A FABRICATION TECHNIQUE OF THREE-DIMENSIONAL NANOCHANNEL BRIDGES WITHOUT NANOLITHOGRAPHY

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ABSTRACT

We present a simple, flexible fabrication technique to develop three-dimensional nanochannel arrays that can be embedded in a micro/nano-fluidic system using direct laser writing. We easily obtained a nanochannel bridge between two microfluidic channels on a glass slide by laser-scanning photosensitive materials filled in microchannels. We also fabricated a vertical nanochannel array, thus showing the feasibility of three-dimensional nanochannel fabrication. We envision that the nanochannel array fabrication technique will facilitate to increase the functionality of microfluidic systems.

KEYWORDS

Nanochannel fabrication, nano-bridge, vertical nanochannel array, direct laser writing, nanofluidic system

INTRODUCTION

Nanofluidic systems are a powerful tool for manipulating DNA, proteins, and nanoparticles [1]. Nanochannels play an essential role in nanofluidic systems [2]. To fabricate nanochannels, e-beam lithography [3], step sidewalls [4], CMOS fabrication technique [2], and nanoimprinting [5] have been reported. However, three-dimensional nanochannel integration in micro/nano-fluidic systems has yet to realize mainly due to their two-dimensional fabrication manners that require complicated fabrication steps including multiple sacrificial layers deposition and etching to achieve 3D nanochannels. Thus, simple fabrication to develop nanochannel arrays integrated in micro/nano-fluidic systems and three-dimensional nanochannel arrays is still challenging using the previously reported methods. Two-photon direct laser writing can be an alternative method due to a simple, flexible fabrication fashion to realize 3D structures with hundreds nanometers resolution; two-photon-laser scans into a photosensitive material and can draw 3D arbitrary structures. Moreover, the laser can scan into a pre-built micro/nano-fluidic system filled with a photosensitive material, thus facilitating the 3D nanochannel integration into micro/nano-fluidic systems. Previously, we verified the potential of two-photon direct laser writing for nanochannel fabrication applications [6]. Here, we propose a fabrication technique for the integration of 3D nanochannels into a micro/nano-fluidic system and the development of 3D nanochannel arrays by two-photon direct laser writing (Fig.1).

