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Rapid fabrication technique of nano/microfluidic device with high mechanical stability utilizing two-step soft lithography

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ABSTRACT

We established a rapid fabrication technique utilizing two-step soft lithography to realize rigid nano/microfluidic devices which have high mechanical and thermal stability, good chemical resistance and replication accuracy. The proposed technique enables the production of rigid nano/micro structures including inlet and outlet ports by utilizing a mold master made from a soft material, conveniently and inexpensively. A device made from a thermosetting epoxy resin instead of a hard material showed a high replication accuracy, even with a high-aspect-ratio micro structure, and demonstrated sufficient mechanical stability at pressures exceeding 0.4 MPa. It is possible to realize the nano/microfluidic devices with high aspect ratios, high depth, and low surface roughness, such as nano-dot arrays, well structures, nano/micro channels, and other small and/or precise structures.

1. Introduction

The number of applications of nano/microfluidic devices for biological assay, chemical analysis, medical testing, pathogen detection, environmental measurements, etc. has increased significantly in recent years with the development of microfabrication techniques involving micromachining, photolithography, replica molding, which is also called soft lithography, embossing, and injection molding [1–4]. Nano/microfluidic devices have beneficial features such as a reduction of equipment size, rapid analysis, short reaction times, multiple analysis capability through parallel operation, and a reduction of the amounts of sample and reagent required [5,6].

Recently, in order to achieve much higher sensitivity and throughput in single-biomolecule analysis, detection of rare earth metals, water quality surveys, and other techniques, nano/microfluidic devices made from hard materials such as glass, silicon and steel have been developed [7,8]. Highly sensitive detection utilizing nanochannels for single biomolecule analysis has been realized [2,9]. Since mechanical stability under the high pressures caused by fluid flow in the nano channels was necessary, hard materials have mainly been used. Microfluidic devices for heavy metal detection, in which organic solvents are generally used to extract the metals, have employed hard materials because of their chemical resistance. However, hard materials, which have advantages of mechanical and thermal stability and chemical resistance, commonly require the use of fabrication techniques involving wet and dry etching, photolithography, electron beam lithography, bonding machines, and a variety of other techniques, all of which require the use of clean-room facilities and expensive equipment. Furthermore, they also require the process to create connection to bulk such as inlet and outlet ports, and tubing. Therefore, nano/microfluidic devices made from hard materials tend to have higher costs and require difficult fabrication processes [10,11].

In contrast, poly-dimethylsiroxane (PDMS) is a typical soft material for various nano/microfluidic devices, and can also be used in specific fluidic components such as valves, pumps, and regulators because of its elasticity [7,12–14]. PDMS has excellent fabricability: low cost, high reproducibility, quick curing, facile processing, and controllable adhesion by modification of the surface composition. The fabrication process of PDMS devices consists of two steps. First, a mold master is made from a rigid material, and then a flexible PDMS device is replicated from the mold master by pouring, curing, and releasing. Because PDMS is elastic, it is easily moldable, so it is possible to fabricate nano/micro structures without any etching or embossing [15–17]. Additionally, the fabricated substrate is easy to seal with the other substrates by the adhesive properties and the deformability of PDMS. Thus, a fabrication process based on soft lithography will be cheaper and easier than fabrication techniques involving hard materials. However, it is impossible to apply

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soft materials to molecular analysis devices utilizing nanochannels and measurement devices under high pressures because their elasticity leads to poor pressure resistance [18]. Furthermore, PDMS is unfit for heavy metal extraction with organic solvents because these organic solvents can cause unanticipated swelling.

In this article, we propose a rapid fabrication technique to make rigid nano/microfluidic devices with high mechanical and thermal stability, and good chemical resistance. The technique realized excellent fabricability such as rapid and facile processing, low cost, high reproducibility, and easy bonding by utilizing two-step soft lithography. In the present technique, both of the nano/micro structures with inlet and outlet ports on a mold master made from a soft material using two-step soft lithography were transferred into the epoxy resin. In addition, the fabricated structure was easily sealed with a resin, glass and silicon substrate because of the strong adhesion. In order to verify the efficiency of this technique, the replication accuracy and mechanical stability of the resulting devices were assessed.

2. Fabrication technique

Generally in a molding process, a photocurable or thermally curable soft material replica is formed by pouring onto a mold master made from a hard material. Then, the cured replica is released from the master by utilizing its elasticity. When the process is applied to a hard material replica and a mold master also made from a hard material, the devices often crack or suffer other damage. To overcome these problems, a fabrication technique utilizing two-step soft lithography enable to produce nano/microfluidic devices with high mechanical stability replicated from a mold master made from a soft material. The fabrication procedure shown in Fig. 1 consists of four steps, as follows: (a) pre-mold master fabrication, (b) mold master fabrication, (c) device replication, and (d) bonding and connecting of tubes.

