ABSTRACT

Flow lithography is a powerful synthesis tool that enables the creation of microparticles with complex morphologies and chemical patterns. In current flow lithography, PDMS (polydimethylsiloxane) flow channels are necessary because the process requires local inhibition of polymerization near channel interfaces via oxygen permeation through the PDMS. This current requirement places restrictions on both device construction and the use of solvents and/or monomers which do not swell the PDMS. Here, we present flow lithography that utilizes hydrodynamically focused inert fluids in oxygen impermeable channels made from NOA (Norland Optical Adhesive) channels. The new process greatly expands the compatible monomer and solvents, as well as on-the-fly height particle adjustment and allows for use of more durable channel materials.

KEYWORDS: Flow lithography, NOA, Flow focusing, Solvent

INTRODUCTION

Stop flow lithography (SFL) is an emerging technique that combines photolithography with microfluidics. The in-situ synthesis technique has been used to produce free-floating microparticles, offering precise control over particle size, shape, and chemical patchiness [1]. This method has led to novel applications in assembly, MEMS, photonics, diagnostics and tissue engineering [2]. The technique relies on the lubrication layer induced by atmospheric oxygen diffusing in through the porous PDMS channels and locally inhibiting polymerization near channel walls [3]. By virtue of this layer, particles are advected through unpolymerized prepolymer solutions without sticking to the PDMS walls. Unfortunately, this fundamental need for oxygen lubrication does not allow for extending the process of flow lithography to devices that are impermeable to oxygen, such as glass channels. As a result, solvents and monomers that swell PDMS channels cannot be used in the current platform. Here, we present FL that utilizes hydrodynamically focused inert fluids in gas impermeable NOA (Norland Optical Adhesive) channels. Three-dimensional homogeneous NOA channels were designed and fabricated to structure microflows inside channels. Durable and conformal nano-adhesives were prepared by iCVD (Initiated Chemical Vapor Deposition) and employed to strongly seal the interface between top and bottom NOA channels [4]. Oxygen inhibition of polymerization is no longer needed in this version of FL since the inert fluid layers serve to lubricate the synthesized particle. The inert layers also allow for on-the-fly alteration of particle size to produce particles with heights much smaller than the channel height. This new technique greatly expands the synthesis capabilities of FL and has not yet been reported in the literature. Here we not only describe and quantify this new technique, but also show an application in infrared proton sensing using carbon nanotubes embedded within FL synthesized particles.

THEORY

In one embodiment of this new mode of SFL, particles are synthesized in the middle monomer fluid that is sandwiched between inert fluids. As a result, particle heights can be approximated as the middle flow layer thickness (H_m). To predict H_m, volumetric flow rates were estimated from inlet pressures using hydrodynamic resistances. We controlled pressures at the inputs instead of volumetric flow rates as the pressure control system could quickly stop and start the flows while the flow rate control system typically had a slow response time [5]. From the estimated volumetric flow rates and mass conservation,

\[ B = \frac{Q_1}{Q_2} = \frac{\int_{h_c}^{h_m} \rho vzdz}{\int_{0}^{h_m} \rho vzdz} \]

(1)

where B is the ratio of the volumetric flow rates of inert flow (Q_1) divided by the volumetric flow rates of middle monomer flow (Q_2), \( \rho \) is the density of flow, \( v \) is the velocity of flow, \( h_c \) is the half of the channel height, and \( h_m \) is the half of the middle flow layer thickness. When different fluids comprise adjacent layers, the viscosities and densities of the streams should be matched to prevent velocity disparity and flow flipping [6]. For the fluids used in this study, we assume all densities and viscosities of layered flows are identical. As the aspect ratio of our channel is fairly small (slit-like), we can also assume the layered flows inside channels have velocity profile of Poiseuille flow [7]. Here, the aspect ratio is defined to be the ratio of the channel height divided by the channel width.

\[ v(z) = v_{max}(1-(\frac{z}{h_c})^2) \]

(2)
where \( v_{\text{max}} \) is the maximum velocity of flow.

