Rapid Fabrication of Nanofibrous Membranes inside Microchannels using Femtosecond Laser Micromachining

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ABSTRACT

In the present work, we show a rapid single-step technique to fabricate membrane-based microfluidic channels by femtosecond laser micromachining. Using the proposed technique, both the nanoporous membrane and microfluidic channel can be fabricated in a single step under ambient conditions. The femtosecond laser pulses ablate the Si substrate and first fabricate the microchannel and subsequently using different machining parameters, the nanoporous membrane will be synthesized. The ablation of the substrate causes an accumulation of mass quantity of nanoparticles which forms a porous fibrous nanostructure in the microchannel. Since the membrane is synthesized and grown in the microchannel, strong bond between it and the silicon substrate is attained. This technique has a great potential in various membrane/filtration/separation applications.

Keywords: Ultrafast Laser, Nanofibrous structure, Deposition,

1 INTRODUCTION

The usage of membranes in microfluidics has been growing interestingly. Membranes are composed of randomly directed fibers ranging from microns to nanometers in diameter (nanofibers) which are used to control the passage of some kinds of species [1]. Silicon has become a promising material for microfluidic devices owing to its high chemical and thermal stability. Also, the results of the previous researches suggest that microfabricated silicon nanoporous membranes are inert and relatively nontoxic [2]. Several techniques have been developed to fabricate nano/micro-porous membranes such as lithography [3], ion track technique, and sol-gel [4]. However, most of the techniques suffer from manufacturing intricacy, either in the membrane fabrication or during assembly process after constructing the microfluidic system [5]. For instance, in the sel-gel technique, the material is too expensive and a ceramic support layer, fabricated by solid state sintering, is required [6]. Also, the ion track technique has limitations because of the inefficiency caused by the thick membrane and inconvenient deployment in other microfluidics systems. Therefore, a simple technique to fabricate a microchannel filled with nanoporous membrane in a single-step would be in a great interest. Herein, we propose a simple technique to fabricate porous nanostructure membrane inside microfluidic channels using the femtosecond laser machining. The proposed method fabricates both the nanoporous membrane and microfluidic channel in a single step under ambient condition. The ablation of the substrate causes an accumulation of mass quantity of nanoparticles which forms a porous nanofibrous structure inside the microchannel. Since the membrane is synthesized and grown in the microchannel, strong bond between the silicon substrate and the membrane is achieved.

2 EXPERIMENTAL DETAILS

Experiments have been carried out by a 1040nm-wavelength direct-diode-pumped Yb-doped fiber amplified ultrafast laser system. The maximum output power of the Laser is 15 W and pulse frequency ranging is from 200 kHz to 26 MHz. Due to solid state operation and high spatial mode quality of fiber lasers, Yb-doped fiber-oscillator/fiber-amplifier functions under low noise performance. In addition, parameters of the laser, such as repetition rate, pulse width and beam power are computer monitored, which allows a simple interaction with the performed experiments. The target was a polished blank silicon wafer with <100> crystal orientation. The specimens have been then characterized using scanning electronic microscopy (SEM) followed by Electron-induced x-ray fluorescence (EDS) analyses.

3 RESULT AND DISCUTION

First, primary experiments have been performed to optimize laser scanning parameters including scanning cycles and speed. It has been found that at low laser scanning speed and higher scanning cycles the depth of the microfluidic channel increases and its width decrease. In the case of high cycling scanning, more fibrous structure will be synthesized. By increasing the scanning speed wider channel is formed in which nanofibrous structure star to grow. On the other hand, at lower speed due to the longer dwell time on the specific spot narrower and deeper channel is formed. This narrow channel leads to lack of enough space for growing nanofibrous structure making the structure pack together. Figure 1 shows growth mechanism of fibrous structure for different number of scanning cycle. First of all microchannel has been fabricated at low scanning speed with few cycles. Afterward, high speed scanning has been used to grow nanofibers inside the channel. As the number of cycles increase more fibrous structure grows on the channel's wall. By using the optimum number of cycles for particular channel shape, nanofibrous structures grow and interwove to each other and form the uniform membrane structure.

