SIMPLE, HIGH ACTUATION POWER, THERMALLY ACTIVATED PARAFFIN MICROACTUATOR

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ABSTRACT

This paper presents a new yet simple family of microactuators that provide both large displacements (2-5 μm) and high forces (∼1 N) hence suitable for microvalves. The actuators use the high volumetric expansion of a sealed, surface micromachined patch of paraffin heated near its melting point to deform a sealing diaphragm. Two types of actuators were fabricated using a simple 2-mask process. The first device consists of a 9 μm-thick circularly patterned paraffin layer covered with a 2 μm-thick metallized p-xylene diaphragm. Devices 200-400 μm in radius produced a 2.7 μm peak deflection. The second device includes a constrained volume reservoir that magnifies the diaphragm deflection producing a 2.1-3.1 μm deflection with a paraffin thickness of only 3 μm. Actuators were constructed on both glass and silicon substrates. The glass devices using 50-200 mW of power showed response times of 30-50 ms. The response time for silicon devices was much faster (3-5 ms) at the expense of a larger 0.5-2 W actuation power.

INTRODUCTION

In the past decade many low voltage electromechanical microactuators based on electrostatic, magnetic, bimorph, thermopneumatic, and shape-memory forces have been fabricated. A parameter that characterizes the ability of an electromechanical actuator to exert work on a load is the actuation energy [1] \( F_a \epsilon_a \) where \( F_a \) is the actuator force and \( \epsilon_a \) its maximum displacement. Actuators can be scaled and operate under various conditions. Therefore a more suitable parameter is the actuation energy divided by the total actuator volume,

\[
P_a = \frac{F_a \epsilon_a}{V_a}
\]

when the actuator is operated under low voltages. \( P_a \) has units of pressure (or \( \text{J m}^{-3} \)) and approximately “normalizes” these differences.

Table 1 shows \( P_a \) extracted for several low voltage microactuators [2-5]. The majority of these devices can provide either a large deflection but not a large force or vice-versa. It is clear that the electrostatic actuators hold the lowest density and the thermal actuators have the highest [4]. Among these thermopneumatic and SMA microactuators pack the largest density. This is not surprising as they are convert electrical to mechanical work through a high density working substance.

Shape memory actuators provide very large forces, but their linear deformation strain is limited to about 8% [4]. Therefore SMA often use mechanical advantage schemes to increase displacement. Thermopneumatic actuators provide both large displacements and forces, but their fabrication and integration in large microsystems is often cumbersome [6] due to the necessity of loading the working substance, typically a liquid, into a sealed cavity.

The working substance can be not only a liquid but also a solid. For example, Fig. 1 shows the volumetric expansion of two paraffins [7]. The large thermal expansion at the solid-liquid phase transition is a general property of long chained polymers, but the low transition temperature is a property of paraffins (∼50-chain long). From Fig. 1 these materials can provide very large \( P_a \approx 10^7 \text{ J m}^{-3} \). Like conventional thermopneumatic actuators, once the polymer melts it transmits

<table>
<thead>
<tr>
<th>Actuator Type</th>
<th>( P_a ) (J m(^{-3}))</th>
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<tbody>
<tr>
<td>Electrostatic comb drive</td>
<td>( 10^2 )</td>
</tr>
<tr>
<td>Electrostatic par. plate</td>
<td>( 10^3 )</td>
</tr>
<tr>
<td>Magnetic</td>
<td>( 10^4 )</td>
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<tr>
<td>Thermo bimorph</td>
<td>( 10^5 )</td>
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<tr>
<td>Thermo pneumatic</td>
<td>( 10^6 )</td>
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<tr>
<td>SMA</td>
<td>( 10^7 )</td>
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Table 1: \( P_a \) (J m\(^{-3}\)) for several low voltage microactuators

Figure 1: Measured volumetric expansion characteristic for two paraffin materials
pressure, a useful hydraulic property for force and deflection multiplication. These two properties make paraffin actuators particularly attractive for the fabrication of simple integrated miniature valves in microfluidic systems.

Macroscopic paraffin actuators have been developed for many applications [8] with the earliest use in automotive thermostats [9] and more recently in satellite antenna positioning systems [10] and medical devices [11].

In this paper we present a family of microactuators that use paraffin as a working substance. Unlike conventional thermopneumatic actuators, the fabrication of paraffin based microactuators is very simple because films of paraffin can be patterned using surface micromachining techniques. This permits the fabrication of many actuators on the same die without any working fluid filling or post-processing sealing operations.

**DEVICE STRUCTURE**

The microactuator shown in Fig. 2 is based upon the thermal expansion upon melting of a 3-10 μm-layer of high actuating power paraffin preferably from the n-Alkane group of organic materials. The paraffin layer is deposited on either a glass or silicon substrate with an Al heater. The wax layer is sealed using a thin layer of parylene-C. With n-Alkanes a volumetric expansion of 10 - 30% can be reached when heated at temperatures ranging from 65-150°C depending on the length of the polymer chain. A much larger deflection is achieved from the microactuator because the volume is constrained on the edges by a diaphragm, reaching a deflection between 25-50% of its thickness at peak.

