PARAFFIN-PDMS COMPOSITE THERMO MICROACTUATOR WITH LARGE VERTICAL DISPLACEMENT CAPABILITY

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Abstract:

We have micromachined and tested the first paraffin–PDMS composite thermal microactuator having multi shot large vertical displacement capabilities (~160 µm for 1 mm diameter device). A solid to liquid phase change of trapped paraffin into the PDMS is used to create a large volume dilatation of the composite (18%, for a temperature varied from 20 to 80 °C). The elasticity of the PDMS ensures the reversibility of the actuation. The paraffin-PDMS composite also facilitates fabrication and confines the melted paraffin when the device is actuated. This actuator has large force capabilities illustrated in our demonstrator by lifting a heavy mass for microsystems (60 mg).
The actuator consists of a glass cavity filled with a paraffin-PDMS composite, a micro hotplate at the bottom of the cavity, and a nozzle-like silicon structure sealing the top of the cavity. The polyimide-aluminium micro-hotplate bonded to the bottom of the cavity heats (160 mW @ 2 V) the composite to obtain up to 160 µm out of plane vertical displacement.
Keywords: thermal actuator, paraffin, PDMS, composite, micro-hotplate, reversible, phase change

Introduction

Thermal actuation based on phase change of paraffin is known for its exceptional combination of high energy density (4 J/cm^3) and displacement [1-3]. However this actuation principle is not widespread in MEMS actuators, partially due to the difficulty of sealing large volumes of paraffin in deformable cavities made from polymer materials. Our approach combining a paraffin-PDMS composite with anodic bonding of polyimide-aluminium hotplate on glass enables the fabrication of robust multi shot actuators (see Fig. 1).

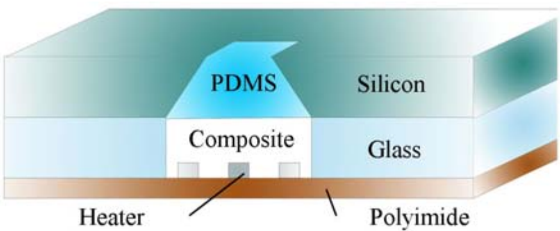

Fig. 1: *The microactuator consists of a low-power micro heater that heats a PDMS-paraffin composite confined into a glass cavity. The optional conical channel filled with PDMS was designed to magnify displacement and prevents eventual slight leakage of paraffin trapped into the PDMS.*

The main advantage of this approach compared to previously reported paraffin based microactuators [1-3] is related to the encapsulation of small droplets of paraffin into elastic PDMS. When the paraffin droplets in the composite melt and expand, they stretches the PDMS and the whole PDMS-paraffin composite increases its volume (see Fig. 2). When these liquid droplets are cooled down, the elasticity of the PDMS confines them again in their initial positions. Most reported paraffin actuators do not come back easily to their initial position due to the difficulty of confining large volume of paraffin while cooling it down.

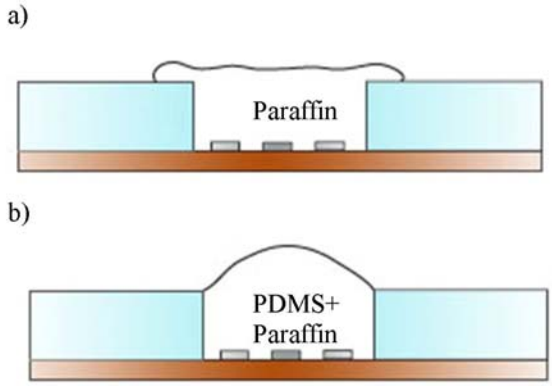

Fig. 2: *Comparison between the same thermo actuator having its heated cavity either filled with paraffin a) or with paraffin-PDMS composite b). The one filled with the composite presents the advantage of not having the actuation media pouring out of the cavity in a liquid phase.*

In addition, this approach facilitates manipulation and packaging. The paraffin is packaged inherently without the need of designing a complex sealed system capable of expanding and retracting. Therefore the use of this composite material favours simple designs where no confinement with rigid embodiment is needed. Possible applications can concern tilting of micro-mirrors, deformable mirrors and lenses, fluid handling in µTAS, pointing devices and unfolding structures for space applications.

Working principle

The actuation is based on the phase change of trapped paraffin into PDMS that occurs at about 60 °C for the paraffin used. If the paraffin is heated from 20°C to 80°C, its volume expansion is 18% [3]. When a voltage is applied to the micro-heater (see Fig. 3), depending on the actuation power, the heat generated by Joule effect diffuses through the composite material and melts partly or completely the trapped paraffin. Further heating of the paraffin can induce a higher dilatation. In such actuator, heating paraffin above its boiling point (about 370 °C) should be avoided.

