ABSTRACT
We fabricated a hybrid axisymmetric flow-focusing device (h-AFFD) by combining photolithography and stereolithography for producing monodisperse microsized-emulsions (~12 μm). We realized three-dimensional and high-resolution structures in the h-AFFD, these structures can not be embedded using either stereolithography or photolithography alone. While the h-AFFD still maintains the same hydrodynamic performance as the monolithic AFFD, the h-AFFD can produce the smaller droplets than the monolithic one due to its narrow orifice (~50 μm) fabricated by photolithography. In addition, as the wetting problem does not occur in the h-AFFD, we succeeded in producing monodisperse emulsions containing single cells without surface modifications.

KEYWORDS: monodisperse emulsions, flow-focusing, cell encapsulation, hybrid stereolithography

INTRODUCTION
Monodisperse emulsions have great potential for various fields. There are many approaches to produce small uniform emulsions using two-dimensional microfluidic devices [1]. However, the wetting on the surface of the devices still remains as a critical problem, especially when we produce emulsions with particles such as cells or bacteria. To avoid the wetting problem, we developed the axisymmetric flow-focusing device (AFFD) by stereolithography [2]. The AFFD allows us to produce monodisperse emulsions with different combinations of fluids and control the size of these emulsions by varying flow-rate ratio. But, the AFFD was not able to produce smaller emulsions than 50 μm in diameter because stereolithography can only
produce the orifice over 250 μm in diameter; this diameter determines the minimum size of emulsions. A hybrid process of stereolithography and other methods is effective to solve such a resolution problem [3]. In this work, we combined photolithography with stereolithography for fabricating the hybrid AFFD (h-AFFD) (Fig. 1). Using photolithography, the h-AFFD have the high accuracy orifice with 50 μm in diameter and the properties of the AFFD are preserved in the h-AFFD.

EXPERIMENTAL
For fabricating the h-AFFD, we needed a thick and high-resolution narrow orifice. As a SU-8 sheet has the advantage of thick and high-resolution, we produced a thick film with a micro-sized hole using a SU-8 sheet (100 μm in thickness) including Parylene layer on a Si wafer (Fig. 2a-d). By using the Parylene layer, the SU-8 sheet can be peeled off easily from the Si substrate (Fig. 2e) [4]. Figure 3a shows that the SU-8 sheet stays flat with a hole at the center. We embedded this SU-8 sheet in the AFFD during stereolithography process (Fig. 2f-h). Figure 3a and b show that the SU-8 sheet with the hole was located on the h-AFFD coaxially and the hole was not clogged with photoreactive resin during the process of stereolithography. Then, the h-AFFD consisting of the narrower orifice has the similar geometry characteristics to the monolithic AFFD fabricated by stereolithography only.

Figure 2. Process flow of fabricating the h-AFFD. (a-e) Process flow of producing the SU-8 sheet using Parylene. We got the SU-8 sheet by peeling off this sheet from the Si substrate. (f-h) The SU-8 sheet fitted in the crater of the upper layer. This crater helped the alignment of SU-8 sheet to the upper layer.

Figure 3. (a) Cross sectional view (A-A’ in fig. 3b) for the upper layer. The hole is placed on the upper layer coaxially. (b) Photo of the h-AFFD.
RESULTS AND DISCUSSION

For presenting the hydrodynamic properties, we produced monodisperse droplets using the h-AFFD and compared them to droplets using the monolithic AFFD (Fig. 4a). This result indicates our method provides the same hydrodynamic performance as the monolithic AFFD. And, these droplets produced by the h-AFFD are monodispersed (Fig. 4b,c) since the coefficient variation of them is under 5%. In addition, we achieved these small droplets at a few hundreds per second by the h-AFFD. As the h-AFFD do not lose the advantageous properties of AFFDs for producing monodisperse droplets, we think that our combination process is useful to fabricate the h-AFFD. Finally, we demonstrated single cell encapsulations using the small emulsions generated by the h-AFFD without any surface modification since the h-AFFD avoids wetting problem. Thus, we think that the h-AFFD can produce droplets with many kinds of particles and oil droplets.

![Figure 4](image)

Figure 4. (a) The diameter of emulsions generated by the AFFD and the h-AFFD. This graph shows that the h-AFFD can produce smaller emulsions than the AFFD and the curves drawn by the h-AFFD are similar trend to that of the AFFD. (b) The photo of minimum monodisperse droplets and the diameter distribution of these droplets using the h-AFFD including the diameter of the narrow orifice in 50 um.

CONCLUSIONS

We believe that our combination method has the possibility to be applied when fabricating three-dimensional, high-resolution objects. And, the h-AFFD will be a convenient tool for the formation of monodisperse emulsions.

REFERENCES