

Reliability of freestanding polysilicon microheaters to be used as igniters in solid propellant microthrusters

Danick Briand*, Phuong Quyên Pham, Nicolaas F. de Rooij

Institute of Microtechnology, University of Neuchâtel, Rue Jaquet-Droz 1, P.O. Box 526, CH-2002 Neuchâtel, Switzerland

Abstract

This paper presents the design, fabrication and characterisation of surface micromachined polysilicon microheaters to be used as microigniters for micropropulsion applications. The microigniters are heated up by Joule effect and the thermal losses through the substrate are minimised by suspending the microheaters above the substrate. The developed process was compatible with the integration of the nozzle part of the microthruster. The electrical, thermal and mechanical characteristics of the microheaters were studied with the aim of evaluating their reliability. Temperatures up to 470 °C could be reached with an electrical power of 45 mW/beam. The current–voltage relation followed a linear characteristic at low power; at high bias voltages, a drift of the electrical resistance was measured after a few I – V cycles at power higher than 40 mW/beam. The elastic and plastic deformation threshold of the microheaters in operation and their maximum deflection before rupture were measured. The microheaters could dissipate relatively high constant powers for a few minutes to hours. The fabricated microheaters are promising candidates for the ignition of solid propellant microthrusters.

Keywords: Microheater; Microigniter; Polysilicon; Microthruster; Solid propellant; Surface micromachining

1. Introduction

The miniaturisation of huge spacecrafts into micro- or nano-spacecrafts has led to the development of micropropulsion systems. Their integration in microspacecrafts offers considerable advantages in terms of downscaling, mass and volume reduction as well as mission costs lowering. Several solutions are investigated, such as solid propellant microthrusters [1–4], cold-gas microthrusters [5,6], field emission electric propulsion (FEEP) [7], bi- or mono-propellant microthrusters [8,9] or vaporising liquid microthrusters [10]. By combining MEMS technology and energetic material science, large quantities of energy can be obtained. In this perspective, solid-state propellant microthrusters have been developed. Compared to other solutions, solid propellant microthrusters present the following advantages: no liquid fuel leakage due to the use of solid propellant, no moving parts and ignition possible with a low power consumption. Their single-shot characteristic can be compen-

sated by an array configuration of the micropropulsion system [11].

The ignition of the solid propellant is triggered by the microigniter, which usually consists in a Joule effect microheater. Due to the major role played by the igniter in the device functioning, special attention should be paid to its design and to its characteristics in order to achieve a successful ignition. Joule effect microheaters as microigniters have been reported in the literature: polysilicon microheaters thermally insulated from the substrate by means of a thick dielectric membrane [2], polysilicon heaters on a thin dielectric membrane and fabricated by bulk micromachining [11,15], platinum/titanium microheaters on a diaphragm [3] or nickel chromium aluminum copper wire inserted in a slot of the microthruster [4]. All these methods present some drawbacks. In [2], the power consumption is relatively high to an insufficient thermal insulation of the igniter from the substrate. In the case of igniters on membranes, low-power is ensured but filling of the igniter with propellant becomes problematic, ignition success rate is an issue and debris are created due to the breaking of the membrane during the combustion [3,11]. Despite that polysilicon exhibits a long term drift of its electrical resistance at relatively high temperatures [21],

* Corresponding author. Tel.: +41 32 720 5564; fax: +41 32 720 5711.
E-mail address: danick.briand@unine.ch (D. Briand).

it remains a suitable heating material for the micropropulsion application due to the short time required to ignite the solid propellants. Depending of the solid propellant used, the ignition time is in the order of a few to few hundreds of milliseconds.

The exploitation of polysilicon surface micromachining have been mostly performed for mechanical and electrostatic micro actuators and sensors [16,20]. The surface micromachining of polysilicon as heating element has been reported lately [17–19]. Beside the work we have been performing on this topic for application in the field of PowerMEMS [17], surface micromachined polysilicon igniters exhibiting high power consumption have been integrated in a gas turbine microengine [18]. In micro-satellites the electrical power available is limited and moreover it can be needed to fire several thrusters at the same time to obtain the thrust profile needed for a given manoeuvre of the satellite. In this paper, we report on the use of surface micromachining to fabricate freestanding polysilicon microigniters to be integrated in solid propellant microthrusters with reduction of the power needed for the ignition of the propellant. Polysilicon surface micromachining is an established process in the field of microsystems and the igniters realised exhibit some more advantages compared to the igniting technologies reported so far for this type of application. This processing technology allows eliminating the use of fragile membranes while maintaining low-power operation, and simplifies the fabrication, the propellant filling and the assembling of the microthrusters, as it will be described in the next section.

