Magnetically driven temperature-controlled microfluidic actuators

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ABSTRACT

Using polymer-based fabrication and microfluidic tectonics, we show here temperature-controlled actuators, specifically a ‘smart’ micropump and micromixer. Temperature-responsive hydrogels that act as an autonomous clutch were utilized for realizing and testing the ‘smart’ micropump and micromixer. Both actuators actively respond to the surrounding environmental temperature. Under the constant influence of an external rotating magnetic field, the micropump pumps fluid when the local temperature reaches over 30 °C and ceases to do so below 16 °C. Flowrates reaching 3.1 µL/minute have been obtained. The temperature-sensitive (programmable) micromixer allows for fluid mixing at the microscale. A single micromixer (in an array) can be individually controlled by local environmental temperatures. Such microcomponents have potential for being integrated into microsystems for many microelectronics and biological applications.

Keywords: microfluidic, micromixer, micropump, responsive hydrogel, temperature-sensitive.

INTRODUCTION

Microsystems are sensitive to environmental temperatures, especially microelectronics and recently, biological microfluidics. Devices can succumb to failure if temperatures are too high (or too low). Many levels of thermal management exist, including air jet flow, dielectric fluids, fans, cold plates, and refrigeration systems [1]. Here, closed loop temperature-controlled microcomponents are shown that actively responds to the surrounding environmental temperature.

Microelectromechanical systems (MEMS) technology has allowed for the development and fabrication of such microcomponents, as well as a variety of other sensors, actuators and microstructures. Using this technology, researchers have demonstrated a variety of micropumps designed for various applications, including microfluidics, drug delivery, etc. [2, 3]. Polymer-based fabrication has recently established itself as a platform for rapid developments in microfluidic technology. Microsystems can be fabricated using photosensitive polymers without the need for cleanroom facilities. Using this platform, researchers have created temperature-sensitive microactuators [4] and valves [5, 6], and micromixers [7]. In this work, we use microfluidic tectonics (µFT) [8], which uses liquid-phase photopolymerization (LPP), to allow for rapid fabrication of microfluidic systems.

Hydrogels can be made responsive to many biological and physical stimuli including light, electric fields, pH, and temperature [9]. We previously exploited these materials and processes to fabricate programmable micromixers that can be individually controlled by pH [10]. Here, we present a first demonstration of magnetically driven temperature-controlled actuators, specifically a ‘smart’ micropump and micromixer. The devices are realized by using temperature-sensitive hydrogels [6] to control the pumping actuation [11] and mixing, respectively, and have potential for thermal management applications (Figure 1). Fabrication of microcomponent devices in situ (inside the

![Figure 1. Conceptual diagram of using temperature-sensitive hydrogels (poly(NIPAAm)](6) to control the actuation of the Ni micromixer. (a) The micromixer does not rotate since low temperature causes the poly(NIPAAm) ring to expand. (b) The micromixer rotates freely since high temperature causes the poly(NIPAAm) ring to shrink in volume.)
microfluidic channel) and their programmable operation via local fluid parameters are shown here.

**EXPERIMENTAL METHODS**

**Fabrication process**

Magnetically driven structures are fabricated using polymer-based microfluidics and nickel (Ni) electroplating. The polymer structures are formed using a non-responsive and responsive pre-polymer. Both pre-polymers are made sensitive to ultraviolet (UV) light for photopatterning.

The non-responsive pre-polymer solution consists of a monomer—iso-bornyl acrylate (IBA), crosslinker—tetracycylene glycol dimethacrylate (TeGDMA), and photoinitiator—2,2-dimethoxy-2-phenylaceto phenone (DMPA). Exposure to a UV source causes the pre-polymer to harden (poly(IBA)) due to photopolymerization.

Here, we use temperature-responsive hydrogels to control the actuation of micromixers (see Figure 1). This hydrogel consists of five components: N-isopropyl acrylamide (NIPAAm), N,N'-methylenebisacrylamide (NMBA), 2,2- dimethoxy-2-phenylaceto phenone (DMPA), dimethyl sulfoxide (DMSO), and deionized (DI) water. Exposure to UV light renders a gel matrix that changes its volume configuration depending on its surrounding (temperature) environment.

Figure 2 shows the fabrication process flow. Devices are fabricated on pre-cleaned microscope glass slides (76.2 mm × 25.4 mm × 1 mm) that have been coated

![Figure 2](image)

*Figure 2. General process flow for fabricating Ni-based devices (top view). (a) A cavity created between the substrate (coated with Ti/Cu/Ti) and high resolution transparency mask is filled with the IBA-based pre-polymer mixture and exposed to UV light. (b) The top Ti-layer is removed, exposing the underlying Cu-layer. (c) Ni electroplating is performed with the poly(IBA) serving as the mold [12]. (d) The poly(IBA) and seed metal layers [13] are removed. The poly(IBA)-based channels, mixing chamber, and central-core post are patterned within a self-containing polycarbonate cartridge. (e) The poly(NIPAAm)-based post is patterned at the center of the Ni micromixer, encasing the poly(IBA) central-core post. (f) After Ni release, a side-view of a functional Ni micropump.*
with Ti/Cu/Ti (0.05/0.35/0.05 µm) using a DC sputterer. The Cu-layer serves as the seed layer for future Ni electroplating. High resolution transparency masks (3600 dpi) are used to pattern the structures.

