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Liquid Filling Method for Nanofluidic Channels Utilizing the High Solubility of CO_2

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We developed a fabrication method and a liquid filling method for a nano chemical reactor that used Y-shaped nanochannels specially designed for mixing and reacting. In order to reduce the pressure loss and to utilize the characteristics of the nanochannel, inlet microchannels were fabricated just beside the nanochannels. We investigated an initial liquid filling method into the nanochannels that ensured there were no air bubbles that could cause a flow stack due to the capillary pressure. In our method, the micro- and nanochannels were filled with carbon dioxide and any remaining air during the initial liquid introduction was dissolved utilizing the high solubility of carbon dioxide. We propose that chemical reactions in nanospaces can be realized by utilizing these fabrication and liquid introduction techniques.

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Introduction

The miniaturization of analytical systems, called micro-TAS or lab-on-a-chip, has attracted much attention from scientists and engineers because these systems have such merits as eliminating tedious operations, using a lower sample volume, and providing higher reproducibility than conventional systems.[1-3] As the fabrication techniques advance, nano-scale integration of the analytical systems has lately become of major interest. Recently, nanostructures, for example nanochannels, carbon nanotubes,[4] nanopillers[5] and nanoporous membranes,[6] were utilized in miniaturized analysis systems. Among papers on nanostructures, those dealing with nanochannels for liquid flow are very important in the research field of flow analysis. Nanochannels for liquid flow were fabricated by various methods, for example wet etching,[7] nano imprinting,[8] and dry etching.[9] In most reports about nanochannels, they have been applied only to DNA electrophoresis.[10,11] General chemical processes in nanochannels have not been reported because of the difficulty of pressure-driven operation of nanofluidics.

Since the specific interface area is extremely high in the nanochannels, the liquid properties and chemical reactions are expected to be size-dependent. Some reports based on experiments about capillary action have suggested that viscosity changes occurred in the nanochannels.[9,12] Other size-dependent phenomena, such as ion-enrichment and depletion,[13] an entropic effect of DNA[11] and the fluorescent lifetime[9] have also been observed.

One of the most important fields for miniaturization techniques has been the integration of flow chemical processing, which allows considerably complex chemical processing to be carried out. In particular, we have proposed the concepts of continuous flow chemical processing (CFCP) and microunit operations (MUOs),[15] and have realized immunoassay, multi-ion sensing, and chemical synthesis in microchips.[16-18] In these microscale applications, a short diffusion length and a high specific interfacial area on the microscale were utilized. By utilizing nanochannels for CFCP, more effective chemical processes will be achieved. However, no simple chemical processes in nanochannels have been achieved.

As an example of nano chemical reactor systems, we have fabricated Y-shaped nanochannels. In order to realize mixing and reactions in the nanochannel, two flows should be made confluent at the Y-junction point. Pressure-driven flow control in nanochannels is very difficult because of the very large pressure loss occurring in them. Therefore, micro-nano combined structures have been investigated in order to shorten the nanochannel length and to reduce the pressure loss.

Although micro-nano combined structures are suitable for a nano chemical reactor system, a serious problem still remains. When pure water or a solution is introduced into the air-filled micro- and nanochannels, air bubbles often remain in the microchannel part. Once air bubbles are formed there, it is difficult to replace them with a liquid because air cannot travel from the microchannel to the nanochannel due to the very high negative capillarity. Since the remaining air bubbles cause a flow stack, a new technique for the initial liquid introduction

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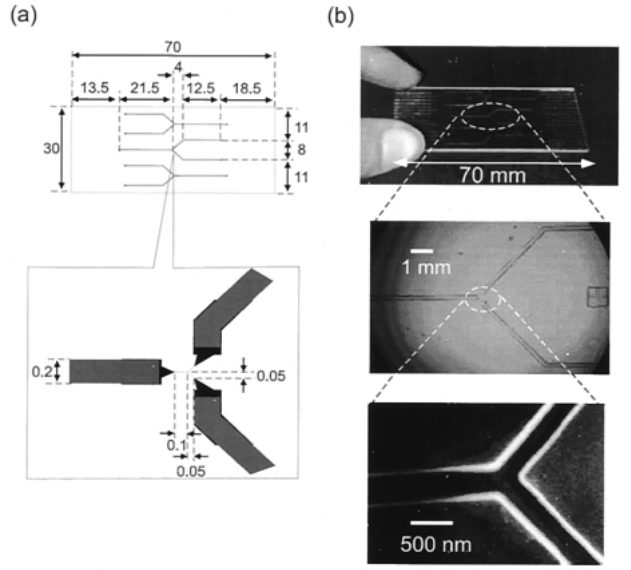

