

## DESIGN AND FABRICATION OF A MICRO THERMAL ACTUATOR FOR CELLULAR GRASPING\*

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**ABSTRACT:** The development of a novel polymer-based micro robotic gripper that can be actuated in a fluidic medium is presented in this paper. Our current work is to explore new materials and designs for thermal actuators to achieve micromanipulation of live biological cells. We used parylene C to encapsulate a metal heater, resulting in effectively a tri-layered thermal actuator. Parylene C is a bio-compatible dielectric polymer that can serve as a barrier to various gases and chemicals. Therefore, it is suitable to serve as a thermal/electrical/chemical isolation material for protecting the metal heater from exposing to an aqueous environment. We have demonstrated parylene actuators ( $2\text{ mm} \times 100\ \mu\text{m} \times 0.5\ \mu\text{m}$ ) to operate in an aqueous environment using 10 to 80 mW input power. The temperature of these actuators at full deflection was estimated to be  $\sim 60^\circ\text{C}$ , which is much lower than the typical requirement of  $> 100^\circ\text{C}$  to actuate other conventional MEMS actuators. *Danio rerio* follicles in fluidic medium were captured successfully using these actuators. Moreover, these actuators were found to be responsive to moderate rise in environmental temperature, and hence, we could vary the fluidic medium temperature to actuate trimorphs on a chip without any input of electrical energy, i.e., raising the fluidic temperature from  $23^\circ\text{C}$  to  $60^\circ\text{C}$  could actuate the trimorphs to grasp follicles of  $\sim 1\text{ mm}$  size in diameter. At  $60^\circ\text{C}$ , the embryos inside the follicles were observed to be alive, i.e., they were still moving in the biological fluid isolated by the follicle membrane. The smallest follicles grasped were  $\sim 500\ \mu\text{m}$  in diameter using  $800\ \mu\text{m} \times 130\ \mu\text{m} \times 0.6\ \mu\text{m}$  actuators. The fabrication process, modeling, and optimization of the trimorph actuators are presented. Based on the successful operation of these polymer-based actuators, we are currently developing multifinger thermal microgrippers for cellular grasping and manipulation, which can potentially be hybridly integrated with circuits for computer control.

**KEY WORDS:** thermal actuator, microgripper, cell manipulation, underwater microactuator

### 1 INTRODUCTION

Microrobotics consists of a variety of research areas including microassembly<sup>[1]</sup>, microhandling<sup>[2]</sup>, micro mobile robots and etc. Some of the potential applications of microrobotics with growing interest are cell manipulation, cell isolation, and micro injection in the biomedical field. For example, biologists usually use pipettes for cell isolation prior to carrying out micro injection. However, the functionality of this method is limited by the size of the cells, i.e., the cells cannot be too small compared to the pipette; otherwise, a bundle of cells could be drawn into the pipette

at once. In addition, the pipette cannot be used to rotate individual cells, a function which is highly desirable during a micro injection process. To address these problems, we are currently developing a system that can manipulate and isolate cells controllably, and that can potentially be used to conduct localized cell probing and measurements.

Most of the existing MEMS actuators are limited to specific or narrow applications due to their limited displacement, force output, and necessary working environment. As described by S. Shoji<sup>[3]</sup>, each micro actuation principle, including electrostatic, piezoelec-

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tric, electromagnetic and thermal, has their own advantages and disadvantages. For example, the problem encountered in electrostatic and piezoelectric is limited deflection. Magnetic actuators currently still need off-chip magnetic source to actuate them effectively. Thermal actuators, however, can produce large force and deflection but they require large power and may affect the temperature of the surrounding environment. For the purpose of micromanipulation, more specifically for cell manipulation, actuators are required to operate in biological fluid environment. Electrostatic actuation is inefficient in ion-rich fluid and the deflection is small<sup>[4]</sup>. Therefore, thermal actuators were considered by some researchers to operate in solution-based environments. Generally speaking, thermal actuator consisting of two layers, in which one of the layers would be a heater, is called a "bimorph".

