FORMATION OF PRESSURE DRIVEN PARALLEL AQU/ORG TWO PHASE FLOW IN EXTENDED-NANO SPACE BY A FIB-BASED PARTIAL HYDROPHOBIC MODIFICATION METHOD

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ABSTRACT

We report formation of parallel two-phase flow in extended-nano space by a novel partial modification method for the first time. Hydrophilic/hydrophobic partial modification with 10 nm order-resolution was achieved by the method using focused ion beam (FIB) with inclined extended nanochannel (10-1000nm). Our study will contribute to develop nanofluidic systems using multi-phase flows for chemical applications.

KEYWORDS: partial modification, patterning, liquid/liquid, two-phase flow, focused ion beam, micro, nano, nanofluidics, extended-nano, continuous flow chemical processing, Laplace pressure

INTRODUCTION

Recent studies of extended nanospace have suggested potential of new engineering field of integrated chemical systems by revealing specific properties of liquid and chemical reaction [1]. In order to develop fluidic systems by extended nanochannels, a methodology for integration of chemical processes is strongly required. Our group has developed a concept of integration using parallel multi-phase flows (immiscible liquids or gas/liquid) [2]. Unit of chemical process, e.g., mixing, reaction, separation, have been integrated by connecting in parallel and series. In order to apply these methods to extended-nano space, formation of parallel two-phase flow in extended-nano space is required. However, previous work revealed that formation of parallel two-phase flow in extended-nano space is difficult only by pressure driven flow control because of instability of aqu/org interface [3]. In order to stabilize aqu/org interface, partial hydrophobic modification in extended nanochannel was tried by using near-field optics ablation. However, control of near-field optics and optical alignment were difficult [3]. The aim of this study is to develop a novel partial hydrophobic modification method without any nanoscale alignment and form the parallel two-phase flow in extended nanochannel.

THEORY

Figure 1 shows a schematic illustration of stabilization of aqu/org interface by Laplace pressure. If aqu/org interface is deformed at surface, Laplace pressure works to recover interface. Figure 2 shows a schematic illustration of the parallel aqu/org two-phase flow in extended nanochannel by FIB-based partial hydrophobic modification method.

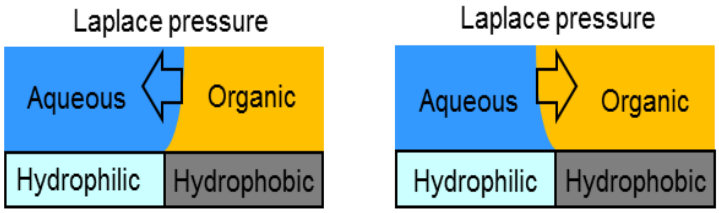

Figure 1: Schematic illustration of stabilization of parallel aqu/org two-phase flow by partial modification.

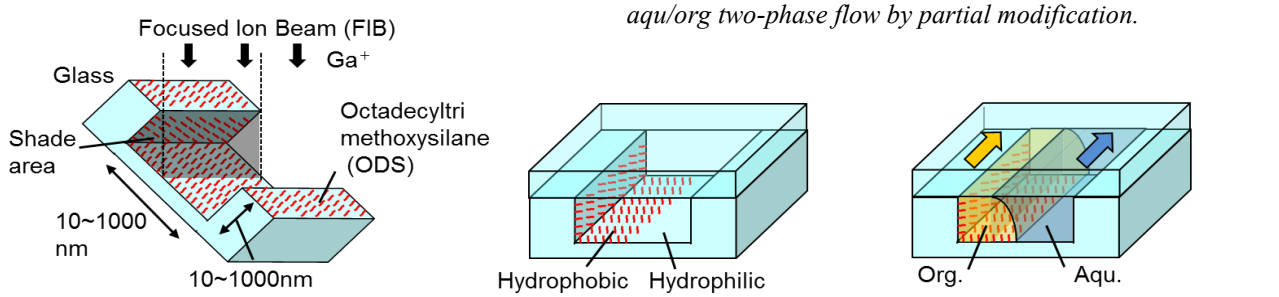

Figure 2: Schematic illustration of formation of parallel aqu/org two-phase flow in extended nanochannel by FIB-based partial hydrophobic modification method.

