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# MICROFLUIDIC PUMPING WITH OPTICALLY INDUCED ACTUATION OF A CARBON NANOTUBE MEMBRANE

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## ABSTRACT

We present the design; fabrication and testing of a Polydimethylsiloxane (PDMS)-based microfluidic pump with optically induced membrane actuation. The thin membrane consists of a layer of PDMS (100 *μm*) and a layer of carbon nanotubes (190 *nm*). An applied infrared laser opto-mechanically activates the film of carbon nanotubes (CNT), leading to membrane deformation and subsequent fluid motion. Photomechanical actuation offers an alternative way to drive microfluidic devices and provides distinct advantages over alternative methods. The advantages include simplistic, low-cost device fabrication, Wireless actuation, remote controllability electrical–mechanical decoupling, low noise and the elimination of electrical circuits. The performance of this pump in terms of pressure head and flow rate is substantially high. In addition, the micro pump is self-priming and insensitive to particles and bubbles in the pumped media.

## INTRODUCTION

All mechanical microfluidic pumps require a mechanically driven actuator. Actuators can be categorized by their physical principles that include external and integrated actuators. External actuators include electromagnetic actuators with solenoid plungers and external magnetic field, disc-type or cantilever-type piezoelectric actuators, stack-type piezoelectric actuators, and pneumatic actuators. Integrated actuators are micromachined with the pumps. The most common integrated actuators are electrostatic actuators, thermopneumatic actuators, electromagnetic actuators, and thermomechanical (bimetallic) actuators [1].

Compared to electromechanical transduction, photomechanical actuation offers an alternative way to couple energy into actuator structures and brings distinctive advantages such as wireless actuation, remote controllability, electrical–mechanical decoupling, low noise, easier scaling down and elimination of electrical circuits. Unfortunately, few material systems have been shown to exhibit photomechanical actuation properties and are often not compatible with CMOS processing techniques. Recently, increasing use of the photomechanical actuation properties of CNTs has achieved optical–mechanical energy transduction in various different CNTs and CNT/polymer composite systems [2].

In this paper, we report the integration of CNT films into micro-mechanical systems in to a microfluidic pump with the design and, fabrication of Polydimethylsiloxane (PDMS)-based microfluidic pump with embedded thin film of carbon nanotubes. The PDMS membrane is activated with a collimated beam of laser illumination (808 *nm*) at 200 *mW*. The pump body mold was fabricated using cast SU8-50 molds while the membrane was created with long spin times of uncured to form a constant membrane thickness with an embedded CNT film.

The photomechanical actuation of the membrane has been shown to have deflection of 0.726 *μm* and a volume displacement of 750,000 $\mu m^3$ (0.75 *nL*).

## DESIGN

The pump has a single, circular pump chamber and is photomechanically actuated. It consists of a PDMS pump body and a CNT and PDMS composite membrane. The microfluidic chip and pump dimensions are given in Figure 1. The pump has a uniform depth of 50 *μm* and microchannel width of 500 *μm*. The diffuser neck is 100 *μm* wide. The pump chamber diameter is 2.0 *mm*. The membrane consists of a 100 *μm* thick PDMS layer and a uniform CNT film thickness of 190 *nm*.

The design of a valve-less, single mechanically driven membrane, nozzle/diffuser microfluidic pump design was created and tested previously [3]. The advantages of this design include simplified fabrication and that it is insensitive to the

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density, ionic strength, or pH of the media. By incorporating a similar design the performance of this new opto-mechanical actuator can be directly compared to previous, similar designs.

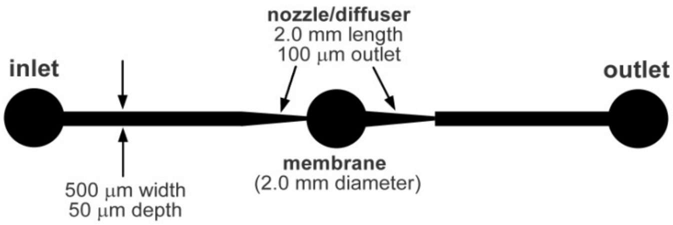


**Figure 1** Design of the microchannel structure for the optically driven PDMS/CNT pump

## MICROFABRICATION

The pump's circular membrane was fabricated using a process consisting of a CNT film formation/film transfer/membrane release steps. Single-wall carbon nanotubes were first dispersed uniformly into isopropyl alcohol by ultrasonication followed by vacuum filtration to produce uniform CNT films of 190 *nm* thick on a mixed cellulose ester (MCE) filter, as shown in Figure 2a. The CNT film on a MCE filter is transferred onto a Parylene C coated silicon substrate by compressive loading. The MCE filter is then removed by multi-baths of acetone rinse to dissolve the MCE filter and leave pure CNT film on top of the substrate. The concentration and transfer of CNT to a silicon wafer has been demonstrated previously [4].