A set of characterisations related to the targeted application was performed to investigate the reliability and robustness of these poly-Si igniters. The electrical power that could be delivered by the microigniters was evaluated. The instability of polysilicon electrical properties operated at high temperature was also examined. Temperature measurements were done in order to investigate the thermal characteristics of the devices. Measurements of the shape of their profile have been made to evaluate their mechanical deformation in operation and their mechanical robustness. The microheaters could dissipate relatively high constant powers for a few minutes to hours and are a promising solution for the ignition of solid propellants stored in micromachined cavities.

2. Design

2.1. Microthruster design

The design of the microthruster was a so-called vertical design: the different parts were fabricated on separated silicon wafers and assembled together to form the microthruster. The millimeter-scale already developed device and on which this work is based [11] consisted in a stack of four wafers (Fig. 1): the microigniter, which is a polysilicon microheater thermally isolated on a dielectric membrane and fabricated by bulk micromachining, a chamber (1.5 mm × 1.5 mm) filled with the solid propellant and closed by a seal, and a nozzle through which the combustion gases expand.

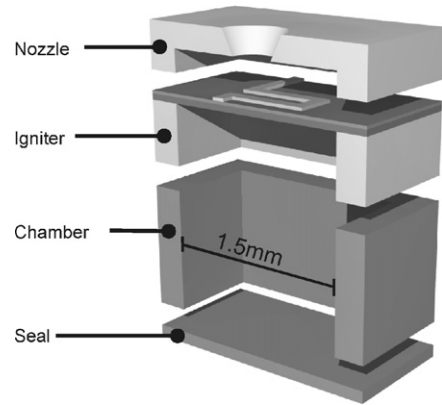


Fig. 1. Schematic drawing of a millimetre scale solid propellant microthruster made of silicon. It is composed of a stack of four parts: the nozzle, the igniter, the chamber and the seal. The igniter is thermally insulated from the substrate by means of a thin dielectric membrane; it is fabricated by bulk micromachining.

500 μm [17]. A more energetic propellant, zirconium potassium perchlorate (ZPP), has been chosen to ease the ignition and the combustion process. Depending on its composition, ignition is obtained at a temperature of 200–300 °C maintained for few tens of milliseconds. The microthruster design has been modified in order to simplify the fabrication and assembling processes by making the igniters using polysilicon surface micromachining. Using this process, the suspended microheaters were thermally isolated from the substrate by an air gap and could be directly integrated around the nozzle throat, as shown in Fig. 2. This allowed the reduction of the number of parts composing the thrusters from 4 to 2.

2.2. Sub-millimeter scale igniter design

The suspended microigniters were made of P-doped polysilicon resistors fabricated on a silicon substrate. They were composed of a set of 2–8 parallel heating beams functioning as hot spots around the nozzle aperture (Fig. 3). The beams width was set to 20 μm and their length to 180 μm ; a gap of 20 μm separated them from each other. The heating bridges were sus-

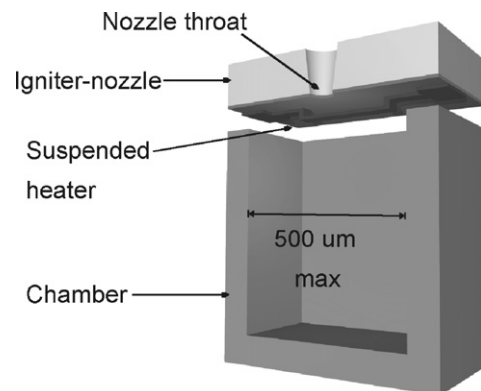


Fig. 2. Schematic drawing of a sub-millimeter scale solid propellant microthruster made of silicon and composed of two parts: the igniter-nozzle and the sealed chamber.

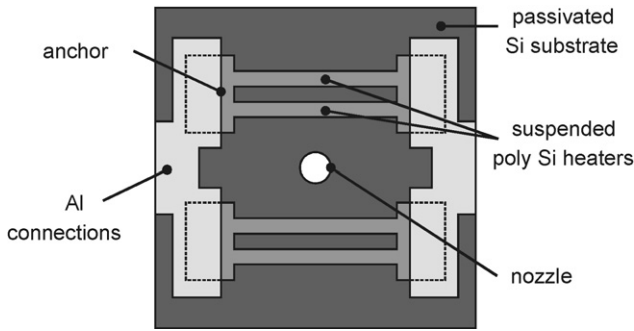


Fig. 3. Schematic drawing of a micrometer-scale microigniter with an integrated nozzle on a silicon substrate. The polysilicon microheaters are suspended above the passivated substrate and anchored to the substrate at their extremities, where they are electrically connected with aluminum lines.

pendent above the passivated substrate. The design as well as the fabrication process of the igniters allowed the integration of a divergent nozzle through which the combustion gas can be evacuated.