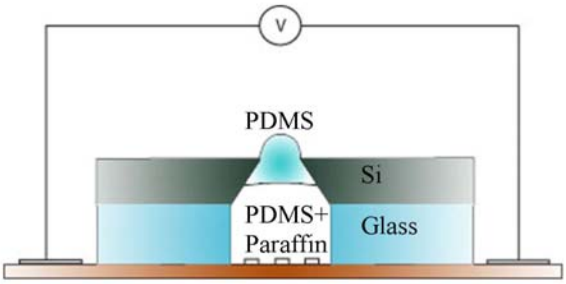

Fig. 3: *Schematic drawing showing the working principle of the actuator having a PDMS elastomeric membrane sealing the paraffin-PDMS composite material.*

Fabrication

To obtain the paraffin-PDMS composite solution, we liquefied paraffin with ultrasounds in iso-octane, a solvent compatible with PDMS (Smooth-ON dragon skin). We optimized the paraffin-PDMS-solvent solution in order to obtain a composite material that has a low volume contraction during solvent evaporation (iso-octane/{paraffin+PDMS} m/v ratio of 3 ml/g) and a large volume expansion capability once the PDMS is polymerized (paraffin/PDMS v/v ratio 1:1).
The surface of the paraffin-PDMS shows a particular aspect where the paraffin forms aggregates having a size varying between 5 to 100 µm that are trapped into PDMS (see Fig. 4).
The fabrication process of the paraffin-PDMS composite can produce on the surface some free-standing paraffin aggregates (100 to 500 µm) that are not trapped into the PDMS (see Fig. 5).

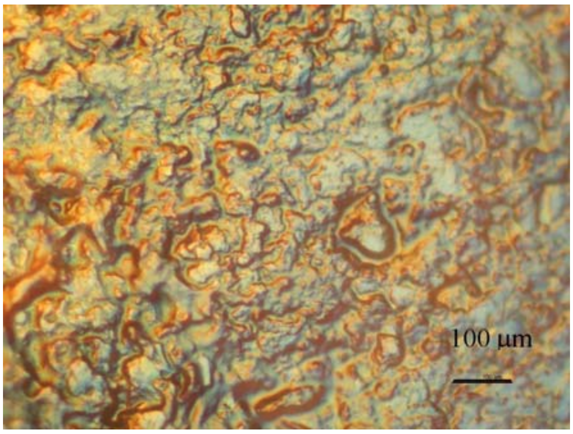

Fig. 4: *Optical picture of the paraffin-PDMS composite. The structure of the surface is formed by the paraffin aggregates that are trapped into the PDMS.*

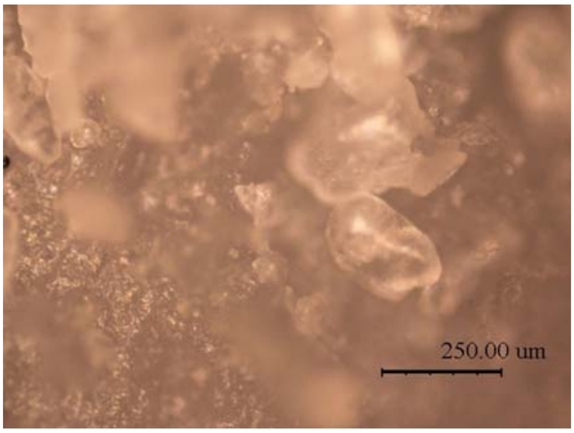

Fig. 5: *Free standing paraffin aggregates that form on the paraffin-PDMS composite surface after polymerization can be found in some areas.*

The actuator microfabrication process is based on the separate micromachining of micro-hotplates, Pyrex and silicon chips and their assembling by anodic bonding and gluing (see Fig. 6).

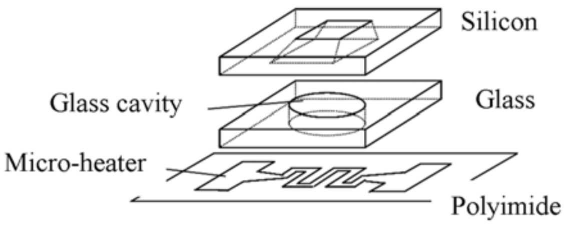

Fig. 6: *Schematic view of the three microfabricated parts of the actuator before assembling.*

A 250-nm-thick aluminium film was evaporated on a 50-µm-thick polyimide sheet (Upilex-S) and wet etched to form the micro-heaters (see Fig. 7)[4]. The Al layer was also used to fix the micromachined glass chip by anodic bonding.