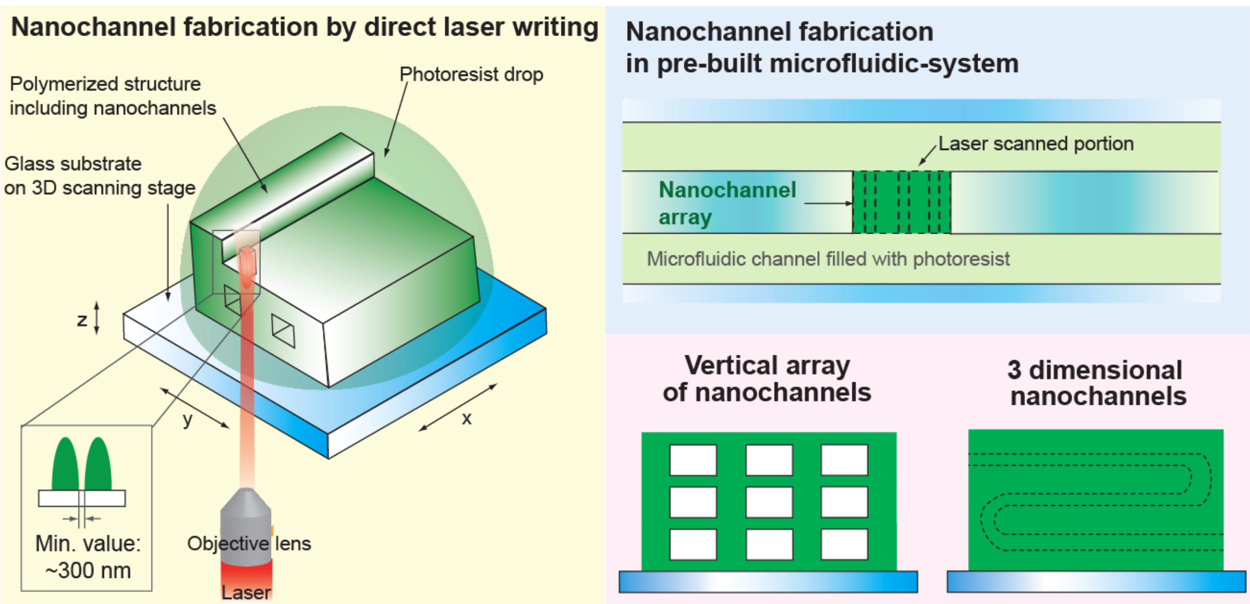

Figure 1. Conceptual illustration of the nanochannel fabrication technique by direct laser writing. This method allows us simple nanochannel fabrication without conventional lithography including several complicated layer deposition / etching steps and sealing process. Laser can scan into photoresist filled in a pre-built micro/nano-fluidic system, thus enabling nanochannel integration into the system. Also, the method can develop vertical nanochannel arrays and 3D arbitrary nanochannels that are difficult to develop using other technologies. Thus, the laser-writing nanochannel fabrication method will facilitate to develop high-throughput, high-functional micro/nano-fluidic systems.

EXPERIMENT

Figure 2a illustrates the process flow to fabricate nanochannels. We used a two-photon direct laser writing system (Photonic Professional, Nanoscribe GmbH equipped with a 100×, Numerical Aperture=1.4, oil immersion objective). Laser powers were 9.2–9.6 mW and piezoscanning velocities were 500 μm·s^{-1}. In addition, we used 'Continuous Mode' to connect neighboring points, resulting in a smooth line. Three-dimensional piezo-stage movement was automatically operated according to pre-loaded design to control software. Two-photon laser scans into the dropped photoresist (IP-L 780, Nanoscribe GmbH) on a circular cover glass of 30 mm in diameter (Fig. 2b). The liquid-type photoresist, IP-L, provides a simple fabrication manner because it does not require pre-baking, spin-coating, and post-baking steps. Glass slides were silanized to enhance adhesion between polymerized photoresist and glass slides. To silanize glass slides, first, glass slides were cleaned by acetone. The slides were plasma-treated for 10 min. Then, the slides were maintained in 1 mM of 3-methacryloxypropyltrimethoxysilane (Polysciences, Inc.) in toluene (Wako Pure Chemical Industries, Ltd.) for 1 hour. The slides were washed using Milli-Q water, then blow-dried. To develop nanochannels, the laser scans into the materials layer-by-layer along z-axis. First, the laser scans squared-area with nano-gaps (Fig. 2c). Then, piezo-stage moves 0.8 μm above the interface set point (0.2 μm below interface between photoresist and a glass slide), and scans squared area to cover the structures with nanogaps (Fig. 2d). If 2 and 3 steps of Fig. 2a are repeated, we can develop nanochannel array stacks. After developing in SU-8 developer for 20 min, we have obtained nanochannel arrays. The cross-section of structures has oval shapes (Fig. 2c and d) because polymerization volume exposed to laser focus, voxel, is oval-shaped; the oval-shaped voxel is the characteristics of two-photon absorption.