In order to demonstrate the concept of freestanding polysilicon microigniters, the fabricated structures were designed to fit in a $1.0\text{ mm} \times 1.0\text{ mm}$ chamber. An appropriate layout of the microheaters would allow their integration in smaller chambers: one pair of parallel bridges could be arranged in $500\text{ }\mu\text{m} \times 500\text{ }\mu\text{m}$ chambers.

3. Fabrication

The igniters were fabricated on $525\text{ }\mu\text{m}$ thick silicon wafers, polished on the top side. The fabrication process is illustrated in Fig. 4. It started with the passivation of the substrate by a thermally grown silicon dioxide and a LPCVD silicon nitride. The

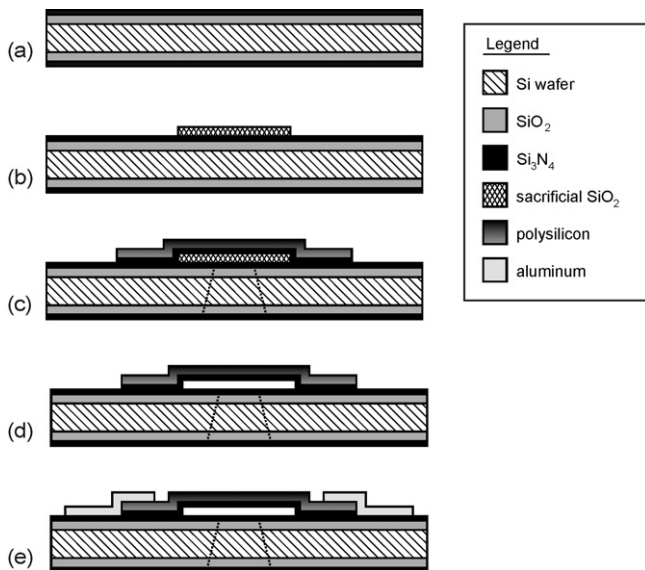


Fig. 4. Fabrication process of the microigniter (cross-section): (a) oxidation and Si_3N_4 deposition; (b) sacrificial APCVD SiO_2 deposition and patterning; (c) Si_3N_4 and poly-Si deposition, doping and patterning (in dashed lines: nozzle etching if also integrated); (d) sacrificial layer etching; (e) aluminum contacts deposition.

sacrificial layer consisting in a $1.2\text{ }\mu\text{m}$ thick layer of APCVD silicon oxide was then deposited, densified at $625\text{ }^\circ\text{C}$ for 15 min under a nitrogen atmosphere and patterned. On top of it was deposited a double layer of 200 nm of low stress LPCVD silicon nitride and 700 nm of LPCVD polysilicon. The silicon nitride had a residual tensile stress whereas the polysilicon had a compressive stress. The deposition of polysilicon was performed at $600\text{ }^\circ\text{C}$ and its doping was achieved by the diffusion of phosphorous from a layer of doped APCVD silicon dioxide. The next step consisted in patterning the double layer of silicon nitride and polysilicon by reactive ion etching (RIE) to form the electrical resistors. The release of the polysilicon resistors was performed by wet etching the sacrificial APCVD silicon dioxide layer in a solution of 50% hydrofluoric acid. Then the aluminum interconnections were evaporated through a shadow mask in order to prevent the stiction of the microheaters to the substrate. Finally, the aluminum was annealed at $450\text{ }^\circ\text{C}$ for 30 min under a nitrogen atmosphere to form ohmic contacts with the polysilicon.

In order to integrate the nozzle during the igniter fabrication, a few additional process steps can be performed. First the thermally grown passivating silicon dioxide would be opened by

