Flow lithography in ultraviolet-curable polydimethylsiloxane microfluidic chips

Junbeom Kim,^{1,2} Heseong An,^{1,3} Yoojin Seo,^{4,5} Youngmee Jung,^{4,6}
 Jong Suk Lee,^{3,7} Nakwon Choi,^{2,6,a),b)} and Ki Wan Bong^{1,a),b)}

¹*Department of Chemical and Biological Engineering, Korea University, Seoul 02841, South Korea*

²*Center for BioMicrosystems, Brain Science Institute, Korea Institute of Science and Technology (KIST), Seoul 02792, South Korea*

³*Materials Architecturing Research Center, Materials and Life Science Research Division, Korea Institute of Science and Technology (KIST), Seoul 02792, South Korea*

⁴*Center for Biomaterials, Biomedical Research Institute, Korea Institute of Science and Technology (KIST), Seoul 02792, South Korea*

⁵*NBIT, KU-KIST Graduate School of Converging Science and Technology, Korea University, Seoul 02841, South Korea*

⁶*Division of Bio-Medical Science & Technology (Biomedical Engineering), KIST School, Korea University of Science and Technology (UST), Daejeon 34113, South Korea*

⁷*Department of Chemical and Biomolecular Engineering, Sogang University, Seoul 04107, South Korea*

(Received 10 January 2017; accepted 17 April 2017; published online 27 April 2017)

Flow Lithography (FL) is the technique used for the synthesis of hydrogel microparticles with various complex shapes and distinct chemical compositions by combining microfluidics with photolithography. Although polydimethylsiloxane (PDMS) has been used most widely as almost the sole material for FL, PDMS microfluidic chips have limitations: (1) undesired shrinkage due to the thermal expansion of masters used for replica molding and (2) interfacial delamination between two thermally cured PDMS layers. Here, we propose the utilization of ultraviolet (UV)-curable PDMS (X-34-4184) for FL as an excellent alternative material of the conventional PDMS. Our proposed utilization of the UV-curable PDMS offers three key advantages, observed in our study: (1) UV-curable PDMS exhibited almost the same oxygen permeability as the conventional PDMS. (2) The almost complete absence of shrinkage facilitated the fabrication of more precise reverse duplication of microstructures. (3) UV-cured PDMS microfluidic chips were capable of much stronger interfacial bonding so that the burst pressure increased to ~ 0.9 MPa. Owing to these benefits, we demonstrated a substantial improvement of productivity in synthesizing polyethylene glycol diacrylate microparticles via stop flow lithography, by applying a flow time (40 ms) an order of magnitude shorter. Our results suggest that UV-cured PDMS chips can be used as a general platform for various types of flow lithography and also be employed readily in other applications where very precise replication of structures on micro- or sub-micrometer scales and/or strong interfacial bonding are desirable. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4982698>]

I. INTRODUCTION

Flow lithography (FL) is the technique used for the synthesis of hydrogel microparticles, which combines photolithography with microfluidics. This technique allows for the precisely controlled fabrication of microparticles with various complex shapes and distinct chemical

^{a)}N. Choi and K. W. Bong contributed equally to this work.

^{b)}Electronic addresses: nakwon.choi@kist.re.kr and bong98@korea.ac.kr.

compositions, by exposing photopatternable polymers, which are inserted into a microchannel in the form of laminar flow, to cyclic pulses of ultraviolet (UV; typically 365 nm) light.^{1–4} Owing to this merit of FL, new applications have emerged for *in vitro* diagnostics,^{5–13} self-assembly of microparticles,^{14,15} tissue engineering,^{16–18} and drug delivery.¹⁹

Materials that enable microfluidic devices to perform FL must satisfy two major requirements.²⁰ First, the materials that are in contact with the photopatternable polymers and photoinitiators ought to be permeable to oxygen, which is the most critical criterion. The oxygen molecules that permeate through the materials serve as great radical scavengers, which consequently generates thin boundary layers of photocrosslinking inhibition (a few micrometers in depth) at the contact surfaces between the materials and the photopatternable polymers. Therefore, photocrosslinked microparticles drift away from the site of UV exposure so that free-floating microparticles can be collected at downstream of the microchannel.^{1,21} Unless one introduces inert layers that preclude photocrosslinking with a microchannel constructed with oxygen-impermeable materials,²² it is imperative to satisfy this criterion. Second, the materials have to be optically transparent so that UV light penetrates through them and traverses the microchannel. An additional requirement includes, but not limited to, compatibility with soft lithography and replica molding in order to facilitate the ready fabrication of microfluidic chips.

