A VAPOR BASED MICROFLUIDIC SAMPLE CONCENTRATOR

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ABSTRACT

We report a PDMS microfluidic sample concentrator based on active evaporation through temperature gradient mediated mass transfer. The configuration design consists of multiple passes on the channel side walls interfacing to the ambient environment. With a thermal gradient, liquid in the channel can evaporate through the passes, and therefore resulting in a more concentrated fluid flow without breaking the liquid/vapor interface due to the hydrophobic nature of PDMS material. Experiments are performed using a dye and fluorescein to monitor the concentration change. With ease of fabrication, such system can be monolithically integrated to existing microfluidic devices for sample preparation.

KEYWORDS: Concentrator, Microfluidics, Evaporation

INTRODUCTION

Lab-on-a-chip systems are able to integrate micro pumps, switches, separators, filters and mixers onto a single platform providing the benefits of high performance, versatility, less reagent consumption, miniaturization and less processing time [1]. However, it remains that most sample preparation, including cleaning, concentrating and mixing are mainly conducted off chip prior to analysis [2]. To fully utilize the advantages of Lab-on-a-chip systems, integration of these sample pretreatment functions is necessary. Here, we present a microfluidic sample concentrator, based on temperature gradient mediated mass transfer, that is easy to fabricate and integrate into microfluidic devices.

THEORY

When a small water droplet is placed on a rough substrate, the surface profile becomes an important factor determining the contact angle formation, which results in two possible energy equilibrium states: Wenzel State and Cassie State. We studied the transition from Cassie state composite contact to the Wenzel state wetting contact by depositing a water droplet on a super-hydrophobic surface consisted of microposts [3]. When the substrate surface was cooled, a reduction of the contact angle occurred as a temperature gradient was generated between the water drop and the air-filled cavities. We hypothesized that the temperature gradient mediated a mass transfer process of water evaporating from the droplet and condensing among the microposts. To further study the details of this transition, a polydimethylsiloxane (PDMS) hydrophobic microchannel with concaved structures at the two sidewalls was designed. As shown in Figure 1, a rapid condensation was observed in the air-filled cavities displacing air volume at the presence of a temperature gradient [4], which provides an explanation of the mechanism for the energy state transition in the surface property of super-hydrophobic surfaces.
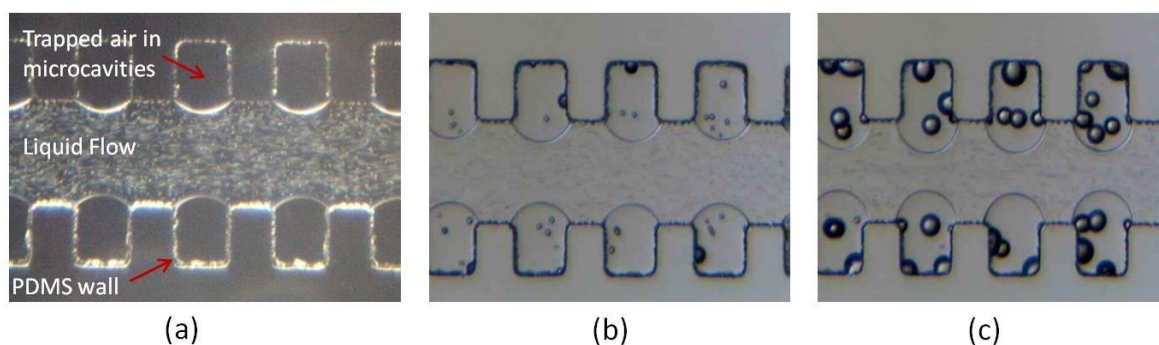

(a)   (b)   (c)

Figure 1: Condensation occurs in the air-filled cavities in a microchannel. (a) A water filled channel with air trapped inside the microcavities due to the hydrophobicity of PDMS. (b)Upon the application of current, nanodroplets immediately appeared in the air cavities. (c) Condensations grew to large drops and displaced air into the main section of the channel with continuous current applied.

