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A study on three-dimensional electrode arrays fabricated by PolyMUMPs® for AC electro-osmotic pumping

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ABSTRACT

This paper presents four three-dimensional (3D) micro-electrode arrays for pumping liquid by utilizing AC electro-osmosis (ACEO) mechanism. Fabricated by using PolyMUMPs® process, these electrode arrays are made of polysilicon and subject to a surface oxide layer, which does not exist on conventional gold electrodes. An ACEO finite element model (FEM) accounting for the surface oxide on polysilicon electrodes is integrated in this work. The relationship of the velocity of driven liquid vs. the frequency of the electrical driving signal is obtained for the four electrode arrays through simulation and testing. Impacts of the electrode configuration and surface oxide are analyzed by comparing simulation and experimental results.

1. Introduction

Micropumps possess great potential for a wide variety of applications, including applications for biological, medical, chemical and microelectronic engineering [1,2]. Micropumps that exploit AC electrokinetic phenomena have low power consumption and no moving components [1]. Ramos et al. first described the mechanism of AC electroosmosis (ACEO) pumping with two parallel symmetric electrodes [3]. Intensive studies were carried out thereafter aiming to improve the pumping performance, including the recent studies on planar asymmetric and 3D stepped electrode arrays [4–6]. The 3D stepped micro-electrode array can induce a faster flow compared to its counterpart planar ones [5]. PolyMUMPs®, a process with three polysilicon layers, provides a simple and cost-effective alternative to the costly yet repeatable gold electroplating process [7,8], for fabrication of 3D stepped electrode arrays. However, electrodes fabricated from PolyMUMPs® are subjected to a surface layer of silicon dioxide [9]. The influence of this surface oxide on mechanical properties has been studied [10], but its impact on microfluidic pumping has yet been addressed. For ACEO pumping, such oxide layer on the electrodes could inhibit Faradaic current at low frequencies, shift the flow peak velocity frequency, and elevate the threshold voltage of initiation of the liquid. As such, the study on the impact of such surface oxide on the pumping performance is necessary.

In this report, we investigate four 3D stepped micro-electrode arrays fabricated using PolyMUMPs® process. The performance of these four arrays is studied, followed by the analysis of the impacts from both electrode configurations and the surface oxide layer of polysilicon. Finally, the experimental results are compared with the FEM models and some insights to the performance of PolyMUMPs® electrode arrays for ACEO pumping are given.

2. Designs

Cross-sectional views of the four electrode designs are shown in Fig. 1 with detailed dimensions. Three layers of polysilicon are Poly0, Poly1 and Poly2 with a thickness of 0.5 μm, 2 μm and 1.5 μm, respectively.

Each array consists of a series of periodic electrode pairs (see Fig. 1). The left electrodes in the periodic pairs are all electrically connected to an AC voltage, while the right ones in the periodic pairs are all connected to an AC voltage with a phase difference of 180° to the left ones'. The electrodes in the Array-1 and -2 have the same height but different gap distance. The electrodes in the Array-1 and -3 have the same gap distance but different height. The electrodes in the Array-4 have a longer Poly1 step, which is equal to the length of the Poly0 in the other arrays.

3. ACEO theory

ACEO flow is mediated through the motion of liquid along the electrolyte–electrode interface, where a layer of charges is induced

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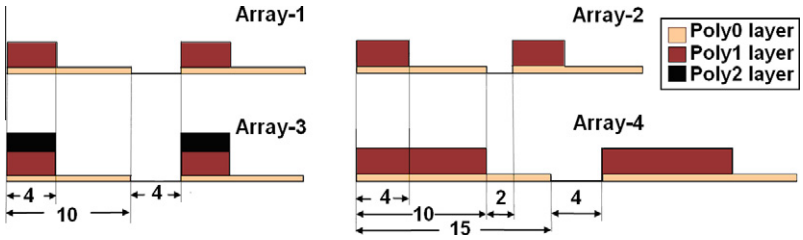

Fig. 1. The electrode dimension and gap distance of Array-1 to -4 (unit: μm).

by an externally applied AC electric field. The charge distribution of ACEO at the electrolyte–electrode interface is often described by a double-layer model – a stern (or immobile) layer and a diffuse layer [11,12]. Coulombic forces are exerted on the mobile ions in the diffuse layer when an external electric field is applied [11–13]. The tangential component of the electric field (parallel to the electrode surfaces) creates a driving force on the ions in the diffuse layer resulting in fluid motion. Suppose the bulk flow is electrical quasi-neutral, and thus the complex valued electric potential Φ in the bulk satisfies Laplace equation [14]

