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可筛选乳胶微粒的介电泳陷阱和微马达：从分立单元到片上实验室

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摘要：提出了可分析、筛选乳胶微粒的介电泳陷阱与微马达，并以此为核心单元讨论了片上实验室的组建。设计了可集中样本预处理、分离筛选与微马达驱动等多个功能于一体的微分析芯片，并优化了各分立单元的作用效果。用新的螺旋-叉指和螺旋-城堡电极代替传统的螺旋状或者叉指、城堡状电极，可以不必借助电渗流的作用分开大小不同的乳胶微粒，分离效率达 90%以上。当激励信号为驻波时，样本分离电压比普遍使用的行波信号降低 50%。对于起介电泳筛选作用的城堡状电极进行了侧向和轴向的非均匀化处理，提高了对微粒尺寸的敏感性，可以将 70%的小微粒从混合液中分离。有限元分析和实验结果表明，与参考文献中提到的芯片结构相比，电极的新排布方式增加了轴向场强梯度，分离电压比传统方法降低了 80%。另外，微马达和探测电极的集成，为旋转性质的测电学量提供了便利。

关　键　词：生物芯片；介电泳；微机电系统，微流体
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Dielectrophoretic traps and micro-motor for driving and sorting latex spheres: from discrete devices to a lab-on-a-chip

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Abstract: This paper reports dielectrophoretic traps and a micro-motor for driving and sorting latex spheres on a chip with complex structures. A scheme containing function modules for pre-separating, sorting and driving micro-particles in a single chip is proposed. In order to optimize the system design, comparative researches on various electrode geometries of discrete devices from different separation principles are undertaken. Different from the obtained results before, the electrode shapes of all parts have been modified, which makes the dielectrophoresis effects better than those of traditional approaches. Moreover, a novel spiral interdigital or a spiral-castle electrode is used to replace the old spiral electrodes, and more than 90% target particles can be obtained. The separation voltage signal also can

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be decreased by 50% while using a standing wave instead of a conventional traveling wave. Otherwise, the lateral or axial inhomogeneously castellated electrode is constructed, by which 70% target particles can be sorted. Moreover, for the dielectrophoretic micro-motor composed of a coplanar and quadrupolar electrode structure, it is observed that annular array shaped electrodes in the center can make the device obtain high rotation speed under a low voltage condition.

Key words: biochip; dielectrophoresis; MEMS; microfluid

1 Introduction

Microfluidic systems for the contactless manipulation and test of micro-particles are traditionally based on either electrophoresis or optical methods[1-3]. However, Dielectrophoresis (DEP) with advantages of a rapidity, convenience, label free and low sample volumes, can often separate particles difficult to distinguish by traditional physical or biochemical methods[4-6]. In the last few decades, many kinds of separation electrodes were designed and applied into the DEP, twDEP and dielectrophoretic trapping. The techniques combining several approaches together have been used to improve separation efficiency or to construct micro total analysis systems[4]. Today, DEP devices can be generalized into four categories based on their geometries: parabolic electrodes, castellated electrodes, electrode arrays, and electrodeless devices[8-11]. Each of them has its niche in particle manipulations. However, some disadvantages limit their applications. For example, castellated electrodes excel at generating wells of positive dielectrophoresis (pDEP) and negative dielectrophoresis (nDEP) for gathering cells, but can hardly separate the particles with similar dielectric properties. Recently, group J. T. Y. Lin have reported that triangular-shaped electrodes can make up such deficiencies of the rectangular parallel track array[12]. It can be concluded that the inhomogeneous alignment of electrodes may be a way to solve this problem. Dielectrophoretic micro motors, autonomous transporting and sensing systems, have been studied by group Sreeja B. Asokan[13]. It may play an important role in nanoscale technologies such as analytical and electromechanical systems. In order to be convenient for their integration with silicon electronics, we decrease a driving electric field by two orders of magnitude using an additional structure of electrode.