EXPERIMENTAL

We utilized the observed mass transfer phenomenon of hydrophobic microchannels to design a configuration of multiple passes on the channel side walls connected to the ambient environment for fluid manipulation. As shown in Figure 2, we fabricated a straight microfluidic channel, 3 cm x 150 μm x 50 μm, in PDMS, with a series of 40 μm wide passes (virtual walls) using soft lithography. Maintaining the liquid/vapor interface during fluidic flow, these virtual walls were also connected to side structures (air chambers) providing room for aqueous evaporation and condensation. Two small openings were cut manually to allow air chambers remain open to ambient environment for the ease of evaporation, and the size of the opening affected the evaporate rate.

We used electrokinetic flow to pump fluid and create a thermal gradient, which caused water of the aqueous solutions flowing through the channel to evaporate through the virtual walls. This effectively concentrates solutes in the fluid as it flows the length of the channel. For demonstration, a 50 mM sodium phosphate buffer solution was loaded into the microchannel to conduct electroosmotic flow (EOF). A green food dye or 0.1 μM fluorescein (Fisher Scientific, Pittsburgh, PA) was added to measure concentrations. We filled the channel initially by manual injection of the fluid, and followed by simultaneously loading 150 μL of solution into both reservoirs located at ends of the microchannel to prevent gravity-driven flow. To induce the electrokinetic flow, platinum electrodes were built into both reservoirs to generate an electrical field of 184V/cm supplied by a high voltage module.
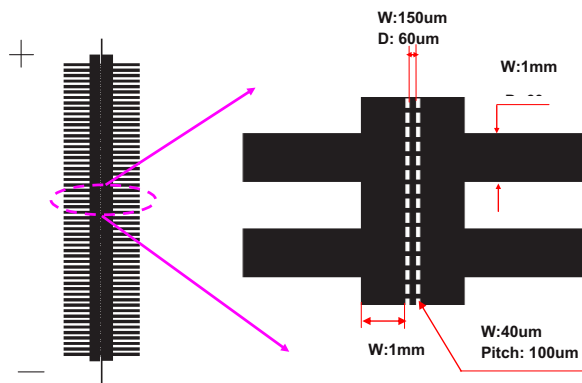

Figure 2: Schematic view of the microfluidic sample concentrator. The main channel is 3 cm long, 150 μm wide and 50 μm deep with multiple 40 μm wide passes to air chambers, which consist of 1 mm wide straight paths parallel and perpendicular to the main channel.

RESULTS AND DISCUSSION

As shown in Figure 3, experiments demonstrated the ability of the microfluidic concentrator device to efficiently transport water vapor to surrounding air chambers. Upon the application of an electrical field, formation of small condensed droplets in the air chambers was immediately observed, created by a temperature-mediated mass transfer process. As temperature of the buffer increased due to Joule heating effects, water evaporated from the liquid-vapor interface, and soon saturated the regions along the virtual walls. When the water vapor encountered a lower temperature environment in the air chambers, condensation was induced. As the electrical field was applied continually, this evaporation and condensation phenomenon would continue and form large water drops, and therefore, concentrate the solution in the channel.
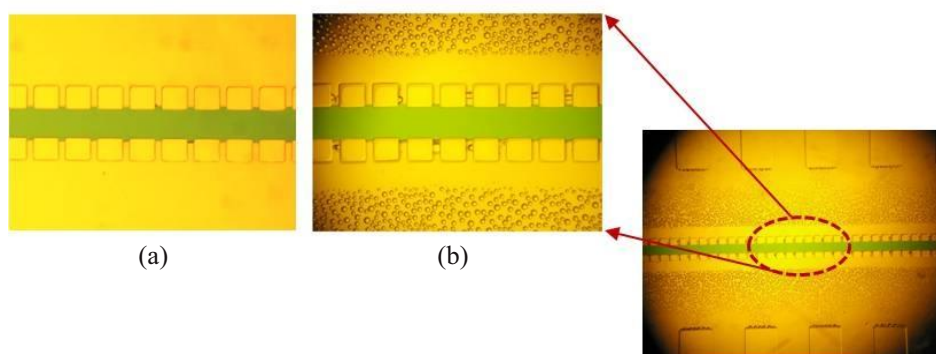

Figure 3: Pictures showing the evaporation and condensation of water from the main channel to the air chambers. (a)A green dyed buffer solution filled the channel with virtual walls maintaining the liquid/vapor boundary due to surface tension and the hydrophobic PDMS. (b) Droplet formation were observed seconds after the application of an electrical field of 184 V/cm.

