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MECHANICAL IMPULSE ENHANCEMENT IN A MICROSYSTEM BASED ON NANOPOROUS SILICON COMBUSTION

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Abstract. Nanostructured porous silicon impregnated by solid state oxidizer has been studied in order to provide the mechanical impulse for jet-propulsion microsystems. The system with jet-propulsion motion on a silicon chip has been tested for impulse measurements. The silicon chip has been fastened on a carrying platform through an elastic spacer. The elastic spacer promotes the combustion and prevents from explosion of porous silicon fast oxidation. It is shown that such a microsystem gains the impulse up to 200-220 mN·s.

Keywords: combustion, explosion, mechanical pulse, microthruster, multichip structure, nanoporous silicon

1. Introduction

Microthrusters have received significant attention during the last few years, though early development in the microelectromechanical systems (MEMS) field began approximately 15 years ago. The principle applications of microthrusters are for primary propulsion and attitude control of microspacecraft and micro-, nano-, picosatellites. These small-scale satellites require efficient propulsion systems that can approach and maneuver around objects in a space orbit. Technological efforts are converging from two directions: the miniaturization of conventional thrusters and the development of new solid energetic materials and device concepts [1]. One of the solutions for the aforementioned problem is to use energetic nanocrystalline porous silicon as an energy source.

Nanoporous silicon is an inert material, usually formed by the anodization of a silicon wafer in the electrochemical etch process [2,3]. Nanoporous silicon becomes an energetic material when its nanopores are infused with an oxidizer [4]. Porous silicon impregnated with solid state oxidizers has demonstrated the combustion and explosion processes [5,6]. It could be used in silicon based MEMS [7,8]

In this paper we present the measurements of thrust generation using nanoporous energetic silicon fastening a carrying platform with an intermediate spacer from elastic material.

2. Experimental and calculation details

Silicon wafers of p-type (B-doped) with resistivity of 10 Ω·cm were used to fabricate porous silicon samples using the anodization technique in the HF/ethanol electrolyte (3 parts of 48% HF to 1 part of ethanol) at the current density of 50 mA/cm^2. Ethanol helps to wet the hydrophobic surface of silicon and to remove H_2 bubbles. The porous region was etched from the front surface defined by a mechanical O-ring mask with an internal diameter of 12 mm. The etching time was varied to get porous layer thicknesses from 40 µm to 70 µm. The samples were rinsed in ethanol and the residual ethanol in the pores was slowly evaporated at normal laboratory conditions. The porous silicon samples were then impregnated by ethanol

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saturated solution of $NaClO_4$. The oxidizer is applied (the pores are filled) by dropping oxidizer solution with a pipette directly on the porous silicon. In all cases we fill the pores with two drops of the solution. Then samples dried in an oven at 40°C.

We designed a simple propulsion system by attaching the silicon chip to a carrying platform (circular metal plate) using a glue. The part of silicon chips has been attached to the carrying platform through an elastic spacer made from rubber (Fig. 1). Another part of silicon chips has been fastened directly on the carrying platform surface. Combustion ignition and explosion processes in the porous layers were initiated by putting the samples to a hotplate heated up to 500^0C. After the explosion took place, the thrust lifted up the whole system from the ground. A video camera records (30 frames per second) the motion of the propulsion system, and a scale in the background was used to calculate the velocity and height that the device achieved. The impulse was estimated as

$$P = m(\Delta l/\Delta t), \tag{1}$$

where m is the mass of the carrying platform, Δl is the distance that the carrying platform passed within the time (Δt) of recording the picture by the camera.