For thermal actuators to operate in for aqueous environments, heat convection to a solution medium can be as significant as conduction to the substrate. Consequently, micro actuation in an aqueous medium requires much higher input power than actuation in air. Lin et al.<sup>[4]</sup> have demonstrated a 2-layer thermal/electrostatic actuator ( $200 \mu\text{m} \times 45 \mu\text{m} \times 1.1 \mu\text{m}$  with polyimide/Au layers). This thermal actuator can operate in air with 7V at 4mA. However, for actuation in liquid, it requires voltage as high as 100V and causes overheat of the actuator. Ataka et al.<sup>[5]</sup> also fabricated a thermal bimorph actuator ( $500 \mu\text{m} \times 100 \mu\text{m} \times 6 \mu\text{m}$  with polyimide/Au layers).

The temperature of the actuator rose up to  $260^\circ\text{C}$  for actuation, which will definitely kill cells.

Owing to the disadvantages of silicon- and metal-based thermal actuators to operate in aqueous environments, new materials and designs for thermal actuators must be explored to achieve micromanipulation of live biological cells. In this paper, parylene C is chosen to encapsulate a middle metal heater, resulting in a tri-layered thermal actuator. Parylene C, which is a polymer, has excellent mechanical and electrical properties. Comparison between the properties of parylene C and common used materials in MEMS are shown in Table 1. It has a large coefficient of thermal expansion (CTE) and a high dielectric constant. It can withstand temperatures up to  $\sim 180^\circ\text{C}$  and is extremely conformal<sup>[6]</sup>. It is bio-compatible and can serve as a barrier to oxygen, moisture, chemicals, solvents, and carbon dioxide. Therefore, we have chosen it to protect the metal from exposing to fluid while the actuator is working in an aqueous environment. Moreover, as the metal heater is covered by parylene, heat can be trapped and thus heat loss to the surrounding can be reduced. Also, it can protect the metal layer from reacting with the fluid. Parylene C has been used to create microfluidic devices such as microchannel<sup>[7]</sup> and micro check valve<sup>[8]</sup> by other researchers. Here, we explore the advantage of parylene to potentially develop a polymer-based micro thermal gripper for micromanipulation in aqueous environment to capture cells.

**Table 1 Comparison on physical properties of various thin film materials**

	Platinum	PolySi	SiO <sub>2</sub>	Parylene
coefficient of thermal expansion (CTE)/K <sup>-1</sup>	$9 \times 10^{-6}$	$2.5 \times 10^{-6}$	$12 \times 10^{-6}$	$3.5 \times 10^{-5}$
density/(kg·m <sup>-3</sup> )	2145	2300	2300	1289
Young's modulus/GPa	146.9	170	83	3.2
thermal conductivity/(W·m <sup>-1</sup> ·K <sup>-1</sup> )	69.23	28	1.38	0.082

## 2 MODELING

### 2.1 Design of the Dimension of Actuator

The motion of this polymer-based thermal actuator can be estimated by a three-layer cantilever beam model. In our current design, the middle layer is platinum and the top and bottom layers are parylene. When current passes through the platinum, the entire structure will be heated up. Due to the difference in coefficient of thermal expansion (CTE) between platinum and parylene, each layer would expand differently and lead to the curling up of the beam. By considering the interaction of forces and moments between the layers, the bending radius of curvature  $r$

due to temperature change  $\Delta T$  can be calculated by Eqs.(1)~(5).

$$r = \left(1 - \frac{1}{2}AD^{-1}C\right) / -AD^{-1}B\Delta T$$

$$= g(A, B, C, D) \cdot \frac{1}{\Delta T} \quad (1)$$

where

$$A = \frac{1}{\sum_{i=1}^3 E_i I_i} \begin{bmatrix} \frac{t_1}{2} & t_1 + \frac{t_2}{2} & t_1 + t_2 + \frac{t_3}{2} \end{bmatrix} \quad (2)$$

$$\mathbf{B} = \begin{bmatrix} \alpha_1 - \alpha_2 \\ \alpha_2 - \alpha_3 \\ 0 \end{bmatrix} \quad (3)$$

$$\mathbf{C} = \begin{bmatrix} t_1 + t_2 \\ t_2 + t_3 \\ 0 \end{bmatrix} \quad (4)$$

$$\mathbf{D} = \begin{bmatrix} \frac{1}{E_1 t_1 b_1} & -\frac{1}{E_2 t_2 b_2} & 0 \\ 0 & \frac{1}{E_2 t_2 b_2} & -\frac{1}{E_3 t_3 b_3} \\ 1 & 1 & 1 \end{bmatrix} \quad (5)$$