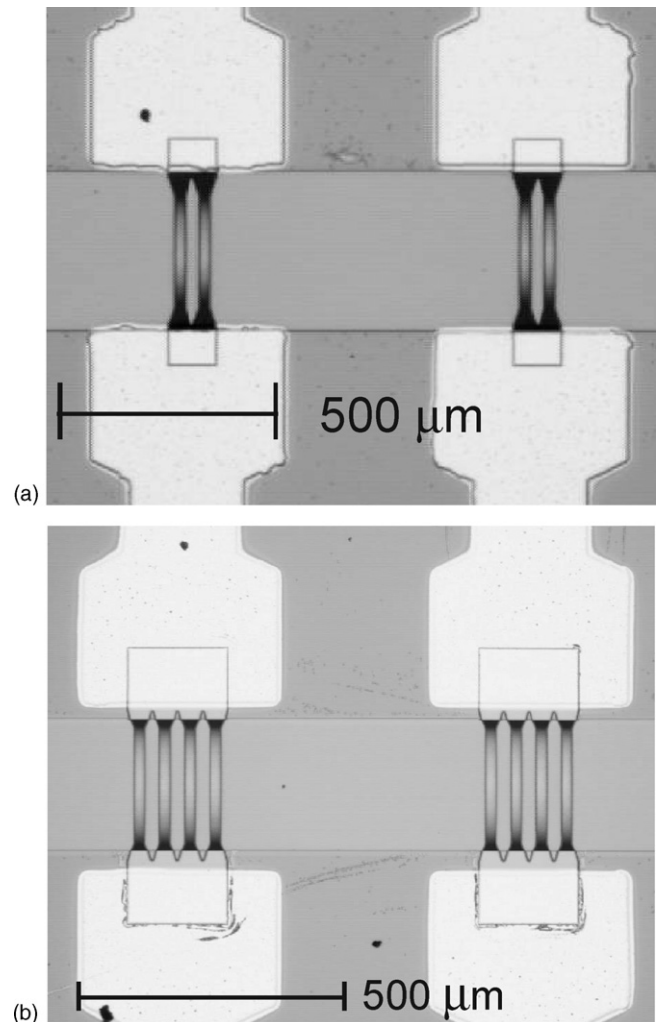


Fig. 5. Pictures of different designs of polysilicon surface micromachined igniters composed of (a) 2×2 suspended beams and (b) 2×4 suspended beams.

BHF after its deposition (Fig. 4a) in order to have bare silicon where the nozzles would be etched. After the patterning of the resistors (Fig. 4c), the nozzle etching mask would be deposited and patterned: it would consist in a double layer of thick resist on a thick CVD silicon dioxide opened by BHF. The underlying passivating silicon nitride would be etched by RIE and the substrate by deep reactive ion etching (DRIE) through the whole thickness of the wafer to form the nozzle. After the stripping of the resist, the oxide mask would be removed by wet etching together with the sacrificial layer (Fig. 4d). This process has been proven to work with surface micromachined igniters made on SOI wafers [22].

4. Characterisation

Polysilicon microigniters have been successfully fabricated by surface micromachining (Fig. 5). The electrical resistance of a single beam was of $2.8 \text{ k}\Omega$. The suspended microheaters were completely released after the etching of the sacrificial layer. No stiction of the structures on the substrate could be noticed and the structures were freestanding.

The profile of the unbiased beams has been measured by means of a dynamically focussing optical profilometer from

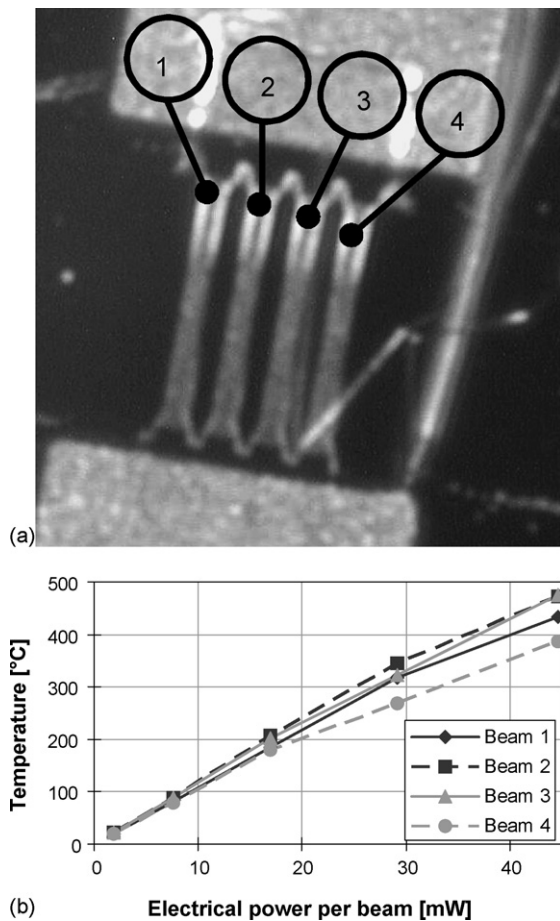


Fig. 6. (a) Close view on a set of four beams of a 2×4 beams microigniter; the thermocouple used for the measurement is shown on their right and (b) measured temperature at the center of the beam as a function of the applied electrical power per beam.