The thin PDMS membrane is then constructed by spinning PDMS over the CNT/Parylene C substrate (Fig. 2b). Previously it has been shown that thin (< 100 μm) PDMS films have been obtained from long spin times [5]. By spinning PDMS at 500 rpm for 52 seconds, a uniform membrane thickness of 100 $\mu m$ was achieved. The Parylene C coating was necessary to aid in the release of the thin, PDMS/CNT membrane. The PDMS coated substrate was then cured on a hot plate at $95^oC$ for 2 hours.

The microchannel structures of the pumps were fabricated using cast molding of PDMS. The molds were constructed of SU8-50 on a silicon substrate using standard photolithography (Fig. 2c). The SU8 mold was 50 $\mu m$ in height and resembled the microchannel structure in Fig. 1. The SU8 microchannel mold was placed in a Petri dish and was covered with PDMS and cured in a $65^oC$ oven for a minimal period of four hours (Fig. 2d). Next, the pump body was removed from the mold was irreversibly bonded to the thin PDMS substrate with oxygen plasma. After oxygen plasma exposure and conformal contact with each other, this assembly was placed on a 95$^o$C hotplate for one hour (Fig. 2e). After the bonding is complete the PDMS membrane was trimmed manually with a razor along the perimeter of the pump body. The Parylene C coating on the silicon substrate allowed for the membrane to be easily released from the substrate upon removal of the whole device (Fig. 2f).

An AFM image of the composite PDMS/CNT film is shown in Figure 3.

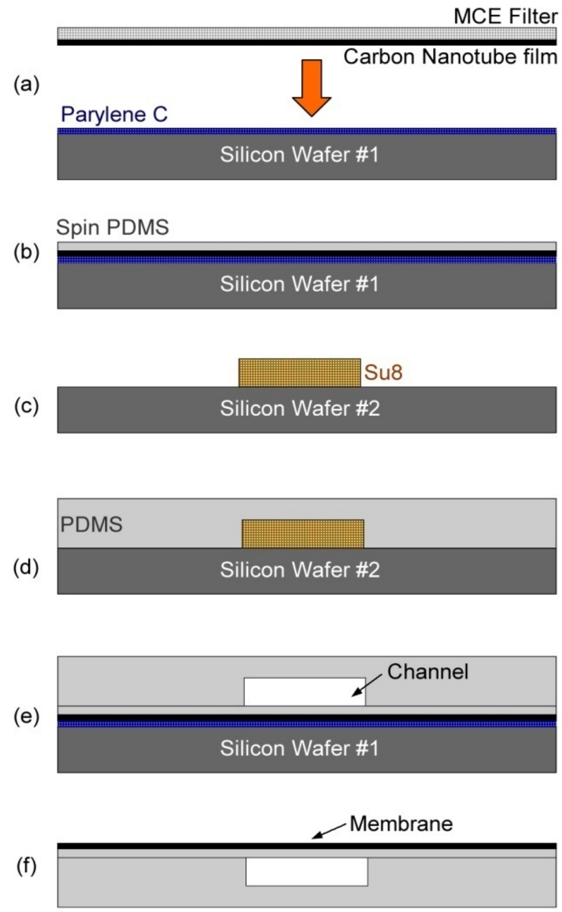


**Figure 2.** The fabrication processes of the PDMS/CNT microfluidic pump

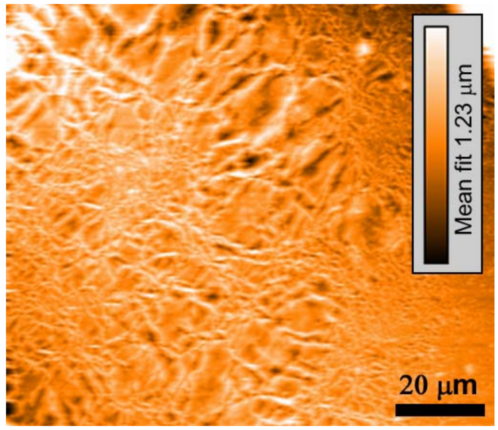


**Figure 3.** AFM of the PDMS/CNT membrane


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## EXPERIMENTAL

The completed microfluidic pump was mounted under a standard light microscope. The pump was manually filled with water in the inlet through the nozzle, membrane chamber, and diffuser and partially filled the microchannel immediately before the outlet port. The plug at the interface between the water and air was visualized with the microscope and an image was acquired with a digital camera. The laser was then activated and the 1.5 mm laser spot was applied to the PDMS/CNT membrane of the microfluidic chip. An illustration of the opto-mechanical deflection of the membrane is illustrated in Figure 4. The displacement of the water plug was determined with the acquisition of a second digital image and directly comparing it to the initial, captured image before laser activation. Volume displacement of the membrane was determined from known microchannel dimensions and the lateral displacement of the plug.