The subscript  $i$  is the parameter for the  $i$ th-layer. In the above equations,  $\alpha$ ,  $t$ ,  $b$ ,  $E$  and  $I$  are the coefficient of thermal expansion, thickness, width, Young's modulus and moment of inertia of the corresponding layers, respectively. The vertical displacement of the beam can be calculated by the following equation, in which  $L$  is the length of the beam.

$$d = r \left[ 1 - \cos \left( \frac{L}{r} \right) \right] \quad (6)$$

From Eq.(1), the bending radius is inversely proportional to temperature change and, in our case,  $\Delta T = 30^\circ\text{C}$  is set as the maximum allowable temperature change. For this  $\Delta T$ , biological cells may still survive. In order to have a smaller radius of curvature of beam with less temperature change, it is necessary to minimize the function  $g(\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D})$ , which is a function that is inversely proportional to the difference in CTE of the layers, i.e., if the top and bottom layers of the polymer-based actuator are made of the same material,  $g(\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D})$  is inversely proportional to  $(\alpha_{\text{heater}} - \alpha_{\text{polyene}})$ . Therefore, one way to optimize the design is to choose a metal that gives larger CTE difference. Another way is to deal with the thickness and width of the beam. In our case, it is assumed that the widths of the top and bottom layers are the same. After rearranging  $g(\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D})$ , it depends only on  $t_1$ ,  $t_{21}$ ,  $t_{31}$ ,  $E_{21}$ ,  $E_{31}$  and  $b_{21}$ .  $E_{ij}$  is the Young's modulus ratio of layer  $i$  to  $j$ . Since  $g(\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D})$  is an unbounded function, we cannot find a close form solution for optimizing those variables. The relationship between the radius and the thickness ratios is shown in Fig.1. The thickness ratio of layer  $i$  to  $j$  is given by  $t_{ij}$ . It is found that  $t_{21}$  and  $t_{31}$  should be small in order to give a smaller radius of curvature. However, it is also found that  $t_1$  must be small. Therefore, it is necessary to perform a numerical analysis for solving  $t_1$ ,  $t_{21}$  and  $t_{31}$  in a

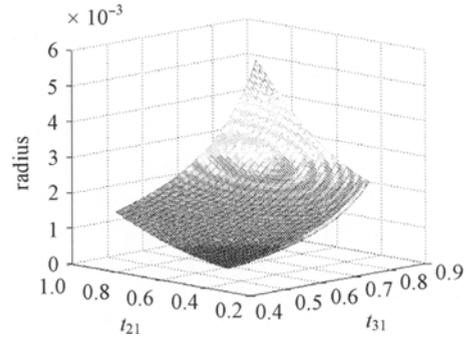


Fig.1 Relationship between radius and thickness ratios

certain range. And it is found that  $t_1$  has greater effect on the radius. After the values of thickness are determined, we can find the optimal width ratio  $b_{21}$  by Eq.(7). Then, by arbitrarily choosing  $b_1$ ,  $b_2$  can be determined.

$$b_{21} = \text{sqrt} \left[ (1 + 4t_{31} + 12t_{21}t_{31} + 12t_{21}^2t_{31} + 6t_{31}^2 + 12t_{21}t_{31}^2 + 4t_{31}^3 + t_{31}^4) / E_{21}t_{21}^2 \right] \quad (7)$$

## 2.2 Heat Convection to Aqueous Media

Ideally, if the electrical current passed to a heater is converted into thermal energy that is efficiently used to heat up a bimorph or trimorph structure, the input electrical power can be minimized to actuate the actuators. However, majority of the heat converted will be lost through conduction to the substrate, i.e., convection heat loss to the surrounding is insignificant compare to the conduction heat loss. This is especially true for micro structures because the heat conduction length to the substrate is extremely short due to the limited film thickness obtainable for constructing MEMS structures. In the case of operating MEMS actuators in aqueous environment, the convection may become significant since the free-convection coefficient in water is much higher than in air. In order to better understand the power requirement of our trimorph actuators, a simple analysis was performed to evaluate the heat transfer mechanisms of the structure. We applied the heat equation<sup>[9]</sup> to the anchor of the actuator and compared the heat transfer when operating in water and in air. The anchor and its equivalent thermal circuit are shown in Figs.2 (a) and (b). The input energy is generated by passing a current  $I$  through a platinum heater with resistance  $R$  and volume  $V$ . There are two ways for energy loss: convection to surrounding fluidic medium and conduction to substrate. By considering the control volume of the platinum heater and applying the heat equation, we get