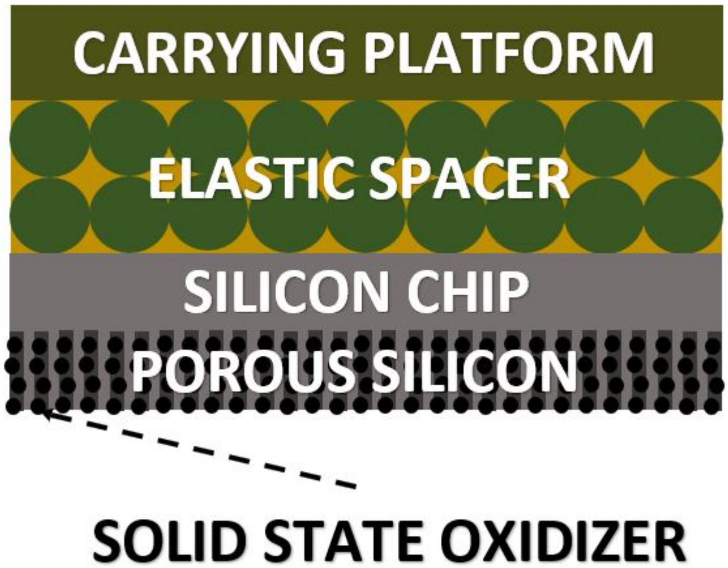
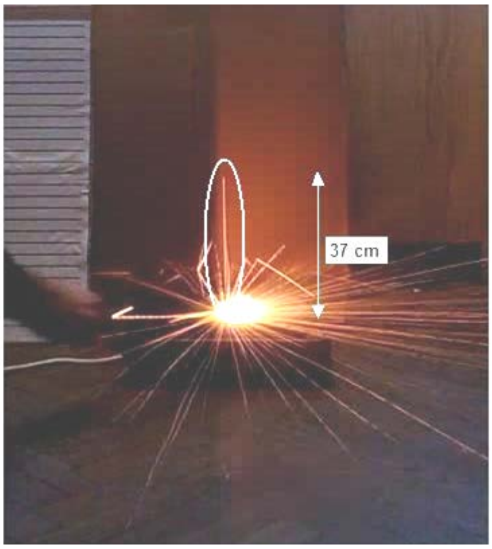


Fig. 1. Schematic view of the propulsion system consisting of the load carrying platform with the silicon chip attaching through the elastic spacer

3. Results and discussions

In our samples, impregnated by ethanol saturated solution of $NaClO_4$, the lateral dimension of the porous layer is a few orders of magnitude larger than the layer depth. As a result, the reactive forces arising from the explosion process push the sample in the direction perpendicular to the surface plane.

Figure 2 shows the fragments of the jet-propulsion test when the carrying platform is horizontally placed on a hotplate and moves in the vertical direction after ignition. The flight track during the first frame reaches 37 cm while the second frame indicates additional 35 cm. Flight tracks can be seen due to deflagration process in porous silicon. Taking into account the mass of the tested samples, we have calculated the mechanical impulse of the jet propulsion system depicted in Fig. 3 for different porous silicon thickness. Our samples could gain the mechanical impulse up to 130 mN·s for carrying platform mass of 13 g.



a)

b)

Fig. 2. Fragments of the jet-propulsion test: *a)* ignition and the first frame of testing flight, *b)* the second frame of testing flight (the flight track is marked by the white oval)

Recently we have found that porous silicon with a thickness more than 30 µm and impregnated by solid state oxidant demonstrated the explosion process with appearance of a shock wave [5]. Fixing the porous silicon chip on the platform, which mass exceeds the chip, changes shock wave propagation conditions. The sound intensity of shock wave decreases with mass increasing because the shock wave decays intensively for systems with larger mass indicating the explosion process energy to be converted into the mechanical impulse rather than to the shock wave.

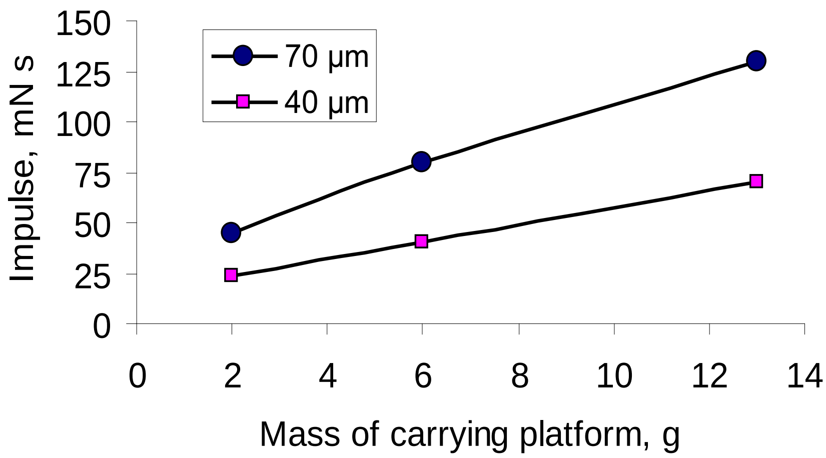


Fig. 3. Estimated impulse versus mass of carrying platform with porous silicon thickness of 40 and 70 µm

As known, p-type porous silicon includes nanoparticles with size in the range from 1 to 15 nm [2,3]. If the shock wave intensity is decreased, only small portion of particles with diameters of a few nanometers leads to the explosion (Fig. 2a). Another portion of particles with sizes of about 10 nm provides the deflagration process (fast combustion) with the lifetime of few milliseconds (see Fig. 2a, b).

