ELECTROOSMOTIC FLOW IN MICROCHANNEL WITH BLACK SILICON NANOSTRUCTURES

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Electroosmotic flow (EOF) is an electrokinetic phenomenon. The fluid motion originates from the electrical body force acting on the excess counterions in the electrical double layer (EDL) when an external electric field is applied across a microchannel. It can be employed in numerous microfluidic applications, ranging from pumping to chemical and biomedical analyses. Nanoscale networks/structures are often integrated within microchannels for a broad range of applications, such as sieving matrices for electrophoretic separation of biomolecules, and its introduction has been known to reduce EOF [1, 2]. Hitherto, the mechanics for EOF reduction due to nanostructured surfaces is still not well understood. To better elucidate the mechanics, we develop a novel fabrication method to produce microchannel with large-area nanostructures for investigation. The micro-/nanostructures produced demonstrate good regularity over a relatively large area and can be mass-produced cost-effectively. Despite the availability of various micro-/nanofabrication techniques, the existing techniques do not satisfy the aforementioned criteria.

Microchannels with/without nanostructures on the bottom wall (see Figure 1) were fabricated by a series of steps which can be divided into four phases: fabrication of master structures on a silicon (Si) wafer, creation of negative mold insert via electroplating, injection molding with Topas 5013L-10 Cyclic Olefin Copolymer (COC), and thermal bonding and integration of practical inlet/outlet ports. The type of nanostructures employed in our investigation was black silicon nanostructures (prolate hemispheroid-like structures with diameter of 270.0 ± 73.2 nm, height of 175.2 ± 22.3 nm and spatial distance of 350.6 ± 89.2 nm). The fabrication scheme involves a two-step reactive ion etching (RIE) process for (1) construction of the microchannel and (2) production of the black silicon structures. This maskless method provides an easy and fast alternative for large-area nanopatterning within the microchannel as compared to other conventional techniques, such as electron beam lithography which is prohibitively costly and time consuming for large-area structuring.

The effect of black silicon nanostructures on EOF behavior was studied experimentally by current monitoring method (see Figure 2) and numerically by finite element simulation (COMSOL Multiphysics) (see Figure 3). The average EOF velocity of 1mM sodium bicarbonate ($NaHCO_3$) in microchannel with black silicon structures was calculated from the displacement time measured by current monitoring experiment, in comparison to the smooth microchannel (see Figure 4). It can be observed that the average EOF velocity is reduced by approximately 10 ± 5 % with the introduction of black silicon nanostructures. This is in good agreement with the simulation results as shown in Figure 4, which indicates a reduction in average EOF velocity by approximately 7%. EOF originates from the interaction between the EDL and the applied electric field. The numerical simulation reveals that the nanostructures distort the local electric field distribution at the wall, resulting in the decrease of average electric field, and hence reduce the overall flow velocity.

The outcomes of this investigation enhance the fundamental understanding of EOF behavior, with implications on the precise EOF control in devices utilizing nanostructured surfaces for chemical and biological analyses.

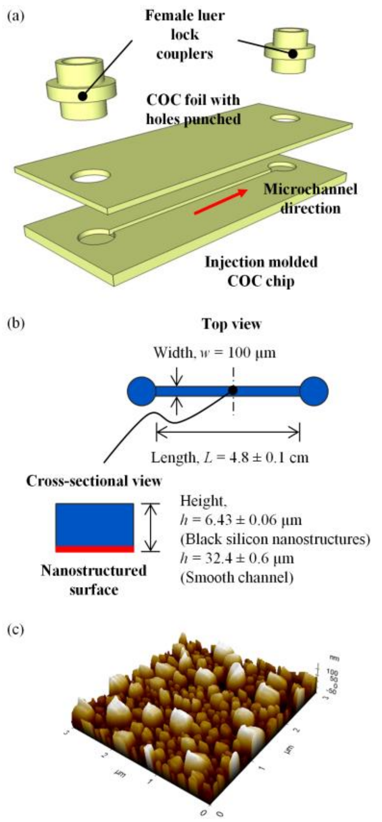

Fig. 1 (a) Exploded view of micro-/nanofluidic device. (b) Schematic diagram of microchannels with/without nanostructures. (c) Atomic force microscope (AFM) image of black silicon nanostructures on the bottom wall of microchannel.

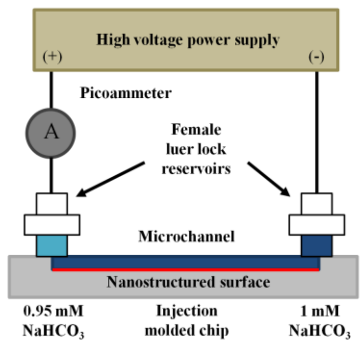

Fig. 2 Schematic diagram of experimental setup for current monitoring method.

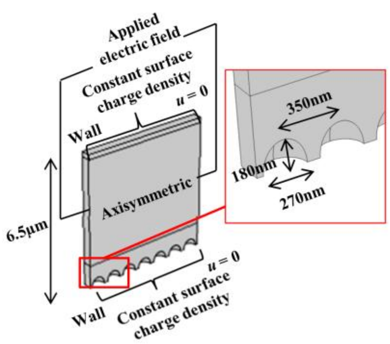

Fig. 3 3-D simulation domain.

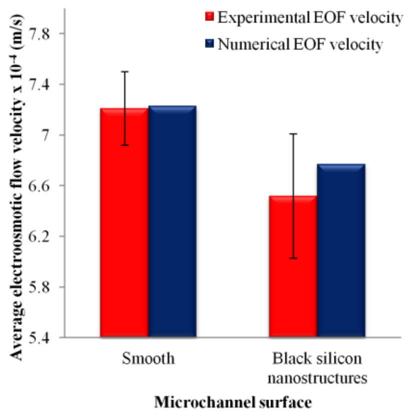

Fig. 4 Experimental and numerical electroosmotic flow (EOF) velocities for microchannel with black silicon nanostructures, in comparison to smooth microchannel.

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