Polydimethylsiloxane (PDMS) has been used most widely as almost the sole material that meets the aforementioned criteria.^{23,24} Specifically, thermally curable PDMS has been the predominant material in use, but the undesired shrinkage of microstructures, which was reported to be proportional to the temperature generated by thermal curing,²⁵ can be problematic, for instance, when aligning multiple layers.²⁶ This issue can possibly be ascribed to the thermal expansion of the masters used in replica molding. In addition, the PDMS microfluidic chips used for FL typically have the low burst pressure as around 190 kPa. This has been a limiting factor that results primarily from interfacial delamination between two PDMS layers that are bonded by thermal curing of a micropatterned PDMS replica onto a partially cured PDMS layer. In general, a treatment of the oxygen plasma applied to PDMS layers is a simple yet effective way to allow for relatively strong bonding between the layers.^{27,28} However, the oxygen plasma not only activates the PDMS surfaces, which generate the silanol group (i.e., Si-OH) to form covalent bonds, but also oxidizes the PDMS surfaces, which inevitably creates a thin layer of glass (i.e., SiO₂).²⁹ Obviously, the higher the proportion of the plasma that is applied onto PDMS, the more oxygen-impermeable the vitrified PDMS becomes.³⁰ Therefore, exposure to the oxygen plasma should be avoided for the fabrication of PDMS microfluidic chips used for FL. The issues above clearly indicate that there is a trade-off between the advantage of stronger interfacial bonding and the disadvantage of vitrification and gas impermeability.

The typical FL process consists of cyclic repetition of both UV exposure through a photo-mask and the purging of photocrosslinked microparticles by inlet pressure. Therefore, an approach to enhance productivity (i.e., the number of microparticles synthesized per FL cycle) is to shorten flow time by applying higher inlet pressure in order to flush the photocrosslinked microparticles out and replenish the photopatternable polymer, thereby reducing the duration of each FL cycle without drawbacks. Note that inlet pressure does not affect other operational factors in the FL cycle.² Specifically, productivity relies much more on the flushing time necessary for contact flow lithography where a longer microchannel is employed.³¹ In addition, our previous study showed that a relatively narrow range of inlet pressure could limit control over the determination of the topography of a microchannel and the shapes of microparticles via lock-release lithography, where pressure-induced deformation of a microchannel plays a crucial role.³² Thus, further research is necessary to enable greater tolerance of higher inlet pressure in order to achieve both enhanced productivity and more precise control in various categories of FL. Recently, a nanoadhesive layer coated on PDMS via initiated chemical vapor deposition (iCVD) has tolerated remarkably high inlet pressure.³³ However, the nanoadhesive layer has been yet unsuitable for FL due to oxygen-impermeability.²²

Here, we propose the utilization of UV-curable PDMS for FL as a more optimal alternative material to conventional PDMS. Specifically, we were able to fabricate microfluidic chips simply by placing a micropatterned replica (fully cured by UV) on a partially cured layer, without any heat or plasma treatments. Along with nearly identical optical transparency and compatibility with the results of soft lithography, our proposed utilization of UV-curable PDMS offers three additional key advantages. First, UV-curable PDMS exhibited almost the same oxygen permeability and allowed for the synthesis of polyethylene glycol diacrylate (PEGDA) hydrogel microparticles via stop flow lithography (SFL). Second, the almost complete absence of shrinkage of UV-curable PDMS facilitated the fabrication of more precise reverse duplicates of the microstructures. Finally, the microfluidic chips made of UV-curable PDMS were capable of forming much stronger interfacial bonds so that burst pressure increased up to approximately 0.9 MPa of inlet pressure. Owing to this operational benefit, we demonstrated a substantial improvement of SFL productivity by applying a flow time (40 ms) an order of magnitude shorter.

II. MATERIALS AND METHODS

A. Fabrication of microfluidic chips with UV-curable PDMS

Microfluidic chips employing UV-curable PDMS were fabricated through the following procedures (Fig. 2(a)), based on the manufacturer's specification sheet.³⁴ (1) A base polymer (X-34-4184A; Shin-Etsu) and a curing agent (X-34-4184 B; Shin-Etsu) were thoroughly mixed in a 1:1 weight ratio. (2) After degassing in a vacuum chamber, the mixture was poured gently onto a SU-8 (SU-8 50; MicroChem Corporation) master that consisted of positive microstructures ($51 \pm 0.15 \mu\text{m}$ in height). (3) Photocuring of the micropatterned top layer was initiated by exposing it to UV in a chamber (365 nm, 4.3 mW/cm^2 ; Minuta Tech. Co.) for 8 min (total energy dose of $\sim 2 \text{ J/cm}^2$). Next, the master was left for complete curing for 4 h at room temperature. (4) After peeling off the UV-cured elastomer block, inlets and outlets were created by punching holes (1 mm in diameter) in order to connect with the pipette tips (TR-222-Y, Axygen). (5) To prepare the partially cured bottom layer, 500 μl of the mixture of X-34-4184 was spread uniformly on a glass slide ($24 \times 60 \text{ mm}$) and exposed to UV in the chamber for 8 min. Next, the slide was left at room temperature additionally for 5 min. (6) Finally, the fully cured top layer was placed on the partially cured bottom layer, which was left for complete curing for 4 h at room temperature.