The deflagration process supplies additional jet propulsion effect during the take-off resulting in the highest mechanical pulse of 130 mN·s for porous silicon with the thickness of 70 μm. Testing samples with porous silicon thickness of more than 40 μm without the carrying platform were completely destroyed after ignition (Fig. 4a) [7]. Testing samples fixed on the carrying platform with the mass more than 3 g and less than 20 g were destroyed partially (Fig. 4b, c) and with mass more than 20 g kept integrity after testing (Fig. 4d).

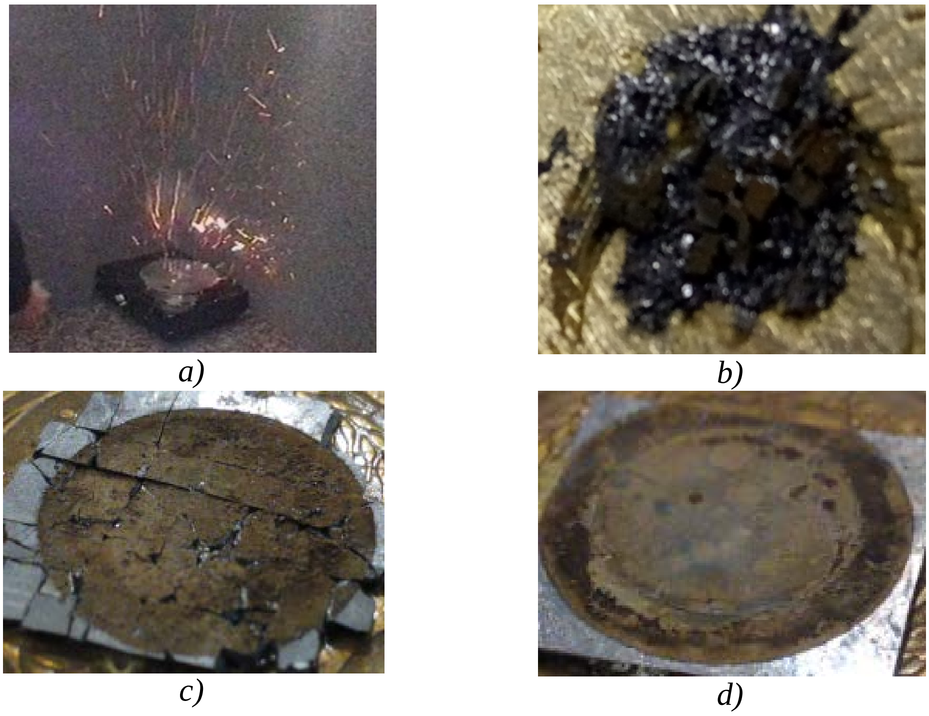


Fig. 4. Photos of experimental samples after testing: *a)* silicon chip (without carrying platform) destroying during explosion process, *b)* porous silicon chips fastened on carrying platforms with mass 3 g, *c)* with mass 10 g and *d)* with mass 20 g after testing

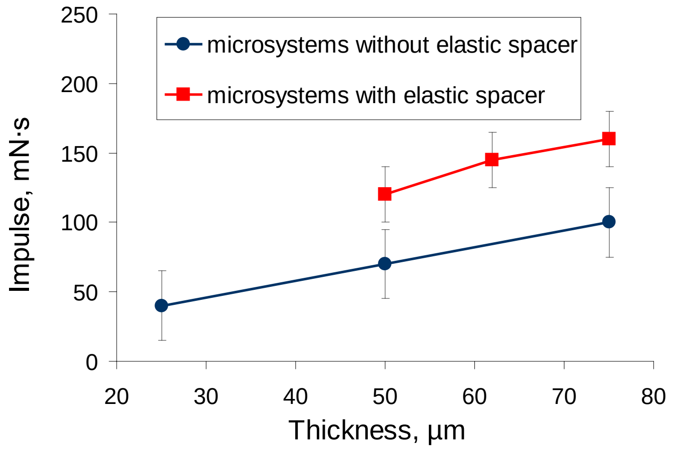


Fig. 5. Dependence of the pulse intensity versus porous silicon thickness for investigated propulsion systems (for carrying platform mass 10 g)

