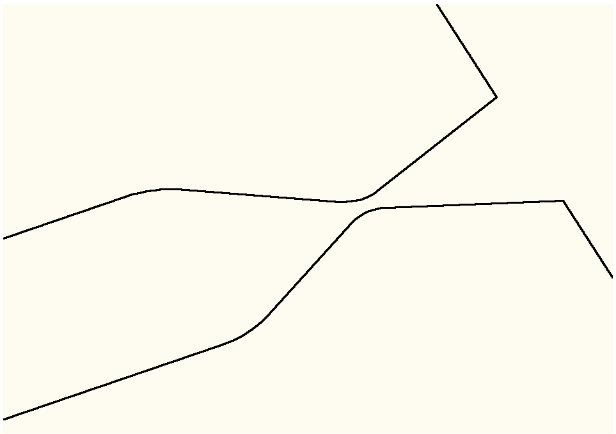


Figure 1. Crop from CAD image of nozzle. Width is 350 µm at nozzle exit (top right), and 40 µm at the throat.

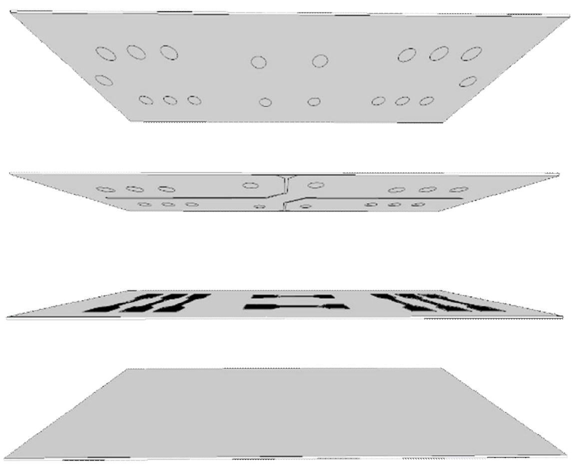


Figure 2. Exploded view of the thruster chip design. Bottom layer is unpatterned, second layer is printed with sensor and heaters, third layer has embossed thrusters and fluid channels, as well as vias for electrical connections. Top layer has vias and gas interfaces. The size of the thruster is 25×10 mm.

Complete thrusters, as well as component samples, were studied using microscopy, thermal imaging, and flow measurements. Studies of the effect of the heaters were conducted by varying power to the heater (0.6, 1.1, and 1.6 W) at a fixed feed pressure of 0.5 bar, while monitoring mass flow. Characterization of the calorimetric sensor was done by measuring the resistance of the down-stream conductor while varying flow rate, and keeping the power of the central heater constant at 0.5 W. This resistance was then plotted versus time.

RESULTS

When sintered, the YSZ8 tape shrunk approximately 20-25% in all directions, figure 3.

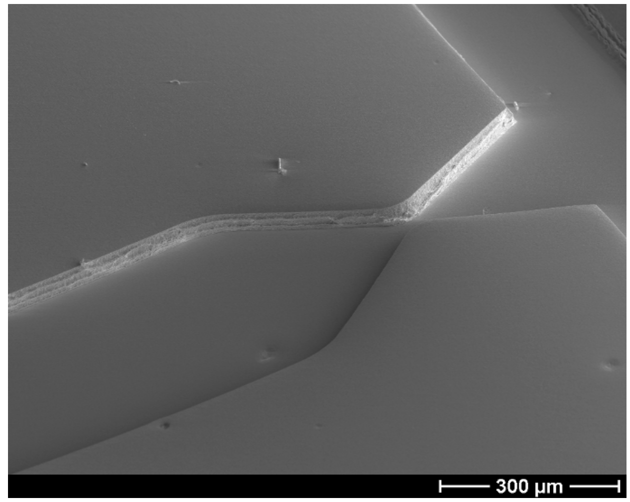


Figure 3. SEM image of unsealed microthruster nozzle.

