Reduction of nonspecific surface-particle interactions in optoelectronic tweezers

Hyundoo Hwang, Youngjae Oh, Jae-Jun Kim, Wonjae Choi, and Je-Kyun Park
Department of Bio and Brain Engineering, Korea Advanced Institute of Science and Technology (KAIST), 335 Gwahangno, Yuseong-gu, Daejeon 305-701, Republic of Korea

Se-Hwan Kim and Jin Jang
Department of Information Display, Kyung Hee University, 1 Hoegi-dong, Dongdaemun-gu, Seoul 130-701, Republic of Korea

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We demonstrate three-dimensional optoelectronic tweezers (3D OET) for the adsorption-free manipulation of microparticles. In typical OET, nonspecific interactions between the manipulated particles and the device surfaces, such as hydrophobic, Van der Waals, and electrostatic interactions, interfere with the effective microparticle manipulation. Here, by using the 3D OET device, which is composed of two photoconductive layers, we succeeded in three-dimensional focusing and manipulating polystyrene microbeads in a channel-less microenvironment without the particle adsorption. The 3D OET with the light-induced negative dielectrophoresis also shows a higher particle trapping efficiency and less particle adsorption rate than typical OET. © 2008 American Institute of Physics. [DOI: 10.1063/1.2834901]

Programmable manipulation of microparticles, including biological cells, has attracted much attention in many biological, chemical, and medical applications. Several techniques, including optical tweezers, electromagnetic, and dielectrophoresis (DEP) devices, have been applied for automatic and parallel manipulation of microparticles. Recently, a principle termed optoelectronic tweezers (OET) has been proposed. In the OET, the suspended microparticles can be freely controlled by projecting a dynamic image on a photoconductive material using a display device such as digital micromirror device and liquid crystal display (LCD). When a light pattern is projected on the photoconductive layer of OET device, the illuminated area becomes a virtual electrode, resulting in a nonuniform electric-field gradient that induces the dielectrophoretic movements of target particles. The OET has become one of the fastest growing technologies not only because it requires much lower optical power and offers higher massiveness than typical optical tweezers but also because we do not have to address and control several patterned electrodes.

In typical OET, both lateral and vertical DEP forces acting on the particles are induced from the isotropic electric field, which is formed by the partial illumination of photoconductive film. The unidirectional vertical forces always make the particles move to one side surface of the device. For example, when the manipulated particles follow a negative DEP, they are positioned close to the ground electrode. As a result, they frequently become attached to the electrode surface by nonspecific surface-particle interactions, including hydrophobic, Van der Waals, and electrostatic forces, as shown in Fig. 1. The nonspecific interactions interfere with the effective and noncontact particle manipulations within the scheme of OET. In addition, some attached particles attract other nearby particles around them by electrostatic particle-particle attractions, thus, limiting their smooth movements and their stable long-term processes.

With biological samples that can easily be contaminated or damaged by an external stimulus, the interactions with device surfaces may exert fatal influences on them. Nevertheless, the surface-particle interactions are unavoidable for a conventional OET device in which the vertical DEP forces, which act on only one direction by negative or positive DEP forces, are uncontrollable.

In order to address these problems of typical OET device, the three-dimensional trapping of particles are required to focus the manipulated particles vertically to segregate from the device surfaces. Therefore, we suggest an OET platform termed three-dimensional optoelectronic tweezers (3D OET), which are composed of double photoconductive layers. In the 3D OET device, the liquid sample which contains microparticles is sandwiched between two photoconductive layers [Fig. 2(b)] in a different manner than the OET device composed of photoconductive and ground layers [Fig. 2(a)].

