HIGH POWER MICROMECHANICAL THRUSTERS WITH EMBEDDED ELASTOMER

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Abstract: Micromechanical thrusters have been fabricated and characterized. Utilizing a new fabrication process, soft elastomer springs were integrated into a silicon frame. Poly(dimethylsiloxane) has been identified as a suitable elastomer because of its mechanical and chemical properties. The fabricated thrusters were used to store 1.3 μJ of energy and then release it in 5 ms for a power density of 333 mW/mm^3 in the springs. This energy was used to propel a 2 mg 0603 sized resistor 1.35 cm across a wafer.

Keywords: Poly(dimethylsiloxane), silicon-on-insulator, thruster, energy storage

INTRODUCTION

Attention to microrobotics has grown dramatically in the past decade. Various mobility methods for microrobots have been developed including walking [1], flying [2], and crawling [3]. The research presented in this paper was pursued in the interest of developing jumping microrobots [4], which require high power actuators such as thrusters. Prior work on MEMS thrusters includes [5], which uses chemical propellants that are thermally ignited and [6] which uses electrostatic comb drives to store energy in polysilicon flexures. In [5], Currano demonstrated a transfer of approximately 500 mJ and an applied force of 67 mN. In [6], Rodgers demonstrated storage of 19 nJ and an applied force of 735 μN.

Systems [5] and [6] both allow for a single energetic event, so applications of the devices are limited. The elastomer devices demonstrated in this paper do not have a comparable output force to [5], but can be used repeatedly. Previous elastomer-based thrusters were demonstrated in [7] using a low yield process that required post-fabrication assembly. In [7], Bergbrieter demonstrated the storage and release of 1.2 μJ to propel a 0.6 mg capacitor 1.5 cm across a glass slide.

A new fabrication technique has allowed for the fabrication of an elastomer in a silicon-on-insulator (SOI) process. Thrusters that can rapidly release mechanical energy in elastomer springs have been fabricated with this process, shown in Figure 1. The devices described in this paper were fabricated with a process that eliminates the necessity for any post-fabrication assembly, dramatically increasing the yield and robustness.

This paper begins with a discussion of the design of the thrusters. The fabrication of devices is then described and characterized. Finally, the use of a thruster to propel 2 mg resistor is demonstrated.

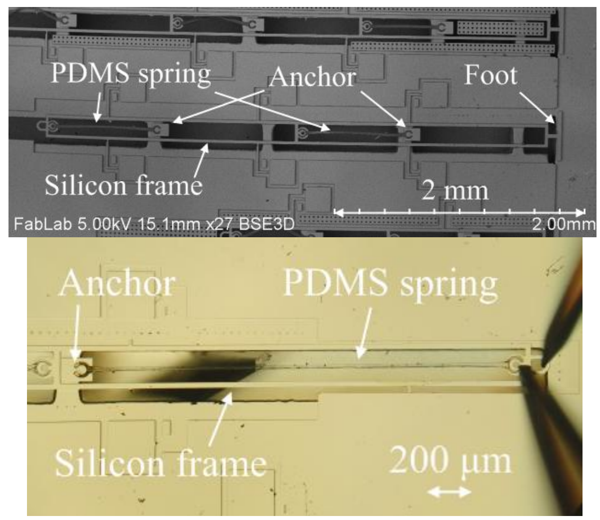

Figure 1: Micromechanical thruster

THRUSTER DESIGN

The design of the thrusters is similar to the device used in [4]. As shown in Figure 1, elastomer springs are anchored in place at one end and attached to a rigid frame at the other end. The frame can be moved laterally with a probe to store energy in the springs and freed to release the energy. The maximum theoretical energy that can be stored in the elastomer spring is:

$$U_{\max} = V_o \int_0^{\varepsilon_{\max}} \sigma(\varepsilon)\, d\varepsilon \qquad (1)$$

where V_o is the initial volume the spring, $\sigma(\varepsilon)$ is the stress as a function of strain (determined from a stress-strain diagram), and ε_{max} is the maximum strain. This equation assumes that the strain is constant throughout the elastomer and that the volume does not change throughout the straining process. Eq. 1 can be