Several studies were conducted to monitor the change in solute concentration in the channel. Figure 4 (a) shows the change of concentration along the 3 cm main channel at six different locations by measuring the dye intensity along the channel. The photos were analyzed by Matlab and the image intensity was calculated to represent the concentration of green dye. The results clearly demonstrate that a concentration gradient can be produced in the channel using this design and thermally induced mass transfer effect. The fluorescence intensity at a specific location (5 mm from the cathode reservoir) was also monitored to examine the rate of sample concentration as shown in Figure 4 (b). The results show that the fluorescent intensity, and corollary the sample concentration, increased to four times its initial value within four minutes.

During experimental setup, the device was sensitive to the hydraulic pressure since liquid was confined inside the microchannel mainly by utilizing surface tension and hydrophobicity. The solution could penetrate into the air chambers if too much pressure was exerted during initial fluid loading. The design can be improved by reducing the dimension of the passes, for example, employing nanopatterned side walls. Integration of the concentrator to electrokinetically driven microsystems can also prevent the hydraulic pressure issue.
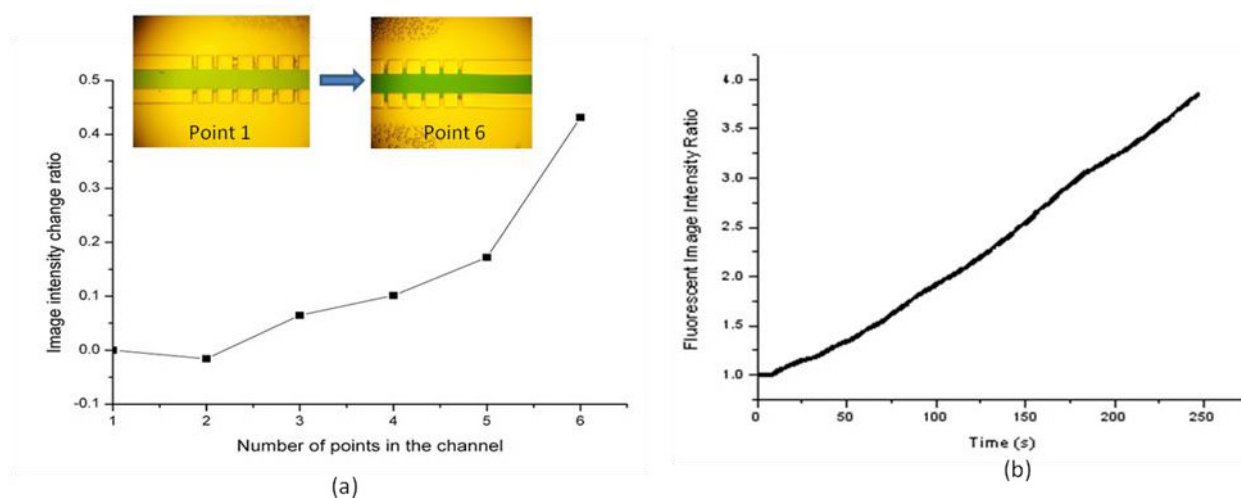

Figure 4: (a) Concentration change at six different locations along the microchannel exhibiting a concentration gradient due to joule heating. The two pictures show the full color change from the beginning of the channel to its end.
(b) Fluorescent image intensity ratio calculated from videos of concentrator channel (imaging positioned 5 mm from the cathode reservoir) recorded during testing. Image intensity ratio was obtained by dividing all image intensity values by the image intensity at t=0 s.

CONCLUSION

We present a novel microfluidic sample concentrator based on active evaporation and temperature gradient mediated mass transfer, which cleverly utilizes the hydrophobicity of PDMS. The device successfully concentrated an aqueous solution in a microchannel with micro-sized passes along its channel side walls that provided evaporation and condensation paths. Experimental results have demonstrated the usefulness of electrical field induced Joule heating to actively enhance the evaporation for sample pre-concentration in a microchannel within a matter of minutes. Moreover, this system provides a simple approach for monolithic integration to an existing polymer microfluidic device for its simplicity in design, fabrication and operation.

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