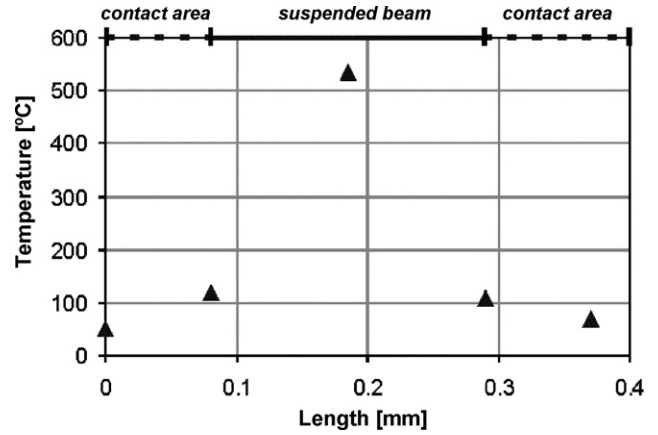


Fig. 7. Temperature profile along a single beam length at 50 mW/beam of a 2×2 beams microigniter.

UBM GmbH, which has a resolution of 10 nm . The measured profile in Fig. 8a showed an upward buckling of the beams; the air gap between the center of the suspended bridge and the anchors was of about $10 \mu\text{m}$, which is higher than the sacrificial layer thickness. The double layer of polysilicon and silicon nitride resulted in a residual tensile stress that explains the upward buckling of the beams.

The thermal, mechanical and electrical characteristics of the microigniters in operation were studied and the results are presented in the following sub-sections. The results will be discussed in Section 5.

4.1. Temperature measurements

The glowing of the biased microheaters indicated that the resistors could reach temperatures of at least $500 \text{ }^\circ\text{C}$. In order to evaluate more precisely the temperature, measurements have been performed with a microthermocouple made of platinum

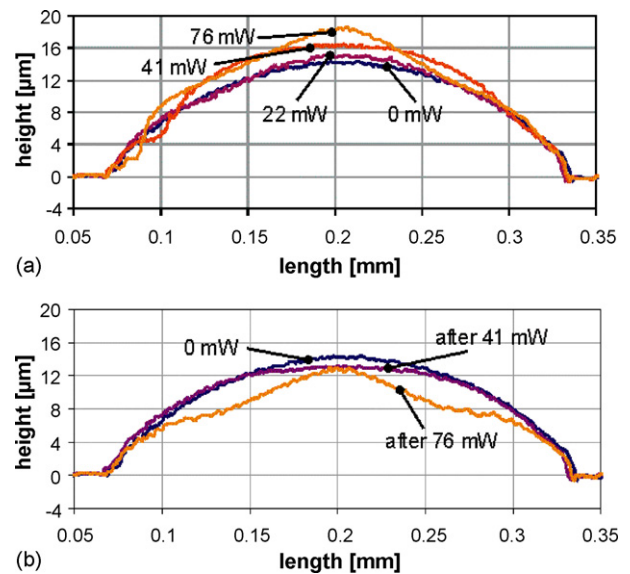


Fig. 8. Measured profiles of a single beam along its length (a) under a constant power and (b) at 0 mW after thermal cycles. The measures were performed on a 2×2 beams microheater.

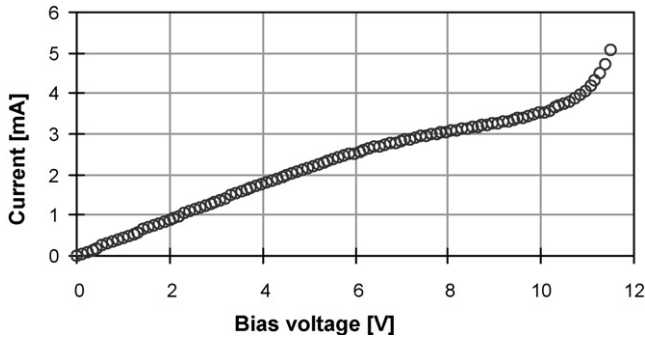


Fig. 9. I - V characteristic of a single beam: the relation is linear until about 20 mW/beam; at higher power, the resistance decreases.

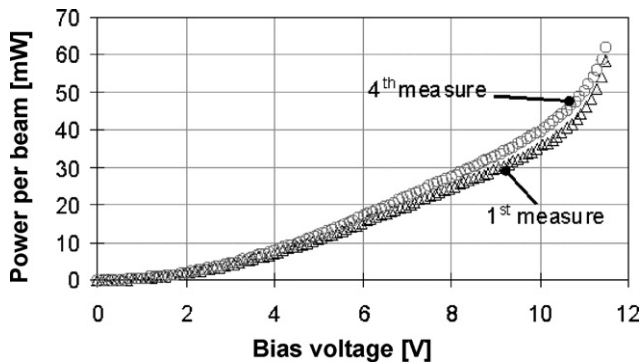


Fig. 10. Electrical power per beam vs. bias voltage: the decrease of the resistance value after several I - V cycles results in an electrical power drift.

and platinum/rhodium wires of 1.3 μm of diameter (S-type thermocouple). The measurements were performed at the FEMTO-ST laboratory, in the laboratory room environment with a monitoring of the ambient temperature. This laboratory has a

strong know-how in the fabrication and the use of such microthermocouples [23]. The thermocouple was put in contact with the beams using an X - Y - Z micromanipulating table under an optical microscope. Precision on the temperature measurements is normally estimated to be 2% over the whole temperature range due mainly to the thermal contact resistance. Fig. 6b shows the measured temperatures as a function of the applied power on the center of each of the four beams indicated on Fig. 6a. The measured structure was a 2×4 beams microigniter.