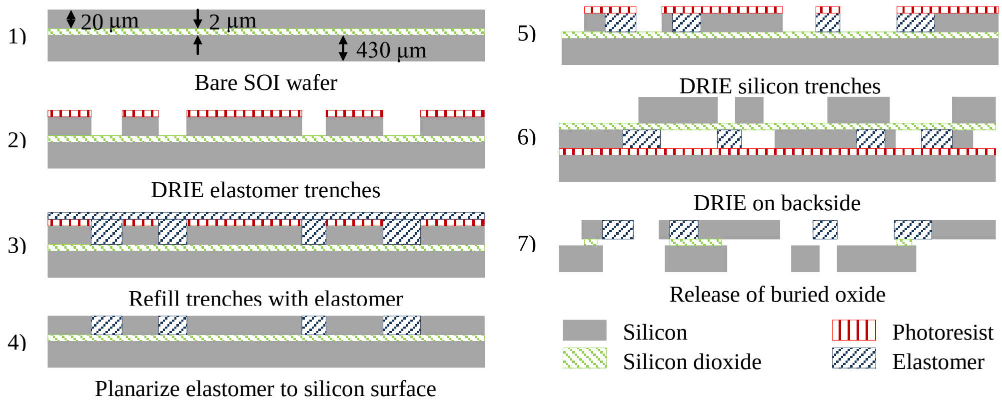

Figure 2: Microfabrication Process

used as a guide for both the material selection and physical design.

For material selection, Eq. 1 can be manipulated slightly to show maximum energy per unit volume:

$$\frac{U_{\max}}{Volume} = \int_{0}^{\varepsilon_{\max}} \sigma\left(\varepsilon\right) d\varepsilon \tag{2}$$

A full description of the material selection process is presented in [8], and is not repeated here. It can be seen, however, that a high Young's Modulus and yield strain will improve energy density. Poly(dimethylsiloxane) (PDMS) was chosen because of its attractive physical properties including Young's Modulus of about 1.8 MPa [9], maximum allowable strain of greater than 180% [9], and a low dissipation factor [10] (a measure of loss during relaxation of the spring). A material with a much higher Young's Modulus, such as silicon, was not used because it does not integrate well with existing force limited electrostatic actuators [11]. PDMS is already a common cleanroom material, as it is used frequently in microfluidics. PDMS is also largely chemically inert and can withstand the harsh manufacturing steps of the fabrication process (DRIE and hydrofluoric acid release).

From Eq. 1, it can also be seen that greatest energy storage is possible when the overall volume of the spring is maximized. Considerations for the ultimate size of the thruster must also be made, however. For these initial trials, simple linear springs were designed.

FABRICATION

The primary innovation in this paper is the integrated silicon-PDMS process for the fabrication of micromechanical thrusters (Figure 2). The process is very similar to the commercially available SOI-MUMPS® process with the addition of an extra mask step to define the PDMS features [12]. Devices were all fabricated on a silicon-on-insulator (SOI) wafer (430 µm handle layer thickness, 2 µm buried oxide (BOX) layer thickness, and 20 µm device layer thickness). In step 2, photoresist was patterned on the device layer and a deep reactive ion etch (DRIE) was performed down to the buried oxide.

Sylgard® 184 PDMS from Dow Corning was mixed in a 10:1 ratio of base to curing agent and degassed in vacuum at 1 Torr for 15 minutes. In step 3, the PDMS was spread across the surface, degassed again, and cured.

The PDMS was planarized to the surface of the wafer in step 4. This was accomplished by using a razor blade as a squeegee to scrape the wafer surface. The remaining photoresist was used to liftoff any residual PDMS. The liftoff leaves small particles of PDMS on the surface of the wafer, so a brief soak in n-methylpyrrolidone (NMP) and tetrabutylammonium fluoride (TBAF) in a 3:1 ratio [13] was performed.

In step 5, photoresist was again patterned on the device layer of the wafer and another DRIE was performed down to the buried oxide. Photoresist was then spun on the top of the wafer to protect it during later processing steps.