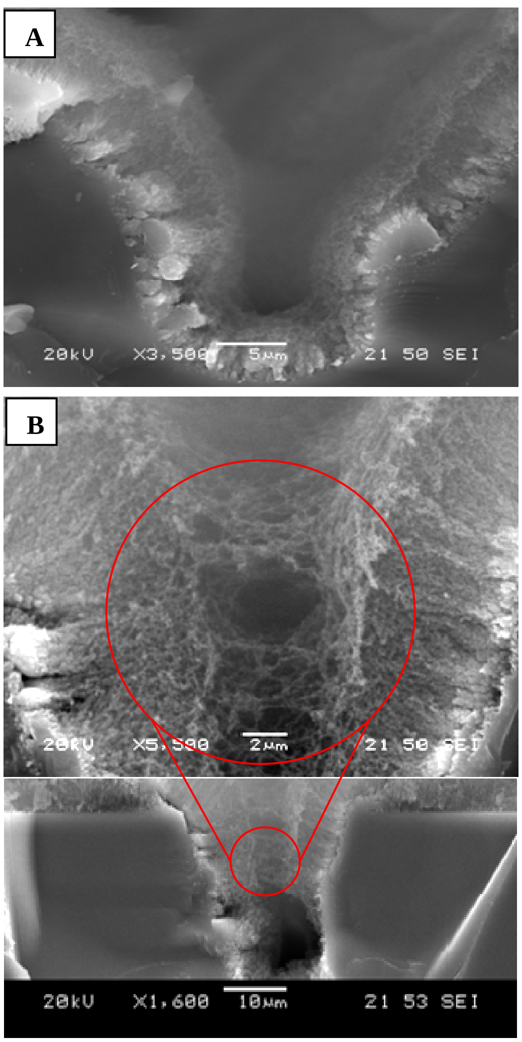

Figure 1: SEM micrographs of nanofibrous structure growth sequences inside the microfluidic channel formed by laser beam of 1024 nm wavelength at freq. of 26 MHz after A) 5 scanning cycles and B) 15 scanning cycles.

In our previous work, the synthesis of silicon fibrous nanostructure using ultrafast laser ablation was demonstrated. It was shown that the formation of fibrous structure was possible only if the pulse frequency is higher than 1 MHz. Thus to obtain maximum nanofibrous structure, we have performed the experiments at laser frequency of 26 MHz.

Basically, a massive nanoparticles aggregation is required to form fibrous nanostructures. Therefore, continuous arrival of the laser plume is required to keep the nucleus density at a certain level. The formation of fibrous structure is only possible if the sequential laser pulses are arrived in substrate before a critical time. This critical time was estimated to be 1 μs [7]. Thus, as the pulse repetition rate ascends more fibrous structure is generated. Our experiments have been carried out at laser frequency of 26 MHz in which time interval between pulses is about 38 ns. As a result, more fibrous structure results in decrease the pore size and increase the pore density.