A thermosetting epoxy resin (Stycast 1266, Emerson & Cuming) proved suitable for use in the proposed technique [19]. Young's modulus of the resin is 1400 MPa, which is approximately the same as that of PMMA (Table 1) [20]. The ratio of base to cross-linking agent used for the polymerization was 10–3 (w/w), and to cure, the resin was heated to 75 °C for 20 min. The resin also has the following advantages: strong adhesion with resin, glass and silicon substrates, good optical transparency, and excellent chemical resistance [21]. The material is optically transparent to visible light (400–700 nm), with an absorbance similar to that of PDMS, and it has been reported that its auto-fluorescence is low [22,23].

Table 1
Young's modulus (from product specification sheet).

Material	Young's modulus (MPa)
Presented resin (Stycast 1266, Emerson & cuming)	1400
PMMA (SUMIKA ACRYL Co., Ltd.)	1470–2450
Quartz glass (Covalent Materials Co.)	50,000–72,000
Borosilicate glass (Pyrex glass, Corning Inc.)	63,000
Thiol-ene photopolymer (NOA81, Norland Products)	1400

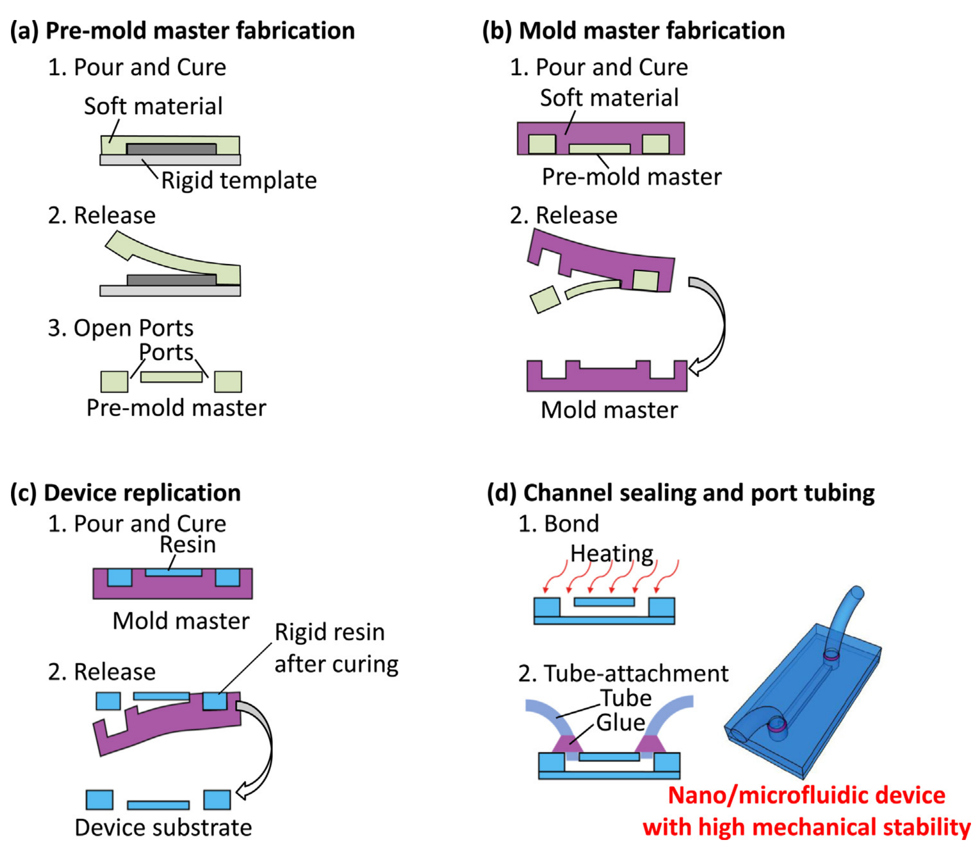

Fig. 1. Fabrication procedure. (a) Pre-mold master fabrication. A pre-mold master made from a soft material, typically PDMS, with nano/micro structures is formed using conventional soft lithography. Inlet and outlet ports are created by punching. (b) Mold master fabrication. A mold master made from a soft material is replicated by molding onto a pre-mold master. (c) Device replication. A device substrate with a nano/micro structure is replicated by molding onto the mold master. (d) Bonding and connecting of tubes. The device substrate is bonded to another rigid substrate, and tubes are connected to the ports.