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Modeling of cellular pearl chain formation using a double photoconductive layer biochip

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ABSTRACT

A typical double photoconductive layer biochip focusing biological cells and forming specific pearl chains has been studied theoretically in this paper. It was composed of two photoconductive layers coated on the bottom and top of ITO-based glass. A light pattern was used to create face-to-face virtual electrodes and the resulting oscillatory spatial electric field was employed to induce the motion of polarizable neutral particles. In order to estimate the behaviors of the suspended particles, a numerical model including dielectrophoretic forces, dipole–dipole forces and other forces, was implemented by means of the Monte Carlo method. The results indicated that steady-state chains could be formed in a uniform electric field owing to the dipole moment effect. In a non-uniform electric field created by the use of a light pattern, the positive DEP force created a more focused pattern of chains. The work concerning the numerical simulation indicated that this chip could form fixed-length particle chains in perpendicular alignment to satisfy the structured assembly of tissues in the histological engineering application.

1. Introduction

DEP (dielectrophoresis) technology provides facile force for transporting particles to a desired location; this property of DEP has helped it gain significant interest for biomedical and environmental applications associated with micron-sized biological particles, such as enrichment, separation, transport, sorting and focusing. Last three years have seen considerable research work, demonstrating the ability of optically induced dielectrophoresis (ODEP) force to manipulate and assemble particles based on the optoelectrofluidic chip platform, which is a good advantage over traditional DEP using metal microelectrodes. In the traditional DEP, creating a spatial electric field using the metal microelectrodes is complicated and inflexible. Moreover, the fabrication process of metal microelectrode structure needs etching technology, and the projected light pattern used to create virtual electrodes enable a reduction in the process steps relying on both thin amorphous silicon films. For the first time, Chiou et al. [1] introduced that the living and dead B cells were separated in a massively parallel fashion across a large area with an incoherent light source. Since then, much work on using ODEP for manipulating cells has been reported. For example, Park et al. [2] presented a novel optoelectrofluidic chip of the inverted photoconductive film and reported its application to enhance the transport efficiency of oocytes due to the reduction of the friction force. Furthermore, Lee et al. [3] illustrated that single or triple fluorescence-carrying plasmid was effectively transfected into different types of mammals to achieve gene transfection with the help of ODEP electroporation.

Many experiments concurred that subjecting particulates suspended in liquid to a uniform electric field resulted in an oriented chain structure [4–7], and the formation of a pearl chain is attributed to the dipole moment of particles polarized in the external electric field, wherein because of the induced dipole moment, the arrangement aligns parallel to the applied field direction. Cellular microarray has been investigated for the structured assembly of tissues in order to develop cell-based artificial tissues. With the property of rebuilding cellblocks, cellular alignment plays an important role in tissue engineering, cell-based biosensors, medical diagnostics, and drug delivery [8,9]. Towards this end, it is worthwhile to study the forming chain means to assemble the compact stripe-like cell culture based on the optoelectrofluidic chip. This paper presents a numeric model related to the double photoconductive layers, which could induce the formation of pearl chains for cells on the perpendicular electric field. The Monte Carlo method is

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used to obtain the motion of polarizable neutral particles experiencing the electrostatic forces. Simulation results indicate that the particles can attract each other to form chains in the effect of an electric field.

2. Structure and fabrication of the double photoconductive layers biochip

A double photoconductive layer biochip similar to optoelectronic tweezers (OET) is presented in Fig. 1(a). An aqueous layer is placed between an ITO glass at top, and a photosensitive layer and an ITO glass at bottom. The ITO glass are coated with a photoconductive material that consists of n^+ a-Si:H, intrinsic a-Si:H, and SiCx (or SiNx) [10], as shown in Fig. 1(b). Dynamic light patterns from an incoherent light source (e.g., LED or halogen lamp) are projected onto the photoconductive surface through a digital micromirror display or optical lens. In regions without illumination, the intrinsic a-Si:H photoconductive layer works as an insulator that dominates the voltage drop and causing leakage of a small part of the electric field into the aqueous layer. Conversely, the conductivity of intrinsic a-Si:H increases exponentially as the light intensity increases, causing that the aqueous area to exert a strong electric field upon the neutral polarizable particles.

In Fig. 1(b), the top and bottom photoconductive layers have been fabricated by the plasma-enhanced chemical vapor deposition method [3,10]. Photoconductive layers are comprised of an ~50 nm n^+ a-Si:H layer, ~1 μm intrinsic a-Si:H photoconductive layer, and ~25 nm silicon carbide SiCx passivation layer. The conductivity of intrinsic a-Si:H with or without light illumination is 0.7×10^{-3} or 5×10^{-7} S/m, respectively. The structure of double photoconductive presented by Park's group decreases the frictional forces of the surface–particles interaction at the first time, and this enhances the transport efficiency of the particles [11]. In addition, they also demonstrated that the two particles suffered from electrostatic attraction or repulsion in a traditional OET [12]; however, only few particles subjected to the different types of DEP force (i.e., positive or negative DEP) have been studied. Therefore, a few particles' interaction with an external electric field in the double photoconductive layers biochip based on the Monte Carlo method has been investigated.