Fig. 1 (a) Layout of the nano chemical reactor. The depths of the gray pattern and black pattern were 40 μm and 400 nm, respectively. The numbers in this figure are "mm". (b) The top two pictures are optical micrographs of the nano chemical reactor, and the bottom picture is an electron micrograph of it.

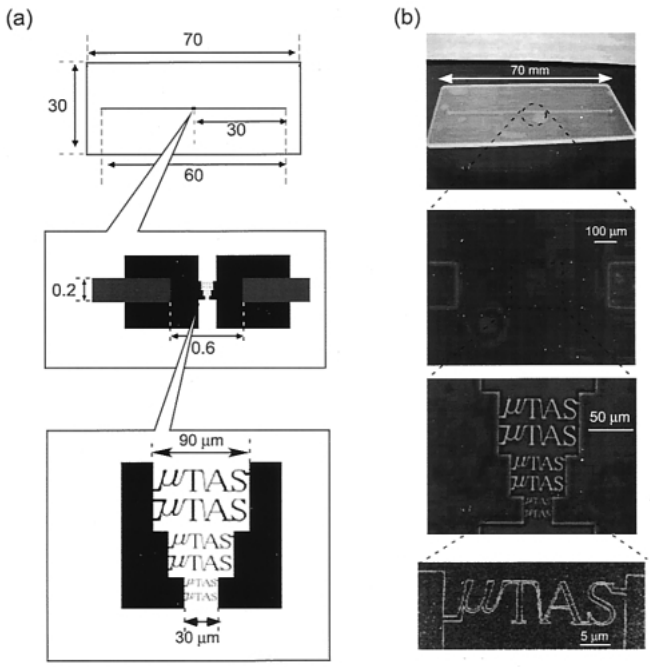

Fig. 2 (a) Layout of the complicated nano channels. The depths of the gray pattern and black pattern were 50 μm and 250 nm, respectively. (b) The top picture is a photograph of the chip. The middle two pictures are optical micrographs and the bottom picture is an SEM image of the complicated nanochannels connected to the microchannels for liquid introduction.

process is required. An outgas technique utilizing a vacuum pump was proposed for filling microchannels.[19] However, this technique is not suitable for filling nanochannels, because their volume is extremely small. A new method for filling nanochannels is required.

In the present work, we fabricated micro-nano combined channels on fused-silica substrates, and investigated a novel liquid filling method, whereby the high solubility of CO_2 in water is utilized. In order to confirm the effectiveness of this method, we also demonstrated liquid introduction into nanochannels having complicated shapes.

Experimental

Nanochannel fabrication

Rectangular shaped fused-silica plates (0.7 mm thick; 30 and 70 mm sides) were used as substrates. A nanochannel pattern was transferred to a spin-coated electron-beam-resist layer (ZEP-520, Zeon Corporation, Tokyo, Japan) on a fused-silica substrate with an electron-beam lithography system (ELS-7500, Elionix, Tokyo, Japan). In order to prevent charge accumulation by the electron beam, a conductive polymer layer (Espacer300, Showa Denko, Tokyo, Japan) was spin-coated on the resist layer. The exposed nanochannel pattern was developed with xylene and the fused-silica surface was etched with a neutral-loop density plasma etching system (NE-550, Ulvac Inc., Tokyo, Japan). The microchannels connected to the nanochannels were fabricated by sand blasting after laser-beam patterning of a polyimide resist film. After fabricating the micro- and nanochannels, the substrate was thermally bonded to another substrate in a vacuum electric furnace (KDF-900GL, Denken Co. Ltd., Kyoto, Japan). The bonding temperature was 1030°C.