In step 6, photoresist was patterned on the backside of the wafer, after which the device layer of the wafer was bonded with a thin layer of photoresist to another handle wafer. A DRIE was performed on the backside of the SOI wafer down to the buried oxide. A solvent release was used to separate the SOI wafer from the handle wafer. Finally in step 7, a 6:1 buffered hydrofluoric acid (BHF) etch of the buried oxide was used to release some of the silicon and PDMS features. For this, alternating dips in BHF and deionized (DI) water were performed to ensure the survival of the PDMS in the BHF.

PROCESS CHARATERIZATION

To better quantify the adhesion of the silicon and

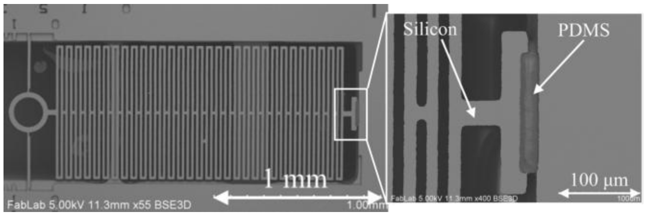

Figure 3: SEM of test structure used to test normal adhesion

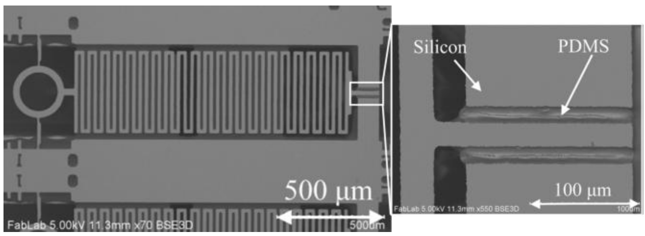

Figure 4: SEM of test structure used to test shear adhesion

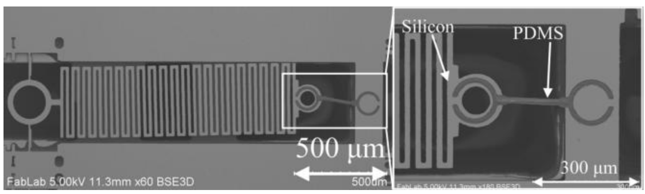

Figure 5: SEM of test structure used for stress-strain

PDMS, test structures for primarily normal (Figure 3) and primarily shear (Figure 4) forces were fabricated. When normal forces were applied, the ultimate pressure at which PDMS delaminated from the silicon varied from structure to structure, but was always in excess of 0.8 MPa, and was as high as 2.5 MPa. When shear forces were applied, the PDMS typically delaminated from the silicon around 140 kPa. The difference between the shear and normal conditions is quite dramatic and the mechanism for the difference is still being investigated.

Adhesion between silicon and PDMS also changes over time. While no quantified data is currently available, it has been repeatedly observed that the silicon/PDMS adhesion improves after sitting in a dry box for several days. The authors are examining the extent of the improvement and the mechanism causing it.

Other mechanical properties of the system measured were stress and strain, the Young's Modulus, and the ultimate failure strain. The test structure in Figure 5 was used to determine all of these properties. Two stress-strain curves for these structures are shown in Figure 6. For the post-fabrication PDMS springs, the Young’s Modulus was calculated at 1.4 MPa in the linear interval of the stress-strain curve. This is in relatively close agreement to the Young's Modulus for un-processed PDMS features reported in [9] of 1.8 MPa, although

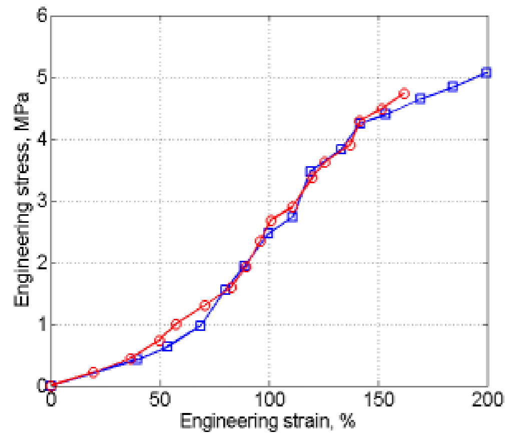

Figure 6: Measured stress-strain for PDMS

this number is artificially high since it incorporates points where the strain is non-linear. Since the stress-strain curve of PDMS is non-linear at higher strains, a best-fit curve was generated so that it could be applied to Eq. 2; an energy density for the PDMS of 4.9 mJ/mm^3 at 200% strain was calculated. The stress-strain curve for PDMS also exhibits the expected strain-toughening, where the Young's Modulus increases with strain, as can be seen in Figure 5. An ultimate strain of 200% was observed, though typically the PDMS delaminated from the silicon before the PDMS broke.