2 Theory

The DEP is defined as the lateral motion imparted on uncharged particles as a result of polarization induced by non-uniform electric fields. The induced dipole moment is subjected to a DEP force. For an isotropic and homogeneous dielectric spherical particle, the DEP force can be approximated by

$$F_{\mathrm{DEP}}=2\pi\varepsilon_{\mathrm{m}}a^{3}\mathrm{Re}(f_{\mathrm{CM}})\nabla E_{\mathrm{rms}}^{2}, \qquad (1)$$

where ε_{m} is the permittivity of surrounding medium, a is the radius of the particle, E_{rms} is the root-mean-square magnitude of the electric field and it is a function of position. Re denotes the real part. f_{CM} is called the Clausius-Mossotti (CM) factor. For a homogeneous spherical particle, f_{CM} is given by

$$f_{\mathrm{CM}}=\frac{\tilde{\varepsilon}_{\mathrm{p}}-\tilde{\varepsilon}_{\mathrm{m}}}{\tilde{\varepsilon}_{\mathrm{p}}+2\tilde{\varepsilon}_{\mathrm{m}}}, \qquad (2)$$

where $\tilde{\varepsilon}_{\mathrm{p}}$ and $\tilde{\varepsilon}_{\mathrm{m}}$ are the complex permittivity of the particle and surrounding medium, respectively. They are given in the forms of $\tilde{\varepsilon}_{\mathrm{p}}=\varepsilon_{\mathrm{p}}+$

$\sigma_p/j\bar{\omega}$ and $\tilde{\varepsilon}_m=\varepsilon_m+\sigma_m/j\bar{\omega}$, where ε_p, ε_m are the permittivity of the particle and medium, and σ_p, σ_m are the conductivities of the particle and medium. The sign of $\mathrm{Re}(f_{CM})$ determines the particle experiencing positive or negative DEP force. When $\mathrm{Re}(f_{CM})>0$, the DEP force is aligned with the increasing direction of the electric field intensity and then the particle is attracted to the electric field intensity maximum. When $\mathrm{Re}(f_{CM})<0$, the DEP force is aligned with the decreasing direction of the electric field intensity and then the particle is attracted to the electric field intensity minimum.

In the traveling-wave dielectrophoresis, the applied electric field has varied magnitudes and phases, which induces both the real and imaginary part of the Clausius-Mossotti factor on the particles. On the radial section, the horizontal component of the travelling wave dielectrophoretic force is defined by:

$$F_{TWD}=2\pi\varepsilon_m a^3\,\mathrm{Im}(f_{CM})(\nabla E_{x0}^2\nabla\varphi_x+\nabla E_{y0}^2\nabla\varphi_y+\nabla E_{z0}^2\nabla\varphi_z)\ , \qquad (3)$$

Where E_{x0}, E_{y0}, E_{z0} are the magnitudes and φ_x, φ_y, φ_z are the phases of each field component. The TWD (Travelling Wave Dielectrophoresis) force FTWD term in (3) relates to the out-of-phase component ($\mathrm{Im}(f_{CM})$) of the induced dipole moment and the field phase non-uniformity factor $\nabla\varphi$.

3 Methods and experiments

A scheme containing function modules for pre-separating, sorting and driving micro-particles in a single chip is proposed (Fig. 1), then, a microchip using standard one layer metal process is fabricated. After the silicon wafer is cleaned to remove the organic coating and residue, AZ3312 photoresist is spin-coated on the top of a metal layer. Following standard photolithography procedure, the photoresist is exposed and developed, and the pattern of the electrodes exposed is left. Subsequently, a 0.02 μm of chromium layer is deposited as an adhesion layer followed by 0.2 μm of gold layer by using the sputtering deposition technique. The unexposed photoresist is stripped by acetone, and the patterned electrodes on the silicon substrate are left.

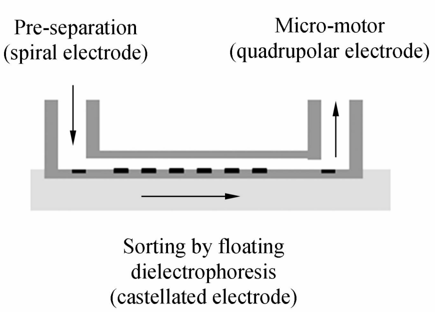
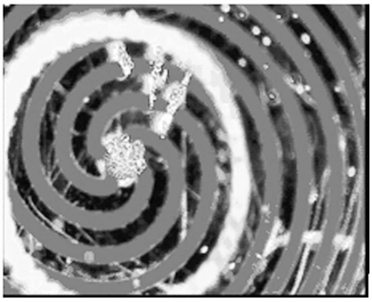