As an additional note, energy doses of UV [J/cm^2], as long as a threshold dose (e.g., 2 J/cm^2) is applied, do not affect periods of time for the completion of curing. In other words, the exposure time of UV (energy dose of UV while power density [mW/cm^2] is kept identical) does not serve as a rate determining parameter.

B. Synthesis of hydrogel microparticles via stop flow lithography in UV-curable PDMS microfluidic chips

The synthesis of hydrogel microparticles was accomplished via SFL using a similar method to previous work,³⁵ with the caveat that we utilized UV-curable microfluidic chips. 200 μl -pipette tips that contained PEGDA (MW 700 Da; PEG700DA) pre-polymer solutions were inserted into the inlets of the UV-curable PDMS microfluidic chips. Tygon tubing (OD: 0.06 in.; ID: 0.02 in.) was connected to the pipette tips through which the inlet pressure was applied. PEGDA pre-polymer solutions for microparticles shown in Figs. 1 and 3 were composed of 40% [v/v] PEG700DA, 20% [v/v] PEG600, 35% [v/v] deionized (DI) water, and 5% [v/v] Darocur 1173. For those shown in Figs. 4 and 5, 95% [v/v] PEG700DA and 5% [v/v] Darocur 1173 were used. To synthesize fluorescently labelled microparticles, rhodamine acrylate (Fig. 3(b)) and water-soluble methacrylated quantum dots (QDs) (Fig. 3(c); red, Mag-QuTM-91002 Qdot-615 nm-methacrylate; green, MagVi-genTM Customize-61002 GA-Qdot-535 nm-methacrylate; and blue, MagQuTM-91002 Qdot-460 nm-methacrylate; NVI-GEN) were mixed with the PEGDA pre-polymer solutions.^{13,36} PEGDA hydrogel was photocrosslinked upon exposure to UV for 100 ms sequentially through a filter cube set (XF02-2, Omega Optical), a film photo-mask, and a $20\times$ objective lens (EC Plan-Neofluar, NA 0.5; Zeiss) for demagnification by a

FIG. 1. Processability of flow lithography with UV-curable PDMS (X-34-4184). (a) Schematic illustrations of experiments to qualitatively assess the mobility of PEGDA microparticles immediately after UV-crosslinking for 100 ms either with (top) or without (bottom) UV-curable PDMS (blue). (b) Optical micrographs showing fixed areas of UV exposure to monitor photcrosslinked microparticles between two layers of either UV-curable PDMS (top) or glass (bottom), immediately after photocrosslinking denoted as 0 s (left), after 10 s (upper right), and 600 s (lower right). The gray dotted circle represents the original position of the microparticle shown in the upper left panel. The scale bar is 50 μm .

factor of ~ 8 . The UV light source was a collimated UV (365 nm) light emitting diode (LED) (M365L2-C4, Thorlabs) and was controlled by using a UV LED driver (LEDD1B T-Cube LED driver, Thorlabs). In order to control the microflow of the PEGDA pre-polymer solutions and the UV exposure in a synchronized manner, both the UV LED driver and a pressure regulator (ITV-0031, SMC Korea) were operated by a custom-LabVIEW (National Instruments) code via a data acquisition (DAQ) board (CDAQ-9171, National Instruments) and an analog voltage output module (NI 9264, National Instruments) similarly as reported previously.¹³ A representative cycle for the SFL with the UV-cured PDMS chips, for example in order to synthesize the microparticles shown in Fig. 3, was comprised of the following four consecutive steps: (1) flow for 40 ms at an inlet pressure of 400 kPa, (2) stop and hold for 200 ms, (3) expose to UV for 100 ms, and (4) hold for 100 ms.

Synthesized PEGDA microparticles were collected immediately after purging in a 1.5 ml tube in which 500 μl of 0.05% [v/v] Tween-20 was added. Then, the microparticles were rinsed with the Tween-20 solution 3 times prior to imaging.

C. Imaging of synthesized hydrogel microparticles

The PEGDA microparticles in the Tween-20 solution were dispensed between two glass slides (170 μm in thickness) and mounted on an inverted fluorescence microscope (Axio Observer.A1, Zeiss). 8-bit color (red-green-blue; RGB) fluorescence and bright field images (Figs. 3 and 4) were acquired with a digital single-lens reflex (DSLR) camera (EOS 6D, Cannon), and 16-bit monochrome images (Figs. 1 and 5 and Fig. S1 in the [supplementary material](#)) with a scientific complementary metal-oxide-semiconductor (sCMOS) camera (optiMOS, QImaging), respectively.

D. Measurement of height of the SU-8 master

Heights of positively patterned microstructures on the SU-8 master used in this study were measured with a surface profiler (Alpha-Step IQ, KLA-Tencor Corporation). Adjusted profiles were acquired by levelling raw profiles using Alpha-Step analysis software.