Both of the photoconductive layers in the OET and the 3D OET devices were comprised of four layers: a 180 nm thick indium tin oxide (ITO) layer, a 50 nm thick n+ doped hydrogenated amorphous silicon (n+ a-Si:H) layer, a 800 nm thick intrinsic hydrogenated amorphous silicon (intrinsic a-Si:H) layer, and a 20 nm thick silicon nitride (SiNₓ) layer. Because the intrinsic a-Si:H has shorter carrier diffusion length and higher optical absorption coefficient than crystalline silicon, it is a good photoconductive material to make virtual electrode patterns of higher resolution. In the 3D OET device, we turned one photoconductive layer upside down and placed it on the top of the other photoconductive layer at the regular gap space of 120 μm using double-stick tape as a spacer. While utilizing the OET device, the ITO ground layer was replaced in the upper photoconductive layer of the 3D OET device. The simplest OET platform previously reported was utilized for this study. A 1.3 in. monochromatic LCD module was used for the image projection on the photoconductive layer, generating the virtual electrodes. An interactive control program, which we developed, was utilized for the image pattern manipulation. Plain
polystyrene beads (PolySciences, PA, USA) diluted with de-ionized water were used for the particle manipulation. A sample droplet was sandwiched between two photoconductive layers (or a photoconductive and a ground layer). The bias voltage of 20 V\text{peak-to-peak} at 100 kHz produced from a function generator (AGF3022; Tektronix, USA) was applied across the conductive ITO layers of both devices. We recorded the bead movements and analyzed the video files with a MATLAB analysis program.

The electric field distribution in the liquid chamber of 3D OET was simulated and described in comparison to typical OET [Figs. 2(a) and 2(b)]. The electric field was calculated using a commercial computational fluid dynamics (CFD) solver (CFD-ACE; ESI US R&D Inc., Huntsville, AL, USA). According to the light-induced DEP regime of OET, almost all of the voltage drops across the sample liquid when a partial area of the photoconductive layer is illuminated because the electrical conductivity of photoconductive material significantly increases due to the generation of electron-hole pairs. As a result, we could assume that almost the same voltage was applied to the illuminated areas in the OET and 3D OET devices. We assumed that the ac signal with 20 V\text{peak-to-peak} and 100 kHz was applied to the illuminated area of the bottom photoconductive layer of both devices. In the OET device, all areas of the top ground layer were assumed to be a ground. In contrast, for the 3D OET device, only the illuminated area of the top photoconductive layer, which is the same as the bottom photoconductive layer, was assumed to be a ground.

The DEP forces ($F_{\text{DEP}}$) act on the particles is defined as:

$$F_{\text{DEP}} = 2\pi r^3 \varepsilon_m \text{Re}(\varepsilon_{CM}) \nabla E^2,$$

where $r$ is particle radius, $E$ is the electric field, and $\varepsilon_m = \varepsilon_p \varepsilon_r$ is the permittivity of the fluid, where $\varepsilon_r$ is the relative permittivity of the fluid and $\varepsilon_p$ is the permittivity of free space. The Clausius-Mossoti factor $f_{CM} = (\varepsilon_p^* - \varepsilon_m^*)/(\varepsilon_p^* + 2\varepsilon_m^*)$, where $\varepsilon_p^*$ and $\varepsilon_m^*$ are the complex permittivities of the particle and fluid, respectively.

According to the definition of DEP force and the simulation results of electric field distribution, the microparticles, which follow negative DEP such as those under our experimental conditions (permittivity of polystyrene bead=$2.56\varepsilon_0$, permittivity of deionized water=$78\varepsilon_0$), would move in the direction of the strong electric field region to the weak electric field region. In other words, the microparticles in the 3D OET device would be focused onto the middle of the liquid layer and kept apart from the surface of the device [Fig. 2(b)]. Consequently, we can manipulate the target particles free of any surface-particle interactions, when using the 3D OET device.

The polystyrene microbeads that are completely attached to the device surface could not be manipulated in our experimental setup. Through counting the number of unmovable beads as changing the image pattern, we could measure the probability of particle adsorption in the OET and 3D OET devices. The percentage of attached particles according to their size is shown in Fig. 3(a). While more than 50% of particles were adsorbed in the OET device, only a few particles were adsorbed in the 3D OET device. The adsorption of microparticles by surface-particle interactions becomes more apparent when we manipulate relatively larger beads.