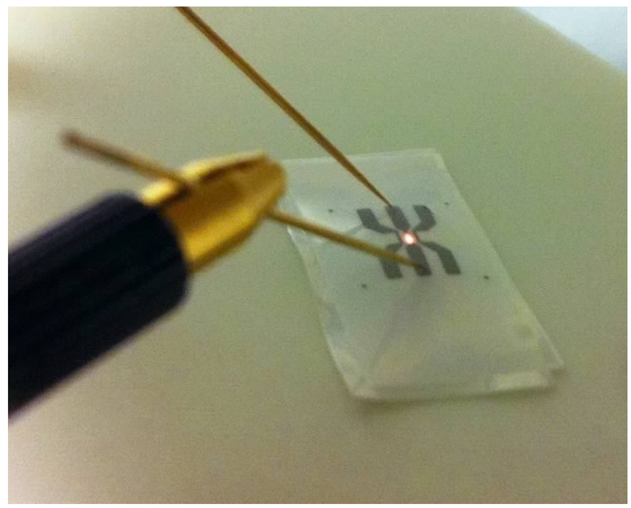


Figure 4. Photograph of surface flow sensor structure, with central heater at 1000°C.

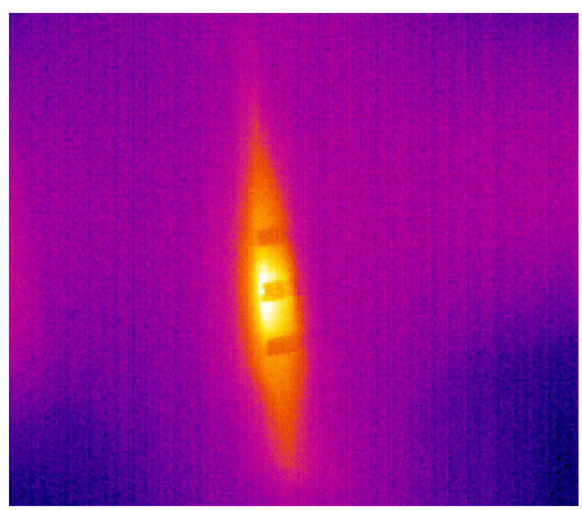


Figure 5. Thermograph of flow sensor. Visible is the heat transfer in a channel from a central activated heater. The heaters are 200 µm wide.

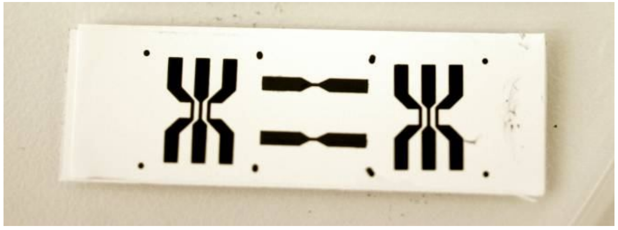
Partial samples were studied and shown to operate with local heating above 1000ºC, figure 4. Thermal imaging of the heaters in a silicon covered PDMS channel showed transfer of heat from the central heater, figure 5.

Measurements of the flow rate from the thruster showed a decrease in mass flow with increased heater power, table 1.

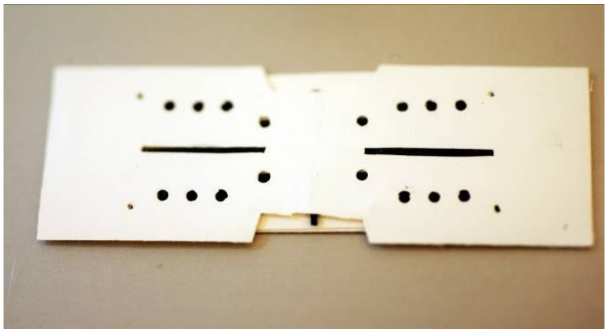
In the finished, sealed, YSZ components, the heat transfer was measured as a change of resistance in the neighboring conductor. Figure 6 shows the conductor layer, with two sets of three conductors for the flow sensors, and two heaters for the thrusters, and the stack before the top layer is applied. The resistance change was plotted versus time, figure 7, with a flow of 180 sscm nitrogen turned off at t = 20 s, and back on at t = 75 s.

Table 1. Mass flow reduction at different heater power in the thruster.

Heater power (W)	Mass flow reduction (%)
0.6	1.6
1.1	2.0
1.6	4.2



(a)



(b)

Figure 6. Conductor layer, (a), and fluidic layer, (b), of the microthruster. Length is 25 mm, width is 10 mm.