E. Estimation of the thickness of oxygen inhibition layers in PDMS microchannels

To access quantitative information about the thickness of the oxygen inhibition layers in the microchannels, the height of the PEGDA microparticles immediately after the photocrosslinking and that of either the conventional or the UV-curable PDMS microchannel were measured (Figs. 2(d), 2(e), and 4). We intentionally synthesized cylindrical microparticles ($30\ \mu\text{m}$ in diameter) so that the microparticles toppled over within 5–10 s, without applying pressure in the PDMS microchannels (Fig. 4(a)). After acquiring bright field images of the microparticles and cross-sections of the microchannels, the height was estimated using ImageJ (NIH). Next, the total thickness of oxygen inhibition layers ($2\delta_{\text{O}_2, \text{inhibition}}$) was calculated by subtracting the height of the microparticles ($h_{\text{microparticle}}$) from the mean height of the microchannels ($h_{\text{microchannel}}$).

F. Measurement of oxygen permeability and diffusivity through PDMS

The permeation rates of oxygen (99.999%, Shin Yang Oxygen Co.) through $\sim 200\ \mu\text{m}$ -thick membranes of either Sylgard 184 or X-34-4184 were evaluated by using a standard isochoric technique at 1 atm and $35\ ^\circ\text{C}$.³⁶ The $200\ \mu\text{m}$ -thick PDMS membranes were obtained by flattening PDMS poured on a hydrophilic film with a Baker applicator (YBA-4, Yoshimitsu Seiki Co., Ltd.). Any hydrophilic film that is commercially available can be used to efficiently delaminate the PDMS membrane. More detailed descriptions of the permeation measurement process are available elsewhere.³⁷ The oxygen permeability was calculated as $P = (V_D L / R A p_0)(dp(t)/dt)$,

FIG. 2. Fabrication process and characteristics of UV-cured PDMS microfluidic chips. (a) Schematic illustration showing the fabrication process of UV-cured PDMS microfluidic chips: (1) casting X-34-4184 mixture on a SU-8 master, (2) curing by exposing to UV, (3) peeling off a replica after 4 h at room temperature, (4) punching to create inlets and outlets, (5) placing the fully cured replica on partially cured X-34-4184, and (6) further curing for 4 h at room temperature to construct UV-cured PDMS microchannels. (b) Photograph of a UV-cured PDMS microfluidic chip with 3 inlets and 1 outlet. Blue ink was injected into microchannels for visualization. The scale bar is 5 mm. (c) Plot of height of a positively patterned microstructure on the SU-8 master, corresponding to the merging microchannel shown in (b). (d) Optical micrographs showing cross-sections of the merging microchannel fabricated with UV-curable (X-34-4184; left) and thermally curable (Sylgard 184; right) PDMS. The x -direction indicates the axis along which the height was measured. The scale bar is $50\ \mu\text{m}$. (e) Bar graph showing the mean height of the SU-8 master (white) and UV-cured (blue) and thermally cured (gray) PDMS microchannels. The dotted line indicates the height of the SU-8 master. Error bars represent the standard deviation. **** denotes the statistical significance with $p < 0.0001$.

where P is the gas permeability in Barrer ($1 \text{ Barrer} = 10^{-10} \text{ cm}^3 \text{ (STP) cm}/(\text{cm}^2 \text{ s cmHg})$), V_D is the downstream volume, L is the thickness of the membrane, R is the gas constant, A is the effective area of the membrane, T is the absolute temperature, p_0 is the feed pressure, and $dp(t)/dt$ is the uprising rate of downstream pressure in a steady-state. The diffusivity of oxygen in PDMS was derived as $D_{\text{O}_2, \text{PDMS}} = l^2/6\theta$, where l is the thickness of the membrane [m] and θ is the time lag [s].³⁸ The latter was calculated on the basis of a linear steady-state regime in a plot of downstream pressure rise versus time.

G. Measurement of the elastic modulus

Cylindrical posts (6 mm in diameter and 4 mm in height) made with conventional and UV-curable PDMS were mounted on a universal testing machine (Instron, model 5567). To obtain stress-strain curves, a 10k-Newton-maximum load cell at a cross-head speed of 1 mm/min was applied until the height of the cylindrical post reached 60% height deformation (i.e., strain). Next, the slope value of a linear regime in the stress-strain curve was considered the elastic (Young's) modulus.

H. Measurement of burst pressure at the PDMS-PDMS interface

The inlet pressure was gradually elevated into a PDMS microchannel without an outlet, fabricated by either thermal curing¹⁹ or UV-curing. The critical pressure, at which the interface between the top patterned block and the bottom flat layer was delaminated, was recorded as the interfacial burst pressure. The inlet pressure was applied at intervals of 25 kPa to the thermally cured PDMS chips and those of 50 kPa to the UV-cured PDMS chips.

I. Statistical analysis

Statistical comparisons of the microchannel height, microparticle size, oxygen inhibition layers, and burst inlet pressure were performed using Prism (GraphPad). The statistical significance was assessed using unpaired t -tests (Figs. 2(e), 4(c), and 4(d)) or one-way analysis of variance (one-way ANOVA) (Fig. 5(b)). ns, **, and **** denote $p > 0.05$, $p < 0.01$, and $p < 0.0001$, respectively.

