SINGLE-LAYER MICROFLUIDIC "DISC" DIODES *VIA* OPTOFLUIDIC LITHOGRAPHY FOR ULTRA-LOW REYNOLDS NUMBER APPLICATIONS

Ryan D. Sochol*, Christopher J. Deeble, Vivian Shen, Mariko Nakamura, Ben J. Hightower, Thomas A. Brubaker, Kye Y. Lee, Shan Gao, Minkyu Kim, Ki Tae Wolf, Kosuke Iwai, Casey C. Glick, Luke P. Lee and Liwei Lin
Berkeley Sensor and Actuator Center, University of California, Berkeley, USA

ABSTRACT

Autonomous fluidic components that function at ultra-low *Reynolds number* (*e.g.*, $Re < 0.1$) are critical to the advancement of integrated microfluidic circuitry. Here we present a single-layer microfluidic "disc" diode, which includes a free-moving *cylindrical* "disc" – constructed *in situ* using optofluidic lithography – that is transported to or away from the entrance of a docking channel to obstruct or promote fluid flow, respectively. COMSOL simulations yielded a theoretical *Diodicity* (*Di*) of 27.8. Experimental results revealed *Di's* ranging from 2.29±0.58 to 3.84±1.76 for a one-disc system, and 4.69±1.21 to 6.66±1.10 for a four-disc (in series) system, corresponding to $Re \leq 0.025$ flow.

KEYWORDS: Optofluidic Lithography, Check Valve, Diode, Integrated Microfluidic Circuitry

INTRODUCTION

The advent of self-regulating microfluidic circuit components holds significant potential for chemical and biological fields [1]. Microfluidic platforms offer a variety of benefits for biochemical applications, such as low reagent volumes, rapid reaction times, and the ability to passively mix, transport, and/or array suspended microbeads and cells [2]. At present, the majority of integrated microfluidic circuits require significant external (*i.e.*, "off-chip") regulation during device operation (*e.g.*, to actuate "on-chip" valving mechanisms) [3, 4]. Consequently, research has shifted toward alternative, self-regulating microfluidic technologies that do not require external control schemes [5]. In particular, researchers have focused on engineering microfluidic diodes to rectify flow in microfluidic systems; however, difficulties associated with low *Re* functionality and microfabrication complexity have limited the utility of such systems [6, 7]. To benefit from single-layer fabrication processes, recent works have demonstrated microfluidic diodes that utilize suspended microbeads as dynamic resistive elements; however, using spherical beads to block fluid flow through rectangular channels is inherently limited [8]. At µTAS 2012, we presented a microbead-based diode that utilized a targeted *circular-shaped* microchannel to enhance the "geometry match" between the *spherical* blocking element (*i.e.*, the microbead) and the docking channel [9]. Although this closer geometry match was found to improve device performance *versus* systems with only *rectangular* microchannels, time and labor-intensive procedures were needed to fabricate the targeted circular microchannel and load the microbead into the diode chamber.

Previously, researchers have employed optofluidic lithography methods to fabricate free-moving microscale pistons and check valves in two to four-layer microfluidic systems; however, the efficacy of such components remains limited due to the high pressures that are required for operation [10]. Although several single-layer microfluidic circuit components have been successfully fabricated using optofluidic lithography, device functionality required changes in fluidic properties including pH and temperature, which lack the versatility associated with regulation using alternative flow characteristics, such as flow polarity or pressure [11]. In prior works, we used optofluidic lithography processes to fabricate two types of microfluidic components capable of flow rectification: (*i*) microfluidic "domino" diodes, which include freely-rotating microstructures [12], and (*ii*) microfluidic "spring" diodes, which include free-standing polymeric microsprings [13]. One limiting factor of these diodic components is that the photoexposed microstructures must be "anchored" at specific locations, thereby necessitating precise manual alignment [12, 13]. To overcome this drawback, here we introduce a single-layer microfluidic "disc" diode, which includes a free-moving *cylindrical* disc that functions as a dynamic resistive element to enable flow rectification under ultra-low *Re* conditions (Fig. 1).