Liquid introduction

A syringe pump (KDS-200, KD Scientific Inc., Holliston, MA) was used for the conventional introduction method. The microchip was stabilized by a holder and the liquid was introduced through a capillary, which was connected to a Teflon screw. Details of this conventional introduction method were described previously.[20]

A polyethylene glove bag was used as a chamber for the CO_2 replacement method. A glass desiccator was used as a vacuum vessel. Details of the CO_2 replacement method are described later. For fluorescent visualization of liquid introduction, an aqueous solution of 10^{-5} M fluorescein was used.

Results and Discussion

Fabrication

The layout of the micro- and nanochannels is shown in Fig. 1(a). The respective lengths of the nanochannels before and after the junction point were 70 μm and 100 μm.

Ordinarily, photolithography and wet-etching by hydrofluoric acid are used for microchannel fabrication. However, the nanochannels on the substrate were also etched by hydrofluoric acid when we applied the wet-etching method. In order to prevent their being etched, we utilized sand-blast etching after laser-beam patterning. Since the nano- and microchannels were fabricated by different methods, adjusting the origin and inclination of the coordinate axis was required. Therefore, laser-beam patterning was performed based on mark patterns fabricated with electron-beam lithography.

Figure 1(b) shows a photograph of the microchip (upper), a micrograph of one microchannel around the nanochannels (middle) and an SEM image of the nanochannels (lower). The nanochannels have a width of 300 nm and a depth of 400 nm and the microchannels have a width of 200 μm and a depth of 40 μm. No deformation of the nanochannels due to

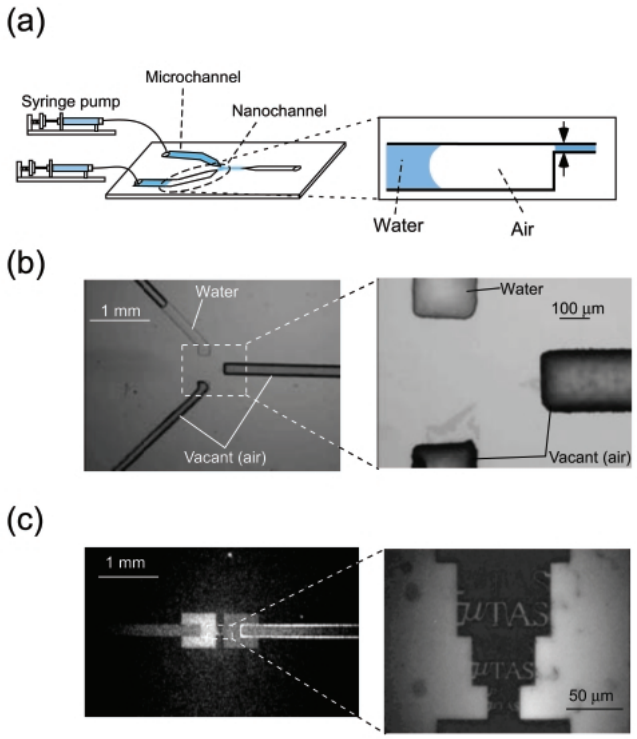

Fig. 3 (a) Illustration of liquid introduction by syringe pumps. (b) Results of liquid introduction into the Y-shaped nano chemical reactor. Water was introduced from the upper microchannel. Air remained in the nanochannel and microchannels. (c) Result of liquid introduction into the complicated nanochannels. The white area corresponds to fluorescent aqueous solution while the black area corresponds to an empty channel.