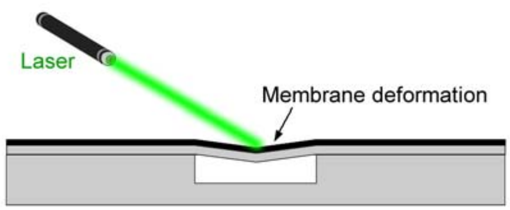


**Figure 4.** Illustration of opto-mechanical actuation of microfluidic membrane and the direction of deflection.

## RESULTS AND DISCUSSION

When an infrared laser light of 200 $mW$ is applied to the pump's circular membrane it deflects inward, compressing the fluid and resulting in fluid movement. Due to the arrangement of the nozzle and diffuser (Fig. 1) bulk fluid motion will move towards the outlet of the microfluidic device. A 30 $\mu m$ displacement in the water plug was observed with the application of the laser to the PDMS/CNT membrane (Figure 5). The photomechanical actuation of the membrane causes the defection of the membrane into the pump, resulting in the displacement of water in the pump channel (Fig. 5b).

With the known cross-sectional dimensions of the microchannel (500 μm x 50 μm) the lateral displacement of the plug (30 μm) was used to estimate the displaced volume of the deflected membrane of 750,000 $\mu m^3$ (0.75 nL). This information can be used to approximate the maximum deflection of the circular membrane.

Assuming a circular diaphragm with all edges fixed, the deflection, $w$, of a plate under uniform pressure, $P$, is given by [6]

$$w(r) = \frac{Pa^4}{64D}\left[1-\left(\frac{r}{a}\right)^2\right]^2$$

where $a$ is the radius of the plate, $r$ is the radial distance from the center of the plate, and $D$ is the flexural rigidity, given by

$$D = \frac{Eh^3}{12\left(1-\nu^2\right)}$$

where $E$ is Young's modulus, $h$ is plate thickness, and $\nu$ is Poisson's ratio. From above, the maximum displacement is

$$w_{\max} = \frac{3Pa^4\left(1-\nu^2\right)}{16Eh^3}$$

By integrating (1) the volume $V$ of the displaced diaphragm is

$$V = 2\pi\int_0^a r\,w(r)\,dr = \frac{\pi a^2}{3}\,w_{\max}$$

For 750,000 $\mu m^3$ volume and a 2.0 $mm$ diaphragm the maximum deflection of the membrane was calculated to be 0.72 $\mu m$. Future research will be conducted to confirm this value. This estimation, however, may be inaccurate due to (i) the circular membrane is not completely fixed on all edges, (ii) the concentration of CNT is not entirely uniform across the membrane, and (iii) the applied laser power is not uniform across the membrane as typical laser beams are Gaussian in their distribution.

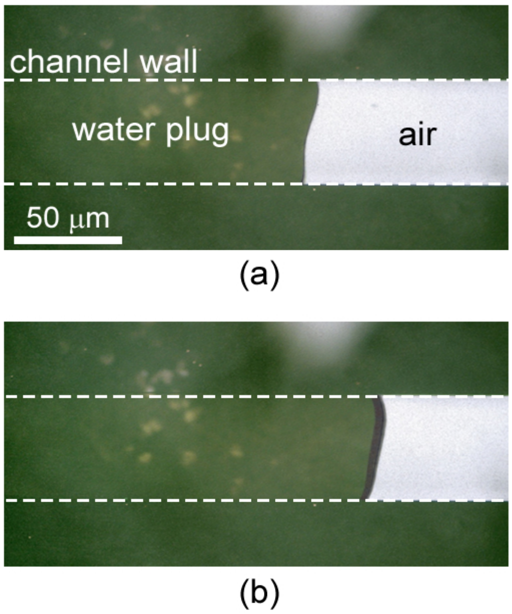


**Figure 5.** The location of the water plug within the microchannel (a) before and (b) after the application of the laser for the opto-mechanical actuation of the membrane.

From the calculations of the maximum membrane deflection, additional parameters can be determined. For the estimated maximum deflection (24.2 μm), Poisson's Ratio of PDMS (0.5), and Young's Modulus of PDMS (360 to 870 kPa), the resulting mechanical pressure was 1.8 to 4.4 Pa (accounting


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for the range in Young’s Modulus). The influence of the mechanical properties of the 190 nm CNT film on membrane deflection have been neglected.

## CONCLUSIONS

This manuscript demonstrates an optically driven mechanical actuation of a composite PDMS/CNT circular diaphragm for microfluidic pumping applications. A volumetric displacement of 0.75 *nL* of water was demonstrated with the application of a 200 *mW* infrared laser to a 2.0 *mm* diameter membrane. This optically driven microfluidic device has advantages over existing pumping techniques including ease of fabrication, remote controllability, and the absence of electrical connections. This technique will likely impact the design of future, optically driven microfluidic devices.

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