DIRECT ETCH METHOD FOR MICROFLUIDIC CHANNEL AND NANO-HEIGHT POST FABRICATION BY PICOLITER DROPLETS

Utkan Demirci, Mehmet Toner
Harvard Medical School, Massachusetts General Hospital, Shriners Hospital for Children, Boston, MA,USA

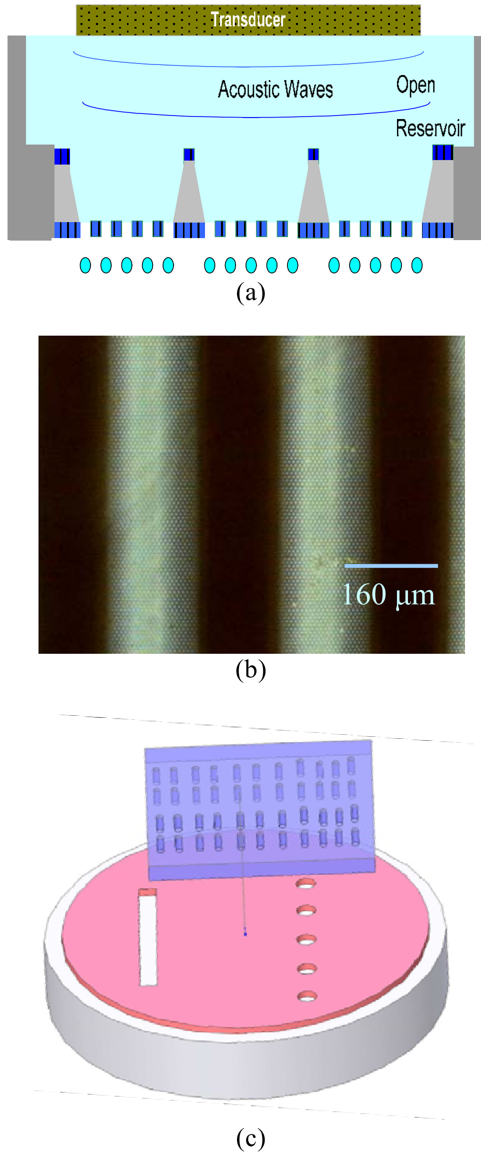
ABSTRACT

Photolithography is an expensive and significant step in microfabrication. Approaches that could change lithography could create impact on semiconductor and microelectromechanical systems fields. We demonstrate a droplet based direct etching method by ejecting etchant droplets at desired locations by using microdroplet ejector arrays. This method could be used for easy fabrication of poly(dimethylsiloxane) microfluidic channels; nanometer height post-like structures in microfluidic channels.

1. INTRODUCTION

Droplet generation methods have become crucial as numerous applications are posed by today's technology in the fields of semiconductors and biotechnology. The capability to generate fluid droplets enables various biological applications. For instance, bio-arrays for drug testing could utilize controlled droplet generation techniques, two dimensional arrays of cells placed on a surface could be tested with droplets of drugs; DNA arrays could be printed by micro-droplet ejectors [1].

Various methods for generating fluid droplets have been reported [2-7]. Here, we utilize an ejection method, where acoustic plane waves actuate periodically spaced multiple orifices of a thin rectangular membrane [8]. A droplet ejection method that prints photoresist onto the wafer surface drop-by-drop has the potential to minimize the photoresist wasted by spin coating method and eliminate the lithography step for feature sizes as small as 10 µm [3-5]. Here, a complementary method to direct photoresist printing that involves solvent ejection instead of photoresist ejection, and photoresist etching instead of deposition is demonstrated. This has several advantages, since the solvents are easier to eject than photoresist. Solvent droplets as small as 3 µm diameter can be ejected through 10 µm diameter orifices [3]. Moreover, there are concerns in photoresist ejection as to not to damage photoresist in order to achieve repeatable and uniform deposition. Therefore, inkjet technology could not be utilized for photoresist ejection, whereas it could be used for solvent or other etchant ejection [3-6]. Also, the evaporation of ejection fluid is lesser of an issue as long as the fluid is supplied plentiful to the ejection reservoir.

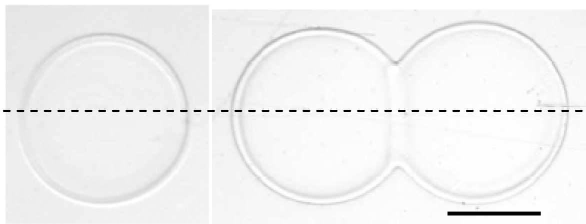


(a) (b) (c)

Fig.1 (a) The design and operation of the micromachined droplet generator, (b) micromachined multiple orifice Si_xN_y membrane based 2D ejector arrays, and front view of Si_xN_y membranes with 3 µm orifices with 9 µm periodicity, (c) the setup for droplet based etching.

