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Short communication

Inexpensive three-dimensional dielectrophoretic microfluidic devices using milled copperclad substrates

Stuart J. Williams [a, *], Nathan Romero [a], Liam Parkes [a], Douglas J. Jackson [b], John F. Naber [b]

[a] Department of Mechanical Engineering, University of Louisville, Louisville, KY 40292, United States
[b] Department of Electrical and Computer Engineering, University of Louisville, Louisville, KY 40292, United States

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ABSTRACT

This manuscript demonstrates an inexpensive method of fabricating 3D dielectrophoretic microfluidic devices using a milling machine equipped with a sub-millimeter end mill. Features were milled into a copperclad substrate, otherwise typically used for printed circuit boards. Milled electrodes themselves serve as walls of the microfluidic channel therefore delivering a stronger electric field throughout the depth of the microchannel compared to traditional, coplanar electrode designs. Dielectrophoretic particle trapping and concentration were demonstrated with 8 μm polystyrene beads at voltages no greater than 10 V. The method of fabrication will be discussed as well as advantages and challenges associated with this technique.

Introduction

Dielectrophoresis (DEP) is the translation of a polarizable particle when subjected to a non-uniform field. DEP is a well-known particle manipulation technique that has been able to capture, sort, concentrate, and characterize a variety of particles and biological entities as small as a few nanometers [1–3]. In the past several decades there has been a thrust in the development of DEP microsystems enabled, in part, by the development of microfluidic techniques and microfabrication methods of depositing sub-millimeter electrode geometries. The recent, rapid expansion of DEP has demonstrated that this technique is a viable method for micro-total analytical systems, especially for point-of-care and bedside diagnostics [2]. There have been several advances in DEP fabrication with the goal of increasing sample throughput, though most of these techniques require expensive fabrication equipment and facilities to create their electrodes. This manuscript describes the fabrication and preliminary results of using an inexpensive, user-friendly microfluidic DEP platform without the need for microfabrication equipment. The motivation of behind our fabrication approach is presented, preliminary results of dielectrophoretic manipulation of 8 μm particles are demonstrated, and, finally, the advantages and challenges of our fabrication technique are given.

Background

DEP refers to the translation of a polarizable particle in the presence of a non-uniform field. This phenomena has been studied for decades and extensive literature exists on relevant theory and resultant dielectrophoretic forces [1,4,5]. In brief, the DEP force is proportional to the gradient of the electric field squared (∇E_{rms}^2) and the real part of the Clausius–Mossotti factor ($Re[f_{CM}]$). The Clausius–Mossotti factor is a function of the applied AC frequency and can be positive or negative depending on the dielectric properties of the medium and the particle. If $Re[f_{CM}]$ is negative, the particle experiences negative DEP and is repelled from non-uniform field gradients (negative DEP). If $Re[f_{CM}]$ is positive, the particle is attracted towards these regions (positive DEP). Modified f_{CM} expressions are available for multi-shelled and non-spherical particles [4,6].

Current state of DEP devices

The magnitude of the DEP force depends on the electric field strength and, therefore, is inversely proportional to the distance

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Abbreviations: DEP, dielectrophoresis; PCB, printed circuit board; PDMS, polydimethylsiloxane; CNC, computer numerical control.

* Corresponding author. 200 Sackett Hall, University of Louisville, Louisville, KY 40292, United States. Tel.: +1 502 852 6340.

E-mail address: stuart.williams@louisville.edu (S.J. Williams).

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between neighboring electrodes. The electric field intensity and the nature of its non-uniformity are guided by the DEP system's electrode design and fabrication. The most prevalent DEP systems use planar metal electrodes [7]. A variety of electrode shapes have been studied including interdigitated, castellated, quadropole, sawtooth, and spiral design. However, there are several significant disadvantages with traditional planar DEP systems. Inherent with the planar design, the DEP force is greatest close to the surface of the electrodes but exponentially decreases with height above the electrode plane and, therefore, throughput is limited. Wider channels could be used, but taller channels would reduce the overall device footprint. This geometrical limitation can be improved by placing electrodes on the top and bottom of the channel [8,9], but precise alignment between both electrode substrates and subsequent sealing of the microchannel is not trivial.

Recent 3D electrode fabrication techniques for DEP systems have offered improvements over traditional two-dimensional (2D) designs [10]. 3D metal electrodes can be fabricated using electroplating, effectively providing stronger DEP trapping forces [11]. However, these electroplated structures are limited in their structural stability and microfabrication of 3D microelectrodes is not trivial. Heavily doped silicon can be patterned using deep reactive ion etching (DRIE) to pattern electrodes for DEP [12,13]. Fabrication, though, is complex and requires expensive equipment for anodic bonding and DRIE. Additional 3D DEP techniques like insulator-based DEP [14] and contactless DEP [15–18] use insulating structures to indirectly generate non-uniform fields. These techniques, however, may require large voltages (up to 1000 V), leading to unwanted electrokinetic effects which may induce device dielectric breakdown or disturb biological samples [19]. 3D carbon electrodes can also be created through pyrolysis [20,21], though it requires high temperatures (900 °C–2000 °C) and the pyrolyzed material shrinks 30–90% anisotropically. More insight on 3D DEP techniques is available through a review article by Martinez–Duarte (2012).