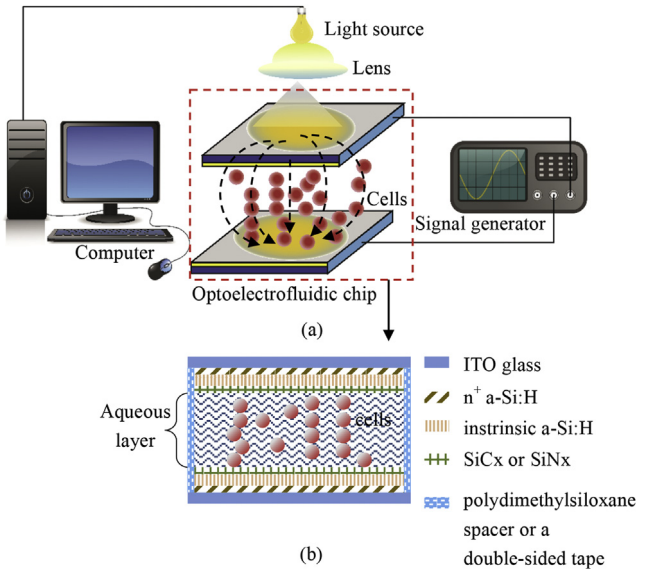

Fig. 1. Schematic structure of the double photoconductive layer biochip: (a) Illustration of the induced pearl chains by an induced light pattern projected onto double photoconductive layers. (b) Cross-section view of the double photoconductive layer biochip structure.

3. Mathematical model

The Monte Carlo method is a computational algorithm for simulating particle motion comprehensively, and it relies on repeated random sampling for accurately predicting kinetic results. To date, this method is utilized to simulate motion of micro or nanoparticles such as magnetic fluid particles [13], colloidal nanoparticles [14], and silver nanoparticles [15]. Detailed forces related to the applied electric field have been described below.

3.1. Electrostatic forces

Marszalek [16] estimated the threshold potential of a pearl chain formation with particles of 5 μm radius. Two distinct types of DEP phenomena may be identified: imposed field and mutual particle interaction. Imposed field implies that a single particle or an ensemble of non-interacting particles is influenced by an externally applied electric field. To simplify the high-order multipole [11,17], the dielectrophoretic force of an isolated particle can be expressed by,

$$\begin{aligned}\vec{F}_{DEP} &= \frac{1}{2}\mathrm{Re}\left[(p(\vec{r})\cdot\nabla)E(\vec{r})^*\right] \\ &= 2\pi a^3\varepsilon_m\mathrm{Re}\left[CM^*\right]\nabla\left|E(\vec{r})^*\right|^2\end{aligned} \tag{1}$$

where $p(\vec{r})$ is the dipole moment, $E(\vec{r})$ is the applied electric field, a is the particle radius, and CM^* is the well-known Clausius–Mossotti (CM) factor $CM^* = (\varepsilon_p^* - \varepsilon_m^*)/(\varepsilon_p^* + 2\varepsilon_m^*)$. Subscripts p and m denote properties of the particle and the aqueous solution, respectively. The complex permittivity is $\varepsilon^* = \varepsilon - i\sigma/(2\pi f)$, where ε is the permittivity, σ is the conductivity, and f represents the frequency of the external electric signal. The complex polarizability CM factor is expressed in terms of permittivity of the particles and the external medium in a range of frequencies. The effective averaged potential energy of the isolated particle is given by Refs. [17], and can be expressed mathematically as

$$U_{eff}(\vec{r}) = -2\pi a^3\varepsilon_m\mathrm{Re}\left[CM^*\right]\left|E(\vec{r})^*\right|^2 \tag{2}$$

The motion of a particle due to positive or negative DEP force depends on the applied frequency. When a uniform electric field is employed in an aqueous solution, the local presence of particles distorts the electric field. If individual particles are close to each other, the non-uniform electric field around each particle becomes asymmetric with respect to its center, and a mutual DEP force is induced which acts on each particles. Assuming that the high-order multipole terms are neglected, the effective potential energy can be given in Eq. (3),

$$\begin{aligned}U_{ij}^{dep} &\approx -\frac{1}{2}\mathrm{Re}\left(p_i(\vec{r}_i)\cdot E_j(\vec{r}_i)^*\right) \\ &= -\frac{1}{2}\mathrm{Re}\left(p_j(\vec{r}_j)\cdot E_i(\vec{r}_j)^*\right)\end{aligned} \tag{3}$$

where $E_j(\vec{r}_i)$ ($E_i(\vec{r}_j)$) is the electric field generated by the dipole in the particle j (i) at the position $\vec{r}_i$ ($\vec{r}_j$), $p_i(\vec{r}_i)$ ($p_j(\vec{r}_j)$) is the dipole moment induced on the i- (j-) particle by the external field $E(\vec{r}_i)$ ($E(\vec{r}_j)$). Furthermore, the average effective potential energy can be expressed as follows [17,18],