2. THEORY and DESIGN

A diagram of microdroplet ejector array used for the droplet generation is shown in fig. 1(a). The acoustic waves travel through the fluid reservoir. If there is enough force exerted by acoustic radiation pressure at the orifices to overcome the surface tension forces of the fluid, then droplets will be ejected. Chu et. al. gives the Langevin radiation pressure ‘ℵ’ by the mean energy density of the acoustic beam at the surface of the air liquid boundary [9]. Hunter et al. gives the average intensity of the incident wave ‘$I_{initial}$’ and the Langevin radiation pressure ‘ℵ’ as in equation $I_{initial}=p^2_{\text{initial}} / 2c\,\rho_{bulk}$ and $\aleph = 2I_{initial}/c$, where ‘$p_{initial}$’ is the pressure amplitude of the incident acoustic wave, ‘ρ_{bulk}’ is the bulk density of the liquid, ‘c’ is the velocity [10].



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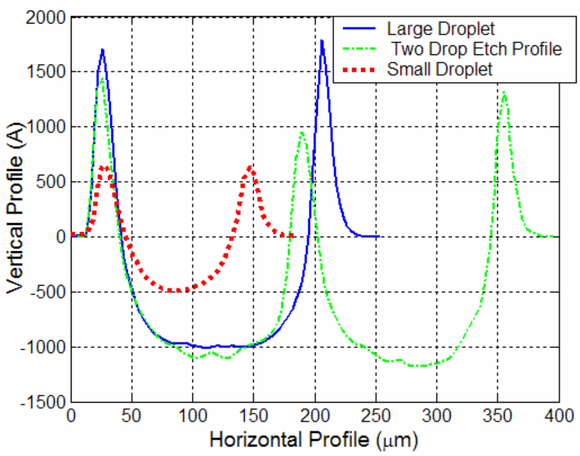

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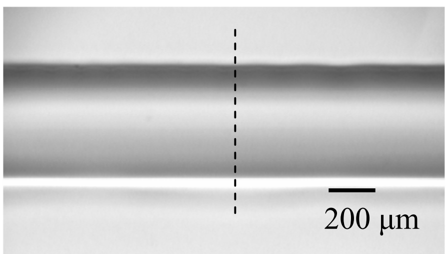

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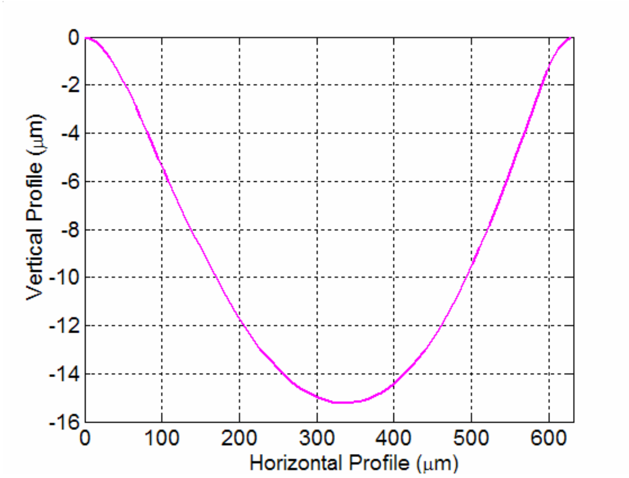

(d)

Fig. 2 (a) A single acetone droplet and two overlapping droplets placed side by side etching photoresist coated surface of a 4 inch wafer, (b) the profiles of the etch through the profile lines of 2(a), (c) multiple overlapping droplets ejected on photoresist etching a 4 inch line and (d) the profile of the etched line through the profile line of 2(c).

The resonant frequencies of a rectangular membrane under fluid loading were calculated by finite element simulations (ANSYS 5.7). These membrane resonances do not match with transducer actuation frequencies of 500 KHz, 1 MHz, 2.25 MHz and 3.5 MHz (Panametrics, MA). Outside the resonances membrane displacement is small and the ejection is dominated by acoustic wave radiation pressure enhanced by the fluid reservoir shape and membrane displacement has small effect on droplet generation [8]. A part of multiple orifice ejector array is shown in fig. 1 (b). The multiple orifices are 3 µm diameter and periodically spaced by 9 µm on a 160 µm x 2 mm rectangular membrane array.

3. RESULTS

The current poly(dimethylsiloxane) (PDMS) process involves first deposition of a SU-8 photoresist followed by masking and developing steps. This step is followed by placing PDMS on the wafer surface and micro-structures are formed by topography of the wafer surface generated by photolithography process. The direct etch method could remove the need for a mask and subsequent photolithographic step at micron scale. A wafer is spin-coated with photoresist and then droplets of photoresist developer or solvent are ejected to desired locations. The topography on wafer surface is created by etching on a resist coated wafer as shown in fig.1 (c).