There are few methods to partially modify steric surface. In extended-nano scale, light diffracts and is difficult to use for partial modification. FIB has 6 nm resolutions, not diffracts at channel wall and has enough energy to break hydrophobic material. Modified hydrophobic material at inclined substrate was partially broken by FIB. Hydrophobic material only at shade area made by channel wall was not broken. In this way, extended nanochannel was partially and uniformly modified in 10 nm order-resolution without alignment. By a calculation of the surface energy with the Owens-Wendt and Fowkes theory, L shape hydrophobic modification is appropriate to form two-phase parallel flow.

EXPERIMENTAL

Extended-nano and microchannels were fabricated on the glass substrate by electron beam lithography and plasma etching. Extended nanochannel was partially modified by novel partial modification method. Firstly, the principle of this novel partial modification method was verified (Figure 3(a)). Cr was sputtered to glass substrate which had 2000 nm width and 600 nm depth channel for observation with scanning ion microscope (SIM). After FIB-based partial modification method was verified, octadecyltrimethoxysilane (ODS) was used as hydrophobic material to make two-phase parallel flow because ODS is chemically stable, uniform and small volume self-assembled-monolayer enough not to change channel size. ODS was modified to entire chip and partially broken by FIB-based method (Figure 3(b)). After that, Lift-off resist dissolved and only ODS in the channel was remained. Substrate was bonded with another glass substrate by Low temperature bonding, not to destroy remained partially modified ODS.

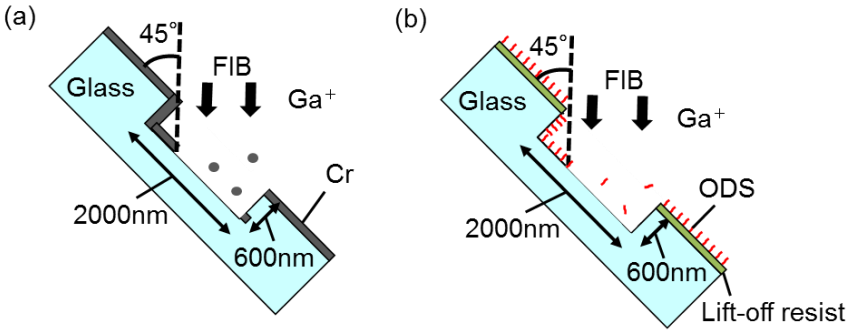

Figure 3: Schematic illustration of FIB-based partial modification method. (a) Verification of spatial resolution by using Cr, for SIM observation. (b) ODS partial modification for making two-phase flow.

RESULTS AND DISCUSSION

The principle of the novel partial modification method was proved as shown in Figure 4(a). Partially modified extended nanochannel was observed by cross-section SIM image. Black area was glass and white area was Cr. Partial modification area which coincided the design and had 10 nm order-resolution was observed. Based on FIB breaking process, this method identically can be applicable to 50 nm channel in minimum. Partial modified ODS was observed by fluorescent microscope (Figure 4(b)). ODS was fluorescently labeled by Rhodamin B. Applicability of partial hydrophobic modification in extended nanochannel was verified.

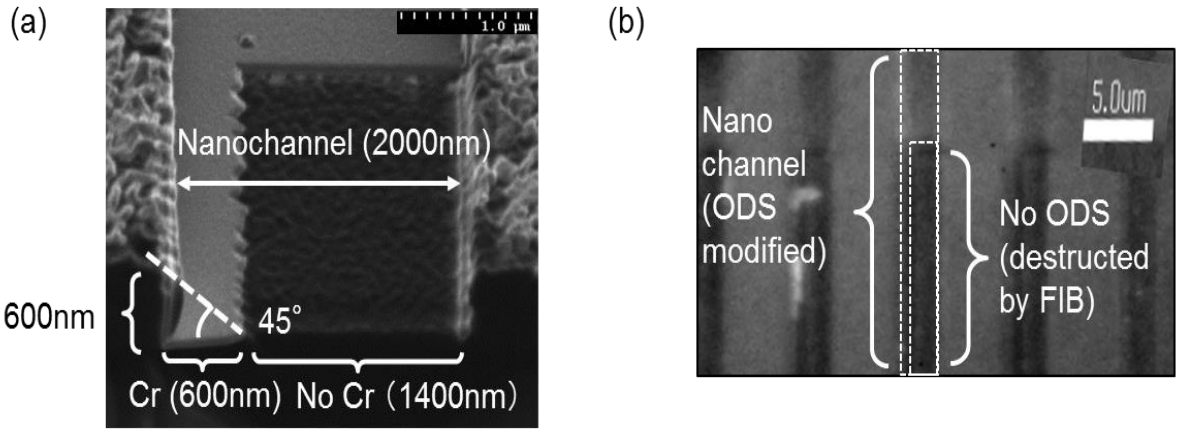

Figure 4: (a) Partially broken Cr at the extended nanochannel (SIM image, 45 degree inclined). (b) Partially modified ODS (fluorescent image)