III. RESULTS AND DISCUSSION

A. UV-curable PDMS as a material of microfluidic chips for flow lithography

Before fabricating microfluidic chips for SFL, we first verified whether oxygen was permeable to UV-cured PDMS as reported previously.²⁰ When we photopolymerized the PEGDA prepolymer solution through two glass slides either with or without UV-cured PDMS (Fig. 1(a)), the synthesized cylinders in contact with UV-cured PDMS became mobile immediately after UV exposure for 100 ms (top panels in Fig. 1(b)). However, in the absence of the PDMS layers, the cylindrical posts were immobilized (bottom panels in Fig. 1(b)) as expected. These results clearly confirm that UV-cured PDMS precluded the precursor from photopolymerization near contact surfaces. Furthermore, our quantitative measurements showed that the oxygen permeability through UV-cured PDMS was 784.6 Barrer which appeared to be slightly greater than the permeability observed through the conventional PDMS (734.3 Barrer). Therefore, UV-curable PDMS is indeed an appropriate material for microfluidic chips in FL.

B. Fabrication of microfluidic chips with UV-curable PDMS

We were able to successfully fabricate microfluidic chips simply by placing a fully cured block of a micropatterned top layer onto a partially cured bottom layer, which required only two separate stages of UV exposure (Fig. 2(a)). Furthermore, the translucence of UV-curable PDMS has been shown to be nearly identical to that of conventional PDMS (Fig. 2(b)).³⁹

We also found the additional greater advantage that our method provided very precise replication of microstructures on masters; in other words, the structural integrity of the microchannels remained unchanged (Figs. 2(c) and 2(d)). Fig. 2(e) shows the microchannel height of a

SU-8 master and that of thermally and UV-cured PDMS replicas. The height of the SU-8 and UV-cured PDMS was very similar (i.e., 50.9 ± 0.154 and 51.5 ± 0.592 μm , respectively), whereas that of thermally cured PDMS was slightly lower by $\sim 5\%$ (i.e., 48.5 ± 1.51 μm). Conceivably, this shrinkage, despite its small extent in terms of the scale used in this study, resulted from the thermal expansion of the SU-8 master during thermal curing at 80°C .⁴⁰ Our proposed fabrication would generally become more useful when the precise replication of microstructures is crucial.

C. Stop flow lithography with UV-curable PDMS

Based on the high oxygen permeability, the microfluidic chips fabricated as described above can be used to synthesize anisotropic multifunctional particles via SFL. We were able to synthesize intrastructurally not only homogeneous PEGDA microparticles with the green QDs

FIG. 3. Stop flow lithography (SFL) in UV-cured PDMS microfluidic chips. (a) Schematic illustration depicting the synthesis of 3 color-coded microparticles by cyclically (1) exposing UV through a photomask to a laminar co-flow of blue, red, and green PEGDA solutions in a microchannel and (2) applying inlet pressure to purge photocrosslinked microparticles. (b) and (c) Schematic top-down views of the microchannel shown in (a). Orange (left panel in (b)) and co-flow of blue, red, and green (left panel in (c)) PEGDA solutions were exposed to UV through photomasks (black circles and round-rimmed rectangles). Optical micrographs showing synthesized cylindrical (middle panel in (b)) and bar (middle panel in (c)) microparticles. Scale bars in (b) and (c) are 100 and 50 μm , respectively. Fluorescence micrographs displaying the microparticles conjugated with rhodamine-acrylate (orange; right panel in (b)) or blue-, red-, and green-quantum dots (QDs; right panel in (c)).

immobilized (Fig. 3(b)) but also heterogeneous microparticles encoded with blue, red, and green QDs (Fig. 3(c)), which can be employed for encoding^{10,11} and the multiplexed detection of biomolecules.^{7,13} Structural variations of the homo- and heterogeneous microparticles remained minimal with the coefficient of variation (CV) of less than 2% during the entire period of SFL (Figs. 3(b) and 3(c)).

Next, we investigated the more detailed characteristics of the synthesized PEGDA microparticles and microchannels made of both thermally and UV-cured PDMS (i.e., Sylgard 184 and X-34-4184), respectively. When we synthesized the microparticles under the same condition, the diameter of all the microparticles was $\sim 30\ \mu\text{m}$ (top panels in Fig. 4(b) and top panel in Fig. 4(c)) which was an expected value from a photomask with holes of $233\ \mu\text{m}$ in diameter. Note that this mask size was demagnified via projection lithography by a factor of ~ 7.8 when a $20\times$ objective lens was used. However, the height of the microparticles synthesized in the UV-cured PDMS ($46.7 \pm 0.857\ \mu\text{m}$) microchip was persistently greater than that in the thermally cured PDMS chip ($43.7 \pm 1.48\ \mu\text{m}$) (bottom panels in Fig. 4(b) and bottom panel in Fig. 4(c)).

