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Dielectrophoretic tweezers using sharp probe electrode

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Abstract

The pick and place ability, precise positioning and high spatial resolution of end-effector can be defined as the functional requirements of dielectrophoretic tweezers. The tweezers can manipulate objects in any direction with the strength of dielectrophoretic force. A localized and 3D movable electric field configuration is proposed here and analyzed for the functional requirements of dielectrophoretic tweezers. To achieve a steeply focused field, an electrochemical machining method was developed for a sharp probe electrode, and the developed dielectrophoretic tweezers was used to manipulate cells and beads.

Keywords: Dielectrophoresis; Tweezers; Electrochemical machining

1. Introduction

Manipulating single cells for operating various functions and probing characteristics of cell is important in biotechnology. Two major approaches have been developed to manipulate individual biological objects. First, a mechanical approach that uses instruments such as miniaturized tweezers and scanning probe microscopes [1,2]. Second, a trapping approach that uses the interaction between a field and an object, such as optical tweezers and dielectrophoretic (DEP) trapping [3,4].

DEP manipulation has advantages over other methods. First, the magnitude and direction of a force can be manipulated by controlling the voltage frequency. It enables to pick and place the micro/nano particle with a simple control of DEP voltage. Secondly, various field configurations with a high gradient can be designed and performed with the aid of microelectrodes. The high gradient of electric field guarantees the deterministic motion of the particle by overcoming the random motion such as Brownian motion of the particle in fluid environment. These advantages and application environment make dielectrophoresis an important application in biotechnology, particularly in fields such as microfluidic systems [5].

For advanced manipulation, DEP tweezers can be used to actively choose a target from a range of objects and, with its pickup and placement ability, can precisely position the target. Microelectrode methods have been used for this purpose; for example a dual disk sealed in a capillary and a single capacitively coupled electrode [6,7]. However, these methods require analysis for the electric field and definition of the functional requirements of DEP tweezers.

Previous works using DEP have used a geometry of 2D microelectrode. They have limitations on the movement and placement of a particle at a desired position. The methods using 2D microelectrodes have shown results mainly on trapping of multiple particles. In general, the size of 2D microelectrode is larger than the objects such as a single bead or cell, which causes the difficulty in manipulation for a single particle.

In this paper, for the functional requirement of the tweezer such as pickup, positioning and placement, a probe-type tweezer is fabricated using electrochemical etching. For a single particle manipulation, an ultra sharp electrode with the range of 200–300 nm in its radius of curvature (ROC) was chosen for the tweezer. The performance of picking and placement of a single bead or cell using dielectrophoretic manipulation is demonstrated.

2. System configuration

When a polarizable object is affected by an external electric field, the relationship between the induced dipole (p) and the

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electric field (E) can be expressed as follows:

$$p = \alpha E \quad (1)$$

where α is the relative polarizability of the object to the medium.

The resultant force (F) of the interaction between the electric field and the induced dipole can be expressed as follows:

$$F = -\nabla U = -\nabla(-p \cdot E) = \alpha \nabla E^2 \quad (2)$$

where U is the potential energy and ∇E^2 means the non-uniformity of the field that also determines the direction and magnitude of the force [3].

In DEP case, the DEP force (F_{DEP}) can be expressed as follows:

$$F_{\text{DEP}} = 2\pi r^3 \varepsilon_{\text{m}} Re\left(\frac{\varepsilon_{\text{o}}^* - \varepsilon_{\text{m}}^*}{\varepsilon_{\text{o}}^* + 2\varepsilon_{\text{m}}^*}\right) \nabla E^2, \quad \varepsilon^* = \varepsilon - j\frac{\sigma}{\omega} \quad (3)$$

where ε_{m} is the medium permittivity, and ε_{o}^* and ε_{m}^* are the complex permittivity of the object and the medium. The complex permittivity defined in Eq. (3) is composed of the permittivity (ε), the conductivity (σ) and the voltage frequency (ω). Because $Re((\varepsilon_{\text{o}}^* - \varepsilon_{\text{m}}^*)/(\varepsilon_{\text{o}}^* + 2\varepsilon_{\text{m}}^*))$ is a frequency dependent parameter, the DEP force to objects in the medium can be changed by applying a varied temporal electric field.