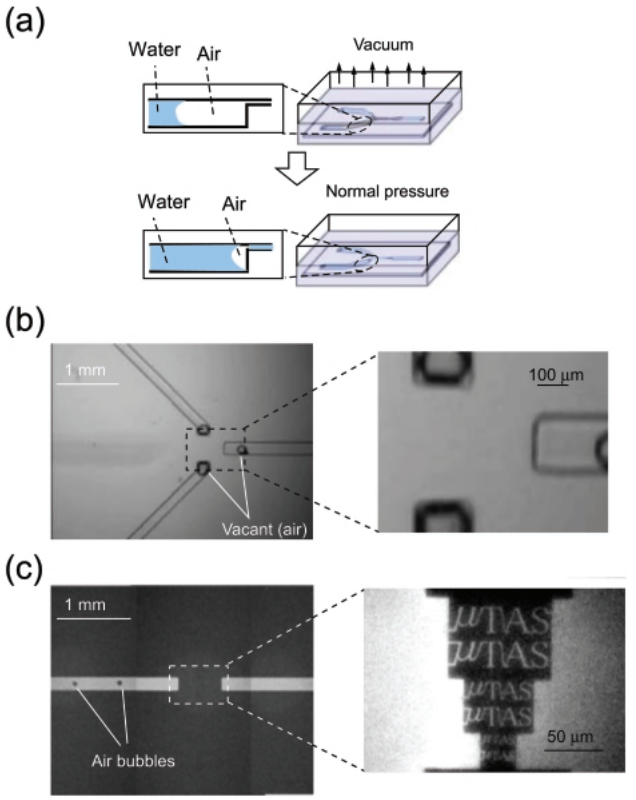

Fig. 4 (a) Illustration of the liquid introduction method utilizing reduced pressure (vacuum method). (b) Results of liquid introduction into the Y-shaped nano chemical reactor. Tiny bubbles remained in the microchannels. (c) Results of liquid introduction into the complicated nanochannels. The white areas on the pattern correspond to fluorescent aqueous solution. Some bubbles (black) remain in the microchannel.

microchannel fabrication was observed.

In order to confirm the effectiveness of our liquid introduction method, nanochannels having complicated shapes were also fabricated. Figure 2(a) shows the layout of the micro- and nanochannels. Figure 2(b) shows photographs and an SEM image of fabricated channels, where the nanochannels were patterned as the letters "µTAS". The top two nanochannels, middle two, and lower two have minimum widths of 450 nm, 300 nm, and 150 nm, respectively.

Liquid introduction to a nanochannel

In order to realize mixing and chemical reactions in the Y-shaped nanochannel, liquids are introduced from two directions. When the liquids were simply injected with a syringe pump from two inlets, it was difficult to control their introduction time into the nanochannels. Although the two liquids should be introduced simultaneously, one liquid arrived at the nanochannel sooner than the other liquid. Therefore, the nanochannel was filled with the first liquid by capillary action, and an air plug or bubbles remained between the nanochannel and the second liquid. Once the liquid was introduced into the nanochannel, the latter liquid flow was stacked because replacement of liquid in the nanochannel with air bubbles requires a high pressure due to the negative capillary force, as illustrated in Fig. 3(a). For example, 0.3 MPa was required to replace water in a 300-nm wide and 300-nm depth nanochannel that included some air. Figure 3(b) shows a micrograph of water introduction into the nano chemical reactor done using syringe pumps. Although water was introduced from the upper inlet-microchannel to the nanochannel, air remained in the other microchannel. Air also remained in the nanochannel. When water was introduced in the nanochannel, no channel pattern could be seen in the picture because the refractive indices of glass and water are similar. In Fig. 3(b), some part of the nanochannel can be seen in the picture, and we considered that air also remained in the nanochannel. Figure 3(c) shows a micrograph of aqueous solution introduction into the complicated nanochannel. The white area on the photograph corresponds to an aqueous solution, while the black area corresponds to an empty channel. The fluorescent solution was not completely introduced into the nanochannel.