FIG. 4. Characterizations of microparticle dimensions and oxygen inhibition layers. (a) Schematic illustrations depicting an experimental set-up immediately after UV exposure to measure the diameter ($d_{\text{microparticle}}$) of photocrosslinked PEGDA microparticles (top) and 5–10 s after UV exposure to measure the height ($h_{\text{microparticle}}$) of the microparticles (bottom). Light and dark red represent a PEGDA pre-polymer solution and photocrosslinked microparticles, respectively. The dotted red rectangle in the bottom panel is the original position of the microparticle shown in the top panel. (b) Optical micrographs showing photocrosslinked microparticles in thermally (Sylgard 184; left) and UV (X-34-4184; right)-cured PDMS chips. The scale bar is $50\ \mu\text{m}$. (c) Bar graphs displaying $d_{\text{microparticle}}$ and $h_{\text{microparticle}}$ of the microparticles shown in (b). (d) Bar graph displaying the sum of two oxygen inhibition layers ($2\delta_{\text{O}_2 \text{ inhibition}}$) in contact with top and bottom of PDMS. ns and **** denote the statistical insignificance with $p > 0.5$ and significance with $p < 0.0001$, respectively.

We found that this significant difference originated from the aforementioned heights of the microchannels. Meanwhile, since both thermally and UV-curable PDMS were permeable to oxygen to a similar extent, the total thickness of each of the two oxygen inhibition layers (i.e., $2\delta_{\text{O}_2 \text{ inhibition}} = h_{\text{microchannel}} - h_{\text{microparticle}}$) was correspondingly identical, $\sim 5 \mu\text{m}$ (Fig. 4(d)). This estimation agrees quite well with the theoretical calculation^{21,41,42} by $\delta_{\text{O}_2 \text{ inhibition}} \sim \sqrt{D_{\text{O}_2, \text{PEGDA}}/k} = 2.72 \mu\text{m}$, where $\delta_{\text{O}_2 \text{ inhibition}}$ is the thickness of the oxygen inhibition layer, $D_{\text{O}_2, \text{PEGDA}}$ is the diffusivity of the oxygen in PEGDA ($2.84 \times 10^{-11} \text{ m}^2/\text{s}$),⁴³ and k is the pseudo 1st order rate constant for the inhibition of photochemical chain reactions (3.87 s^{-1} ; see the [supplementary material](#) for a more detailed calculation). The equation is valid as long as the inhibition reaction enabled by the oxygen proceeds much more rapidly than the diffusion of oxygen in PEGDA (i.e., Damköhler number, $Da \gg 1$). Moreover, our measurements of oxygen diffusivity in X-34-4184 ($D_{\text{O}_2, \text{X-34-4184}} = 4.01 \times 10^{-9} \text{ m}^2/\text{s}$) and Sylgard 184 ($D_{\text{O}_2, \text{Sylgard 184}} = 3.85 \times 10^{-9} \text{ m}^2/\text{s}$) confirm that the diffusion of oxygen through both types of PDMS does not serve as a limitation on forming the oxygen inhibition layers.

In addition, UV-curable PDMS showed long-term stability regarding the oxygen permeability for up to 8 months. We confirmed the long-term stability by synthesizing PEDGA hydrogel microparticles via SFL (Fig. S2 in the [supplementary material](#)). Furthermore, nearly no residual photocatalysts remained in the UV-cured PDMS. We observed the obstruction of SFL, resulting in undercrosslinked microparticles, due to the undesired absorption of UV by residual photocatalysts when an insufficient energy dose of UV was applied. All of these results verify that UV-cured PDMS chips are undoubtedly compatible with FL.

D. Stronger interfacial bonding of UV-cured PDMS chips

Next, we explored another advantageous capability of UV-curable PDMS by measuring the interfacial burst pressure between the two layers of the UV-cured PDMS chips (Fig. 5(a)). When we increased the inlet pressure on an outlet-blocked microchannel, the UV-cured PDMS (i.e., X-34-4184) chips remained sealed under remarkably high inlet pressure; that is, we observed an interfacial burst starting from $925 \pm 54 \text{ kPa}$ (Fig. 5(b)). On the other hand, the thermally cured PDMS (i.e., Sylgard 184) chips burst at a much lower pressure of $192 \pm 18 \text{ kPa}$. We suggest that there are two conceivable reasons why the interfacial bonding strength of the UV-cured PDMS chips was significantly higher by a factor of 4.8: (1) a thermal expansion of thermally cured PDMS and (2) an increased number of crosslinks at the interface between the two layers of UV-cured PDMS.