THRUSTER RESULTS

The results of the process characterization can be used to design and fabricate micromechanical thrusters. In [8], Bergbrieter shows that 25 µJ of energy is required for a 10 mg microrobot with a 60° takeoff angle to reach a jump height of about 15 cm in air. Using the energy density calculated above, 5.1x10^{-3} mm^3 of PDMS would be sufficient to store enough energy for such a jump. The fabricated springs shown in Figure 1 each had a volume of 3.9x10^{-4} mm^3, for a total volume of 7.8x10^{-4} mm^3 of PDMS in the device, so they are expected to store a maximum energy of 3.8 µJ at 200% strain.

The fabricated thrusters were used to propel a 2 mg 0603 sized surface mount resistor in order to demonstrate the quick energy release capabilities. A probe was used to pull the frame of the thruster back, straining the two PDMS springs, shown in Figure 1. The springs were stretched about 1 mm, or to 130% strain. The energy stored in the springs was estimated at 1.3 µJ with Eq. 1, where ε_{max} is the maximum strain that was achieved before the release. The release took about 5 ms, for a power output of 333 mW/mm^3. Five frames from the video of the resistor moving from right to left are shown in Figure 7; 1 is at 0 ms, 2 is at 8 ms, 3 is at 12 ms, 4 is at 17 ms, and 5 is at 23 ms.

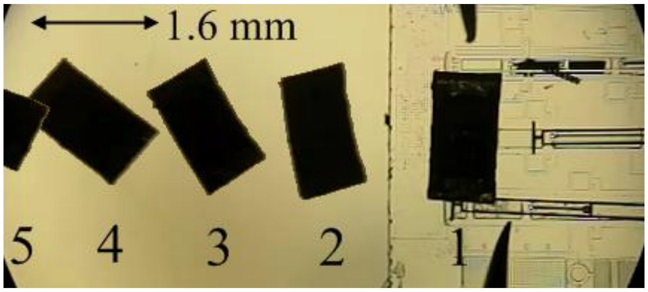

Figure 7: A thruster propelling a 2 mg resistor

The path of the resistor is unknown since it was outside the view of the microscope.

Upon release, the thruster propelled the resistor off the edge of a silicon die with an estimated kinetic energy of 95 nJ, for an energy transfer efficiency of about 7%. The kinetic energy was calculated with the velocity of the resistor in the first few frames of captured video (Figure 7); the calculated rotational energy was negligible. The resistor fell 430 μm vertically off the die and travelled 1.35 cm horizontally across a silicon wafer. After the release, the thruster was not broken and was used to propel the resistor multiple times. Using the same calculations as [4], 95 nJ would enable a 10 mg microrobot to jump about 725 μm in air. In comparison, storing the 25 μJ from the example above and transferring 7% of the energy would result in a jump of about 13 mm in air.

CONCLUSIONS

A MEMS process for integrating silicon and elastomer features was described. Using this process, a micromechanical thruster system which could be strained and released repeatedly was demonstrated. The system was used 1) to store 1.3 μJ of energy in an elastomer spring and 2) release that potential energy and transfer 95 nJ into translational kinetic energy of a 2 mg resistor that travelled 1.35 cm. This translates to an output power of 333 mW/mm^3 in the PDMS.

FUTURE WORK

The process must be refined to increase the adhesion of the PDMS to the silicon sidewall, and several mechanical and chemical methods are being examined. The goal is to refine the process enough that the yield strength of the elastomer and not the adhesion is the limiting factor in the process. Trials are also underway to see if PDMS can be used as thin film to increase the friction in electrostatic gap closing inchworm motors such as [11]. Another application under investigation is in compliant hinges for microrobotics. Ultimately, jumping microrobots will be designed and fabricated.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Maryland NanoCenter and its FabLab. This work was supported under DARPA YFA Grant No. HR0011-08-1-0043.

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