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<th>A continuous flow micro filtration device for plasma/blood separation using submicron vertical pillar gap structures</th>
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<td><strong>Author(s)</strong></td>
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<tr>
<td><strong>Citation</strong></td>
<td>Kang, T. G., Yoon, Y.-J., Ji, H., Lim, P. Y., &amp; Chen, Y. (2014). A continuous flow micro filtration device for plasma/blood separation using submicron vertical pillar gap structures. Journal of micromechanics and microengineering, 24(8), 087001-.</td>
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<tr>
<td><strong>Date</strong></td>
<td>2014</td>
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<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10220/24160">http://hdl.handle.net/10220/24160</a></td>
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1. Introduction

Plasma or serum, the cell-free part of blood, is typically the sample of choice for most biochemical blood tests performed in clinics and hospitals. For example, detection of protein biomarkers like troponins or creatinine kinases in plasma is used for the diagnosis of cardiovascular diseases, such as myocardial infarction (heart attack [1]). Besides the detection of biomarkers, separation of the plasma from whole blood is routinely carried out for the analyses of electrolyte concentration, glucose, lactate, total cholesterol, among others. However, these sequential procedures on single-batch blood collections are time consuming and they limit detection throughput.

A number of techniques are available for the separation of plasma from whole blood; most common are physical methods. Among these physical methods, membrane separation and centrifugation are the two most well known for blood-plasma separation in the last couple of decades [2]. However, these processes are known to be labor intensive, expensive, as well as time consuming for getting analytical results.

Given the significant relevance of the plasma/blood separation and the current interest in miniaturized and integrated bioanalytical systems, several efforts on the development of microchips for plasma separation and their reviews have been reported [3–18] previously. An example is the partial separation of plasma from blood in a microchannel flow by applying a standing acoustic wave [5, 6], leading to the enrichment of red blood cells (RBCs) in the middle of the microchannel. Alternatively, RBCs were separated from plasma using bifurcation geometry [7–10] with either a blood-skimming effect [7] or a Zweifach-Fung effect [8–10]. Unique microfluidic architectures such as high-aspect-ratio inverted T-shaped microchannel structure [7], Y-shaped microchannel with different flow resistance on the split downstream microchannel...
Note

2. Design and working principle

The working principle of the proposed separator is the size-based exclusion of cells through cross-flow filtration [4]. Due to the biconcave disk shape of an RBC, whose dimension is around $6 \sim 8 \mu m$ in diameter and $1 \sim 2 \mu m$ in thickness, it can penetrate the pillar gap if its size is bigger than the RBC’s thickness. Moreover, the RBC can escape through the pillar gap even though the pillar gap is smaller than its thickness due to its flexibility and deformability. A higher haematocrit level of the whole blood sample from a finger prick (near 50% or higher) is another aspect, which provides higher chances for RBCs to escape. Thus, one of the most important issues is to reduce the pillar gap as much as possible. In this work, we decided to reduce the size of pillar gap smaller than $1 \mu m$. With a submicron-sized pillar gaps structure, which is located tangential to the main flow path of the blood sample (figure 2), only plasma is allowed to pass through the submicron vertical pillars.

The feasible depth of microchannel ($d$), which is formed by silicon deep RIE process, is $50 \mu m$ based on micromachining capabilities. The channel width for the blood flow ($W_d$) and the pillar size have been designed as $100 \mu m$ and $30 \mu m \times 30 \mu m$, respectively. In addition to the pillar structure and blood flow channel, several narrow channels, with dimensions of $10 \mu m$-width and $300 \mu m$-length, have been introduced at the downstream of the main blood flow channel in order to build up sufficient pressure in the blood flow channel, and thereby enhance the separation speed of the plasma.

3. Fabrication process

Figure 3 depicts the key fabrication process flow of the microfluidic device. The reduction of the pillar gap has been implemented by a combination of repeating SiO$_2$ layer deposition and dry-etching steps without any masking layer. The
approach facilitates the SiO$_2$ layer to accumulate on the side-wall of the pillars, thus resulting in a submicron pillar gap (figure 3(b1–5)).

The microfabrication process starts with a 1$\mu$m-thick SiO$_2$ masking layer deposition, followed by its patterning by photolithography process (MASK #1, figure 3(b1)). Due to the limitation of contact lithography (EVG aligner), the minimum pillar gap pattern of 2.5$\mu$m (figure 4(a)) has been achieved from the lithography. After the patterning of the SiO$_2$ layer, the silicon deep RIE etching process has been performed for forming a 50$\mu$m deep micropillar structure. Since the minimum pattern size of gap on the masking layer (SiO$_2$) has been 2.5$\mu$m, the formed 50$\mu$m-depth silicon pillar gap has been designed for 2.6$\mu$m ~ 2.9$\mu$m, which is much bigger than the required specification of less than 1$\mu$m. Thus, the pillar gap reduction process, as shown in figure 3(b1–5) has been introduced. The pillar gap reduction process consists of deposition of 1$\mu$m-thick SiO$_2$ layer followed by dry-etching of SiO$_2$ layer without any masking layer for the same thickness. The deposition and bare etching process retains SiO$_2$ layer on the side-wall of the etched silicon surface thus reducing the pillar gap width. In fact, by performing a single repetition of deposition and bare etching of 1$\mu$m-thick SiO$_2$ layer, we can only reduce around 0.6 ~ 0.7$\mu$m width (0.3 ~ 0.4$\mu$m from each side). Thus, after repeating these steps three times, the 2.6 ~ 2.9$\mu$m size of the pillar gap (figure 4(a)) is reduced to 0.6 ~ 0.9$\mu$m (figure 4(b)).