Temperatures up to 470 $^{\circ}\text{C}$ could be reached with a power of 45 mW/beam. The measured temperatures were higher on the inner beams than on the outer ones with a difference of about 50–100 $^{\circ}\text{C}$. This was identified to be due to the mutual influence of the parallel beams. The temperature profile along a single beam at 50 mW/beam (Fig. 7) shows that the thermal losses through the contacts were very low: the contacts stayed at a temperature close to room temperature whereas the center of the suspended beams could reach temperatures higher than 500 $^{\circ}\text{C}$.

4.2. Mechanical deformation

The deformation profile along the beam length was measured at room temperature—0 mW—and when operating at constant power in laboratory environment, ramping up the power each time from 0 mW to be able to look at when plastic deformation occurs (Fig. 8a). Power was kept up for few tens of seconds the time to acquire the profile of the beam using the optical profilometer.

The Joule heating effect of the electrical beams induced by the electrical current triggers the thermal expansion of the structures and causes their mechanical buckling [24]. The elastic deformation threshold has been measured around 25 mW/beam, which corresponded to a temperature of about 250 $^{\circ}\text{C}$. As more power

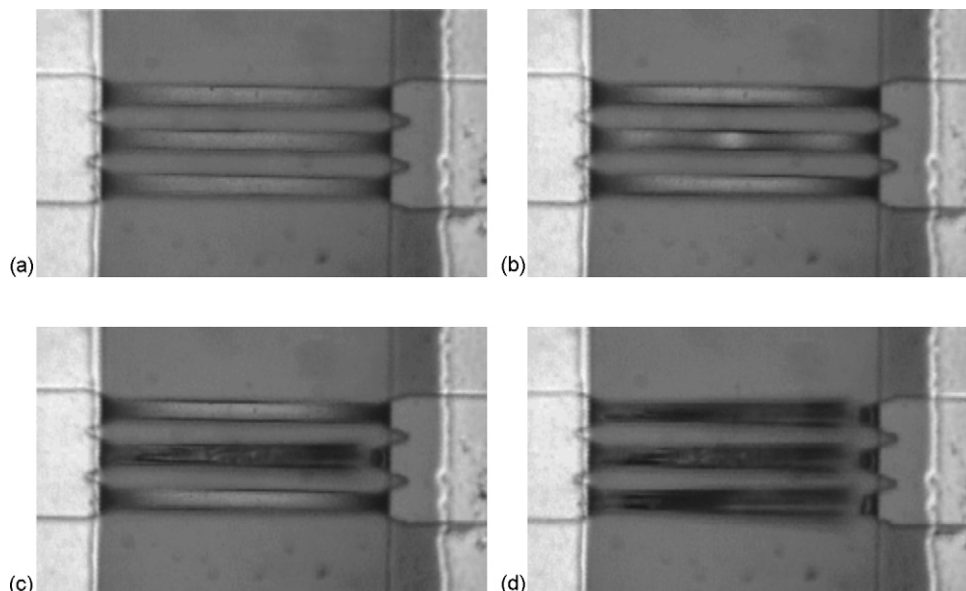


Fig. 11. Pictures showing the rupture of a set of three beams, with a slow voltage sweep starting at 0 V and increasing with a step of 100 mV every 500 ms: (a) time t_0 at 0 V; (b) buckling of the middle beam; (c) rupture of the middle beam; (d) rupture of the outer beams.

was dissipated, the temperature increased, leading to a higher thermal expansion and deformation of the beams. The plastic deformation threshold of the microheaters occurred at about 40 mW/beam (Fig. 8b). A deflection of 4.5 μm was measured at 76 mW/beam.

4.3. Electrical properties

The electrical properties of the microigniters were also studied. The current to voltage characteristic of a single beam is shown on Fig. 9. The I - V relation was linear until about 20 mW/beam. A decrease of the electrical resistance was noticed after 35 mW/beam, resulting in a significant increase of the injected current.