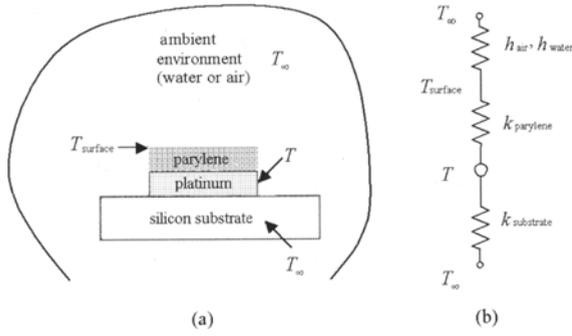


Fig.2 (a) Schematic of an anchor for the actuator; (b) The corresponding equivalent thermal circuit

$$\rho C_p b_{\text{platinum}} \frac{\partial T}{\partial t} = \frac{I^2 R}{V} b_{\text{platinum}} - \left( \frac{T - T_{\text{surface}}}{b_{\text{parylene}}/k_{\text{parylene}}} + \frac{T - T_{\infty}}{b_{\text{substrate}}/k_{\text{substrate}}} \right) \quad (8)$$

where  $\rho$ ,  $C_p$ ,  $V$  and  $b_{\text{platinum}}$  are the density ( $\text{kg}\cdot\text{m}^{-3}$ ), specific heat capacity ( $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ ), volume ( $\text{m}^3$ ) and thickness (m) of the platinum heater, respectively;  $T$  is the temperature (K) of the platinum heater,  $T_{\text{surface}}$  is the temperature (K) on the parylene surface,  $T_{\infty}$  is the ambient temperature (K),  $b_{\text{parylene}}$  and  $k_{\text{parylene}}$  are the thickness (m) and thermal conductivity ( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ) of parylene layer, respectively; and  $b_{\text{substrate}}$  and  $k_{\text{substrate}}$  the thickness (m) and thermal conductivity ( $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ ) of substrate, respectively.

We assume that the temperature of the substrate always equals to ambient temperature (297K). In order to eliminate  $T_{\text{surface}}$  in Eq.(8), we apply the heat equation to the control volume of parylene layer and obtain

$$\frac{T - T_{\text{surface}}}{b_{\text{parylene}}/k_{\text{parylene}}} = \frac{T_{\text{surface}} - T_{\infty}}{1/h_{\text{medium}}} \quad (9)$$

From Eqs.(8) and (9)

$$\rho C_p b_{\text{platinum}} \frac{\partial T}{\partial t} = \frac{I^2 R}{V} b_{\text{platinum}} - \left[ \frac{T - T_{\infty}}{(b_{\text{parylene}}/k_{\text{parylene}}) + (1/h_{\text{medium}})} + \frac{T - T_{\infty}}{b_{\text{substrate}}/k_{\text{substrate}}} \right] \quad (10)$$

$$q''_{\text{internal}} = q''_{\text{resistive}} - (q''_{\text{medium}} + q''_{\text{substrate}}) \quad (11)$$

where  $h_{\text{medium}}$  is the convection heat transfer coefficient of air or water ( $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ ).

In Eq.(11), there are two terms of heat loss from heating:  $q''_{\text{medium}}$  and  $q''_{\text{substrate}}$ , which is heat convection to air or water through parylene layer and heat conduction to the substrate, respectively. The comparison between these heat losses is shown in Fig.3. The parameters used to obtain Fig.3 are shown in Table 2. It obvious from that the heat loss due to conduction is much larger than convection as the size of the anchor decreases. In addition, if the actuator is used in water instead of in air, the heat loss due to convection to water is nearly six times more than that of convection to air. Therefore, it can be verified that, in order to actuate the actuator underwater, more power is required compared with that in air. As a result, it is necessary to select a suitable insulating material for trapping heat or reducing the heat loss through convection, and parylene thus serves the purpose. Another way to reduce heat loss is by adding an insulating material between the platinum heater and silicon substrate to reduce conduction to substrate.