For a circular diaphragm under uniform pressure, the deflection is approximated by [12]

\[ u(r) = u_{\text{max}} (1 - \eta^2)^2, \]  

(2)

where \( \eta = r / r_a \), \( r_a \) is the radius of the diaphragm, and \( u_{\text{max}} \) is the maximum deflection. Eq. (2) depends somewhat on the boundary conditions chosen at the rim. The volume underneath the deflected diaphragm is then calculated

\[ V_d \approx u_{\text{max}} \int_0^{r_a} 2\pi u(r) dr = \frac{1}{3} \pi u_{\text{max}} r_a^2. \]  

(3)

This volume must be occupied by the expanding paraffin. Therefore

\[ u_{\text{max}} = 3 m t_p, \]  

(4)

where \( t_p \) is the thickness of the paraffin layer, and \( m \) is the percent volume expansion coefficient of the material. For \( t_p = 9 \mu m \) and \( m = 0.1 \), \( u_{\text{max}} = 2.7 \mu m \).

The center diaphragm deflection can be further increased by rigidly confining a portion of the diaphragm thus allowing a smaller surface area of the diaphragm to deflect an increased distance. This is practically achieved by introducing etched support posts for the sealing diaphragm for \( r > r_a \) as shown in Fig. 3. The deflection is then magnified by a factor of four.

**FABRICATION**

The device shown in Fig. 2 is completely fabricated using micromachining techniques. Fig. 4 shows a simplified process flow. The actuators are fabricated by first patterning aluminum heaters on the substrate followed by the thermal evaporation of paraffin wax. The paraffins used in this paper are Logitech 0CON-195 and n-Hexatriacotane (C_{29}H_{58}), both with a melting temperature \( T_m = 75°C \). Because of the low paraffin melting temperature, it is necessary to keep all subsequent processing steps at temperatures below \( T_m \). Next, a 0.5 μm-thick layer of p-xylene (parylene) is vapor deposited on the paraffin film. A thin 300/3000 Å Cr/Au layer is next evaporated on top of the parylene.

A 2.7 μm-thick layer of photoresist (PR1827) is next spun casted and softbaked at 60°C for approximately 2 hours until
it is no longer tacky. The resist is then exposed and developed but not hardbaked. Next the Cr/Au layer is wet etched to form the hard physical mask. The parylene and paraffin beneath are then selectively patterned in O₂:CF₄ plasma in an Applied Materials 8300 reactor with a water cooled chuck (10-17°C). A 2.4 μm-thick layer of paraffine is next deposited on the paraffin to form the sealing diaphragm. Finally, after etching the contact holes, aluminum contact pads are evaporated and patterned. Fig. 5 shows a microscope photograph and SEM of unposted microactuators. The actuators shown have a 9 μm-thick layer of thermally evaporated paraffin covered by a Cr/Au/parylene stack. Fig. 6 shows a microscope photograph of a posted diaphragm microactuator.

![Microscope photograph of a posted diaphragm microactuator](image)

**Figure 5:** (a) Top view of sealed actuator with heater clearly visible (b) SEM photograph of device. The evaporated paraffin thickness is 9 μm.

The paraffin actuators are being used as the active elements for microfluidic valves. The actuators, when activated, can constrict the flow of gas or liquid from a channel through an outlet hole. Fig. 7 shows an example valve application where the actuator is located directly below the outlet hole.

**EXPERIMENTS**

Deflection measurements were performed using a Wyko NT-2000 optical profilometer. Fig. 8 shows the diaphragm deflection for the unposted 9 μm-thick Logitech paraffin devices for different heater voltages. The deflection for the 300 and 400 μm devices was also 2.7 μm. The measured deflection was very close to the calculated value justifying the expansion coefficient m = 1. Fig. 8 also shows the measured peak deflection as a function of power for a 200 μm radius diaphragm on a glass substrate. To achieve the 2.7 μm deflection height requires approximately 100 and 150 mW for the 200 μm and 400 μm devices.

Fig. 9 shows the measured time response for the devices on glass substrates using the methods in [13]. Cutoff frequencies were determined from phase measurements of the heater impedance. Measured response times ranged from 30 to 50 ms for 400 to 200 μm devices consistent with the high thermal storage of the latent heat of fusion for paraffin (∼150 J/°C).

![Characteristics of 200 μm diaphragm device](image)

**Figure 8:** Measured results for 200 μm diaphragm device (a) deflection height vs voltage (b) deflection height as a function of input power.

![Characteristics of 200 μm diaphragm device](image)

**Figure 9:** Measured response time for the 200 μm radius diaphragm device (a) phase response showing 30 Hz cutoff (b) test circuit and waveform used to determine actuator response time.
For the silicon devices, the time constant is reduced by a factor of 10 (3.5 ms) at the expense of much larger power dissipation as shown in Fig. 11.

Fig. 10 shows the measured diaphragm deflection for a 400 µm pinned-diaphragm device. The deflection was 3.1 µm and silicon substrates. The deflection for the first device on glass was 2.7 µm for a 9 µ-thick layer of paraffin. For 200-400 µm radius devices the response time ranged from 30-50 ns and the power consumption from 100-150 mW, respectively. The response time for silicon substrate devices is 10 times smaller. Devices with mechanical advantage were also fabricated and obtained much larger deflections and lower response times using thinner films. These devices are easily fabricated using a two mask process.

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References