Fig. 1(a) shows the proposed electrode configuration, which consists of a probe and planar electrodes, which also defines the probe angle (θ), the probe diameter (d) and the electrode distance (h). Fig. 1(b) shows the electric field. The arrow refers to E and the contour indicates the gradient of the electric field square (∇E^2) that is proportional to the DEP force. The convergent DEP force, which is formed near the probe-end, can be defined as the end-effector of the DEP tweezers. In a positive DEP case, the object within the spatial resolution of the probe-end moves to the end-effector and this phenomenon can be defined as a pick process. In a negative DEP case, the object moves away from the end-effector, and this phenomenon can be defined as a place process. Because this configuration is inherently unstable in a positive DEP case, we achieved stable trapping of the end-effector by imposing radial stabilization and by using the boundary of the probe-end for vertical stabilization, which means that the vertical motion of a object is blocked due to contact at the electrode boundary [8].

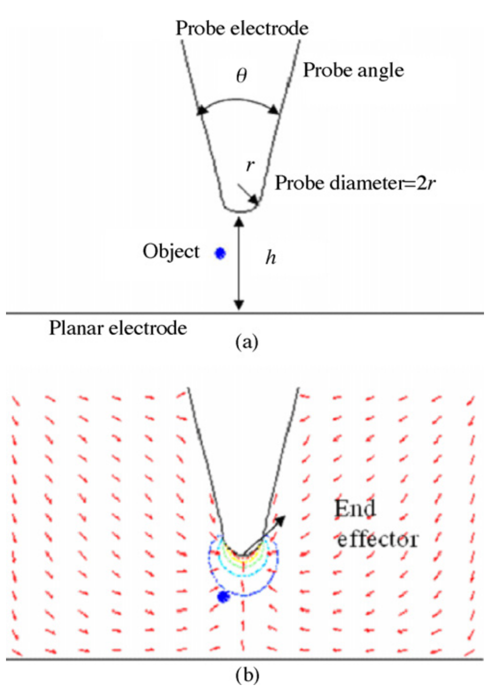

Fig. 1. Configuration of the probe–planar electrodes: (a) schematic diagram of proposed probe–planar electrode geometry and (b) direction of dielectrophoretic force applied on the particle.

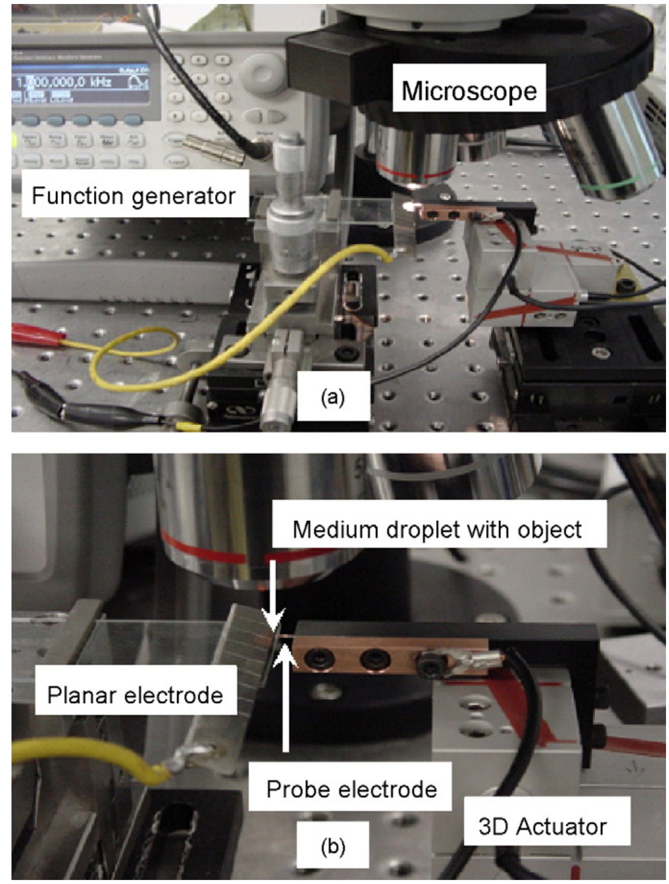

Fig. 2. The experimental setup: (a) experimental apparatus integrated with the inverted microscope and (b) the components of the experimental setup; knife edge as a planar electrode, tungsten electrode as a probe electrode, and 3D piezo actuator for linear 3D actuation.

Fig. 2 shows the experimental setup. The actuating system places the end-effector at a desired position, while the vision system senses the motion. The function generator controls the magnitude and frequency of the electric field between the electrodes, and the resultant concentric and 3D movable DEP force distribution is defined as the DEP tweezers.

3. Simulation and analysis

The spatial resolution and force magnitude of the DEP tweezers are critical factors for deterministic, individual manipulation. We therefore defined these critical factors as objective functions and analyzed their performance in relation to the