The enhancement of a mechanical pulse in the propulsion systems under investigation can be provided by increasing the role of the combustion process. However, the generation of a shock wave in our propulsion system should be avoided. The elastic spacers, which connect carrying platforms with silicon chips, provide necessary conditions for combustion in the testing propulsion system. In this case the accompanied sound was like a muffed clap, meantime the accompanied sound in a microsystem without elastic spacers was close to a gunshot. The external view of tested microsystems, which keep integrity, does not indicate the appearance of the shock wave. Moreover the elastic spacer acts as an accumulator for porous silicon combustion energy. At the beginning of porous silicon combustion we have the maximum energy exit. The size of observed flash (Fig. 2) supports this statement.

The part of porous silicon combustion energy converts to the potential energy of the compressed elastic spacer at the first stage as it is schematically shown in Fig. 6a. Then the intensity of porous silicon combustion decreases (Fig. 6b) and potential energy of the compressed elastic spacer releases in a way of moving microsystem (Fig. 6b). After that combustion process finishes and the microsystem moves due to inertia (Fig. 6c).

It is found that an elastic spacer increases the mechanical pulses of designed microsystems up to 30-50% in comparison with one without it (Fig. 5). The developed approach allows us to obtain the mechanical pulses up to 180 mN·s for porous silicon thickness of 70 μm. For increasing the mechanical pulse we have developed a microsystem based on several Si-chips with a porous silicon layer. The Si-chips have been attached to a carrying platform through the elastic spacers as it is shown in Fig. 7a.

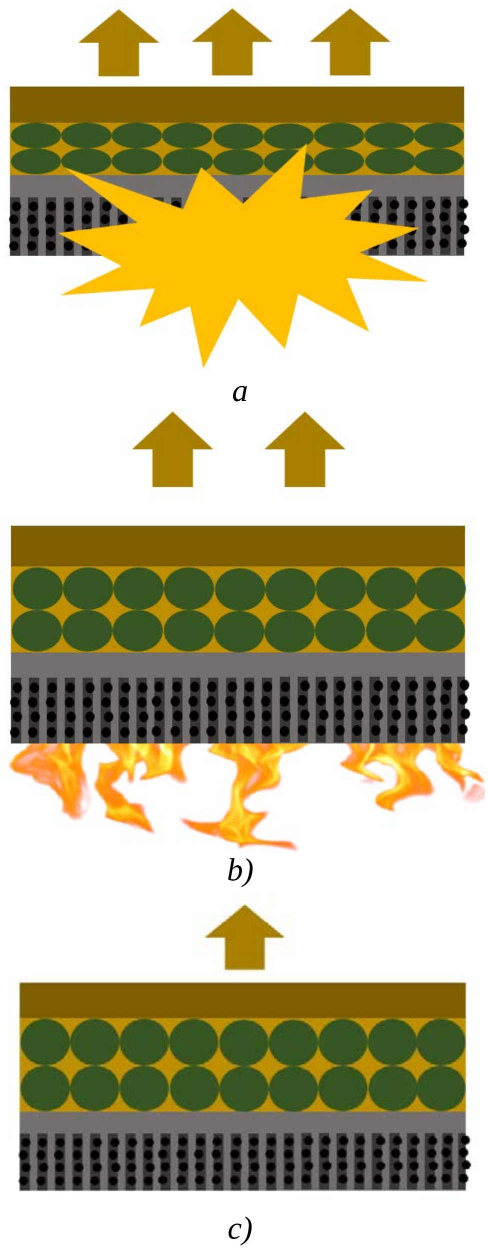


Fig. 6. Propulsion microsystem on different stages of testing: *a)* combustion initiation and motion beginning; *b)* motion in the process of burning out the porous silicon; *c)* motion due to inertia

The silicon chips containing porous silicon layers consecutively subjected to fast combustion process (Fig. 7b, 7c, 7d) in the case of elastic spacers with thickness in the range from 0.5 to 1 mm. The thickness of elastic spacers less 0.5 mm resulted in an explosion process for all silicon chips with the fast (microseconds) destruction of silicon chips. This explosion process provided the mechanical pulse less than 100 mN·s. In the case of elastic spacer thickness of more than 1 mm, the ignition of fast oxidation in the porous layer of silicon chips did not result in subsequent ignition process for the other silicon chips of the microsystem developed. The measurements of mechanical pulse for the developed microsystem with multichip structure have shown that subsequent ignition of porous silicon combustion provides the pulse values up to 220 mN·s for a platform mass of 20 g. The accompanying sound of this process (muffled clap) and the duration of light emission (milliseconds) correspond to the fast porous silicon combustion process.