A poly(IBA) mold is formed to serve as a masking layer during the future Ni electroplating. A cavity (depth can be varied) is created between the glass slide and transparency mask using 125-µm thick double-sided adhesive tape. The pre-polymer is flowed into the cavity and polymerized using UV light (Figure 2(a)). UV dose ranges from 94 mJ/cm² to 131 mJ/cm² depending on the desired poly(IBA) thickness. The remaining pre-polymer is washed away using ethanol.

The top Ti-layer is removed using HF:H₂O= 1:10, exposing the Cu-layer (Figure 2(b)). The device is placed in a nickel sulfamate bath (Microfab® NI 100, Enthone-OMI, Inc., West Haven, CT) and Ni is electroplated (current density = 5×10⁻⁴ A/mm²) [12] (Figure 2(c)). Electroplated Ni thicknesses range from 125–250 µm at a rate of approximately 125 µm/hour. The poly(IBA) mold is removed by soaking the device in methanol for several hours. The metal seed layers are also removed using HAC:H₂O₂:H₂O=1:1:10 to selectively etch Cu [13] (Figure 2(d)). A polycarbonate cartridge (HybriWells™, Grace-Bio Labs, Inc., Bend, OR) with an adhesive spacer layer of 375 µm is affixed to the glass slide, filled with the pre-polymer using the filling ports, and polymerized, forming the channels, fluidic chambers, and central-core post (Figure 2(d)). The precursor hydrogel solution is introduced into the channels and poly(NIPAAm) posts are polymerized in situ (dose is ~150 mJ/cm²), encasing the existing poly(IBA) posts (Figure 2(e)). A side-view of the final device is shown in Figure 2(f). The Ni structure is finally released by flowing in Ti and/or Cu-etching solutions.

**Experimental setup**

Experiments were videotaped directly to a computer using a Sony Hyper HAD CCD-Iris/RGB camera (Sony Corp., New York City, NY). An external rotating magnetic stirrer was used to drive the Ni microstructures (Cole Parmer, model 84000-00, Vernon Hills, IL).

**RESULTS AND DISCUSSION**

A ‘smart’ temperature-controlled micropump has been developed that is controlled by a clutch-based mechanism using a responsive hydrogel. The autonomous clutch here uses a parameter-sensitive hydrogel ring to control the clutch operation (on and off). It allows the micropump to be self-sufficient in that it turns on/off despite the constant presence of a rotating external magnetic field (see Figure 1). If the surrounding environmental temperature is too warm (here, above 30 °C), the micropump pumps fluid until the temperature cools down sufficiently to constrict the pumping actuation (here, < 16 °C). Figure 3 shows the micropump in action as it pumps yellow dye through the top channel and recirculates it through the bottom at high rpm (~3100 rpm) when the water temperature is above 30 °C. Infusion of cold water (~5 °C) renders the device to cease pumping (see Figure 3(c)).

Two micropump designs were tested here: (i) four straight blades, each measuring 1.50 mm × 0.35 mm (shown in Figure 3), and (ii) four curved blades, each measuring about 1.37 mm × 0.36 mm. Here, the micropumps deliver an average maximum flowrate and pressure [11] of: (i) 1.53 µL/minute; 0.355 Pa, and (ii) 3.068 µL/minute; 0.712 Pa. Flowrates and pressures can be further optimized by modifying the configuration of the micropump, e.g., shape, size, and number of blades, and channel dimensions.

Previously, we showed that pH-sensitive hydrogels can be used to create a programmable micromixer allowing individual access to an array of micromixers [10]. Extending the capabilities of this fabrication process, a temperature-controlled programmable micromixer has been developed whose functionality is similar to that of the ‘smart’ micropump. Figure 4
Figure 4. A Ni micromixer showing the feasibility of controlling fluid mixing at the microscale using poly(NIPAAm) posts. (a) In-flow of warm water at t₀. (b) The micromixer stops spinning at t₁ = t₀ + 11 seconds upon in-flow of cold water. (c) Warm water is flowed in at t₂ = t₁ + 7 seconds. (d) The micromixer starts spinning at t₃ = t₂ + 3 seconds. Scale bar represents 1.25 mm.

Here, the poly(NIPAAm) has a lower critical solution temperature (LCST) of about 30 °C where the hydrogel exhibits a dramatic decrease in size. By tuning the recipe of the hydrogel, it is feasible to change the LCST and even acquire larger volume changes [14]. This would further allow fabrication of temperature-controlled actuators to fit any critical temperature change criteria, potentially being applied towards thermal management.

CONCLUSION

Polymer-based fabrication and µFT has allowed for the fabrication and testing of a ‘smart’ temperature-controlled micropump and micromixer. Using temperature-responsive hydrogels, the micropump actuates and pumps fluid through the channels with flowrates ranging from 1.5 to 3.1 µL/minute. All the while, the microcomponent is controlled only by the surrounding environmental parameters.

Additionally, both microcomponents function as self-sustaining, closed loop temperature-sensitive devices without the need for on-chip wiring or electricity. Complete and autonomous microsystems for various applications can be fabricated here.

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REFERENCES