Putting equation (2) into (1), we can get an analytical expression for \( H_m \):

\[
H_m = 2h \cdot \cos\left(\frac{1}{3} \arccos\left(\frac{1}{B+1}\right) - \frac{2\pi}{3}\right)
\]  

(3)

**EXPERIMENTAL**

As a model gas impermeable channel, we fabricated two-layer NOA81 channels (Figure 1A). Briefly, a droplet of NOA81 was put on a silicon wafer and sandwiched between the wafer and a glass slide. Then, the NOA81 was exposed to UV (365 nm) for 10 min giving a bottom NOA channel on the glass slide. In a similar manner, a drop of NOA 81 was put on a silicone wafer and sandwiched between the wafer and silane-treated PDMS with punched inlet holes. Silane treatment of PDMS substrate facilitates bonding between PDMS and NOA. Again, the NOA81 was exposed to UV (365 nm) for 10 min giving a top NOA channel on the PDMS. Next, we used high-strength nano-adhesive prepared by iCVD to combine these two channels. The ring-opening curing reaction of epoxy with amine group can form a strong covalent bond between the two substrates. To finish the construction of the two-layer NOA device, the top NOA channel was assembled on the bottom channel and the device was fully cured under vacuum at 90 °C for 24 hr. Compared to the micro-patterned stickers for 3D fluidic devices [8], our technique can provide a general way to apply NOA molds to numerous substrates with easy inlet fabrication that does not require punching glass slides and installing connection supporters. The NOA81 devices showed much greater solvent resistance than PDMS devices (Figure 1B). Also, the channels have higher Young’s modulus, favorable optical properties, and biocompatibility [8, 9].

![Figure 1: 3D homogeneous NOA81 channels](image)

**RESULTS AND DISCUSSION**

Recently, we developed flow focusing technique to create stacked flows in two-layered channels for particle synthesis [10]. We showed that multiple flows can be stacked by increasing the number of inlets entering sequentially from the bottom layer of the device. Using this method, we generated three-layer flows inside the NOA81 channels and successfully synthesized particles in the middle monomer layer between two inert flows (Figure 2A). This is the first demonstration to extend the process of flow lithography to devices that are impermeable to oxygen. Also, the use of inert fluids easily and rapidly varies particle heights in a channel with a fixed height (Figure 2B). We modified the previous model in estimating hydrodynamic resistances. Previously, we calculated hydrodynamic resistances from the channel geometries and fluid viscosities. However, the model does not consider additional resistances that results from inlets, channel defects, and dust clogging. The modified model experimentally determined total hydrodynamic resistances by lumping all factors. Then, shown in Theory section, we could estimate inlet pressures required for the target particle height.

![Figure 2: On-the-fly particle fabrication.](image)

The most valuable feature of this technique is that we can now synthesize geometrically and chemically patterned particles from various solvents. As an example, we demonstrate synthesis of shaped particles from toluene solution that contains...
water-insoluble monomers including TMPTA (Trimethylolpropane triacrylate) and PUA (Polyurethane acrylate) (Figure 3A and B). Also, we prepared PEG (polyethylene glycol) particles containing SWNTs (single-walled carbon nanotubes) by toluene solvation and demonstrated the proton sensing abilities of these particles in the NIR (near-infrared) region. Figure 3C shows the shift in the emission spectrum of embedded SWNTs upon introduction of 2.4 M HCl.

**Figure 3: Anisotropic particles synthesized from toluene**

**CONCLUSION**

We have presented flow lithography that uses inert fluids as lubrication layers in gas impermeable devices. To achieve this approach, devices were prepared as 3D channels for flow-stacking. Combining soft-lithography with iCVD, we introduced a facile fabrication route to prepare 3D gas impermeable NOA channels. The homogeneous NOA devices have shown great solvent resistance to prevent distortion of channel geometries by swelling in the presence of solvents. Through flow layering inside these devices, we successfully produced anisotropic particles without oxygen lubrication layers. Also, the use of tuning fluids led to easy and rapid adjustment of particle height in a channel with a fixed height. The thickness of the tuning layers was adjusted by varying the inlet pressures of the streams. Finally, we demonstrated particle synthesis from organic solvents such as toluene. As examples, we showed particles synthesized from water-insoluble monomers and embedded SWNTs for near-infrared proton sensing. We believe that this technique can provide a powerful way to generate new functional particles.

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**REFERENCES**


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