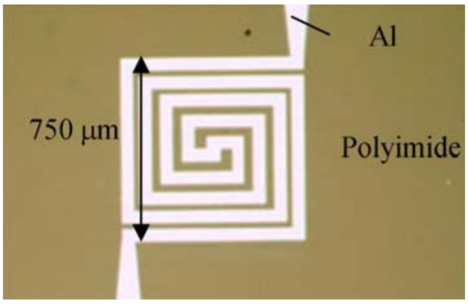

Fig. 7: *Spiral heater patterned in aluminium on top of a polyimide sheet.*

Ultrasonic machining was used to fabricate 1-mm diameter holes through a 500-µm-thick 100 mm in diameter glass wafer for holding the paraffin-PDMS composite. The glass chips with an area of 4×5mm^2 were separated using a dicing saw.
Conical vertical channels were wet etched (KOH process) into 390 µm-thick 4" silicon wafers to form the nozzle of the actuator (the bottom orifice measures 1×1 mm^2 and top orifice 0.45×0.45 mm^2, chip size of 4x4 mm^2). We used a patterned Si_3N_4 film as mask during the etching process. The assembling starts with the anodic bonding of the micromachined glass chips on the aluminium rims patterned on the polyimide (1 kV @ 320°C, see Fig. 8).

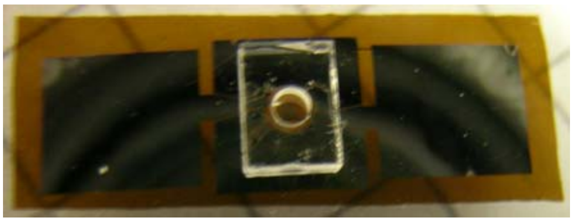

Fig. 8: *Photo of the actuator structure after the first assembling step which consists in the anodic bonding of the glass chip on the polyimide sheet with the patterned micro-heater.*

Then the glass cavities were filled with the liquid paraffin-PDMS composite, which is poured on top of the orifices and polymerized. Due to the solvent evaporation two cycles of pouring were needed to obtain the proper filling of the cavity (about 60% filling after the second filling cycle). After each pouring cycle, the solvent was evaporated and the composite polymerized in an oven at 40°C during 5 hours.
The top silicon chip having a conical vertical orifice was glued with the same PDMS (Smooth-On) on top of the glass chip. A PDMS drop was poured on top of the glass, and then the silicon chip is slightly pressed on top. Finally the PDMS was polymerized in an oven at 40°C during 2 hours (see Fig. 9).

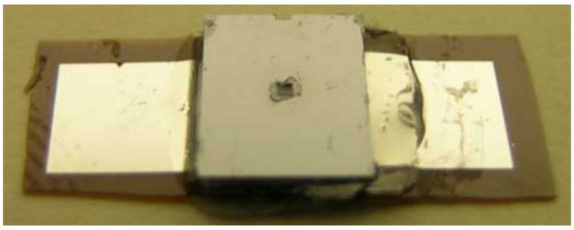

Fig. 9: *Fabricated paraffin thermo microactuator having a stack of glass and silicon chip bonded on a polyimide micro-hotplate. The moving part is the PDMS that fills the square orifice in the center of the silicon chip on top of the device.*

Characterization

First we measured on the macro scale the dilatation of the composite. We polymerized the composite in a glass tube and obtained 18% volume dilatation for a temperature varied between 20°C to 80°C, similar to the one of pure paraffin [3].
Then we characterized the micro-hotplates in order to estimate the temperature reached as a function of the input power. We measured as well the displacement response of the microactuator under different actuation and load conditions.
The thermal coefficient of resistance (TCR α=3.88*10^{-3}°C^{-1}) of the fabricated Al micro-heaters was measured on a hot chuck. Later on, this coefficient was used to estimate the temperature θ of the micro-hotplate as a function of the resistor value of the heater R (R_0=24Ω @ 20°C, equation 1).

$$\theta = \theta_0 + \frac{R - R_0}{R_0 \alpha} \quad (1)$$

We determined the hotplate temperature vs. electrical power applied for a hotplate in contact with paraffin-PDMS composite (see Fig. 10). We expect the temperature within the paraffin-PDMS to follow a gradient.

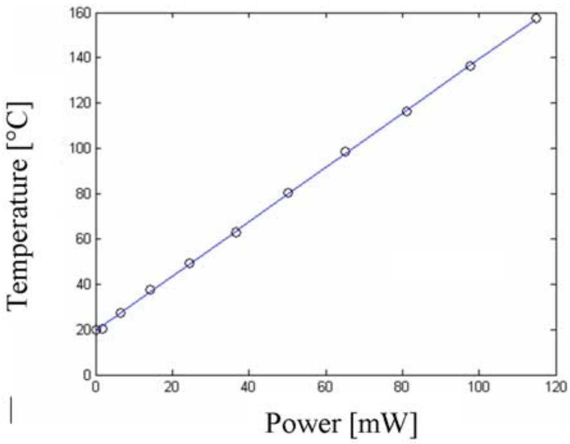

Fig. 10: *Temperature of a micro-hotplate vs. electrical power applied. The glass cavity is filled with paraffin-PDMS composite. The maximum temperature is obtained at 2 V.*

At 2 V actuation voltage, when a maximum temperature of 160°C is reached on the hotplate, displacements as large as 160 µm were measured for actuators without nozzles (see Fig. 11). Smaller displacements of 90 µm were observed for devices having a soft PDMS elastomeric membrane on top of the composite material.