Motivation

The commonality for typical DEP techniques is the use of expensive microfabrication equipment or access to a clean room facility. Although there are a variety of inexpensive, non-photolithographic methods of creating sub-millimeter microfluidic features [21,22], there does not exist an inexpensive method of creating controlled, sub-millimeter 3D metal electrodes. In addition, the previously-mentioned 3D DEP systems do not encompass all of the desired characteristics of a less expensive, high throughput, low voltage (<20 V), device that can be created using low cost equipment and facilities (i.e. without a clean room).

The work herein provides preliminary results demonstrating a 3D metal electrode DEP system encompassing all of these favorable characteristics using a copperclad substrate typical of PCB manufacturing using neither clean room facilities nor photolithography. Rather, fabrication uses a CNC milling machine equipped with a sub-millimeter end mill. A copperclad board provides the substrate for the system. Milled features will serve as the microfluidic network with the copper electrodes also serving as the sidewalls of the channels. The procedure of milling copperclad boards is well known by the PCB industry and hobbyists. In addition, sub-millimeter end mills are commercially available for under $50 (USD) including those with diameters of 25 μm, 50 μm, and 100 μm (Harvey Tool Company, LLC, Rowley, MA).

Materials and methods

3D metal electrodes were fabricated using a 9″ x 12″, 1 oz. copper clad board ($8 per board, Newark element14, Chicago, IL). The thickness of metal on a “1 oz. copper” board is approximately 36 μm. Our first designed and fabricated DEP system was a quadropole electrode configuration (Fig. 1a). Quadropole electrodes are a fundamental geometry that has been extensively used for DEP investigations. First, bulk features and the perimeter of the chip were milled with a larger diameter (1 mm) bit using the ProtoMat S100 (LPKF Laser and Electronics, 0.25 μm resolution, 1000 rpm spindle speed). Next, a 100 μm bit was used to mill the center portion of the device to define the quadropole center, shown in the thin ‘crosshair’ feature in Fig. 1a. Care was taken to minimize penetration beyond the copper cladding, though not too shallow to cause electrical shorting. To ensure the proper penetration depth, the 100 μm bit milled the perimeter of a 1 mm square at a location separate from the device area for a particular programmed depth of the mill. If there was a measurable electrical resistance between the copper clad substrate and milled square an electrical short was present and the depth needed to be increased. Subsequently, a null measurement corresponds to a depth completely through the copper layer. This process was repeated until the proper penetration depth of the mill was determined and, thus, fixed for subsequent milling.

The milled copper features serve as the microfluidic network, therefore the copper electrodes themselves serve as channel sidewalls. After the microchannels were milled, holes were drilled through the PCB for fluid access. Channels were sealed with either a glass coverslip or, for flow-through devices, an adhesive-backed PDMS piece as previously implemented elsewhere [23]. Adhesive (or uncured PDMS) was applied to the perimeter of the lid to prevent leakage at the milled features. The incorporation of microfluidic features is illustrated in Fig. 1b.

The devices were mounted on an inverted microscope (Nikon Ti–U) for fluorescent detection of 8 μm polystyrene particles suspended in deionized water (measured conductivity of 0.05 mS/m). The electrodes were connected to a benchtop waveform generator (Keithly, Model 3390).

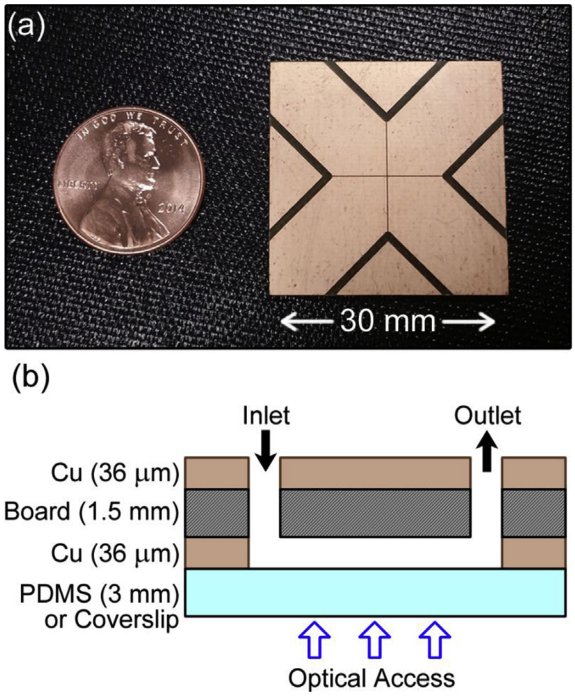

Fig. 1. (a) The milled PCB platform for quadropole DEP. (b) Illustration of fluidic featured incorporated with the platform.