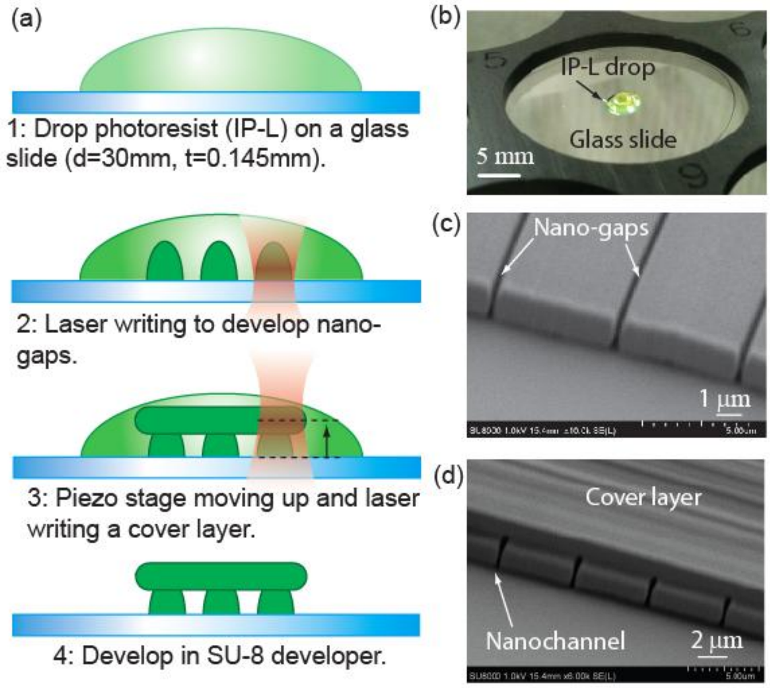

Figure 2. (a) Fabrication process. Two-photon laser scans into photosensitive materials according to pre-loaded design to operating software. (b) Photoresis drop on a cover glass described in a1. (c) Developed structures with nanogaps of ~300 nm in width. (d) Cover layer laser-written on the obtained structures in c.

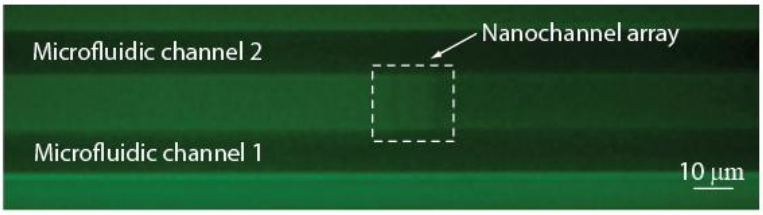

Figure 3. Nanochannel bridge. The nanochannels embedded between two open microchannels. This preliminary test showed that a nanochannel array could be integrated into the pre-built microfluidic-system.

RESULTS AND DISCUSSION

In experimental study, we tested the feasibility of nanochannels integration into micro/nano-fluidic system and 3D nanochannel fabrication. We demonstrated that nanochannel array could integrate into a pre-built microfluidic-system, as shown in Fig. 3. In this preliminary test, we developed two microfluidic channels using photoresist. Then, nanochannel array was created between the microfluidic channels to bridge them. To realize the full potential of the technique, nanochannel array fabrication has to be incorporated with glass-based micro/nano-fluidic devices that include inlet, outlet, and sealed-cover. When the photoresist is filled in the pre-built devices, laser can scan into the photoresist and form nanochannel arrays in the devices. If the technique lives up to its promise, the laser-writing fabrication method would provide opportunities for increasing functionality of micro/nano-fluidic systems. For example, at the nano-bridge, it is possible to apply very-local chemical exchange between two microflows. Despite of the benefits and promises of the technique, some technical challenges remain. In particular, bonding top and bottom glass slides has to be studied. Since thin cover glass has to be used in direct laser writing system, thickness of top and bottom glass slides is different. Thickness difference can cause glass breakage during anodic bonding process. In the future study, alternative bonding methods have to be tested instead of anodic bonding process.