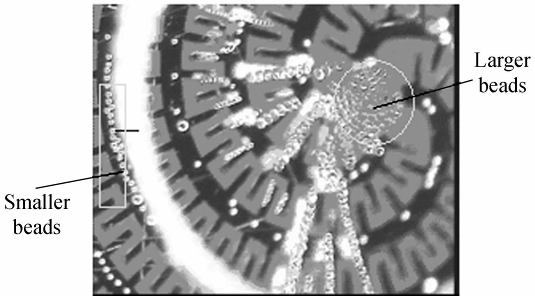
Fig. 1 View of whole chip

The voltage for dielectrophoresis is generated up to 2.5 V peak-to-peak in the frequency range 500 Hz to 15 MHz. In order to simulate the sizes of normal cells and cancer cells, the diameters of the beads used in our experiments are 10.9 μm and 21.3 μm. DEP responses of colloidal polystyrene particles suspended in deionized water are measured. Spiral-castle electrode, inhomogeneously castellated electrode and quadrupolar electrode structure modified by annular array shaped electrodes in the center are used for pre-separating, sorting and driving micro-particles, respectively. Fig. 2 and Fig. 3 show the comparisons between the two electrodes we designed and the traditional geometries.

The electric field distributions are simulated by the ANSYS finite element analysis. Fig. 4 shows the rotation of a micromotor, the region marked by white circle demonstrates the position change of the same particles. Fig. 5 shows the contour plots of the electric field intensity. It is concluded that the local minimum points and global minimum points of the electric field intensity produced by our design can separate particles with similar dielectric properties by its size.



(a) Can't sort



(b) Particle spiral electrode

Fig. 2 Separation of spiral- interdigital electrode

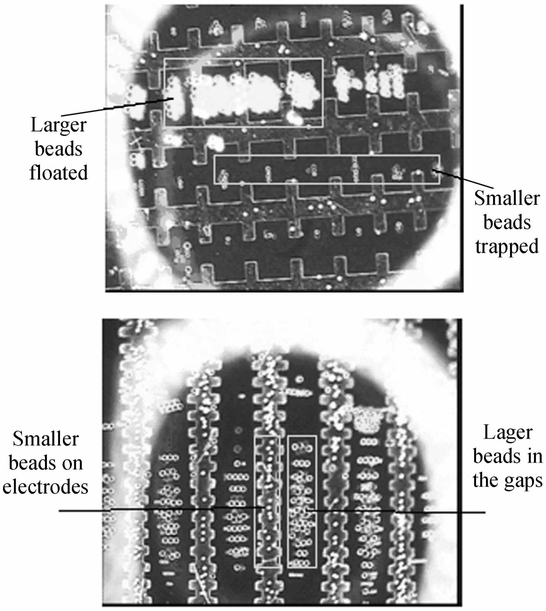


Fig. 3 View of nonuniform castellated electrodes

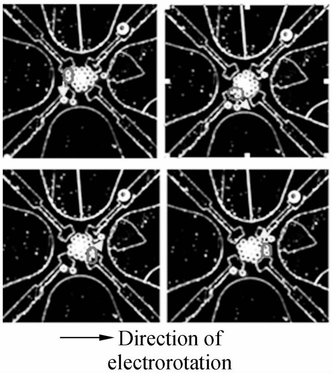


Fig. 4 Rotation of micro-motor

Fig. 5 Contour plots of electric field intensity gotten by ANSYS finite element analysis

4 Conclusions

This paper reports dielectrophoretic traps and a micro-motor for driving and sorting latex spheres on a chip with complex structures. Firstly, a novel spiral- interdigital or spiral-castle electrode is used to replace the old spiral electrodes by which more than 90% small particles can obtained, and results show that the standing waves can decrease excitation signal by 50% as compared with that of the conventional traveling wave. Secondly, the lateral or axial inhomogeneously castellated electrode is constructed, and it can sort 70% target particles by floating targets selectively while the castellated electrode can not. Compared with traditionally castellated electrodes, the excitation signals have been decreased by 50%. Moreover, for the dielectrophoretic micro-motor composed of a coplanar and quadrupolar electrode structures, it is observed that annular array shaped electrodes in the center can make the device obtain high rotation of speed urder a low a voltage condition.

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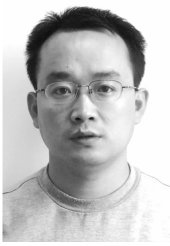

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