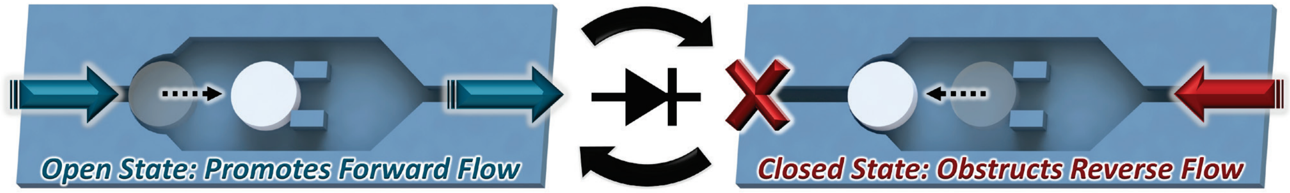

Figure 1. Conceptual illustrations of the single-layer microfluidic "disc" diode. (Left) For forward flow, the free-moving cylindrical disc element (which is constructed in situ via optofluidic lithography) is transported away from the entrance of the rectangular docking channel in order to promote fluid flow through the microfluidic system. (Right) For reverse flow, the disc element is guided back to the entrance of the docking channel, thereby obstructing fluid flow through the microchannel. This process functions autonomously based on the flow polarity.

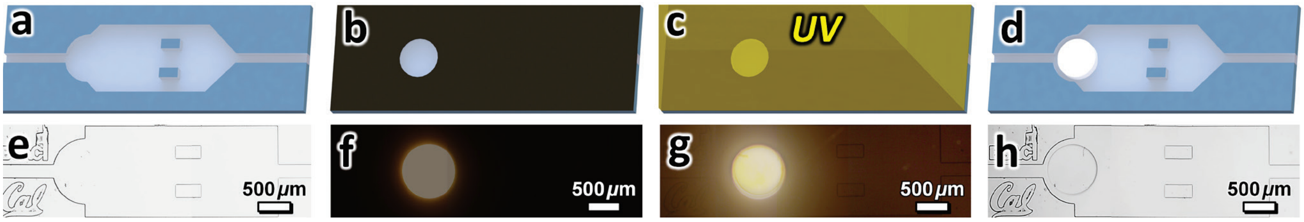

Figure 2. The single-layer microfluidic "disc" diode fabrication process and results. (a-d) Conceptual illustrations and (e-h) experimental results of using optofluidic lithography to fabricate microfluidic "disc" diodes. (a, e) PEGDA with 5% photoinitiator is loaded into the channel. (b, f) A photomask is placed in contact with the microdevice. (c, g) After general alignment, the device is exposed to UV light for in situ photopolymerization of the cylindrical disc element. <u>*Note*</u>*: The cured disc element does not bond to the PDMS due to an oxygen layer from the surrounding PDMS. (d, h) The remaining uncured liquid is evacuated and replaced.*

MICROFABRICATION

The overall microfluidic system was fabricated using soft lithography and optofluidic lithography processes as described previously [12-15]. Briefly, micromolded poly(dimethylsiloxane) (PDMS), with channel heights of 100 μm, was thermally bonded to glass slides coated with an 80 μm layer of PDMS (for PDMS-PDMS bonding). Figure 2 shows sequential conceptual illustrations (a-d) and experimental results (e-h) of the fabrication process for a free-standing disc element *via* optofluidic lithography. First, a solution of poly(ethylene glycol) diacrylate (PEGDA) with 5% photoinitiator (2,2-dimethoxy-2-phenylacetophenone) was loaded into the device (Fig. 2a, e). A photomask was placed in contact with the device and aligned (Fig. 2b, f). The device was then exposed to UV light, resulting in photopolymerization of the disc *in situ* (Fig. 2c, g). Due to the oxygen layer of the surrounding PDMS, the cured PEGDA did not bond to the surrounding PDMS, and was slightly smaller in height compared to the microchannel (approximately 5-10 μm). Afterward, the remaining uncured PEGDA was evacuated from the device and replaced with a solution of PEGDA without photoinitiator (Fig. 2d, h). Figure 3 shows SEM micrographs of fabrication results for the microfluidic "disc" diode.

RESULTS AND DISCUSSION

Three-dimensional COMSOL Multiphysics simulations were performed to investigate the potential performance of the microfluidic "disc" diode. The simulation results revealed a theoretical Di of 27.8 (Fig. 4). Figure 5 shows experimental results for the dynamics of the free-moving disc element (based on the flow polarity). For forward flow, the microscale disc element is displaced from the entrance of the docking channel, thereby promoting the flow of fluid through the channel. For reverse flow, the disc element returns to the closed position, thereby obstructing fluid flow.

Figure 6 shows quantified Di results for the microfluidic "disc" diode. For $Re \leq 0.02$, experiments revealed enhanced Di performance with increasing Re, resulting in maximum Di's of 3.84 ± 1.76 and 6.66 ± 1.10 corresponding to one-disc and four-disc (in series) systems, respectively. For $Re > 0.02$, however, this trend was found to reverse, leading to resistor-like behavior (*i.e.*, $Di \approx 1$) at higher Re. This was likely due to the surrounding PDMS deforming (*i.e.*, increasing in height/width) at higher pressures/Re, thereby allowing unwanted leakage during *reverse flow*. Such phenomena also provide a basis for the difference in theoretical *versus* experimental performance. To offset these effects, future applications should utilize PDMS (or other materials) with reduced flexibility.