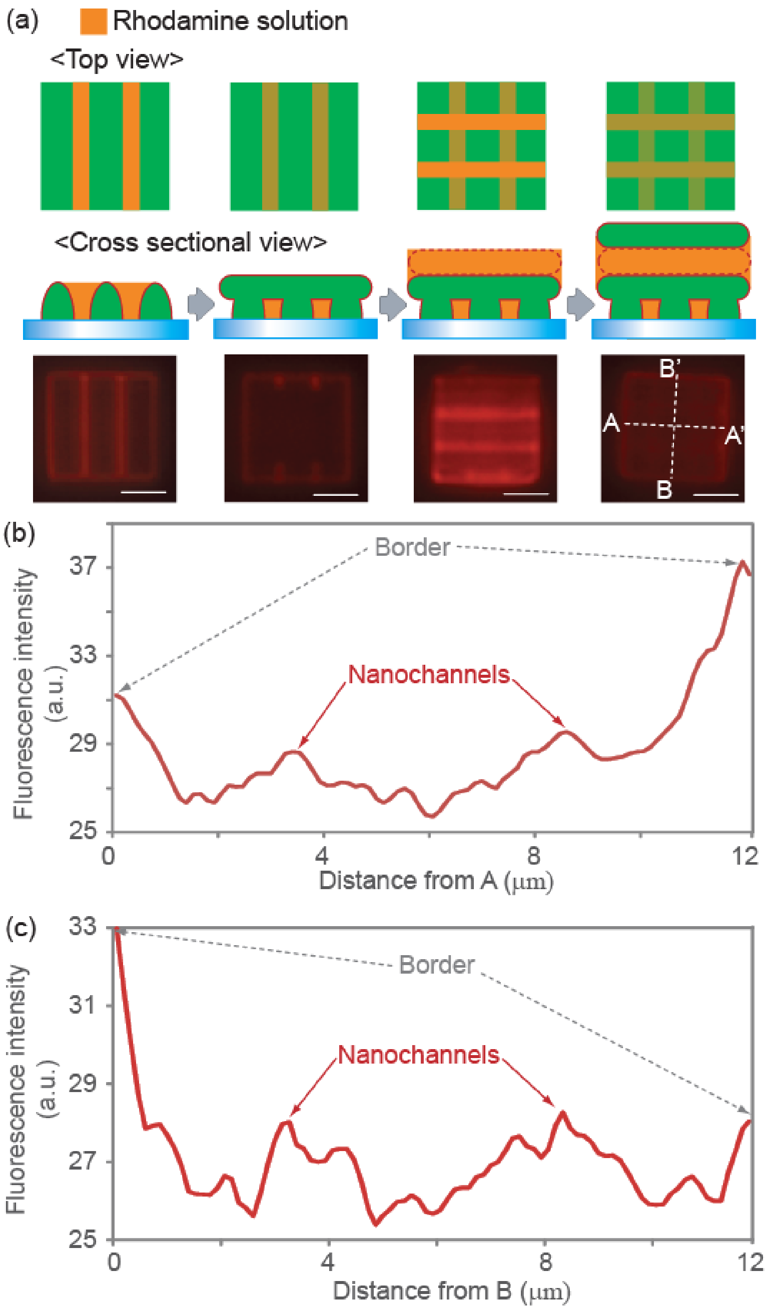

Figure 4. Vertical array of nanochannels. (a) Vertical array of nanochannels fabricated by laser-writing process in Fig. 2. The dye solution could flow into the nanochannels. Scale bars indicate 5 μm. Fluorescence intensity along line (b) AA' and (c) BB'. 4 nanochannels in the vertical array could flow the dye solution. The border of the structures glowed due to dye absorption.

We also developed vertical nanochannel arrays. In 10 μm (width) ×10 μm (length) dimension, we drew 4 channels of 1000 nm (width) ×10 μm (length) in two stacked layers; the size of nanochannels was designed to have larger than the resolution of this method due to microscopic measurement. To demonstrate nanochannels, rhodamine solution of 100 μM was flowed into the nanochannels by capillary force. The portions of the nanochannels showed higher fluorescence intensity than other portions. We concluded the 3D nanochannel array was successfully obtained by the laser-writing technique. The fabrication method can extend to fabrication of multi-stacked (more than 2) or 3D complex nanochannels. Therefore, although further technical refinement should be conducted, the laser-writing fabrication method would provide opportunities for the simple development of 3D nanochannel arrays embedded in micro/nano-fluidic systems, thereby resulting in increasing the functionality of the systems.

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