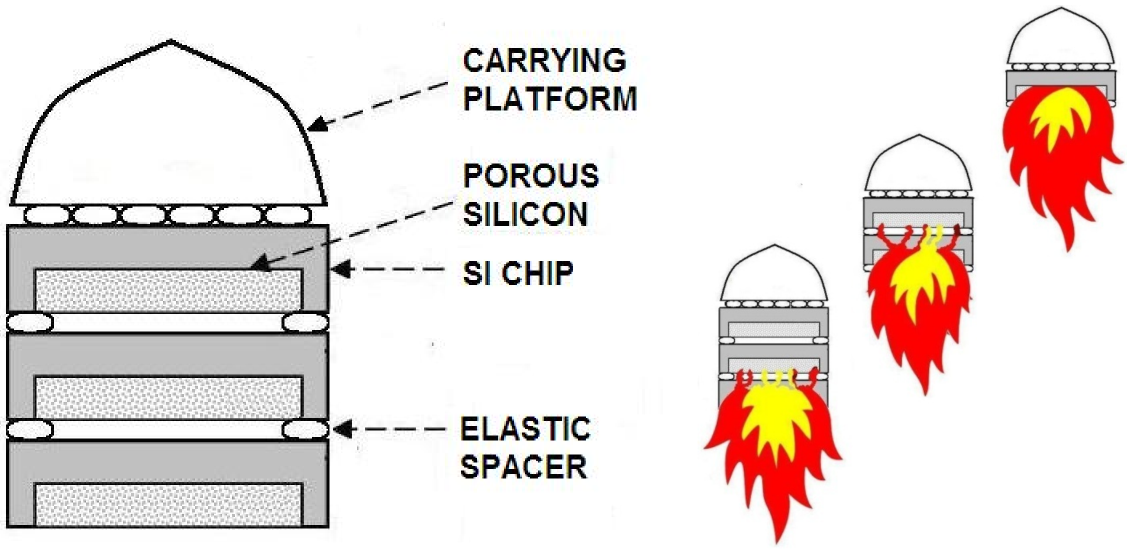


Fig. 7. Schematical view of the propulsion system based on three silicon chips with porous silicon nanoenergetic materials: *a)* general view, *b)* ignition of porous silicon of first, *c)* second, and *d)* third chips respectively

4. Conclusions

The performed investigations allow us to determinate conditions of porous silicon combustion process in microsystems based on silicon chips containing porous silicon layers. For preventing the porous silicon explosion process, we suggest increasing carrying platform mass and using the special elastic spacers between silicon chips and the carrying platform. It resulted in reducing pressure change during fast oxidation of porous silicon and it supplied the controllable combustion process.

We have shown that our system based on porous silicon provides mechanical impulse which increases with accumulation of porous silicon combustion energy. The estimated impulse value is 200-220 mN·s that is very promising, as an energetic material, for MEMS. The developed microsystem can be incorporated in silicon integrated circuit using for controlling and driving.

It should be specially noted that nanostructured silicon is an energy carrier alternative to hydrocarbon fuels. In particular, the flint used in ancient times to obtain fire is nothing other than a nanostructured mineral formation composed of quartz (SiO_2) and chalcedony. The chalcedony mineral differs from quartz in that it has a nonstoichiometric composition: specifically, an increased mass content of hydrogen, as high as several percent. That is, this mineral is "underoxidized" as compared with quartz, and it is this circumstance that is responsible for its unusual properties, that allow its particles to catch fire after a mechanical impact. Taking into account that silicon constitutes ~30% of the Earth’s crust, various silicon-containing minerals and silicates can be regarded as potential sources of energy, alternative to hydrocarbon fuel. Consequently, a study of the combustion and explosion processes in nanostructured silicon can be of use in solving the energy problem of humankind.

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