Theoretically, if we estimate the equivalent vertical displacement of pure paraffin filling 60% of the glass channel heated at 160°C (no temperature gradient considered in this simplification) and expanding by 30% [1], we obtain 90 µm elongation. Therefore even though the paraffin-PDMS were mixed in 1:1 v/v ratio the dilution of paraffin into PDMS did not reduce the displacement as one would expect. Further investigations are needed to explain this behaviour.

We think that the lower displacement observed for the actuator having an elastomeric PDMS membrane is essentially due to heat conduction within this additional PDMS mass and silicon chip. After a complete actuation cycle, the paraffin-PDMS composite completely recovered its initial position without hysteresis (see Fig. 11). Devices having an elastomeric PDMS membrane appeared to be more stable over time. We think that the slow degradation of devices without PDMS elastomeric membrane is related to paraffin evaporation below its boiling point, which would result in a slow leakage of paraffin through the PDMS mass.

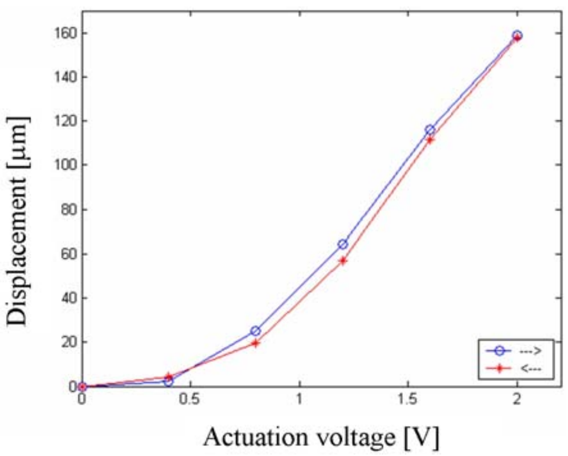

Fig. 11: *Paraffin-PDMS microactuator without elastomeric PDMS membrane cycled back and forth to its maximal displacement (central point).*

Paraffin-PDMS actuators generate high forces: the measured displacement exhibited no substantial dependence on the mass of small loads within the range of 18 to 60 mg. However, our set-up did not enable us to apply the high loads needed to measure the force-displacement properties of the actuator.

We linked the displacement reduction between a non-loaded state and a loaded one to the additional cooling created by the silicon chips used as loads. To fully characterize the load effect, one would have to develop an other set-up where larger loads could be applied.

We believe that the 40s time response measured results from a time delay needed for the temperature to stabilize within the whole paraffin-PDMS mass. The Al hotplate patterned on the polyimide film heats first the paraffin-PDMS in contact with it, and then heat propagates within the paraffin-PDMS mass and the glass chip. An improved actuator design could allow reducing its time response.

Conclusion

This study demonstrates that using a PDMS-paraffin composite in a phase-change thermo-microactuator enables achieving outstanding performances while keeping the fabrication simple and the design compact. Displacements as high as 160 µm were observed for 1 mm^2 (active area) devices without elastomeric PDMS membrane, while a maximum displacement of 90 µm was measured on the device having this additional soft PDMS membrane. The lower displacement observed in that case was attributed to additional thermal losses through this layer.

A set-up would have to be developed to apply the high mechanical loads needed for measuring the force-displacement characteristics without modifying significantly the heat loss.

The elastomeric PDMS membrane increased the lifetime of the device compared to devices having the paraffin-PDMS composite in contact with ambient air.

Such actuators are well suited for producing large forces and displacements in a very confined geometry. In order to fabricate this actuator on the wafer scale, efforts would have to focus on optimizing the dispensing method of the composite. An improved design considering heat conduction within the different components could enhance time response and displacement.

References

[1] E. T. Carlen and C. H. Mastrangelo, *J. Microelectromech. Syst.*, vol. 11, pp. 408-420, 2002.

[2] P. Selvaganapathy, E. T. Carlen, and C. H. Mastrangelo, *Sens. and Actuators, A*, vol. 104, pp. 275-282, 2003.

[3] L. Klintberg, M. Karlsson, L. Stenmark, and G. Thornell, *Sens. and Actuators, A*, vol. 96, pp. 189-195, 2002.

[4] D. Briand, S. Colin, A. Gangadhariah, E. Vela, P. Dubois, L. Thiery, and N. F. de Rooij, Proc. EurosensXIX, Barcelona, Spain, Sept. 2005.