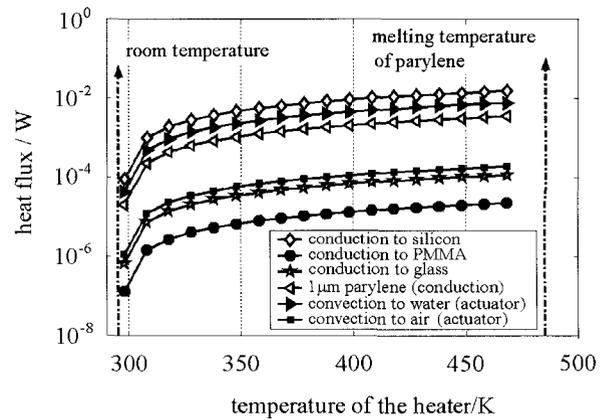


Fig.3 Comparison of heat conduction to substrate and convection to air and water

Table 2 Parameters used to model the actuator heat transfer mechanisms

Parameters	Values
$b_{\text{substrate}}$	525 $\mu\text{m}$
$b_{\text{parylene}}$	0.1 $\mu\text{m}$
$h_{\text{air}}$	5 $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$
$h_{\text{water}}$	200 $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$
$k_{\text{parylene}}$	0.082 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
$k_{\text{substrate}}(\text{silicon})$	148 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$

### 3 FABRICATION PROCESS

Several designs of our polymer-based micro thermal actuators were batch fabricated on a 4 inch silicon

wafer using surface micromachining technology. The fabrication process is shown in Fig.4 and is briefly described below. Aluminum ( $\sim 1\mu\text{m}$ ) was first deposited onto the silicon substrate. This layer serves as the sacrificial layer for the actuator. The first parylene C ( $\sim 0.3\mu\text{m}$ ) layer was deposited by the PDS 2010 LABCOTER®2. This polymer layer was patterned by photolithography and etched by oxygen plasma. Next, Titanium ( $\sim 500\text{\AA}$ ) and then platinum ( $\sim 2000\text{\AA}$ ) were deposited by sputtering onto the substrate. Due to the poor adhesion between platinum and silicon, the titanium was deposited before platinum layer to promote adhesion. These two metal layers were patterned by lift-off at the same time, and serve as the heater for the actuator. A second parylene C layer was then deposited and etched by oxygen plasma. Finally, the structure was sacrificially released by etching the aluminum layer with  $\text{H}_2\text{SO}_4$  solution. An actuator fabricated using the process described above is shown in Fig.5.

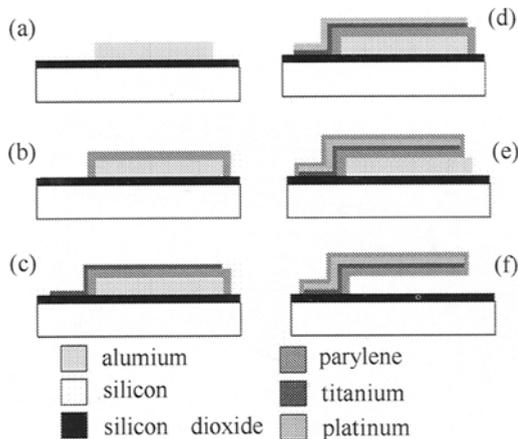


Fig.4 Fabrication process of the polymer thermal actuators

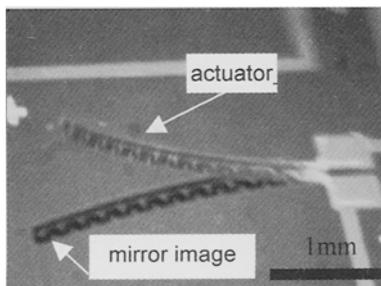


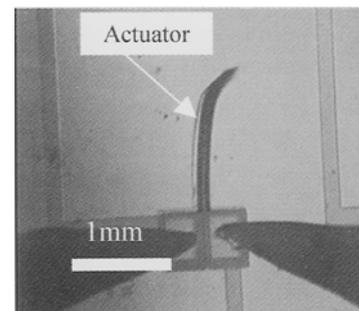
Fig.5 Hirox 3D microscope image of a fabricated actuator under water. Note that parylene C is transparent, so only the metal heater is seen clearly in the photograph

## 4 EXPERIMENTAL RESULTS

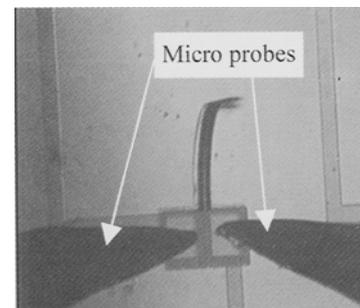
There are two methods to actuate these actuators: (1) passing a current through the heater to induce resistive heating in the actuator, and (2) changing the temperature of the medium which surrounds the actuators, i.e., if the temperature of a bath of solution that contains a cell culture is increased, the actuators will deform to trap cells. For the former one, some preliminary results were presented in our previous paper<sup>[10]</sup>. The following describes in more detail of our current results, in addition to results of actuation by fluidic temperature increase.

