MEMS MIXER AS AN EXAMPLE OF A NOVEL CONSTRUCTION METHOD OF MICROFLUIDICS BY DISCRETE MICROPARTS

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ABSTRACT

This paper describes a novel approach to construct and/or functionalize a microfluidic chip with discrete microparts that are microfabricated small enough to place them in a microchannel. A preliminary demonstration was shown as a passive mixer. Microparts of several hundred micrometers were fabricated by double-sided etching with ICP RIE. The parts were manually placed in a typical Y-shaped PDMS microchannel. Fluorescence observation revealed that the constructed microfluidics had the same mixing ability as a fully silicon MEMS mixer. The configuration that is unattainable by the normal preassembled structure can also be fabricated.

KEYWORDS

micromixer, microreactor, μ TAS, microfluidics

INTRODUCTION

A typical microfluidic chip consists of a microfabricated plate bonded to another plate [1]. **The chip size is from a postal stamp to name card, and channel width is submicrometer to several hundreds micrometer.** Not only can some complicated and sophisticated 2D patterns of the channel provide functionality [2] to the channel, but the addition of a microstructure such as fins [3], pillars [4], and grooves [5, 6, 7] to a limited part of an inside wall of the microchannel provides a wide variety of options to functionalize the channel. Some microfluidics require heterogeneous materials [8, 9] or a more complicated 3D structure [10-13]. However, the fabrication process for such microstructures is complicated for a silicon MEMS structure, and it is expensive to produce a mold, although the preassembly nature of a photolithography-based method and/or mold-based method has some advantages. Bead-packing [14, 15] is almost the only method to introduce microstructures into a channel after the bonding process of the two plates.

We have recently reported a passive silicon MEMS mixer that rearranges a two-layered laminar flow into a four-layered flow [3]. The structure of the mixer has a horizontal plate at a half-depth in the channel. The requirement of double-sided etching to form the plate constrains the whole chip design. The integrated flow channel should be formed only by a double-sided covering with glass plates. The fine MEMS process for the mixer simultaneously fabricated the long flow channel that shared the wide area of the chip and required less accuracy, resulting in low productivity and high cost.

Simple solution to reduce the fabrication cost is the division of the process to fabricate a chip with flow channel and the process to fabricate a fine and/or complicated microstructure to functionalize a part of the flow channel. In this case, assembly process of the microstructure into the flow channel is required. The method similar to the slurry-packing method of beads into flow channel may reduce the assembly cost. Alternatively, a microstructure of the size fitted to a flow channel can obtain an accurate position relative to the channel without any external precise alignment apparatus.

Recently, some researchers employed a new fabrication processes for microstructure: the self-assembly of microparts [16-21]. In particular, the self-assembly can instantly construct multiple parts by a simple operation. The self-assembly requires moderate selectivity and interaction with the driving forces such as tensile stress [22], electrostatics [23], capillary force [24], electromagnetic force [25-27], DNA interactions [28], and hydrophobic interactions [18, 29-35]. The self-assembly by

hydrophobic interaction has demonstrated the capability to assemble microparts with high efficiency and accuracy because surfaces are overwhelming in the size domain of microstructures. The application to electronics, optics and mechanics such as light emitting diodes (LEDs) [36] is proposed to achieve these benefits. Not only the self-assembly method but also normal assembly with intentionally controlled placement address discrete microparts. However, no studies have reported a discrete micropart assembled into the flow channel as a mixer. Prior to perform the self-assembly in a flow channel, the discrete microparts must first be fabricated.

Based on the above-mentioned background, we propose a novel approach to functionalize a flow channel at low cost. The method consists of three steps as follows: 1) fabrication of a discrete micropart smaller than the channel size, 2) slurry packing of the discrete microparts, and 3) self-assembly of the discrete microparts in a flow channel. In this research we functionalize a flow channel only with the first step. A micropart of the size fitted to a flow channel was employed for easy alignment by manual direct handling to place them into the channel. The discrete microparts are suitable for mass production because they can be densely fabricated on silicon wafers. As the first example, the passive silicon MEMS mixer of the same inner dimension but once clipped from a Si wafer as a discrete micropart (Fig. 1) and placed in a PDMS microchannel is demonstrated.