For initial liquid introduction into the nanochannels, two different methods were tested: a conventional vacuum method and a CO_2-vacuum method. Figure 4(a) is a schematic presentation of the former vacuum method. First, the nano chemical reactor chip was immersed in a water-filled dish and the dish was put in a vacuum vessel. By decompressing the vessel, the air pressure in the channels was reduced. Then, the vessel was returned to atmospheric pressure and liquid was introduced into the channels by utilizing a pressure difference. Figure 4(b) shows a micrograph of the channels after the introduction of water. Although water filled the nanochannel and most parts of the microchannels, tiny bubbles remained in the microchannels because the vacuum pressure is limited by the saturation vapor pressure of water (3 kPa at 25˚C.) Figure 4(c) shows a fluorescent micrograph of channels having complicated nanochannel patterns, where the same procedure was applied, as in the former case. This time the solution was

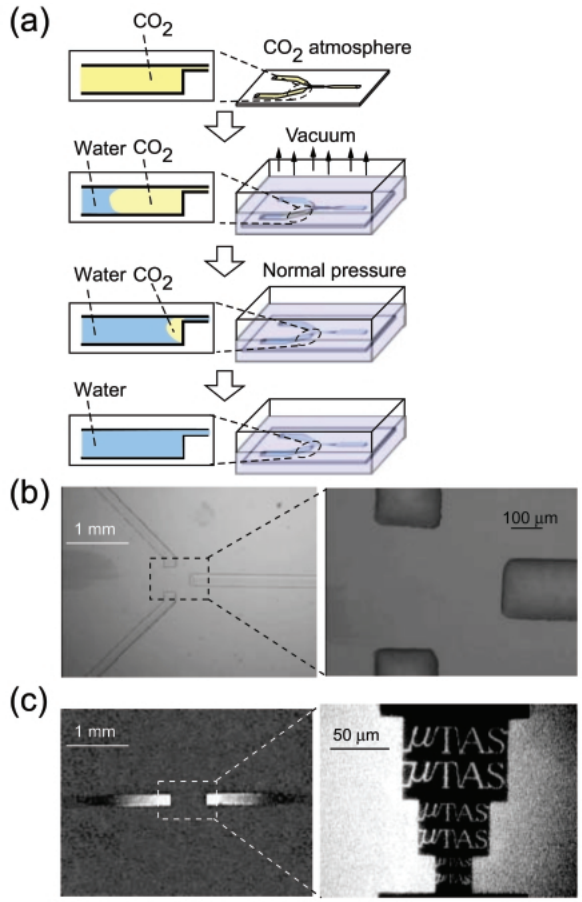

Fig. 5 (a) Schematic illustration of the liquid introduction method utilizing reduced pressure and high solubility of CO_2. (b) Results of liquid introduction into the Y-shaped nano chemical reactor. Water filled the microchannels and the nanochannel. (c) Results of liquid introduction into the complicated nanochannels. The white areas correspond to fluorescent aqueous solution. All patterns were filled with the solution.

satisfactorily introduced into the complex nanochannels. However, air bubbles still remained in the microchannel.

Next, the CO_2-vaccum method was tested. Figure 5(a) is a schematic of this method. First, the chip was set in a CO_2 atmosphere and air in the channels was replaced by CO_2. The chip was immersed in a water-filled dish and the dish was put in a vacuum vessel. By decompressing the vessel, the CO_2 pressure in the channels was reduced. Then, the vessel was returned to atmospheric pressure and water was introduced into the channels by utilizing the pressure difference. Since the solubility of CO_2 is high, the remaining CO_2 was dissolved into the water. Figure 5(b) shows a micrograph of the Y-shaped channels after introduction. Water filled the micro- and nanochannels completely. When the fluorescent solution was introduced into the complicated nanochannels by the CO_2-vacuum method, they were also completely filled with solution (Fig. 5(c)). By utilizing this method, no bubbles remained even in the nano-structure. The liquid filling method presented here will contribute to realizing nano chemical processing in a micro-nano combined structure.

Conclusions

A Y-shaped nano chemical reactor was successfully fabricated by combining micro- and nano-fabrication methods. In the micro-nano combined structure, each end of the nanochannels was connected to a microchannel to cut the pressure loss. Then, a liquid filling method for the channels with no air bubbles was developed. By utilizing the high solubility of CO_2 in water, the channels could be completely filled with water. Water filling for complicated channels was also demonstrated. In the future, a pressure-driven nano chemical reactor and its application to a chemical reaction in the Y-shaped nanochannels will be investigated. Our method will contribute significantly to development of nano reactor systems.

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