### 4.1 Actuation by Applying Voltage

The sequence of motion of a thermal actuator actuated underwater by an applied voltage is shown in Fig.6. The initial curl up of the actuator was caused by the residual stress developed during fabrication process. The experiment was carried out under DI water. Resistance of the heater is  $\sim 90\Omega$ . Dimension of the actuator is  $2\text{mm} \times 100\mu\text{m} \times 0.5\mu\text{m}$ . The voltage

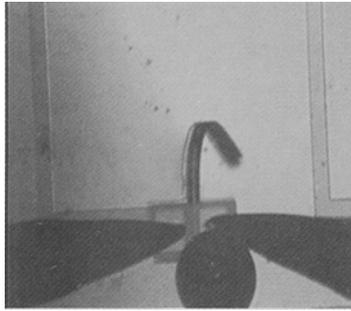


(a)



(b)

Fig.6 Sequence of images on the motion of an underwater actuator actuated by applying voltage across the metal heater to induce resistive heating. In (c), the actuator has deflected more than 50% of full deflection



(c)

Fig.6 Sequence of images on the motion of an underwater actuator actuated by applying voltage across the metal heater to induce resistive heating. In (c), the actuator has deflected more than 50% of full deflection (continued)

was varied from 0 V to 2.6 V, corresponding to current increment from 1.8 mA to 69.9 mA. The relationships of current, voltage and power are shown in Fig.7. Bubbles, due to electrolysis, are generated from probe pads when the apply voltage is up to 1.8 V as shown in Fig.6(c). For this applied voltage, the actuator was curled up  $\sim 50\%$  of full deflection and the power used was 33 mW. It should be note that in Ref.[10], we demonstrated an actuator that required 5 V for actuation, which was higher than the current requirement. The improvement is due to the improvement of our fabrication process. However, bubbles are generated for both cases, which affect the performance of actuators. But, we have found recently that this problem can be solved by covering the bond pads with a very thin film of parylene, that is, direct contact between platinum and water should be avoided. We have pro-

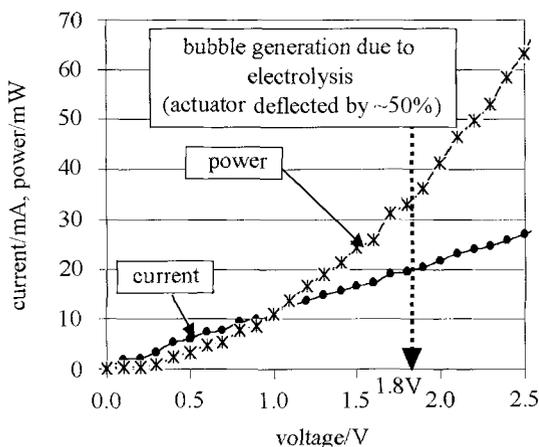


Fig.7 I-V curve of actuation by applying voltage to the resistive heater

ved that even up to 30 V, no bubble will be generated if parylene is deposited on top of the metal bond pads. We will incorporate this process in future generations of actuators.

#### 4.2 Actuation by Water Bath Heating

For actuation by increasing the medium temperature, the experiment was also carried out underwater. Instead of applying voltage to the actuators, the temperature of the water was increased directly in order to raise the temperature of the actuators. Beside an actuator, numbers of follicles fertilized eggs of *Danio rerio*, with diameters ranging from  $500\ \mu\text{m}$  to 1mm were put into the water. The experimental setup is shown in Fig.8. A hot plate was used for heating. The sequence of images on the motion of an actuator capturing a follicle is shown in Fig.9. In Fig.9(a), the actuator is initially curled up due to residual stress developed throughout the fabrication process. And, as shown, the actuator can be used to grasp a biological cell (Fig.9(b)) as the temperature of the water was changed from  $23^\circ\text{C}$  to around  $60^\circ\text{C}$ . The whole