The decrease of the resistance could be caused by the recrystallisation of polysilicon at high temperatures, as it has been described in the literature [21,25]. A drift of the electrical power after a few cycles above 40 mW/beam was observed (Fig. 10); according to the temperature versus power graph of Fig. 6b and to the temperature profile measurement (Fig. 7), temperatures higher than 450 $^{\circ}\text{C}$ were reached by the suspended beams at that power and could lead to the polysilicon recrystallisation, thus to a change of the electrical resistance. Nonetheless, because of the required short ignition time and the one-shot characteristic of the application, it is assumed that the power drift of polysilicon does not prevent a good functioning of the microigniters.

4.4. Robustness

The rupture of the microigniters was studied in order to investigate their robustness. The experiments consisted in applying a relatively high constant power during a few minutes to a few hours. The microheaters could deliver powers up to 80 mW/beam for a few minutes; a lower power of 60 mW/beam could be applied for hours without beam rupture.

As a result of the short time required to ignite the propellant, it was also important to examine the short term robustness of the microheaters. Fig. 11 shows a series of video frames taken during the rupture of the microigniter bridges under an increasing voltage sweep starting at 0 V until its breakage. One can see that the resistive heating of the microheaters caused their self-buckling. As the power and temperature were further increased, the beams broke off: the inner beam broke first, probably due to the fact that it reached higher temperatures than the outer ones, as explained previously. For a fast voltage sweep, i.e. with a voltage increment of 100 mV every 50 ms, beams rupture occurred at a power higher than 80 mW/beam.

4.5. Ignition tests

Drops of ZPP solid propellant, with a diameter of approximately 1 mm, were deposited on the fabricated and characterised polysilicon micro-heaters, as shown in Fig. 12a. Ignition tests were performed on the coated microigniters in laboratory environment using a electrical probing station. The ignition tests were filmed using a video camera to get information on the com-

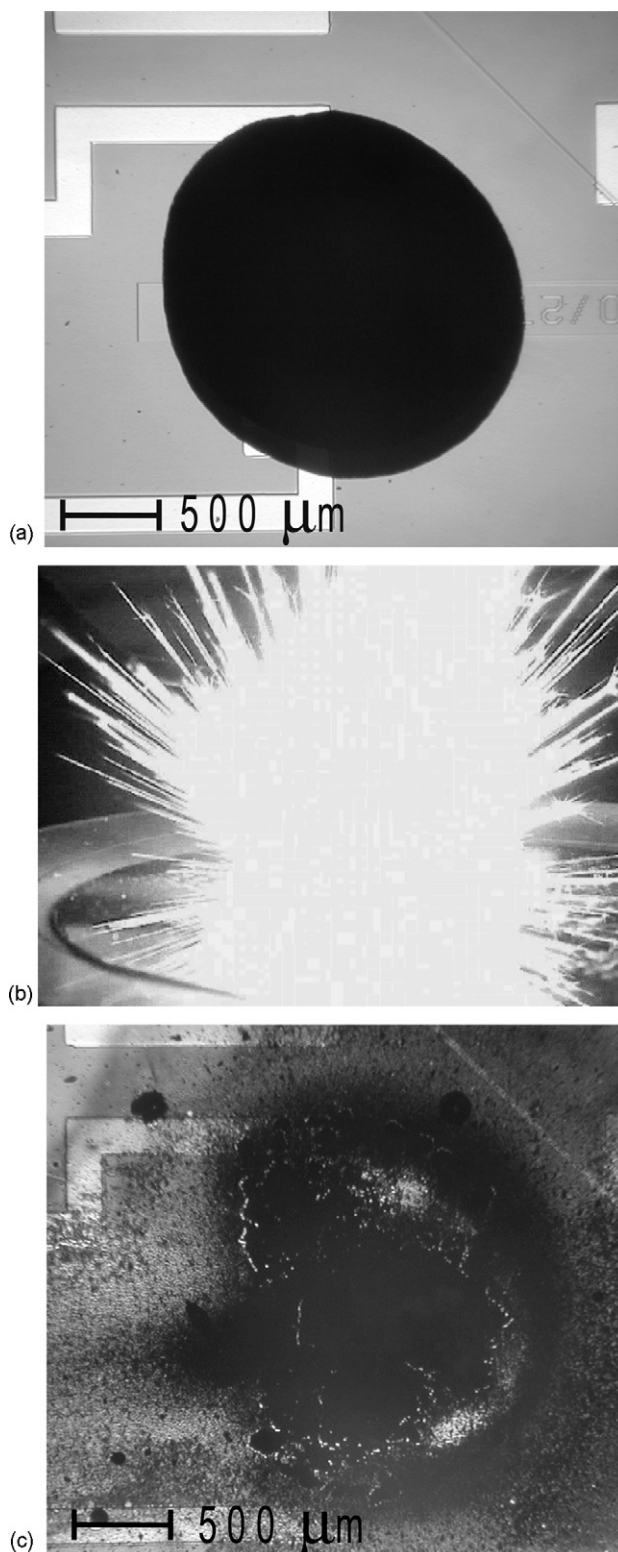


Fig. 12. Pictures of the ignition test: (a) Microigniter composed of 2x4 beams covered with a drop of ZPP propellant (b) during the ignition at 80 mW/beam and combustion (c) after the successful ignition test.