EXPERIMENTAL

Fig. 2 shows a process overview. The process starts by wet thermal oxidation of a 4 inch Si wafer (300 μm thick) at 985 degree C to reach 1.0 μm oxide thickness. Photoresist used was THMR-ip3100 (Tokyo Ohka Kogyo). The front side SiO_2 of the wafer was photolithographically patterned to leave the area of vertical walls (Fig. 2 (a)). Additionally, photoresist was patterned to leave the area of the vertical walls and horizontal plates (Fig. 2 (b)). All DRIE employed Bosch process at 600 W coil power and 25 W low frequency platen power with 130 sccm SF_6 flow. The first DRIE process of 90 cycle etched the areas to be penetrated with the mask of the photoresist and SiO_2 (Fig. 2 (c)). After removal of the photoresist, the second process of 130 cycles additionally etched the area of the horizontal plates with the mask of SiO_2 only, giving a step structure (Fig. 2 (d)). The area around a mixer was also etched from the first etching process. The backside of the wafer was then patterned to leave the area of the vertical walls (Fig. 2 (e)). The front side of the Si wafer was glued to another (dummy) plate with cool grease to prevent the micromixer from dropping into the process chamber of DRIE (Fig. 2 (f)). The back side of the Si wafer was etched once by DRIE to form a discrete micromixer ($L400 \times W300 \times D300 \mu\text{m}$) in the glue (Fig. 2 (g)) and soaked in solvent to release the micromixer (Fig. 2 (h)).

The mold that turns into a model of a channel in the same fabrication process as the mixer was also produced. Because the microchannel depth is 300 μm and both the size of the microchannel and the mixers must be the same, two types of molds were fabricated. One was a typical Y-shaped form, and the other was a Y-shape with an additional inlet downstream of the Y-shape. The additional inlet was designed to be a half-height branch at an angle of 45 degrees to flow only into the upper layer of the channel (Fig. 3). In this case, one of two inlets 1 was choked, and the other was connected to a syringe pump. The PDMS microchannel was fabricated with these molds. The fabricated mold was bonded to a flat PDMS plate with the assistance of an O_2 plasma. The PDMS prepolymer was poured onto the mold and baked for 2 h on a hotplate at 80 $^\circ\text{C}$. A manual operation with tweezers finally integrated the fabricated micromixer into the PDMS microchannel ($W300 \times D300 \mu\text{m}$).

Two methods were used for incorporating a mixer with a microchannel. The first method incorporates a mixer with a microchannel so that the mixer may become the same form as the preassembly type. The second method rotates a mixer 90 degrees about the axis of the flow direction and incorporates it into the Y-shape flow channel with the additional inlet. To confirm the mixing ability of the device incorporating a mixer, an experiment which used fluorescent dye (FITC) was performed. Ethanol and the ethanol with FITC were used for the experiment. The flow velocity was the same (100 $\mu\text{L}/\text{min}$) as for the preassembled type of the same dimension to compare the devices. Moreover, to investigate the performance of the device that rotated 90 degrees, the mixing condition of

the depth direction was observed by a confocal microscope (TCS-STED-CW, Leica Microsystems).

RESULTS AND DISCUSSION

Based on our first estimation, 800 sets of MEMS mixers can be designed on a 4-inch wafer, while only 30 chips can be designed on this wafer. The yield actually became approximately 30% because the etching rate of DRIE on the wafer side had a considerable dispersion. However, these numbers were larger than the amount of products of the microfluidic chip from the Si wafer. Fig. 4 shows an SEM image of the fabricated discrete Si MEMS mixer and the PDMS microchannel with an additional inlet. Ethanol and ethanol with FITC were flowed to form two layered laminar flows in the PDMS microchannel. Fig. 5 shows a fluorescence view around the micromixer in the channel, and Fig. 6 shows the fluorescence intensity distribution. Both mixers rearranged the **two-layered** stream to the **four-layered stream**. The results show that the discrete MEMS mixer has the same mixing ability as the preassembled type of the same dimension.

Fig. 7 shows a simple example of the usefulness of the proposed method with the complicated configuration that is unable to be formed by the preassembled fabrication method. Although the parts are placed manually in this research, the resulting total chip fabrication cost is still high. This method becomes cost-effective when combined with a low-cost assembly method.