A wafer was placed on an x-y stage and moved at a speed to determine the separation between the ejected droplets as shown in fig. 1 (c). The ejection was achieved at three transducer resonant frequencies of 500 KHz, 1 MHz and 3.5 MHz. The ejection frequency and speed of the x-y stage can be changed so that there was more or less fluid deposited at a location. At a high wafer translational speed we were able to obtain single droplets on a SU-8 coated silicon wafer surface as shown in fig. 2 (a, b). The single droplet etch profiles were observed to be uniform. Small droplets were observed to have an etch depth of 50 nm, whereas larger droplets had an etch depth of 100 nm as shown in fig. 2 (b). The surface roughness at the plateau of the etched profiles was 15 nm at the worst location. Picture of two droplets overlapping by 20 μm and their etch profile are given in fig. 2 (b). When PDMS is poured on top of droplet etched topography, nano-height posts could be formed. One could imagine etching a nanochannel or a microchannel by just continuing the ejection of more overlapping droplets on a SU-8 coated wafer surface. We fabricated a 9 cm long 15.2 μm deep uniform dome shaped microchannel as in fig. 2(c) and its profile is demonstrated in fig. 2 (d). This channel was formed by droplets at 1 MHz which corresponds to a million droplets per second and at stage translational speed of 2.1 cm/sec. Hence, the separation between two neighboring droplets was 0.021 μm. The experiments were conducted in a dry laboratory environment. A solvent saturated environment would be better for control on the etching process.

The isotropic wet etch profiles were observed as solvent droplet etches in all directions. The etching was observed to stop when amount of etchant was consumed by the reaction. It was observed that the channel depth and width could be varied by changing interrelated parameters such as the stage speed, ejection frequency, droplet size and overlap separation of ejected droplets on the surface. Microchannel etch depths of 1.2 μm, 3.4 μm were experimentally obtained by varying the stage speed. These channels were observed to have uniform profiles along the channel as shown with the 15.2 μm deep microchannels and could be obtained repeatably. The surface roughness at the plateau of etched profiles was 15 A through the microchannel. The etched surface profiles were obtained by Dektak (Veeco Ins.,Woodbury,NY) profilometer with a 5 A vertical resolution.

One concern could be possible splash of an ejected droplet. The splashing-deposition boundary is given by Ohnesorge number, '$Oh= W_e^{1/2}/R_e$, where '$R_e=2\rho v_d r_d /\eta$' is Reynolds number and '$W_e=2\rho v_d^2 r_d$' is Weber number, 'v_d' is the ejected drop velocity and 'η' is dynamic viscosity of the liquid [11]. The Ohnesorge number is smaller than the critical limit and splash of the droplet on the surface is not theoretically feasible since it is a small droplet size and surface tension is great enough to hold the droplet together at the droplet landing velocities we operate at the range of 1 m/s to 10 m/s and the droplet size range that we operate at of 2 μm to 10 μm in diameter [3-7]. However, the droplet spreads out on the surface to a larger area than its initial diameter in air depending on the initial droplet size, velocity and properties of the surface [11]. This spread is further increased during the isotropic etching of droplet on the surface by diffusion.

The edges were observed in the single droplet profiles. These were initially thought to be due to the initial velocity that the drop landed on the surface. However, considering the fact that the droplet further etches towards the sides after landing on the surface, the side edges could be due to the distribution of the droplet fluid on the surface during the etching. The control on etching of resist and the final profile depend on the volume and concentration of etching solution and type of reaction. The edges were observed to be smaller for smaller droplets and droplet spread area would be smaller at smaller droplet velocities. The edges were observed to disappear for microchannels since etching solution was etching possible side edges. Further research would be necessary to investigate droplet surface interactions in the presence of a chemical etching reaction.

We demonstrate a control on the etching reaction by limiting the volume of one of the reactants down to a droplet size of femtoliter to picoliter range. This could be used to perform and monitor reactions at a small scale. Ejector arrays capable of drop on demand would provide benefit of better control on etching of surfaces by droplets. The etching reaction could be stopped by flowing etch stopping solution over the wafer. This method could also be used to etch lines into a metal coated surface or any other organic or non-organic surfaces.

4. CONCLUSIONS

We demonstrated a method of fabricating PDMS microfluidic channels and nano-height posts by a direct develop method of SU-8 at desired locations by using microdroplet ejector arrays. This method did not require photolithography, which is the most expensive step in microfabrication. The smallest feature size is determined by the droplet diameter and the etch reaction. The future of droplet ejectors predicts new applications in semiconductors, biotechnology and nanotechnology.

5. ACKNOWLEDGEMENTS

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Authors can be reached by e-mail at "utkan@stanfordalumni.org", "mtoner@sbi.org"