At the last step of the pillar gap reduction, we deposited a layer that was only 0.5$\mu$m-thick SiO$_2$ to make the microchannel surface hydrophobic (figure 3(e)). Once the submicron pillar gap structure was formed, laser drilling was performed for forming inlet/outlet microfluidic interconnections. Finally, the microfabrication processes of the submicron pillar gap structured micro blood/plasma separator was anodically bonded with a Pyrex glass substrate for capping the pillar structure (figure 3(d)). The overall size of the fabricated micro blood/plasma separator was 12 mm $\times$ 16 mm $\times$ 1.25 mm as shown in figure 5.
4. Experimental results and discussion

Figure 6 shows the conceptual illustration of the experimental setup for the plasma separation test. A microscope and CCD camera was used for capturing the images of plasma separation. In order to provide the microfluidic inlet and outlet interconnections to the microseparator devices, customized plastic packaging was designed and fabricated, in which o-rings were used for preventing fluidic leakage through the interfacial surface between the microdevice and plastic packaging, and fluidic channels (0.7 mm in diameter) were drilled for interconnecting the microseparator device with outside tubes (figure 6(b)). Figure 7 shows the microscopic images of the plasma separation through the submicron pillar gap structures at an input blood flow rate of 5 µl min⁻¹. As shown in figure 7, the filtered plasma is coming out from pillar gap structure at a random position. In fact, it is quite hard to control the initial position of the plasma coming out from the array of the pillar gap structure. Therefore, the plasma collection rate varies with time. The plasma collection rate presented in this paper is the time-averaged value for 30 min.

Plasma collection rates and filtration efficiencies (figure 8(a)) are calculated by measuring the volume of collected plasma within a certain time interval (30 min) and comparing the number of RBCs in collected plasma with those in whole blood, respectively. The definition of the plasma collection rate and filtration efficiency is as follows, respectively:

\[
\text{plasma collection rate [µl/min]} = \frac{\text{volume of collected plasma [µl]}}{\text{time interval for collecting plasma [min]}}
\]

\[
\text{filtration efficiency [%]} = \frac{N_w - N_c}{N_w},
\]

where \(N_w\) and \(N_c\) are the number of RBCs in the same volume of whole blood sample and collected plasma, respectively.

Due to the non-Newtonian fluidic property of the blood, the plasma collection rate shows a rapid increase in high-flow rate of blood input, while the filtration efficiency drops (figure 8(a)). The higher plasma collection rate is due to higher pressure
differences between the blood flowing channel and the separated plasma flowing channel with the higher input flow rate. Under a higher pressure difference, there is a higher chance for RBCs to penetrate the pillar gap. Due to an RBC’s flexibility and highly deformability, it can escape through the pillar gap, even though the gap is smaller than its minimum feature size. The measured maximum filtration efficiency is more than 99.9% with a plasma collection rate of 0.67 µl min⁻¹ at 12.5 µl min⁻¹ input blood flow rate. The hemolysis phenomenon is observed above 30 µl min⁻¹ of the input blood flow rate.

The correlation of the volumetric separation ratio, which is the ratio of the volume of collected plasma in µl to that of the input of the whole blood sample in the same unit, does not show a monotonic relationship (figure 8(b)). It may be due to trapped air-bubbles occurring randomly in the separated plasma flowing microchannel during the separation process, which causes the plasma flow to be inconsistent.

5. Conclusion

This work demonstrated a continuous flow plasma/blood separator using a silicon-based vertical submicron pillar gap structure for cross-flow, size-based exclusion filtration. The microplasma separation device was fabricated by using a single mask silicon deep RIE process with a simple-gap reduction process. Based on the experimental results, we can conclude that the proposed device shows the potential for application in plasma separation from the whole blood sample as a part of the integrated POC diagnostics systems.

References

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Tae Goo Kang received the B.S., M.S., and PhD degrees in mechanical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, in 1994, 1997, and 2005, respectively. After his PhD, he joined the Korea Institute of Machinery and Materials (KIMM), Daejeon, as a Postdoctoral Researcher. Since October 2006, he has been with the Institute of Microelectronics (IME), Singapore, as a Senior Research Engineer. His current research interests are design, fabrication, and performance test of microfluidic devices including droplet-based digital microfluidic devices, integrated microPCR (micropolymerase chain reaction) chips, and microfiltration devices.

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