Pressure-driven parallel aqu/org two-phase flow was formed in extended nanochannel of 1600 nm width and 800 nm depth as shown in Figure 5. Pure water and dodecane were used as aqueous and organic liquid, respectively. 10 μm length parallel two-phase flow was formed. The flow velocity was 17 mm/s by calculation. It took 5.9×10^{-4} s to flow formed two-phase flow. Diffusion time t is expressed by equation (1).

$$t = L^2/2D \qquad (1)$$

L means diffusion length and D means diffusion coefficient. Considering channel length was 800 nm and typical ion diffusion coefficient is bigger than 1.0×10^{-5} cm/s, t was calculated to at most 3.2×10^{-4} s. From these considerations, 10 μm is enough length for reaction or extraction in extended-nano space. The flow state gradually changed to new specific flow, which aqueous phase seemed encircle the organic phase. Because this state was unstable in bulk scale from surface

energy calculation, it remained subject to investigate interface property in extended-nano space. In the future work, unit of chemical processes in extended-nano space will be established by improving the condition of this study.

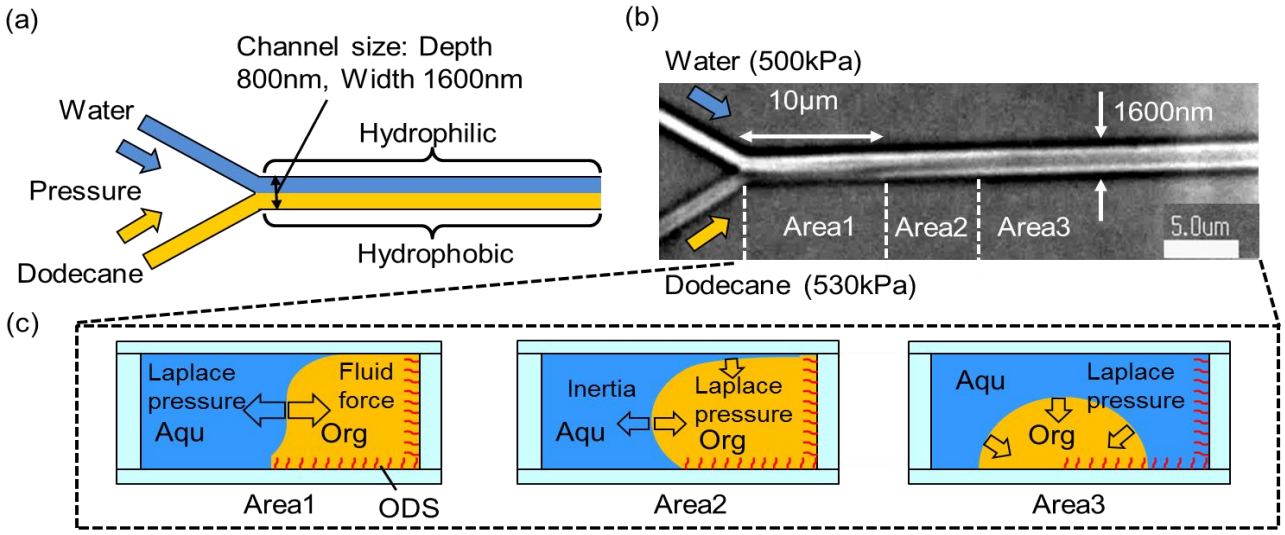

Figure 5: Formation of pressure driven parallel aqu/org two-phase flow in extended nanochannel. (a) Schematic of the experiment. (b) Result (bright field image). (c) Consideration of new specific flow.

CONCLUSION

We realized the parallel two-phase flow in extended-nano space by a novel partial modification method for the first time. Hydrophilic/hydrophobic partial modification with 10 nm order-resolution was achieved by inclined extended nanochannel with Focused Ion Beam. Our study will contribute to develop nanofluidic systems using multi-phase flows for chemical applications.

ACKNOWLEDGEMENTS

This work was partially supported by Specially Promoted Research.

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