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Research paper

Fabrication of microfluidic devices with 3D embedded flow-invasive microelements

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ABSTRACT

A process is demonstrated for fabricating microfluidic devices with pre-fabricated microelements embedded within a microchannel orthogonal to the flow. The microelements constitute a functional three-dimensional (3D) structure that can be used for a broad range of applications. The process is demonstrated using PDMS and glass and conventional microfabrication processes. The use of this process for applications of dielectrophoresis and magnetophoresis is discussed.

1. Introduction

Microfluidic devices based on dielectrophoresis and magnetophoresis are increasingly used for the detection, sorting, and analysis of microscale biomaterials including cells, bacteria, viruses, and beads/particles [1–3]. Many of these devices are fabricated using conventional top-down clean room based techniques that have been adapted from the microelectronics industry [4]. However, these methods are not well-suited for producing 3D microstructures within a microchannel to provide, for example, a desired electric field/force distribution that spans the entire height of the channel. One way to achieve this is to arrange elements within a microchannel in a stair-step fashion as shown in Fig. 1. This figure shows electric and magnetic field distributions within a microchannel due to 3D configurations of conductive and magnetic microelements, respectively. The electric and magnetic fields for a conventional planar arrangement of conductive and magnetic microelements on the base of a microchannel are shown in Fig. 1a and c. Note that the effective range of the fields is limited to a close proximity to the elements. However, the field distributions can be significantly extended if the elements are arranged in a stair-step fashion and embedded lengthwise along the width of the channel orthogonal to the flow as shown in Fig. 1b and d. Voltages can be applied to embedded electrodes to create the desired electric field distribution throughout the height of the microchannel as shown in Fig. 1b. This 3D stair-step structure will provide enhanced dielectrophoresis over conventional electrode configurations. Similarly, Fig. 1d, shows a 3D stair-step arrangement of rectangular soft-magnetic microelements within a microchannel. When an external bias field is applied, the elements become magnetized and produce a magnetic field throughout the height of the microchannel that provides enhanced magnetophoreis [5]. The ability to fabricate such 3D structures can enable the use of deep microchannels for dielectrophoresis and magnetophoresis, which in turn enables enhanced throughput and enhanced performance.

To date, researchers have integrated 3D electrodes in microfluidic devices for applications involving dielectrophoresis and magnetophoresis. Several researchers have realized 2D arrays of 3D vertical electrodes arranged inside a microchannel by electroplating gold or electroforming copper using a SU-8 mold as well as coating SU-8 pinfins with carbon [6,7]. 3D vertical metallic electrodes have also been created on the sidewalls of a microchannel by electroplating, directly on the wafer, as well as manually aligning metallic structures, including spheres and cubes, during assembly of the final microdevice [8–10]. Horizontal electrodes are usually created by curing a slurry of liquid PDMS and electrically conductive powder that is filled in perpendicular slots that open towards the fluidic channel. Silver powder and carbon nanotubes have been used as the conductive powder [11,12]. In

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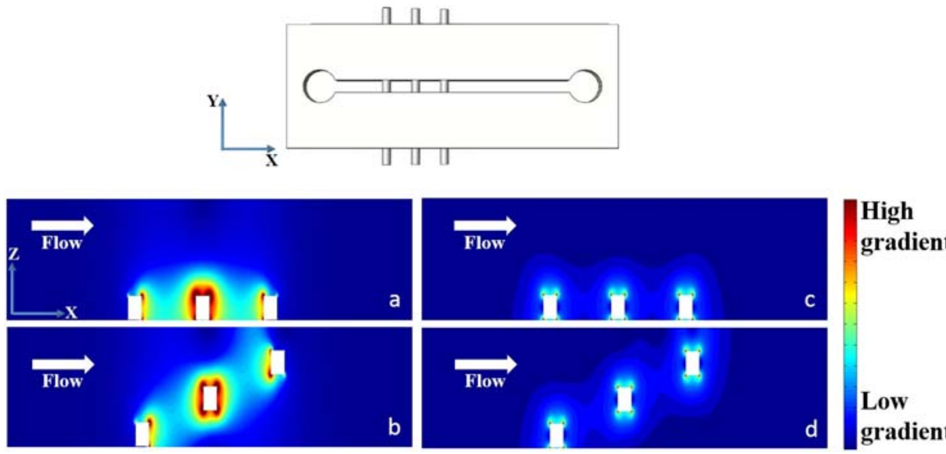

Fig. 1. Cross-section view of field gradients inside a microchannel due to different arrangements of microelements: a and b show the electric potential due to electrodes; c and d show the magnetic field due to soft-magnetic elements subjected to a bias field. A conventional arrangement of elements on the base of the channel shown in a and c, and stair-step arrangement of elements shown in b and d.

