PLANAR CAPILLARY PUMPED INK DELIVERY APPARATUS FOR DIP PEN NANOLITHOGRAPHY (DPN™)

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Abstract

This work demonstrates the design, analysis, simulation, fabrication and testing of a microfluidic delivery apparatus for simultaneously coating an array of DPN (Dip Pen Nanolithography) pens with different inks. The objective of this work is to deliver different water-based inks from reservoirs into appropriately spaced inkwells using micro-capillary flow, for multi-pen array dipping. The reservoirs, inkwells and their connecting micro-channels were etched in silicon wafers using photolithography and reactive ion etching. Different inkwell designs were evaluated for their filling efficacy, to eliminate bubble formation, and for characterizing dipping and writing.

Keywords: DPN, DRIE, VOF Method, micro-capillary flow.

1. Introduction

The DPN process uses a chemically coated scanning probe tip (the “pen”) to directly deposit a material (“ink”) with nanometre precision onto a substrate (“paper”) [1]. Under ambient conditions, the DPN process (Figures 1 and 2) can deposit a variety of organic and biological molecules onto a variety of substrate types [2]. When using oligomer or protein-based inks, DPN method can produce nanoscale spotted features which are much smaller than other bio-arrays [3].

![Figure 1. Schematic of Dip Pen Nanolithography (DPN).](image)

![Figure 2. DPN method-generated patterns of 16-mercaptohexadecanoic acid (MHA) on gold.](image)

The objective of this work is to enable parallel writing of multiple patterns using the DPN process. An nScriptor™ system integrated with a multi-pen array of inked pens was developed to simultaneously write multiple patterns. This configuration requires selective deposition of ink chemistries onto the individual pens, which is accomplished by “dipping” the multi-pen array into an array of “inkwells.” The device delivers 4 aqueous inks (for genomic applications) into appropriately spaced inkwell array. Fluid actuation occurs by open channel meniscus driven flow (wicking) in micro-channels array, which distribute liquid from reservoirs into an array of terminal inkwells connected by tributaries (Figure 3).

2. Theory

To understand the ink-delivery it was necessary to calculate the filling times of microchannels of different sizes and the meniscus division from microchannels into tributaries. The flow rates in the micro-channels were calculated from a balance of the capillary and viscous forces (and neglecting inertial forces):
\[ \Delta p = \frac{4 \sigma \cos \theta}{D_h} = \frac{1}{2} \rho u^2 f \frac{L}{D_h} \]  

(1)

Where, \( \Delta p \): pressure drop in channel flow, \( \sigma \): coefficient of surface tension, \( \theta \): contact angle, \( D_h \): hydraulic diameter of the channel, \( \rho \): density of liquid flowing in the microchannels, \( u \): average velocity in the microchannels, \( f \): Fanning’s friction factor, \( L \): length of the channel. For laminar flow in circular channels, \( f = \frac{64}{Re_{D_h}} \), where \( Re_{D_h} = \frac{\rho u D_h}{\mu} \), and \( \mu \) is the kinematic viscosity of the working liquid. Using the above formulation for \( f \) (valid for \( Re_{D_h} < 2000 \)) Equation (1) can be simplified as:

\[ u L = D_h \sigma \cos \theta / 8 \mu \]  

(2)

Equation (2) can be used to estimate the filling time (\( \tau \)) as:

\[ \tau = \int_{L_1}^{L_2} \frac{\partial L}{u} = \frac{1}{2} \left( L_2^2 - L_1^2 \right) \frac{8 \mu}{D_h \sigma \cos \theta} \]  

(3)

Equation (3) can be written in non-dimensional form as:

\[ \left[ \frac{\sigma \cos \theta / D_h}{4 \mu} \right] \tau = \frac{L_2^2 - L_1^2}{D_h^2} \]  

(4)

Equation (3) is used to calculate filling time of microchannels of different hydraulic diameters using the properties of water and is plotted in Figure 4. The results show that for the same length the wider channels (larger \( D_h \)) fill up faster than the narrow channels. This is due to capillary forces (~1/Dh) being retarded by even larger pressure drop (~Dh^2) in narrow microchannels. Figure 5 shows simulation of meniscus break-up from a 5\( \mu \)m wide channel into a 2\( \mu \)m wide tributary (both 10\( \mu \)m deep) using the Volume of Fluids (VOF) method (CFD-ACE+, CFD Research Corporation). The analytical results for liquid velocity and filling times were consistent with the simulation values.

3. Fabrication and Experimental Apparatus:

Different wet and dry etching methods were investigated to fabricate features with high aspect ratio (10:1) for minimizing evaporative loss of liquid. Deep Reactive Ion Etching (DRIE) using the Bosch process (STS Limited) was found to be the most suitable method (Figure 6). Nano-liter volume droplets were deposited into the reservoirs using a syringe with a micro-needle (Hamilton Company) for filling the reservoirs. The movements of the menisci in the micro-channels were recorded using an imaging
apparatus, comprising of a high resolution Pullnix-TM1300 camera (1280X1028 pixels), a Road Runner R12 frame grabber, Nikon-SMZ10A trinocular microscope (coaxial illumination) and PC for data acquisition. Image Pro Express software (Media Cybernetics) was used for image analysis.

4. Results and Discussion

Figure 7 shows temporal sequence images of meniscus movement from a reservoir into the array of inkwells. Figure 8 shows an image showing the alignment of the passive multi-pen array and the dipping of the pens into the inkwells filled with EasyInk™. The dipped pens were used to write nanoscale patterns on a glass surface (Figure 9). The designs incorporating a satellite reservoir (which also serves as a bubble trap) had the most desirable characteristics for inkwell filling (Figure 10).

5. Conclusions

An optimal inkwell layout was selected based on the efficacy of filling, minimization of evaporation, incorporation of a bubble trap satellite reservoir and ease of dipping and writing using a multi-pen array. The dipped pens were successfully used to simultaneously write multiple patterns on a glass surface.

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Figure 4. Filling time ($\tau$) in micro-seconds for capillary pumped flow of water in microchannels of different length ($L$) and hydraulic diameter ($D_h$) using Equation 3.

Figure 5. Temporal simulation of meniscus shapes for microchannel filling

Figure 6: SEM images of inkwells. (A) Overview of reservoir and inkwells. (B) Close-up view of reservoir. (C) Close up of inkwells. (D) Cross-section of reservoir.
Figure 7. Time sequence images of meniscus motion in microchannels at 10 ms intervals.

Figure 8. (A) Multi-pen array is aligned with the inkwells (light on). (B) Tips are dipped into the wells (light off). (C) Illuminated image showing dipped pens reflecting light differently than the un-dipped pens. (Courtesy of Dr. Nabil Amro, NanoInk Inc.)

Figure 9. Lateral Force Microscopy (LFM) image of pattern written on glass substrate using DPN pen dipped in EasyInk.

Figure 10: Optimal design selected from this study incorporating a satellite reservoir as a bubble trap.

References