Generally, PDMS microfluidic chips used in FL have been fabricated through the thermal curing of a fully cured block on a partially cured elastomer-coated glass slide.⁴⁴ Due to the thermal expansion of PDMS (thermal expansion coefficient of $3.1 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$), it is inevitable for compressive stress to exert the interface between PDMS layers during cooling at room temperature. To assess more quantitatively, we measured the interfacial burst pressure of PDMS (i.e., Sylgard 184) chips cured at room temperature for $\sim 100 \text{ h}$. For the preparation of partially cured PDMS-coated glass slides, we found that partial curing at room temperature for $\sim 22 \text{ h}$ was optimal to avoid not only the percolation of nearly uncured PDMS into microchannels on fully cured blocks but also the immediate detachment of the micropatterned block. Intriguingly, the PDMS chips cured at room temperature showed significantly stronger interfacial bonding strength (burst pressure of $450 \pm 57.7 \text{ kPa}$) compared with the thermally cured PDMS chips (Fig. 5(b)). Therefore, the interfacial bonding at room temperature evidently leads to stronger bonding by eliminating undesired deformation due to thermal expansion and shrinkage. Furthermore, the PDMS chips cured at room temperature still burst at a lower inlet pressure of $\sim 50\%$, compared with the UV-cured PDMS chips (Fig. 5(b)). These results suggest that both the interfacial bonding process at room temperature and chemical compositions almost equally contribute to the high bonding strength of the UV-cured PDMS chips. Since the UV-curable PDMS does not require the input of any heat during the fabrication of microfluidic devices (Fig. 2(a)), such interruption of PDMS-PDMS bonding by thermal expansion and shrinkage is eliminated inherently.

FIG. 5. Stronger interfacial bonding and enhanced productivity in UV-cured PDMS chips. (a) Schematic illustration depicting an experimental set-up designed to measure the interfacial burst pressure: moderate (left) and excessive (right) inlet pressures into PDMS microfluidic chips. The red droplet represents the interfacial leakage due to burst. (b) Bar graph displaying the measured burst pressure of thermally cured PDMS (Sylgard 184) chips at 70 °C (left) and room temperature (middle) and that of UV-cured PDMS (X-34-4184) chips (right). ** and **** denote the statistical significance with $p < 0.01$ and $p < 0.0001$, respectively. (c) and (d) Stop flow lithography (SFL) in thermally (Sylgard 184 (c)) and UV (X-34-4184 (d))-cured PDMS chips with a flow time of 40 ms and inlet pressures of 20 (c) and 400 (d) kPa, respectively. Optical micrographs in left panels show PEGDA microparticles immediately after UV exposure (top) and those after 1 cycle of SFL (i.e., stop-UV exposure-hold-flow; bottom). Yellow dotted arcs represent the field of view of a 20 $\times$ objective lens (1.25 mm in diameter) through which photomasked UV is propagated. Optical micrograph in the right panel shows an undesired block of PEGDA (c) and intact microparticles (d) photocrosslinked along the microchannel after 25 cycles of SFL, respectively. Scale bars in the left and right panels are 200 and 50 μm .

The smaller molecular weight of the base polymer of UV-curable PDMS could facilitate the increased number of crosslinks at the interface. The Mark-Houwink equation indicates that the molecular weight of a base polymer (M) is proportional to $\eta^{1.43}$, where η is the viscosity of the base polymer.⁴⁵ Given the fact that a viscosity ratio of X-34-4184 (2900 cP) to Sylgard 184 (5100 cP) is approximately 0.57,^{34,46} the molecular weight ratio of UV-curable PDMS to thermally curable PDMS is approximately 0.45. Moreover, not only because the density of both types of the base polymer is identical to 1.03 g/ml but also because both types of PDMS are crosslinked by catalytic hydrosilylation,⁴⁷ the smaller molecular weight indicates that a greater number of precursors of UV-curable PDMS exist in a unit volume. This could induce more interfacial crosslinks and thus stronger bonding while a partially cured bottom layer continues undergoing hydrosilylation in contact with another block of UV-cured PDMS, which also appears to be consistent with other research.⁴⁸

E. Enhanced productivity of stop flow lithography with UV-cured PDMS chips

We hypothesized that we could exploit the stronger PDMS-PDMS bonding to enhance the productivity of SFL by shortening the flow time. Recall that the total duration of each SFL cycle consists of flow, stop, exposure, and hold times. Although SFL productivity relies on this total period of time, we focused on altering only the flow time in this study because the other parameters are independent of inlet pressure.² Considering that the flow time of 400–800 ms and the inlet pressure of 14–24 kPa have typically been used for SFL with thermally cured PDMS chips,^{16,44,49} we tested a flow time (40 ms) an order of magnitude shorter in duration in combination with a pressure of 400 kPa (higher than the burst pressure for conventional PDMS chips) in the UV-cured PDMS chips. As expected, the application of 20 kPa for 40 ms in thermally cured PDMS chips obviously precluded photocrosslinked PEGDA microparticles from being flushed out of a region of UV exposure after 1 cycle (left top and bottom panels in Fig. 5(c)). In contrast, a pressure of 400 kPa applied to UV-cured PDMS chips allowed microparticles to travel ~ 1.2 mm downstream for over the course of 40 ms (left top and bottom panels in Fig. 5(d)). Our use of a pressure of 400 kPa originated simply from the practical reason that this level of pressure was just below the upper limit a pressure regulator used for SFL could tolerate. In other words, higher inlet pressure can be applied to the further reduction in the flow time as long as regulators tolerate higher pressure and UV-cured PDMS chips do not burst. In addition, 40 ms was a lower limit selected in order to run our custom LabView code without failure. These results confirm that a flow time an order of magnitude shorter combined with an inlet pressure greater than 200 kPa was suitable for the application to the UV-cured PDMS chips in SFL.