Fig. 8 shows the fluid simulations of the device, which were incorporated. The mixer rotated 90 degrees, and the result of fluorescence is observed on the area around a mixer. Ethanol and ethanol with FITC were made to flow from one side of the Y-shaped inlet and the additional side inlet. Two-phase flow streams through the mixer at a 90 degree rotation were simulated with ANSYS CFX. In this simulation, the average flow velocity of the main flow and the side flow was set at 4.94 and 14.8 mm/s, respectively. Because the side channel depth was half of the main channel, an interfluent stream from the side channel remained in the top-right area in the cross-section of the flow. This position was confirmed both based on the simulation (Fig. 8(e)) and based on the confocal image (Fig. 8(h)). If one assumes that the interfluent area from the side is square larger than the quarter of the whole cross-section as shown in Fig 8 (b) and apply the simple consideration that the MEMS mixer rearranges the stream as shown in Fig 1, the stream becomes Fig 8 (c) and (d). The flow becomes four-layered downstream of the mixer, and the cross-section of the bottom half becomes asymmetric. The right half flow upstream that has no horizontal concentration difference comes to the top-side without a horizontal concentration difference, while the left half flow has the difference that results in the partial stream in the bottom half (Fig 8 (d)). Such a tendency was confirmed both on the simulation and the confocal images. Fluorescence observed in the top-middle of Fig. 8 (i) shows a gap between the fabricated micromixer and the channel that may due to fabrication error, and improvement of the etching rate dispersion in DRIE steps may avoid such a problem. These results show that we could fabricate devices that have impossible configurations in the preassembly method.

CONCLUSIONS

This research proposed a novel construction method for microfluidics by discrete fabrication of microparts assembled in a microchannel. The proposed method enables us to fabricate more complicated and higher level microfluidic chips than the conventional configuration or preassembled structures. The MEMS mixer that required three plates in the previous research could be formed in a typical two-plate microfluidic. To verify the possibility of this research, the mixing ability of the microfluidic chip that was fabricated by incorporating a discrete MEMS mixer with a microchannel was confirmed. Possible configuration of the assembly structure only was determined by changing the method of arrangement of the MEMS mixer. Fluorescence observation revealed that the discrete type had the same mixing ability as the preassembled type. The device that incorporated the mixer rotated 90 degrees. This configuration could not be established by the preassembly method. These results illustrate the possibility of constructing a complicated and high level microfluidic chip. Unfortunately, the resulting total chip fabrication cost is still more expensive than the conventional manufacturing method because the microparts were placed manually in this research. The combination of a low-cost

assembly method, such as the self-assembly method, creates a novel fabrication method for microfluidics.

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BIOGRAPHIES

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Legends

Figure 1: Schematic overview of the Si MEMS mixer fabricated in this research and its mixing process. Two liquid layers are divided and rearranged into 4 layers from 2 by the mixer

Figure 2: Fabrication process for the discrete Si MEMS micromixer. Photoresist and SiO₂ were used to fabricate a partition plate into the micro mixer. The front side SiO₂ was patterned (a) and additionally patterned with photoresist (b), followed by the first DRIE (c), and the second DRIE after the removal of photoresist (d). Back side was patterned (e), and front side was glued (f) Then, the wafer was glued to another plate, and back side DRIE divided the parts from the wafer (c), and the fabricated microstructures were finally released from the plate (d).

Figure 3: The microchannel for the mixing observation of the depth direction. To pour partially into the upper layer from the middle of Y-shape microchannel, a mold was fabricated so that the inlet has only a half-height.

Figure 4: SEM view of the fabricated discrete micromixer and Y-shape microchannel with the additional inlet.

Figure 5: Fluorescence view of the mixing area of the chip. Fluorescent dye was flowed from left to right. The black area is the Si MEMS microstructure

Figure 6: Distributions of fluorescence intensity across the channel. Solid lines shows the results from the previous preassembled chip, and dotted plots show the results from this research. Blues are before mixing, and reds are after.

Figure 7: Special configuration of the 3 microstructures. The center microparts were placed with 90 degree rotation.

Figure 8: Mixing process of micromixer with 90 degree rotation. (a) shows observed microchannel that incorporated the micromixer. These show the simple fluid considerations (b) (c) (d), CFD simulations (e) (f) (g) and the results of fluorescence observation (h) (i) (j). The cross-section perpendicular to the flow direction at the upstream of the mixer (b) (e) (h). and at the downstream (d) (g) (j), the side cross-section (f) (g) (i) around the mixer, and the color bars for relative fluorescence intensity from experimental results (k) and simulation (l).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Figure(s) 6

Fig. 7

Fig. 8