CONCLUSIONS

In this work, we presented a single-layer microfluidic "disc" diode that utilized free-standing disc elements – fabricated *in situ via* optofluidic lithography – to rectify fluid flow under $Re < 0.1$ conditions. Several adaptations of the presented technique could enable improved Di performance, such as using PDMS (or alternative materials) with higher stiffness to limit PDMS deformation at higher pressures/Re. Nonetheless, the presented optofluidic lithography-based

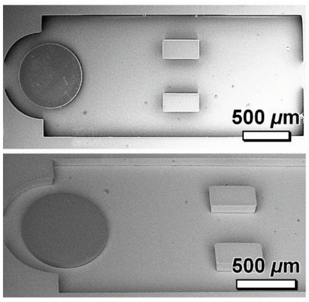

Figure 3. SEM images of fabrication results showing "Top" and "30°" views.

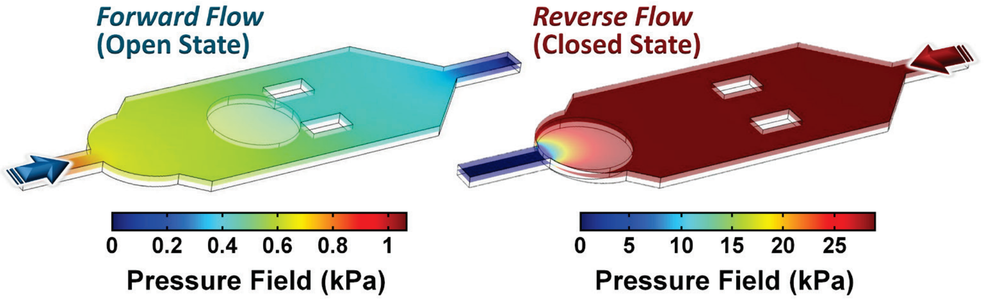

Figure 4. Three-dimensional COMSOL Multiphysics simulation results for the microfluidic "disc" diode. (Left) Pressure field results for the forward flow case. (Right) Pressure field results for the reverse flow case. Theoretical Di ≈ 27.8.

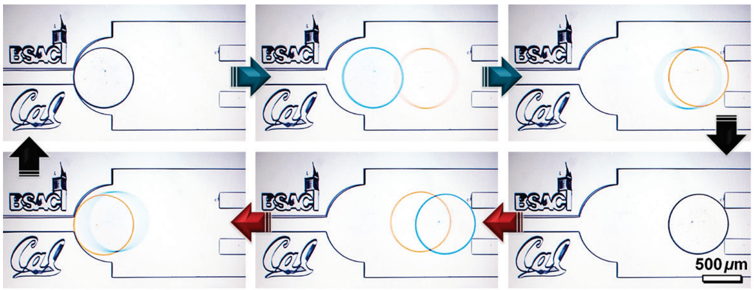

Figure 5. Sequential micrographs of experimental results captured from real-time video of microfluidic "disc" diode dynamics due to the flow polarity. (Top) Forward flow case. (Bottom) Reverse flow case. Cyan and orange "discs" are stroboscopic artifacts that denote time-points one and two, respectively, within one second.

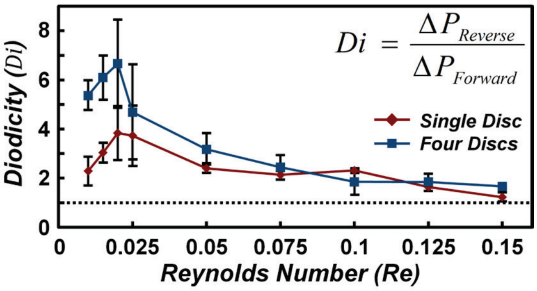

Figure 6. Experimental results for Di versus Re for one-disc and four-disc (in series) microfluidic diodes. $\Delta P_{Forward}$ and $\Delta P_{Reverse}$ denote the pressure drops for the forward and reverse flow cases, respectively. Error Bars denote s.e.m.

methodology for engineering microfluidic components could be applied to create novel, single-layer microfluidic circuits for chemical and biological applications, including point-of-care molecular diagnostics and on-site chemical detection.

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CONTACT

*R.D. Sochol, tel: +1-410-935-8971; rsochol@gmail.com