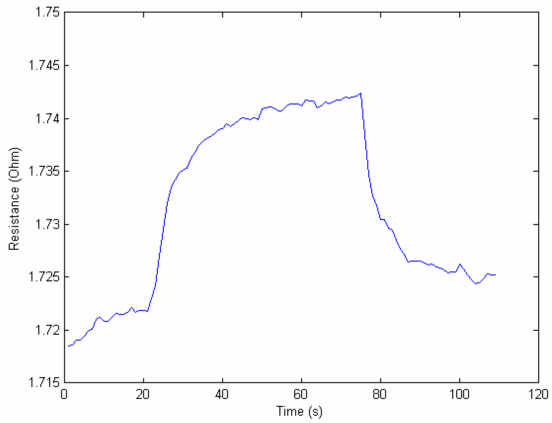


Figure 7. Resistance of the flow sensor wire plotted versus time. At t = 20 s, a 180 sscm flow of nitrogen is turned off, and at t = 75 s it is turned back on.

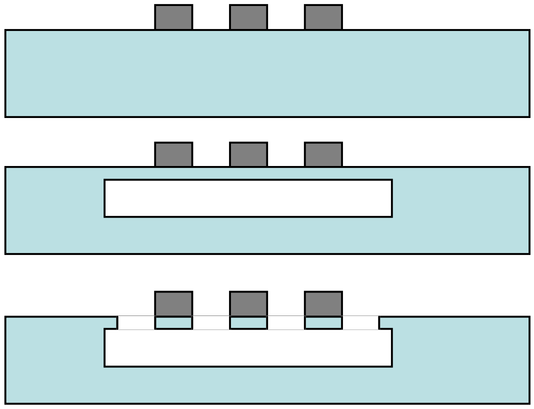


Figure 8. Cross section of three different flow sensor designs, with increasing thermal insulation. Gray is platinum, blue is YSZ. Conductors printed directly on substrate (top), on a membrane (middle) and on bridges (bottom).

DISCUSSION

The method of fabrication used for these thrusters is scalable for larger quantity production, and offers the possibility of prototyping of single components at a reasonable cost. For this study, tools developed for single components were modified and combined to fabricate larger, more complex components. A redesign of the silicon tools, and screens for metallization would have reduced the number of necessary steps for each layer, thereby simplifying the manufacturing process considerably, and improving the layer alignment.

In the current design, the heaters are printed directly on the YSZ substrate without dielectric layer. YSZ becomes conductive at higher temperatures, generally requiring an insulating layer around conductor paths. Since the heaters are straight and only powered in short periods, this is not expected to have affected the resistance of the adjacent conductors.

Besides, any power lost to the immediate surroundings will contribute to heating of the gas in the channel.

Zirconium dioxide has the advantage over silicon of much lower thermal conductivity, reducing the risk of cross-talk in the substrate. In order to further increase the sensitivity of the flow sensors, the material under the heaters can be minimized, e.g. by printing on a thin membrane, rather than directly on the bulk substrate. Also, the paths can be separated by fabricating bridges, figure 8.

The difference in resistance in the sensor wire, figure 7, may seem small but represents a temperature change of several degrees. For performance improvement, the measurement can be differential using also the upstream sensor.

It should be emphasized that both in the case of the flow sensor and the heaters, the limitations of the materials have not yet been reached, and further improvements can be made by increasing power even further. The results from surface sensors, figure 4, support this.

Whereas the limits of performance of microthrusters fabricated in this fashion is far from exploited, the prospect of integrating e.g. flow sensors in current electronics enclosures or solid-oxide fuel cells makes this a promising material in MEMS and microfluidics. Although a thermoelectric flow sensor will see a decrease in performance at elevated ambient temperatures, the survivability of the component at extremely high temperatures is very useful.

CONCLUSIONS

The results of this study has demonstrated a means of high-resolution MEMS fabrication of YSZ8 tape, and the integrity and function of the resulting components.

- Design and fabrication of a ceramic heated cold-gas microthruster with integrated flow sensor is possible.
- The suitability of YSZ8 for high-temperature microcomponents has been demonstrated.
- Embedded heaters improve efficiency of the thruster by decreasing mass flow.
- Channels for microfluidics created by embossing and lamination remain unobstructed and sealed.
- Components survive being heated locally above 1000ºC.

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REFERENCES

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

[2] M. Elwenspoek, *Proceedings Semiconductor Conference 1999*, vol.2 pp 423-435

[3] Ville Lekholm, Kristoffer Palmer, Fredric Ericson, and Greger Thornell, *Proceedings PowerMEMS 2010*, pp. 291-294

[4] Yoshihiko Imanaka, *Multilayered Low Temperature Cofired Ceramics (LTCC) Technology*, Springer NY, 2005