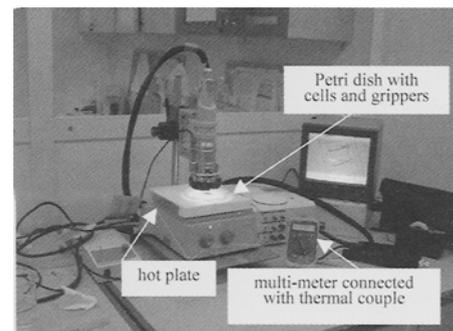
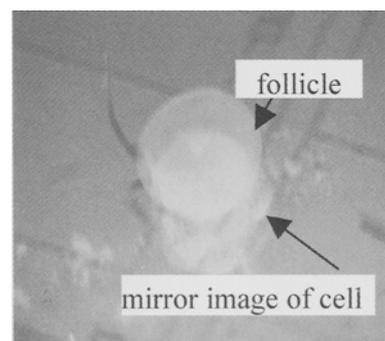
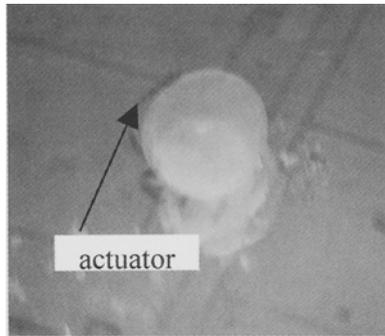


Fig.8 Experimental setup for water bath heating

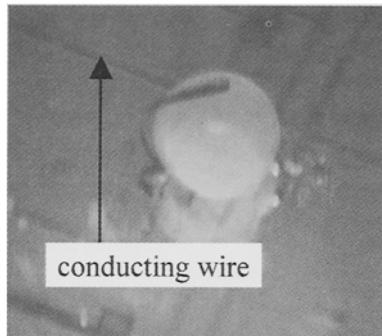


(a)

Fig.9 Sequence of images on the motion of an underwater actuator by water bath heating method



(b)



(c)

Fig.9 Sequence of images on the motion of an underwater actuator by water bath heating method (continued)

process takes 4 minutes, which is the time required to heat up the water bath in our experiment.

#### 4.3 Micro Injection

After the success in cell grasping, we have tested the process of micro injection using these actuators to hold the cells. It is common for biologists to use a pipette and Agarose Gel for cell isolation, manipulation and micro injection. However, by using a microgripper, it is convenient to grasp a cell and carry out injection as illustrated in Fig.10. Development is

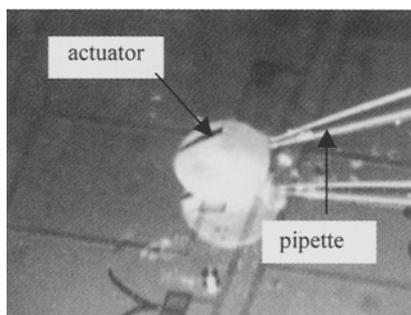


Fig.10 Injection of dye to a captured follicle

underway to fabricate microgrippers with five or six fingers. These actuators will then be hybridly integrated with IC chips so as to allow computerized control (see Fig.11).

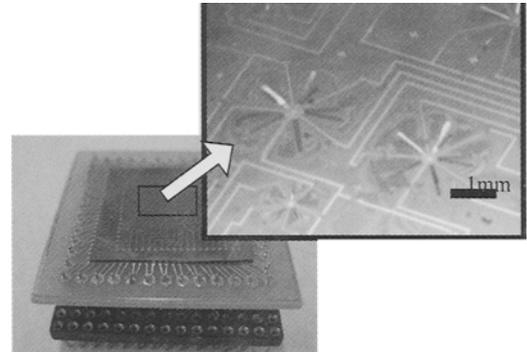


Fig.11 Samples are attached on top of an IC package, which can be connected to circuits for computer control

## 5 CONCLUSION

A novel polymer-based micro robotic actuator suitable for underwater actuation is presented in this paper. We have demonstrated actuation of micro parylene trimorphs in an aqueous environment by two methods: (1) actuation by resistive heating ( $< 100 \text{ mW}$ ) to induce thermal strain, and (2) varying the temperature ( $\Delta T < 40^\circ\text{C}$ ) of the aqueous medium that surrounds the actuators. Moreover, grasping of *Danio rerio* follicles were demonstrated with actuation temperature of  $\sim 60^\circ\text{C}$ . For future work, we will control multifinger microgrippers through a computer and quantitatively evaluate the performance of the microgrippers in terms of frequency response, force output etc.

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