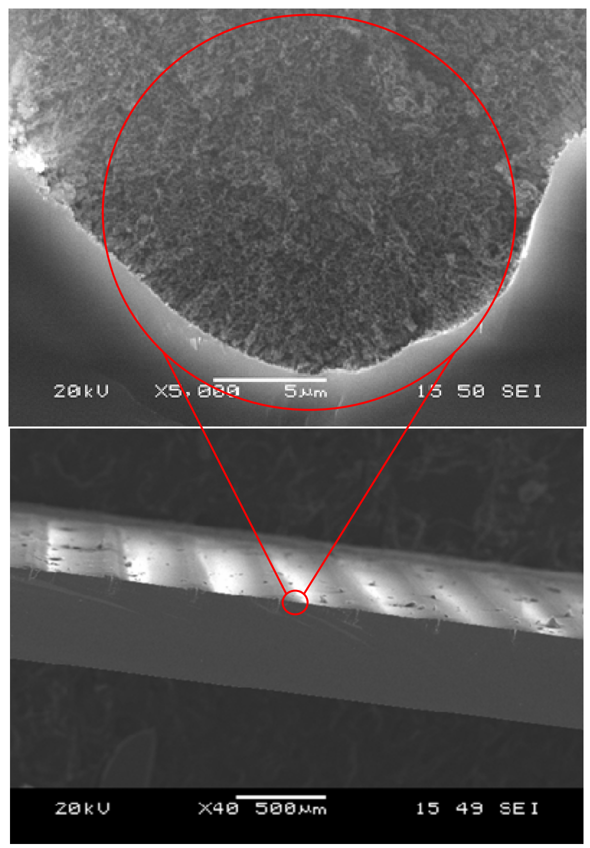

Figure 2: SEM micrographs of synthesized membrane inside the microfluidic channel formed by a laser beam of 1040 nm wavelength at the frequency of 26 MHz, a) 3D view of the microchannels on the Si substrate, and b) the cross-section view of the membrane inside the microchannel

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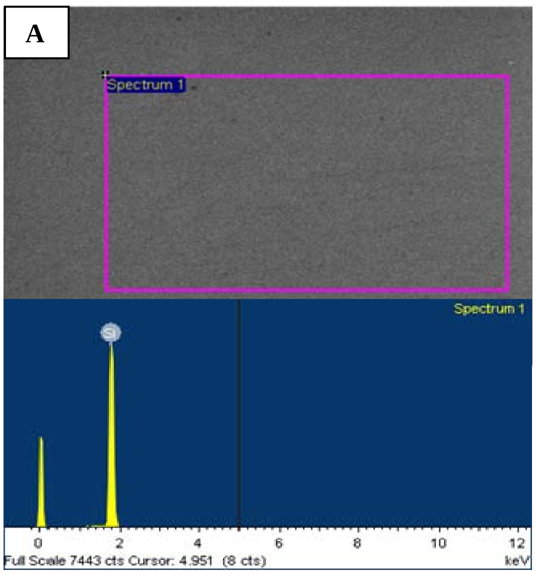
Figure 2 depicts the SEM micrographs of membrane fabricated at frequency of 26 MHZ. The results have revealed that membrane pore size decreases as pulse repetition rate increases. While the density of pore increases with increasing the repetition rate. The Membrane has average pore areas of 254 nm at 26 MHz.

In order to examine the composition of nanofibrous structure, Electron-induced x-ray fluorescence (EDX) analysis, an integrated feature of a scanning electron microscope, has been used. Since experiments have been performed at ambient condition, the presence of oxygen along with silicon (Si) is noticeable in Figure 3. The concentration of silicon oxide level in the nanofibrous structure can be modified using a vacuum chamber or oxygen atmosphere.



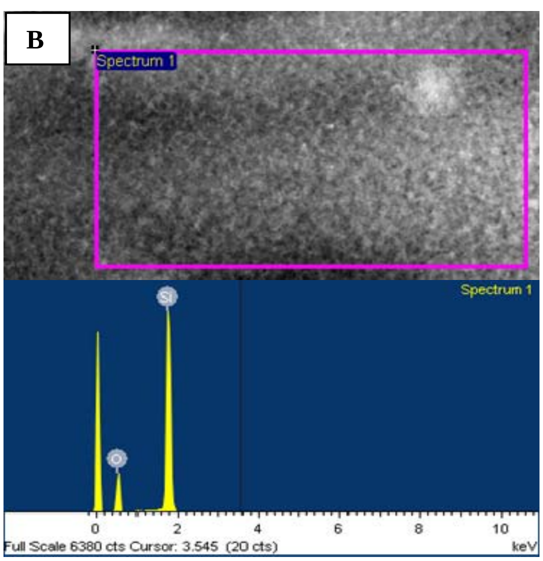


Figure 3: Electron-induced x-ray fluorescence (EDX) analyses of A) pure Si, and B) silica nanofibrous membrane.

4 CONCLUSION

In this paper, we demonstrate a robust method to fabricate a microchannel filled with silicon dioxide nanofibrous structure using a Femtosecond laser. This method makes it possible to generate both the microchannel and the fibrous nanostructure for a wide variety of materials in a single step at ambient condition. This would pave the way for extensive application of nano-filters in various membrane/filtration/separation applications. EDX analysis shows oxygen concentration in the membrane structure which is attributed to oxidation of ablated material at ambient atmosphere. The membrane composition can be changed by using a vacuum chamber or oxygen atmosphere.

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