addition, it is also common to use planar electrodes on both the top and bottom substrates of a microfluidic device for maintaining a desired field distribution over the entire height of the microchannel [13,14]. However, while planar electrodes can be considered to form a 3D configuration, they do not create the same effect as the fully 3D electrode structure described above. With regards to magnetophoretic chips, there has been several successful attempts at realizing vertically as well as horizontally aligned magnetic elements within a microfluidic device. One such method involves electroplating a single nickel microstructure that is horizontally aligned along the direction of flow and located centrally inside the microchannel [15]. Magnetophoretic chips have been fabricated by embedding magnetic elements on both sidewalls of the microchannel in order to generate a magnetic field gradient across the width of the microchannel [16]. In another scenario, horizontally aligned magnetic elements that span the entire width of a microchannel are integrated on the bottom surface via electroplating or sputtering [17,18]. Recently, a magnetophoretic chip has been developed with vertically aligned multiple magnetic elements (composite of carbonyl-iron microparticle and PDMS) arranged in an in-line fashion and located centrally inside the microchannel [19]. Magnetophoretic chips have also been developed with sub-millimeter strips of magnetic elements placed externally on top of the microdevice such that the tip aligns with the side wall of the microchannel [20].

Below we detail a novel microfabrication process for embedding horizontal prefabricated microelements within a microfluidic device so that they span the width of a microchannel lengthwise, in a stair-step fashion as shown in Fig. 2. This process can be used to create novel functional 3D microstructures that are useful for a broad range of microfluidic applications, e.g. dielectrophoresis and magnetophoresis as described above. To our best knowledge, no microfabrication process has been reported for creating such structures.

2. Methods

The envisioned microfluidic device, with embedded 3D prefabricated microelements, is shown in Fig. 2. The structure is made up of two layers, PDMS and glass. The microchannel including the microelements and manifolds are contained in the PDMS layer while the glass substrate functions as the lid. The microdevice contains three metallic microelements that are horizontally embedded lengthwise in a stair-step fashion, orthogonal to the flow in the microchannel. The proposed approach to fabricating this device is depicted in Fig. 2. In the first step of the process shown in Fig. 2a, a PDMS substrate is created with slots of varying depths but with the same planar dimensions. The width of each slot is the same as the width of the microelement. Next, the pre-fabricated microelements are positioned inside each slot as shown in Fig. 2b, following which the PDMS substrate is sealed with the glass plate, Fig. 2c. Next, liquid PDMS is introduced into these slots from the outside to fill the slots via capillary action. Once the slots are filled, the microdevice is baked to cure the PDMS in the slots, which yield the final device structure of Fig. 2d.

Standard microfabrication processes such as multi-layer photolithography, casting, and bonding are used for building the microdevice. The casting PDMS mold is created by carrying out multi-layer photolithography on a silicon wafer which functions as the substrate. The microfabrication process layout for realizing the mold is depicted in schematic form in Fig. 3. SU-8, specifically SU-8 2075, is used as the photoresist. With this particular photoresist it is possible to build layers with thickness close to the diameter of the microelements, which in this case is 127 μm. Multi-layer photolithography is used to build this microdevice since the microelements are to be positioned at different heights. The process starts with spin coating (WS650HZB-23NPP/UD3/UD3B/OND from Laurell Technologies Corporation) the first SU-8 layer on the silicon wafer, as illustrated in Fig. 3a and b. This is followed by further processing of the first layer including a pre-exposure bake (Cimarec Digital Hotplate from Thermo Scientific), UV exposure (Dilase 650 from KLOE, Montpellier, France) and post-exposure bake. The front view of the process layout is shown on the left side of Fig. 3 while that on the right side is the top view. The recipe used for each step associated

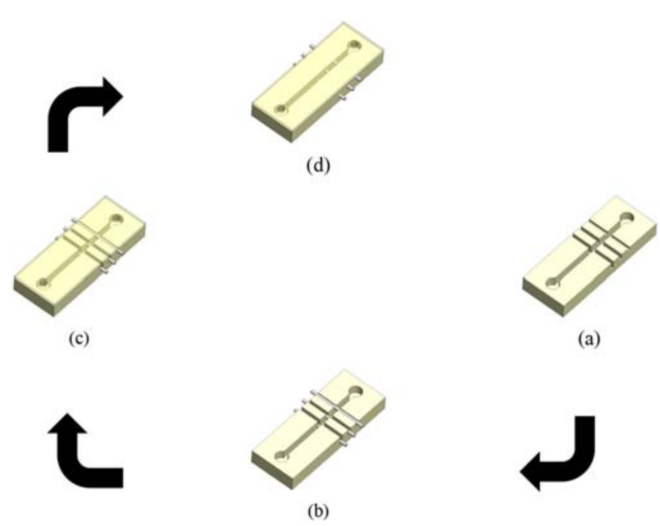

Fig. 2. Schematic of the proposed microdevice and microfabrication process.