While we continued increasing the number of cycles (e.g., 25 cycles), the status of SFL remained virtually unchanged in the UV-cured PDMS chip (right panel in Fig. 5(d) and Movie S1 in the [supplementary material](#)). However, in the thermally cured PDMS chip, the synthesis of microparticles started failing because of repetitive photocrosslinking of the microparticles generated in previous cycles, which consequently led to an undesired block in a microchannel (right panel in Fig. 5(c) and Movie S2 in the [supplementary material](#)). We observed the identical phenomenon in an additional test in which a UV-cured PDMS chip was used while all the operational parameters were the same (Fig. S1 and Movie S3 in the [supplementary material](#)).

The stop time can be also reduced to further contribute to the enhancement of productivity. This operational parameter is associated with a response time scale (τ) over the course of which an elastic channel, deformed (dilated) due to pressure, is restored to its original form. τ is known to be inversely proportional to the elastic modulus (E).² Our measurements of the elastic modulus of UV-curable PDMS and conventional PDMS revealed 3.85 ± 0.460 MPa for X-34-4184 and 2.71 ± 0.165 MPa for Sylgard 184. This result indicates that the increase in the elastic modulus by a factor of 1.42 in the UV-cured PDMS chip would allow for a reduction in the response time by 30% (i.e., $\tau_{X-34-4184} = 0.7 \tau_{\text{Sylgard 184}}$). In this study, we used 200 ms as the stop time, compared with a typical range of between 300 and 500 ms in thermally cured PDMS chips.

In brief, we were able to successfully increase the throughput [cycle/min] of SFL by a factor of at least 2.04 and of up to 3.64 by reducing the cycle time to 440 ms, compared with a typical cycle time range of 900–1600 ms.^{16,44,49} We performed the SFL experiment with a cycle time of 900 ms with a conventional PDMS chip as a conservative control (Table I).

TABLE I. Operational parameters of SFL and consequent throughput.

Material of microfluidic chips	Flow time (ms)	Stop time (ms)	UV exposure (ms)	Hold time (ms)	Cycle time (ms)	Throughput (cycle/min)
Conventional PDMS	400	300	100	100	900	67
UV-curable PDMS	40	200	100	100	440	136

IV. CONCLUSIONS

We have demonstrated that UV-curable PDMS (X-34-4134) serves as an excellent alternative material for microfluidic devices used in FL, resulting in favourable performance compared with that of conventional PDMS (e.g., Sylgard 184). Specifically, UV-curable PDMS was permeable to oxygen, optically transparent, and compatible with soft lithography. In addition, curing with UV only allowed for more precise reverse duplication of microstructures owing to the absence of shrinkage caused by thermal expansion. Furthermore, UV-cured PDMS microfluidic chips were capable of withstanding a high inlet pressure of up to ~ 0.9 MPa through stronger interfacial PDMS-PDMS bonding. By reducing the flow time by an order of magnitude (i.e., 40 ms) and reducing the stop time to 200 ms, we were able to demonstrate a substantial improvement in productivity in the process of synthesizing PEGDA microparticles via SFL. Our proposed approach could be used as a general platform for various types of flow lithography including, but not limited to, contact flow lithography and lock-release lithography. The UV-cured PDMS microfluidic chips could also be readily adopted for use in other applications: for example, very precise replication of structures in micro- or sub-micrometer scales and/or strong interfacial bonding.

SUPPLEMENTARY MATERIAL

See [supplementary material](#) for the estimation of pseudo 1st order rate constant k for the inhibition of photochemical chain reactions; parameters used for the estimation of pseudo 1st order rate constant, k (Table S1); SFL in a UV-cured PDMS chip with a flow time of 40 ms and an inlet pressure of 20 kPa (Fig. S1); long-term stability of a UV-cured PDMS chip (8 month-aged) regarding oxygen permeability for SFL (Fig. S2); movie clip showing a few early cycles of SFL in a thermally cured PDMS chip with a flow time of 40 ms and an inlet pressure of 20 kPa (Movie S1); and movie clips showing a few early cycles of SFL in a UV-cured PDMS chip with a flow time of 40 ms and inlet pressures of 400 (Movie S2) and 20 kPa (Movie S3).

ACKNOWLEDGMENTS

This work was supported by the Engineering Research Center of Excellence Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (NRF-2016R1A5A1010148), the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (NRF-2015R1C1A1A02037452), and a grant from the Korea University (K1615331). This research was also supported through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (NRF-2016R1A2B2008691 and NRF-2016M3C7A1913845), and the KIST Institutional Program (Project Nos. 2E26840 and 2V05570).

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