$$\nabla^2\Phi = 0 \tag{1}$$

The charge conservation in Eq. (2) holds for electrode–electrolyte interfaces,

$$\mathbf{n}\cdot\sigma_m\nabla\Phi = j\omega C_{DL}\Delta\Phi_{DL} \tag{2}$$

where $\Delta\Phi_{DL} = \Phi \pm V_R$ is the double layer potential drop which is the difference between the electric potential at outer side of the double layer and the potential applied to the electrodes. The reference potential V_R is the potential applied to electrodes by a voltage source; σ_m is the medium conductivity; the double layer capacitance is $C_{DL} \approx \varepsilon_m/\lambda_D$ [15,16] where ε_m is the permittivity of the medium and λ_D the Debye screening length; $\mathbf{n}$ is the unit normal vector, $j = \sqrt{-1}$ and ω is the angular frequency of the sinusoidal voltage. At the electrolyte and non-electrode interfaces, the normal component of the electric field is zero, which can be described by:

$$\mathbf{n}\cdot\nabla\Phi = 0 \tag{3}$$

The electric potential is determined by numerically solving the partial differential equation (1) with the boundary conditions illustrated by (2) and (3). The magnitude of the electro-osmotic velocity in a DC electric field is given by Helmholtz–Smoluchowski formula and the tangential velocity for the electrode surfaces is given by [17]:

$$u_t = \frac{\varepsilon_m\zeta}{\eta}\mathbf{t}\cdot\mathbf{E} \tag{4}$$

where ζ is zeta potential, $\mathbf{E} = -\nabla\Phi$ is the electric field, $\mathbf{t}$ is the unit tangential vector and η is the viscosity of the medium. The time-averaged slip velocity tangential to the electrode surface for a small double layer voltage (<25 mV) is given in (5) by approximating the zeta potential as the diffuse layer potential [15–17]

$$\langle u\rangle_t = -\frac{\varepsilon_m}{2\eta}\Lambda\mathrm{Re}\{(\Phi \pm V_R)\mathbf{t}\cdot\nabla\Phi^*\} \tag{5}$$

where Λ is the ratio of the voltage across the diffuse layer and the double layer. The symbol $*$ denotes the complex conjugate. The bulk fluid driven by shear stress moves in a manner of laminar flow and the viscous term in the incompressible Navier–Stokes equation dominates for small Reynolds's number for microscale flows [18]. This is expressed in Eqs. (6) and (7)

$$\nabla\cdot\langle\mathbf{u}\rangle = 0 \tag{6}$$

$$\eta\nabla^2\langle\mathbf{u}\rangle - \nabla\langle p\rangle = 0 \tag{7}$$

where $\langle\mathbf{u}\rangle$ is the time-averaged velocity and $\langle p\rangle$ is the pressure. The bulk fluid velocity can be numerically evaluated according to Eqs. (6) and (7) with the boundary conditions specified in Eq. (5). Finally, a "no slip" boundary condition is applied to the interfaces between the non-electrode surface and electrolyte.

4. Simulation

Using the ACEO theory outlined previously, simulation is performed using COMSOL Multiphysics™ (version 3.5a). The Array-1 is used as an example to illustrate how the governing equations and boundary conditions are applied to the graphical model (see Fig. 2). The electric potential and fluid velocity is constrained by the periodic boundary condition at the two sides of this unit to mimic an infinite long electrode array.

The conventional ACEO model only describes the performance of ideal electrodes that are perfectly polarizable and conductive [5,11]. However, polysilicon electrodes fabricated by PolyMUMPs® process, unlike gold electrodes, are subject to a surface oxide layer on each polysilicon layer due to the galvanic attack, i.e., they are not ideal electrodes [10]. The galvanic attack takes place in the HF release step where 49% HF solution is used to dissolve the sacrificial layers between polysilicon layers. After the removal of the sacrificial layers, the polysilicon structures are exposed to the HF solution and a galvanic cell is formed leading to a surface oxide layer on polysilicon [19]. The surface oxide layer on Poly2 is insignificant and thus it is ignored [10] in the model. For our case the thickness of sacrificial layer on top of Poly0 is almost 4 times thicker than that on Poly1, and Poly1 is stacked on Poly0. In the final release step, Poly1 is exposed to the galvanic attack earlier and for a longer time. Therefore, the surface oxide layer on Poly0 is also excluded and only the surface oxide on Poly1 is taken into account for a qualitative analysis. According to MEMSCAP, the surface oxide

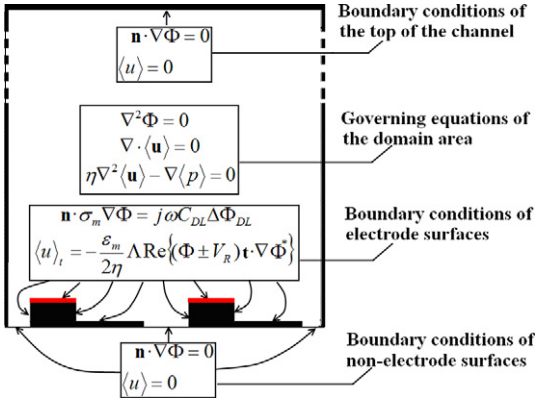

Fig. 2. A schematic diagram of Array-1 showing the governing equations and boundary conditions. A surface oxide layer of the polysilicon electrode is highlighted by red color (not to scale). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)