![Figure 1](image1.png) FIG. 1. (Color online) Particle adsorption in typical OET. An isotropic DEP force is induced from the light-activated virtual electrodes. As a result, the particle becomes adsorbed to the surface of ground layer by nonspecific surface-particle interactions.

![Figure 2](image2.png) FIG. 2. Schematic diagram of (a) OET and (b) 3D OET. The electric field profiles in the liquid chamber, when 20 V\text{peak-to-peak} at 100 kHz was applied, are also represented. In the OET device, microparticles which follow negative DEP would be moved upward and adsorbed to the surface of ground layer. In the 3D OET, the microparticles would be focused onto the middle of the liquid chamber free of the nonspecific surface-particle interactions.
For the 3D OET, we could manipulate most of the 90 μm diameter beads, despite their size that is large relative to the height of liquid chamber (d/h=0.75, where d and h are the bead diameter and the gap height of device, respectively). In contrast, more than 95% of the microbeads were adsorbed onto the surface of the upper ground electrode and failed to be manipulated in the OET device.

We also measured the velocities of beads according to their size in the OET and the 3D OET [Fig. 3(b)]. We selected only the unattached particles and measured their moving velocities when they are around the image edge, where they moved fastest. The velocity of unattached particles increases as their diameter increases in both OET and 3D OET devices. This result is in a good agreement with the theoretical values, which we can calculate using Stoke’s formula, \( V_{\text{DEP}} = \frac{F_{\text{DEP}}}{6 \pi \eta r} \), where \( \eta \) is the fluid viscosity. The size of the particle being manipulated depends on the gap height of the liquid chamber and the applied voltage, because \( F_{\text{DEP}} \) can be changed by adjusting the applied voltage and the distance between two parallel electrodes. In this study, the minimum particle size, which can be effectively manipulated by OET and 3D OET devices, was 15 μm when we used the gap height of 120 μm and an applied voltage of 20 V peak-to-peak. If we reduce the thickness of spacer and increase the applied voltage, the minimum particle size would be decreased. According to the simulation results shown in Figs. 2(a) and 2(b), the electric field gradients in x axis at the middle of the liquid chamber of 3D OET are almost the same with those at the top region of the liquid chamber of OET. Therefore, we can estimate that the DEP forces, \( F_{\text{DEP}} \), act on the same size particles in both devices would be almost the same. This means that the velocities of moving particles, \( V_{\text{DEP}} \), in both devices would be almost the same. In the experimental results, however, the velocity difference between the 90 μm diameter beads in the OET and them in the 3D OET significantly increased. It is caused by the reason why the frictional forces induced from the surface-particle interactions in the OET device interfere with the DEP movements of microbeads, resulting in the lower particle velocities. The effect of frictional forces that act on the particles becomes magnified as the ratio of bead diameter to liquid chamber height, \( d/h \), becomes close to 1. On the other hand, the particles in the 3D OET were not affected by the surface-particle interactions because they were focused onto the middle of the liquid chamber, segregating from the device surfaces. Therefore, the frictional forces by surface-particle interactions are negligible in the 3D OET.

In this study, we demonstrated the 3D OET, composed of two photoconductive layers as a pair, for three-dimensional trapping and manipulation of microparticles using light-induced negative DEP. We could prevent the surface-particle interactions, which frequently occur in typical OET, with the concept of 3D OET. For the 3D OET device, about 90% of target particles were manipulated without surface attachment, while about 50% of particles were adsorbed onto the device surface in the OET. With the 90 μm diameter beads in the 120 μm liquid layer gap height, about 95% of the beads were adsorbed onto the surface of OET device. Moreover, the velocities of polystyrene beads in the 3D OET become significantly faster than those in the OET as the bead size increases, because the frictional forces by surface-particle interactions were prevented in the 3D OET device. The higher trapping efficiency and adsorption-free particle manipulation resulted in the 3D OET platform to be a more compatible tool for the manipulation of microparticles, including live cells and polymer beads.

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