bustion time of the propellant drop. A constant voltage pulse was applied and the current measured to determine the power dissipated by the igniters. Successful ignitions of the propellant were obtained within few tens of milliseconds with a power of

80 mW/beam. From the video of the ignition test, it has been deduced that the combustion time was smaller than 120 ms.

5. Discussion

The mechanical characterisation of the microigniters indicated that the air gap between the polysilicon and the substrate was much higher than the sacrificial layer thickness and increased with the temperature. The micro-heaters were therefore perfectly released with no stiction and the large air gap limited the heat losses through the substrate. The filling of the structures with the solid propellant might cause the rupture of the suspended beams because of their buckling; however, it is likely that the propellant would deform the flexible beams without breaking them. Indeed the large air gap could help to avoid the sticking of the polysilicon beams on the substrate when covered with propellant. The ignition tests performed on drops of propellant showed that these polysilicon heaters could operate in a reliable manner and deliver the required power to achieve a successful ignition.

The temperature measurements showed that temperatures higher than the 200–300 °C for few tens of milliseconds required to ignite the ZPP propellant could be reached by the fabricated microheaters. Indeed glowing of the polysilicon beams was obtained. The power applied during the ignition tests was higher than the expected ignition power, 80 mW/beam instead of 20–30 mW/beam measured to reach the required 200–300 °C. This can be explained by the additional thermal mass for the igniters coated with propellant. Nevertheless, with drops of 1 mm in diameter, the volume of the drops of propellant was bigger than the volume that would be needed to fill up the 500 μm wide chambers of the sub-millimetre scale thrusters presented in Section 2.2. These igniters would be therefore suitable for the ignition of ZPP stored in sub-millimeter scale chambers, considering that for few tens of millisecond even higher power could be delivered by the polysilicon micro-heaters.

The experiments showed that despite the electrical power drift of polysilicon at high temperature, due to the small time needed for the ignition of solid propellant, the microigniters fulfil the ignition requirements for ZPP in terms of temperature and energy as well as the electrical specifications needed for the application.

6. Conclusion

This communication described the fabrication and the characterisation of freestanding polysilicon micro-heaters to be used as microigniters for solid propellant microthrusters. The realisation of polysilicon microheaters was successfully achieved by surface micromachining. Temperatures up to 470 °C could be reached with an electrical power of 45 mW/beam. The beams could withstand up to 80 mW for a few seconds before rupture; with a maximum relative deflection of 4.5 μm. Thermal cycles at high temperatures resulted in the plastic deformation of the beams as well as in a change of their electrical resistance, which led to a drift in the power characteristic. These surface micromachined polysilicon micro-heaters are promising for the ignition

of solid propellant. Further work would consist in testing these microigniters in a fully assembled micrometer-scale thruster.

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Biographies

Danick Briand received his BE degree and MASc degree in Engineering Physics from École Polytechnique in Montréal, in collaboration with the Laboratoire des Matériaux et du Génie Physique (INPG) in Grenoble, France in 1995 and 1997, respectively. He obtained his PhD degree in the field of micro-chemical systems from the Institute of Microtechnology, University of Neuchâtel, Switzerland in 2001, where he is currently a project leader. He is in charge of European and industrial projects and of the supervision of doctoral students. His research interests in the field of microsystems include PowerMEMS, polymeric MEMS, the integration of nanostructures on microsystems, and the development of micro-analytical instruments for gas-sensing applications.

Nicolaas F. de Rooij received his PhD degree from Twente University of Technology, The Netherlands in 1978. From 1978 to 1982, he worked at the Research and Development Department of Cordis Europa N.V., The Netherlands. In 1982, he joined the Institute of Microtechnology of the University of Neuchâtel, Switzerland (IMT UNI-NE), as Professor and head of the Sensors, Actuators and Microsystems Laboratory. Since October 1990 till October 1996, he was acting as Director of the IMT UNI-NE. Since 1987, he has been a Lecturer at the Swiss Federal Institute of Technology, Zurich (ETHZ), and since 1989, he has also been a Professor at the Swiss Federal Institute of Technology, Lausanne (EPFL). His research activities include microfabricated sensors, actuators and microsystems.